An Innovative Nb_3Sn-Based Approach for Superconducting RF Cavities

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Abstract: The development of high-gradient superconducting RF (SRF) is important for the advancement of the next generation of particle accelerators. With the majority of SRF cavities using niobium (Nb), this research proposes to exploit niobium-three-tin (Nb_3Sn). Nb_3Sn has a quality factor Q_0 at 4.2K that is 30 times larger than Nb, which is currently operated at 2K, and can be used in liquid rather than superfluid helium, with substantial savings in operation costs. This feature alone would make Nb_3Sn the SRF material of choice for light sources, but, in addition, the theoretical accelerating gradient of Nb_3Sn is expected to be double that of Nb. If this were indeed achieved, linear high energy accelerators would become possible at half the cost. An electro-chemical technique to coat either Nb or copper (Cu) 3D surfaces with Nb_3Sn for SRF and superconducting shielding applications was developed and made reproducible at FNAL in the last couple of years [1]. The proposed technique is innovative with respect to the decade-long vapor deposition approach to coat just Nb. It uses electroplating, which was originally developed for industrial large bulk applications and is among the most inexpensive technological processes. It was also already proven on flat and cylindrical samples. This research offers to apply the technique to more complex 3D surfaces as well as actual SRF Nb and Cu cavities.

Background

The two most important aspects in evaluating SRF performance are the quality factor Q_0 and the accelerating field. The accelerating gradient in SRF cavities is proportional to the peak magnetic field on the cavity wall, which is itself limited by the metastable superheating field. The expected theoretical value of the latter is 0.42 T for Nb_3Sn as compared to 0.25 T for Nb. The larger critical temperature T_{c0} of 18K for Nb_3Sn as compared to 9.2K for Nb also allows the cavities to operate at 4.5K rather than at the typical superfluid helium temperature of 2K used for Nb. This translates to large refrigeration saving and more cryogenic economy and reliability. Nb_3Sn coated SRF cavities produced by the vapor diffusion process followed by thermal reaction at temperatures up to 1300°C have been demonstrated to improve Q_0, but have produced just 20% of the theoretically expected gradient. The vapor deposition technique is not easily scalable to multicell SRF assemblies, and presently not feasible even for light sources applications.

Past Results

In this call, an alternate, novel electro-chemical technique to produce Nb_3Sn films on Nb substrates is proposed. This technique was developed and made reproducible at FNAL, where an electro-chemical lab was designed, procured and commissioned, using $20K/year since 2016 from within a U.S.-Japan Science and Technology Cooperation Program in HEP. The Nb_3Sn phase is obtained by electrodeposition from acqueous solutions of Sn layers and Cu intermediate layers onto Nb substrates. The electroplating is performed at near room temperature and atmospheric pressure. Subsequent thermal treatments in inert atmosphere are realized at a maximum temperature of 700°C to obtain the Nb_3Sn superconducting phase.

Dozens of superconducting Nb_3Sn films were obtained on Nb substrates by studying and optimizing the parameters of the electro-plating process. Samples were characterized at FNAL, but also at JLAB, NIMS and KEK. This included Scanning Electron Microscope (SEM) and Electron Probe Microanalysis (EPMA), transport test of critical current $I_c(B)$ up to 14 T to determine the upper critical magnetic field as a free parameter in the $I_c(B)$ data fitting, resistive and inductive critical temperature T_{c0}, as well as SQUID measurements of the lower critical field $H_{c1}(4.2K)$. The T_{c0} results obtained using a resistance and a SQUID measurement were compared for several samples. The results were remarkably consistent, with T_{c0} values of 17.5K or larger regularly achieved. For all samples, an upper critical magnetic field of 23 T or larger was obtained [2]. No Cu was detected in the Nb_3Sn, as the Cu diffuses through the Sn away from the Nb.

The electroplating technique was also scaled-up to 3D surfaces using simple Nb cylinders of one-inch diameter, obtained by shaping 0.3 mm thick Nb sheets. The anode diameter was 1 cm [3]. Adequate current densities, deposition times, and pulse frequencies were searched for, until the process was successful.

Goals of this Proposal

The advantages of electrodeposition are simplicity, low cost, and especially accurate control. The process can be performed on any 3D surface, such as the inner surface of SRF cavities. Its excellent control should also provide a more homogenous Nb_3Sn coating than in vapor deposition. Improving the quality of the Nb_3Sn could reduce the large gap between the theoretical and measured metastable superheating field. This is vital to achieve the expected double accelerating gradient. Electrochemical techniques may also eliminate the problem of low Sn concentration at the Nb interface, which is a fundamental limit of current vapor deposition.

Using the best developed techniques and acquired know-how, the complete process will be implemented on single-cell Nb/Nb_3Sn cavities as a first step. An appropriate design of the anode with flow diverters has been conceived for this purpose. We will start with small 3.9 GHz cavities, then proceed with 2.45 GHz, and finally come to the larger 1.3 GHz cells. If the method works for the latter, we will attempt it also on the low frequency cavities planned for an Electron Ion Collider. The single-cell test is expected to be the most challenging of the process, and will determine the upper limit, if any, of the allowable size of Nb SRF cavities for Nb_3Sn coating. Once the technique is proven on single cells, the electroplating can be implemented directly to complete assemblies.

In parallel with the application work above, we will investigate coating Cu cavities with Nb_3Sn. Because it is energetically impossible to electro-deposit Nb on any metal, we will sputter Nb on a Cu surface. To meet the stoichiometric requirements, only 2 micrometers of Nb are necessary to produce 3 micrometers of Nb_3Sn after reaction. This is more than sufficient for SRF operation. FNAL has an existing High-Power Impulse Magnetron Sputtering (HIPIMS) system that will be used for sputtering the Nb. The subsequent steps of electroplating Sn layers and Cu intermediate layers onto Nb substrates wil be the same. It has been proven [4] that Cu can withstand the 700°C required to obtain the Nb_3Sn superconducting phase during heat treatment. Cu is preferred over Nb for the SRF cavity body for its excellent thermal properties, which reduce heating during operation and allow more margin for temperature perturbations. An SRF Cu cavity coated with Nb_3Sn is considered as the holy grail in the field.

Use of Funding

The proposed research requests funding for 50% of the PI salary, a postdoc, the Nb and Cu cavity fabrication, consumables, and cryogenic testing of the cavities at JLAB, leveraging the existing collaboration.

Thanks to the scalability of electroplating, the proposed method has a high likelihood of success for broad SRF applications such as light sources, medical applications, water treatments, etc., since Nb_3Sn SRF cavities have been proven to achieve superior quality factor. Were this technique to generate also the expected accelerating gradient, or at least an accelerating gradient much closer to the theoretical limit than what vapor deposition has seen so far, this would produce a major impact on high energy particle accelerators and HEP at large.

References

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