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THE NEED FOR Nb_3Sn COATED Cu CAVITIES FOR FUTURE ACCELERATORS *

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Abstract

Based on current efforts in the U.S. on the novel concept of parallel-feed RF accelerator structures made of Cu, and in the U.S. and abroad in producing Nb_3Sn films on either Cu or bronze, we recommend that the Particle Physics community foster R&D in Superconducting Nb_3Sn coated Cu RF Cavities instead of costly bulk Nb. The paper includes methods to process the coated cavities at temperatures consistent with Cu retaining its shape. A devoted global effort in developing Cu cavity structures coated with Nb_3Sn would make the ILC or Higgs factories more affordable and more likely to be built. Not only do parallel-feed RF structures enable both higher accelerating gradients and higher efficiencies, but they would be applicable to both Cu and Nb_3Sn coated Cu cells. Increased effort on these two techniques would synergize expenditures towards progress, which will converge on the choice of technology for the RF of an ILC or any future accelerator. The current methods of Nb_3Sn coatings on Cu or bronze can be geared also towards standard cavity cells. In conclusion, the use of distributed coupling structure topology within improved performance parameters together with Nb_3Sn coating technology can lead to a paradigm shift for superconducting linacs, with higher gradient, higher temperature of operation, and reduced overall costs for any future collider.

INTRODUCTION

For a majority of particle accelerators and/or colliders, a large fraction of the capital cost is in the superconducting and heavily processed bulk Nb SRF cavities. The need of a cryogenic plant required to cool these cavities down to 2 K superfluid helium impacts the operational cost too.

Since the decision in 2003 of the International Technology Recommendation Panel (ITRP) to focus on SRF, the technology in Normal-Conducting RF (NCRF) has made considerable progress [1], achieving linac gradients exceeding 160 MV/m with cryo-cooled Cu. C3 is a concept that is aimed at developing NCRF accelerator technology to operate at high gradient with high RF-to-beam efficiency. The two principal innovations for the C3 concept are: (1) the use of highly-optimized reentrant cells with distributed coupling to power the linac without cell-to-cell RF coupling, and (2) the operation of the Cu accelerating structure at liquid nitrogen temperatures (77~K). The necessary structure is machined in two halves (see Figure 1).

SRF cavities with a thin layer of Nb_3Sn coated onto their inner surface should produce accelerating gradients on the order of 100 MV/m, twice that expected for Nb cavities. With a T_{c0} double that of Nb, they also deliver a cavity quality factor Q_0 about 30 times larger than for Nb cavities. The larger T_{c0} of Nb_3Sn has also the advantage of allowing the cavities to operate at 4.5 K rather than in superfluid helium at 2 K that is used for bulk Nb cavities to obtain a higher gradient. With Nb as one of the main cost drivers of SRFs, producing Nb_3Sn through chemical electrodeposition on inexpensive and thermally efficient metals such as Cu or bronze, while pursuing in parallel the novel U.S. concept of parallel-feed RF accelerator structures, would enable colliders with higher gradient, higher temperature of operation, and reduced overall costs. This cannot be achieved with the Sn vapor diffusion process, which is carried out at a temperature of ~1100°C, i.e. higher than Cu melting point. A technology that synergistically uses the aforementioned advanced tools would make an ILC or equivalent machines more affordable and more likely to be built, it would readily apply to other HEP machines, such as Higgs Factories and Muon Colliders, and to accelerators beyond HEP. It is essential to bridge the gap on the basic research that is needed to integrate distributed coupling structure topology within improved performance parameters with Nb_3Sn coating technology [2].

GOALS

To achieve the described vision, progress in materials science has to be combined with synthesis and modeling to enable advanced manufacturing and novel chemical processes for Superconducting Radiofrequency Cavities (SRF). Any scientific understanding and know-how acquired can be promptly applied to regular Cu elliptical cavities.

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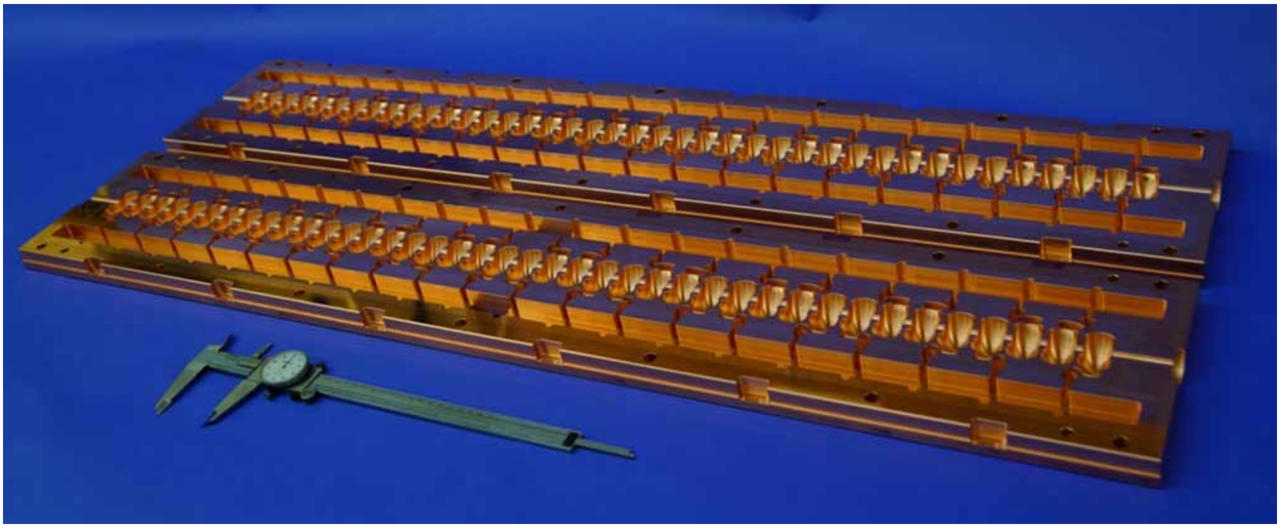

Figure 1: Meter-scale prototype of Cu C3 structure.

Superconducting Nb_3Sn with A15 crystalline structure is formed through solid diffusion of the Sn into the Nb. In the presence of Cu as ternary element, the maximum temperature needed for Nb_3Sn formation is easily less than 700°C. When Cu is not present in the system, as for instance in the Sn vapor diffusion process, the temperature required from the binary phase diagram is much higher.

An electroplating technique to coat Nb surfaces with Cu and Sn layers from aqueous solutions and produce Nb_3Sn below 700°C was developed and made reproducible at FNAL in 2016-2018. In electro-chemical deposition the metallic coating is deposited on another metal surface through an electrolyte solution. The metal to be plated acts as the cathode and when the appropriate current is applied, positively charged ions traveling from the anode into the solution will discharge and get deposited on the cathode until a film of desired thickness is formed. First, using the Nb as cathode and a Cu anode, a thin seed layer of Cu is deposited in an acid solution. The Cu lowers the formation temperature for the A15 compound and suppresses the unwanted $NbSn_2$ and Nb_6Sn_5 phases. In a second electroplating step, the resulting Nb/Cu sample is used as cathode, and a thick layer of Sn is deposited with a Sn anode within a commercial Sn-rich solution. And finally, on the resulting Nb/Cu/Sn sample, a Cu layer is again deposited using a Cu anode. Each electrodeposition step is carried out at near room temperature and at atmospheric pressure [3]. Nb_3Sn is then formed through solid diffusion by heat treating the multi-layered samples in inert atmosphere (argon) at a maximum temperature of 700°C. After reaction, the Cu and bronze phases formed on the outer surface of the Nb_3Sn are removed with aqua regia.

A goal of this proposal is to implement this electroplating technique on Cu surfaces after sputtering them with Nb by using magnetron systems or an electron-beam evaporation and ion-plating apparatus. The advantages of electro-deposition are its simplicity, accurate control, and low cost.

As mentioned, a key innovation for the C3 concept is the use of highly-optimized reentrant cells with distributed coupling to power the linac without cell-to-cell RF coupling. The necessary structure is machined in two halves by low-cost numerically-controlled milling machines. This machining process produces ultra-high vacuum (UHV) quality surfaces that need no further machining before a standard Cu surface etch. This manufacturing technique provides an ideal Cu surface to be coated with superconducting films, as it allows complete access to the inner cavity surface for the coating process. After coating, the system is then assembled by joining the two blocks. Clamped structures can be used to confirm the performance of the geometry and coatings first. In the split geometry there are no currents crossing the gap so a bond is not necessary. Electron beam welding has to be explored for a more confined vacuum space. Brazing and diffusion bonding are traditional methods to join these cavities but they require high temperatures and long holding times which will negatively impact the Nb_3Sn coating, whereas electron beam welding will only have a localized heat input in the joint area.

Key gaps in basic research that have been identified include 1). Characterization of the electrochemical coating process and characterization of the resultant coating; 2). Local joint area effects on C3 split-cell interface material and the Nb_3Sn coating due to heating from the joining process; 3). Local joint area effects on the chemistry, microstructure, and superconductivity of the Nb_3Sn coating due to electron beam welding; 4). Characterization of thickness, roughness, purity, porosity, and adhesion of Nb substrate coated on Cu which enables electrochemical coating of Nb_3Sn; 5). Effect of the coating and electron beam welding processes on the superconducting properties of the cavity. Relevant key technology areas include materials and chemistry, physics and engineering, computing and data.

METHODS

This research proposal was developed by a team of three U.S. national labs, a Japanese institution, two industries and one university, i.e. FNAL, SLAC, JLAB, NIMS and OSU leverage the expertise and facilities to develop, test, and validate experimental designs, results, and prototypes. The transition to commercialization will be accelerated by the technology transfer to and from Faraday Technology, Inc. and RadiaBeam Technologies, LLC. With the extensive characterization facilities of its Superconducting R&D lab and SRF

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expertise, FNAL can provide the testbed for the cryogenic testing of the novel SRF cavities. The activities currently proposed for a successful fabrication, plating, heat treatment and welding of a prototype structure at C-band and of regular Cu elliptical cavities are as follows.

FNAL

This lab is well equipped for characterization and testing of superconducting samples, and for cryogenic testing of Nb_3Sn coated SRF cavities. Superconducting samples are characterized by transport test of critical current $I_c(B)$ up to 15 T to determine the upper critical magnetic field as a free parameter in the $I_c(B)$ data fitting, and resistive and inductive measurements of critical temperature T_{c0}.

SLAC

Among this lab's expertise is the study of different distributed coupling topologies for various phase advance cavities (180°, 135°, 120° etc.) in relation to several manufacturing plans (two-split blocks, multi-split blocks, stacking turned parts along the axis etc.) from the perspective of various Nb_3Sn coating techniques.

NIMS

Superconducting samples are characterized with Scanning Electron Microscope (SEM) and Electron Probe Microanalysis (EPMA), and SQUID measurements of the lower critical field H_{c1}(4.2K).

OSU

OSU is well prepared to characterize process and properties of the materials required for downstream electrochemical deposition; to characterize process, joint microstructure, and superconductivity of electron beam welding of Cu coated with Sn-Nb-Nb_3Sn and similar layered coating structures; to develop thermomechanical models of joining process; to use this fundamental knowledge in partnership with the team to coat and assemble a prototype cavity to enable testing of SRF properties.

Faraday Technology

This company has been producing Nb_3Sn coating through electrodeposition on flat samples, and it can scale-up the process and apply it to C3 prototypes. Further studies will include: 1). Effect of Nb and/or Cu surface cleaning conditioning procedure on Cu/Sn/CuP adherence through thermal treatment to produce Nb_3Sn; 2). Models to predict electrodeposition tooling to apply uniform Cn/Sn/CuP layers to shapes like the C3 prototype; 3). Development of tooling to apply Cu/Sn/CuP to C3 prototype; and 4). Demonstration of Cu/Sn/CuP application onto C3 prototype.

RadiaBeam

This company can design a clamped (weld free) split-cell testbed, including conduction cooling to the liquid helium bath and fundamental power coupler; fabrication of clamped split-cell Cu substrates following high gradient NCRF best practices.

JLAB

This lab can supply small Cu elliptical cavities, e.g. 3 GHz, to quickly apply the developed coating and reaction processes. It can also contribute to the design optimization of Nb_3Sn cavities and use the developed methods to optimized cavity geometries. This lab is ready to perform cryogenic tests of the above.

Other

C3 prototype structures made of Cu will be fabricated by U.S. vendors. The sputtering of Nb on Cu surfaces will be performed by NIMS or by U.S. vendors.

CONCLUSION

High gradient, inexpensive superconducting cavities (SRF) will be needed for future accelerators. However, the accelerating field of Nb cavities is limited by the peak magnetic field on the cavity surface. Nb_3Sn SRF cavities should produce larger accelerating gradients and a larger quality factor, Q_0, than Nb cavities. Also, the higher T_{c0} of Nb_3Sn allows cavities to operate at 4.5 K rather than ~2 K that is used for Nb cavities to obtain a higher gradient. This yields less expensive refrigeration and more cryogenic reliability.

Nb_3Sn coated SRF cavities, with Nb_3Sn produced by Sn vapor diffusion followed by a thermal reaction at very high temperature, have achieved only a fraction of the theoretical predicted gradient. In addition, this process cannot be used on Cu RF cavities as it requires ~1100°C, which is higher than Cu melting point. Methods of Nb_3Sn coating on Cu (or bronze) should be pursued instead. Whereas these processes are scalable in principle to standard cavity cells, the open-faced Cu RF structures developed at SLAC are the ideal Cu surfaces for coating with superconducting films, since they allow complete access to the inner cavity surface for the coating process, before joining the two half- blocks. Much more progress with respect to that achieved could be made if focus by the funding agencies were on methods that are promising for coating Cu or bronze with Nb_3Sn. With appropriate support, it is extremely likely that these R&D approaches will succeed and be available by the same time as the novel concept of parallel-feed RF accelerator structures. A technology that synergistically uses both of these advanced tools would deliver higher gradient and higher temperature of operation and reduce the overall capital and operational costs of any future particle collider and/or accelerator.

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