Title: Development of next-generation Nb_3Sn superconductors for energy-frontier circular colliders

Principle Investigator Name & Job Title: Xingchen Xu, Peoples Fellow
Institution: Fermi National Accelerator Laboratory
PI Phone Number & Email Address: 630-840-8388, xxu@fnal.gov
Year Doctorate Awarded: 2016

Number of Times Previously Applied: 1
Topic Area: Accelerator Science and Technology Research & Development, High Energy Physics
DOE National Laboratory Announcement Number: **LAB 19-2019**

Objectives

This project aims to develop a new generation of Nb_3Sn superconductors for accelerator magnets.

As pointed out by the P5 report, "*A very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window*". The present record of particle collision energy is 13 TeV, achieved by the Large Hadron Collider (LHC). Further push of the energy frontier requires improvement of magnetic field (B, in T), as particle energy (E, in TeV) $\approx 0.3R \bullet B$, where R (in km) is the radius of a circular accelerator. This is endorsed by the P5 Strategic Plan, Recommendation 24: "*Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.*" This need was substantially reiterated in the HEPAP Accelerator R&D subpanel report.

Nb_3Sn is a workhorse superconductor for building the magnets for the next energy-frontier p-p circular collider (*e.g.*, the planned Future Circular Collider – FCC, which plans to reach 100 TeV collision energy). As stated by the FCC design study report [1], "*The key technology R&D for the FCC-hh comprises superconductor (SC) development and high-field magnet design.* ***Nb_3Sn is one of the major cost & performance factors for FCC-hh and requires highest attention.***" However, the properties of present state-of-the-art Nb_3Sn superconductors are insufficient for building magnets with very high fields (*e.g.*, 16 T required by FCC). This is a top technical challenge for the magnets and the whole collider [2]. Developing high-field Nb_3Sn magnets requires significant improvement of the following two properties:

(1) Critical current density (J_c). The magnetic field B generated by a coil is mainly determined by the coil size and electric current density in the coil (J_{coil}), which is limited by the J_c of superconductors. Because the cost for fabricating magnets increases sharply with coil size, higher field requires higher conductor J_c. Taking the planned FCC for example, to keep coil size within a reasonable range, it requires Nb_3Sn J_c to be at least 50% higher than what the present state of the art can deliver [1]. Without such a 50% J_c improvement, the amount of Nb_3Sn conductors needed to achieve the targeted 16 T has to be nearly doubled (from the baseline 8000 tonnes [1]), causing an increase of project cost by billions of U.S. dollars, along with other important issues. There is no doubt that improving J_c of Nb_3Sn superconductors is one of the key challenges for future high-energy circular colliders. On the other hand, the record J_c of Nb_3Sn has plateaued since the early 2000s; extensive efforts have been made since then to improve the record J_c, but with no success. Clearly, a revolutionary technique is needed to further improve Nb_3Sn J_c.

(2) Stability. On one hand, Nb_3Sn conductors in operating magnets are exposed to perturbations such as conductor motions or epoxy cracking which generate heat and may cause conductors and the whole magnets to quench (i.e., suddenly become resistive). Present Nb_3Sn dipole and quadrupole magnets normally quench long before reaching their conductor critical currents and designed fields. The reached currents and fields can increase gradually by quenching the magnets for a number of times (which is termed "training"), but training is a very slow and costly process for Nb_3Sn magnets. For a real collider such as FCC or HE-LHC, this requires either high cost and long time for training all the magnets, or use of a large margin for magnet design, which again transfers to high cost if a certain field (e.g., 16 T) is to be reached. The Goal 1 of the U.S. Magnet Development Program (MDP) comprises "*significantly reducing or eliminating training*" of Nb_3Sn accelerator magnets. On the other hand, Nb_3Sn conductors are intrinsically unstable: for example, at low fields they may have flux jumps and may quench even without

external perturbations when carrying transport current. Higher J_c would make conductors more intrinsically unstable, thus requiring more attention to the stability issue.

Technical Approaches

The Principle Investigator (PI) of this proposal aims to significantly improve the above two properties of Nb_3Sn conductors with the following two promising innovative techniques.

(1) J_c. For Nb_3Sn superconductor, higher J_c requires more fluxon pinning centers such as grain boundaries (which means smaller Nb_3Sn grain size leads to higher J_c). Significant efforts have been made in this area since the 1980s to introduce additional pinning centers, but without success. This was finally realized by applying the internal oxidation method in Nb_3Sn wires by the PI [3], which forms ZrO_2 particles (with size of 1-10 nanometers) in Nb_3Sn by internally oxidizing Nb-1%Zr. Results on proof-of-principle wires have shown that this technique can refine grain size by half and triple the Nb_3Sn layer J_c at 15-20 T in wires with Ta dopant, and it also leads to other important features, such as shift of pinning force peak, indicating that ZrO_2 particles serve as new pinning centers. Preliminary results on prototype conductors have demonstrated J_c values 50% higher than present state of the art. These results show that this novel technique is very promising to make a new type of Nb_3Sn conductors with much higher J_c. This project aims to further optimize this new technique and transform it to practical magnet-grade conductors.

(2) Stability. An important reason for instability of Nb_3Sn conductors is their low specific heat (C, J/m^3-K) at the operational temperatures (1.9-4.5 K), as temperature rise equals to Q/C, where Q is heat (in J/m^3). Because it is impossible to avoid all heat perturbations during magnet operation, improving C of conductors is one of the most promising approaches to improving magnet stability. This can be done via addition of substances with extremely large specific heat (*e.g.*, Gd_2O_3, whose C is hundreds of times higher than those of Cu and Nb_3Sn at 1.9-4.5 K). Recently the PI came up with a design to realize this in practical Nb_3Sn superconductors [4]. The structure of wires is prudently modified in a way that is well compatible with present manufacturing technology without affecting J_c or other properties. Measured results of proof-of-principle Nb_3Sn conductors based on the new technique demonstrated significantly improved intrinsic stability as well as energy margin in comparison with standard Nb_3Sn conductors [4]. This project aims to further optimize this new type of Nb_3Sn conductors to make this technique more effective, transform it to practical magnet-grade conductors, and explore its effects in magnets.

Finally, this project will combine the above two techniques and aim to deliver a new generation of Nb_3Sn superconductors, which not only have high J_c (at least 50% higher than present state of the art), but also are more stable. The fundamental mechanisms for the improvements and other potential chances will also be explored. If successful, this will be a key enabling technology for any future energy-frontier p-p circular colliders (such as HE-LHC or FCC), and will also reduce their costs by billions of dollars.

[1] M. Benedikt, F. Zimmermann, “Status of the Future Circular Collider Study”, CERN-ACC-2016-0331

[2] CERN, “FCC-hh Conceptual Design Report”, Dec. 2018, https://fcc-cdr.web.cern.ch/

[3] X. Xu et al., “Ternary Nb_3Sn conductors with artificial pinning centers and high upper critical fields”, *Supercond. Sci. Technol.* **32,** 02LT01, 2019

[4] X. Xu, P. Li, A. V. Zlobin and X. Peng, “Improvement of Stability of Nb_3Sn Superconductors by Introducing High Specific Heat Substances”, *Supercond. Sci. Technol.* **31,** 03LT02, 2018

Title: Development of next-generation Nb_3Sn superconductors for energy-frontier circular colliders
Principle Investigator Name & Job Title: Xingchen Xu, Peoples Fellow
Institution: Fermi National Accelerator Laboratory
PI Phone Number & Email Address: 630-840-8388, xxu@fnal.gov
Year Doctorate Awarded: 2016
Number of Times Previously Applied: 1
Topic Area: Accelerator Science and Technology Research & Development, High Energy Physics
DOE National Laboratory Announcement Number: **LAB 19-2019**

PI's Collaborators and Co-editors:

Last name	First name	Affiliation
Chiesa	Luisa	Tufts University
Collings	Edward	The Ohio State University
Cooley	Lance	Florida State University
Dietderich	Dan	Lawrence Berkley National Laboratory
Gourlay	Stephen	Lawrence Berkley National Laboratory
Kovacs	Chris	The Ohio State University
Majoros	Milan	The Ohio State University
Marchevsky	Maxim	Lawrence Berkley National Laboratory
Peng	Xuan	Hyper Tech Research Inc.
Rochester	Jacob	The Ohio State University
Sabbi	Gianluca	Lawrence Berkley National Laboratory
Sumption	Michael	The Ohio State University
Tomsic	Mike	Hyper Tech Research Inc.
Wang	Xiaorong	Lawrence Berkley National Laboratory
Zeller	Al	Michigan State University

PI's Graduate and Postdoctoral Advisors and Advisees:

Last name	First name	Affiliation
Akbar	Sheikh	The Ohio State University
Fraser	Hamish	The Ohio State University
Sumption	Michael	The Ohio State University