CONCEPTUAL DESIGN OF A SUPERCONDUCTING SEPTUM FOR FFAGs*

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Abstract

The fixed magnetic field in FFAG (Fixed Field Alternating Gradient) accelerators means that particles can be accelerated very rapidly. This makes them attractive candidates for many applications, for example for accelerating muons for a neutrino factory or for charged particle therapy (CPT). To benefit fully from this the particles have to be extracted at the same rate. In combination with the high magnetic rigidity of the particles this represents a significant challenge, especially where variable energy extraction is required, which implies extraction at variable radius.

This paper presents a conceptual design of a 4T superconducting septum for the PAMELA accelerator, which is an FFAG for a combined proton/carbon ion therapy facility. The field in the septum is varied as a function of the horizontal position, which allows variable energy extraction without the need for sweeping of the magnetic field.

INTRODUCTION

FFAGs have recently been reconsidered for a number of applications due to their inherent advantageous: due to the fixed magnetic field particles (at least in principle) can be accelerated very quickly. This makes them attractive also for commercial applications, for example charged particle therapy.

PAMELA, which is an acronym for PArticle Accelerator for MEdicaL Applications, is a design study of a so-called non-scaling, non-linear FFAG for a combined proton, carbon ion therapy facility. PAMELA is designed to deliver protons up to 250 MeV and carbon ions up to 400 MeV per nucleon. More details about PAMELA can be found in [4, 5].

One attractive feature of an FFAG is the relatively small footprint; the drawback of this is that little space is available for the extraction elements. A further complication is that particles need to be extracted at different energies, which in practise is required to paint the tumour at different tissue depths. This implies that particles at different energies experience a different field to keep the bending radius constant.

EXTRACTION

In PAMELA particles are extracted vertically, which means a horizontal magnetic field is required in the septum. The present layout of the extraction elements is shown schematically in Fig. 1; the requirements for the extraction are described in more detail in [7].

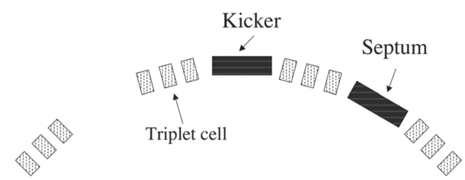

Figure 1: Schematic view of the extraction layout of the PAMELA accelerator. Each magnet of the triplet is 0.633 m long, with a drift section of 0.633 m in between. The drift section between triplet cells is 2.065 m.

The available space for the septum is 1.2 m. The horizontal beam aperture is about 200 mm; particles at lower energies will be located at the inner radius, whereas higher energy particles will be radially outwards.

The application of the machine implies that either the field of septum has to be changed between 1.6 and 4 T (depending on the particle energy) or the field has to vary as a function of horizontal position.

A simple calculation reveals that a normal conducting, pulsed septum is challenging: for a peak magnetic field of 4 T the stored energy in the septum (0.2 m^3) is about 1.3 MJ. Assuming a peak acceptable current of about 30 kA the inductance of the septum would be 3 mH. The necessary rise and fall-time would be about 0.25 ms (1 kHz repetition rate), which is equivalent to a maximum $\mathrm{d}I/\mathrm{d}t$ of 2×10^8 A/s. The required peak voltage is therefore 600 kV.

A better approach is therefore to a septum where the field changes as a horizontal position. The required field profile can be described by the so-called scaling law[6]:

$$B_\mathrm{y} = B_0 \left(\frac{r}{r_0}\right)^k . \tag{1}$$

In this equation B_y is the vertical magnetic field, k the field index, r_0 the reference radius of the lattice and B_0 a reference field. For this paper we use a k value of 42, a reference radius of 9.3 m and a reference field B_0 of 2.61 T. The field is required for a radius from 9.2 to 9.4 m.

A SUPERCONDUCTING 4T SEPTUM

Geometry

The geometry of the septum is shown in Fig. 2. The entire length of the septum is 1030 mm; the length of the iron

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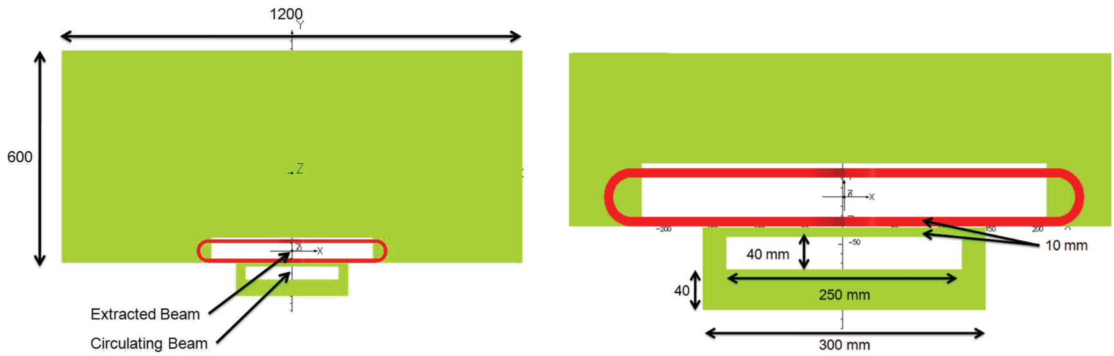

Figure 2: Geometry of the septum.

yoke is 600 mm with a total cold mass of about 3.2 tons. The current distribution in the current sheets is realized by 26 bedstead coils, which extend longitudinally beyond the yoke. The coils are arranged in two groups differing in the direction of the horizontal return path, which minimizes the overall length. The thickness of the septum is about 20 mm, which includes 10 mm for the conductor and 10 mm for an iron shield to minimize the effect of the stray field on circulating particles. The usable aperture of the septum is about $40 \times 200\ \mathrm{mm}^2$.

Realization of the Varying Septum Field

A fixed horizontal magnetic field can be created by two parallel current sheets with current flowing in longitudinal direction (see for example [3]). To realize a magnetic field which varies as a function of the horizontal position the current density in the sheets has to be varied.

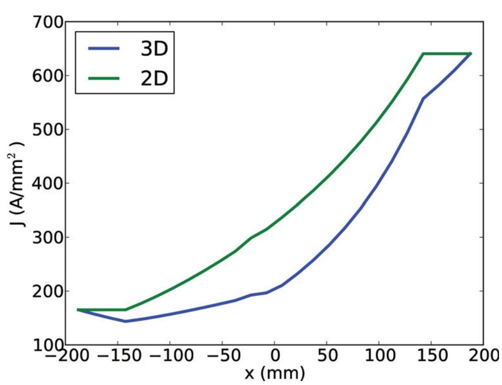

Figure 3: Current density in the racetrack coils. Shown are the theoretically required current density for a 2D case and the final current density in the model, which takes into account the different lengths of the bedstead magnets and non-linearities of the iron yoke.

For linear materials in 2D this is straight forward, as the magnetic field directly depends on the magnitude of the current density at that horizontal position. In 3D and using realistic BH-curves for the soft-iron the situation is more complicated due to the non-linearities and the different lengths of the individual racetrack coils.

Opera 3D (from VectorFields/Cobham) was used to evaluate the magnetic field. The problem was optimized in subsequent iterations, until the magnetic field was found to be in agreement with the desired field to within 1%. In the simulations we use the 'default' BH curve (good quality soft iron).

Fig. 3 shows the resulting current density as a function of the horizontal position. The figure also shows the theoretical result for an infinitely long current sheet. The resulting integrated values of the horizontal and vertical magnetic field in the aperture are shown in Fig. 4.

Load Line

With an average current density of about 650 A/mm^2 the peak field on the conductor is 6.7 T, which is shown in Fig. 5. The current density exceeds that of conventional NbTi wire, even when assuming a relatively low Cu:Sc ratio of 2:1 or 3:1. We therefore propose to use Nb_3Sn.

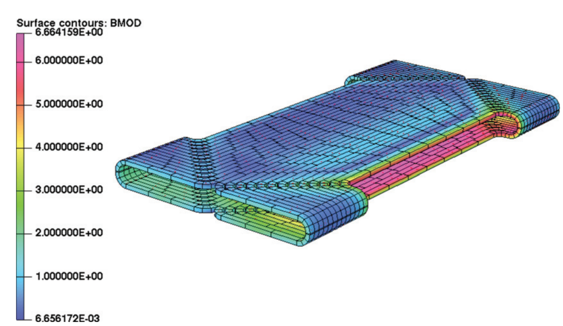

Figure 5: Peak field on the conductor.

The critical current density of Nb_3Sn is calculated using data from [1, 2], assuming a mechanical strain of 0.45% in the superconductor. This strain value was found to produce a good agreement of the critical current density with the published data of commercial Nb_3Sn wire manufacturers.

The load line is shown in Fig. 6. As shown in the figure, the temperature margin of the septum is more than 6 K, which will help to cope with possible heating effects from stray particles hitting the septum.

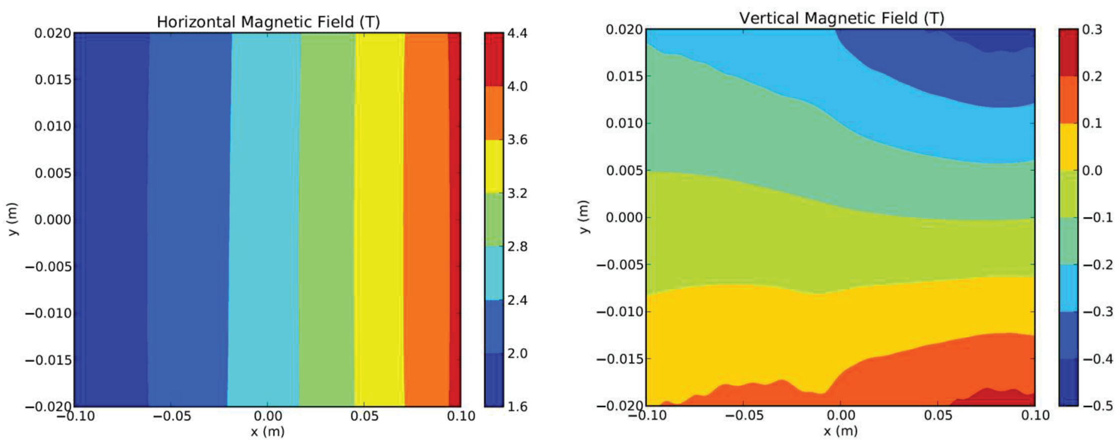

Figure 4: Horizontal (left) and vertical (right) magnetic field in the septum.

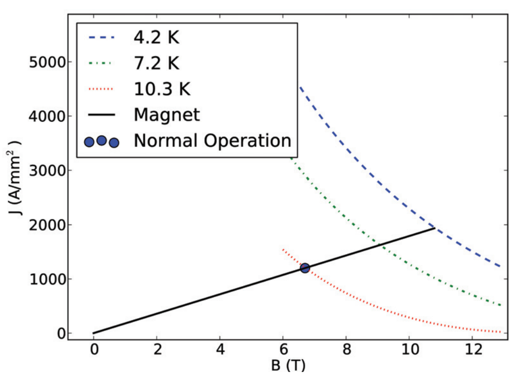

Figure 6: Load line of the PAMELA septum for the carbon ring. The current density is shown for the non-Cu part of the conductor.

Fringe Field

A concern of this septum is the relatively large stray field. Fig. 7 shows the stray horizontal field experienced by the circulating beam for different horizontal positions (at a vertical distance of 1 mm with respect to the beam pipe/iron shield).

The stray field occurs primarily in the region underneath the bedstead coils, which is not covered by soft-iron. The integrated field strength is less than 30 mTm, which is considered acceptable.

CONCLUSION

This paper presents a conceptual design of a 4 T septum for carbon ion radiotherapy. The design avoids the need for sweeping by varying the longitudinal current as a function of the horizontal position using 26 bedstead coils.

Further work should concentrate on minimizing the iron volume, which will also reduce the cold mass. Tracking studies should be carried out, to verify that the stray fields are acceptable. The heating from stray particles should be estimated using a suitable simulation software.

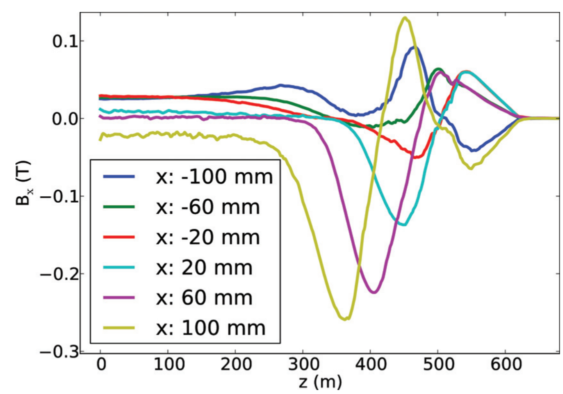

Figure 7: Stray field (hor. component) seen by the circulating beam at different horizontal positions.

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