June 6, 2012

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**11 T Nb3Sn Dipole for the LHC Collimation System Upgrade**

The LHC operational experience at 3.5 TeV proton beam energy and approximately 30% of the design luminosity indicates that the losses in the experimental regions from interaction debris can be an issue for both proton and for ion beams. The losses in the dispersion suppressors of interaction regions IR1, IR2 and IR5 have already affected the LHC operational efficiency including radiation effects on electronics, delayed access to the machine during beam operation due to radiation constraints, potential impact on magnet lifetime, etc. To improve the collimation efficiency by a factor of 15-90, additional collimators are foreseen in the DS regions around several LHC straight sections.

The mission of this project is participation in and contribution to upgrades of the LHC beam collimation system planned at CERN for 2017-2021. The goal of the LHC collimation system upgrades is to provide reliable and efficient machine operation with proton and ion beams at the nominal and later at the ultimate beam intensity and luminosity. These upgrades involve installation of additional collimators in LHC lattice in the dispersion suppression (DS) areas around interaction regions (IR) in points 1, 2, and 5 and in the momentum and betatron cleaning insertions near points 3 and 7. The required space for the collimators will be provided by replacing some regular LHC dipoles (MB) with shorter but stronger dipoles with the same bending strength. Due to the scale of the work and the complexity of its integration into an operational machine, the final magnet assembly, magnet testing and installation will be managed by CERN. The need for the U.S. and FNAL is to maintain the world-wide leadership in the area of High Field Accelerator Magnets. This need will be met by contributing to the project, participating in the magnet design and the construction of the magnet cold masses.

The goals of the proposed project are in harmony with those expressed in the Strategic Plan of the DOE Office of Science to “explore the fundamental interactions of energy, matter, time and space,” as well as with its mission to “keep the U.S. at the forefront of intellectual leadership” (DOE/SC-0079, February 2004). These goals have been endorsed through internal as well as external reviews of the U.S. GAD Program and LARP, and were supported by the EPP-2010 study conducted by the National Academy. For example, the first itemized finding of the EPP-2010 report states: “The study of LHC physics will be at the center of the U.S. particle physics program during the coming decade,” and the report’s major action item commends: “The highest priority for the U.S. national effort in elementary particle physics should be to continue to be an active partner in realizing the physics potential of the LHC experimental program.” This envisions full participation in LHC upgrades: “As potential upgrades to the detectors and the accelerator are motivated and defined through scientific results, the U.S. particle physics program should consider the provision of in kind contributions as appropriate.” The most recent P5 subpanel of HEPAP in its 2008 report “U.S. Particle Physics: Scientific Opportunities - A Strategic Plan for the Next Ten Years” states: “Significant U.S. participation in the full exploitation of the LHC has the highest priority in the US high-energy physics program. The panel recommends support for the US-LHC program, including U.S. involvement in the planned detector and accelerator upgrades.”

To provide a 3.5 m longitudinal space needed for the additional cryo-collimators, a solution based on 11 T Nb3Sn dipoles as a replacement for several 8.33 T Nb-Ti LHC MBs is being considered. These twin-aperture dipoles will operate at 1.9 K and be powered in series with the main dipoles. They will deliver the same integrated strength of 119 T∙m at the LHC nominal current of 11.85 kA. Recent progress in the development of Nb3Sn accelerator magnets in U.S. indicates that this technology can meet the requirements. Providing the same space for warm collimators in the cold LHC ring without using 11 T dipoles would involve design and fabrication of several complicate cryo-components as well as removing, bringing to the surface and re-installing 32 cold objects including 24 main magnets, 2 connection cryostats (new types), 2 shuffling modules, 2 DFBAs, 2 warm-cold transitions (new design). The longitudinal and radial displacement of several quadrupole and dipole magnets will certainly provide a negative impact on beam dynamics jeopardizing the LHC performance.

Technical risks for the LHC associated with implementation of 11 T Nb3Sn magnets are limited since thanks to the positive results achieved at FNAL during the past decade in the framework of core High Field Magnet R&D program and participation in US-LARP. The back-up plan to the construction and installation of Nb3Sn dipoles in LHC is the painful, but viable, relocation of existing magnets and cryoboxes in the LHC lattice.

To demonstrate the feasibility of this approach, CERN and FNAL have started in 2010 a joint R&D program with the goal of building by the end of 2014 a 5.5-m long twin-aperture Nb3Sn dipole prototype suitable for the DS region upgrade. This joint R&D effort will provide also conditions for the transfer of Nb3Sn magnet technology to CERN.

The first phase of this program is the design and construction of a single-aperture 2-m long demonstrator dipole magnet, delivering 11 T at 1.9 K in a 60 mm bore with 20% margin. The main goal of this model is to demonstrate the quench performance, nominal field, and operation margin of the Nb3Sn coils in a single aperture structure. In addition, the data on magnet field quality and quench protection will be acquired for the further optimization and selection of conductor, magnet design and fabrication technologies. The first single-aperture 2-m long demonstrator dipole has been designed and manufactured and now is being tested at FNAL.

The second phase of the program includes the fabrication and test of two 2 m long, twin-aperture demonstrator dipoles in 2013 to confirm the final magnet design, demonstrate the magnet performance parameters and their reproducibility as well as transfer Nb3Sn technology to CERN/Europe. And finally, the third phase will focus on the design scale up and prototype development and test in 2014.

Following the successful long dipole prototype and the completion of the LHC consolidation in 2014, CERN would be in the position to make a decision on the feasibility of the overall scheme to replace Nb-Ti magnets with 11 T Nb3Sn magnets for the insertion of additional collimators around the LHC ring in IR1, IR2 & IR5 and later, in IR2 and IR7. If this approach will be accepted, CERN and FNAL would share the responsibility for design, construction and collaring of the coils, while CERN would assemble the collared coils with iron yokes, install the cold masses in cryostats, and test the magnets. The construction phase would be managed by CERN with active participation by FNAL as deemed appropriate and approved by funding agencies.

Both FNAL and CERN have appropriate infrastructure including laboratories for SC strand and cable testing; cabling machines to produce multi-strand Rutherford-type cables; magnet production facilities with short and long tooling for coil fabrication and equipment for magnet assembly; magnet test facilities to test magnet models and prototypes in superfluid and normal helium. Both laboratories have skillful personnel including magnet scientists, engineers and technicians capable of designing, fabricating and testing SC accelerator magnets as well as supporting infrastructures to provide magnet and tooling design, components procurement and quality control. To perform the described R&D and later to accomplish the collared coil fabrication according to CERN schedule for LS2 and LS3, FNAL infrastructure will need some upgrades as well as the FNAL magnet group staff has to be adjusted accordingly.

**Schedule and Cost Range, Funding Profile**

The production period is planned for 6 years and assumes 50-50 distribution of the collared coil production between FNAL and CERN. It divided in two phases, 3 years each, starting collared coil production for 11 T dipoles in FY2015. The preliminary cost estimate for the 11 T dipole project is shown in Table below using fully loaded Labor rates for various categories at FNAL in FY11 and 3.5% per year escalation rate. Contingency to take into account the program risks is not included. The cost range estimate was made using inputs from US-LHC project, US-LARP Magnet R&D and FNAL HFM core program.

The 11 T dipole R&D is in progress at FNAL and CERN. Funds of 4M$ are needed to develop the 11 T dipole preliminary engineering design and fabricate and test two 2-m long twin aperture demonstrators in FY13, and then 5.5-m long dipole prototype in FY14. Additional funds of 1M$ are needed in FY15 to support the development and modification of critical infrastructure for the construction of 5.5 m long Nb3Sn dipole magnets.

Table. Cost estimate (w/o contingency).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **R&D, M$** | **Prototype, M$** | **Infrastructure, M$** | **LS2 (8D+1), M$** | **LS3 (8D+1), M$** | **Total, M$** |
| **FY13** | 2.0 |  |  |  |  | 2.0 |
| **FY14** |  | 2.0 |  |  |  | 2.0 |
| **FY15** |  |  | 1.0 | 5.2 |  | 6.2 |
| **FY16** |  |  |  | 13.7 |  | 13.7 |
| **FY17** |  |  |  | 5.4 |  | 5.4 |
| **FY18** |  |  |  |  | 5.7 | 5.7 |
| **FY19** |  |  |  |  | 15.2 | 15.2 |
| **FY20** |  |  |  |  | 5.9 | 5.9 |
| **FY21** |  |  |  |  |  |  |
| **Total** | 2.0 | 2.0 | 1.0 | 24.3 | 26.8 | 55.1 |

Possible scenarios:

1. Fabrication of 8+1(spare) dipoles for the partial collimation system upgrade during LS2. Project duration - FY15-FY17, total cost including R&D+Prototype and 40% contingency for Infrastructure+Production – 40 M$.
2. Fabrication of 16+2(spare) dipoles for the complete collimation system upgrade during LS2 and LS3. Project duration – FY15-FY20, total cost including R&D+Prototype and 40% contingency for Infrastructure+Production – 77 M$.