A RADIOACTIVE ION BEAM AND ISOTOPE PRODUCTION FACILITY FOR ITHEMBA LABS

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Abstract

iThemba LABS is a multidisciplinary research facility that provides accelerator-based facilities for physical, biomedical and material sciences, treatment of cancer patients with neutrons and protons and the production of radioisotopes and radiopharmaceuticals. The demand for beam time by the 3 main users, namely radioisotope production, nuclear physics research and medical applications, exceeds the available time by far.

During the past 3 years a feasibility study for a new radioactive ion beam and radioisotope production facility at iThemba LABS has been in progress. A dedicated isotope production facility is proposed which will free up the existing K=200 separated-sector cyclotron facility for nuclear physics research with stable beams. A facility for the production of low-energy radioactive ion beams is planned using the K=200 cyclotron as driver for the production of radioactive beams. A technical overview of the proposed isotope production and radioactive-ion beam facility will be given.

INTRODUCTION

iThemba LABS, located at Faure near Cape Town, operates a number of accelerators of which the Separated-Sector Cyclotron (SSC) is the largest. The SSC, a variable-energy machine, is extremely versatile and capable of producing high-intensity proton beams, a large variety of heavy ions and polarized protons at energies sufficient to probe the structure of sub-atomic matter. The SSC is primarily shared by three disciplines: nuclear physics research, proton/neutron therapy – along with radiation biology research – and radioisotope production. Over the past number of years it has become increasingly evident that the current beam allocation schedule is counterproductive and cannot satisfy the high demand for beam time from both research disciplines and radioisotope production.

The usual mode of operation is that nuclear physics research is conducted over weekends, while the rest of the week is scheduled for radiotherapy and the production of both short- and long-lived radioisotopes. iThemba LABS uses a 66 MeV proton beam from the SSC with currents of up to 250 μA to produce radioisotopes. The available beam time for radioisotope production is essentially fixed due to the current schedule and in order to expand the isotope production capacity, it became necessary to introduce a number of innovations. These include the installation of flat-topping systems for the injector cyclotron (SPC1) and the SSC, a new vertical-beam target station and beam-splitting. For operation with higher beam currents it also became essential to develop and implement non-destructive beam diagnostic equipment. Since, under present operating conditions, any further increase in the beam time for radioisotope production can only be achieved at the expense of one or more of the other programmes, it has now become essential to acquire a dedicated cyclotron for radioisotope production.

The long-term research strategy for the SSC includes the study of neutron-rich nuclei, which is rapidly becoming the focus of international research in order to understand how the elements were formed in astrophysical environments such as stars and supernovae. A forerunner to the long-term strategy is the already partially funded Low-Energy Rare Isotope Beam (LERIB) project, which aims at understanding the astrophysical processes that led to element formation. LERIB will make use of a high intensity 66 MeV proton beam from the SSC to produce different neutron-rich species. For the second phase it is envisaged that low-energy RIBs (<50 keV) will be accelerated to high energies, using a post accelerator.

The various projects will be carried out in phases. Phase 1 will involve the installation of a dedicated 70 MeV H-minus cyclotron for radioisotope production and the LERIB project. During Phase 2, a post-accelerator capable of accelerating radioactive beams from the LERIB project to an initial energy of ~ 5 MeV per nucleon will be installed.

RECENT INFRASTRUCTURE UPGRADE

Cooling Towers and Chillers Upgrade

The facility relies on a central cooling plant comprising four water-cooled chillers, seven cooling towers and associated pumps to supply chilled water at 6 °C with a cooling capacity of 4.4 MW. Chillers are operated in parallel and switched on demand as the heat load increases. During 2011 the cooling towers were replaced. Subsequently funds have been approved to replace the chillers and pumps this year. The new equipment will not only be more reliable, but will also offer a sustainable

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energy saving due to the high Coefficient of Performance (COP) of the modern technology chiller units.

4 MVA Uninterruptable Power Supply Battery Replacement

A total of 4 banks, each consisting of 264 X BAE 25 OGI 2000 batteries, were installed. The new installation of low-antimony alloy, vented lead-acid batteries has a lifespan of 20 years. The capacity of the installation is designed to keep the accelerator facilities operational for 20 minutes at full load.

New Digital Low-Level RF Control System

A new digital low-level RF (DLLRF) control system to replace the 30-year-old analogue RF control systems has successfully been developed. The system [1] shown in Fig. 1 is field-programmable-gate-array (FPGA) based and is capable of synthesizing RF signals between 5 MHz and 100 MHz in steps of 1 μHz. It can achieve a closed-loop amplitude stability of better than 1/10000 and a closed-loop phase stability of less than 0.01°. Six of the systems are currently in operation on the two injector cyclotrons. In total, 35 production systems have been manufactured and installation will be completed during the coming months.

Figure 1: The new digital, low-level RF control system.

THE RADIOISOTOPE PRODUCTION FACILITY

To increase beam time for research and to the production capacity of radioisotopes, a dedicated production facility is proposed. Full use will be made of existing building infrastructure to establish an independent radioisotope production facility. A commercial 70 MeV H-minus cyclotron will be installed in the current underutilised neutron therapy vault, while the proton therapy vault and a third redundant vault will house a number of isotope production target stations (see Fig. 2). Repurposing of existing building infrastructure makes this configuration the least complex and potentially realises significant savings from an investment and future maintenance point of view. The existing radioisotope production facilities will provide increased opportunities for research regarding new radioisotopes and will also be available as an emergency backup for the new facilities. With this proposal, beams from the 70 MeV cyclotron could also service all the nuclear physics vaults as well as the target ion source of the LERIB project. An additional vault can be added next to the current proton therapy vault for dedicated radiation biology research. This approach is preferred, because of the cost saving aspect and the versatility of delivering beams to a large number of different end users and it also does not preclude neutron and proton therapy research from continuing. The department concerned is currently drafting long-range plans to support the continuation of the research, closely linked to radiation biology and radioisotopes research.

The proposed timeline realises the completion of Phase 1 in four years, i.e. three years to build the cyclotron and the fourth year for installation, testing, commissioning and ramping up of the beam intensities to the required levels for routine radioisotope production and research.

70 MeV H-Minus Cyclotron

The 70 MeV cyclotron will be procured from a commercial manufacturer. The cyclotron will have a dual beam delivery system with beam current up to 350 μA on each delivery port. Preliminary studies and discussions with two manufacturers have shown that it will be possible to fit the cyclotron from either manufacturer into the neutron therapy vault, as shown in Fig. 2. Detail information regarding the two commercially available cyclotrons can be found in references [2, 3]. Procurement will be done by means of a tender process that will request the 70 MeV cyclotron to be supplied inclusive of the switching magnets at the two extraction ports. Determining factors for a successful bid will include aspects like the maximum beam current delivery per extraction port, beam loss in the cyclotron and beamlines, ease of maintenance/service of cyclotron and final cost.

The components required for the beamlines that will deliver the beams to the four target stations will be designed and manufactured by iThemba LABS.

Radionuclide Production Target Stations

The design of the bombardment stations for radionuclide production with 70 MeV proton beams of high intensity will be similar (but not identical) to the existing horizontal-beam target station ("Elephant") that has been in routine operation at iThemba LABS for 26 years [4]. The targets will be irradiated outside the beamline vacuum, surrounded by a composite radiation shield during bombardment (see Fig. 3). A helium-cooled, double-foil Havar window will serve to isolate the vacuum from the station. A four-sector graphite collimator located in the radiation shield immediately upstream of the double-foil window will assist with the beam focusing and centering, by providing current read-out on each sector. The beam will be swept in a circular mode around the beam axis in order to spread the thermal load over a larger surface area of the target. An electro-pneumatically controlled pusher arm will connect the cooling water to a target holder.

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All target stations will be serviced by an electrically-driven target transport trolley which moves on rails, connecting the irradiation vaults to a hot-cell complex, target loading facility and a target store. The transfer of target holders to and from a target station and the transport trolley will be facilitated by means of a remote-controlled robot arm. Each target station will be electrically isolated from earth and the beam transport infrastructure in order to permit accurate measurement of the beam current and accumulated charge. Each target station will therefore act as a faraday cup.

Development of new targetry, compatible with a 70 MeV proton beam and intensities up to 350 µA, has commenced. An optimized tandem target for the simultaneous production of 82Sr and 68Ge will consist of a stainless-steel (S316) encapsulated Rb disc in the high-energy slot and a Nb-encapsulated Ga disc in the low-energy slot. The relevant energy windows of the Rb and Ga target materials will be 61.8 – 37.7 MeV and 24.8 – 0 MeV, respectively. The "dead layers" in the target are due to the encapsulation materials, cooling water layers and the beam entrance window located on the target holder: such dead layers are unavoidable.

The evaluation of the local radiation shield has recently been performed by means of Monte Carlo simulations with the code FLUKA [5]. The cylindrical geometry of a target station and the off-centre location of the target holder were modelled accurately, as shown in Fig. 3. Also, the tandem target described above was accurately modelled, including the cooling-water. Fig. 4 shows the results of a neutron fluence scan when a 70 MeV proton beam of 350 µA is incident on the target. The origin was defined as the center of the beam spot on the front face of the target, the z-axis along the beam direction, a vertical y-axis and a horizontal x-axis. The scan shown in Fig. 4 is along the positive x-axis. A similar plot is shown with the local radiation shield omitted. The vertical dashed lines indicate the intersection of the shielding material boundaries and the x-axis. It is clear that at the location of the outer surface of the target station, the neutron fluence is between 2 and 3 orders of magnitude lower than what would be the case if the shielding is omitted. Inside the station, the presence of the shield leads to a build-up of the neutron fluence. Most of the attenuation and absorption occurs in the paraffin wax layer (20 cm thick, containing 4% B4C by weight). This hydrogenous layer, however, is only effective for thermalizing neutrons entering with relatively low energies (below about 4 MeV) and finally capturing more than 99% of them. This is why a 50 cm thick inner Fe layer is required. The Fe layer effectively slows down fast neutrons to intermediate energies by inelastic scattering. The outer Pb layer mainly serves to attenuate gamma-rays, in particular the 2.2 MeV photons emitted in the capture of thermal neutrons by hydrogen. The total thickness of the local radiation shield is largely dictated by the available space, while the optimum thicknesses of the three complementary shielding materials have been determined by means of Monte Carlo simulations.

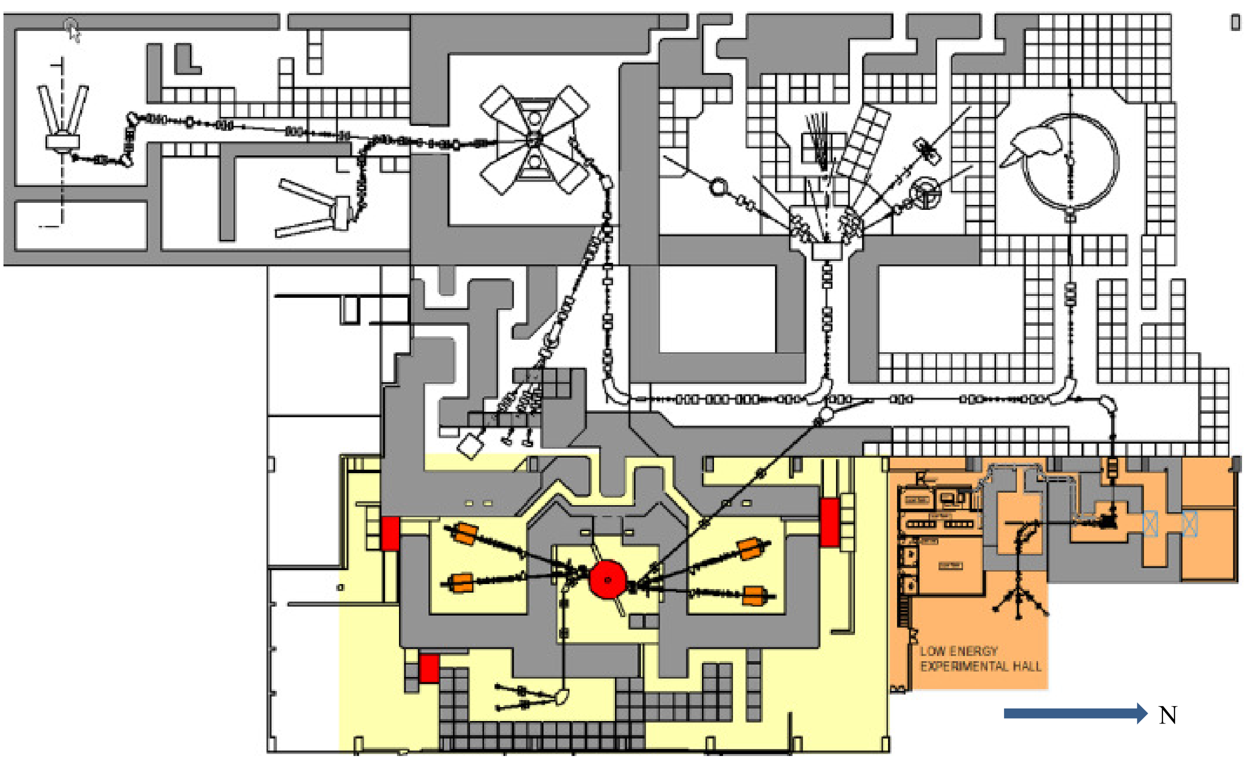

Figure 2: Layout of the new cyclotron and radioisotope production facilities utilising the existing and redundant therapy vaults shown on yellow background. The 70 MeV cyclotron is shown in red and the 4 target stations are shown in brown. The LERIB facility in relation to the existing infrastructure is shown on the brown background.

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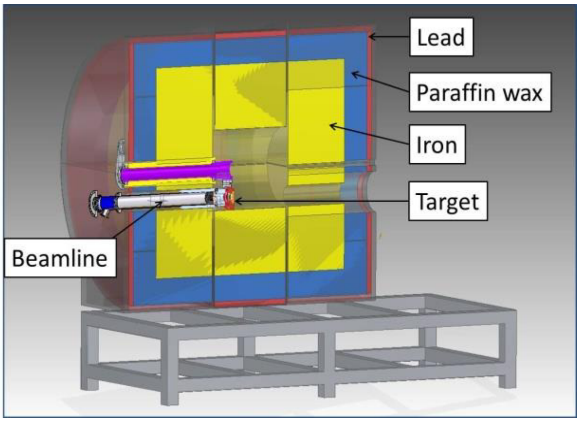

Figure 3: A vertical section along the beam axis through the local radiation shield of the target station.

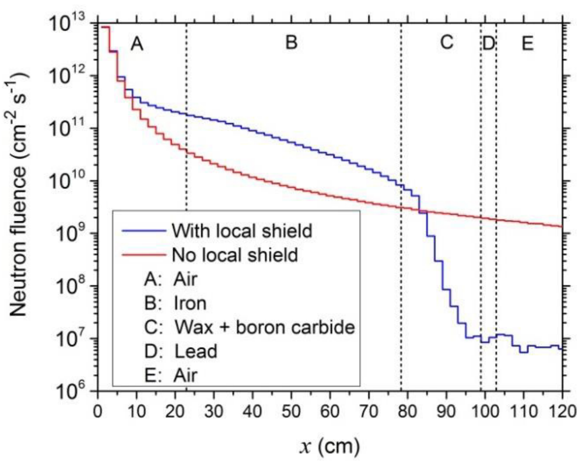

Figure 4: Neutron fluence scan, performed with the FLUKA code, along the x-axis (see text) through the target station for the case of an incident 70 MeV proton beam of 350 µA intensity on a tandem Rb/Ga target.

Shielding/Radiation Safety

To accommodate the cyclotron, beamlines and target stations, extensive modifications have to be made to the shielding of therapy vaults. To enlarge the vaults parts, mainly corner sections, of the vault walls will have to be modified. Because the planned beam intensities are much higher and the beam directions will be different, additional shielding, in the form of large blocks, will have to be attached to some walls. For the same reasons the existing labyrinths, for access of staff and equipment, will no longer provide sufficient shielding and they also partly block the installation route for the cyclotron. Some of the existing blocks will be rearranged to form a new, much narrower, labyrinth for the cyclotron vault. For the two production vaults lack of space does not allow the use of labyrinths and a combination of movable doors and blocks is planned. An essential requirement is provision for transport of the targets from the four target stations through labyrinths to the existing radioisotope production vault.

The existing air-conditioning equipment and ducts in the shielding walls will be used. The installed cooling capacity allows nine air changes per hour. In the existing radioisotope production vault the air is changed six times per hour. The only modification required is installation of HEPA filters and extraction fans in the air outlets from the vaults.

A radiation and equipment safety-interlocking system will monitor the status of vaults, doors, faraday cups, neutron shutters, radiation monitors and power supplies to prevent unsafe conditions and interrupt the beam in case of equipment failure.

Tentatively, the maximum permitted dose rate in areas where radiation workers will regularly work has been specified as 2.5 µSv/h. In less accessible regions, such as on top of the roof beams, at a height 7 m and more, a dose rate of 15 µSv/h is considered acceptable.

It is foreseen that during the early stages of operation, beam currents of several tens of micro-amperes will be stopped on copper faraday cups to optimize the cyclotron and beamline settings. In the cyclotron vault, it will sometimes be necessary to insert faraday cups in the beamlines from both ports. Because of the low beam losses in the cyclotron and its self-shielding characteristics, radiation from the faraday cups will be the determining factor for the shielding dimensions.

The present design of the new shielding layout, taking into account access for services, equipment and personnel, is based on reports about the design of the existing facilities [6, 7, 8, 9] and more recent data [10, 11], as well as on radiation dose rate measurements at iThemba LABS. Scaling and interpolation of the data, as well as calculations, led to the present design.

To verify that the calculations are not too crude, measurements of the dose rates were made, using a 10 µA, 66 MeV proton beam on faraday cups in vaults with different roof beam dimensions. The results were compared with calculations based on the graphs and table of Chen et al. [11], from which the neutron source term and attenuation lengths in concrete were determined. For comparison with results in the literature it is important to note the differences in concrete densities that are used.

Neutron dose rates of 21 µSv/h and 0.6 µSv/h per µA were measured for 1.5 m and 2 m thick roof beams, respectively, for a beam height of 1.5 m and a roof height of 3 m, below the concrete beams, which have a density of 2.35 g/cc. The copper thickness of the faraday cup and its support from the beam position to the top is 5 cm. The wall thickness of the stainless steel vacuum chamber is 3 mm.

For the cyclotron vault, 4 layers of roof beams with a total thickness of 3 m are planned. For the production vaults three layers with a total thickness of 2.25 m will be sufficient. The foundations of the vault basements consist of an 800 mm thick layer of concrete which can be increased to a total thickness of 2 m to limit ground water activation. Finally, Monte Carlo simulations will be done to determine whether the objectives have been met and if significant savings can be made by reducing the number of roof beams and simplifying the labyrinth of the cyclotron vault. The maximum permitted dose rates and beam currents that will be stopped on the faraday cups have to be reconsidered and finally specified.

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LOW-ENERGY RARE ISOTOPE BEAM FACILITY

To enhance and supplement existing research platforms and to stay globally competitive through the promotion of new research opportunities in the field of nuclear physics, iThemba LABS initiated a flagship project to establish a Rare Isotope Beam (RIB) facility. Specific areas of interest include the study of neutron-rich nuclei, which is only achievable by way of the production and analysis of RIBs.

A Strategic Research Infrastructure Grant from the National Research Foundation (NRF) had been approved to fund a pilot project for the construction of a Low-Energy RIB (LERIB) facility. The facility will be used to develop and refine the techniques for RIB production and analysis. Knowledge, experience and equipment gained through this endeavour will be carried forward into a full-fledged RIB facility that will include beam cooling, high-resolution mass separation, charge-breeding and post-acceleration.

The LERIB facility and infrastructure will be housed in a new building as illustrated in Fig. 2. The new building will be strategically placed to allow the SSC to be used as a driver to deliver high intensity 66 MeV proton beams to the LERIB test facility. The location of the new building is such that future expansion to the north of the current accelerator complex will be possible. A number of end-stations for low-energy (<50 keV) experiments will be provided. The isotope of interest will be transported to the end-stations after passing through magnetic mass separator with a mass resolution of 1 in 3000.

Target Ion Source

A formal collaboration agreement between the NRF and the Instituto Nazionale di Fisica Nucleare (INFN) in Legnaro, Italy had been signed in February 2015. As part of the collaboration a replica of the fully developed Front End containing the Target Ion Source (TIS) which had been developed by Laboratori Nazionali di Legnaro (LNL) in Legnaro, Italy for their SPES project, has been constructed for iThemba LABS. The TIS exploits the Isotope Separation On-line (ISOL) method of producing neutron-rich radioactive ions and will form the basis of the proposed LERIB test facility at iThemba LABS.

The required characteristics of the ISOL target are both a high fission production yield and the capability to release the fission products as fast as possible. The most critical element of the TIS unit is the Multi-Foil Direct Target. The target configuration consists of several thin disks suitably spaced in the axial direction in order to improve the cooling of the UCx target by thermal radiation and to avoid large temperature differences with respect to the graphite box containing the target discs. The open structure of the target assembly also promotes the quick release of fission products. The advantage of this configuration is the simplicity of the cooling system and the consequent relatively low cost.

To guarantee an efficient RIB production rate the TIS target has to work at elevated temperature levels up to 2200°C. The proton beam power is not sufficient to heat the graphite box and the target discs in a uniform temperature profile. Therefore it was crucial to introduce an additional and independent electrical heating system.

Neutral atoms diffuse from the target assembly into the hot-cavity surface ionizer via a transfer tube. The surface ionization mechanism produces mainly singly charged particles that are accelerated up to 50 keV by the extraction electrode assembly. Accelerated particles then enter the low-energy beam transport system for transportation via a mass separator to the low-energy experimental areas.

During 2014 an online test had been performed at iThemba LABS [12] to validate the theoretical results of the thermal finite element simulations of the multi-foil target system. A 60 µA, 66 MeV proton beam from the SSC was stopped on the target assembly comprising 13 thin silicon carbide discs housed in a graphite container. The test results confirmed that the power dissipation capability of the multi-foil target system is suitable for ISOL-RIB production.

REFERENCES

[1] W. D. Duckitt, et al., “A new Digital Low-Level RF Control System for Cyclotrons”, Cyclotrons’16, Zurich, Switzerland, Sep. 2016, this conference
[2] F. Poirier, et al., “Studies and Upgrades on the C70 Cyclotron Arronax”, Cyclotrons’16, Zurich, Switzerland, Sep. 2016, TUD02.
[3] V. Sabaiduc, et al., “BEST 70P Cyclotron Commissioning at INFN LN Legnaro”, Cyclotrons’16, Zurich, Switzerland, Sep. 2016, TUD04.
[4] G.F. Steyn et al., Nucl. Instrum. Meth. A 727 (2013) 131.
[5] A. Ferrari et al., FLUKA: a multi-particle transport code, (CERN-2005-10, INFN/TC_05/11, 2005)
[6] J.C. Cornell, “Shielding Walls“, NAC-SH 77-1 internal report (1977).
[7] J.C. Cornell, “Labyrinth Design“, NAC-SH-78-2 internal report (1978).
[8] J.C. Cornell, “Neutron Therapy Vault“, NAC-SH-78-3 internal report (1978).
[9] J.C. Cornell, “Neutron Shutters“, NAC-SH 82-1 internal report (1982).
[10] L. Sarchiapone and D. Zafiropoulos, “Radiation Protection Aspects of the SPES Project at LNL”, LNL Technical Design Report, Chapter 10, 2008.
[11] C.C. Chen et al., “Calculations of Neutron Shielding Data for 10-100 MeV Proton Accelerators”, Radiation Protection Dosimetry, Volume 116, No. 1-4, 2005, p. 245.
[12] A Monetti et al., “On-line test using multi-foil SiC target at iThemba LABS”, Eur. Phys. J. A (2016) 52: 168.

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