An Impartial Perspective for Superconducting Nb_3Sn coated Copper RF Cavities for Future Linear Accelerators

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This Letter of Interest is to make the case for more vigorous R&D in the direction that would be most profitable for HEP accelerators and, perhaps even more so, for accelerators in general. On one hand, ICFA has been endorsing the idea of a high-energy linear electron-positron collider such as the ILC since the 1990s. The ILC is supported also by numerous national HEP communities and some government officials. This includes for instance the German "Committee for Elementary Particle Physics", the French CEA that was heavily involved in the European XFEL, and the Italian INFN. For the U.S., both the OHEP Associate Director and the Under Secretary of Energy for Science look forward to Japan hosting and proceeding with the ILC [1]. Lastly, this past May the CERN Council approved and published the European strategy which, once more, puts an electron-positron Higgs factory with c.m. energy of 250 GeV as the highest-priority next collider.

Despite the unanimous global consensus, completion of the TDR for a 500 GeV collider by 2013, and reduction of the energy and the cost by two in 2017, the 5.5 billion ILCU (an ILC unit is 1$ at 2012 value) capital cost and the 0.3 billion ILCU yearly operational costs have been all along considered problematic. This is now further exacerbated by concerns on the economy due to Covid. The production chain for ILC's Nb SRF cavities includes a long series of processes, such as electron beam welding, high-pressure rinsing, electro-polishing, furnace heat treatments. Although projects like CEBAF, SNS, XFEL, LCLS-II and ESS have produced scale-up capabilities, cost-driving requirements remain in the materials specifications and fabrication. The additional complexity of surface doping/infusion with nitrogen and its associated requirements have increased process costs of Nb SRF cavities. It is not clear whether the saving in operation costs will offset such a capital increase in a reasonable time.

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 [2], achieving linac gradients exceeding 160 MV/m with cryo-cooled Cu. For an NCRF machine, as for any large collider with high power beams, the dominant capital and operating cost is the cost of the RF sources, which is itself driven by the peak power and operating voltage that the RF system must deliver to the linac, as well as of the wall power cost. SRF accelerators must therefore also make progress to remain competitive.

Within the European EuCARD-2 funded R&D project for next-generation accelerators at CERN, CERN and other European institutions started pursuing Nb_3Sn for SRF applications. Prior to that, several groups were already active in the thin film area [3]. The two most important properties for SRF performance are the accelerating field E_{acc} and the cavity quality factor Q_0. The accelerating gradient in SRF cavities is proportional to the peak magnetic field on the cavity wall. At RF frequencies, E_{acc} is limited by the peak magnetic field reaching or exceeding the superheated critical magnetic field, H_{sh} [4]. The maximum accelerating gradient expected for Nb cavities is ~50 MV/m. With a theoretical H_{sh} of 0.42 T, as compared to 0.25 T for Nb [5], 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. With a higher T_{c0} of up to 18 K, as compared to a T_{c0} of 9.2 K for Nb [5], SRF Nb cavities coated with Nb_3Sn also produce a cavity quality factor Q_0 about 30 times larger than for Nb cavities [6]. 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. This would decrease capital costs for the cryogenic plant, as well as operation costs, by a substantial amount. This feature alone would make Nb_3Sn the SRF material of choice, even just when coated on Nb cavities, for SC linacs of light sources.

In the U.S. most of the funding on Nb_3Sn has been on a Sn vapor diffusion process on the internal surface of a Nb bulk cavity proposed 30 years ago [7-9]. Unfortunately, because of the absence of Cu as a ternary element in the diffusion diagram, the process must be carried out at very high temperatures of ~1100°C.

To exploit the full potential of Nb_3Sn while reducing the capital cost of ILC, the R&D should be pushed on producing Nb_3Sn on inexpensive and thermally efficient metals such as Cu or bronze, since Nb is one of the main cost drivers of SRFs. The lower cost and thermal efficiency of the Cu are the reasons why CERN chose to use Cu cavities lined with Nb for decades for its accelerators and is planning to continue to do so for FCC.

There are a number of small groups that have nevertheless made progress on both thin and thick Nb_3Sn films to be produced on Cu despite very limited funding. Some examples follow:

1. Among the most promising approaches for Nb_3Sn film deposition on Cu is sputtering, which can be performed either sequentially to form a multi-layer structure of Nb and Sn followed by post-reaction; in a co-sputtering [10] mode from two targets, or from a single stoichiometric target [11]. Using two separate targets in a co-sputtering setup allows tuning the kinetic energies of both elements independently. This process leads to the superconducting phase formation at much lower substrate temperatures as compared to thermal diffusion conditions. For instance, direct Nb_3Sn deposition was achieved on fused silica substrates by magnetron co-sputtering at 435°C, with a T_c of 16.3 K [10]. This approach paves the way for the use of Nb_3Sn as a coating in cryogenically efficient copper-based cavities avoiding the detrimental interdiffusion of Cu.

2. An electro-chemical technique to coat either Nb or Cu 3D surfaces with Nb_3Sn for SRF and superconducting magnetic shielding applications was developed and made reproducible at FNAL in the last few years [12-14]. The know-how was also successfully transferred to KEK, which continued to develop it in partnership with a Japanese company, AKITA KAGAKU Co., Ltd. This technique is innovative with respect to the vapor deposition approach that has been in development for decades. In addition, heat treatment at a maximum temperature of 700°C allows implementing the method on Cu surfaces previously sputtered with Nb. The advantages of electro-deposition are its simplicity, accurate control, and low cost.

3. The Japanese National Institute for Materials Science has invented methods to either produce Nb_3Sn on bronze substrate or on Oxygen-free Cu [15]. Both processes build upon the A15 superconducting wire technology and also exploit the heat treatment temperature reduction effect of the Cu. It is thought that these processes would be suitable to use on SRF cavities fabricated by hydro-forming. Some efforts have started in the U.S. where Nb films are deposited on a bronze substrate and subsequently annealed to form the A15 phase [16, 17].

The white paper will present a comprehensive study of methods that produces Nb_3Sn on inexpensive metals and will evaluate their potential to real life SRF applications.

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