Letter of Interest for Snowmass 2021

Innovative Materials and Surface Treatments for SRF applications

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Superconducting radio-frequency (SRF) cavities are the current state-of-the-art technology implemented in particle accelerators for high energy physics, nuclear physics and basic energy science. Multiple machines are currently exploiting this technology (EXFEL, CEBAF, LCLS-II, LHC, SNS) and many are in planning for their future construction (ILC, LHC-ee, CEPC). At the same time, the SRF technology have become transformative in fields such as quantum information science and particle detections, due to the high intrinsic quality factors this technology permits to achieve.

Currently, basic SRF R&D is mostly focused on improving the performance of bulk niobium SRF cavities to allow for more affordable accelerators for multi-TeV and high duty-cycle or CW applications. Treatments such as nitrogen doping [1] and nitrogen infusion [2] demonstrated how small traces of interstitials elements in niobium can drastically modify the performance of SRF cavities and that the engineering of the diffusion profile [3,4] is key to push the gradient reach and still allowing for high Q-factors. Nevertheless, the spectrum of thermal treatments that can be studied with the current tools available are limited to diffusion of inert gas species such as nitrogen and the community is currently blind regarding the effect of different elemental interstitials.

In the search of alternative materials for SRF applications, some effort has been devoted to the study of NbN and NbTiN in thin film form [5], but MgB_2 [6] and Nb_3Sn [7] are currently the only ones under study. While MgB_2 is a fragile material prone to oxidation, Nb_3Sn is instead a more solid choice due both to its stability and the favorable thermodynamics of the vapor-solid reaction to grow this material inside Nb SRF cavities.

In order to further increase the performance of SRF resonators beyond what has been achieved so far, it is mandatory for the community to investigate new materials and innovative surface treatments. In this LOI we lay out several innovative possible routes to push forward the SRF technology for particle accelerators, particle detection, and quantum information science applications:

- Higher Q-factors at higher gradients for multi-TeV machines can be achieved by engineering diffusion profiles of interstitials atoms in bulk niobium cavities [2,4], allowing for Q-factors above 1e10 at gradients > 40 MV/m. Even better performance is expected by growing layered structures at the cavity surface. By cleverly selecting the type of material and its thickness, superconductor-superconductor and superconductor-insulatorsuperconductor structures should be capable of allowing for accelerating gradients up to ~100 MV/m [8,9,10]. Less explored, but promising, is the possibility of increasing the accelerator gradient by slowing the nucleation process of RF vortexes at the surface. Certain elemental superconductors possess long vortex nucleation times allowing in principle to increase the accelerating gradient reach and allowing the study of the non-equilibrium dynamics of superconductors.

- Alternative doping elements for niobium might allow for higher Q-factors and for higher maximum fields, while growing A15 superconductors with higher T_c than Nb_3Sn could allow for high Q-factor application at 2 K and 4.2 K.

- Transformative technological advancement in the field of quantum information science could be achieved by deposit onto SRF cavities oxides and insulating layers with low density of two-level systems to improve the coherence time of SRF-based qubits. In addition, higher Q-factor SRF cavities for axion detection could be attained by depositing thin films of s-band superconducting materials that can withstand multi-tesla fields, meanwhile developing solutions for artificial pinning of vortices to minimize the vortex surface resistance.

We believe that all the R&D topics cited above can be explored by means of chemical vapor deposition (CVD), atomic layer deposition (ALD), and magnetron sputtering of thin films onto SRF cavities, and we advocate for the further developing of these techniques to serve the development of the SRF technology. In summary, we believe that by investigating these innovative surface treatments and new materials, the performance of SRF cavities in both accelerating and quantum regimes can be pushed to a new frontier. More details into the possible outcomes and the physics behind the diverse R&D paths laid out in this LOI will be discussed in the Snowmass 2021 contributed paper.

References

[1] A. Grassellino et al., Supercond. Sci. Technol. 26, 102001 (2013)
[2] A. Grassellino et al., Supercond. Sci. Technol. 30, 094004 (2017)
[3] M. Checchin and A. Grassellino, Appl. Phys. Lett. 117, 032601 (2020)
[4] V. Ngampruetikorn and J. A. Sauls, Phys. Rev. Research 1, 012015(R) (2019)
[5] R. Di Leo et al., J. Low Temp. Phys. 78, 41 (1990)
[6] T. Tan et al., Sci. Rep. 6, 35879 (2016)
[7] S. Posen and D. L. Hall, Supercond. Sci. Technol. 30, 033004 (2017)
[8] A. Gurevich, AIP Advances 5, 017112 (2015)
[9] T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017)
[10] M. Checchin et al., TUPLR024, in Proc. of LINAC 2016