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QUADRUPOLE MAGNET FOR A RAPID CYCLING SYNCHROTRON*

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Abstract

Rapid Cycling Synchrotrons (RCS) feature interleaved warm and cold dipole magnets; the field of the warm magnets is used to modulate the average bending field depending on the particle energy. It has been shown that RCS can be an attractive option for fast acceleration of particles, for example muons which decay quickly.

In previous studies it was demonstrated that in principle warm dipole magnets can be designed which can provide the required ramp rates, which are equivalent to frequencies of about 1 kHz. To reduce the losses it is beneficial to employ two separate materials for the yoke; it was also shown that by employing an optimized excitation coil geometry the eddy current losses are acceptable.

In this paper we show that the same principles can be applied to quadrupole magnets targeting 30 T/m with a repetition rate of 1kHz and good field quality.

INTRODUCTION

A number of accelerators have been proposed recently to facilitate rapid acceleration. One application which requires extremely fast acceleration is a potential future Muon Collider; the rapid acceleration here is necessary due to the short lifetime of the particles.

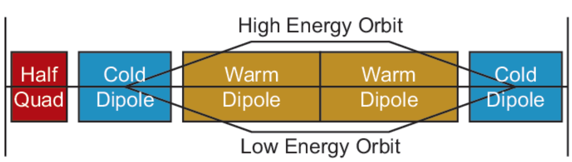

Figure 1: Rapid Cycling Synchrotron - Lattice.

Hybrid synchrotrons have been shown to be an attractive alternative to accelerate muons [1]. A hybrid synchrotron features interleaved warm and cold dipole magnets as shown in Fig. 1; the warm dipole magnets are expected to be ramped at rates equivalent to 400–1000 Hz with a repetition rate of 15 Hz in order to achieve the correct integrated bending strength for the particles.

In previous papers we have outlined solutions for those dipole magnets [2–4]; in this paper we show that the same design ideas are applicable to quadrupole magnets.

MAGNET REQUIREMENTS AND CONCEPT

The lattice requires 35 T/m quadrupole magnets, but 30 T/m are acceptable even though this increases the total installed length of the quads from 520 m to 606 m. The good field region is ±30 mm horizontally and ±12.5 mm vertically. The RCS for the muon collider requires a gradient quality of $1 \cdot 10^{-3}$ or better.

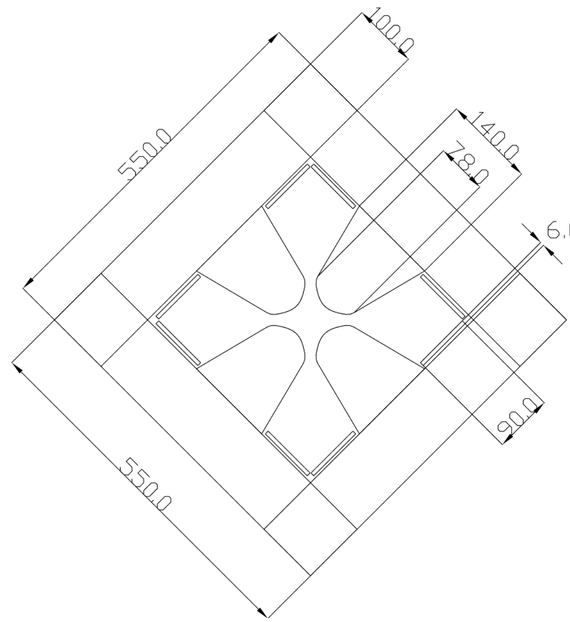

Figure 2: Magnet Geometry (all dimensions in mm).

Due to the high frequency it is of vital importance to minimize the losses in the quadrupole. In general there are two contributions:core losses in the yoke and eddy current losses in the excitation coil.

We employ two different materials for the yoke of the magnet in order to lower the overall losses. One material (3% SiFe) is used for the pole due to its higher saturation value [5]. The rest of yoke is made of 6.5% SiFe, which has very low losses at high frequencies [6]. The yoke of the magnet is assumed to be made of laminations with 100 μm (6.5% SiFe) and 127 μ (3% SiFe) thickness. In addition, the poles of the quadrupole are tapered to minimize the amount of iron at higher saturation.

To minimize the eddy current losses in the excitation coils thin current sheets are employed. Each sheet is 2 mm thick; three of these sheets (with Kapton insulation in between) are bundled together to form a bus-bar with total dimensions of $90 \times 6\ \text{mm}^2$.

Figure 2 shows the geometry of the magnet; the pole shape is hyperbolic with an inscribed radius a of 30 mm ($y = a^2/2/x$).

SIMULATION RESULTS

For computer simulations we employ the commercial software package COMSOL Multiphysics[1]. 2D magnetostatic

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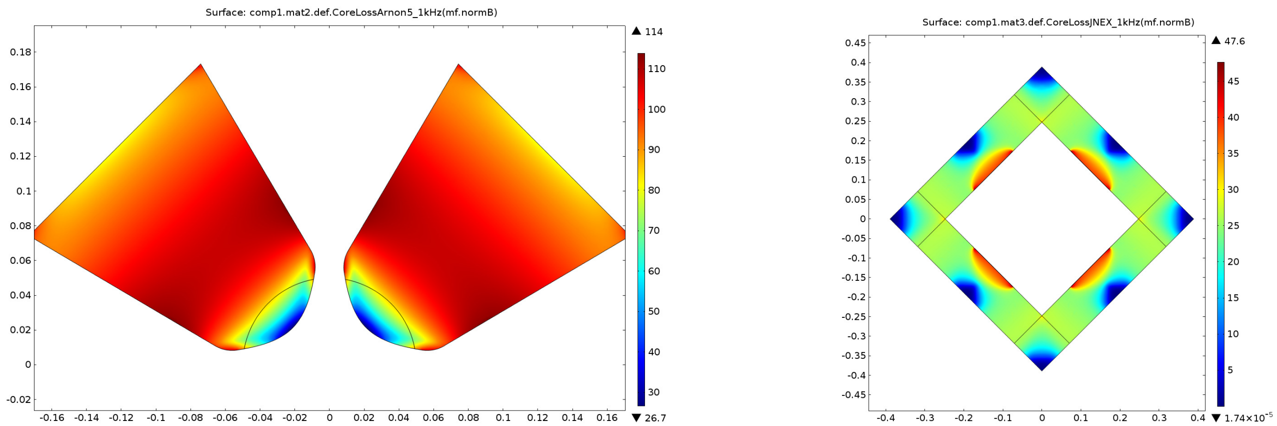

Figure 3: Core loss (in W/kg) in the pole of the magnet (left figure) and the return yoke (right figure) at a frequency of 1 kHz.

simulations are employed to evaluate the field quality and core losses at various gradient strengths. 2D transient magnetic simulations are used to determine eddy current losses in the excitation coil as well as the required voltage to drive the necessary current through the coils.

The magnetostatic simulations take into account the non-linear behaviour of the material used for the yoke. For the transient simulations we assume linear material properties ($\mu_r = 5000$).

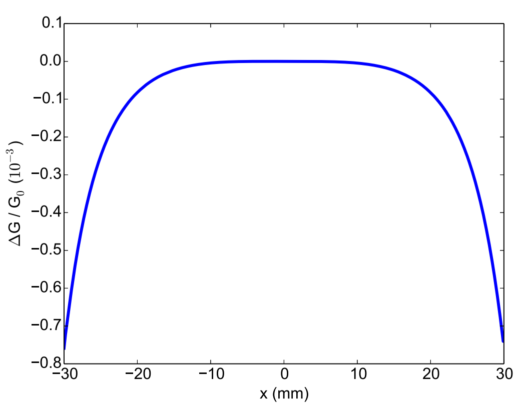

Figure 4: magnet Geometry (Gradient Quality).

The simulations show that a gradient of 29 T/m can be achieved. Figure 4 shows the achieved gradient quality in the region of the beam. Table 1 summarizes the field harmonics at an inscribed radius of 28 mm. The table shows that the higher order harmonics are well behaved.

POWER LOSSES

Figure 3 shows the core losses in the pole and yoke of the magnet. The figure shows that the concept of using two materials for the yoke pays off to lower the overall losses: the losses in the pole are about 100 W/kg at a frequency of 1 kHz whereas the core losses in the rest of the yoke are lower by a factor of four.

Table 1: Normalized Harmonics

	Normal	Imaginary
1	0.01748	-0.00119
2	10000	-0.10564
3	-0.02068	0.02212
4	-0.00576	-0.01979
5	-0.02226	-0.00918
6	-0.14483	0.07908
7	0.00996	-0.01139
8	-0.10607	0.01381
9	0.01375	-0.00222
10	0.19022	-0.0609

Figure 5 shows the total power loss for the quadrupole magnets per m length taking into account the repetition rate of 15 Hz. The largest contribution to the losses are the excitation coils; the losses in the pole and yoke are about the same. The total power loss is about 2 kW/m; assuming 606 m total quadrupole length in the accelerator the total power loss is about 1.2 MW.

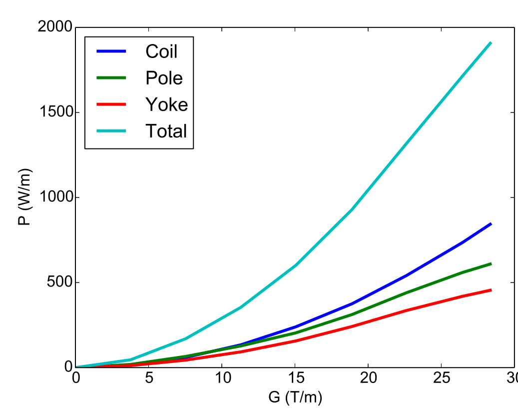

Figure 5: Total power loss in the quadrupole per m length.

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COOLING

Similar to the dipole design we envisage that the yoke will be cooled via cooling channels in the yoke. Provided a sufficient flow rate can be sustained the temperature gradient in the yoke should be minimal. This was verified in a thermal simulation; the result is shown in Fig. 6. The figure shows that the expected temperature gradient is less than 4 K.

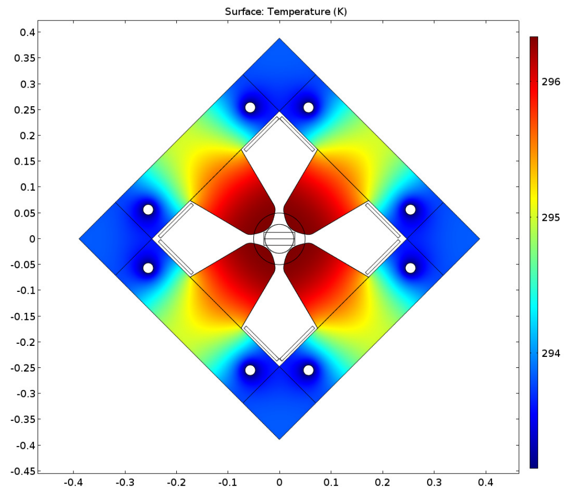

Figure 6: Temperature gradient in yoke.

For the excitation coil we foresee a similar system as outlined in [2]; the bus-bars can be conduction cooled via their faces. Ample space within the yoke exist to facilitate this, and the expected temperature gradients should be minimal.

The required water flow rates can be estimated using [7] $q = 2.388 \cdot 10^{-4} P/\Delta T$. For the 1 kW in the yoke and excitation coil for each a flow rate of 0.24 l/s will suffice to keep the temperature rise in the water to less than 1 K.

POWER SUPPLY REQUIREMENTS

Due to the large cross-section of the bus-bars the load for a power supply is almost entirely inductive (about 20 µH). We propose to power each quadrupole with four independent power supplies to limit the voltage. Per m length of quadrupole 750 V are required to drive a sinusoidal current of 22.6 kA as shown in Fig. 7.

CONCLUSION

This paper outlines a conceptual design of a quadrupole magnet with a gradient strength of 29 T/m. the quadrupole magnet can be swept at frequencies of 1 kHz with a repetition rate of 15 Hz. The total power dissipation is rather low due to the use of two different materials for the pole and the rest of the yoke, and by minimizing eddy current effects in the excitation coil.

The quadrupole magnet is demanding in terms of the required power supply, which should be addressed in a future study.

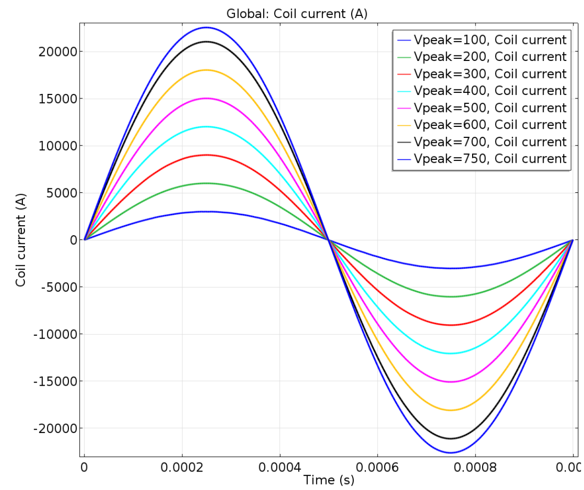

Figure 7: Current in one excitation coil as a function of applied voltage.

REFERENCES

[1] J. S. Berg and A. A. Garren, "Hybrid Fast-Ramping Accelerator to 750 GeV/*c*: Refinement and Parameters over Full Energy Range," Tech. Rep. BNL-98171-2012-IR, MAP-doc-4335, BNL, 2012.

[2] H. Witte, J. S. Berg, P. Kovach, M. D. Anerella, and M. L. Lopes, "Rapid Cycling Dipole Magnet," *NA-PAC 2013, Pasadena, USA*, pp. 762–764, 2013.

[3] H. Witte, J. S. Berg, and M. Lopes, "Progress on the Dipole Magnet for a Rapid Cycling Synchrotron," *PAC 2014, Dresden, Germany*, p. TUPRO115, 2014.

[4] J. S. Berg and H. Witte, "Pulsed Synchrotrons for Very Rapid Acceleration," Tech. Rep. BNL-106023-2014-CP, AAC 2014, San Jose, CA, USA, 2014. http://www.osti.gov/scitech/biblio/1165711.

[5] Arnold Magnetic Technologies, "Non Grain Oriented Electrical Steel Arnon 5." Online: http://www.arnoldmagnetics.com/Non_Grain_Oriented_Electrical_Steel.aspx, September 2013.

[6] H. Ninomiya, "Personal communication." JFE Steel Corporation, Electrical Steel Section, Tokyo, Japan, 2012.

[7] J. T. Tanabe, *Iron Dominated Electromagnets: Design, Fabrication, Assembly and Measurements*. World Scientific Pub Co Inc, 2005.