PAMELA MAGNETS – DESIGN AND PERFORMANCE*

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Abstract

PAMELA is a design study of a non-scaling FFAG for hadron therapy aiming to deliver 250 MeV protons and 400 MeV/u carbon ions. This paper outlines the general magnet design required for the 250 MeV proton case. The magnet design is challenging because of the combination of required field strength (up to 4T), geometric constraints (the magnets need to be short) and large beam aperture (larger than 230 mm). All magnets are combined function magnets with dipole, quadrupole, sextupole and octupole field components of good field quality.

INTRODUCTION

PAMELA, which is an acronym for PArticle Accelerator for MEdicaL Applications, is a non-scaling, non-linear fixed-field alternating-gradient accelerator (FFAG) for hadron therapy [8]. The present design assumes that PAMELA will consist of two rings; the first will accelerate protons from 30 MeV to 250 MeV and carbon ions from 8 to 68 MeV. The second ring is exclusively for carbon ions, which will be accelerated from 68 to 400 MeV/u. There is a possibility that the injection energy for the first ring will be 70 MeV for protons (19 MeV/u for carbon ions).

The lattice consists of 12 identical cells of triplets, each with two F and one D magnet [9]. Each of the magnet has an envisaged length of 314 mm; F and D are separated by a gap of equal length (314 mm).

This paper deals with the principle magnet design for the proton ring; the next section discusses the requirements in terms of magnetic field and coil bore.

PAMELA MAGNET DESIGN

Requirements

The present PAMELA lattice evolved from the scaling FFAG, where the magnetic field follows the scaling law:

$$B_{\text{Vertical}} = B_0 \left(\frac{r}{r_0}\right)^k \tag{1}$$

B_0 is reference field, r_0 is reference radius, k is the field index and r is the radius. This magnetic field in theory contains an infinite number of higher order multipole components.

In PAMELA, however, the scaling law is broken in that multipole components higher than octupole are not considered. Typically, this leads to a deviation of the vertical magnetic field from the optimum of a few milli-Tesla. Tracking results show stable conditions for a working point with $k = 38$ at a reference radius of 6.251 m. B_0 is 1.67T and -2.44T for F and D, respectively.

From the previous lattice specification it is clear that the length of the magnet cannot be larger than 628 mm; in this paper we allow a maximum length of about 560 mm. The minimum required coil bore is about 23 cm, which can be deduced from figure 1. The figure shows the horizontal particle position versus the travelled particle distance. The figure shows schematically the position of the two F magnets and the D magnet. Even though the horizontal beam excursion is only about 18 cm, due to the curvature of the particle traces the coil bore has to be larger than 23 cm. In this paper we assume a coil bore of 28 cm. If the injection energy for protons is 70 MeV, the bore can be smaller by 5 cm. The vertical beam aperture is about 20 mm.

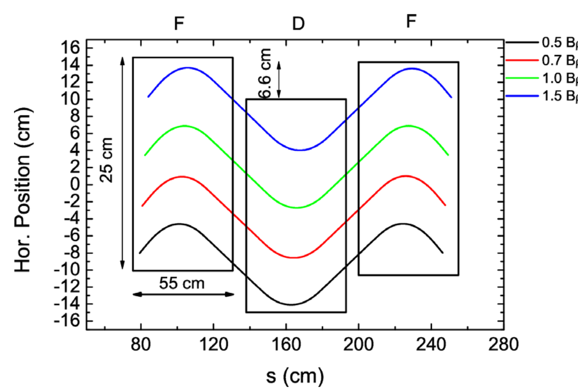

Figure 1: Horizontal particle position in triplet for different magnetic rigidities.

As shown schematically in figure 1, the centres of F and D are offset longitudinally by about 66 mm. The magnetic field both magnets have to provide is shown in figure 2 for an injection energy of 30 and 70 MeV.

Table 1: Polynomial Coefficients

	70 MeV		30 MeV	
	F	D	F	D
C0	1.95	-1.89	2.26	-2.11
C1	11.81	-11.57	13.60	-12.88
C2	36.17	-35.74	40.96	-39.28
C3	68.42	-68.387	77.44	-75.14

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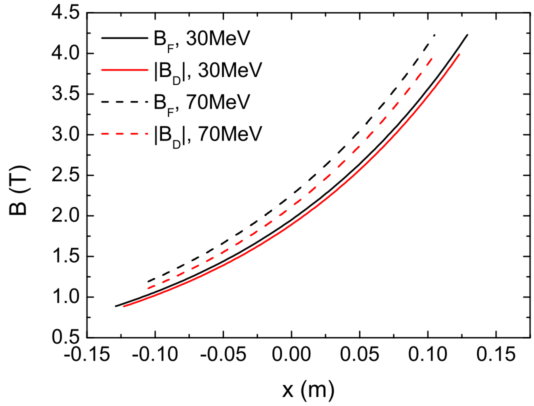

Figure 2: Required equivalent magnetic field.

It can be seen that the F and D magnet have to provide almost the same magnitude of magnetic field; for an injection energy of 30 MeV the magnetic field of D is slightly lower. We therefore develop two magnet designs for F, one for each injection energy, which also satisfies the requirements of D. Table 1 shows the polynomial coefficients of the vertical magnetic field.

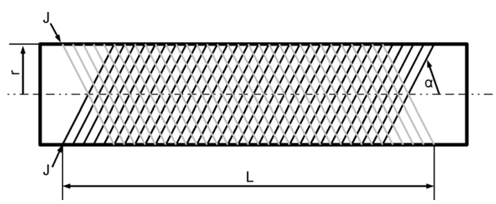

Figure 3: Schematic of a double-helix dipole.

Concept

The PAMELA magnets represent a significant challenge: The magnets have to be very short in comparison to their bore; at the same time they have to produce a substantial field. The peak field of more than 4T rules out conventional iron cored coils; superferric coils of type 'picture frame' (see [4] for more details) were considered but dismissed as it was found that the higher order multipole components are difficult to control. Conventional superconducting cosine-theta magnets suffer from coil end problems.

For this design we employ superconducting so called 'helical' or 'double-helix' coils. The principles of this technology were already established in the 1970s [7]; more recent work is mentioned in [3]. Space precludes a detailed description; as an example we show a dipole in figure 3, where the field is created by oppositely tilted solenoids.

In helical coils the path of the current in a cartesian coordinate system can be described with the following equations:

$$x = R \cdot \cos(\theta) \tag{2}$$

$$y = R \cdot \sin(\theta) \tag{3}$$

$$z = \frac{h\theta}{2\pi} + \frac{R}{\tan\alpha}\sin(n\theta) \tag{4}$$

R is the coil radius, θ is the azimuthal angle, h is the winding pitch and α is the tilt angle of the solenoid. The multipole order is given with the parameter n (for a dipole n equals one, for a quadrupole two and so on).

PAMELA requires multipole components up to octupole. Even though in principle it is possible two combine two multipoles in one double-helix coil, we opt for a more flexible design. We nest four helical coils in each other, which results in a combined function magnet with dipole to octupole component.

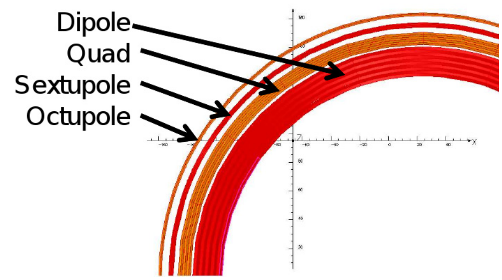

Figure 4: PAMELA combined function magnet.

As shown in figure 4, the dipole is the innermost coil. The next is the quadrupole coil, followed by the sextupole and octupole. The ordering was done according to the maximum field strength the individual multipoles have to provide. The dipole provides the highest magnetic field; to minimize the magnetized air volume it was placed on the inside.

The Coil Designs

The coil designs were optimized in several iterations using Opera 3D from VectorFields. The temperature margin was evaluated using data for NbTi from Bottura for two potential conductors with a Cu:Sc ratio of 2:1 ($T_{margin1}$) and 1.3:1 ($T_{margin2}$) [1]. We assume a packing factor of 70%.

Table 2 shows the final coil designs for both injection energies. As shown, all magnets are close to the set coil length limit of 560 mm. For the higher injection energy the peak fields on the wire are between 4.3 and 5.36T (for an injection energy of 70 MeV). The required current densities are between 180 and 280 A/mm^2. The coils were optimized to have a temperature margin of about 1.5 K using the conductor with a Cu:Sc ratio of 2:1.

The coil design for an injection energy of 70 MeV is very similar to the 30 MeV case. The table shows that an injection energy of 70 MeV is less challenging in terms of the magnets, which is indicated by the increased temperature margins which are generally larger than 2K.

Performance

Figure 5 shows a plot of the horizontal and vertical magnetic field for different horizontal positions. The vertical

Table 2: PAMELA Magnet Specifications for 30 and 70 MeV Injection Energy.

	30 MeV Dipole	Quad	Sextupole	Octupole	70 MeV Dipole	Quad	Sextupole	Octupole
Length [mm]	560	565	555	564	551	553	551	543
Inner Radius [mm]	140	162	177	185	110	132	143	150
Outer Radius [mm]	160	173.2	183	187	130	139.5	145	152
J [A/mm^2]	275	278	217	182	221	261	334	104
Tilt angle [°]	50	50	60	60	50	50	55	60
No. double layers	5	4	4	1	5	3	2	1
B_{max} F/D [T]	5.05/4.95	5.36/5.25	4.9/4.78	4.3/4.3	4.3	4.45	4	3.42
$T_{margin1}$ F/D [K]	1.6 /1.7	1.4/1.5	1.9/2	>2/>2	>2	>2	>2	>2
$T_{margin2}$ F/D [K]	2/2.1	1.8/1.9	>2/>2	>2/>2	>2	>2	>2	>2

field is shown for the centre plane ($y = 0$), whereas the horizontal field is shown for a vertical position of 10 mm. The field shape can be approximated using the well known Enge-function [2]. A good fit is obtained for $c_0 = -0.1$, $c_1 = 0.6$, $c_2 = -0.02$, $c_3 = c_4 = 0$ and $c_5 = 0.001$ and a fringe field extent of 27 cm. The Enge coefficients allowed us to create a 3D field map, which was used in tracking studies with the code ZGOUBI [6]. Using a field map we determined the earlier defined working point and the traces of the particles in the triplet shown in figure 1.

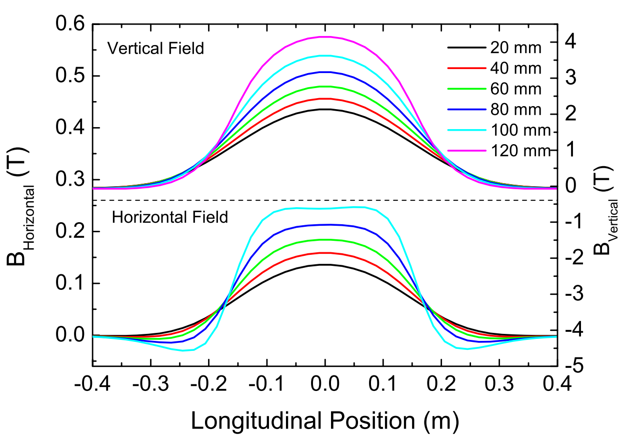

Figure 5: Examples of the horizontal and vertical magnetic field in the PAMELA F magnet for various horizontal positions.

The field quality is obtained by evaluating the field harmonics for various radii. In general, the field quality is better than the required minimum of 1×10^{-3}. The field quality of the quadrupole and sextupole is about 1×10^{-4}; the field qualitites of the dipole and octupole are slightly worse with 3×10^{-4}.

CONCLUSION

This paper outlines a conceptual design of a magnet solution for PAMELA. The PAMELA magnets are challenging because of the physical length restriction and large coil bore in combination with the required magnetic field.

We have shown that a coil geometry can be found which satisfies the geometric constraints with ample temperature margin. Superconducting double-helix coils appear to be an attractive solution in this respect. The obtained field qualities are better than the minimum requirement. Each multipole field component is created by one designated coil; this should allow to tune the individual multipole component within reason after assembly.

If the injection energy is 70 instead of 30 MeV, the temperature margins increase even further. The margins can be used to shorten the coil or decrease the radial winding thickness.

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