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Fermilab's SC Accelerator Magnet Program for Future U.S. HEP Facilities

Introduction

The invention of SC accelerator magnets in the 1970s opened wide the possibilities for advancing the energy frontier of particle accelerators, while limiting the machine circumference and reducing their energy consumption. The successful development of SC accelerator magnets based on NbTi superconductor have made possible a proton-antiproton collider (Tevatron) at Fermilab, an electron-proton collider (HERA) at DESY, a relativistic heavy ion collider (RHIC) at BNL and recently a proton-proton collider (LHC) at CERN. Further technological innovations and inventions are required as the US HEP looks forward towards the post-LHC energy or/and intensity frontiers. A strong, goal oriented national SC accelerator magnet program must take on this challenge to provide a strong base for the future of HEP in the U.S. The results and experience obtained by Fermilab during the past 30 years will allow us to play a leadership role in the SC accelerator magnet development in the U.S., in particular, focusing on magnets for a Muon Collider/Neutrino Factory [1]-[2]. In this paper, we summarize the required Muon Collider magnet needs and challenges, summarize the technology advances in the Fermilab accelerator magnet development over the past few years, and present and discuss our vision and long-term plans for these Fermilab-supported accelerator initiatives.

Muon Collider Magnet Needs and Challenges

While the HEP community eagerly anticipates the imminent full commissioning of the LHC and the subsequent reach into the HEP energy and mass frontier, plans are already being made for the LHC upgrades and the next generation of accelerators. Among the future energy/intensity frontier machines a Muon collider/Neutrino factory is seen at the present time as the most exciting option for the future of Fermilab as the lead HEP Lab in U.S.

Requirements for a Muon collider/ Neutrino factory pose significant challenges beyond the existing superconducting magnet technology. Three areas were singled out for Muon collider magnet R&D: a) large-aperture high-field NbTi or Nb_3Sn solenoids for 6-dimensional (6-D) muon beam cooling channel, b) ultra-high field HTS solenoids for final cooling; c) large aperture, high field collider dipole and quadrupole magnets with large operation margin with respect to beam and collision energy depositions.

a) 6-D cooling muon collider designs call for a 10^6 combined transverse and longitudinal emittance reduction. Because of the muon's very short lifetime, the muon cooling must be performed efficiently. While there have been several schemes proposed to accomplish this, the two primary ideas are a "FOFO Snake" which consists of tilted ~10 T solenoids combined with localized absorbers and RF cavities; and the Helical Cooling Channels (HCC) which consists of transversely offset ~8-15 T "helical solenoid" (HS) rings integrated with RF cavities filled with pressurized gas. The FOFO Snake is conceptually simpler and practically ready to build, while the HCC, being conceptually efficient in cooling, requires some R&D effort.

The major challenge for any 6-D cooling scheme is incorporating RF cavities for the longitudinal momentum regeneration. For the RF cavity in HCC, being directly exposed to the large (>5T) magnetic fields proposes a major challenge to its performances. For the HS magnets, the integration of a helical RF cavity into the magnet structure, i.e. the required magnet aperture to accommodate the cavity with adequate support structure and thermal insulation; the penetrations into the magnet structure to accommodate the RF feed throughs, etc., will have a deleterious effect on the magnetic field, which is tightly coupled to the magnet geometry. The relatively high operational field and stored energy will provide significant challenges for the magnet mechanical structure and its quench protection.

b) The final cooling stage prior to acceleration can be accomplished by a series of very high field solenoids. One proposed lattice contains six 1 meter long solenoids, of alternating polarity, interspersed with regenerating RF cavities. While the solenoid field strength requirement is not well defined, a 50 T bore field has been used in muon collider accelerator simulations. To minimize the power consumption during operation, it is hoped that such a magnet could be made from superconductors, either purely from HTS or a superconducting hybrid with HTS in the highest field regions.

Paper studies have demonstrated that the operation field of 50 T is extremely demanding requirement for HTS or HTS hybrid solenoids. The stress on the conductor during excitation is enormous, exceeding 1000 MPa. The price for adding structural support to intercept this stress is an increased SC engineering current density (Je). Thus the amount of HTS material and the solenoid cost at present Je values would be astronomical. It should be noted that a ~50 T solenoid with resistive inserts, and very high field resistive pulsed magnets have been successfully built. SC solenoids with lower field in the range of 20-30 T have been built or are proposed. What is needed is to develop a HTS-based conductor and technology which would lead to a cost effective high field solenoid (>30 T) with good field quality and operation margin that can be manufactured and operated at a reasonable cost.

c) muon beams of opposite charge are brought into collision through a colliding ring made of dipole and quadrupole magnets. Since all muons decay, the aperture must either be large to accommodate beam energy absorbers, or they must have an open mid-plane to allow the electrons to escape the helium volume.   IR magnets must accommodate the large decay deposition, as well as a wide aperture for the expected low beta. The present baseline design calls for "10 T" magnets, as this seems to be within reach of present technologies and is not considered to be technology limiting. However there is a direct correlation between magnets field and luminosity.   Stronger magnets mean smaller ring circumference and thus more collisions/muon lifetime. A 50% increase in field should translate in the 50% or more luminosity. Therefore, a long term goal would be to produce ~15 T large aperture dipoles and quadrupoles with high operation margins based on A15 commercial superconductors (Nb_3Sn or Nb_3Al).

The described magnets require innovative magnet design approaches, new superconducting and structural materials, advanced fabrication processes and quality control methods, etc.

Magnet R&D Plans

The midterm goal of the proposed accelerator magnet R&D program is to support the Fermilab and national efforts towards demonstrating the feasibility of a muon collider/neutrino factory. The long term goal is to support the building of this machine on the Fermilab site.   Note that many of the R&D tasks related to the high-field dipoles and quadrupoles will also be of direct benefit to the LHC IR and energy upgrades. To this end the follow 5-year programs are proposed or ongoing:

- Within 5 years, produce a 6-D cooling demonstration unit based on the FOFO Snake or, if necessary, on the HCC with a helical superconducting magnet system integrated with RF cavities. This program will demonstrate the technical feasibility and the production cost of the magnet system for 6-D muon beam cooling. The work will also include experimental studies of helical solenoid models to select and optimize superconductor and structural materials, magnet design and technology; RF cavity tests; design, fabrication and integration of helical solenoid and RF system. Design studies of the "far end" of a multistage HCC will be also performed in collaboration with Accelerator Physics Center (FNAL) and Muon Inc.
- Within 5 years, develop accelerator quality collider dipole and quadrupole models with an operating field up to 15 T, with provisions for passing or intercepting the muon beam decay by products. The work will include magnet conceptual design studies including calculations of magnet operation margins, model magnet R&D, and superconductor and structural material studies.
- The 5 year goal for the ultra-high field solenoid is focused on HTS-based conductor and solenoid technology development.   The work will also include the development of solenoid specifications and conceptual design studies. Conductor improvements will be centered on increased engineering current density, greater stress/strain tolerance, lower sensitivity to field orientation and reduction of cost.   As a charter member of the National HTS collaboration, whose initial goal is to improve the Bi 2212 round wire performance, we will contribute in development and study of Bi 2212 cables.   We will also continue to study the alternative HTS (YBCO) and LTS materials required for ultra-high field solenoids with hybrid coils.

Is a breakthrough possible?

The SC magnet program at Fermilab has a long history of successful development of advanced accelerator magnets based on NbTi superconductor starting from the Tevatron main ring, two interaction regions for CDF and D0, then dipole magnets for SSC and most recently, quadrupoles for the LHC Interaction Regions (IR). During the past ten years Fermilab's magnet R&D program has also made significant progress in advancing accelerator magnet technology based on Nb_3Sn superconductor. This program started in 1998 as a platform for developing accelerator quality 10-12 T arc dipoles for a Very Large Hadron Collider (VLHC). In 2003, the emphasis was shifted to support the US-LARP initiative for Nb_3Sn quadrupoles for a future LHC IR upgrade. Along the way Fermilab has contributed to several advances in Nb_3Sn accelerator magnet technology. The most important breakthroughs made at Fermilab include the development and demonstration of reliable and reproducible production-ready short and long coil fabrication technology, accelerator quality mechanical structures and coil pre-load techniques, high-performance Nb_3Sn strand and cables. While to date, there are no Nb_3Sn magnets in operation in any HEP accelerator, the abovementioned advances in technology make it possible **for the first time to seriously consider such magnets in any present or future accelerator.**

In the process of developing SC accelerator magnets, Fermilab has built a unique infrastructure for successful magnet R&D including a) world-class SC R&D laboratory for SC strand and cable characterization in magnetic fields up to 17 T and temperature range from superfluid helium to liquid nitrogen: b) a compact cabling machine which can produce up to 42 strand Rutherford cables; c) short and long coil winding, curing, reaction and epoxy impregnation tooling and equipment for magnet assembly; d) Magnet Test Facility with 4-m long vertical Dewar and up to 15-m long horizontal cryostat to test magnet models and prototypes in superfluid at 1.9 K and normal helium up to 4. 5 K, power supplies up to 30 kA and 400 channels of instrumentation. Skillful personnel including magnet scientists, engineers and technicians, and infrastructure with an adequate program funding provide a solid base for the success of the proposed programs.

What is the expected impact?

The Muon Collider requires significant advancements in superconducting magnet designs and technologies. The proposed magnet R&D program is a key part of the demonstration of Muon collider feasibility and will provide a solid foundation for its realization. Fermilab is arguably the only facility in the U.S. with the technical resources to lead such a multi-faceted program. The results of this program will also advance magnet technologies used in HEP (such as beam transfer lines and detector magnets) as well as in fusion, energy storage, material science, biology and medicine.

References

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[2] Steve Geer, Muon Colliders and Neutrino Factories, Annu. Rev. of Nucl. Part. Sci. 2009.59:347-65