A NOVEL CONCEPT FOR SUPERCONDUCTING RING-CYCLOTRON MAGNETS

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ABSTRACT

A conceptual design study of the superconducting magnet configuration for an isochronous ring cyclotron in the GeV range has been carried out during 1987 at PSI (formerly SIN). The main design considerations are reviewed and the approach adopted for determining the geometrical characteristics of such magnets from only a few cyclotron and field specifications is discussed. In order to meet the unique field and special design requirements a novel superconducting coil configuration is proposed and analysed. Results obtained by numerical field computation for a suitable choice of design parameters are presented. These results indicate that the proposed coil configuration holds great potential for applying superconductivity to ring cyclotrons with the same advantages as in "conventional" superconducting cyclotrons.

1. INTRODUCTION

Superconducting isochronous cyclotrons for ion energies up to 200 MeV per nucleon have been successfully developed and brought into operation over the past decade.[1-3] The magnet configuration of such cyclotrons - featuring only one or two superconducting solenoid pairs and "warm", largely saturated iron parts - is conceptually straight-forward and very efficient, but limits the range of ion energies and/or extractable beam intensities owing to the inherent properties of the magnetic field. The focusing limit of the field is always reached around 200 MeV per nucleon: at the ν_x stop band for three-ridged pole configurations; and as vertical focusing becomes marginal when the number of ridges is increased and other design restraints are taken into account. Efficient extraction of beams with intensities exceeding even 100 pnA is already extremely difficult in the strong magnetic field typically encountered in such cyclotrons. In a general sense, therefore, the present state of superconducting cyclotrons is reminiscent of that of room-temperature isochronous cyclotrons more than twenty years ago, when the concept of ring cyclotrons was explored at SIN to overcome similar limitations. A number of proposals for superconducting ring cyclotrons have indeed been made and analysed already.[4-6] The different concepts used in their magnet design provide interesting features and field properties, as discussed in more detail below, but unfortunately none of these proposals has actually been realised yet.

Ring cyclotrons in the GeV range have been investigated at the former SIN from the early eighties for the ASTOR (Acceleration and Storage Ring) proposal[7] using room-temperature magnets with fields up to 2 tesla, and assuming proton beams injected from the existing 590 MeV ring. In 1986, fresh interest arose for a larger version of ASTOR as post-accelerator with proton energies up to 3.6 GeV requiring magnetic fields well in excess of saturation at extraction, and thus superconducting coils. The problem was to find a suitable solution for producing the necessary field in such magnets under the special and stringent design requirements for ASTOR. For this purpose a conceptual design study of the magnet configuration for a superconducting ASTOR was carried out during 1987. In the course of this work a novel superconducting coil configuration was proposed and investigated. Although the idea of a superconducting ASTOR is no longer pursued at PSI, the results obtained are presented in this paper because of the potential for wider applications of such coils in ring cyclotrons.

2. DESIGN CONSIDERATIONS

2.1 ASTOR-Requirements

For the purpose of the design study it was assumed that ASTOR should have 18 magnets and use a harmonic number h=18 for the same resonance frequency (50.63 MHz) of the cavities as in the existing 590 MeV ring. This leads to injection and extraction radii of 13.4 m and 16.6 m respectively. At any particular radius the space available for the cavities is determined by the azimuthal magnet width (angle), but in total also by the azimuthal twist of the magnets due to the spiral angle required for vertical focusing. The pole plates cover a radial range between 13.2 m and 16.7 m from the cyclotron centre. The magnet angle should be about 6 ° which is equivalent to an azimuthal width of 1.4 m to 1.7 m. In order to provide isochronism with a constant bending angle of 20 °, the representative (hill) field in the pole gap should increase by a factor 3 from values far below saturation (1 tesla) at injection to values considerably above saturation (3 tesla) at extraction. The radial field gradient becomes particularly high for such magnets towards extraction (approaching 4 tesla/m), but at the same time the azimuthal field shape has to provide the necessary vertical focusing of the beam by means of sharp fringe fields and suitable spiral angles. The latter must be chosen together with magnet angle and azimuthal field shape, so as to provide a constant vertical betatron frequency of $\nu_z \approx 0.7$ throughout the cyclotron. The spiral angle may range from 0 ° up to 70 °, but should be kept as small as possible in order to minimize the total azimuthal twist of the magnet from injection to extraction.

2.2 Magnet Design Options

When considering various options it soon becomes evident that none of the superconducting magnet design concepts proposed so far for ring cyclotrons is suitable to meet the requirements for the ASTOR magnets as laid down above. It is nevertheless useful and very instructive to discuss these concepts briefly, as an aid in assessing the present proposal.

2.2.1 Existing design proposals. The two concepts used so far in existing design proposals are well known from room-temperature cyclotron magnets. One makes use of circular main coils at the cyclotron perimeter just outside extraction,[4] while in the other the coils are wrapped around the pole circumference.[5,6] In both cases the steel structure consists of three or more identical magnets which are separated from each other azimuthally and have the return yoke closing around extraction. A second return leg closing around injection is added when H-magnets are proposed for larger rings. Above saturation - utilizing superconductivity to the full - the essential limitation of these two concepts is that neither coil configuration can simultaneousely provide both a strong radial field increase and sufficient azimuthal field variation as required in isochronous cyclotrons particularly at higher energies per nucleon. Circular coils produce excellent radial field gradients, but have rotational symmetry and would in any case not be suited for ASTOR because they obstruct the valleys. Pole-wrapped coils give rise to very sharp fringe fields (negative field "gullies"),[5] but the radial field rise can not be provided without increasing the magnet angle (pole flaring), which is associated with extremely high spiral angles.

2.2.2 Discussion of design alternatives. Suitable designs for superconducting magnets must rely on their coils. In this context the removal of the coils from the valleys is essential for ring cyclotrons. In order to achieve this the coils can be wrapped around the return yoke. Rather surprisingly (in terms of conventional magnet technology) large radial and azimuthal field gradients are then produced with comparable ease, although such a design has other limitations (e.g. yoke saturation) and disadvantages (e.g. severe stray fields) which make it unsuitable for most applications.

A direct comparison of the options discussed so far provides the clue to another alternative which is presented schematically in fig. 1(a). In this concept only the essential common conductor sections between the poles and return yoke are retained and supplemented with simple vertical and horizontal conductor sections to form the coils as indicated in figs. 1(c) and (d). Thus such coils are confined to each magnet and can in fact also be used in combination with any of the other design concepts discussed earlier. The coil configuration investigated for the ASTOR magnets for instance is represented in fig. 1(b).

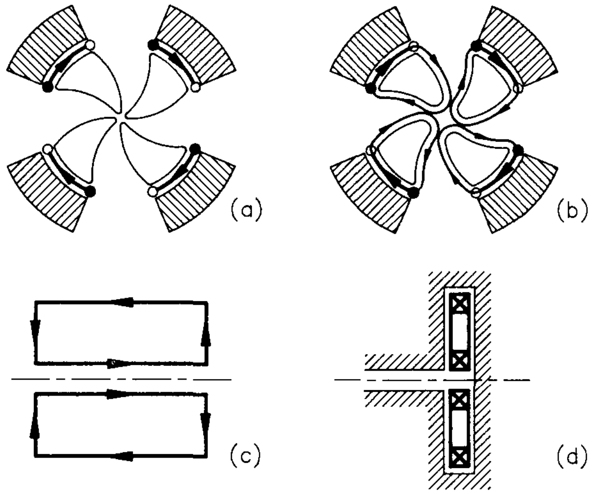

Fig.1 Schematic representation of the novel design concept proposed for superconducting C-magnets of ring cyclotrons showing the new "S"-coils (a) between the poles and return yoke, and in (c) radial and (d) azimuthal elevation, as well as (b) in combination with pole-wrapped coils.

The proposed coils are particularly suited to superconducting technology and its application in ring-cyclotron magnets. The coil size is relatively small, and the basic coil geometry very simple. The position in the magnet provides "natural" support from almost all sides, and the essential properties of superconducting coils (small cross-sections and high current densities) provide for design efficiency. The coil field (fig. 2) contributes considerably - and towards extraction increasingly - to both the radial and azimuthal field gradients, but does not cause field reversal in the valleys (inside extraction) or excessive stray fields. In fact the amount of steel required for the yoke is considerably reduced by the characteristics of the coil field. Perhaps the most important practical result of this design concept is, however, that it provides field control right through saturation, thus restoring the accustomed freedom required for the design of such magnets.

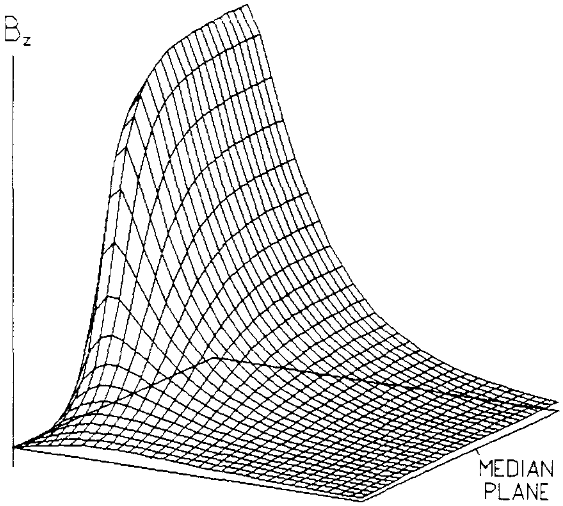

Fig.2 The magnetic field computed in the median plane (1.5m × 1.5m of one quadrant) for the 4 horizontal conductor sections (each 0.2m × 0.2m wide; the inner 0.3m and the outer 1.4m apart) of a 2m long straight "S"-coil.

With this novel concept (which also has obvious applications in "conventional" superconducting cyclotrons where it is in fact already used indirectly and with circular coil geometries for adjusting the radial field gradient), the magnet design for cyclotrons is approached from the relativistic side, without losing the ability to control the field in the centre by conventional methods. Since S-shaped current directions, superconductivity, saturation and sideward positioning at poles are essential characteristics, and because sector cyclotron magnets are the first important application envisaged, the name "S"-coils is suggested. The main drawback of such "S"-coils could be the relatively high magnetic field and force encountered by the conductors.

3. DESIGN AND ANALYSIS OF ASTOR MAGNET

3.1 Radial Magnet Characteristics

Adopting the usual iterative approach, we first investigated the radial design characteristics. For this purpose the two-dimensional code POISSON was used to compute the field numerically for geometries with rotational symmetry about the cyclotron axis. Extreme care must be taken to achieve convergence when H-magnets and "S"-coils are analysed together in this way. Figures 3 and 4 show some of the results obtained for a reasonable choice of parameters. Since the limited azimuthal width of the "S"-coils and magnet is not taken into account by such a model, the actual field can be about 5 to 10% lower in a sector magnet, thus requiring increased excitation currents.

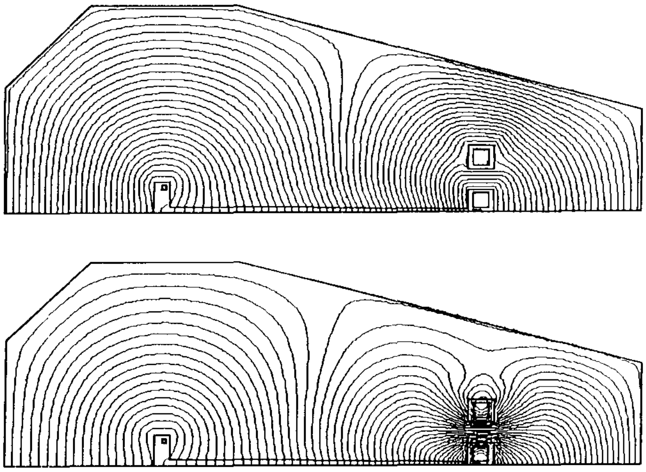

Fig.3 Radial flux distributions computed in a magnet for ASTOR when the "S"-coils are switched off (top) or excited to 2.33 × 10^6A (bottom).

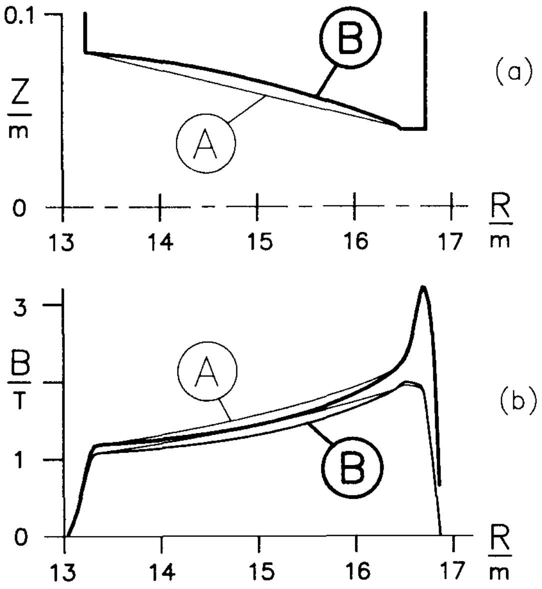

Fig.4 Two radial gap (a) and associated field (b) profiles computed for the ASTOR magnet with and without excitation of the "S"-coils as in fig. 3.

The dramatic effect of turning the "S"-coils on to 2.33 x 10^6A-turns in such a magnet becomes evident when the two radial flux plots in figure 3 are compared. In both cases only 7.68 x 10^4 A-turns are supplied to the small coils providing the main field. An enormous amount of flux is "sucked" through the core of the excited "S"-coils, thus relieving all other yoke sections, especially in the iron above (and below) the outer "S"-coil conductors, where a zero-field region and field reversal are encountered. In fact the yoke size could be reduced even further without serious consequences to the field in the pole gap, which leads to much smaller magnets and considerable savings in costs. In contrast the low-field side of the yoke at injection must be kept relatively large. The effect of the "S"-coils is also very beneficial below saturation, however, as can be seen in figure 4(b), because it allows us to provide any field shape merely by choosing the pole gap versus radius to suit the excitation of the small coils. The steel reluctance becomes negligible for these coils right through saturation, because the "S"-coils provide all the magneto-motive force required. Field control also becomes very easy under such circumstances. Above saturation the pole gap is kept constant (see fig. 4), but the field rises rapidly with radius due to the proximity of the inner "S"-coil conductors. Field gradients up to 6 tesla/m are achieved.

The dimensions of the "S"-coil section are 200 mm x 200 mm in these cases, with 50 mm all round for cooling, insulation and support. This gives an overall current density of less than 40 A/mm^2 which is well within the usual technological limits for superconducting coils. The peak field encountered by the superconductor is about 6.5 tesla, and the direction of the forces predominantly axial. Both can be reduced significantly by making the coil sections wider radially and thinner vertically without changing the conducting area. Unfortunately the coil field does not penetrate as far into the pole gap then. The core of the "S"-coils should always be filled with magnet steel bridging the gap between the pole and yoke, so that the outer "S"-coil section is completely surrounded by steel. This helps considerably to reduce the peak field and current in the coil. By changing the vertical aperture (0.35 m) of the "S"-coil core the amount of flux passing through it can be increased or decreased as required for a particular magnet.

3.2 Azimuthal Magnet Characteristics

The results of the radial analysis have been utilized to evaluate the azimuthal features of the ASTOR magnet for general scrutiny and 3-dimensional field calculations. The azimuthal fringe field can be represented for this purpose by the local gap width and the distance between the pole and effective field boundaries to determine the spiral angle required for ν_z=0.7 and the pole boundaries. Fig. 5 shows the magnet obtained for the radial design "A" of figure 4. The sector angle increases from 5 ° at injection to 6.65 ° near 3 GeV, but then decreases to 6 ° at 3.6 GeV. At injection a 0.13 m wide chamfer of the pole edges is necessary to keep ν_z=0.7 even without a spiral angle. The latter increases gradually up to 67 ° at extraction, however, leading to a total azimuthal twist of 8.5 °, thus leaving 6 ° or ~1.5 m for inserting the cavities radially between adjoining magnets.

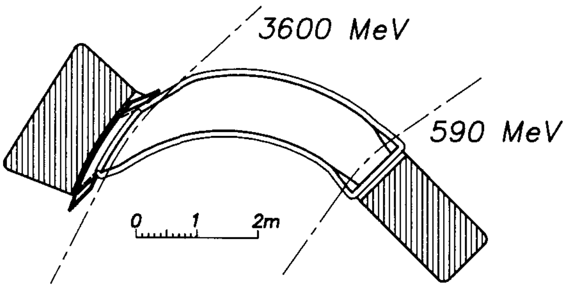

Fig.5 Plan view of a superconducting ASTOR magnet design utilizing "S"-coils in addition to the usual coils wrapped around the pole.

The centre of curvature of the "S"-coils coincides with that of the extraction orbit in the magnet, and the azimuthal width (~2 m) is chosen to provide a 20 ° aperture from this centre. These coils can be shifted somewhat azimuthally and their vertical sections are twisted in order to contribute a spiral component to the field. The results obtained so far by 3-dimensional field computations for such magnet geometries are still crude owing to limitations in time and modelling refinement, but they clearly confirm the expected radial and azimuthal field characteristics, and thus the viability of the "S"-coil concept. Much more work would be necessary to address detailed design features and field properties in the extraction region.

4. CONCLUSION

The new design concept of "S"-coils proposed for sector magnets of superconducting cyclotrons is particularly suited to provide the magnet and field characteristics required in relativistic ring cyclotrons, and can be used to overcome limitations of present superconducting cyclotrons. Many detailed design questions and technological problems must still be resolved, but the use of "S"-coils for superconducting ring cyclotrons in general seems to be established.

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