PROGRESS WITH A NEW RADIOISOTOPE PRODUCTION FACILITY AND CONSTRUCTION OF RADIOACTIVE BEAM FACILITY AT iTHEMBA LABS

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Abstract

With the termination of the neutron and proton therapy programs at iThemba LABS, the use of the Separated Sector Cyclotron (SSC) has now shifted to nuclear physics research with both stable and radioactive ion beams, as well as biomedical research. A dedicated isotope production facility with a commercial 70 MeV H-minus cyclotron has been approved and both the cyclotron and isotope production target stations will be housed in the vaults that were previously used for the therapy programs. The status of this new facility will be reported. In the future the SSC will mostly be used for nuclear physics research, as well as the production of isotopes that cannot be produced with the 70 MeV H-minus cyclotron. At present the production of the α-emitting radionuclide Astatine (^{211}At) with a 28 MeV alpha beam is being investigated. Progress with the construction of a facility for production of radioactive beams will be discussed. There will also be reports on development work on the ECR ion sources and progress with implementation of an EPICS control system.

DEDICATED 70 MeV CYCLOTRON FOR ISOTOPE PRODUCTION

The initial idea to simultaneously produce radioisotopes and radioactive ion beams with a dedicated 70 MeV H-minus cyclotron was discarded due to a number of reasons as explained in [1]. A feasibility study has shown that a very cost effective, dedicated isotope production facility can be constructed at iThemba LABS by making use of the existing infrastructure, which became available when iThemba LABS discontinued proton and neutron therapy. The layout of the proposed facility is shown in Fig. 1. There will be two isotope production vaults (Fig. 1, vaults A and B) with two bombardment stations in each. The 70 MeV H-minus cyclotron will be housed in a separate vault (Fig. 1, vault C) located between the two isotope production vaults. The irradiated targets will be transported via a rail transport system, through new labyrinths that will be connected to existing labyrinths, to the existing hot cells. Detailed FLUKA calculations have been done for the different vaults and labyrinths to ensure that all the radiation safety requirements will be met.

With a dedicated isotope production facility available, the bulk production of isotopes with the SSC will end. In future the SSC will then mainly be used for nuclear physics research and the development of new radioisotopes that cannot be produced with the dedicated isotope production facility, such as the alpha emitter ^{211}At.

Following approval of the project by the Board of the National Research Foundation, a contract for the manufacturing, delivery and installation of the 70 MeV cyclotron and associated beamlines has recently been signed after an open tender process. The 70 MeV H-minus cyclotron is capable of delivering two 375 µA beams simultaneously from two extraction ports placed 180 degrees apart. The consulting engineers for the design, development and construction of the required infrastructure have also been appointed. The infrastructure of the 70 MeV project will be completely separated from the infrastructure of the existing SSC facility to ensure that the new facility can operate independently from the SSC facility.

The time schedule for completion of this project is 3 years. The cyclotron and beamlines will be delivered within 2 years after contract signature. During this time, the infrastructure and the modifications to the 3 vaults will be completed and the 4 target stations will be designed, built and installed. Commissioning of the new equipment will take place during the third year.

ISOTOPE PRODUCTION TARGET STATIONS

The current plan is to build four new target stations that will receive beam from the 70 MeV cyclotron. They will be similar in design to the existing horizontal-beam target station (HBTS or Elephant) at iThemba LABS, but with thicker local radiation shields and several other smaller modifications and improvements. These target stations will be identical in all respects except for the aperture of the entrance collimator, which can have different sizes on different stations. During bombardment, a target will be completely surrounded by a composite radiation shield, consisting of an inner iron layer, a borated paraffin wax middle layer and a lead outer layer. This local shielding will reduce the neutron flux into the vault by about three orders of magnitude and reduce the thickness of the concrete shielding required for the vault significantly. More details on the station design can be found in [2]. Target transfer between a station and an electric rail transport system will be facilitated by a robot arm. All target handing, including the connection of cooling water, will be done by remote control.

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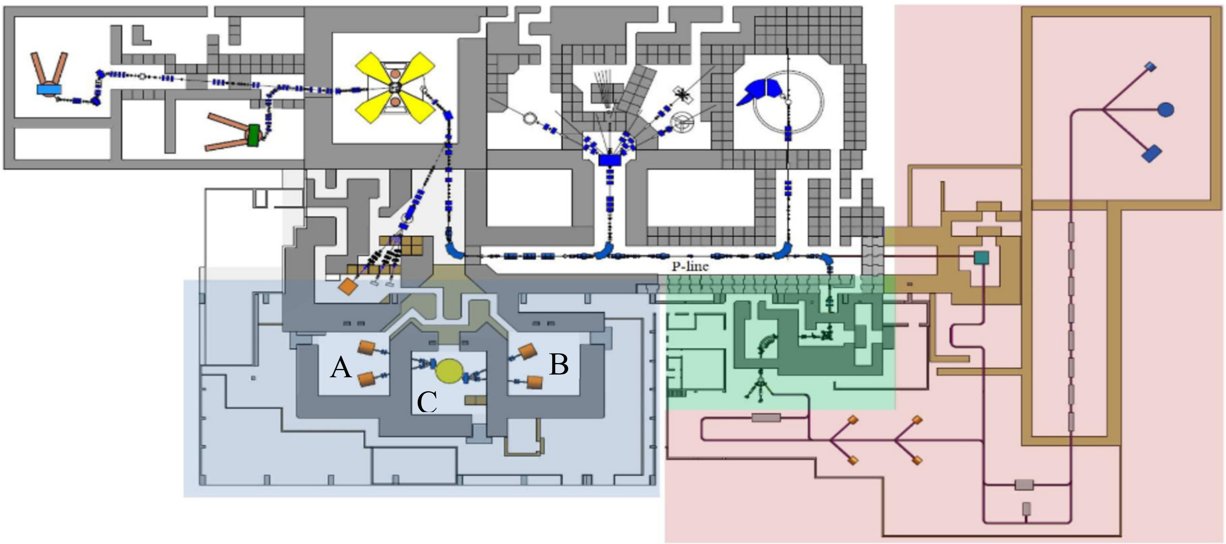

Figure 1: Layout of the main facility at iThemba LABS, with the new 70 MeV isotope production facility shaded in blue, the LERIB facility shaded in green and the second phase of the rare-isotope facility shaded in pink.

While target capsules with inner diameter sizes up to 52 mm have been foreseen for the future, it was not clear whether such large targets should be introduced from the outset. Currently, the largest target diameter of batch targets for radionuclide production in use by iThemba LABS is 40 mm, employing 66 MeV proton beams from the SSC with intensities up to 250 µA in the vertical-beam target station (VBTS). The decision was recently made to introduce the larger diameter of 52 mm from the outset with the new targetry for the long-lived radionuclides ^{22}Na, ^{68}Ge and ^{82}Sr on the 70 MeV cyclotron. This will increase the available target surface area in contact with cooling water, enabling an increase in beam intensity that a target can withstand. The thickness of individual cooling water layers will also be increased by 50% (from nominally 1 mm to 1.5 mm). This requires the volume flow rate of cooling water to be nearly double than currently being employed on the VBTS. Changes made to the cooling-water pusher arm and target holder will allow a flow rate of 250 l/min at a differential pressure of less than 10 bar. The new target holders will be very similar in design to the ones currently in use at iThemba LABS but upscaled to accommodate the bigger targets and increased flow rate.

PRODUCTION OF THE ALPHA EMITTER ASTATINE-211

The design of a dedicated target station for the production of the alpha emitter ^{211}At has recently been completed at iThemba LABS and construction is expected to start in due course. Targets consisting of a layer of Bi plated onto a water-cooled Al backing will be bombarded with a 28 MeV alpha-particle beam delivered by the SSC. A beam intensity up to 50 µA is anticipated. The targets will have a slant angle of 9° with respect to the beam axis to reduce the dissipated power density resulting from stopping the alpha particles within the Bi layer. The ^{209}Bi(α,2n)^{211}At reaction will be employed. The beam energy of 28 MeV is the maximum that can be employed as the ^{209}Bi(α,3n)^{210}At→^{210}Po reaction becomes significant above this energy. Since ^{210}Po is both long-lived and poisonous, its co-production has to be avoided. An agreement has recently been reached with the Department of Nuclear Medicine of the University of Pretoria, who will use the ^{211}At produced at iThemba LABS for targeted alpha-particle therapy (TAT).

RARE-ISOTOPES AT ITHEMBA LABS

Once the routine radionuclide production has been moved to the 70 MeV cyclotron, the SSC will be largely dedicated to research. To explore new frontiers in the field of nuclear physics, iThemba LABS has embarked on a project to establish a Low-Energy Rare-Isotope Beam (LERIB) facility, indicated in Fig. 1. The project will use the Isotope Separation On-Line (ISOL) method to produce radioactive isotopes of special interest in, for example, the study of neutron-rich nuclei involved in the r-process.

The project is proceeding in phases. Following a Memorandum of Agreement between the NRF and the Istituto Nazionale di Fisica Nucleare (INFN), a “front-end” Target/Ion Source (TIS) has been manufactured and delivered to iThemba LABS. It is being incorporated into an offline test facility as seen in Fig. 2. The TIS in the foreground, HV platform, extraction beamline complete with analysing magnet in the background is nearing completion and will be commissioned during the last quarter of 2019.

A complete EPICS-based control system is under development and will control all elements of the TIS, as well as the beamline components. With this test bench only stable beams will be produced by means of an oven technique and will be used to measure beam emittance from the TIS front end, ionisation yields of the surface ion source and efficiency of the extraction system. Provision is also made for experimenting with plasma and resonant laser ionisation techniques.

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Figure 2: The LERIB test-bench contains a target/ion source (foreground) on a high-voltage platform, and a beamline with an analysing magnet (background).

The next phase will see the construction of an on-line test facility, "LERIB Phase 0", over the next two to three years. RIBs will be produced through the bombardment of boron- and silicon carbide targets with a 1 µA, 66 MeV proton beam from the SSC. It will still be largely dedicated to the development of new RIB production techniques, such as the Versatile Arc Discharge Laser Ion Source (VADLIS) [3] and the use of carbonyl molecules to ionise refractory elements.

The construction of LERIB Phase 1 will follow, and will be capable of accommodating 66 MeV proton beams of up to 50 µA from the SSC. Uranium carbide targets will be fissioned in the TIS to produce neutron-rich ions of up to 60 keV energy. The facility will include a heavily shielded bombardment station, long term storage for spent targets, dedicated laboratories for target manufacture and later disposal, and an experimental hall.

The next step beyond LERIB, Phase 2 (see Fig. 1), will be to post-accelerate the low-energy RIBs to high-energies, sufficient to initiate nuclear reactions. Because LERIB will use the SSC as the driver accelerator, a new post-accelerator will be required. The requirement of high beam transport efficiency and beam purity leads to a system needing an RFQ beam cooler and high-resolution mass separator to refine the LERIB beams. Next, they will be charge bred for post-acceleration in one of two ion sources, i.e. an ECRIS or an EBIS. The post-accelerator is envisaged to be a LINAC in order to optimize transport efficiency. Post-accelerated energies will initially be approximately 5 MeV/A.

ECR ION SOURCE DEVELOPMENT

The two electron cyclotron resonance (ECR) ion sources at iThemba LABS can be operated simultaneously, i.e. the required beam for cyclotron acceleration is delivered from one source, while the second source can be used for beam development. ECRIS4, which was originally built by GANIL for the Helmholtz-Zentrum Berlin [4] delivers ion beams from gases and fluids. In addition, the source was equipped with an injection system for the so-called Metal Ions from Volatile Compound (MIVOC) method [5]. Due to the request for nuclear physics experiments with metallic ions of isotopes with low natural abundance, a program to produce metallocene from enriched elements was developed resulting in, for example, ion beam intensities of 30 eµA of $^{62}\mathrm{Ni}^{8+}$ [6]. A second ECRIS (GTS2) that is based on the design of the Grenoble Test Source [7] is used to supply beams for nuclear physics experiments, which require elements like ^{1,2}H, ^{3,4}He, ^{12}C, ^{14}N, ^{16,18}O, ^{20,22}Ne, ^{36,40}Ar, ^{86}Kr and ^{129,132,136}Xe. In addition, under our collaboration with the ion source group of the Flerov Laboratory of Nuclear Reactions at the Joint Institute of Nuclear Research in Dubna, experiments for the production of intense metallic ion beams by oven technique were performed. With a modified micro oven [8] stable beams of Li, Mg, Ca and Bi with intensities of tens of µA were produced and are available for new fields of nuclear physics experiments at iThemba LABS [9].

NEW DIGITAL LOW-LEVEL RF CONTROL SYSTEM

iThemba LABS has successfully designed and implemented a new broadband digital low-level RF control system for cyclotrons that operates over a wide frequency range of 2-100 MHz and can achieve peak-peak amplitude and phase stabilities of 0.01% and 0.01°, respectively [10, 11, 12]. The systems have been successfully integrated at iThemba LABS into the K=8 and K=10 injector cyclotrons (SPC1 and SPC2), the K=200 separated sector cyclotron (SSC), the SSC flat-topping system, the pulse-selector system and three RF bunchers (AX, J and K-lines). In total there are 13 RF control systems now in full time operation since July 2017 [11, 12].

The systems have led to a substantial improvement in the beam quality of the SSC with a reduction in beam losses by more than 90% at high current intensities when 66 MeV proton beams are produced for isotope production [11]. The reduction in losses results in less activation of the extraction components.

Furthermore, the integration with EPICS and EtherCAT [12, 13] based actuator and motion control has resulted in a highly adaptable and easily implementable system at other facilities.

Not only have all the RF control systems at iThemba LABS been efficiently upgraded, but as a further indicator of the success of the system, ease of implementation and adaptability, the system was also installed and commissioned on the Helmholtz-Zentrum K=132 separated sector cyclotron in Berlin during April 2017 [14], contributing to the highly successful patient treatment program, as well as the execution of physics experiments.

EPICS AND ETHERCAT

iThemba LABS has made significant progress in migrating its distributed control system to EPICS [15, 16], a process made difficult by the need to support and upgrade 30-year-old legacy electronic systems. The adoption of EtherCAT [1, 10, 13] as the new industrial fieldbus has greatly simplified the migration process. The RF control systems upgrade project pioneered the way for the adoption of EtherCAT and EPICS templates that were created to implement several other projects such as the

UPS monitoring system, water leak monitoring system, the Tandetron motion control, actuator and beamline control system, RF power amplifier automation, radiation protection and radiation monitoring systems.

The operator's displays used at iThemba LABS have evolved from MEDM [16] and QT displays to the industry standard in CSS. The need to keep up with modern trends in software prompted iThemba LABS to develop a modern React based progressive web app base front end [17]. This software, which is called React Automation Studio, is currently being used as a front end for the beam diagnostics system and the new LERIB Test Bench [13, 17]. We foresee many exciting times ahead with the React Automation Studio and will be open sourcing the framework for the greater EPICS community.

CONCLUSIONS

To stay relevant in an ever-evolving nuclear physics research environment, iThemba LABS reviewed its current capabilities and devised a number of new strategies to develop a long-range plan as a road map for moving into the future. The dedicated isotope production facility comprising a commercial 70 MeV H-minus cyclotron and beamlines to four target bombardment stations has been approved and will be implemented over the next 3 to 4 years. New targetry and bombardment stations are being developed to handle the higher intensity 70 MeV proton beams ranging up to 375 µA per target. Once radionuclide production has been moved to the 70 MeV cyclotron facility, the SSC will be largely dedicated to research. iThemba LABS has also embarked on a project to establish a Low-Energy Rare-Isotope Beam (LERIB) facility, of which an offline test facility is nearing completion. Later phases will establish a fully developed low-energy RIB facility including post acceleration. The design of a dedicated target station for the production of the alpha emitter ^{211}At has recently been completed and construction is expected to start soon. The introduction of 13 in-house developed variable frequency, low-level RF control systems has improved operational stability and reduced beam losses, and therefore extraction component activation, by more than 90%. iThemba LABS has made significant progress in migrating the distributed control system to the open source EPICS platform. The adoption of EtherCAT as the new industrial fieldbus has greatly simplified the migration process and opened more avenues for future control system developments.

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