A RADIOACTIVE ION BEAM FACILITY at iTHEMBA LABS: SUMMARY

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ABSTRACT

The Separated Sector Cyclotron (SSC) accelerator at iThemba LABS, already the premier nuclear accelerator in Africa and the southern hemisphere, is part of a multidisciplinary facility that supports research into nuclear and material 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 the multidisciplinary facility has reached the point where further growth of the respective disciplines is restricted – the different disciplines interfere with each other and indeed, South African science and radiation medicine is losing its place at the international forefront of these disciplines as a result.

We propose the phased development of a radioactive 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 phase would see the addition of a high current, 70 MeV negative ion cyclotron to iThemba LABS, together with a renewal of the existing facilities to better exploit the added beamtime.*

Several beams can be extracted simultaneously from a negative-ion cyclotron, thus allowing the parallel operations of neutron therapy, radioisotope production, and proton therapy and nuclear physics research. The SSC would now be dedicated to proton therapy and nuclear physics. For proton therapy, the number of different types of cancers and patients that could be treated would be increased considerably, while for nuclear physics, the training capacity would double and the links with international collaborations would be considerably strengthened due to the increased availability of beam time. The additional beamtime provided by the new accelerator would effectively double the capacity for neutron therapy treatments and radioisotope production.

- *The second phase would see the production of radioactive beams to bring nuclear and materials research and training in South Africa to the international forefront.*

The “terra incognita” of nuclear physics – the so-called neutron rich nuclei, are those nuclei which cannot be produced with beams of stable atoms such as those found in nature. Internationally, interest is focussing on the study of these nuclei, because they hold the key to completing our understanding nuclear forces and the origin of the elements of which we are composed. To study neutron rich nuclei, one needs beams of artificially produced radioactive nuclei. In the ISOL method, proposed for iThemba LABS, two accelerators are needed, one to produce the radioactive atoms, and the other to accelerate them for research purposes. Because several beams can be extracted

simultaneously from the negative-ion cyclotron proposed for the first phase, the new cyclotron can also be used to create radioactive beams, which can then be post-accelerated by the SSC for use in nuclear physics experiments. Radioactive beams are also of considerable attraction for materials research. The radioactive ions can be implanted into a material of industrial interest, such as semi-conductors, and the perturbations of their decay can yield important information of the atomic structure of the material.

The production of radioactive 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 strongly linking to South African Universities and Technikons.

The new facility will require expenditure on

I. A high-intensity, negative-ion cyclotron
II. A new isotope production facility
III. A new vault and gantry for neutron therapy
IV. Target stations and handling facilities for radioactive beam production
V. Upgrades to existing infrastructure for
    a. physics research
    b. proton therapy
VI. Civil engineering to accommodate the new facilities

The overall cost of the project, expended over an eight year period, is estimated to be between R1000M and R1300M, depending on the level of implementation. Once completed, the new facility will add to the operating costs of iThemba LABS.

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FOREWORD

This document summarizes a proposal under development for the introduction of a new accelerator at iThemba LABS. The objective is to update the laboratory and more than double the beam time available for its core activities – research, hadron therapy and radioisotope production - and to create a radioactive beam facility to maintain South African researchers at the international forefront of nuclear and applied physics.

iThemba LABS invites all interested parties to participate and contribute to the development of this proposal.

INTRODUCTION

iThemba LABS at Present

iThemba LABS is a multi-disciplinary laboratory specializing in accelerator based sciences and applications. The main driver for this laboratory is human resource development in the fields in which it has an internationally established profile: basic nuclear physics research, hadron therapy, radionuclide production, material and environmental research. It operates most of South Africa's research accelerators, with the premier device being the Separated Sector Cyclotron, sited at Faure, in the Western Cape. It is an extremely versatile machine, capable of producing high intensity proton beams and also capable of accelerating any other beam species to energies high enough to induce nuclear reactions.

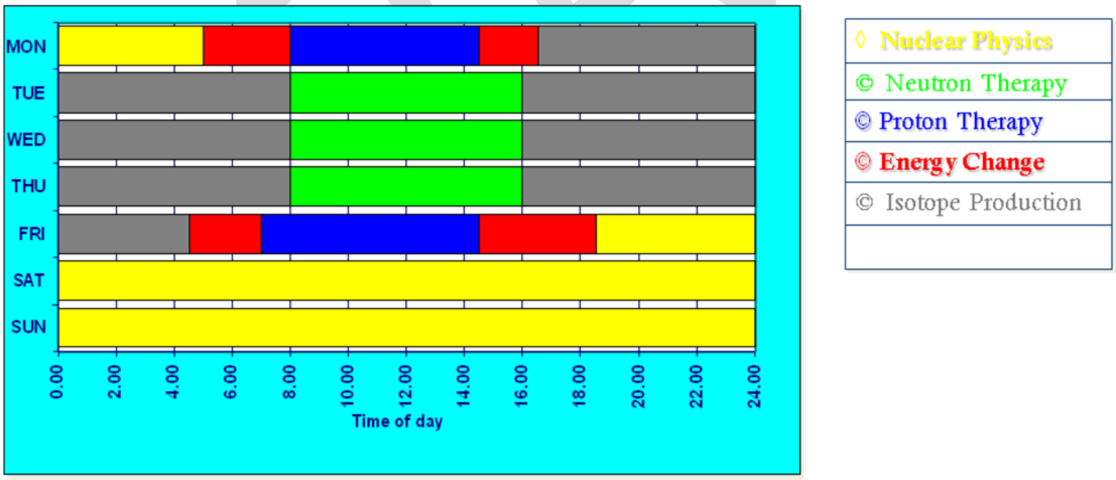

Figure1. Present weekly schedule of iThemba LABS SSC beamtime

The SSC is shared principally by four disciplines:

- nuclear physics research
- proton therapy
- neutron therapy
- radioisotope production.

Except for maintenance shutdowns, the accelerator is operated on a continuous basis, 24 hours per day, according to a weekly schedule, as shown in Figure 1. The usual mode of operation is that nuclear physics research is conducted over weekends, while during the week, proton therapy, using a proton beam of 200 MeV energy, takes place on Mondays and Fridays. The remainder of the time is shared by neutron therapy and radioisotope production, which require a 66 MeV proton beam. The radioisotopes are produced overnight, and when the neutron therapy beam would otherwise be idle.

Present Distress

In an ideal world, each of these four disciplines would have their own dedicated accelerator. The shared use of the SSC has always involved compromises which have meant that certain disciplines have not reached their full potential, and indeed, are severely restricted.

Proton Therapy

The application of proton therapy in the treatment of cancers is perhaps the application most restricted under the present operating mode. Proton radiation is seldom administered in a large single dose, but is divided into several treatment sessions, or fractions (up to 30 or more, depending on the condition being treated). This technique allows normal healthy cells which suffer sub-lethal damage in the previous session to repair (recover), while the unhealthy cancer cells are unable to recover during this period.

However, with the present beam schedule, only two fractions per week can be administered, restricting treatment to only certain types of intracranial and base of skull conditions and some small paraspinal tumours. The inability to provide 30 or more fractions per treatment makes it impossible to treat the majority of malignant tumours.

For example, if fractions could be administered five days a week, the following malignant tumours could be treated (see Appendix 1) :

- Paediatric Tumours
- Ophthalmological Tumours
- Brain Tumours
- Gastro-intestinal Cancers
- Prostate Tumours
- Head and Neck Tumours
- Spinal Cord and Paraspinal Tumours

iThemba LABS has long recognized this limitation and it is part of the motivation for the iThemba Proton Therapy Center (iTPTC). 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 is presently the subject of a review by the consultants Quartile Capital.

Neutron Therapy

Conventional (conformal) neutron therapy as currently offered by iThemba LABS is of limited interest to the radiation oncology community, largely because it provides a clinical gain for only a limited number of tumour types. The large relative biological effectivenes of fast neutrons can lead to increased normal tissue toxicities if the dose in these tissues is too high. The biological advantages of fast neutrons are therefore often spoiled in practice by the difficulties to restrict the neutron dose to the target volume. This fundamental problem, combined with the fact that the availability of fast neutrons is restricted to a few expensive accelerator based facilities, has lead to a worldwide decline in fast neutron therapy. The enormous advances made in photon therapy, proton therapy, and especially in carbon ion therapy, have also contributed to the decline of interest in fast neutron therapy.

The current neutron therapy facility is based on a p(66)/Be isocentric gantry that is equipped with a multi-blade trimmer device to shape the treatment field. The blades of this device cannot be adjusted dynamically and the amount of neutron transmission through the blades is relatively high (about 15%). The mechanical precision of the gantry and that of the treatment couch has deteriorated over the more than 20 years that the unit has been in operation.

Research in fast neutron therapy can only be revitalized if a fundamentally new treatment technique, such as intensity modulated neutron therapy (IMNT), can be introduced. This would require a new gantry with adjustable trimmer blades.

Research: Nuclear Physics

In nuclear physics research, demand for the available beamtime is oversubscribed by a factor of two, and rising. This puts a severe restriction on the number of MSc and PhDs which can be produced by the facility. Furthermore, many experiments requiring longer periods of continuous beamtime are not feasible under the current arrangements. Potential overseas collaborations are discouraged by the lack of continuous beamtime due to the extended stay required to complete an experiment. Moreover, the field is moving toward the study of neutron rich nuclei using radioactive beams – beams which cannot be produced with the present accelerators. These factors are to the detriment of both the international competitiveness of research 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.

Note that even if the iTPTC goes ahead, the removal of proton therapy from the SSC will not remove the restrictions placed on nuclear physics research imposed by the sharing of the SSC with neutron therapy and isotope production.

Medical Isotope Production

The quantity of radioisotopes produced is dependent on the available beam current and beam time. The available beam time is essentially fixed by the schedule presented in Fig. 1. To increase isotope production, iThemba LABS has introduced a number of innovations to increase the available beam current. These include the introduction of “flat-topping” in the SSC, a new vertical target station, and beam-splitting. The possibilities for further increases in beam current with the SSC are now exhausted. Any further growth in production is now restricted because it must be met by an increase in beam time.

Accelerator Reliability

The frequent energy changes demanded on the SSC by the present beam schedule stresses accelerator components and degrades accelerator reliability.

Future Opportunity

A New Cyclotron

The solution to these restrictions is to build a new cyclotron. The most economical solution is to build a machine capable of taking over the load of neutron therapy and isotope production, since both share the 66 MeV proton beam.

Once neutron therapy and isotope production move to the new machine, the SSC will be freed to be used entirely for research (chiefly nuclear) and proton therapy. It is envisaged that the available beam time will be divided into two blocks of approximately five months duration between the two disciplines, as shown in Figure 2. In this way, sufficient contiguous time could be given to proton therapy to allow the full spectrum of tumours to be treated.

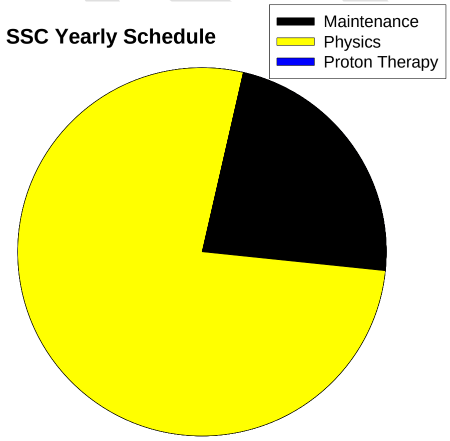

Figure 2 Proposed yearly beamtime schedule

Radioactive Beams

With this scheme, there is another benefit to research in South Africa. It becomes possible build a radioactive beam facility at iThemba LABS. In the field of nuclear physics, this would fulfil the ten-year research plan of the Nuclear Physics Department, to enable the study of “neutron rich nuclei” – the last frontier which is rapidly becoming the focus of international research, while the study of materials would be greatly enhanced by the implantation studies using radioactive ions.

A Radioactive Beam Facility

In the past, nuclear accelerators propelled stable atoms – those occurring naturally – to energies required for nuclear or material physics research. Often the goal was to create artificial radioactive nuclei. The study of these nuclei allows theories of nuclear forces to be tested but the tests are limited to those nuclei that can be produced with a stable beam – these are the neutron *deficient* nuclei. The neutron *rich* nuclei are largely unknown and represent a severe gap in our knowledge of nuclear structure and nuclear forces.

To create neutron rich nuclei, two methods are available. The Projectile Fragmentation (PF) method accelerates a beam of heavy-ions and breaks them up by passing them through a target. If protons are knocked from the atoms of the beam by the target, a new *neutron rich* radioactive beam is produced. However, to penetrate the target and maintain focus, extremely high energies are required, necessitating the construction of an expensive accelerator. Furthermore, because the beam is relativistic, it cannot easily be used for many studies of interest.

The second way of producing radioactive beams is the Isotope Separation OnLine (ISOL) method. Here, a driver accelerator delivers a high-intensity, possibly low-energy, beam which strikes a very thick production target. The radioactive ions produced in this target are initially trapped within it, but are liberated by heating the target to high temperatures. The radioactive species diffuse out of the target, are ionized, selected, charge-bred, and injected into a second (post-) accelerator for transport to an experimental station. Thus in this method two accelerators are required.

At iThemba LABS, a new 70 MeV proton accelerator would be ideal as a driver accelerator while the existing SSC is potentially already suitable, with a new injection accelerator and improvements to the vacuum and control system, as a post accelerator. The addition of a Radioactive Ion Beam (RIB) production target and ion-source would complete the system.

To be able to be used for both RIB production and for isotope production and neutron therapy, a negative-ion cyclotron is required one for which it is possible to extract two or more beams simultaneously.

The Project – a Phased Approach

iThemba LABS envisages a Radioactive Beams Project, divided into phases, that meets the needs for additional beamtime for research and human resource development, maintains and develops South African research at the international forefront, and increases isotope production.

Phase 0

This phase can be understood as encompassing the project development, design and approval process and to some extent continues during Phase 1.

Phase 1

In the first phase, isotope production and neutron treatment capacities are doubled when a new cyclotron complex is constructed. A new gantry for neutron therapy is installed so that the development of IMNT can begin. Physics research with stable beams benefits from a doubling of beamtime on the SSC.

Already in this phase key technologies can be demonstrated. The technology required for the RIB production target and ion sources can be developed and tested with the existing beams from the SSC. Its immediate application is in the study of the β-decay properties of neutron rich nuclei and, for materials research, ion-implantation studies.

Phase 2

The second phase envisages the creation of radioactive beams using the new driver cyclotron. These beams will have multidisciplinary application touching not only nuclear physics but also astrophysics and material science. The production target and ion-sources for radioactive beam production will be installed. Protons from the new accelerator will be used to fission uranium, which produces hundreds of different neutron rich species with relatively heavy atomic masses of between approximately 80 and 130, or alternatively, be used to induce reactions to create radioactive beams of neutron deficient species, or light neutron rich species, both for nuclear physics research and as the desired probes for material analysis. The desired species must be selected from a “cocktail” of reaction products and post-accelerated to form the radioactive ion beam.

In parallel with the above phases, new apparatus, including a large acceptance spectrometer and an active target, will be developed and installed to make full use of the new beams.

Beyond this Proposal

Future expansion of the facility could be an upgrade to increase in beam intensities for isotope and radioactive beam production.

Any expansion beyond this is likely to require additional accelerator(s). These could, for example, be another cyclotron following the SSC to obtain higher beam energies; or a linac driver accelerator to create extremely neutron deficient nuclei using projectile fragmentation reactions. Such expansion would occur beyond two decades in the future.

BENEFITS OF THE PROJECT

Human Resource Imperative

Transformation and Skills Development

Transformation in order to attain an equitable race and gender distribution in both industry and academia remains an urgent need. Presently, the flow of appropriate graduate and postgraduate degrees needed to address these imbalances is inadequate.

Furthermore, it is well known that South Africa faces a severe shortage of critical skills, particularly in the fields of science, engineering and technology.

- A substantial skills base in nuclear technology is a priority, as the energy crisis facing South Africa has by no means been averted, and it remains the policy of the Government of South Africa to continue to build a substantial nuclear power industry. Indeed, Cabinet recently approved the 20-year Integrated Resource Plan, which provides for 9.6 GW of nuclear power, the equivalent of approximately six 1600MW Pressurized Water Reactors. This implies an investment of over two hundred billion Rands in nuclear energy in South Africa.

- Sub-Atomic skills are 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.

Clearly, the demands on human resources required to support a nuclear industry of the proposed dimensions are considerable. To support a nuclear industry and to further the progress of transformation, a substantial investment in human resources is required at the highest levels.

The research facilities at iThemba LABS play an important role in post-graduate training in a wide variety of fields that include subatomic physics, medical physics, materials and nanoscience, radiobiology and radiochemistry. Strong links exist between research and training through the involvement of post-graduate students in research projects by 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 the post-graduates to internationally competitive research and research equipment and simultaneously enhance training opportunities in a variety of technical fields

The new cyclotron project will benefit transformation, training and research in the following ways:

1. *By generating new opportunities for multidisciplinary technological development*

The development of radioactive beams is a large project with numerous technological challenges. In fact, the human resources required to bring the project to completion are not available at the laboratory. It is therefore necessary for the laboratory to build up capacity by training students in the design and construction of the facility. It is envisaged that students and trainees from South African Universities and Technikons at various levels and across a number of disciplines will be involved in the design and development of the project. Thus the training provided by the project is not confined to its immediate research aims, but will draw on related fields of engineering, information technology, chemistry etc.

2. *By effecting transformation*

Because the project is multidisciplinary, the potential for outreach and increase involvement of Historically Disadvantaged Universities, which may not have formerly been involved in the nuclear sciences, is far greater than had the project 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, 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 University of Zululand. A further graduate course, an MSc in Organisation of Nuclear Energy (MSONE), in collaboration with the University of Johannesburg and the Tshwane University of Technology has just started this year 2010.

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.

3. *By substantially increasing the available beam time.*

Upon project completion, a stepping up of research intensity due to the doubling of available beam time. An important point is that a commensurate increase in the number of MSc and PhD degrees completed can be expected.

4. *By opening up new research fields accessible only with radioactive beams*.

Post-graduate students need to be exposed and trained in research fields that are at the forefront of science. In nuclear physics, while much still remains to be done with stable beams, the availability of radioactive beams will keep South African researchers at the forefront of the study of the neutron rich nuclei. In material science, the application of radioactive beams as probes of solid state structure (e.g. Mössbauer spectroscopy) will allow research that is presently not possible within South Africa.

5. *By stimulating interest in science*

Large projects that are at the forefront of international science and technological development, play a significant role in stimulating interest in science and technology. They are important to attract top students into careers in these fields.

University Research Chairs

New equipment requires staff to use them efficiently. The proposed facility at iThemba LABS will be no exception. Universities in South Africa have been under severe financial strain during the last 20 years. For example, the three physics departments in the Western Cape have, shown no real growth in staff numbers over the last 20 years. It is therefore important that the proposal for the cyclotron addresses the staffing issue. The original proposal for he SALT telescope included funding for post(s) at universities. This never happened, with the results that the astronomy community in South Africa did not grow by the time the telescope was completed. In the case of the radio telescopes (KAT and MEERKAT and the SKA proposal) there has been a concerted effort to provide personpower. In this regard five SARCHI chairs have been provided to universities.

We therefore propose that similar Research Chairs be funded to support teaching and training associated with the facility.

Research with the New Facility

The physics research conducted at the new facility will broadly fall in line with the goals of the five and ten year research plan. It is after the second phase that radioactive beams will become available, pushing the South African nuclear physics and material science research to the international forefront. In particle therapy and nuclear medicine new opportunities will arise with IMNT and the use of Positron Emission Tomography (PET). The development of the facility itself will create numerous opportunities for research within the field of accelerator physics.

In general terms, the research opportunities are described below:

Nuclear Physics

Phase 1

Let us begin by highlighting some aspects of the research programme on the SSC, which comprises pure and applied nuclear physics.

The pure research programme tests models of the nucleus under extreme conditions. Special programmes are underway to test predictions of nuclei having exotic shapes resembling pyramids (tetrahedrons) or stretched pears (hyperdeformation). The possibility of exotic triaxial shapes gives rise to new degrees of freedom which manifest as wobbling motions and introduces the possibility of chirality - whether the nuclear system can be regarded right-handed or left-handed. Some of the research questions the basic assumptions of the low-lying modes of excitation of the nucleus. Are they actually vibrations as has been assumed or are they really due to differing configurations of paired nucleons? At higher excitation energies, giant vibrations of protons relative to neutrons occur. The formation of these vibrations is studied at the laboratory using the K600 spectrometer. This instrument is now able to operate at zero degrees and related questions arising about the formation of the elements in supernova explosions will be answered. With the addition of a polarimeter, it will also be able to answer detailed questions about how the force between nucleons changes within the nucleus. At the other extreme, research has also been conducted into possible ways of artificially forming superheavy elements – elements so heavy that they are unlikely to have been formed even in supernova explosions.

In the applied programme are the development of neutron detectors and dosimeters for commercial aircraft and the international space station. These monitors are vital for the safety of air crew and astronauts exposed to cosmic radiation.

Most of these areas of research will benefit greatly from extended beamtime, by allowing experiments that would otherwise be practically impossible, since high statistics are required to resolve weakly populated structures, while for other experiments, extended beamtime is required to set up delicate instrumentation.

Phase 2

On the chart of the nuclides, shown in Figure 3, the known nuclei, those that occur naturally (black) or those that have been artificially produced (yellow), comprise approximately half of all the species that are predicted to exist.

The still unknown nuclei, (green) lie predominantly on the neutron rich side of the naturally occurring isotopes. Indeed even of the known neutron rich nuclei, very little other than their existence and a few basic properties are known.

Thus the neutron rich region, “terra incognita”, is also to be regarded as a “final frontier” in low-energy nuclear physics. It is in this region that the nuclear shell model – the “standard model” of the nucleus - has been subjected to the most stringent of tests and has been found wanting. The shell model correctly predicts the location of especially stable nuclei in naturally occurring isotopes, with shell gaps at the so-called magic numbers of protons and neutrons. However, extended theoretical calculations and the little evidence that we already have from radioactive beam laboratories overseas, points to the dissolution of the shell gaps in neutron rich nuclei. The shell model, which has been the basis of our understanding of nuclear structure for over 40 years, has been exposed as inadequate and requiring the inclusion of charge and isospin exchange forces in addition to the spin-orbit force. This evidence has been gleaned only from very light neutron rich nuclei – the effect of exchange forces and tensor forces in heavier neutron rich nuclei is largely untested.

The heavier neutron rich nuclei are also expected to show modified behaviour due to the existence of a neutron skin. This is also expected to influence the shell structure but it should be possible to observe new modes of the giant vibrations that scientists at iThemba LABS have been studying with stable beams. These new modes are called the pygmy resonances – in effect a vibration of the neutron skin around the core.

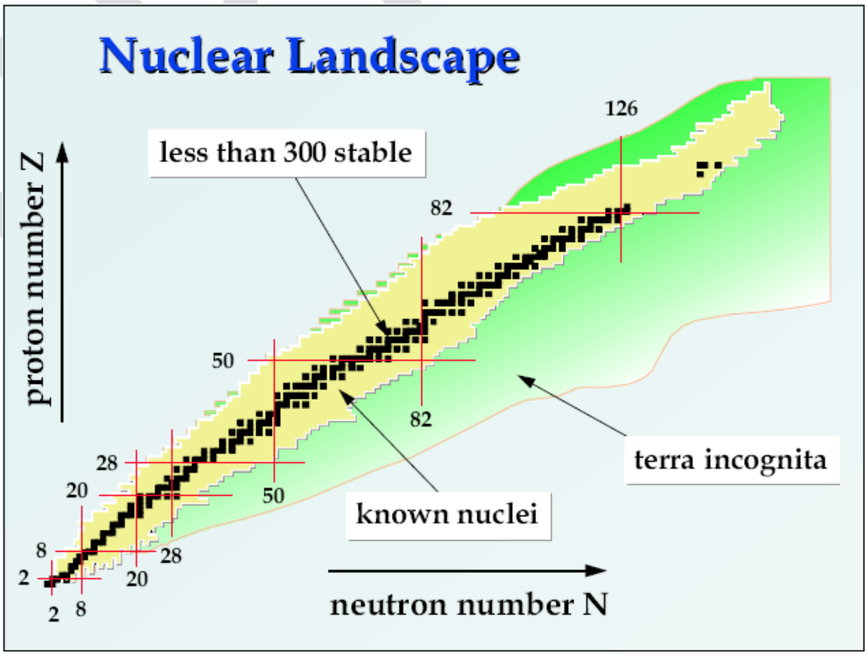

Figure 3. The “nuclear landscape”, showing the unknown region in green (from RIA taskforce report)

Astrophysics

The ramifications of our poor knowledge of nuclear forces extend beyond the realms of strictly nuclear physics and into astrophysics. It is in stars that the elements were created but for elements heavier than iron, it is more accurate to say that they were created in exploding stars, or supernova. In supernova large fluxes of neutrons necessarily created neutron rich nuclei. To understand the precise details of this process, the so-called “r-process”, and to be able to explain the abundances of the naturally occurring elements, it is necessary to have an understanding of neutron rich nuclei, and of the location of the shell gaps. Unfortunately, since the shell model has been shown to be deficient, our understanding of the origin of the elements remains imprecise.

A radioactive beam facility, delivering neutron rich nuclei from the fission of uranium, will allow South African researchers, and indeed international collaborators, an unprecedented opportunity of understanding the fundamental forces of nature and the origin of the elements.

Material Science

In condensed matter and solid state research the use of radioactive nuclei as probes for the study of structural and/or electronic / magnetic lattice environment in materials (metals, insulators or semiconductors) on surfaces and interfaces is of critical importance for technical development. Most of these studies are concentrated on the investigation of defects and impurities in semiconductors like Si, Ge, III-V or II-VI compounds. The main topics of such investigations are implantation induced lattice damage and its annealing behaviour, the lattice site of the implanted ion after annealing, the interaction between impurities or impurities and intrinsic defects, the electronic and optical properties of the implanted species and the identification of defects and impurities. For example the microscopic insight into the structure and the thermodynamic properties of materials formed by interacting defects can be obtained by detecting the hyperfine interaction between the nuclear moments of the radioactive dopants and the electromagnetic fields present at the site of the radioactive nucleus.

The understanding and the control of diffusion profiles of intrinsic and extrinsic defects particularly in semiconductors is significantly enhanced using radioactive tracer diffusion. In this process a thin layer of material containing the tracer is deposited on the surface of the sample under study [1]; alternatively the radioactive tracer can be implanted using highly selective and pure isotopes accelerated from suitable ion sources. Subsequently the system is heated for a predetermined time and temperature ranges. After cooling back to room temperature, the sample is sectioned into thin slices step by step and either the content of the radioactive tracer in each slice or in the unsectioned part of the sample is measured. From this measurement the diffusion profile of the tracer is determined. By repeating this experiment for several diffusion times and/or temperatures the diffusion parameters of the tracer, especially its activation enthalpy is determined. From these values and the shape of the diffusion profile, conclusions about the diffusion mechanism can be inferred. For this type of work the use of radioactive beams with half-lives of minutes is desirable.

The MRG with its long history of thin film systems research in binary or ternary metal-semiconductors systems will benefit immensely if a beam line for radioactive ion implantation is available. There are many institutions within South Africa that definitely will make use of such a facility. Of especial interest is the Nano African Network (NanoAFNET) and the Accelerators for Sustainable Development in Africa (ASDA) network which are African bodies currently developing an intense training programme of African scientists working in NanoScience and interested in using the resources at iThemba LABS for the purpose of continuing research on diffusion in solids, particularly in relation with the synthesis and characterization of nano-materials. At the MRG the current post-graduates and/or African visitors turnover is about 12 per month and this is without counting the number of students registered for MSc and PhD theses at South African universities doing research at the MRG.

An important part of materials science research at the MRG, iThemba LABS is the study of the behaviour of materials under radiation conditions. It has been recognised that bombardment with energetic particles offers a unique method to create controlled populations of defects and atom displacement in solids. These phenomena produce chemical effects in solid materials since they affect the way atoms of various species are arranged in space and thus, irradiation can promote or inhibit phase changes. One of the main interests is the study of Pt-thin film coated systems subjected to radiation effects as a state variable which can induce phase and structural changes with particular interest for ordering transition. There is a set of superstructures (superlattices) that have been predicted to appear at particular temperature ranges, and the knowledge of the interactions of Pt with thin films of other compatible metals is of utmost interest. These effects are very important for many applications of the Pt coated systems as catalyst, gas sensors and optical devices.

The use of radioactive beams for the study of polymer based track edge membrane diffusion profile and interface behaviour is also of importance for the nano-sciences research group at MRG.

Medical Physics

In the medical field, the effect of nuclear radiations on biological tissue is under investigation.

Proton therapy

Clinical research output will be stepped up proportional to the number of patients treated. With a minimal beam delivery system assembled in the spare vault, there will be an opportunity to fully exploit medical physics research capacity for the first time. This will use the 200 MeV beam during idle time and throughout nights and weekends.

Proton beam time availability on consecutive days makes it possible to conduct fractionated proton radiation biology experiments. This is needed to investigate dose-volume effects applicable to modern radiosurgery applications using particle beams.

Neutron therapy

Since the neutron therapy gantry will be moved to the new accelerator, it can be reassembled with a new motorized leaf collimator. This will create the opportunity to initiate research on Intensity Modulated Neutron Therapy, a completely new field of research as yet unopened. It offers the possibility of more effective treatment by shaping the neutron beam to better conform to the tumour.

With IMNT, the physical dose differential of neutrons can be increased significantly, thereby allowing a reduction in the dose to normal tissues and an escalation in the dose to the target volume. IMNT, when combined with modern image guided technologies, will bring fast neutron therapy back to the level of the current state-of-the-art in photon radiotherapy. Such technological improvements, combined with the biological advantages inherent to fast neutron therapy, will make it an optimal treatment modality for many tumour types. It is reasonable to expect that IMNT would present (at least for certain tumours) a competitive alternative for the very expensive carbon ion therapies that are currently only available in a few centers worldwide

Radioactive beams

An area of research that can be started is the clinical diagnostic applications of radioactive beams. This can be directed to obtain accurate in-vivo beam range measurements using C-11, Ne-19, Ne-20, that can help resolve one of the major uncertainties in proton therapy.

Positron Emission Tomography Imaging

To enhance nuclear medicine research in South Africa, emphasis should be placed upon the development and radiolabelling of PET (Positron Emission Tomography) radionuclides, for diagnostic as well as therapeutic purposes. PET imaging, with the use of ^{18}FDG, revolutionalised the world of nuclear oncology, while substantial progress has also been made in the development of radionuclide therapy, particularly radioimmunotherapy and radiopeptide therapy. PET imaging has been introduced to the local nuclear medicine community only recently and much work is required to unlock the potential of this technology.

Fluorine-18 has been the only radionuclide to be used in PET imaging in South Africa thus far and is still regarded as the radionuclide of choice in Europe, due to its favourable radiophysical characteristics. ^{18}F-labelled FDG is currently being used for imaging purposes (for brain tumours and determining Alzheimer’s Disease), but new carrier candidates such as FLT, F-MISO, FES and F-DOPA have been clinically evaluated in Europe, indicating a possible wider range of uses for the radionuclide using PET technology. Some of these radiotracers complement each other: ^{18}F-labelled FDG, for example, is not specific for malignancies, while ^{18}F-labelled FLT specifically targets the proliferate activity of malignant lesions.

Carbon-11 is also a popular radionuclide to be used for PET imaging, although its disadvantage is its short half-life. It has been proven to be effective in determining brain tumours, but what makes it a remarkable radionuclide is the fact that practitioners can distinguish between Alzheimer’s Disease and Frontotemporal Lobar Degeneration. To overcome the problem of the short half-life, it is suggested that a ^{11}C laboratory be erected as part of the proposed building, such that the radionuclide can be used in the study and imaging of animals. This would naturally necessitate the presence of an animal testing facility, including a micro-PET scanner.

Proton Therapy with the New Facility

While proton therapy should ideally have a dedicated accelerator to provide fully fractionated proton therapy throughout the year, this proposal will at least realize five consecutive months for proton therapy (still a vast improvement compared with the present schedule of two days per week, four months of the year).

With modest improvements to the existing beam delivery system, patient chair and treatment planning systems, fractionated therapy will be possible to treat the pathologies listed in the appendix.

The number of patients that can be treated is difficult to estimate, as different conditions require prescriptions of different durations and fractions. A maximum of approximately 100 patients per annum is estimated.

Neutron Therapy with the New Facility

The relocation of neutron therapy to the new cyclotron will allow treatment on six days a week, rather than the present three, so that up to twice as many patients per week can be treated.

Radionuclide Production with the New Facility

Due to the recent installation of “flat-topping” in the SSC and the commissioning of a beam-splitter, an extremely large current of up to 350 μA can be directed to two different target stations for isotope production (with a maximum of 250 μA per target station). A conservative estimated production from this facility, assuming 54 hours per week allocated to isotope production, is given in Tables 1 and 2 (column 2). The theoretical revenue from the full utilization of this operation is up to R28M.

While future growth in radionuclide production will be dependent on market forces, no expansion will in any case be possible with the current facility due to restrictions on beamtime and beam current. With a new accelerator, more weekly hours of beamtime can be delivered, and if in addition, a beam splitter is also added to this setup, for simultaneous operation with neutron therapy, the theoretical maximum revenue would nearly triple to R75M. This value could even be exceeded, if more than 250 μA of current was available, and the beam splitter was used to direct the beam to two target stations.

Notice that Sr-82 and Na-22 together accounted for approximately 62% of revenues in 2009. These two isotopes require an accelerator capable of reaching energies of up to 70 MeV. A list of isotopes produced at iThemba LABS is given in Table 3, along with the energies required for their production.

Table 1 Radionuclide weekly production capacity

Radionuclide	*Production capacity (2008)*	*Production capacity (SSC with B/Splitter)*	*Production Capacity (70 MeV Cyclotron & B/Splitter)*
Ga-67	~250 mCi	~250 mCi	~250 mCi
I-123	~230 mCi	~230 mCi	~230 mCi
Rb-81 (2 productions)	~60 mCi	~60 mCi	~60 mCi
18F-FDG (4/5 productions)	~6 000 mCi	~6 000 mCi	~7 500 mCi
Sr-82	600 mCi	1000 mCi	3300 mCi
Ge-68	100 mCi	160 mCi	480 mCi
Na-22	None	20 mCi	58 mCi

Table 2 Radionuclide annual revenue

Radionuclide	*Annual Revenue (2008) (actual) R1000's*	*Annual Revenue (SSC with B/Splitter) R1000's*	*Annual Revenue (70 MeV Cyclotron & B/Splitter) R1000's*
Ga-67	1500	1500	1500
I-123	1300	1300	1300
Rb-81 (2 productions)	50	50	50
18F-FDG (4/5 productions)	1900	1900	2500
Sr-82	8400	14100	42300
Ge-68	3000	5800	18000
Na-22	0	3000	9300
TOTALS	**R15,750**	**R27,650**	**R74,950**

Table 3 Radioisotopes produced at iThemba Labs

Radionuclide	*Target*	*Nuclear reaction*	*Needed Energy (MeV)*	*Production Yield 2) (MBq/μAh)*	*Suitable for export 1)*
	Isotopes produced in the last two years				
^{67}Ga	Zn	Zn(p,xn)	37 - 22	36	+
^{67}Ga	Ge	Ge(p,X)	62 - 39	75	
^{123}I	NaI	I(p,5n) $^{123}\mathrm{Xe}\rightarrow{}^{123}\mathrm{I}$	63 - 48	265	
$^{81}\mathrm{Rb}/^{81m}\mathrm{Kr}$	Kr	Kr(p,xn)	53 - 45	518	
$^{81}\mathrm{Rb}/^{81m}\mathrm{Kr}$	RbCl	Rb(p,X)	63 - 58	245	
^{18}F -FDG	$H_2{}^{18}O$	^{18}O(p,n)	18 - 12		
$^{82}\mathrm{Sr}/^{82}\mathrm{Rb}$	RbCl	Rb(p,xn)	63 - 40	5.4	+
^{68}Ge	Ga	^{69}Ga(p,2n)	34 - 0	75	+
^{22}Na	Mg	Mg(p,X)	62 - 40	.61	+
	Isotopes produced in other years				
^{52}Fe	Mn	Mn(p,4n)	63 - 48	12.1	+
^{55}Fe	Mn	Mn(p,n)	35 - 11	.21	+
^{85}Sr	RbCl	Rb(p,xn)	21 - 0	2.2	
^{111}In	$\mathrm{In}/\mathrm{In}_2\mathrm{O}_2$	$\mathrm{In(p,xn)}^{111}\mathrm{Sn}\rightarrow{}^{111}\mathrm{In}$	63 - 54	28	
^{133}Ba	CsCl	Cs(p,n)	21	.01	+
^{139}Ce	$\mathrm{Pr}_6\mathrm{O}_{11}$	Pr(p,X)	62 - 20	83	+
^{201}Tl	Tl	$\mathrm{Tl(p,xn)}^{201}\mathrm{Pb}\rightarrow{}^{201}\mathrm{Tl}$	29 - 21	11.4	+ (US)
^{56}Co	Fe	Fe(p,n)	20 - 12		
^{103}Pd	Ag	Ag(p,n)	63 - 22	14	+
^{75}Se	KBr	Br(p,n)			
^{83}Sr	RbCl		40 - 25		
^{85}Sr	RbCl		21 - 0	2.2	
^{18}F -FDG	Ne	Ne(p,X)	63 - 58	930	

1) Depends on the half life

2) Divide MBq by 37 to get the amount in mCi

TECHNICAL CONSIDERATIONS

Production of Radioactive Beams

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. 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 Legnaro, INFN, Italy, which makes use of a 70 MeV proton machine, originally developed for radioisotope production. Since a ~70 MeV proton beam will be used for the neutron and isotope programmes, 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 ISOL technique, and could, for example, produce neutron rich species using proton-induced fission on a production target of uranium carbide. Alternatively, the proton beam could be used to produce neutron deficient beams, using (p,xn) reactions. These beams are also of interest for the material sciences.

A schematic diagramme showing the different stages of possible RIB production using the ISOL method at iThemba LABS is given in Figure 5 below.

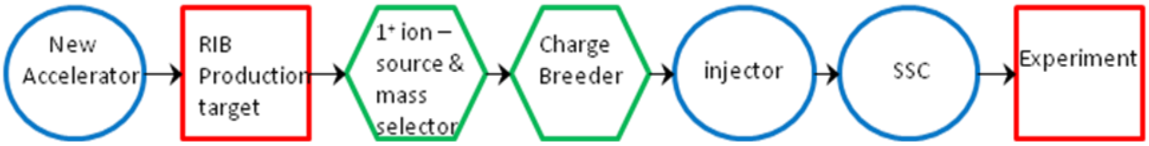

Figure 5. Phases in the production of radioactive ion beams.

Radioactive atoms are produced in the production target, on a high voltage platform, using beams from the new accelerator. To extract radioactive ions from this target, it will be heated up, and atoms which migrate out of it will be ionized to the 1+ charge state using an ion-source located adjacent to the target. A number of ionization techniques are available, including surface ionization, plasma ionization with a FEBIAD ion source, or using laser ionization (RILIS). Already a workshop on Lasers and Accelerators has been held at the University of Stellenbosch where it was clearly shown that the expertise to build RILIS ion sources exists in South Africa. Ionization to the 1+ charge state alone is insufficient to select the desired radioactive species; final selection is achieved by using a mass analyser.

At this point, a choice can be made: whether to post-accelerate the radioactive ions with the SSC to high energies for nuclear physics, or to use the platform voltages to implant the beams into materials for analysis.

If the beam is to be post-accelerated using the SSC, it must be “charge bred” with a second ion-source to reach the charge state that is needed to obtain the specified final energy of the beam. This charge breeding can be performed by an ECR ion-source. Thereafter the beams must be injected into the SSC using a special accelerator, or “injector”. The present injectors are expected to be able to inject into the SSC with an efficiency of up to 45%, which would represent a loss of more than a factor of two in beam intensity. To recover this intensity, a new injector is desirable. For light ions, the SSC can provide beam energies of up to ~40 MeV per nucleon while for isotopes in the mass range 80 to 130, such as the fission products, the SSC should be able to deliver beam energies of between 5 and 7 MeV per nucleon without severely limiting RIB intensities. It is expected that with a primary beam current of ~100μA, 10^{13} fissions/s can be created, giving rise to RIB intensities on target similar to those of the SPES proposal of Legnaro, shown in Figure 6 below.

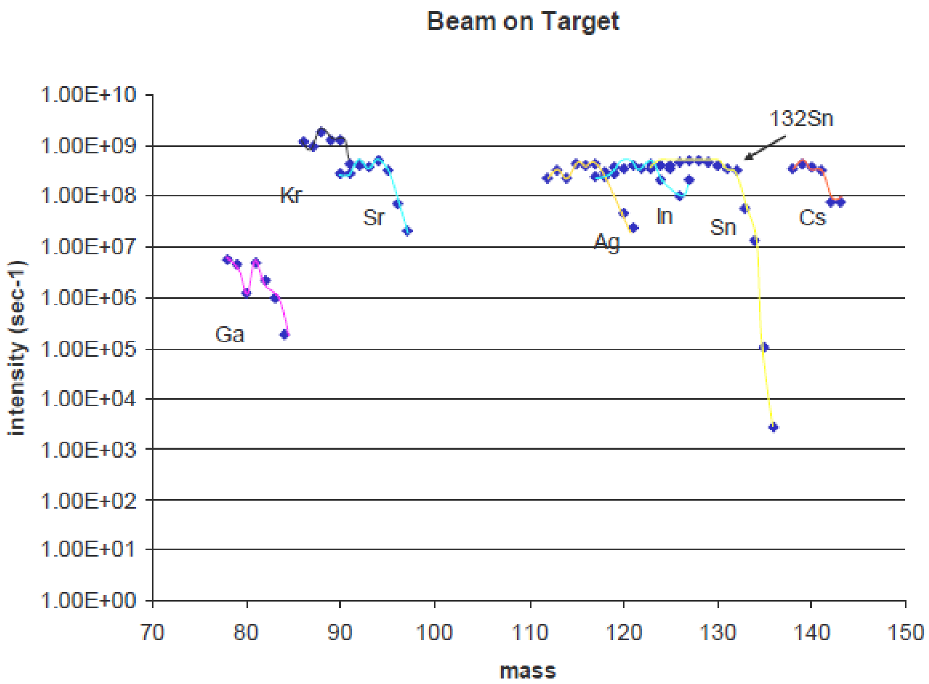

Figure 6. Calculated beam on target for the SPES proposal from Legnaro

Performance Characteristics of the New Accelerator

Beam intensities required for RIB production

Because radioactive ion beams are artificially produced, their intensities have generally been many orders of magnitude smaller than those of stable beams. The latest ISOL 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. As shown in Table 3, to make internationally competitive RIB intensities from the fission of U, the primary beam current should be at least 100 μA of 70 MeV protons, or about 7 kW. This will generate approximately 10^{13} fissions/s, similar to the SPES proposal of INFN Legnaro, Italy (8kW), and exceeded only by the SPIRAL II project at GANIL, France, which are expected to have 10^{13} and 10^{14} fissions/s, respectively.

Table 3 Beam intensities expected from international ISOL facilities.

Facility	*Beam Energy*	*Beam Current*	*Power on target*	*Fissions/s*	***^{132}Sn beam intensity (pps)***
HRIBF, USA	40 MeV	10 μA	0.4 kW	4×10^{11}	2×10^{5}
ISOLDE, CERN	1.0 –1.4 GeV	2 A	0.4 kW	4×10^{12}	10^{7}
TRIUMF	450 MeV	70 μA	17 kW		
HIE ISOLDE upgrade				4×10^{12}	2×10^{8}
HRIBF upgrade	54 MeV	20 μA	1.8 kW	10^{12}	5×10^{5}
SPIRAL II	40 MeV	5 mA	200 kW	10^{14}	2×10^{9}
SPES	40 MeV	200 μA	8 kW	10^{13}	3×10^{8}
iThemba LABS (Phase 2, proposed)	70 MeV	100 μA	7 kW	10^{13}	3×10^{8}
iThemba LABS (Phase 3, expansion)	70 MeV	500 μA	35 kW	5×10^{13}	1.5×10^{9}

To remain competitive, iThemba LABS should make provision for future enhancements for up to ~500 μA of proton beam. In effect, a provision should be made for a future “Phase 3”.

Required Isotope Production Beam Intensities

The present maximum proton beam intensity that can be employed on a single target, at 66 MeV, is ~ 250 μA. With beam splitting, the SSC presently can split a 350 μA beam in two, and direct the two beams onto two different targets. Therefore, the new cyclotron should be able deliver at least 250 μA and have additional current in reserve for future growth with a beam splitter.

Beams Required for Neutron Therapy

Currently, neutron therapy utilizes a 66 MeV proton beam from the SSC. The 66 MeV proton beam bombards a beryllium target in the neutron therapy gantry to produce the neutron beam for therapy. The intensity of the 66 MeV proton beam on the beryllium is between 25 to 35 μA. The existing gantry for neutron therapy is shown in Figure 6.

The shape of the neutron beam, or treatment field, which strikes the tumour is controlled by a multi-blade trimmer device. These trimmers should be replaced so that the treatment field can be adjusted *dynamically* to better conform to the tumour. This is known as Intensity Modulated Neutron Therapy (IMNT).

Figure 6 Neutron gantry at iThemba LABS

IMNT places additional demands on beam delivery. Beams of up to 100 μA would now be required. This beam must be “switched off” while the trimmers are re-configured for a different treatment field and then “switched on” again. The time specified to effect a switch-on is 100 ms while that for a switch-off is 1 ms. This could be achieved at the ion-source of the accelerator, but so doing would also interrupt RIB or isotope production. Therefore, a rather challenging fast gating of the high-energy beam is required.

Accelerator Specifications

The accelerator must be able to supply simultaneous proton beams of up to 70 MeV to meet the requirements of neutron therapy, isotope production and radioactive beam production, with a minimum total current of at least 450 μA, but ideally closer to 1 mA.

This requirement can be met, for example, by the negative-ion IBA C70 cyclotron, pictured below.

Figure 7 IBA C70 cyclotron

Its maximum total current is approximately 700 μA, delivered through two extraction ports. One port could be used for RIB production, the other for isotope production. The addition of a beam splitter could allow a part of the isotope beam to be split off for neutron therapy. In addition, since not all of the RIBs of interest can be created by the fissioning of uranium, a variable energy machine is desirable so that beams for (p,*x*n) reactions can be supplied. This can be realized in a negative-ion cyclotron by extracting the ion from the appropriate orbit.

Integration of the New Accelerator with the Existing Accelerator Complex

The main factors to be considered are for the integration of the new accelerator with the current accelerator complex are:

- The cost.

- The simultaneous operation of neutron therapy, isotope production, and physics programmes, with minimal interference on each other – servicing or setting up the new accelerator and its associated beam lines and end stations for neutron therapy and isotope production must not influence the operation of the SSC for the delivery of beams for physics and proton therapy, and vice-versa.
- The transmission of the radioactive beams – the new accelerator must not be placed too far away from the SSC in order to keep the transfer beam lines from the production target to the injector as short as possible.
- The location of the neutron therapy gantry – with the new cyclotron close to the injection accelerator, as motivated above, it will be extremely costly to integrate the new cyclotron with the current neutron therapy gantry without interfering with the operation of the SSC for physics experiments or proton therapy. Servicing components on the beam line from the new accelerator to the gantry would also cause an interruption of the beam delivery from the SSC. Moving the current gantry to a new dedicated vault for neutron therapy close to the new accelerator is the most cost effective solution, and has the advantage that it allows the simultaneous delivery of proton and neutron therapies.
- Isotope production and chemical separation and preparation of products – to increase production new bombardment vaults will be required. However, the present vaults would be retained as backup in exceptional circumstances. The existing pharmaceutical production facilities would be retained.
- New vaults would be required for experimental apparatus for materials research and nuclear physics.

Apparatus Required for Nuclear Physics at the New Facility

The latest experimental apparatus is essential to make best use of the new beams and beamtime provided by the new facility.

To exploit the additional beamtime provided by Phase I of the proposal, the laboratory proposes to upgrade the existing K600 spectrometer with a focal plane polarimeter. A radioactive beam ion-source test station is proposed in order to prototype technologies for Phase 2 production of radioactive ion-beams. This test station would be on a platform of approximately 100 kV, so radioactive beams provided by such a source wil be able to be implanted for material studies or be used to study the properties of neutron rich nuclei following β-decay.

Since even the most intense RIBs are expected to be at least an order of magnitude lower in intensity than presently used in stable beams, the efficiency of the detector systems must be improved to compensate. Already some of the first steps have been made within the physics group to begin to construct new detector systems required to exploit the radioactive beams of Phase 2. These steps include a new digital data acquisition system and a funded purchase of a gamma-ray tracking detector. For this phase, the group has identified the need for a minimum of eight gamma-ray tracking detectors and a Large Acceptance Spectrometer (LAS). Active targets and particle detector arrays will need to be developed to perform reactions in inverse kinematics.

Requirements for Material Science

It is vital that a special implantation chamber for material science experiments be constructed at the radioactive beam line. The chamber should provide: Ultra high vacuum capability of the order of 10^{-8} mbar or more; facility to do ion implantation of up to

10 samples at variable temperatures without breaking the vacuum; and should be fitted with a sputtering and annealing system which allow *in-situ* sample preparation before (cutting, cleaning, etching) and after implantation (thermal annealing, electrical contacts, etc).

Hyperfine techniques such as Mössbauer spectrometry (MS), Perturbed Angular Correlation (PAC) and Emission Channelling (EC) should be implemented as well. They all depend on the availability of radioactive isotopes with very specific decay properties.

Radio-tracer techniques which combine radioactive probe atoms with conventional semiconductor physics methods like Deep Level Transient Spectroscopy (DLTS), Capacitance Voltage measurements (CV), Hall-effect measurements or Photoluminescence Spectroscopy (PL) are also desirable in the same chamber or in an additional one.

The most useful recommended isotopes, from a list of about 100 in current use for this kind of research, are: ^{7}Be, ^{22}Na, ^{28}Mg, ^{31}Si, ^{38}Cl, ^{47}V, ^{42}K, ^{43}K, ^{65}Ni, ^{67}Cu, ^{67}Ga, ^{69}Ge, ^{71}As, ^{73}Ga, ^{110}Sn, ^{111}Ag, ^{113}Ag, ^{117}Cd, ^{119}Sb. Half-lives of these isotopes are in the range of hours which is most convenient for diffusion, defects evolution and structural studies.

New Bombardment Facilities for Radioisotope Production

The new bombardment facility for radioisotope production should be implemented in the following way:

- Vaults should be prepared for, but not immediately equipped with, target stations for an eventual 500μA of beam. At least three beamlines are envisioned.
- Irradiated batch targets should be transported to the existing hot-cell complex in a way similar to the Los Alamos Radioisotope Production Facility (using a target transporter).
- The new building and existing RPG building (D-Block) will be linked with two passages, one for personnel and one for the target transporter (i.e. an extension of the service passage).
- Isotopes produced in a semi-permanent target installation, such as ^{18}F and ^{18}F(FDG) should have their entire production moved to the buildings of the new facility. The new rooms may be shared with a ^{11}C production facility if sufficient space is allowed for such an expansion.

Taking account of the above requirements, a possible integration of the new facilities with the existing facilities is shown below. The new buildings are indicated within red ovals. The smaller area on the right encloses a new experimental area for nuclear physics. The larger oval encloses the bulk of the new facility. The new cyclotron is located near the centre of the oval, below it are the new neutron therapy and isotope production vaults while above it is the proposed RIB production facility.

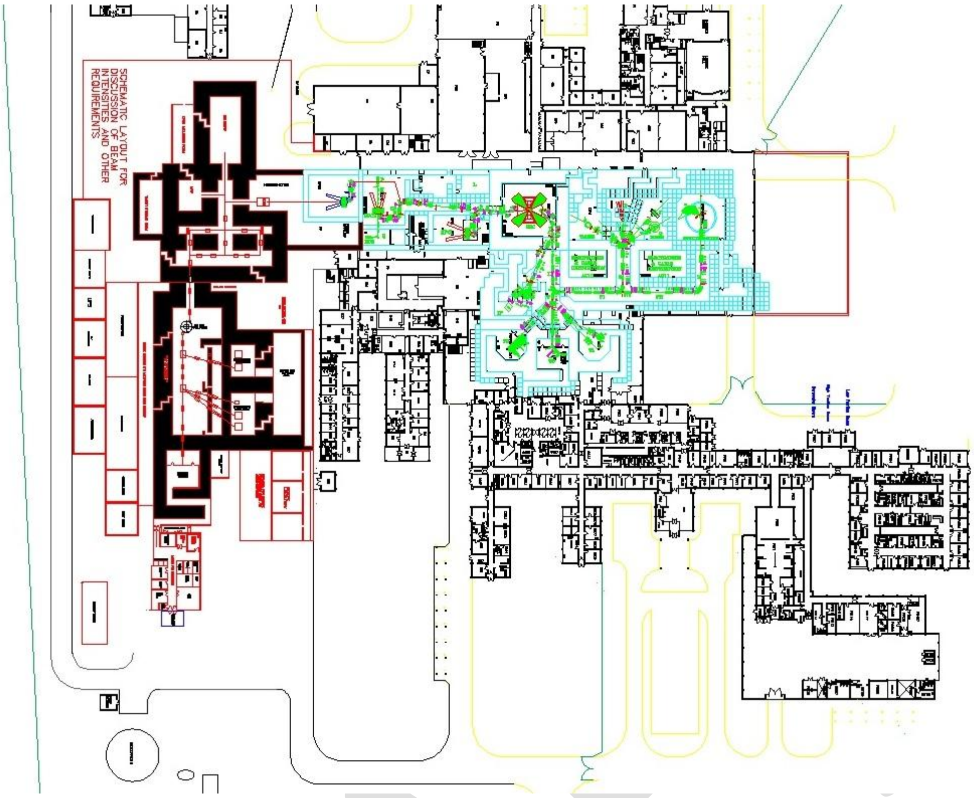

Figure 8. Integration of new accelerator complex (circled red) with the existing complex at iThemba LABS

COSTS, TIMELINES AND OUTCOMES

A suggested timeline, divided into phases, is given in Table 5. Phase 0 represents the initial feasibility study, and beginning of the design and funding process. The new accelerator, isotope production and neutron therapy facilities are installed in Phase 1, while the radioactive beam production facility is constructed in Phase 2. Phases 1 and 2 require approximately 4 years each. Research and development of the radioactive beam facility can continue during Phase 1.

Table 5 Approximate Timelines for RIB Project

TASKS	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	PHASE 0		PHASE 1				PHASE 2			
Feasibility Study	🟦	🟦	🟦							
LIS low energy beam development		🟦								
Construct Laser Ion Source			🟦							
Total Facility Proposal	🟦	🟦	🟦							
Design Process	🟦	🟦	🟦	🟦						
Approval Process	🟦	🟦	🟦	🟦	🟦					
Upgrade SSC		🟦	🟦							
Construct New Cyclotron		🟦	🟦							
Construct Isotope Production Facility			🟦	🟦	🟦	🟦				
24/7 SSC Physics Programme							🟦	🟦	🟦	🟦
Construction RIB Target/Beam Trans.							🟦	🟦	🟦	
RIB Physics										🟦

The estimated cost is strongly dependent on the overall scope of the proposal. A breakdown of major contributions to the cost is given in table 6. If all ideas were implemented, the total project cost could exceed R1.3 billion. However, this need not be the case. For example, the level of interest for IMNT in the medical community is untested; if a 50% lower intensity of radioactive beams is acceptable, a new injector would not be required; contingencies may also be reduced with a feasibility study; international collaborators may be interested in contributing to experimental facilities. Hence it is very possible that the total project cost could be reduced to below R1.0 billion.

The process of realizing all phases stretches over nearly a decade, implying an average annual funding of approximately R100M. These numbers must be regarded as extremely tentative and will not be known with precision until a feasibility study is completed. Estimates for Phase 2 presently rely on budgets for similar international facilities, such as the SPES proposal of INFN Legnaro, Italy.

Table 6 Estimated Costs of Project

PHASE I	Million Rands
IBA C70 accelerator	163
Isotope production vaults	180
Building and Shielding	74
Services	26
Beamlines & Power supplies	32
Neutron Therapy	200
Contingency	50
Sub-Total	725
PHASE 2	
RIB Target Vaults	54
Beam Transport to injector	86
Injector	100
Buildings & Infrastructure	20
Safety & Control	50
Contingency	50
Sub-Total	360
PHYSICS EXPERIMENTS (Phase 1 & 2)	
Active Target	10
Tracking Detectors	50
Large Acceptance Spectrometer	50
Polarimeter	32
New Experimental Area (heavy-ions)	70
Materials Research Experiments	30
Sub-Total	244
TOTAL	**1327**

After completion of the construction phases, additional support will be required to maintain and operate the facility. The running costs after Phase 1 of the project – principally incurred to by isotope production – should be met in part by isotope production revenues, while approximately R14M annually would be required for operation of the RIB facility (completed in Phase 2).

Technical Design and Feasibility Study

There are uncertainties in the costs involved in both phases of the project, particularly in the second. This is in part because the technology for producing radioactive beams is not mature and detailed design studies will be required to determine the best methods to create and transport the radioactive beams to the experimental target stations. In turn, new scientific apparatus must be designed to perform experiments with these beams.

Given the uncertainties in cost and the limited time available, a technical design study is therefore urgently required to address these issues.

It may even be possible to reduce the cost of the project after a feasibility study is completed. Estimated cost of the study is R15M chiefly over a two year period. It is expected that much of the design work can be carried out by students, but additional physicists will be required to provide expertise and guidance. Liaison will be extremely important with potential users groups and costs for travel and conferences are included.

Outcomes Summary

Proton Therapy

Up to 100 patients treated annually.

Neutron Therapy

Up to 110 patients treated annually.
Development of IMNT.

Isotope Production

Revenues of up to R75M annually.

Research and Human Resource Development

Thirty-two MSc and 16 PhD degrees in the design and construction phase.
Once operational, up to 40 MSc and 30 PhD degrees annually.

APPENDIX 1

Clinical Pathologies for Proton Therapy

Brain Tumors
- Acoustic neuronal (Schwannoma)
- Astrocytomas
- Chondrosarcomas
- Chordomas
- Ependymomas
- Gliomas
  - Brain stem gliomas
  - Gangliogliomas
  - Glioblastomas
- Meningiomas (benign, atypical and malignant)
- Pineal tumors
- Pituitary tumors
- Primative neuroectodermal tumors (PNET)
- Single metastatic sites
- Skull base tumors

Gastrointestinal Cancers*
- Carcinoma of the rectum
- Heptocelluar carcinoma
- Liver (primary and metastatic)

Head and Neck Tumors
- Chondrosarcomas
- Chordomas
- Nasal/Sinus tumors
  - Ethmoid sinus
  - Maxillary sinus
  - Nasopharyngeal carcinoma including recurrent lesions and retreatment
  - Paranasal sinus carcinoma
- Oropharyngeal/Parapharyngeal malignancies (select cases) *
- Salivary gland

Ophthalmological Tumors
- Malignant/benign tumors of the orbit
- Optic nerve gliomas
- Retinal tumors

Pediatric Tumors
- Astrocytomas
- Atypical Teratoid Rhaboid Tumors (ATRT)
- Craniopharyngioma
- Ependymoma
- Gliomas
  - Brain stem gliomas
  - Gangliogliomas
  - Glioblastomas
- Medulloblastomas boosts
- Neuroblastoma
- Pituitary tumors
- Primative neuroectodermal tumors (PNET)
- Retinoblastoma
- Rhabdomyosarcoma

- Sarcoma subtypes (select cases)

Prostate Cancer

- Initial treatment of localized prostate cancer
- Recurrent prostate cancer
- Patients with unilateral hip replacements

Spinal Cord and Paraspinal Tumors

- Chondrosarcomas
- Chordoma
- Ependymomas
- Nerve sheath lesions
- Paraspinal soft tissue malignancies
- Single metastatic sites
- Spindle cell sarcoma