CATHODIC ARC GROWN NIOBIUM FILMS FOR RF SUPERCONDUCTING CAVITY APPLICATIONS

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Abstract

Experimental results on the characterization of the linear and nonlinear microwave properties of niobium film produced by UHV cathodic arc deposition are presented. Surface impedance Z_s as a function of rf field and intermodulation distortion (IMD) measurement have been carried out by using a dielectrically loaded resonant cavity operating at 7 GHz. The experimental data show that these samples have a lower level of intrinsic non-linearities at low temperature and low circulating power in comparison with Nb samples grown by sputtering. These results make UHV cathodic arc deposition a promising technique for the improvement of rf superconducting cavities for particle accelerators.

INTRODUCTION

The superior performances and advantages of Super Conducting (SC) cavities for particle acceleration is now worldwide established, at the point that the project of the new International Linear Collider is based on the superconducting technology. Nowadays the SC cavities for particle acceleration are mainly based on Nb bulk technology [1]. The Nb/Cu technology was proved a valid alternative, for relatively low accelerating fields (up to ≈ 10 MV/m), by the successful operation of the LEP II acceleration system [2] and it offers well known advantages with respect to the bulk Nb one. So far though, the quality factor of magnetron sputtered cavities slopes down with increasing RF magnetic field [3], thereby limiting their applicability to the new very high-energy, high field SC linear accelerators.

The reasons for the Q degradation are still an hot discussion topic and no agreement has been reached so far. Several models have been presented in the recent years to explain the Q-slope in the SC Nb cavities. In our opinion the most promising one is the model proposed by Palmieri[4] that explains most of the observed behavior in film and bulk cavities. According to the Palmieri’s picture the electron mean free path in the superconductor is the dominating parameter in determining the Q-slope for film and bulk cavities. Following this idea alternative coating techniques able to produce niobium film of high quality and purity, such as arc coating in ultra-high vacuum (UHV)[5], are extremely promising. The main advantages of arc deposition over sputtering are the highly ionized state of the evaporated material, the absence of gases to sustain the discharge and the high energy (larger than 100eV, tunable with bias) of ions reaching the substrate surface.

Another possible cause for the Q degradation is the small incidence angle of arriving sputtered atoms on the cavity surface [3]. In this respect the arc deposition technique offers the advantage that ions arrive almost perpendicular to the substrate surface. Recent results show that the morphological and structural properties of films deposited by arc are not affected by the angle between the cathode and the substrate[6] as it happens for sputtered deposited films. The niobium arc grown films promise to be less sensitive to substrate roughness in respect to the sputtered films and therefore less sensitive to the sample chemical preparation.

The main disadvantage of the technique is the production of microdroplets (also called macroparticles) from the cathode material that become embedded in the film. A magnetic filter to remove macroparticles from the plasma (and therefore from the film) has been developed and a new version with possible better performance is under construction.

EXPERIMENTAL SET-UP

Niobium film samples have been deposited using a planar arc set-up filtered against macroparticles. The planar arc source is housed in a UHV chamber pumped down to 10^{-10} Torr . For arc ignition one must produce a small plasma burst of sufficient density to form a high-conductivity path between cathode and anode, which in our case is generated by a 50mJ Nd-YAG pulsed laser focused onto the cathode surface. Such a triggering system provides ultra-clean and reliable ignition. A sketch of the deposition system is shown in Fig.1; a detailed description of the deposition system can be found elsewhere [7]. The samples are deposited on sapphire and copper substrates and structural and electrical properties similar to bulk have been obtained with excellent reproducibility [5,8].

For the investigation of the microwave response shown by the arc produced films, we used an open-ended dielectric single-crystal sapphire puck resonator [9] excited with a transverse electric mode (TE_{011}) and operating at 7 GHz. The resonator enclosure is made of Oxygen Free High Conductivity (OFHC) Copper, as well as the sample holder, placed in the centre of the cavity in close proximity with the dielectric single-crystal. The sapphire puck is of 8 mm height and 16 mm diameter, separated by the copper wall by a sapphire spacer. The puck-to-sample distance is chosen, depending on the material under test, by using a micrometer screw. The cavity is taken under vacuum using a copper can, which includes a double layer μ-metal shield, and inserted in a liquid helium cryostat. To investigate the nonlinear microwave properties, we performed in the same system configuration the measurement of the surface losses and of two-tone intermodulation as a function of the input power.

Power dependence measurements were performed using a Vectorial Network Analyser. For the measurement of IMD third order products, two closely spaced tones with equal amplitudes at frequencies f_1 and f_2 are generated by two phase-locked CW synthesizers. The signals, symmetrically separated around the centre frequency of the cavity by an amount δf, are combined and applied to the resonant structure. All IMD data presented here are taken with δf=10 kHz, whereas the 3 dB resonance bandwidth is at least a factor 10 larger at all temperatures below T_C. The output signals coming from the cavity (the two main tones at $f_1$and f_2 and the two third-order IMDs at $2f_1$-f_2 and $2f_2$-f_1) are detected using a Spectrum Analyzer. No amplifier is used to avoid unwanted non-linearities.

The small puck-to sample distance (less than 1 mm) ensures a very good signal-to-noise ratio even at very low input power level. Further details are given elsewhere [9].

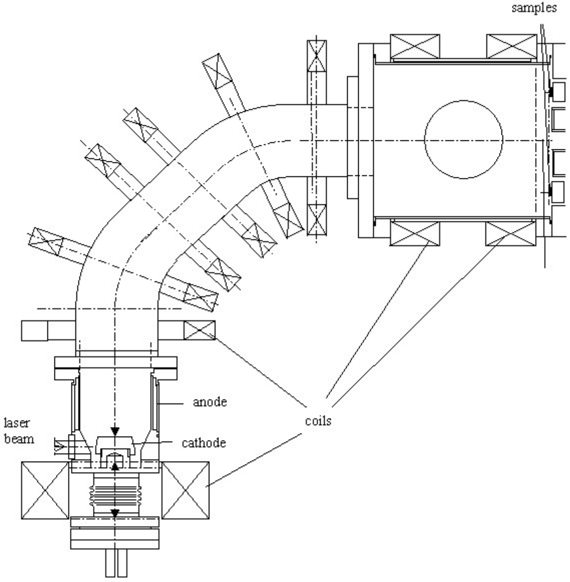

Fig. 1. Schematic drawing of the UHVCA system in the filtered configuration. The plasma is generated on the cathode and the magnetic field transport it through the chamber on the samples. The macroparticles are trapped on the chamber walls.

RESULTS

We measured three Nb films 1 μm thick, deposited on sapphire, whose RRR ratio range between 20 and 40. All the samples under test have a similar behaviour as a function of power. For the sake of clarity we will show the experimental results obtained on one sample only, which is the one better and more carefully characterised. This film shows T_c=9.24K, ΔT_c=0.02K (inductive measurement), RRR=30.

The surface resistance as a function of the power circulating in the cavity P_{circ} is measured at T=4.2 K. The power circulating in the dielectrically loaded cavity is evaluated using the following expression [9]:

$$P_{CIRC} = 10\log\left(\frac{2Q_L}{10^{-\frac{IL}{20}}}\right) + P_{OUT} \qquad (1)$$

where Q_L is the loaded quality factor of the cavity, IL represents the insertion losses and P_{out} is the output power of the main tone. P_{circ} and P_{out} are expressed in dBm.

The evaluation of the circulating power makes the comparison among different measurement techniques simpler, since the dependence of the electrodynamic response on this quantity does not depend either on the input coupling or on the resonator quality factor. Besides that, P_{circ} is directly proportional to the square of the mean amplitude of the microwave applied field H_{rf}, that is the relevant quantity for the study of the intrinsic properties in superconducting samples. Data show an almost flat behaviour, with a less than 5% increase in the surface resistance R_S versus P_{circ}, ($\propto H_{rf}^2$) up to a threshold value at P_{circ} = 27 dBm, likely determined by thermal heating. We believe that this low field region describes intrinsic nonlinearities arising in the microwave response of this sample, and it can be used to compare the electrodynamic properties of superconducting samples grown by different techniques.

For a better understanding of this power region, we carried out third order intermodulation products at the same temperature, limiting the circulating power below 20 dBm. In Fig. 2 the IMD data as a function of the circulating power P_{circ} are presented for the sample under test at 4.2 K. In the same plot we have reported for comparison the result of ref. [10] on a Nb film grown by sputtering and measured using a microstrip technique.

To allow a meaningful comparison between data taken with different techniques, IMD amplitudes are normalised by using the following relation [11]:

$$P_{NORM} = \frac{P_{OUT}^{IMD}}{10^{-\frac{IL}{20}} Q_L} \qquad (2)$$

A major feature in the figure is that the sputtered Nb film shows a higher level of intrinsic non-linearities at low temperature and low circulating power in comparison with our sample. This fundamental improvement in the electrodynamic response in the microwave region of the filtered UHV cathodic arc grown Nb samples is also confirmed by the preliminary results obtained by H. Padamsee and A. Romanenko [12] on niobium films deposited on copper substrate by the same technique. These samples show a constant surface resistance for RF magnetic field up to 450 Oe mainly limited by the niobium host cavity.

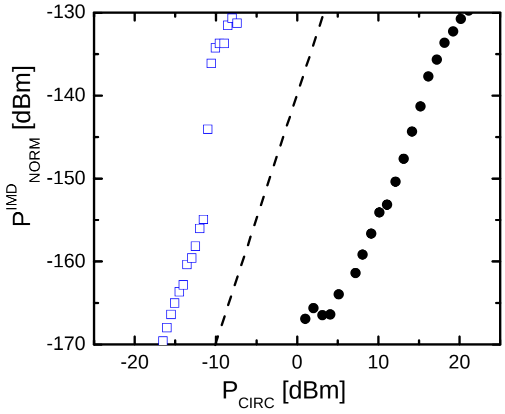

Fig. 2. The normalised output power of the IMD third order products are displayed as a function of the circulating power at 4.2 K for the sample under test (●). For comparison the IMD products versus the circulating power at 4.2 K for a Nb film grown by sputtering (ref.[10]) are shown (□). dashed line illustrates slope 3.

CAVITY DEPOSITION

The results being quite encouraging, the problem on how to coat a cavity have been afforded and different solutions are under study. While SINS'group in Poland have constructed a cylindrical UHV arc deposition system, the INFN group in Rome have developed UHV planar arc sources in filtered and unfiltered configuration [8]. In the filtered configuration the plasma transport on vacuum chamber longer than 1 meter have been demonstrated. The cavity deposition can be easily achieved using two cathode sources placed from the two cavity sides. However the use of a single cathode source would represent a technical and economical advantage and therefore preliminary experiments have been performed. The magnetic field in the coils and coil position should be optimised to obtain a relatively uniform film. Preliminary results obtained in a stainless steel cavity with a Tesla shape have shown that a niobium film could be easily deposited on the cavity equator and on the upper part of the cell surface. The result is particular encouraging since it has been obtained with no magnetic field optimisation showing that it is possible to coat a cavity using two planar arc sources. More work is needed to understand if it is possible to use a single planar cathode. The used geometry is not filtered for macroparticles but it can be implemented adding a 90 degree magnetic filter without increasing the deposition system complexity.

CONCLUSIONS

We have use a filtered UHV cathodic arc source to produce niobium films of high quality suitable for superconducting cavity deposition. Samples have been characterized using a dielectrically loaded resonant cavity operating at 7 GHz. The surface resistance versus the circulating power feeding the cavity and the IMD products at 4.2K have been measured. Comparison with previous results on sputtered Nb films have shown that filtered UHV cathodic arc grown Nb samples have a significantly lower level of intrinsic nonlinear losses. These results encourage the study of solutions to deposit single cell cavities for particle accelerators by using the UHV cathodic arc technique.

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