RAPID CYCLING DIPOLE MAGNET*

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Abstract

Accelerating muons to 750 GeV and higher is most efficiently accomplished using a hybrid synchrotron. Such a machine interleaves superconducting dipoles with bipolar dipoles ramping at an effective frequency of 400–1000 Hz and with maximum fields of around 1.8 T. Previous designs for the rapid cycling dipoles for this lattice have been based on grain oriented steel, which possesses good magnetic properties in the direction of the grains. Grain oriented steel however is highly anisotropic, which can potentially lead to field quality problems. In this paper we present an alternative design, which we expect to have lower losses, a higher peak field, and better field quality.

INTRODUCTION

A hybrid synchrotron is the most efficient known option for accelerating muons to their highest energies in a TeV-scale muon collider. A hybrid synchrotron bends particles by interleaving fixed field superconducting dipoles with bipolar rapid cycling dipoles. This permits rapid acceleration, to reduce muon decay, while making a significant number of RF cavity passes to achieve good efficiency. To maximize the RF efficiency, minimize decay, and maximize the energy range of a single ring, it is essential to have the highest field possible for both the superconducting and the rapid cycling dipoles.

A design accelerating muons from 375 to 750 GeV has been proposed [1] (shown schamatically in Fig. 1), which was a variation and refinement on earlier designs [2]. It has a circumference of 6300 m, with arc cells containing 2.7 m 8 T dipoles and 7.9 m rapid cycling dipoles. The field in the rapid cycling dipoles swings from -1.8 T to $+1.8$ T in 0.5 ms; there are about 2200 m of these dipoles in the ring. The beam will be accelerated 15 times per second.

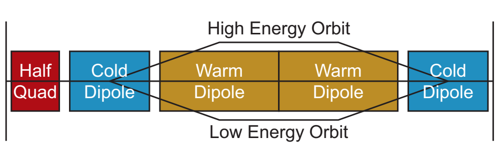

Figure 1: Structure of a quarter cell, showing the expected deviation of high and low energy closed orbits.

This report outlines a potential solution for the rapid cycling dipoles. We propose a solution operating at a frequency of 400 Hz (proposed in [2], gives more decays than [1]). The aperture required will be 60 mm horizontally (required for horizontal beam aperture) and 13 mm vertically (primarily to keep impedances reasonable). We also discuss a 25 mm vertical aperture, which might be required if a ceramic beam pipe is used.

MAGNET GEOMETRY

We consider the geometry shown in Fig. 2, which shows the 13 mm gap case. For a 25 mm gap the pole width increases to 132 mm because of field quality reasons. Each coil area is 87 × 30 mm^2 in cross-sectional area.

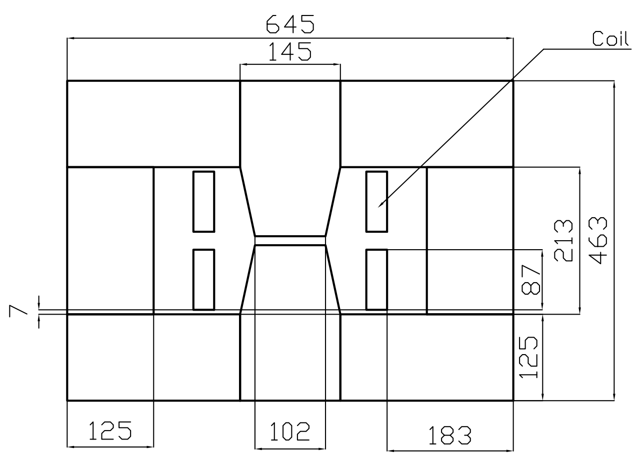

Figure 2: Geometry of the dipole magnet (in mm).

MATERIALS

Previous studies focused on grain-oriented 3% SiFe, which possesses good magnetic properties in the rolling direction [3]. A concern however is the high anisotropy of the material, which in studies has shown to affect the field quality.

For this study we focus on alternative isotropic materials, which promise lower losses while at the same time can achieve higher peak magnetic fields. The coil design employs two materials: 6.5 %SiFe and FeCo (49% Co, 1.9% V and 49% Fe). 6.5% SiFe, which has a relatively low magnetization saturation, is chosen for the very low losses. FeCo (with relatively large losses) has a very high magnetization saturation and is used for the poles of the magnet. For this design we consider Vacoflux 48 from Vac-

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uumschmelze[1] and 10JNEX900 from JFE[2]. The material data for hysteresis, magnetization curves and loss calculations were obtained from the manufacturers [4, 5]. The laminates are assumed to be 100µm thick. For comparison reasons we also estimate performance and losses for a design using isotropic 3% SiFe with thicknesses of 178µ and 250µm [6, 7].

PERFORMANCE AND FIELD QUALITY

The magnet performance using the different materials was evaluated in a 2D non-linear static finite element simulation. For a field of 2T an average current density of 4 A/mm^2 is required (25 mm gap: 7.88 A/mm^2). Fig. 3 shows the expected field quality $\Delta B/B_0$ as a function of the peak magnetic field on the centre plane. The figure shows the obtained results for an all 3% SiFe yoke and FeCo/6.5 %SiFe (13 mm and 25 mm gap). As shown in the figure, the field quality using 3% SiFe starts to deteriorate for fields in excess of 1.5 T. Using FeCo in principle allows to achieve more than $1.9 - 2$ T assuming a required field quality of 1×10^{-3}.

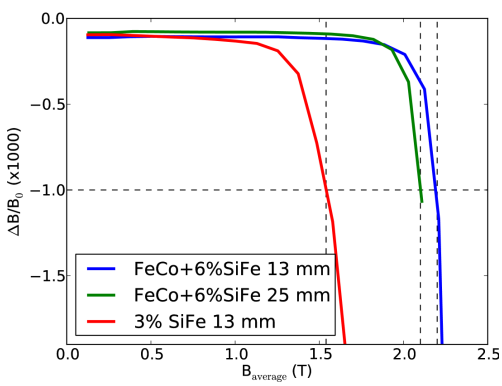

Figure 3: Field quality.

It was found that the field quality is unaffected by eddy currents in the yoke, hysteresis effects and mechanical tolerances other than the tolerance on the poles of the magnet.

POWER LOSSES

Resistive Losses in Coil

It was found that eddy current losses in the coils are a serious concern. To mitigate this the coils are placed in an area inside the yoke where field leakage is minimal. Instead of standard rectangular conductor (with a circular hole for water cooling) the coils are made of thin copper sheets, which are insulated against each other with 25µm thick Kapton tape. To determine the ideal thickness of the sheets a time-transient eddy current study was set-up. The simulation assumes that the coil area remains fixed, while the number of sheets is varied (and the thickness of each sheet is $d_{\text{Sheet}} = w_{\text{coil}}/N$, with N as the number of sheets).

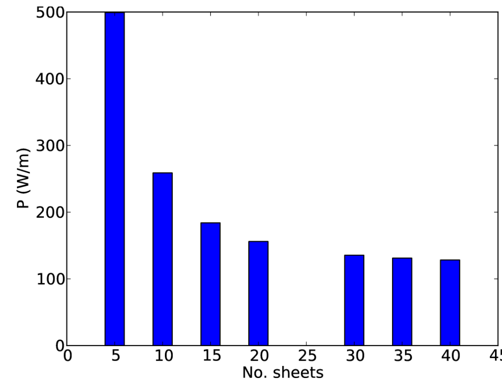

Figure 4: Power loss per m of magnet for different numbers of conducting sheets.

Fig. 4 shows the simulated power loss per pulse for a one meter long magnet. The figure shows that increasing the number of sheets up to 20 significantly reduces the power loss. A number of 30 sheets (each 1 mm thick) was chosen for the final design.

Core Losses

The core losses consist of eddy current losses, hysteresis losses and so-called anomalous losses. To estimate the core losses we rely on measured data from the manufacturers of the materials [4, 5]. Fig. 5 shows the results for an all 3% SiFe yoke with 178µ and 250µm thick laminates in comparison to a yoke made of 6.5% SiFe and FeCo. The losses are calculated assuming 2 km total dipole length in the ring.

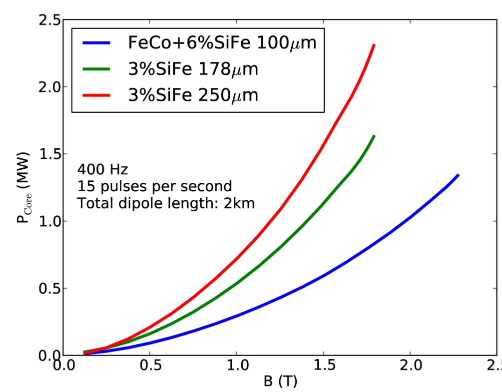

Figure 5: Core losses.

The figure shows that the here presented design is more efficient in comparison to a yoke made of 3% SiFe. For a peak field of 1.5 T the core losses are calculated to 0.5 MW for the entire ring in comparison to 1–1.5 MW for 3% SiFe. The core losses for 178µm thick 3% SiFe are expected to be lower than for 250µm thick laminates due to the better suppression of eddy currents.

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[2] JFE Steel Corporation, Electrical Steel Section, Tokyo, Japan

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Total Power Loss

The total estimated power loss for the entire ring (core and coil losses, total dipole length 2 km) are shown in Fig. 6. The figure shows the losses assuming a 13 mm and 25 mm gap. The losses for the 178µm thick 3% SiFe laminates are shown as well. At 1.5 T the total losses using FeCo and 6.5 %SiFe are expected to be about 0.75 MW for the entire ring. At 2 T this increases to 1.5 MW. The power losses are lower by a factor of two or more in comparison to a design using 178µm thick 3% SiFe.

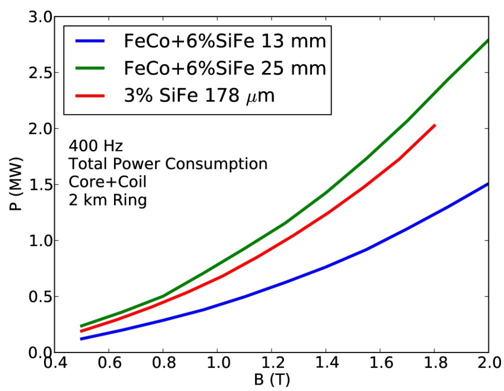

Figure 6: Total power loss for entire ring.

ENGINEERING CONSIDERATIONS

Mechanical Design

To contain the forces during operation the dipole magnet is housed in an external clamp. The peak forces during operation were evaluated using the Maxwell stress tensor and Biot-Savart-Law. It was found that the only significant force component acts on the poles, which is about 170 kN in vertical direction for a 1 m long magnet with a 13 mm gap (towards the centre of the magnet). The force acting on the coils is negligible.

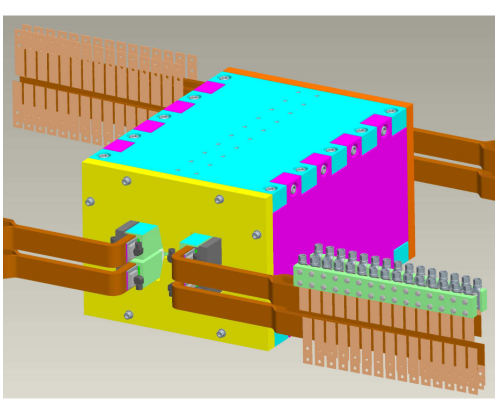

Figure 7: Rapid cycling dipole assembly.

The support structure of the magnet is designed to deal with the forces and to minimize the deflection to achieve the desired field quality. Fig. 7 shows the mechanical design of the dipole magnet.

Cooling

The average power dissipation in both the yoke as well as the coil is relatively low due to the repetition rate of 15 Hz. The coils can be conduction cooled on each side. A finite element simulation shows that the temperature gradient in the coil can be kept to 2 K or less provided 500 W (for a 1 m long dipole magnet) can be transferred to the coolant. The yoke can be conduction cooled via the external faces.

SUMMARY

A conceptual design of a dipole magnet is described in this paper which is suitable to be operated at 400 Hz with a repetition rate of 15 Hz. Using two different materials for the yoke (FeCo and 6.5 %SiFe), the losses can be minimized while at the same time achieving high magnetic fields. The presented design delivers a good field quality up to about 2T. For this field level the average power loss for an entire ring (2 km total dipole length) is about 1.5 MW.

It is planned to carry out activation studies of the yoke, which is a concern due to the cobalt content.

REFERENCES

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

[2] D. J. Summers, L. M. Cremaldi, R. Godang, B. R. Kipapa, H. E. Rice, and R. B. Palmer. Muon Acceleration to 750 GeV in the Tevatron Tunnel for a 1.5 TeV $\mu^+\mu^-$ Collider. In *Proceedings of PAC07, Albuquerque, New Mexico, USA*, page 3178. IEEE, 2007.

[3] D. Summers, L. Cremaldi, T. Hart, L. Perera, M. Reep, et al. Test of a 1.8 Tesla, 400 Hz Dipole for a Muon Synchrotron. *Conf.Proc.*, C1205201:3542–3544, 2012.

[4] C. Bach. Personal communication. VAC Sales USA LLC, 2935 Dolphin Drive, Suite 102, Elizabethtown, KY 42701, USA, 2012.

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

[6] AK Steel. DI-MAX HF-10, Cold Rolled Fully Processed Nonoriented Electrical Steel, Product Data Bulletin. Technical report, AK Steel Corporation, 9227 Centre Pointe Drive, West Chester, OH 45069, USA, 2013.

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