# Upgrading of the Accelerator Facilities at iThemba LABS to increase the Production of Radionuclides

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**Abstract.** iThemba LABS provides accelerator and ancillary facilities that are used for research and training in nuclear and accelerator physics, radiation biophysics, radiochemical and material sciences, radionuclide production and radiotherapy. Proton beams are accelerated to an energy of 66 MeV in the K = 200 separated sector cyclotron (SSC) with a solid-pole injector cyclotron (K=8) for use in the production of radionuclides and neutron therapy. Radionuclides produced at iThemba LABS are used in research and industry, various radiopharmaceuticals are prepared for diagnostic imaging at nuclear medicine centers. The cyclotrons and beam lines are being upgraded in order to increase the intensity of the 66 MeV proton beam for radionuclide production. Improvements of the facilities for increasing the beam intensity for radionuclide production include flat-topping systems for the light ion injector and SSC, and an additional buncher. A new vertical beam line and a vertical target station have been constructed. A beam splitter in the existing beam lines is planned to extend the facilities for the production of radionuclides.

## 1. Introduction

The operating schedule for the accelerator facilities at iThemba LABS is shown in Fig. 1. Beam is delivered to the different users for 24 hours per day and seven days per week. Radionuclide production and neutron therapy run from 16h00 on Mondays until 5h00 on Fridays. Patients are treated during day time and between treatments the beam is switched to the radionuclide production vault and the intensity is increased to 100µA. On Mondays and Fridays a 200 MeV beam is used for proton therapy and over the weekend beams of light and heavy ions as well as polarized protons, pre-accelerated in a second solid-pole injector

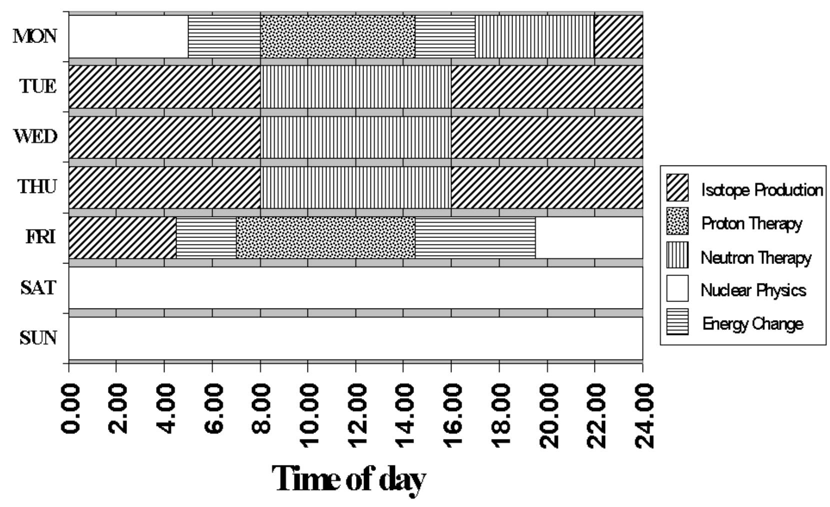


*FIG. 1. Operating schedule for the accelerator facilities at iThemba LABS.*

cyclotron, are used for nuclear physics experiments. The proton beam that is used for the production of radionuclides and neutron therapy, is pre-accelerated in the first solid-pole injector cyclotron (SPC1) to an energy of 3.14 MeV and then finally in the separated-sector cyclotron (SSC) to an energy of 66 MeV at an RF frequency of 16.37 MHz. Some of the isotopes that are regularly produced are listed in Table I below.

TABLE I: RADIONUCLIDES THAT ARE REGULARLY PRODUCED AT iTHEMBA LABS.

| **Radionuclide** | **Target Material** | **Energy Window MeV** |
|---|---|---|
| $^{67}Ga$ | Zn<br>Ge | 34.3 → 18.1<br>60.7 → 38.7 |
| $^{68}Ge$ | Ga | 34.0 → 2.4<br>34.0 → 0 |
| $^{81}Rb$ | RbCl | 62.6 → 57.7 |
| $^{82}Sr$ | RbCl | 61.5 → 39.4 |
| $^{103}Pd$ | Ag | 61.5 → 20.0 |
| $^{123}I$ | NaI | 62.6 → 47.6 |
| $^{201}Tl$ | Tl | 28.6 → 21.0 |
| $^{22}Na$ | Mg | 61.5 → 40.0 |
| $^{139}Ce$ | Pr | 61.5 → 25.5 |

External beam intensities of up to 180 µA have been used for radionuclide production with the 66 MeV proton beam, with beam losses of less than 0.8 µA. Due to overheating of the production targets the beam current is normally limited to 100 µA. With the present tight beam schedule it remains difficult to satisfy the requirements for beam time. Projects for increasing the intensity of 66 MeV proton beam to 400 µA and extention of the facilities for radionuclide production are currently in progress.

A 600 µA proton beam can be extracted with a 94% efficiency from SPC1 using the newly installed flat-top system [1]. The system reduces the energy spread in the beam and allows beam extraction from the ion source over a larger fraction of the RF cycle. A second buncher, that operates at a harmonic frequency of the existing one, is under construction and will be installed in the transfer beam line between the cyclotrons to accommodate the longer beam pulses that are extracted with the flat-topping system in SPC1. The longer beam pulses fall outside the linear range of the present buncher. A fixed-frequency flat-topping system has been installed in the SSC to prevent the longer beam pulses from acquiring excessive energy spread during acceleration [2]. It is expected that a beam current of 400 µA will be available from the SSC with these new additions. The present targets for radionuclide production cannot handle such high beam currents. A vertical beam line and a second target station have therefore been built and installed for production of radionuclides at the higher beam intensities. A beam splitter and another production beam line are now under construction to deliver beam to two target stations simultaneously. The design of the flat-topping systems, the additional buncher and the new beam lines are discussed below.

## 2. The Flat-topping System for the light-ion Injector Cyclotron

One of the two flat-topping systems [1] of SPC1 is shown in Fig.1. A fifth harmonic, 81.8 MHz, of the main RF frequency is superimposed on the main dee voltage. The flat-topping resonators, that can be tuned by moveable short-circuit plates, are capacitively coupled to the main resonators and are driven by remote power amplifiers through 50 Ω cables. The main and flat-top dee voltages are 49 kV and 1.96 kV, respectively. The power consumption for a flat-topping dee voltage of 1.96 kV, is 900 W. Although both the main and harmonic power amplifiers deliver power to the same dees care has been taken that power is not fed from one amplifier into the other.

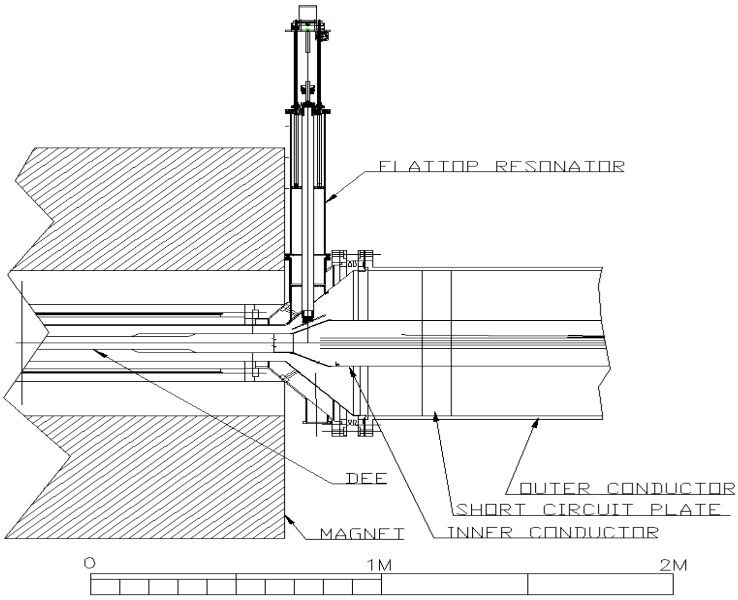


*FIG. 2. A side view of a capacitively coupled flat-topping resonator mounted on a main resonator of SPC1.*

### 3. Additional Buncher

An additional buncher [1] is under construction to handle the larger beam pulses from SPC1. This new double-gap buncher will be installed in the transfer beam line between SPC1 and the SSC and will operate at 65.5 MHz, i.e. four times the main cyclotron RF frequency and twice the frequency of the existing buncher. The power consumption in the quarter-wave resonator at a voltage of 14 kV is 190 W. The distance between the two gaps is 187 mm. Calculations have shown that beam pulse lengths of 40°, in terms of the main RF frequency, from SPC1 are within the linear range of the double-drift system formed by the two bunchers together.

### 4. Flat-topping System for the SSC

To minimise the energy spread acquired by the 66 MeV beam in the SSC, and therefore also broadening of the beam, a fixed-frequency flat-topping sytem has been built and installed in one of the two valley vacuum chambers [2]. In order to limit the down time of the cyclotron and interruption of beam delivery as well as the cost it has been decided that the resonator has to be installed through one of the existing vacuum ports in a valley vacuum chamber instead of manufacturing a new vacuum chamber. This places severe restrictions on the design of the resonator. The only type that could meet all the requirements is a horizontal half-wave resonator with short-circuit plates at injection and extraction. The resonator operates at the third harmonic, 49.12 MHz, of the main RF frequency and a dee voltage of 66 kV at approximately halfway between the injection and extraction radii. Since the dee voltage is zero at injection and extraction this type of resonator has the advantage that the orbit separation in these critical areas remain unchanged. Fig. 3 shows a three-dimensional drawing of the resonator.

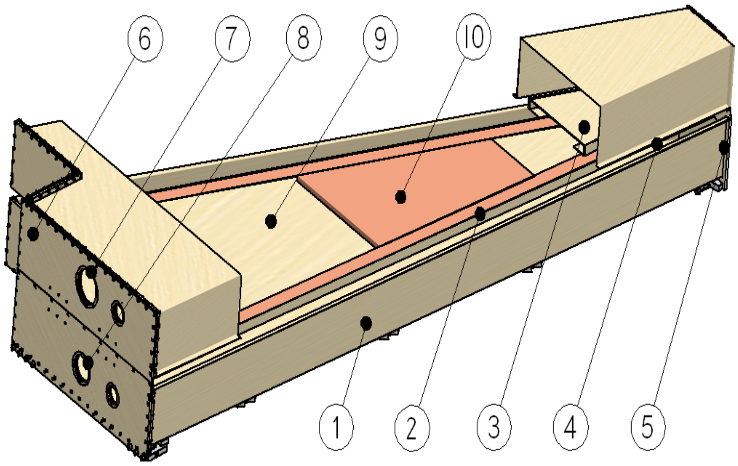


*FIG. 3. Three-dimensional drawing of the flat-top resonator for the SSC with the top part cut away showing: 1. lower dee housing 2. acceleration gap 3. top of the upper dee plate 4. beam gap 5. short-circuit plate at injection 6. short-circuit plate at extraction 7. and 8. ports for coupling and tuning components 9. top of the bottom dee plate 10. plate for detuning of an unwanted resonance mode.*

The height of the resonator is 0.465 m and the length is 3.017 m. The acceleration gap increases from 60 mm at injection to 100 mm at extraction. The calculated power dissipation and Q-value are 8.6 kW and 11000, respectively, with no beam. The measured Q-value is 8300. During operation with beam, power will be transferred from the beam to the resonator. Fig. 4 shows the resonator during installation through a port in the valley vacuum chamber.


*FIG. 4. The flat-top resonator for the SSC during installation through a port in a valley vacuum chamber.*

**5. New vertical Beam Line for Radionuclide Production**

In order to utilize the increased beam intensity for radionuclide production at 66 MeV a new vertical beam line [3], shown in Fig. 5, was installed. The 90° bending magnet, with zero degree entrance and exit angle, directs the beam away from the horizontal line. The beam then passes through two quadrupole magnets and two H-type sweeper magnets, the purpose of which is to sweep the beam in a circular pattern with a radius of 10 mm over the target at a rate of 3 kHz. The coils of the sweeper magnets are tuned with capacitors and are driven by audio power amplifiers. The steering magnets together with a diagnostic vacuum chamber that contains a harp, Faraday cup, and a phase probe for non-destructive beam current measurements are positioned downstream from the steering magnets. The beam is focused on the target that has a diameter of 40 mm.

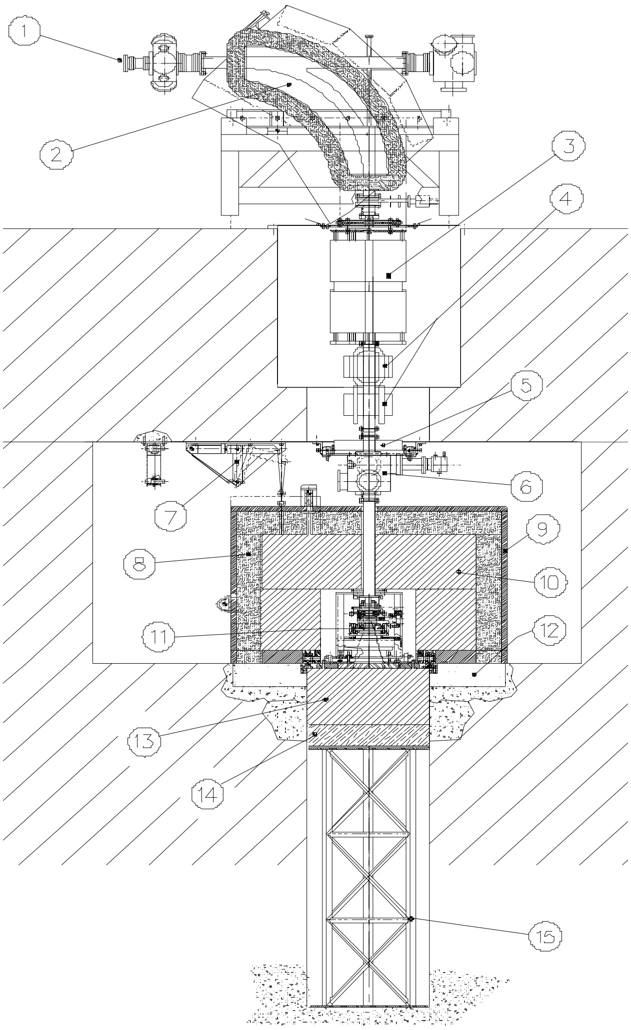


*FIG. 5. Layout of the vertical beam line for the production of radionuclides showing: 1. the horizontal beam line 2. the 90° bending magnet 3. two quadrupole magnets 4. sweeper magnets 5. steerer magnet 6. vacuum chamber for diagnostic equipment with a Faraday cup, harp and capacitive probe for current measurement 7. shielding lift mechanism for target exchanges 8. 9. and 10. inner iron shield 11. target 12. water tanks with a 4% ammonium pentaborate solution 13. iron shield 14. borated paraffin-wax shield 15. support structure.*

## 6. Beam Splitting for Radionuclide Production

The irradiation of two targets at the same time can be accomplished by splitting the beam [3] as shown in fig.6. The beam will be deflected with an 800 mm long electrostatic channel, which operates with a negative deflector voltage of 70 kV across a 30 mm gap. Only two thirds of the beam will be used in the vertical beam line. The deflected beam will be diverted around the 90° bending magnet before it is taken to the radionuclide production vault. Diverging the beam at the entrance to the electrostatic channel can minimize the beam losses in the septum magnet. The beam loss is expected to be about 1 μA for a 400 μA total beam current. The septum magnet deflects the beam through 20°. To adjust the beam height in the septum magnet, a quadrupole magnet positioned directly after the electrostatic channel is used. The deflected beam is focused by three quadrupole magnets to a double waist in the switcher magnet with zero entrance and exit angles.

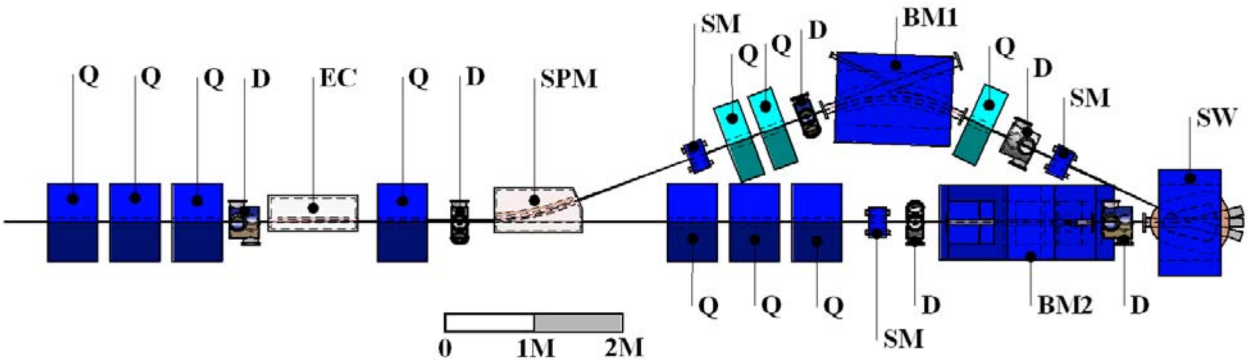


*FIG. 6. Layout of the planned beam lines for supplying two targets for radionuclide production simultaneously with beam. The main components are the electrostatic channel EC, the septum magnet SPM, the bending magnet BM1and the existing switcher magnet SW. The bending magnet BM2 deflects the beam downward into the vertical beam line. Q, SM and D designate quadrupole magnets, steering magnets and diagnostic vacuum chambers, respectively.*

## 7. Improved Beam Diagnostic Equipment

Non-destructive beam position monitors were developed [4] and have been installed at eleven positions in the transfer beam line between SPC1 and the SSC and the high-energy beam lines to align and monitor the high-intensity beams. In Fig.7 a monitor and a drawing that indicates the main dimensions are shown. The monitors have been designed to measure the beam position in both the horizontal and vertical directions and to fit in the diagnostic vacuum chambers together with existing equipment. In order to prevent modifications to the chambers the monitors are installed through the beam ports and are fixed with an internal clamp. The electronic signal processing equipment, for each monitor, consists of an RF signal processing module and a data acquisition and control module, and has been developed by Forschungzentrum Jűlich as part of a collaboration agreement[1] with iThemba LABS.

[1]Supported by BMBF and NRF, project-code **39.1.B0A.2.B.**


*FIG. 7. A non-destructive beam position monitor and cross-section drawings showing the main dimensions.*

Software has been developed to automatically align the beam and monitor it continuously. Fig. 8 shows one of several different types of the displays of the beam position information after automatic alignment on the second monitor. In the transfer beam line proton beams with intensities as low as 40 nA could be aligned. In the high-energy beam line proton beams of about 0.7 µA are used for alignment. Pickup from the main RF systems and buncher has been reduced to –135 dBm. The signal strength at the fourth harmonic of the main RF frequency, at which some measurements are made, is –90 dBm for a 1 µA beam.

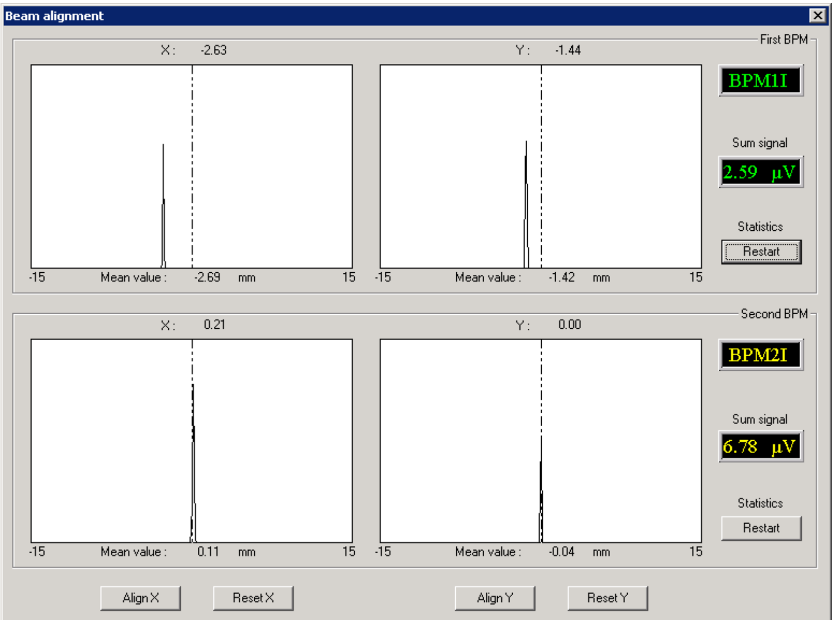


*FIG. 8. Beam position display with the non-destructive beam position monitors after automatic alignment at the second monitor (bottom).*

A remote-controlled beam stop for optimisation of the beam transmission through the separated-sector cyclotron at high beam intensities has been installed in the high-energy beam line close to the cyclotron. The beam stop has a length of 660 mm and a 120 mm square aperture. It has been designed to stop a 50 kW beam of 66 MeV protons, provided that the beam diameter is not less than 35 mm. For a beam diameter of 10 mm the maximum beam power is 32 kW. The main parts of the beam stop are two 600 mm long water-cooled copper blocks mounted at an angle with respect to each other, as shown in Fig. 9. Current measurements on insulated electrodes around the entrance of the beam stop are used for interlocking to protect beam line components. The meter long vacuum chamber of the beam stop is surrounded with a 50 mm thick lead shield.

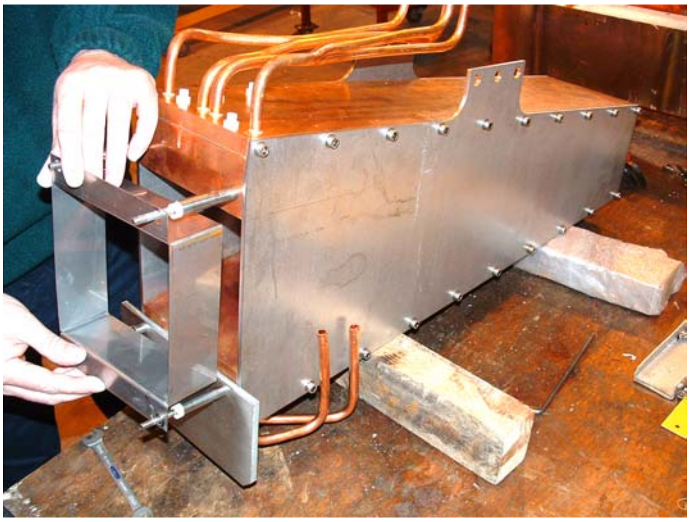

*FIG. 9. The water-cooled copper blocks of the high-power beam stop during assembly.*

## 8. Conclusions

The flat-top systems for both SPC1 and SSC have been operated at full power with beam and are now in the final stage of commissioning. The vertical beam line for radionuclide production has been installed. The beam diagnostic equipment has been improved to the extent that the higher beam intensities can be measured, aligned and monitored non-destructively. Regular operation at the higher beam intensities will start within the next few months. Beam splitting and the additional beam line are expected to be completed during 2007.

## 9. References


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