11th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity - TFSRF2024

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Book of Abstracts

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Introduction talk

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We Shall recall the ongoing and future projects using SRF thin films and list the opening of new synsergies

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Exploring Performance Degradation in Niobium Thin Film Radio-Frequency Cavities: A Comprehensive Study

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"Niobium thin film radio-frequency (RF) cavities have historically shown performance degradation as the RF field increases, posing limitations on their use in particle accelerators where the real-estate gradient has to be maximized. This issue, often referred to as the medium field Q-slope problem, has not yet been fully understood and is currently undergoing extensive studies.
We examined the RF performance of various niobium thin film cavities reported in the literature, covering frequencies ranging from 100 MHz to 1.5 GHz. These cavities were fabricated by depositing niobium thin films using various coating techniques on copper substrates of different shapes, obtained through distinct manufacturing processes. Despite these notable differences, the performance degradation in all analysed cavities is consistently described by the same experimental law, solely dependent on RF field, resonance frequency, and temperature.
In this study, we present our analysis of the RF performance of niobium thin film cavities and evaluate how accurately the performance degradation is predicted through a systematic comparison with measurements, reported in the literature, at different resonance frequencies and several temperatures ranging from 1.9 K to 4.5 K. Based on our findings, we propose a theoretical explanation, involving non-equilibrium superconductivity, which may offer a new perspective for addressing the Q-slope problem."

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Superheating field in superconductors with nanostructured surface

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We report calculations of a dc superheating field H_s in superconductors with nanostructured surfaces. Numerical simulations of the Ginzburg-Landau (GL) equations were performed for a superconductor with an inhomogeneous impurity concentration, a thin superconducting layer on top of another superconductor, and superconductor-insulator-superconductor (S-I-S) multilayers. The superheating field was calculated taking into account the instability of the Meissner state with a nonzero wavelength along the surface, which is essential for realistic values of the GL parameter κ, particularly $\kappa \simeq 1$ for Nb. Simulations were done for the materials parameters of Nb and Nb_3Sn at different values of κ and the mean free paths. We show that the impurity concentration profile at the surface and thicknesses of S-I-S multilayers can be optimized to enhance H_s above the bulk

superheating fields of both Nb and Nb_3Sn. For example, a S-I-S structure with 90 nm thick Nb_3Sn layer deposited on Nb can boost the superheating field up to $\approx$ 500 mT, while protecting the SRF cavity from dendritic thermomagnetic avalanches caused by local penetration of vortices.

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Frequency Shift Regimes and Quality Factor of the Superconducting Cavities within the Dynes Superconductor Theory

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Within my contribution, I want to focus on the theory of the Dynes superconductors and its implications for the studies of the superconducting cavities. Assuming various regimes of pair-breaking and pair-conserving disorder within our approach leads to rich behavior of the resonant frequency shift close to ⊠⊠. I want to elaborate on the following points. A) Present a more finalized discussion about the different regimes of the superconducting frequency shift in the vicinity of the critical temperature (that we can reconstruct in the qualitative agreement with the experiment). B) Present our estimate of the mean free path values in various regimes. C) Discuss the relevance of the anomalous normal state. D) Discuss the implication of the missing coherent peak on the frequency shift behavior close to ⊠⊠. In the end, I want to discuss the effect of disorder in the part of the Quality factor, which is related to the residual resistance, within our approach.

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Suppression effect on Nb3Sn films: Effects of Coating Growth Duration on the Topography of Sn Vapor-Diffused Nb3Sn

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While Nb3Sn theoretically offers better superconducting RF cavity performance (Q0 and Eacc) to Nb at any given temperature, peak RF magnetic fields consistently fall short of the ~400 mT prediction. The relatively rough topography of vapor-diffused Nb3Sn is widely conjectured to be one of the factors that limit the attainable performance of Nb3Sn-coated Nb cavities prepared via Sn vapor diffusion. Here we investigate the effect of coating duration on the topography of vapor-diffused Nb3Sn on Nb and calculate the associated magnetic field enhancement and superheating field suppression factors using atomic force microscopy topographies. It is shown that the thermally grooved grain boundaries are major defects which may contribute to a substantial decrease of achievable accelerating field. The severity of these grooves increases with total coating duration due to the deepening of thermal grooves during the coating process.

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Layered iron-based superconductors for SRF cavities

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"High-Tc superconductors (HTS) have recently become competitive options in superconducting magnet applications. It is natural to investigate their potential in superconducting RF (SRF) cavities. The most advanced HTS, the copper oxide family, has been successfully developed for low-field cavities for dark matter experiments under strong static magnetic fields. However, their gapless nature may be a fundamental limitation to be used in high-field applications. Iron-based superconductors are known to have gap-full structures and, therefore, potentially an interesting candidate for SRF cavities. In this talk, we discuss some of the first theoretical attempts to calculate the surface resistance and field reach of layered iron-based superconductors and compare them with experimental data available in the literature.

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Surface heating in HTS-based high field pulsed RF cavities

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“Recent technological advances allow the use of HTS Coated Conductors in RF devices by soldering the tape onto an appropriately shaped substrate. This opens up the possibility of manufacturing entire RF accelerating cavities using this technology. A collaboration between CERN, ICMAB, KIT and SLAC aims at assessing the performance attainable by RF components produced with this technology by applying HTS tapes on a part of a special demountable cavity, tested in pulsed regime up to extremely high RF surface currents, equivalent to an RF accelerating field of the order of 100 MV/m if scaled to a standard elliptical cavity.
In this frame, one of the possible problems arising is the superconductor surface temperature increase due to the high deposited RF power. Because of the strong temperature dependence of the superconductor surface resistance Rs, at constant RF field amplitude, a temperature increase would lead to an increase of the deposited RF power, through the relation: P_rf=1/2R_s 〖(T)H〗_rf^2. This process can induce a thermal runaway, driving the superconductor into the normal state (cavity quench).
In this talk, following Wilson [1], by solving the heat equation for the system under consideration, we discuss the conditions leading to thermal runaway. In particular, we estimate the upper limit for the HTS tapes transverse thermal conductivity to safely achieve RF accelerating fields corresponding to an order of 100 MV/m. Measurements of the tapes thermal conductivity are in progress within the collaboration.

[1] I. Wilson, “Surface heating of the CLIC main linac structure”, CLIC note 52, https://cds.cern.ch/record/255087”

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EQP energy and mass analyser

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“Magnetron sputtering (MS) is a common technique used for the production of thin films. In such process, the sputtered ions are ejected from the target material with high kinetic energy and deposited onto the substrate to form the coating. This result in an energy transfer between the bombarding particles and substrate, affecting film growth or crystallization.
While DC and pulse DC are commonly used in MS, new techniques where developed such as High Power Impulse Magnetron sputtering. The latest can be beneficial in coating and interface engineering [1], coating of complex substrates [2], and in tailoring the film properties [3].

Here, we investigate the behaviour of the positive ions formed from a niobium (Nb) target through mass spectrometry using both unipolar and bipolar HiPIMS. The electrical parameters, pressure conditions and characteristic of the reverse positive potential were varied to optimise the ion energy of the species of interest.
Such analysis could potentially help in improving techniques to produce the SRF cavity.

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Reducing the Thermal Effects during Coating of SRF Cavities: A Case Study for Atomic Layer Deposition of Alumina with a Combined Numerical and Experimental Approach

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Coating the inner surface of superconducting radio frequency (SRF) cavities is one of the approaches to push ultimate limits in next generation accelerators. One of the potential coating techniques for such intricate and large volume structures is atomic layer deposition (ALD), as it offers full and uniform layer coverage. In order to predict the process parameters for coating SRF cavities on the large substrates with ALD, we simulate the ALD of alumina (Al2O3) using the ANSYS Fluent 19.1 commercial package by solving vapor transport and chemistry equations. The computational domain in the numerical model is based on the homemade ALD setup for thin film sample chamber and a 1.3 GHz Tesla-shaped niobium cavity. Trimethlyaluminum (TMA) and water (H2O) were used as precursors. In the simulation process for the cavity, two steps were carried out: first, the simulation of precursor distribution, followed by the simulation of surface reactions. The simulations show that saturation is achieved with precursor pulses of only 50 ms after 1.05 s for TMA and 750 ms for H2O, obviating the necessity for prolonged exposure times. Furthermore, the resulting predicted growth per cycle of these process times of ≈1.22 Å for Al2O3 was experimentally validated, affirming the credibility of our simulations. Experimental findings also showcased a remarkable 66.2% reduction in process time while upholding film homogeneity and quality. Our approach presented here carries profound importance, particularly for coating intricate and large volume structures, like SRF cavities, and provides another approach to minimize time- and resource-intensive parameter scans. The methodology is also transferable to other coating materials and volumes.

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Status of HIPIMs develpments at CERN

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The SRF cavities made with a niobium coating on a copper substrate (Nb/Cu) offer several advantages over those made with bulk niobium. This is mainly attributed to the excellent thermal properties of copper, enabling operation at higher temperatures and consequently reducing cryogenic costs. The Nb/Cu technology has been employed at CERN since the 1980s, being currently used in the LHC and HIE-ISOLDE SRF systems. Furthermore, it has been chosen as the baseline for the FCC accelerator. Despite the advantages, a systematic degradation of the performance at high accelerating gradients has been historically observed. To comprehend and address this degradation, a vast R&D program has been carried out at CERN in recent years. The main objective was to identify an optimized recipe to manufacture these cavities, while ensuring scalability to meet the extensive requirements of the FCC project. Initially, for selecting the best coating deposition technique, small flat samples were tested using a quadrupole resonator. Once determined, these coatings were applied to 1.3 GHz cavities. Different manufacturing techniques were explored for producing the copper substrates too. This presentation offers an overview of the progress and the current status of the research campaign.

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Ion bombardment energy effect on microstructure and critical current density of Nb/Cu thin films for SRF application.

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"The Future Circular Collider (FCC), foreseen to be built at CERN, relies on the Nb/Cu technology for the 400 MHz RF system. In view of reaching the requested specifications, it is of uttermost importance to push the SRF performance of the Nb thin films to its limits. To do so, it appears critical to understand what are the underlying physical phenomena that drive the Q-slope. Such an effect has been tracked back to be partly due to magnetic flux pinning in the films that eventually dissipates power once the applied RF field amplitude increases [1].
Nb thin films elaborated using DC-biased HiPIMS are known to lead to dense films and address the contribution to the Q-slope attributed to film porosities [2,3]. Using the critical current density, JC, as a metric of the density of pinning sites in our films, we find a dependency with film thickness as well as with the ion bombardment energy. We manage to identify the defect family responsible for tuning the Jc and use an analytical model to explain the optimal bombardment energy found to minimize it. This study leads to the identification of an optimal bias voltage value to be used in view of minimizing defects in Nb films. "

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HiPIMS Deposition of Nb Coatings with Bias Voltage: Preparation and Characterization at IHEP

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The Nb/Cu film superconducting cavities offer several enhancements over traditional bulk niobium RF cavities, including improved mechanical and thermal stability, as well as a reduced sensitivity to DC magnetic fields. Despite these advantages, Nb/Cu film cavities produced via DC magnetron sputtering often exhibit a pronounced Q-slope issue, potentially due to the low-energy deposition process. In contrast, high power impulse magnetron sputtering (HiPIMS) allows for greater peak power by employing a small duty cycle, to generate a higher ionization rates of target atoms, which in turn can control the deposition energy of the particles through the substrate bias voltage adjustments, thereby improving film quality. Therefore, we developed the application of HiPIMS with bias voltage for the preparation of Nb films by adding a cylindrical mesh as an anode on the previous 1.3 GHz dummy cavity coating system.

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Addressing the Medium-Field Q-Slope Challenge in Nb Thin Film Cavities

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In this study, we addressed the persistent medium-field Q-slope issue in Nb thin film cavities, which, despite their high Q at low RF fields, exhibit a significant Q-slope at medium RF fields compared to bulk Nb cavities. Traditional heat treatments, effective in reducing surface resistance and mitigating the Q-slope in bulk Nb SRF cavities, are challenging for Nb thin film cavities. We employed DC bias HiPIMS to deposit Nb film onto a 1.3 GHz single-cell elliptical bulk Nb cavity, followed by annealing treatments. Annealing at 340 ℃ increased the quench field from 10 to 12.5 MV/m. Annealing at 600 ℃ and 800 ℃ for 3 hours resulted in a quench field increase of 13.5 and 15.3 MV/m respectively. A 6-hour anneal at 800 ℃ boosted the quench field to 17.2 MV/m. Analysis of RF results and material characterization before and after annealing provided valuable insights into the effect of Nb film's microstructure and impurity levels on the evolution of the Q-slope in Nb film cavities. Our results demonstrate a promising strategy to overcome the medium-field Q-slope by optimizing the film

properties and impurity levels in Nb film cavities, potentially paving the way for more efficient superconducting RF technologies.

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HiPIMS Nb/Cu cavities at 1.3 GHz

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Bipolar HiPIMS-deposited Nb3Sn films: What we know so far

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"As part of efforts to reduce both energy and helium consumption in future particle accelerators, such as the Future Circular Collider (FCC), investigations into alternative methodologies to bulk Nb and Nb/Cu technologies are of paramount importance. Thanks to its higher transition temperature (Tc) and lower BCS surface resistance (RBCS), Nb3Sn coated cavities should produce a quality factor at 4.2K similar to the quality factor of bulk Nb at 2K. This will significantly decrease the cryogenic requirements of future particle accelerators, making them more viable.

The majority of research into Nb3Sn coatings has focused on depositing a Nb3Sn layer onto bulk Nb cavities via a Sn diffusion process, with encouraging results so far [1]. At CERN, a different approach of depositing a Nb3Sn layer onto Cu cavities has been pursued. Initial work focused on using DC MS to elaborate the Nb3Sn films [2]. However, given the densification of the deposited layers observed by using HiPIMS to elaborate Nb layers on Cu, and the subsequent improved quality factors [3], recent efforts have focused on using Bipolar HiPIMS for Nb3Sn deposition. We report the effects of different deposition parameters on the resultant Nb3Sn films.

[1] S. Posen et al., "Advances in Nb 3 Sn superconducting radiofrequency cavities towards first practical accelerator applications,"Supercond. Sci. Technol., vol. 34, no. 2, p. 025007, Feb. 2021, doi: 10.1088/1361-6668/abc7f7.
[2] E. A. Ilyina et al., "Development of sputtered Nb3Sn films on copper substrates for superconducting radiofrequency applications,"Supercond. Sci. Technol., vol. 32, no. 3, p. 035002, Mar. 2019, doi: 10.1088/1361-6668/aaf61f.
[3] M. Arzeo et al., "Enhanced radio-frequency performance of niobium films on copper substrates deposited by high power impulse magnetron sputtering,"Supercond. Sci. Technol., vol. 35, no. 5, p. 054008, May 2022, doi: 10.1088/1361-6668/ac5646."

Beyond Nb: Alternate materials and mulilayer structures / 63

Nb3Sn films on Cu by Magnetron Sputtering for SRF cavities at INFN-LNL

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"he development of Nb3Sn films on copper as coatings for the accelerating cavities of next generation particle accelerators is mainly driven by the sustainability goals being at the core of the I.FAST project. The successful development of a Nb3Sn/Cu scalable prototype would allow for the operation

of the SRF system at 4.5 K, resulting in a reduction of the needed cryogenic power by a factor 3 with respect to what normally needed for bulk Nb cavities, operated at 2 K. Several research activities are carried out at the INFN-LNL laboratories to develop new technologies for the application of Nb
Sn, including seamless spinning of cavity prototypes, surface chemical preparation, cavity coating, and testing. Also, the Liquid Tin Diffusion (LTD) technique is being explored to produce Nb3Sn cylindrical targets for elliptical cavity coatings. At the same time, an optimized recipe for Nb
Sn films deposited via DCMS was first established on small flat samples and is discussed in this work. The recipe delivered films showing a critical temperature Tc ≈ 17 K at deposition temperatures ≤ 650 ℃ on a copper substrate pre-coated with a 30
m thick buffer layer of Nb. The deposition recipe was then validated on bulk Nb by measuring the RF properties on a QPR sample, with the results being also discussed in this work. A surface resistance of 23 nΩ at 4.5 K (at 20 mT, 417 MHz, with quench field > 70 mT) was measured, which is about one order of magnitude larger than the baseline specifications for the LHC Nb/Cu cavities, and already fulfills the requirements for the FCC-ee. Finally, the next challenge lies in the scalability of the coating recipe from small flat samples to an elliptical cavity prototype."

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Research of Niobium Cavity Coating with Nb3Sn Film at IHEP

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Nb3Sn has significant potential for superconducting radio-frequency (SRF) application in future particle accelerators, especially compact accelerators, which have attracted the attention of many scientific researchers. This work reports the setup and process of Nb3Sn coating at the Institute of High Energy Physics (IHEP), and presents the results of 1.3 GHz 1-cell cavities coated with Nb3Sn. The cavities had a matte, non-reflective gray visual appearance after coating. Various parameters were used in the coating processes of Nb3Sn cavities, which resulted in different performances. The characteristics of witness samples at different locations inside the cavity revealed the uniform quality of the Nb3Sn coating. Experimental results indicated that less defects and a smoother surface can result in an improved performance of cavity.

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First results from Nb3Sn cavities in a CEBAF cryomodule

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We will present on the evolution of Nb3Sn-coated accelerator cavity performance from the qualification test to the test in CEBAF cryomodule. Two Nb3Sn-coated 5-cell accelerator cavities were first measured at 4 K and 2 K in the vertical dewar test, then assembled into a CEBAF quarter cryomodule. Several precautions were taken and changes were implemented in the assembly procedures to preserve the performance of the cavities. In the cryomodule we measured one cavity up to Eacc = 7.5 MV/m and the other cavity up to 13 MV/m at 4 K. We will discuss the challenges of preserving RF properties of coated cavities and opportunities of this approach for the future.

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Cu-based Nb3Sn QPR sample preparation via ETS bronze route

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Copper-based Nb3Sn cavity is a promising candidate for next generation accelerator applications in the field of superconducting radio frequency (SRF). It combines the excellent thermal conductivity of copper and the superior superconducting properties of Nb3Sn, and has the potential to greatly improve the performance of the SRF cavity. The electrochemical and thermal synthesis (ETS) bronze route is one of the proven methods to achieve Nb3Sn coating on copper. Its advantages are low cost, simple operation, suitable for complex cavity types and mass production. In this paper, we have prepared a copper-based Nb3Sn sample specifically for Quadrupole Resonator (QPR) testing. We provide a complete set of QPR sample preparation processes from copper electropolishing, Nb sputtering, electrodeposition and heat treatment to synthesize Nb3Sn. By optimizing the entire preparation process and key parameters, a new Cu-based Nb3Sn QPR sample was successfully prepared, and its RF properties will be characterized by QPR testing system at HZB soon.

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Investigations Towards Nanoscale Precise Polishing of Nb3Sn Thin Films for SRF Applications

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Copper-based Nb3Sn cavity is a promising candidate for next generation accelerator applications in the field of superconducting radio frequency (SRF). It combines the excellent thermal conductivity of copper and the superior superconducting properties of Nb3Sn, and has the potential to greatly improve the performance of the SRF cavity. The electrochemical and thermal synthesis (ETS) bronze route is one of the proven methods to achieve Nb3Sn coating on copper. Its advantages are low cost, simple operation, suitable for complex cavity types and mass production. In this paper, we have prepared a copper-based Nb3Sn sample specifically for Quadrupole Resonator (QPR) testing. We provide a complete set of QPR sample preparation processes from copper electropolishing, Nb suttering, electrodeposition and heat treatment to synthesize Nb3Sn. By optimizing the entire preparation process and key parameters, a new Cu-based Nb3Sn QPR sample was successfully prepared, and its RF properties will be characterized by QPR testing system at HZB soon.

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Nb3Sn on Cu in High Field

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Nb3Sn has shown much promise in recent years for use in superconducting radio frequency SRF cavities. Applying and reacting a large-area thin film homogenously on the inside of a cavity requires new ingenuity in material science. We present methods to form a range of Cu-Sn composition on Cu substrates using evaporation, and we achieve Cu-Sn phases with high tin activity to facilitate optimization of Nb3Sn film properties. Subsequent deposition of Nb leads to Nb3Sn films, where we compare a "hot bronze"route, where high deposition temperature leads to instant reaction upon arrival of Nb atoms, to post-reaction routes, where Nb3Sn forms via solid state reaction after a Nb film has grown. Challenges of achieving uniform, continuous, and homogeneous Nb3Sn thin films with good properties are presented by porosity, stress cracking, oxidation, Cu-Sn phase changes,

and management of the coefficient of thermal expansion mismatch. For example, films with critical temperature as high as 17.5 K have been demonstrated, but microstructural observations suggest dis-connection between Nb3Sn grains. Films with uniform, well-connected microstructure exhibit a sharp critical temperature transition, suggesting homogeneous properties, but with a critical temperature onset of 15.5 K.

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Microwave Vortex-dynamics Characterization in Nb3Sn under High Magnetic Fields

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"Nb3Sn coatings in accelerating cavities have been proposed as an alternative to drastically reduce the overall cryogenic cost in modern SRF complex accelerators. Furthermore, Nb3Sn films are among the candidates conceived to cover the interior of superconducting cavities for the search of axions (haloscopes). Thus, there is noticeable interest in assessing the superconducting properties of Nb3Sn films in very different conditions: while the SRF cavity operates in the vortex-free (Meissner) state, the vortex (mixed) state is unavoidable in haloscopes, where the axion-photon power conversion benefits from high magnetic fields.

In this work, the microwave (~[8-27] GHz) vortex-motion in high static magnetic fields (up to ~12 T) is thoroughly studied in Nb3Sn samples grown with different techniques: high isostatic pressure sintering (HIP), vapor diffusion (VD), and DC magnetron sputtering (DCMS). Using dielectric loaded resonators, dual frequency surface impedance measurements are exploited to obtain both the transport properties of the finite-thickness coatings and the main vortex parameters.

The results lead to discrete conclusions: the polycrystalline HIP bulk sample presents clear signs of collective pinning. In the VD sample, the collective pinning regime is exceeded at relatively low fields, above which the flux line lattice sets into motion against the weak opposition of point pins, as described by the phenomenological Dew-Hughes model. In the DCMS sample, the preliminary results show an exponential increase of the surface resistance from the vortex penetration, whose characteristic field is seen as the dephasing field of the Josephson junction network of grain boundaries.
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Nb3Sn Hot Topic Discussion

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SRF Thin Film Deposition of Material Other Than Nb For SRF Cavities.

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In this study we report on PVD deposition of Nb3Sn sputtered directly from an alloy target at elevated temperature about 600 ℃ with and without of interlayer of thick Nb layer deposited on copper substrate producing a multilayer of Cu/Nb/Nb3Sn and Cu/Nb3Sn.
The dependence of superconducting properties of the total structure on deposition parameters is been determined. The films have been characterized via, SIMS, RBS, SEM, XRD, EDX, measurements and SQUID magnetometer. RF properties was examined with choke cavity at 7.8 GHz.
Analysis showed that the composition in both room and elevated temperature was within the desired stoichiometry of 24–25 at%, however the superconducting properties was only observed for elevated temperature deposition or post annealing at 650 ℃. The critical temperature was determined to be in the range of 16.8 to 17.4 K

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Progress on MgB2 coating for Cu superconducting RF cavities

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With a higher Tc and higher critical field Hc than Nb and many Nb compounds and alloys, MgB2 is anticipated to be a promising material to be used for superconducting RF (SRF) cavities at ˜20 K. We report our continuing effort towards MgB2 coated SRF cavities. MgB2 films as thick as 5 um were coated on 1.3 GHz TESLA type Cu RF cavities by hybrid physical-chemical vapor deposition (HPCVD). The mock cavities were home-made by deep drawing. A pair of clamshell resistive heaters were employed to heat the cavity through conduction. Generations of Mg heaters were designed and tested. MgB2 films grown on 1 cm × 1 cm Cu substrates attached on the inside wall of cavities show Tc up to 34 K, measured by AC susceptibility [1]. Recent efforts of moving the Mg and B sources to coat MgB2 more uniformly and making RF surface resistance measurement are underway.

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Development of Nb3Sn films for single and multilayer structures

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This work describes recent developments for Nb3Sn films from sintered and stoichiometric 2-inch niobium tin targets by PVD. The final objective is to develop high quality thick Nb3Sn films (on Nb and on Cu), and SIS multilayers on SRF cavities. The effects of the target power, coating thickness, annealing temperature, and annealing time on the superconducting properties of films (RRR/Tc) were evaluated. In addition to the superconducting properties, the film morphology (AFM), chemical composition (EDS), and crystalline phases (XRD-GXRD) measurements are presented.

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Effects of deposition parameters on superconducting NbTiN thin films for use in SRF multilayer structures

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"For the last few decades, the material of choice for SRF cavities has been bulk niobium. RF performance of bulk Nb cavity has already approached its theoretical limit. To enhance RF cavity performance and cost-efficiency, research has shifted towards the use of other alternative higher T_c materials, such as NbN, $NbTiN$, MgB_2, etc. However, the use of alternative superconducting materials, despite their higher T_c, may not allow high accelerating gradients and quality factors greater than Nb due to their smaller H_{c1}. Addressing this problem, Alex Gurevich in 2006 proposed a theory involving superconductor-insulator-superconductor (SIS) structures to shield an underlying superconductor from the applied magnetic fields, thus increasing the maximum accelerating gradient beyond the bulk Nb limits.

$NbTiN$ is one of the most promising alternative materials to Nb, which already displayed high-quality factors in coated cavities for research. The present work focuses on the deposition of high T_c (17.3 K) $NbTiN$ thin films, primarily due to their high T_c and they also encompass all the benefits of NbN while displaying superior metallic conduction characteristics with higher titanium content. We used the industrial coating machine, CC800, to deposit single layers of $NbTiN$ thin films onto silicon (Si), a thick film of Nb, and aluminium nitride (AlN) substrates using DCMS and HiPIMS techniques. The primary focus here is solely on optimizing $NbTiN$ thin films for potential future use in SIS structures. The impact of various deposition parameters on the microstructure, phase formation, and subsequent superconducting properties of $NbTiN$ films deposited on various substrates are presented. The results indicate that HiPIMS yields films characterized by higher density and fewer voids in comparison to DCMS. Following the successful optimization of $NbTiN$ thin films, they will be utilized for the development of SIS structures."

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Thin-film study of Nb3Sn-AlN-Nb and NbN-AlN-Nb on 3GHz cavity by DC magnetron sputtering.

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We introduced the New DC magnetron sputtering apparatus at KEK to create multi-layer structure on the inner surface of a superconducting radio-frequency cavity. This apparatus has the capability of coating Nb3Sn, NbN, and AlN to the elliptical 3 GHz SRF cavity as well as flat substrates up to 2-inche diameter area. The film formation using the flat sample is useful for searching the ideal condition of film formation with various sputtering parameters. The film-formation test to the flat substrate can be done with changing the temperature of the substrate by heater. Using these functions, we will synthesize Nb3Sn-AlN-Nb and NbN-AlN-Nb structures to flat samples as well as to cavities. In the first stage, we performed the film-formation tests of the Nb and NbN thin-films, and the mixture layer of Nb, Sn and AlN. In addition, we tried to evaluate the sputtering speed and the degree of adhesion on several films of different characteristics. We will report on the film-formation apparatus and the results of several film-formation tests, and will discuss the future plan.

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Enhancement of the lower critical field in Fe(Se,Te)-coated Nb structures for superconducting radio-frequency applications

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Bulk Nb superconducting radio-frequency (SRF) cavities are widely used in accelerators, and their accelerating gradient and general performance are limited by the superheating field (Bsh). To push the theoretical limit of the Bsh, new multilayer structures are required. We fabricated Fe(Se,Te)-coated Nb films using pulsed laser deposition, performed structural characterizations, and measured the

transport and magnetic properties for this superconductor-superconductor bilayer structure with smooth surface. Additionally, the measured Bc1 of Fe(Se,Te)-coated Nb film is greatly enhanced, while the Bsh of the Fe(Se,Te) layer is expected to be higher than that of bulk Nb, yet the superconducting transition temperature (Tc) is less than 10 K. We presents the first fabrication of a new coating layer: Fe(Se,Te) deposited on Nb, showing the possibility of using iron-based materials for multilayer structures in SRF cavities.

Advanced substrates / 79

Copper full-seamless substrate cavity manufactured by hydroforming

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The general method for manufacturing superconducting accelerating cavities with an elliptical cell shape is to press-form niobium sheets into a bowl shape and join them together using electron beam welding (EBW). Research on manufacturing cavities at a low-cost using hydroforming instead of EBW has been achieved. Another research has been actively conducted in recent years to manufacture the cavity body from copper and coat niobium inside to develop superconductivity for reducing the cost of superconducting cavities. The purpose of this research is to manufacture a seamless cavity from a single copper tube. In 2023, through collaborative research with Neuron Japan Co. Ltd., we succeeded in prototyping a 1.3 GHz one-cell copper cavity. We tried forming a single tube into a hollow shape at once but found it difficult, so we devised a two-step forming process. Two kinds of dice are prepared and finished by hydroforming only. Copper has better formability than niobium, but there is no industrial application to expand such an enormous size by hydroforming. Here, it is necessary to increase the circumference by 2.4 times. In this process, the material is expanded significantly, so an elongation of the material is significant, but minimizing the wall thickness distribution is even more critical. So far, we have successfully manufactured more than ten cavities and confirmed high reproducibility. This study collaborated with CERN, and the two completed copper full-seamless cavities were coated with niobium inside using a magnetron sputtering at CERN. The thickness of the niobium film is approximately 5 µm. Afterward, RF tests were performed at KEK. The acceleration gradient attained CERN's target value of 12 MV/m at 4.27 K. The Q value was a little low. Also, at 1.85K, the maximum acceleration gradient of 15.7 MV/m was obtained. We got a good result for the first cavities.

Advanced substrates / 80

Additive manufacturing at LNL

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3D additive fabrication of Cu cavity with cooling channeling at CEA

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One of the most promising avenues of research for next-generation superconducting cavities is to increase the operating temperature ≥ 4.2 K by depositing new thin-film superconducting materials with temperatures at least twice as high as the Niobium currently used. These possibilities pave the way for the development of new cooling techniques (cryocooler with liquid He cooling circuits integrated into the cavity wall). One of the major problems is the evacuation to the cold source of the energy deposited inhomogeneously inside the cavity. I will present the materials and surface characterization of pure Cu 3.9 Ghz cavities fabricated by additive manufacturing (selective laser melting) with cooling channels imbedded in the walls. The cryogenic test will also be presented.

Advanced substrates / 82

Plasma Electrolytic Polishing for SRF

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"The performance of superconducting radio frequency (SRF) cavities is critically influenced by surface preparation. Traditionally, electropolishing (EP) has been employed to achieve a clean, low-roughness surface on both niobium (Nb) and copper (Cu) substrates, despite requiring harsh and corrosive acids. Since 2019, our research at LNL has focused on an alternative approach: Plasma Electrolytic Polishing (PEP). This method uses only diluted salt solutions, presenting several advantages over EP, including a superior removal rate (2-8 μm/min for Nb and 3-30 μm/min for Cu) and achieving a surface roughness (Ra) lower than tens of nm. Additionally, we have significantly optimised the process by using external cathodes instead of internally placed ones inside the elliptical cavity.

In 2022, we established the initial recipes for PEP, and four of them were subsequently patented in 2023. Our first successful applications included a Cu 6 GHz elliptical cavity. Since then, the workflow for cavity preparation at LNL has incorporated PEP, effectively substituting EP. Our achievements allowed us to extend PEP to QPR samples, underscoring its versatility and effectiveness. PEP has demonstrated its potential not only for SRF cavities but also for other accelerator components, such as couplers. We have achieved remarkable results on 3D-printed substrates, suggesting that PEP is nearing readiness for production and optimisation phases.

Scaling up such a process is extremely difficult, as the working and peak current densities are close to 0.2-0.6 A/cm^2, meaning that a 1.3 GHz cavity might require a few hundred amperes of current. In this work, we present our results on successfully applying PEP to dummy bulk Cu 1.3 GHz samples, followed by PEP testing on a 1.3 GHz cavity scheduled for this month. This abstract outlines our journey and the promising future of scaling up PEP for Cu substrates."

Advanced substrates / 83

Rapid electropolishing of niobium in non-aqueous solvents

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Niobium EP and BCP progress has the problems of slow polishing rate and high risk of electrolyte. In order to solve this, our team uses a less hazardous and more environmentally-friendly HF-free electrolytes, non-aqueous solvent as electrolyte. High efficiency polishing of niobium can be achieved by applying high pulse voltage. The polishing rate is dozens or even hundreds of times that of traditional electric polishing. The polishing rate is tens or even hundreds of times that of traditional EP. The influence of working parameters on the electropolishing rate and surface effect of niobium is investigated.

SRF Thin Films Characterization / 84

Depth-resolved characterization of superconductor-superconductor bilayer properties beneficial for SRF applications

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Coating Nb with thin layers of one or more superconductors with longer penetration depths, λ, has been proposed to achieve accelerating gradients, E_{acc}, beyond Nb's fundamental limit. Such heterostructures can sustain the Meissner state above each layer's superheating field, B_{sh}, due to the strong suppression of the screening currents in the surface layers by a ''counter-current" in the substrate and the presence of interfacial energy barrier between material junctions. We infer the presence of interfacial energy barrier by measuring the first-flux-penetration field, $\mu_0 H_{\mathrm{vp}}$ in superconductor-superconductor (SS) $\mathrm{Nb_3Sn}$(2 µm)/Nb samples using muon spin rotation (μSR). Using thin Ag foils as energy moderators for the implanted muon spin probes, we profiled $\mu_0 H_{\mathrm{vp}}$ at sub-surface depths between 10 µm and 100 µm, finding that $\mu_0 H_{\mathrm{vp}}$ is depth-independent with a value of 234.5 ± 3.5 mT, consistent with Nb's metastable B_{sh} and a surface energy barrier preventing flux penetration. Similarly, evidence for current suppression in SS $\mathrm{Nb_{1-x}Ti_xN/Nb}$ samples was observed from nanoscale (depths
$lesssim$ 150 nm) measurements of their Meissner screening profiles in applied fields ≤ 25 mT using the low energy μSR. The observed bipartite form of the screening profiles quantitatively confirm the Meissner response predicted by the ''counter-current" model, which we use to identify the optimal $\mathrm{Nb_{1-x}Ti_xN/Nb}$ coating thickness for maximizing the $\mu_0 H_{\mathrm{vp}}$. Our results of strong suppression of the Meissner currents in the surface layer suggest that multilayered structures with several superconducting and insulating layers are necessary to reach the highest E_{acc}.

SRF Thin Films Characterization / 85

Positron annihilation spectroscopy: pursuing point defects in superconducting film

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"Positron annihilation spectroscopy (PAS) is a precise probe of point defects in nanomaterials. It enables to sense defect densities in the range of 1015-1019cm-3. Positrons localize in the neutral and negatively charged open volume defects, i.e. vacancies and their agglomerations, extended defects or pores. The time to annihilation of the positron with an electron depends on local electron density and it scales with the open volume size. The annihilation process itself leads to emission of gamma radiation, which is subsequently measured. Positrons pre-accelerated to a given kinetic energy can be implanted into solids, allowing depth profiling. In a defect positron lifetime increases and the energetics of the annihilation photons changes. These characteristics are measured using two main measurement techniques, namely positron annihilation lifetime (PALS) and coincidence Doppler broadening spectroscopy (cDBS), respectively. Both techniques are available at the user facility ELBE (HZDR, Germany). PALS allows to evaluate the defect size and concentration, while cDBS is sensitiv to the local atomic chemistry.
This contribution discusses the role of defects in superconducting materials, candidates for coatings of SRF cavities. The advantages of using PAS to evaluate defect concentration and chemistry in Nb have been demonstrated for vacancy-hydrogen complexes during low temperature baking [1] as well as in case of vacancy kinematics and evolution of native Nb oxides for baking at larger temperatures [2]. A combination of PAS and DFT calculations has transformed the experimental results into defect types/sizes and highlighted the role of vacancy complexes and Nb oxides onto performance of cavities. We will present the most recent evaluation of defect microstructure in DC- and HiPIMS-sputter deposited Nb, NbN, and NbTiN films.
[1] M. Wenskat et al., Sci. Rep. 10 (2020) 8300
[2] M. Wenskat et al., Phys. Rev. B. 106 (2022) 094516"

SRF Thin Films Characterization / 86

Thermal Conductance measurements of SIS & Nb3Sn coated samples at cryogenic temperatures

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Stable operation of a cavity generally requires Joule-heating, generated in its walls, to be conducted to an outer helium bath. Therefore, it is of interest to experimentally evaluate how present and future cavity treatments affect thermal characteristics. We present an instrument for measuring the thermal performance of SRF cavity materials at cryogenic temperatures. To get an idea of the instrument's sensitivity and how standard cavity treatments influence thermal resistance, samples are tested post fabrication, polishing and 800 ℃ baking. Furthermore, first measurements of the thermal conductance at 2K of SIS coated Nb samples and of Nb3Sn coated Nb samples are presented.

SRF Thin Films Characterization / 87

Development of 1.3 GHz Cavity Test Facilities

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At Daresbury Laboratory, two new cryogenic facilities have been designed, built and tested for RF testing of 1.3 GHz thin film coated cavities. The first facility is a high power vertical test stand that has been designed to test both single-cell and multi-cell cavities in LHe at 2 and 4.2 K. The advantage of this facility is that it will be operating in the SuRF lab facility that is already equipped with all necessary infrastructure (RF, cryogenic, vacuum, clean room, HPR, trained staff). However, this facility is shared with other projects, limiting the number of tests per year.

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Progress in the design and testing of thin film on longitudinal split RF cavity

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Copper cavities can be deposited with a thin film of superconducting material in order to test the RF performance of the thin film. Traditional thin film copper cavities are produced from 2 half cells, which are then welded across the equator, however these cavities can suffer from poor coating quality and field enhancement on the weld.
An alternative approach instead involves producing cavity halves that are split longitudinally, parallel to the surface current. This means that a gap can be introduced, that the fields are unable to couple into. As a result, the weld can occur further from the fields in the cavity which may improve cavity performance. Additionally, longitudinally split cavities offer advantages such as enabling different deposition processes and facilitating easier quality control due to their open-face design.
This paper discusses the performance of a range of thin film coatings on a 6 GHz longitudinally split cavity as well as improvements to the future design of the cavity which should result in reduced uncertainties when testing thin films on the cavity.

SRF Thin Films Characterization / 89

RF Characterisation of Planar Thin Film Coated Sample

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At Daresbury Laboratory, fast RF characterisation of planar thin film coated samples is being performed on a dedicated facility. It is a LHe-free facility using a 7.8 GHz Choke Cavity to test planar samples 90-130 mm in diameter and 2-10 mm thickness. A simple sample mounting procedure, and straightforward measurements of surface resistance using an RF-DC compensation method, allows this facility to achieve a high throughput of 3 sample tests per week at temperatures from 4.2 K and low peak magnetic fields up to 20 mT. With this facility, mass deposition parameter studies have been performed with Nb, Nb3Sn and NbTiN, and is suitable for other materials such as V3Si, MgB2 and SIS structures. This facility is an easily available step prior to RF testing with more complex sample geometries such as QPR and split cavities, enabling low-effort, thin film optimisation prior to cavity depositions.

SRF Thin Films Characterization / 90

First magnetic field penetration results of Multilayer samples and A15 materials for the use in SRF applications.

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Superconducting radiofrequency cavities made of bulk Nb are reaching their theoretical limits in the maximum accelerating gradient, Eacc, where Eacc is limited by the maximum magnetic field, B, that can be applied on the surface of the accelerating cavity wall. To increase Eacc, the maximum B field, Bmax, which can be applied to the surface, must also be increased. The A15 materials or multilayer structures are the potential solution to increase Bmax., Since coating and RF testing of full size RF cavities is both expensive and time consuming, one need to evaluate new ideas in superconducting thin films quickly and at low cost. A magnetic field penetration experiment has been designed and built at STFC Daresbury Laboratory to test superconducting samples (< 100 mm ⊠). The facility produces a parallel DC magnetic field, which applied from one side of the sample to the other similar to that in an RF cavity. The facility applies an increasing magnetic field at a set temperature to determine the field of full flux penetration which can give an insight into the quality and structure of the superconducting structure. The facility has been characterised using both type I and type II superconductors and is now producing results from new novel materials such as the A15 and Thinfilm samples which will be presented.

SRF Thin Films Characterization / 94

Enhancement of magnetic flux expulsion in multilayer structures

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A program of quantitative measurements of the expulsion of magnetic flux from flat macroscopic samples has been used to categorise expulsion efficiency, and to assess the practical expulsion effects of closed-topological cooling on thin film structures. Specifically, the closed-topology cooling has permitted systematic and repeatable measurements of the magnetic response over the superconducting transition for bulk, thin film and multilayer samples. Particular interest is the magnetic response of superconductor-insulator-superconductor (SIS) multi- layer structures that exhibit a magnetic response that is both enhanced and characteristically different to that of bulk niobium. For SIS multi-

layer samples under closed topology cooling, we observe a response that we term "flux ratcheting"
.

Functional Layers -Synergies / 95

Characterization of PEALD Coated Thin Films for SRF Cavity Research

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This study aims to assess the quality of PEALD-based SIS films and involves several steps to show significant correlations between different measurement results. The growth per cycle is determined by XRR, from which the respective thicknesses of the PEALD-coated thin films are derived. The results are used to determine the London penetration depth λL of a thin superconducting NbTiN layer during a LE-μSR measurement. The penetration depth is further used to predict the theoretical superheating field Hsh and the optimal value for the maximum applied magnetic field that multilayer-coated niobium can withstand. The investigation of the magnetic flux expulsion of multilayer-coated Nb samples, presented by D. Turner et al., shows that post-deposition annealed thin films exhibit tremendous magnetic flux expulsion even if they do not achieve a high critical temperature Tc due to presumed oxygen diffusion. Further Tc measurements on SIS-coated Nb and Si samples yield the maximum value of Tc,NbTiN = 15.96K, which is the highest value of such thin films coated by ALD ever measured. All these results contribute to the understanding of the underlying theoretical model, predictions for SIS multilayer films and their potential in future applications.

Functional Layers -Synergies / 96

Point Contact Tunneling Spectroscopy for Qubits and SRF cavities

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Point Contact Tunneling Spectroscopy (PCTS) is a powerful technique ideal for investigating the surface superconducting properties of materials. Since it utilizes the oxides present on the sample's surface to probe the superconducting density of states, this tool is valuable for studying devices such as qubits and SRF cavities, where a native or engineered oxide layer is present on the surface. PCTS can uncover various phenomena at the oxide/superconductor interface, such as the presence of magnetic impurities or the proximity effect, which might play a significant role in the performance limitations of superconducting devices. Therefore, PCTS is highly useful for understanding the mechanisms that limit the capabilities of these devices, potentially leading to technological solutions. I will present PCTS results obtained on Ta/Nb samples for Qubits applications as well as Nb3Sn and ALD-coated Nb samples for SRF applications.

SRF Thin Films Characterization / 97

CW mode test and electromagnetic-thermal simulation of conduction-cooled SRF cavities at PKU

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A liquid helium-free cryostat for RF testing of superconducting cavities has been designed and constructed. G-M cryocoolers are used to provide cooling capacity, with heat leakage less than 0.02 W at 4 K. The vertical test of the Nb3Sn cavity and the horizontal test of the Nb cavity were carried out with the cryostat using different connection structures between the 4 K stage of the cryocooler and the cavities. Both cavities are cooled down to 4 K and stable CW operation was achieved at low Eacc The Q0 of Nb3Sn cavity tested was very close to that in 4.2 K LHe when the EACC was less than 1.2 MV/m. The maximumEacc of Nb3Sn cavity and Nb cavity reached 1.75 MV/m and 0.43 MV/m, respectively. The test results showed that the thermal uniformity of the cavity can be effectively improved by cold spraying a ˜2 mm thick Cu layer on the outer surface of the cavity. An electromagnetic-thermal coupling simulation model for superconducting cavities was established and a novel connection is designed based on the cold spraying process and high thermal conductivity Cu and Al. Under worst-case conditions, the simulation results indicated that the cavity temperature can be controlled at about 5 K when the RF loss is 2.7 W using this connection. For a Nb3Sn cavity prepared by the authors (Q0=2×109 @ Eacc=10 MV/m), the Eacc is expected to reach at least 7 MV/m. A Nb3Sn cavity cold-sprayed with a 2 mm thick Cu shell and flanges is currently being processed to validate this connection design.

Functional Layers -Synergies / 98

Surface engineering by atomic layer deposition and heat treatment for 3D Niobium resonators for applications in superconducting qubits

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"Superconducting radio frequency (SRF) resonators are newly being used in the quantum regime (at temperatures below 1 Kelvin) for integration into 3D quantum computing processing units. The motivation behind these new applications lies in the fact that SRF cavities offer a coherence lifetime that is 1000 times longer than other 2D qubit architectures and provide sensitivities that are orders of magnitude higher. Nonetheless, SRF cavities still suffer from dielectric losses arising from two-level systems (two-state defects) dissipations present in the native oxide layers that forms once the superconductor is exposed to air. In this context, we are testing an approach consisting in passivating the surface of Niobium with thin ALD-deposited oxide films followed by thermal treatments. This approach resulted in a significant reduction of TLS and a great enhancement of their quality factor at low fields [1]. In our talk, we will present cavity results from various surface engineering routes that have state-of-the-art quality factors (Q ˜ 1011 at low fields). Surface characterization such as XPS and TEM will also be discussed in order to correlate the changes in the quality factors with the chemical and structural aspects of the surface.

[1] Yasmine Kalboussi et al, Reducing two-level system dissipations in 3D superconducting Niobium resonators by atomic layer deposition and high temperature heat treatment. Applied Physics Letters, 2024, 124 (13), pp.134001. ⟨10.1063/5.0202214⟩. ⟨hal-04470953⟩"

Functional Layers -Synergies / 99

Atomic layer deposition of Ta2O5 - a new material for coating cavities

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To achieve higher acceleration gradients, we are investigating alternatives to classical superconducting niobium cavities. New concepts, such as passivating the high-loss native oxide surface or employing multilayer systems, are promising approaches. Atomic layer deposition (ALD) has proven to be a suitable method for coating the inner surface of a cavity homogeneously and with sub-nanometer precision without shadowing effects using various materials. Our research team has successfully coated several cavities with Al2O3 and conducted cryogenic RF tests. Preliminary measurements of the secondary electron yield and crystallization temperature of Ta2O5 deposited in our ALD reactor, reveal promising results compared to Al2O3. Consequently, process optimization for tantalum oxide must be conducted, focusing on minimizing the thermal load on the cavity to prevent parasitic diffusion of interstitial atoms. Samples will be placed at various positions in a cavity and characterized ex situ as-prepared and after post-deposition treatments by a variety of surface analysis techniques, e.g., SEM, EDX, SEY and XRD. Finally, after fully understanding the process, a single-cell SRF cavity will be coated and tested.

Functional Layers -Synergies / 101

Thin films to mitigate multipacting

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Multipacting in particle accelerator elements such as drift tubes, superconducting radiofrequency resonating cavities (SRF), couplers⋯is a major challenge. The multipacting phenomenon is strongly dependent on the surface total electron yield (TEEY) and developing thin film coatings materials to reduce the surface TEEY is of critical importance. In most cases however, the surface dissipation induced by the RF field is also a critical parameter and the thin film electrical conductivity has to be tuned accordingly. For each application, an optimal set of TEEY and the conductance values is required. In order to be able to control both independently, a possible solution is to develop a thin film heterostructure based on the mixing of a low TEEY, electrical conductor material with a high TEEY, dielectric material in order, for instance, to obtain a low TEEY, dielectric coating that will prevent both Multipacting and a decrease of surface losses quality factor. We choose Atomic Layer Deposition method to achieve that goal and we will present results obtained with coatings made of multiple layers to verify that this solution is relevant. Electrical conductivity and TEEY measurements carried out on these multimaterial multilayered coatings shown that, effectively, both properties vary according to their composition and their structure

Functional Layers -Synergies / 102

Status of the Inner-wall Thermal Conducting Film (ITCF) Study

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To enhance heat-transfer efficiency in SRF cavities, we previously introduced a novel approach that coats the cavity with an inner-wall thermal-conducting film (ITCF). Simulation results showed that ITCF absorbs heat from the RF surface and transmits it to cooler neighbouring regions on the inner wall, thereby reducing the heating-point temperature via an extra heat-transfer route. This work presents the set-up of the cryogenic temperature multi-test system in IMP, the preliminary thermal conductivity test for relevant materials that include substrate and film, and the coating properties of ITCF candidates on small samples.

Perspective of SRF thin films in accelerators and other applications / 103

Exploring the perspectives of superconducting materials in SRF for quantum sensing

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RF properties of superconductors (SC) in high magnetic fields have recently become of great interest in view of their applications in large experiments in fundamental physics. Indeed, the quantum sensing of dark matter axions [1] and other elusive signals such as high frequency gravitational waves (GW) [2], or the beam screen for the CERN Future Circular Collider (FCC) [3], can greatly benefit from SC low RF dissipation in the vortex state.
The realization of high-Q SC rf cavities for quantum sensing of axions (haloscopes), and possibly of GW, requires both the understanding and subsequent optimization of the surface impedance Z of the material, with a focus on the dynamics of pinned vortices which govern the achievable Q, and the related development and tuning of the coating technique.
Beside the leading actors (vapor diffused Nb3Sn, sputtered NbTi [1], YBCO tapes glued on multipiece cavities), other innovative SC, namely Fe-based and Tl1223, could play a role due to the potentially more scalable deposition techniques (electrodeposition and high pressure reaction, respectively), despite the present embryonic development phase.
Starting from measurements of Z in the 14-27 GHz range, in dc magnetic fields, in well-developed SC (NbTi, YBCO), we identify the main physical properties responsible for the performances of haloscopes. Although obviously vortex pinning plays a major role, the often-disregarded flexibility of vortex lines and the length of the penetration depth strongly affect the overall Q in real haloscopes, so that the choice of the material is not obvious.
Based on these findings, we present an improved comparison of the potential performances of several SC materials, including more exotic Fe-based, evaluated in a large (temperature, field, frequency) parameter space [4].

Acknowledgments
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4. A. Alimenti et al, Instruments 6, 1 (2022)"

Perspective of SRF thin films in accelerators and other applications / 104

SRF compact accelerators

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The development of simpler, compact Superconducting RF (SRF) systems represents a new research thrust in accelerator science. These compact accelerators rely on advancements made to both Nb3Sn SRF cavities and commercial cryocoolers, which together allow to get rid of the operational requirement for liquid cryogenics. This approach to SRF cavity operation, based on novel conduction cooling schemes, has the potential to drastically extend the range of application of SRF technology. By offering robust, non-expert, turn-key operation, such systems enable the use of SRF accelerators for

industrial, medical, and small-scale science applications. An overview of the significant progress being made around the world will be given, including stable cavity operation at 10 MV/m. The primary challenges of this new field and their potential solutions will be discussed, along with an overview of the various applications which could benefit the most from this technology

Thin films Roadmap (in common with IFAST WP9) / 105

IFAST report

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CERN roadmap for thin films R&D

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Thin film road map in Snowmass

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Roadmap discussion 1: R&D on Nb/Cu

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Roadmap discussion 2: Nb3Sn

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Roadmap discussion 3: Other Superconductors

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Roadmap discussion 4: R&D on SIS

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Roadmap discussion 5: R&D on Surface functionalization

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Roadmap discussion 6: Copper substrate fabrication and surface preparation

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Roadmap discussion 7: General characterization/surface sciences

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Roadmap discussion 8: Cavity preparation and RF testing

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Roadmap discussion 9: theory

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Roadmap discussion 10: Industrialization

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Discussion time

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Closing remarks