A RADIOACTIVE-ION BEAM FACILITY

AT iTHEMBA LABS

SCIENTIFIC AND TECHNICAL REPORT

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ABSTRACT

One of the ‘Grand Challenges’ identified by the DST which is most relevant to the role that iThemba LABS plays in the South African community is that of Energy Security. Electricity – 1.8 GW – has been generated by two nuclear power plants in the Western Cape since 1984/85. The country’s ‘Integrated Resource Plan’ of 2010 calls for an increase to 9.6 GW of nuclear power by 2030. Human capacity to support the necessary infrastructure will be critical.

Another of DST’s ‘Grand Challenges’ is Space Science and Technology, which is also dependent on sub-atomic skills. iThemba LABS has already played a key role in calibrating radiation detectors for the International Space Station and the recent NASA Curiosity mission to Mars. The present proposal would put iThemba LABS in a position to support South African satellite initiatives through radiation-hardness testing of materials and electronics.

iThemba LABS plays a leading role in the training of post-graduates in the nuclear sciences in South Africa. The separated-sector cyclotron (SSC) accelerator at iThemba LABS – already the premier nuclear particle accelerator in Africa and in the Southern Hemisphere – is part of a multidisciplinary facility that supports research into nuclear and materials sciences, provides cancer therapy based on neutron and proton beams and provides hospitals in South Africa and abroad with radioisotopes for medical diagnostics. It supports the wider South African nuclear community by vigorously developing the human resources required for these fields.

However, the shared use of this multidisciplinary facility has now reached the point where further growth of the respective disciplines is restricted: the different disciplines compete for the limited beam time and, as a result, South African science and radiation medicine are losing their place at the international forefront of these disciplines.

We propose a staged development of a radioactive-ion beam facility at iThemba LABS to address these issues and to bring the laboratory to a position of international leadership in these fields.

The first stage would see the addition of a high-current, 70-MeV negative-ion (H⁻) cyclotron to iThemba LABS.

This cyclotron would take over the production of radioisotopes, 24 hours a day, thus releasing the SSC to be dedicated to physics research – mainly nuclear physics – and to neutron radiotherapy. Proton therapy is assumed to be transferred to the proposed iThemba Particle Therapy Centre, a private-public partnership which is currently before Cabinet for approval.

In parallel with the first stage, a Research and Development programme into radioactive-ion beam production will be launched, with a 2-year Technical Design Study to study innovative technologies and risk minimization, along with construction of a Target & Ion-Source Test Facility in collaboration with the Italian INFN-Legnaro laboratory and with JINR-Dubna in Russia.

The capacity for training in physics would be doubled and the links with international collaborations would be considerably strengthened owing to the increased availability of beam time – currently restricted to weekends only, which is unsatisfactory for sustained data-taking. The income from the greatly increased production of radioisotopes would provide significant cost-recovery for the capital outlay.

The second stage would see the production of radioactive-ion beams, bringing nuclear and materials research and training in South Africa to the international forefront.

The so-called ‘terra incognita’ – the unknown part of the table of nuclides – includes the unstable ‘neutron-rich’ nuclei, which cannot be produced using beams of the stable atoms found in nature.
Internationally, interest is focusing on the study of these nuclei, because they hold the key to our understanding of nuclear forces and the origin of the elements of which the Universe is composed. Neutron-rich nuclei can only be created and studied in the laboratory by using beams of artificially produced radioactive-ion beams from an accelerator such as a cyclotron.

Since two H⁻ ion beams can be extracted simultaneously from the proposed new 70-MeV cyclotron, one of these will be used to produce radioactive ions via the isotope-separation-on-line (ISOL) method. These ions will then be formed into a beam which can then be post-accelerated by the existing SSC for use in nuclear physics experiments.

Radioactive-ion beams are also attractive for materials science. The radioactive ions can be implanted into materials of industrial interest such as semiconductors, and the perturbations of their decay can yield important information on the atomic structure of the material.

The production of radioactive-ion beams is intellectually challenging and will require considerable development and design effort. We propose to use this as an important opportunity for human resource development by linking to South African universities and technikons.

**Cost-recovery from radioisotope sales** is expected to exceed R60-million per annum, more than doubling the present annual income.

The new facility will require expenditure on:

- a high-intensity 70-MeV H⁻ cyclotron;
- target stations for radioactive-ion beam production;
- new target stations for isotope production;
- upgrades to existing infrastructure for physics research;
- civil engineering to accommodate the new facilities;
- temporary staff and students during the construction period.

The temporary staff and students engaged in this innovative project will form an ideal source for replacement of existing personnel who leave iThemba LABS or reach retirement age. Some of these will also be required for ongoing maintenance and operation of the enlarged accelerator facility.

The overall cost of the project is estimated to be of the order of R994-million, expended over a number of years. Once completed, the new facility will add to the operating costs of iThemba LABS.
1 INTRODUCTION

We propose that a new radioactive-ion beam and isotope production facility be constructed at iThemba LABS. The project is divided into several stages, corresponding to two main phases plus a preliminary research and development phase. The phases are therefore:

- **Research and Development Phase:** As this is a very large project at the cutting edge of RIB production, a *Technical Design Study* will be required, commencing in 2012, which will study the areas where technological development is needed, and act as a risk-minimization action. This Technical Design Study will be of immense value in providing training for a number of MSc and PhD students in Physics and Engineering, and will also be a source of manpower for the implementation of the later phases of the project. The *Technical Design Study and its various Work Packages are described in detail in a separate proposal.*

A *Target/Ion-source Test Facility* for radioactive-ion beam production studies will be constructed in an existing shielded area, where a beam of protons of up to 66 MeV energy from the SSC can be used to test targets and ionization methods, and demonstrate the ability to produce radioactive-ion beams. Construction of the facility will start in 2012. *This Test Facility and is described in detail in a separate proposal.*

The production of neutron-rich radioactive beams using the so-called ‘converter’ method will also be studied during this phase, for future implementation in the main project.

This R&D phase will run in parallel with the following phases.

- **Phase 1:** A commercial 70-MeV cyclotron will be installed in a new shielded building, with beamlines serving several target stations in two radioisotope production vaults, together with ancillary service buildings for control and operation of the facility. *We note that delivery of such a machine can take approximately 3 years after ordering, which underlines the need for this phase to start in 2012.*

- **Phase 2(a):** New target areas will be constructed for the production of low-energy radioactive-ion beams using the Italian SPES target/ion-source. It will include an extension to link the existing Accelerator Hall to the buildings of Phase 1, and will contain two well-shielded radioactive-ion beam production vaults, together with beamlines and experimental areas for low-energy materials science and nuclear physics.

A Memorandum of Understanding between iThemba LABS and the INFN laboratory in Legnaro, Italy, has already been drawn up, which includes testing the SPES target at iThemba LABS in the Target/Ion-Source Test Facility mentioned above.

- **Phase 2(b):** The radioactive-ion beams will be accelerated to high energies, using the existing Separated-Sector Cyclotron (SSC). A beamline will transport the radioactive ions through the basement to a so-called ‘charge-breeder’ to increase their charge-state. The high-charge-state ions will then be injected from below into the existing SPC2 injector cyclotron, which will then permit re-acceleration in SPC2 and the SSC to high final energies.

The high-energy radioactive-ion beam will subsequently be transported to existing and new experimental areas for nuclear physics and materials science.

Figure 1.1 overleaf illustrates these phases in relation to the plan of the existing accelerator facilities. More detailed plans of Phases 1 and 2 are also shown in later sections (i.e. figures 6.4 and 7.23 respectively).
Fig. 1.1: The location of buildings in Phase 1 (pink) and Phases 2(a) (yellow) and 2(b) (green) at iThemba LABS. Existing buildings are shown in black, with the shielded walls already present outlined in blue. More detailed drawings of Phases 1 and 2 are shown later (in figures 6.4 and 7.24 respectively).
1.1 OUTLINE OF THE PROJECT

1.1.1 A NEW COMPACT CYCLOTRON

To limit costs, the project is based on the acquisition of a single commercially-available negative-ion (H⁻) compact cyclotron capable of delivering two high-current beams (each up to 350 µA) of 70-MeV protons for the production of radioactive-ion beams (RIBs) for nuclear physics and materials science research, as well as cost-recovery from increased radioisotope production.

1.1.2 EXPANDED RADIOISOTOPE PRODUCTION FACILITY

Phase 1 of the present proposal (see figure 1.1 and also figure 6.4 in section 6.3) includes construction of a shielded concrete vault to house a commercially-available 70-MeV compact cyclotron, with beamlines leading to two shielded isotope production vaults, comprising:

- A ‘medium-intensity’ vault equipped with three beamlines, two of which will be provided with well-shielded target containers similar to those already in use at iThemba LABS, for routine production of short-lived radioisotopes for the local market, plus a third beamline for development and testing of new target materials and production methods;

- A ‘high-intensity’ vault with two beamlines for relatively long production runs of isotopes for export (with two- to four-week runs), typically with molten-metal targets, again inside heavily-shielded target containers;

- Rooms for power supplies, switchgear, electronics, air-handling and cooling water will also be constructed. Feeds of power and water supplies will be routed via the basement level. Control will be exercised from the existing cyclotron Control Room via a fibre-optical or Ethernet connection. A small local control room will be needed to control access and a rail-based target transport system, respectively, as in the present Radionuclide Production building.

As this new facility will run 24 hours a day, the amount of radioisotopes produced will be significantly increased over what is currently possible, with a consequent increase in the amount of revenue earned from exports. A full description of the expected production is given in section 5.1.

1.1.3 RADIOACTIVE-ION BEAM FACILITY

Phase 2(a) of the proposal includes two well-shielded concrete vaults for production of RIBs. (See figure 1.1 and figure 7.24 in section 7.5.) One of these will initially be equipped with a copy of the SPES ‘direct’ target/ion-source assembly of INFN Legnaro. The second vault will be available for different target/ion-source assemblies, such as a ‘converter’ target, discussed in section 1.1.4 below. The target components will quickly become very radioactive, and these will need to be removed and replaced using a dedicated remote-handling robot. This will store the active components in a suitably-shielded storage rack, as is done at CERN-ISOLDE, for example.

Because laser ionization is very selective method of ionizing atoms, a small laser laboratory will also be needed to produce and direct suitable laser beams into the ion sources.

The RIBs produced will be pre-analysed to reduce the amount of unwanted radioactive ions as well as contaminant ions such as oxygen, nitrogen, etc. Thereafter a high-resolution mass-spectrometer will resolve and separate both isotopes and isobars. To improve the transmission of this device, a beam cooler will be installed, in which the beam exchanges energy with a noble gas such as helium, thus reducing its energy and consequently its emittance, leading to a smaller focused beam.

The mass-analysed RIBs will then be used in low-energy nuclear physics and materials science, in the extension of the present Accelerator Hall. The beam energy will be about 60 keV, depending on the extraction voltage used for the target/ion-source platform.

3
In Phase 2(b), we propose to inject the RIBs into the existing injector cyclotron SPC2, via the normal axial injection line in the basement. However, to increase the energy of the final beam, it will be necessary to boost the charge-state of the ions by means of a so-called ‘charge-breeder’. Present plans foresee the use of a commercial charge-breeder, such as the PHOENIX ECR ion source manufactured by Pantechnik in France.

Another promising device is the ‘electron-beam ion source’ offers superior charge-breeding efficiency for some ions. An EBIS could replace, or be built in parallel with, an ECR source. To reduce charge-exchange losses in the long beamline leading to SPC2, the charge-breeder must be fairly close to SPC2, i.e. in the new basement area adjacent to the existing building.

After injection into SPC2 the RIBs will be accelerated successively, first in SPC2, then in the existing separated-sector cyclotron (SSC), and finally directed to the existing nuclear physics experimental vaults. An additional experimental area for both nuclear physics and materials science is also proposed in this phase.

Planned revision of the SPC2 injection system, a new double-drift buncher before SPC2, and addition of variable-frequency flat-topping systems for both SPC2 and the SSC, plus improvements to the vacuum systems of both SPC2 and the SSC, should lead to much improved transmission through the accelerators and beamlines, i.e. approaching 30% overall.

With a revised schedule of operation, each week in a 20-week period of the year will be shared between radiotherapy and physics, while two 12-week periods will be dedicated to nuclear physics (and materials science) for continuous periods of operation without interruptions for radiotherapy or isotope production. (Short maintenance periods will occupy the remainder of the year.)

1.1.4 RESEARCH AND DEVELOPMENT

The Research and Development Phase will include a Technical Design Study, and a radioactive beam Target/Ion-Source Test Facility.

The two-year Technical Design Study will target the areas of technological innovation needed for RIB production, and will aid in risk minimization. The Target & Ion-Source Test Facility will be installed in an existing heavily-shielded vault and used to investigate targets and ion sources. The intention is to install a copy of the SPES target/ion-source assembly, for which a MoU has been drawn up jointly by INFN-LNL and iThemba LABS. This programme will begin in 2012 and continue until Phase 2.

A laser ion source will also be used in this preparatory phase, for which a small laser laboratory will be established, and which will facilitate investigation of suitable laser frequencies for selective ionisation of rare isotopes. This laboratory will later be transferred to Phase 2, along with the entire target station.

This Test Facility will also be used to investigate a so-called ‘converter’ target, in which a rotating target-wheel is bombarded with protons to produce an intense flux of neutrons, which will then irradiate a uranium carbide target (UC₃) to produce fission products.

It has been shown by calculation that the ‘converter’ method plus a UC₃ target can lead to an order of magnitude more ions than the ‘direct’ method of protons on a UC₃ target, especially for isotopes far from stability.

Such a ‘converter’ target can be installed in one of the two RIB production vaults of Phase 2. Since the two RIB vaults can be accessed by the same robot, it will also be possible to use either vault for ‘direct’ target production, which is in principle simpler than using the ‘converter’.

A number of studies will be required to make these developments possible, and some of these will be ideal subjects for MSc or PhD theses.
2 THE GRAND CHALLENGE

2.1 ENERGY SECURITY AND HUMAN RESOURCE DEVELOPMENT

One of the ‘Grand Challenges’ identified by the DST that is most relevant to the role iThemba LABS plays in the South African community is that of Energy Security. The Integrated Resource Plan of 2010 calls for 9.6 GW of nuclear power by 2030, in a programme estimated by the Energy Minister, Dipuo Peters, to cost at least R1-trillion (Reed, 2012). However the challenge is not only financial, but also in human capacity building in the nuclear sciences to service such a large project.

Clearly, the demands on human resources needed to support a nuclear industry of the proposed dimensions are considerable, requiring a substantial investment in human resources at the highest levels. While nuclear reactor technology is the province of nuclear engineering, the radiation safety and protection of both workers and the environment are fields which require personnel trained in the measurement techniques of nuclear physics.

2.2 SPACE SCIENCE AND TECHNOLOGY

Another of DST’s ‘Grand Challenges’ is Space Science and Technology, which is also dependent on sub-atomic skills. iThemba LABS has already played a key role in calibrating radiation detectors for the International Space Station and the recent NASA mission which landed the Curiosity rover on Mars. The present proposal would put iThemba LABS in a position to support South African satellite initiatives through radiation-hardness testing of materials and electronics.

Sub-atomic skills are also critical in many industries: in nuclear medicine for the diagnosis and treatment of diseases; in radiation monitoring in the mining, construction, food and health industries; in environmental studies and palaeontology and geological dating; in water-resource studies using isotope ratios; and in analytical methods in geology and materials sciences.

2.3 RESEARCH AND TRAINING

The research facilities at iThemba LABS play an important role in post-graduate training in a wide variety of fields that include sub-atomic physics, medical physics, materials science and nanoscience, radiobiology and radiochemistry. Strong links exist between research and training at iThemba LABS through the involvement of post-graduate students in research projects, and making research facilities and expertise available to students from all Universities. In order to expand the present training programmes and to maintain quality as a non-negotiable principle, strong teaching and research groups in both the Universities and in National Laboratories are needed. The latter are essential for the location of major and expensive items of equipment to ensure their maintenance, development and full utilization by all members of the scientific community.

Research infrastructure has to be upgraded continuously, in order to allow scientists to contribute to research at the forefront of developments in these fields, and thus to expose post-graduates to internationally competitive research and research equipment and simultaneously enhance training opportunities in a variety of technical fields.

Because the project is multidisciplinary, the potential for outreach and increased collaboration with Historically Disadvantaged Universities – which may not have formerly been involved in the nuclear sciences – is far greater than if the project had been confined to nuclear physics alone.

iThemba LABS has been vigorous in its attempts to address the skills shortage with training programmes that include its jointly-run graduate schools, i.e. MARST (Masters in Applied Radiation Science and Technology) at the North West University, and MANuS (Masters in Accelerator and Nuclear Science) and MatSci (Masters in Materials Science), a joint graduate school run together with the University of the Western Cape and the University of Zululand. A further graduate course,
an MSc in Organisation of Nuclear Energy (MSONE), started in 2010 in collaboration with the University of Johannesburg and the Tshwane University of Technology.

iThemba LABS considers it a priority to promote the participation of Historically Disadvantaged Universities in all stages of the project. Support in the form of bursaries, appointments, travel funds and local infrastructure will need to be integral to the project. As an indication of the success which has been achieved in the past, we have attached a list of previous MSc and PhD students who had completed their research using the SSC at iThemba LABS by the year 2008, together with their present employment, in Appendix 1.
3 THE PHYSICS CASE

In this section we highlight the physics to be addressed by the new facilities. We divide them into nuclear physics and materials sciences.

3.1 NUCLEAR PHYSICS

The nuclear physics programme will evolve through the different phases of the project. The increase of stable beam time after Phase 1 is completed will allow experiments that previously could not be contemplated, due to the shortage of beam time on the SSC. After the completion of Phase 2, experiments utilizing radioactive-ion beams will commence. Experiments using stable beams can still be performed, in the times when the radioactive-ion beams are used for materials research, or when a new radioactive-ion beam is being prepared.

3.1.1 NUCLEAR PHYSICS: GRAND CHALLENGES

The discovery of the atomic nucleus is now over a century old. Nevertheless, a complete mathematical description of the nucleus remains elusive. This is in no small part due to the complexity of the nuclear force and the computational difficulty of solving the Schrodinger equation for a many-body system. A couple of examples serve to illustrate the difficulties.

The first is the famous Hoyle state of Carbon-12. Its existence was postulated in 1954 by Fred Hoyle, [Hoyle 1954] as a necessary condition for the synthesis (in stars) of elements heavier than helium. The significance of this state is that without it, the elements of which all life on earth is made would not have been created in abundance. Although the predicted state was experimentally verified within a few years [Cook 1957], the theoretical description of this state has proved elusive until last year (2011), nearly 60 years after its discovery, with the publication of the first ab initio calculation of the Hoyle state [Epelbaum, 2011]. However, ab initio calculations presently end at $^{12}$C. For heavier masses, theorists rely on nuclear models of various levels of sophistication to make predictions of nuclear properties.

Our next example highlights the difficulties of calculating a quantity as basic as the mass of the nucleus. In figure 3.1, the differences between the prediction of various mass models and measured masses for isotopes of caesium, are plotted. Where the masses have been measured ($60 < N < 93$) the agreement between the models and with data is good. Outside of this range, the poor agreement between the models reflects the weaknesses of modern nuclear structure theories: even a quantity as fundamental as nuclear mass cannot be predicted accurately.

Nuclear Physics is thus a field which is heavily dependent on measurements to verify nuclear models. Unfortunately, measurements of nuclear properties have, until very recently, been confined to the study of naturally occurring nuclides and those that are deficient in neutrons.

This is because in the past, studies of nuclear phenomena at low energies have been restricted to reactions induced by stable beams. This restriction has limited the number and type of artificially produced nuclei that can be studied and it has limited the way in which they can be studied – in other words, it is not enough merely to create an artificial nucleus, it is also necessary to excite it in such a way as to reveal its inner structure.

Firstly, consider the production mechanisms: typically the species that have been produced have been neutron-deficient nuclei – isotopes that have fewer neutrons than their stable counterparts. This is a consequence of two factors. The first is that light stable beams usually have nearly equal numbers of protons and neutrons. But stable heavy nuclei have increasingly more neutrons than protons as their mass increases. This implies that when a light beam fuses with a heavy target, to produce an even heavier (and radioactive) nucleus, it will necessarily be neutron-deficient. This is compounded by the second factor: that is that the fused nucleus preferentially decays by neutron emission, as neutrons are not confined by the Coulomb potential.
Fig. 3.1: Predictions of various mass models compared with known masses (60<N<93). For N>93, where measured masses are unavailable, the models differ from each other considerably. [Blaum 2006]

Thus the nuclear chart (shown in figure 3.2) is much better studied in the region of stability and neutron-deficient nuclei than it is in the neutron-rich region. In this figure, “terra incognita” represents the region of nuclides that are expected to exist but which have not been observed yet. It is bounded on the neutron-rich side by the so-called neutron “drip-line”, beyond which additional neutrons cannot be added to the nucleus as they are expected to be unbound. The exact position of the neutron drip-line is unknown, being subject to theoretical uncertainties. In contrast, the proton drip line, the line beyond which nuclei are particle-unstable to the addition of extra protons, has already been reached.

Secondly, to understand the inner structure and dynamics of the nucleus, it must be possible to excite the nucleus by different means. This excitation is often provided by the nuclear reaction which created the artificial nucleus in the first place, but if this reaction does not reveal the required information, a second reaction is required. This can be done if a beam is formed from the products of the first reaction, and is then allowed to react with a second target.

Different excitation mechanisms populate different excited states of the nucleus and provide stringent tests of nuclear models. Coulomb excitation and transfer reactions are not possible, even on neutron-deficient nuclei, unless these nuclei are produced artificially and accelerated as radioactive-ion beams. These reaction mechanisms are important probes of the nuclear shape and of correlations between particles in the nucleus. They would allow basic tests of nuclear phenomena, such as pairing and surface vibrations, which are still not fully understood despite decades of research.
Thus the focus of international research in nuclear physics is now moving towards the study of the hitherto inaccessible regions of the nuclear chart – the so-called neutron-rich nuclei and even proton-rich nuclei which could not previously be studied in an appropriate manner.

![Nuclear Landscape](image)

**Fig. 3.2: Nuclear chart showing known and unknown nuclei. Those coloured in black are stable; yellow delineates observed nuclei, while green defines the region of unknown nuclei. No nuclei are expected to exist beyond the proton and neutron drip-lines (red contours). [ISOL 1999]**

### 3.1.2 Evolution of Shell Structure

In 1949 Maria Goeppert-Mayer and J. Hans Jensen developed the nuclear Shell Model (SM) for which they received the Nobel Prize in 1963. This model has been the cornerstone of understanding the properties of nuclei ever since. The addition of the spin-orbit force to the “mean-field”, experienced by protons and neutrons within the nucleus, explained the so-called “magic numbers” – particular combinations of proton and neutron numbers for which the nuclear binding energy is particularly large. It posited the existence of energy levels filled by nucleons; large gaps between these levels give rise to the large nuclear binding energies observed, and so nuclei with filled shells at these magic numbers are especially stable. Nuclei which are “doubly-magic” (in which both proton and neutron numbers are “magic”) correspond to nuclei which have a spherical shape, while those with numbers in between the magic numbers are deformed, typically with a rugby-ball shape.

The SM was soon extended to cover deformed nuclei by Nilsson, Bohr and Mottelson (for which the latter two shared the Nobel Prize with Rainwater in 1975). With this innovation it became possible to predict the existence of shell-gaps at deformed shapes, and excited states of nuclei with extremely elongated shapes such as superdeformation and hyperdeformation. Finer details of nuclear structure could be explained by including “residual interactions” to the shell-model potential, of which the pairing interaction is one of the most important.
However, despite the incredible success of the SM over the decades, it remained a model tested in nuclides located chiefly near the line of stability and to the neutron-deficient side. Moreover, because the nuclear force must overcome the Coulomb repulsion between protons to bind them to a nucleus, there are expected to be many more neutron-rich nuclides than neutron-deficient species. The neutron-rich region remains a much larger testing ground of nuclear models. In recent years, the study of neutron-rich nuclei has presented severe challenges to the traditional nuclear shell model.

The neutron-skin: modifying the shell model potential

The nuclear shell model is a mean-field model: it assumes that nucleons move in an average potential created by the other nucleons of the nucleus. As such, the mean field closely follows the density of nucleons in the nucleus. A good approximation to the nuclear potential is the Woods-Saxon potential. It is approximately a smoothed-out “square-well” potential. When the number of protons and neutrons in a nucleus are similar, their distributions throughout the nucleus are also similar – their rms radii are almost equal. It is only when there is a large excess of neutrons over protons that differences appear. In heavy stable nuclei, which have an excess of neutrons over protons, there is the emergence of a neutron “skin”.

For example, in the case of the doubly-closed shell nucleus $^{208}\text{Pb}$, which has 126 neutrons compared to only 82 protons, a neutron skin thickness of 0.17–0.25 fm has been measured [Tamii 2011]; and in tin isotopes, an increasing neutron skin thickness with increasing neutron number has been reported [Krasznahorkay 1999]. This picture is supported by e.g. Skyrme Hartree-Fock calculations, which predict that with the addition of even more neutrons, the skin will thicken further [Werner 1997]. The nuclear potential is expected to become smoother, and since the strength of the spin-orbit potential is proportional to the gradient of the mean field, the smoothing of the nuclear density will also weaken the spin-orbit force. Consequently the Shell-Model level structure is expected to change and evolve to a shell structure similar to that of a pure harmonic oscillator. The shell-gaps at the magic numbers known in stable nuclei are expected to weaken and disappear with increasing neutron number, to be replaced by new magic numbers appropriate for a harmonic-oscillator potential.

Approaching the neutron drip-line: coupling to the continuum

One of the most exciting challenges faced by the traditional shell model in recent years has been due to the discovery of “nuclear halos” as the neutron drip-line is approached in very light nuclides [Riisager 1994]. The energy required to separate a neutron from a nucleus, $S_n$, is given by

$$S_n = -\lambda - \Delta_n$$

where $\lambda$, the Fermi level, is a measure of the shell model level spacings, and $\Delta_n$ the neutron pairing gap, a measure of the strength of the residual pairing interactions.

Near the neutron drip-line $S_n = 0$, so that unlike nuclei near the line of stability, the pairing field can no longer be considered a perturbation, but is of similar order to the shell model level spacings. Levels close to the Fermi level couple to unbound states in the continuum [Dobaczewski 2007]. The mixing of loosely bound states leads to extremely extended wave-functions of the valence neutrons.

The classic examples of this situation are the so-called “halo nuclei”. For example, $^6\text{He}$ is a nucleus which is regarded as having a halo – comprised of a pair of neutrons – outside of an alpha particle core. The halo of $^{11}\text{Li}$ is of extremely large extent, giving it the size of the much heavier nucleus $^{208}\text{Pb}$ (figure 3.3).
These neutron-rich isotopes are presently inaccessible at iThemba LABS, but the subject of coupling to the continuum is one of intense interest at the laboratory.

Clustering in nuclei becomes important for states in nuclei that lie close to their cluster decay threshold and is intimately connected with continuum coupling. A classic example of clustering in nuclei is in fact the Hoyle state, which is understood to be cluster of three alpha particles. It lies at 7.65 MeV, just above the triple-alpha threshold at 7.275 MeV. It is the triple-alpha structure of this level that has eluded description by shell model calculations. If the Hoyle state is in fact a cluster state, it should be deformed and able to rotate, yet it was not until 2009 that scientists were able to detect a $2^+$ resonance that could be identified with the rotation of the Hoyle state. This breakthrough was performed at iThemba LABS using the K600 spectrometer [Freer 2009] (figure 3.4).

Cluster structures are studied predominantly via break-up reactions. In exotic nuclei, cluster properties are predicted to be of importance in neutron-rich to extremely neutron-rich systems. The study of resonances can be used to study in detail the structure of nuclei above the particle-
decay thresholds. Important information such as total and partial widths, excitation energies and spins should be extracted. Light-ion neutron-rich beams can be used to populate cluster states in inelastic reactions. For instance $^6\text{He}$ beams are extremely useful to probe the molecular states involving neutron-rich helium isotopes in $^{12}\text{Be}$, $^{22}\text{O}$, $^{26}\text{Ne}$. The two-proton pick-up or two-neutron stripping reactions can both be used to study neutron-rich nuclei.

Gas targets involving $^{14}\text{C}$, $^{18}\text{O}$ or $^{22}\text{Ne}$ can be used to determine the properties of $^{12}\text{B}$, $^{16}\text{C}$, $^{20}\text{O}$ and $^{24}\text{Ne}$ nuclei. Those nuclei are particularly interesting owing to their alpha-like cluster configurations stabilized with valence neutrons. Light neutron-deficient nuclei such as $^{14}\text{O}$ and $^{18}\text{Ne}$ are of great interest for cluster state studies for 2-proton unstable nuclei.

3.1.3 The Tensor Force

While the inclusion of the spin-orbit force in the nuclear shell model has been critical to its success, it is only recently that the importance of the tensor interaction – which has its origin in the pion-exchange process – is becoming fully appreciated through the study of neutron-rich nuclei [Otsuka 2001]. The tensor force operates between protons and neutrons in spin-flip partner orbits. Thus the traditional shell-model gap at neutron number N=20 – manifest in the stable nucleus $^{32}\text{Si}_{16}$ – is in fact caused by the tensor force and disappears in neutron-rich $^{24}\text{O}_{16}$, only to be replaced by a new shell gap at N=16. The massive changes in the nuclear shell model due to the tensor force are not confined to relatively light nuclei in the mass 30 region but are universal, with evidence that it also influences the spacings of shell-model orbitals such as the $g_{7/2}$ and $h_{11/2}$ orbitals in the Sn region [Otsuka 2005].

3.1.4 Towards the Superheavy Elements

The heaviest known doubly-magic nucleus (that is, with both proton and neutron shells closed), is lead-208. Elements heavier than lead are unstable; those with atomic number greater than Z = 100 are particularly unstable against fission. The nuclear forces are no longer able to overcome the destabilizing effect of increasing Coulomb repulsion. Nevertheless, extra stability is predicted as a result of shell effects. Perhaps the most exciting is the prediction of an island of relative stability around a new, super-heavy, doubly-magic nucleus. Just as nuclear masses become uncertain as one extrapolates into the neutron-rich region, the precise location of the “island of stability” is subject to theoretical uncertainty due to the necessity of extrapolating nuclear models. Most estimates, and indications from experiment, point to Z = 114 and N = 184 as the likely values for the new doubly-magic nucleus (i.e. the flerovium nucleus $^{298}_{114}\text{Fl}_{184}$) [Nilsson 1995].

These numbers place the island of stability firmly in the region of “super-heavy elements” that must be synthesized artificially. The reaction cross-sections for the production of these elements are extremely low, in the picobarn region, or approximately 12 orders of magnitude smaller than that of a typical fusion-evaporation reaction [Oganessian 2010]. Hence, for example, only six atoms of element Z=117, with 176 neutrons, have been produced and detected to date. Two types of reaction are used to populate the superheavy elements, the so-called cold fusion and hot fusion reactions. As the name implies, in hot fusion the compound nucleus is created at high temperature: this temperature would normally imply an increased probability of fission, but it has been found that the survival probability of the compound nucleus increases with increasing neutron number.

This information points towards extra stability as a closed shell – presumably at N=184 – is approached. Conversely, in cold fusion reactions, the compound nucleus is formed at low temperatures, and in this way reduces the fission probability. In practice a cold nucleus is formed by using as low a beam energy as possible. In this case, it is important to take into account of the probability that the beam will quantum mechanically tunnel through the Coulomb barrier to fuse with the target. Subtle effects now become important: for example, the deformation of the target and beam nuclei can split the barrier into a distribution of barriers which may enhance fusion at low energies.
Because N=184 is so neutron-rich, it will be impossible to synthesize $^{208}_{114}$F without neutron-rich radioactive beams. Unfortunately, radioactive beam intensities with the present generation of facilities will be of insufficient intensity to compensate for the very low production cross sections. Nevertheless, it will be possible to study the reaction mechanisms leading to super-heavy element creation, particularly in the case of cold fusion reactions, where it is necessary to understand the barrier penetration of the beam into the target nucleus. Because the flux transmitted through the barrier is related to the flux that is scattered from the barrier, the barrier distribution can be determined by measuring the quasi-elastic scattering of the beam, a process which has a relatively large cross section. In fact, iThemba LABS is one of the pioneers of this technique, having measured the barrier distribution for the $^{84}$Kr + $^{208}$Pb reaction, (which, would correspond to the super-heavy element with $Z = 118$) [Ntshangase 2007].

An obvious and important extension of this study is to map out the fusion barriers for reactions leading to the synthesis of $^{208}_{114}$F (see figure 3.5). In particular, it is important to study the modifications to the barrier as a result of increasing neutron number, in order to optimize the production of superheavy elements for future facilities.

Fig. 3.5: Smoothed fusion-barrier distribution for the $^{84}$Kr + $^{208}$Pb reaction, measured at iThemba LABS. [Ntshangase 2007]

3.1.5 EXOTIC SHAPES AS A TEST OF SHELL STRUCTURE

The extension of the shell model to deformed shapes, such as the Nilsson model, has provided another avenue to stringently test the model. In this model, exotic shapes such as “superdeformation” – where the nucleus is twice as long as it is wide – are predicted to be stabilized by new shell gaps that open up, not as a function of proton or neutron number, but as a function of deformation. The most spectacular example of the success of the deformed shell model, is the prediction of a superdeformed shape in the nucleus $^{152}$Dy, which was confirmed experimentally by a former Director of iThemba LABS and his co-workers [Twin 1986].

Superdeformation was the subject of intense research throughout the 1990s, but the deformed shell-model has also predicted other exotic shapes such as “hyperdeformation” – where the nucleus is three times as long as it is wide – and even tetrahedral shapes, where the nucleus has been dubbed a ‘nuclear pyramid’, as shown in figure 3.6. [Cwiok 1994, Dudek 2002, Werner 1992].
Unfortunately, to date, neither the gamma-decay of hyperdeformed nor tetrahedral nuclei have been observed. iThemba LABS has had an active research programme searching for both of these shapes. As a result of work done at the laboratory, some of the best candidates for the tetrahedral shapes in nuclei accessible with stable beams have been ruled out [Bark 2010, Ntshangase 2010]. What remains are exciting predictions of nuclei with tetrahedral ground states in neutron-rich zirconium isotopes, $^{104-112}$Zr [Schunck 2004]. The proposed facility would be capable of producing these Zr beams with sufficient intensity to test the prediction of tetrahedral shapes.

3.1.6 VIBRATIONAL DEGREES OF FREEDOM

While the giant resonances represent large amplitude collective motions of the nucleus, another form of collective motion are the smaller-amplitude surface vibrations. In the simplest picture, the collective model developed by the Nobel prize winners Bohr and Mottelson, they are described by harmonic-oscillator potentials, with the vibrations quantized into phonons [Bohr 1975]. The simplest vibrations are the one-phonon quadrupole and octupole vibrations, which in spherical nuclei give rise to $2^+$ and $3^-$ states. It is when vibrations with two or three phonons are excited that the picture of harmonic vibrations in nuclei becomes uncertain.

The two-phonon quadrupole vibrations should form a triplet of states with spins 0, 2 and 4 while three phonons would give rise to a quintuplet. Such multiplets have been observed, for example, in the text-book case of the cadmium isotopes; the energy systematics fit the simple picture extremely well. But recent research, employing improved experimental techniques, has allowed the simple picture to be tested more thoroughly. By using Coulomb excitation for example, it is possible to measure electromagnetic transition rates and moments. The $\gamma$-ray decay from the multiplets is found to be in discord with the collective model [Garrett 2010].

A more complex picture emerges where many of the members, assumed originally to be part of the vibrational multiplets, apparently are not of vibrational character at all, but are rather caused by the excited nucleus assuming a different shape, together with its corresponding rotation. This phenomenon is known as “shape-coexistence”, the most spectacular examples being that of superdeformation, described above. However, the vital question of whether nuclei can truly be said to vibrate is an open one that can only be tested by detailed and thorough experimental analysis.

Such investigations are already underway at iThemba LABS, but without radioactive beams. Coulomb-excitation studies, for example, can only probe the select nuclei (such as the isotopes of Cd) that lie near the line of stability. Coulomb excitation of nuclei away from the line of stability can only be performed with radioactive beams, where the beam itself is Coulomb-excited.
3.1.7 The study of angular momentum coupling schemes.

The subject of high-spin physics has been one of understanding the response of the nucleus to rotation and the different ways angular momentum can be accommodated. One way is through the collective rotation of the entire nucleus; another is through the alignment of the angular momenta of the individual nucleons. The nucleonic angular momentum may align with the deformation of the nucleus to form the so-called “high-K states”, where K is the quantized angular momentum component on the deformation axis. Such high-K states are relatively pure and their $\gamma$-decay is inhibited by the conservation of the K-quantum number.

A rare decay of a six-particle, K=25 isomer in osmium-182 to the ground-state band (with K=0) is a classic example of the violation of this principle and an indication of K-mixing leading to impurities in the wave-function [Chowdhury 1988]. The integrity of the K-quantum number with particle number excitation is an open question. To form high-K states with many more than six particles requires the occupation of shell-model orbitals with large K-projection. These are located at the top of a given shell. In the mass 180 region, it is the N=6 neutron shell that provides the highest-K orbitals. To occupy these orbitals, one needs to produce relatively neutron-rich nuclei that ideally lie to the right of the line of stability in the mass 180 region and heavier.

In the chart of the nuclides, osmium-182 is itself two neutrons to the left of stability; but to create a nucleus even on the line of stability at high-spin (i.e. high-K), one would need a heavy, neutron-rich beam to fuse with a neutron-rich target. Although calculations show that such a reaction would immediately favour the evaporation and loss of neutrons, they also predict that nuclei on the line of stability would be populated appreciably at high spins. For example, heavy osmium isotopes could be produced at high-spin with the use of a radioactive $^{144}$Ba beam on a stable $^{48}$Ca target, as shown in the figure below.

*Fig. 3.7: Calculated yields as a function of beam energy for the reaction $^{144}$Ba + $^{48}$Ca*
In triaxial nuclei, it has been predicted [Frauendorf 1997] that the nucleus can accommodate angular momentum on three axes simultaneously, the core angular momentum being aligned with the intermediate axis, with proton or neutron angular momentum aligned on the remaining axes. The coupling scheme can in principle be left- or right-handed giving rise to “nuclear chirality”. However, nuclear chirality depends on favourable conditions [Lawrie 2010], one of the most basic being a triaxial nucleus. As a result it is only found in limited regions of the nuclear chart. Chirality has recently been extended to the mass-80 region in work performed at iThemba LABS through a collaboration with China [Wang 2011], but to firmly establish the phenomenon it will be necessary to push into hitherto unexplored regions on the neutron-rich side of the chart.

3.2 THE ORIGIN OF THE ELEMENTS

One of “The 11 Greatest Unanswered Questions of Physics”, identified by the National Research Council of the USA, is “How were the elements from iron to uranium made?” [Haseltine 2002].

The question is as much one of nuclear physics as one of astrophysics. It is well understood that most of the nuclides between carbon and iron are produced in nuclear fusion reactions inside red-giant stars, but beyond iron, the process is mysterious because many of the nuclear reactions must now involve nuclides in the unknown, neutron-rich, region of the nuclear chart.

3.2.1 THE R-PROCESS

For elements heavier than iron, fusion reactions become endothermic and are no longer a favoured production mechanism. Production of these elements occurs by a combination of $({\text{n}}, {\gamma})$ neutron capture reactions, where the target nucleus captures a neutron and emits a $\gamma$-ray, the reverse process, photodisintegration (${\gamma},{\text{n}}$), and $\beta^-$-decay, which increases the proton number by one unit [Burbidge 1957].

Depending on the neutron flux, there are two equally important processes by which it is known that neutron capture proceeds – the slow s-process and the rapid r-process. As the name implies, the s-process occurs in the stellar environment where ($n, {\gamma}$) reactions proceed slowly, for example, where the flux of neutrons is relatively low, such as in a red-giant star. In the s-process, nuclei that have captured a neutron then $\beta$-decay to the line of stability before a subsequent capture; the whole process proceeds along the line of stability through nuclei that are relatively well studied.

By contrast, the r-process must occur in an environment with an intense neutron flux ($\sim 10^{32}$/cm$^2$) over a short period of time (10–100 sec). The astrophysical site for such an explosive environment is not firmly identified, but a supernova explosion, the merging of two neutron stars into a black hole, or on accretion disks in gamma-ray bursts, are possible sites that have been considered. Faced with a rapid neutron-bombardment, a nucleus quickly captures neutrons to enter the unknown region of extremely neutron-rich isotopes. For a given atomic number, the addition of neutrons stops at the point where the neutron binding energy becomes too low to support additional neutrons. These “waiting points” occur at two places: towards the neutron drip-line, and near closed neutron shells. At the waiting points, $\beta$-decay competes with neutron capture and increases the atomic number of the nucleus by one unit. If the waiting point is not at a closed shell, the process repeats until extremely heavy elements are produced or until a closed shell is reached. Indeed it is only through the r-process that elements such as thorium and uranium can be created. If the waiting point is one of the closed shells (e.g. N=50 and N=82) it will act as a bottleneck where the population of neutron-rich nuclei will collect. After the nuclear explosion has passed, this population is “frozen” and the subsequent $\beta$-decay of these nuclei to the line of stability gives rise to peaks in the abundance distributions.

Hence an understanding of the creation of the elements is intimately connected with an understanding of shell structure. Unfortunately, shell structure is unknown in the neutron-rich
regions where the r-process takes place. Indeed, discrepancies in the abundance distributions have been cited as evidence of a quenching of the shell-model magic numbers.

Because the site of the r-process is obscure, and because it occurs in nuclides that are experimentally unknown, the r-process is not on as firm a footing as the s-process. Nuclear masses and neutron separation energies, photo-nuclear cross sections, β-decay half-lives and shell structure in the neutron region are critical ingredients that need to be measured and understood to complete our understanding of the r-process and the creation of the elements.

3.2.2 THE RP-PROCESS

Not all heavy elements can be explained by invoking the r- or s-processes. The rapid proton-capture process (rp-process) is analogous to the r-process but now protons are captured instead of neutrons. Because the proton is a charged particle, proton-capture reactions require high energies to overcome the Coulomb barrier. Thus the astrophysical environment requires high temperatures in addition to a high flux of protons, such as when a neutron star accretes material from a hydrogen-rich companion in a binary star system.

Explosive hydrogen burning on the surface of the neutron star or white dwarf gives rise to a nova or an X-ray burst. The products of these explosions can be identified by spectroscopic observations of the ejected material. However, in this case, the reactions which created the material have involved radioactive, proton-rich nuclides. In order to understand the rp-process and the influence it has on the observed abundances, it is therefore necessary to measure proton-capture reaction rates with radioactive proton-rich beams. The iThemba LABS RIB facility will be flexible enough to produce proton-rich RIBs through the use of interchangeable target/ion-source combinations.

3.2.3 GIANT RESONANCES AND STRENGTH FUNCTIONS

Photo-excitation and de-excitation of the nucleus through \((n,\gamma)\) and \((\gamma,n)\) reactions is an essential ingredient of r-process nucleosynthesis. The ability of nuclear matter to emit or absorb photons is measured by the Relative Strength Function (RSF).

One of the oldest known and most famous contributions to the RSF is the giant-dipole resonance (GDR). This is a large amplitude collective motion where the protons and neutrons of the nucleus oscillate against one another. The separation of the centres of mass of the protons and neutrons give rise to a large electric dipole moment and corresponding electric dipole (E1) transition strength. In heavy nuclei it is a broad resonance several MeV wide, at an excitation energy of around 15 MeV. In fact, the excitation energy is inversely proportional to the nuclear radius, so that in deformed nuclei, where the radius is different along the different principle axes of the nucleus, the resonance splits up into two or three smaller resonances.

In neutron-rich nuclei, another type of splitting is observed, giving rise to a small resonance located below the GDR in the vicinity of the neutron-emission threshold. It is the so-called Pygmy Dipole Resonance (PDR), caused by the oscillation of the neutron skin against the remainder of the nucleus. Its proximity to the neutron threshold means that it will strongly influence the \((\gamma,n)\) and \((n,\gamma)\) reactions critical to the r-process and would be expected to become more important as the neutron excess increases.

A measurement of strength functions gives a window on the neutron skin, so critical for understanding of the evolution of shell structure and the synthesis of the elements. Already, researchers from iThemba LABS, in collaboration with German and Japanese partners, have measured the neutron skin thickness of the stable nucleus \(^{208}\text{Pb}\), by relating it to the E1 strength distribution though the dipole polarizability [Tamii 2011].

At even lower energies, iThemba LABS researchers in collaboration American partners have developed a new experimental method to measure the relative strength function (RSF) at energies down to 2 MeV [Wiedeking 2012]. They confirmed an earlier measurement of a strongly enhanced
RSF right in the energy range of importance in astrophysical settings, in the nucleus $^{95}$Mo [Guttormsen 2005]. Its nature and extent remains a mystery. With the RSF determined for stable nuclei it has to be extrapolated to the region of unstable nuclei for any astrophysical model calculations. This is due to the complete lack of experimental information for nuclei far away from stability. Establishing the RSF for neutron- and/or proton-rich nuclei cannot be accomplished at existing stable beam laboratories but only at radioactive-ion beam facilities. As iThemba LABS researchers unambiguously established the existence of the enhancement, iThemba LABS together with its collaborators is poised to lead the effort to understand this new property of nuclear matter and to study it in the region of nuclear instability.

3.3 APPLICATIONS OF NUCLEAR TECHNOLOGY

3.3.1 SPACE APPLICATIONS AND RADIATION-HARDNESS TESTING

An increasing number of nations have a footprint in space. South Africa is no exception with the proclamation of the South African National Space Agency and the launch of its second satellite, built by SunSpace in Stellenbosch, in 2009. One of the major difficulties faced by any space application is the increase in radiation dose to equipment and personnel when one no longer has the protective shield of the Earth's atmosphere. With increasing altitude, protons and neutrons take over as the most prominent form of radiation (figure 3.2). The primary cosmic-ray flux constituents are protons, with a broad energy distribution peaking around 300 MeV. iThemba LABS, with neutron and proton beams of up to 200 MeV energy, is in an ideal position to test and calibrate detectors and electronic components for radiation hardness.

There have been enquiries from SunSpace, Nelson Mandela University, Stellenbosch University and private concerns to perform radiation-hardness testing.

![Graph showing contribution to dose from different types of radiation as a function of altitude.](image)

*Fig. 3.8: Contribution to dose from different types of radiation as a function of altitude.*

The testing of radiation hardness of electronic devices is a potential field of interest for external customers from industry. South Africa's second satellite in space, the Sumbandila satellite, launched in 2009, rapidly suffered damage due to solar particle radiation. Shortly after its launch, a power distribution failure sent the craft tumbling in its orbit. Later failures of this unit caused the craft to cease to respond to commands from the ground.
Radiation hardness of electronic components is clearly a serious issue for space sciences for which iThemba LABS could play a key role, given the availability of more beam time. Interest has been expressed by a private company to perform radiation hardness screening of components on a routine and “on demand” basis. Such a commercial service is at present only available at a few laboratories overseas (e.g. at the Indiana University Cyclotron Facility) and at a very high cost.

**Neutron Dosimetry & Calibration**

There is a high level of interest across the world in the use of well-characterized fast neutron beams that span a wide range of applications. These include radiation protection at high-energy accelerators and during space missions, radiation hardness testing of electronic devices, and measurements for fusion energy research. The neutron energy range up to 20 MeV is well covered by the existing monoenergetic neutron beam facilities worldwide. However, the situation is different in the energy range above 20 MeV where cyclotrons with proton beam energies well above 20 MeV are required for the production of neutron beams. Such facilities are rather scarce world-wide, at least outside Japan. The neutron beam facility at iThemba LABS is thus a unique facility which has been well characterized in recent experiments.

Recent work using these beams has included testing new instruments for dosimetry for high-energy accelerators and for space applications, as well as for the investigation of the biological effects of high-energy neutrons. At iThemba LABS, neutrons are already used by the European Radiation Dosimetry Group on a regular basis to develop and calibrate detectors for space applications, such as for use on the International Space Station. The testing of radiation hardness of electronic devices is a potential field of interest for external customers from industry. iThemba LABS is also making more precise measurements of fission cross sections which are standards for neutron detection in the energy range from 60 MeV to 200 MeV, and which needed for the development of new compact high-energy neutron spectrometers.

A current example of the work undertaken using the fast neutron beams at iThemba LABS is the calibration of the “Radiation Assessment Detector” (RAD), which forms part of the new Mars rover “Curiosity” launched by NASA and which landed on Mars on the 6th of August 2012. RAD is a low-mass energetic particle analyser designed to characterize the spectrum of energetic particle radiation at the surface of Mars, including galactic cosmic rays, solar energetic particles, secondary neutrons and other particles created both in the atmosphere and in the Martian regolith. The RAD instrument will be used throughout the mission, including the cruise phase, to characterize the radiation environment both on the surface of Mars and in free space.

![Image: NASA/JPL-Caltech/SwR](image-url)
3.3.2 STUDIES OF $\beta$-DECAY FOR THE DESIGN OF SAFE NUCLEAR REACTORS

In the near future, nuclear reactors will provide a significant fraction of South Africa’s electricity. Fossil fuels are limited and their burning damages the environment with the emission of large amounts of CO$_2$. In contrast, nuclear power is based on the fission process and is less damaging to the environment. Nuclear accidents can, however, be disastrous and must be prevented.

In a working reactor, $\beta$- and $\alpha$-decays represent 8% of the produced heat. However, following the reactor shutdown, 100% of the heat in the core arises from the $\beta$-decay of elements produced in the fission of uranium. The lack of information for the decay properties of specific nuclei that are important contributors to the heating of the reactor during and after operation, and to the management of radioactive waste, may lead to the wrong shielding and safety procedures and, potentially, to a disaster such as the one in Fukushima.

It is important therefore, to measure the total energy released in the $\beta$-decay of a fission product. This has in the past been underestimated because many weak Gamow-Teller decay branches have been unobserved. A large increase in the mean energy released from the decays of $^{104-105}$Tc nuclides was found by measuring the $\gamma$-ray energy component of the decay-heat – i.e. the Gamow-Teller distribution $B(GT)$ – with total-absorption gamma spectroscopy (TAGS) in the pioneering work of Algora and co-workers [Algora, 2010]. This work solved a long-standing discrepancy in the cooling period of the reactor core between 4 and 3000 seconds after shutdown.

The TAGS technique uses a large NaI detector, usually in the form of a solid cylinder. The radioactive nuclei produced in the RIB facility are transported with a tape system to the inside of the large NaI crystal covering a solid angle of 4$\pi$, where they $\beta$-decay. The high efficiency of the NaI crystal allows a complete collection of $\gamma$-rays emitted by the daughter nucleus, including those feeding high-energy states. Finally, an accumulated $B(GT)$ distribution is collected as a function of the $\gamma$-ray energy. Germanium detectors can also be placed at the collection point to monitor the purity of the radioactive sources.

3.4 RADIOACTIVE IONS AS PROBES OF THE STRUCTURE OF MATERIALS

Materials modification and characterisation via ion implantation studies falls within the “Advanced Materials” focus area of the DST’s Ten Year Innovation Plan. The international importance of ion beam methods in the realization of the next generation of advanced materials is reflected by the several dedicated conferences: the *International Conference on Ion Beam Analysis*, the *International Conference on Ion Beam Modification of Materials*, the *International Conference on Applications of the Mössbauer Effect*, the *International Conference on Hyperfine Interactions*, and the *International Symposium on Industrial Applications of the Mössbauer Effect*.

The European Commission has defined “Nanotechnologies, Intelligent Materials and New Production Processes” as one of seven thematic research topics within its program. In addition, the IAEA within its program on “Effective Utilization of Particle Accelerators” has, during the past years, initiated several programmes related to ion beam modification and analysis of materials: “Use of Ion Beam Techniques for Analysis of Light Elements in Thin Films, including Depth Profiling”, “Application of MeV Ion Beams for Development and Characterization of Semiconductor Materials” and “Ion Beam Modification of Insulators”. (See for example IAEA CRP: F20022, F41023 & F1201.)

Amongst the wide variety of materials that are discussed at the forefront of Ion Beam Analysis conferences are various insulating and dielectric materials such as carbon compounds, diamond and diamond-like carbon and carbides, nitrides, oxides and oxide ceramics, glasses and silica, ionic crystals and polymers. Of increasing interest in recent years is the formation of metallic and semiconducting nanoparticles and nanoclusters embedded in metal oxides and other dielectric materials. The different applications of these materials cover optics, micro- and optoelectronics, spintronics, electrochemistry and biomedicine.
The search for new materials with specially tailored properties is driven by the potential high-impact applications of such new materials in important areas such as information technology, energy management, environmental protection, human health, etc. Most of these applications require devices comprising epitaxial thin films/near-surface layers/crystalline matrices that are appropriately doped to produce the required properties and structure. Of particular relevance in this quest has been the utilization of ion implantation methods which offer accurate control of dopant species and implantation profile, and overcome incorporation barriers due to thermodynamic equilibrium considerations.

A necessary requirement for a dopant atom to be electrically active is that the atom must reside in a regular lattice position in the substrate. Hence detailed information is required on the lattice location of the dopants and their diffusion behaviour, the annealing characteristics of lattice damage induced by the implantation process, and the complexes formed by the implanted ions. In this respect the use of radioactive-ion beams are particularly important, as illustrated by the three applications of radioactive-ion beams that we wish to establish at iThemba LABS, namely i) emission channelling, ii) emission Mössbauer spectroscopy, and iii) perturbed $\gamma-\gamma$ angular correlations.

3.4.1 EMISSION CHANNELLING

In emission-channelling measurements, the yield of charged particles emitted by radioactive isotopes implanted into single crystal samples is measured outside the sample as a function of angle relative to the principal axial directions. Channelling effects on the emitted charged particles by the positively charged atomic rows of the crystal lattice lead to anisotropic emission yields whose angular pattern is characteristic of the lattice site occupied by the emitter. For electron-emitting probes, details of the sites occupied by the radioactive probes are determined from comparisons of the observed patterns with theoretical simulations based on the many-beam formalism of electron diffraction.

Figure 3.10 shows theoretical simulations for conversion electrons emitted by radioactive $^{59}$Fe implanted in diamond for probes located at substitutional (S) and tetrahedral interstitial (T) sites.
Comparison of the experimentally observed 2-axial direction dimensional emission patterns collected along the <110> and either the <100> or <111> would give direct information on the lattice location of the implanted probe ion.

Radioactive nuclei which are useful for emission-channelling studies include $^8$Li, $^{21}$Na, $^{59}$Fe, $^{59}$Cu, $^{73}$As, $^{111}$In/$^{111}$Cd, $^{141}$Cs/$^{141}$Pr, $^{149}$Gd/$^{149}$Eu, $^{173}$Tm.

### 3.4.2 EMISSION MÖSSBAUER SPECTROSCOPY

Mössbauer Spectroscopy is a versatile method, giving information about probe-atom interactions with its nearest neighbours. Simultaneously information on the valence state of the probe atoms, site symmetry, and magnetic interactions is obtained. In most laboratories, Mössbauer spectroscopy is usually applied on samples containing stable Mössbauer isotopes (e.g. $^{57}$Fe or $^{119}$Sn) and the use of long-lived radioactive sources ($^{57}$Co ($T_{1/2} = 270$ d) and $^{119m}$Sn ($T_{1/2} = 290$ d)) that are commercially available. Useful samples for such experiments, however, require probe concentrations in excess of 0.1 atomic %.

Under such conditions the probe atoms interact between themselves and with atoms of the substrates and where solubility is low, unintentional precipitation can be a problem, significantly limiting the physical applications. Additional problems arise from lattice damage induced by the high dopant-atom concentrations.

Emission Mössbauer spectroscopy can be applied in many different contexts in material science and solid-state physics. The method using radioactive isotopes opens up many new possibilities compared to traditional Mössbauer spectroscopy. Among them is the possibility of working with extreme dilution ($<$10$^{-4}$ at.%) where the probe atoms are true impurities used to give essential information on the materials studied. Furthermore working with short-lived isotopes with lifetimes of minutes in on-line experiments, e.g. $^{57}$Mn ($T_{1/2} = 1.5$ min) and $^{119}$In ($T_{1/2} = 2.1$ min), allows for studying interactions with defects generated in the implantation process in concentration, time, and temperature regions inaccessible by other methods.

The mean time for accumulation of a spectrum with good statistics is 10 minutes using an accelerator, compared to 7–10 days for a sample implanted with $^{57}$Fe and with a $^{57}$Co source of >30 mCi strength, thus allowing studies of temperature- and fluence-dependence to be completed within a few hours. Further, the extremely low concentrations used in emission Mössbauer spectroscopy ($10^{-3} – 10^{-4}$ at. %) ensure that there is no overlap of implantation tracks, and that there is no clustering of the implanted ions.

Significant recent applications of the technique has included annealing studies on: (i) $^{57}$Mn/$^{57}$Fe and $^{119}$In implanted in group IV elemental and compound semiconductors: diamond, Si, Ge, SiC, SiGe and SiC, and (ii) investigations on magnetic effects induced in ZnO and metal oxides, and in the group III-Nitrides. Sample spectra are shown in the figures below:

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*Fig. 3.11: Emission Mössbauer spectrum following the implantation of radioactive $^{57}$Mn in ZnO, showing a distinct magnetic components, which were determined to be due to Fe$^{3+}$ in paramagnetic complexes with unusually long relaxation times (>20ns).*
3.4.3 Perturbed $\gamma$-$\gamma$ angular correlations.

In essence, perturbed $\gamma$-$\gamma$ angular correlation (PAC) measurements consist of implanting excited probe nuclei into a host material, and measuring the angular correlation between the $\gamma$-rays emitted in the decay of the probe state and those that populate the probe state. Information on the lattice sites of the probe is inferred from the perturbation of the $\gamma$-$\gamma$ angular correlation produced by the hyperfine interactions between the quadrupole moment of the excited nuclear state and the electric field gradients (EFGs) at the implantation sites.

In $\gamma$-$\gamma$ PAC measurements with a conventional four-detector (180°, 90°) geometry, twelve time spectra are collected. The spectra are characterised by the lifetime of the probe state and the perturbation frequencies at the sites of the implanted probes. In the analysis the count rates $N$ are used to generate the ratio $R_{\text{exp}}(t)$, which is defined by

$$R(t) \approx A_{\text{eff}}^{22} G_{22}(t)$$

where $A_{\text{eff}}^{22}$ is the effective gamma ray angular correlation coefficient, and $G_{22}(t)$ the perturbation function.

Fig. 3.12: Emission Mössbauer spectra of $^{57}$Mn/$^{57}$Fe implanted into CVD diamond obtained in online measurements at the temperatures indicated. The annealing of implantation induced lattice damage is evident, with the fraction of ions at essentially defect free substitutional sites in excess of 30%.
The probe atoms may be exposed to several different microscopic environments, each with its characteristic perturbation function. The measurement of the $R(t)$ function allows the perturbation function to be deduced, which in turn yields information about the local electric field at the implantation site. In this way it is possible to learn where the dopant is sited.

In summary, radioactive-ion beams are finding increasing applications in the development of advanced materials. Characterization techniques such as emission channelling coupled with the hyperfine interaction techniques of emission Mössbauer spectroscopy and $\gamma$-$\gamma$ perturbed angular correlations, which we propose to establish at iThemba LABS, have a major role to play in this development.

3.4.4 ION-IMPLANTATION/RADIOTRACER DIFFUSION STUDIES

The depth profiles of elements diffusing into materials can be studied using radioactive tracers. For macroscopic samples, the material may be sliced after the implantation and diffusion of a radioactive tracer. The activity of the slices is measured afterwards, to determine the extent of the diffusion of the radioisotope through the material. In microscopic or nanoscale substrates, information is obtained from the energy distribution of the decay products as a function of sample temperature. The method is used to reveal important information for the manufacture of semiconductor devices.
3.4.5 Initiatives already in place:
A number of South African scientists have established research programmes using radioactive-ion beams from the ISOLDE facility at CERN. These groups expressed their support for a local RIB facility in South Africa at the RIB Workshop held in iThemba LABS. South African research teams have established expertise in ion implantation, Mössbauer spectroscopy and emission channelling.

i) Mössbauer group
Initiatives already in place include the group lead by Prof Krish Bharuth-Ram (UKZN), which participates in emission-channelling and emission Mössbauer spectroscopy measurements following the implantation of radioactive ions at the ISOLDE on-line radioactive-ion beam facility at CERN. (Recent publications of this group include: Gunnlaugsson 2010a, 2010b, 2010c; Masenda 2010; Mølholt 2010, 2012; Baruth-Ram 2012a, 2012b, 2012c.)

ii) Complimentary techniques
A facility for complementary magnetisation measurements has been set up at iThemba LABS under the direction of Prof Terry Doyle, with the recently acquired Vibrating sample magnetometer. Measurements have already been conducted on several ZnO samples implanted with various ions.

iii) Facility for swift heavy-ion irradiation
Several authors have proposed that irradiation of samples with swift heavy ions to implant transition metal (TM) ions is more effective in inducing the formation of nanoclusters in host materials, as well as in controlling the shape and hence the magnetic behaviour of the TM clusters. An special chamber to investigate this has been developed at iThemba LABS and will be tested in a first irradiation of samples during 2013 using 20 MeV iodine ions.

3.5 Major Instrumentation
The proposal brings completely new science to South Africa, which in turn demands new experimental techniques. Two new experimental halls are envisaged for radioactive beam physics – a low-energy beam hall and a high-energy beam hall – the latter using beams accelerated by the SSC. The proposed facility will be able to produce world-class radioactive-ion beam intensities. Nevertheless, the greatest experimental challenge, especially for the high-energy beams, is that radioactive beam intensities are often many orders of magnitude lower than those commonly used in stable beam experiments. To compensate, radiation detector efficiencies must approach as near as possible to 100% efficiency. Furthermore, whereas in stable beam experiments the beam ions are usually lighter than the target, with radioactive beams the situation is reversed – the beam ions are heavier than the target, and reactions are said to take place in inverse kinematics.

3.5.1 Nuclear Physics
The scientific case calls for a nuclear physics programme to uncover both the reactions leading to the formation of exotic nuclei, and the properties of these nuclei, such as their masses, charge-radii, spins, parities and the electric and magnetic moments and transitions rates of excited states. The important excitation mechanisms to probe these properties are briefly summarized as follows:

Beta-decay
Beta-decay is technically one of the simplest methods of exciting a neutron-rich nucleus since the parent nucleus need only be trapped in the sight of gamma-ray or electron detectors to observe its decay to the excited states of a daughter nucleus and the subsequent decay of these states to the ground state of the daughter. The build-up of radioactivity from the decays of granddaughters etc. reduces the experimental sensitivity by increasing the level of background radiation. For this reason beta-decay stations usually employ a device such as a tape drive to transport long-lived radiation away from the view of the detectors.
Coulomb excitation and quasi-elastic scattering

Coulomb excitation represents one of the most powerful ways to measure the collectivity of excited states of a nucleus. In this process, the beam energy is kept low enough to avoid interference from nuclear forces; both the beam and the target nucleus are excited solely by their respective electric fields as they pass one another. The excitation probabilities are strongly dependent on the quadrupole and octupole matrix elements linking the states. It is thus a powerful way to probe the shape of a nucleus and its low-lying vibrational modes. While less effective in populating single-particle states, Coulomb excitation represents a powerful method to measure deformation, or lack thereof, and whether or not a nucleus lies near to a closed shell.

In practice one detects the scattered particles in a high-granularity, 4π-array of detectors. Elements of such an array, employing commercially available "S4" detectors, are presently being implemented at iThemba LABS for use with stable beams. Particle detectors do not normally have resolution sufficient to distinguish excited states; therefore, these measurements are usually performed in coincidence with an array of high-purity germanium (HPGe) gamma-ray detectors to resolve excitation probabilities to individual nuclear levels.

Transfer and inelastic scattering reactions

Light-ion transfer reactions represent one of the most efficient ways to probe the single-particle structure of a nucleus. Information obtained from such reactions, such as energies, spins, parities and spectroscopic factors are crucial to elucidate shell structure. Correlations due to residual interactions outside of the mean nuclear potential, such as the pairing force, can be probed by pair-transfer reactions. Reactions that are commonly employed are (³He, d), (³He,p), (d,t), (p,d), (d,p), etc. The (d,p) reaction can also be used as a surrogate reaction for the astrophysically important (n,γ) reaction.

High-resolution magnetic spectrometers have traditionally been used for such reactions. iThemba LABS is equipped with such a device: the K600 spectrometer which has been employed in such breakthroughs as the observation of the rotation of the Hoyle state. It will be useful for light radioactive beams but a different approach will be required for heavy-ion beams in inverse kinematics. An “active target”, which combines high efficiency with the ability to study reactions in inverse kinematics, is an option discussed in section 3.8.2 below.

Fusion reactions and deep-inelastic reactions

Coulomb excitation and light-ion transfer reactions, while powerful tools in their own right, have limitations in the kind of states they can populate. The population of high-spin states is largely the domain of fusion-evaporation and deep-inelastic reactions. With fusion-evaporation reactions, the projectile fuses with a target nucleus to form a compound nucleus at high angular momentum and high temperature. Cooling occurs by evaporation of neutrons, as unlike protons, they are not confined by the Coulomb potential. Thus, while calculations show that these reactions will provide an efficient method to populate high-spin states close to the line of stability (refer to figure 3.7), ultimately this method is self-defeating if one wishes to populate extremely neutron-rich nuclei.

Deep-inelastic reactions involve the transfer of energy, angular momentum, and nucleons between a heavy projectile and target as the two spend some time in contact with each other without fusing to form a compound nucleus. Due to the statistical nature of the particle transfer, a large number of different nuclear species are populated around the projectile and target nuclides. This is illustrated in figure 3.14 below, where the cross sections calculated for the reaction of radioactive neutron-rich ¹³⁰Sn with ²³⁸U are shown. The inelastic excitation of ¹³⁰Sn is by far the strongest channel, but more importantly, even more neutron-rich species are populated in this reaction.
Fig. 3.14: Yields from the reaction $^{130}\text{Sn} + ^{238}\text{U}$ at 7 MeV/nucleon, calculated using the GRAZING code [Grazing 2012].

Furthermore, this kind of reaction allows one to create a higher population of neutron-rich nuclides, already excited to high energy and spin, than could be produced at the RIB ion source, then accelerated as a radioactive-ion beam and afterwards excited to high energy and spin. As an example, consider Table 4.1, which shows the baseline high-energy beam production rates for the proposed facility. Only 20 particles per second (pps) of accelerated $^{130}\text{Cd}$ can be delivered to an experiment. These must then be excited to high energy or angular momentum by a process such as Coulomb excitation or even deep inelastic scattering.

If instead, a $^{130}\text{Sn}$ beam, of $1.6\times10^8$ pps is used in a deep-inelastic reaction with a $^{238}\text{U}$ target, one starts with nearly seven orders of magnitude more beam. Even if the cross section for creating $^{130}\text{Cd}$ is three orders of magnitude lower (~1 mb) and the detection efficiency 2 orders of magnitude lower, one would still have created two orders of magnitude more excited $^{130}\text{Cd}$ nuclei than if a $^{130}\text{Cd}$ beam had been used. Thus the advantages of the deep-inelastic process are obvious.

Table 4.1: Baseline yields for accelerated beams in the SPES project.

<table>
<thead>
<tr>
<th>$^{130}\text{Sn}$</th>
<th>$^{131}\text{Sn}$</th>
<th>$^{132}\text{Sn}$</th>
<th>$^{133}\text{Sn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.6\times10^8$</td>
<td>$6.8\times10^7$</td>
<td>$3.1\times10^7$</td>
<td>$2.8\times10^6$</td>
</tr>
<tr>
<td>$^{128}\text{Cd}$</td>
<td>$^{129}\text{Cd}$</td>
<td>$^{130}\text{Cd}$</td>
<td>-</td>
</tr>
<tr>
<td>2900</td>
<td>250</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
However, figure 3.14 also makes clear the main disadvantage of this type of reaction: it is not selective. Unlike fusion-evaporation reactions, in which the reaction products are confined to one or two nuclides, this reaction mechanism populates fifty or more different species, the separation of which represents an experimental challenge.

The solution is a large-acceptance spectrometer similar to the VAMOS and PRISMA spectrometers of GANIL and INFN Legnaro, respectively.

The above considerations motivate the three major experimental devices of the project: an active target for high-efficiency detection of transfer reaction products; a large acceptance spectrometer for deep-inelastic reactions, and a high-efficiency array of HPGe detectors. These devices are discussed below.

3.5.2 Active Target

The relatively low beam intensities obtained from radioactive beam facilities imply the use of very efficient detectors. Moreover, the beams available using fission source techniques involves inverse kinematic reaction studies i.e., with a target lighter than the projectile, and preferably with large cross sections. “Active-target” technology is currently under development in most radioactive-ion beam facilities to deal with this new experimental challenge. An ACtive TARget (ACTAR) is basically a “time-projection chamber” (TPC) where the detecting gas is also the target. These detectors cover close to 4π of solid angle and have low energy thresholds which allow very high-efficiency measurements. The pressure within the reaction chamber can be adjusted to define the target thickness. Therefore, the incoming beam sees its energy degraded through the target material and nuclear reactions can be scanned from the incident beam energy down to the energy threshold. This has the tremendous advantage of making full use of the radioactive-ion beam.

The gas can be purely the target of interest, or a mixture of a standard detection gas such as isobutane (C\textsubscript{4}H\textsubscript{10}) with the target of interest. Typical targets are \textsuperscript{1,2}H, \textsuperscript{3,4}He but can even be Ne, Ar, Xe isotopes at various pressures ranging from mbar, hundreds of mbar or even bar. The beam is directed into the detector itself and the charged particles arising from nuclear reactions ionize the gas along their path and lose their kinetic energy until they are stopped. The electrons from ionization drift in an electric field applied to the chamber and are detected on the side or the cap of the active targets. Three-dimensional imaging of the tracks is used to reconstruct the events. Particle identification can be performed efficiently if a magnetic field is also applied parallel to the electric field, allowing complete reconstruction of the events. The beam energy is degraded through the gas target, but the energy of the incident particle can be deduced from the location of the interaction point by means of energy-loss calculations. This has the advantage of making use of a single beam energy to measure an excitation function. The combination of gamma detectors along with the active target can be envisaged.

An active target is a complex apparatus involving state-of-the-art electronics and detection systems. The first step in the implementation of such a piece of equipment consists in a simple gas cell to be used as a target. A thin entrance window allows the incoming ions to penetrate the cell and two large highly-segmented silicon detectors are placed downstream the cell to determine the energy and trajectory of the outgoing particles (see figure below).
A number of reactions involving light charged particles as an ejectile such as \((p,p')\), \((d,p)\), \((^3He,p)\), \((\alpha,\alpha')\), \((^6He,\alpha)\) in direct or inverse kinematics are ideal owing to the rather low dispersion in energy and angle of protons and \(\alpha\)-particles compared to heavier particles. This technique is rather simple and has proved to be very efficient in determining the excited states of exotic nuclei. Such a combination of a gas target and segmented silicon detectors is a logical step towards ACTAR technology to gain experience and produce experimental data with early radioactive-ion beams.

### 3.5.3 LARGE-ACCEPTANCE SPECTROMETER

iThemba LABS personnel have extensive experience in the use of magnetic spectrometers, chiefly with the use of its own K600 Spectrometer. The spectrometer is designed principally to detect the scattering of light ions (protons, deuterons, alphas etc) off heavier targets, and has a relatively small solid angle of 5.8 mSr. It is not suitable for studying reactions of relatively low-intensity radioactive-ion beams in inverse kinematics, which would demand a much larger acceptance, in part to compensate for the low beam currents. Furthermore, as we have seen in figure 3.14, deep-inelastic collisions can produce a multitude of reaction products which need to be identified by the spectrometer. A complex set of detectors is required in the focal plane in order to accomplish this task.

Two existing large-acceptance spectrometers, called VAMOS at GANIL (France) [Schmitt 2010] and PRISMA at INFN Legnaro (Italy) [Latina 2004] fulfill the present requirements. VAMOS has a solid angle of 100 mSr, a mass-resolution of better than 1/200, and an atomic number \(Z\)-resolution better than 1/30, while PRISMA (see figure 3.16) has a slightly smaller solid angle of 80 mSr, but superior mass- and \(Z\)-resolution (1/300 and 1/60 respectively).

**Fig. 3.15:** Schematic diagram of a gas cell backed with highly-segmented silicon detectors for particle identification and tracking.

**Fig. 3.16:** The PRISMA spectrometer at INFN Legnaro, Italy.
To achieve these measurements, both spectrometers measure time-of-flight, $x$ and $y$ positions in the focal plane, followed by energy and energy-loss measurements of the detected particle.

For example, PRISMA uses a microchannel plate (MCP) detector as a start detector and an array of multi-wire parallel-plate avalanche counters (MWPPAC) as both a stop detector and a position detector. Energy and energy-loss is measured 60 cm further downstream in an array of ionization chambers.

### 3.5.4 Gamma-ray Detector Array

Gamma-ray decay is a ubiquitous process that accompanies nearly all of the excitation mechanisms discussed above. Hence the detection of $\gamma$-rays is of critical importance to exploring nuclear structure and nuclear processes. iThemba LABS has an array of high-purity Ge (HPGe) detectors called AFRODITE, shown in figure 3.17. It chiefly comprises 9 “clover” detectors and 8 low-energy photon spectrometers (LEPS) for an absolute efficiency of about 1.8% for 1.3 MeV $\gamma$-rays.

Most of the efficiency of the array at high energies is due to the clover detectors. A schematic of one is shown at left in figure 3.18. It consists of four HPGe crystals closely packed in a clover arrangement. This kind of technology was “state-of-the-art” in the early 1990s but is now superseded by highly segmented detectors. Two requirements are placed on an HPGe detector for in-beam $\gamma$-ray spectroscopy: the first is absolute efficiency and the second is energy resolution. The design of the clover detector was an improvement over earlier generations by virtue of its large volume (achieved by the close-packing of four smaller crystals) which improves efficiency, and its ability to better localize the first interaction point on the $\gamma$-ray within the detector, due to its four-fold segmentation. This latter feature is important because it allows one to improve the energy resolution by correcting for the Doppler broadening caused by the emission of a $\gamma$-ray from a nucleus in flight. The clover detector is completed by surrounding the HPGe crystals with a Compton-suppression shield. The latter is made of a high-efficiency material (bismuth germanate) to detect any $\gamma$-ray scattered out of the clover detector and to reject such events as a means of improving the signal-to-noise ratio.

![The AFRODITE array of HPGe detectors at iThemba LABS.](image)
Since the advent of the first radioactive beams in the late 1990s, the demands for yet higher detection efficiency (due to the low intensity of radioactive beams) and better ability to correct for Doppler broadening (due to the higher velocities of radioactive beams in inverse kinematics) led to the development of larger and more segmented “clover” detectors of the EXOGAM type shown in the middle of figure 3.18. In these detectors, larger crystals are used which are electronically segmented to give even better position resolution. The EXOGAM array [Exogam 2012], comprising sixteen such detectors, has an absolute efficiency at 1.3 MeV of 21% in a detector forward geometry and 11% in a detector back geometry.

The latest evolution of this concept is the TIGRESS detector [Scraggs 2005], shown on the right of figure 3.18, where the EXOGAM detectors are also segmented in the longitudinal direction. Together with modern digital electronics which can record the pulse shape in all segments of the detector, the TIGRESS detector is able, by analysing the pulse shapes, to achieve a position resolution of better than 1 mm on the interaction position of the first γ-ray [Svensson 2005]. iThemba LABS has recently commissioned its own digital data acquisition system based on the pulse-processing ADCs of the XIA corporation. It has also acquired a TIGRESS detector to develop pulse shape analysis techniques for position measurement.

However, the TIGRESS detector does not represent the ultimate in HPGe performance. Ultimately, the efficiency of an array of EXOGAM or TIGRESS detectors cannot reach 100% of 4π due to the Compton Suppression Shields surrounding each detector. These can be done away with, to create a truly 4π-HPGe array, if each detector has a very high segmentation and all detectors are packed closely together. In this way, each scatter of every γ-ray to strike the array can be “tracked”, their pulse shapes recorded, and their precise interaction points calculated. Such complex devices have been under development by large collaborations for nearly a decade in the USA and Europe where the respective projects are known as GRETA [Gretina] and AGATA [Simpson 2005]. They have only now reached the demonstrator phase, at this stage only covering small fractions of 4π. Ultimately, they are expected to reach absolute efficiencies of up to 40% at 1.3 MeV.

![Fig. 3.18:Schematic diagram showing the arrangement of crystals and their segmentation for the AFRODITE clover detectors (left), EXOGAM detectors (centre), and TIGRESS detectors (right).]
Clearly, the AFRODITE array, with only 1.8% efficiency, and based on technology over 20 years old, will not be able to compete with AGATA or GRETA, let alone with the EXOGAM or TIGRESS arrays. It is clear that a minimum detection efficiency of 10% and the ability to track $\gamma$-ray scatters for improved energy resolution is mandatory. iThemba LABS has taken its first step in this direction with the addition of a TIGRESS detector to the AFRODITE array. The decision whether to remain with this technology, or to adopt the GRETA or AGATA technology will be made in the future as the performance and costs become clearer.

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Proposal for a Radioactive-Ion Beam Facility at iThemba LABS

Section 3
4  CAPACITY CONSTRAINTS AT ITHEMBA LABS

4.1 PRESENT OPERATION

At present, particle beams from the SSC are delivered to the various different users for 24 hours per day and seven days per week. Beams currently offered are:

- Proton therapy: 200 MeV protons, 30 nA
- Neutron therapy: 66 MeV protons, ~30 µA
- Isotope production: 66 MeV protons, up to 250 µA
- Nuclear physics: various beams from protons to heavy ions, as required.

Radionuclide production and neutron therapy run from 16h00 on Mondays until 5h00 on Fridays. Patients are treated during daytime hours and between treatments and at night the beam is switched to the radioisotope production vault. On Mondays and Fridays a 200 MeV beam is used for proton therapy and over the weekends beams of light and heavy ions (as well as polarized protons), pre-accelerated in solid-pole injector cyclotrons SPC1 or SPC2 respectively, are delivered to nuclear physics users. This is illustrated in the figure below.

![Fig. 4.1 The present SSC beam delivery schedule at iThemba LABS.](image)

In spite of this extremely tight schedule it remains very difficult to satisfy the beam requirements of the different users.

4.2 PHYSICS

In nuclear physics research, demand for the available beam time (limited to less than 60 hours per week) is oversubscribed by a factor of two, and rising. This puts a severe restriction on the number of MSc and PhD theses which can be produced by the facility. Furthermore, many experiments requiring longer periods of continuous beam time are not feasible under the current arrangements. Potential overseas collaborations are discouraged by the lack of continuous run-time, owing to the extended stay required to complete an experiment. Moreover, the field is moving towards the
study of neutron-rich nuclei using radioactive-ion beams, which cannot yet be produced with the present accelerators.

These factors are to the detriment of both the international competitiveness of research at iThemba LABS and of the development of human resources in South Africa. The situation is particularly acute considering the future demands of the nuclear power industry for people trained in the nuclear sciences.

4.3 RADIOISOTOPE PRODUCTION

The quantity of radioisotopes produced is at present dependent the amount of beam time available, as illustrated in figure 3.1 above. To increase production, iThemba LABS has introduced a number of innovations, including “flat-topping” of the accelerators’ radio-frequency waveforms to increase the beam current, a new vertical-beam target station and a beam-splitter to permit dual production targets to be irradiated simultaneously. The users of medical radioisotopes require regular and reliable supplies on specific days each week, so that the present schedule of production cannot be changed.

The possibilities for further increases in beam current with the existing SSC cyclotron are now exhausted. Further growth in production is now restricted simply by the limitation on available of beam time.

4.4 MEDICAL RADIATION: PROTON THERAPY

Proton therapy for the treatment of cancer is in most cases offered as a series of doses on consecutive days. At iThemba LABS only 2 fractions per week are currently available, which means that only benign brain tumours can be treated. At least 5 consecutive fractions are required for the majority of other tumours, with up to 30 fractions being used at times. If 5 fractions could be offered, the following tumours could be treated:

- Paediatric tumours
- Tumours close to critical structures
- Brain tumours
- Gastro-intestinal tumours (rectum, liver, pancreas)
- Prostate tumours
- Lung tumours
- Recurrent tumours

Proton therapy must now also compete with in-hospital photon therapy, using a new technique called “intensity-modulated radiation therapy” (IMRT). At iThemba LABS, the passive-scattering beam delivery system used unfortunately precludes the use of dynamically modulated proton therapy. [Levin 2008]

iThemba LABS has long recognized this limitation, which is part of the motivation behind the proposal for the iThemba Particle Therapy Centre (iTPTC) to be constructed in future, either on iThemba site or elsewhere. In this proposal, a private-public partnership would set up to administer proton therapy on a commercial basis. A dedicated accelerator for proton therapy would be purchased so that the full suite of tumours could be treated. This proposal has been the subject of a review by the consultants Quartile Capital. It is now before Cabinet for consideration.

However, the competition for beam time for uninterrupted nuclear physics runs and routine isotope production are not resolved by this. Thus the iTPTC project does not address the needs of the remaining disciplines and does not form part of the present proposal.
4.5 THE SOLUTION: A NEW 70-MeV CYCLOTRON

The solution proposed is the purchase of a commercially-available, compact, 70-MeV negative-ion (H⁻) cyclotron. The energy of such a cyclotron is ideal for the production of radioactive-ion beams and also for radioisotope production.

Because this cyclotron accelerates H⁻ ions, i.e. hydrogen atoms with an extra electron, these can be extracted from the cyclotron by using electron-stripping foils. Now since a thin foil allows some of the beam to pass through it without stripping, until it encounters a second (thicker) foil, more than one beam can be extracted from the cyclotron simultaneously. The machine can therefore provide two independent beams of protons at energies up to 70 MeV: one of these beams will then be available 24 hours a day for isotope production, thus removing many of the constraints discussed above, while the other beam is used for RIB production. Note that if required, the full beam intensity can be extracted into the beamline for radioisotope production.

There are currently two companies offering dual-beam, 70-MeV negative-ion compact cyclotrons, namely Ion Beam Applications s.a. (IBA) and Best Cyclotron Systems Inc. (BCSI): their respective accelerators are illustrated below.

Fig. 4.2: The IBA C70 H⁻ cyclotron (left), and the 70-MeV H⁻ cyclotron from BCSI (right).

4.6 NEW BEAM SCHEDULE FOR THE SSC

When proton therapy is shifted entirely to the proposed iTPTC, the beam schedule for the SSC can then be completely revised, and a suggested schedule is shown below in figure 3.3; in this case neutron therapy patients are treated from Monday through Wednesday over a 20-week period, while physics experiments are done from Thursday through Sunday. Two other 12-week periods are dedicated to physics, permitting long continuous runs to be scheduled. Note that isotope production does not appear in the schedule, since that will be provided by the 70-MeV cyclotron.

Up to 500 µA can be extracted via a single extraction channel, with the remainder on the other extraction channel. In principle therefore, after completion of Phase 2 of the programme, 500 µA could be used for radioactive-ion beam production and 200 µA for radioisotope production – or vice-versa, by splitting the radioisotope production beam into two different beamlines to irradiate two target stations. [We note also that it may also be possible to increase the total available beam current from this cyclotron to 1.5 mA in future.]
Fig. 4.3: A new schedule for the SSC beam, divided between neutron therapy and physics, which makes provision for long continuous runs for nuclear physics.

During the nights between therapy days, and between therapy treatments, the 66 MeV beam from the SSC would also be available for additional production of long-lived radioisotopes using the present production vaults, assuming that this could be handled with the available manpower.

Details of cost-recovery from the projected isotope production achievable with the new cyclotron are given in section 5. However, the additional increase in production of these long-lived isotopes is not included.

4.7 INCREASE IN STUDENT TRAINING ON THE SSC AND NEW ACCELERATOR

Presently, over 20 post-graduate students are attached to the Department of Nuclear Physics at the laboratory. These students use the SSC as the principle accelerator for their research, with approximately 80 days of beamtime per annum is available to them. With the new beam schedule, up to 240 days per year would be available for nuclear physics experiments. Due to the time taken to prepare beams for experiments, the actual annual time available (beam on target) could be between 170 and 200 days, which still represents more than a doubling of beamtime. Furthermore, when stable beam experiments are performed using the SSC, experiments using low-energy radioactive beams from the new 70 MeV machine can still be performed. There is a strong demand for these beams from the material science community as well as the nuclear physics community. The implication is that the total increase in beamtime could, in effect, more than triple the capacity for graduate student training associated with the main accelerator complex. This estimate does not include students involved in the research and development activities of the proposal. Presently at the Italian INFN laboratory at Legnaro, approximately 30 post-graduate engineering students are involved in R&D activities with 10 graduating per annum.

REFERENCE:

5 BASELINE PERFORMANCE

5.1 RADIOACTIVE-ION BEAM PRODUCTION AND INTENSITIES

Although there are numerous radioactive beam facilities around the world, the technology for the production of RIBs is still under development, particularly with regard to increasing beam intensities. Because radioactive ion beams are artificially produced, their intensities have generally been many orders of magnitude smaller than those of stable beams. The latest facilities in the world – some under construction, others being planned – have RIB intensities approaching just one order of magnitude smaller than those used in stable beam experiments. Here we give an outline of the proposed production techniques and performance; more details are given in Chapters 7 to 9. The intention of the iThemba LABS proposal is to draw on past international experience through collaborative efforts.

The present proposal is similar to the SPES proposal of INFN-Legnaro in Italy, which makes use of a 70-MeV proton cyclotron, originally developed for radioisotope production. Since a 70-MeV proton beam will be used for the isotope programme, production of RIBs will be most cost-effective if it can be produced by the same beam. This beam energy is in fact ideal for the isotope-separation-on-line (ISOL) technique, and can, for example, produce neutron-rich species using proton-induced fission on a production target of uranium carbide, or by using the proton beam to create neutrons on a so-called “converter target” and using the neutrons to induce fission in uranium carbide. The advantage of a converter target is partly that more primary beam power can be used without danger of melting the uranium carbide. Alternatively, the proton beam could be used to produce neutron-deficient beams directly, using (p,xn) reactions. These beams are also of interest for the materials sciences.

A schematic diagram showing the different stages of possible RIB production at iThemba LABS is given in figure 5.1 below.

![Diagram](image)

**Fig. 5.1: Stages in the production of RIBs at iThemba LABS.**

Radioactive ions from the production target will be collected in an ion source directly connected to the target, and then ionized to the 1+ charge-state. A number of ionization techniques are available, including surface ionization, plasma ionization with a FEBIAD (“forced electron-beam-induced arc discharge”) ion source, or using a resonant-ionization laser ion source (RILIS).

Ionization to the 1+ charge-state alone is insufficient to select the desired radioactive species: final selection is achieved by using a high-resolution magnetic spectrometer as a mass analyser. The highest resolution is only obtained by cooling the beam, using a radio-frequency quadrupole (RFQ) cooler, in which the ions exchange energy with a noble gas (e.g. helium), thus losing transverse energy and improving the emittance of the resulting beam.

Before the beam is injected into the injector cyclotron SPC2 (which will deliver the beam for injection into the SSC), the ions in the beam must have their charge-state increased, either by charge-stripping in a foil or else in another ion-source which acts as a charge-breeder. This charge-breeding can be performed by an Electron Cyclotron Resonance (ECR) ion-source, with the final charge-state determining the ultimate beam energy achieved in the SSC. For light ions, beam energies of up to 40 MeV per nucleon should be possible. For isotopes in the mass range 80 to 130, such as fission products, the SSC should be able to deliver beam energies of between 7 and 9 MeV per nucleon without severely limiting the RIB intensities.
What is important to note is that the final intensity of accelerated beam on target is a product of the production rate of the radioactive species, $N$, and the efficiencies, $\varepsilon$, of the various stages of beam transport shown above, and a factor, $e^{-t/\tau}$ which is especially important for short-lived isotopes, to account for the radioactive decay of the beam. Thus the intensity of beam on target is given by:

$$I(\text{target}) = N \times \varepsilon_{1+} \times \varepsilon_{M.S.} \times \varepsilon_{C.B.} \times \varepsilon_{SPC2} \times \varepsilon_{SSC} \times \varepsilon_{EXP} \times e^{-t/\tau}$$

Where $\varepsilon_{1+}$ is the 1+ ionization efficiency, $\varepsilon_{M.S.}$ is the efficiency of transporting the beam through the mass selector to the charge breeder, $\varepsilon_{C.B.}$ is the charge breeding efficiency, and $\varepsilon_{SPC2}, \varepsilon_{SSC}, \varepsilon_{EXP}$ are the efficiencies for transportation of the beam through SPC2, the SSC and on to the experimental target station.

For the SPES proposal at INFN Legnaro, Italy, it is expected that with a primary beam current of 200 µA, at 40 MeV, (or 8 kW), $10^{13}$ fissions/s can be created using direct fission. Assuming $\varepsilon_{C.B.} \approx 0.04$ and the equivalent of $\varepsilon_{SPC2} \times \varepsilon_{SSC} \times \varepsilon_{EXP} \approx 0.5$ gives rise to RIB intensities on target shown in figure 5.2 below, for, as an example, the Sn isotopes. The sharp drop-off in intensity for high neutron numbers is not only due to lower production rates $N$ of neutron-rich species, but also due to their increasingly short half-lives ($\approx 100$ms). Thus the release times from the target, charge breeding times and transportation times become increasingly important. The intensities for the SPES project are a baseline: the RIB intensity on target for the SPES project could be doubled by increasing the proton beam energy to 70 MeV or further increasing the beam current.

At some point, a limit to the amount of power that can be deposited in a direct target will be reached. It is partly for this reason that a converter target is proposed for SPIRAL II, at GANIL, in
France. Estimated initial yields from the SPIRAL II project, which will eventually use a 200kW primary beam are also shown in figure 5.2.

The higher primary beam power translates into a higher RIB yield near $^{132}$Sn, but the advantage diminishes for extremely neutron-rich isotopes due to the time lost in releasing the isotope from the production target. Two estimates of yields are given in figure 5.2 for a converter target to be used at iThemba LABS with primary beam intensity varying from 350 µA to 1 mA. The two differ in the amount of uranium and in the release times of the radioactive products. At the expense of less uranium to fission, a gas transport system can substantially reduce the release time and therefore radically improve the intensity of very neutron-rich RIBs on target.

Further increases in yields can be had without increasing primary beam intensity, but by improving the various efficiencies. Clearly one of the biggest losses is in charge breeding, where 95% of the beam is lost in an ECR ion-source. An alternative is an Electron Beam Ion Source (EBIS), which can offer higher efficiencies for some ions, and it may be useful to have both ECR and EBIS charge-breeders.

The iThemba LABS proposal will begin with the SPES primary target and ion-source before upgrading to higher primary beam intensities and to a more efficient charge breeder. Hence the baseline performance of the iThemba LABS facility is similar to that of the SPES facility. These are compared with other international facilities in the next section.

5.1.1 INTERNATIONAL BENCHMARKS FOR RADIOACTIVE-ION BEAM INTENSITY

As shown in Table 5.1 below, to make internationally competitive RIB intensities from the fission of uranium, the primary beam current should be at least 100 µA of 70-MeV protons. This will generate approximately $10^{13}$ fissions/s, similar to the SPES proposal of INFN Legnaro, Italy, and exceeded only by the SPIRAL II project at GANIL, France, which is expected to generate some $10^{14}$ fissions/s, using an intense deuteron beam. Nevertheless, $^{132}$Sn intensities are multiples of $10^8$ pps for all facilities; hence it is clear that the iThemba LABS facility will be competitive with all the major facilities of Europe and the USA.

Table 5.1: Comparison of worldwide facilities for RIB production.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Beam Energy</th>
<th>Beam Current</th>
<th>Power deposited in target</th>
<th>Fissions per second</th>
<th>$^{132}$Sn beam intensity (pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRIBF, Oak Ridge, USA</td>
<td>40 MeV</td>
<td>10 µA</td>
<td>0.4 kW</td>
<td>$4 \times 10^{11}$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>ISOLDE, CERN, Switzerland</td>
<td>1.0–1.4 GeV</td>
<td>2 A</td>
<td>0.4 kW</td>
<td>$4 \times 10^{12}$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>TRIUMF, Canada</td>
<td>450 MeV</td>
<td>70 µA</td>
<td>17 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIE ISOLDE upgrade, CERN</td>
<td></td>
<td></td>
<td>$4 \times 10^{12}$</td>
<td></td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>HRIBF upgrade, Oak Ridge, USA</td>
<td>54 MeV</td>
<td>20 µA</td>
<td>1.8 kW</td>
<td>$10^{12}$</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>SPIRAL II, GANIL, France, initial</td>
<td>40 MeV (d)</td>
<td>5 mA</td>
<td>200 kW</td>
<td>$10^{14}$</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>SPES, INFN-Legnaro, Italy, initial</td>
<td>40 MeV</td>
<td>200 µA</td>
<td>8 kW</td>
<td>$10^{13}$</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>iThemba LABS (Phase 2)</td>
<td>70 MeV</td>
<td>115 µA</td>
<td>8 kW</td>
<td>$10^{13}$</td>
<td>0.2-1 $\times 10^8$</td>
</tr>
<tr>
<td>iThemba LABS (later upgrade)</td>
<td>70 MeV</td>
<td>500 µA</td>
<td>35 kW</td>
<td>$5 \times 10^{14}$</td>
<td>0.8-4.0 $\times 10^8$</td>
</tr>
</tbody>
</table>

iThemba LABS will make provision for future enhancements for up to ~500 µA of proton beam. The compact cyclotron envisaged for the project is designed to provide 700 µA of protons at energies from 35 to 70 MeV, which would serve both radioactive-ion beam and radioisotope production.
5.2 RADIOISOTOPE PRODUCTION – COST RECOVERY

5.2.1 DIAGNOSTIC TECHNIQUES IN NUCLEAR MEDICINE

Diagnostic techniques in nuclear medicine use radioactive tracers which emit gamma rays from within the body. These tracers are generally short-lived isotopes linked to chemical compounds which permit specific physiological processes to be scrutinised. They can be given by injection, inhalation or orally. The first type is where single photons are detected by a gamma camera which can view organs from many different angles. The image is enhanced by a computer and viewed by a physician on a monitor for indications of abnormal conditions.

A more recent development is Positron Emission Tomography (PET) which is a more precise and sophisticated technique using isotopes produced in a cyclotron. A positron-emitting radionuclide is introduced, usually by injection, and accumulates in the target tissue. As it decays it emits a positron, which promptly combines with a nearby electron resulting in the simultaneous emission of two identifiable gamma-rays in opposite directions. These are detected by a PET camera and give very precise indication of their origin. PET’s most important clinical role is in oncology, with fluorine-18 as the tracer, since it has proven to be the most accurate non-invasive method of detecting and evaluating most cancers. It is also often used in cardiac and brain imaging.

New procedures combine PET with computed X-ray tomography (CT) scans to give co-registration of the two images (PETCT), enabling 30% better diagnosis than with a traditional gamma-camera alone. It is a very powerful and significant tool which provides unique information on a wide variety of diseases from dementia to cardiovascular disease and cancer (oncology).

Positioning of the radiation source within the body makes the fundamental difference between nuclear medicine imaging and other imaging techniques such as X-rays. Gamma-ray imaging by either method described provides a view of the position and concentration of the radioisotope within the body. Organ malfunction can be indicated if the isotope is either partially taken up in the organ (cold spot), or taken up in excess (hot spot). If a series of images is taken over a period of time, an unusual pattern or rate of isotope movement could indicate malfunction in the organ.

A distinct advantage of nuclear imaging over X-ray techniques is that both bone and soft tissue can be imaged very successfully. This has led to its common use in developed countries where the probability of anyone having such a test is about one in two and rising.

Many medical radioisotopes are made in nuclear reactors, while others come from cyclotrons. Generally neutron-rich ones and those resulting from nuclear fission need to be made in reactors, while neutron-depleted ones are made in cyclotrons. The table below lists medical and calibration sources made using cyclotrons: those produced at iThemba LABS are shaded.
### Table 5.2: Uses of cyclotron-produced medical and calibration radioisotopes.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>½-life</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-11</td>
<td>20.4 m</td>
<td>Positron emitters used in PET for studying brain physiology and pathology, e.g. localising epileptic focus, and in dementia, psychiatry and neuropharmacology studies. A significant role in cardiology.</td>
</tr>
<tr>
<td>Nitrogen-13</td>
<td>9.96 m</td>
<td></td>
</tr>
<tr>
<td>Oxygen-15</td>
<td>122.2 s</td>
<td></td>
</tr>
<tr>
<td>Cadmium-109</td>
<td>463 d</td>
<td>Calibration sources.</td>
</tr>
<tr>
<td>Cobalt-57</td>
<td>272 d</td>
<td>A marker to estimate organ size and for in-vitro diagnostic kits.</td>
</tr>
<tr>
<td>Copper-64</td>
<td>13 h</td>
<td>Study of genetic diseases affecting copper metabolism, e.g. Wilson's and Menke's diseases, and for PET imaging of tumours, and therapy.</td>
</tr>
<tr>
<td>Copper-67</td>
<td>2.6 d</td>
<td>Beta emitter, used in therapy.</td>
</tr>
<tr>
<td>Fluorine-18</td>
<td>109.8 m</td>
<td>FLT (fluorothymidine), F-miso (fluoromisonidazole), 18F-choline used as tracers. F-18 in FDG (fluoro-deoxy glucose) is important in detection of cancers and monitoring of treatment, using PET.</td>
</tr>
<tr>
<td>Gallium-67</td>
<td>78 h</td>
<td>Tumour imaging, localisation of inflammatory lesions (infections).</td>
</tr>
<tr>
<td>Gallium-68</td>
<td>68 min</td>
<td>Positron emitter used in PET and PET-CT units. From Ge-68.</td>
</tr>
<tr>
<td>Germanium-68</td>
<td>271 d</td>
<td>Generator to produce Ga-68. Calibration sources.</td>
</tr>
<tr>
<td>Indium-111</td>
<td>2.8 d</td>
<td>Specialist diagnostic studies, e.g. brain studies, infection and colon transit studies.</td>
</tr>
<tr>
<td>Iodine-123</td>
<td>13 h</td>
<td>Diagnosis of thyroid function: a gamma emitter without the beta radiation of I-131.</td>
</tr>
<tr>
<td>Xenon-122</td>
<td>20.1 h</td>
<td>Generator for iodine-122, a positron emitter used for PET brain blood-flow (perfusion) studies.</td>
</tr>
<tr>
<td>Iodine-124</td>
<td>4.18 d</td>
<td>Used as a tracer.</td>
</tr>
<tr>
<td>Krypton-81m</td>
<td>13 sec</td>
<td>Kr-81m gas can yield functional images of pulmonary ventilation, e.g. in asthmatic patients, and for the early diagnosis of lung diseases and function.</td>
</tr>
<tr>
<td>Rubidium-81</td>
<td>4.6 h</td>
<td>Generator for Kr-81m.</td>
</tr>
<tr>
<td>Rubidium-82</td>
<td>1.26 min</td>
<td>Convenient PET agent in myocardial perfusion imaging.</td>
</tr>
<tr>
<td>Sodium-22</td>
<td>2.2 y</td>
<td>Positron-annihilation studies</td>
</tr>
<tr>
<td>Strontium-82</td>
<td>25 d</td>
<td>Generator for producing Rb-82.</td>
</tr>
<tr>
<td>Thallium-201</td>
<td>73 h</td>
<td>Diagnosis of coronary artery disease and other heart conditions such as heart muscle death and for location of low-grade lymphomas.</td>
</tr>
<tr>
<td>Iron-52</td>
<td>8.3 h</td>
<td>Generator for manganese-52, a positron emitter used for PET diagnostics. Fe-52 itself is a positron emitter used as an iron tracer for the study of red blood cell formation and brain uptake.</td>
</tr>
<tr>
<td>Magnesium-28</td>
<td>21 h</td>
<td>A tracer in bone studies.</td>
</tr>
<tr>
<td>Barium-128</td>
<td>2.43 d</td>
<td>Generator for positron-emitting cesium-128, a potassium analogue, used for heart and blood-flow imaging.</td>
</tr>
<tr>
<td>Ruthenium-97</td>
<td>2.79 d</td>
<td>A gamma emitter that is used for imaging cerebrospinal fluid and blood flow in liver.</td>
</tr>
<tr>
<td>Tin-117m</td>
<td>13.6 d</td>
<td>A gamma emitter that is used for bone pain palliation.</td>
</tr>
<tr>
<td>Yttrium-88</td>
<td>106.7 d</td>
<td>Calibration sources.</td>
</tr>
</tbody>
</table>
5.2.3 **HIGH-ENERGY CYCLOTRONS**

There are very few high-energy cyclotrons (>45 MeV energy) in the entire world that are able to produce the commonly required radionuclides such as Na-22, Ge-68, Xe-122, Zn-65, Co-55, Bi-206, Mg-28, Tl-201, Ba-128, Cu-67, Ru-97, Sn-117m and Sr-82. These cyclotrons are limited to the facilities as shown in Table 5.3 below.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton energy</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iThemba LABS, South Africa</td>
<td>Up to 66 MeV</td>
<td>250</td>
</tr>
<tr>
<td>INR, Russia</td>
<td>Up to 600 MeV</td>
<td>120</td>
</tr>
<tr>
<td>Cyclotron Co., Russia</td>
<td>Up to 22 MeV</td>
<td>1000</td>
</tr>
<tr>
<td>ARRONAX, France</td>
<td>Up to 70 MeV</td>
<td>700</td>
</tr>
<tr>
<td>TRIUMF, Canada</td>
<td>Up to 500 MeV</td>
<td>100</td>
</tr>
<tr>
<td>LANL, United States</td>
<td>Up to 100 Mev</td>
<td>200</td>
</tr>
<tr>
<td>BNL, United States</td>
<td>Up to 100 Mev</td>
<td>100</td>
</tr>
<tr>
<td>PEPF, South Korea (under construction)</td>
<td>Up to 100 Mev</td>
<td>300</td>
</tr>
</tbody>
</table>

The global demand for these radionuclides cannot be met, because many of these facilities have a radionuclide production programme that competes with other nuclear physics research and/or medical therapy programmes for the available beam time.

5.2.4 **EXISTING OPERATIONS**

The iThemba LABS Radionuclide Production Department (RPD) uses the 66 MeV proton beam with high currents (up to 250 µA-h) to produce high-grade radionuclides. Primarily it uses these radionuclides to produce regularly, on a weekly basis, radiopharmaceuticals under Good Manufacturing Practices for the health benefit of the South African community and secondarily to produce longer-lived radionuclides for the export market to assist cost recovery.

Generally short-lived accelerator-based radiopharmaceuticals cannot be imported into South Africa because of their relatively short half-life (and hence the life-span of product) ranging from 2h to 3 days, thus making iThemba LABS an important link in the service chain for nuclear medicine studies and applications in South Africa.

Long-lived radionuclides are produced and despatched to clients. iThemba LABS still remains the only supplier of Na-22 positron sources in the world.

A quality assurance system in line with current Good Manufacturing Practice (cGMP) requirements encompassing all customer-related activities, legal requirements and production processes is constantly maintained. These processes are planned and monitored, using well documented and recorded systems. This system ensures consistent efficiency, reliability and quality of both the radiopharmaceuticals and services rendered to clients. Non-delivery or delayed delivery was mainly attributable to a) unscheduled power outages, b) cyclotron downtime, c) breakdown of ageing equipment and infrastructure.

In July 2012 a dedicated 11-MeV cyclotron will be installed and commissioned for the production of the PET ¹⁸F-FDG product.

Note that even if only 80% of the isotopes produced are sold, the estimated cost-recovery will amount to more than double the present revenue which can currently be generated per annum.

This calculation is based on one extraction port dedicated to radionuclide production, without a beam-splitter (i.e. only a single beam).
In addition, the beam current available will also be increased: however, the maximum that can be accepted by a target station is 250 \( \mu \)A, and a beam-splitter will therefore permit two targets to be irradiated simultaneously, thus increasing the production tempo.

This preliminary study only takes into account the present sales of radioisotopes and radiopharmaceuticals with the present cyclotron beam time allocation, escalated for a 70-MeV cyclotron by the amount of beam time that will become available. It also excludes the increased production capacities that could be realised with the higher currents that the 70-MeV cyclotron could offer and the possibility of the development of new products.

5.2.5 IThemba LABS MARKET SHARE

In order to ensure that the products produced by the 70-MeV cyclotron are in line with market demand, a comprehensive market survey needs to be undertaken. Various recent world market surveys are available and we have identified a report entitled *Global Radiopharmaceuticals Market (PET/SPECT Imaging & Therapy) - Current Trends & Forecasts (2010 - 2015)* [Markets & Markets] to serve as a starting point in providing useful input into the development of a commercial business plan for radionuclide production using the 70-MeV cyclotron. It is expected that preparation of this business plan will be conducted by a reputable external consultant. We estimate the cost of this to be in the order of R1 million.

REFERENCES

FRIB http://groups.nscl.msu.edu/frib/rates/fribrates.html


6 PHASE 1: THE 70-MeV CYCLOTRON AND RADIOISOTOPE PRODUCTION

To restrict costs and to minimize the research and development effort, we propose to purchase a commercial “off-the-shelf” compact 70-MeV H⁻ cyclotron. The price of such a machine is of the order of R100 million, to which must be added the costs of a suitable building equipped with 3 m thick shielding walls, cranes, beamlines, two isotope-production vaults with 4 m thick walls, as well as additional service areas for power supplies, electronics, air handling, water chillers, etc.

6.1 A NEW COMPACT CYCLOTRON

There are at least 2 companies currently marketing 70-MeV compact cyclotrons, namely Ion Beam Application s.a. (IBA) and Best Cyclotron Systems, Inc. (BCSI). IBA have already supplied such an H⁻ machine to ARRONAX in France. BCSI has contracted to supply a 70-MeV cyclotron to INFN-LNL in Italy, at a considerably lower price. The latter cyclotron has the following specifications:

<table>
<thead>
<tr>
<th>Energy (variable):</th>
<th>30–70 MeV</th>
<th>Magnet $B_{max}$:</th>
<th>1.6 tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Beam Current:</td>
<td>&gt;700 µA</td>
<td>Magnet power:</td>
<td>30 kW</td>
</tr>
<tr>
<td>No. of beam ports:</td>
<td>2</td>
<td>No. of sectors:</td>
<td>4</td>
</tr>
<tr>
<td>Extraction:</td>
<td>Stripping</td>
<td>Total mass:</td>
<td>210 tonnes</td>
</tr>
<tr>
<td>Dimensions:</td>
<td>4.5 m diameter</td>
<td>Vacuum pressure:</td>
<td>$2 \times 10^{-7}$ mbar</td>
</tr>
<tr>
<td></td>
<td>1.7 m height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonator frequency:</td>
<td>58 MHz</td>
<td>Resonator power dissipation:</td>
<td>15 kW/cavity</td>
</tr>
<tr>
<td>Dee voltage:</td>
<td>60–80 kV</td>
<td>Harmonic mode:</td>
<td>H=4</td>
</tr>
</tbody>
</table>

![CAD drawing of the proposed 70-MeV compact cyclotron, due to be supplied to INFN-LNL in Legnaro by Best Cyclotron Systems, Inc. [BCSI 2009]](image)

6.1.1 SOURCE

The source used for the BCSI Cyclotron is a multicusp ion source, providing 15–20 mA of current. The source assembly consists of a tubular plasma chamber with ten columns of permanent magnets to provide a stronger multi-cusp field, a three-electrode extraction system, and a top cover with a confinement magnet inside. In the extraction system, there are two pairs of small
permanent magnets embedded in the extractor for electron filtration and a compact electric ring-magnet for axial steering of the beam. The ion source has a double filament, which proves to be better than single filament.

40 keV is required for injection into the cyclotron, and the ion source extraction configuration has been designed in order to provide a H⁺ beam with 0.605π mm-mrad of normalized emittance.

6.1.2 Injection
In the BCSI cyclotron the beam is injected upward into the cyclotron by mean of an axial transport line and a spiral inflector which bends beam by 90° into the median plane in the central region. The DC beam of 40 keV energy is injected from the ion source located below the magnet of the cyclotron. The injection line utilizes two solenoids and three quadrupole magnets for transverse focusing and a buncher for longitudinal bunching. For the H⁺ beam, space-charge effects are taken into account and 95% neutralization is used, which can be achieved with a vacuum of better than 10⁻⁴ Pa (10⁻⁶ mbar).

The spiral inflector should be capable of bending the H⁺ beam onto the median plane with a transmission efficiency of higher than 80%. The preliminary design of the spiral inflector sets the voltage at 13.8 kV (i.e. ±6.9 kV) for a gap of 8 mm.

6.1.3 Magnet Structure and Power Supply
The 70-MeV cyclotron consists of a top and a bottom yoke, 4 return yokes, 8 magnet poles, 16 shimming bars and two central plugs. The top/bottom and the return yokes are cast and other parts forged. The height of the magnet is 2.46 m and the diameter of the top/bottom yoke is 4.54 m. The radius of the magnet pole is 1.4 m. The hill gap is variable: it is 6.03 cm in the central region and gradually reduces to 4.69 cm at the outer radius. The total weight of the iron is 195 tons.

The main coil system consists of a pair of normal conducting, water-cooled coils. The magnet needs 126,855 ampere turns for the maximum field, and each coil has 546 turns, with nominal current of 116.43 A. The size of the conductor is chosen to keep the current density to 1.085 A/mm². The DC power supply for main coil provides 30 kW (120A/250V) with a stability of ±10⁻⁵.

6.1.4 RF System
The radiofrequency system consists of two independent cavities separated and shielded at the centre, providing a symmetrical dee voltage distribution for optimum beam centering. The two separate resonators are driven by individual amplifiers and low-level radiofrequency (LLRF) control. The cavity design adopts the “triangular” stem structure for increased dee voltage distribution toward the outer radii (to reduce Lorentz stripping).

Each cavity design is a half wavelength of the fourth harmonic of the fundamental frequency, with the following design parameters:

- Single stem triangular structure and double acceleration gap
- Capacitive coupling and tuning
- Angle between gaps: 33°
- Cavity height: 1262 mm
- Resonant frequency: 56–58 MHz (to be fixed after mapping)
- Quality factor: 11467
- Voltage distribution: 60–80 kV
- Average shunt impedance along the acceleration gap: 167 kΩ
- Estimated power dissipation: 13.6 kW.

The RF system will be equipped with two independent 50-kW amplifiers, each driving a cavity. Each amplifier will be fully contained in three cabinets. There is also the option of a separate positioning of the main high voltage supply for the amplifier tube, so that power supplies can be located in an adjacent electrical room, or a shielded basement area.
The power budget for the RF amplifier is as follows:

- Extraction energy 70 MeV
- Beam intensity 700 µA (possibly upgradeable to 1.5 mA in future)
- Beam Power 49 kW
- Cavity dissipation (under ideal conditions) 2 x 27.2 kW
- Cavity dissipation (RF engineering) 2 x 38 kW
- Low-level control power reserve 2 x 10 kW
- Total power for 2 amplifiers 97 kW

6.1.5 Extraction

The 70-MeV high-intensity cyclotron is designed to deliver proton beams with energies in the range of 35–70 MeV. The cyclotron will be equipped with two extraction combination magnets, placed at 180° with respect to each other. Any proton beam extracted by the H⁻ stripping process in the energy range 35–70 MeV, will be transported to a crossover point inside one of the extraction magnets, which is the starting point of the extraction line.

The total beam current measured outside the two extraction combination magnets should not be lower than the 99% of the full beam current at the extraction radius.

The two stripping probes are inserted in the radial direction towards the cyclotron centre (see figure 6.2). The position of a stripping probe required to extract a proton beam at the lowest energy (35 MeV) is 92 cm. In order to extract beams of higher energy, the stripping probes are moved radially outwards.

Fig. 6.2: Positions along a radial line (red) of stripper foils for extracting two separate proton beams. The foil position determines the energy selected. The two stripped H⁺ beams are automatically directed to the respective extraction dipoles (shown as rectangles), which steer them into the extraction beamlines. [Legnaro 2010]

For stripping extraction, separate carbon foils are used on each of the stripping probes. For an extracted energy of 70-MeV, the stripping efficiency is about 99.96% when the carbon foil
thickness is 120μg/cm². In order to reduce the time needed for changing foils, the stripping foils are housed in two carousels located in independent vacuum chambers.

6.1.6 **BEAM TRANSPORT SYSTEM SUPPLIED WITH THE 70-MeV CYCLOTRON**

For the SPES project, a transport system has been designed for each short beamline leading to a target area, as shown in figure 6.3, and will be provided by BCSI. Similar unit beamlines will be required at iThemba LABS, although we prefer to use quadrupole triplets instead of doublets.

![Diagram](image)

*Fig. 6.3: One of the beamlines designed for the SPES project. (See text).*

The beam transfer lines have been designed in order to deliver the proton beams extracted from the cyclotron at different energies varying within the 35–70 MeV range and at a maximum current of 700 μA. The beam lines are designed for high extraction efficiency and low beam loss. Optical
matching of the beam lines with the matrix of the fringe field is provided and dispersion effects during extraction are taken into account. Initially it is expected that a maximum of 350 μA will be available for each of the two extracted beams.

The beamline shown in figure 6.3 above contains:

- A combination magnet placed in the cyclotron yoke to bend the extracted beams of different energies into one common line.
- A gate valve.
- A diagnostics box with slits to cut beam halo, a Faraday cup and beam-profile wire scanner.
- A steering magnet to adjust the vertical beam position (the horizontal direction can be adjusted by using the switching magnet).
- A ±30° switching magnet to direct beam to different targets; a pumping station is connected to the vacuum chamber of the switching magnet to obtain the high vacuum of 1×10^{-5} Pa (10^{-7} mbar).
- A gate valve.
- Two doublets to focus the beam.
- A wobbling magnet to scan the beam on the target to provide beam current-density uniformity better than 5%.
- A high-vacuum pumping station.
- A diagnostic box with Faraday cup and beam scanner.
- A collimator before the target to limit the beam to a 40 mm diameter spot on the target.

6.1.7 VACUUM SYSTEM

The cyclotron vacuum is supplied by 4 cryopumps, with a roughing vacuum supplied by two mechanical pumps, giving an operating pressure of 2×10^{-7} mbar.

The ion source and injection line vacuum system requires a very high hydrogen pumping speed. Consequently two turbomolecular pumps are needed. The mechanical pumps mentioned above provide the roughing vacuum, while a dedicated mechanical pump backs the turbomolecular pumps.

Each beam line possesses its own vacuum system comprised of two cryopumping stations located on each beam line section such as that shown in figure 6.3 above. Each additional section of beamline will require its own vacuum system. Target areas will require their own, independent vacuum pumping stations, with an associated “nuclear” air handling and filtration system.

6.1.8 TECHNICAL REQUIREMENTS

The technical requirements for the BCSI cyclotron equipment are as follows:

- Temperature to be maintained around 20° and relative humidity around 45–75%;
- An air-cooling system (28.6 kW to be removed from the cyclotron vault);
- Air change or ventilation;
- Water cooling requirements (a chiller with a 250-kW cooling capacity);
- A compressed-air system;
- Industrial gas plant (high purity hydrogen and dry nitrogen bottles);
- Electrical power of 325 KVA.
Note that this cyclotron can only accelerate protons, which means that it does not require the trim-coils needed for accelerating deuterons and/or alpha particles. This keeps the interior of the vacuum chamber free of insulating epoxy resin and similar materials, which helps considerably in attaining the high vacuum needed. (Poor vacuum would lead to beam losses due to stripping caused by interactions with the residual gas, and at high beam currents the collisions between the resulting the neutral hydrogen ions and the chamber walls then lead to even poorer vacuum.)

Discussions with personnel from SPES indicate that the possibility of upgrading the maximum beam current to 1.5 mA in future has been contemplated, and could – in principle – be possible with such a cyclotron. This would mean that high beam currents of the order of 750 μA could then become available for both of the extracted beams simultaneously.

6.2 BUILDINGS FOR PHASE 1

The proposed building for the 70-MeV cyclotron and new radioisotope production area can be seen in the diagram below. Darker colours indicate where basement areas are planned for power and water reticulation and an isotope transporter.
The existing cyclotron control room (not shown above) will be used for control of the new facility, via a fibre-optical or Ethernet link, while access to the production vaults and operation of the rail-based radioisotope transporter will be monitored from the Isotope Control Room.

For Phase 1, the shielded areas will be constructed with solid concrete shielding roofs, which will avoid the need for expensive concrete roof beams, and make a costly overhead travelling gantry crane unnecessary. Small travelling cranes will nevertheless be needed inside the various vaults to permit installation and maintenance of beamline components, etc.

One implication of this is that the door to the cyclotron vault itself must be wide enough (4.5 m) to permit the cyclotron to be installed. [Note: The IBA personnel prefer to install the completed cyclotron in this way: BCSI personnel may have other preferences.]

Shielding doors to the radioisotope production vaults will be wide enough to permit a dedicated fork-lift truck to enter the isotope production vaults in order to remove and replace shielded target modules. These will then be serviced in the adjacent Isotope Service Lab. Radioisotopes produced in these modules will be transported directly from the production vault to a receiving hot cell via an automatic rail-based transporter in the basement, as is presently done in Block D. Some isotopes will have to be transported in shielded containers to the existing radioisotope hot cells in Block D for further processing, as is current practice at Los Alamos in the USA.

An alternative is a short basement tunnel linking into the existing basement: this would allow the automatic rail-based transporter system to carry irradiated targets directly to the receiving hot-cell via the existing transporter. However, because of the high water-table and the need to integrate the waterproofing into that of the existing basement, the practicality of this option will require detailed investigation by consulting engineers.

6.2.1 BEAM TRANSPORT

The beam transport system will use pairs of doublet or preferably triplet quadrupole magnets. Pairs of triplets operate in a point-to-point mode, and the symmetry of the system reduces the beam width everywhere except inside the central quadrupole of each triplet. We believe that placing the targets inside heavily shielded containers will minimise the radiation damage to the coil insulation of the quadrupoles, and the last triplets can be placed inside the vaults, to focus the beam onto the targets. Where targets are not shielded in this way, mineral-insulated coils will be required.

At the end of Phase 1, beams available from the second (western) extraction port of the 70-MeV cyclotron will be available for nuclear physics and materials science experiments, as well as for tests of targets and ion sources for RIB production.

6.3 RADIOISOTOPE PRODUCTION

The proposed new cyclotron will greatly increase the beam time available for isotope production, compared to what is presently available. Firstly, the beam will be available on a 24-hour basis, instead of being limited to 66 MeV beam-time shared with neutron therapy or after-hours irradiation. Secondly, it will be possible to install a beam-splitter to irradiate two radioisotope production target stations simultaneously.

An additional advantage will be that the heavily-shielded production stations will be designed to be removable via a fork-lift vehicle, so that the modules can then be serviced in the adjacent Isotope Service Laboratory, away from the high radiation levels present in the production vaults themselves. The size of such a module is shown in figure 6.5: this is the existing (non-movable) module. The module opens automatically to permit targets to be installed or removed via the hydraulic arm which is visible in the figure, and placed in an overhead transporter carriage. Radioisotopes produced in the new modules will then be transported to a receiving hot cell via an automatic rail-based transporter in the basement, as is presently done.
To save on the considerable cost of building a new hot-cell facility, some isotopes will have to be transported – in shielded containers – via a fork-lift to the existing radioisotope hot-cells in Block D for further processing. A similar system is used safely at Los Alamos, in the United States.

Two radioisotope production vaults are proposed, designated as “medium-intensity” and “high-intensity” areas, respectively. The medium-intensity vault will be provided with two beamlines terminating in fully shielded target modules for routine production of radioisotopes, as well as a third, semi-shielded line for development of new production techniques. Controlled personnel access will be possible, since the shielded target modules will contain most of the highly activated infrastructure.

The redundancy of having several operable stations at all times allows for fast turnaround in the event of a catastrophic target failure, without significant dose to maintenance staff and with minimal or no beam downtime. The high-intensity stations will receive in excess of 1,000,000 µAh of beam a year and will therefore be highly activated. Components will thus need to be removed remotely and with ease.

6.3.1 SUMMARY OF PHASE 1

A commercial 70-MeV H⁻ compact cyclotron will be installed in a room constructed with 3m concrete walls and a concrete roof, on a concrete floor slab with a basement below.

Beamlines from one extraction point (east) will lead to one of 5 target stations, housed in 2 separate vaults with 4 m of concrete shielding walls and roof slab, over a basement area.

Several target stations will be provided with shielded containers, similar to the module already used in the existing isotope production vault.

These shielded target modules will be removable for maintenance using a dedicated fork-lift vehicle to remove them to the maintenance area.

Each vault will have a shielding door wide enough for the fork-lift vehicle.
After production, the targets will be transported via the basement area to an adjacent receiving hot cell, using a rail-based transporter as presently used in the existing Radio-nuclide Production building.

3 beamlines from the other extraction point (west) can be installed leading to areas where nuclear physics or materials science experiments can be performed, or where tests of targets and ion sources for RIB production can be done. [These beamlines have been included as the early part of Phase 2.]

REFERENCES


Vermeulen 2012: E. Vermeulen, Radionuclide Production Group, iThemba Labs, 2012 (private communication).
7 PHASE 2(A): RADIOACTIVE-ION BEAMS VIA THE ISOL METHOD

Several methods exist for RIB production. We propose to use the isotope-separation-on-line (ISOL) method, in which rare isotopes are produced in a thick target and then diffuse out and effuse into an ion source. There the atoms are ionized, extracted into a beamline and later mass-analysed and purified before being led to low-energy experimental areas (or re-accelerated).

Initially we shall use a so-called “direct” target. A suitable target/ion-source system has been designed by the SPES team, with a prototype currently being prepared for testing at iThemba LABS in collaboration with local scientists and engineers.

In parallel we shall investigate a “converter” target, in which neutrons are produced in a primary target, leading to fission in a secondary actinide target. This method can potentially lead to significantly higher yields of neutron-rich isotopes.

[The neutron “converter” target option is discussed fully in section 9.2.]

7.1 DIRECT TARGET

The simplest type of target is the “direct” target, where the primary proton beam impinges directly on a thick target, inducing nuclear reactions which produce a large number of atomic species. (We note, however, that this kind of target places limitations on the maximum beam current which can be used without melting the target.)

Reactions on targets of light elements (e.g. carbon) emit many charged particles, allowing both proton-rich and neutron-rich beams to be produced. On heavier mass targets, fusion-evaporation reactions dominate, producing nuclei close to the line of stability on the proton-rich side. The main advantages of this kind of reaction are the high cross-sections and the high intensity of the primary beam available.

When rare neutron-rich isotopes are sought, fission can be induced in very heavy, neutron-rich materials like the actinides. Protons at 70-MeV can be used to cause fission directly in a depleted uranium target. In this case, secondary neutrons lead to further fission via (n,f) reactions in the uranium. Because the fission fragments have to diffuse out of the target material, they must be heated to high temperatures (around 2000°C), and so uranium carbide (UC₇) is a better target material than pure uranium. In this direct method, the beam current is limited by the amount of power which can be deposited in the UC, without melting it. (The melting point of the ceramic form of UC₂ is 2350°C; other forms of UC₂ have a higher melting points.)

7.1.1 RIB PRODUCTION

Experiments performed at HRIBF in Oak Ridge show that the radioisotopes shown in the table below can be produced – with varying degrees of difficulty – with 40 MeV protons. (A 70-MeV proton beam at iThemba LABS will generally give higher yields.)

The figures in the table below are for singly-charged ions produced by 200 µA of 40 MeV protons on direct (non-fission) targets, as well as for re-accelerated beams (40–60 MeV) assuming a charge-breeder efficiency of 3–4 %, and 50% post-accelerator transmission. We note in passing that three different types of ion source were used. These are described in more detail later. [Missing figures indicate no measurement of yield was made.]

The yields from the fission of ²³⁸U measured at HRIBF are summarized in figure 7.1 below. A major advantage of the uranium fission target is the large number of different ion beams (over 500) that can be produced from a single target.
Table 7.1: RIBs produced at HRIBF with 200 µA of 40 MeV protons on direct targets.
[Gramegna 2010]

| Element | A  | \( T_{1/2} \) (sec) | \( 1^\circ \) RIBs at 60 keV (pps) | Available* RIBs re-accelerated 40-60 MeV (pps) | Target material (alternatives) | SIS= surface source LIS= laser ion source FEBIAD= plasma
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>7</td>
<td>4.60x10^6</td>
<td>--</td>
<td>2 x 10^7</td>
<td>( \text{B}_4\text{C} )</td>
<td>LIS-FEBIAD</td>
</tr>
<tr>
<td>Be</td>
<td>10</td>
<td>--</td>
<td>3 x 10^7</td>
<td>( \text{B}_4\text{C} )</td>
<td>LIS-FEBIAD</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>17</td>
<td>6.48x10^6</td>
<td>--</td>
<td>2 x 10^7</td>
<td>( \text{HfO}_2, \text{ZrO}_2 )</td>
<td>LIS-FEBIAD</td>
</tr>
<tr>
<td>F</td>
<td>18</td>
<td>6.58x10^6</td>
<td>--</td>
<td>2 x 10^9</td>
<td>( \text{Al}_2\text{O}_3 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Na</td>
<td>21</td>
<td>2.25x10^1</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, Al}_2\text{O}_3, \text{CeS} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Na</td>
<td>22</td>
<td>2.60 sec</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, Al}_2\text{O}_3, \text{CeS} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Mg</td>
<td>22</td>
<td>3.86 sec</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, Al}_2\text{O}_3, \text{CeS} )</td>
<td>LIS-FEBIAD</td>
</tr>
<tr>
<td>Mg</td>
<td>23</td>
<td>1.13x10^1</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, Al}_2\text{O}_3, \text{CeS} )</td>
<td>LIS-FEBIAD</td>
</tr>
<tr>
<td>Al</td>
<td>24</td>
<td>2.05 sec</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, Nb}_3\text{Si}_3 )</td>
<td>SIS + LIS</td>
</tr>
<tr>
<td>Al</td>
<td>25</td>
<td>7.18 sec</td>
<td>--</td>
<td>1 x 10^4</td>
<td>( \text{SiC, Nb}_3\text{Si}_3 )</td>
<td>SIS + LIS</td>
</tr>
<tr>
<td>Al</td>
<td>26</td>
<td>6.35 sec</td>
<td>--</td>
<td>1 x 10^7</td>
<td>( \text{SiC, Nb}_3\text{Si}_3 )</td>
<td>SIS + LIS</td>
</tr>
<tr>
<td>Si</td>
<td>26</td>
<td>2.22 sec</td>
<td>--</td>
<td>1 x 10^4</td>
<td>( \text{Al}_2\text{O}_3\text{CeS} )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Si</td>
<td>27</td>
<td>4.16 sec</td>
<td>--</td>
<td>1 x 10^4</td>
<td>( \text{Al}_2\text{O}_3\text{CeS} )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>P</td>
<td>29</td>
<td>4.10 sec</td>
<td>--</td>
<td>--</td>
<td>( \text{SiC, CeS} )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Cl</td>
<td>34</td>
<td>1.53 sec</td>
<td>--</td>
<td>5 x 10^7</td>
<td>( \text{Ce}_3\text{Se}_2, \text{CeO}_2 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>As</td>
<td>73</td>
<td>6.94x10^6</td>
<td>1.45x10^4</td>
<td>2.9 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>As</td>
<td>74</td>
<td>1.54x10^6</td>
<td>1.89x10^4</td>
<td>3.8 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Br</td>
<td>78</td>
<td>3.88x10^6</td>
<td>3.0 x 10^4</td>
<td>6.0 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Br</td>
<td>80</td>
<td>1.08x10^7</td>
<td>3.4 x 10^6</td>
<td>6.8 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Rb</td>
<td>83</td>
<td>7.45x10^6</td>
<td>3.5 x 10^6</td>
<td>7.1 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>SIS</td>
</tr>
<tr>
<td>Rb</td>
<td>84</td>
<td>2.83x10^6</td>
<td>4.0 x 10^4</td>
<td>8.0 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>SIS</td>
</tr>
<tr>
<td>Sr</td>
<td>85</td>
<td>5.60x10^6</td>
<td>2.2 x 10^5</td>
<td>4.4 x 10^4</td>
<td>( \text{ZrC, ZrO}_2 )</td>
<td>SIS</td>
</tr>
<tr>
<td>Cs</td>
<td>131</td>
<td>8.37x10^6</td>
<td>8.2 x 10^6</td>
<td>1.6 x 10^5</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Cs</td>
<td>132</td>
<td>5.60x10^6</td>
<td>8.9 x 10^7</td>
<td>3.5 x 10^5</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>I</td>
<td>126</td>
<td>1.13x10^6</td>
<td>1.8 x 10^4</td>
<td>--</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>FEBIAD</td>
</tr>
<tr>
<td>Ba</td>
<td>131</td>
<td>9.94x10^6</td>
<td>--</td>
<td>--</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>La</td>
<td>133</td>
<td>1.41x10^6</td>
<td>--</td>
<td>--</td>
<td>( \text{CeS} )</td>
<td>SIS</td>
</tr>
<tr>
<td>La</td>
<td>134</td>
<td>4.00x10^6</td>
<td>--</td>
<td>--</td>
<td>( \text{CeS} )</td>
<td>SIS</td>
</tr>
<tr>
<td>La</td>
<td>135</td>
<td>7.02x10^6</td>
<td>2.3 x 10^4</td>
<td>4.5 x 10^4</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>La</td>
<td>136</td>
<td>5.92x10^6</td>
<td>2.9 x 10^5</td>
<td>5.6 x 10^4</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Ce</td>
<td>135</td>
<td>6.39x10^6</td>
<td>--</td>
<td>--</td>
<td>( \text{La}<em>{17}\text{Ce}</em>{23} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Lu</td>
<td>179</td>
<td>1.65x10^7</td>
<td>--</td>
<td>--</td>
<td>( \text{TaC} )</td>
<td>SIS</td>
</tr>
<tr>
<td>Hf</td>
<td>173</td>
<td>8.50x10^7</td>
<td>--</td>
<td>--</td>
<td>( \text{TaC} )</td>
<td>FEBIAD</td>
</tr>
</tbody>
</table>

*Intensities available at HRIBF, and the estimated re-accelerated intensities at SPES assuming a charge-breeding efficiency of 3-4% and a post-accelerator transmission efficiency of 50%. Missing numbers indicate that no measurement of intensity was made or calculated.
Fig. 7.1: Production rate of fission fragments by direct fission of $^{238}$U using a 50 MeV proton beam. [Stracener 2010]

For materials science, a number of radioisotopes are of special interest. For example, long-lived isotopes with half-lives in the range of hours are suitable for diffusion studies, defect evolution and structural studies. We summarize some of these in more detail in the table 7.2 below, listing the methods used at ISOLDE for their production. (These isotopes are produced at CERN using a 1 GeV proton beam, so their measured yields are not directly applicable to production via a 70-MeV proton beam.)

Note that the table is colour-coded according to the type of ion source used. The specific ion sources used at CERN are the result of many years of study to determine the most efficient method for producing the isotopes required.

7.1.2 COLLABORATION WITH INFN-LNL

A direct target has been the subject of considerable development effort for the SPES project at the INFN-LNL laboratory in Legnaro, Italy. Both SiC and a UC$_x$ (fission) targets have been developed. Their R&D has reached the stage where in-beam tests are required.

A Memorandum of Understanding (MoU) has been drawn up between iThemba LABS and the INFN laboratory in Legnaro, (LNL), to test their SPES direct target at iThemba using 40 MeV protons and high beam current (~100 µA). Complete design drawings will be available from LNL, and a copy of the structure will be manufactured locally in South Africa. These tests are proposed for the Research and Development Phase, in the RIB Target/Ion-Source Test Facility. Thereafter, we propose to use this copy of the SPES direct target assembly at iThemba LABS for Phase 2.
Table 7.2: Isotopes produced at ISOLDE which are of interest for materials science, colour-coded by type of ion source used. [CERN 2011]:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Target material</th>
<th>Target thickness (g/cm²)</th>
<th>Ion Source</th>
<th>Yield from high-energy p at ISOLDE (ions/µC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>³⁶Cl</td>
<td>ThO₂</td>
<td>46.7</td>
<td>Negative SIS</td>
<td>6.3E+06</td>
</tr>
<tr>
<td>⁴²K</td>
<td>Th/Ta foil/powder</td>
<td>5.5 (Th)</td>
<td>Plasma source</td>
<td>2.6E+06</td>
</tr>
<tr>
<td>⁴³K</td>
<td>UC₆</td>
<td>13</td>
<td>WSI (W surface)</td>
<td>2.4E+07</td>
</tr>
<tr>
<td>⁴³K</td>
<td>Ta metal foil</td>
<td>122</td>
<td>WSI (W surface)</td>
<td>5.0E+07</td>
</tr>
<tr>
<td>⁶⁵Ni</td>
<td>Ta foil</td>
<td>93</td>
<td>RILIS</td>
<td>2.0E+06</td>
</tr>
<tr>
<td>⁶⁷Cu</td>
<td>ZrO₂ felt</td>
<td>6</td>
<td>RILIS</td>
<td>3.0E+05</td>
</tr>
<tr>
<td>⁶⁷Ga</td>
<td>ZrO₂ felt</td>
<td>6</td>
<td>WSI</td>
<td>5.0E+07</td>
</tr>
<tr>
<td>⁶⁷Ge</td>
<td>Nb metal foil</td>
<td>46.2</td>
<td>FEBIAD</td>
<td>9.1E+07</td>
</tr>
<tr>
<td>⁷¹As</td>
<td>ZrO₂</td>
<td>6.3 (Zr)</td>
<td>FEBIAD 2000°C</td>
<td>1.0E+08</td>
</tr>
<tr>
<td>⁷³Ga</td>
<td>ZrO₂ felt</td>
<td>6</td>
<td>RILIS (W)</td>
<td>3.7E+06</td>
</tr>
<tr>
<td>⁷³Ga</td>
<td>UC₆</td>
<td>52</td>
<td>RILIS (Nb)</td>
<td>4.8E+05</td>
</tr>
<tr>
<td>⁷³Ge</td>
<td>ZrO₂ felt</td>
<td>5.8</td>
<td>FEBIAD</td>
<td>7.0E+06</td>
</tr>
<tr>
<td>¹¹⁰Sn</td>
<td>TeCl⁴</td>
<td>6</td>
<td>FEBIAD (hot line)</td>
<td>3.0E+08</td>
</tr>
<tr>
<td>¹¹¹Ag</td>
<td>UC₆</td>
<td>9.7</td>
<td>FEBIAD at 1950°C</td>
<td>3.0E+10</td>
</tr>
<tr>
<td>¹¹¹Ag</td>
<td>Ta metal foil</td>
<td>122</td>
<td>FEBIAD</td>
<td>5.3E+04</td>
</tr>
<tr>
<td>¹¹³Ag</td>
<td>UC₆</td>
<td>9.7</td>
<td>FEBIAD at 1950°C</td>
<td>2.8E+09</td>
</tr>
<tr>
<td>¹¹⁷⁶Cd</td>
<td>UC₆</td>
<td>9.7</td>
<td>FEBIAD at 1950°C</td>
<td>6.2E+07</td>
</tr>
</tbody>
</table>

7.1.3 THE SPES DIRECT TARGET

Three important parameters are required to optimize a fission ISOL target: firstly, a high number of fission reactions (to provide high RIB intensities), then a low power deposition in the target materials (to avoid melting temperatures) and finally a fast isotope release time (to improve extraction efficiency).
The main problem for a direct target configuration concerns the power deposited by the incident beam in the production target. In order to solve this issue, only the protons with high $^{238}$U fission cross-section will be exploited and the thermal aspects of the target designed accordingly.

As it happens, the $^{238}$U fission cross-section and the stopping power for protons in UC$_x$ depend differently on the proton energy, as shown in figure 7.2 below. After penetrating into the UC, the protons lose energy, and the resulting low-energy protons (below 15 MeV) have high stopping power and release high power in the target, but are not very efficient for isotope production because of their low fission cross-section. An important phenomenon is the Bragg peak caused by high energy deposition at the end of the proton range, which could lead to excessive heating and melting of UC$_x$. Therefore the last section of the target will consist solely of carbon, which has a much higher melting point than UC$_x$ (e.g. 2350°C for UC$_2$ versus 3500°C for C).

If the low-energy protons (with energy lower than about 15 MeV) penetrate into a passive graphite dump, the remaining beam power is deposited in the dump; however, because of the reduced fission cross section at such a low energy, the overall number of fission reactions is almost unchanged. The $^{238}$U fission cross-section is more-or-less constant above this energy. Note that above 100 MeV, spallation would enter in competition with fission and transuranium elements (alpha-emitters) would be produced, complicating the radiation protection management.

The SPES target at LNL is designed for a proton energy of 40 MeV (with a possible upgrade up to 70 MeV). It is therefore sensible for the iThemba RIB project to start with 40 MeV, to benefit from the R&D done for SPES. Although 70-MeV protons would increase the yield of rare ion beams by about a factor of 2, it would require some R&D to achieve this with higher power deposition. It may be more rewarding to direct this research into a so-called “converter” target, which is discussed in section 9.2. We note, however, that high-power 66-MeV proton beams are routinely available at iThemba LABS, without upgrading the accelerators, so that using this energy would simplify the process of beam delivery to the target area.

![Fig. 7.2: Stopping power (red curve) and fission cross section (blue curve) plotted for protons entering a UC$_x$ target from the right. The insert shows disks of the UC$_x$ target (yellow) and thicker C disks of the beam dump (dark grey). [SPES 2010]](image)

A critical parameter is the release time of the reaction products from the target material. This can be divided into two parts – the time taken for the radioactive atoms to diffuse out of the target material itself, and then the time to effuse to a region in the ion-source where ionization of the atoms can take place. It is critical because isotopes far from the line of stability have short half-lives (milliseconds) and can decay before ionization if the diffusion and effusion times are too long.
In order to optimize the release time (and the heat dissipation) of the fission products, the target is split into a number of disks: the UC$_x$ target disks are spaced along the beam direction (figure 7.3) in order to assist in the effusion of the rare ions towards an adjacent ion source.

![Fig. 7.3: CAD drawing of the SPES target assembly, showing the UC$_x$ disks (yellow) in a graphite tube and also the beam dump disks (dark grey). [SPES 2010]](image)

Efficient diffusion of the rare ions out of the UC$_x$ target material requires external heating to high temperatures (~ 2000°C). This is provided by enclosing the target disks in a graphite tube, placed inside a thin tantalum (Ta) tube; this tube is held in place by and electrically connected to copper clamps, through which an electric current from a 10-kW power supply flows, heating the tube by resistive heating. (See figure 7.4 above.)

![Fig. 7.4: The SPES target (chamber lid removed), designed for a 40 MeV proton beam entering from the right. The heating current flows through the Ta tube, between the copper clamping bars at each end. The small central tube connects the target chamber to the ion source. [Andrighetto 2011]](image)
Tantalum is chosen because it is highly corrosion-resistant, able to conduct heat and electricity, and able to operate at very high temperatures. At a pressure of $10^{-4}$ Pa (the pressure inside the chamber during the working conditions) Ta only begins to sublimate at approximately 2200°C. Further, owing to its low emissivity (0.26 at 2000°C), tantalum is able to screen the target box efficiently, limiting the cooling by thermal radiation.

7.2 ION SOURCES

Before the rare isotopes can be formed into a beam of particles, the neutral atoms must first be ionized in an ion source. A number of different kinds of ion source exist, and the figure below shows the nuclides which can be ionized with the various methods used for RIB production at CERN-ISOLDE:

![Table of the elements showing the ionization methods which are used for producing some neutron-rich isotopes at ISOLDE. [Andrighetto 2011]](image)

In the sections below we discuss the different kinds of ion source used for ionization of RIBs:

- surface ion sources (SISs)
- laser ion sources (LISs) – which use photo-ionization
- plasma ion sources, such as “forced electron-beam-induced arc-discharge” (FEBIAD) sources.

7.2.1 SURFACE ION SOURCES

When a tungsten cavity or tube is heated to a temperature well above 2300K, high ionization efficiencies for elements with modest ionization potentials can be reached. These ion sources produce a high degree of selectivity for certain elements.
Materials with high work functions and which can be heated to high temperatures, like tantalum ($\varphi = 4.19$ eV), tungsten (4.53 eV) and rhenium (5.1 eV) are used to construct positive surface ionization sources. With this ionization technique, extreme selectivity can be obtained if the elements of which isotopes are produced in the same nuclear reaction have very different ionization potentials. For example, the elements krypton, rubidium and strontium are often produced in the same nuclear reaction. The ionization potentials of krypton (14.0 eV), rubidium (4.18 eV) and strontium (5.70 eV) are very different. Using tungsten as surface ionizing material at a temperature of 3000K then results in a very pure beam of rubidium ions.

7.2.2 LASER ION SOURCES

During the laser-ionization process, atoms are excited in a stepwise manner by laser photons, leading finally to the continuum, to auto-ionizing states, or to highly excited states close to the continuum. In the latter case the final ionization step is achieved through infra-red irradiation, an electrical field or atomic collisions. The ionization process consists of typically two or three steps and, because of the resonant nature of most of these steps, resonant laser ionization is very efficient and chemically selective, resulting in isobarically pure and, if the laser bandwidth is narrow enough, isomerically pure beams. The method is illustrated in the figure below.

![Fig. 7.6: Schematic atomic level scheme showing the principles of resonant photo-ionization of nickel. [Van Duppen 2006]](image_url)

Laser ionization has already been demonstrated on the test bench using stable atoms, in a collaboration between iThemba LABS and Stellenbosch University. [Makhathini, 2012]

In principle, the lasers can also be directed into a surface ion source with little or no modification, as long as the normally-hot surface is instead kept cool.

One major prerequisite to study shorter-lived or lower-yield radioisotopes at ISOL facilities is the availability of ion beams without isobaric interference. The conventional ionization mechanisms of surface or plasma ion sources can be very efficient, but are chemically non-selective. The resulting degree of isobaric contamination would render many experiments impossible.
The resonance-ionization laser ion source (RILIS) addresses this problem by applying the highly selective and efficient technique of stepwise resonant ionization of the element of interest using up to three overlapping laser beams of different wavelengths in the ionizer tube of the target unit.

At CERN the ISOLDE RILIS currently uses up to three dye lasers: two broad-band lasers and one narrow-band laser. The lasers are optically pumped simultaneously by a Nd:YAG laser which provides 8-10 ns pulses at a repetition rate of 10 kHz with a total output power of typically 100 W in the second harmonic. If necessary, a third harmonic beam of up to 20 W can be generated for blue to green dyes that require UV pump beam. A typical RILIS system with dye lasers is shown schematically in figure 7.7. Figure 7.8 shows the achievable wavelengths using dye lasers.

**Fig. 7.7: Diagram of a dye laser RILIS system, pumped by a Nd:YAG laser. [Fedosseev 2011]**

**Fig. 7.8: The range of wavelengths achieved by means of different dyes. [Fedosseev 2011]**

Up to three days of preparation are needed for such a system if a different element is requested, which includes a change of the dye solution (more than ten different dyes are used), laser set-up and alignment of the beams into the ion source. However, CERN has now upgraded their system to include solid-state titanium-sapphire (Ti:Sa) lasers, and we shall also use these.
For SPIRAL2 a system of 3 solid-state Ti:Sa lasers from TRIUMF is being assembled, pumped by a Nd:YAG pump laser, with a system of frequency-doublers, triplers or quadruplers developed at Mainz University, as shown in figure 7.9. This is the current state-of-the-art system, and we intend to use this type of set-up. Figure 7.10 shows the achievable wavelengths using dye lasers and Ti:Sa lasers and their higher harmonics.

Fig. 7.9: SPIRAL2 will use three Ti:Sa cavities pumped by a Nd:YAG laser, together with frequency-multipliers to reach lower wavelengths. [Delahaye 2011]

Fig. 7.10: Overview of the achievable wavelengths using Ti:Sa lasers and their higher harmonics, compared to dye lasers. [Rothe 2011]

7.2.3 FEBIAD PLASMA ION SOURCES

In these sources the electrons are extracted from a heated cathode and accelerated into a low-pressure plasma. Very high efficiencies up to 50% are obtained with these sources. The lightest
atoms (e.g., helium, neon) have a lower efficiency as their residence time inside the plasma is too short for efficient extraction. In general, arc-discharge ion sources are not selective. The energy spectrum of the electrons is broad and allows ionization of virtually every element. Thus the ionization efficiency for the heavy elements (bismuth, lead, xenon, tin, silver) is close to 50%, while it is much lower for krypton, argon and for neon (1%).

However, by changing the temperature of the transfer tube between the target chamber and the ion source, isotopes of less volatile elements adsorb on its walls while isotopes from gaseous elements or gaseous molecules reach the ion source. In this way a very high degree of selectivity can be obtained. This type of ion source will therefore also be used at iThemba LABS.

7.3 RIB TARGET & ION SOURCE FROM SPES

The layout of the SPES target/ion-source (TIS) can be seen from figure 7.1.1 below, and from the subsequent photograph of the SPES test set-up at Legnaro (figure 7.12). The target-holder is a modified version of a standard target used at CERN-ISOLDE.

![Diagram of SPES target/ion-source](image)

*Fig. 7.11: The RIB production facility designed for the SPES project. The primary proton beam (PPB) enters from the side, as shown, striking the “target block” inside the removable target chamber. [Manzolaro 2007]*

Because iron and steel become quite active under neutron bombardment, with the production of long-lived isotopes, the majority of the structural components are manufactured from aluminium. Induced activity in the aluminium is relatively short-lived.
In figure 7.12 the SPES prototype target/ion-source assembly is shown, which we shall copy with the collaboration of the team in Legnaro. The white insulating columns and insulating tube support and separate the high-voltage section containing the target and ion source from the rest of the assembly. This high voltage accelerates the extracted beam to around 60 keV as it leaves the ion source, depending on the high voltage used. The modular section which holds this target/ion-source structure will become activated over time and can be separated from the rest of the beamline and removed, to permit personnel access to the vault.

For the SPES project, three different types of ion source have been developed, all based on the same modular design derived from a standard ISOLDE ion source. The sources are respectively (a) a surface ion source, (b) a laser ion source and (c) a FEBIAD plasma ion source, as were described above. We shall be able to profit from these developments at iThemba.

For on-line operation at SPES, the target/ion-source complex shown in figure 7.12 will be housed in a concrete vault, and equipped with beamline elements needed to transport the beam out of the vault. These include electrostatic quadrupoles and a Wien filter to make a preliminary mass selection. A similar system will be installed at iThemba LABS in Phase 2(a).

Because of the high activation of the target/ion-source assembly, a purpose-built robot for each of the two vaults has been designed for SPES to remove the assembly and place it in a lead container, before transporting it to one of their two storage areas. In our case, a “staggered” design of the building allows one robot to service both vaults. We also prefer to follow the ISOLDE approach, and to use a dedicated commercial robot for this purpose.
7.4 Beam Transport

The rare ion beams extracted from the ion source must be transported out of the production vaults in a beam pipe and towards a mass analyser. Owing to the low energy of this ion beam, electrostatic beam transport elements can be used. For focusing, electrostatic quadrupole triplets will be used. Drawings will be available from SPES at Legnaro and/or from SPIRAL2 at GANIL.

To reduce activation, it is useful to use either a Wien filter (as at SPES) or a small 90-degree dipole magnet (as at SPIRAL2) as a pre-separator, which purifies the beam by removing the majority of the unwanted ions from the beam with a system of slits. Such a dipole only needs to have a fairly low resolving power, and one of the small dipoles previously obtained from HMI in Berlin can serve this purpose.

We therefore intend to use a small 90-degree dipole as a pre-separator.

7.4.1 Mass Separator

High mass-resolution is required, both to separate isobars and also because many different elements can be ionized by chance in the target/ion-source assembly, and the tails of distributions of the more abundant isotopes will always be present in the beam. This is illustrated in the figure below:

![Spectrum of an ion beam obtained after mass separation. The peaks have long asymmetric tails, caused by collisions of ions with gas molecules when the ions are extracted and transported through the beam lines. As a consequence, at every mass peak, contributions from nearby (intense) mass peaks can be observed, even when the mass resolution is very good. [Van Duppen 2006.]](Fig. 7.13)

For high-resolution mass separation, and especially for isobar separation, a more sophisticated system will be needed than the pre-separation mentioned above. This can be seen from the following figure, which shows the resolution required to separate isobars for mass 36 and mass 80, as examples.
Fig. 7.14: Masses of isobars plotted for mass 36 and for mass 80. It can be seen that even a mass resolution of 15,000 would not be able to separate all the isotopes. [Kurtukian 2010]

Note that in figure 7.14, extremely high mass resolution would be needed to separate some of the isotopes shown. However, this is generally true only for isotopes at or close to stability. For most other isotopes a mass-resolution of 30,000 will be sufficient to separate them, even with finite beam emittance and slit sizes.

A system of two 60-degree dipoles plus two quadrupoles and a multipole magnet was designed at ANL in Argonne, USA, for the CARIBU project, with a mass-resolution of 20,000. This design has been modified for the SPES project, while a dual 90-degree version has been designed for SPIRAL2. This latter version (called the HRS-180) uses two dipoles, each having a radius of 85 cm, and the combination has a theoretical mass-resolution of 31,500.

We propose to build a copy of the SPIRAL2 version, shown schematically in figure 7.15 below, as it has a very high mass-resolution. This is a state-of-the-art separator, and is still at the design stage since the field homogeneity needed (at the $10^{-5}$ level) is at present only achievable over a pole-width of 100 mm, and sextupole and octupole corrections must be included.

For a beam emittance of $3\pi$ mm-mrad and 1 mm slit widths, and for isobars differing in mass by only 1 in 20,000, this device is calculated to have a transmission of 77%, with 1.4% cross-contamination. However, for an emittance of $1\pi$ mm-mrad the separator has a 97% transmission, with only 0.09% cross-contamination. This shows the importance of reducing the RIB emittance, which can be achieved using a radiofrequency quadrupole cooler, described below.

Drawings of the components of this separator can probably be obtained from GANIL. We are also in contact with the person at CENBG who is designing the separator, and the magnet designer at GANIL. However, the final drawings would presumably be the property of the manufacturer, from whom we could request a quotation for supplying the magnets. iThemba LABS personnel have also very successfully designed and manufactured a large number of dipole, quadrupole and steering magnets in the past, which can reduce the cost significantly when compared to that of imported magnets.
Section 7

7.4.2 RADIO-FREQUENCY QUADRUPOLE (RFQ) COOLER

Why will we need a cooler? The RIB emittance from the ion source is large (typically 10π mm.mrad in each plane) and then the finite magnet pole-width in the mass-separator implies that the slit size must be large, e.g. 5 mm wide, to reduce the divergence and avoid exceeding the uniform-field area inside the dipoles. This would reduce the resolving power of the separator by a factor of 5, compared with that when 1 mm slits are used. It would thus reduce a mass-resolution of 30,000 to just 6,000. To make the dipole poles wider would be very expensive and consume more power.

A cooler can reduce the emittance by the required factor of 5, so that 1 mm slits can be used.

An RFQ cooler works by allowing collisions between the beam ions and a light buffer-gas such as helium, which removes thermal energy from the beam, thus reducing the emittance. The RFQ – on an HV platform – provides radial focusing of the beam, and an axial DC component of the field guides the ions towards extraction, as shown in the figure 7.17 below.

The RFQ cooler, together with pumps, insulators, vacuum pumps, an electrostatic quadrupole triplet and a revised “pepper-pot” emittance meter are now being set up and tested on a beamline at GANIL. Details of the RFQ cooler and the assembled beamline are shown in figure 7.18.
For low-intensity (nA beam current) Cs⁺ beams, the measured transmission to date is close to 90%, while for µA currents, transmission is 70%. Cooling time is in the millisecond range and the cooler can be operated in CW mode. [Lunney 2012]

**Fig. 7.17:** The principle of operation of an RFQ cooler. [Calabretta 2010]

**Fig. 7.18:** Drawing of the RFQ cooler, with pumps etc., on a test beamline for SPIRAL2. [Boussaid 2011]

### 7.4.3 BEAM ANALYSIS

Traditionally an RIB mass-identification station uses a tape transport system to capture the isotopes, which are then identified by their decay gamma-rays, using scintillators and photomultiplier tubes. Several methods developed for SPES are illustrated in figure 7.19 below. A preliminary analysis can be achieved by examining the mass spectrum of the RIB isotopes as the beam is scanned across the exit slits by varying the field of the analysing magnet(s). At GANIL, a typical tape system is proposed for their identification stations. The tape-transport system is shown in figure 7.20 below, and we shall also require such a system.
Fig. 7.19: Low-energy RIB imager/identifier, as used at LNL in Legnaro. There are three different targets, positioned one above the other, with different read-out methods: (1) a plastic scintillator with a photomultiplier tube for RIB imaging, (2) a CsI(Tl) plate scintillator for stable (pilot) beam imaging, and (3) a tape system for isotope identification and counting. [Cosentino 2010]

Fig. 7.20: Tape transport system proposed for RIB identification stations for SPIRAL2. [Etasse 2010]
For the iThemba LABS setup, these various systems will have to be developed and compared. Initially, a tape-transport system will be used: these exist at many laboratories around the world from which drawings and operational information can be obtained.

### 7.4.4 BEAM DIAGNOSTICS

While conventional diagnostic methods, such as rotating-wire scanners, multi-wire “harps”, etc. can be used for beams of normal intensity, a completely different approach is needed when it comes to low-intensity beams of exotic ions. Even capacitive devices, which are non-destructive, are limited to beams of nanoamp or higher intensities.

For RIBs, the intensity of the final beam current can span several orders of magnitude, becoming critical for beam diagnostics below $10^8$ particles per second (pps), and even worse below $10^5$ pps.

Several alternative methods have been proposed for the SPES and SPIRAL2 projects, and these are discussed below. The available techniques are based on semiconductors, gas detectors, secondary emission detectors and scintillators, as well as other techniques like diamond detectors, residual-gas and Cherenkov detectors.

Low-intensity beam diagnostics is an area where much development is needed at iThemba LABS, and students will be able to contribute by acquiring expertise from other laboratories overseas, and by refining developments initiated elsewhere.

#### For low-energy RIBs:

- Position-sensitive semiconductors can be used for beams below $10^4$ pps.
- A silicon $\Delta E-E$ detector telescope can be used with a thin gold foil target.
- Scintillators are a trade-off solution between robustness, ease-of-use, and cost: CsI(Tl), doped glass, and plastics (for low intensities) offer good performance.
- A beam-profile monitor based on micro-channel plates has been successfully tested at INFN-Legnaro with a 50 keV beam of $^{15}$O ions, and a similar device is being developed at GANIL.

#### For post-accelerated RIBs:

- Plastic scintillators can be used for beam intensity measurements.
- Position sensitive silicon detectors can be used for real-time beam imaging.
- A beam profile monitor based on a pair of scintillating fibres for scanning the beam has also been developed at INFN, shown in figure 7.21.
- GANIL has also developed a secondary-emission micro-channel plate device, illustrated in figure 7.22.
A scintillating-fibre beam scanner developed at INFN Legnaro. [Consentino 2010]

A secondary-emission multi-wire profiler with gas circulation has now been developed at GANIL for post-accelerated beams, as shown in figure 7.23. The principle is that of a gas ionization chamber. Resolution is better than 1 mm for $10^2$ to $10^6$ pps with a gas pressure of 10 mbar of $\text{C}_4\text{H}_{10}$ or $\text{C}_3\text{F}_8$ and with an input window thickness of 6 $\mu$m of Mylar®.
7.4.5 VACUUM PUMPS

Because the rare ions are produced in (relatively) small numbers, it is necessary to reduce losses due to charge-exchange with residual gas in the beamlines as much as possible. Calculations to determine the rate of charge-exchange loss as a function of pressure have been done for high charge-state ions, showing that beam-line pressure is important. (Refer to section 8.2.2)

For singly-charged ions, charge-exchange is somewhat less important, but for the long beamline between the mass-spectrometer and the charge-breeder, it does become a significant problem. It is clear however, that the pressure in the beamlines must be reduced to $10^{-7}$ mbar wherever possible, to minimise charge-exchange losses.

This will be achieved with turbomolecular pumps. In principle these can reduce the pressure to $10^{-8}$ mbar, although at such low pressures ion pumps may be more efficient. In addition, oil-free (dry) backing pumps must be used. For lower pressures (~$10^{-8}$ mbar), cryopumps will have to be used.

Cryopanels in the beam lines have also been used at laboratories elsewhere to trap unwanted radioactive gases from the ion source, to prevent them spreading throughout the beam pipes. For safety, therefore, these will be inserted close to the RIB target vaults.

7.5 BUILDINGS FOR PHASE 2

Phase 2 includes the construction of two shielded concrete vaults, adjacent to Phase 1, in which radioactive-ion beams can be produced. (See figure 7.24.) The two vaults will permit semi-permanent installation of different types of target (e.g. “direct” and “converter” targets as described in sections 7.1 and 9.2 respectively). In addition, an extension of the existing Accelerator Hall will link Phase 1 to the existing accelerator complex. This will provide space for the purification and mass analysis of the radioactive beams, and for experimental areas for low-energy materials science and nuclear physics with radioactive-ion beams (RIBs) in Phase 2(a), and for breeding of the RIBs to high charge-states for injection into the SSC in Phase 2(b).

Access to the two RIB vaults has been planned so that handling and storage of radioactive targets can be accomplished by means of a single remotely-controlled robotic vehicle on rails.
Fig. 7.24: Buildings for Phase 1 (pink) and Phase 2 (yellow) of the project. Darker shades indicate where basements are proposed. (The North Experimental Area extension for Phase 2(b) is shown in figure 1.1 presented earlier.)

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Lunney 2012  D. Lunney, CSNSM, France, 2012 (Private communication.)


SPES 2010  http://www.lnl.infn.it/~spes_target/ENG/the-target-1.php


8 PHASE 2(b): POST-ACCELERATION IN THE SSC

For nuclear physics experiments with radioactive-ion beams, it is often necessary to accelerate the ions to higher energies. This is also true for deep implantations for materials science, for example. This can be achieved if the RIBs produced can be introduced into the accelerator chain at iThemba LABS. We propose to do this by injecting the ions into an existing beamline leading to the SPC2 injector cyclotron, after which the accelerated beam will be transported to the SSC for further acceleration.

8.1 CHARGE-BREEDING

For reaching higher energies, a charge-breeder is required to increase the charge of the RIB ions from 1+ to n+. Charge-breeding can be done by stripping, as at ISAC at TRIUMF (which is simple, fast and has a high efficiency for light ions and pure beams, but has low efficiency for heavy ions), or with an ECR ion source or an EBIS ion source. These have different properties, discussed below.

In order to minimise beam losses through charge-exchange with residual gas molecules in the beam pipes, it will be beneficial to locate the charge-breeder in the basement, relatively close to SPC2. However, since space is already limited below SPC2, the charge-breeder will be in the adjacent basement below the new extension of the Accelerator Hall.

One aspect which is a matter of some concern is the low efficiency of charge-breeders (10% at best for an ECR, 20% at best for an EBIS breeder), which implies that 80–90% of the exotic ions produced will be lost in the breeder. In some cases in can be more efficient to use a stripping foil, but this cannot always be used efficiently, especially for heavy radioactive ions.

8.1.1 ELECTRON-CYCLOTRON-RESONANCE ION SOURCE (ECRIS) AS CHARGE-BREEDER

We will initially use an ECR ion source for the charge-breeding of radioactive ions. ECR sources are presently in operation at iThemba LABS and the laboratory is experienced in their installation and operation. For example, staff are currently developing beams from an ECR ion source at iThemba LABS, in collaboration with a group at CERN, to produce ions for use in a large experiment on the Linear Hadron Collider (LHC).

The more complex EBIS may be installed at a later date – the relative merits of the two types of charge-breeder are discussed in the next section.

In an ECR ion source, the incoming RIB ions are slowed down by a platform voltage and then simply trapped in the field dip of a “magnetic bottle” (see figure 8.1). Injected microwave power creates a plasma in which electrons are stripped off the trapped ions. Finally the ions leak out of the magnetic confinement and are extracted by the electric field gradient. The beam is therefore continuous, and will then need to be bunched at a frequency corresponding to the frequency of the subsequent accelerator into which it will be injected (i.e. SPC2).

The figure below shows the components and the shape of the magnetic field, together with a photograph of the Phoenix ECRIS, which is undergoing further development for SPIRAL2.

A “turn-key” Phoenix ECR ion source, including all power supplies, supports, control cabinet, safety interlocks, X-ray protection, capable of delivering a beam (but without any analysis system) will cost about 750 k€ (approximately R7.5 million). [Villari 2011]
Fig. 8.1: Schematic diagram of an ECR ion source, such as the PHOENIX charge-breeder, together with its magnetic field. [Kester 2007]

Fig. 8.2: The measured efficiencies of charge-breeding with the PHOENIX charge-breeder. [Kester 2007]
8.2 **INJECTION INTO THE SSC**

8.2.1 **BEAM TRANSPORT**

The singly-charged rare-isotope beams will be mass-selected as described above and then transported using electrostatic beamline elements to the charge-breeder, before being injected into the SPC2 injector cyclotron. To minimize charge-exchange losses in long beamlines, the charge-breeder should be located in the new basement area, but as close as possible to SPC2. The beamline from the charge-breeder will then join into the existing ‘Q’ beamline, leading into the ‘AX’ axial injection beamline into SPC2 from below.

As these exotic isotope beams are often of very low intensity, the usual practice at RIB facilities elsewhere is to start by accelerating a so-called “pilot” beam of a stable heavy-ion species with mass and charge-state close to those of the radioactive-ion beam in question. At iThemba LABS this will be furnished by the ion source normally used for stable heavy-ion beams, which feeds directly into the Q beamline.

Thereafter, since the mass and charge-state of the pilot beam are never exactly identical to those required, a computer program is used to scale the various beamline element settings up or down by a small amount to suit the exotic ions, so that after acceleration in the SSC, they will be transported efficiently to the RIB experimental area.

A new RIB experimental area is also proposed, situated at the north end of the existing Accelerator Hall. (Refer back to figure 1.1 of Section 1.) This will require a large 90° dipole to bend the beam into a westerly direction, similarly to that for the existing spectrometer. An existing 1.5 m radius dipole magnet can be used for this. Since this has a different radius to that of the first 90° dipole (2 m radius) which feeds the ‘P’ beamline, the system will not be completely symmetric, but can still operate properly in the doubly-dispersive mode which is routinely used with the existing spectrometer. It can also be run in a nearly achromatic mode, if this is required.

[The 1.5 m radius dipole is the same magnet which is proposed as a high-resolution mass-separator for the Test Facility in the R&D Phase, after which it will again become available for Phase 2(b), as described here.]

8.2.2 **VACUUM CONSTRAINTS ON BEAM TRANSMISSION**

Calculations have been made to estimate the overall transmission between the charge-breeder and the RIB experimental area, using the present measured pressures as input. The sections of beamlines and the cyclotron vacuum chambers are shown schematically below, and the measured pressures are given in the table below.

![Diagram](image.png)

*Fig. 8.3: Schematic diagram of the beamlines from charge-breeder to user areas (not to scale).*
Table 8.1: Measured pressures in the beamlines and cyclotrons shown in the figure above.

<table>
<thead>
<tr>
<th>Station</th>
<th>Pressure (mbar)</th>
<th>Station</th>
<th>Pressure (mbar)</th>
<th>Station</th>
<th>Pressure (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>$2.0 \times 10^{-8}$</td>
<td>J2</td>
<td>$8.3 \times 10^{-7}$</td>
<td>P1</td>
<td>$3.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>AX</td>
<td>$1.5 \times 10^{-8}$</td>
<td>SSC N. Valley</td>
<td>$1.2 \times 10^{-6}$</td>
<td>P2</td>
<td>$6.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>SPC2</td>
<td>$1.8 \times 10^{-7}$</td>
<td>SSC E. Valley</td>
<td>$3.2 \times 10^{-7}$</td>
<td>A</td>
<td>$3.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>K1</td>
<td>$2.0 \times 10^{-7}$</td>
<td>SSC S. Valley</td>
<td>$4.5 \times 10^{-7}$</td>
<td>D</td>
<td>$3.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>K2</td>
<td>$3.0 \times 10^{-6}$</td>
<td>SSC W. Valley</td>
<td>$8.0 \times 10^{-7}$</td>
<td>F</td>
<td>$3.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>K3</td>
<td>$1.8 \times 10^{-6}$</td>
<td>X1</td>
<td>$1.2 \times 10^{-6}$</td>
<td>S</td>
<td>$9.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>J1</td>
<td>$4.2 \times 10^{-6}$</td>
<td>X2</td>
<td>$8.3 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For purposes of calculation, the beamlines and accelerators shown schematically above were grouped into sections as shown below. Average pressures were then used for each respective section, and the theoretical transmission calculated for each section. The product of these is then the theoretical total transmission for the present pressures.

Variations in transmission are due to different turn numbers required in the various cyclotrons, depending on charge-state and final energy, different losses in beamlines for higher charge-states and differences in transit time according to energy.

Table 8.2: Percentage transmission per section, between charge-breeder and the user area, and total transmission resulting from charge-exchange with residual gas molecules, for different charge-states and final energies.

<table>
<thead>
<tr>
<th>Isotope and charge-state</th>
<th>Final energy MeV/nucl.</th>
<th>Present pressure* in mbar:</th>
<th>Present overall transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.0x10^-8</td>
<td>1.8x10^-7</td>
<td>1.4x10^-6</td>
</tr>
<tr>
<td>132Sn^{20+}</td>
<td>5</td>
<td>91%</td>
<td>91%</td>
</tr>
<tr>
<td>132Sn^{26+}</td>
<td>8</td>
<td>95%</td>
<td>92%</td>
</tr>
<tr>
<td>132Sn^{28+}</td>
<td>10</td>
<td>95%</td>
<td>88%</td>
</tr>
<tr>
<td>132Sn^{40+}</td>
<td>10</td>
<td>93%</td>
<td>88%</td>
</tr>
<tr>
<td>132Sn^{50+}</td>
<td>20</td>
<td>93%</td>
<td>91%</td>
</tr>
<tr>
<td>132Sn^{50+}</td>
<td>30</td>
<td>88%</td>
<td>84%</td>
</tr>
<tr>
<td>132Sn^{50+}</td>
<td>33</td>
<td>88%</td>
<td>91%</td>
</tr>
</tbody>
</table>

*Measured pressures: some are averages over several different sections or vacuum chambers.
It is clear from the table above that (for charge-exchange losses only) the transmission in the long K beamline is the most serious limitation, while the Q-line and the injector cyclotron SPC2 also contribute to transmission losses.

The pressure in SPC2 could be reduced by inserting additional cryopanels into the vacuum chamber. The Q-beamline has many O-rings which could be replaced with metal seals when the beamline from the charge-breeder is joined into this line. The poor pressure of the K beamline is due in part to the presence of the buncher, and this should be improved with additional pumping stations.

If we plot the calculated transmission versus pressure (figure 8.5) for each section, for Sn\(^{26+}\) ions accelerated to 8 MeV per nucleon, as an example, together with polynomial fits to the curves, we can see that an increase of 1 order of magnitude is required to increase the transmission for any given section from 95% to 99%.

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**Fig. 8.5:** Plot of the calculated transmission of Sn\(^{26+}\) ions versus pressure in the different sections of figure 8.4. A polynomial fit extends the curves towards 100% transmission.

For the X, P and S-beamlines a pressure of 1 x 10\(^{-6}\) mbar is already attained; for the K & J beamlines 5 x 10\(^{-8}\) would be difficult, but achievable. For the SSC, cryopumps will reduce to pressure to 1 x 10\(^{-7}\), giving a transmission of 98%. For SPC2, 1 x 10\(^{-6}\) should be achievable with cryopumps. Finally, for the Q-beamline, a pressure of better than 1 x 10\(^{-7}\) can be attained, giving a transmission of some 85–90% for this case of Sn\(^{26+}\). Thus, considering charge-exchange losses alone (for this typical ion and final energy), we can expect an overall transmission of about 85%.

### 8.2.3 Improvements to overall transmission

To maximize the transmission of the n+ ions through SPC2, it will be advantageous to have a buncher in the beamline before injection. The beam transport system from the mass-separator to SPC2, including the vertical beamline from ground level to basement level will have to be studied.

Examination of logs of recent stable heavy-ion beams produced, such as \(^{136}\text{Xe}^{22+}\), reveal that the total transmission is generally far lower than the figures calculated above. This is mostly due to the poor efficiency of injection into SPC2 with the current spiral inflector, which leads to a transmission of only around 3% through SPC2 after cleaning up the beam with slits. It is anticipated that this figure can be raised significantly with a redesigned inflector, which is currently being studied.

The Accelerator Group has launched an ongoing investigation into the poor transmission through SPC2, has identified a number of reasons for this, and has suggested solutions. The primary
problem is at injection, where the first orbit cannot always pass through the “puller-slits” provided in the nose of the dee. This is complicated by the fact that there are 3 different inflector positions, with different orbit patterns and 3 closely adjacent puller-slits in the dee. Another problem is the present vacuum pressure (around 10^{-6} mbar), which leads to charge-exchange owing to interaction between the ion beam and residual gas molecules, as discussed above.

A number of improvements are now planned, which will remedy this problem: Firstly the inflector will be redesigned and repositioned to inject the beam at a different angle inside SPC2, making it easier for the first orbit to pass through a revised set of puller-slits in a dee. The acceleration electrodes will also be improved. Small quadrupole magnets may also be installed after the first turn, to improve the vertical focusing.

Secondly, a double-drift buncher system will be installed in the injection beamline before SPC2. This system should permit up to 80% of the beam to be bunched into the phase-acceptance of SPC2.

Thirdly, a system of 5th-harmonic flat-topping has been proposed, identical to that already installed on SPC1. The latter is already a variable-frequency device, although the power supplies presently used are fixed-frequency (suited to 66 MeV protons). This will extend the phase acceptance of SPC2 and also decrease the energy spread of the beam.

Finally, new cryopumps will be installed, reducing the pressure to around 10^{-8} mbar, which will greatly reduce the losses from charge-exchange.

These improvements are regarded as part of the routine upgrading of SPC2’s performance, and will benefit stable heavy-ion beam transmission as well as transmission of the proposed RIBs. With all the proposed improvements, it is likely that the transmission will be about 50–60% for heavy ions. Transmission of heavy ions through the SSC is currently fairly poor, depending on the charge-state being accelerated, and can be as low as 10% for very heavy ions and high charge-states. This is primarily due to both charge-exchange losses and limitations of the phase-acceptance.

The following upgrades should dramatically improve the transmission:

The fixed-frequency 3rd-harmonic flat-topping system currently used (for high-intensity proton beams) will be replaced with a variable-frequency 3rd-harmonic flat-topping system tuneable over the operating frequency range of the SSC.

New cryopumps will reduce the present vacuum pressure by an order of magnitude, from 10^{-6} mbar down to 10^{-7} mbar, with consequent improvement in charge-exchange losses.

With the greatly improved vacuum, the transmission through the SSC is expected to improve to 60%. Together with the upgraded flat-topping system, this efficiency should rise to between 70 and 80%. Much higher transmission is fairly unlikely. (Better transmission can of course be obtained from a dedicated linear accelerator, but at a very high price.)

Taken together, the improvements to SPC2, to the SCC and to the beamline vacuum are expected to deliver an over-all transmission from ion source (or charge-breeder) to user target of 30%.

Another planned improvement is a reduction of the base vacuum of all the beamlines to the low 10^{-7} to high 10^{-8} mbar range (especially the Q, AX, K and J beamlines).

With the improvements detailed in the sections above (which are expected to be implemented over the next decade), the following table summarises the transmissions achievable:
Table 8.3: Expected transmission efficiencies from charge-breeder to the experimental area.

<table>
<thead>
<tr>
<th>Section</th>
<th>Efficiency</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q and AX beamlines</td>
<td>95%</td>
<td>Limited by charge-exchange due to vacuum</td>
</tr>
<tr>
<td>SPC2</td>
<td>50–60%</td>
<td>Limited by the new inflector constraints and vacuum</td>
</tr>
<tr>
<td>K and J/2 beamlines</td>
<td>80%</td>
<td>Limited by charge-exchange due to vacuum at the buncher</td>
</tr>
<tr>
<td>SSC</td>
<td>70–80%</td>
<td>Limited by injection/extraction elements and vacuum at extraction</td>
</tr>
<tr>
<td>X, P and S beamlines</td>
<td>40–80%</td>
<td>Limited by mass-selection and emittance-defining slits</td>
</tr>
<tr>
<td>TOTAL</td>
<td>≤30%</td>
<td>Depending on beam emittance, spot size and impurities</td>
</tr>
</tbody>
</table>

While improvements to the vacuum in various sections will help to maximise the overall transmission, the limitations of SPC2 and the SSC will always limit this transmission to about 30%. We note for comparison that the transmission of the CIME cyclotron at GANIL is reportedly 20–40% (Chautard 2007). The energy range available from CIME is 1.2 MeV/A to 25 MeV/A, while for the SSC the theoretical maximum is around 40 MeV/A for q/A = 0.45.

8.3 ADDENDUM: POST-Acceleration Options Considered

In order to post-accelerate the RIBs produced, a number of options were examined. These were:

- A new post-accelerator, such as a linear accelerator. A superconducting linac is fairly efficient, with good transmission. However, this is an extremely expensive option. For example, the HIE-ISOLDE linac upgrade from 3 to 10 MeV/nucleon was estimated at M15.8 CHF, i.e. R146 million, while for EURISOL the cost of a 150 MeV/nucleon superconducting heavy-ion linac post-accelerator alone was estimated at 138.88 MEuro, i.e. R1.4 billion.

- Accelerating the RIBs with an RFQ and a small linac, to reach the injection energy required by the SSC. The RFQ and linac would have to be variable-energy devices. This option is used at RIKEN in Japan and at TRIUMF, but would require a lot of research and development.

- Modification of SPC1 to allow axial injection from below, similar to the system used for SPC2. This would require a major re-design and re-build of SPC1, and would also mean that it would be out of action for some considerable time.

- Injecting the RIB directly into the SPC2. This is technically feasible, and will only require leading the RIBs into the basement, where they could be directed into the beamline from an existing ion source using electrostatic devices, for axial injection into SPC2.

This last option is the simplest, cheapest, and will cause the least disruption of the operation of the cyclotrons at iThemba LABS, and is therefore the chosen option for this proposal.

References


Villari 2011: A.C.C. Villari, Pantechnik s.a., France, 2012 (Private communication).
9  RESEARCH AND DEVELOPMENT BEYOND BASELINE PERFORMANCE

9.1  THE RIB TARGET/ION-SOURCE TEST FACILITY

There is much enthusiasm for using RIBs by both nuclear physicists and materials scientists at iThemba, but such a production facility will inevitably be fairly expensive. Therefore, in order to develop the resources needed for such a facility, and to encourage students to study the problems which arise and to develop the expertise necessary for constructing and operating an RIB production unit, we have proposed first to build a small “Target/Ion-Source Test Facility”. (A separate application has been made for funding for this.)

This unit will be located on the present 'N' beamline – originally the location for the Beam Swinger facility – indicated in the figure below. This is a heavily shielded vault, designed for intense neutron beam production, and is ideally suited to small-scale RIB production.

![Diagram](image)

Fig. 9.1: The proposed location of the Target/Ion-Source Test Facility on the N beamline.

Some repositioning of shielding concrete blocks will be necessary, along with some additional roof beams for the N vault. (Some of the original roof beams have been removed to the radiotherapy linac area.) The Test Facility layout is shown in the schematic diagram of figure 9.2 below.

Interest has been expressed by the SPES group from INFN, Legnaro, in collaborating with iThemba LABS to construct this Test Facility, so that their target/ion-source assembly can be tested here, using 40 MeV protons at 200 microamps. If this test facility is funded, then the Accelerator Group will have to investigate whether 200 microamps can be achieved at this energy, as the flat-topping system for SPC1 is at present powered by fixed-frequency amplifiers, selected to provide high currents of 66-MeV proton beams. Nevertheless, it will make sense for us to start with the same beam energy as that required for the SPES tests (40 MeV).

Later high-current tests at 66 MeV will also be very close to simulating the effects of a 70-MeV proton beam, i.e. the maximum available from the cyclotron currently on order for the SPES Project, and also proposed for iThemba LABS.
A full set of drawings of the SPES target/ion-source assembly is available and can be obtained from the SPES team, allowing us to manufacture a complete copy of the whole assembly and its supporting structure. The target/ion-source will become activated after irradiation, and will require placing in a dedicated Pb container for storage and to permit personnel access to the irradiation vault. This can be done with a small crane inside the vault controlled from a safe distance, or by using the existing overhead crane; however, the latter option is less palatable, as it will involve removal of a number of the heavy roof beams to allow this.

SPES personnel have indicated that either SiC or UCx targets, constructed at INFN-Legnaro, can be provided by them for the tests. Initially we propose to use a plasma ion source, giving a broad range of radioactive species. Later tests will be made with a laser ion source, which has more selectivity. An MSc student has already been working with suitable lasers at Stellenbosch University, and trial laser-ionization has already been achieved.

The ion source will be located on a high-voltage platform inside the vault: such a platform exists at iThemba, obtained from the Hahn-Meitner Institute (HMI) in Berlin. The voltage of this platform (e.g. 60 kV) determines the energy of the singly-charged ion beam (60 keV), which can then be transported and focused by electrostatic quadrupoles, drawings for which can be obtained from the SPES or SPIRAL2 project teams.

Mass analysis of the ion beam will be done using dipole magnets. A small dipole for pre-analysis and a larger dipole for higher-resolution analysis are available at iThemba, both having been obtained from HMI in Germany. The beamline will transport the RIB into a small new experimental area, constructed with light shielding walls on the existing external concrete floor-slab under the canopy roof outside the main Accelerator Hall. (This area was used for external shielding and collimation of the neutron beams from the old beam-swingers.)
An analysis station will be needed to identify the radioactive ion species, before the beam is switched towards the experimental apparatus to be used by nuclear physics and materials science experimenters.

9.2 **The Converter Method**

An alternative to the direct fission of uranium is the so-called “converter” method, in which the high power of the primary proton beam is dumped in a well-cooled neutron production target, and the resulting neutrons – whose power deposition is much smaller than that of the primary beam – then travel through a secondary target of UC\textsubscript{x} material. The radioactive-ion production mechanism is neutron-induced fission (n,f), with the neutrons originating in (p,xn) reactions in the converter target. The main advantages of this method are the higher beam power that can be used, and perhaps more importantly, the higher yield of very neutron-rich fission fragments. Such an upgrade is deemed necessary for iThemba LABS to remain competitive with future facilities.

Figure 5.2 – repeated here as figure 9.3 – compares the potential on-target yield of accelerated neutron-rich Sn isotopes, using the converter method, produced by 70-MeV proton beams of between 350 µA and 1 mA on the converter, compared with contemporary RIB projects. The SPES and FRIB projects use direct fission, and fragmentation, respectively, of uranium to produce radioactive beams. The baseline yield of the SPES project is expected to be less than the initial yield of the SPIRAL 2 project, which uses a deuteron beam on a carbon converter target. Both estimates are subject to considerable uncertainty, mainly pertaining to the various efficiencies discussed in Chapter 5, and it is likely that these numbers can be improved with future developments. Nevertheless, due to the possibility of higher yields of neutron-rich species, and of refractory elements (with gas transport) using the converter method, iThemba LABS will embark on an R&D exercise to develop a converter target.

![Graph showing the potential yield of neutron-rich Sn isotopes](image)

**Fig. 9.3:** The potential yield of neutron-rich Sn isotopes which can be produced at iThemba LABS using the converter methods (shaded plots). Two converter methods are plotted, with different assumptions of release times. The grey region shows the estimated yields from a thick, hot target with a 3.2 s release time, while the green area is from an IGISOL setup with a 0.2 s release time.
A converter target only produces neutrons and does not need to have porosity or other characteristics to promote diffusion, and various materials with high thermal conductivity are possible candidates. Carbon and carbides are examples. The total thick-target yields of neutrons were investigated for the SPIRAL2 project for 80 MeV protons, and the results can be seen in the figure below.

![Neutron Yield Graph](image)

Fig. 9.4: Thick-target neutron yields from various target materials, for 80 MeV deuterons (curve ‘d’) and protons (curve ‘p’) respectively, versus atomic number $A$. The target thickness and diameter were both 2 proton stopping ranges for each material. [Ridikas 1998]

Clearly deuterons are better than protons on a light target material, but in our case the proton beam current from a 70-MeV $^3$He cyclotron is much higher than that of deuterons. (The deuteron option can therefore be excluded from the new cyclotron’s specifications, with significant cost saving.)

Heavier metals with high melting points such as Ta (2980°C) have higher total thick-target neutron yields, but their distributions are less forward-peaked than light target materials, and they have a higher ratio of low-energy to high-energy neutrons, so are less suitable for fissioning $^{238}\text{U}$ (which requires neutron energies above about 15 MeV).

Yield curves for $(p,xn)$ reactions at this energy are hard to locate in the literature. However, in figure 9.5 we show the predicted thick-target yields for $^{238}\text{U}(p,xn)$, $^{56}\text{Fe}(p,xn)$ and $^9\text{Be}(p,xn)$ calculated at GANIL for 200 MeV protons, using the LAHET code. Plots in figure 9.6 show experimental values for 113 MeV protons. In both cases the higher yield of high-energy neutrons from $^9\text{Be}$ is clear.

This implies that Be is the most favourable target for the productions of neutrons with a 70-MeV proton beam. It will be instructive to investigate pure Be targets, as well as targets made of Ta, for example.

For a Be target used with a proton beam at 70 MeV and 100–200 µA, a rotating target wheel will be required, similar to that designed for the SPIRAL2 project at GANIL in France.
Fig. 9.5: Predicted yields of neutrons from $^{238}$U(p,xn), $^{56}$Fe(p,xn) and $^9$Be(p,xn) in stopping-length targets. Note that the yield from $^9$Be exceeds that from $^{238}$U above about 20 MeV. [Ridikas 1998]

Fig. 9.6: Experimental yields of neutrons from 113 MeV protons on stopping-length targets of beryllium (top) and uranium (bottom), compared with calculations with the HETC code. The yield of high-energy neutrons from Be is almost an order of magnitude higher than from U. [Meier 1989]
A rotating target wheel will be a possible future extension of the proposed Target/Ion-Source Test Facility. It will therefore be useful to compare the neutron yields and thermal properties of small, fixed targets of Be and Ta, for example, with the RIB Test Facility, using much lower beam currents (circa 1 µA). The observed yields can then be scaled up directly with current.

A converter target is being developed for SPIRAL2, in which a high-intensity deuteron beam from a linear accelerator strikes a carbon disk mounted on a wheel, with a water-cooled panel behind it to absorb the radiated heat. In our case deuterons are not an option, as the 70-MeV H⁻ compact cyclotron does not offer intense deuteron beams. The graphite disks designed for the SPIRAL2 converter are shown in figure 9.7, and the rotatable target assembly in figure 9.8.

![Fig. 9.7: Graphite disks designed for the SPIRAL2 converter target: the 200-kW disk is much larger than the 50-kW disk. [Tecchio 2010]](image1)

![Fig. 9.8: The complete converter target assembly for SPIRAL2. [Tecchio 2010]](image2)
Note that the proposed converter for iThemba will need to accept 70-MeV protons at 400 µA, i.e. only a 28-kW beam. The converter wheel needed for this will thus be much smaller than the metre-radius device being constructed for SPIRAL2.

9.2.1 Hot Uranium Carbide
The UC\textsubscript{x} target disks behind the converter target need to be heated to some 2000°C to promote diffusion of the rare ion species out into the spaces between the disks. As with the direct target, this can be achieved in much the same way, with an electrically conducting tubular Ta container. However, in order to maximize the amount of uranium exposed to the neutron flux — which is less forward-peaked for a proton beam — the uranium carbide disks may have to be of a larger diameter. This is a matter for calculation, using the RIBO (“radioactive-ion beam optimiser”) code, which is now available at iThemba LABS, with subsequent on-line experimental tests of the target geometry with a 66 MeV proton beam.

9.3 Ion-Guide ISOL (IGISOL) Method
Nuclides resulting from reactions in a material such as UC\textsubscript{x} have to diffuse out of the material, and then effuse through the chamber until they reach the ion source where the neutral atoms are ionized. Diffusion is generally slow — with time-constants of the order of 1000 milliseconds in the best cases — while effusion can add another ~200 ms. For extremely short-lived exotic isotopes, there is a problem in that the diffusion time alone can exceed the half-life of the isotope. Furthermore, the refractive elements, (those between Zr and Pd), have very long diffusion times, far exceeding any possible half-lives.

One method which has been used to circumvent the diffusion time is the “ion-guide ISOL” method (IGISOL). This uses one or more thin foils as targets surrounded by a noble gas (He or Ar), so that the fission fragments escape immediately into the gas, which then slows them down to thermal energies. A gas-flow system then guides the atoms of interest towards a sextupole ion guide (SPIG) while lasers are used to ionize selected atomic species, and the buffer gas is pumped away. A possible variation would be to use a converter target to generate neutrons, followed by several uranium foil targets in an IGISOL setup.

We propose to embark on a research and development programme on the RIB Target/Ion-Source Test Facility to investigate enhancing RIB yields using the converter and IGISOL methods. Should this be successful, an alternate target/ion-source (TIS) to the SPES TIS can be installed in the second RIB production vault.

9.4 Electron Beam Ion Source (EBIS)
An alternative to the ECR charge-breeder discussed earlier is the electron-beam ion source (EBIS). The EBIS is more complicated than the ECR, but has some advantages, including shorter breeding times and higher efficiency for some ions and the EBIS can reach lower values of A/q.

In an EBIS, the 1+ ions are injected into the magnetic field of a solenoid magnet and slowed down via a series of drift tubes. (See figure 9.9 below) The potential barrier at the injection end is then raised, preventing escape of the ions. A beam of electrons from an electron gun strips off electrons from the ions, raising the charge-state of the ion. Finally the potential barrier at the entrance is lowered, creating a potential drop which allows the ions to escape. The operation is therefore pulsed.

Injection into the EBIS is greatly improved with a Penning trap (like REXTRAP) or a beam coolerbuncher (such as ISCOOL) before the EBIS. A trap will also be useful as a way of trapping the ions which arrive while the EBIS potential barrier is closed during the charge-breeding part of its cycle.
Fig. 9.9: Schematic diagram of an EBIS charge-breeder, such as the REXEBIS at ISOLDE (shown at right), together with its operating cycles. [Kester 2007]

Fig. 9.10: The measured efficiencies of the REXEBIS charge-breeder for various ions. [Kester 2007]
Proposal for a Radioactive-Ion Beam Facility at iThemba LABS

Table showing a comparison between EBIS and ECRIS charge-breeder at ISOLDE:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>REXEBIS+REXTRAP – Pulsed mode</th>
<th>PHOENIX booster – CW mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>4–20%</td>
<td>2–12%; broader charge-state distribution</td>
</tr>
<tr>
<td>Breeding time</td>
<td>From 13 to 500 ms depending on A</td>
<td>100 ms to 300ms</td>
</tr>
<tr>
<td>A/q</td>
<td>2 – 4.5</td>
<td>4 – 8</td>
</tr>
<tr>
<td>A</td>
<td>No real limitation</td>
<td>Injection difficult A&lt;20</td>
</tr>
<tr>
<td>Mode</td>
<td>Pulsed or partially CW</td>
<td>Continuous or pulsed (‘afterglow’)</td>
</tr>
<tr>
<td>Imax</td>
<td>A few nA</td>
<td>&gt; 10 μA</td>
</tr>
<tr>
<td>Acceptance</td>
<td>11 mm·mrad (95%) for 60 keV</td>
<td>&gt;55 mm·mrad at 18 keV (90%)</td>
</tr>
<tr>
<td>emittance</td>
<td>15-20 mm·mrad (95%) for 20q keV</td>
<td>10 mm·mrad at 19.5q keV (90%)</td>
</tr>
<tr>
<td>Background</td>
<td>&lt;0.1pA beside residual gas peaks</td>
<td>Usually &gt;2 nA</td>
</tr>
<tr>
<td>Reliability</td>
<td>Cathode is fragile (needs a different gun design) and overall system is complex.</td>
<td>Robust and simple (only ΔV tuning, but quite reproducible settings).</td>
</tr>
</tbody>
</table>

For the EURISOL Project, for example, it was suggested that both ECRIS and EBIS charge-breeders should be installed, to give the best operation. The advantages of such a dual system would be the following:

- Charge-states between A/q=2-3 and A/q=7 can be obtained over the whole chart of nuclides, with the lowest A/q from an EBIS.
- Efficiencies well above the percent range for any A, Z range can be obtained, with a wide range of isotopes for which efficiencies are around or higher than 5%.
- An ECRIS will cover masses above 20 while an EBIS covers the whole chart of isotopes.
- Charge-breeding times are well below one second (whatever the charge-breeder), and are shorter than typical diffusion-effusion times from ISOL targets.
- Clean exotic beams of medium to very low intensity – as low as $10^2$–$10^3$ pps – can be charge-bred by the EBIS charge-breeder, with very good beam purity.
- CW operation will be possible using the natural mode of operation of the ECRIS charge-breeder, or two EBIS charge-breeders in “push-pull” mode.
- However, since the EBIS is a pulsed device, and also requires a “trap” to collect the rare ions produced, it is not suggested for the early stage of the project, but could be of benefit at a later stage.

REFERENCES


Steyn 2011: D. Steyn, iThemba LABS, 2011 (Private communication).

Tecchio 2010: L. Tecchio et al., LEA-COLLIGA Workshop, Legnaro, 19 November 2010; [http://agenda.infn.it/getFile.py/access?contribId=76&sessionId=22&resId=0&materialId=slides&confId=2660](http://agenda.infn.it/getFile.py/access?contribId=76&sessionId=22&resId=0&materialId=slides&confId=2660)
10 Radiation Safety and Shielding

10.1 Legal Requirements

The following legal requirements and Codes of Practice will be applicable to ensure the safe operation of the facility and to ensure the safety of the personnel, environment and the public from the potentially harmful effects of ionizing radiation.

2. DLUG 91-1: Ionizing Radiation Dose Limits and Annual Limits on Intake of Radioactive Materials.
5. IAEA TSR-1: Regulations for the Safe Transport of Radioactive Material, 2005 Edition

In South Africa we have a unique situation whereby there are three regulatory bodies involved in the licensing and handling of radioactive material.

At present, the regulator for iThemba LABS is the Department of Health (DoH); Directorate of Radiation Control. The specific function of the DoH is the control of all “non-nuclear” radioactive materials. The term non-nuclear refers to any radioactive material excluding thorium/uranium and the transuranics.

The National Nuclear Regulator (NNR) is the regulatory body for all processes and procedures that mine, process and use uranium. The NNR are the regulators for Koeberg Nuclear Power Station (KNPS), the Nuclear Energy Corporation of South Africa (NECSA), and all mining/refining operations that extract thorium/uranium either as a primary product or as a by-product from other operations.

The Department of Energy (DoE) is the overall regulatory body for all nuclear-related materials and equipment.

iThemba LABS will meet the requirements of all three regulatory bodies, and will liaise with them continuously throughout the design and construction process to ensure that compliance is built in to the design from an early stage.

10.1.1 Shielding for Prompt Neutron Radiation and for Gamma Radiation

During operation the primary radiation of concern is that of neutrons displaced by protons during the bombardment of the targets. The neutron flux is measured in terms of neutrons per second and a facility such as this would generate between $10^{14}$ to $10^{16}$ neutrons per second. iThemba LABS has a great deal of experience in handling high neutron fluxes as well as neutron-induced activation in its existing isotope production facility. Some of the existing concrete shielding walls are 5 m thick, designed to shield against 200-MeV neutrons. However, recent shielding calculations performed at iThemba LABS for a 70 MeV cyclotron and target vaults indicate that concrete shielding walls approximately 3 metres thick would be required to reduce the dose rate outside the shield wall to less than 0.5 µSv per hour. Similar calculations performed for the SPIRAL and SPES facilities also confirm these calculations.

Depending on the size of the bombardment stations for radioisotope production, a combination of iron, boron-enriched wax and lead surrounding the bombardment station will further protect the concrete shielding walls from long-term neutron damage and activation. This should be less of a
problem for radioactive ion beam production, as personnel access will be extremely limited (i.e. after a cooling-down period of days or weeks), and with remote-controlled robotic handling of the targets.

It should also be taken into account that the possibility of upgrades in the future might increase the shielding requirements and allowance should be made for this.

Post bombardment, the primary radiation of concern is gamma radiation, emitted by the various materials that have been irradiated by protons and the resulting neutron flux. A similar situation occurs currently in the Radionuclide Production facility at iThemba, with gamma dose rates in excess of 6 sieverts per hour being measured on certain targets after bombardment. Experience has shown that built-in redundancy (dual systems) can greatly reduce the down-time required for handling and maintenance requirements and significantly reduce the radiation dose to the workforce.

10.1.2 AIR-HANDLING UNITS.

The existing Radioisotope Production facility has recently had an upgrade to its air handling units to ensure that the release limits as specified by the DoH are not exceed.

The creation and transportation of radioactive gases and particles will necessitate “nuclear-grade” air-handling units that have the capability to handle worst-case scenarios, such as a simultaneous burst target and loss of vacuum. These will be more fully defined when the safety studies for each particular part of the facility are completed by the Safety Group at iThemba.

All locations where the primary targets are bombarded and stored will be considered high-risk areas. These areas will require “nuclear” air-handling units, with filters for trapping gaseous fission products and radioactive particles.

The Radionuclide Production building will need to have specialised air-handling systems to deal with problems currently experienced with hot, acidic, radioactive gases being released during the production processes. This will incorporate a liquid scrubber system, high-efficiency particle-in-air (HEPA) filters and the ability to divert all gaseous effluent to a pressurised holding tank, packed with activated charcoal for the absorption of difficult-to-filter noble gases.

It must be noted that the current “cascade” system of air handling in the radionuclide facility is not ideal and a multi-purpose system will therefore be considered. Dedicated supply and exhaust fans for each area, together with standby fans, will be investigated.

10.1.3 RADIATION MONITORING SYSTEMS

The automated radiation monitoring system (ARMS) system has a two-fold purpose (i) neutron & gamma detectors to indicate the radiation levels external to the vaults and (ii) gamma detectors inside the vaults for beam diagnostics. These two systems need to be kept separate from each other to enable calibration and response checks without interfering with day-to-day operations.

10.1.4 VISUAL MONITORING SYSTEMS

Visual monitoring of all the critical components (via CCTV and/or Webcams) will be available for diagnosis of problems prior to entering the vaults to repair or reset equipment. A similar system in the present radioisotope production vault has proved invaluable in diagnosing problems without exposing staff to high radiation levels.

10.1.5 ACCESS CONTROL SYSTEMS

The existing interlock system on all vault doors must be extended to include all the new vaults. The system should be linked up to the Radiation Protection database to ensure all staff members who wish to enter the vault are qualified radiation workers. Failure to attend medicals or refresher training will result in access being withdrawn until re-qualification can be done.
10.1.6 REDUNDANCY FOR HIGH-DOSE COMPONENTS AND STORAGE FACILITIES
Experience at the present Isotope Production facility has shown that redundancy of equipment has a huge bearing on the radiation dose accrued during maintenance. This is true for both RIB production and isotope production vaults. For the RIB vaults, a system of rails is the best approach, whereby the recently-irradiated component can be rolled out of the vault into a shielded area to allow the decay of short-lived isotopes. The new non-irradiated replacement can be rolled into place. Not only does this have benefits for the radiation protection program, it also ensures a quick turn-around time for subsequent experiments.

A long-term storage facility must also be made available for RIB target/ion-source components or targets that require long-term decay. Ideally this would be a shielded vault with remotely-controlled robotic handling, to reduce radiation exposure and shielding requirements.

10.1.7 REQUIREMENTS FOR NEW RADIOISOTOPE PRODUCTION FACILITY
The existing Radioisotope Production facility was designed as a small research and production facility with limited consideration for future expansion. The quantity of radioisotopes now being produced is already more than ten times higher than the initial design specification.

A major concern is the radiation exposure to staff working at the hot cells where the radioisotopes are produced. Remote-handling hot cells will therefore be installed to reduce radiation exposure of staff to acceptable levels. These are off-the-shelf items and NECSA use a similar system.

10.1.8 HANDLING OF LIQUID & GASEOUS RADIOACTIVE EFFLUENT
Radioactive gaseous and liquid effluent is an unfortunate by-product of radionuclide production and RIB targetry. We have shown that a reverse-osmosis (RO) system is the best method of cleaning up the liquid effluent. We therefore recommend that the gaseous effluent is converted into liquid effluent by means of a wet scrubber and treated as such. The RO system then converts the liquid effluent into solid waste by means of RO membranes, filters and resins which can then be treated as solid nuclear waste.

10.1.9 HANDLING & LONG-TERM STORAGE OF SOLID RADIOACTIVE WASTE
With RIB production, there will be a relatively small volume of highly-active waste but any waste handling facility should take into account the current stock of high-level waste as well. One of the better solutions is employed at Koeberg Nuclear Power station whereby thick-walled concrete drums are filled with radioactive material and “capped” using a clean concrete mixture. A batching plant is installed on site to manufacture the wet concrete which is then poured over the waste material to effectively seal and shield it for long-term burial.

The other advantage of this system is the licensing and approval for preparation and burial has already been performed by Koeberg.

10.2 PHASE 1 SHIELDING
10.2.1 SHIELDING AGAINST PROMPT RADIATION
Calculations of the radiation dose rates to be expected in a 70-MeV proton facility have been done at iThemba LABS and at INFN LNL. We present results from both facilities.

The calculations at iThemba LABS, using the MCNPX Monte-Carlo code, investigated a theoretical accidental beam-loss incident. In this case a 70-MeV proton beam of 350 µA was assumed to hit a stainless steel object (e.g. a beam pipe or valve) close to the concrete shielding wall shown in figure 10.1 below. [This is very much a “worst-case” scenario: for such an incident further away from the wall, inverse-square fall-off would apply and the resultant dose would be much reduced.]
Fig. 10.1: Plots of a calculation with MNCPX for a 350 µA, 70-MeV proton beam striking an iron plate next to the 3 m concrete shielding wall around a hypothetical cyclotron vault. [Ngcobo 2012]

The neutron dose-equivalent rate just outside the 3 m thick wall – point ‘X’ in figure 10.1 – is then 4.34 x 10^{-5} Sv/hr, whereas the photon dose rate is 2.45 x 10^{-6} Sv/hr. Thus the total dose-equivalent rate is 45.8 µSv/hr. This rate is of course high, but such an abnormal situation would only last a few seconds at most, since local radiation monitors will sound an alarm and automatically interrupt the beam at the ion source. The resulting total dose to anyone in the vicinity would therefore be extremely low.

With 4 m thick concrete shielding walls, for comparison, the neutron dose-equivalent rate is much lower, i.e. 3.63 x 10^{-7} Sv/hr, and the photon dose rate is 1.96 x 10^{-8} Sv/hr, giving a total of only 3.8 x 10^{-7} Sv/hr (i.e. 0.38 µSv/hr). (See plot in figure 10.2.)

Similar shielding calculations were done at INFN with FLUKA for beam losses inside a 70-MeV cyclotron and 750 µA of protons, and the results are in good agreement with the iThemba LABS calculations. They show that 3 m of concrete will be needed to reduce the prompt radiation dose-equivalent to below 1 µSv/h: the losses in the cyclotron were assumed to be 15% or 112.5 µA.
Fig. 10.2: Plot of the total dose-equivalent versus shielding thickness for a 350 µA 70-MeV proton beam striking an iron plate just inside a thick concrete wall calculated with MNCPX at iThemba LABS. This is a worst-case scenario, and a 4m thickness reduces the dose equivalent to 0.38 µSv, well below the maximum permitted dose-equivalent.

Calculations were also done for the SPES project using the FLUKA code for a RIB-production vault. These calculations assume 300 µA of protons striking a UC₆ target, which also produces a large number of neutrons. These results apply equally to our RIB-production vaults in Phase 2, and the results are plotted in figure 10.3 below.

Fig. 10.3: FLUKA calculations of the neutron dose-equivalent around a vault in the proposed SPES facility. A 300 µA beam of 70-MeV protons bombards the target station. [Lunardi 2009]
It can be seen from the plot in figure 10.3 that in the forward direction about 3.5 m of concrete is needed to reach a dose-equivalent of 1 µSv/h. Laterally, 3 m of concrete will suffice.

Figure 10.4 shows a FLUKA plot for a vertical section through the SPES building, and it confirms that 3 m is sufficient concrete shielding in both vertical directions for a target station bombarded with 300 µA of 70 MeV protons. Note, however, that any apertures (including beam pipes) will lead to high leakage fluxes of neutrons, as shown.

![FLUKA calculation of neutron dose-equivalent around a vault in the proposed SPES facility](image)

*Fig. 10.4: FLUKA calculations of the neutron dose-equivalent around a vault in the proposed SPES facility, showing a vertical slice through the target viewed from the beam direction. [Lunardi 2009]*

10.3 PHASE 2 SHIELDING

With high beam currents of protons at medium energies (e.g. 40-70 MeV) on thick targets, there is always a high flux of neutrons which requires sufficient shielding around the target area.

Secondly, this neutron flux leads to high levels of activation of materials in the vicinity of the target, which gives rise to high gamma radiation levels, which can remain for a long period after bombardment of the target ceases. This radiation level can take many days or even months to decay sufficiently to allow radiation workers access to the target area. Calculations have therefore been done to evaluate these problems.

10.3.1 SHIELDING AGAINST PROMPT RADIATION

Calculations have been performed at iThemba LABS using the MNCPX code, which is a Monte-Carlo particle-transport code. In the first instance, a 70-MeV proton beam of 350 µA intensity was considered to strike a target in the centre of the proposed Test Facility vault on the N beamline. The results also apply directly to the production vaults in Phase 2.

For simplicity a closed room was studied, with a single penetration in the shielding walls for the radioactive-ion beamline to emerge towards the experimental area. The calculated neutron flux and the prompt gamma-radiation flux (generally an order of magnitude less intense) are both given by the code, and the total tissue-equivalent dose is illustrated in figure 10.5 below.
The multiple layers in the concrete surrounding the vault are not physical, but show where the code artificially increases the surviving neutron flux to aid in having enough particles reaching the outside areas to permit statistically significant dose calculations. The calculated tissue-equivalent dose rates are shown in figure 10.5 above. Note that for radiation workers the maximum permitted dose rate is 10 µSv per hour, while for public areas it is 0.3 µSv per hour.

It is clear from the results above that the extracted RIB area will require additional shielding to reach an acceptable dose rate outside the building. However, the plot of figure 10.5 shows that the tissue-equivalent dose rate at the location just outside the experimental area is 0.2 µSv/h. The cyan coloured areas all have similar safe dose rates. A similar result will apply for the vertical direction, which implies that roof shielding totalling 3 m thickness and any basement below the vaults themselves would also require the same shielding, unless these areas are out of bounds and closed off during RIB production. This will be the case for the proposed 1 m thick floor slabs.

The lesson from this calculation is that while 3 m of concrete is sufficient to reduce the tissue-equivalent dose rates to safe levels, any aperture in the wall for the RIB beam pipe will lead to high leakage of energetic neutrons, so that the extracted RIB area will also have to be provided with
sufficient shielding. This will apply to all extracted beam areas up to and including the mass analyser.

10.3.2 Activation and decay times

Calculations have been done at LNL for the SPES project to determine the amount of activation of the target and ancillary structures within the RIB production vault. For this calculation, it is assumed that a proton beam of 70 MeV energy and 300 μA current irradiates the target continuously for 14 days.

An initial calculation performed for a SiC target shows that the target itself becomes extremely active, and will have to be encased in a lead container before it is safe to approach. However, the residual gamma radiation in the rest of the “front end” structure decays to a dose rate of 2.7 mSv/h at 1 metre within 10 days.

Table of calculated residual gamma-ray dose rate around a silicon carbide target, after 14 days of continuous irradiation with 300 μA of 70-MeV protons.

<table>
<thead>
<tr>
<th>Cooling time</th>
<th>Residual gamma dose rate at 1 m from SiC target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target</td>
</tr>
<tr>
<td>1 second</td>
<td>9.8 Sv/h</td>
</tr>
<tr>
<td>1 day</td>
<td>0.5 Sv/h</td>
</tr>
<tr>
<td>10 days</td>
<td>0.1 Sv/h</td>
</tr>
<tr>
<td>1 year</td>
<td>2.0x10^{-3} Sv/h</td>
</tr>
</tbody>
</table>

For a UC₃ target, a similar calculation shows the same kind of activation of the target, about a factor 5 greater than for SiC. If we assume a similar increase in the “front-end” activation, it would lead to a dose rate of some 13.5 mSv/h after 10 days. In practice the RIB production will run for the duration of an experiment, typically 7–14 days.

Table of calculated residual gamma-ray dose rate around a uranium carbide target, after 14 days of continuous irradiation with 300 μA of 70-MeV protons.

<table>
<thead>
<tr>
<th>Cooling Time</th>
<th>Residual gamma dose rate at 1 m from UC₃ target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second</td>
<td>50 Sv/h</td>
</tr>
<tr>
<td>1 month</td>
<td>0.1 Sv/h</td>
</tr>
<tr>
<td>1 year</td>
<td>2 mSv/h</td>
</tr>
<tr>
<td>3 years</td>
<td>1 mSv/h</td>
</tr>
</tbody>
</table>

For a 7-day irradiation time (which approximates to reaching saturation dose rate) some calculations done at LNL show the activity during irradiation and cooling, plotted in figures 10.6 and 10.7.

It is clear that the target itself will have to be removed (using a robot or a remotely-controlled overhead crane) and placed in a lead box, before personnel access to the vault could be contemplated. This is common practice at existing RIB production facilities, such as ISOLDE and SPIRAL. The target will then have to be treated as solid radioactive waste material.
Fig. 10.6: Activity calculated for a UC₆ target irradiated with 40 MeV protons at 200 µA for 7 days continuously. [SPES 2008].

Fig. 10.7: Cooling down calculated for a UC₆ target irradiated continuously for 7 days with 40 MeV protons at 200 µA. Note the log-log scale. [SPES 2008]
10.3.3 AIR ACTIVATION

Calculations of expected air activation have been done at LNL for 300 µA of protons at 70 MeV, which corresponds to the maximum beam which is likely to be used at iThemba LABS (without an upgrade of the cyclotron). More than 99% of the total activity expected in the air would be due to nuclides with half-life lower than 75 days (i.e. \(^{7}\)Be, \(^{11}\)C, \(^{13}\)N, \(^{15}\)O, \(^{41}\)Ar). At the beam current quoted above, less than 2 hours “storage” time is sufficient to lower the concentration to 1 Bq/g: in this condition release to the environment is permitted without further authorization. For lower beam intensities, the concentration of 1 Bq/g may never be reached, so that prompt evacuation and release would be permitted. A suitable air-extraction system should nevertheless be provided, with an exhaust stack monitored for the air activity.

Some nuclides will be produced with longer half-lives, namely tritium (\(t_{1/2}=12.3\) y), \(^{14}\)C (\(t_{1/2}=5730\) y) and \(^{32}\)S (\(t_{1/2}=87.5\) d), but the total release rate will be less than \(5 \times 10^6\) Bq/week, so that the total effective dose-equivalent will be insignificant.

10.3.4 COOLING WATER CIRCUIT

Cooling of the targets will require a water circuit to remove heat radiated from the hot target components. This water will be irradiated, and will become radioactive. The present current practice of providing a separate cooling circuit for items with potentially high activation levels will be extended to these targets. Heat-exchangers are then used to remove the heat, without any risk of cross-contamination of the normal cooling system, which removes the heat via chillers and external cooling towers.

10.3.5 ROBOTICS

For removal of the activated target/ion-source assembly, we propose to use an industrial robot on a rail track, as shown in the figures below. The vehicle and the robot will be remotely controlled. Such a system (without rails) is presently being installed for ISOLDE at CERN.

Fig. 10.8: A remotely-controlled vehicle, carrying an industrial robot for removal and replacement of target/ion-source assemblies, presently being installed at CERN. [Catherall 2010]
Fig. 10.9: Conceptual view showing a remotely-operated vehicle carrying a robot to place a used (activated) target/ion-source assembly into a storage locker, equipped with Pb shielding doors at CERN-ISOLDE. [Catherall 2010]

REFERENCES

Catherall 2010 R. Catherall, ISOLDE Technical Report, ISCC Meeting, 4th November 2010


Lunardi 2009: S. Lunardi, Il progetto SPES: un acceleratore di fasci radioattivi a Legnaro
http://www.pd.infn.it/segreterie/segred/trasparenze/2009/Lunardi.ppt


http://agenda.infn.it/getFile.py/access?contribId=13&sessionId=4&resId=0&materialId=slides&confId=2660
11 CONTROL SYSTEM

The control system is a critical component in the operation of the planned facility. It connects the various parts of the system together, and allows users to monitor and control hardware. An important aspect is that the new system must interconnect seamlessly with the existing control system at iThemba LABS. This is not self-evident where the proposed new commercial cyclotron is concerned, since such devices are generally supplied with their own stand-alone software and graphical user interface (GUI). However, this should not be a major problem, since the 70-MeV cyclotron offered by Best Cyclotron Systems Inc. uses a Siemens Programmable Logic Controller operating under a PC-based Windows XP operating system, with thin-wire Ethernet hardware.

The central component of any control system is a local-area network (LAN), which allows the various components of the control system to communicate with each other. The control system contains graphical workstations which communicate with operators (typically in the main cyclotron control room), hardware control computers that interface with the hardware (power supplies, stepping motors, diagnostic devices, safety interlocks, etc.), and “back-office” computers that perform archiving and other tasks. A diagram of the iThemba LABS control system is shown in figure 11.1 below.

11.1 CONTROL OF HARDWARE

Hardware devices (power supplies, measurement devices, beam diagnostics, etc.) are connected via interface electronics to the interface computers. These latter are “industrialised” PCs housed in 19-inch racks. The interface electronics modules themselves are slotted into a series of daisy-chained SABUS crates, located in electronics areas close to the respective hardware devices.

11.1.1 USER INTERFACE

The user interface computers run programs that communicate with other computers in the control system and provide the user with the status and values of the hardware devices, via a graphical user interface (GUI). These programs also allow the user to interact with the control system by means of touch-panels, joysticks or mouse-selected options to send commands to the hardware devices.

11.1.2 'BACK-OFFICE' COMPUTERS

Other computers in the control system are needed for backing-up, to save configuration settings, log files and archived measurements and set-up routines: these are termed “back-office” computers.

11.2 EPICS SOFTWARE

In order for the control system to communicate with the existing cyclotron control system, it must be based on EPICS: the Experimental Physics and Industrial Control System.

EPICS is a set of software tools and applications which provide a software infrastructure for use in building distributed control systems to operate devices such as particle accelerators, large experiments and major telescopes. Such distributed control systems typically comprise tens or even hundreds of computers, networked together to allow communication between them and to provide control and feedback of the various parts of the device from a central control room, or even remotely over the internet.

EPICS uses Client/Server and Publish/Subscribe techniques to communicate between the various computers. Most servers (called input/output controllers or IOCs) perform real-world I/O and local control tasks, and publish this information to clients using the “channel access” (CA) network protocol. CA is specially designed for the kind of high bandwidth, soft real-time networking
applications that EPICS is used for, and this is one reason why it can be used to build a control system comprising hundreds of computers.

Fig. 11.1: Schematic diagram of the iThemba LABS control system. At the lower level, the interface electronics is housed in a daisy-chained series of SABUS racks.
EPICS is also the name of the collaboration of organizations that are involved in the software's development and use. It was originally written jointly by Los Alamos National Laboratory and Argonne National Laboratory, and is now used by many large scientific facilities throughout the world, including iThemba LABS. Development now occurs cooperatively between these various groups, with much sharing of I/O device support and client applications.

The diagram shown in figure 11.2 shows the EPICS software architecture, and how EPICS can link into a commercial cyclotron’s control system, via a programmable logic controller (PLC).

![EPICS Software Architecture Diagram]

Fig. 11.2: Schematic diagram of the EPICS software and hardware architecture at iThemba LABS, linked to the programmable logic controller supplied with a commercial compact cyclotron.

### 11.2.1 Manpower Requirements for Control System

Most of the required software development will be done by existing Control System programmers. The biggest challenge will be the interfacing of the turn-key Windows-based control system and GUI supplied by the cyclotron vendor with the EPICS system used at iThemba LABS. However, there are several ways of doing this, and no major difficulty is anticipated.
12 Cost Estimation

12.1 Summary of Costs

12.1.1 Phase 1 Capital Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>MRand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings and concrete shielding</td>
<td>83.109</td>
</tr>
<tr>
<td>70-MeV cyclotron from BEST Cyclotron Systems Inc.</td>
<td>108.150</td>
</tr>
<tr>
<td>5 Radioisotope production stations with ‘nuclear’ air handling system</td>
<td>142.500</td>
</tr>
<tr>
<td>5 Beam lines: magnets and power supplies</td>
<td>28.423</td>
</tr>
<tr>
<td>Beam diagnostic equipment</td>
<td>4.027</td>
</tr>
<tr>
<td>Vacuum pumping systems</td>
<td>1.948</td>
</tr>
<tr>
<td>Control system</td>
<td>1.751</td>
</tr>
<tr>
<td>Radiation detection and interlocking</td>
<td>0.750</td>
</tr>
<tr>
<td>Uninterruptable power supply and power distribution network</td>
<td>15.094</td>
</tr>
<tr>
<td>Water cooling and air handling system</td>
<td>11.499</td>
</tr>
<tr>
<td>Site</td>
<td>0.660</td>
</tr>
<tr>
<td>Contingencies</td>
<td>40.000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>437.911</td>
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</table>

12.1.2 Phase 2 Capital Costs, excluding Physics Instrumentation

<table>
<thead>
<tr>
<th>Item</th>
<th>MRand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building, shielding and infrastructure with ‘nuclear’ ventilation for RIB vaults</td>
<td>34.000</td>
</tr>
<tr>
<td>RIB target vaults and associated equipment</td>
<td>53.300</td>
</tr>
<tr>
<td>Beam transport (70-MeV proton beams)</td>
<td>36.240</td>
</tr>
<tr>
<td>Beam transport (RIBs)</td>
<td>86.500</td>
</tr>
<tr>
<td>Building, north experimental area</td>
<td>13.050</td>
</tr>
<tr>
<td>RIB transport in north experimental areal</td>
<td>37.380</td>
</tr>
<tr>
<td>Safety and control</td>
<td>50.000</td>
</tr>
<tr>
<td>Contingencies</td>
<td>30.000</td>
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<tr>
<td><strong>TOTAL</strong></td>
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12.1.3 Physics Instrumentation Capital Cost

<table>
<thead>
<tr>
<th>Item</th>
<th>MRand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear physics and materials science equipment</td>
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</tr>
</tbody>
</table>

12.2 Detailed Cost Breakdown

A more detailed breakdown of the costs shown above is given in the tables below.
12.2.1 COST ESTIMATE FOR PHASE 1: RADIOISOTOPE PRODUCTION WITH A COMPACT CYCLOTRON

Detailed costing was based on known costs wherever possible. The cyclotron cost was taken from SPES, with conversion rate of 1€ = R10.30, valid at 27 January 2012. VAT is included in all costs.

<table>
<thead>
<tr>
<th>Item</th>
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<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buildings and shielding</strong></td>
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<td></td>
</tr>
<tr>
<td>Excavation and piles below heavy shielding walls</td>
<td>1.164</td>
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</tr>
<tr>
<td>Floor slabs, shielding walls and roof slabs</td>
<td>34.548</td>
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</tr>
<tr>
<td>Heavy sliding shielding doors</td>
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<td></td>
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<tr>
<td>Conventional buildings, and external hall shell</td>
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<tr>
<td>Cranes (5-ton and 15-ton)</td>
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<tr>
<td>Consulting engineers and architects fees @ 15%</td>
<td>10.840</td>
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<tr>
<td><strong>Cyclotron</strong></td>
<td></td>
<td>108.150</td>
</tr>
<tr>
<td>70-MeV H- machine from Best Cyclotron Systems Inc.</td>
<td>86.520</td>
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</tr>
<tr>
<td>add 25% for duties, VAT and transport</td>
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<tr>
<td><strong>Radioisotope production</strong></td>
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<td>142.500</td>
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<tr>
<td>4 production target stations</td>
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</tr>
<tr>
<td>Water cooling system</td>
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<td></td>
</tr>
<tr>
<td>Helium cooling system</td>
<td>6.000</td>
<td></td>
</tr>
<tr>
<td>‘Nuclear’ ventilation system</td>
<td>7.000</td>
<td></td>
</tr>
<tr>
<td>Targetry hot cells (3)</td>
<td>11.000</td>
<td></td>
</tr>
<tr>
<td>Targetry transport, workshops and infrastructure</td>
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</tr>
<tr>
<td>Quality control infrastructure and radiopharmacy</td>
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</tr>
<tr>
<td>Batch delivery hot cells (3)</td>
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<td></td>
</tr>
<tr>
<td>Micro-PET/CT scanner</td>
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<tr>
<td>subtotal:</td>
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</tr>
<tr>
<td>add 14% VAT</td>
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<td><strong>Beam lines and power supplies</strong></td>
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</tr>
<tr>
<td>Quadrupole magnets (33)</td>
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<tr>
<td>Switching magnet (1)</td>
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<td>Power supplies (34)</td>
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<tr>
<td>Steering magnets and power supplies (10)</td>
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<td>Beam pipe</td>
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</tr>
<tr>
<td>Beamline supports and cooling infrastructure</td>
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<td>Sweeper systems for targets (3)</td>
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<td>Neutron shutters (5)</td>
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<td>Cabling</td>
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<td><strong>Diagnostic equipment</strong></td>
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<td>4.027</td>
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<tr>
<td><strong>Vacuum systems</strong></td>
<td></td>
<td>1.948</td>
</tr>
<tr>
<td><strong>Control system for diagnostics, safety &amp; interlocking</strong></td>
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<td>1.751</td>
</tr>
<tr>
<td><strong>Radiation detection and interlocking</strong></td>
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<td>0.750</td>
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<tr>
<td><strong>UPS and power distribution</strong></td>
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<tr>
<td><strong>Water cooling and air-handling</strong></td>
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<td>11.499</td>
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<tr>
<td><strong>Site</strong></td>
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</tr>
<tr>
<td><strong>Contingency</strong></td>
<td></td>
<td>40.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>437.911</td>
</tr>
</tbody>
</table>
12.2.2 **Cost estimate for Phase 2 of an RIB facility**

Prices are based partly on SPES project estimations, based on similar items at ORNL, TRIUMF, CERN & GANIL. Buildings and infrastructure costs are based on costs from SPES, SPIRAL2 & ARRONAX.

<table>
<thead>
<tr>
<th>Item</th>
<th>MR</th>
<th>MR</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RIB Target Vaults (x2) and associated equipment</strong></td>
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<td></td>
<td>53.300</td>
</tr>
<tr>
<td>Vacuum systems</td>
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<tr>
<td>Target chambers</td>
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<tr>
<td>Special materials</td>
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<tr>
<td>Laser ion source</td>
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<tr>
<td>Front end</td>
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<tr>
<td>Power supply</td>
<td>2.000</td>
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<td></td>
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<tr>
<td>60 kV platform</td>
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<tr>
<td>Mass selector (1/250)</td>
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<tr>
<td>Sensors &amp; Controls</td>
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<td>Services</td>
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<tr>
<td><strong>Subtotal:</strong></td>
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<td></td>
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<tr>
<td>For two RIB vaults:</td>
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<td>41.800</td>
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<tr>
<td>Lasers (approx. 300 k euro at Jyvaskyla)</td>
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<tr>
<td>Remote handling robot for targets</td>
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<td>3.000</td>
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<td>Hot cell for target maintenance</td>
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<tr>
<td><strong>Beam transport (70-MeV beams)</strong></td>
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<td>Beam lines (3)</td>
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<tr>
<td>Diagnostics</td>
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<td>4.000</td>
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<tr>
<td>Vacuum system</td>
<td></td>
<td>2.000</td>
<td></td>
</tr>
<tr>
<td>Control system</td>
<td></td>
<td>2.000</td>
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</tr>
<tr>
<td>Radiation detection &amp; interlocking</td>
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<td>750</td>
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<tr>
<td>Power distribution: cables to power supplies only:</td>
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<td><strong>Beam transport (RIBs)</strong></td>
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<td>Beam identification system</td>
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<tr>
<td>Vacuum system</td>
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<tr>
<td>Isotope separator</td>
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<tr>
<td>Beam lines</td>
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<tr>
<td>Cooler (estimate)</td>
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<td>Charge-Breeder</td>
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<tr>
<td>60 kV platforms (2)</td>
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<tr>
<td><strong>Buildings &amp; infrastructure</strong></td>
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<tr>
<td>Target areas and experimental area</td>
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<tr>
<td>Technical plant</td>
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<td>10,000</td>
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<tr>
<td>‘Nuclear’ ventilation system (estimate)</td>
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<td>7,000</td>
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</tr>
<tr>
<td><strong>Radiation safety, interlocking and computer control</strong></td>
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<td>50.000</td>
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<tr>
<td><strong>Building: North Experimental Area for RIBs</strong></td>
<td></td>
<td>13.050</td>
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</tr>
<tr>
<td><strong>Beam transport for accelerated RIBs (North Exptl. Area)</strong></td>
<td></td>
<td>37.380</td>
<td></td>
</tr>
<tr>
<td><strong>Safety and personnel control systems</strong></td>
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<td>50.000</td>
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<tr>
<td><strong>Contingency:</strong></td>
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<tr>
<td><strong>Total for Phase 2 capital costs:</strong></td>
<td></td>
<td>MR</td>
<td>340.471</td>
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</tbody>
</table>
NOTE: It is assumed that no special removable roof beams are required, because of thick slab roofing. For the North Experimental Area, low RIB intensities will not require shielding roof beams.

12.2.3 COST ESTIMATE FOR PHYSICS INSTRUMENTATION IN NORTH EXPERIMENTAL AREA

<table>
<thead>
<tr>
<th>Item</th>
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</thead>
<tbody>
<tr>
<td>Nuclear physics:</td>
<td></td>
</tr>
<tr>
<td>TIGRESS type detectors (x8)</td>
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</tr>
<tr>
<td>Large-acceptance spectrometer</td>
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</tr>
<tr>
<td>Active target</td>
<td>11.00</td>
</tr>
<tr>
<td>K600 spectrometer instrumentation</td>
<td>3.00</td>
</tr>
<tr>
<td>Neutron Physics beamline (stable beams)</td>
<td>2.00</td>
</tr>
<tr>
<td>Position-sensitive proportional avalanche counter</td>
<td>2.00</td>
</tr>
<tr>
<td>Materials science equipment:</td>
<td>10.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>134.00</td>
</tr>
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</table>

12.3 CASH FLOW

12.3.1 PHASE 1 CONSTRUCTION CAPITAL CASH FLOW

<table>
<thead>
<tr>
<th>Item</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings and shielding</td>
<td>10</td>
<td>20</td>
<td>24</td>
<td>20</td>
<td>28</td>
<td>74</td>
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<tr>
<td>70-MeV H⁺ cyclotron</td>
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<td>20</td>
<td>20</td>
<td>20</td>
<td>28</td>
<td>108</td>
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<td>Radioisotope production</td>
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<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>18</td>
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<td>Beam lines and power supplies</td>
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<td>14</td>
<td>28</td>
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<tr>
<td>Diagnostic equipment</td>
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<td>Vacuum systems</td>
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<td>Control system</td>
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<td>2</td>
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<tr>
<td>Radiation detection and interlocking</td>
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<td>1</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>UPS and power distribution</td>
<td>7</td>
<td>8</td>
<td>15</td>
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<td></td>
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<tr>
<td>Water cooling and air-handling</td>
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<td>6.5</td>
<td>11.5</td>
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<tr>
<td>Contingency</td>
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<td>30</td>
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12.3.2 PHASE 2 CONSTRUCTION CAPITAL CASH FLOW

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<th>Year 6</th>
<th>Year 7</th>
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</thead>
<tbody>
<tr>
<td>Buildings, shielding &amp; plant</td>
<td>10</td>
<td>10</td>
<td>14</td>
<td></td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>RIB . vaults &amp; infrastructure</td>
<td>13</td>
<td>20</td>
<td>20</td>
<td></td>
<td>53</td>
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<tr>
<td>Beam transport in Phase 1</td>
<td>9</td>
<td>9</td>
<td>18</td>
<td></td>
<td>36</td>
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</tr>
<tr>
<td>Beam transport (RIBs)</td>
<td>26</td>
<td>31</td>
<td>30</td>
<td></td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>Buildings: North. Exptl Area</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>RIB transport: N. Exptl Area</td>
<td>20</td>
<td>170</td>
<td></td>
<td></td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Safety and control</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Contingency</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td><strong>Totals (MR)</strong></td>
<td>19</td>
<td>19</td>
<td>114</td>
<td>91</td>
<td>97</td>
<td>340</td>
</tr>
</tbody>
</table>
Note that Phase 2 overlaps with Phase 1, so that those technical staff employed on a contract basis can move from Phase 1 to Phase 2 with no break in employment. Assembly of the 70-MeV beam transport systems leading from the cyclotron towards the RIB vaults can begin immediately after Phase 1, before Phase 2 buildings are completed.

12.4 PERSONNEL REQUIREMENTS AND SALARY COSTS DURING CONSTRUCTION

An estimate has been made for the additional staff required during these two construction phases. The existing staff at iThemba will be involved, but are fully occupied with current operation, maintenance and development programmes.

New staff members may be either permanent appointments or contract appointments for the duration of the construction phases. The new permanent employees would eventually replace existing staff at the latter’s retirement.

12.4.1 PHASE 1 SALARIES CASH FLOW

<table>
<thead>
<tr>
<th>Staff</th>
<th>No.</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project manager</td>
<td>1</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>3.00</td>
</tr>
<tr>
<td>Accelerator Group Staff:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design draughtsman</td>
<td>2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>3.50</td>
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<tr>
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<td></td>
<td></td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>1.05</td>
</tr>
<tr>
<td>Vacuum asst (mechanical)</td>
<td>1</td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>Electronic technician</td>
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<td></td>
<td></td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>2.10</td>
</tr>
<tr>
<td>Technical asst (electronic)</td>
<td>2</td>
<td></td>
<td></td>
<td>0.4</td>
<td>0.4</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>Mechanical technician</td>
<td>4</td>
<td></td>
<td></td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>4.20</td>
</tr>
<tr>
<td>Coded welder</td>
<td>1</td>
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<td></td>
<td>0.4</td>
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<td>0.4</td>
<td>1.20</td>
</tr>
<tr>
<td>Welder</td>
<td>1</td>
<td></td>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.90</td>
</tr>
<tr>
<td>Electrician</td>
<td>1</td>
<td></td>
<td></td>
<td>0.35</td>
<td>0.35</td>
<td></td>
<td>0.70</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>Mechanical assistants</td>
<td>2</td>
<td></td>
<td></td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>1.20</td>
</tr>
<tr>
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<td>1.30</td>
<td>4.85</td>
<td>6.00</td>
<td>6.00</td>
<td>19.45</td>
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<tr>
<td>IT Staff (for control and safety-interlock systems):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics technician</td>
<td>2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>2.80</td>
</tr>
<tr>
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<td>0.45</td>
<td>0.45</td>
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<td>Software developer</td>
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<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
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<td>0.4</td>
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<td>2.75</td>
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<td>8.75</td>
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### 12.4.2 Phase 2 Salaries Cash Flow

<table>
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<th>Staff</th>
<th>No.</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6</th>
<th>Year 7</th>
<th>Year 8</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project manager</td>
<td>1</td>
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<td>0.6</td>
<td>0.6</td>
<td>1.80</td>
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<td></td>
</tr>
<tr>
<td><strong>Accelerator Group Staff:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design draughtsman</td>
<td>2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>2.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum technician</td>
<td>1</td>
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<td>0.35</td>
<td>0.35</td>
<td>1.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum asst (mechanical)</td>
<td>1</td>
<td>OVERLAPS</td>
<td>0.2</td>
<td>0.2</td>
<td>0.7</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
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<td>WITH</td>
<td>0.2</td>
<td>0.2</td>
<td>0.7</td>
<td>2.10</td>
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<tr>
<td>Technical asst (electronic)</td>
<td>2</td>
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<tr>
<td>Mechanical technician</td>
<td>4</td>
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<td>1.4</td>
<td>1.4</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Coded welder</td>
<td>1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welder</td>
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<td>OVERLAPS</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Electrician</td>
<td>1</td>
<td>WITH</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>Electrical assistant</td>
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<tr>
<td>Mechanical assistants</td>
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<td>1.20</td>
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</tr>
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<td>0</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>18.00</td>
</tr>
<tr>
<td><strong>IT Staff (for control and safety interlock systems):</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics technician</td>
<td>2</td>
<td>OVERLAPS</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
<td>Electronics engineer</td>
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<td>WITH</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>Software developer</td>
<td>3</td>
<td>PHASE 1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>Electronics assembler</td>
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<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
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<td>2.75</td>
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<td>8.25</td>
</tr>
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<td>8.75</td>
<td>8.75</td>
<td>26.25</td>
</tr>
</tbody>
</table>

### 12.5 Total Project Cost

The estimated Total Project Cost including capital costs and salaries for Phase 1 and 2 plus the cost of Physics instrumentation is shown below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6</th>
<th>Year 7</th>
<th>Year 8</th>
<th>Totals (MR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>30.00</td>
<td>70.00</td>
<td>85.00</td>
<td>128.00</td>
<td>125.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>19.00</td>
<td>19.00</td>
<td>114.00</td>
<td>91.00</td>
<td>97.00</td>
<td>340.00</td>
</tr>
<tr>
<td>Instruments</td>
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<td>9.00</td>
<td>7.00</td>
<td>10.00</td>
<td>12.00</td>
<td>20.00</td>
<td>37.00</td>
<td>32.00</td>
<td>134.00</td>
</tr>
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<td>Salaries</td>
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<td>7.60</td>
<td>8.75</td>
<td>8.75</td>
<td>8.75</td>
<td>8.75</td>
<td>8.75</td>
<td>58.35</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>39.55</td>
<td>83.05</td>
<td>99.60</td>
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<td>164.75</td>
<td>142.75</td>
<td>136.75</td>
<td>137.75</td>
<td>970.35</td>
</tr>
</tbody>
</table>
The chart below plots the capital costs for Phases 1 & 2, with a 2-year overlap, as well as estimated salary costs plus instrumentation costs for nuclear physics and Material Science. The colours in the chart reflect the corresponding rows in the table above.

**Fig. 12.1: Chart illustrating the cash-flow envisaged for the entire project, assuming an 8-year duration.**

### 12.6 ADDITIONAL PERSONNEL FOR OPERATION

Additional personnel will be needed to operate the new facility. A careful survey has been made, based on experience with the existing facility and its infrastructure, and the resulting estimated requirements are tabled below (and continued overleaf).

<table>
<thead>
<tr>
<th>Group</th>
<th>Level</th>
<th>Physicists</th>
<th>Engineers</th>
<th>Technicians</th>
<th>Tech.Assts</th>
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</thead>
<tbody>
<tr>
<td>Cyclotron Operation:</td>
<td>Operators</td>
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<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accelerator Physicist</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isotope Production:</td>
<td>Physicist</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Engineer</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronics Engineer</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ion Source lab:</td>
<td>Physicist</td>
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<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum:</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Electronics technician</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diagnostics:</td>
<td>Electronic Engineer</td>
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<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronic Technician</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Technician</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling systems:</td>
<td>Refrigeration Mechanic</td>
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<td></td>
</tr>
<tr>
<td>Magnet group:</td>
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<td></td>
</tr>
<tr>
<td>Radiation Safety:</td>
<td>Physicst</td>
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<td></td>
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<td></td>
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<tr>
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<td>Electrician</td>
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<tr>
<td><strong>Totals:</strong></td>
<td>5</td>
<td>5</td>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Average salaries per category: | 0.5 | 0.5 | 0.32 | 0.2 |

| **Total Salary Costs:**        | 2.5 | 2.5 | 3.84 | 0.2 |

**Total Additional Salary Cost:** 9.04 MR per annum

It is anticipated that a number of individuals employed during the construction and installation stages will be available to fulfil these requirements. They will also have been trained in the necessary skills during this period, and will thus be eminently suitable candidates for these positions.

12.7 **ADDITIONAL ELECTRICITY COSTS**

It is assumed that the present operational cost of the SSC, the injectors and the rest of the iThemba facility and would remain approximately the same as at present. The costs for 2011/12 amounted to R15.2 million, while for 2012/13 a figure of R19.3 million has been provided for in the budget.

In future, the 70-MeV cyclotron would operate continuously for approximately 300 days per annum (with 65 shutdown days for maintenance). Energy consumption for the new accelerator facilities is estimated to be 43,400 kWh, plus an additional 6000 kWh per day for general use (offices, laboratories, etc).

The total additional cost will then be R6.6 million per annum

In order to be able to obtain the additional power, the Notified Maximum Demand would have to be increased from 5000 kVA to 7500 kVA, and a once-off fixed charge of approximately R2 million will be payable to ESKOM, based on the increase in kVA. A once-off “security deposit” (R1.1 million) may also be payable to ESKOM.
ANNEXE 1: NUCLEAR SCIENCE GRADUATES FROM ITHEMBA LABS AND PRESENT OCCUPATIONS
(Up to 2008)

LIST OF GRADUATES WHO CONDUCTED RESEARCH USING THE SSC WITH THE PHYSICS DEPARTMENT AT ITHEMBA LABS (MATERIAL SCIENCE NOT INCLUDED)

Saalih Allie – PhD, Prof. U. Cape Town
Gillian Arendse – PhD, STAC iThemba LABS
Bruce Becker – MSc, INFN Fellowship, Italy
Marco Benatar – PhD
Peter Bester – MSc, National Nuclear Regulator
Jacques Bezuidenhout – PhD, Lecturer U. Stellenbosch military Academy
Andy Buffler – PhD, Prof, U. Cape Town
Zinhle Buthelezi – PhD, Scientist Physics iThemba LABS
Susan Bvumbi – MSc, PhD student, iThemba LABS
Wesley Damon – MSc, Fuel Division PBMR
Dawid De Villiers – PhD, NECSA
Justus Dlamini – MSc, Dept of Stat.
Siegfried Förtsch – PhD, Scientist Physics iThemba LABS
Dieter Geduld – MSc, PBMR
Colin Henderson – MSc, Deceased
Greg Hillhouse – PhD, Prof, U. Stellenbosch
Taofiq Ibrahim – PhD, Post Doc, U. Stellenbosch
Noel Jacobs – PhD, Lecturer, U. Stellenbosch Military Academy
S Jones – MSc
Peani Maleka – MSc, Lecturer, U. Western Cape
Zain Karriem – MSc, PBMR
Onalenna Kegopotsemang – MSc, Radiation control DOH
Ian Korir – PhD, NNR?
Tebogo Kupi – MSc, Radiation Officer, iThemba LABS
Tsepiso Lakaje – MSc, lecturer, UNIZULU
France Lukhele – MSc, ESKOM, Deceased
Given Mabala – PhD, NECSA?
Justin Mabiala – PhD
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Senekile Pheto – MSc, NNR
John Pilcher – PhD, Group Head, Information Technology, iThemba LABS

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Proposal for a Radioactive-Ion Beam Facility at iThemba LABS

Annexe 1

David Roux – PhD, Lecturer U. Western Cape
Lerato Sedumedi – MSc, DEM
Obed Shirinda – MSc, registered for PhD
Daphney Singo – MSc, registered for PhD
Trevor Stevens – PhD
Steph Steyn – PhD, Head Reactor Physicist, Koeberg
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I Usman – PhD, Post Doc, iThemba LABS
S Walton – MSc
William Whittaker – MSc
JJ van Zyl – MSc, Lecturer U. Stellenbosch
Preston Vymers – MSc, Reactor Physicist Koeberg
David Whittall – PhD, General Manager, LESEDI
Shaun Wyngaardt – PhD, Lecturer U. Stellenbosch
Marian Oliver – MSc
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Douw Steyn – PhD
Bramsby Nangu – MSc
Frank Komati - MSc
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Maureen Masikhwa - MSc
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Nceba Mhlahlo – MSc
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Deon Steyn – PhD, physicist, iThemba LABS
Charles Stevens – M.Dip.Tech, engineer Quad Tech, UK
Nico van der Walt – PhD, radiochemist, Prof, CPUT
Clive Naidoo – PhD, radiochemist, Head Radionuclide Production Group, iThemba LABS
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Khosro Aardaneh – PhD, radiochemist
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Stuart Dolley – B.Tech., radiochemist, iThemba LABS (registered for M.Tech.)
Ellen Visser – B.Tech., chemical technologist ESKOM, Koeberg
Fabian Smith – B.Tech., chemist, Vital Health Foods
Elaine Abrahams – B.Tech., chemist, Fine Chemicals
Amanda Mawu – B.Tech., chemist, period of work at MRU, industry
Brenda Fikani – B.Tech, chemist
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J Garret de Villiers – PhD, Physicist, Acc. Grp., iThemba LABS
Mohammed EM Eisa – PhD, Sudan Univ. of Sci. and Tech., Sudan
S Johnson – MSc
CL Ndlangamandla – MSc
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Frans Weehuizen – PhD, Massey Univ., New Zealand

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Niek Schreuder – MSc, ProCure, USA
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Peter Binns – PhD, MIT BNTC, USA
Sam Bakhane – MSc
D Wagener – MSc
T Ransome – MSc
N van Hoesslin – MSc
P van Wyk – BSc(Hons)
L van der Bijl – MSc
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Sam Tsoue – MSc, Elec. Eng. U. Cape Town
M Seotsayana – MSc
Avril O’Ryan – BTech
Shaheeda Rhoda – BTech, Med. Phys iThemba LABS
Shaheida Fredericks – BTech, Med. Phys iThemba LABS
Shafeeqa Schroeder – BTech, Med. Phys iThemba LABS
Basil Martin – BTech
LIST OF GRADUATES WHO CONDUCTED RESEARCH WITH THE ENVIRONMENTAL GROUP OF THE PHYSICS DEPARTMENT AT ITHEMBA LABS. (MATERIAL SCIENCE NOT INCLUDED)

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Peane Maleka – MSc
RF Manavhela – MSc
Khatse Maphoto – MSc, NNR
NB Mbatha – MSc
TJD Modisane – MSc
Thobogo Motlhabane – MSc
Lerato Sedumedi – MSc
Wilcot Speelman – MSc, Still studying
S Tahla – PhD
Damon Wesley – MSc