THE ACCELERATOR FACILITIES OF THE NATIONAL RESEARCH FOUNDATION IN SOUTH AFRICA

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Abstract

iThemba L(aboratory) for A(ccelerator) B(ased) S(ciences) operates three cyclotrons and a 5.5 MV Van de Graaff accelerator at Faure, near Cape Town, as well as an EN Tandem accelerator in Johannesburg. During recent years extensive development work has been carried out on these machines to improve the intensity, quality and variety of the beams for basic and applied research, particle therapy and radioisotope production. The main characteristics of the accelerators are reviewed. New developments and the resulting improvements in the beam characteristics and operation of the accelerators are discussed.

INTRODUCTION

iThemba LABS, originally named National Accelerator Centre (NAC), was established in the late nineteen seventies under the auspices of the South African Council for Scientific and Industrial Research. First, a variable-energy K200 separated-sector cyclotron (SSC) with a K8 solid-pole injector cyclotron (SPC1), using an internal PIG ion source, for acceleration of light ions were constructed [1,2]. During the early nineties a second K8 injector cyclotron (SPC2) with two external ion sources: a Minimafios electron cyclotron resonance ion source (ECRIS) and a source for polarized hydrogen ions, using the atomic beam method, were built [3]. Beams from the SSC were available for nuclear physics research by the end of 1986. During 1987 facilities for the production of radioisotopes with a 100 µA, 66 MeV proton beam were commissioned. In the same year the gantry for neutron therapy was tested with a 30 µA, 66 MeV proton beam. The beam line for proton therapy was completed early in 1993.

Beams are delivered to the different user groups for 24 hours per day and seven days per week. The 66 MeV proton beam is available for radionuclide production [4] and neutron therapy from Mondays until midday on Fridays. Patients are treated [5,6] during daytime and between treatments the beam is within seconds switched to the radionuclide production vaults, and the intensity increased to 250 µA. Weekends are scheduled for proton therapy, using a 200 MeV beam, and for nuclear physics research [7,8]. The main goals for the development of the cyclotron facilities in recent years were to: increase the intensity of the 66 MeV proton beam, develop non-destructive beam diagnostic equipment, build new beam lines for radioisotope production to allow simultaneous irradiation of two targets, and to install new ECR ion sources capable of delivering heavy ions with high charge states and beam intensities.

The 5.5 MV CN Van de Graaff accelerator at Faure was acquired in 1964 for the Universities of Stellenbosch and Cape Town and was later incorporated into the NAC. The 6 MV EN tandem Van de Graaff accelerator, that originally formed part of the facilities of the University of the Witwatersrand (WITS), became part of iThemba LABS early in 2005. The two Van de Graaff accelerators were refurbished and their beam lines redesigned and rebuilt.

THE INJECTOR CYCLOTRONS

The layout of SPC1 is shown in Fig. 1. The H-type solid-pole magnet has four 45° radial sectors. The magnetic field can be adjusted by 5 trim-coils, two sets of harmonic coils and two cone coils. The extraction radius is 0.476 m. The two 90°-dees can be tuned over the frequency range 8.6 MHz to 26 MHz with movable short-circuit plates in cylindrical quarter-wave transmission lines. Harmonic numbers 2 and 6 are used. Dee voltages of up to 60 kV, and three constant-orbit geometries are used to accommodate the desired energy ranges for light ions. The beam is internally defined with a puller electrode, two radial slits and two axial slits. The beam is extracted with an electrostatic channel, two active magnetic channels and one passive channel. For the 66 MeV proton beam, a beam intensity of 300 µA at an energy of 3.1 MeV was typically extracted.

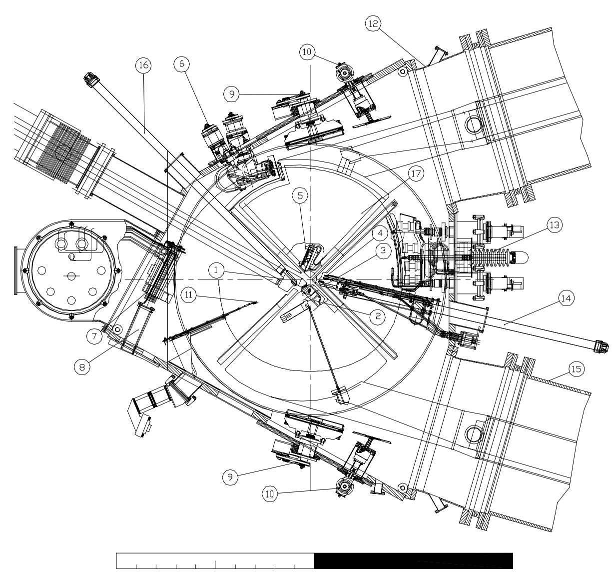

Figure 1: Layout of SPC1 showing 1. the ion source 2. the puller electrode 3. a differential probe 4. the first radial and axial slit 5. the second radial slit and 11. the second axial slit.

To increase the external beam intensity flat-topping systems were installed [9]. Because of the limited space available between the main dees, ion source and diagnostic equipment, separate dees could not be used for the flat-topping system. Fifth-harmonic voltages are therefore superimposed on the main dee voltages by means of the small additional resonators that are capacitively coupled to the main resonators as shown in Fig. 2.

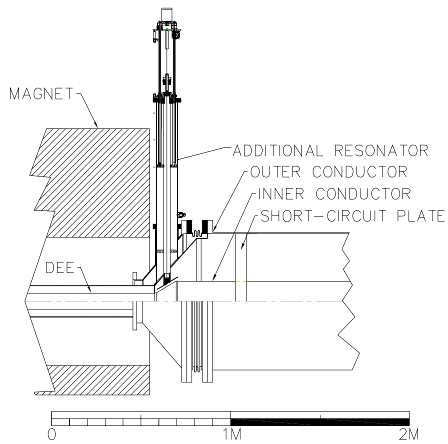

Figure 2: A main and additional resonator of SPC1.

Fig. 3 shows the orbit patterns without and with flat-topping. With flat-topping the maximum external beam intensity is above 600 µA.

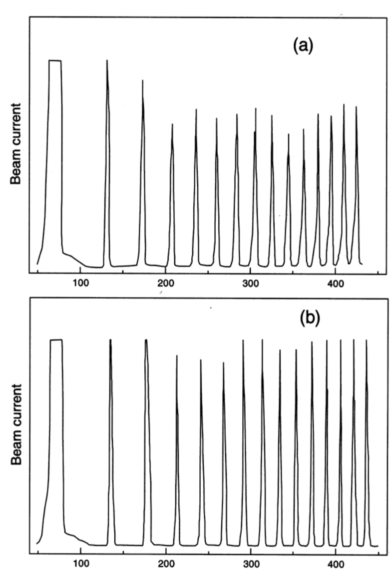

Figure 3: The orbit pattern in SPC1 (a) without and (b) with flat-topping.

SPC2 is in many respects similar to SPC1, except that the ion sources are external and the beam is injected axially with three spiral inflectors corresponding to the three orbit geometries that are being used. Heavy ions with mass numbers up to that of xenon are delivered by an electron-cyclotron resonance ion source (ECRIS). Proton beams from an atomic beam polarized ion source are also accelerated with this injector cyclotron. It is planned to replace the present electron-beam ionizer with an ECR ionizer to improve the reliability of beam delivery for polarized protons.

The ECR source has been in use since 1994. Two new ECR ion sources will in future deliver beams with significantly higher charge states and beam intensities. A 14.5 GHz source, donated by the Hahn Meitner Institute (HMI), will be operational by September 2008. An 18 GHz Grenoble GTS source [10] is under construction. With this source $^{129}Xe^{37+}$-ions will be available for acceleration to 2.2 GeV in the SSC.

THE SEPARATED-SECTOR CYCLOTRON

The layout of the SSC is shown in Fig. 4. The maximum design energy for protons is 200 MeV, but protons have occasionally been accelerated to 227 MeV for special purposes. The four separate magnet sectors, each with a mass of 350 tons, have an overall diameter of 13 m. A sector angle of 34° has been chosen to avoid the $\nu_z = 1$ resonance, for the 200 MeV proton beam near extraction, and the $\nu_x+2\nu_z = 4$ inherent resonance. The maximum flux density of 1.3 T can be obtained in the 66 mm pole gap by means of the main coils around the poles and additional coils around the yoke pieces. The magnetic field can be increased radially by 20% with 29 trim-coils outside the magnet vacuum chambers that are mounted in the pole gaps.

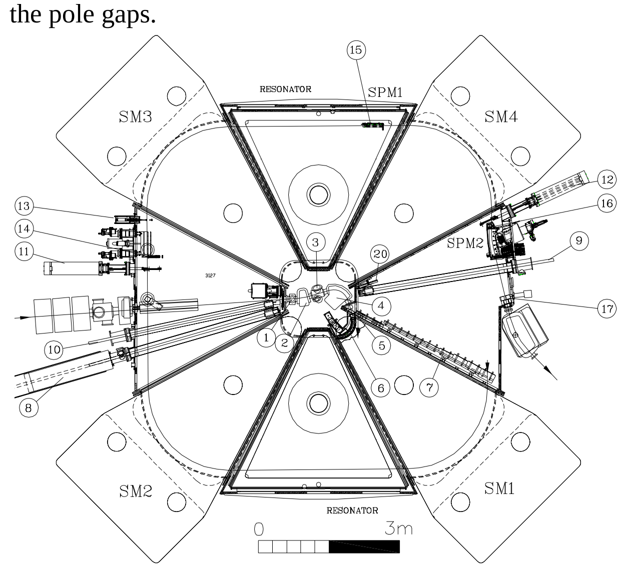

Figure 4: Layout of the SSC.

The two vertical half-wave resonators can be tuned with movable short-circuit plates and adjustable capacitors over the frequency range 7 MHz to 27 MHz. The maximum dee voltage is 220 kV at a power level of 80 kW per resonator. The two resonators are capacitively coupled to two 150 kW power amplifiers. The beam is inflected with two bending magnets and a magnetic inflection channel and extracted with two septum magnets. A deliberately introduced beam centring error equal to the orbit separation at extraction, allows beam extraction with two septum magnets only. Two multi-head probes and a beam stop that can be moved over the full radial range, and two profile grids (harps), that can be moved over a limited radial range near extraction, are available for measurement of the beam characteristics. The profile grids allow a quick and direct way of minimizing the energy spread in the beam at extraction and also give a good indication of the orbit centring.

Proton beams with an intensity of more than 100 μA at 66 MeV have routinely been extracted from the SSC with a transmission efficiency of 99.85%, without the flat-topping systems of SPC1 in operation. To improve the extraction efficiency at higher beam intensities a flat-topping resonator [11] that operates at the third harmonic of the main dee voltage, has been installed in one of the valley vacuum chambers of the SSC. The design of the resonator, shown in Fig. 5, is such that it could be installed through an existing port in the vacuum chamber without any machining being done to the chamber.

Figure 5: The flat-topping resonator of the SSC.

It is a half-wave resonator with fixed short-circuit plates at injection and extraction, which means that the dee voltage is zero at injection and extraction and has a maximum in between. An advantage of this design is that the orbit separations in these two critical areas are therefore not reduced by the flat-topping voltage. The resonator is tuned with a rotatable short-circuited loop, at the extraction side. Coupling to the power amplifier is also done with a coupling loop that can be rotated to obtain an input impedance of 50 Ω. A characteristic of this type of resonator is that the frequency of an unwanted resonance, corresponding to the condition that the voltages on the top and bottom dee plates being 180 degrees out of phase, coincides with the desired operating frequency, because the top and bottom dee plates and the top and bottom cover plates form three strip lines of the same length. Since the coupling and tuning loops, one above the dee and the other below, create serious vertical asymmetry in the resonator, it was imperative to shift the frequency of the unwanted resonance away from the operating frequency. The solution was to install two copper plates, one on the inside of each of the two dee plates, radially near the centre of the dee, to act as capacitors to tune the unwanted resonance to a frequency away from the operating frequency. Two capacitor plates, one above the dee and the other below, and radially in the centre of the resonator, are manually adjusted before installation to even out asymmetry in the resonator construction.

At present, with both flat-topping systems in operation, a 250 μA beam of 66 MeV protons is routinely extracted from the SSC with a transmission efficiency of 99.7%. It is expected that eventually a beam intensity of 400 μA will be available from the SSC.

BEAM LINES FOR RADIOISOTOPE PRODUCTION

Initially, a single horizontal target station, with local shielding in the vault and an automatic target handling system, was provided for the production of radioisotopes at a maximum beam intensity of 100 μA. Two laminated magnets are used to sweep the beam in a circular path over the target at a frequency of 450 Hz. A vertical beam line [12], designed for a maximum beam intensity of 400 μA, was completed a few years ago and is since in routine use. Ferrite magnets are used to sweep the beam in an adjustable circular pattern over the target at a frequency of 3 kHz.

These beam lines are currently being modified to allow simultaneous irradiation of two production targets [8]. An 800 mm long electrostatic channel, operating with a deflector voltage of 100 kV across a 30 mm gap, will be used to deflect about a third of the beam away from the existing beam line. Two thirds of the beam will then be used in the vertical beam line while the deflected beam will be diverted around the 90° vertical bending magnet before it is directed to the horizontal beam line for radionuclide production. The expected beam loss for a 400 μA total beam current is 2.2 μA. To prevent instability in the horizontal beam position from increasing the beam loss in the septum of the electrostatic channel, the beam is rotated through 90° with five quadrupole magnets that are rotated through 45° with respect to the standard orientation of quadrupole magnets. The entrance of the septum magnet is 2 m downstream from the entrance of the electrostatic channel. The beam splitter is in an advanced stage of construction.

BEAM DIAGNOSTIC EQUIPMENT

Operation with high beam intensities made non-destructive diagnostic equipment for alignment and continuous display of the beam position and intensity along the beam lines essential. Non-destructive beam position monitors (BPMs), shown in Fig. 6, were developed in co-operation with the Forschungszentrum Juelich in Germany and installed in the transfer beam line between SPC1 and the SSC and in the beam lines to the neutron therapy and the radioisotope production vaults [13,14].

These monitors have been designed to fit into the available space inside the existing diagnostic chambers and use existing flanges for signal feedthroughs. This limits the overall length of a monitor inside the shortest

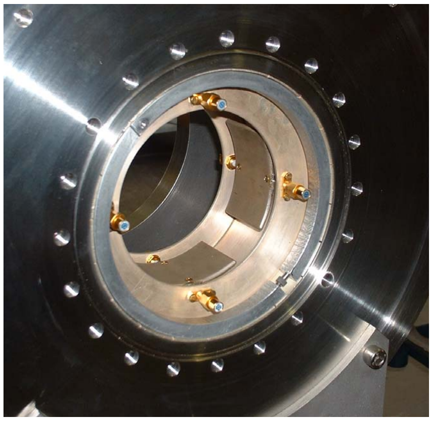

Figure 6: A BPM inside a diagnostic chamber.

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 the 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 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 nineteen BPMs that were installed have become indispensable diagnostic tools at beam intensities above 300 nA. In addition to the BPMs ionisation chambers that can be clamped around the beam pipes are used as stray-beam detectors.

Beam intensity is another important parameter to be monitored continuously during target bombardment at high intensities. The construction of the high beam power target does not facilitate direct current measurement, since the target itself is electrically grounded. The target current can therefore only be measured non-destructively. Capacitive probes and digital signal processing provide the most economical solution to non-destructive current measurement. A CompuScope 85G PCI-bus based oscilloscope card, which can perform analog to digital conversions at a rate of $5 \cdot 10^9$ samples per second with 8-bit resolution, is used to digitize the signal waveform. The measuring software processes the digitized waveform; it cleans the beam pulse from RF-pickup, detects its boundaries and calculates the electric charge contained in the beam bunch [15].

The supports of the capacitive probes that are presently being used for beam phase measurement in the SSC intercept beam. These probes can therefore not be used for continuous display of the beam phase as a function of radius in the SSC. New non-destructive and more sensitive phase probes are being planned for the SSC. These probes will also facilitate field isochronization during energy changes. To avoid time-consuming development work, the possibility of measuring the beam phase with a commercial RF lock-in amplifier model SR844 from Stanford Research Systems was investigated. The phase of beams with intensities in the nA range was measured with a commercially available lock-in amplifier, using a multi-head probe and the first non-interceptive phase probe that was installed in the separated-sector cyclotron, by partly cancelling the pick-up signal with a harmonic derived from the dee voltage by using an AD9952 synthesizer [16].

THE CN VAN DE GRAAFF

In recent years the reliability of the accelerator deteriorated drastically. A major effort therefore had to be made to increase the reliability of this forty-year-old accelerator and to improve the beam quality. Beam delivery was intermittent due to sparking in the electrostatic lens directly downstream from the ion source. To eliminate sparking the pumping speed in the electrostatic lens system was increased by remachining every electrode to remove all material not required for mechanical strength, or which does not contribute to beam focusing, in order to enhance gas flow. The effect of these modifications to the electrodes was studied with the program TOSCA to ensure that the beam optical characteristics would not be influenced negatively. With these improvements in the pumping speed the variation in beam intensity due to discharges is now less than 2%.

The ion source characteristics and optimal operating conditions were determined on an ion source test bench. The measured beam characteristics were used to calculate the beam envelopes through the accelerator, from the ion source up to the analysing magnet directly after the accelerator, and in the different beam lines, using the computer codes TRANSPORT, IGUN and TOSCA. These calculations showed that with two additional quadrupole magnets, new object slits, and repositioning of the image slits, the energy resolution could be improved from 1% to 0.15% for a 1 mm slit aperture. An energy resolution of 0.12% was obtained in practice. Operation of the Nuclear Microprobe, at proton energies in the energy range 1 MeV to 4 MeV, with beam intensities of tenths of pA on target surface is now possible. These improvements also resulted in a remarkable increase in the reliability and stability of the beam in the microprobe facility [17].

The pole gaps of the magnets in the beam line magnets were increased by 60%. With these larger apertures and the additional steering magnets and diagnostic equipment that installed it is now much easier to set-up the accelerator and beam lines, especially with computer control and readout systems that were installed.

THE EN TANDEM VAN DE GRAAFF

The two-and-a-half-year refurbishment of the accelerator, including the associated beam lines and infrastructure commenced early in 2005. The interior of the accelerator building was reconstructed into the following dedicated areas: accelerator vault, experimental vault, control room, electronics room, data capture room, offices and user areas. All beam lines were removed from the accelerator vault, which left only the accelerator and three large magnets in place. The injection and extraction beam lines were redesigned based on beam optics calculations with the programs TRANSPORT and TOSCA. Following these simulations, new vacuum chambers, diagnostic components (slits and faraday cups) and the beam transport system layout were designed and manufactured. Beam profile monitors and additional steering magnets were also installed.

The 860A SNICS (Source of Negative Ions by Cesium Sputtering) ion source was upgraded to an 860C for improved beam emittance. The 860C electronics control rack was completely rebuilt and optical links installed for control of the high-voltage components. A new turbo-molecular pump was installed to improve the vacuum conditions inside the source.

The belt-charge system was replaced with a dual Pelletron charging system. New high-voltage grading resistors and resistor mounts were installed. The accelerator tubes were replaced with new tubes featuring axial electric field and spiralled magnetic field for electron suppression. The gas stripper was modified to a recirculating gas stripper by installing a turbo-molecular pump in the high-voltage terminal to recycle the stripping gas. A new terminal potential stabilizer (TPS) system was installed. The corona probe, generating voltmeter (GVM) and capacitive pick-offs (CPOs) were refurbished and re-installed. The TPS also incorporates a slit feedback control option for beam energy stabilization. Optical alignment of the entire beam transport system, including the accelerator tubes, was completed towards the end of the installation period.

The entire vacuum system was redesigned to suit the new installation. Some new turbo molecular pumps and vacuum valves were added in critical areas and the system is fully computer controlled. A computerized control system and customized software was developed to allow full monitoring and control of all system parameters from a central console in the control room. Existing power supplies were fitted with control interfaces. New current measurement electronics, SABUS control modules, control modules for diagnostic components and new power supplies were installed in the electronics room. A safety-interlock system (SIS) was introduced to prevent critical components from being damaged due to operator error or unexpected power failures. Beams of carbon and hydrogen ions have been accelerated successfully up to terminal voltages of 4 MV.

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