COMMISSIONING OF THE NAC SEPARATED-SECTOR CYCLOTRON

A.H. Botha, H.N. Jungwirth, J.J. Kritzinger, D. Reitmann, S. Schneider
National Accelerator Centre, CSIR
P.O. Box 72, Faure, 7131, Republic of South Africa

Summary. The separated-sector cyclotron (SSC) at the National Accelerator Centre has recently been completed. Proton beams have been extracted from the injector cyclotron, injected into the SSC and accelerated to the full design energy of 200 MeV at the extraction radius. Proton beams with energies of 66 MeV and 200 MeV have been extracted from the SSC. The maximum design energy of 200 MeV for protons has therefore been achieved in terms of both internal and external beams. The main subsystems such as magnets, rf, diagnostic as well as injection and extraction components perform satisfactorily. By employing three 2200 l/s turbomolecular pumps and two 25 m^3/s cryopumps a pressure of 7×10^{-7} mBar has been achieved. The SSC-resonators have been operated with dee voltages up to 250 kV which corresponds to a maximum proton energy gain per turn of 1 MeV. Parameter settings such as currents for the main and trim coils and injection and extraction components predicted by field measurements and orbit calculations have to a large extent been verified in practice. By analysing the 40 million measured field data accumulated previously, the magnetic field in the SSC can be evaluated to within a few parts in 10^4. A deflection efficiency of 95% has been achieved for 66 MeV protons with relatively little effort. The same efficiency could not be obtained for 200 MeV protons because of the larger number of turns and the relatively long pulse length of 15°. Characteristics of the main components of the SSC and practical results obtained during acceleration of the above-mentioned beams are presented below.

Introduction

A k=200 MeV separated-sector cyclotron and a k=8 MeV solid-pole cyclotron SPC1, as light-ion injector, have been constructed at Faure near Cape Town.[1,2,3] A second injector cyclotron SPC2, for pre-acceleration of heavy and polarized ions is presently under construction.[4] An ECR source for heavy ions and a polarized ion source are on order and will be delivered during 1988. Beams from these sources will be axially injected into the second injector cyclotron. The beams delivered by these machines will mainly be used for radiotherapy, the production of radioactive isotopes and for basic research in nuclear physics. The layout of the cyclotrons and experimental facilities is shown in Fig. 1. A 66 MeV isocentric system for neutron therapy has been installed and will be commissioned in the near future. The facilities for basic research in nuclear physics consist of a 1.5 m diameter scattering chamber, a three-armed gamma-ray correlation table, a high-energy gamma-ray detector, a k=600 QDD spectrometer (presently under construction) and a beam swinger facility, which is now being designed, for neutron time-of-flight measurements. An automatic target changing system for isotope production is under construction.

The separated-sector cyclotron is a four-sector machine with a sector angle of 34°. Twenty-nine trim-coils, some of which can be independently adjusted in the individual sectors, make provision for isochronising the field. The two $\lambda/2$-resonators provide

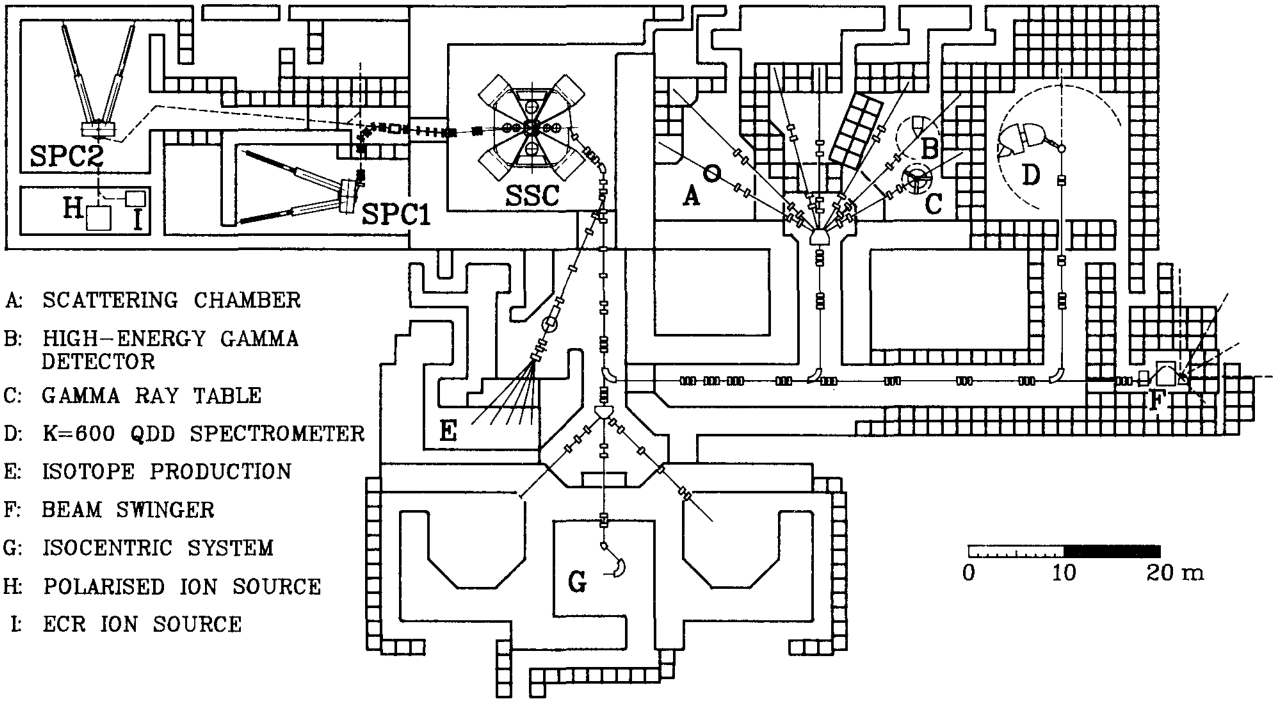

Fig. 1 The lay-out of the NAC cyclotrons and experimental facilities.

an energy gain of 1 MeV per turn for protons. Beam is injected into the SSC by means of a steering magnet at the entrance of a valley vacuum chamber, two bending magnets, BM1 and BM2, in the central region of the machine, and a magnetic inflection channel in the pole tip of a sector magnet. Extraction is done with an electrostatic channel and two septum magnets, SPM1 and SPM2. Figure 2 shows the fully assembled separated-sector cyclotron.

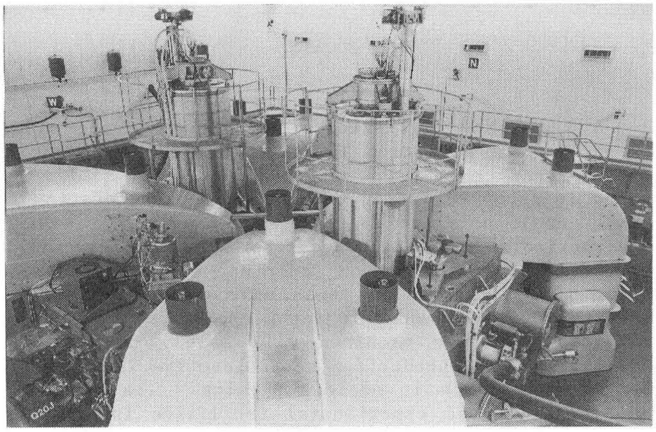

Fig. 2 The assembled SSC.

The main components of the SSC were assembled during September and October 1985. Figure 3 shows a bar chart of the commissioning of the SSC and other facilities at the NAC. The first internal beam of 66 MeV protons was accelerated on the 9th of October 1985. The maximum design energy of 200 MeV for protons was achieved in May 1986 with an internal beam. During July a 66 MeV beam of protons was extracted from the SSC. Early in September a 200 MeV beam of protons was extracted.

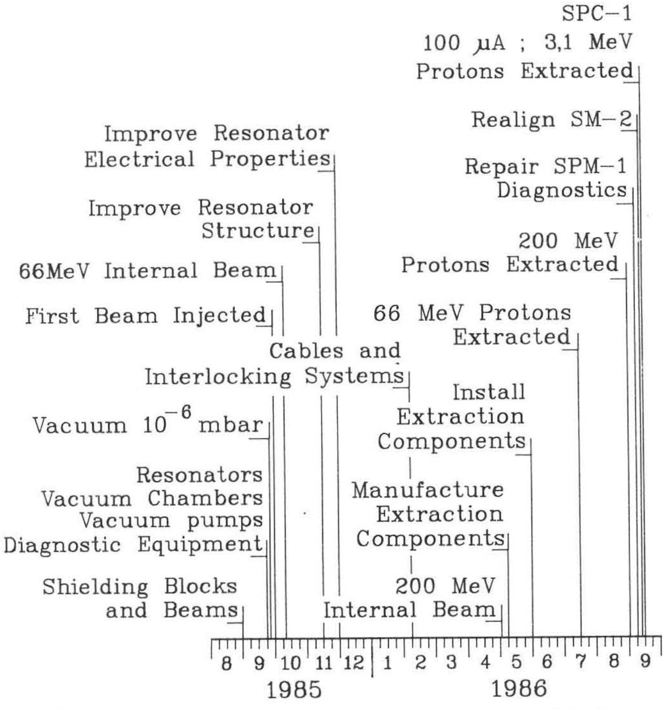

Fig. 3 A bar chart of the activities at the NAC during the past year.

Acceleration of protons in the SSC

The SSC, apart from the extraction components, was assembled early in October 1985. After pump-down a dee voltage of 70 kV could be maintained without excessive sparking. Attempts to inject a 3.1 MeV beam of protons showed that the last steering magnet, with a $B\ell$-value of 3.2 mT.m, in the transfer beamline had insufficient capacity to steer the beam along the centre line of the south valley chamber. Calculation of the beam path, in the stray field between sector magnets, showed that a $B\ell$-value of 0.2 T.m was required to inject protons of up to 8 MeV into the SSC. A few days later a new magnet was installed and 3.1 MeV beam of protons was directed to the central region of the SSC and injected into the machine with relatively little effort. By adjusting the currents through the last steering magnet and the injection components the beam could be directed to make a complete turn in the SSC with the rf voltage off. The radial position of the beam at two differential probes and a beam stop were noted. The rf was then switched on and the phase adjusted to position the beam at the same radial values as before. The phase of the dee voltage was then increased by 90°. When the probes were then moved out radially the different orbits could be observed as the beam was accelerated. The beam disappeared about halfway through the machine as the probes were moved out. By lowering the magnetic field by 0,1% with respect to its predicted value a 2 μA beam could be accelerated to 66 MeV at the extraction radius with 100% transmission through the injection components and remaining part of the SSC. No adjustments were made to the trim-coil currents. The first injection of the beam and acceleration to the extraction radius took 8 days. During this beam experiment it became apparent that the SSC operates reliably and repeatably. The current settings of the different magnets and coils remained the same from day to day for the same beam patterns. The ease with which the beam could be steered, without loss through the injection components, was particularly encouraging. Because urgent construction work had to be carried out no further beam development was done during 1985.

During the remaining months of 1985 the voltage holding capability of the SSC resonators was increased to 250 kV and on the 1st of May this year a 1 μA beam of protons was accelerated to 200 MeV with 100% transmission up to the extraction radius. The same procedure was followed as before for the 66 MeV beam with the only difference being that because of the larger number of turns it was necessary to adjust both the trim-coil and main coil currents in order to keep beam phase within reasonable limits. Again parameter settings were repeatable and stable.

During May and June the extraction components were installed and during July extraction of a 66 MeV beam of protons was attempted. A 3.1 MeV beam with an energy spread of 10^{-3} and a phase length of 12° was injected. The two differential probe heads were used to centre the beam. A radial beam pattern obtained by driving a 0.12 mm thick vertical wire through the beam is shown in Fig. 4.

The decrease in beam current at larger radii, is due to the decreasing sensitivity of the wire with energy while the drop in current during the first few turns and the subsequent increase in current is due to a vertical oscillation of the beam. The oscillation was caused by a tilt of one of the sector magnets which amounted to a vertical displacement of 1.2 mm at the injection orbit and zero displacement at the extraction radius. The effect of the vertical displacement of the magnet on the beam is accentuated by the fact that ν_z is close to unity. Calculation indicated a vertical oscillation amplitude of 10 mm for a beam injected in the median plane and the above-mentioned magnet displacement. The beam phase was measured with a capacitive probe which can be moved radially. Figure 5

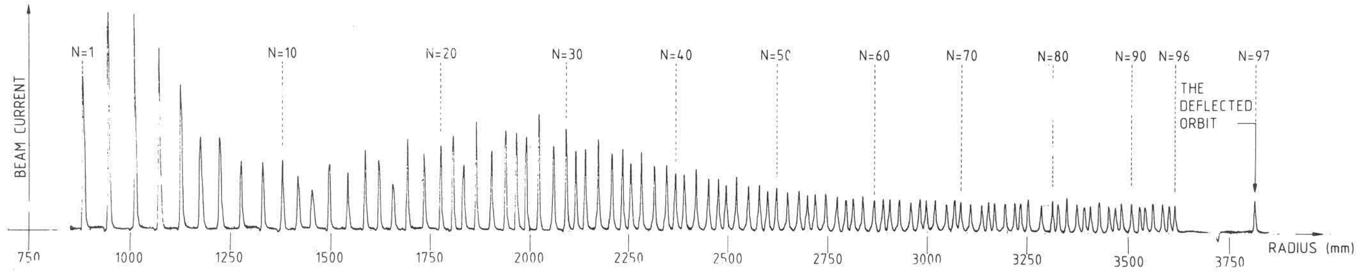

Fig. 4 An orbit pattern of a 66 MeV proton beam.

shows the beam phase as a function of radius. While determining radial orbit patterns it became apparent that the beam width increases strongly with radius. The reasons for this were the increase in energy spread in the beam due to the wrong injection phase with respect to the rf and the fact that the magnetic field deviates appreciably from isochronism as can be seen in Fig. 5. Because of the high energy gain of 0.8 MeV per turn and the low injection energy of 3.1 MeV the injection phase has to be optimised to within a fraction of a degree in order to minimize the energy spread and therefore beam width at extraction. The beam was extracted with the following fields in the extraction components: 26.6 kV/cm in the electrostatic channel and 55 mT and 0.47 T respectively in the two magnetic channels. A 3 μA beam of protons was extracted with practically 100% transmission through the SSC in spite of the above-mentioned vertical oscillation. Extraction of the beam took place with remarkable ease. The last beam peak in Fig. 4 shows the horizontal beam distribution after the beam had passed all three extraction components. The distribution of the extracted beam in the horizontal and vertical directions is shown in Fig. 6. The same beam patterns and extraction efficiency could be obtained from day to day with the same parameter settings.

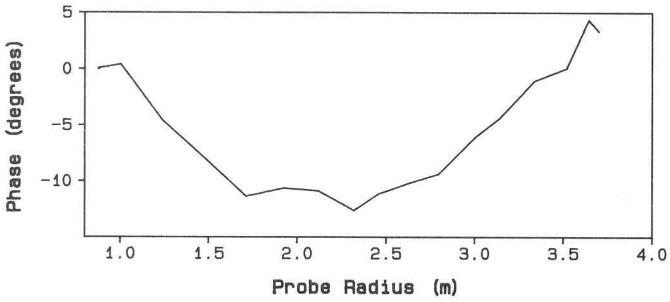

Fig. 5 The phase history of a 66 MeV proton beam.

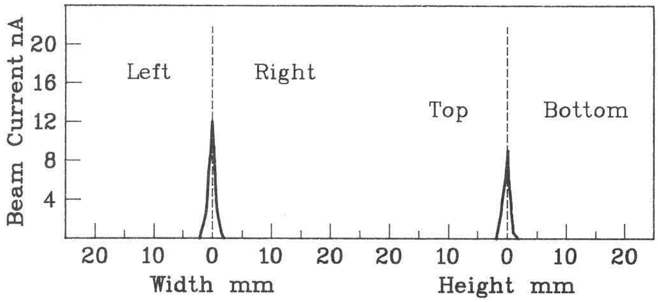

Fig. 6 Horizontal and vertical beam distributions of the extracted beam.

At the beginning of September a 200 MeV beam of protons was extracted. A computer program was developed to predict improved trim-coil current settings from measured phase values. Figure 7 shows the reduction in the phase excursion by employing the above-mentioned program.

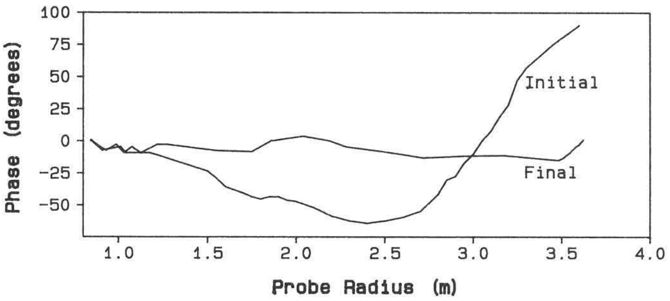

Fig. 7 The phase history of a 200 MeV proton beam before and after adjustment of the trim-coils.

In the case of the 200 MeV beam the vertical displacement caused much more trouble because the ν_z-value approaches unity both at injection and extraction and also because of the larger number of turns in both these regions. Calculations and measurements showed that oscillation amplitudes as large as 13 mm can occur for a beam injected in the median plane. Because of the long pulse length (the buncher for the transfer line will only be installed during December) and the larger number of turns, single turn extraction and 100% transmission through the machine could not be achieved. After extracting a 200 nA beam of 200 MeV protons, we decided to realign the magnets and wait for installation of the buncher before attempting to improve the extraction efficiency above the present 10% for 200 MeV protons. The 200 MeV beam was extracted with the following fields in the extraction components: 60 kV/cm in the electrostatic channel and 0.1 T and 0.94 T respectively in the two magnetic channels.

The Sector Magnets

The four 34° sector magnets required little attention during commissioning and initial operation of the SSC, because most operational problems had already been sorted out in the course of the field measurements. Details of the magnet characteristics and of the field control provided with 41 power supplies have been described previously.[5] Five of these supplies are used for the main excitation of the magnets and the remaining 36 supplies for radial field trimming. The bending limit of the magnets is equivalent to 230 MeV for protons, but decreases gradually to k=210 MeV for very heavy ions. The power supplies are operated via a CAMAC interface and the NAC control system. Field setting is carried out under computer control according to a very effective procedure which provides stable (10^{-5}) fields in the SSC after only 2 to 4 hours depending on the final field level.[6] The repeatability of the field is better than 10^{-4} for any given final excitation, independent of the excitation at the start of the procedure.

Commissioning of the SSC provided the first opportunity to demonstrate the quality of the field in the SSC and to determine by how much the predicted excitation currents have to be adjusted in practice. Predictions are based on a special isochronization method which makes use of the excitation properties of the magnets determined from the results of field measurements. For this purpose the magnetic field in the SSC can be compiled for any given set of currents by means of superposition from a data base which has been established by analysing and processing nearly 800 measured sector fields. The main excitation currents predicted initially for 66 MeV and 200 MeV proton beams have resulted in field levels which were 0.1% too high, most probably because the reduction of the 66 mm pole gap by up to 0.06 mm due to the additional atmospheric forces on the magnet vacuum chamber had not yet been taken into account. It was particularly encouraging, however, that only minor adjustments of the radial field shape were necessary to optimize the phase history of the beam. Neither first nor second field harmonics were significant enough to require correction. The most serious problem was caused by the 1.2 mm vertical misalignment of sector magnet SM2 at injection.

Vacuum System

Commissioning and initial operation of the vacuum system have turned out to be easier than anticipated, and indicate that the SSC has very good vacuum properties. The lay-out of the system and the characteristics of the pumps provided are shown in Fig.8 The vacuum enclosure features eight separate chambers which are connected by means of pneumatic expansion seals operating at a pressure of 2 bar. The chambers have a combined volume of 50 m^3 which, together with a calculated gas load of 10^{-1} mbar ℓ/s (after 15 hours of pumping), was used as the basis for selecting the sizes of the pumps as shown. The gas load includes outgassing and permeation from all elastomer seals (~ 40%), as well as some leakage. The pumps are installed only on the two resonators and the two valley chambers.

Due to the unconventional construction of the magnet vacuum chambers all coils and steel surfaces of the sector magnets are excluded from the vacuum region. The vacuum system is operated and interlocked using a microprocessor-based control system.[7]

The leak tightness and sealing characteristics, as well as the outgassing properties of the vacuum envelope are quite satisfactory. Only a few leaks had to be corrected during the final preparations for the first pump-down of the SSC, and some poorly soldered joints between stainless steel and copper pipes for water cooling have been found to be prone to develop leaks in the initial operating phase. All significant leaks were repaired, however, and the SSC is now virtually leaktight. Figure 9 shows the total amount of gas which the vacuum envelope of the SSC presents to the pumps after different periods of pumping and exposure to atmosphere.

More than 90% of the rest-gas is water vapour. The calculated design value applies only when the exposure is short enough (a few hours) and the system has been flushed with nitrogen. During the first pump-down (and also when the SSC is kept open for a few days or longer) the gas load was initially much higher than expected. About 5 to 8 days pumping was necessary to reduce the gas load (and outgassing rate) to the same level as for a short exposure during operation at a later stage. Rf-operation of the resonators helps to clean some surfaces more quickly.

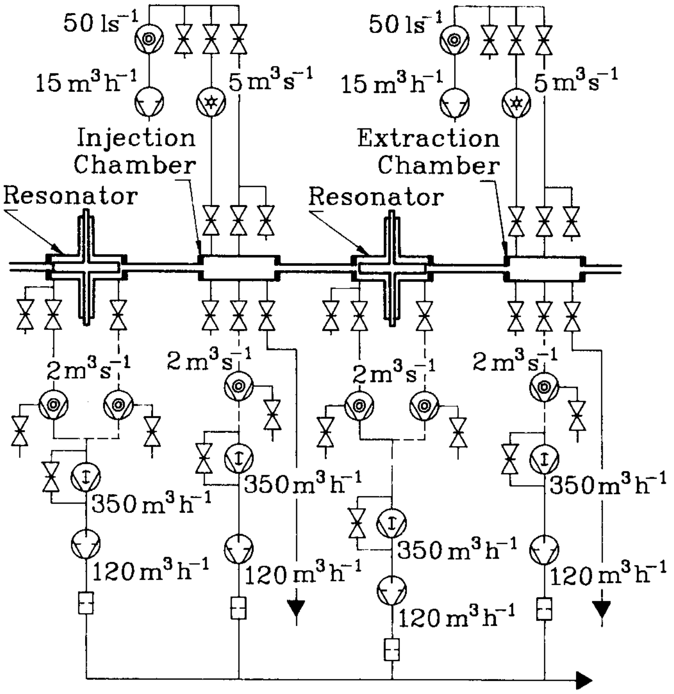

Fig. 8 The lay-out of the SSC vacuum system.

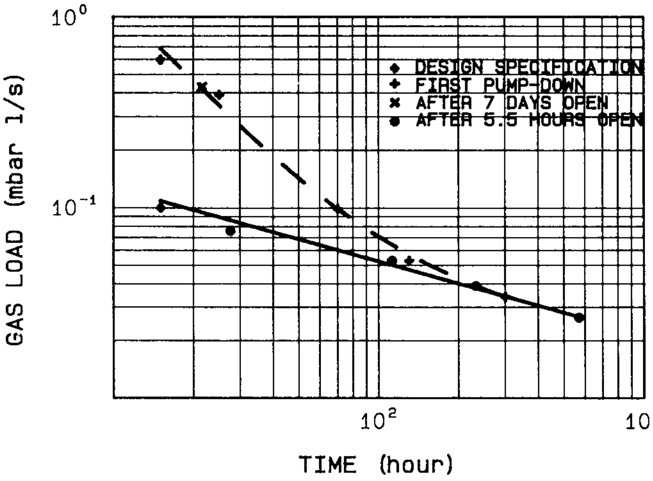

Fig. 9 Evolution of the gas load in the SSC with pumping time after different periods of exposure to atmosphere.

Installation and operation of the eight inflatable seals between the chambers did not cause serious problems. When all chambers were in position the pneumatic stainless steel cushions (130 mm wide) were inflated with argon gas to 2.3 bar, and the space between the two (inner and outer) O-rings forming the guard vacuum on either side of the cushions was evacuated to test each seal for leak-tightness. Two seals on the extraction valley chamber leaked in the beginning. One leak was caused by a bolt head protruding too far from one of the retaining strips provided for the O-rings. The other seal leaked because the O-rings had been forced out of their retaining strips when the chamber was lowered into its final position during installation. For correcting these leaks the chamber had to be retracted slightly.

The guard vacuum is now about 0.5 mbar under typical operating conditions, for which the argon pressure in the cushions is reduced to 1.8 bar.

The seals are operated manually at present from a local control panel in the SSC-vault, but a remote control panel is ready for installation.

When the SSC was pumped down for the first time the operating pressure ($\sim3\times10^{-6}$ mbar) was reached after approximately 100 hours of pumping. Only three of the six turbo-molecular pumps indicated in Fig. 9 were installed then. Also the control system was not yet available, but it has since been commissioned and now gives reliable service. The two 2200 ℓ/s turbo-molecular pumps shown in Fig.9 are still not mounted on the valley chambers as replacements for two larger ones (6500 ℓ/s) which vibrate too much for this application. In spite of this handicap the operating pressure is now reached regularly in 30 to 40 hours, when the cryopumps are introduced early enough (at 10^{-4} mbar), except if the SSC has been open to the atmosphere for too long. Figure 10 shows a typical pump-down characteristic of the SSC, when the cryopumps are introduced at different and somewhat later times.

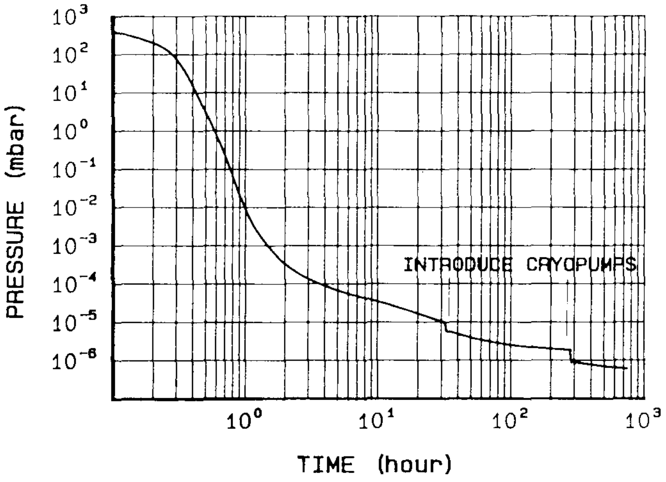

Fig. 10 The pump-down curve for the SSC.

The 10^{-7} mbar range is only reached after more than 200 hours of pumping. Under these conditions the two cryopumps are sufficient to maintain the SSC operational pressure without turbomolecular pumps, because they also pump the resonators through the aperture of each magnet vacuum chamber which has a conductance of 2000 ℓ/s. Operation with one cryopump is still possible, but not without both of them, for instance when they both have to be regenerated. From this point of view it is essential that the remaining turbomolecular pumps are installed on the valley chambers.

The RF System

The main characteristics of the rf system are are listed in Table 1.[8] The resonator was tested on its own prior to the evacuation of the SSC ring by using blanking plates on the two sides where the magnet vacuum chambers normally fit. Owing to the sensitive protection of the amplifiers it was not possible to attain voltage on the evacuated resonator by using the same fast-rise method which is suitable for the resonators of the injector cyclotron. However, moving the coupling capacitor closer to the inner delta enabled voltage to be attained. A high power level during the first µsec is crucial to overcome multipacting, hence a "kick-pulse" method was developed. The 15 µsec pulse at 100 kW level is followed by a 10 kW sustain level. This avoids tripping the reflected-power and over-current relay-protection of the amplifier while ensuring reliable voltage starting with the coupling capacitor in the 50 ohm position. The tuned circuits in the amplifier limit the rf rise-time at the resonator to 1 µsec. It is also important that the power must be completely switched off for at least one second before applying the "kick-pulse". In very difficult starting conditions even one or two minutes was required. For a successful start the resonator must be tuned exactly to the required frequency or slightly lower, but definitely not higher. During this test period voltage up to 150 kV was achieved at 15 MHz.

Table 1.
Main characteristics of the rf system

2 Resonators:	
Frequency range	6 - 26 MHz
Range for adjustment of	
short circuiting plates	12,5 - 26 MHz
capacitor plates	6 - 12,5 MHz
Automatic fine-tuning	2 Capacitor plates
Power coupling	Capacitive for 50 Ω
Maximum voltage	250 kV
Maximum power per resonator	100 kW
Total height	10 m
Mass of a resonator	25000 kg
2 Power Amplifiers:	
Frequency range	5,5 - 27,5 MHz
Fully automatic tuning in time	40 sec
Maximum output power per amplifier	150 kW
Low noise	
Control and Stabilization:	
Phase variation	0,1 degree
Amplitude variation	1×10^{-3}
Microcomputer control	
Control-console control	

The second resonator was installed in the vault during August and both were positioned as part of the SSC ring during September. After evacuation of the ring, the two resonators accelerated the first internal beam to 66 MeV on 9 October 1985. For these tests, at 16,4 MHz, the voltage could not exceed 90 kV. Subsequent tests during October and November revealed that the voltage limitation was caused by a spurious 1 MHz oscillation of the driver-stage decoupling circuit when the amplifier was driving the resonator at more than 15 kW. This did not happen when the amplifier was connected to the dummy load. The problem was solved by adding a capacitor to the driver decoupling circuit. The problem only occurred in one amplifier.

For the first tests additional contact-fingers were added between the upper and lower inner-delta halves but some became dislodged during repeated evacuation and venting. The exposed sharp edges limited the voltage to 150 kV. Full design voltage (250 kV peak) was achieved at the end of November after removal of the additional fingers. Frequencies used during these tests were 12.5, 15, 16.4, 18, 22.5 and 26 MHz.

The stray field of the sector magnets has a very strong influence on multipacting and the X-ray level in a resonator. Operation at fields above 0.6 tesla was initially impossible, even with the "kick-pulse". The following conditioning procedure was found to give the best results. The resonator voltage was started at 22.5 MHz with a field below 0.6 tesla and increased to 150 kV. The magnetic field was then slowly increased (e.g. 2% step every 20 minutes). Each step resulted in a poorer vacuum condition. This gradually returned to the previous level in approximately 20 minutes. In this manner operation at maximum field was achieved after about 8 hours. Further operation at this level was beneficial. The process was repeated at 26 MHz. Most of the conditioning gave permanent improvement and venting to atmosphere does not cause a significant change. After a few months of operation the resonators are now so well conditioned that starting is no longer a problem at any magnetic field level. A resonator normally keeps running during the total field excursion from zero to negative maximum and then to positive maximum, as is used for resetting of the magnetic field.

Residual-gas analysis showed strong peaks of the following masses during conditioning: 44 (carbon-dioxide), 28 (carbon-monoxide), 18 (water vapour), 12 (carbon) and 2 (hydrogen). Subsequent inspection of the resonator rf surfaces showed areas with a thin carbon layer in the regions where the stray magnetic field is strongest and in the vicinity of the short-circuiting plates. These results confirm that multipacting is caused mainly by a layer of hydrocarbons, left on the metal surfaces after manufacture. The method described above is a quick and effective procedure to remove the contamination.

The west resonator was open between December 1985 and March 1986 to complete the installation of the first extraction magnet, which is positioned between the upper and lower inner delta halves of the resonator. With the aid of a frame it is possible to lift the complete top half of the resonator and to remove it from the vault.

Operation at 26 MHz (for 200 MeV protons) was reasonably successful although some discharges, only causing detuning, were experienced above 200 kV. Uninterrupted operation at 250 kV for periods up to 4 hours was achieved, but acceleration was normally done at 200 kV to avoid interruption. The discharges cause the amplifier to trip because the reflected power exceeds 15 kW. Restarting by an operator usually took a few minutes unless monitoring was continuous. Automatic restoration of voltage under microcomputer control has now been implemented and permits continuous operation at maximum voltage. Resonator sparkover only occurs above 260 kV. This confirms that the gap spacing in the resonators (95 mm at injection and 150 mm at extraction) is adequate for operation at 250 kV.

The vacuum performance and stability of the resonators have been excellent. Only one of the two fine-tuning capacitors is normally in use. Between 5 and 100 kW power level this capacitor only moves 3 mm to keep the resonator tuned. The thermal time-constant is approximately 10 minutes. After 20 minutes at high power the short-term phase variation is 0.2°. The automatic tuning system (with a 1° dead band) moves the fine-tuning capacitor after intervals of longer than a minute.

Large forces are exerted on the top and bottom plates of the resonator chamber while it is evacuated. These forces caused each transmission line to move inward by 2 mm and to tilt forward by 3 mm. The latter movement resulted in some loss of contact between the upper and lower inner delta halves. A support beam was added near each outer conductor, on the side which deflects most. Tilting is counteracted by adjustment of the 8 bolts at the centre of this beam. The ends of the beam is supported on opposite edges of the horizontal plate (where the side walls provide rigidity). The contact fingers between the inner delta halves now operate properly.

The Injection System

The pre-accelerated beam is injected through the south valley vacuum chamber into the central region of the SSC, where it is directed by two bending magnets, BM1 and BM2, into the magnetic inflection channel (MIC) in the pole-tip of one of the sector magnets. With the aid of only these three injection components the beam can be guided onto the desired orbit for beam acceleration. Only the MIC can be moved by about 45 mm to account for the various injection orbits for the variable-energy ion requirements. A view onto the central region is shown in Fig. 11. The design parameters of the injection components are summarised in Table 2.

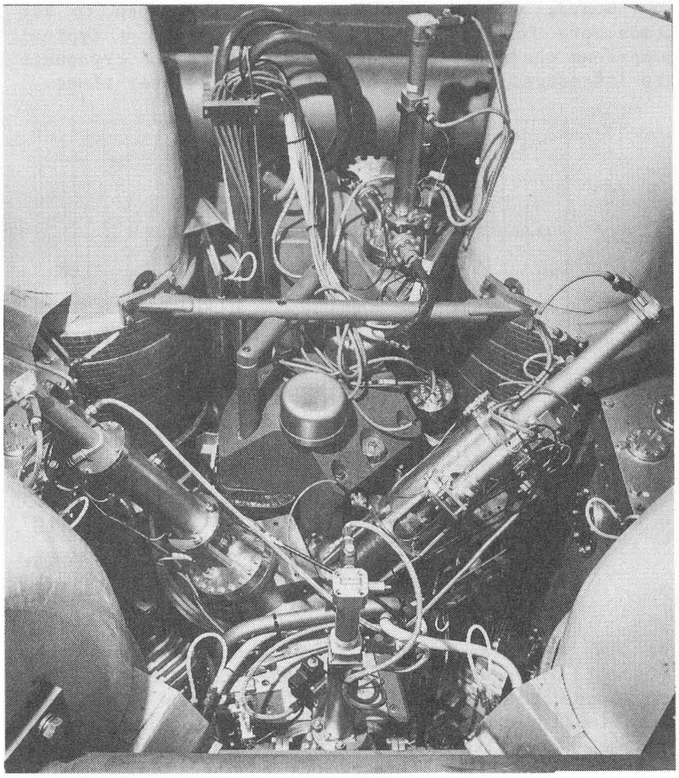

Fig. 11 A view of the crowded central region of the SSC as seen from the top of the injection valley vacuum chamber. As the beam enters the central region it is first bent by 18° to the left by bending magnet BM1 and then by 88° to the right by bending magnet BM2 before entering the magnetic inflection channel in the pole-gap of sector magnet SM1 (upper right). The remainder of the central region vacuum enclosure is mainly occupied by a harp in front of BM1, a beam profile scanner and capacitive phase probe between BM1 and BM2, and a second harp between BM2 and the MIC.

During the initial beam acceleration trials (to 66 MeV) precessional injection had to be used in order to increase the orbit separation to clear the MIC after the first turn, because the maximum available rf voltage was limited to only 70 kV. Centred orbits can be seen in Fig. 4 for an rf voltage of 190 kV. Protons with the maximum injection energy of 8 MeV have also been injected successfully; with a maximum rf voltage of 250 kV the required 43 mm orbit separation could be obtained.

Table 2.

Parameters of the injection and extraction components

Parameter	Injection Components			Extraction Components		
	BM1	BM2	MIC	EEC	SPM1	SPM2
Field required for 8 to 200 MeV protons [T]	0,65	1,35	1,07+0,22	50kV/cm	0,10	0,94
Excitation current for 8 to 200 MeV protons [A]	450	560	1000	few μA	500	1460
Maximum field value [T]	0,88	1,69	1,07+0,30	80kV/cm	0,20	1,30
Maximum power consumption [kW]	9,3	20	26	0,6	11	145
Usable aperture [mm]: gap width x height	50x36	50x36	50x27	(5-15)x30 adjustable	30x30	40x40
Radius of curvature along centre-line [mm]	650	304	325	straight	straight	2600
Angle of deflection [degrees]	18	88	~107	0,3	0,8	15,1
Number of turns of coil	48	80	12	-	6	18

Our concept of only a limited number of injection channels each with a wide acceptance - the MIC has a useable gap-width of about 50 mm - turned out to be a good solution. Without much optimization virtually 100% beam transmission is achieved through the injection system. We are furthermore pleased with the stability, repeatability and ease of operation. The latter is also due to the diagnostic devices (harps and scanners) in the central region and the ability to measure beam currents from the MIC collimators and liners.

The Extraction System

The extraction system of the SSC consists of an electrostatic extraction channel (EEC) in the south valley vacuum chamber, a small septum magnet (SPM1) inside the west-resonator and a larger septum magnet (SPM2) in the north valley vacuum chamber for the final deflection of the beam out of the SSC into the high-energy beamline.[9] The main design parameters of the extraction components are also summarized in Table 2.

The maximum design voltage of 120 kV was applied to the EEC after a day of conditioning without difficulty. The stringent design requirements placed on SPM1 have been met to our satisfaction. This magnet is mounted with its driving mechanism and flexible water and current supply leads inside the vacuum enclosure and limitedavailable space of the inner delta. Furthermore the strong rf stray fields, the fact that a scanner is mounted onto this magnet and the inaccessibility to the whole SPM1 had to be considered during the design and construction phase. The second septum magnet has been designed for high current densities (up to 200 A/mm^2) in order to produce the necessary flux densities envisaged for this magnet with the limited available septum width to deflect the beam out of the valley vacuum chamber. To reduce the power consumption larger return conductors were used for the coil. Each of the 18 turns is individually water-cooled. All the extraction components have been tested under full operating conditions and we are satisfied with their performance. The EEC and SPM2 are shown in Figures 12, 13 and 14.

The first particles extracted from the SSC were 3 μA 66 MeV protons. Special attention was paid to obtain fairly well-centred orbits with clear beam separation at the extraction radius as can be seen from the orbit pattern shown in Fig. 4. A very encouraging feature was the high extraction efficiency (i.e. ⩾ 95%) obtained during the first few hours of the initial trial runs. In actual fact, after the initial positioning and setting up of the three extraction components to their calculated values for beam extraction, the beam stop was driven beyond the extraction radius and the beam was deflected out of the valley-vacuum-chamber.

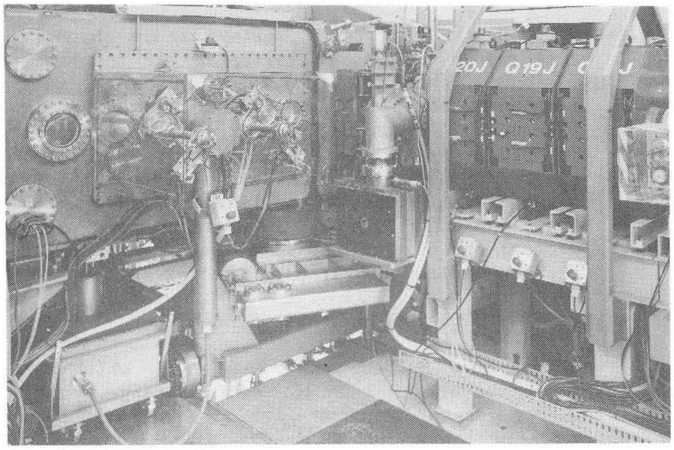

Fig. 12 The EEC installed in its final position on the injection valley vacuum chamber. The independent drive mechanisms, the cover housing the high-voltage feedthrough as well as the high-voltage damping resistor (on the floor) are clearly visible. Part of the transfer beamline from SPC1 can be seen on the right hand side.

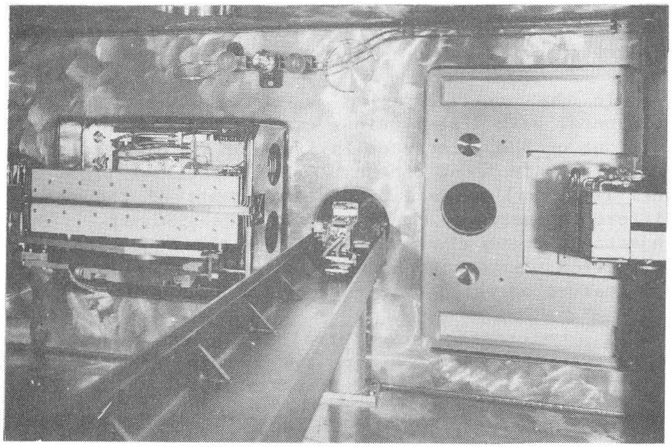

Fig.13 A view inside the extraction valley vacuum chamber facing part of the rear wall. In the direction of the beam we see the second septum magnet (left) with the second multi-head probe behind it and the copper extraction collimator (right) mounted onto a big flange which will eventually carry the set of capacitive phase probes.

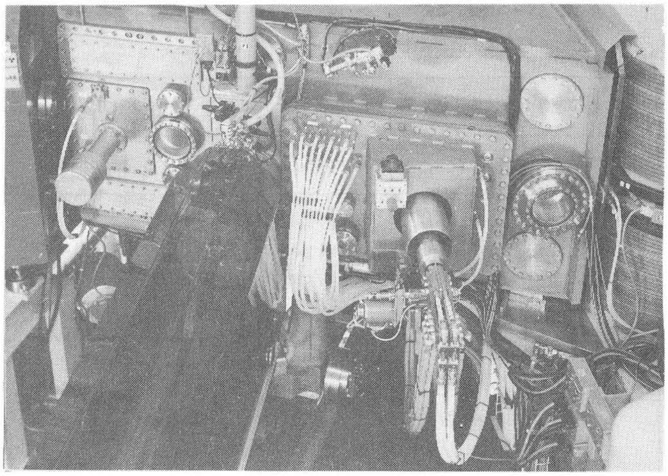

Fig.14 View of the extraction valley vacuum chamber. From the right i.e. the direction of the beam, we have a viewing port onto which we will eventually mount the extraction probe; the big flange onto which the second septum magnet is mounted with all its cooling-water supplies; the multi-head probe with its semi-transparent cover; the extraction collimator flange which will actually carry the stationary phase probes; and part of the first bending magnet in the high-energy beamline on the far left.

The Beam Diagnostic System

Two multi-head probes and a beam stop, which can be positioned over the whole radial range, make provision for measurement of orbit patterns, beam intensity, beam phase and intensity distributions in the horizontal and vertical directions. Four heads, i.e. a 3-finger differential head, a tomography head, a 4-finger head and a capacitive pick-up head, have been installed on each of the two probe heads. Beams with energies up to 200 MeV and 10 kW beam power can be intercepted by the beam stop.

Axial graphite collimators, installed above and below the median plane in one of the valley chambers, limit the axial beam aperture to 26 mm. Beam currents can be measured from each of the 20 jaws of the 10 collimator pairs.

In the central region of the SSC vertical and horizontal beam distributions can be observed on a harp in front of BM1, a scanner in front of the BM2 and on a second harp in front of the MIC. A capacitive probe in this region allows accurate measurements of the phase difference between the beam and the SSC rf. The injection vacuum chamber as well as the injection and extraction components have been amply provided with collimators on which beam current can be measured.

A microprocessor-controlled beam current measurement system monitors 64 static and dynamic current measurement channels for the SSC.

At present two radially moveable harps are being manufactured for the SSC. They will be installed in front of the EEC and SPM2. Twenty stationary phase probes, which will be mounted along a valley centre-line, as well as four differential probes, which will be installed in the magnet vacuum chambers, are being designed.

The diagnostic equipment of the SSC have been described in more detail elsewhere.[10]

High-energy Beamlines

The high-energy beamlines to the isotope-production area, one of the therapy vaults and up to the switching magnet in the nuclear physics area have been constructed. Three beamlines for nuclear physics experiments are nearly completed. Proton beams at 66 MeV have been directed along the therapy line to the Faraday cup in front of the therapy vault.

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