CYCLOTRONS AT ITHEMBA LABS

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Abstract

At iThemba LABS (previously the National Accelerator Centre) proton beams, accelerated in a K=200 separated sector cyclotron (SSC) with a K=8 solid-pole injector cyclotron (SPC1), to an energy of 66 MeV are utilized for the production of radioisotopes and for neutron therapy. Proton therapy is done at an energy of 200 MeV. Low intensity beams of light and heavy ions as well as polarized protons, pre-accelerated in a second injector cyclotron with a K=11, are available for nuclear physics research. Additions and improvements to the cyclotrons and beam lines currently in progress, for increasing the beam intensity for radioisotope production, include flat-topping systems for the light-ion injector and separated sector cyclotrons, and an additional buncher. A new vertical beam line is under construction and beam splitting in the existing beamlines is being planned to extend the facilities for the production of radioisotopes. The design and construction of these components, some new diagnostic equipment, and plans for new facilities for proton therapy are discussed.

INTRODUCTION

The cyclotrons at iThemba LABS [1, 2] are operated 24 hours per day and 7 days per week, except for the planned shutdowns (four weekends during the year, a week in July and four weeks in January). Proton therapy is scheduled for Mondays and Fridays from 08h00 to 16h00. Beam is available for production of radioisotopes from 16h00 until 06h00 the next day from Monday until Friday morning and for neutron therapy during normal working hours on Tuesdays, Wednesdays and Thursdays. Between treatments the beam is switched to the radioisotope production vault and the intensity is increased to between 100 µA and 150 µA. It nevertheless remains difficult to meet the beam time requirements of the different disciplines. An increase in the intensity of the 66 MeV proton beam delivered by the existing cyclotrons and more diverse facilities for the production of radioisotopes would alleviate this problem to some extent. At present the beam intensity is limited to 150 A by excessive beam losses at extraction in the separated-sector cyclotron. The maximum beam intensity that can be obtained from the injector cyclotron is 320 A. At this intensity the effect of longitudinal space-charge forces is noticeable and an increase in the internal beam intensity does not lead to an increase in the external beam current.

Experiments with a flat-topping system in the injector cyclotron showed that a 600 A proton beam can be extracted with an extraction efficiency of 94% [2,3]. The longer beam pulses extracted with a flat-topping system fall outside the linear range of the buncher in the transfer beam line. A second buncher, operating at a harmonic frequency of the existing one, is therefore being built. To prevent the longer beam pulses from acquiring excessive energy spread in the separated sector cyclotron a flat-topping system for this cyclotron has also been installed. With these modifications implemented it is expected that a 400 µA will be available from the SSC. At present radioisotopes are produced in only one vault. A vertical beam line is under construction and beam splitting is being planned to irradiate more than one target at a time. To increase the availability of beam for proton therapy an additional accelerator seems to be the only solution.

FLAT-TOPPING FOR THE LIGHT ION INJECTOR CYCLOTRON

The experimental flat-topping system for SPC1, with which a fifth harmonic voltage is superimposed on the main dees with short additional resonators capacitively coupled to the main resonators, was designed for variable-frequency operation. Similar systems have since been incorporated in other solid-pole cyclotrons [4]. The design of the additional resonators and their power amplifiers has recently been modified for more reliable fixed-frequency operation at 81.8 MHz, the fifth harmonic of the main RF frequency at which the 66 MeV proton beam for radioisotope production is accelerated. The resonators and amplifiers have been installed and are now in operation. The power dissipation per dee is 900 W for a harmonic dee voltage of 1.96 kV, corresponding to a fundamental dee voltage of 49 kV. About half the power is dissipated in the 514 mm long additional resonator. The external beam current available for further acceleration in the SSC is now 600 µA. The measured, full width at half maximum, beam pulse length is 20 degrees in terms of the fundamental RF frequency. The corresponding energy spread is 0.1%.

ADDITIONAL BUNCHER

The additional buncher in the transfer beam line between SPC1 and the main cyclotron will operate at 65.5 MHz, i.e. four times the cyclotron RF frequency and double the frequency of the existing buncher. The distance between the two gaps is 187 mm and the voltage across the gaps is 14 kV. The power dissipation in the 891 mm long quarter-wave resonator is 190 W. The operating voltage of the existing buncher has to be increased from 62 kV to 69 kV. This has been experimentally verified as possible. Calculations have shown that beams with a total pulse length of 40 fundamental RF frequency degrees from SPC1 can be bunched to a total pulse length of 10 degrees, which will be suitable for further acceleration in the separated sector cyclotron with a flat-topping system. The additional buncher is presently under construction.

FLAT-TOPPING FOR THE SEPARATED SECTOR CYCLOTRON

The fixed-frequency flat-topping system [5] of the separated-sector cyclotron operates at 49.12 MHz, i.e. at the third harmonic of the main RF frequency at which the 66 MeV proton beam for radioisotope production and neutron therapy is produced. The single horizontal half-wave resonator, shown in fig. 1, has zero dee voltage at injection and extraction and a maximum value in between. The main reason for this design is that the resonator can be installed through one of the existing ports in a valley vacuum chamber without any modifications to the chamber, which would have been costly and would have resulted in a long down time of the cyclotron. An additional advantage is that the orbit separations at injection and extraction remain unchanged. The resonator has a radial length of 3.017 m, a maximum width of 1.150 m, a height of 0.465 m and a sector angle of 16.5°. The vertical aperture for the beam is 40 mm and the acceleration gaps increase radially from 60 mm to 100 mm from injection to extraction.

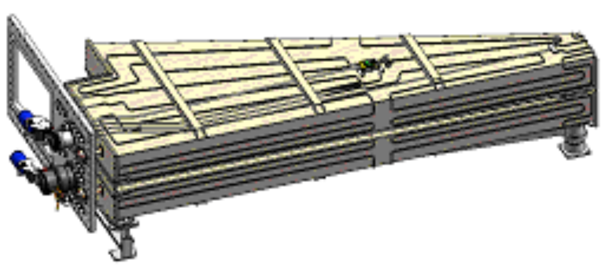

Figure 1: Three-dimensional drawing of the horizontal half-wave flat-topping resonator for the separated sector cyclotron.

The 15 kW power amplifier is connected via a 50 Ω cable to the resonator through a coupling loop. Fine-tuning of the resonator is done by rotation of a closed loop. For the required dee voltage of 62 kV the power dissipation without beam is 9.6 kW. A more detailed description of the system and commissioning of the system are reported elsewhere in these proceedings [6].

NEW BEAMLINES FOR RADIONUCLIDE PRODUCTION

The Radionuclide Production Programme

The Radionuclide production Group (RPG) has established a comprehensive production programme that is based on a 66 MeV proton beam. Beam currents up to 100 µA are presently being used for routine production of a range of radionuclides. Targets are irradiated in a dedicated bombardment station [7]. Ion exchange chromatographic separation methods are mainly used to process these targets after bombardment, to recover and to purify the appropriate radionuclides. With the 66 MeV protons it is possible to exploit nuclear reactions with higher thresholds than with smaller commercially available cyclotrons. It is therefore not necessary to use enriched target material. The beam can also be degraded to any desired lower energy. iThemba LABS is the only producer of accelerator radionuclides in South Africa and radiopharmaceuticals produced from these radionuclides are supplied to more than 50 nuclear medicine centres throughout South Africa.

Routine Radionuclide Production

Routine production of the important short-lived medical radionuclides ^{67}Ga, ^{81}Rb and ^{123}I is done on a twice-weekly basis [8, 9]. ^{67}Ga and ^{123}I are used to prepare radiopharmaceuticals for the local users. The radionuclidic purity of these products is greater than 99.9 % and the ^{67}Ga contains less than 10 µg of Ge, 4 µg of Zn and 20 µg of Fe. ^{67}Ga citrate is used for imaging sites of infection and for tumour location. ^{123}I radiopharmaceuticals, in different chemical forms, are used for tumour localization and for observing heart, kidney, thyroid and brain function. ^{81}Rb is used to manufacture the ^{81}Rb/^{81}mKr generator for lung perfusion studies. The target materials and beam energies at which these and other radionuclides are produced are listed in Table 2.

Table 2: Radionuclides that are regularly produced at iThemba LABS

Radionuclide	Target Material	Energy Window MeV
^{67}Ga	Zn Ge	34.3 → 18.1 60.7 → 38.7
^{68}Ge	Ga	34.0 → 2.4 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

Longer-lived radionuclides, ^{22}Na, ^{68}Ge, ^{82}Sr, ^{88}Y and ^{139}Ce are also produced, mainly for export. ^{22}Na is used in positron sources and the RPG has recently shipped sources to users in Germany, Switzerland, China, Italy and England. iThemba LABS produces about 10 – 12 of these positron sources per annum. ^{68}Ge and ^{82}Sr are produced for the United State’s Department of Energy (DOE). The bombarded targets are shipped to the Los Alamos National Laboratory for processing.

Upgrading of Facilities and New Products

Several projects are underway to increase the radionuclide production capacity at iThemba LABS. A new vertical beam line [10] and target station (VBTS), shown in fig. 2, are currently in the construction phase and will near completion towards the end of 2004 or early 2005.

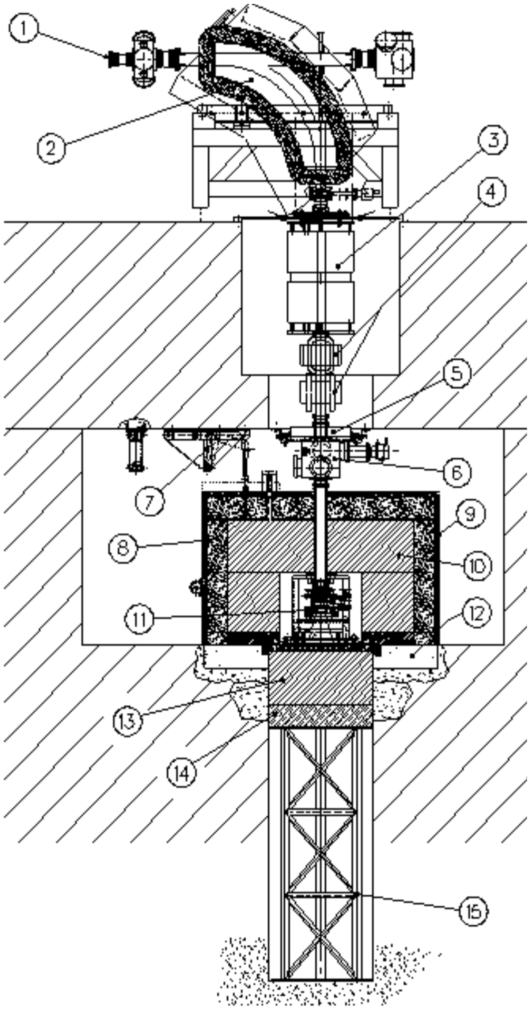

Figure 2: Layout of the vertical beam line for the production of radionuclides showing: 1. the horizontal beam line 2. the 90° bending magnet 3. two quadrupole magnets 4. sweeper magnets 5. steerer magnet 6. vacuum chamber for diagnostic equipment with a Faraday cup, harp and capacitive probe for current 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.

The targetry for the VBTS is being upgraded to utilize higher beam currents up to 250 µA mainly for the production of the long-lived radionuclides. This facility will be used in addition to the existing facilities and increase the beam utilisation for radionuclide production from the current level of about 300 000 µAh per annum to more than 700 000 µAh per annum. Beam splitting in the existing horizontal beam line is also planned to irradiate more than one target at a time [10].

Four new hot-cells have been designed and will be constructed in 2005 in order to handle the higher activation when routine operation of the VBTS commences.

Current developments and research on 67Ga and 68Ga-labelled peptides can lead to an increase in the demand for highly pure 67Ga and 68Ga.

A high-pressure ^{18}O gas target is being designed to produce ^{18}F. A commercial system will be purchased early in 2005 to produce ^{18}F-FDG.

Several other investigations are in progress, e.g. for the production of ^{139}Ce and ^{139}Pd as shown in Table 2. Other radioisotopes that are produced on demand are ^{18}F, ^{52}Fe, ^{55}Fe, ^{111}In, ^{133}Ba and ^{202}Tl.

DIAGNOSTIC EQUIPMENT

Beam Stop

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 figure 3. 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. The design was bought from a commercial company.

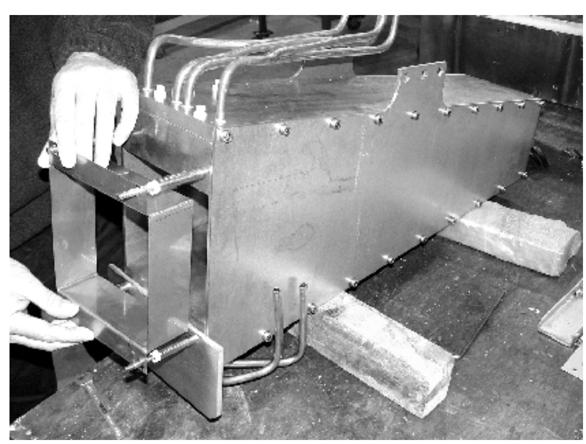

Figure 3: The water-cooled copper blocks of the beam stop during assembly.

Beam Position Monitor

A prototype beam position monitor for non-destructive alignment and continuous display of the beam position of the more intense beams, used for neutron therapy and the production of radioisotopes, in the beamlines have been developed and tested. Eleven such monitors, which should measure the beam position in both the horizontal and vertical directions, are planned for the transfer and high-energy beam lines. The monitors have been designed to fit in the available space inside the existing diagnostic chambers, as shown in fig. 4, and use existing flanges for feedthroughs. This limits the overall length of a monitor, inside the shortest diagnostic vacuum chamber to 60 mm, with allowance for existing diagnostic elements in the chamber. The inner diameter has to be larger than 100 mm to prevent interception of beam and the outer diameter smaller than 150 mm to allow installation through one of the round beam ports. Four 40 mm long electrodes with an inner radius of 65.5 mm, each of which subtends an angle of 68°, are mounted co-axially inside a copper shield that is fixed to the chamber housing by turning a single nut on an internal clamp that presses contact fingers on the shield over the full circumference to the inside of the vacuum chamber port and thereby eliminating any inductance in the support structure of the shield. The associated computer-controlled electronic equipment which measures the signal levels on the four electrodes at a harmonic of the main RF frequency, and processes the data to determine the beam position has been developed by the Institute for Nuclear Physics at the Forschungszentrum Jülich GmbH* [11]. The signal strength for a 1 µA beam is -90 dBm in the transfer beam line and -107 dBm in the high-energy beam line. Pick-up from the buncher and cyclotron RF systems is less than -135 dBm at the fourth harmonic of the main RF systems and the second harmonic of the buncher. The monitor is insensitive to ground and cable arrangements inside the chamber and the position of other diagnostic components. The remaining monitors and electronic processing units are under construction.

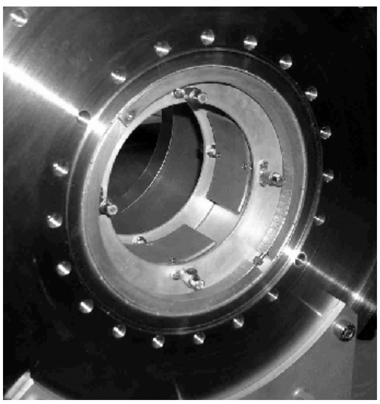

Figure 4: A beam position monitor inside a diagnostic vacuum chamber.

Beam Phase Measurement

An automated phase history measurement and trim-coil adjustment system has been developed for the SSC. It applies a Tektronix TDS 5052 digital oscilloscope to digitize the signal waveform delivered by the capacitive pick-up in the cyclotron. The pick-up is mounted on a multi-head probe and it can be moved between the radii of 850 mm and 4250 mm. The control software runs on a Windows PC. It moves the probe to the required radius, reads the signal waveform from the oscilloscope, separates the bunch signal from the RF-noise with a digital algorithm and determines the beam phase. There are two different modes of operation: in Fast Mode the probe is moved between the innermost and outermost positions without stopping and the measured phase data is used for quick evaluation of the phase history of the beam. In Normal Mode the probe is stopped on each radius that is included in the set of reference radii for trim-coil calculations. The acquired more accurate phase data is used to calculate the necessary adjustments in the trim-coil currents to get a better approximation of the isochronous magnetic field. After approval by the operator these new current values are downloaded to the trim-coil power supplies.

Beam Current Measurement

The beam current measuring system of the cyclotrons and beam lines has been upgraded. All Keithley 485 picoammeters have been equipped with GPIB-interfaces and a computer controlled multiplexer, based on HP 34904A matrix switches, has been added to the system. Every function of the picoammeters is now available from the user interface of the control software running under Windows. It also controls the multiplexer in accordance with the selected beam line and connects the Faraday-cups installed in the active line to the Keithleys. An automatic offset removal function has also been implemented in the control software. It puts all picoammeters connected to devices behind the first inserted Faraday-cup into Relative Mode.

Development of a non-destructive current measuring system for the vertical beam line is in progress. The current is calculated from the pulse signal induced by beam bunches on a capacitive pick-up. A 5 GS/s digital oscilloscope card (CompuScope 85G) is used to digitize the signal waveform. The measuring software processes the digitized waveform; it cleans the beam pulse from RF-noise, detects its boundaries and calculates the electric charge contained in the beam bunch. The effect of high frequency fluctuations in the bunch intensity is cancelled by digital filtering. The preliminary tests show that the system will be able to provide the required measurement precision of a few percent in a wide beam intensity range.

FACILITIES FOR PROTONTHERAPY

New facilities [12] for proton therapy, based on a commercial 230 MeV cyclotron, are being planned. In addition to the three existing therapy vaults three further vaults will be provided for proton therapy for increased throughput of patients. The layout of the planned

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

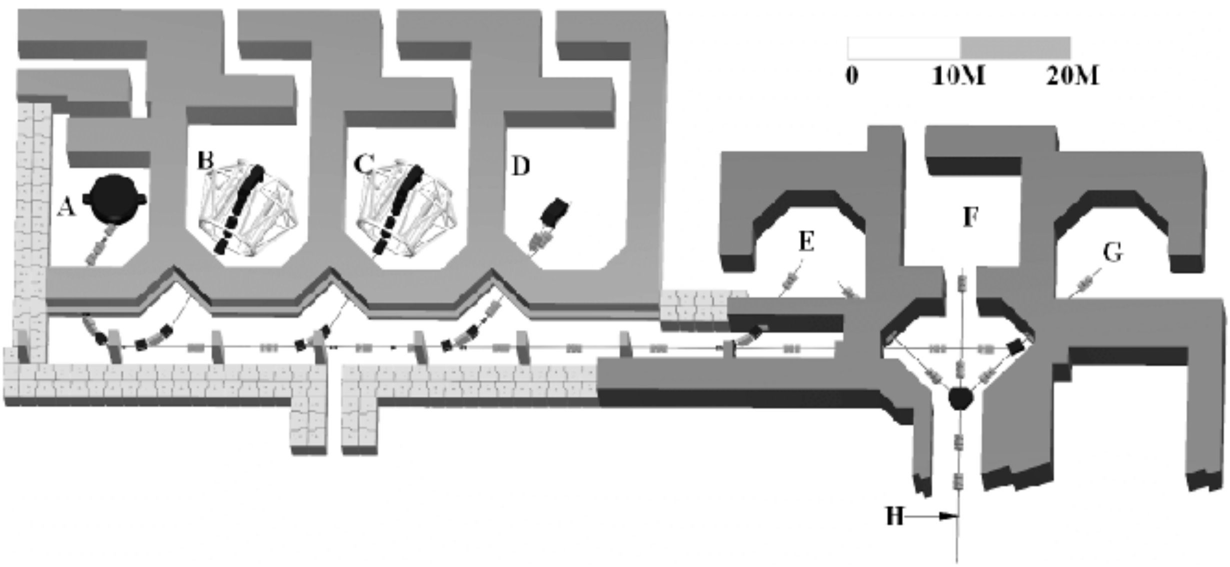

Figure 5: Layout of existing facilities for proton and neutron therapy and planned extensions for proton therapy. A 230 MeV cyclotron in vault A will supply beam to gantries in vaults B and C. For vault D two fixed beam lines, one horizontal and one at an angle of 30° with respect to the vertical, both using spot scanning, are planned. Vaults E and G are reserved for future applications. Vaults F and G house, respectively, the existing iso-centric system for neutron therapy and horizontal beam line, using scattering, for proton therapy. H indicates the beam line from the separated-sector cyclotron.

facilities is shown in fig. 5. Two vaults will be equipped with gantries, which would make use of either scattering or scanning. In another vault two beam lines using scattering, one with an angle of 30° with respect to the vertical and one horizontal, are planned. Beam from the 230 MeV cyclotron will also be available in the existing vaults, E and G, for proton therapy. The existing hospital and accommodation for staff will also be extended. The new infrastructure will increase the number of patients that can be treated annually from the present 50 to 1500. The total cost of the project, including financing costs, is estimated at 96 million US$. The project has not been funded yet.

CONCLUSIONS

Several projects for improving the facilities for production of radioisotopes are in progress. The flat-topping systems, buncher, beam stop and vertical beam line are scheduled for completion by the end of 2004. Operation with split beams is planned for 2006.

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