Snowmass 2021 Letter of Interest

R&D of Very High Field Superconducting Magnets for a Muon Collider

Accelerator Frontier (AF), Multi-TeV Colliders (AF4)

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Introduction

High-field magnets have been and continue to be developed for a wide range of applications: in fundamental-physics, materials sciences, nuclear magnetic resonance (NMR), particle accelerators/detectors, and fusion reactors. Here we propose a program to develop innovative design concepts and enabling technologies for a very high-field (>30 T) solenoid superconducting magnet for high energy particle physics experiments.

Muon beams have a great potential for high-energy physics [1]–[4]. Over the past decades, there has been significant progress in innovative concepts and technologies needed to produce, capture, and accelerate sufficient muons, paving the way for construction of muon-based facilities such as muon colliders and neutrino factories. High-field solenoids are essential for these applications: 1) for confining the pions radially and guiding them into a decay channel; and 2) for the final cooling to achieve low transverse beam emittances (very high field). A high luminosity muon collider (e.g. 1.5 TeV) requires a very small transverse beam emittance of 25 µm, while it accepts 72 mm longitudinal emittance. This can be achieved by final cooling systems consisting of very high field, small bore solenoids, inside which the muons pass through liquid hydrogen absorbers. An optimized design study was performed earlier at the Brookhaven National Laboratory (BNL) based on a 40-T field to meet the required minimum transverse and longitudinal emittances [5], [6].

Very High Field Magnet State-of-the-Art

Various solenoid magnets have been developed to generate very high fields, leaving aside pulse magnets which can generate up to 100 T in milliseconds but are not practical for use in particle accelerators. Significant examples include:

1) Resistive (Bitter) magnet – NHMFL 41.5 T [7];
2) Hybrid (resistive/superconducting) magnet – NHMFL 45 T [8] and 45.5 T [9].
3) All superconducting magnets –NHMFL 32 T [10], IEE CAS 32.3 T [11], MIT FBML/PSFC 30.5 T (1.3-GHz NMR, to be completed 2022) [12];

Direct-current (DC) high magnetic fields over 40 T have been achieved by using a resistive bitter magnet alone or together with background/insert superconducting magnets. The world record DC magnetic field of 45.5 T mm at the National High Magnetic Field Laboratory (NHMFL) is composed of a 31.1-T resistive magnet and a 14.4-T REBCO insert with a 14-mm cold winding diameter. However, operation of these magnets requires a large amount of electric power (14–32 MW) and equivalent water cooling to remove the electric power. All-superconducting magnets, operating with almost zero power consumptions, are mandatory in HEP experiments. The maximum field, practically achievable by low-temperature superconductors (LTS), is <25 T because of their limit of field-dependent critical current (I_c). High-temperature superconductors (HTS) can carry sufficient current under very high field, enabling an all-superconducting magnet generating magnetic fields significantly exceeding 25 T; a design study has shown that even a 100-T all-REBCO DC magnet could be technically feasible [13]. In 2017, an all-superconducting 32-T, 34-mm cold-bore magnet that combined 15-T LTS background and 17-T HTS insert, was successfully tested at the

NHMFL [10]. Recently, the Institute of Electrical Engineering, Chinese Academy of Sciences (IEE CAS, China) reported reaching 32.35 T (15 T LTS background + 17.35 T HTS insert) with a 35-mm cold bore [11]. At the MIT Francis Bitter Magnet Laboratory (FBML)/Plasma Science and Fusion Center (PSFC), we have been developing a 1.3-GHz (30.5 T), 56-mm bore LTS/HTS NMR magnet [12], [14]. The 3-nested-coil 18 T HTS insert will be will be manufactured and combined with an existing 12.5 T LTS magnet and tested by 2022.

Our Proposals to Address Technical Challenges of Very High Field Solenoids

Recent achievements of >30 T all-superconducting magnet together with continued improvements in HTS conductor performance, gives confidence that we can move forward in realistically achieving >30-T fields. Based on this belief, we propose an R&D program focused on development of an all superconducting solenoid magnet in the 30–50 T range. The program will be focused on resolving significant technical challenges of HTS magnets, that we have learned from our experience, including:

1) **HTS conductor** – superconducting magnet design is strongly dependent on conductor properties, current-carrying capacity, electromagnetic, mechanical, thermal, dimensional tolerances. However, there still exist uncertainties even in the commercial product HTS conductors, which may affect the entire magnet performance, such as non-uniform I_c (B, θ), irregular thickness, bonding strength against delamination. Also, the quality and the price are strongly dependent on manufacturers.
2) **Screening-current-induced stress** – most high-field HTS magnet designs are limited by the maximum allowable stress/strain level. Screening currents, induced in the REBCO layer by a time-varying field, not only affect the center field intensity but also, and more seriously, generate a magnetic torque along the conductor, thus causing an additional stress. Field-shaking, I_{op} or T_{op} control methods can be used to reduce screening currents [15]–[17].
3) **I_c degradation by thermal or operation cycles** – there have been several reported HTS magnets degraded during thermal cycles and/or operation cycles, caused by delamination of the superconducting layer [18], [19].
4) **Quench protection** – It is very difficult to detect an early stage of quench in an HTS magnet because of very slow normal zone propagation and low signal at voltage taps. There has been recent work both in optical fiber based and acoustic based quench detection methods [20]. Another significant challenge is to dissipate the stored energy quickly either within the magnet itself and/or in external dump resistors We will explore using AC fields for rapidly and uniformly quenching the superconductor [21].
5) **Cost effective engineering design** – It is challenging to design HTS magnets that are practical and cost-effective. New and innovative ideas, such as the No Insulation (NI) winding technique [22] needs to be investigated for design optimization and compared with conventional methods to increase performance and safety while reducing costs.
6) **Liquid-hydrogen absorber integrated with magnet cooling** – We also propose studying the possibility of integrating the 20 K liquid hydrogen absorber required for the muon collider final cooling system, directly into the magnet system bore.

Summary

Based on our accumulated knowledge and experience in high-field HTS magnet/cryogenic technologies we are poised to design a viable very high field (>30 T) solenoid magnet for the final cooling channel in muon colliders or any other advanced HEP experiments. Apart from this, our HTS magnet/cryogenic R&D can include other high field magnets, essential for particle accelerators and many other experiments for high energy and nuclear physics such as >15-T large-bore for muon collider 6D cooling, >20-T large-bore Axion dark matter experiments, and ALPHA-g experiments. We are also prepared to explore compact, cost-effective high-field (<25 T) all-HTS magnet operating at or above 10 K without using liquid helium [23].

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