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THE SOUTH AFRICAN ISOTOPE FACILITY

J. L. Conradie, L. S. Anthony, F. Azaiez, S. Baard, R. A. Bark, A. H. Barnard, P. Beukes, J. I. Broodryk, J. C. Cornell, J. G. De Villiers, H. Du Plessis, W. D. Duckitt, D. T. Fourie, P. G. Gardiner, M. E. Hogan, I. H. Kohler, J. J. Lawrie, C. Lussi, N. R. Mantengu, R. H. McAlister, J. P. Mira, K. V. Mjali, H. W. Mostert, C. Naidoo, F. Nemulodi, M. Sakildien, V. Spannenberg, G. F. Steyn, N. P. Stodart, R. W. Thomae, M. J. Van Niekerk, P. A. van Schalkwyk,
iThemba LABS, Somerset West, 7129, South Africa

Abstract

iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) has developed a strategy to respond to the need to expand the research agenda of the facility, as well as to seize the opportunity to exploit the growing global demand for radioisotopes. This strategy will depend on the existing accelerator and isotope-production infrastructure, as well as the acquisition of a cyclotron capable of accelerating protons to 70 MeV at beam currents in excess of 700 microamperes. This development will be approached in two phases: Phase 1 will include the migration of the existing radioisotope production from the separated-sector cyclotron (SSC) to a new 70 MeV cyclotron. This rearrangement will increase the isotope production capability and also free up the SSC for research. In Phase 2, beams of artificial isotopes will be produced at energies up to 5 MeV/nucleon to allow iThemba LABS to expand its research capabilities to new frontiers. The various different aspects of the proposed project will be discussed.

INTRODUCTION

iThemba LABS is a multi-disciplinary research centre, providing accelerator facilities for research and training in the physical, biomedical, and material sciences, production of radioisotopes and radiopharmaceuticals for use in nuclear medicine and also providing accelerator mass spectrometry services. The K=200 separated sector cyclotron (SSC) facility [1] has been in operation for more than 30 years. The facility operates two solid-pole injector cyclotrons, one for light ions and one for heavy ions and polarized protons, for the injection of beams into the K=200 SSC. The main applications of this facility over the past 30 years were isotope production, nuclear physics research, and neutron and proton therapy. Nuclear physics research is conducted over weekends, while the rest of the week is scheduled for the production of both short- and long-lived radioisotopes.

A decision was taken that iThemba LABS would not continue with proton and neutron therapy but rather assist the medical community to pursue a dedicated proton therapy centre for South Africa. With the progress in the dedicated proton therapy centres as well as the reduction of cost of these facilities (single treatment-room facilities) a dedicated facility for proton therapy at one of the large public hospitals will benefit the country much more than the therapy facilities at iThemba LABS. IThemba LABS can only provide limited services due to the restricted beam time available for therapy.

To increase the beam time for isotope production and nuclear physics research, the establishment of a facility currently known as the South African Isotope Facility (SAIF) is proposed, which will consist of two parts:

(i) The Accelerator Centre for Exotic Isotopes (ACE Isotopes) will be a dedicated facility for isotope production. A commercial high-current 70 MeV H^- cyclotron for the production of isotopes will free the SSC and allow an increase in beam time for nuclear physics research.

(ii) The Accelerator Centre for Exotic Beams (ACE Beams) will be a radioactive ion beam (RIB) facility for nuclear physics research. The SSC will be used as a driver for an isotope separation on-line (ISOL) facility. Up to 50 μA of a 66 MeV proton beam will be delivered by the SSC for producing radioactive beams from a target ion source. The first stage of this project will be a low-energy radioactive ion beam (LERIB) project without post acceleration. The second stage will be the post acceleration of the radioactive beams with a linear accelerator to energies of 4 to 5 MeV per nucleon.

EXISTING ISOTOPE PRODUCTION

The routine radioisotope production programme with the SSC started in 1988 at the horizontal beam target station (HBTS), producing short-lived radioisotopes. Towards the late 1990s, production methods for the long-lived radioisotope ^{22}Na were developed and commercialised. This was followed by the targetry development of ^{68}Ge, ^{73}As and ^{82}Sr. In 1996 a second target station was designed and built for the bombardment of semi-permanent targets. This initially included ^{18}F, but production was later transferred to a dedicated Siemens 11 MeV cyclotron. In 2006, the vertical beam target station (VBTS) was commissioned to exploit high-intensity proton beams delivered by the upgraded SSC. Target development focussed on the production of long-lived and high-value radioisotopes such as ^{22}Na, ^{68}Ge, and ^{82}Sr. The technology for bombarding tandem targets with a high-intensity beam was developed. When a beam splitter was commissioned it allowed the simultaneous bombardment of 4 targets.

These upgrades were all undertaken to increase production of long-lived radioisotopes to meet high market demand, but the options for further growth have now been exhausted. Growth can only be met by an increase in allocated beam time - which would come at the expense of other programmes - or by procuring a dedicated cyclotron for the production of radioisotopes. This last option will be implemented by the new ACE Isotopes facility.

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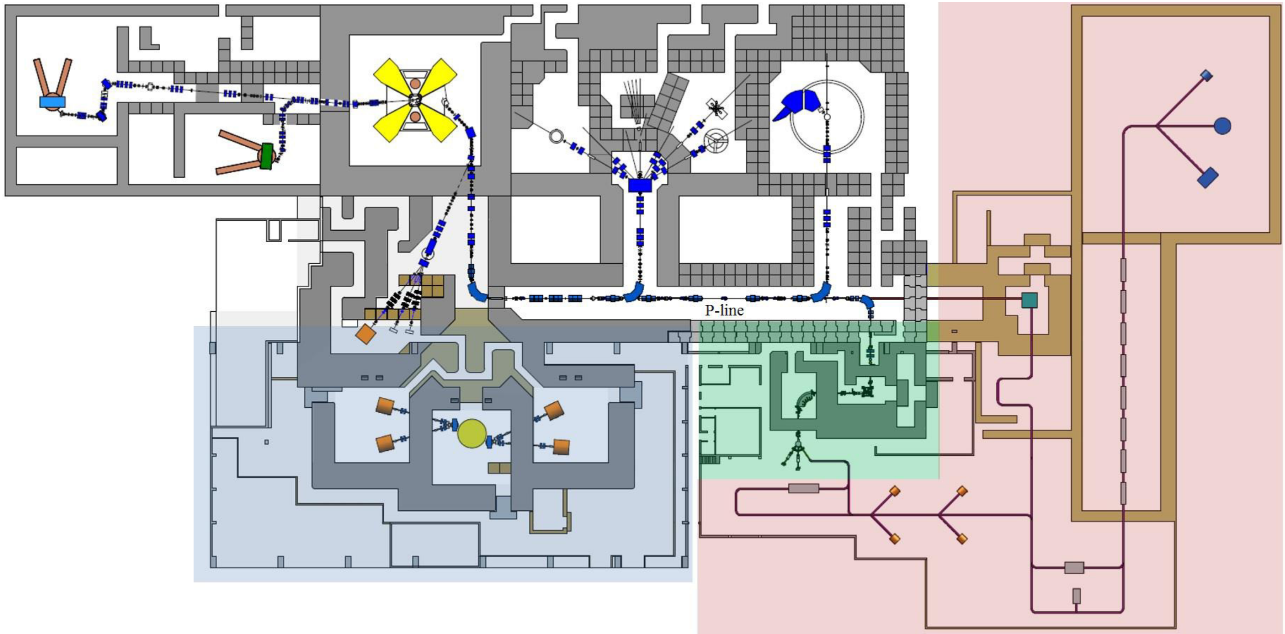

Figure 1: Layout of the main facility at iThemba LABS, with ACE Isotopes (shaded blue), LERIB (green), and the second phase of ACE Beams (pink).

ACE ISOTOPES

The new isotope production facility will make use of 3 concrete vaults previously occupied by the radiotherapy program, as shown in Fig. 1. The layout of ACE Isotopes is shown in Fig. 2: The cyclotron will be placed in the central vault, with target bombardment in the two side vaults. This ensures flexibility since the production vaults are independent of each other and production can continue in one while the other is used for maintenance.

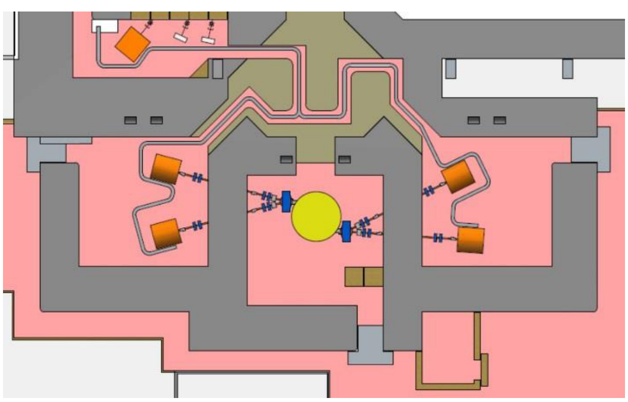

Figure 2: Layout of ACE Isotopes, showing the cyclotron vault (middle), production vaults (left and right) and the proposed target transport system.

Each production vault contains two isotope production stations. These stations are classified as either high intensity (350 μA) for bombardment of long lived isotopes, or low intensity (100 μA) for bombardment of short lived isotopes. To maintain uninterrupted production of batch targets, two high intensity stations (one per production vault) and one low intensity station will be required. The fourth station will be for experimental development work or a semi-permanent target.

The four beam lines all follow the same design: beam leaving a cyclotron's extraction port passes through a switching magnet, and then continues through a straight section of beam pipe to the target station. Sets of quadrupole doublets are to be used for focussing. A 'wobbler' system for sweeping the beam over the target surface is located after the last quadrupole. Diagnostic systems include profile grids for low-intensity beams and non-destructive capacitive beam position monitors for high intensity beams.

The targets will be transported to a processing hot-cell facility by means of a trolley moving on an automated rail system, accessing the vaults via a shielded labyrinth. The transport system and processing facilities will be largely based on the existing isotope production infrastructure at iThemba LABS.

The construction of ACE Isotopes is expected to take 4 years. The first 3 years will be spent on preparing the vaults for the arrival of the cyclotron, building of servicing infrastructure, upgrading the isotope production facilities and setting up the beam lines. The delivery of the cyclotron can be expected at the start of the 4^{th} year, followed by commissioning and initial production runs. The project cost is estimated at €40 000 000.

70 MeV Cyclotron

The new 70 MeV cyclotron must be capable of delivering 700 μA protons beams, split over two extraction ports. There are currently two commercially-available cyclotrons meeting these specifications: The BEST 70P cyclotron, and the IBA Cyclone 70 [2, 3].

Radiation Shielding

The main sources of neutron radiation include the cyclotron, where about 35 μA (estimated as a 5% loss of the 700 μA accelerated current) is stopped, on Faraday

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cups capable of stopping 50 µA each, and shielded target stations where a maximum of 350 µA will be stopped. FLUKA calculations, supported by analytic estimates based on published fitting parameters, are being performed to determine the shielding requirements.

The exterior walls of the vaults are currently 3.5 m thick which calculations show to be adequate. The roof of the cyclotron requires 4 layers of 0.75 m thick removable roof beams, while the production vaults require 3 layers. Personnel entrance to the vaults will be via removable 'concrete-plug' doors, running along rails on the floor. They are stepped to prevent radiation from passing through the gap between the doors and the walls. Access for pipes and cables is via a set of holes drilled diagonally through the exterior wall into the partially shielded vault basement. Calculations indicate that holes of up to 120 mm in diameter can be used when they slope upwards at angles around 45°. Neutron shutters located in the cyclotron vault can be used for isolating a production vault from the cyclotron vault, enabling maintenance to take place in one production vault while bombardment continues in the other vaults.

Restricted areas at iThemba LABS are classified as blue (less than 200 µSv/h) or red (above 200 µSv/h), and an administrative limit of 200 µSv per entry is imposed on all radiation workers. The layout of the red area in ACE Isotopes has been chosen so that it is contiguous, and movement within the area never requires having to leave it. There are two entrances to the red area, leading to blue regions with decontamination facilities and monitoring equipment.

Radioisotope Production Target Stations

The transfer of the radioisotope production programme from the SSC to ACE Isotopes will take several years. The existing target stations will continue to receive beam from the SSC while the new target stations are being built and commissioned.

Currently, the transfer of batch targets between the two target stations (HBTS and VBTS [4]) and the processing hot-cell complex is by means of a Telelift rail system [5]. This system will be expanded to the two new production vaults, while also replacing the existing rails and modernising the transporter control system.

The design of the new batch-target stations, shown in Fig. 3 is now in an advanced stage. The three planned stations will be identical in all respects except for the entrance collimator aperture, which will be smaller in the low-intensity station. The local radiation shield will consist of complementary shielding materials, namely an inner iron shield, followed by borated paraffin wax as a middle layer, followed by an outer lead shield. Monte Carlo radiation transport simulations provided the optimal layer thicknesses in order to achieve a dose attenuation factor of 3 orders of magnitude. The new stations will all be fitted with a target magazine that can hold three target holders, which constitutes a significant simplification to the current HBTS magazine that can hold nine target holders.

A new tandem Rb/Ga prototype target has recently been assembled and pressure-tested. It will allow for about a 20% higher flow-rate at the same differential pressure as the existing VBTS targets. While the current target-capsule outer diameter is 40 mm, similar to VBTS targets, provision is made for increasing the diameter of future target capsules up to 52 mm. This will enable an increase in beam current from the current maximum of 250 µA to more than 300 µA.

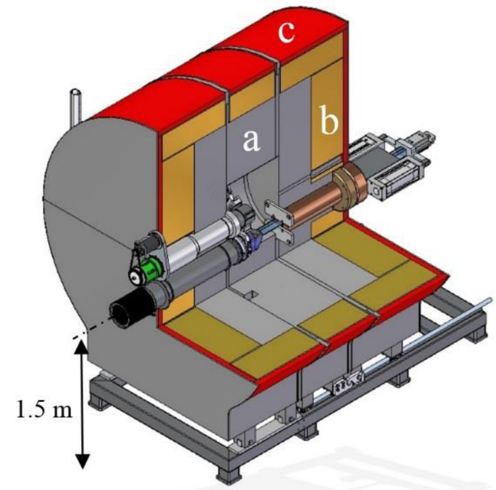

Figure 3: Cutaway view of the production station, with the beamline (left) and cooling-water pusher arm (right). The shielding consists of (a) an inner iron layer, (b) borated paraffin wax and (c) an outer lead shield.

Radioisotopes

The planned SAIF radioisotopes are listed in Table 1.

Table 1: Radioisotope Production at ACE Isotopes

Radioisotope	Main Application
^{67}Ga	Localisation of certain tumour regions and inflammatory regions
^{123}I	Thyroid studies. Localisation of certain tumours such as neuroblastomas
^{68}Ge/^{68}Ga	Typically used for localisation of neuroendocrine tumours
^{82}Sr	Used as a ^{82}Sr/^{82}Rb generator for heart studies
^{22}Na	Used for positron annihilation studies

ACE BEAMS

Many beams desired for research consist of atoms that do not exist naturally and must be artificially created. At the planned ACE Beams facility such radioactive-ion beams (RIBs) will be produced using the Isotope-Separation-On-Line (ISOL) method, pioneered at the ISOLDE facility at CERN.

LERIB

A RIB test facility at iThemba LABS, presently under construction, will be upgraded to become LERIB, the main ISOL bombardment target/ion-source for ACE Beams. LERIB, shown in Fig. 1, is centred on a collaboration between iThemba LABS and INFN Legnaro. Good progress has been made with the design and layout of the dedicated LERIB facility. At present work is continuing on the detailed design of the LERIB building, with special attention being given to target handling, cooling systems, radiation safety and future expansions.

Target Ion Source

The LERIB target/ion-source (TIS) comprises a target assembly and a hot-cavity ion source constructed on a high-voltage platform. The TIS or "front-end" is identical to that of the SPES project [6]. An off-line RIB Test Facility (shown in Fig. 4) is being constructed to serve as a test-bench for LERIB. The test-bench comprises a complete front-end and beam line incorporating an analyser magnet. The test-bench will be used to do all future development work and experimentation with ionisation techniques, and also on beam extraction and transport utilising stable beams. The test-bench will also be used to set up and test new target chamber assemblies before installation on the LERIB system. A robotic system that is based on a custom design mounted on an automated guided vehicle will also be developed to manipulate the target chambers in the high-radiation areas of the LERIB facility.

Figure 4: The LERIB test-bench contains a target/ion-source (foreground) on a high-voltage platform, and a beam line with an analysing magnet (background).

A CAD model of a multi-foil target system was developed by scientists of the Legnaro Institute in Italy. Thermal finite-element analysis was used to provide theoretical results of the heat dissipation of an array of SiC disks. To validate the CAD model, an online test was performed at iThemba LABS during 2014 [7]. The target assembly, consisting of 13 thin SiC disks housed in a graphite container, was bombarded with a 60 µA, 66 MeV proton beam. Since test results compared very favourably with the theoretical results, the CAD model could be validated.

Physics Beam Line

To deliver the 66 MeV proton beam from the SSC to the LERIB facility, the physics beam line (P-line) must be extended. A 90° bending magnet will be added at the end of the P-line that will bend the beam into the LERIB facility. The high-intensity 50 µA beam has a higher energy spread than ordinary beams along the P-line. The two 90° magnetic bends in the P-line produce significant dispersion if the bending magnets are operated in double-focusing mode. However, the dispersion after the first bending magnet can be limited by focussing the beam in the centre of the bending magnet. The second bending magnet can then be used to completely cancel out and remove the dispersion. At the end of the P-line a quadrupole doublet focusses the beam on the UC_x targets housed in the LERIB front end. A beam sweeper located after this doublet will sweep the beam in a circular motion on the target assembly, maximising interaction of the proton beam with the UC_x targets, and controlling the heat distribution on the disks.

Low-Energy Beam Line

The front end will be operated at 40 kV to produce low-energy RIBs that will be transported to a large mass-analyser magnet with a resolving power of 2700. The analysed beams will be transported to any one of three end stations by means of an electrostatic switcher. Experimental stations include Beta-decay tape stations that are presently under construction and will be equipped with clover detectors, $LaBr_3$:Ce detectors for fast timing, and an electron spectrometer for conversion electron spectroscopy.

POST ACCELERATION

Because LERIB will use the SSC as the driver accelerator, ACE Beams will require a new post-accelerator to produce beams with sufficient energy to induce nuclear reactions, in the second phase of the ACE Beams project. This is expected to be a linear accelerator in order to optimize transport efficiency. Prior to injection into the LINAC, beams from LERIB will be cooled with an RFQ cooler, mass-selected with a high-resolution mass-separator, and charge-bred for post-acceleration. Post-accelerated energies will initially be approximately 5 MeV/A.

CONCLUSION

The ACE Isotopes and ACE Beams projects are well under way and should result in a dedicated radioisotope production facility, as well as freeing up the SSC to focus on scientific research, including a new RIB programme.

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