POTENTIAL ENHANCEMENT OF MAGNETIC DEFLECTION IN THE CHALK RIVER SUPERCONDUCTING CYCLOTRON EXTRACTION SYSTEM

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ABSTRACT

The electrostatic deflector in the Chalk River superconducting cyclotron is often required to operate at its high-voltage limit. To ease the operating constraints this limit imposes, a study has been undertaken to explore the potential effects of increasing the intrinsic magnetic deflection that is available in iron extraction elements (hill lenses), immediately following the deflector. Modifications to the hill lens geometry and compensation elements have been identified that significantly increase the magnetic steering. Beam orbit calculations show that a 20% reduction in deflector voltage may be possible, in principle, for ion beams of interest when the dipole fields in the hill lenses are changed by about 0.1 T. However, resulting perturbation effects must be well compensated to avoid substantially reducing the benefit.

1. INTRODUCTION

One of the limits to beam extraction from the Chalk River superconducting cyclotron[1] is reliable high-voltage operation of the electrostatic deflector, which often runs at its performance limit. Deflector development work at Chalk River has pursued several options to improve overall performance. Companion papers at this conference report on improvements made to the existing deflector,[2] and on an alternative deflector configuration that has electrodes between the conventional sparking plates and the high-voltage electrode.[3] This paper describes results of a study to reduce the beam deflection required in the electrostatic deflector by enhancing the magnetic deflection available in extraction elements (two hill lenses) immediately downstream from the deflector along the extraction trajectory. In the following sections the layout of the extraction system is briefly described, some guidelines for changes are given, hill lens modifications and corresponding changes to magnetic field compensation are identified, and the calculated performance is presented.

2. EXTRACTION SYSTEM

Figure 1 shows schematically the extraction system in the cyclotron midplane and identifies the major elements, which are fixed. Briefly, the beam entering the deflector (A) in a dee gets an electrical push outwards, to escape the confining magnetic field and enter the magnetic channel (D,E), contained within magnet cryostat (G). The hill lenses (B,C) generate a radial gradient in the axial magnetic field, to provide radial focusing to offset the strong radial defocusing of the fringe field of the magnet. The hill lenses also produce a significant dipole field that steers the beam. The magnetic channel contains superconducting coils and passive iron structures, to provide radial focusing and steering. The iron elements generate perturbation fields in the midplane acceleration region that must be adequately compensated, especially for first harmonic perturbations in the regions where $\nu_r = 1$. Iron bars (F) opposite the hill lenses, and (H) opposite the iron of the channel, provide the compensation. The superconducting coils are designed with compensation windings included. The extracted beam exits the cyclotron through a hole in the iron yoke (I).

Figure 2(a) gives the cross section of the iron elements of lens 1 (B in Fig. 1). The cross section of lens 2 (C in Fig. 1) is identical to that of lens 1, except that each of the bars on the right-hand side has its vertical height reduced from 12 mm to 11.25 mm. Each lens subtends an azimuthal width of 10 degrees at the cyclotron centre, and a space 16 degrees wide separates the two lenses. Stainless steel brackets mounted on the cryostat wall hold the lenses in

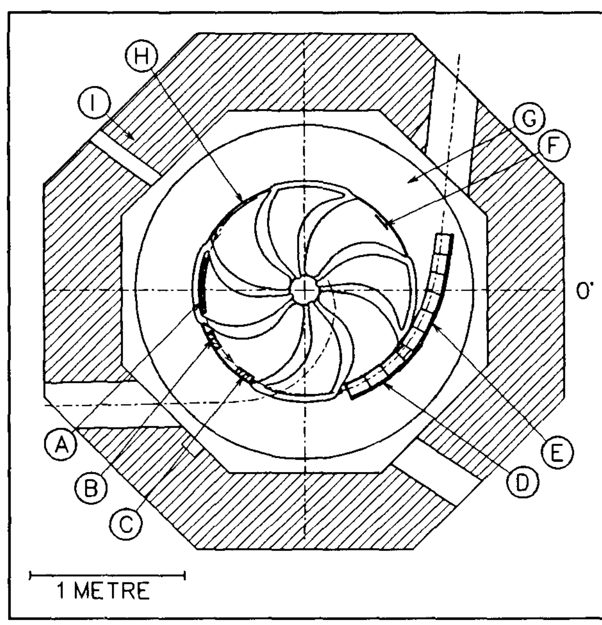

Fig. 1 Extraction system midplane layout.

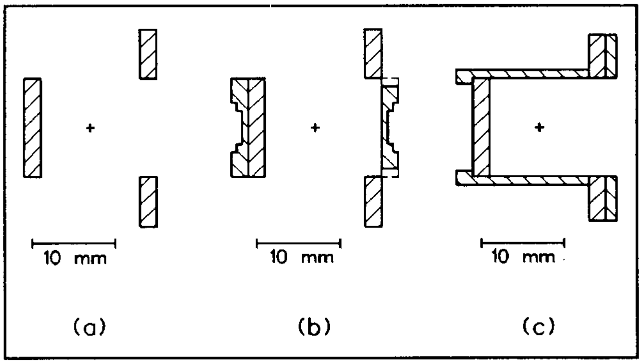

Fig. 2 Cross section of hill lenses: (a) lens 1 without modifications; (b) modified lens 1; (c) modified lens 2.

place in a hill gap.

2.1 Requirements

It is highly desirable for operational reasons that any changes to the extraction elements have as small an impact as possible on the beam circulating in the acceleration region. In particular, the co-ordinates of the beam entering the deflector should not be altered appreciably, especially the radial momentum.

Extraction of beams with the revised system should not require magnetic channel winding currents that are significantly different from those required in the unmodified system. This means that the radial momentum at the channel entrance for a given beam must not be altered appreciably. By providing radially outward deflection, both hill lenses make the radial momentum at the channel entrance more positive; i.e., the beam is directed outwards more. This increased radial momentum would require channel currents outside the operating range for some beams. The remedy is to steer the beam radially inwards in lens 2 after it has experienced strong outward steering in lens 1. In effect, the beam should be "dog-legged" in the revised system by the changed iron in the hill lenses.

3. LENS MODIFICATIONS

3.1 Lens Additions

Initial calculations with the code SUPERGOBLIN,[4] modified to allow superposition of uniform dipole fields on the extraction region field maps for the unmodified hill lenses, showed that field changes of about 0.1 T could lead to an interesting reduction in the deflection required in the electrostatic deflector. However, the field changes would have to act over longer lengths of beam path than the existing lenses. The fields would be reduced in lens 1 and increased in lens 2 by roughly equal magnitudes, and the path lengths over which the fields act would be adjusted to maintain the radial momentum of the beam at the channel entrance so that it is essentially the same as the value without the modifications.

To identify the shape of iron pieces that could be added to the lenses to get the desired field changes at the azimuthal middle section of the lenses, infinitely long, straight iron bars of rectangular cross section, magnetically saturated, were modelled analytically as current sheets.[5] Vertical surfaces of the cross sections were aligned with the background magnetic field, which ranged from about 2 to 5 T. The cross section for required iron was built up by trial and error, to give the desired dipole field in the azimuthal middle section. Once the cross section of the iron additions was defined, calculations were performed using a two-dimensional code, EXMAP, based on the Biot-Savart law, to verify that the dipole fields were acceptable when the curved shape and finite length of the lenses were taken into account. The resulting cross sections for the iron changes are shown in Fig. 2(b) for lens 1, and Fig. 2(c) for lens 2. The azimuthal extent of the iron additions to lens 1 is from 204 degrees to 225 degrees. Lens 2 modifications extend from 225 degrees to 240 degrees. EXMAP was used to calculate maps of the fields generated in the acceleration region and along the extraction path. These maps were combined with the maps for the unmodified pieces, to give a composite set of maps to use in SUPERGOBLIN.

3.2 Compensation of Perturbations

After detailed field maps were calculated for the extraction region, and used in SUPERGOBLIN to verify that the magnetic geometry produced the desired effects along the extraction path, the perturbation fields in the acceleration region were calculated and Fourier analyzed. The perturbation fields requiring correction were the average field change and the first harmonic.

The compensation strategy was to first identify iron pieces that adequately cancel the first harmonic perturbations introduced by the iron additions to the hill lenses. Then, iron additions to deal with the average field perturbations were sought. These pieces were added to the system in diametrically opposite pairs, which avoided the generation of additional first harmonic fields. All iron additions are made in a symmetrical fashion about the midplane, to preserve the midplane symmetry. This process leads to an inevitable increase in second harmonic perturbations. Compensation of second harmonics is not easily dealt with, because suitable locations for appropriate compensators are not available.

The compensator for the first harmonic was an iron bar, rectangular cross section 2.5 mm high by 0.5 mm thick, bent to have the inner surface on an arc of radius 664 mm. It subtends 10 degrees at the machine centre. This piece is

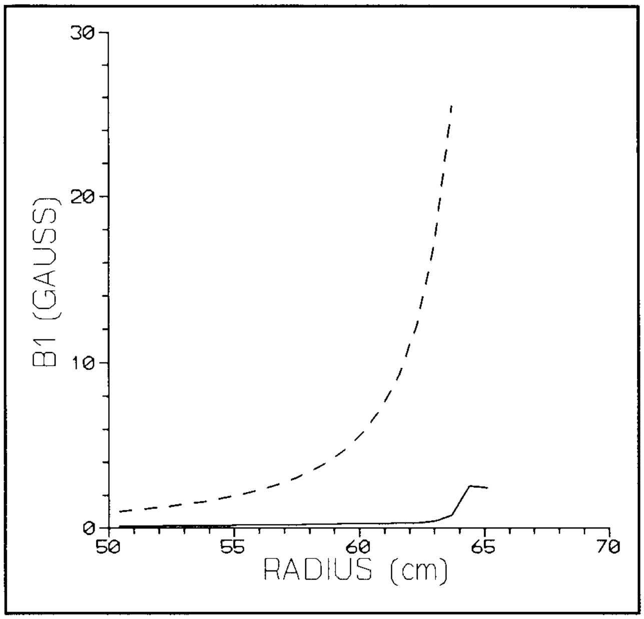

Fig. 3 Plot of first harmonic perturbation fields B1 from the iron additions to the hill lenses; dashed line, uncompensated; solid line, compensated.

a simple addition to the existing compensating bar for the hill lenses. Figure 3 shows the first harmonic perturbations from the modifications to the lenses, before and after the compensation was added. The residual first harmonic at 63 cm radius generated by the iron additions exceeds 18 G, but is reduced to 0.4 G when compensation is added.

Figure 4 gives the midplane layout and the cross section of the compensator for the average field perturbations that the lens modifications generate. One pair of these pieces, arranged symmetrically about the midplane (Z=0), is located radially in front of the modified lenses, and another pair is 180 degrees away, radially in front of the first

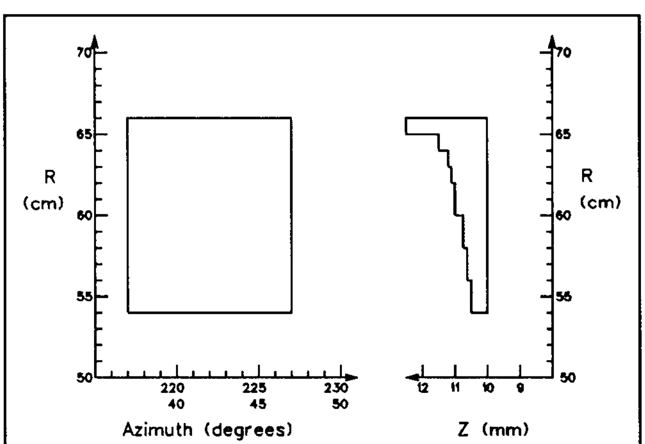

Fig. 4 Schematic of the iron used to compensate average field perturbations caused by the hill lens modifications.

harmonic compensator. Figure 5 shows the compensation of the changes to the average field. The poorest compensation is at the inner edges of the iron (see Fig. 4).

4. RESULTS

Extensive calculations were performed with SUPERGOBLIN using the composite field maps generated for the revised hill lenses. Two kinds of calculations were done. First, a wide selection of beams, with an average field ranging from 2.5 to 5.0 T, was run through the extraction system, starting at the entrance of the deflector. The setup of the cyclotron and the beam initial co-ordinates were those of the originally calculated beams for no modifications to the hill lenses. Second, calculations were done for several different beams, starting at injection of the beam into the cyclotron, followed by foil stripping, and acceleration out to the deflector entrance. The average field ranged from 2.5 to 3.2 T. Again, cyclotron setup and the beam initial co-ordinates were those for the system with the original hill lenses. However, the field maps contained the perturbations from the modifications to the lenses. Dee voltage was adjusted for entry into the deflector on the same turn as in the unperturbed calculation.

Figure 6 illustrates the general trend of the calculated results. The upper curve represents the case with no perturbations in the acceleration region. About a 20% decrease in deflector voltage occurs for beams such as 45 MeV/u carbon, which has an average midplane field of 3.0 T. However, when the beam experiences the perturbations in the acceleration region from the additional iron, it is evident that the benefit may be decreased substantially. This situation arises because the radial

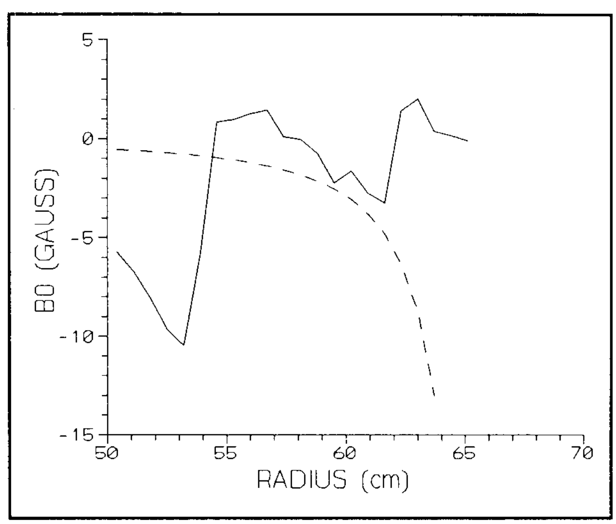

Fig. 5 Plot of the average field perturbations generated by the hill lens modifications; dashed line, uncompensated; solid line, compensated.

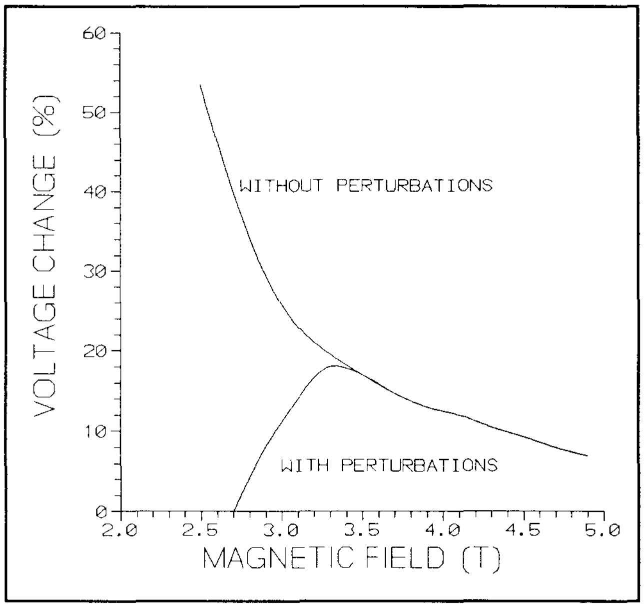

Fig. 6 Plot of the deflector voltage change resulting from enhanced magnetic deflection in the hill lenses.

momentum at the deflector entrance is more negative than in the unperturbed case, and thus results in a smaller decrease in deflector voltage.

Figure 7 displays some examples of the outer 10 turns for carbon (45 MeV/u, 3.0 T) and chlorine (8.5 MeV/u, 2.5 T) beams with and without the additions to the lenses.

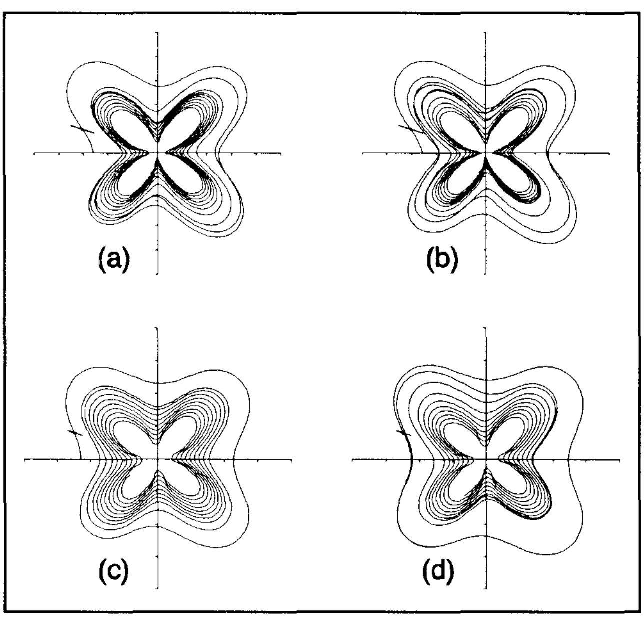

Fig. 7 Orbit plots for C, 45 MeV/u without (a) and with (b) lens modifications; and for Cl, 8.5 MeV/u without (c) and with (d) lens modifications. Scale interval: (a) and (b), 1 cm; (c) and (d), 2 cm.

The origins are at radii of 62 and 60 cm for the carbon and chlorine plots respectively. The short, slanted line in the second quadrants indicates the entrance face of the deflector. (The entrance midpoint is at a radius of 65.2 cm.) The orbit sensitivity to the small changes in the perturbations is evident. Calculations for several beams, with the average field B0, first harmonic B1 or second harmonic B2 perturbations removed from the perturbation field maps, showed that the B0 and B1 perturbations were consistently detrimental. However, B2 perturbations had radial momentum at the deflector entrance increased for some beams.

We have reported the preliminary results from this study for compensating the incremental perturbation fields arising from iron added to the extraction system. Future work on this method of enhancing magnetic deflection will consider improved compensation for all of the extraction system perturbations, and the implications for redetermining the setup parameters for the more than 50 different ion beams that have been extracted to date.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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