8th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

Monday, 8 October 2018 - Wednesday, 10 October 2018

INFN - Laboratori Nazionali di Legnaro

Book of Abstracts

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ARIES WP15 - Thin Film for Superconducting RF Cavities

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The ARIES H2020 collaboration has started in May 2017. One of the main goals of ARIES is to developing and demonstrating novel concepts and further improving existing accelerator technologies. A successful proposal for a work package on systematic studying and developing the superconducting thin film for superconducting RF cavities joint a team of 8 partners (research groups) from 7 countries. In this talk we will report the 4-year collaboration program and results obtained in the 1st year.

Thin film for SRF cavities perspectives / **49**

EASITrain, an innovative network on superconductor & cryogenics

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The greatest challenges for wide-spread adoption of new applications of superconductivity remain the limited understanding of how to apply the fundamental principles on an engineering level and the capability to deploy the technology cost effectively on a large-scale.
EASITrain offers a cross-sectoral training program that is a fine blend of engineering, fundamental research and the development of real-scale applications in close collaboration with industry.
The EASITrain initiative aims to train the next generation of experts and establish a solid education curriculum to exploit the huge transformative potential of superconductivity.
Key research objectives include: Advance superconductor wire performance and production, develop industrial production methods, develop large-scale energy efficient cooling and deepen our understanding of the underlying mechanism of superconductivity.
In this contribution an overview is given of the EASITrain network and its part in current research.

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN)receives funding from the European Union's H2020 Framework Programme under grant agreement no. 764879.

Nb film technology & RF performance / 53

Energetic Condensation For The Mitigation Of Nb/Cu Q-Slope

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With the development of energetic vacuum deposition techniques, high quality Nb films have been produced supporting the promise of high RF performance. In energetic condensation, the controlled incoming ion energy enables a number of processes such as desorption of adsorbed species, enhanced mobility of surface atoms and sub-implantation of impinging ions, thus producing improved film structures at lower process temperatures. Significant progress has been made in recent years in using ion energy and thermal energy provided during growth to influence the nucleation, structure and material quality of Nb films. By decoupling the film-substrate interface, nucleation and subsequent growth, one can create a favorable template for optimising the final surface exposed to SRF fields. Films deposited by HiPIMS (high power impulse magnetron sputtering) and ECR (electron cyclotron resonance) plasma show promise in improved superconducting and RF behavior compared to magnetron sputtered Nb films. This contribution presents the ongoing efforts at JLab to optimize energetic condensation Nb/Cu films for RF Q-slope mitigation.

Nb film technology & RF performance / 48

Nb thick films deposited in multilayer mode onto 6GHz resonant cavities

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Thick films shows the possibility to obtain a mitigation of a Q-slope in Nb on Cu superconductive resonant cavities. In the framework of EASITrain project and CERN-INFN-STFC collaboration, the multilayer technique was applied in order to deposit a 70-microns thick film of Niobium onto 6 GHz seamless copper cavities. In this contribution, we report the results and challenges of the RF characterization and the future developments in order to increase the reproducibility of the 6GHz superconductive cavities performances.

Nb film technology & RF performance / 11

Ar-Nb ion energy distribution and thin film properties in HiPIMS with a positive voltage pulse

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The Wide Open Waveguide (WOW) Crab cavity [1] has been designed in the framework of the Future Circular Collider study. It features a thin Nb film sputtered on bulk copper [2]. The main advantages with respect to bulk Nb include the improved thermal stability, and the reduction of the cavity frequency sensitivity to the external liquid He bath pressure variations as well as to the Lorentz force detuning. However, the complexity of the geometry, including concave and convex surfaces on meter scale, constitutes the main drawback. The necessity to get a dense and defect-free Nb film to satisfy the Radio-Frequency (RF) specifications requires dedicated investigations to identify and optimize the coating technique as well as the cathode design.
In this work we focus on High Power Impulse Magnetron Sputtering (HiPIMS) with the inversion of the voltage after the main negative pulse to accelerate the ions towards the substrate. This is a potential candidate to avoid the biasing of the cavity during the coating process. The evidence of a high energy population of Ar and Nb ions is first presented by implementing an energy and mass analyser. Features of thin films obtained from DCMS (with and without biased substrate) and from HiPIMS (with and w/o biased substrate, with and w/o reverse voltage) are compared. In particular, Focused Ion Beam (FIB) analysis has been performed on coated samples tilted at 0o, 45o and 90o with respect to the target.

[1] R. Calaga, Proceedings of Chamonix 2012 workshop on LHC Performance.
[2] A. Grudiev, et al. Proceedings of SRF 2015, Whistler, BC, Canada.

Nb thin film technology in QWR / 23

Niobium coating of complex accelerating cavities geometries

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Superconducting thin film coatings offer a valuable alternative to conventional bulk niobium cavities mainly by reducing the cost of raw material and enhancing the heat exchange efficiency thanks to the copper substrate thermal conductivity. The current and future superconducting radiofrequency (SRF) cavities designs and working frequencies lead to a variety of shapes and sizes to be coated. In this work we present an update of CERN activities in this field with an overview of current cavities production and R&D. We will focus on the coating of HIE-ISOLDE substrate using a double cathode setup to minimize the inner and outer conductor thickness differences and on the coating of the Wide Open Waveguide (WOW) cavity, an alternative Nb/Cu crab cavity, with support of plasma and transport simulations. Finally, we will discuss the impact of the substrate quality and preparation and the way it affects the coated layer properties.

Nb thin film technology in QWR / 3

325 MHz Dummy QWR Cavity Coating Experiences at IMP

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The possibility that CIADS uses only Nb/Cu cavities has been discussed at IMP. A 325 MHz dummy QWR cavity has been fabricated at IMP for technique demonstration. The cavity has been coated for a few runs, with small samples attached to the inner surface and bare cavity only. The small samples manifested a complete superconducting coverage. Vertical testing results suggested the Nb/Cu technique is a promising candidate for the next phase CiADS project.

Nb thin film technology in QWR / 56

QWR coating @ LNL in the framework of ALPI accelerator upgrade for the SPES project

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In the framework of the ALPI Upgrade for SPES project, new cryostats with 8 new high beta QWR cavities needed to be produced. In order to carry out this upgrade, a refurbishing of the sputtering system for QWR coating was performed. Now the sputtering system is working and first test coating on quarts'substrate are in progress. Simultaneously the chemical plant and QWR cold test facility maintenance is going on. The talk summarizes the LNL upgrade activity on ALPI accelerator last years, especially for SPES project and the status of QWR coating.

Theoretical modelling of RF behaviour / 29

A simple model for the RF field dependence of the trapped flux sensitivity based on a non-linear pinning force

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Recently, the improvement of RF superconducting cavities performances has motivated a considerable research effort to elucidate the effect of trapped magnetic flux. Here we will show that by introducing a non-linear pinning force in the Gittleman-Rosenblum equations for the RF power dissipation due to an external trapped magnetic field in a superconductor, we can describe most of the common experimental features. In particular, the linear dependence on the RF field amplitude , the proportionality between the RF-field-dependent and independent parts and , and the frequency dependence of stem naturally from this approach.

Theoretical modelling of RF behaviour / 16

Two different origins of Q-slope problem in a Nb film cavity for HIE-ISOLDE

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Since their invention, the performance of Nb film cavities has always been limited by a strong Q-slope. Recent tests at CERN of the newly developed seamless Quarter-Wave Resonator (QWR) showed an interesting decomposition of the Q-slope, which might help to explain/cure this limitation. One is caused by non-linear trapped flux oscillation in the residual component, whose surface resistance depends linearly on the RF field strength. The other is the medium-field Q-slope, which depends exponentially on temperature and RF field. Once the trapped flux is suppressed by using magnetic field compensation during cool down upon superconducting transition, the cavity's Q-slope at superfluid temperature was as small as for bulk Nb cavities up to peak magnetic fields of 120 mT. We argue that the Q-slope problem in low-frequency Nb film cavities originates from environmental conditions. These cavities are typically operated in normal fluid without magnetic shielding. Thermal gradients in the previous design of HIE-ISOLDE QWRs may give rise to thermoelectric currents during cool down, and thus dominate trapped-flux induced Q-slope in the residual resistance. We also study the fundamental cause of medium-field Q-slope and compare it with several models. Reducing the Q-slope of Nb coated cavities would make them an interesting and cost-effective alternative to bulk Nb cavities for an increased number of applications.

Theoretical modelling of RF behaviour / 28

Trapped flux sensitivity in the low amplitude radio-frequency regime

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In this study, the radio-frequency complex response of trapped vortices in superconductors calculated for small values of applied radio-frequency field, will be presented. In agreement with experimental data on bulk niobium radio-frequency cavities, the calculated surface resistance shows a non-monotonic trend as a function of the mean-free-path and a sigmoidal-like trend as a function of the frequency. These two trends are shown to be generated by the interplay of two different dissipation regimes - pinning and flux-flow - which can be tuned either by acting on the material parameters (mean-free-path, pinning sites configuration, pinning strength, coherence length and penetration depth) or on the resonator frequency. Important perspective on the trapped flux surface resistance for thin films and innovative materials at low RF field values will be also discussed.

Theoretical modelling of RF behaviour / 7

A theory of field-dependent surface resistance and possibilities of engineering optimal SN and SIS surface nano-structuring of the SRF cavities

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We propose a theory of the nonlinear surface resistance of a dirty superconductor in a strong RF field, taking into account realistic materials features, such as magnetic and nonmagnetic impurities, subgap states originating from finite quasiparticle lifetimes, and a proximity-coupled normal layer at the surface. The Usadel equations with the RF pair-breaking current are solved to obtain the quasiparticle density of states (DOS) and the low-frequency surface resistance Rs as functions of the RF field amplitude H0. It is shown that interplay of the broadening of the DOS peaks and a decrease of a quasiparticle gap caused by the RF field produce a minimum in Rs(H0) and an extended rise of the quality factor Q(H0) with the RF field. Paramagnetic impurities shift the minimum in Rs(H0) to lower fields and can reduce Rs(H0) in a wide range of H0. Subgap states can give rise to a residual surface resistance while reducing Rs at higher temperatures. A proximity-coupled normal layer at the surface shifts the minimum in Rs(H0) to lower fields and can reduce Rs below that of the perfect surface without the normal layer. The theory shows that the behavior of Rs(H0) can change as the temperature and the RF frequency are increased. Our results explain why the field dependence of Q(H0) can be very sensitive to the materials processing and suggest that the surface resistance can be minimized by engineering optimum impurity concentration or properties of the surface normal layer. Applications of the theory to the SIS structures and multilayer coatings of the SRF cavities are discussed.

Open Discussion / 60

Nuclotron based Ion Collider fAcility - Injection complex development

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The New Injector Linac for Nuclotron-Nica is the proposed replacement for LU-20 accelerator. The possibility of old DTL LU-20 replacement by the new superconducting (SC) linac of 30 MeV energy for protons and ≥7.5 MeV/nucleon for deuterium beam is discussed now. The development of the SRF technologies is the key task of new Russian - Belarusian collaboration. The collaboration of JINR, NRNU MEPhI, INP BSU, PTI NASB, BSUIR and SPMRC NASB started in 2015. According to the concept of the new SC Linac for Nuclotron-NICA, 162.5 MHz quarter-wave resonators (QWR) with geometric velocity of 0.12c will be used for the first group of the cold part of the accelerator. The second group of cold cavity resonators is designed for a frequency of 324 MHz, velocity 0.21c and 7.7 MV/m accelerating gradient. Currently JINR, NRNU MEPhI and INP BSU start the new collaborative R&D project "Investigation of the features of obtaining and metrology of the coating of the Nb and Nb3Sn system based on Cu in order to create superconducting high-frequency resonators for mega-rate accelerators". Results of lianc and SRF technologies will presented in this report

Other SC Materials beyond Niobium / 10

Development of MgB2/Cu cavities by HPCVD

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MgB2 is a promising superconductor to replace Nb for SRF cavities. Clean MgB2 thin films have a low residual resistivity (<0.1 μΩcm) and a high Tc of 40 K, promising a low BCS surface resistance. Its thermodynamic critical field Hc is higher than Nb, potentially leading to a higher maximum accelerating filed. The lower critical field Hc1 of MgB2 is lower than Nb, but it can be enhanced by decreasing the film thickness. MgB2 coated Cu cavities have an added advantage from the high thermal conductivity of Cu, which will enhance the heat transfer from the MgB2 layer, improving the cavity's resistance to "quenching."MgB2 coated Cu cavities working at 20 - 25 K will eliminate the need for liquid He refrigeration. I will present the latest results of our research on the coating of mock 3.9 GHz Cu cavity by hybrid physical-chemical vapor deposition (HPCVD). The materials issues involved in MgB2 thin films on Cu will also be discussed.

Other SC Materials beyond Niobium / 15

Initial results from investigations into the use of NbN thin films sputter coated onto copper for SRF applications.

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Considerable research is currently underway to utilise alternative materials to bulk Nb in SRF cavities. This is with the aim to increase their performance to that required by future accelerators. In this contribution, the results of two investigations into dc magnetron sputtered Nb thin films on Cu substrates are summarized, as well as initial results from research which has been conducted into the use of NbN thin films as an alternative to Nb thin films. This is part of the EASITrain and ARIES programs. The Nb samples were prepared using a high and low value for the deposition temperature, bias voltage and cathode power to observe the effects on the film adhesion. To test the adhesion the films were subjected to scratch tests. In the second part, the deposition parameters remain unchanged to investigate the effects of the substrate preparation method on the properties of Nb thin films. Five different pre-treatments have been investigated: electrochemical polishing (EP), tumbling, EP plus SUBU, and SUBU. The latter have been done at two different institutes, CERN and INFN, the rest at INFN only. Samples were prepared in a Cemecon CC800 commercial coating system. The Initial NbN samples focused on the effects of varying N2 partial pressure, in an Ar-N2 gas mixture, on the film thickness, surface roughness and Nitrogen content. Samples have been characterised using, AFM, SEM, EDX, SIMS and XRD measurements.

Other SC Materials beyond Niobium / 21

Surface Characterization of NbTiN multilayer films for accelerator applications

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Further enhancement of superconducting accelerating cavity performance calls upon the development of materials beyond bulk niobium (Nb). Superconducting RF (SRF) is a surface phenomenon; for most superconducting materials the RF penetration depth is in the range of hundreds of nanometers. Due to the field penetration enhancement occurring in films with a thickness smaller than their nominal penetration depth, multilayer superconductor/insulator/superconductor (SIS) structures are theorized to have potential to support surface magnetic fields beyond the reach of the current SRF cavities. A candidate superconductor for SIS structures is the ternary compound NbTiN. SIS structures based on NbTiN and AlN are currently under development at JLab. NbTiN can be deposited with nominal superconducting parameters using DC reactive magnetron sputtering. This contribution presents the characterization of surface, material and superconducting properties of NbTiN films and SIS structures.

Other SC Materials beyond Niobium / 1

RF characterization of thin films at Cornell

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A TE mode niobium sample host cavity was used to characterize the RF performance of large 5" diameter thin film samples at 4 GHz. Exciting results were obtained from industry partner Ultramet' s CVD Nb3Sn grown on a copper substrate. These results indicate that slight alterations to the deposition process and use of higher purity precursors could lead to high-performance Nb3Sn coatings on copper, which would be a breakthrough accomplishment. In addition, encouraging RF measurements for bi-layer ALD NbN-Nb and ALD multilayer NbN-AlN-Nb, obtained from industry partner Veeco-CNT, were obtained. These initial results demonstrate the potential of ALD and CVD for use in SRF cavities.

Other SC Materials beyond Niobium / 51

First RF characterization of an SIS sample

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RF-surface resistance measurements have been performed on an S-I-S multilayer sample.

The sample was prepared at JLab using DC-magnetron sputtering of a 75 nm NbTiN layer on a 15 nm AlN insulator layer on bulk niobium. The sample (and sputtered area) was a circular disc of 75 mm diameter, welded on an 85 mm high Nb pipe of the same outer diameter. This geometry allowed performing RF measurements of the film using the HZB quadrupole resonator. The sample was tested at two frequencies: 420 and 850 MHz. Sample temperatures ranged from 2 K up to the transition temperature of NbTiN of ~17.3 K.

The measured surface resistance exhibits an unexpected temperature dependence: Rather than rising monotonically as expected from BCS theory, a distinct local maximum is observed. This means that there is a temperature range for this SIS system, where surface resistance is dropping with increasing temperature, which seems to contradict BCS at first glance. Measurements of the baseline Nb sample prior to coating exhibited no such behavior; hence, systematic errors from the experimental apparatus can be excluded as the explanation. Measurements were limited by hard magnetic quenches near 20 mT, suggesting that the sample is limited by early flux penetration. Measurement results will be presented and discussed in detail.

Other SC Materials beyond Niobium: Nb3Sn / 50

State-of-the-art Nb3Sn films by electrochemical deposition

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Other SC Materials beyond Niobium: Nb3Sn / 4

Nb3Sn Multilayer Sequential Sputtering at Jefferson Lab

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Nb3Sn-coated Nb SRF cavities are studied due to their potential of providing a higher accelerating gradient over Nb SRF cavities. Magnetron sputtering can be a feasible alternative to conventional tin vapor diffusion process to fabricate Nb3Sn for SRF cavities. By depositing Nb and Sn layers separately and annealing afterward, the stoichiometry of the coated films can be controlled to create Nb3Sn. To understand the formation of Nb3Sn at higher annealing temperatures, a comparative study of deposition and processing conditions is required. We have sputtered Nb and Sn multilayers and post-deposition annealed at 850, 950, 1000, 1100 and 1200 ℃ for 3 hours. The structural properties of the annealed films were characterized by X-ray diffraction (XRD) and compared to as-coated films. The film microstructures and compositions were examined by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The superconducting transitions of the films were measured by surface resistivity data obtained down to cryogenic temperatures. A new cavity deposition system with a cylindrical magnetron has been designed to implement the sequential sputtering technique onto a single-cell cavity.

Other SC Materials beyond Niobium: Nb3Sn / 5

Nb3Sn growth on niobium in vapor diffusion process and its application to large RF surface

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Nb3Sn-coated SRF cavities can potentially achieve superior performance in terms of quality factor, accelerating gradient, and operating temperature. Tin vapor diffusion process of Nb3Sn coating on Nb is a simple, yet efficacious technique to fabricate Nb3Sn-coated SRF cavities. The process comprises two¬ steps: "nucleation"followed by "deposition". The crucible with Sn/SnCl2 and the substrate at a constant temperature of about 500 ℃ for several hours is the "nucleation"; the crucible and the substrate at a constant temperature, typically, above 1000 ℃ is the "deposition"step. Using custom-built sample coating chamber, we have coated over a hundred samples to systematically study the vapor diffusion process under varying process conditions and at different stages of the coating process. The surfaces, thus obtained, were investigated with surface studies techniques, such as SEM/EDS, AFM, XPS, SAM, SIMS, EBSD and TEM. Based on the experimental results, we will discuss nucleation and growth of Nb3Sn coating during vapor diffusion process
Translating small sample coatings to large surface areas presents a number of challenges. Processes typically must be modified to provide coating conditions in different areas adequate for the desired

film growth. Besides process development challenges, large surface areas are more likely to host defects, which compromise film growth. Recently we started coating CEBAF 5-cell cavities to study and develop Nb3Sn vapor diffusion process for larger structures. Coated cavities were visually inspected and, in some case, RF tested at cryogenic temperatures. Samples coated along with the cavities were studied with surface studies techniques. Process evolution and the current understanding of the film growth and its limitations on such substrate will be discussed.

Other SC Materials beyond Niobium: Nb3Sn / 20

Synthesis of Nb3Sn on copper and Sapphire

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Nb3Sn alloy is a type II superconductor with maximum Tc of 18 K and predicted superheating field of 400 mT and potentially may offer improvements in both cryogenic efficiency and maximum accelerating field. Hence, Nb3Sn thin film can be an alternative superconducting coating either as a single or multilayer for SRF cavity production.
Nb3Sn has been deposited from stoichiometric alloy target on copper and single crystal sapphire substrate at room and elevated temperature and with and without Nb buffer layer. 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 ⊠C. The critical temperature was determined to be 16.8 K.

Other SC Materials beyond Niobium: Nb3Sn / 22

Cryogenic RF performances of Nb3Sn films on Copper

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Superconducting radio frequency (SRF) cavities, made of niobium films on copper (Nb/Cu), are currently employed for a large variety of particle accelerators. At the same time, the Nb/Cu technology, being very cost effective, also represents one of the main options for upcoming machines like the future circular collider (FCC).
While research and development continue on the Nb/Cu technology, there is still a performance gap with respect to the best results that can be obtained with bulk Nb.
Alternative superconducting materials, with larger critical temperature Tc and superheating field Hsh, might pave the way towards higher performance. In this respect, materials in the A15 family, like Nb3Sn, are among the most promising. At CERN, a reliable coating procedure for Nb3Sn films on copper, using niobium or tantalum as intermediate layer, has been developed. The films are reproducible and show excellent DC transport properties (Tc up to 17 K), morphological and structural characteristics. A comprehensive RF characterization of these films was still missing though.
In this work, we report the results of a Nb3Sn film coated on a copper sample, measured in the CERN

quadrupole resonator (QPR). The QPR enables the characterization of small samples at different temperatures, RF frequencies and field values.
The main results are compared with those from Nb bulk and Nb/Cu samples, measured with the same technique.

Advanced cleaning of substrates / **40**

Evaluation of the Copper Polishing procedures in the framework of ARIES H2020 Collaboration

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Thin film technology moves the surface preparation from Nb to Cu, because the Nb thin film cannot be chemical treated. For the Nb on Cu resonant cavities two principal copper cleaning and polishing treatments were studied: one is the electropolishing (EP) and the other one is the chemical polishing with SUBU solution. The influence of surface preparation is deeply studied in bulk Nb cavities and it is responsible for the main performances advancement. Similar considerations can be done for Nb on Cu cavities, because the morphology and the roughness of the copper surface are replicated by the Nb growing film. A better understanding of the surface effects and their impact on the thin film and later on RF-properties of the coating is mandatory in order to to improve the performances of superconducting (SC) cavities by coating techniques.
A comparison of the 4 principal cleaning and polishing process of Copper was done through the evaluation of the superconductive and morphological properties of Nb thin film coated on Cu planar samples, that are cleaned and polished with different procedures.
The cleaning and polishing procedures were carried out at CERN and at LNL-INFN. The deposition processes were carried out at STFC, University of Siegen and LNL-INFN, using the same procedure and parameters. Different surface characterizations have been applied in order to compare the impact of different substrate preparations on films'SC properties: roughness measurements, SEM, EDS, XRD, AFM, and thermal and photo-stimulated exoelectrons measurements, in 4 different institutions (INFN, Siegen, STFC, RTU). Superconducting properties of Nb films were evaluated with PPMS at Institute of Electrical Engineering of Bratislava.
The authors would like to acknowledge the support provided by European Union's ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871.

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Plasma cleaning for LCLS-II cavities

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Field emission is one the major limitations to the maximum usable accelerating gradient of SRF cavities in cryomodules. Taking advantage of the plasma chemistry, field emitting and decreasing the field emission. A collaboration between FNAL, SLAC and ORNL was established to develop a plasma processing system capable to minimize and overcome the problem of field emission in LCLS-II cryomodules. The plasma processing system is inspired to the one already built at the Spallation Neutron Source (SNS), that is capable to process in-situ cavities from hydrocarbon contaminants, by means of a neon-oxygen reactive plasma mixture. Here we present an innovative approach needed to ignite reliably the plasma in LCLS-II cavities, using a mixture of high order modes. In addition, the first results obtained on contaminated samples and single-cell cavities are shown together with the future plan of the project.

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Optimization of mechanical polishing of Niobium for SRF applications

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The reduction of construction and operation costs are major aims for future superconducting radio-frequency (SRF) applications. So as to reduce the construction cost of the particle accelerators, the standard expensive chemical treatments (electropolishing (EP) or buffered chemical polishing (BCP)) of bulk Niobium (Nb) cavities can be significantly reduced or even suppressed thanks to mechanical polishing (MP) techniques. MP of Nb is also really promising to prepare high quality substrates for thin film deposition of alternative superconductors (Nb3Sn, multilayers…). Since quality of thin-film depends on the quality-state of the substrate, development of the mechanical polishing procedure of substrate is a key point to produce high quality films. A 2-steps MP method, inspired from metallographic techniques has been developed and optimized on Nb for SRF applications to achieve mirror-finished surfaces on flat samples. The surface morphology, damaged layer (EBSD) and surface pollution (SIMS) analysis are presented.

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Improvement of Nb thin film on Cu substrate by Nd:YAG laser radiation

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The properties of Nb thin films deposited on planar Cu substrate were studied after its laser annealing. Five samples were prepared employing different substrate preparation techniques and were subsequently coated with 3-μm thick Nb film with the same deposition parameters. Afterwards, the Nb films were irradiated using Nd:YAG laser in order to increase crystallinity and improve adhesion of the Nb layer. The non-irradiated and irradiated surfaces were studied employing SEM, EDS, XRD and optical microscopy. It was found that the non-irradiated Nb film is delaminated in some places. This effect probably occurs due to mechanical stresses after the deposition of a very thick Nb film on Cu substrate. This is suggested by the observed Nb presence under the delamination layer according to EDS measurements. Irradiation of the structure by the Nd:YAG laser leads to increase of the Nb grain size according to SEM measurements. The study of the irradiated structure by XRD method revealed decrease of mechanical strain by a factor of two.

Typical for the Nb/Cu samples studied is the presence of pinholes with size up to 500 nm. Only for one of the samples the surface is characterized by chaotically distributed scratches with lengths up to 10 μm. In one case the pinholes are longitudinal and orientated with length up to 5 μm. After irradiation by pulsed Nd:YAG laser (λ= 1064 nm, τ =6 ns and intensity up to I=200 MW/cm2) in scanning mode with step 5μm in Ar atmosphere, the longitudinal pinholes fully disappeared and a periodical structure - Laser-Induced Periodic Surface Structures (LIPSS) appeared, with period 1 μm and amplitude up to 5 nm. The surfaces became smoother, but with some cracks up to 5 μm length. The surface roughness decreased by a factor 10 for all the samples.
To study the impact of laser annealing on superconducting properties, the samples were measured at VSM/PPMS in a perpendicular magnetic field before and after laser irradiation
The authors would like to acknowledge the support provided by European Union's ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871.

Advances in cavity substrate fabrication / 43

State of the art of 400 MHz copper SRF cavity production via Spinning in the framework of FCC study

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In the framework of the FCC study, niobium-coated copper cavities are considered to operate at 400 MHz. Spinning is a potential alternative to conventional shaping methods of copper half cells.
A step by step presentation of the complete spinning process will be explained, observing the effects of the stresses induced by the forming and the actions chosen to fight this specific behaviour of OFHC copper.

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Surface quality and improvements on the SRF cavity manufacturing by electrohydraulic forming

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In the framework of CERN's Future Circular Collider (FCC), fabrication of high-performance superconducting radiofrequency (SRF) cavities is crucial to attain energy levels relevant for breakthrough research in particle physics. Damage to the inner surface of copper and niobium cavities must be minimized to ensure proper growth of the superconducting film and prevent quenching during operation. An alternative technique to traditional shaping methods, such as deep-drawing and spinning, is electrohydraulic forming (EHF). In EHF, half-cells are formed through high-speed deformation of blanks using shockwaves induced in water by a pulsed electrical discharge. Results on the microstructural properties of formed Cu and Nb half-cells are presented and compared with spun and machined parts. The main reported advantages of EHF are reduced springback, increased shape accuracy, a conservation of the large grain microstructure at the inner surface, and less contamination of the RF surface from the absence of contact with a metallic punch or mandrel. Finally, an update on the fabrication of 6 GHz seamless Cu cavities, one of the objectives of the EASITrain program, is presented.

RF characterization for SRF films / 17

Measuring field penetration on thin film Samples above 150 mT

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Developing thin films deposited with complex superconductors like Nb3Sn or multilayers requires being able to test the maximum field achievable on numerous samples. In classical magnetometer where the sample is immersed in homogenous field, there is always some ambiguity resulting from the fact that the penetration of field can start on the back or the edges of the samples.
We have tried to develop a local magnetometer where the coil is much smaller than the sample such that the sample can be considered as an infinite plane and the transition field can be measured in conditions close to cavity operation. Nevertheless at high field, holding the infinite plane approximation required to have very large samples.
By developing an insert of an insulating, cryogenic effective ferrite, we were able to reach fields the order of 150 mT at 2 K, with field so localized, it become possible to use smaller samples. In principle, the magnetometer can produce by design fields higher than 200 mT, 2K, but we were not able to fully test it yet by lack of the appropriate high performance sample.
With this available tool at our disposal, we can now measure not only thin film samples but also a variety of bulk samples, since the measurement inform us about the field penetration but also about the pinning behavior of the samples, and can thus provide hints about the defect content of the samples. Some examples of such measurements will be shown.

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Tunneling spectroscopy - correlations between superconducting properties and RF performances

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I will present recent analysis of tunneling spectroscopy data measured on cut out samples from a N doped cavity, and from commonly processed hot and cold spot regions of a BCP cavity. The hot spot samples reveal small gap area consistent with a proximity effect model along with spectroscopic signature of magnetic impurities, caracteristic of two level systems. The cold and N doped samples on the contrary show near ideal BCS superconducting properties. From these results and complementary surface characterization technics we can draw general correlations between RF dissipation, inelastic scattering processes and gap values.

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Characterizations of superconducting materials at HZB with Quadrupole Resonator

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At the present time more and more low temperature superconducting materials and compounds are being developed around the world for new applications in future accelerators and industry. However, the production processes and recipes are not fully developed and require measurement tools for studies and optimization. The Quadrupole Resonator (QPR) is a cavity that is able to perform the most complete and precise characterizations of superconducting materials. The HZB QPR makes RF characterizations of superconducting materials (such as surface resistance as a function of magnetic field and temperature) over a wide temperature and magnetic field range, at frequencies of 433, 866 and 1300 MHz. In this contribution we summarize the latest measurement results of compact "detachable lid sample", produced by DESY from Large grain Nb and report on production status of 10 base samples in the "Research Instruments"(including Nb-Cu welded) that will be sent to interested stakeholders for thin film coating. Also we present current status and plans for new upgrades of HZB QPR.

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Microscopic Investigation of Materials Limitations of Superconducting RF Cavities

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Based on the needs of the SRF community to identify and evaluate defects on Nb surfaces, a novel near-field magnetic microwave microscope was successfully built using a magnetic writer from a conventional magnetic recording hard-disk drive [1]. This magnetic writer can create an RF magnetic field in the 100 mT range, localized and strong enough to drive Nb into the mixed state, and may have sub-micron resolution.
In our experiments on Nb surfaces we observed that the amplitude of 3rd harmonic response-V_3f(T,H_rf) is relatively small below a temperature dependent onset rf field amplitude H_0(T) (the DC field is nominally zero). For rf amplitudes H_rf > H_0(T) there exists measurable harmonic response signal with periodic dips at H_rf amplitudes= H_1(T), H_2(T), H_3(T)⋯Similar behavior is observed in both bulk Nb and thin film Nb samples. The periodic response is shown to arise from the sample and is only observed in the superconducting state. The origin of this response is most likely nonlinearity generated by a Josephson effect at or near the surface. Numerical calculations based on the rf-current-biased Resistively and Capacitively Shunted Junction (RCSJ) model can be fit very well to the data using reasonable parameters. Another possible model based on the paper by Gurvich and Ciovati [2] is being investigated, where interaction between the core of a vortex semi-loop and nearby pinning sites is modeled. COMSOL simulations are used to solve the Time-Dependent Ginzburg Landau equation and investigate the nonlinear response produced by such interaction.

Acknowledgement:
This work is funded by US Department of Energy through grant # DE-SC0017931 and CNAM.

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On application of photothermostimulated electron emission for characterisation of Nb films, deposited on copper

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Photothermostimulated exoelectron emission (PTSE), being observed when solid specimen is simultaneously heated and excited by photons with energy close to photoemission threshold, often is related to the annealing of structural defects and hereby, could become the tool to test quality, or amount of imperfections, of the superconductive Nb films.

The present study explores PTSE of the Nb films, deposited on Cu substrates, processed by different methods: tumbling, electropolishng, chemical polishing by SUBU solution, and combination of electro- and chemical polishing. PTSE current was measured in vacuum by SEM detector; specimens were heated from 20oC to 510oC at the rate 10oC/s and excited by 4.96 eV photons.
PTSE demonstrated two peaks that could correspond to annealing of two type of structural imperfections: low temperature peak at 320 −380oC, and high temperature peak at 460 −520 oC. Each peak was approximated by Randal-Wilkins expression, and characterised by activation energy E, that was 0.58 −0.68 eV (first peak) and 0.95 −1.65 eV (second peak) for all specimens, except those with substrate, processed by both electropolishing and chemical polishing (~1.4 eV and ~ 2.5 eV)..
The interpretation of the results required additional research to understand processes, underlying PTSE, nevertheless, alterations of the activation energies indicates that structure / nature of imperfections in the Nb film is changed due to different pre- processing of the Cu substrate.
The research is supported by EU ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871.

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X-ray Computed Tomographic Investigation of the defect on Niobium coated copper radio frequency cavity

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Defects on the niobium superconducting radio frequency (SRF) can have an important impact on quality factor at low accelerating fields. However, the quantification of the defects can be difficult due to shape of cavity. In this work cracks formed on niobium at copper substrate is examined using high resolution X-ray computed tomography (X-ray CT). The observations are validated by comparisons of cross-sectional views of features obtained using focus ion beam (FIB) scanning electron microscopy and X-ray CT. The X-ray CT technique is shown to be capable on a correlation between the locations of the defects on niobium thin film surface, and in the copper substrate. Furthermore, the volumes of defect are revealed on niobium surface. The locations and EDS analysis of the crack indicate that they are probably generated by impurities during BCP and EP of copper or dissolved hydrogen, the cool down rate, and interstitial impurities serving as nucleation centres for forming hydrides on niobium coating.

Superconducting film beyond SRF / 52

High Tc superconducting films for FCC beam screens

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CERN is studying the feasibility of a new proton-proton collider reaching an unprecedented centre-of-mass energy of 100 TeV, the Future Circular Collider (FCC). The proton beams will be steered by 16 T superconducting magnets cooled at 1.9 K, whose cold bore is protected from the intense synchrotron radiation by a coaxial beam screen maintained at 50 K, temperature which stems from a compromise between vacuum quality and cryogenic efficiency. Beam dynamics and stability, in particular at injection, require that the surface impedance of this screen which surrounds the proton beam be as low as possible. CERN is currently exploring the option of using a High-Temperature Superconductor (HTS) coating for this purpose. We will discuss in detail the motivations for this novel application of HTS, and the status of the study conducted in collaboration with several European Institutions.

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HTS superconducting films for microwave applications

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We review r.f. measurements of the surface impedance Zs=Rs+iXs of YBCO films films deposited on sapphire or MgO . The measurements are performed by a microstrip dielectric resonator and cavities techniques using a meander line geometry. The power dependence of Zs is studied at different temperatures and frequencies in the range 1-18 GHz. The effects of a d.c. magnetic field applied with different orientations is also studied. The data are analyzed in the context of different models . The data will be discussed for possibile interest for different application including ollective coupling with spin ensembles and MASER