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# PROGRESS IN EUROPEAN THIN FILM ACTIVITIES*

C. Pira†, O. Azzolini, R. Caforio, E. Chyhyrynets, D. Fonnesu, D. Ford, V. Garcia, G. Keppel, G. Marconato, A. Salmaso, F. Stivanello, INFN Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
M. Bertucci, R. Paparella, INFN LASA, Segrate (MI), Italy
M. Bonesso, S. Candela, V. Candela, R. Dima, G. Favero, A. Pepato, P. Rebesan, M. Romanato INFN - section of Padova, Padova, Italy
C. Z. Antoine, S. Berry, Y. Kalboussi, T. Proslier, Université Paris-Saclay, CEA, Département des Accélérateurs, de la Cryogénie et du Magnétisme, Gif-sur-Yvette, France
D. Longuevergne, O. Hryhorenko, Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
E. Seiler, R. Ries, Institute of Electrical Engineering SAS, Bratislava, Slovakia
S. Keckert, O. Kugeler, J. Knobloch, Helmholtz Zentrum Berlin, Germany
S. Prucnal, S. Zhou, Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Dresden, Germany
X. Jiang, T. Staedler, A. Zubtsovskii, Institute of Materials Engineering, University of Siegen, Siegen, Germany
R. Berton, D. Piccoli, F. Piccoli, G. Squizzato, F. Telatin, Piccoli S.R.L., Noale (VE), Italy
A. Medvids, A. Mychko, P. Onufrievs, Laboratory of Semiconductor Physics, Riga Technical University, Riga, Latvia
C. Benjamin[2], O.B. Malyshev[2], T. Sian[2], L. Smith[2], R. Valizadeh[2], ASTeC, UKRI/STFC Daresbury Laboratory, Daresbury, Warrington, UK
G. Burt[2], N. Leicester[2], S. Marks[2], D. Seal[2], D. Turner[2] Engineering Department, Lancaster University, Lancaster, UK
J. W. Bradley[2], S. Simon[2], Liverpool University, Liverpool, UK
A-M. Valente-Feliciano, Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
[1]also at Universität Siegen, Siegen, Germany
[2]also at Cockroft Institute, UKRI/STFC, Daresbury, Warrington, UK

*Abstract*

Thin-film cavities with higher Tc superconductors (SC) than Nb promise to move the operating temperature from 2 to 4.5 K with savings 3 orders of magnitude in cryogenic power consumption. Several European labs are coordinating their efforts to obtain a first 1.3 GHz cavity prototype through the I.FAST collaboration and other informal collaborations with CERN and DESY. R&D covers the entire production chain. In particular, new production techniques of seamless Copper and Niobium elliptical cavities via additive manufacturing are studied and evaluated. New acid-free polishing techniques to reduce surface roughness in a more sustainable way such as plasma electropolishing and metallographic polishing have been tested. Optimization of coating parameters of higher Tc SC than Nb ($Nb_3Sn$, $V_3Si$, NbTiN) via PVD and multilayer via ALD are on the way. Finally, rapid heat treatments such as Flash Lamp Annealing and Laser Annealing are used to avoid or reduce Copper diffusion in the SC film. The development and characterization of superconducting coatings is done on planar samples, 6 GHz cavities, choke cavities, QPR and 1.3 GHz cavities. This work presents the progress status of these coordinated efforts.

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† cristian.pira@lnl.infn.it

## INTRODUCTION

The WP9 from IFAST, "Innovative superconducting cavities", is focused on improving performance and reduce cost of SRF acceleration systems based mostly on the use of thin films. It comes after several European projects on the topics (WP12.2 within Eucard2, WP15 within Aries) that helped bringing together the teams working on that topic in Europe and keep in touch with the international community [1]. The European members are from France, Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA), Centre National de la Recherche Scientifique (CNRS),from Germany, Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Universität Siegen (USI), from Italy, Istituto Nazionale di Fisica Nucleare (INFN), PICCOLI SRL (PICCOLI), from Latvia, Rigas Tehniska Universitate (RTU), from Slovakia, Institute of Electrical Engineering, Slovak Academy of Sciences (IEE), and from the United Kingdom, United Kingdom Research And Innovation (UKRI) but we have also external collaborators, formal (JLAB); and informal (CERN, DESY).

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The objective of IFAST is to pass from developments on samples to the first RF prototypes and merge all the developments that have been mastered over the last years. I.FAST WP9 focuses on optimizing and innovating the entire production chain of superconducting thin-film cavities by exploring new technologies and developing those already used in SRF for each individual step. The different activities range from forming, polishing, superconductive and protective film coatings to characterization techniques. One part of the job (task 9.1) is also contributing at building together a global strategy to be able to produce Superconducting RF (SRF) cavities coated with a superconducting films, and participating to the corresponding chapters (thin films) initiatives like e.g. the Snowmass propositions [2] or the European Accelerator R&D Roadmap Implementation [3].

Listed below are the different activities carried out at I.FAST, divided by macro-areas: cavity forming, surface polishing, thin film coatings, post treatments and RF evaluation of samples.

## ACTIVITIES

### *Cavity Forming*

**6 GHz Additive Manufacturing @INFN** Cavity production is a key process: The performance of SRF films is highly dependent on the quality of the substrate. Classical cavity production methods introduce defects or inclusions on the substrate. In addition, cold working could cause dislocations and cracks on the material surface. Additive manufacturing (AM) is free of such problems and is therefore a promising candidate for seamless SRF cavity fabrication. Moreover, AM enables the production of geometries that are impossible to obtain with traditional techniques.

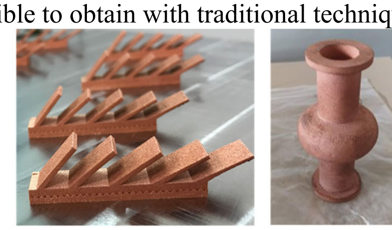

Figure 1: On the left Cu AM printability test of overhang surfaces. On the right the first Cu 6 GHz AM prototype.

In I.FAST the production of seamless 6 GHz elliptical cavities by additive manufacturing is explored (Fig. 1). The cavities are made of both bulk Nb and Cu (the latter subsequently coated with a Nb film by PVD). The bulk Nb cavities exhibit the expected Tc of 9.2 K and RF tests are in progress. The maximum density obtained from the Nb samples produced is above 98.7 %. For Cu is > 99.8%. Both Nb and Cu cavities showed a leak rate at room T <10-12 mbar·l/s.

The main limitations of AM is its high roughness. The starting surface has a roughness Ra>30 µm. In collaboration with Rossler, INFN has developed a protocol involving several vibrofinishing steps before chemical and electrochemical polishing, which allow the roughness to be reduced to values below 400 nm that are more compatible with SRF applications.

A Nb bulk 6 GHz cavity has been fully polished and RF testing is planned to measure its Q as a function of the accelerating field. More details in [4-6].

**Seamless Spinning @INFN** INFN, in collaboration with Piccoli Srl, aims to improve the quality of spinning seamless cavities production, in particular the reproducibility, by using numerically controlled machines instead of traditional semi-automatic lathes used up to now. Efforts are also being made to reduce surface defects by studying the effect of annealing temperature and evaluate new strategies for reducing cold work stress. The annealing study was first conducted on small samples to evaluate the possibility of lowering the standard annealing temperature of 500 °C used by Piccoli. The aim is to maintain the mechanical properties achieved with standard annealing temperature, but reducing the grain size, which ensures better machinability of the material.

Three different annealing temperatures were tested and then hardness and stress-strain characteristic of the material were measured at the University of Padua. In Fig. 1, the results show where it is evident that it is possible to reduce the annealing T to 400 °C by obtaining mechanical properties comparable to those of annealing at 500 °C.

The second part of the study turned to work on cavities. To standardize the results, two identical OFHC Copper plates were started from which eighteen cavity simulacra were obtained and used to develop the spinning process using numerically controlled machines and test the effect of intermediate and final annealing. Characterized samples were obtained from the cavities at INFN and the University of Padua. All annealing processes were carried out at INFN's UHV furnace.

The tests first showed the possibility of successful manufacture of a seamless cavity with CNC machines and then the reduction of surface defects with intermediate annealing. A mold was also made to include an initial forming via deep drawing in order again to reduce surface defects. More details in [7].

### *Surface Polishing*

**Plasma Electropolishing @ INFN** Plasma Electropolishing (PEP) is an innovative method for polishing metal surfaces that has been studied at LNL over the past three years particularly for Copper and Niobium. Compared to traditional electropolishing and chemical polishing techniques, it has several advantages that make it extremely attractive: 10 times faster erosion speed, higher smoothening efficiency (lower roughness for the same amount of material removed), and most importantly, the bath is much more environmentally sustainable, since it is not composed of the traditional concentrated acid solutions, but of dilute aqueous solutions of salts [8]. However, the high currents and powers involved make scalability to 1.3 GHz cavities a challenge.

Two aspects were studied in more detail: reproducibility and scalability to closed geometries and large area. Temperature turns out to be a key parameter. It was seen that it is necessary to thermalize the bath at about 85 °C to maintain constant temperature and current density throughout

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the process. Otherwise, temperature variation during the process can produce localized oxidation lowering limiting polishing uniformity.

Another huge advantage of the PEP process over conventional EP is the lower sensitivity to cathode geometry. It has been shown to be possible to internally polish a 6 GHz Copper cavity without the aid of an inner cylindrical cathode, but only with an outer cathode (first results in Fig. 2). This clearly greatly simplifies the polishing set-up and makes it possible to treat complex geometries hitherto the preserve of chemical polishing alone. More details about the reproducibility and scalability of the process to elliptical geometries in [9].

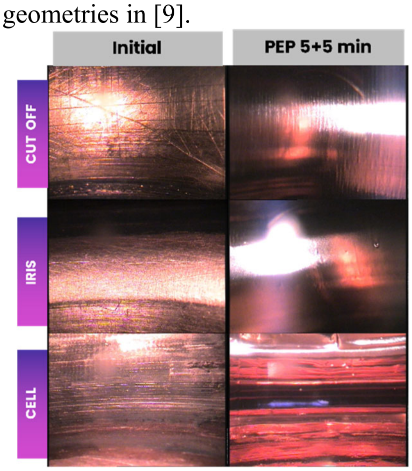


Figure 2: Internal surface inspection of a Cu 6 GHz cavity before (on the left) and after (on the right) PEP treatment.

**Metallographic Polishing @IJCLab** A new metallographic polishing technique optimized for SRF applications on Niobium sheets has been developed at IJCLab in collaboration with IRFU [10].

It consists of 3 steps to firstly, remove the damaged layer created during Niobium fabrication, secondly, reduce roughness down to few tens of nanometers and finally recover a high purity and pristine cristaline structure at the expense of a slight increase of roughness (reappearance of grains). Moreover, this technique is of great interest to provide high quality substrate for thin-film deposition. In the framework of I-fast project, several type of Niobium samples, a disk for STFC Choke cavity and QPR sample for HZB (See Fig. 3), have been polished showing very good results in term of surface resistance during baseline test [11]. Moreover, as a part of the French Japanese collaboration (FJPPL), this technology has been transferred to the production of a one-cell 1.3 GHz cavity. Further details can be found in [12].

Figure 3: Nb bulk QPR sample after methallographic polishing prior to heat treatment @IJCLab.

### *Thin Film Coatings*

PVD technique is one of the most versatile techniques for PVD deposition, successfully used for deposition of Nb cavities on Cu on LEP, LHC, ALPI and HIE-ISOLDE. In the I.FAST collaboration, it has been selected for the growth of superconducting films at higher Tc than Nb on Copper substrates. In parallel, the ALD technique is being explored for the growth of nanometer-thick oxide films that can be used as insulating layers in SIS structures or as a protective layer to lower SEY.

**Nb3Sn by Magnetron Sputtering @ INFN** The deposition of $Nb_3Sn$ on Cu is a challenge for several reasons. The $Nb_3Sn$ phase can be obtained pure at temperatures above 930 °C, otherwise the risk is to have spurious phase in addition to the A15 phase. The Copper substrate limits the annealing temperature to maximum values of 600-700 °C. It should be considered, however, that in PVD processes in addition to thermal energy the Nb and Sn atoms arrive on the substrate with a certain kinetic energy that depends on the deposition parameters used.

Another critical issue is the fact that Nb and Sn have very different melting points, so the risk of tin evaporation during the sputtering process is very high, particularly in the single-target configuration. At INFN, however, the single-target configuration has been found to be the most scalable to elliptical cavities. Development is underway on two different activities: the fabrication of cylindrical Nb3Sn targets via dipping and the optimization of deposition parameters via magnetron sputtering from single targets.

Producing cylindrical targets of Nb3Sn is one of the many challenges to be achieved, and LNL are addressing it with an original approach, which is to use a bulk Nb target and grow a thick film of Nb3Sn on it via dipping, that is, dipping the target in molten tin and promoting the reaction between Nb and Sn by annealing at temperatures above 1000 °C. More details in [13].

Optimization of PVD deposition parameters is performed by depositing multiple substrates in the same run and varying for each run one parameter among annealing temperature, process pressure and power applied to the magnetron. The films are deposited via DCMS from a planar stoichiometric 4” Nb3Sn commercial target. Each Nb3Sn coating process is performed on three different substrate types: sapphire, OFHC Copper and OFHC Copper pre-coated with a 1 μm Niobium barrier layer.

In Fig. 4, it can be seen that the coatings on sapphire show a clear trend related to power applied to the target, pressure and deposition/annealing temperature. In fact, an increase in Tc is seen as the target power decreases and the sputtering pressure increases. Both can be explained by a reduction in target temperature and consequent reduction in target tin evaporation. In fact, the evaporated Sn atoms have lower energy than the sputtered ones, making the formation of the A15 phase more difficult. Increasing the substrate temperature, on the other hand, is necessary to increase the mobility of the atoms that arrive on the surface and thus can more easily nucleate and form the A15 phase by reacting with each other.

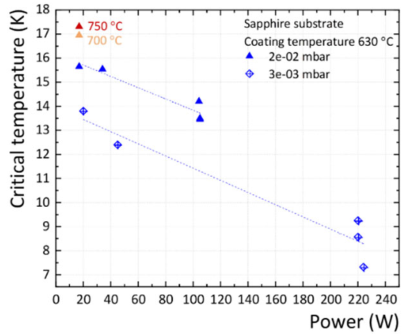


Figure 4: Dependence of the critical temperature of the $Nb_3Sn$ films on the cathode power. The films on sapphire substrate show trends with cathode power, coating pressure and coating temperature.

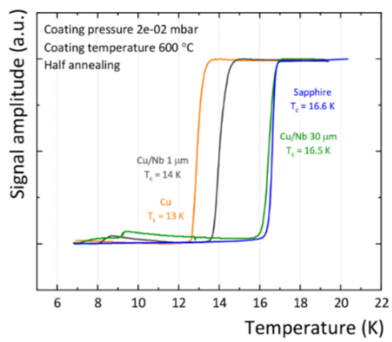


Figure 5: Superconducting transition curves of samples deposited at 600 °C. The $Nb_3Sn$ coated onto a thick Nb barrier layer shows same Tc as sapphire substrate ones.

However on Cu samples there appears to be no correlation between deposition parameters and Tc. On Copper, no sample showed a Tc above 14 K. There is also a slight increase in Tc in Nb barrier layer samples, but Tc still remains in the range of 14 K. This suggests that diffusions at the interface have a dominant effect. We therefore increased the barrier thickness by growing a 30-micron thick film of Nb. In Fig. 5 we can see that the coating on Cu exhibits a very broadened transition, in some cases even absent, while with a one-micron barrier layer we already get a sharp transition, but at a lower Tc than with sapphire. With a thick film, most of all, the Tc moves to values comparable to those obtained on sapphire and close to nominal $Nb_3Sn$ Tc. Now, as optimization continues on planar samples, the next step is to deposit a QPR and then subsequently 6 GHz cavity and split cavity for surface strength measurement and characterization of SRF properties. Further details can be found in [14].

**Nb3Sn, V3Si, NbTiN PVD coatings @ UKRI/STFC** At UKRI, the SRF R&D activity is progressing towards cavity coating. Several cylindrical magnetrons with permanent magnet design have been commissioned to be installed for both 6 and 1.3 GHz cavity. For 6 GHz cavity, two configurations of open (co-called split) and closed cavity is developed. The 6 GHz open cavity is deposited with both conventional planar magnetron and permanent magnet cylindrical magnetron. This type of cavity allows surface resistance of thin film to be evaluated at low RF field at the moment. The capability of evaluation at higher RF field is underway. The initial measurement proved to be more dependent on the surface preparation of Cu cavity with the one polished with EP at INFN showing lower surface resistance than the machined surface. The results of SRF measurements for the split 6 GHz cavity are discussed below and the referenced within in.

Other SRF activity is synthesis of high Tc SRF thin films of A15 SC such as Nb3SN and V3Si as well as B1 group such NbTiN. These are deposited on the flat samples as well as the 6 GHz cavities. The RF surface resistance is evaluated by the choke cavity for planar samples and in 3D geometry by 6 GHz cavity. An example of surface resistance as a function of temperature for a planar Nb/Cu and NbTiN/Cu samples is shown in Fig. 9. The results will be reported at the SRF23 conference [15-17].

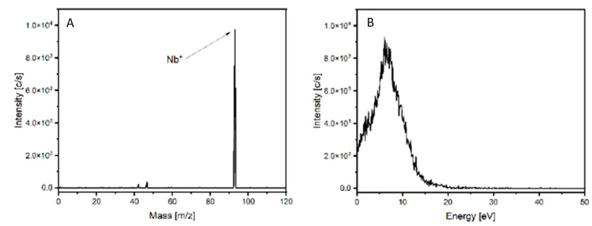


Figure 6: The mass (A) and energy (B) scans of the positive ions coming to the inner surface at the equator of the elliptical Copper cavity.

Another R&D activity that recently is commenced is plasma evaluation using Hiden EQP Series quadrupole mass spectrometer systems which are designed for direct analysis of plasma ion mass and energy in both plasma characterisation and process diagnostic applications. The activity is focused on plasma characterisation of permanent magnet cylindrical magnetron for 1.3 GHz cavity. It evaluates the plasma generated with HIPIMS with and without positive kick. Initially the study is based on Nb deposition but later will be focused on A15 and B1 group of material.

Figure 6 A and B represent the mass and energy scans of the positive ions coming to the inner surface at the equator of the elliptical Copper cavity. the scan was done in triplicate and the measure was average over the three scans. Pressure was 5.3 x $10^{-3}$ mbar and power of 100 W, PRR of 1000 Hz and PW of 100 µs.

**HiPIMS deposition of superconducting films @ USI** Previous studies of Nb and NbN deposition using high power impulse magnetron sputtering (HiPIMS) demonstrated better film performance in comparison with the deposited films by DC magnetron sputtering. Significant outcome has been achieved in the improvement of the quality of the deposited Nb and NbN by the densification of the films and reduction of the surface roughness, which subsequently led to the improvement of the superconducting characteristics such as the critical temperature $T_c$ and the penetration field $H_{c1}$. Furthermore, this approach was applied to obtain multilayer SIS structures, i.e. HiPIMS-Nb / DC-AlN / HiPIMS-NbN, as a novel material for SRF application [18, 19]. Characterization of such HiPIMS SIS coatings in terms of superconductivity and RF properties

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revealed lower Tc and $H_{c1}$ than for independent Nb and NbN films that opens a path for further improvement and optimisation of deposition procedure. However, by itself, HiPIMS method showed better performance compared to conventional DC or RF MS techniques. Thus, the approach was implemented also for deposition of NbTiN films.

At the first stage, a co-sputtering from separate HiPIMS-Nb and DC-Ti targets is assumed to apply this configuration later for multilayer S(I)S coatings. The presence of two independent Nb and Ti sources suggests the possibility of varying the composition of the resulting NbTiN thin films, which provides an additional parameter for this system. However, due to the considerably large distance between two targets, a wide rocking angle of the sample stage was chosen in order to perform a uniform coating of the substrates. After the optimal rocking angle of 80° has been found, the influence of other deposition parameters is currently being studied. For example, the cathode power density of Nb and Ti targets is set to relatively small values (3.5-4.5 $W/cm^2$) to prevent the formation of unwanted NbN and TiN phases. The effect of $N_2$/Ar ratio as well as deposition pressure will also be studied in the near future. In addition, the usage of a single alloy NbTi target in the HiPIMS deposition is planned.

**ALD @ CEA** We investigate the impact of thin films surface engineering on SRF cavities performances through the use Atomic Layer Deposition (ALD). Several research directions are being explored:

The first research direction investigates the synthesis of high quality superconducting thin films and SIS multilayer structures to enhance the accelerating gradient of SRF cavities. We have successfully synthesized AlN/NbTiN with Tc up to 16 K with an enhancement of the first penetration critical field measured by SQUID on a Nb ellipsoid of 30 mT for a NbTiN film thickness of 60 nm. Two Nb cavities have been coated with an SIS structure but delamination occurred in the beam tubes after the post thermal treatment. The RF performances were degraded as compared to the Nb baseline. Further investigation in needed to prevent the thin film delamination.

The second research direction focuses on controlling the secondary electron yield and the conductivity by synthesizing nanometer thick films by ALD. Various alloys are being investigated, TiN in particular have been successfully applied on a SRF cavity to suppress its multipacting.

The third research thrust aims at investigating the impact of nanometers thick surface layers on the Quality factor of SRF cavities at low and high accelerating fields.

The last research direction explores the growth of diffusion and insulating barriers by ALD on Copper for post HIPIMS Nb and A15 compound deposition in order to limit the Cu/SC interactions (diffusion at high temperature, thermocurrents). In that respect preliminary results indicate that we found a stable thin film alloy at 750°C on Cu, the highest temperature reported so far and compatible with $Nb_3Sn$ deposition. We are also investigation the use of $Al_2O_3$ on Cu and its effects on Nb deposition by HIPIMS. Further details can be found in [20, 21].

### *Post Treatments*

**Laser Annealing @ RTU** A15 superconducting films generally require some annealing time to crystallize in the phase at nominal Tc. In ARIES, the possibility of using the laser annealing technique for annealing the superconducting film alone, avoiding heating of the bulk and subsequent diffusion at the interface, was successfully explored [22]. In I.FAST, the goal is to scale the process from the small planar samples used in ARIES to cylindrical geometries to demonstrate its applicability to elliptical cavities.

The cylindrical Copper tubes with Nb on Cu were effectively scanned using irradiation by Nd:YAG laser with wavelength 1064 nm, pulse duration 6 ns, repetition rate of 10 Hz and laser beam diameter of 0.5 mm, in an Ar chamber. After irradiation of Nb by the laser, the film of Nb surface became lighter, like a mirror, as shown in Fig. 7. This happened because the irradiated Nb surface roughness decreased more than ten times compared to the non-irradiated surface. X-ray diffraction analysis showed that there were no traces of Nb oxide present in both - the non-irradiated and irradiated samples. The number of cracks on the irradiated samples increased, but they became smaller in size after laser processing.

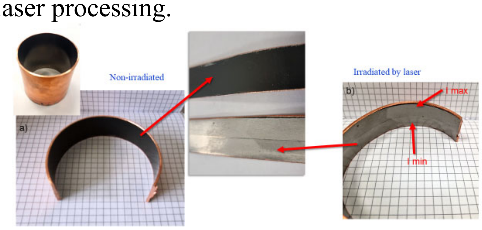


Figure 7: Samples formed from cylindrical Copper tube with Nb film: (a) non-irradiated; (b) irradiated in Ar chamber by ns laser radiation.

**Flash Lamp Annealing @ HZDR** In addition to laser annealing, flash lamp annealing (FLA) is also being explored [23-25]. FLA is a non-equilibrium annealing method on the milli-second time scale which excellently meets the requirements of thin film processing. In general, an FLA system consists of an energy storage system and a flash chamber. The energy storage system comprises a capacitance (made of one or several capacitors) to store the energy, an inductance to form the pulse, a charging device, and the required electronics including high power switches for control. The optical spectrum of the output light pulse extends from the UV to the near infrared and is composed of the broad thermal emission of the hot plasma and a couple of discrete spectral lines originating from bound-to-bound emissions of the noble gas.

Being much different from conventional RTA, during FLA only a small amount of energy is input into the processed surface, leading to a local high temperature in well-confined thickness. FLA consumes around 40% less energy and meets the "Green deal" requirement. It has already been used in microelectronics, mostly after ion implantation, to activate dopants, to recrystallize amorphous semiconductor layers, and to anneal out defects. The flash lamp can be easily scaled up to a length of meters and mounted inside the cavities. This flexibility can allow the

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processing both thin films of high temperature SC and cavities made from them.

### *DC/AC Superconducting Property Evaluation*

First of all, after TF deposition one need to know whether the sample is superconducting. This work is performed with a simple 4-point resistance probe in STFC and a magnetic test at INFN. More detailed magnetisation studies are performed at IEE and HZDR.

**Magnetometry @ IEE** At the IEE, measurements of virgin DC magnetization curves and magnetization loops are preformed using a Vibrating Sample Magnetometer setup. Small samples of about 2 x 2 mm$^2$ are placed in a homogenous magnetic field with the superconducting thin film oriented parallel to the field [26]. The main characteristic determined is the field at which the magnetic flux starts entering the SC's volume – the first flux entry field $B_{en}$. It is detected as the applied field at which the virgin magnetisation curve starts to deviate from the initial linear Meissner-type dependence. The shape and the details of the magnetisation loops can further suggest on possible presence of the surface barrier in the flux penetration.

The critical temperatures are determined with the help of the DC magnetisation measurements as well, using the temperature dependence of the magnetic moment in a constant applied magnetic field.

**Magnetic Field Penetration @ UKRI/STFC** The magnetometry measurements described above provide an important information about SC properties of deposited film. However, the experimental conditions in these measurements are different from ones in the RF cavity. In the RF cavity, the magnetic field is applied from the side of the TF surface only, while in PPMS facilities a small sample is placed inside a respectively large magnetic coil. Thus, the following idea was realised in STFC: a small C-shaped magnet provides a magnetic field up to 0.6 T in a 2-mm gap. The magnet is placed in front of the sample thus magnetic field is parallel to the SC surface, similar to the one in the RF cavity. The magnetic field is measured with two Hall probes: between the magnet poles to measure an applied magnetic field $B_1$, and on the opposite side of the sample to measure a penetrated field $B_2$. This configuration allows to defile the full penetration field $B_{fp}$ which is equal to the applied magnetic field when it penetrated through the sample and detected on the opposite side of the sample. Such measurements can be performed at various sample temperatures $T_s$ as a function of magnetic field $B_1$ increasing from zero to a desired value. Then these results could be analysed with a simple formula for a parameter R: $R = 1 - B_2/B_1$

The SC film is fully screening an applied magnetic field when $R = 1$, and magnetic field penetrates through the film as soon as $R < 1$, thus. the full penetration field $B_{fp}$ is equal to the applied magnetic field at the transition from $R = 1$ to $R < 1$. An example of results $R(B_1, T_s)$ for $Nb_3Sn$ is shown in Fig. 8. The results are reported as $B_{fp}(T_s)$. The details of the facility and methods of data analysis are reported in [26]. The results of $R(B_1, T_s)$ and $B_{fp}(T_s)$. allow to compare different samples in the conditions similar to the ones in the RF cavities [1, 27-31].

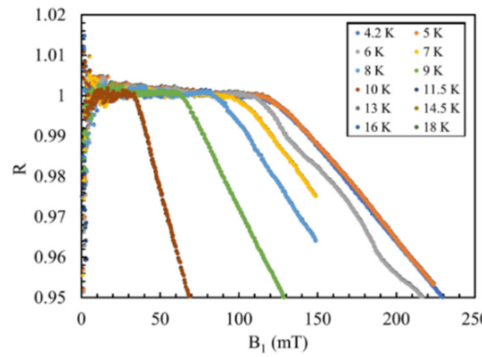


Figure 8: An example of parameter $R(B_1, T_s)$ for $Nb_3Sn$.

In the future, we are going to relate this value to behaviour of $Q_0(E_{acc})$ plots.

### *RF Evaluation of Samples*

For RF characterisation, a dual-purpose facility is used to measure the average surface resistance of thin films.

**Choke Cavity @ UKRI/STFC** Planar deposition systems are ideal for systematic study of various deposition parameters and their impact on TF properties. Planar samples are ideal for surface characterisation instruments and PPMS. However, for complete evaluation it would be also beneficial to study such samples at the RF conditions.

The choked cavity facility is described in Refs. [11, 31, 32], it uses a test cavity consisting of two parts: a choke cavity (a half-cell elliptical bulk Nb cavity surrounded by quarter-wavelength RF chokes), and a planar sample disk ~100 mm diameter made from either bulk Nb or STF coated Cu with any thickness between 1 and 20 mm. The test cavity operates at 7.8 GHz in the TM010 mode. The sample is thermally isolated from the choked cavity and its temperature can be varied in the range 4 K ≤ $T$s ≤ 30 K. This allows for a simple measurement of the average sample surface resistance ($R$s) employing an RF-DC compensation method at peak magnetic fields $B$pk ≤ 1.2 mT. The sample surface resistance $Rs$ can be measured at fixed applied magnetic field and at fixed $T$s with variable $B$pk, i.e. $R$s ($T$s) and $R$s ($B$pk), respectively. Figure 9 shows examples of results for Nb/Cu and NbTiN samples. The simplicity of facility design and the samples allows a quick low power evaluation of the samples: up to 3 samples a week. However, it is not suitable for high field study. Thus, such facility a complementary tool for a quick RF evaluation and optimisation of STF before preparing a sample for QPR test.

**SPLIT Cavity @ UKRI/STFC** Films on a cavity-like geometry are measured using a novel longitudinally split single cell 6 GHz cavity. The cavity cut is made along the electric field lines; therefore, the surface electric current is not crossing an orbital cut and a weld, which is present in most of usual cavities and is a potential source of imperfection for Cu base and STF. Such geometry allows coating this cavity with either a conventional planar magnetron or in a tubular geometry used for RF cavities. After coating it

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also allows an easy visual inspection and surface analysis [31, 33–36]. Recently, a split single cell 6 GHz cavity coated with Nb TF has reached $Q_0 \approx 5 \times 10^6$ at 4.2 K [35].

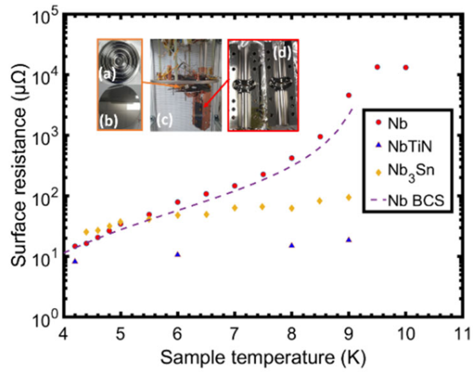


Figure 9: An example of surface resistance as a function of temperature for a planar Nb/Cu and NbTiN/Cu samples. Inset: (a) the choke cavity, (b) Nb/Cu planar sample, (c) RF facility, (d) a split cavity.

Both sets of measurements (the choke and split cavities) can be performed in the range $4\ \mathrm{K} \leq T \leq 30\ \mathrm{K}$. Measurements are presently made at low peak magnetic fields up to 1.2 mT due to radiation safety controls, however this will increase to ≈ 15 − 20 mT after moving to an RF bunker in a few months.

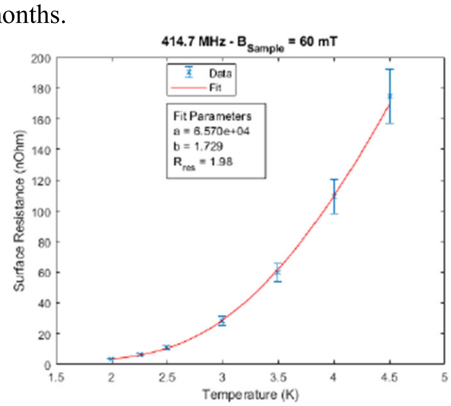


Figure 10: QPR sample RF test after optimized metallographic polishing. Rres value better than 1 nΩ demonstrate that QPR is now able to measure R_res with same accuracy and precision as an SRF cavity.

**QPR @ HZB** In the course of ARIES and I.FAST, the measurement precision of the HZB quadrupole resonator has been upgraded such that's it now is able to measure surface resistance values in the 1 nΩ regime making QPR measurements directly comparable to $Q_0$ measurements on SRF cavities, see [37]. This achievement was for the first time implemented to test a metallographically polished [10] QPR sample provided by IJCLab, Paris, France. With the optimized polishing procedure, the performance of the baseline sample was improved to values better than 2 nΩ which in turn enabled measurement at increased magnetic fields up to 80 mT, see Fig. 10. By this, a reliable method to create reproducible baseline samples for future thin film investigations within I.FAST.

**Future 1.3 GHz Cavity Test** RF testing on the 1.3 GHz cavities is expected in the second half of 2024 and will be carried out at the RF facilities of HZB, INFN LASA, CEA and STFC/UKRI.

## CONCLUSION

Moving operations to 4.5 K while maintaining the same performance as cavities in Nb bulk at 2 K is indeed a challenge. So is coordinating a working group of more than 10 different laboratories. The results so far, however, show that the path taken is the right one, and that through collaboration and exchange between different laboratories it is possible to make much more efficient progress than could be done individually and arrive at the expected goals faster. Still a lot remains to be done, but recent developments have shown that I.FAST collaboration is on the right track for the development of high-quality SC coatings and several solutions to explore are available to overcome the various issues encountered. After 2 years of the project the goal of I.FAST remains to produce the first 1.3 GHz thin-film cavity prototype of $Nb_3Sn$ on Cu and prove that a full change of technology is possible after more than 50 years of bulk Nb domination.

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