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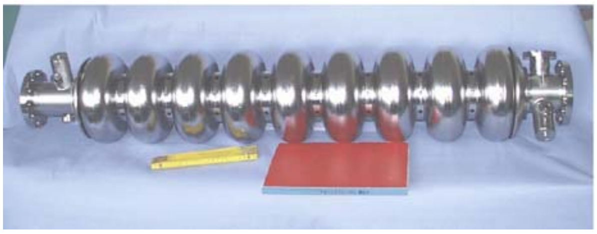
SRF 

Deposition and Characterisation of Niobium Films for SRF Cavity Application

L. Catani[1], A. Cianchi[1], D. Di Giovenale[1], J. Lorkiewicz[1], V. Merlo[2], R. Polini[2], C. Granata[3], R. Russo[3,1], M.J. Sadowski[4], M. Salvato[2], P. Strzyzewski[4], S. Tazzari[1,2]

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Abstract

Niobium coated copper cavities are an interesting alternative to bulk niobium ones for Superconducting Radio Frequency (SRF) applications to particle accelerators. The magnetron sputtering is the technology developed at CERN for depositing niobium films and applied over the past twenty years. Unfortunately, the observed degradation of the quality factor with increasing cavity voltage, not completely understood, prevents the use of this technology in future large accelerators designed to work at gradients higher than 30 MV/m, with quality factors of the order of 1010 (or higher). At the beginning of the new millennium some new deposition techniques have been proposed to overcome the difficulties encountered with the sputtering technique. This paper compares the properties of niobium films obtained with the magnetron sputtering and with a cathodic arc deposition in ultra-high vacuum (UHVCA). The UHVCA-produced Nb films have structural and transport properties closer to the bulk ones, providing a promising alternative for niobium coated, highvoltage and high-Q copper RF cavities, with respect to the standard magnetron sputtering technique. Preliminary results and possible approaches to whole cavity UHVCA coating will be presented and discussed.

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***Abstract*— Niobium coated copper cavities are an interesting alternative to bulk niobium ones for Superconducting Radio Frequency (SRF) applications to particle accelerators. The magnetron sputtering is the technology developed at CERN for depositing niobium films and applied over the past twenty years. Unfortunately, the observed degradation of the quality factor with increasing cavity voltage, not completely understood, prevents the use of this technology in future large accelerators designed to work at gradients higher than 30 MV/m, with quality factors of the order of 10^{10} (or higher). At the beginning of the new millennium some new deposition techniques have been proposed to overcome the difficulties encountered with the sputtering technique. This paper compares the properties of niobium films obtained with the magnetron sputtering and with a cathodic arc deposition in ultra-high vacuum (UHVCA). The UHVCA-produced Nb films have structural and transport properties closer to the bulk ones, providing a promising alternative for niobium coated, high-voltage and high-Q copper RF cavities, with respect to the standard magnetron sputtering technique. Preliminary results and possible approaches to whole cavity UHVCA coating will be presented and discussed.**

***Keywords*—SRF cavities, Niobium film, superconducting properties, UHVCA, vacuum arc, cavity deposition**

I. INTRODUCTION

The majority of superconducting RF resonators presently operating are made of bulk niobium [1]. Among pure elements, niobium has the highest critical temperature (9.25 K in its bulk form) and the highest thermodynamic critical field H_{th} (1.6×10^5 A/m) [2]. Its mechanical properties, even if not excellent ones, are good enough to permit the manufacturing of resonating devices with the required accuracy and reliability. The production of bulk niobium cavities has been the object of intense research and development, particularly in high-energy physics laboratories. A considerable improvement of their performances during the last decades has been achieved [1]. The surface resistance of very pure bulk niobium at liquid helium temperature (4.2 K) is ~900 nΩ at 1.5 GHz and, due to its exponential temperature dependence, it is expected to be only a few nΩ at 1.7 K [3], corresponding to a Quality Factor (Q) of a few 10^{10}. At lower temperatures the surface resistance usually saturates to a temperature independent limiting value called Residual Surface Resistance, R_{res}, [4] ranging from few nΩ to several hundreds nΩ, mainly depending on the material purity and surface preparation .

There are several economical and technological benefits to be obtained by the use of the superconducting technology with respect to the warm copper technology, as recognised by the international committee, which has recently decided that the future International Linear Collider (ILC) accelerator will be built using high field superconducting cavities [5].

However, at high accelerating fields local defects can induce the dissipation of energy, causing thereby local heating, which (because of the poor thermal conductivity of niobium) may trigger thermal instabilities, making possible the cavity quench (thermal runaway) [1].

The thermal stability can be improved by improving the cavity thermal conductivity by the use of high purity Nb. In recent years considerable progress has been made in increasing the thermal conductivity of the bulk niobium, mainly by improving the purification techniques and by minimising surface defects by means of raw material inspection methods and by using the electro polishing instead of buffered chemical polishing treatment [1,6]. On the other hand one should note that an external electromagnetic field, because it decays exponentially inside a conductor, can only penetrate to a characteristic penetration depth, λ, from the conductor surface. For superconducting purified bulk niobium λ is only ~30 nm. It follows that the superconducting properties of the cavity are determined by a very small fraction (less than 1 micron) of the wall cavity thickness, so that the rest of the wall plays only the role of a mechanical support, which in the case of superconductors (in general) and of Nb (in particular) has poor thermal conductivity [1].

For most applications, where only few small cavities are needed, bulk niobium is the best choice, but in the case of future accelerators using a very large number of cavities or cavities operating at low frequency (below ~500 MHz) the cost of bulk niobium of adequate purity (usually RRR > 300) and the fabrication cost, mainly machining and Electron Beam welding, can become a serious issue.

For such applications it has been recognized and proven by the pioneering work done at CERN that resonators, built by depositing thin superconducting layer on a high conductivity, relatively low-cost supporting structure provide much better thermal stability at lower costs. Copper is an obvious choice for the resonator wall material because it has an excellent thermal conductivity,

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it is relatively inexpensive, easy to machine and commercially obtainable in high purity grade, combined with relatively easily produced high quality Nb films.

In addition, to achieve better performance or to enable higher operating temperatures, it can be in principle envisaged using other superconductors for the film, such as Nb(Ti)N, high T_c superconductors, or the newly discovered MgB_2 [3].

While at present the performance of such new materials for the resonator application has not yet been shown to reach the desired quality, it is expected to be improved in future time and eventually to allow upgrading existing devices by removing the Nb film and replacing it by a more efficient one.

As regards the film deposition, in the 80's (in the framework of the LEP energy upgrade project) CERN started developing the technique for depositing thin Nb films onto Cu (Nb/Cu) cavities by the magnetron sputtering [7]. By the end of 1998, the LEP2 upgrade was completed, and 272 niobium-coated copper resonators, operating at an average accelerating field of ~10 MV/m at 352 MHz, were built and installed in the accelerator, thus raising the top beam energy from 46 GeV to 100 GeV [8]. The successful operation of the LEP2 demonstrated the feasibility of using the film technology on a large scale, at the top performance and excellent reliability.

Nevertheless, in order to scale the resonator performance up the ~40 MV/m level, required for superconducting colliders such as ILC, a quality factor $Q \geq 10^{10}$ at the highest field should keep the electric power dissipation of the whole facility within tolerable limits, while sputtered Nb/Cu cavities show that Q is decreasing with an increase in RF fields.

To understand this behaviour a systematic investigation of the physical properties of niobium-copper resonators was started at CERN in 1994, mainly in order to identify possible correlations between the resonator performance and film- as well as substrate-properties. As a result, several improvements of the deposition technique were made and different roles of the substrate and the film have been clarified, e.g. [9-13]. The best cavities did reach accelerating fields up to 20 MV/m, but the Q degradation was still observed, with Q dropping below 10^{10} at around 15 MV/m and reaching $5x10^9$ at around 20 MV/m.

Such behaviour, clearly observable on a much less pronounced scale [6], also in today's highest performing bulk Nb resonators, remains still unclear although several models have been presented. In the 90's it was widely believed that "Q-degradation" in thin films could be due to extrinsic factors, such as grain boundary losses. In particular, a model based on the assumption that the grain boundaries behave in RF fields like Josephson Junctions (JJ) seemed to explain the phenomenon, at least qualitatively [14], but the authors themselves concede that the model applies to highly granular films only, and not to the compact, dense structure of Nb films produced using the latest technologies. Models ascribing the RF losses to grain boundaries have been further refined and improved by several authors, and exhaustive treatments can be found e.g. in [15, 16]. Recently several measurements have also been performed on cavities coated with larger grains (having less grain boundaries) Nb films. They have shown that the RF performance does not improve with an increase in the grain size [9].

In the authors' opinion, from among the several existing models the one proposed in [17] explains not only most of the observed behaviours of film- and bulk-cavities, but it is also closer to being an outright theory than a simple model. According to its picture, the dominating parameter determining the Q-slope is the electron mean free path in the superconductor, i.e. a shorter mean free path results in a higher slope, which means that the way to further improvements of the Nb/Cu resonators performance is to improve the film purity.

In the early 2000's, besides new methods designed to improve the sputtering process, such as High Peak Power Pulsed Sputtering, conformal cathode and bias sputtering [18], there were proposed two alternative coating techniques: arc coating in ultra-high vacuum (UHVCA) [19-21] and Electron Cyclotron Resonance post-ionisation [22,23], in order to produce ultra-pure, more bulk-like Nb films. Their main features are the absence of the auxiliary gas needed for sputtering, and the absence in the plasma of atoms of the material to be deposited, since applied plasma is fully ionised. First experimental results were presented in 2001 at international workshops [19, 22].

In this paper we compare properties of films deposited by either the magnetron sputtering or UHVCA coating upon sample substrates trying to find possible correlations with the performance of superconducting RF cavities. Finally, the first results and possible approaches to the cavity coating with the UHVCA will be presented and discussed.

II. TRANSPORT AND SUPERCONDUCTING PROPERTIES

In many laboratories the first estimate of the film purity is based on the strong effect, that impurities have on the transport and superconducting properties of Nb films, since it is well known that impurities act as electron scattering centres increasing the film resistivity [24].

The Residual Resistivity Ratio (RRR) of Nb films is defined as

$$RRR = \frac{R_{300K}}{R_{10K}} = \frac{\rho(300K)}{\rho(10K)} \approx \frac{\rho_{phonons}(300K) + \rho_{defects}}{\rho_{phonons}(10K) + \rho_{defects}},$$

where $\rho(T)$ is the electrical resistivity at the temperature T. To measure RRR one should measure, using the "four leads" technique, the film DC electrical resistance at a room temperature (R_{300K}) and just above the transition to the superconducting state, e.g. for Nb at 10 K (R_{10K}). When the sample is homogenous the measurement does not depend on its geometry. When the sample is not homogeneous, the four leads must be connected in line to avoid spurious effects [25]. Care should be taken about controlling the sample temperature, and the current intensity must be low enough (in order to deposit insignificant heat). For a low resistance, thick films using AC current and a lock-in amplifier will reduce errors due to spurious signals.

The approximate expression for RRR in the latter equation has been obtained using the Matthiessen's rule and assuming $\rho_{defects}$ to be temperature independent. These assumptions, generally speaking a rough approximation [26] only, are good for Nb films and one can safely assume that the resistivity is the sum of two independent terms: $\rho_{phonons}$ (resistivity caused by electron scattering due to the lattice thermal motion) and $\rho_{defects}$ (resistivity caused by scattering of electrons from lattice defects). The electrical resistivity, ρ, is inversely proportional to the relaxation time τ, which enters in the definition of the mean free path of a conduction electron $l = v_F\tau$ where v_F is the Fermi velocity. The product ρl can be considered constant for a given metal, e.g. for Nb it amounts to $3.75\pm0.05\times10^{-16}$ Ωm^2, and it can be use to estimate the mean free path once the resistivity is known.

At 300 K the net resistivity $\rho = \rho_{phonons}(T) + \rho_{deffects}$ is usually dominated by collisions between the conduction electrons and the lattice phonons, but at 10 K it is dominated by collisions with impurity atoms and imperfections disturbing the periodicity of the lattice. The value of $\rho_{phonons}(T)$ can be safely assumed to be $1.45\pm0.05\times10^{-7}$ Ωm at 300 K, and negligible (~10^4 times lower) at 10 K. Using these values and the measured RRR it is possible to estimate $\rho(10K)$ and the electron mean free path l.

The RRR values for Nb films deposited on glassy quartz and on copper substrates by means of the magnetron sputtering, at a substrate temperature of 150^0C, typically range from 5 to 30, depending on the discharge gas used and the voltage applied to the cathode [27]. The RRR of Nb films deposited at temperatures below 100 ^{0}C by the UHVCA stays consistently in the range of 20 - 50, in agreement with expectations based on the fact that there are no auxiliary gases to poison the film.

An other important information about the Nb film quality is given by the superconducting critical temperature value T_c. In Nb films T_c is very sensitive to impurities and stresses. In fact small amounts of impurities can lower the film T_c, whereas the compressive stresses can raise it up to ~9.6 K [28]. There are several ways of measuring T_c, and the most common ones are the "four leads" resistive technique (used also to measure RRR) and the "inductive" one. The resistive measurement gives less accurate information since, when a superconducting path is created between four leads (actually between the two leads measuring the voltage), the characteristic zero voltage signal appear even if portions of the sample are still in the normal conducting state. The working principle of inductive methods is as follows: screening currents are induced upon the sample surfaces by a low frequency field generated by a primary (excitation) coil, during the transition the screening currents change the voltage induced in a secondary (pick-up) coil. In the single coil method the excitation coil acts as the secondary one tuned to the third harmonic of the primary frequency [23]. Examples of T_c inductive measurements on UHVCA-coated Nb films are shown in figure 1. The results show that high quality films with properties close to the bulk Nb can be consistently obtained with the UHVCA technique.

It should be mentioned that the superconducting transition temperature of the magnetron-sputtered Nb films is reported to be 9.5 K - 9.6 K [4]. Usually Nb films on Cu, deposited by magnetron sputtering and having RRR values higher then 5 have a T_c higher than 9.1K. In fact the T_c value ranges from 9.1 K to 9.6 K and the differences with respect to bulk Nb are related to the presence of high compressive stress in the films. The origin of the compressive stress in the films is mainly related with the magnetron sputtering process [9, 11].

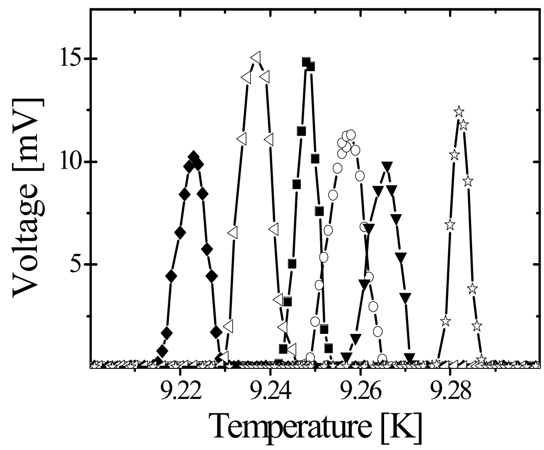

Figure 1. Measurements of T_c of various, different Nb films, made using the third harmonic inductive method after the final optimization of arc parameters: all T_c values are in the range from 9.21 K to 9.28 K, with ΔT_c less than 0.02 K [23, 24].

When the copper substrate is removed by dissolution in ammoniumpersulfate or nitric acid, the critical temperature of the sputtered Nb films decreases significantly and it approaches the nominal value for bulk Nb. Such films are found to be stress free, as expected according to the theory stating that stress effects on T_c are reversible, as further discussed in the paragraph on structural properties of films. Higher T_c value implies lower BCS surface resistance [4] and it can be an advantage for applications requiring the liquid He operating temperature (4.2 K), where BCS is the dominant resistive term. At lower temperatures, where the BCS contribution to the surface resistance is negligible, there is no clear correlation between the critical temperature (as long as it stays above 9 K) and the residual surface resistance R_{ress}.

III. STRUCTURAL PROPERTIES

The structure of films deposited on substrates may significantly differ from that of the bulk material. Films have usually smaller grains, more defects, and they are more stressed than the corresponding bulk material. To investigate these structural properties the best method is the X-Ray diffraction technique, which is based on the reflection of an X-ray beam from the material crystallographic planes, according to the well known Bragg relation $2d\sin\theta = n\lambda$ where d is the distance between lattice planes, ϑ is the X-ray beam incidence angle, λ is the X-rays wavelength, and n is the order of the reflection.

The position of the maximum of the reflected radiation line determines the value of the inter-plane distance, while the line width and shape contain information about grain size and micro-strain. The line intensity is related with the presence of a texture.

Typical results of the lattice constant measurement for the magnetron sputtered films upon copper substrates range from 0.3315 nm to 0.3330 nm, while for the

UHVCA-deposited Nb films upon the identical substrates range from 0.3300 nm to 0.3315 nm. These values, when compared with the lattice constant of bulk Nb (0.3303 nm), indicate a larger deformation of the lattice constant in the sputtered Nb film in a comparison with the UHVCA-coated one, due to a larger stress induced in the Nb film by the sputtering deposition process (see below).

The XRD measurements have also been used to obtain information about the average micro-strain in the deposited films. It should be noted that the spectra obtained at the grazing incidence provide more information than those recorded in the Bragg-Brentano configuration, since in the latter configuration the peaks diffracted at large angles (if present) are more noisy due to the finite film thickness. To quantify the micro-strain, provided the shape of the peak is sufficiently well defined, it is necessary to evaluate the 2θ value of the peak of each line and the line width, β, conventionally defined as its FWHM value expressed in radians. The data can then be arranged as a Williamson-Hall plot, which in principle enables to separate contributions to the peak broadening due to micro-strains and finite grain size, respectively [29]. Denoting by D - the grain size, δd/d - the average dispersion of the inter-planar spacing (due to micro-strains), and λ - the wavelength of the X-ray radiation, from basic considerations one can expect the dependence in the form as follows:

$$\beta_{strain} = \eta \tan\theta \qquad (1)$$

$$\beta_{grain} \propto \frac{\lambda}{D\cos\theta}, \qquad (2)$$

which in turn (combined together) gives

$$\frac{\beta}{\lambda}\cos\theta = \frac{1}{D} + \frac{\delta d}{d}\frac{4}{\lambda}\sin\theta\,. \qquad (3)$$

In the absence of microstrain, i.e. for $\delta d = 0$, equation (3) reduces to the so called Scherrer formula, relating peak broadening to crystallite size. Note that the Scherrer formula is therefore correctly applicable only to powder samples (with no strain) but is often erroneously applied to thin polycristalline films.

Looking at the few samples data plotted in figure 2a one can easily see that the behaviour of the width, β, of sputtered films is linear in $Tan\theta$. According to the equation (1) it denounces a strain, so that the Scherrer's formula should not be applied. Therefore, it can be concluded that the observed broadening of the peaks is mainly due to the micro-strains of the lattice. The same data (and other similar ones referring to different samples and not shown here) demonstrate also that the data from the Nb films grown with UHVCA are qualitatively in agreement with equations (1) and (3) (see figure 2b). Hence, from the slope of the linear fit, one can directly obtain a value of $\delta d /d$. The figure 2b shows also that the y-axis intercept of the linear fit is at about 0.005 nm^{-1} for the UHVCA-deposited film, and on the basis on equation (3) the grain size D can be estimated to about 200 nm, in agreement with the AFM results. For the sputtered film the intercept on the y axis is too close to zero to extract the grain size.

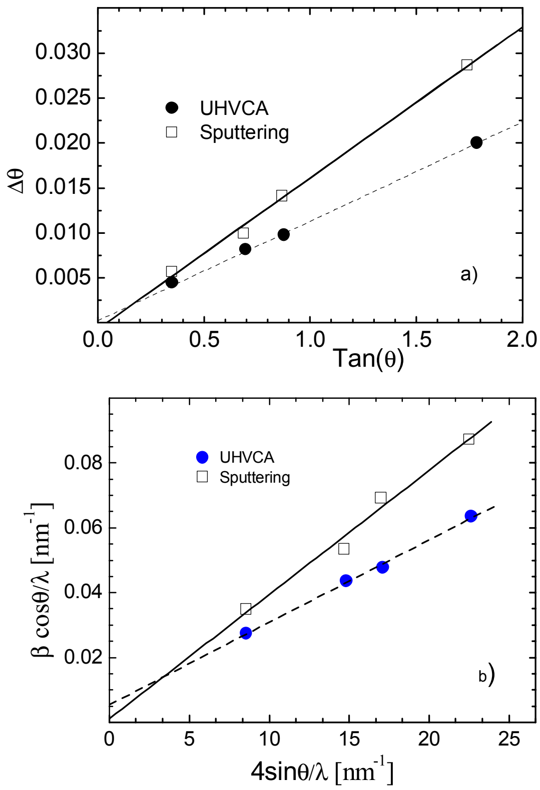

Figure 2. (a) Width of the diffracted peak as function of the tangent of its position for the sputtered film (squares) and a UHVCA-deposited film (dots). The close-to-zero fit line intercept confirms that the width of the diffracted peak is related with a micro-strain more than with a grain size, but the smaller slope of UHVCA-deposited films indicates that they are less strained than sputtered ones. (b) Williamson-Hall plot obtained from the same experimental data. The intercept on the y axis indicates the grain size of the order of 200 nm in agreement with the AFM results obtained for the UHVCA sample, whereas for the sputtered film the intercept on the y axis is too close to 0 to determine the grain size.

As reported in literature, thin films (including Nb ones) deposited by the magnetron sputtering at relatively low partial pressures usually undergo intrinsic compressive stresses [4, 11, 30]. This has been normally attributed to the effect of the bombardment by ions and neutrals, to which the growing film is exposed, but the UHVCA deposited films, continuously bombarded by higher energy ions have recently been shown to be much less stressed [21, 30].

It is worth to point out that the compressive stress in thin films is due to the presence of the substrate which constrains the film in the deposition x-y plane. As a consequence, the deposited film expands in the z direction which results in an $a_{\perp}$ value larger than that of bulk (generating confusion of some authors). This kind of stress is responsible for the critical temperature increase reported in section 2.1 and it disappears when the substrate is chemically dissolved. The film microstrain, and consequently the peak broadening, are of course not affected by the substrate dissolution, as confirmed by Williamson-Hall plots (or similar ones).

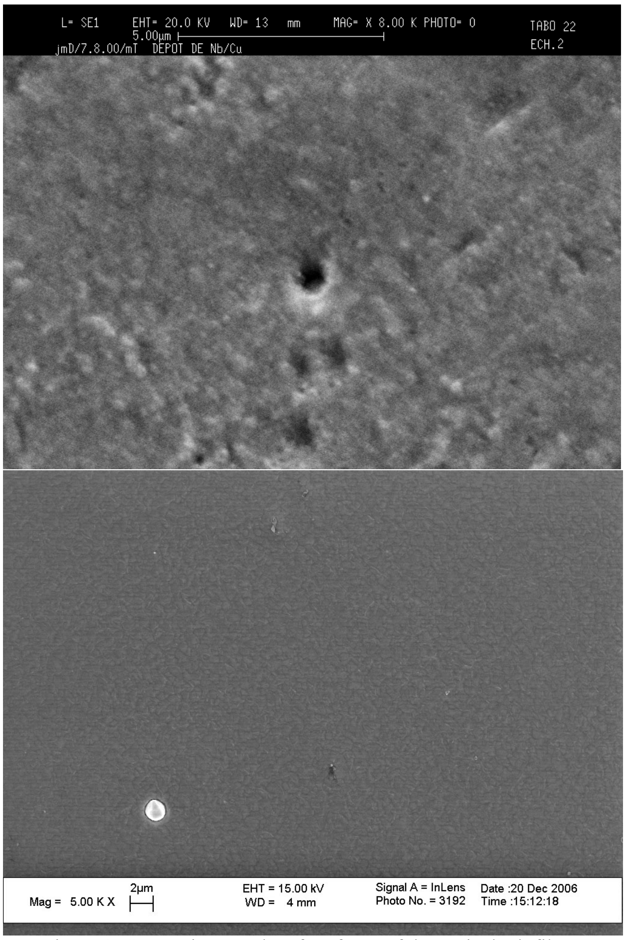

Figure 3. SEM micrographs of surfaces of the typical Nb films: (a) deposited by means of the magnetron sputtering upon copper, and (b) deposited with UHVCA upon a sapphire substrate.

IV. MORPHOLOGICAL PROPERTIES

The film morphology is studied mainly with SEM (Secondary Emission Microscopy), but also by means of AFM (Atomic Force Microscopy), optical microscopy and roughness measurements. The film roughness has been found to be one of the causes of the residual surface resistance. The roughness and large scale morphology of Nb films are largely determined by the roughness of the copper substrate, since the film growth follows the substrate surface. In the UHVCA-coated films, however, it is possible to control roughness using a negative pulsed bias of the substrate and/or adjusting the voltage bias and the duty cycle. During the negative pulse bias Nb ions reach the growing film preferentially upon film protrusions with energy sufficient to induce some sputtering of it, what reduces the deposition rate in such micro-regions. The negative pulsed bias can also remove loosely bonded atoms from the film surface and perform some annealing in the first mono-layers, reducing the number of voids and defects in the growing film. Examples of the film morphology, as observed on copper and sapphire substrates, are shown in figure 3. The small sphere visible in figure 3b is a macro-particle, which might be explosively emitted from the cathode in the form of micro-droplets during the arc discharge.

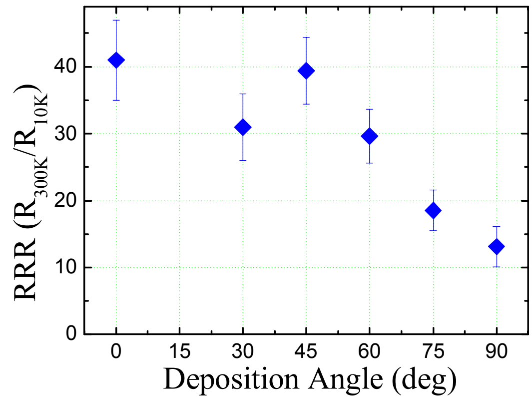

Figure 4. RRR values of UHVCA-deposited Nb films versus the angle between the normal to the sample surface and that to the cathode, as measured for samples at -40 V bias.

It is not clear at the moment whether macro-particles will limit the RF cavity voltage performance, by either field emission and RF field enhancement or the creation of voids in the film. Recent results, as obtained at the Wuppertal University, show that pure Nb spherical macro-particles resting upon the film surface should not be expected to increase the field-emission, at least up to RF fields of ~40 MV/m [31], but other effects (such as voids left in the film, due to macro-particles shadows) influencing the RF cavity response still need further investigation. Magnetic filters can also be used to remove most of the macro-particles from the plasma column, so that they can not reach the film [21].

V. INFLUENCE OF DEPOSITION ANGLE

In the case of the magnetron-sputtered films, if the incidence angle between a cathode and substrate is not normal to the surface, some irregularities of the substrate may produce shadows and film heterogeneities. In fact, at small incident angles the sputtered film structure changes and its roughness increases [32, 33]. The results obtained by measurements of helium permeability show a significant increase in the film porosity with a decrease in the incidence angle. The fraction of the film surface permeable to helium increases from ≊4.4 ppm at the equator, to ≊ 25 ppm at the iris [10]. The application of the UHVCA has therefore the advantage that, due to the deposition via ions, using a negative bias of the substrate the ions incidence angle can be made almost normal, independently at what angle the substrate is seen from the cathode. Therefore, films produced by means of UHVCA have consistently shown low roughness, almost independent from the cathode-to-substrate angle [33].

We deposited several samples using the planar arc system, without a magnetic filter described in [21]. Transport and superconducting properties of such films, deposited at a room temperature upon sapphire biased negatively (at constant potential of -40 V), were also almost independent from the incidence angle up to 60^0, while the RRR values decreased from ~ 40 to ~20 and ~15 at angles equal to 0^0, 75^0 and 90^0, respectively, as shown in figure 4.

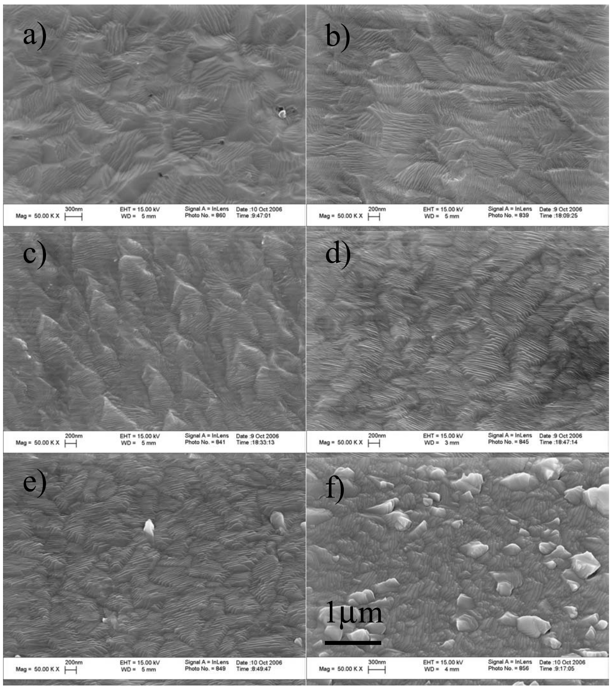

Figure 5. FEG-SEM images of Nb films deposited with the UHVCA techniques, upon negatively biased substrates (-40 V) oriented in relation to cathode at (a) 0^0, (b) 30^0, (c) 45^0, (d) 60^0, (e) 75^0, (f) 90^0

FEG-SEM images of the Nb films deposited with the UHVCA techniques, using negatively biased substrates oriented at different angles with respect to the cathode, are shown in figure 5. Up to 60^0 the surface was flat and the morphology observed upon the film surface was mainly due to an oxide layer. At 75^0 some small defects started to appear, and it became more visible on samples deposited at 90^0.

The deposition angle has an evident influence on the deposition rate. However, even at 90^0 the deposition rate is higher than 100 nm/min for all investigated bias values, what makes possible to deposit thick films in a relative short time (see figure 6)

VI. Influence of the Voltage Bias

As shown in figure 6, we have deposited different samples at different bias values. Some results of the RRR and X-ray measurements for Nb films deposited on sapphire substrate are summarized in Table I.

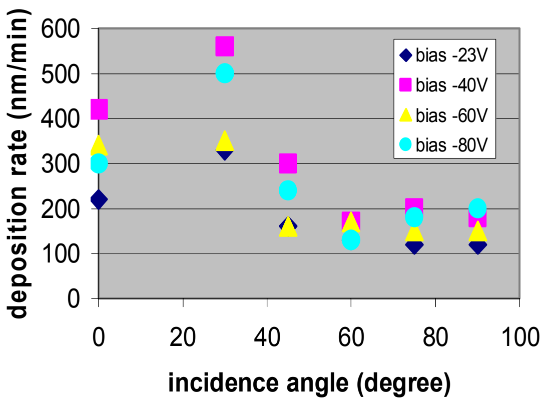

Figure 6. Deposition rates as a function of the incident angle for different bias applied to the substrate, at arc current equal to 120 A.

TABLE I

SUMMARY OF THE RESULTS OBTAINED AT A CONSTANT NEGATIVE BIAS

Bias (V)	Thickness (mm)	RRR	*a* Nb (nm)
-23	0.9-2.8	26	0.3308
-40	0.9-2.6	40	0.3312
-60	1.0-1.7	30	0.3313
-80	0.7-1.0	50	0.3310

The RRR was not strongly influenced by a bias ranging from 26 to 50, and the lattice parameters were quite close to value of bulk Nb (0.3306nm).

An effect of the pulsed bias on the Nb films is under investigation. The first tests have indicated that applying the pulsed bias one can obtain better morphological and structural properties of Nb films. The Nb films deposited at the pulsed bias present larger grains (up to microns) and flat surfaces with less defects. Such large grain size cannot be estimate by means of the x-ray diffraction, which can only give information about stress and strain present in the film. Preliminary analysis has shown that the strain in the grain was reduced, and in some cases it was possible to resolve the Cu-$K_{\alpha 1}$, Cu-$K_{\alpha 2}$ doublet of the x-rays. The superior adhesion and lower stress have been confirmed by the good adhesion of Nb films up to 40 μm in thickness. The figure 7 shows a FEG-SEM image of a 1.4-μm-thick Nb film deposited on the sapphire substrate. To produce the Nb film shown in figure 7, the sapphire substrate was biased at -60 V, and the applied bias was pulsed with a frequency of 10 KHz, with a duty cycle of 50 %. The X-ray spectra have shown that grains are oriented randomly, i.e. no epitaxy appears between the film and substrate. The measured RRR was about 50.

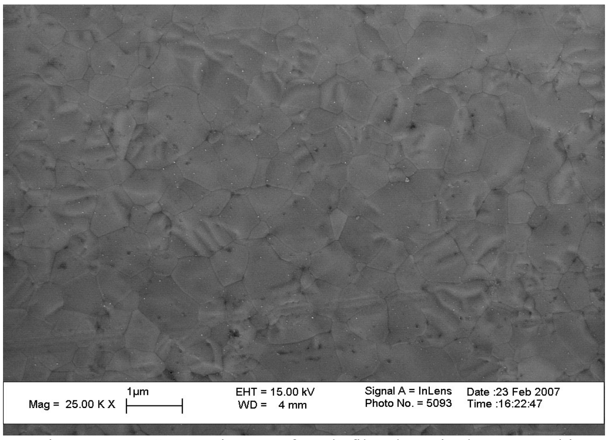

Figure 7. FEG-SEM image of a Nb-film deposited on a sapphire substrate with the use of the pulsed bias.

VII. Cavity System

The device for the vacuum arc coating of RF cavities with pure Nb layers consists of a cathode-anode tandem with a standard CF-100 vacuum T-junction, which serves as a vertical plasma duct and enables pumping of the system with a 180 l/s turbo-molecular pump. A schematic view of the system is shown in figure 8, and a detailed description of the arc source can be found in [21]. On the top of the T-junction there is installed a ceramic isolator, which supports a vacuum chamber shaped as a 1.3-GHz TESLA-type cavity. Another cylindrical isolator, which is mounted on the top of the system, supports a flange equipped with a low-voltage feedthrough. An isolated, horizontal, 7-cm-dia. stainless-steel disc is connected to one of the feedthrough pins, and suspended at the top of the cavity. The disc serves as a plasma ions collector to optimise the plasma transport inside the cavity cell. A magnetic field, needed to guide plasma from the cathode to the cavity cell, is generated by several coils fed by dc-currents. One coil, which surrounds the cone-shaped Nb cathode, contains 1600 windings of 1.5-mm-dia. copper wire. It is used to stabilize the motion of cathode spots. Other identical coils (each consisting of 350 windings) having the inner diameter of 226 mm and height of 26.5 mm are placed around the cavity system. In order to optimize the plasma transport magnetic field lines should be uniform and they should not touch the vacuum chamber. Once the plasma is introduced into the cavity cell, several options are available to coat the cell inner surface. The magnetic bottle configuration and the cusp geometry have already been described in [35]. Another new configuration of the upper coils is shown in figure 8. In this configuration the upper coils should rotate around the cavity axis to get the uniform coating inside the upper cell. In this configuration it is possible to coat the cavity using two arc sources placed at both cavity sides.

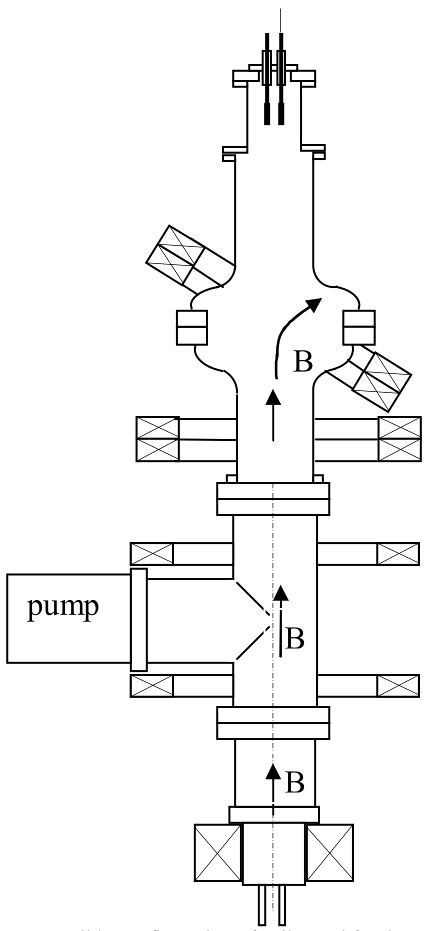

Figure 8. Possible configuration of coils used for the RF cavity coating. The top coils can rotate around the cavity axis to ensure the uniform coating. To make the complete deposition, the second cathode might be placed at the top, or the coated cavity might to be turned upside-down.

At the moment the described system is equipped with a single arc source, and the first tests are to be performed breaking the vacuum and turning the cavity upside-down.

A series of tests have already been performed in order to optimize the Nb plasma transport in the system, using different combinations of dc currents supplying the coils and different coil positions. The magnetic configuration presented in figure 8 seems to be more efficient than the cusp geometry reported previously [35]. The final magnetic configuration and coating conditions are to be determined by the optimisation of the deposition rate and the niobium film quality.

VIII. Conclusion

We compared the properties of niobium films obtained by the magnetron sputtering and by the cathodic arc deposition in ultra high vacuum (UHVCA). The UHVCA-produced Nb films have structural and transport properties closer to the bulk ones, providing the promising alternative for niobium coated, high-voltage and high-Q copper RF cavities with respect to those obtained with the standard magnetron sputtering technique. We deposited several samples with different bias, and various angles in relation to the plasma stream direction. The complete characterization of the samples is undergoing, but we have already observed that there is no dependence of the RRR value from the bias potential, and one can observe only a weak dependence of the thickness on the angle. We are also commissioning a system designed to deposit a single cell RF cavity, in order to demonstrate that it is possible to obtain large ion current upon the inner cavity surface and an overall good film quality. The magnetic field distribution and the use of a pulsed bias are under investigation. The first results on pulsed bias are very promising in term of structure, morphology and transport properties. Finally possible approaches to cavity coating using the UHVCA have been presented and discussed.

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