The MAP Magnet R&D Program

15 August 2010

Abstract

This document (i) describes the special magnet requirements for Muon Colliders and Neutrino Factories, (ii) compares these requirements with the present state-of-the- art, (iii) identifies the main R&D issues, and (iv) describes the MAP magnet R&D program we are proposing to address these issues, and its prospects for success.

1. INTRODUCTION

A Muon Collider and/or Neutrino Factory accelerator complex requires the development of several new magnets. In some cases the magnet requirements go beyond the state-of-the-art. In particular, the unique challenges include:

1. ***High Field Solenoid in a High Radiation Environment***
   To collect as many charged pions as possible, the pion production target at the front end of a Muon Collider and/or Neutrino Factory accelerator complex is in a very high field solenoid. The field for the baseline target solenoid design is 20 T. This target solenoid must also operate in a very high radiation environment.

2. ***6D Muon Cooling***
   The muons initially occupy a large 6D phase space, which must be cooled by a factor $O(10^6)$ to obtain sufficiently bright beams for a Muon Collider. In the 6D muon ionization cooling channel designs that are being studied, the cooling is accomplished through a lattice of offset or tilted solenoid rings in conjunction with momentum regenerating RF. For some channels, the tight interface between magnet, RF and beam is a significant design challenge. Finally, the muons are confined within a lattice of high-field solenoids. To obtain the smallest final transverse emittances, and hence the highest collider luminosities, the highest practical magnetic fields are desired in the last few cooling channel solenoids. The design solenoid fields are beyond the present state-of-the-art for practical magnet construction.

3. ***Heating From Decay Electrons***
   In contrast to electrons or protons, muons decay to produce daughter electrons. When the muons are at high energy, superconducting magnets in the collider ring must be protected against the flux of decay electrons, which typically have energies of about one-third of the muon energy. For example, for a 4 TeV collider, a bunch of 10^{12} muons at 2 TeV produce 10^5 decay electrons per meter with an average energy of 700 GeV.

The proposed MAP magnet R&D program is focused on answering the following questions:

(i) What is the *most effective technology for the target solenoid*, in the presence of the harsh radiation environment near to the target?

(ii) What is the *highest practical field for the last few (high field) solenoids* at the end of the cooling channel, and what is the R&D required before such solenoids can be built?

(iii) What is the *optimal design for the collider ring magnet*s that will enable them to operate in the presence of the decay electrons?

In addition to answering these feasibility-related questions, the MAP R&D program will also:

a) *Develop a first defensible cost-range for a Muon Collide*r. This will require creating an overall parameter list and a cost model for the magnets in each part of the accelerator complex.

b) *Support the design and construction of a short 6D cooling section* for a bench test. This activity awaits the time when the RF technology for the section test and the 6D cooling-channel design have been chosen.

2. R&D ISSUES AND PRESENT STATUS

2.1 Target *Solenoid*

In the present Muon Collider and Neutrino Factory baseline designs, the proton target consists of a free liquid-mercury jet injected into a 20 T solenoid. The proton beam power is 4 MW. This target concept has been successfully demonstrated by the muon accelerator R&D community in the MERIT experiment [1], in which high-speed cameras recorded the interaction of a beam from the CERN PS with a 15 m s^{-1} free liquid-mercury jet injected into a 15 T solenoid. The MERIT results suggest that this target concept will work at proton beam powers beyond the required 4 MW.

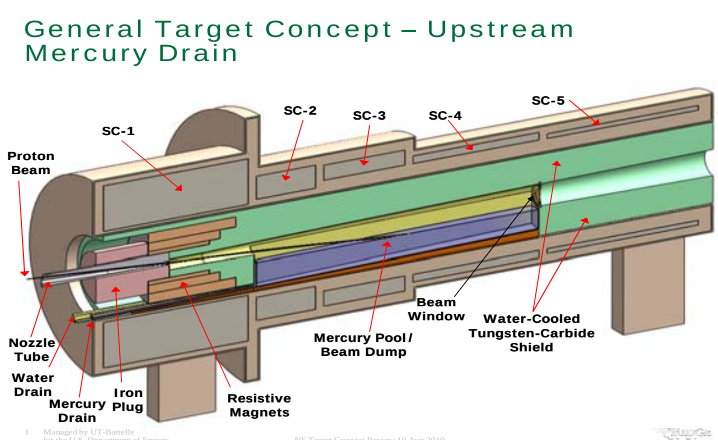

Fig. 1. Target conceptual design showing mercury jet within a 20 T solenoid with resistive insert.

The present design for the target area is shown in Fig. 1, and energy deposition results from MARS simulations are summarized in Fig. 2 and Table 1. Note that only about 10% of the 4 MW beam power is deposited within the target. The rest ends up in the shielding and dump. From these ongoing studies it has become clear that, to arrive at a robust target system design, the shielding and thermal management for the hybrid 20 T solenoid must be carefully considered.

The MAP target solenoid studies are being pursued within the context of the International Design Study for a Neutrino Factory (IDS-NF) which aspires to deliver a "Reference Design Report" by ~2013.

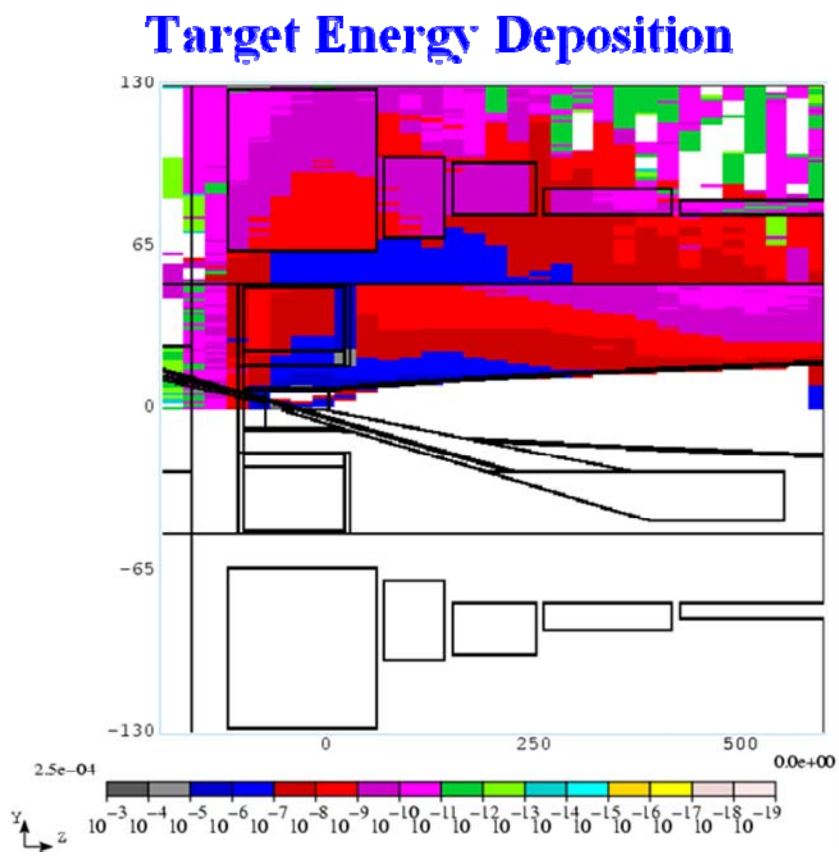

Fig. 2 Target energy deposition results from MARS simulations.

Table 1: Power deposition in SC1 for an 8 GeV, 4 MW proton beam.

Shielding Material	Energy Dep.(GeV)	Power Dep. (kW)
80%WC+20%Water	4.956×10^{-2}	24.780
100%Hg	6.623×10^{-2}	33.115
100%W	4.121×10^{-2}	20.605
60%W+40%Hg	4.783×10^{-2}	23.915

2.2 *Final Cooling Channel Solenoids*

The achievable luminosity in the collider is proportional to the solenoid field at the end of the final cooling channel, up to fields of about 50 T, beyond which the beam-beam tune shift is expected to limit the luminosity. The state-of-the-art for high-field superconducting solenoids is about half of this field, i.e., ~25 T. Thus, to attain the highest luminosity, higher field solenoids need to be developed. Fortunately, R&D on high temperature superconductor (HTS) offers the possibility of achieving fields above 25 T, and perhaps even up to the desired 50 T. For example, the national DOE/ARRA-supported Very High Field Superconducting Magnet Collaboration (VHFSMC) is actively exploring the technical issues associated with developing HTS materials for superconducting magnets.[a] Their short-term goal is to improve the properties of HTS Bi 2212 round wire for the expected high current density, high mechanical stress, and high field magnet environment [2]. Other conductor studies related to magnet development are taking place as part of the DOE laboratory core programs.

In order to develop a self consistent end-to-end design and simulation of a Muon Collider complex, some value for the field in the final cooling channel solenoids must be assumed. This choice will determine the final emittances that can be achieved, and the required acceptance for the accelerating system and the collider ring. The proposed MAP final cooling channel solenoid R&D goals are to:

1. enable us to make an informed decision about the solenoid field we should assume for the last stages of cooling based on present and expected future conductor and magnet technology;

2. determine the R&D that will be required to develop these technologies; and,

3. propose a conceptual design of a practical, affordable, high-field solenoid up to 50 T.

The main issues to be addressed for this magnet are HTS conductor R&D, magnet design, and coil technology.

2.2.1 HTS Conductor R&D

A strong conductor R&D program will be necessary for the development of HTS-based magnets with field above 30 T for the Muon Collider. The conductor properties will drive both the magnet design and coil technology. Industry presently produces a few HTS materials, including BSCCO-2212 round wires and anisotropic 2G YBCO tapes, with diverse advantages and challenges. In most cases, the progress in critical current has been encouraging, but must continue at a significant rate as a function of magnetic field and temperature [3,4]. Figure 3 shows an engineering current density (J_E) comparison at LHe temperature between state-of-the-art LTS and HTS materials up to ~30 T.

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[a] The VHFSMC effort is a two-year program focused on improvement of Bi2212 conductor for very high field magnets. It is concentrating first on improvements at the strand and cable level; the magnet studies at present are limited to small coils and short solenoids. The funding for VHFSMC will end in FY2011. Although discussions have begun, at present there is no follow-on program.

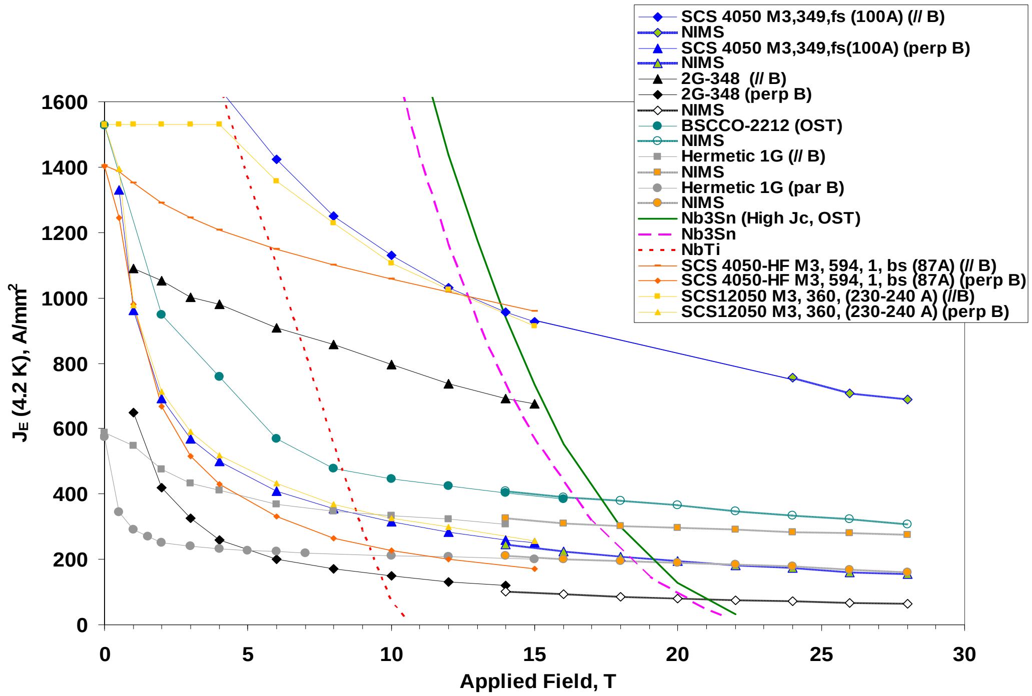

Fig. 3. Engineering current density, J_E, as a function of magnetic field for state-of-the-art LTS and HTS materials [3].

At its present stage of development, the most significant challenges for BSCCO-2212 round wire are improvement in J_c, stringent temperature homogeneity requirements during reaction, and a large strain sensitivity. For the use of BSCCO-2212 cables in magnets, the wire has to be able to withstand the strains induced by deformation during cabling. The most recent 2G YBCO tape has very a high J_c in the parallel field direction and is mechanically strong (~600 MPa). However, its anisotropy and longitudinal inhomogeneity in J_c still somewhat limit its performance for solenoids.

Finally, to reduce the coil inductance as much as possible, cable solutions will have to be studied. Currently, Rutherford-type cables can be made out of BSCCO-2212 round wires [5], and Roebel cables can be fabricated from the 2G YBCO tapes.

2.2.2 Magnet Design Studies

A major challenge in very high field solenoids made of HTS is the large stress levels developed on the conductor due to Lorentz forces. This is especially constraining for BSCCO, a brittle and strain sensitive ceramic material. Recently an analytical study [7] was made to obtain the radial, azimuthal and axial stresses in a solenoid as a function of size, i.e. self-field, and engineering current density for a number of various constraint configurations. Figure 4 shows a typical result, confirming that the hoop stress on the conductor grows dramatically in the desired range of solenoid fields.

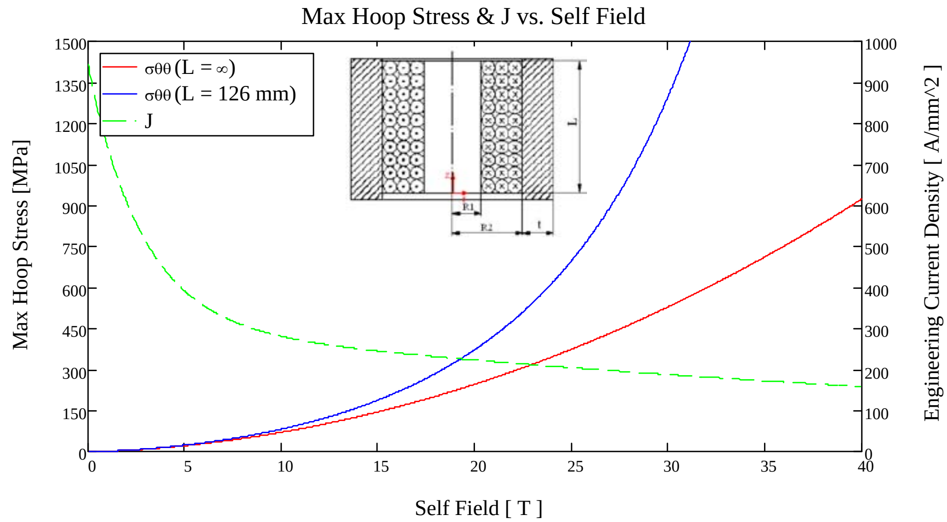

Fig. 4. Max. hoop stress in the coil as a function of coil self-field for a constrained coil with no pre-load (ID=50 mm, OD/ID=4, L/ID=2.52, J=152 A/mm^2, B_0~10 T, coil Young's modulus = 40 GPa).

All of these studies point to the need of strengthening solutions to achieve very high fields in HTS coils. Reinforcement of the strand design in the case of BSCCO-2212, and/or reinforcement of the various types of cables will have to be explored. An example of strain management optimization in the coil itself can be found [6] for a hybrid 45 T coil with ID=50 mm and L = 1 m (see also Fig. 5).

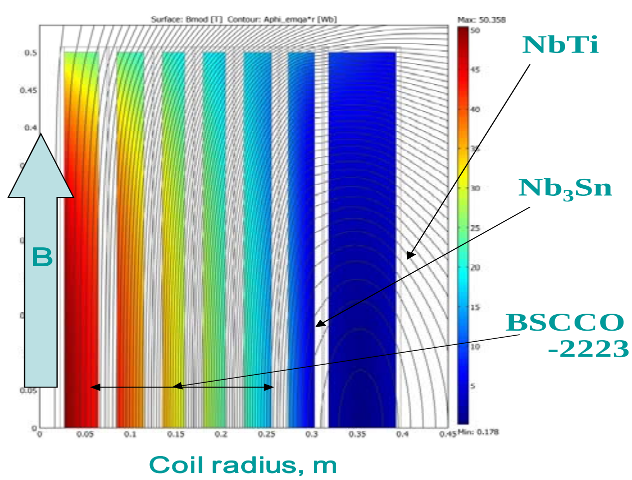

Fig. 5. Strain management optimization in a hybrid 45T coil with ID=50 mm and L = 1m [6].

Another very important aspect that needs to be covered for HTS magnets is the study of quench propagation for magnet protection.

2.2.3 Coil Technology

Coil technology encompasses winding techniques and tooling, impregnation procedures, splicing methods and R&D on thermally conductive insulation. Figure 6 shows an example of co-winding. The MAP program must investigate the various approaches to fabrication for both cable and tape conductors.

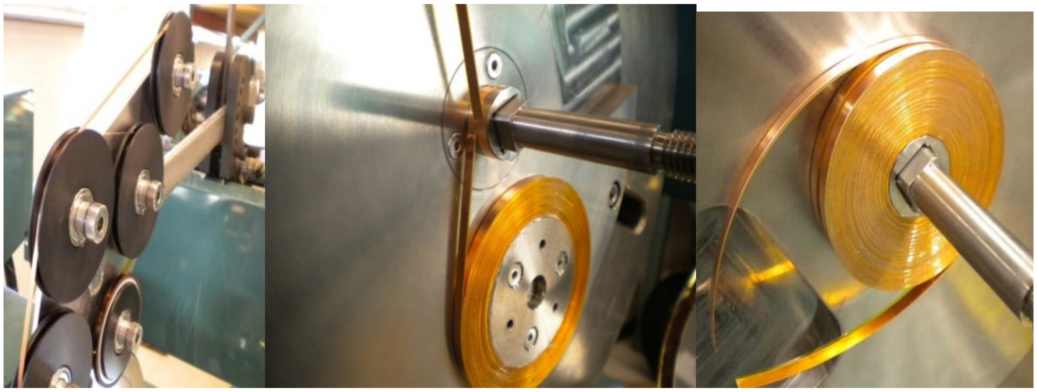

Fig. 6. Co-winding tooling for HTS and insulation tapes (left). Cu practice winding of double pancake coil (center, right).

2.3 *Collider Ring Magnets*

2.3.1 Requirements and R&D Issues

The requirements and operating conditions for a Muon Collider pose significant challenges to superconducting magnet designs and technologies [8]. For instance, contrary to proton machines, the collider ring dipole magnets must accommodate the significant radiation from the decay of the muons. For the dipole magnets, where the radiation is concentrated in the horizontal plane, there are two approaches: a) cos(θ) or block dipole designs with absorber in the magnet aperture, particularly in the coil horizontal mid-plane, and b) open mid-plane dipoles. Both approaches have design advantages but also significant design challenges.

a) ***Absorber Approach***: The success of this approach depends on the efficiency of the absorber to intercept radiation from the decaying muon. The required thickness of the absorber depends both on beam energy, and its location in the lattice. Beam and particle production studies are ongoing, but it is likely that an absorber of tungsten of thickness 30 mm or more will be required along the dipole mid-planes. This absorber will then require the magnet aperture to increase by 60 mm or more, which will more than double the coil aperture as shown below. Magnets of this field and aperture will be very challenging.

b) ***Mid-plane Gap Approach***: A mid-plane gap allows the radiation to escape the superconductor and helium cooling volume. The price for this concept is that the magnetic design is inefficient and subject to unwanted "symmetry allowed" field harmonics. Furthermore, the absence of the mid-plane support structure greatly complicates the magnet mechanical support.

For IR and collider ring quadrupoles, the radiation is not as localized and an open mid-plane design is not an option. The storage ring quadrupole must have a large aperture to allow room for absorbers to accommodate the large decay energy deposition. The IR quadrupoles have an additional aperture requirement because of the beam size at the expected β^*.

2.3.2 Present Status of R&D

Status of Nb_3Sn Magnet Technology

Through the efforts of the DOE-funded LHC Accelerator Research Program (LARP), as well as the DOE laboratory core programs, significant progress has been made in the last decade towards accelerator quality magnets. Over 100 Nb_3Sn coils have been fabricated over the past 10 years, as well as tens of magnets in various field and mechanical configurations. In the LARP program, several 1 m long magnets with the same coil cross section have achieved over 200 T/m field gradient. Over the past year, a 3.4 m magnet has equaled this 200 T/m gradient achievement [9]. With further improvements in the conductor, coil fabrication and mechanical structure, fields up to 240 T/m are expected in the near future. A parallel LARP program to achieve up to 200 T/m in a 120 mm aperture is in progress [10].

Nb_3Sn dipole development has been carried out at both LBNL and FNAL as part of a general accelerator development program that has significant relevance to the muon collider. A 16 T block magnet was built and tested at LBNL [11]. Fermilab built several 44 mm aperture cos(θ) dipoles, achieving >10 T bore fields with performance limited either by conductor J_c and/or conductor instability [12].

Design Studies

As part of an ongoing study of the collider storage ring and IR, preliminary magnet requirements are being developed and several magnet concepts have been proposed. The baseline design for these studies is a Muon Collider storage ring with a 1.5 TeV center of mass energy and an average luminosity of 10^{34} $cm^{-2}s^{-1}$. A storage ring lattice and an IR layout consistent with these parameters were developed and reported [13].

a) MC Storage Ring Magnets:

The MC storage ring design is based on 10-T dipole magnets. The small transverse beam size (σ~0.5 mm) requires a small aperture, only ~10 mm in diameter. However, the muon decay particles are localized in the horizontal direction on the inner side of the storage ring, and a 0.5 kW/m dynamic heat load associated with them needs to be intercepted outside of the magnet helium vessel at a safe distance from the primary beams.

Cross-sections of MC storage ring dipoles based on 4-layer block-type (left) and shell-type (right) coils are shown in Fig.7.

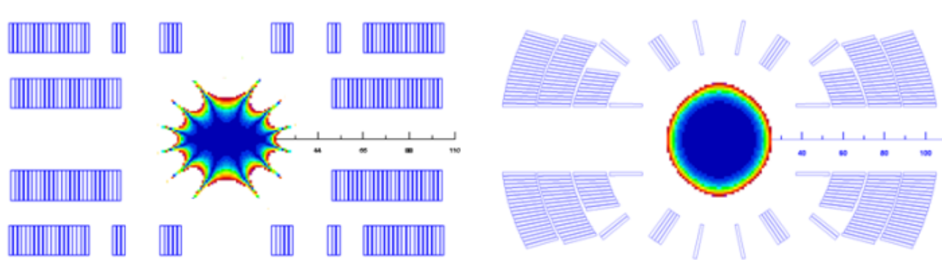

Fig. 7. MC Storage Ring dipole based on 4-layer block-type coil (left) or 4-layer shell-type coil (right).

The main magnet parameters are summarized in Table 2.

Table 2: Storage ring dipole parameters.

Parameter	Block-type design	Shell-type design
B_{max} coil at 4.5K (T)	13.37	13.13
B_{max} at 4.5 K (T)	11.24	11.24
B_{op} (T)	10.0	10.0
Inductance at B_{op} (mH/m)	6.72	9.52
Stored energy at B_{op} (kJ/m)	1280	1100
F_x at B_{op} (kN/m)	4084	3990
F_y at B_{op} (kN/m)	–2216	–1870

The mid-plane coil-to-coil gap in both designs is 30 mm to provide a mid-plane open space of at least 10 mm. Both designs have roughly the same conductor volume and provide a maximum field in the aperture of ~11.2 T, which corresponds to ~11% margin with respect to the nominal operating field at 4.5 K.

These magnet designs have quite large horizontal and vertical Lorentz force components, which lead to high stress levels in the coil. Both components need to be supported by an appropriately robust mechanical support structure to minimize turn motion which could cause quenching and field quality degradation.

b) Large-aperture IR quadrupoles

The IR doublet needs quadrupoles with three different apertures and nominal gradients. Three basic IR quadrupole cross sections are shown in Fig. 8, and the associated magnet parameters are summarized in Table 3.

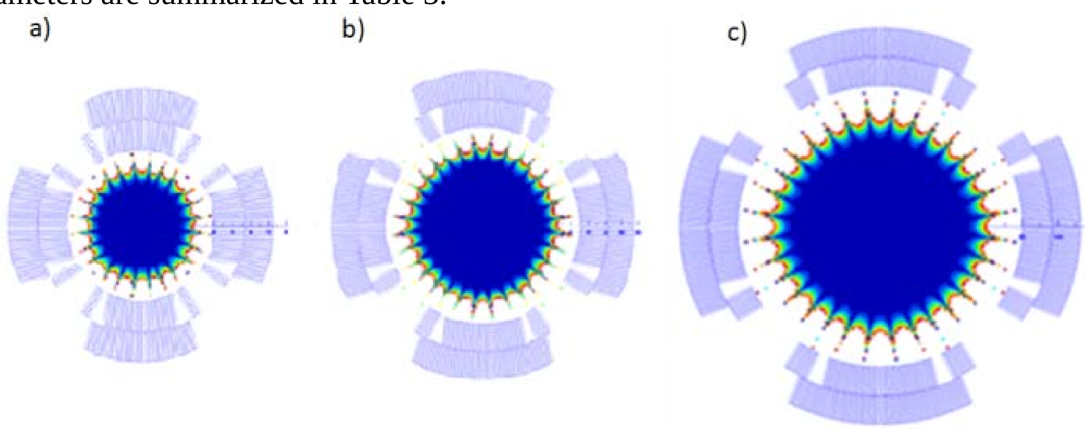

Fig. 8. Q1 (a), Q2 (b), Q3-Q5 (c) cross sections.

The IR quadrupoles are based on 2-layer shell-type coils and a cold-iron yoke separated from the coils by a 10 mm spacer. All the magnets provide ~12% operating margin at 4.5 K. If necessary, the margin could be increased by adding additional coil layers or operating the IR quadrupoles at 1.9 K. The accelerator field quality is achieved within the circles (blue areas in Fig. 8) equal to 2/3 of the corresponding coil aperture.

Table 3: IR quadrupole parameters.

Parameter	Q1	Q2	Q3–Q5
Aperture (mm)	80	110	160
B_{max} coil at 4.5 K (T)	12.76	13.19	13.49
G_{max} apert at 4.5 K (T/m)	281.5	209.0	146.0
G_{op} (T/m)	250	187	130
Inductance at G_{op} (mH/m)	3.57	6.58	12.88
Stored energy at G_{op} (kJ/m)	493.0	771.3	1391.8
F_x at G_{op} (kN/m)	1790	2225	2790
F_y at G_{op} (kN/m)	–2180	–2713	–3380

c) IR dipole

The large vertical beam size in the IR makes the parameters of the IR dipole B1 very challenging. As for the storage ring arc dipole, it is important for the IR dipoles to have an open mid-plane to avoid the showering of muon decay electrons in the vicinity of the superconducting coils, and to reduce background fluxes in the detector central tracker. To remove 95% of the radiation from the aperture to an external absorber, the open mid-plane gap in B1 should be at least $5\sigma_y$. The large 160-mm aperture and the large 6-cm gap limit the magnet nominal field that can be achieved with Nb_3Sn coils, and make it difficult to achieve an acceptable field quality in the area occupied by the beams. The cross section of an IR dipole based on 4-layer shell-type coil and an iron yoke with the ID of 320 mm is shown in Fig.9. The dipole parameters are summarized in Table 4.

The dipole design provides the maximum design field in the aperture of 9.82 T at 4.5 K, which corresponds to ~23% margin with respect to the nominal field of 8 T. Note that the maximum field in the coil is as high as 13 T. The shell-type coil design was chosen due to its better ratio between the magnet aperture and the mid-plane gap. Studies of alternative magnet design approaches for B1 will continue. The Lorentz forces in the IR dipole are as large as those in the storage ring dipole.

The accelerator field quality is provided within the required elliptical area of 50 mm horizontal and 110 mm vertical size (blue area in Fig. 9). It was achieved by an appropriate combination of relatively large values of low-order geometrical harmonics.

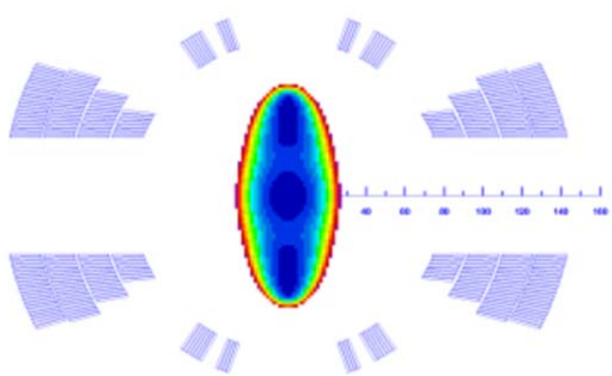

Fig. 9. IR dipole cross section.

Table 4: IR dipole parameters.

Parameter	Value
Aperture (mm)	160
B_{max} in coil at 4.5 K (T)	13.03
B_{max} in aperture at 4.5 K (T)	9.82
B_{op} (T)	8.0
Inductance at B_{op} (mH/m)	15.89
Stored energy at B_{op} (kJ/m)	1558
F_x at B_{op} (kN/m)	3960
F_y at B_{op} (kN/m)	–1650

d) Radiation studies

Energy deposition and detector backgrounds are simulated with the MARS15 code. All the related details of geometry, material distributions, and magnetic fields are implemented in the model for lattice elements and tunnel in the region ±200 m from the IP. To protect the SC magnets and detector, tungsten masks in the interconnect regions, liners in magnet apertures (wherever needed), and a sophisticated tungsten cone inside the detector were implemented in the model and carefully optimized. The muon beam energy assumed in this study is 750 GeV, with 2×10^{12} muons per bunch and 15 Hz repetition rate. The muon beam is aborted after 1000 turns, when the luminosity has decreased by a factor of 3.

Three cases were analyzed: 1) 10-cm thick tungsten masks with $10\sigma_{x,y}$ elliptical bore placed between the IR magnets; 2) additional tungsten liners inside the quadrupoles with $10\sigma_{x,y}$ elliptical bore; 3) case 1, but with the IR quadrupoles displaced horizontally by 10% of their apertures to provide ~2 T bending field. This additional field also helps to facilitate the chromaticity correction and deflect low-energy charged particles from the detector.

The power density iso-contours at shower maximum in the first quadrupole are shown in Fig. 10, while Fig. 11 displays such profiles in the IR dipole B1. The maximum value of the power density is 5.0 mW/g in Q1. Displacing the quadrupoles horizontally reduces the power density but not enough to avoid using liners. Combining all three cases has the potential of keeping the peak power density in the IR magnets below their quench limits.

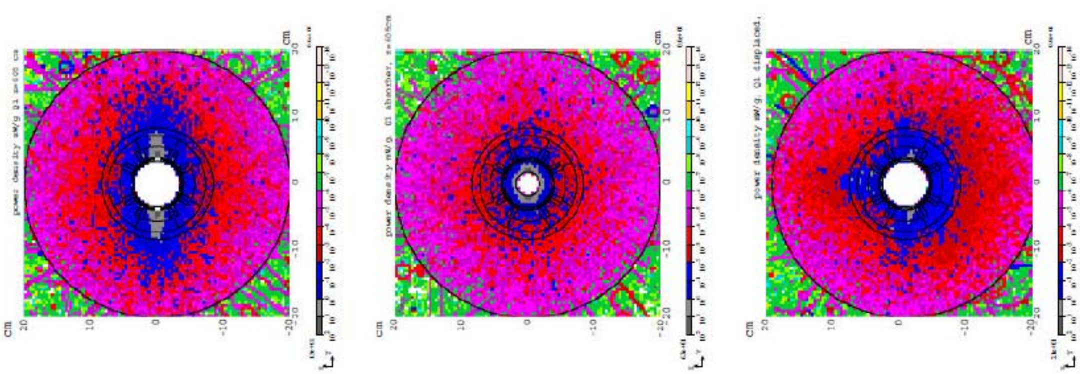

Fig. 10. Deposited power density in Q1 (mW/g) for three cases: "standard" (left), with absorbers inside (center) and with horizontal displacement (right).

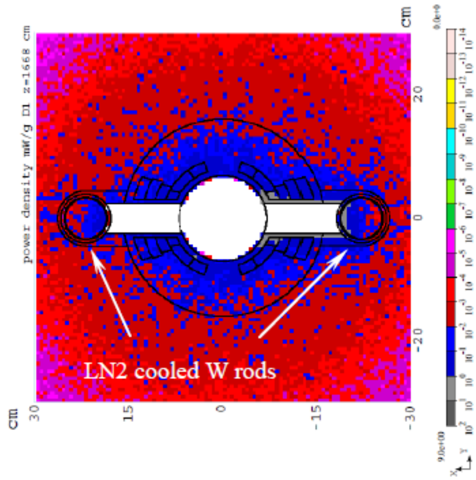

Fig. 11. Power density (mW/g) in B1 dipole for case 3.

2.4 HCC Magnet R&D in Support of the Section Test

Among the 6D cooling channel design options, a Helical Cooling Channel (HCC) filled with high pressure hydrogen gas presents the greatest magnet technology challenges. The HCC has a magnet coil configuration that is novel, and requires an initial conceptual study to understand the engineering issues and establish whether this option might be viable. The initial conceptual studies have largely been completed. Three model HCC magnets have been built, and tests of the last two are scheduled for later this summer.

With these results already in hand, further significant work on the HCC design will only be done if this channel is selected by the RF and 6D channel down-selection process, and would be in the context of designing the 6D cooling channel section test.

2.4.1 Helical Solenoid Studies and R&D

The HCC has been proposed [14] to quickly reduce the six-dimensional phase space of muon beams for muon colliders, neutrino factories, and intense muon sources. A novel superconducting magnet system dubbed the Helical Solenoid (HS) for a muon beam cooling experiment has been studied at Fermilab [14-25]. The solenoid consists of short circular coils shifted in the transverse direction in such a way that coil centers lay on the beam central helical orbit (see Fig. 12).

The main advantage of the proposed system is a substantial reduction of superconducting solenoid dimensions, superconductor volume, and coil peak fields. The HS at 1.6 m helix period generates the required superimposed solenoidal, helical dipole, and helical quadrupole fields merely by spatially shifting circular coils without any need for corrections. Earlier studies of the HCC included the proposed MANX experiment to study muon cooling effects [15,18]. The inner volume of the cooling channel is filled with a high-pressure H_2 gas absorber in which a muon beam passing through will be decelerated and cooled by the process of ionization energy loss. The magnet system parameters are adjusted to match the momentum of the beam as it slows down.

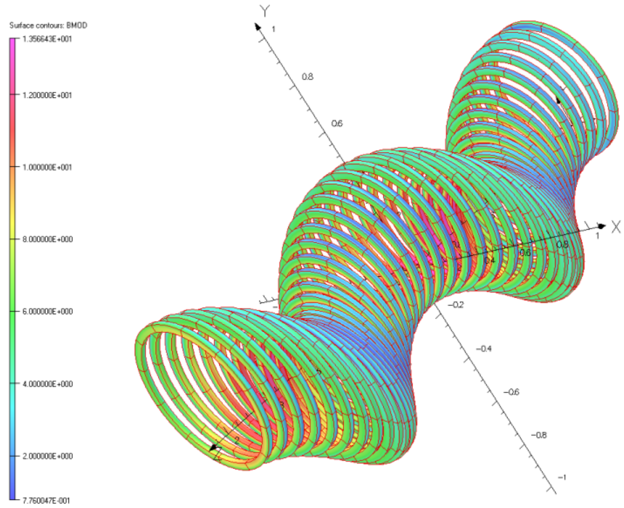

Fig. 12. Helical Solenoid geometry and flux density distribution on the coil surface.

In the case of the geometry shown in Fig. 12, a HS with a helix period of 1 m produces a solenoidal field component that is too large relative to the transverse field. Different HS configurations were studied (see Fig. 13), each capable of meeting the specifications. These versions of the HCC include, respectively, a demagnetization solenoid, a helical dipole winding, trapezoidal coils.

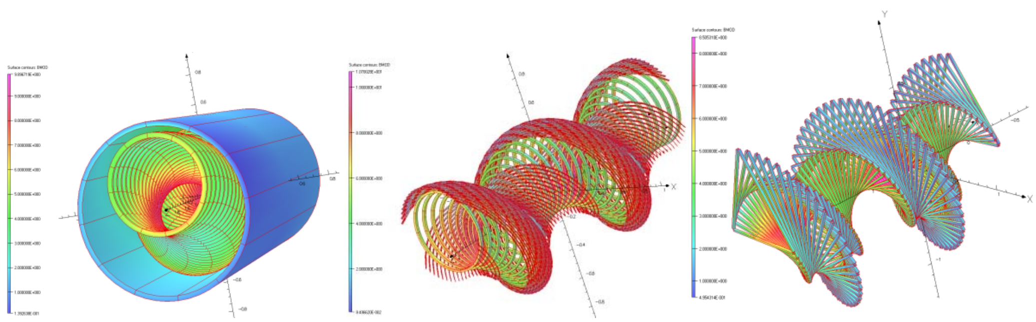

Fig. 13. Various configurations of HS to match the required relationship between solenoidal and transverse field components. HS with demagnetization solenoid (left), HS with helical dipole (center), and triangular coil form (right).

Because the HS has a novel configuration, R&D was initiated to develop magnet fabrication technology and study the HS performance. A HS 4-coil model [17-20] was designed, built, and tested. The mechanical structure design and manufacturing technology open the opportunity to construct any length of HS cold mass without superconductor splices using a continuous solenoid winding and assembly process (see Fig. 14). An improved second 4-coil NbTi model has recently been fabricated and is ready for test.

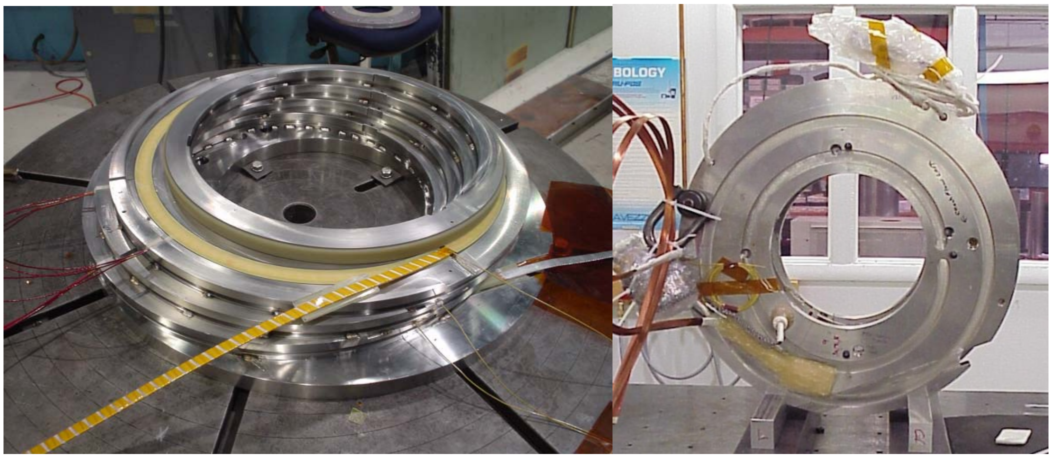

Fig. 14. NbTi 4-coil model fabrication (left) and the final assembly (right).

The cooling efficiency of a Helical Cooling Channel (HCC) was also investigated [16, 19]. These studies proposed a "3 Tier" HCC system with increasing fields and smaller diameters along the length of the channel. The "first tier" front end of the HCC requires fields up to 6 T and thus would be based on NbTi superconductor. The middle section of HCC would use Nb_3Sn superconductor, and a "far end", with required fields up to 30 T, would use Nb_3Sn with HTS inserts. A demonstration "2-coil" HTS magnet is being built in FY2010.

A critical issue in HS R&D is integration with the RF system. Integration of the room temperature RF feed-throughs with the superconducting magnetic coils is a significant challenge. Various concepts to combine the HS and RF are shown in [20, 23]. For the "front end" of the HCC, it seems reasonable to use sections of electromagnetically connected pillbox cavities powered from an RF source through vertical penetrations as shown in Fig. 15. A study of the integration of the RF for the rest of the system is in progress.

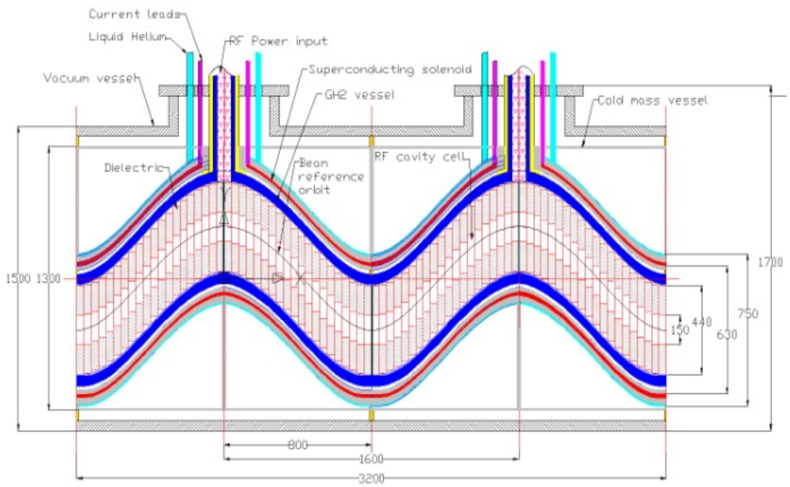

Fig. 15. Helical Solenoid integrated with 201-MHz cavity filled with ceramic.

Another significant challenge is the understanding and control of RF cavity breakdown in the presence of magnetic field. Recent experiments have shown that filling a cavity with hydrogen gas might resolve this issue. Magnetic insulation is another potential solution to the

RF breakdown problem. This was investigated in the MuCool experiment [24]. It was observed that even a 3° cavity rotation in the 3 T magnetic field perpendicular to the electric field caused a substantial drop in the cavity's achievable peak gradient. It should be noted that the HS has a different magnetic field configuration from the straight solenoids used in this experiment. The Helical Solenoid field opens an opportunity to suppress breakdown in RF cavities in the presence of helical dipole and quadrupole fields, as shown in the simulation result from Ref. [25].

3. PROPOSED R&D PROGRAM

3.1 Target Solenoid

Simulations with the MARS code are pointing to the inadequacies of the Study 2 shielding design. The superconducting coils surrounding the target that produce the required 20 T are exposed to excessive energy deposition. We anticipate that any subsequent solution will impact the current magnet configuration such that either the ID of the coils must be increased to allow for more shielding or possibly the hybrid nature of the key first 20-T magnet may need to be augmented with an HTS option. In either case, this will result in a substantial alteration of the magnet layout and consequently considerable design effort will be required. In addition, should the HTS option be pursued, a prototype coil must be fabricated and tested to ensure the viability of such a solution.

3.2 High Temperature Superconducting Solenoids

The goal for this part of the program is to present a realistic conceptual design for a high-field solenoid for the final cooling. As shown in Section 2, progress has already been made on conductor development and characterization. Magnet design studies to date have served to identify the significant design challenges. Still, a practical solution for a 50-T solenoid has not been reached. We propose the following plan to reach our goals.

1) ***Develop functional specifications for the high field solenoid***

As part of the end-to-end muon collider design, a parameter list for this magnet must be fully developed. The present concept is that it is ~1 meter in length, and 20-50 mm in aperture. Beam heating in this stage of the cooling chain is expected to be small. A preliminary lattice study indicates that field quality is not a major design issue. A working parameter list should be developed in the first year of the MAP.

2) ***Evaluate/compile information on state-of-the-art conductors***

The state-of-the-art in HTS conductor is the major factor limiting a practical 50 T design. HTS Materials, with engineering current densities on the order of 500 A/mm^2, excellent strain tolerance, available in long piece lengths and at an affordable price, are essential. We expect that there will be continued significant progress in conductor development during the multi-year time frame of the MAP design study. Some effort in MAP will be devoted to short sample testing of promising materials as they become available and providing these results to the magnet designers. Note that due to very limited resources, MAP will depend on outside programs such as the VHFSMC and SBIRs to actually develop new conductor.

3) ***Build HTS and hybrid inserts to prove technology***

Because of the large amount of time and conductor expense, it is the accepted strategy to prove HTS magnet technology with small diameter "inserts", which are then tested in large aperture coils at various test facilities. Inserts are also an effective way to study manufacturing issues such as coil winding and splices. We will coordinate our activities with the VHFSMC and other DOE laboratory core programs to receive the maximum benefit.

4) ***Perform conceptual design for the highest field practical magnet***

The key issues for this magnet are

- utilizing the state-of-the art conductor anticipated in the next 5 years;
- advanced mechanical support approaches to intercept the significant hoop stress;
- effective insulation schemes to reduce the probability of shorts in these multi-layer structures; and,
- quench protection strategies that react to slow quench propagation and the likely complex coupling of independently powered sub coils.

The conceptual design will build on the existing magnet fabrication of 25-T magnets as well as the ongoing 40-T magnet design studies and insert fabrication.

5) ***Present plan for building magnets in years 1-3 post plan***

During the final 2 years of the program, a plan will be presented for the fabrication of a full scale R&D magnet after the initial 7-year MAP study period. The plan will be based on the MAP high field solenoid conceptual design, using the state-of-the-art conductor at that time.

3.3 Collider Ring Magnet R&D Plan

The goal for collider ring magnets is to produce (sufficiently) detailed conceptual designs for:

1. IR quadrupoles;
2. IR separation dipoles;
3. collider ring arc dipoles; and,
4. collider ring arc quadrupoles.

The designs can be used as a basis for the cost estimate for the collider rings.

In addition to meeting the lattice requirements, conceptual designs will be carried out to push the limit on field and performance, since high field translates into smaller collider rings and higher integrated luminosity.

As shown in Section 2, significant work has already begun on magnet concepts. Working closely with the Collider Ring Design Group started in FY10, field requirements and expected radiation rates are being developed, and are being used as input to the magnet specifications. As shown above, there are significant mechanical and conductor challenges to achieve the field requirements. For the IR and collider ring dipoles, both internal absorber and open mid-plane magnets will be considered.

MAP will depend on the ongoing Nb_3Sn magnet technology development through LARP and the DOE laboratory core programs for conductor and magnet development. In some cases, such as the arc quadrupoles, the magnets are extensions of the 90 mm and 120 mm magnets under development now. The core program will be the primary technology development site for wide-aperture and open-mid-plane dipoles.

3.4 R&D to support 6-D cooling

The focus of the R&D work up to now has been on helical solenoid magnets, as these magnets and their interfaces to RF are recognized to be most challenging. A small amount of effort is envisioned over the first few years of the program on small coil technology development and design studies related to magnet/RF integration. The effort required depends critically on the project's technology choice for the 6D cooling channel.

Whatever the technology choice, the magnet effort will be focused in the later years of the project on the engineering design and fabrication of the 6D cooling bench test.

4. SUMMARY

Target capture solenoids, complex and high field solenoids for 6D cooling, and high field collider ring magnets have been targeted as magnet technologies that pose the highest technological risk to the present neutrino factory and muon collider conceptual designs. While significant progress has been made in the past few years on solving the conductor, magnetic, and mechanical complexities of these magnets, further design work is needed to produce magnet designs that meet the muon collider requirements.

As presented in this paper, the MAP magnet program's goal is to develop credible conceptual designs for these magnets, and identify the necessary technology support studies. These studies will be performed within the MAP framework, as funding permits. In some cases, such as the conductor development and the fabrication of full-scale collider magnets, MAP can and will depend on outside support from industry and other DOE-supported programs such as the VHFSMF and LARP.

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