FEASIBILITY STUDY OF COMBINED FUNCTION MAGNETS FOR A S-FFAG FOR MEDICAL APPLICATIONS*

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Abstract

Non-scaling fixed field alternating gradient (NS-FFAG) accelerators combine a number of advantages, such as rapid particle acceleration and large acceptance. These features make NS-FFAGs particularly interesting for medical applications. NS-FFAGs could be used for cancer therapy, which may lead to significant size and cost reductions in comparison to other accelerator types. Cancer therapy with protons or carbon ions is advantageous in comparison to conventional radiation treatment amongst other things due to the higher biological effectiveness. This paper discusses the basic magnet design issues for the PAMELA project. PAMELA is a prototype proton/carbon-ion therapy facility.

INTRODUCTION

In this paper we discuss the feasibility of the magnets required for PAMELA. PAMELA is an acronym for **P**article **A**ccelerator for **ME**dica**L** **A**pplications. The basis for our study is the lattice suggested by Keil et al. [4].

This lattice consists of three rings. The first and third ring are used exclusively for protons and carbon ions, respectively. Ring 2 is used for carbon ions as well as protons. PAMELA is targeted to generate protons with a kinetic energy between 8–250 MeV and carbon ions between 8–400 MeV/u. Each ring consists of 48 cells of doublets.

PAMELA MAGNETS

The requirements for the PAMELA magnets are summarized in tables 1 and 2. As shown in the tables, each of the PAMELA magnets needs to provide a dipole and quadrupole field. We assume that a field quality of 2–3×10^{-3} is required. A particular challenge is that all coils need to be relatively short; at the same time a relatively large bore is required to accommodate the beam. The coils for ring 1 may be realised by conventional iron dominated quadrupoles; the dipole field can be introduced by offsetting the beam horizontally with respect to the coil's centre. The requirements for the coils for ring 2 and 3 however exclude the possibility of using iron-dominated coils. Therefore we explore the feasibility of a superconducting solution for all rings. Promising in this respect is the so-called 'double-helix' concept.

Table 1: Pamela D-Magnets

	1D	2D	3D
Length [m]	0.18	0.27	0.36
Hor. aperture [mm]	29	79	76
Vert. aperture [mm]	30	26	24
B_{Dipole} [T]	0.635	0.945	1.995
Gradient [T/m]	-13.45	-14.3	-23.55

The double-helix technique allows to create almost perfect multipole fields [5]; in short, a cos-θ current density distribution on a cylinder an be created by nesting oppositely tilted solenoids. The direction of the current density in Cartesian coordinates can be expressed as follows:

$$x = R\cdot\cos(n\theta) \quad (1)$$

$$y = R\cdot\sin(n\theta) \quad (2)$$

$$z = y\cdot\cot\alpha \quad (3)$$

R is the radius of the cylinder, θ is the azimuthal angle, n is the order of the multipole and α is the tilt angle of the solenoid. Space precludes a detailed description, but an example of a coil creating a dipole field is shown in figure 1. Combined function fields can be created by nesting a dipole and quadrupole [2, 6, 8].

Table 2: Pamela F-Magnets

	1F	2F	3F
Length [m]	0.17	0.26	0.35
Hor. aperture [mm]	55	118	116
Vert. aperture [mm]	16	20	14
B_{Dipole} [T]	-0.26	-0.265	-0.69
Gradient [T/m]	15.64	14.32	23.97

The double-helix concept has the invaluable advantage that an ends problem does not exist, as the coil ends are a natural part of the coils. Conventional superconducting magnets would inevitably suffer from a loss in field quality; additionally, conventional perimeter coil ends or of type 'bedstead' require a significant amount of space. In the next section we present preliminary coil designs based on the double-helix concept.

DOULE-HELIX COILS FOR PAMELA

The coil designs were evaluated using Opera 3D from Vector Fields[1]. The helical coil structure is created by an

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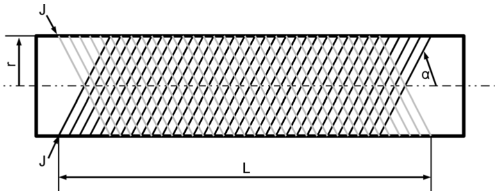

Figure 1: Double-Helix concept.

automated script [7]. The field qualities and integrated field strengths are evaluated using 3D field maps generated by Opera. The accuracy of the field map is better than 10 Gauss. The peak field on the wire is determined by using Opera's inbuilt functions.

Field Quality

Important for PAMELA are the integrated field components and the field qualities of the integrated field [3]. We use field maps with a spacing smaller than $1 \times 1 \times 1$ mm^3. It was verified that this spacing is sufficient when using cubic interpolation in between the grid points. A MATLAB® script is used to calculate the integrated dipole and gradient field. The field qualities Q for the gradient and dipole field are calculated using the following two equations:

$$Q_{\mathrm{Dipole}} = \frac{\int B_{\mathrm{Dipole}}\,\mathrm{d}z - B_{\mathrm{Dipole,average}}}{B_{\mathrm{Dipole,average}}} \tag{4}$$

$$Q_{\mathrm{Gradient}} = \frac{\int G\,\mathrm{d}z - G_{\mathrm{average}}}{G_{\mathrm{average}}} \tag{5}$$

B_{Dipole} is the dipole field and G is the gradient. The average values refer to the intergrated gradient and dipole field.

Changes in the gradient field due to dipole field errors are naturally included in the calculations. We further assume that a local deviation in the gradient field from the average value leads to a dipole field contribution.

Temperature Margins

We assume that the coils are made using standard NbTi superconductor using a copper to superconductor ratio of 2 : 1. We further assume that the packing factor is about 70%. We use data from Bottura to calculate the temperature margins [1].

The Coil Designs

The preliminary coil designs for PAMELA are summarized in tables 3, 4, 5 and 6. The magnetic field for each coil is created by nesting a dipole and quadrupole, each of which employs the double-helix concept.

In ring 1 and 3 the quadrupole is the inner coil. For ring 2 it was found that it is beneficial to place the dipole on the inside, as this leads to a smaller overall outer radius. The coils for ring 1 are the least challenging, as the required field components and aperture requirements are low. The magnets for ring 2 are the most challenging: The field and aperture requirements are similar to the coils in ring 3, but they need to be shorter by about 100 mm. All coils are made of two or more double-layers, which helps to reduce the peak field on the wire by cancelling out unwanted field components.

Table 3: Preliminary Quadrupole Designs - D Magnets

	1D	2D	3D
Inner radius [mm]	25	72	45
Outer radius [mm]	31	90	55
Coil length [mm]	86	170	267
Tilt angle α [°]	65	65	65
No. double layers	2	3	3
Layer thickness [mm]	1.5	3	1.67
Current density [A/mm^2]	400	350	380
Peak field wire [T]	3.8	5.45	5.8
Temperature margin [K]	1.4	1.0	0.8
$\int G\,\mathrm{d}z$ [T]	-2.45	-3.95	-8.47

Table 4: Preliminary Dipole Designs - D Magnets

	1D	2D	3D
Inner radius [mm]	32	50	57
Outer radius [mm]	48	71	102
Coil length [mm]	87	180	260
Tilt angle α [°]	65	60	60
No. double layers	2	3	3
Layer thickness [mm]	4	3.5	7.5
Current density [A/mm^2]	600	345	320
Peak field wire [T]	4.4	5.2	6.35
Temperature margin [K]	0.7	1.2	0.8
$\int B_{\mathrm{Dipole}}\mathrm{d}z$ [Tm]	0.12	0.265	0.735

Table 5: Preliminary Quadrupole Designs - F Magnets

	1F	2F	3F
Inner radius [mm]	38	76	68
Outer radius [mm]	50	100	89
Coil length [mm]	78	156	255
Tilt angle α [°]	65	65	65
No. double layers	3	3	3
Layer thickness	2	4	3.5
Current density [A/mm^2]	527	345	355
Peak field wire [T]	5	6.2	5.65
Temperature margin [K]	0.6	0.7	0.9
$\int G\,\mathrm{d}z$ [T]	2.69	3.7447	8.47

All coils are significantly shorter than the allocated space in the lattice. The magnetic field decays to almost zero outside the allocated space, which may be beneficial for nearby components sensitive to magnetic fields.

We estimate that the F and D magnet in ring 1 store a magnetic energy of about 1 kJ each. For ring 2 the stored

Table 6: Preliminary Dipole Designs - F Magnets

	1F	2F	3F
Inner radius [mm]	51	67.5	90
Outer radius [mm]	61	75.8	102
Coil length [mm]	85	153	253
Tilt angle α [°]	65	60	60
No. double layers	3	3	3
Layer thickness	1.67	1.38	2
Current density [A/mm^2]	500	340	425
Peak field wire [T]	4.61	5.9	5.4
Temperature margin [K]	1	0.9	0.8
$\int B_{\mathrm{Dipole}} \mathrm{d}z$ [Tm]	-0.05	-0.07	-0.25

energy increases to about 11 kJ. The highest magnetic energy is stored in ring 3, which is 41 kJ for the D coil and 25 kJ for the F coil.

Field Qualities

The calculated field qualities are summarized in tables 7 and 8. In general the gradient quality is better than 2.53×10^{-3}. Apart from the 2F coil the dipole field quality is better than 2.45×10^{-3}. The worse dipole field quality for 2F is caused by errors introduced by changes in the quadrupole field. Even though the gradient error is comparable for all coils, the dipole field in the F-coils is much lower than in the D-coils. Therefore, even though the magnitude of the field error caused by the gradient field is comparable, the effect on the overall dipole error is larger.

Table 7: Field Qualities - D Magnets

	1D	2D	3D
$Q_{\mathrm{Quad,min}}$ [10^{-3}]	-1.02	-2.53	-1.95
$Q_{\mathrm{Quad,max}}$ [10^{-3}]	0.67	1.6	1.35
$Q_{\mathrm{Dipole,min}}$ [10^{-3}]	-0.76	-0.7	-0.54
$Q_{\mathrm{Dipole,max}}$ [10^{-3}]	0.25	1.43	1.3

Table 8: Field Qualities - F Magnets

	1F	2F	3F
$Q_{\mathrm{Quad,min}}$ [10^{-3}]	-0.5	-2.05	-1.3
$Q_{\mathrm{Quad,max}}$ [10^{-3}]	0.27	1.32	0.6
$Q_{\mathrm{Dipole,min}}$ [10^{-3}]	-0.66	-2.84	-1.2
$Q_{\mathrm{Dipole,max}}$ [10^{-3}]	1.82	4.55	2.45

An example for the field quality is shown in figure 2, which shows the gradient and dipole field quality across the beam aperture. As shown, the gradient field quality is symmetric to $x = 0$. The dipole field quality is not, which is caused by considering the effect of the gradient field on the dipole field.

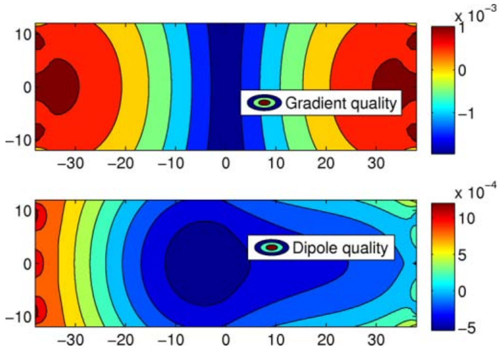

Figure 2: Field Quality Coil 3D.

CONCLUSION

We have evaluated the feasibility of the combined function magnets for the Keil lattice. In general, the magnets appear to be feasible. The magnets are challenging because of space restrictions in combination with a relatively large bore. The double-helix concept allows to design magnets which fit into the allocated space; the typical coil ends problem is completely avoided. The calculated field qualities are within the targeted range apart from the 2F coil. Tracking studies should be carried out to confirm that the field quality is sufficient. In this work we neglect structural considerations as well as quenches, which are not the scope of this study.

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