

A Superconducting Horizontal Bend Magnet for JLab's 12 GeV/c Super High Momentum Spectrometer

S. Chouhan, A. F. Zeller, J. DeKamp, P. Brindza, S. Lassiter, M. Fowler

Abstract— Collaboration exists between NSCL and JLab to developing the reference design of JLab's Super High Momentum Spectrometer (SHMS) horizontal bend magnet. A Superconducting "C" type, superferric dipole magnet that allows the SHMS to reach small forward angles without restricting the SHMS's acceptance, degree of motion or range of particle energy is presented. Spatial requirements for the coexistence of the SHMS at forward angles of -5.5° along with the existing High Momentum Spectrometer (HMS) at 12° to the primary beam line give rise to close tolerances on design parameters. The bending of 12 GeV/c particles by 3° requires an integral field strength up to 2.1 T.m. The current design is "warm-iron" with a nominal yoke length of 600 mm and a minimum pole gap of 350 mm. Choice of superconducting conductor, between surplus re-flattened SSC NbTi Rutherford cable that provides plenty of current margin and cost savings and Nb₃Sn cable, noted for its temperature margin will be highlighted. Coil forces, coil restraint system, energy margins, hot spot and final temperatures, beam radiated heating and superconducting stability will also be presented.

Index Terms—Superferric, warm iron, dipole magnet, cryostat

I. INTRODUCTION

The Super High Momentum Spectrometer (SHMS), planned for the 12 GeV/c upgrade of the Thomas Jefferson National Accelerator, is a dipole, quadrupole triplet and dipole design to be located within the experimental area of Hall C. The SHMS will compliment and coexist with the existing High Momentum Spectrometers (HMS) to form a pair of high luminosity magnetic spectrometers, with the capabilities of detecting with high accuracy and reproducibility, high momentum charged particles with small-forward angle capability. The SHMS spectrometer will be able to analyze up to 11 GeV/c at forward angles down to 5.5° even with the HMS at its forward angle of 12° . It will have a range of angles up to 40° with a solid angle of ~ 5 msr. A small bending magnet will be used to bend the particles in the horizontally direction by 3° to facilitate reaching small forward angles

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without losing solid angle or resolution. Figure 1 with lifted up upper yoke shows the spacial constraints placed upon the bender magnet and the cryostat details. Consideration must be given to interference issues with the existing HMS's Q1 magnet, stray fields along the exit beam pipe, beam heating of the magnet due to close proximity to the scattering chamber as well as its magnetic performance.

The requirements of the Superconducting Horizontal Bending Magnet (SHBM) are within the range of achievable with superferric magnets. An initial conceptual design layout from JLab considered a cold iron design utilizing the iron yoke to support the large coil forces directly on the mid-yoke side, and through a force plate on the open side of the yoke attached to the top and bottom yoke pieces. This concept as received was not developed to a great degree and had very little space (10 mm) given for insulation and any thermal shield on the force plate side. This design gives ample support for the coils but leads to a bulky cryostat with large plates needed outside the iron for the insulating vacuum vessel and a large suspended cold mass. It can create difficulties for assembly, testing, and transportation, for the off site supplier of the magnet. A warm iron design has been investigated to see if it can also be a buildable option for this magnet.

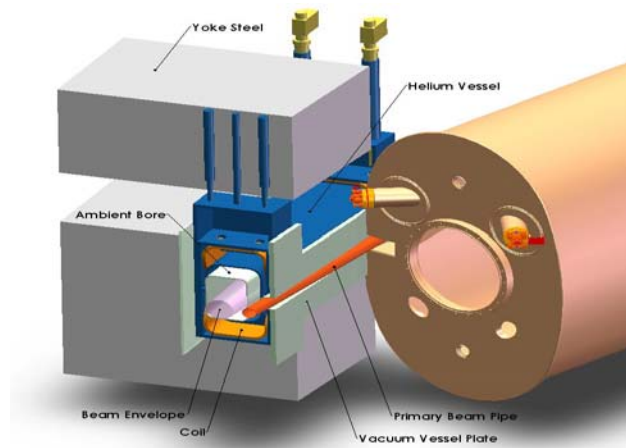


Figure 1: The Superconducting Horizontal Bending Magnet shown with the close proximity of the HMS quadrupole cryostat and primary beam pipe.

II. CONCEPTUAL MAGNET DESIGN

Figure 1 shows the cross-section of the superconducting horizontal bending magnet, with superconducting coil and iron yoke indicated. It's a C-shape "warm-iron" magnet, designed with large horizontal and vertical gap to accommodate the

cryostat and provide the required field at different excitation currents. Thermal insulation for the coils means a larger gap is required as compared to a cold-iron design. An important design aspect of the proposed coil and cryostat is compactness and effective cooling, since the magnet will be exposed to a significant localized radiation load. Measurement of the HB calorimeter model in Hall C measured the actual radiation load of 1 Watt.

In order to analyze the 3D behavior of the magnet, especially the peak magnetic field in the coil area, forces on the coil, a magnetic model has been developed using TOSCA [1], Figure 2. The other main design and extracted parameters of the magnet are given in Table I. This model is used, as well, to determine the effective length and extract the flux density distribution in the mid-plane and elsewhere. The designed stored energies and inductance over the operating range are given in Figure 3 and Table II. Compare to a “cold-iron” dipole design almost ten percent higher excitation current is required to achieve the desired flux density distribution and field integral. An average current density of $2.89 \times 10^8 \text{ A/m}^2$ is designed to achieve the required maximum field 3.12 T in the gap. The peak magnetic field induction in the coil area is about 3.69 T.

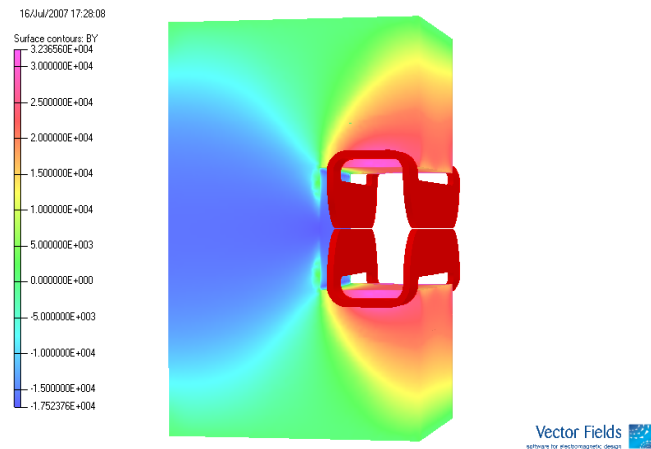


Fig.2. Schematic layout for superconducting Horizontal Bend Magnet without cold mass.

TABLE I PARAMETERS OF SUPERCONDUCTING HORIZONTAL BENDING MAGNET CALCULATED BY TOSCA

QUANTITY	MAGNITUDE
Maximum magnetic field	3.12 T
Magnetic yoke length	0.6 m
Vertical aperture	0.35 m
Horizontal aperture	0.36 m
Number of turns per pole	100
Coil cross section	1627 mm ²
Stored energy at maximum operating current	0.3 MJ
Self inductance at maximum operating current	28.7 mH
Effective length	0.75 m
Maximum operating current	4500 A
Engineering current density	289 A/mm ²
Peak field in the superconducting winding at operational current	3.69 T

III. SUPERCONDUCTING WIRE

The parameters of the wire (surplus SSC outer conductor) are tabulated in Table III [2]. The calculated critical current of the wire for the different field strengths is shown in Figure 4. There are two other parameters that have been studied in the light of present design of SHBM, the current safety margin and the temperature safety margin. The maximum field in the coils appears in the center of inside face of the bedstead coil. At 4500 A, the operating current corresponds to ~30 % of the critical current.

The critical temperature decreases with increasing field and a good fit is given by the relation [3,4]

$$T_c(B) = T_c(0) \left[1 - \left(\frac{B}{14.5} \right) \right]^{0.59}, \quad (1)$$

TABLE II THE DESIGNED STORED ENERGY AND OTHER COMPONENTS OVER THE OPERATING RANGE OF SUPERCONDUCTING HORIZONTAL BENDING MAGNET

J (A/mm ²)	NI (kA/coil)	I (kA)	B (T)	∫Bdz (T.m)	L _{eff} (m)	S.E (MJ)	L (mH)
289	450	4.5	3.1	2.345	0.751	0.291	28.7
229	357	3.6	2.6	1.941	0.751	0.191	29.9
173	269	2.7	2.0	1.523	0.757	0.113	31.1
116	180	1.8	1.4	1.042	0.768	0.052	31.9
58.02	90.5	0.9	0.7	0.527	0.774	0.013	32.2
13.14	20.5	0.2	0.2	0.12	0.775	0.001	32.2

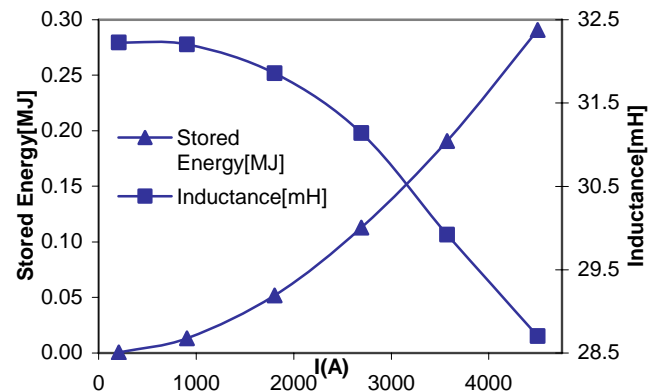


Fig. 3. Stored energy and inductance in the Superconducting Horizontal Bend Magnet.

TABLE III 36 STRAND SUPERCONDUCTING CABLE SPECIFICATION

Cable	
Number of wires in cable	36
Cable cross-section	11.68 mm X 1.156 mm
Critical current at 3.69 T, 4.2 K	15980 A
Number of filaments	~ 4100
Filament size	6 μm
Coil	
Turns per layer	1
Number of layers	100
Size	136 mm X 12 mm
Insulation between layers	0.2 mm

where $T_c(0)$ is the critical temperature for zero field, which is

equal to 9.4 K. T_c ($B=3.69$) is 7.9 K for a 3.69 T field. The current sharing temperature, i.e., the temperature at which the wire starts to generate heat varies between $T_{cs}=T_c(B)$ for zero current and the bath temperature 4.2 K when the transport current approaches the critical current $I \rightarrow I_c$. If one makes reasonable assumption that the current sharing temperature is a linear function of I/I_c , then the following expression provides the current sharing temperature as a function of field and helium bath temperature T_0 as parameters [3], [4]:

$$T_{cs} = T_0 + [T_c(B) + T_0] \left[1 - \left(\frac{I}{I_c} \right) \right]. \quad (2)$$

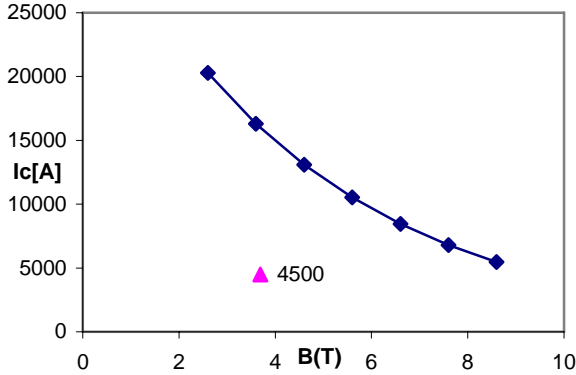


Fig. 4. Critical current I_c of the SSC wire for the proposed JLab-SHBM.

For the SHBM, we consider the coil is immersed in a bath of LHe at 4.2 K, generating a field of $B=3.69$ T at almost 30% of its critical current. The current sharing temperature is $T_{cs}=6.79$ K, so the temperature margin of this coil is 2.59 K. The amount of energy deposition required raising the temperature from the bath temperature to T_{cs} is small since the heat capacity of materials except helium are extremely low around 4.2 K. The heat capacity per unit volume of a composite Cu-NbTi conductor can be parameterized as [3], [4]

$$C = \frac{10^3}{f+1} \left[(6.75f + 50.55)T^3 + (97.43f + 69.81B)T \right] \quad (3)$$

$\left(\frac{mJ}{cm^3 \cdot K} \right)$

where f is the copper: superconductor ratio. Using Eqs. (1), (2) and (3), the enthalpy required to rise conductor from 4.2 K to 6.79 K for $I/I_c=0.3$ as a function of temperature can be determined. Calculated enthalpy for 36-strand SSC cable versus temperature is shown in Figure 5. Approximately 3 mJ/cm^3 of energy deposition is needed to start producing Joule heating in the conductor.

Because the coil is in close proximity to the electron beam there is significant radiation heating. To achieve more temperature margin and better withstand the heating, Nb_3Sn conductor can be used. Even though the field is low, the higher critical temperature of Nb_3Sn is attractive. A cable of identical size could be fabricated and the quench characteristics should be similar because of the amount of copper.

Two problems are obvious when using Nb_3Sn : The cost of the material and having to develop a wind-and-react method for coil fabrication (react-and-wind is difficult because of the small bend radii) is the first problem. The second is flux jump

stability at this low field. Presently, the deposited radiation does not seem to require using Nb_3Sn .

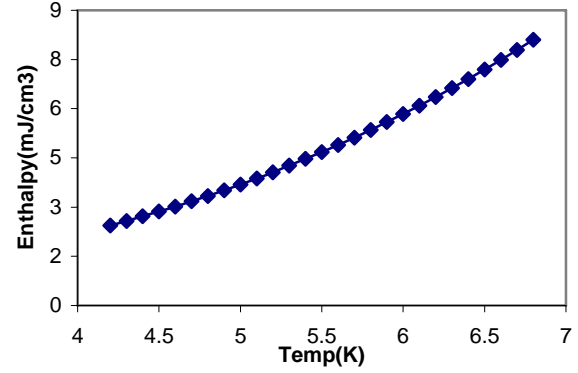


Fig. 5. Enthalpy of SSC superconductor versus temperature for 3.69 T field and with operating current at 0.3 of the I_c .

IV. CRYOSTAT

The warm iron design being presented relies on a robust liquid helium pressure vessel encasing the coils, being capable of carrying the large coil forces. The closeness of the primary beam pipe and the HMS quadrupole cryostat to the dipole cryostat requires specially designed and machined plates for both the liquid helium vessel and the insulating vacuum vessel on that side. This cryostat design leaves room for a thermal shield, having 2 cm of space between the liquid helium vessel and the cryostat vacuum wall in most areas except for the region of the primary beam tube interference. Other features include non-concentric, conical type sections in the area of primary beam tube interference to try and keep possible heat load anomalies a point effect instead of a surface effect to minimize them. A layout of this area with a conceptual design of the basic cryostat is shown in Figure 1.

From the magnetic design with this layout, the transverse coil loads are approximately 1100 kN on the yoke side and 950 kN on the open side. This also creates an unbalanced load toward the yoke side of 150 kN. The vertical loads from the coils are ± 231 kN. In addition to these loads, the liquid helium vessel must support a helium pressure of 5 bar. The present vessel concept consists of 26 mm thick outer walls connected at the median plane by a 10 mm thick rib to the 8 mm vessel bore. For initial analysis, the coil loads were equated to uniform pressures on areas of the vessel and added to the He pressure requirement. Analysis gives stresses of 250 MPa on the side close to the yoke. Stresses of about 460 MPa however are present on the opposite side in the primary bore clearance area. Displacements of each side of the vessel are about 1 mm giving a 2.1 mm total transverse spread and are shown in Figure 6. These values are reasonable and show the possibility of an acceptable design with this concept using standard 316 stainless (yield strength 600 MPa @ 4 K). A 316 LN material (yield strength 1000 MPa @ 4 K) may be chosen if a larger margin is felt necessary. Refinement in the design and appropriate placement of support links may be able to reduce the stresses and displacements to some degree. To keep vessel strength integrity, the outer sides of the vessel could be made from heavier thickness plate with the coil pockets and primary bore interference area machined out. This would give welds

away from high stress and heavy thickness areas.

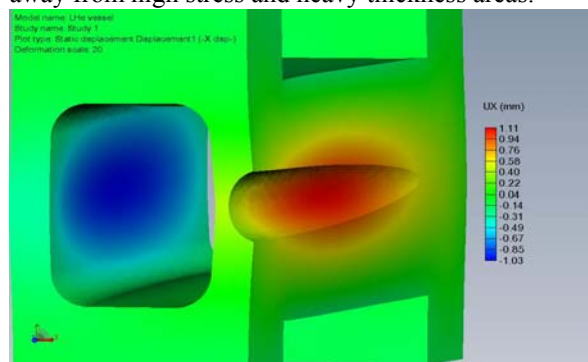


Figure 6: Transverse helium vessel displacements.

Support links would of course be necessary to support the unbalanced transverse load toward the steel as well as maintaining the helium vessel position. For the case of cold iron, unbalanced coil loads are not a problem but the large cold mass is an equivalent situation. The support link requirements for the warm iron design are not that much different than what is needed for a cold iron design but are more difficult because of their placement on a much more compact vessel. If mid-side links are used, the cryostat vacuum wall can be braced to the yoke steel at their locations.

V. QUENCH CALCULATIONS

A quench is the conversion of stored electromagnetic energy into heat. Figure 3 shows the stored energy and inductance with respect to operating current in the proposed SHBM magnet. The inductance decrease with the current is due to increasing saturation in the iron core. The stored energy in the SHBM operating at 4500 A is 0.291 MJ.

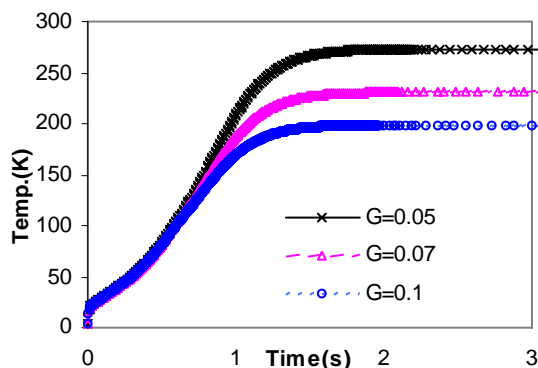


Fig. 7. Hot-spot temperature calculations with varying transverse propagation velocity.

QUENCH [5] calculations were done assuming all the stored energy is dumped into one of the coil with no external dump. The voltage in the coils and hot spot temperature with respect to time as the quench propagates were calculated. The results from numerical calculation are shown in Figure 7-8. Calculations were done for the maximum current, where the stored energy is also at maximum value. Calculation for low current results in smaller voltages and lower hot spot temperatures. The crucial parameter in calculation is transverse quench propagation velocity U_t . The quench

propagation velocity U_t often is a factor 10-100 times slower than the longitudinal quench propagation velocity. Experimentally [6] we have found that tightly ordered wound and potted coils like the proposed coil packs have a rapid transverse quench propagation velocity ratio of 0.05 to 0.1.

The hot-spot temperature as the quench propagates is shown in Figure 7. Three calculated curves are shown for maximum operating current at 4500 A and have been produced for values of G varying from 5% to 10%. The worst-case hot-spot temperature is in the slowest transverse quench propagation and is above 250 K.

The voltage occurring within the coil during a quench is shown in Figure 8. Each proposed coil pack is one conductor wide and has hundred layers, so the maximum potential voltage within the coil is very low.

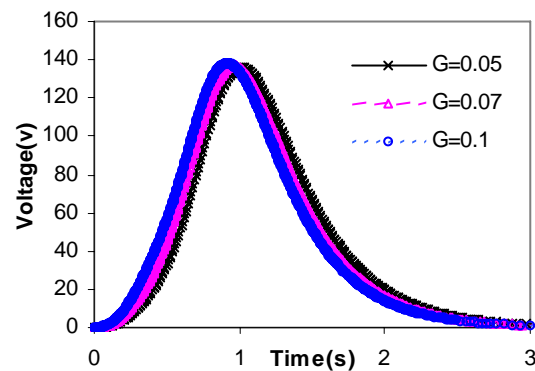


Fig. 8. Quench voltage calculations with varying transverse propagation velocity.

VI. CONCLUSION

A superferric warm-iron dipole for Jlab has been designed. The 3D magnetic simulations show that the designed magnet satisfies the field quality and other requirements both at high and low field. The magnet is self-protecting and compared to cold-iron design ten percent higher excitation current is required.

ACKNOWLEDGMENT

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