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Nuclear Physics News

ISSN: 1061-9127 (Print) 1931-7336 (Online) Journal homepage: https://www.tandfonline.com/loi/gnpn20

iThemba LABS

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To cite this article: Faïçal Azaiez, Rudolph Nchodu, Rudzani Nemutudi & Mathis Wiedeking (2020) iThemba LABS, Nuclear Physics News, 30:4, 5-11, DOI: 10.1080/10619127.2020.1832807

To link to this article: https://doi.org/10.1080/10619127.2020.1832807

Published online: 30 Dec 2020.

iThemba LABS

iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) is the largest multidisciplinary national research facility in South Africa and the largest accelerator facility in the southern hemisphere. With a permanent staff complement of approximately 270 members, 15 post-docs and 90 M.Sc. and Ph.D. students, the facility's operational infrastructure is sited at two campuses, with the main site in Cape Town and the other in Johannesburg. The research programs of the Accelerator Mass Spectrometry (AMS) group are undertaken using the 6MV Tandem accelerator, while those of the Material Research group are generally carried out with the aid of both the 3MV Tandetron and the 6MV Tandem accelerators. The Radioisotope, Radiation Biophysics, and Subatomic Physics research groups primarily rely on the $K = 200$ Separated Sector Cyclotron (SSC) accelerator for their research programs.

It is important to highlight that iThemba LABS is not a conventional facility when compared to other facilities of similar size across the world. With the recent history of South Africa, the landscape for research and technical skills is still in a developing phase, and the mission of iThemba LABS has education and training as one of its main areas of focus in addition to creating a unique research environment. Catering, as it does, to training of postgraduate students and young research scientists from both South Africa and the rest of the African continent, iThemba LABS presents a truly unique, cosmopolitan, and multicultural research environment. One of iThemba LABS' current objective challenges is to develop sufficient local scientific and technical leadership, which is representative of the country's diversity and gender balance, taking into consideration the socioeconomic realities, which are ever-prevalent. Notable progress has been made in providing state-of-the art research equipment to the scientific community over the last decade. These include the refurbishment and commissioning of the Tandem accelerator, the establishment of AMS capabilities in 2017, and the replacement of the Van de Graaff with a new Tandetron accelerator in 2017.

In the first 30 years of its operation, the beam time from the SSC was equally divided between research, particle therapy, and supplying the medical sector with radioisotopes, an aspect that severely limited the competitiveness of each of the three activities and to a larger extent the nuclear physics research program. Through the ambitious Long-Range Plan iThemba LABS elaborated in 2017, the nuclear physics research program and nuclear medicine activities are now set to greatly benefit from the South African Isotope Facility (SAIF) project when the laboratory commissions the 70 MeV cyclotron for radioisotope production and research. Once in operation, the new cyclotron will free the SSC beams that will subsequently be dedicated to basic and applied nuclear physics and radiation biology research.

Subatomic Physics research will continue to play a major part at iThemba LABS. The research programs will focus on niche areas where iThemba LABS will complement the research carried out at cognate laboratories around the world. The research infrastructure has been or is in progress to be significantly improved. Human resources will be supplemented to enable the laboratory to deliver on its core mandate of research, education, and training.

The research topic of Subatomic Physics at iThemba LABS can be broadly classified into Nuclear Reaction, Nuclear Structure, Nuclear Astrophysics, Hadron, Particle, and Applied Nuclear Physics. Hadron and Particle Physics research are primarily conducted at the European Centre for Nuclear Research (CERN) within the A Large Ion Collider Experiment (ALICE) and A Toroidal LHC ApparatuS (ATLAS) collaborations.

We will now briefly review the AMS, Nuclear Medicine, and Material Research before primarily focusing on the Subatomic Physics research facilities.

Accelerator Mass Spectrometry

The AMS facility at iThemba LABS (Figure 1) is the only AMS facility on the African continent and provides a platform for rare isotope measurements, such as ^{14}C, ^{26}Al, and ^{10}Be, which are all used in age-dating in different contexts. Commissioned in 2017, the iThemba LABS AMS has been providing a little more than 1,000 dates per year, a notable achievement in contrast to similar facilities sited elsewhere in the world. The impact of an AMS facility on palaeoscience in South Africa is profound, as more dates allow for fundamentally better science based on reliable data. The high-resolution dating of sites like Waterfall Bluff, and paleoclimate records such as the Baobab tree climate records, were just not possible before the AMS facility was commissioned.

Materials Research

iThemba LABS conducts materials research for applications in information technology (IT), electronics, air pollution, energy efficiency, water purification, thin films coating, and so on. To this end, we make use of the various facilities at the Materials Research Department and at the Tandem

Figure 1. *6MV Tandem accelerator (background) and the new bending magnet followed by the electrostatic analyzer of the AMS facility (foreground).*

and Accelerator Mass Spectrometry (TAMS) Department for synthesis, modification, and analysis of thin films and nanostructured materials using Ion Beam Analysis (IBA) techniques. Instrumentation for materials research at iThemba LABS includes, among others, the state-of-the-art 3 MV Tandetron (Figure 2) and 6 MV Tandem accelerators and two nuclear microprobe facilities at both accelerators.

Nuclear Medicine

The goals of the Nuclear Medicine Department at iThemba LABS are to conduct world-class radiobiology research related to hadron therapy as well as research and development (R&D) on new pharmaceutical radioisotopes.

iThemba LABS was one of the first facilities in the world to develop and operate a proton therapy facility. In the past, the therapy program relied on the radiobiology research program on site and to date our Radiation Biophysics division remains one of the few in the world that conducts research on a dedicated beam-line and biology laboratory that is relevant to particle therapy. The expertise developed at iThemba LABS is unique, and there is a need for such programs in the world to support clinical research. It is worth pointing out that the proton and neutron therapy program, which used vaults historically built for this activity, was phased out in 2017. This was dictated primarily by the lack of patients for which oncologists would recommend particle therapy in the country.

The radiobiology division conducts research leading to a better understanding of the biological effects of different particle radiation types, energies, and radiopharmaceutical compounds, and to serve the broader community by offering bio dosimetry follow-ups.

The Radioisotope division develops methods to produce high-grade radionuclides with a 66 MeV proton beam with 200 μA to produce short-lived radiopharmaceuticals for nuclear medicine in South Africa and longer-lived radionuclides for international supply. The radioisotope division also uses proton beams from the 11 MeV cyclotron, shown in Figure 3, for the production of the radioisotope ^{18}F for supplying local nuclear medicine facilities for imaging purposes. iThemba LABS still remains the only facility in South Africa that can produce certain accelerator-based short-lived isotopes such as ^{123}I and ^{67}Ga to service the medical community.

Two R&D projects on novel radioisotopes for medicine are being pursued, which are the (1) alpha-particle-emitting radioisotopes and (2) theranostic radioisotopes.

Subatomic Physics Facilities

The unique possibilities of combining research equipment to perform cutting-edge measurements have been realized and several major experimental capabilities have been or are in the process of being implemented.

Fast Neutron Beams

One of the main niche facilities at iThemba LABS is the availability of quasi-monoenergetic neutrons with ener-

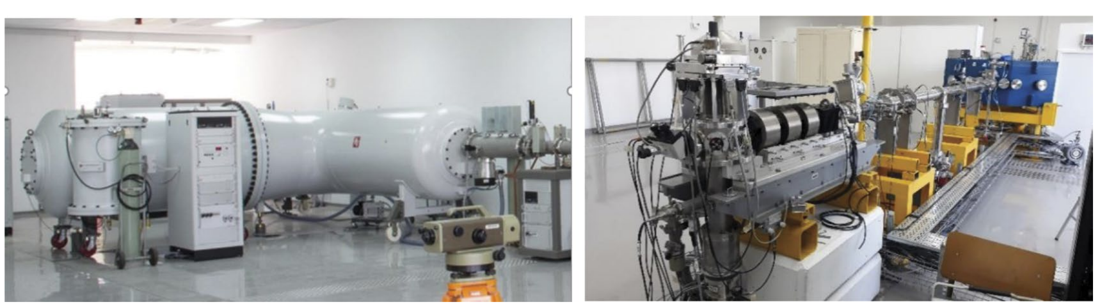

Figure 2. *The newly installed 3MV Tandetron accelerator (left) and its microprobe setup (right).*

Figure 3. *11 MeV cyclotron dedicated to ^{18}F production (left) and hot cells for chemical processing of radio-pharmaceutical isotopes produced with high-intensity 66 MeV protons from the SSC (right).*

gies between 30 and 200 MeV, which are typically produced by the $^{7}Li(p,n)^{7}Be$ or $^{9}Be(p,n)^{9}B$ reactions. Even at high currents and 200 MeV, excellent beam quality can be achieved and a nanosecond-pulsed beam can be delivered, making a background-free interval between pulses possible. The time between beam pulses at 200 MeV is 33 ns, but can be increased to 230 ns by only transmitting one in seven pulses. At 120 MeV, using a 10 mm thick Be target, a quasi-monoenergetic neutron flux of 6.5 x 10^4 n cm^{-2} s^{-1} is obtained at 0° and 5 m downstream of the target.

During 2019, major reconstruction took place to refurbish the neutron vault to meet the requirements for a high-energy neutron metrology and research facility by reducing neutron backgrounds even further. The refurbishment project included additional shielding, improved beam diagnostics, optimized beam stops, a new target system, and an extended flightpath at 16°. The available flight paths now extend from 5 to 11 m at 0° and 5 to 13 m at 16°.

Gamma-Ray Detection Systems

A wide range of γ-ray detectors is available at iThemba LABS. These include background-shielded single-crystal high-purity germanium (HPGe) detectors for activation or environmental radiation studies, a segmented Clover detector, eight HPGe low-energy photon detectors (LEPS), eight fast-timing 2” x 2” $LaBr_3$:Ce detectors, and the AFRican Omnipurpose Detector for Innovative Techniques and Experiments (AFRODITE) and the **A**frican **LaBr**$_3$:Ce **A**rray (ALBA) detector arrays, which will be described in more detail below. Depending on user needs, the γ-ray detectors can be combined with a range of ancillary detectors, which include:

1. the refurbished Siegbahn-Kleinheinz electron spectrometer from Orsay and commissioned at iThemba LABS in 2018;
2. the β-decay tape station, also commissioned in 2018, with a single-spool design and 50 m of 12 mm wide mylar tape;
3. S1-, S3-, or W-type silicon detectors, ranging in thicknesses from 140 µm to 1,000 µm;
4. CsI charged-particle detectors;
5. recoil detectors; and
6. neutron detectors with time-of-flight discrimination of neutron-reaction channels.

AFRODITE is a γ-ray detector array of Compton suppressed HPGe Clover detectors that consisted of nine detectors until recently, when iThemba LABS embarked to expand the detection capabilities significantly. The upgrade of the nine-detector array saw a doubling in the number of detectors, which will greatly improve on possible high-resolution measurements. The completion of AFRODITE was fully funded by the National Research Foundation (NRF), with some of the funds secured through the Gamka consortium of the five South African institutes: iThemba LABS, University of the Witwatersrand, University of the Western Cape, University of Zululand, and Stellenbosch University.

ALBA consists of a total of 21 high-efficiency large-volume (89 x 203 mm) $LaBr_3$:Ce detectors. Coupling these detectors to other particle detection devices and/or combining them with AFRODITE provides a unique and powerful combination. ALBA’s efficiencies are calculated to be ~19% and ~5% at typical target-detector distances for γ-ray energies of 1 and 10 MeV, respectively. This will provide a significant increase in efficiency for new and cutting-edge research that is not feasible with Clover detectors alone. The ALBA array is fully funded by the NRF, both through its national facility iThemba LABS and the afore-mentioned Gamka consortium.

K = 600 Magnetic Spectrometer

The K = 600 magnetic spectrometer, schematically shown in Figure 4, is a high-resolution kinematically corrected magnetic spectrometer for light ions. It has the capability to measure inelastically scattered particles and reactions at extreme forward angles that includes 0°, making it one of only two facilities worldwide (the other being at the Research Center for Nuclear Physics, Japan), where high-energy resolution is combined with 0° measurements at medium beam energies. The advantage of such measurements lies in the selectivity to excitations with low-angular momentum transfer.

The K = 600 consists of five active elements—a quadrupole, two dipoles, and two trim coils—and is based on the design of the former K = 600 magnetic spectrometer at the Indiana University Cyclotron Facility. The average flight path for a particle from the target to the focal plane detector is approximately 8 m. The focal-plane detector is positioned behind the second dipole, and consists of position sensitive multiwire drift chambers and a pair of plastic scintillation detectors. By employing dispersion matching techniques an energy resolution of 30 keV FWHM can be achieved at 200 MeV for (p,p') reactions.

A new scattering chamber was designed and manufactured to accommodate the **C**oincidence **A**rray for **K** = 600 **E**xperiments (CAKE). CAKE consists of five wedge-shaped double-sided silicon strip detectors, placed in a lampshade configuration upstream from the target ladder (Figure 5). It enables coincidence spectroscopy of charged-particle decays following inelastic scattering and transfer reactions detected by the focal-plane detectors of the K = 600.

Coincident γ-ray detection capability was recently added to the K = 600 repertoire through the installation of a frame that allows for interchangeable configurations of up to 30 γ-ray detectors, including AFRODITE, ALBA, and fast-timing detectors (Figure 5). The efficiency and granularity of the new setup, and also the fact that K = 600 measurements can be performed at zero degrees, all combine to make this setup a unique experimental tool.

Nuclear Physics at the Tandetron and Tandem Accelerators

While the majority of subatomic physics research is performed at the SSC, the Tandetron accelerator provides additional opportunities with its low-energy and high-intensity beams, be it for testing purposes of components or studies of sub-barrier (p,γ) and (α,γ) reactions utilizing ALBA and/or AFRODITE detectors. The Tandetron was installed with two multicusp sources for H- and He-negative ions with current thresholds of ~1mA before the low-energy magnet, and ~200 μA post-acceleration. A new beam-line, dedicated to studies of low-energy nuclear reactions, is in progress of being built. The 6 MV Tandem at the TAMS department already has available a dedicated beam-line for low-energy nuclear reaction and spectroscopic studies.

Low-Background Counting Facility

HPGe p-type detectors are customized for measuring low-activity samples and are available for offline counting. Besides being used for counting activated samples following irradiation with accelerated beams, many measurements focus on environmental applica-

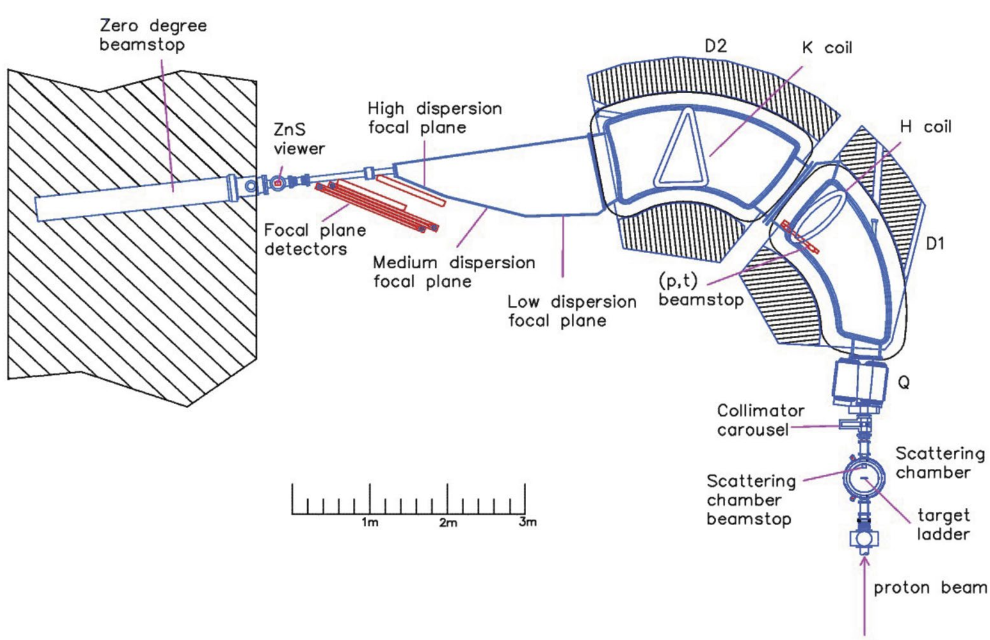

Figure 4. *Schematic of the K = 600 magnetic spectrometer, scattering chamber, and focal plane detectors.*

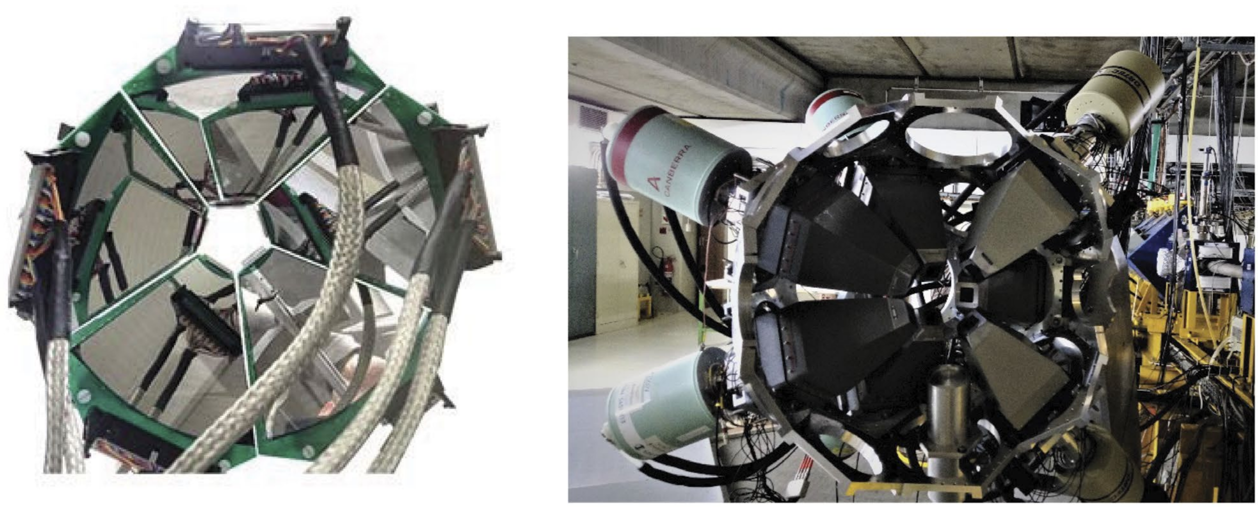

Figure 5. *The CAKE array (left) of five wedge-shaped double-sided silicon strip detectors placed in a lampshade configuration. One hemisphere of the γ-ray detector frame with 30 detector positions for $LaBr_3$:Ce, Clover, fast-timing, or LEPS detectors at the K = 600 magnetic spectrometer (right).*

tion, such as radon activity levels in soil, water, and plant samples with relatively low levels of γ radiation. Most African countries, including South Africa, are rich in mineral resources and have extensive mining activities and environmental radiation measurements are of significant importance. Additionally, in many African countries, expertise to operate and maintain equipment to measure low-level radiation is insufficient or nonexistent. iThemba LABS plays a vital role in training and building of knowledge in environmental radioactivity measurements across the continent.

ALICE Development and Testing Facility

During the second-long shutdown (2019/20), the ALICE Experiment was implementing a major upgrade of the detector. iThemba LABS contributes to the upgrades of the muon spectrometer, consisting of the Muon Identifier (MID) and Muon Tracking Chamber (MCH) detectors. The upgrade of the MID includes the replacement of the front-end and readout to increase the maximum readout rate. iThemba LABS is developing the firmware for the MID common readout unit (CRU), which includes the setup of the CRU readout test bench and the development of the user logic code that will run in the field-programmable gate array of the CRU, and is also participating in the replacement of the MCH on-detector front-end electronics and the implementation of the low-voltage supply system.

The Future of iThemba LABS

The research agenda of iThemba LABS as well as the commercial production of isotopes is accomplished largely through the use of the SSC. In order to elevate the contribution to knowledge production, human capacity development, and consequently mitigate the key risks to sustainability, iThemba LABS has developed a robust strategy in the form of a Long-Range Plan based on four pillars: (1) the SAIF, (2) the Southern African Institute for Nuclear Technology and Sciences (SAINTS), (3) the Technology and Innovation Platform (TIP), and (4) International Research Infrastructure Gateway.

The SAIF project (Figure 6) follows a phased approach:

Phase 1. The establishment of the Radio-Isotopes Facility (RIF), which entails the acquisition of a 70 MeV cyclotron and related infrastructure for isotope production. The SSC will be dedicated to research and training, which will lead to substantial increase in beam time availability and will lead to significant growth in research while enabling an increase in the production of radioisotopes to a growing local and international market. This phase will also see the implementation of a Low-Energy Rare Ion Beam (LERIB) facility, which will initially be dedicated to developing new techniques and radioactive ion beams.

Radioisotope Facility. The 70 MeV cyclotron will be capable of supplying two simultaneous 70 MeV proton beams, which will significantly extend the isotope production capabilities. The layout of the Radioisotopes facility is shown Figure 6. The cyclotron will be located in the center vault, with the bombardment of targets taking place in the two adjacent vaults. This will ensure flexibility because the production vaults are independent of each other, thus production can continue in one vault while maintenance is being performed in the other.

The LERIB Facility. iThemba LABS plans to provide low-energy rare ion beams. The rare ion beams will initially be produced by bombarding a uranium carbide target with the uniquely high-intensity (up to 250 μA) 66 MeV proton beam from the SSC using the Isotope Separation Online technique. The rare ion beam (RIB) production target (front-end) that is currently being commissioned at iThemba LABS will be installed to set up an online facility to produce RIBs (see location in Figure 6).

Phase 1 is well underway, with the procurement of the Cyclone® 70 MeV Cyclotron with four complete beamlines from IBA Radiopharma Solutions in September 2019. The C70 Cyclotron can provide H- beams with energies from 35 MeV to 70 MeV and 750 μA total extracted current, with two extraction ports each delivering up to 375 μA beam current independent of the other port. The cyclotron and beam-line components are provisionally scheduled for delivery in 2021, and beam on target is anticipated for 2022. The time frames will coincide with South Africa hosting the 28th International Nuclear Physics Conference in Cape Town in September 2022.

Phase 2. The establishment of the RIB facility, which will post-accelerate artificially produced radioactive isotopes, thus significantly expanding the research capabilities of iThemba LABS. The high-intensity electron beam from a Rhodotron accelerator (see Figure 6 for location) will be used to produce low-energy RIBs by bombarding a uranium carbide target with high-intensity γ radiation. The uranium fission products yield the exotic isotopes that are fundamental to the so-called r-process that underlies the formation of the elements from iron to the actinides. A combination of heat, laser beams, and electromagnetic fields techniques perfected under the LERIB project in SAIF Phase 1 will be used to extract the exotic isotopes from the uranium carbide target, where they are produced. After charge breeding, the post acceleration of the fission fragments will be accomplished by an injector cyclotron and the SSC.

Technology and Innovation Platform

A TIP is being established at iThemba LABS to promote partnerships with international laboratories and industry for skills and technology transfer purposes. TIP will have state-of-the-art facilities, such as clean rooms, for the manufacturing of electronics boards, semi-conducting and gaseous tracking detectors, sensors, highly integrated electronics, and a big data/machine-learning laboratory. Advanced detectors and electronics required by subatomic physics research will be designed, manufactured, and then tested using the accelerator facilities of iThemba LABS before being deployed to international laboratories. During this process, advanced technologies will be developed in South Africa. Through TIP, iThemba LABS will increase the involvement of South African institutions in the upgrade projects of international research facilities, which will in turn promote the transfer of skills and technology to South Africa. The implementation of TIP is planned to be completed before the end of 2021.

Southern African Institute of Nuclear Technology and Sciences

One of the major challenges faced by South Africa is the shortage of skills in the area of nuclear sciences and technology, which is exacerbated by the natural attrition of personnel who were responsible for the design, installation, and maintenance of the current aging accelerator infrastructure. iThemba LABS initiated the establishment of SAINTS in 2017 to address the shortage of skills in highly technical areas, such as accelerator technology, detector technology, and associated electronics and IT technology. SAINTS comprises taught M.Sc. courses, specialized short courses, staff development, and in-service training programs to complement the current master and doctoral programs at South African universities.

Gateway to International Research Infrastructure

The unique position occupied by iThemba LABS as the premier accelerator-based research facility on the African continent places it in a position to serve as the gateway through which researchers across the continent can access the iThemba LABS research infrastructure as well as the international research infrastructure on a global platform. As an internationally competitive research facility, the global reputation of iThemba LABS has been built over the years by developing and nurturing strong collaborative linkages and networking partnerships with the majority of nuclear research facilities. These strategic networks and international collaborations have been enriched through collaborative agreements that have firmly established iThemba LABS as a truly African Gateway to International Research Infrastructure in accelerator-based sciences.

Further, iThemba LABS actively contributes to the global strategy for Nuclear Physics and its Applications as a member of the International Union of Physics and Applied Physics—Working Group 9 and as an associate member of the Nuclear Physics European Collaboration Committee.

Summary

iThemba LABS is undergoing a transformation process that is defined by

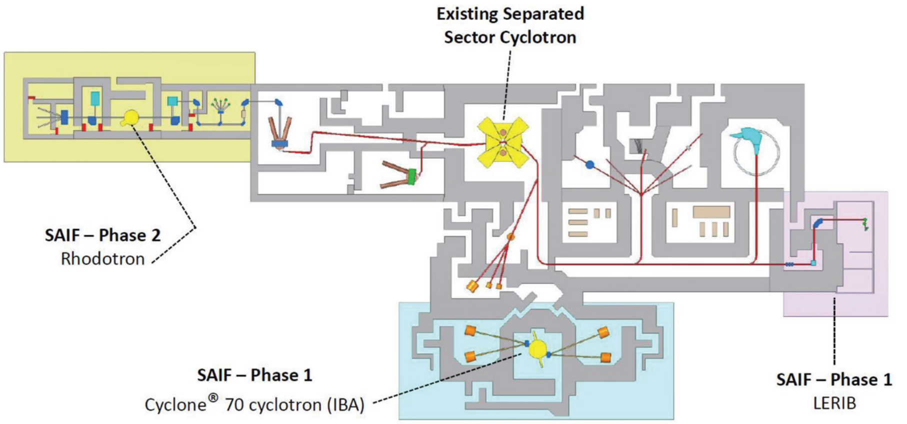

Figure 6. *Layout of the facilities showing the current SSC facility and vaults, the locations for the new 70 MeV cyclotron (light blue) with the four irradiation target systems for radioisotope production, the Low-Energy Rare Ion Beam facility (light purple) using the high-intensity 66 MeV proton beam from the SSC, and phase 2 of SAIF with the Rhodotron (light green).*

its Long-Range Plan 2017–2025. This transformation reaches from the upgrade and renewal of the various research facilities to its organization and mode of operation in order to be sustainable for the coming decades and to best deliver on the important mandate of human capacity building, research excellence, and societal impact for South Africa and the African continent. Several new or improved research facilities have become available recently, expanding the range of applications for accelerated beams at iThemba LABS. Most prominent among those are the AMS facility and the new 3 MV Tandetron for materials research, the refurbished fast-neutron beam facility, and the significant increase in γ-ray detection capabilities. The coupling of the K = 600 magnetic spectrometer with the ALBA and AFRODITE γ-ray detector arrays provides a powerful configuration. The SAIF project, which is well advanced in its first phase, will be a world-class and competitive accelerator complex for nuclear science and applications.

Acknowledgments

The success of iThemba LABS is only possible through the dedication of staff, users, stakeholders, and full support by the National Research Foundation of South Africa with the leadership of its visionary chief executive officer, Dr. Molapo Qhobela. M.W. acknowledges support through the NRF grant number 118846.

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