THE STATUS OF THE SOUTH AFRICAN NATIONAL ACCELERATOR CENTRE

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Abstract.- A National Accelerator Centre has been established in the Republic of South Africa in the vicinity of Cape Town. Two accelerators, an 8 MeV solid-pole injector cyclotron and a 200 MeV separated-sector cyclotron, are being built. The facilities of the Centre will be available for nuclear physics, isotope production and radiotherapy. Progress with the project and its present status are reviewed.

1. Introduction.- The National Accelerator Centre (NAC) was established to provide suitable accelerator facilities for the national needs of research groups working in nuclear physics, radiotherapy and isotope production. It was decided that a 200 MeV separated-sector cyclotron (SSC) would best meet the needs of the various disciplines. For light ions a current of 100μA is required for the energy range up to 100 MeV, while a current of 10μA will suffice in the range 100-200 MeV. For heavy ions a particle current of the order of several 100 particle-nA is expected. It was decided that an 8 MeV solid-pole cyclotron (SPCI) would be the most suitable light ion injector. The planned accelerators and other facilities have been described at the previous cyclotron conference[1] and elsewhere[2-9].

The project was approved in principle in December 1975 and after a period of studies, modelling and conceptual design was financed effectively from April 1978.

At the time of the previous cyclotron conference tenders for the SSC magnet steel were awaited. At that stage little work had been done on the injector cyclotron. Since then a large number of components for both the injector and the SSC have been designed and ordered. Progress with the project and its present status are reviewed below.

2. Lay-out of the facility.- The lay-out of the facility is shown in figure 1. After final acceleration in the SSC the beam can be directed to either the isotope vaults, radiotherapy vaults or experimental areas.

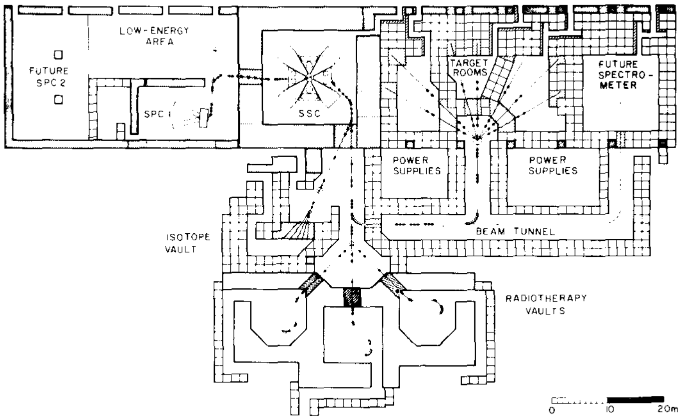

Fig.1: The lay-out of the facility showing the shielded areas and the planned beamlines.

3. The injector cyclotron.- Conditions for matching the injector to the SSC require that protons be accelerated to a maximum energy of 8 MeV at a frequency of 26 MHz, harmonic number 2, an average magnetic field of 0.86 T and an extraction radius of 0.476 m. The injector will also accelerate other light ions and some heavy ions. The main aspects of its design are described elsewhere in these proceedings[10].

The general lay-out of the injector is shown in figures 2 and 3. It is a two dee, four sector machine. The magnetic field can be adjusted by seven trim-coils and two sets of harmonic coils.

The beam is extracted by means of one electrostatic channel and two magnetic channels.

Three differential probes will be used to measure the position, size and vertical and horizontal distributions of the beam. The probes have been designed and are now being manufactured.

Figure 4 shows the assembled yoke in its final position on three adjustable feet. The main coils, main power supply and sectors have been delivered to the NAC. The magnet poles have been machined. The magnetic field measuring system is shown in figure 5. A Hall-probe is moved on a radial line by means of a stepping motor and measures the field at 30 mm intervals. The arm on which the Hall-probe moves is driven pneumatically on the toothed gear at 3° intervals.

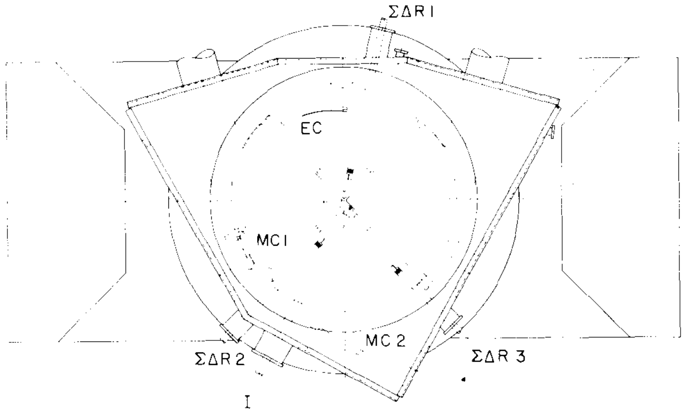

Fig.2: A median plane cross-section through the injector revealing the electrostatic channel EC, magnetic channels MC1 and MC2, ion source I and radial differential probes ΣΔR.

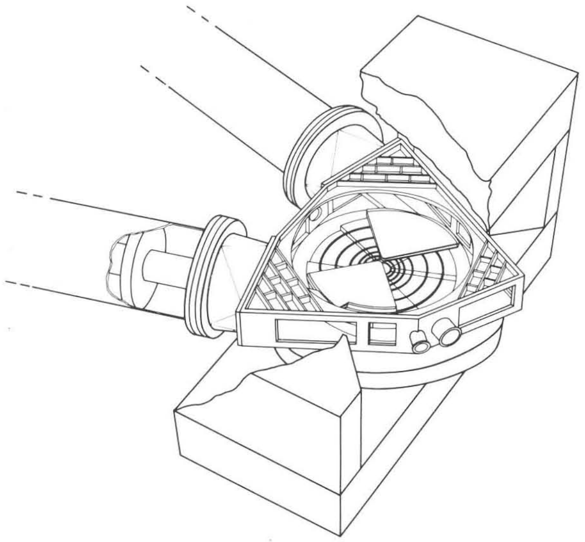

Fig. 3: A perspective view of the injector.

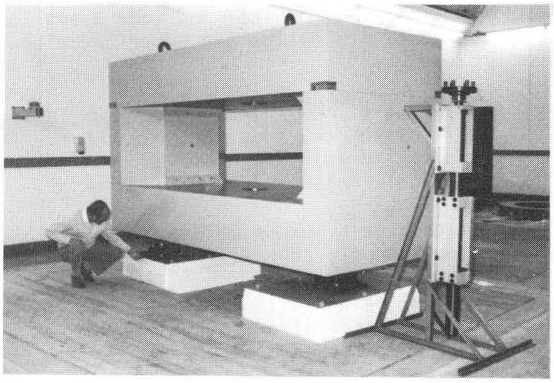

Fig. 4: The assembled yoke parts of the injector magnet.

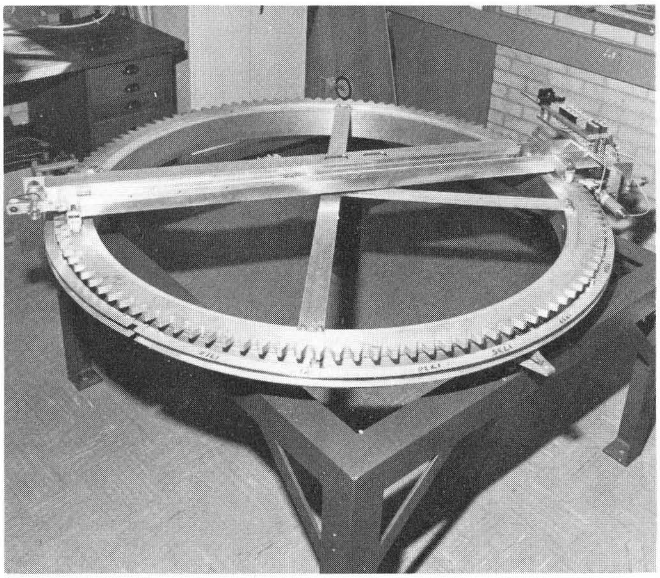

Fig. 5: Magnetic field measuring system for the injector.

The vacuum chamber, trim-coils and harmonic coils are on order. Figure 6 shows the lay-out of the trim-coils which will carry a maximum current of 160A.

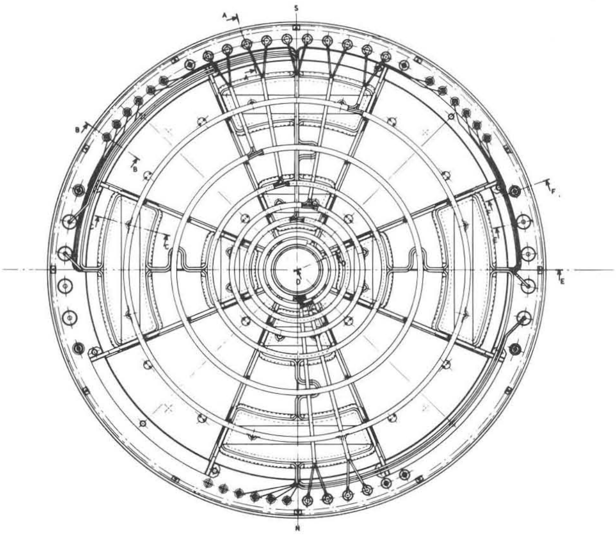

Fig. 6: Lay-out of harmonic and trim-coils for the injector.

Figure 7 shows a schematic diagram of the pumping system. One cryopump will be mounted on each of the two resonators. A turbo-molecular pump, with a roots-pump and rotary-vane pump as fore-vacuum pumps, is mounted on the vacuum chamber. It will be possible to pump the system from atmospheric pressure to 10^{-4}Pa in 2 hours.

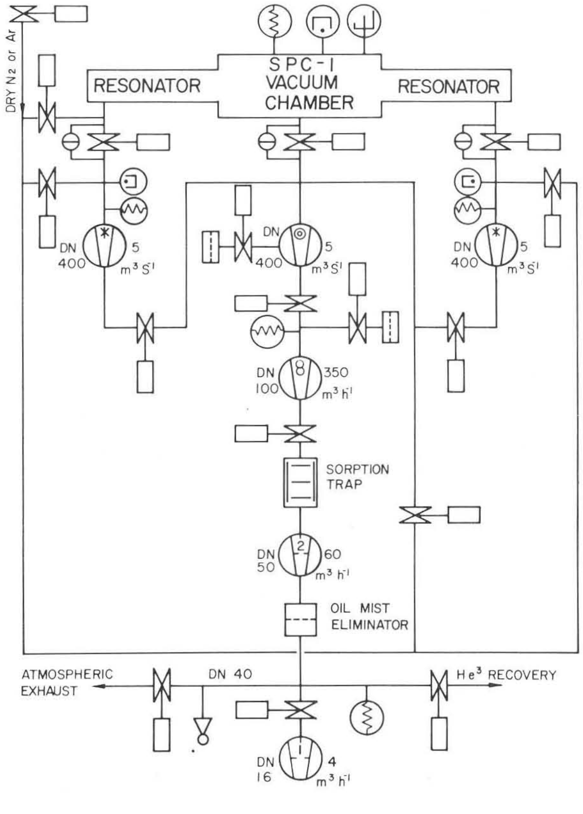

Fig. 7: Schematic lay-out of the injector vacuum system.

The rf system consists of two resonators, with 90° dees, two power amplifiers and small-signal equipment for phase and amplitude stabilization. The system can be tuned over the frequency range 8.6 MHz to 26 MHz.

A circuit diagram of the power amplifier is shown in fig. 8. The anode circuit is built up from a shorted co-axial line which is tuned with a single vacuum capacitor. The load (50 Ω) is connected at a tap-off point on this line and is transformed to a resistive load of 1000 Ω at the tube, an air-cooled power tetrode. The grid circuit consists of a π-network which is tuned by a variable capacitor and a variable inductor. The amplifier can deliver a maximum power of 25 kW at 26 MHz and 12 kW at 8 MHz.

Tests on the prototype amplifier shown in figure 9 have been completed and two amplifiers are now being built.

The resonators will be operated with a maximum dee voltage of 60 kV and each requires 14 kW at 26 MHz for this voltage. The cylindrical, co-axial resonators have diameters of 60 cm and 20 cm for the outer and inner conductors respectively. The mechanical design of the resonators is at an advanced stage.

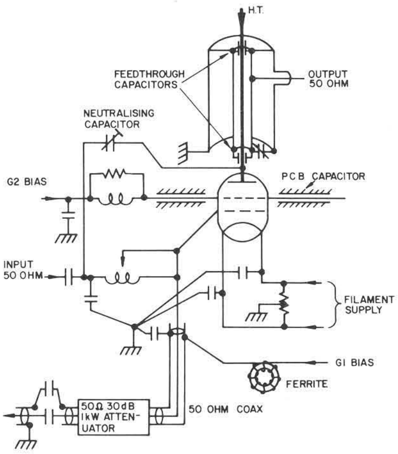

Fig. 8: Power amplifier circuit diagram for SPC1.

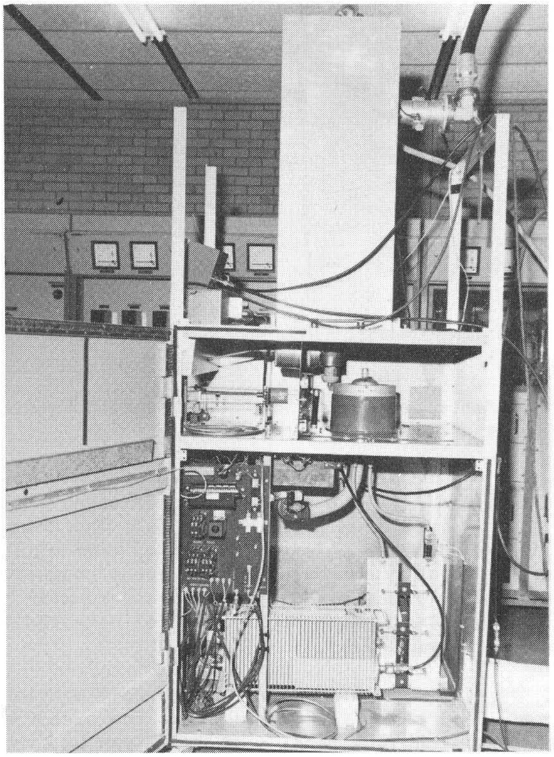

Fig. 9: Prototype power amplifier.

A dee voltage stability of 10^{-3} and a phase stability of 3 degrees have been obtained with the regulating system. Further development of this system will improve these figures.

4. Lay-out and beamlines.- The general lay-out of the NAC beamlines remained very much the same as reported before⁷⁾. The injection beam line shown in fig. 10, has been studied in more detail¹¹⁾. An order has been placed for all the quadrupoles and another is being prepared for the diagnostic elements of this line.

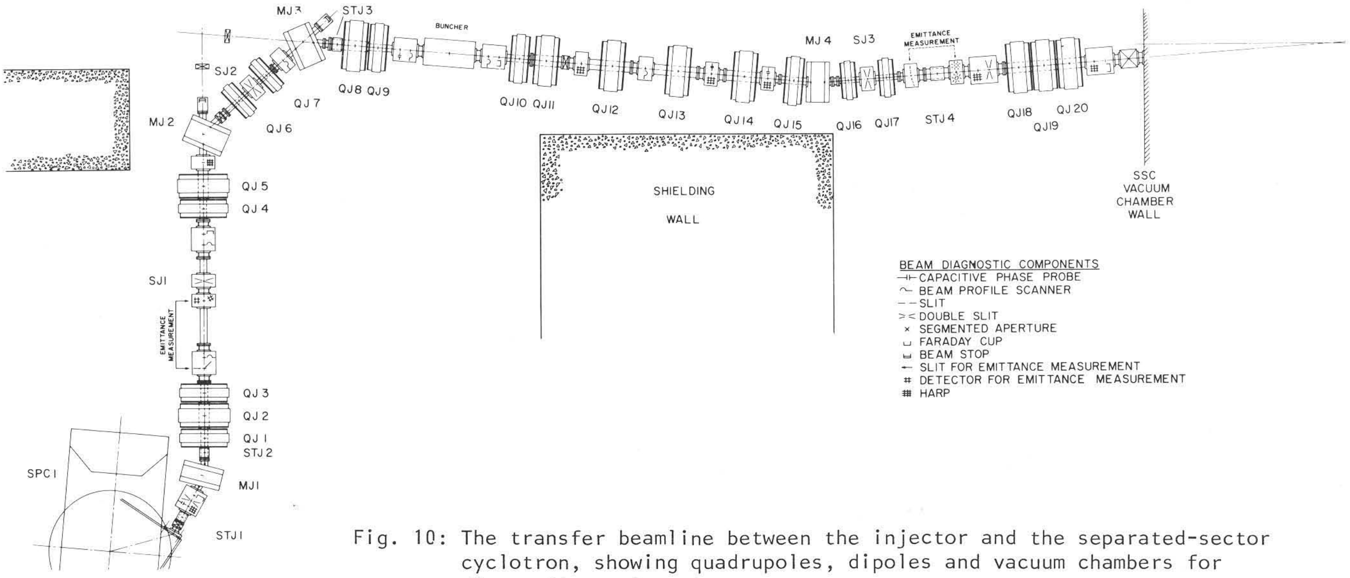

Fig. 10: The transfer beamline between the injector and the separated-sector cyclotron, showing quadrupoles, dipoles and vacuum chambers for diagnostic equipment.

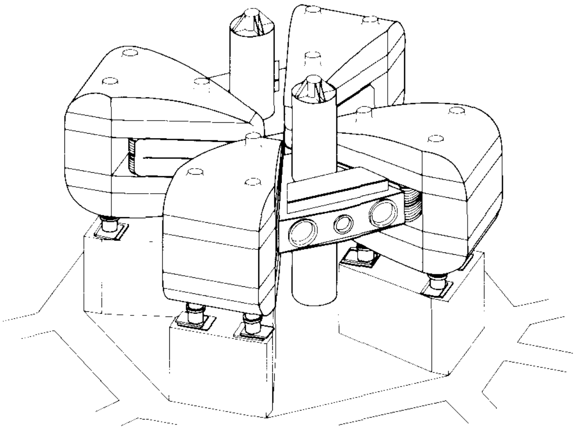

Fig. 11: A perspective view of the separated-sector cyclotron.

5. Lay-out of the separated-sector cyclotron.- As shown in figure 11 the SSC has four sector magnets with vacuum chambers mounted in the pole gaps. The chambers are supported from the poles with studs. Trim-coils will be installed in the gaps between the vacuum chamber walls and pole surfaces. The SSC is designed with two resonators. Two vacuum chambers will be installed in the remaining two valleys.

6. SSC Magnets.- Figure 12 shows a three-dimensional view of one of the four sector magnets. The sector angle is 34°. A 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. These additional coils are used to correct differences between the four magnets.

The field can be increased radially by 20% with 29 trim-coils. The trim-coils follow the shape of equilibrium orbits as shown in figure 13.

Each sector magnet is mounted on three adjustable supporting feet which carry a total load of 350 tons. The magnet can be positioned to an accuracy of 0.1 mm by means of the feet. All twelve supporting feet have been tested and delivered.

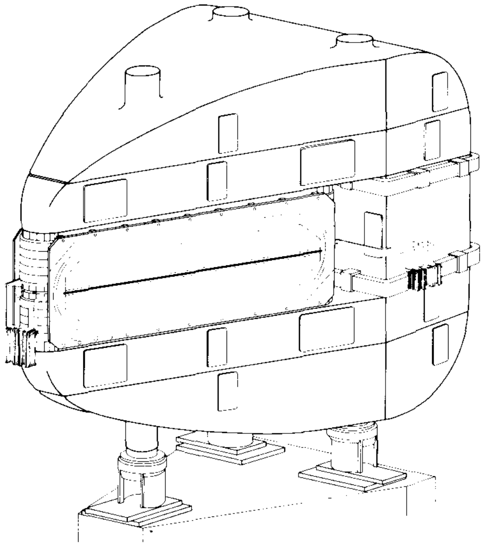

Fig. 12: A perspective view of a sector magnet.

The magnet steel was ordered during the first half of 1979 and delivered during 1980. The poles weigh 30 tons each and were manufactured from hot-rolled plates whereas the yoke pieces were manufactured from low-carbon steel castings.

Progress with the final machining of the first pair of pole plates has been slow due to its prototype character, but should be completed later this year. Figure 14 shows one of the yoke pieces assembled on three supporting feet at the factory where the poles are being machined.

The main coils for each pole consist of 5 identical units, of five single-layer turns each. All 40 main coil units were delivered during 1980, as well as 5 spare units, and are now ready for assembly.

The additional coils, consisting of 4 identical units per magnet with 12 turns each, have also been manufactured and delivered to the NAC.

In both cases a 16 mm square OFHC copper conductor with a 10 mm diameter cooling duct was used. Insulation is provided by epoxy-impregnated glass fibre tapes wrapped around the conductors and again around each coil unit.

The design of the trim-coils shown in figure 13 has been completed and manufacture of the first set is progressing well at present. Due to the special design of the magnet vacuum chamber these coils are situated outside the vacuum region between the walls of the chambers and the pole faces on both sides of the median plane. The trim-coils are made of 3 mm thick copper sheets onto which a 6 mm square hollow copper conductor (with a cooling duct of 4 mm diameter) is welded for direct water cooling. In order to save space and to simplify fabrication this conductor is also used up to the terminals for closing the current loops of the trim-coils. The arrangement of the trim-coil connections at the front part of a pole is shown in figure 15.

Each trim-coil will be coated with nylon-12 for insulation, and all conductors wrapped with epoxy-impregnated glass fibre tape. We also plan to use additional Kapton sheets between the trim-coils and adjoining steel surfaces for further protection.

The magnetic field will be mapped in radial and azimuthal intervals of 2 cm and ¼° respectively. The design and construction of the magnetic field mapping equipment (MFME1) is based on similar equipment developed by SIN for the sector magnets of their injector cyclotron[12] and makes use of two Hall-probes moved in and out along a radial arm which can be adjusted azimuthally. The equipment is fully computer-controlled and measurements will be taken during radial movement of the probes (flying mode) which reduces the time required for generating one field map over 94° (~70 000 data points) to less than 2½ hours. We aim for an accuracy of ~0.1 mm in position and better than 0.1 mT in the field measurements. The MFME1 was delivered at the end of 1980.

The main coils are connected in series to a 420 V, 1600 A power supply. This power supply has been delivered and was tested on a dummy load. It has a current stability of better than 10^{-5} and provision is made for reversing the current direction. A number of power supplies for the additional and trim-coils have been ordered.

The pole gap spacers have been made and are ready for installation.

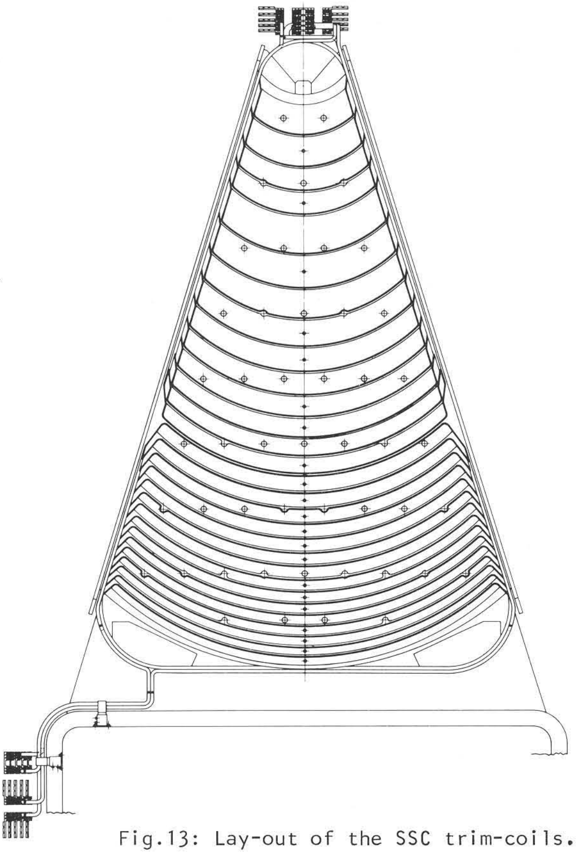

Fig.13: Lay-out of the SSC trim-coils.

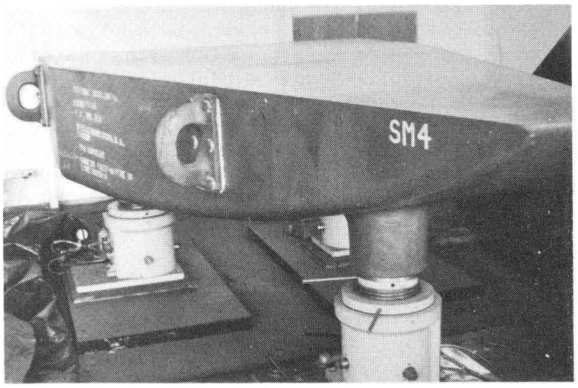

Fig. 14: First stage of mechanical assembly of prototype sector magnet.

7. The SSC rf system.- The SSC is designed to operate with two resonators which can be tuned over the frequency range 6 MHz to 26 MHz by means of short-circuit plates and variable capacitors. An rf power of 100 kW is required to produce a dee voltage of 250 kV at 26 MHz.

Figures 16 and 17 show two views of the main parts of the SSC resonators. The resonators are delta shaped vacuum chambers about one metre high with a rear box section mounted on the top and bottom delta shaped plates to house the capacitor plates. The top cover plate is removable and the remaining case is constructed in one piece. Large tubes, the outer conductors, are mounted on the cover plate and underneath the case. Smaller tubes, the inner conductors, together with the inner deltas are mounted within this structure.

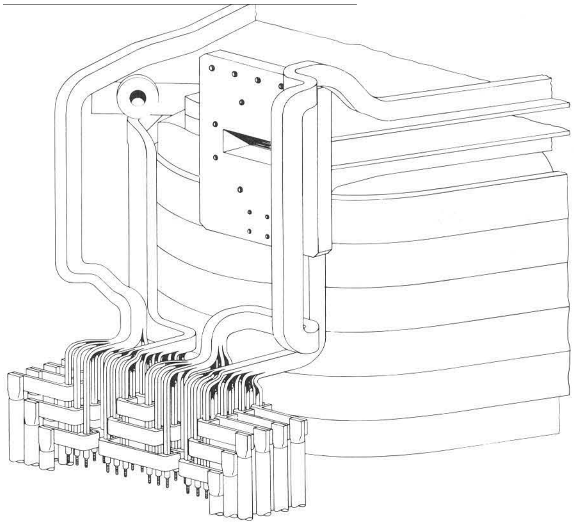

Fig. 15: Arrangement of trim-coil connections.

Originally three types of material were considered for the resonator cases and cover plates. Firstly an all-copper structure was considered, but this was eliminated because of the unavailability of large, thick OFHC copper plates and the difficulty of finding a manufacturer who has had experience in welding thick sections. In addition, cooling would have to be on the exterior of the case, which would interfere on the side flanges with the bellows seal. Secondly a stainless steel structure with a thick layer of copper cladding was considered. Here again, exterior cooling would be difficult. Welding of the sections would be even more intricate and thin sections requiring smooth welded joints to form the outer delta lips would increase the complexity. The third possiblity considered was the use of a stainless steel case with a separate copper liner with cooling tubes attached to it. This last method was chosen.

The delta-shaped case and its cover plate will be fabricated from type 304 stainless steel. The copper liners for the inside of the case and for the cover plate will be made of OFHC. The inner deltas will be made of OFHC with a stainless steel supporting frame. The inner and outer conductors will consist of thick-walled copper tubes with rectangular cooling ducts inside the tube walls. The metal thickness is built up by an electro-deposition process over a long period of time. There will also be a stainless steel support structure at the extreme end of each outer conductor to allow for support and adjustment of the inner conductor and inner delta assembly.

Mounted inside the case are the outer delta liners which are supported on the case both near the lips and at the top and bottom. At the rear, louvres have been provided.

The inner delta consists of a copper skin 3 mm thick. There are radial beryllium copper channel sections supporting the horizontal surface of the inner delta. Underneath the radial channel sections are I-beams fixed to a central cylindrical section. A mechanism is provided to adjust the framework until the lips are in the horizontal position.

The outer conductor will be bolted to the case and an rf seal will provide electrical contact between it and the outer delta. The inner conductor will be welded to the inner delta. This is necessary due to the high electrical current flowing through this junction.

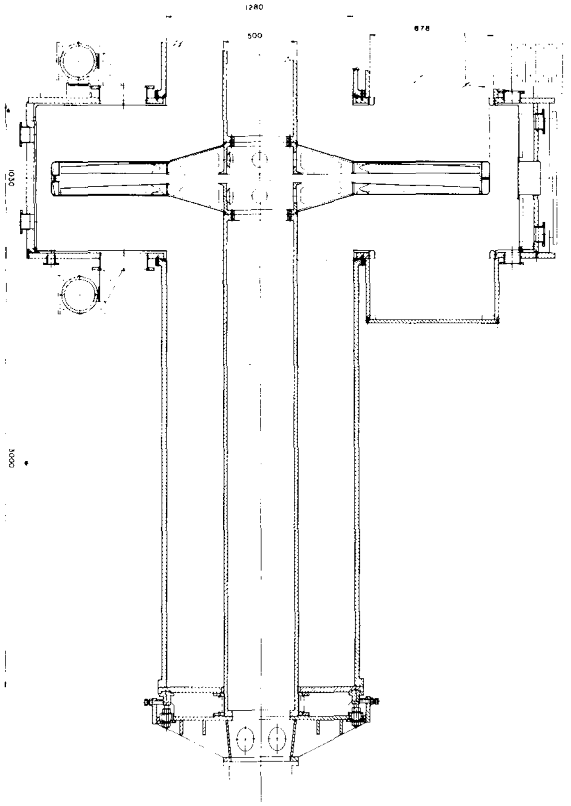

Fig. 16: Sectional side view of the resonator.

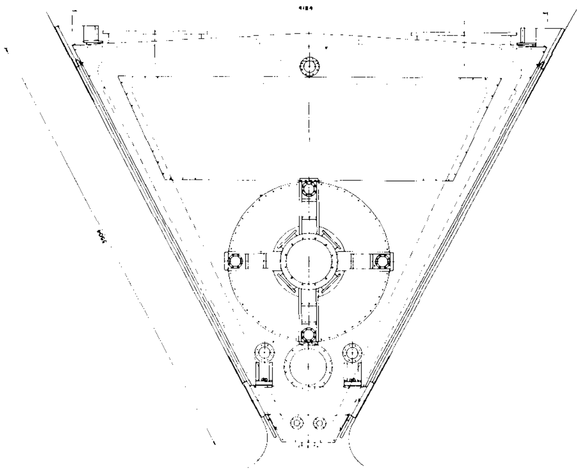

Fig. 17: Top view of the resonator with the position of the accelerating electrodes indicated by dotted lines.

The structure which supports the inner conductor and inner delta assembly consists of four arms on a cylindrical centre section. An adjustment mechanism at the end of each arm will allow for accurate positioning of the inner delta.

8. SSC vacuum chambers.- The SSC is designed with six vacuum chambers which seal against each other with bellows seals. One of these chambers will be installed in the valley through which the beam is injected and a second chamber in the valley where the beam is extracted. The other four chambers fit in the pole gaps of the four sector magnets. Figure 18 shows a three-dimensional view of one of the magnet vacuum chambers. The four magnet vacuum chambers have been ordered but not yet delivered. The two valley chambers will be designed in the near future.

It had been reported$^{5)}$ that the walls of the chambers would be supported from the poles by means of bolts screwed in ferrules on the vacuum chamber surfaces. However, since the previous cyclotron conference, it was decided to use studs instead of ferrules to support the vacuum chamber from the poles. With stud welding the walls of the chamber are not heated to nearly the same extent as with ferrules which would be welded in their respective positions. Consequently there is much less distortion of the chamber walls. It is also easier to manufacture the chambers with studs and it is much less expensive. The studs must be positioned with an accuracy of 0.2 mm and are required to execute an estimated 2200 load-unload cycles, with a maximum load of 12 kN, during the lifetime of the cyclotron. It was experimentally shown that the studs last for ~20000 cycles and that corrosion of the stud welds will not cause problems during the lifetime of the machine.

The magnet vacuum chambers are manufactured from 304 LN stainless steel plates. The walls of the chambers are made from 8 mm thick plates, and the side flanges from 22 mm thick plates, machined to a minimum thickness of 16 mm at the positions of the bellows seals. It is important to ensure that magnetic field perturbations due to the presence of the chambers in the pole gaps of the sector magnets, will be kept below 4×10^{-4}T. For this reason the plates were selected with a magnetoscope. The average permeability of the plates is 1.0046. The peak variation from the average permeability is 0.0004. Permeability measurements were made at 24 regularly spaced points for every chamber. The maximum field variation in a sector magnet, due to the presence of a chamber, including both thickness variations and permeability variations, is 1.2×10^{-4}T.

The stainless steel plates for the vacuum chambers were selected for small thickness variations and low magnetic permeability. They have been 100% tested ultrasonically. Delivery of the first magnet vacuum chamber is scheduled for December 1981. The remaining three chambers will be delivered at 3-monthly intervals.

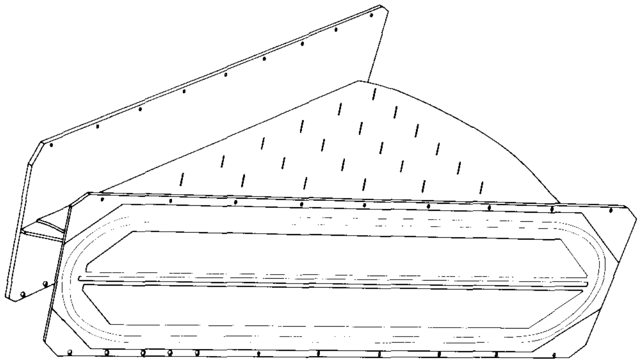

Fig.18: Perspective view of a magnet vacuum chamber.

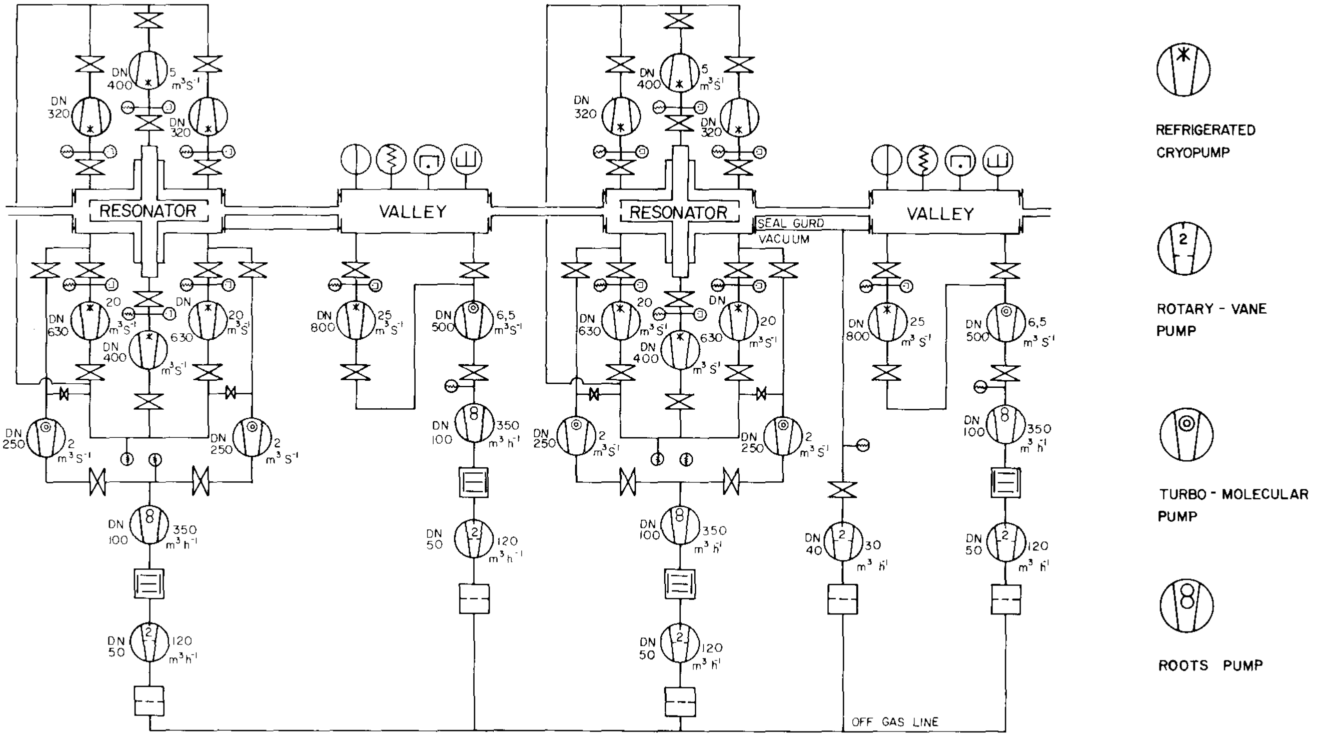

Fig. 19: Schematic lay-out of the pumping system for the separated-sector cyclotron.

9. The SSC pumping system.- The vacuum system for the SSC has to provide and maintain the pressure at approximately 10^{-4} Pa in order to limit beam losses. The pumping system is shown in figure 19. The pressure in the SSC can be reduced to the 10^{-4} Pa range with the rotary-vane pumps, roots-pumps and turbo-pumps, having a total pumping speed of 21 m^3s^{-1}. With the addition of the cryopumps the pressure can be further reduced to the 10^{-5} Pa range.

10. Injection and extraction.- The injection and extraction systems are discussed in detail elsewhere in these proceedings[13]. The injection system consists of two bending magnets and a magnetic channel. All three components have been delivered to the NAC. Magnetic field measurements are being carried out on the larger of the two bending magnets.

The extraction system consists of an electrostatic channel and two septum magnets. Conceptual designs exist for these components. Mechanical designs still have to be made.

11. Control system.- We have based the control system on two 16-bit mini-computers with about 256k words (computer 1) and 384k words (computer 2) of memory, linked to a CAMAC network via a CAMAC executive crate. This is shown in a block diagram in figure 20. Computer 1 will be used primarily as the control processor and computer 2 primarily for software development. However, in order to retain redundancy with respect to the two computers in the control system they will be interfaced to CAMAC in an equivalent way, and will also share all the peripherals which are of importance to the control system, viz., a 120 Mbyte disc storage unit, a line printer, a paper-tape reader and punch, and a hard-copy x-y plotter. In addition, those peripherals which reside on the control consoles, but which connect directly to the computer, i.e. the visual display units (VDU's) and the graphics VDU, will be shared by the two computers: the VDU's will be connected directly rather than via CAMAC to achieve some duplication for accessing the computers from the consoles.

In addition to the two mini-computers, we intend using microprocessors throughout the system: in the man-machine interface for pre-processing and formatting data and for providing uniform access methods for the consoles, and near the accelerator instrumentation for status checking of all equipment, for checking the stability of the magnet power supplies, for cycling the accelerator magnets, for acquiring and pre-processing data during beam diagnostic tasks such as beam profile and emittance measurements, etc.

The two mini-computers shown in figure 20 link into the CAMAC executive crate via the computer interfaces CI1 and CI2. The module IVG is an interrupt vector generator which intercepts the LAM's originating from the

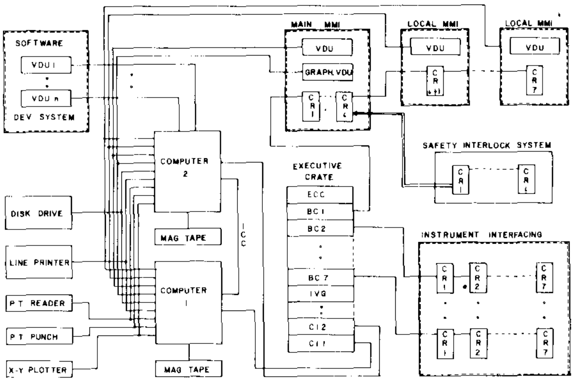

Fig. 20: Block diagram of the control system.

instrumentation, and sets up an interrupt vector of the highest priority LAM. The executive crate controller, ECC, in the right-most position of the executive crate arbitrates between the different command sources which demand access to the backplane of the crate. Up to seven parallel CAMAC branches can be driven from this crate via branch couplers BC1 to BC7. In the figure the accelerator instrumentation is shown as interfacing to the control system via several parallel branch crates. Equally, the interfacing could be done via the crates of one or more serial loops, driven directly from the executive crate. Since it is our intention to use micro-processors in conjunction with auxiliary crate controllers which reside in the instrumentation CAMAC crates, the decision as to whether to use parallel branches or serial loops will depend, inter alia, on whether the arbitration protocol between serial loop crate controllers (type L-2) and auxiliary crate controllers residing in serial loop crates is sufficiently flexible for our purpose.

We envisage that the radiation safety interlock system will be a stand-alone system configured around a micro-computer. The sole function of this system will be to monitor the status of safety interlock signals derived from the instrumentation and to calculate whether the safety equations are being violated or not. If an unsafe condition is found to exist the system should be able to shut down the accelerator directly, i.e. without going through the control system. However, a link from the safety system to the control console will be provided, so that the status of the safety system can be displayed at the console.

The local man-machine interfaces shown in figure 20 are intended to be mobile control panels situated near the accelerator instrumentation, from which the control computer can be accessed; their composition has not yet been determined. They are shown to be on the same parallel branch as the main man-machine interface, but could as easily be placed on the parallel branch(es) of the instrumentation interfacing, or could even be configured as stand-alone CAMAC systems which communicate via a bi-directional link with the instrumentation CAMAC crates.

12. Buildings and services.- During 1978 the NAC, which was then temporarily housed in Stellenbosch, experienced a shortage of workshop and laboratory space. The first building to be erected on the site, at Faure, was therefore an office and laboratory block with a floor space of 1600 m^2. A cooling system was installed to provide cooling water for magnets, power supplies and power amplifiers. This building was completed in 1979. It is indicated as block S on the site-plan shown in figure 21.

It was decided that the remaining part of the complex should be built in phases. Phase one is indicated by the lightly shaded area in figure 21. It includes the cyclotron vaults and their basement areas, service corridors, the power supply room and cable vault, rooms for air handling and the cooling system, the electrical switch room and the transformer yard. One half of block J is also included.

The SSC and injector vaults are provided with a 5-ton and a 2-ton crane respectively, located just below the level of the shielding beams which will seal off these areas. A gantry crane with a lifting capacity of 72 tons and a span of 23 m runs the length of the present hall 13 m above floor level. All the cranes have been commissioned. The SSC vault is shown in figure 22.

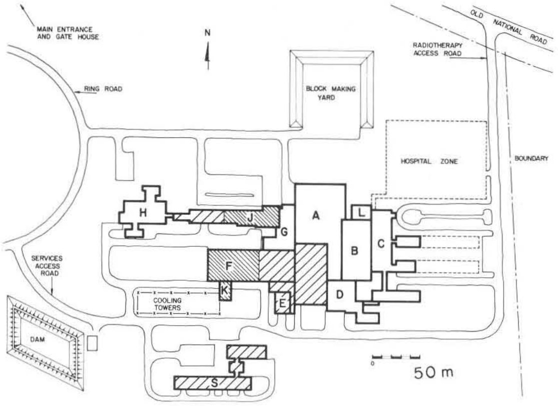

Fig.21: Sketch plan of the NAC site:

A: Cyclotron hall
B: Therapy vaults
C: Patient-handling wing
D: Isotope production wing
E: Electrical switch-rooms
F: Workshops and stores
G: Control block
H: Lecture hall and canteen
J: Office and lab. block
K: Paint shop and store
L: Operating theatres
S: Electronics labs

The power supply room is 35.5 m long and 14.5 m wide. A cross-section through this room and the cable vault is shown schematically in figure 23. During the construction of phase one all the cable racks required for this phase were installed. The cables are routed from the cable vault to their destinations via the service corridor at the -2.96 m level.

The cooling water system has also been designed during phase one. The system consists of a chilled water section, an intermediate circuit, five accelerator circuits and a deionized water supply. The system has a cooling capacity of 4 MW.

Phase one is now complete. Figure 24 shows part of the cyclotron and services building. The remaining parts of block F and block J, indicated by the darker shaded areas in figure 21, are at present under construction. This part of block F comprises the main workshop, assembly area, cooling plantroom (chillers) and store.

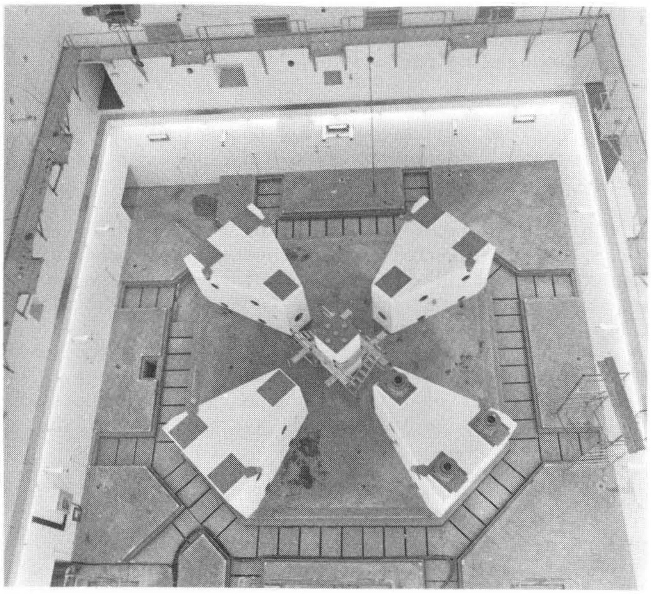

Fig. 22: The SSC vault.

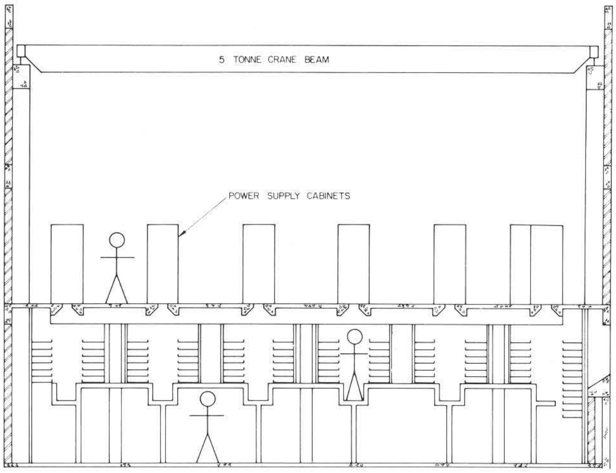

Fig.23: Section through cable vault and power supply room.

Phase two of the building programme is due to commence in September 1981 and will comprise the remainder of blocks A and B as well as the control block (block G).

A well-planned and comprehensive survey network has been designed. In the SSC vault the survey has to operate at three levels namely - 1.5 metres, + 2.0 metres and + 4.0 metres (beamline at + 1.5 metres). At the lowest level survey positions around the perimeter of the vault are connected to three points on each sector magnet foundation. These in turn will be used to planimetrically align each pole piece by optical plumbing (tolerance 0.3 mm). The second level is for the alignment of low and high energy beamlines while the high stations fix three reference points on top of each sector magnet to monitor indirectly any movement of the median plane.

Although the actual survey of this area is in progress at the moment, it is foreseen from a pre-analysis of the network that positional error will be ± 0.1 mm (mse).

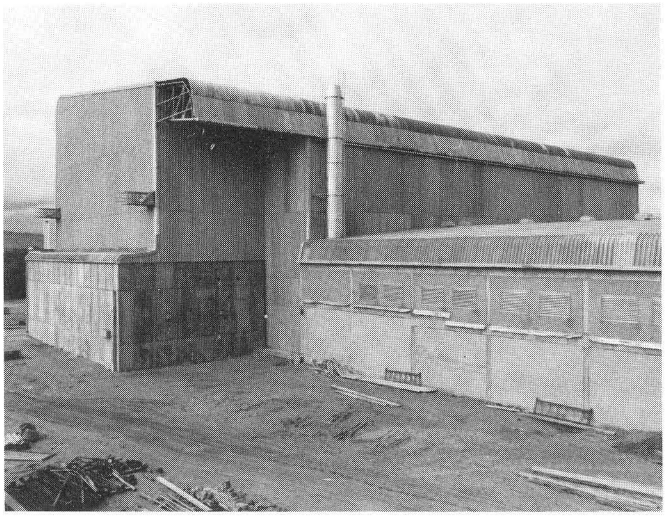

Fig.24: Part of the completed cyclotron and services building.

13. Planning.- It is expected that the injector cyclotron will come into operation by April 1983 and that the separated sector cyclotron will be commissioned towards the end of 1984. External beam is expected early in 1985.

14. Modification of the Pretoria Cyclotron.- The Pretoria Cyclotron, which forms an integral part of the NAC, is now used exclusively for radio-active isotope production. A fast-neutron facility is currently being developed for bio-medical experiments.

At present an external beam intensity of 12μA for 16 MeV deuterons can be obtained regularly. For the fast neutron facility external beams of 50μA or more are required. In order to increase the external beam intensity the extraction system and beamline are being redesigned. Two magnetic channels, in addition to the existing electrostatic channel, are planned for the extraction system. Figure 25 shows the calculated horizontal and vertical beam distributions without any magnetic channels whereas figure 26 shows the same distributions with two magnetic channels with field gradients of 32 T/m and 7 T/m respectively.

References

1. W.L.RAUTENBACH and A.H. BOTHA, Proc. 7th Int.Conf. on Cyclotrons and their Applications, (Birkhäuser, Basel, 1975) p. 117.
2. Technical Report of the Accelerator Task Group, National Accelerator Project, Pretoria 1976.
3. A.H. BOTHA et al., IEEE Trans. Nucl. Sci. NS24 (1975) 118.
4. A.H. BOTHA, Proc. 8th Int.Conf. on Cyclotrons and their Applications, (Bloomington, 1978) p.1896.
5. F.J. MUMFORD, H.N. JUNGWIRTH and P.G. BLAINE, Proc. 8th Int.Conf. on Cyclotrons and their Applications, (Bloomington, 1978) p.1934.
6. National Accelerator Centre Report NAC/AR/78 (1978)
7. National Accelerator Centre Report NAC/AR/79-01 (1979)
8. National Accelerator Centre Report NAC/AR/80-01 (1980)
9. National Accelerator Centre Report NAC/AR/81-01 (1981)
10. Z.B. DU TOIT et al., Aspects of the Design of an 8 MeV Cyclotron as Injector for the 200 MeV Separated-Sector Cyclotron. This conference.
11. C.M. MERRY and J.C. CORNELL, An Orthogonal Quadrupole System. This conference.
12. B. BERKES et al., Fast Field Mapping Device for Cyclotron Magnets. To be published in Proc. Int.Conf. on Magnet Technology. (Karlsruhe, 1981)
13. P.F. ROHWER and S.SCHNEIDER, Beam Injection and Extraction for the Separated-Sector Cyclotron of the NAC. This conference.

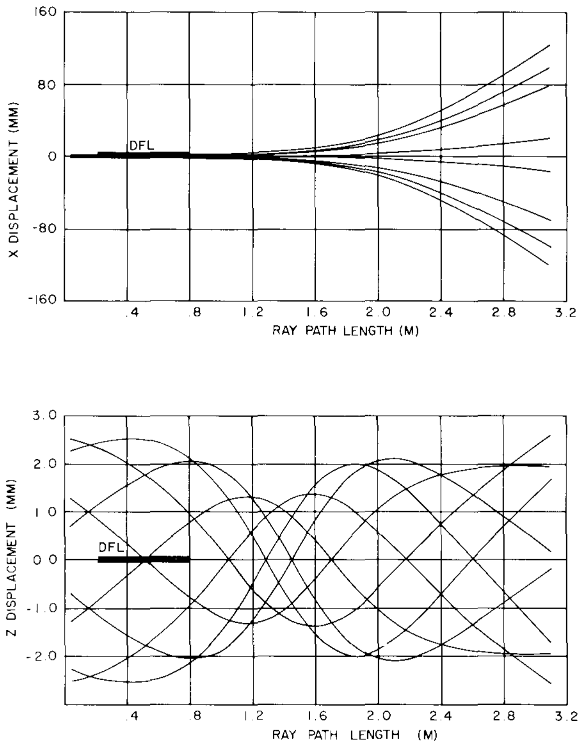

Fig.25: Horizontal and vertical beam distributions with an extraction system consisting of an electrostatic channel.

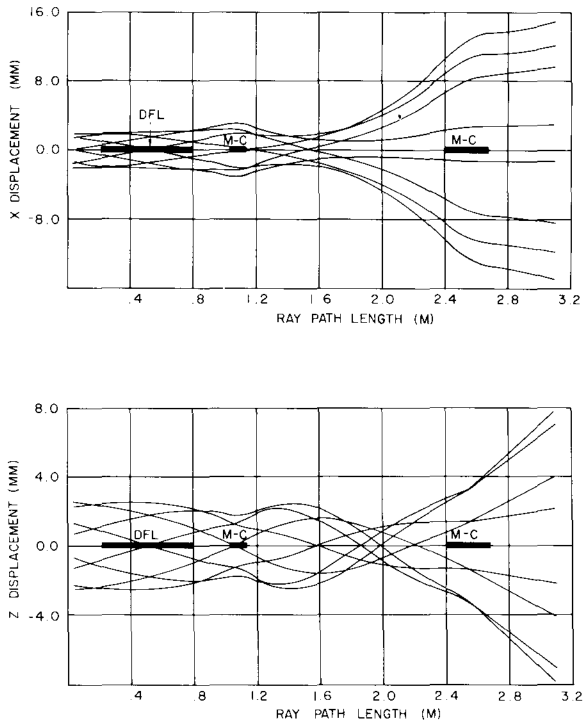

Fig. 26: Horizontal and vertical beam distributions with an extraction system consisting of an electrostatic channel and two magnetic channels.

" DISCUSSION "

M.K. CRADDOCK : When do you expect to begin magnetic field measurements ?

A.H. BOTHA : Field measurements will start within a month for the injector and at the beginning of 1982 for the separated sector cyclotron.

P. LAPOSTOLLE : What is your planning for beam in the injector cyclotron and SSC ?

A.H. BOTHA : The injector will come in operation in April 1983 and the SSC in December 1984.