Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & Energy Reach

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Superconducting RF Technology has been the building block for many high-energy physics accelerators, essentially based on bulk niobium (Nb). Over the past decades, the RF performance of bulk Nb cavities has continuously improved with material and surface developments [1], such as nitrogen surface doping [2] as of late. However, long-term solutions for superconducting radio-frequency (SRF) surfaces efficiency enhancement need to be pursued. The greatest potential for dramatic new performance capabilities lies with methods and materials, which deliberately produce the sub-micron-thick critical surface layer in a controlled way. The development of SRF surfaces with other forms of Nb and other superconducting materials has the potential to further improve SRF cavity performance beyond the Nb sheet material intrinsic limits. This development combined with higher efficiency and quality control are most relevant for structures required for future SRF accelerators. The potential of fully engineered and truly application-tailored SRF surface strategies would dramatically reduce capital and operating costs for future accelerators, lowering the cost-of-entry of SRF technology, both for large scale facilities and compact accelerators.

Next Generation Nb/Cu SRF Cavities Based on Advanced Coating Technology for CW Accelerators

Electron-ion colliders, electron coolers, energy recovery linacs (ERL), X-ray light sources and free electron lasers (FELs) require CW (continuous wave) operation. Minimal cavity residual losses and minimized cryogenic consumption, i.e. high quality factors, Q, at medium gradients are then more essential than high gradients.

Over the years, niobium film on copper (Nb/Cu) technology has positioned itself as an alternative route for the future of superconducting structures used in accelerators with successful demonstrations at CERN with LEP then, now LHC and Hie-ISOLDE, at INFN-LNL with ALPI [3]. Decoupling the SRF surface from the cryogenic system by depositing a thin layer of Nb on the inner

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surface of a Cu cavity offers several advantages: increased temperature stability due to the Cu substrate higher thermal conductivity; operation at 4.5 K, generating capital and operational cost savings; material cost saving, particularly for low frequency structures; easily machinable and castable structures, opening perspectives for significant cryomodule simplification. However, although exhibiting very high Q at low field, Nb/Cu cavities have been plagued with steep RF losses (Q-slope) at medium to high gradients. Recently, R&D efforts, jointly at JLab and CERN, to develop advanced coating technologies (energetic condensation) have produced encouraging results alluding to the promise of superior performing SRF films [4-7]. These techniques, along with careful engineering of surfaces [8], have produced Nb/Cu films with bulk-like properties, greatly improved accelerating field and dramatically reduced Q-slope, demonstrating that the early sputtered Nb/Cu cavity performance is not a fundamental limitation. Further effort is needed to scale up these processes and develop protocols and procedures that can be industrialized.

Successful SRF thin film cavity development will lead to significant savings in cavities and cryomodule costs. It is in line with the demands of the future generation of particle physics machines such as the electron – ion collider (EIC), FCC-ee [9] which require R&D pushing the state of the art and enabling technological breakthroughs to provide the required reliability and keep costs within acceptable levels. Accelerators relying on operation at 4 K and/or on low frequency (large) cavities for which the cost of bulk Nb material becomes prohibitive (precision muon generation) or high-power compact proton and CW ion linear accelerators for isotope production facilities (FRIB) would also benefit.

Advanced Materials and Structures for Higher Gradients and High Q

Alternative materials with higher critical temperature and critical field are the prime candidates to surpass the established bulk Nb technology [10]. Materials such as Nb_3Sn offer order of magnitude improvements in operating efficiency, and a theoretical pathway to 100 MV/m gradient [11]. Recent R&D efforts [12-14] have demonstrated that the persistent Q-slope and gradient limitation observed in the past [15] are not fundamental but process induced and therefore amenable to improvement. Alternative deposition approaches such as sputtering, energetic condensation and atomic layer deposition (ALD) should be fully explored for enhanced properties and conformality. Early results with sequential and stoichiometric deposition both on Nb and on Cu are promising [16, 17] and could prove to push the Nb_3Sn technology further. Other materials such as NbTiN, NbN, Va_3Si, etc. should also be re-evaluated with advanced coating techniques. Newly discovered high temperature superconducting (HTS) materials (pnictides [18]…) would be particularly interesting if any of them turns out to have favorable microwave properties [10].

The combination of such materials with adequate dielectric material in multi-layered structures have been conceived as a performance enhancer for bulk Nb and Nb/Cu film cavities. Theoretical models [19, 20] predict that appropriately fabricated nanometric superconductor-insulator-superconductor (SIS) multilayer films can delay vortex penetration in Nb surfaces allowing them to sustain higher surface fields than any pure material.

Compact SRF Accelerators for Societal Applications

The emergence of reliable, energy efficient high *Q* systems, based on highly performing film-based SRF cavities along with transformative development with cryocoolers [21, 22] would impact societal applications ranging from medicine to industry. Cost effective compact superconducting accelerators will reduce the footprint and capital investment of medical machines for cancer therapy and medical radioisotope production. Other applications include environmental remediation, accelerator-driven systems (ADS) for nuclear waste transmutation or power generation, and high-intensity proton accelerators for homeland security (nuclear weapons detection). For such compact-sized machines, energy efficiency is one of the most critical area of development.

Summary and Path Forward

SRF thin film technology based on advanced coating techniques offers many opportunities to fully engineer SRF surfaces with the deliberate creation of the most favorable interface or functional interlayer, tailoring of the most favorable film(s) structure, properties enhancement with doping, control over the final SRF surface with dry oxidation or cap layer protection. Bulk-like performance Nb films, alternative material films and SIS multilayer structures open the possibility of major system simplifications and enhanced performance. Such developments would be transformative not only for future high energy physics machines but will also bring forth the opportunity to upgrade existing machines to higher performance in achievable energies and cryogenic & power consumption, within the same footprint.

The already well-established and fruitful international R&D collaborations involving JLab, SLAC, ODU, CERN, INFN-LNL, CEA Saclay, STFC, HZB, DESY, KEK, and other institutions should be fully supported and expanded in the following areas of R&D:

- Theoretical and material studies to gain in-depth understanding of the fundamental limitations of thin film superconductors under radio-frequency fields
- Advanced coating technology via energetic condensation (electron cyclotron resonance (ECR), HiPIMS, kick positive pulse…)
- Cavity deposition techniques for alternative materials to Nb: Nb_3Sn, V_3Si, NbTiN …
- Atomic Layer Deposition (ALD)
- Development of superconductor-insulator-superconductor (SIS) nanometric layers to further enhance the performance of bulk Nb and Nb/Cu
- Improved cavity fabrication & preparation techniques (electroforming, spinning, hydroforming, electro-hydro forming, 3D additive manufacturing, environmentally friendly electropolishing, nano-polishing, plasma etching …)
- Cryomodule design optimization
- Improvement of accelerator ancillaries with advanced deposition techniques (HiPIMS Cu coated bellows, power couplers…)

Continued investment is required so this fundamental R&D can mature and become project ready for the next generation accelerators.

References

[1] Padamsee, Hasan. “History of gradient advances in SRF.” arXiv: Accelerator Physics (2020): n. pag.

[2] Bafia, D., Checchin M., Gonnella D., Grassellino A., Martinello M., Melnychuk O., Palczewski A., Posen S., Romanenko A., Sergatskov D. and Zasadzinski J. F. “Understanding and Pushing the Limits of Nitrogen Doping.” Proceedings of 10th International Particle Accelerator Conference (2019), doi:10.18429/JACoW-IPAC2019-WEPRB114.

[3] Sladen, J. “STATUS OF SUPERCONDUCTING CAVITIES IN LEP” , Part.Accel. 60 (1998) 15-25, In *Padua 1997, RF superconductivity, vol. 1, pp. 116-121.

[4] Valente-Feliciano, A.-M., Aull S., Eremeev G., Proslier T., Reece C.E. and Spradlin J.K. “Material Quality & SRF Performance of Nb Films Grown on Cu via ECR Plasma Energetic Condensation.” (2015).

[5] Rosaz, G., M. Taborelli, D. Sonato, A. Ehiasarian, S. Calatroni, T. Junginger and G. Terenziani. “Biased HiPIMS technology for superconducting rf accelerating cavities coating.” (2015).

[6] Burton, Matthew, Rosa Alejandra Lukaszew, Ari Deibert Palczewski, Larry Phillips, Charles Reece and Valente-Feliciano Anne-Marie. “RF Results of Nb Coated SRF Accelerator Cavities via HiPIMS.” (2019).

[7] Avino, F., A. Sublet and M. Taborelli. “Evidence of ion energy distribution shift in HiPIMS plasmas with positive pulse.” Plasma Sources Sci. Technol.28 (2019) 01LT03.
[8] Delsolaro, W. V. and A. Miyazaki. “SEAMLESS QUARTER WAVE RESONATORS FOR HIE ISOLDE.” (2019) Proceedings, 29th Linear Accelerator Conference, LINAC2018, doi:10.18429/JACoW-LINAC2018-TU1A05.
[9] Aull, Sarah, Nikolai Schwerg, O. Brunner and Andy Butterworth. “Material options for the superconducting rf system of the Future Circular Collider.” (2018).
[10] Valente-Feliciano, Anne-Marie. “Superconducting RF materials other than bulk niobium: a review.” Superconductor Science and Technology 29 (2016): 113002.
[11] R.A. Rimmer et al. “Next Generation SRF accelerators based on Nb_3Sn”, LOI SNOWMASS 2021 https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF7_AF3_Rimmer-172.pdf
[12] S. Posen et al., “Nb3Sn at Fermilab: Exploring Performance”, presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THFUB1
[13] G. Eremeev et al. "Nb3Sn multicell cavity coating system at Jefferson Lab." Review of Scientific Instruments 91.7 (2020): 073911.
[14] U. Pudasaini et al. "Growth of Nb3Sn coating in tin vapor-diffusion process." Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films 37.5 (2019): 051509.
[15] P. Kneisel et al, “Nb_3Sn Layers on High-Purity Nb Cavities with Very High Quality Factors and Accelerating Gradients”, in Proc. 5th European Particle Accelerator Conf. (EPAC'96), Sitges, Spain, Jun. 1996, paper WEP002L.
[16] Sayeed, Md. Nizam, U Pudasaini, Hani E. Elsayed-Ali, Michael J. Kelley, C E Reece and G. Eremeev. “MAGNETRON SPUTTERING OF Nb 3 Sn FOR SRF CAVITIES.” (2018).
[17] Rosaz, G., S. Calatroni, F. Léaux, F. Motschmann, Zuzanna Mydlarz, M. Taborelli and W. Vollenberg. “Development of Nb_3Sn Coatings by Magnetron Sputtering for SRF Cavities.” (2015).
[18] Si, Q., Yu, R. & Abrahams, E. High-temperature superconductivity in iron pnictides and chalcogenides”. Nat Rev Mater 1, 16017 (2016).
[19] Gurevich, A. “Maximum screening fields of superconducting multilayer structures”. AIP Advances, 5, (2015) 017112.
[20] Kubo, Takayuki. “Multilayer coating for higher accelerating fields in superconducting radio-frequency cavities: a review of theoretical aspects.” Superconductor Science and Technology 30 (2017): 023001.
[21] Ciovati, G., Jiquan Guo, R. Rimmer, F. Hannon, F. Marhauser, Vashek Vylet, J. Rathke, T. Schultheiss, B. Coriton, M. LeSher, J. Anderson and L. Holland. “Design of a low-cost, compact SRF accelerator for flue gas and wastewater treatment.” (2017).
[22] Stilin, Neil, A. Holic, M. Liepe, R. Porter and J. Sears. “Stable CW Operation of Nb_3Sn SRF Cavity at 10 MV/m using Conduction Cooling.” arXiv: 2002.11755: Accelerator Physics (2020).