MODIFICATION OF THE EXTRACTION SYSTEM OF THE PRETORIA CYCLOTRON

A.H. Botha, S.J. Burger, P.J. Celliers, P.M. Cronje, J.H. Hough,
W.F. van Heerden, J.J. Arnold
National Accelerator Centre, CSIR, P.O. Box 72, FAURE, 7131, REPUBLIC OF SOUTH AFRICA

Summary

The extracted beam current of the Pretoria Cyclotron was limited to 2 μA owing to beam losses in the deflector and fringe field of the cyclotron. Recently a need developed for beam currents in excess of 50 μA. Two magnetic channels, one passive and one active, with gradients of 32 T/m and 6 T/m respectively, have been installed along the extraction orbit in order to improve the horizontal focusing of the beam. Also installed were three profile grids (harps), capable of withstanding currents up to 80 μA, to observe the beam profile. External beam currents of up to 70 μA can now regularly be obtained with a transmission of 90% and 75% respectively for the two magnetic channels.

1. Introduction

The Pretoria cyclotron[1,2] is a classical solid-pole cyclotron with a pole diameter of 113 cm and has been in operation for the past 26 years. It was originally designed for the acceleration of particles with a charge to mass ratio of 1/2 at a fixed radio-frequency. Subsequently modifications[3] to the magnet and radio-frequency system made it possible to accelerate protons, deuterons, ^{3}He and alpha particles in the energy ranges 6 - 15 MeV, 11.5 - 17 MeV, 18 - 39 Mev and 23 - 34.6 MeV respectively. The deuteron beam intensity was, however, limited to 60 μA in the exit chamber and 2 μA on target in the experimental area by the loss of 67% of the beam in the electrostatic deflector and further losses from a lack of horizontal focusing in the fringe field along the extraction orbit. Isotopes requiring large currents for their production were produced internally or in the exit chamber.

Recently a need arose for deuteron beams to be used in a neutron therapy project, requiring external beams of 50 μA and more. A study of the extraction process has been undertaken with the aim of obtaining the required current by improving the extraction system. This investigation eventually led to the installation of two magnetic channels and diagnostic equipment along the extraction orbit. In what follows the theoretical investigation and the design and installation of the magnetic channels are discussed. We also present results of measurements on the beam.

2. Design considerations and calculations

In considering means by which the extracted beam intensity could be increased, it was clear that either the deflection efficiency or the horizontal focusing in the fringe field, or both, had to be improved.

Beam losses in the deflector are high (67%), because of the inherent poor beam quality in the machine. The beam quality can be improved only by extensively redesigning the central region of the cyclotron, inserting slits to obtain better phase selection. This would however be expensive and also require too much downtime for installation and testing, which is unacceptable because of a commitment to the regular production of isotopes for medical use. Alternatively, beam losses can be limited by completely redesigning the deflector, but this would be time-consuming and installation would involve the handling of highly radioactive components in the restricted space inside one of the dees. This solution would also interfere with the regular production of medical isotopes.

We therefore decided to try to obtain the required beam intensities by magnetic focusing of the deflected beam only, which would only lead to small changes in the properties of the beam internally and in the exit chamber of the cyclotron, in order to have the beam uninterruptedly available for isotope production.

A schematic layout of the Pretoria Cyclotron is given in fig. 1 in which the positions of the electrostatic deflector, dees and extraction chamber are shown.

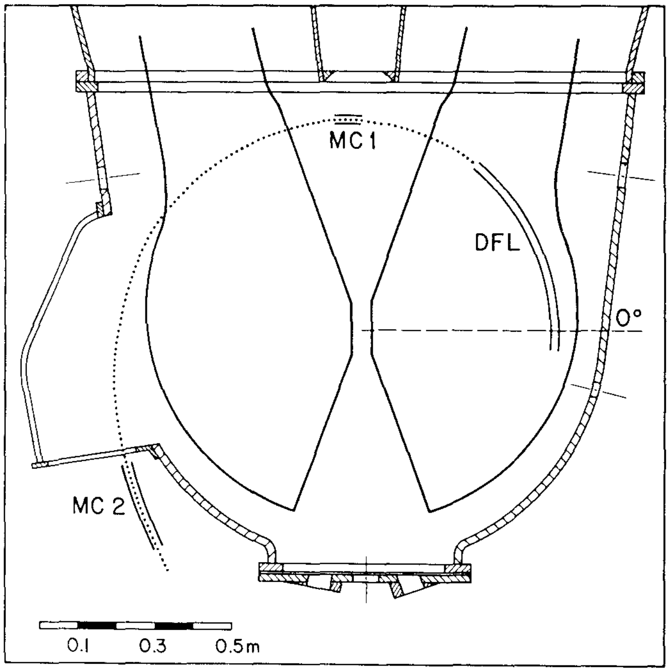

Fig. 1 Schematic layout of the cyclotron, showing vacuum chamber, dees, deflector DFL and possible positions for magnetic channels MC1 and MC2.

The radial line marked 0° is used as the origin for the anticlockwise measurement of the azimuthal angle in a cylindrical co-ordinate system, situated with its origin at the cyclotron centre.

Two positions were available for the installation of magnetic focusing channels. The first position after deflection is between the two dees, which are cut away at an angle of 20°. The second position is further along the extraction orbit, beyond the exit chamber of the cyclotron after the beam has emerged from the second dee.

Extensive beam calculations[4] were performed with the program ORBIT CODE[5] for a 16 MeV deuteron beam, with two objectives in mind:

i) to find an accurate description of the behaviour of the beam on the last orbit before extraction, during extraction, and through the fringe field to the external beamline;

ii) to find the specifications for a magnetic channel or channels which would give satisfactory horizontal and vertical focusing of the extracted beam, diminishing the loss in beam intensity after the electrostatic deflector due to radial spreading of the beam in the fringe field of the cyclotron.

For the orbit calculations to simulate actual conditions properly, we required accurate magnetic and electric field maps. We measured the magnetic field, obtaining a field map at radial intervals of 2 cm over the radial range 40 - 132 cm and at azimuthal intervals of 3°. The electric field in the deflector was determined from its geometrical construction and the applied voltage difference (32 kV) between the septum and deflector.

At the given extraction energy, a representation of the beam on the last orbit before extraction was found by considering the equilibrium orbit at this energy and calculating the parameters of the phase-ellipses describing the linear motion relative to the equilibrium orbit in the horizontal and vertical planes. The beam emittance was taken to be 7.2 π mm mrad for both the horizontal and vertical motion, corresponding to a beam width of 4 mm and a beam height of 5.2 mm at the entrance to the deflector.

To find a representation of the beam during deflection and subsequent motion through the fringe field, we considered the motion of a central particle starting in the middle of the septum-deflector gap at the entrance to the deflector channel. The radial momentum of this central ray was then varied until its position and direction in the extraction chamber of the cyclotron corresponded to those of the actual beam. Intermediate positions of the central ray in the fringe field determined in this way corresponded to positions found from actual measurements on the beam. For a description of the motion of the beam through the deflector channel and fringe field, we considered the motion of the central ray and 8 representative particles on the phase-ellipses mentioned for both the horizontal and vertical motion. Non-linear terms in the equations of motion were included to all orders in the radial motion and to second order in the vertical motion. The calculated beam width and height also corresponded fairly well to measured values, except that the actual beam intensity is distributed more towards the centre of the cyclotron, as measured from the position of the calculated central ray. Ray traces for the calculated horizontal and vertical motion, with respect to the central particle, are given in figures 2 and 3.

The next step consisted of finding a specification for a magnetic channel or channels which could give satisfactory horizontal and vertical focusing of the extracted beam. Calculations showed that sufficient focusing cannot be obtained with a single magnetic channel at the first possible position between the dees near 90°, but that a second channel is also required further along the extraction orbit to refocus the beam horizontally. The first accessible position for this channel is only after 210° where the value of the cyclotron main field has dropped to a value of 0.4 T (as compared to a value of 1.76 T at the centre). In order to obtain a reasonable reversed magnetic field gradient in the weak external field, the second channel would have to be an active channel with a large horizontal acceptance.

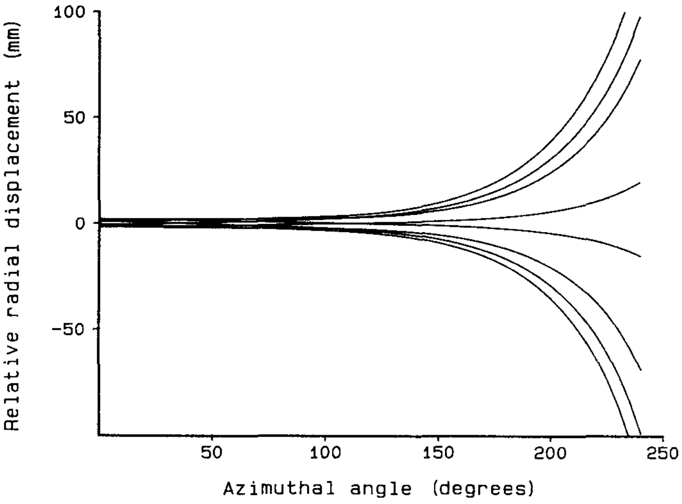

Fig. 2 Calculated relative horizontal motion of 8 representative particles with respect to the motion of the central particle in the absence of magnetic channels.

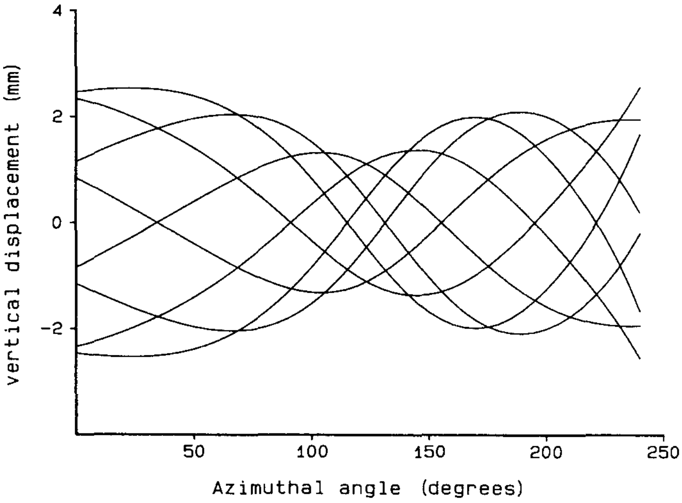

Fig. 3 Calculated vertical motion for 8 representative particles in the absence of magnetic channels.

Calculations performed for magnetic channels in these two positions showed that a sufficiently focused beam is obtained with a passive channel of length 75 mm and field gradient 32 T/m between the dees and with an active channel of length 260 mm and field gradient 5.6 T/m in the extraction chamber (isotope production chamber) at 210 - 225°. Ray traces for the calculated horizontal and vertical motion, with respect to the central particle, are given in figures 4 and 5. The beam is still divergent after it emerges from the second channel, but it can be focused by a set of quadrupoles in the beamline.

3. Magnetic channel design

By placing a magnetic channel which reverses the field gradient in the path of the beam, it is possible to utilise the alternate gradients of the fringe field and magnetic channel to obtain both horizontal and vertical focusing of the extracted beam. Magnetic field calculations[6] were performed to find realistic values of the field gradients obtainable and optimum geometrical shapes for both passive and active magnetic channels. The calculations were made using a two-dimensional relaxation method taking into account saturation effects in the iron components of the magnetic channels.[7]

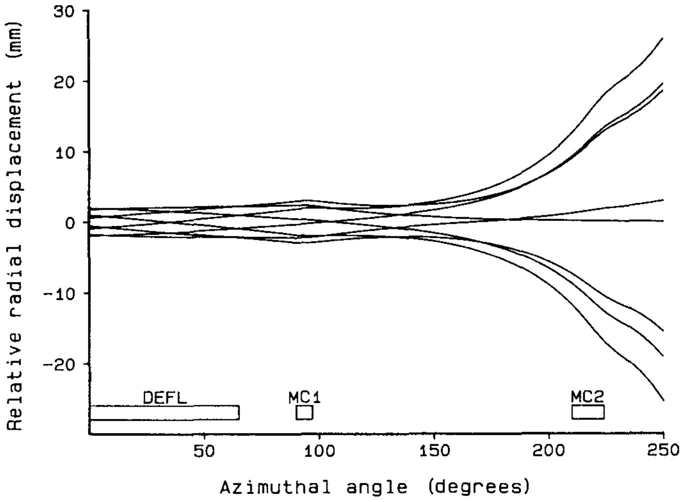

Fig. 4 Calculated relative horizontal motion of 8 representative particles with respect to the motion of the central particle in the presence of magnetic channels with gradients of 32 T/m and 5.6 T/m respectively. The positions of the deflector and channels are indicated.

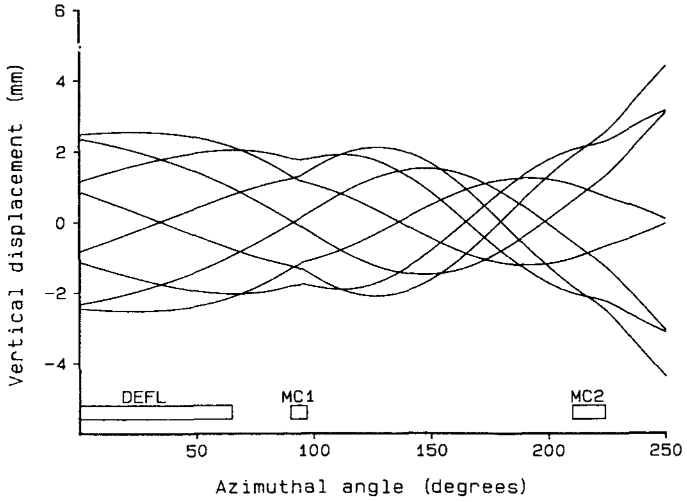

Fig. 5 Calculated vertical motion for 8 representative particles in the presence of magnetic channels with gradients of 32 T/m and 5.6 T/m respectively. The positions of the deflector and channels are indicated.

Preliminary designs were developed for 13 different cross-sectional shapes of the passive channel. In all cases the channel consisted of two identical pieces having a wedge-shaped cross section, which were placed mirror-symmetrically above and below the median plane of the cyclotron. In some cases an additional bar was included to obtain short-circuiting of magnetic flux on the cyclotron side of the channel. These channels proved to have the best characteristics as far as maximum obtainable positive gradient and linearity across the channel was concerned. Cross-sectional views of two of these channels, numbered 5 and 9 respectively, are given in figure 6.

Prototypes were constructed for 5 of the preliminary designs in order to determine how well the calculated fields corresponded to the fields of channels actually placed in the cyclotron. The channels were attached to a measuring table in the cyclotron and fields were measured in the median plane along cross-sectional lines of the channels. Typical results for channels 5 and 9 are given in figure 7. The field gradients obtained varied from 56 T/m for channel 5 at a radius of 55 cm to 12 T/m for channel 9 at a radius of 89 cm. In all cases measured and calculated fields corresponded to within 10%. Channel 5 was selected for use in the first channel position.

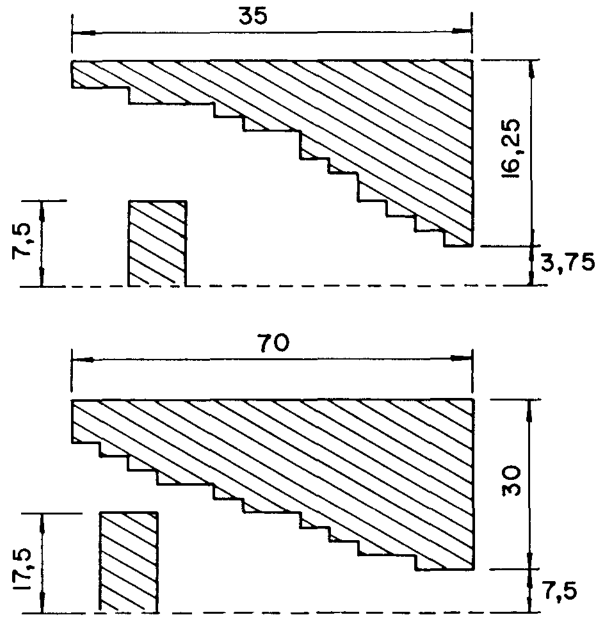

Fig. 6 Cross-sectional views of the upper halves of prototype passive channels numbered 5 (above) and 9 (below). Dimensions are in mm.

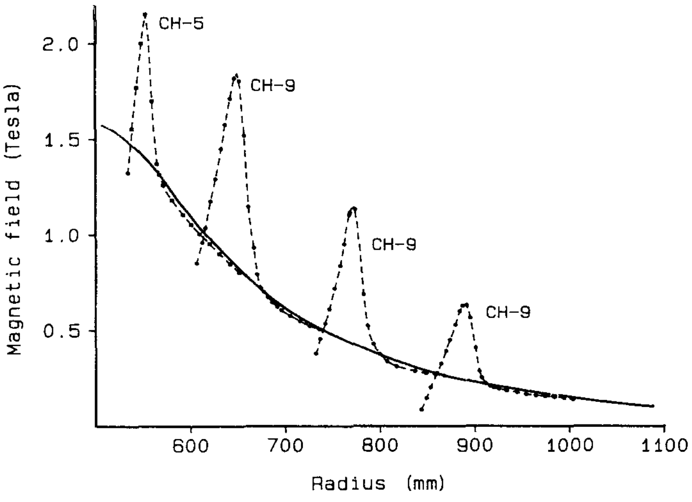

Fig. 7 Normal magnetic field (solid line) and fields obtained by placing channels numbered 5 and 9 at various positions in the field.

Calculations were also performed for an active channel having a uniform field gradient over a radial distance of at least 40 mm, to be used in the second channel position. This channel consists of two coils of 10^4 Ampere-turns wound on iron cores and also has a flux-shorting bar. A cross-sectional view of the active magnetic channel is given in figure 8. A nearly uniform

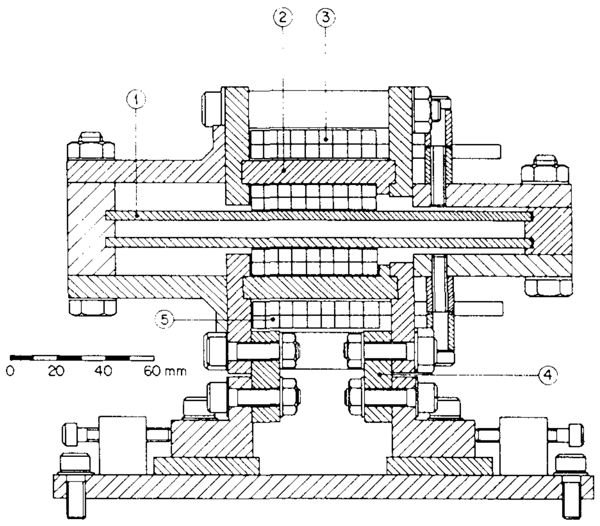

Fig. 8 Cross-sectional view of the active magnetic channel, showing 1: graphite screen, 2: iron core, 3: upper coil, 4: isolator, 5: lower coil.

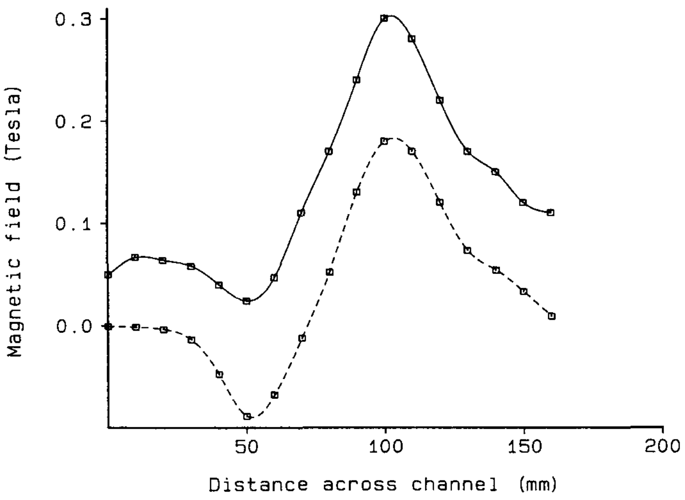

Fig. 9 Measured magnetic field values for the active magnetic channel only (dashed line) and for the channel plus main field of the cyclotron (solid line).

gradient of 6.2 T/m is obtained with this channel. (See fig. 9.)

The magnetic channels introduce an additional dipole component in the magnetic field at the position of the central particle which amounts to 0.31 T and 0.17 T respectively for the two channels. As a result the external beam transport system had to be moved to accept the extracted beam.

4. Diagnostic equipment

Modifications and additions to the diagnostic equipment in the cyclotron were required in order to measure the position and intensity distribution of the deflected beam and to position the magnetic channels along the deflected orbit. For these purposes the channels themselves are used as current measuring devices together with two profile grids to measure the distribution of the deflected beam.

The positioning of the first channel between the dees is critical because the beam dimensions are only a few millimeters at this position. The position of the channel was therefore made continuously variable. A probe is used to measure the current and to determine the position of the deflected beam. The magnetic channel, which is electrically isolated, is then positioned accordingly. A current measurement on the channel indicates the amount of beam falling on the channel.

The positioning of the active channel in the extraction chamber is not critical (in the radial direction); it is therefore not positioned by remote control but bolted into the required position and adjusted manually to obtain the final position. Current measurements are made on the channel and on a screen plate which defines the acceptance of the channel. Beam distribution measurements are made on two profile grids, one before and one after the magnetic channel. Each grid consists of 5 horizontal tungsten wires 0.1 mm in diameter and 11 vertical tungsten wires 1 mm in diameter. The area covered is 270 mm in the horizontal direction by 30 mm in the vertical direction. The grids are capable of withstanding currents up to 80 µA.

5. Final Results

The magnetic channels and diagnostic equipment have been installed and positioned in the cyclotron. External currents of up to 70 µA can now regularly be obtained. The transmission through the two magnetic channels is 90% and 75% respectively.

References

1. J.J. Burgerjon, S.J. du Toit and C.A.J. Kritzinger, Nucl. Instr. 3 (1958) p. 323.
2. J.J. Burgerjon and W. Weideman, Nucl. Instr. and Meth. 8 (1960) p. 261.
3. A.H. Botha, Theoretical and experimental study of the CSIR cyclotron, D.Sc thesis, University of Pretoria, Oct. 1970.
4. S.J. Burger, NAC Internal Report NAC/EI/81-02, July 1981.
5. P.M. Cronje, NAC, ORBIT CODE, unpublished.
6. F.S. van der Merwe, NAC Internal Report NAC/MA/80-02, October 1979.
7. H.N. Jungwirth, Computer programme zur Feldberechnung, NAC Internal Report, November 1976.