A NEW DESIGN PROPOSAL FOR A 200 MEV SUPERCONDUCTING RING-CYCLOTRON MAGNET

H N Jungwirth and J G de Villiers

National Accelerator Centre, P.O. Box 72, Faure, 7131 Republic of South Africa

ABSTRACT

A new magnet design for a superconducting ring-cyclotron with proton energies in the 200 MeV range is presented and discussed. The proposal features four separate 30-ton iron sectors at room temperature and superconducting coils which are confined to each sector and located between the poles and return yoke, outside extraction. The design characteristics of the magnet configuration are examined using results obtained by numerical field computation and orbit integration. A preliminary analysis of these results confirms that the proposal is feasible and can be used to develop a superconducting ring-cyclotron for clinical proton therapy.

1. INTRODUCTION

The interest in radiotherapy with proton beams in the energy range from 200 to 250 MeV and efforts to provide suitable facilities for this purpose have increased dramatically during the past decade [1-5]. A trend from multidisciplinary to fully dedicated accelerators has emerged for such applications, and it is now more important than ever to establish and examine all machine options available. Traditionally the proton energies and beam properties required for radiotherapy fall into the realm of cyclotrons, and indeed most pioneering work in this field has made use of synchrocyclotrons. A superconducting 250 MeV synchrocyclotron for application in hospitals already has been studied[6]. Existing isochronous superconducting cyclotrons have difficulty in reaching the required energy range owing to problems with beam focusing, and their operational characteristics are also less attractive for the demands of clinical treatment schedules. Recently a more conventional isochronous cyclotron has been proposed as an alternative, therefore, which retains the layout and features of superconducting cyclotrons but employs normal coils[7].

Proton-therapy programmes also are supported on a multidisciplinary basis by several ring cyclotrons (a designation which is assumed to include separated-sector cyclotrons in this paper). The better quality and CW characteristic of the beam which can be obtained from such machines hold important advantages for proton therapy, but existing ring-cyclotron facilities are far too complex and expensive to rate as a suitable choice for dedicated radiotherapy centres. Inherently superconducting ring-cyclotrons (SRC) should be well-suited for such applications, because they would combine a relatively compact size and good beam properties with reliable and cost-effective operational characteristics. The complexity could be kept within acceptable limits for a fixed energy SRC operating in the stand-alone mode without the requirement for pre-acceleration, transfer and matching of the beam. A crucial issue is the magnet design for such a machine, because comparable magnets do not exist at present and stringent requirements must be met with simple solutions. A promising design option employing S-coils[8] is currently being studied at the National Accelerator Centre, and the results obtained thus far are presented and discussed below.

2. CYCLOTRON CONSIDERATIONS

The SRC layout is adopted from existing 200 MeV room-temperature ring cyclotrons and features four 34° sector magnets and two $\lambda/2$ rf-resonators. The resonators have triangular ($\lesssim 47°$) dees located in opposite valleys between the sector magnets and operate at the 4th harmonic of the orbit frequency ν_0. The choice of ν_0 = 26 MHz essentially determines the machine size as well as the rf and magnetic field requirements. The rf-system works at a fixed frequency of 104 MHz (FM broadcasting range) and the magnetic field in the cyclotron centre just exceeds 1.7 tesla. The 200 MeV orbit radius is close to 1.04 m and requires an average field of ~2.1 tesla.

The radial field shape is determined by isochronism which must be maintained with extremely high accuracy ($\delta B / B < 10^{-4}$) and inherently yields good radial beam focusing. The azimuthal field shape has to provide sufficient and suitable (resonances) vertical beam focusing to overcome the defocusing effect of the isochronous radial field increase. In order to achieve this without spiral geometries, the field at extraction must typically vary from about 4 tesla in the sectors to $\lesssim$ 1 tesla in the valleys. The iron mass of the magnets should not exceed 120 metric tons under these conditions[9], and superconducting coils are necessary to produce such fields. The relatively low magnetic field in the valleys permits the efficient use of conventional electric and magnetic extraction devices.

A special feature of such an SRC is that the beam would be accelerated right from the centre, most probably by making use of a small internal ion source. Assuming a dee voltage of 60 kV and considering that only a low beam current at fixed energy is required, the magnetic field in this region is acceptable for this purpose. The resonators should be made such that the peak acceleration voltage increases to $\geq$ 200 kV at full radius, thus relaxing magnetic field tolerances significantly and providing strong phase compression of the beam to improve the extraction efficiency. Access to the central region is possible from the valleys which are not occupied by rf-structures. Obviously, an extensive design study would be necessary to determine the details of the central region layout, but it should be less difficult to find a suitable solution here than in conventional superconducting cyclotrons. The essential requirement is that the isochronous magnetic field can be produced and maintained right from the cyclotron centre.

3. MAGNET CONFIGURATION

The design concept, employing S-coils in the proposed magnet configuration, is shown schematically in Fig. 1. Its most attractive feature is that the coils are removed completely from the valleys to a place where they do not take up space which is needed for other cyclotron components, in particular in the central region and at extraction. This characteristic allows the sector geometry to extend right to the cyclotron axis as in conventional superconducting cyclotrons, but retains the conceptual advantages of ring cyclotrons with regard to vertical focusing and extraction of the beam.

The magnet configuration has a diameter of 4.2 m and is 3 m high. A pole radius of 1.15 m was selected to place the onset of the radial fringe field beyond the 200 MeV orbit. A constant pole gap of 20 mm allows sufficient vertical space for the anticipated beam intensities, but excludes trim coils from this region. Each sector magnet features one pair of superconducting excitation coils which are located in a cryostat between the poles and return yoke. The cryostat is accessible from either side of the magnet, and a space of ~100 mm between the warm magnet surfaces and the coils at 4.2 °K should make ample provision for its structures.

The eight identical coils have a simple compact geometry and are relatively easy to fabricate. The azimuthal coil width is just over 1 m and a height of 1 m was found to be adequate. Average current densities in the range of 40 A/mm^2 should be acceptable for coils of this size if the magnetic field does not become too high. A current-carrying coil section of 400 mm × 175 mm was chosen to allow a maximum excitation of the magnets in the order of 2 × 3 MA. The dimensions result in a sturdy coil structure which facilitates mechanical support from the surrounding magnet parts. The substantial electromagnetic forces expected to act on the coils can be reduced by filling the core region of each coil with iron. A filler piece bridging the gap between pole and return yoke through an opening in the cryostat is suggested for this purpose. Alternatively the coils can be wound directly on a full core of magnet steel which is then included in the cryostat and thus cannot extend to the warm magnet parts. Such a design reduces the field in the coils even more and seems to be technologically advantageous.

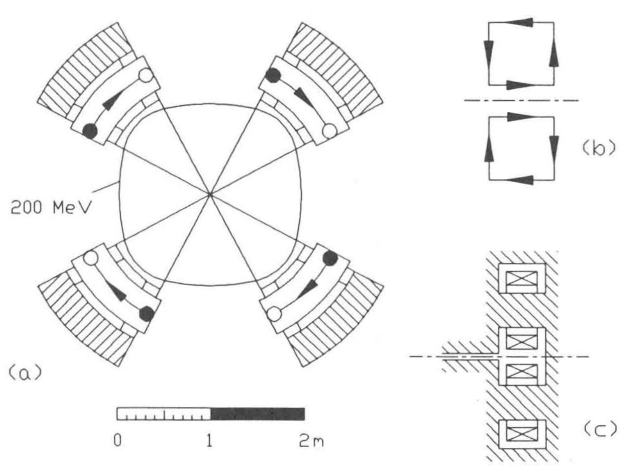

Fig. 1. The schematic lay-out of the proposed sector magnets showing the S-coils (a) located between the poles and return yoke, and in (b) radial elevation and (c) radial section.

4. FIELD ANALYSIS AND ORBIT PROPERTIES

The theoretical assessment of S-coil fields is facilitated by considering that the two coil-sets above and below the median plane are essentially short octupoles with regard to the cyclotron axis, but have opposite polarity and azimuthal conductor sections which result in strong dipole components. On the cyclotron axis and in the median plane only axial components of the dipole field remain, and the field at the axis can be calculated analytically. It is also quite simple to evaluate the field in the median plane if the coils are represented by filaments. A typical result obtained in this way is shown in Fig. 2 and clearly illustrates the characteristic field properties of S-coils in the median plane. Off the axis and median plane the analysis of the coil field becomes much more involved, except for the azimuthally averaged field components to which multipoles cannot contribute, by definition. However, fully 3-dimensional numerical field computations are necessary to evaluate the radial as well as azimuthal field properties of sector magnets with S-coil excitation.

A three-dimensional field analysis of the magnet configuration was carried out at the Paul Scherrer Institute[10] by making use of the TOSCA codes[11].

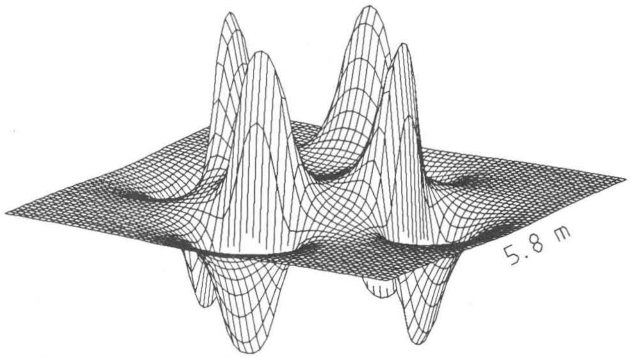

Fig 2. The magnetic field computed in the median plane for a filament representation of four symmetric 34° wide S-coils at a radius of 1.45 m. The filaments with clockwise and anticlockwise current directions are located 1.01 m and 0.19 m away from the median plane respectively.

The field obtained in the median plane for a mean current density of 46.3 A/mm^2 in the S-coils is shown in Fig. 3. Perhaps the most unusual result is that the magnetization contributes up to ~2.5 tesla in the pole gap at smaller radii, but only 1.7 tesla near extraction. This effect is a consequence of the extremely inhomogeneous field produced by the S-coils which use the magnet steel to 'pump' as much as possible magnetic flux into the central region of the cyclotron. It is remarkable that the magnetization field contributed near extraction does not change more than usually over the azimuthal range of the pole gap, in spite of the influence of the high octupole currents and although the iron is fully saturated.

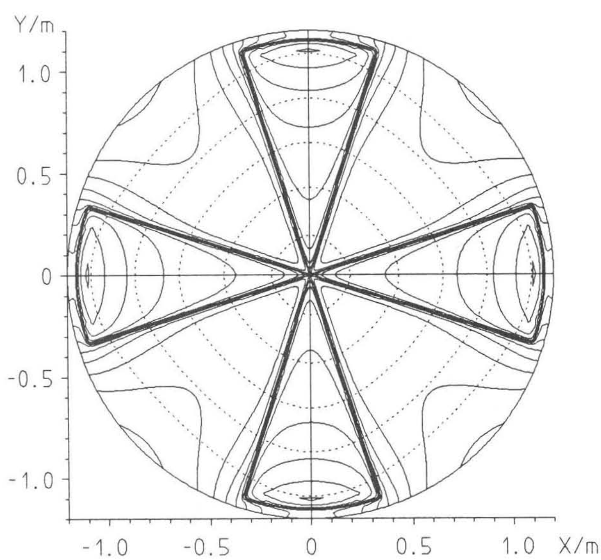

Fig. 3 The magnetic field computed in the median plane of the proposed sector magnets; equi-field contours at 0.3 tesla intervals are shown from 0.6 to 4.2 tesla within a radius of 1.2 m, together with five equilibrium orbits.

Results obtained by numerical orbit integration in this field are summed up in Fig. 4, for orbital frequencies of 26, 26.5 and 27 MHz. The field is too high for all three frequencies, but it becomes approximately isochronous within ~1% when it is multiplied with appropriate scaling factors which correspond to average current densities of 42.7, 44.3 and 46 A/mm^2 respectively in the coils. The apparent 2% field increase in the central region is most probably due to the discretization used in the calculation of the field, but there can be little doubt that only minor modifications of the poles are needed to correct the remaining deviations from isochronism or possible field aberrations which might occur in practice.

The focusing properties are satisfactory for the beam requirements and no unusual resonances are encountered by the beam in the ν_x/ν_z-diagram. For orbital frequencies of 26 and 27 MHz the extraction energy is limited to ~205 MeV by the onset of the radial fringe field or by losing vertical beam focusing, but a maximum proton energy of $\geq$ 220 MeV could be reached for 26.5 MHz if the radial fringe field is used to extract the beam. Under these conditions the fringe field is entered beyond 216 MeV and the $\nu_x = 1$ resonance is

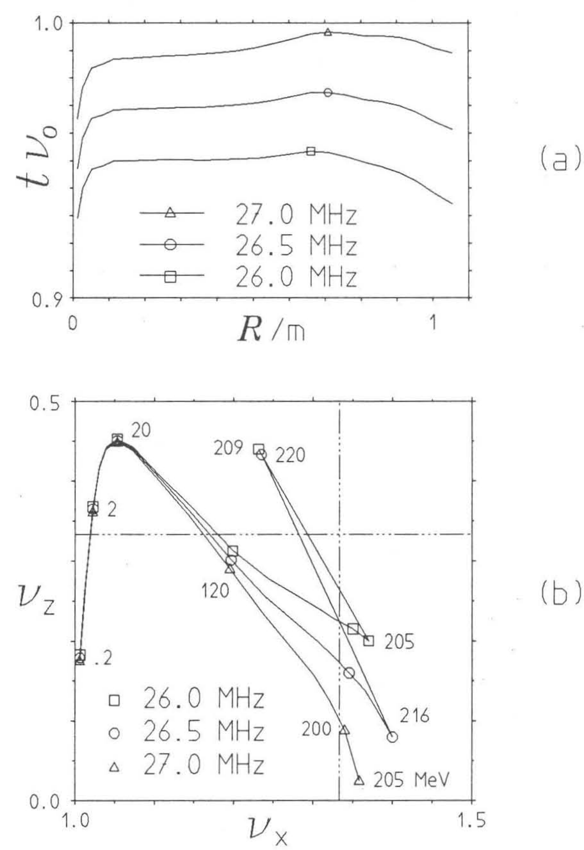

Fig. 4 The radial slope of the normalized revolution time (a) computed for orbital frequencies ν_0 of 26, 26.5 and 27 MHz respectively, and (b) the focusing characteristics obtained for the beam when the field has been made isochronous accordingly.

passed at $\nu_z = 0.75$ between 221 and 222 MeV. The average phase slip is only about 1.5° (rf) per turn in this region and the orbit separation increases to $\gtrsim$ 2.5 mm/MeV in the process. This could be enhanced further to a value between 5 and 7 mm/MeV with the help of coherent beam oscillations at $\nu_x = 1$ which provides favourable conditions for making effective use of extraction devices in a 4-sector machine.

5. MAGNET STRUCTURE

Construction and assembly of the magnets is facilitated considerably by their reduced size, which also has structural advantages. A preliminary assessment of different assembly options indicates that the magnet poles should be integrated into a single cylindrical vacuum chamber by mounting them on the inside of the top and bottom lid of the chamber. The individual pole pieces are ~0.9 m high for such a design and suitable spacers can be inserted on the radial rim of the pole gap to provide the necessary support. The yoke sections and pole pieces of each magnet also must be bolted together to ensure structural integrity, but the requirements are quite conservative. Calculations show that the attraction between the poles will not exceed 1.6 MN per sector at full excitation, and that the deformation of the pole gap is insignificant under these conditions. The strongest structural forces are those transferred from the S-coils which push the magnets radially outwards. Suitable links must be provided between the four magnets at the top and bottom yoke sections to ensure their radial stability.

Without doubt the most difficult mechanical problem is to prevent the S-coils from moving excessively within the confinement of the cryostat. The Lorentz force acting on the coils when they are perfectly positioned has been analysed using the field computed with TOSCA, and the results are presented in Fig. 5. The maximum field across the superconductors does not exceed 5.4 tesla for a mean current density of 44.3 A/mm^2 in the coils, but overall the forces are quite high. Each coil is pushed radially away from the cyclotron axis with 3.8 MN and pulled towards the median plane with 0.9 MN. A force of 4.2 MN acts azimuthally on the vertical coil sections. Although the resulting stresses are far within the acceptable limit for potted coils, the total forces clearly demonstrate how important it is to reduce the field in the coils as much as possible by optimizing the magnet design. Winding the coils directly on a full iron core and increasing the area of the return yoke somewhat would help considerably to attain this goal. The moments acting on the coils for deviations from the ideal position still have to be investigated, and the whole cryogenic design needs proper attention, but it should be technologically feasible to develop and operate such magnets successfully.

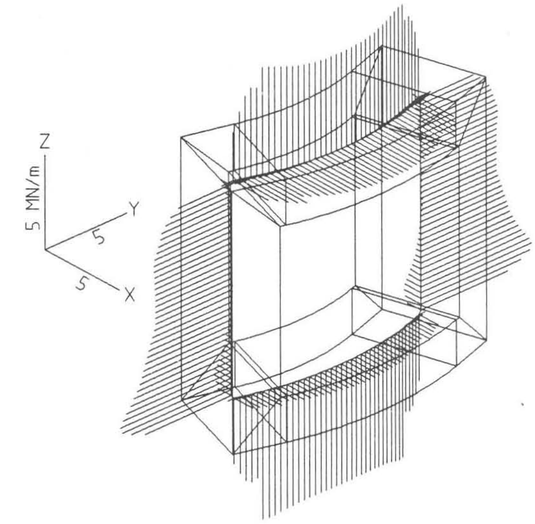

Fig. 5. The Lorentz force components calculated on the centre line of the S-coil above the median plane of the proposed sector magnet for a mean current density of 44.3 A/mm^2.

6. ACKNOWLEDGEMENTS

We would like to thank Dr U Schryber and Mr B Berkes of PSI for making the field calculations possible, Mr D P Brombach of PSI for his untiring efforts to bring them to a successful conclusion, Mr W A G Nel of NAC for carrying out the orbit calculations and Dr A H Botha of NAC for his essential support and discussions concerning the cyclotron.

7. REFERENCES

1) Chuvilo, I.V. *et al.*, **Proc. 11th Int. Conf. on Cycl. and their Applic.** (Tokyo, 1986) pp. 693-696.
2) Cole, R. *et al.*, **Proc. 1989 IEEE Part. Acc. Conf.**, Vol. 2 (Chicago, 1989) pp. 737-740.
3) Mandrillon, P., **Proc. 2nd Eur. Part. Acc. Conf.** (Nice, 1990) pp. 263-267.
4) Fukumoto, S. *et al.*, **Proc. 8th Symp. on Acc. Sci. and Techn.** (Saitama, 1991) pp. 456-458.
5) Inoue, M. *et al.*, ibid, pp. 459-461.
6) Blosser, H.G. *et al.*, **Proc. 11th Int. Conf. on Cycl. and their Applic.** (Tokyo, 1986) p. 165.
7) Jongen, Y. *et al.*, **Proc. 2nd Eur. Part. Acc. Conf.** (Nice, 1990) pp. 274-276.
8) Jungwirth, H.N and Brombach, D.P., **Proc. 12th Int. Conf. on Cycl. and their Applic.** (Berlin, 1989) pp. 498-501.
9) Jungwirth, H.N., **Proc. 11th Int. Conf. on Cycl. and their Applic.** (Tokyo, 1986) pp. 325-328.
10) Brombach, D.P., private communications.
11) Trowbridge, C.W., **Proc. 12th Int. Conf. on Cycl. and their Applic.** (Berlin, 1989) pp. 422-431.