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SC Accelerator Magnet R&D at FNAL
(FY14-16 HFM Program Update)

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1. HFM Program mission and strategy

The mission of the SC Accelerator Magnet Program (High Field Magnet Program) at Fermilab is the development of advanced SC magnets and baseline technologies for present and future particle accelerators. This program secures and expands Fermilab's technical capabilities and leadership role in accelerator based HEP research. This activity is assured to have a strong impact on the future Energy Frontier HEP programs in the U.S. and worldwide, including luminosity and energy upgrades for the LHC as well as the construction of new machines such as the Muon Collider or new Hadron Collider. In ten years the program has to provide technical capabilities and a leadership position for Fermilab to participate in focused R&D and then in construction of the next HEP accelerator complex anticipated in the next decade or two.

During the past decade the program focused on the development of high-field accelerator magnets with operating fields up to 15 T based on Nb_3Sn superconductor. In the long term, the program scope foresees the development of accelerator magnets with operating fields up to 20-25 T. This program also supports the development of new SC strands and cables suitable for use in high-field accelerator magnets, improvements of magnet design and analysis methods and tools, fabrication and test infrastructure, instrumentation, and training of young magnet scientists and engineers at Fermilab.

Fermilab is a key member of the LARP collaboration which has been working on the Nb_3Sn IR quadrupoles for the LHC luminosity upgrade since 2003. The present LARP Magnet program goal is to develop and demonstrate 150 mm aperture Nb_3Sn IR quadrupoles for the new LHC IRs. To demonstrate the feasibility of Nb_3Sn dipoles for the proposed LHC collimation system upgrade, Fermilab in collaboration with CERN has started in FY2011 a joint R&D program with the goal of building by the end of 2015 a 5.5-m long twin-aperture Nb_3Sn dipole prototype suitable for the LHC collimation system upgrade. These magnets can be also used to provide space in the LHC lattice for different insertion devices such as dynamic collimators based on the e-lens concept, corrector magnets, BPMs, etc. In the future, these magnets or their modifications could be considered as a baseline design for a new hadron collider.

2. FY14-FY16 Goal and Plan Update

The original 4-years FNAL-CERN joint R&D program for FY11-14 included three phases of the 11 T dipole R&D and preparation to the participation in dipole collared coil production:

- Phase 1 (FY11-12): the design and construction of a single-aperture 2 m long demonstrator dipole, delivering 11 T at the nominal LHC current of 11.85 kA and temperature of 1.9 K in a 60 mm bore with 20% margin.
- Phase 2 (FY13-14): the fabrication and test of two 2 m long, twin-aperture demonstrator dipoles to confirm the final magnet design, demonstrate the magnet performance parameters and their reproducibility.
- Phase 3 (FY14-15): the design and technology scale up by fabricating and testing a 5.5 m long twin-aperture dipole prototype.

The 1^{st} phase of the program has been essentially completed by testing the first 2 m long Nb_3Sn single-aperture dipole demonstrator in June 2012.

During the FY13 the plan was gradually modified to take into account current CERN priorities and schedule for US contributions to LHC luminosity upgrades and the substantial reduction of the HFM budget for the next 3 years provided by DOE. Based on that the 3^{rd} phase of the program has been cancelled and the scope of the 2^{nd} phase has been optimized. The length of 2-m long models has been reduced to 1 m to cut the cost of the Nb_3Sn cable and magnet parts (mainly collar and yoke laminations). The first 1-m long single-aperture dipole model has been tested in February-April 2013 reaching 11.7 T field in aperture at 1.9 K temperature which is 97.5% of the magnet design field. The work on the 11 T dipole will continue in FY14 on the lower effort level due to budget limitations, concentrating on the 1-m long twin-aperture 11 T dipole model, and will be concluded in FY15. The focus of the program now is being shifted from the focused 11 T dipole development and demonstration back to a more generic high-field accelerator magnet R&D in support of a muon collider (MAP) and a future circular hadron collider.

The updated HFM program plan for FY14-16 includes the following goals and steps:

- FY14: finish the development and demonstration of the 11 T 60 mm Nb_3Sn dipole for LHC upgrades including 1-in-1 and 2-in-1 configurations, transfer technology to CERN.
- FY15: develop 15 T dipole design concept (4-layer coil design), magnet and tooling engineering design based on the 11 T dipole.
- FY16: fabricate and test the first 15 T 60 mm aperture Nb3Sn dipole model.

The proposed approach will largely utilize the available components (cable, coils, iron yoke, bolted skin, end plates, etc.) of the 11 dipole models, tooling (coil winding, curing, reaction and impregnation tooling, contact tooling for coil yoking and skinning, etc.), and fabrication and test infrastructure developed at Fermilab in support of the HFM and LARP model magnet programs. This approach significantly reduces the cost and the development time of the 15 T dipole.

On the longer term the HFM program will focus on the development, fabrication and test of high-field (15+ T) large-aperture (120-150 mm) Nb_3Sn dipole magnets (FY18-20). Such large-aperture high-field dipoles (and quadrupoles) are used in MC storage rings and IRs [5]. They will be also needed to generate a background field up to 15 T in very high-field (20+ T) small-aperture accelerator dipoles based on HTS/LTS coils being considered in some scenarios of a future hadron collider [6].

The main challenge of large-aperture high-field Nb_3Sn magnets is finding an adequate solution for the coil stress management due to large Lorentz forces and the magnet quench protection due to high stored energy. The progress towards 20+ T magnets will depend also on the progress in the development and demonstration of HTS (Bi2212) cables and HTS insert coils. If the HTS conductor development program reaches its goals, in FY21-25 the HFM program could start the development of a 20+ T 40 mm aperture Bi2212/Nb_3Sn dipole for a future hadron collider.

2.1 FY14 Plan and Expected Outcomes

In FY14 the HFM program will continue optimization of the 11 T Nb_3Sn dipole coil design and fabrication process, and transfer the technology to CERN. The development and fabrication of the 1 m long twin-aperture 11 T dipole model will also start.

To improve the quench performance and to study quench protection issues for the 11 T dipole, a 1-m long dipole coil (MBH08) with RRP-108/127 strands, 40-strand cored Nb_3Sn cable and advanced instrumentation will be assembled and tested in the dipole mirror configuration MBHSM01. Two 1-m long coils (MBH09, MBH10) using end parts with short legs (FNAL design) and two coils (MBH11, MBH12) using end parts with flexible legs (CERN design) will be fabricated. The first pair of coils will be assembled and tested in the single-aperture dipole MBHSP03. Then this collared coil will be assembled with previously tested collared coil (MBHSP02) into the 1st twin-aperture dipole model MBHDP01. The second pair of coils (MBH11 and MBH12) will be collared and used in the 2nd twin-aperture dipole model. If needed (and resources allow) these two coils could be also tested in a single-aperture 11 T dipole model (MBHSP04) to demonstrate the performance reproducibility. Based on these results we will finalize the design, parameters and fabrication process of the collared coils for the 1st twin aperture 1-m long 11 T dipole demonstrator.

The mid-term R&D plan for 15 T small- and large-aperture dipole magnets based on Nb_3Sn coils, and the long-term R&D plan for 20-25 T dipole magnet based on hybrid LTS/HTS coils will be further shaped and optimized. We will focus on the design concept, parameters and R&D plan for 15 T Nb_3Sn dipole based on the coil and cable used in the 11 T dipole.

2.2 FY15 Plan and Expected Outcomes

In FY15 the HFM program will finish the development and demonstration of the 11 T dipole based on Nb_3Sn technology for LHC upgrades and start development of a 15 T Nb_3Sn small-aperture dipole for a future circular collider.

We will re-assemble and test the dipole mirror MBHSM01 to finish the magnet quench protection studies started in FY14. The results of these studies are critical not only for the quench protection of the 15 T dipole but also for the LARP QXF quadrupole magnets. We will also assemble and test the 2nd 1 m long twin-aperture 11 T dipole to demonstrate the final magnet performance and its reproducibility – a critical issue for accelerator magnets.

The HFM program will perform comprehensive 2D/3D magnetic and mechanical analysis and develop engineering design of the 15 T 4-layer dipole focusing on the 120-mm outer 2-layer coil compatible with the 60-mm 2-layer coil used in the 11 T dipole, and coil-yoke interface. Coil fabrication tooling and coil parts will be procured and a practice coil will be fabricated. The dipole mirror structure to test a 120-mm outer dipole coil will be developed, using the components of the available dipole mirrors, and procured.

The current collaboration with KEK and NIMS in Japan on the development and demonstration of accelerator magnets based on Nb_3Al cables will continue. A 50 m long unit length of 27-strand cable using 0.7 mm Nb_3Al strand produced in Japan will be fabricated at Fermilab and short samples will be tested if resources allow (including possible funding from KEK/NIMS).

The work on the mid-term R&D plan for 15 T large-aperture dipole magnets based on Nb_3Sn coils, and the long-term R&D plan for 20-25 T dipole magnet based on hybrid LTS/HTS coils will continue.

2.3 FY16 Plan and Expected Outcomes

In FY16 the work on the 60-mm aperture 4-layer Nb_3Sn dipole will continue focusing on the fabrication and test of the 1st 1-m long dipole model. We will fabricate and test Nb_3Sn cable for 3-4 120-mm dipole coils, procure parts and fabricate 2-3 120-mm dipole coils. The 1st 120-mm dipole coil will be assembled and tested in the dipole mirror configuration to qualify the coil fabrication tooling and process. We will procure magnet parts including the iron yoke laminations, coil-yoke spacers and end plates, and assemble the 1st 15 T Nb_3Sn dipole model using two 60-mm coils previously used in the 11 T dipole models and two new 120-mm coils. The magnet model will be tested at Fermilab's VMTF using equipment previously used to test LARP quadrupole and 11 T dipole models.

Collaboration with KEK and NIMS in Japan on the development and demonstration of accelerator magnets based on Nb_3Al cables will continue. A short quadrupole coil will be fabricated and tested using the available at Fermilab quadrupole coil test structure (quadrupole mirror) at various pre-stress levels. This work will demonstrate the Nb_3Al technology for application in accelerator magnets with high Lorentz force level.

The conceptual design study of large-aperture 15 T dipole magnet based on Nb_3Sn superconductor will start. The work on the long-term plans for 20-25 T magnet R&D based on hybrid LTS/HTS coils will continue taking into account the available resources, program priorities and results of the HTS conductor development programs.

3. FY14-FY16 Metrics and Milestones

FY14:

- Fabricate 3 UL of the 40-strand cable with stainless steel core and RRP-108/127 strand by 11/2013
- Assemble and test coil MBH08 with advanced instrumentation and optimized pre-load in the dipole mirror configuration MBHSM01 by 12/2013
- Fabricate coils MBH09 and MBH10 with modified end parts (short legs), RRP-108/127 cored cable by 12/2013
- Fabricate coils MBH11 and MBH12 with modified end parts (flexible legs), RRP-108/127 cored cable by 03/2014
- Assemble and test single-aperture dipole model MBHSP03 by 04/2014
- Assemble and test the 1st twin-aperture dipole model MBHDP01 by 08/2014
- Develop design concept, parameters and R&D plan for 15 T Nb_3Sn dipole by 10/2014

FY15:

- Re-assemble and test dipole mirror MBHSM01 by 11/2014
- Assemble and test the 2nd twin-aperture dipole model MBHDP02 by 01/2015
- Develop engineering design of the 15 T dipole and tooling by 03/2015
- Fabricate cable for the 120-mm dipole practice coils by 05/2015
- Procure parts and tooling and fabricate the 1st 120-mm practice coil by 07/2015
- Develop and procure dipole mirror structure to test 120-mm outer dipole coil by 09/2015

FY16:

- Fabricate and test Nb_3Sn cable for the 120-mm dipole coils by 11/2015
- Procure parts and fabricate three 120-mm dipole coils by 02/2016
- Assemble and test a 120-mm dipole coil in the dipole mirror configuration by 05/2016
- Procure magnet parts, assemble and test the 1st 15 T dipole model by 08/2016
- Develop a design concept with stress management of large-aperture 15 T dipole magnet based on Nb_3Sn superconductor 10/2016

4. Risks to the FY14 Plan

FY14 Goal or Milestone	Threats	Risk Priority (H,M,L)[a]	Mitigation Actions	Owner
Fabricate 3 UL of the 40-strand cable with stainless steel core and RRP-108/127 strand.	Strand cross-overs, cable geometry out of tolerance, large strand degradation.	L	Make initial cabling run using Cu strand and inspect for cross-overs. Control cable width and mid-thickness during fabrication. Test extracted strand samples prior to cable fabrication.	
Assemble and test coil MBH08 in the dipole mirror configuration MBHSM01.	Coil damage during fabrication and assembly.	M	Measure coil size and control pre-stress during assembly using strain gauges.	
Fabricate coils MBH09-MBH12 with modified end parts and RRP-108/127 cored cable.	Cable collapse and shorts during winding, cable degradation during reaction.	H	Control cable tension and insulation during winding. Control temperature, time and Ar flow during reaction. Test coil witness samples.	
Assemble and test single-aperture dipole model MBHSP03.	Coil damage during fabrication and assembly.	H	Measure coil size, control pre-stress during coil collaring and magnet assembly using strain gauges.	
Assemble and test the 1st twin-aperture dipole model MBHDP01.	Coil over-compression during skin welding.	M	Measure collared coil and yoke size and control skin stress during welding using skin strain gauges.	
[a]Risk Priority (HML) H=high; M=medium; L=low				