High field superconducting accelerator magnet technologies based on Bi-2212 high-temperature superconductor for future accelerator facilities

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[Why Bi-2212?] The development of high-temperature superconducting magnets for frontier particle physics colliders was endorsed by the 2014 P5 report and its 2015 accelerator R&D subpanel report and recently again by the 2020 update of European strategy for particle physics. High temperature superconductors (HTS) can generate magnetic fields of 45 T at 4.2 K, nearly two times of the ~23 T limit of two Nb-based superconductors; they also have many applications in other fields of science. Since the early 2000s, progress have been made with developing accelerator magnet technologies with two HTS, REBCO coated conductors and Bi-2212 round wires. Using REBCO coated conductors, CERN has pursued an aligned block dipole design based on a ROEBEL cable assembled from cut REBCO tapes [1], whereas LBNL, within the US magnet development program (MDP) [2], has been developing a canted cosine theta dipole based and traditional cosine theta dipoles both based on CORC®, a round cable made with helically winding REBCO tapes around a Cu core [3].

Bi-2212 is the only high-T_c cuprate material available as an isotropic, twisted, multifilamentary round wire [4]. Commercial wires are available with a diameter that ranges from 0.6 mm to 1.5 mm and a piece length of 2 km (0.8 mm Ø). Bi-2212 wires can thus be made into long-length Rutherford cables, a flat rectangular cable composed of wires twisted and transposed to ensure uniform current distribution between strands within the cable for delivering accelerator field quality, and therefore permit fabrication of magnet geometries developed for the Nb-Ti and Nb_3Sn magnets, including block-type, cosine theta, canted cosine theta (CCT) [5,6], and a recently developed stress management cosine theta [7]. Being a multifilamentary round wire with small magnetization, it also has a strong potential for building >23 T solenoid magnets needed by the >1 GHz NMR magnets. A separated LOI on Bi-2212 solenoid technologies is also submitted to the Snowmass 2021 [8]. *With this letter, we are expressing our interest to develop Bi-2212 accelerator magnet technology, with the 20 T accelerator dipole as a driving goal.*

[Status and opportunities] Since 2016, the development of Bi-2212 accelerator magnet technology has been led by the U.S. MDP [9]. Building on the development of a new overpressure processing at the National High Magnetic Field Laboratory (NHMFL) in 2012 and leveraging an academia, industry, and national lab partnership to develop a new precursor powder, US MDP in 2017 improved the J_E of best Bi-2212 wires by ~60% to 1000 A/mm^2 at 4.2 K and 27 T [10,11]. From 2015 to 2020, the Berkeley lab (LBNL) in collaboration with NHMFL and wire industry, using racetrack coils and CCT as R&D vehicles, has gained experience with Bi-2212 coil fabrication. Applying the overpressure processing and using the new generation of wires, LBNL quadrupled the quench current in their racetrack coils fabricated to 8.6 kA (with a 3.5 T field) using 17-strand Rutherford cables [11,12]. Three CCT coils were fabricated and tested and their field quality was modeled and measured. The most recent CCT coil BIN5a, which used a 9-strand Rutherford cable, achieved 4.1 kA with a dipole field of 1.4 T [13]. Importantly, none of the racetrack coils and CCT coils, either with or without epoxy impregnation, showed quench training and their quench initiation was predictable. The improved conductor technology, fabrication experience gained, and new magnet designs provide an opportunity to add Bi-2212 as a new high-field (>15 T), potentially quench training free accelerator magnet technology.

[Critical questions being addressed by the U.S. MDP roadmap 2020] The updated US MDP program plan for Bi-2212 magnets in the 2020-2024 includes the design and fabrication of CCT magnets with increasing field generation capability at LBNL, and explore prototype coil fabrication using the new stress management cosine-theta (SMCT) dipole concept at Fermilab [14]. A challenge with Bi-2212 accelerator magnet engineering is that its ability to handle transverse pressure is insufficient for building 20 T cosine-theta accelerator dipole magnets. The critical transverse pressure of a Bi-2212 Rutherford cable was determined to be 130-140 MPa by an experiment at the University of Twente [15]. The CCT and SMCT designs utilize a similar philosophy to transfer the Lorentz forces from conductors to the mandrel structure, thus preventing the transverse pressure to cable from accumulating to a dangerous level [16]. Both designs are based on Rutherford cables of Bi-2212 and Fermilab and LBNL will collaborate on improving the Rutherford cable engineering but their design and fabrication also set them apart.

A challenge is that overpressure processing is a delicate step of the coil fabrication and the coil current fails to reach the target if it's not performed properly. Prototype coils so far are relatively short in length. Multiple 1 m long CCT magnets will be fabricated to address this concern. This effort leverages the construction of an over-pressure furnace (Renegade) with a 25 cm diameter 1 m long hot zone at the NHMFL based upon the experience with the existing Deltech furnace (14 cm Ø x 44 cm). By 2024, multiple 1 m long, CCT/SMCT Bi-2212 accelerator magnet dipoles will be built. Magnets will be tested alone; the goal is to generate a dipole field ≥5 T. Field quality will be measured and modeled.

Both CCT and SMCT will be tested in a background field of Nb_3Sn magnets to examine the Nb_3Sn/HTS hybrid magnet technology, including the degree of mechanical coupling, quench detection and protection, the ability of the cable to handle transverse pressure at various stages of magnet fabrication, materials compatibility and selections, and field quality. The goal is that by 2024 Nb_3Sn/Bi-2212 hybrid dipole achieves magnetic fields above 14.5 T, the record field Fermilab recently achieved with a 4-layer Nb_3Sn cosine-theta dipole[17]. This requires a high-field Nb_3Sn/HTS hybrid magnet test facility with a large bore Nb_3Sn dipole magnet. An 11 T, 120 mm bore Nb_3Sn magnet will be constructed by the US MDP for this purpose. These work will help answer these question: (1) How to mechanically assemble Nb_3Sn/Bi-2212 hybrid magnets? (2) Can the accelerator field quality be achieved in hybrid Nb_3Sn/Bi-2212 magnets? (3) Will 16 T class Nb_3Sn/Bi-2212 hybrid accelerator magnets be free of quench training? If no, how to protect Bi-2212 and hybrid Nb_3Sn/Bi-2212 accelerator magnets against quenches, in the limit of zero normal zone propagation velocity in Bi-2212 coils?

[Longer term prospects] By 2025, the field of the Nb_3Sn/Bi-2212 hybrid magnet (50 mm bore) will unlikely go beyond 16 T. We feel that the appropriate goal for 2025-2030 is to demonstrate 20 T Bi-2212 dipoles for particle physics colliders. To achieve this goal, importantly continuous wire improvement is needed, with the wire J_E reliably achieved in coils as the yardstick. An appropriate goal is to improve it to 1000 A/mm^2 at 4.2 K and 20 T. Currently, the best wire J_E (4.2 K, 20 T) achieved in Bi-2212 Rutherford cable coils is ~600 A/mm^2 (extrapolated) in the LBNL RC5/RC6. Continuous conductor improvement is important for making magnet fabrication more robust, increase field generation efficiency, and reduce magnet costs. The critical current density of the best wire so far only achieves <1% of the fundamental material limit, the depinning current density. Moreover, all the above listed technical questions for the US MDP magnets will be needed to be reexamined for the 20 T dipole. Can the coil fabrication be scaled up to 5-10 m long? What are the best tooling materials to use considering the stress in a 20 T dipole magnet and compatibility with Bi-2212 wires during overpressure processing? What is the maximum transverse stress allowed for Bi-2212 coils at any of their fabrication steps and operation? The Rutherford cable in LBNL coils has a relatively low packing factor of <82%. Can it be increased to 90%? What is the cost of building 20 T Nb_3Sn/Bi-2212 accelerator dipoles and how can it be reduced?

[Summary] With the recently improved Bi-2212 wires and two stress management magnet design concepts (CCT and SMCT), an opportunity is present to add Bi-2212 as a new high-field (>15 T), potentially quench training free accelerator magnet technology. This LOI outlines the present status, our approaches, critical questions this research program intends to address, and invite collaborations.

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