Feasibility Study of Large Combined Function Magnets for the Jefferson Lab 12 GeV Upgrade

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***Abstract*—The 12 GeV upgrade at Jefferson Lab [10] has identified two new large spectrometers as Physics detectors for the project. The first is a 7.5 Gev/c 35 m-sr. spectrometer that requires a pair of identical Combined Function Superconducting Magnets (CFSM) that can simultaneously produce 1.5 T dipole fields and 4.5 T/m quadrupole fields inside a warm bore of 120 cm. The second is an 11 GeV/c 2 m-sr. spectrometer that requires a CFSM that simultaneously produces a dipole field of 4.0 T and a quadruple field of 3.0 T/m in a 60 cm warm bore.**

Magnetic designs using TOSCA 3D have been performed to realize the magnetic requirements, provide 3d fields for optics analysis and produce field and force information for the engineering feasibility of the magnets. A two-sector $\cos(\theta)/\cos(2\theta)$ design with a low nominal current density, warm bore and warm iron design has been selected and analyzed. These low current densities are consistent with the limits for a cryostable winding.

The current paper will summarize the requirement definition of these two magnets. The conceptual design arrived at during the feasibility study involving the choice of conductors, thermal and structural analyses will be presented. A discussion of the manufacturing approach and challenges will be provided.

***Index Terms*—Combined function magnets, Nuclear Physics magnets, Detector magnets, spectrometer magnets.**

I. INTRODUCTION

The 12 GeV upgrade at Jefferson Lab has identified two new super conducting spectrometers to complement the existing devices. These new spectrometers are the Super High Momentum Spectrometer(SHMS) and the Medium Acceptance Device or MAD Spectrometer. The SHMS has been proposed as the new companion to the present High Momentum Spectrometer (HMS) in JLAB Hall C and the MAD is the new companion to the High Resolution Spectrometer (HRS) in JLAB Hall A. These new spectrometers require dipole and quadrupole magnets and due to the space constraints of existing experimental facilities and the significantly higher beam energy superconducting combined function magnets selected as the essential elements. The MAD requires two QD120 magnets and the SHMS requires one QD60 magnet. The QD magnets are large aperture 120 cm and 60 cm respectively, low temperature superconductor based magnets that are designed to make use of surplus Superconducting Supercollider (SSC) outer cable available at JLAB. Another common yet important design criterion is that these magnets have to be designed conservatively for extreme reliability and must be cost effective thus excluding any significant prototyping activity. This work presents the design solution that satisfies these requirements.

II. MAGNET SPECIFICATIONS/ REQUIREMENT DEFINITION

The properties for the QD 120 and QD60 magnets are shown in Tables 1 and 2 below.

TABLE I
PROPERTIES OF THE QD120 DIPOLE -QUADRUPOLE MAGNET

Warm bore	1.2 Meter
Overall Length	4.0 Meter
Overall Diameter	3.2 Meter
Stored Energy	45 MJoule
Dipole Current	5125 Amp
Quad Current	5250 Amp
Dipole Field	3.7 Tesla
Quad Gradient	3.3Tesla/Meter
Peak Field	6.4 Tesla
Bend Strength	10 Tesla-Meter
Quad Strength	9.8 Tesla
Eff. Length Dipole	2.8 Meter
Eff. Length Quad	3.0 Meter
Field Tolerance	< 10^-3

TABLE 2
PROPERTIES OF THE QD60 DIPOLE -QUADRUPOLE MAGNET

Warm bore	0.6 Meter
Overall Length	5.0 Meter
Overall Diameter	2.4 Meter
Stored Energy	13 MJoule
Dipole Current	5600 Amp
Quad Current	5040 Amp
Dipole Field	3.6 Tesla
Quad Gradient	3.6Tesla/Meter
Peak Field	5.4 Tesla
Bend Strength	12.5 Tesla-Meter
Quad Strength	11.5Tesla
Eff. Length Dipole	3.5 Meter
Eff. Length Quad	3.4 Meter
Field Tolerance	< 10^-3

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In addition, for each of these three magnets, the required heat leak at liquid helium temperature will be ~30W plus 30 L/hr and ~ 200W at liquid nitrogen temperature. We plan to have a maximum charge time of 30 minutes and a maximum discharge time of no less than 10 minutes. We will also limit the maximum operating current in each of these magnets to be ~ 5000 A, so we can employ reasonably inexpensive power supplies.

III. Magnetic Field and Force Analyses

The magnetic design uses the magnetic code TOSCA to generate cos(θ) type coils with "constant perimeter ends" for the end turn regions. These coils closely approximate the ideal cosine geometry that is well established as a "perfect" generator of high purity fields. Practical considerations, finite current distributions, limited number of sectors and TOSCA's internal approximations all contribute to deviations from the ideal geometry and are the sources of higher order field errors in the design. The yoke is modeled as truly non-linear iron with the nominal properties of 1006 steel. The present results of the optics analysis based on this magnetic design indicate that the level of field quality achieved is already at a level that meets the requirements so no further "trimming" is anticipated. The dipole and gradient field accuracy are of the order of 3 parts in a thousand in the warm bore aperture.

The QD120 combined function magnet produces peak fields in the warm bore of 5.6 T and peak fields in the windings of 6.3 T. These fields are comparable to those achieved in large bore magnets produced 20 years ago for MHD research, particle spectroscopy and ore separation magnets. Even the field volumes are comparable to these large magnets, the stored energy in the MAD magnets are significantly less because of the superimposed dipole and quadruple fields. However, these combined fields also produce a very asymmetric force distribution that has to be studied carefully and taken into account during the structural analysis. Fig. 1 below shows the field profile across the mid-plane of the MAD. The corresponding force distribution pattern is equally asymmetric resulting in significant de-centering forces..

IV. Thermal Analysis and Conductor Selection

A significant quantity of SSC outer cable is available for use on this project therefore the task is to design a composite superconductor for both the QD120 and the QD60 magnets. Using the very conservative Stekly Cryostability Criteria [1] requires soldering the cable into a copper substrate such that the copper to superconductor ratio is 15:1. As shown in Table 3 below the QD60 and QD120 dipole and quadrupole coils exhibit cryostability. Figures 2 and 3 show the load lines for the QD magnets, the SSC cable nominal short sample curves and the SSC cable at the critical temperature. Clearly the margins in temperature, field and current are substantial and the design of the QD magnets is very conservative. Other approaches such as adiabatic stability and cable-in-conduit were also evaluated, but the cable soldered into copper substrate cryostability concept is the most efficient and economical way to make use of the SSC outer cable for the QD magnets.

TABLE 3
Cryostability Properties of the QD60 and QD120

Symbol	QD60 Dipole	QD60 Quad	QD120 Dipole	QD120 Quad
Bmax	4.8	4.1	6.2	6.4
RRR	200	200	200	200
Area	0.8	0.8	0.8	0.8
perimeter	5	5	5	5
Gamma	0.6	0.6	0.6	0.6
Tc	6.97	7.46	6.3	6.15
To	4.42	4.42	5.42	4.42
Tc-To	2.55	3.04	1.91	1.73
Imax	5600	5040	5125	5250
Ic(B,4.2K)	12912	15057	9078	8722
Ic(B,4.4K)	12333	14381	8671	8331
Hcrit	0.2	0.2	0.2	0.2
Rho(273)	1.6E-6	1.6E-6	1.6E-6	1.6E-6
Rho(4.4K)	8.0E-9	8.0E-9	8.0E-9	8.0E-9
Rho(5T,4.4)	3.1E-8	2.8E-8	3.8E-8	3.9E-8
Alpha	0.79	0.48	0.83	0.98

The cryogenics for the MAD/SHMS combined function magnets will be based on the very successful thermal syphon cooling that has been incorporated in nearly all the SC magnets at JLAB. The very high (~100gm/sec) internal flow rates and simple reservoir level control insure very reliable operation with simple controls. These magnets also enjoy ~ 1 hour isolated operation when refrigerator shutdowns occur. The heart of this system is a somewhat complex control reservoir that contains JT valves, bayonet connections, phase separating reservoirs, current leads, relief valves, and instrumentation including level sensors. There are seven of these control reservoirs at JLAB. The standardization of design and function and use of standardized components insures compatibility and reliability. The efficiency of common design results ultimately in cost and operational savings. This combined with the very conservative cryo-stability will result in a very reliable design for the MAD/SHMS spectrometers.

V. Preliminary Structural Analysis and Conceptual Design

For the QD120 magnet, the dipole coils are on the outside of the magnet structure (see Fig. 2) while the quadruple coils are on the inside. The circumferential magnetic pressures on the dipole segments vary from 609 psi to 5773 psi towards the mid-plane and those for the quadruple coil segments vary from 5980 psi away from the mid-plane to 2850 psi towards the mid-plane. The corresponding numbers for the radial magnetic pressures are 343 psi away from magnet center to 69 psi towards the magnetic center, for the dipole segments and 589 towards the magnet center and 1017 psi away from the magnet center, for the quadruple segments. The magnetic pressures in the QD60 magnet are comparable because the fields are comparable.

A Thick Shell analysis was performed. This resulted in adding an outer support ring as well as an inner winding bobbin doubling as the inner wall for the cryostat. Fig. 3 below depicts the structural layout required for the QD120 magnet. That for the QD60 magnet is similar and will not be described here in detail due to a lack of space.

As described in Fig. 3, the results from our analysis indicate that the inner bobbin has to be 2 cm thick of SS304, the outer support ring has to be 2.5 cm thick of SS304 while the coil pack retains a thickness of 14 cm total. More detailed 3D analysis using finite element code will be performed to further optimize the efficiency of the structure.

The next step in the design is to determine what type of support members to use for supporting the cold mass from the outside world and generate a minimum of heat leak. Various concepts were considered including the "jelly roll" approach used in the TPC magnet [4], the "fiber composite straps" idea used in the UTSI MHD magnet [5], the "Universal joint rod" approach used in the CDF magnet [6], the "composite column" type support used in the CCM magnet [7] as well as the SSC dipole construction [8]. The selected cold to warm support for the QD60 and QD120 Magnets is based on the tension support system used at Jefferson Lab for the HMS Super Conducting Dipole[11]. This support system, which uses Titanium rods with ball joint ends in constant tension and angled to best handle the loads at all temperatures have proven to have low heat load and low stress. The Support Rods used at Jefferson Lab have integral strain gauges for monitoring stress levels at all times including during magnet excitation.

DC power for the QD120/QD60 magnets is presently designed around low voltage high current commercial power supplies. A nominal DC current of 5000 amps at 10 volts would be a safe choice for QD120/QD60 magnets due to the relatively low inductance (3 H/0.46 H) and provide easily for a charge time under 30 minutes. Fast discharge voltages under 500 volts are easily obtained with a high current design thus reducing the risk of exposure to high voltages. The very massive cold mass and low current density insures that sufficient material is available in the cold mass to absorb a large fraction of the stored energy at a low temperature during a quench discharge resulting in a safer overall magnet.

Coils of this type are generally the most conservative that can be built and the large size and modest field quality requirements ($\Delta B/B = 3x10^{-3}$) insure that construction tolerances (~1-2 mm) are easily achievable. The de-centering forces arising from inability to place the coil pack exactly equidistant from the surrounding iron yoke can turn out to be large and must be analyzed in detail. These are large coils and sufficient sizable tooling and lifting equipment are required for effective fabrication of the magnets.

VI. SUMMARY AND CONCLUSION

The conceptual design for the Super Conducting combined function spectrometer magnets is presented. These are required for the 12 GeV upgrade effort to be effected at the Jefferson Laboratory. The advantage for this approach is the lower resultant inductance and hence the magnetic stored energy. This concept has been used in much smaller accelerator magnets but never on magnets with large diameters as proposed in this paper. The proposed design also makes use of the existing SSC outer cable available in sizable quantity at JLAB and the locally installed cryogenic system to provide a cost effective and efficient solution to the detector magnet requirements for the upgrade.

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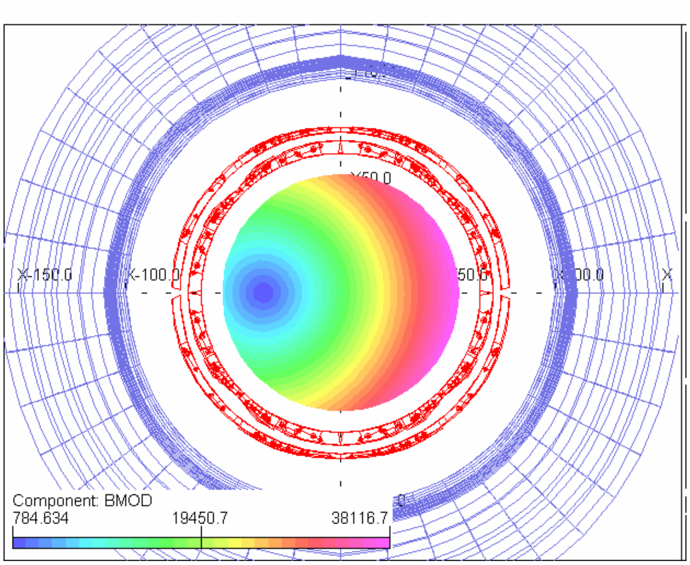

Figure 1 Total Field at z=0 for the QD120 Magnet (1.5 T Dipole Field & 4.5 T/m Quadruple Field)

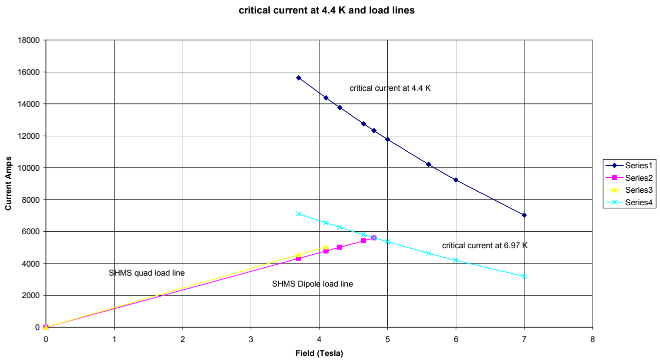

Figure 2 SHMS QD60 Dipole and Quadrupole Load lines and SSC outer cable operating and critical temperature short sample curves.

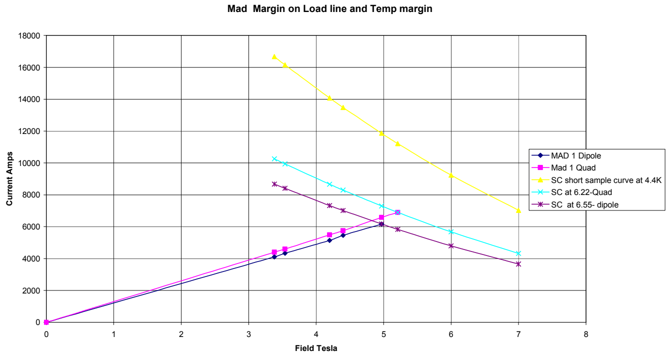

Figure 3 MAD QD120 Dipole and Quadrupole Load lines and SSC outer cable operating and critical temperature short sample curves.