1. NORCIA GROUP ACTIVITY REPORT

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1 Aim of the experiment

The NORCIA experiment is devoted to the studies and construction of SW (standing wave) linear accelerating structures working at 11.424 GH in order to maximize the RF (radiofrequency) performance. All activities are performed in the framework of a INFN-LNF, SLAC (USA), KEK (Japan) and UCLA (Los Angeles) collaboration aim to design, manufacture and test at high power X-band accelerating structures. Moreover, part of the activity is devoted to R&D of key components for existing accelerators and for the next generation of accelerators. New materials and manufacturing techniques including single and multi-layer surfaces with precision-controlled properties are investigated to determine the maximum sustainable gradients in normal conducting RF powered particle beam accelerators operating at X-band with extremely low probability of RF breakdown. Within 2015 we designed, fabricated and characterizated at room temperature two electroformed (or hard) 11.424 GHz high gradient structures coated with Au-Ni and with different roughness. Among the others, investigations and tests of molybdenum coatings have been also performed.

2 Introduction

The next generation of linear accelerators is highly demanding in terms of accelerating gradients. To upgrade performances of X band linacs at 11.424 GHz many resources are devoted to achieve high accelerating gradients with the highest operation reliability. Technological advancements are strongly required to fulfil demands of new accelerators devices from the compact or portable devices for radiotherapy, to mobile cargo inspections and for security, biology, energy and environmental applications, and ultimately for the next generation of colliders [1, 2]. Following the international trend, our research activity [3] has been dedicated to design studies and to the construction of standing wave (SW) linear accelerating structures working at 11.424 GH to maximize the radio-frequency (RF) performance [4, 5, 6]. In particular, to improve the performance of X-band structures in terms of the accelerating gradient, we investigated alternative manufacturing approaches to brazing such as the electroforming, molybdenum sputtering on copper, electron beam welding and also new multilayer coatings. For its electrical and mechanical properties, copper is the main material for RF applications. Among the many options of new materials we also considered molybdenum sputtered on copper, the realization of single and multi-layer surfaces with precision-controlled properties, different copper alloys, etc. In general, we considered materials/structures with an enhanced tolerance to surface fatigue induced by pulsed heating, possibly with a higher fusion point or a specific nano-structure to avoid the fabrication of soft devices as done in conventional brazing [7, 8]. Indeed, a limited experience and unsatisfactory results have been achieved regarding the manufacturing of components made by copper alloys. Moreover, drawbacks exist because alloys typically loose hardness and electrical conductivity when annealed during the brazing cycle.

3 Electroformed structures and RF tests

We manufactured brazed copper and sintered molybdenum bulk X-band RF structures that were tested at high power. The breakdown rates of the Cu structures were comparable to similar structures realized both at SLAC and KEK [4]. On the contrary the breakdown rate of the brazed Mo structure was higher than that of coppers structure for the same RF parameters. The main issues for sintered molybdenum bulk are the long time for machining the cavity, a 300 nm surface roughness using tungsten carbide tools, the gas contamination and an uneven loading stress in the braze region [8]

In 2015 we fabricated and characterized Au-Ni electroformed SW structures at 11.424 GHz with different roughness. In particular, we characterized a hard high gradient RF accelerating structure at 11.424 GHz performing both low-level RF measurements and high power RF tests at the SLAC National Accelerator Laboratory. Based on the same electroforming process we realized also an alternative original layout where a water-cooling of the irises has been implemented for the first time. The SW structures that have been manufactured contain three cells fed by a circular waveguide. The central cell has a gradient twice higher than the adjacent ones used to match the RF power from the input circular waveguide. The mode excited to test the structure is the π-mode. With this layout, breakdowns occur predominantly in the central cell with the highest gradient cell while the two side cells show surface conditions unperturbed by breakdowns [2, 7, 8, 9, 10, 11]

In collaboration with SLAC [12] we are also investigating the possibility of reducing the quadrupolar components of the X-band cells and the associated feedings elements (mode launcher) in order to obtain a high brilliance of beams with numerical simulations by using ANSYS [13]. A TM01 dual feed mode launcher with a 41 dB reduced quadrupolar components on the power output (see Fig. 1) has been designed against the 25 dB of the standard one. The electroformed structures have been manufactured with different roughness from 10 to 70 nm, by changing the shape of each cell, reducing the deposited films porosity and trying, in particular, to maximize the conductivity of the Au film.

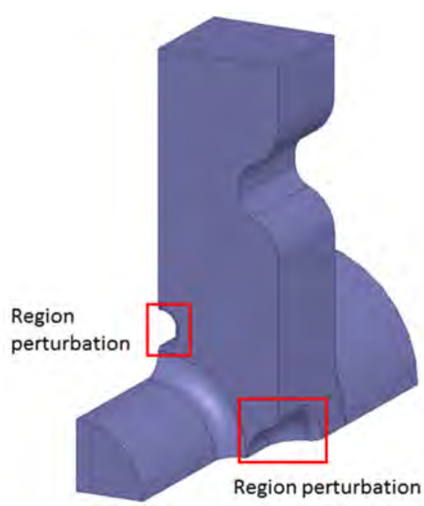

Figure 1: A quarter geometry of the improved TM01 mode launcher for quadrupole components minimization. The two perturbations are located between the rectangular waveguide and the smaller pipe.

In 2015 we exploited also other possibilities offered by the electroforming process such as its natural tendency to leave an open channel in a high aspect ratio component. This natural mechanism offers the possibility to build open channels to cool the device. We completed the experimental evaluation of one prototype where this process has been successfully applied to obtain cooling channels built-in around the irises. Moreover, we investigated also the change of the resistivity as a function of the gold film obtained with the evaporation procedure, a method that may improve the film deposition and, in particular, its purity.

Using X-band Au-Ni standing wave structures manufactured with the electroforming process to avoid the large heat treatment of the metal, we also performed high power RF tests at SLAC. For these devices breakdown rates were obtained as a function of the accelerating gradient in addition to the peak pulse surface heating in the cavity for different pulse length of the accelerating structures. The RF pulse we used has a charging time of 170 ns followed by a flat part ranging from 100 to 600 ns. We run with RF pulses with a flat shaped part and different lengths: 150, 200 and 400 ns to study the dependence with the pulse length. As a result, we may claim that in soft Cu SW structures with a disk-loaded type, the breakdown rate is also highly correlated with the peak pulse heating. Moreover, in these geometries the electric and magnetic RF parameters are well correlated [2)] while no correlation occurs either with RF fields or with the pulse heating for the same breakdown probability. This unexpected behavior can be associated to the non-uniform gold coating in the high magnetic areas or to a diffusion of Ni inside the gold plating.

Finally, we obtained information on the breakdown behavior comparing data between a structure made with soft copper and a second one obtained with the Cu electroforming process. The latter was tested with the same pulse with a flat shaped structure of 150 ns and 200 ns. Tests show that the RF losses in the electroformed structure are 60 % higher than in the soft copper structure of the same type. In spite of the higher RF losses and the slow initial conditioning of the gradient, the breakdown rate of the electroformed structure is similar to the soft copper one with a 200 ns long flat shaped pulse and 20 % lower with a 150 ns long flat shaped pulse.

4 New technological materials

One of the goals of the project is to demonstrate the feasibility of accelerating gradients much higher than 130 MV/m using realistic accelerating structures and practical operating conditions. Actually, the main effects that limit the increase of the gradient are: the RF breakdown and the fatigue cracking due to pulsed surface heating. The structural design of RF structures requires 1-2 μm dimensional tolerances and optical quality surface finish while a high gradient requires high electro-magnetic fields and power flows, both really challenging issues for all materials.

The magnetic field near the surface induces a temperature rise of the material, which, due to its pulsed nature, does not allow heating up the bulk uniformly. The resulting pulsed surface stress will cause a surface breakup by fatigue. The induced surface damage of the material involves a depth comparable to the skin depth at the RF working frequencies. As a consequence, high electric and magnetic fields near the surfaces of real devices trigger RF-breakdowns.

Copper is the most studied material in RF applications due to its high electric and thermal conductivity, as well as for the possibility of a high precision machining. Using thin films deposition combined to precision electroforming new possibilities and new classes of innovative materials may be obtained. Working with coated materials, in principle, we may control composition, internal stress, mechanical properties, roughness, and from micro- to nano-structures. All these properties affect the thermo-mechanical stability of the different coatings and may be tailored to specific applications in a range of values not attainable starting from bulk materials.

A study is in progress at the LNL laboratory to produce coatings for the accelerating structures using their recognized expertise in coatings and multilayer deposition by ionized and conventional sputtering, and the surface characterization using the ion accelerators available at the LNL laboratory [14, 15].

5 Molybdenum coatings and damage characterization

Dedicated RF devices with Mo coatings have been already manufactured. However, although Cu coated by Mo via sputtering under vacuum is a promising approach to increase the accelerating gradient of RF cavities working at high frequencies a lot of work is still necessary to achieve the performances required at high power. Different samples of Mo films have been growth in collaboration with the Istituto di Acustica e Sensoristica of the National Research Council (CNR) using the RF magnetron sputtering [16, 17] More details on the preparation procedures of these coating are available in [19].

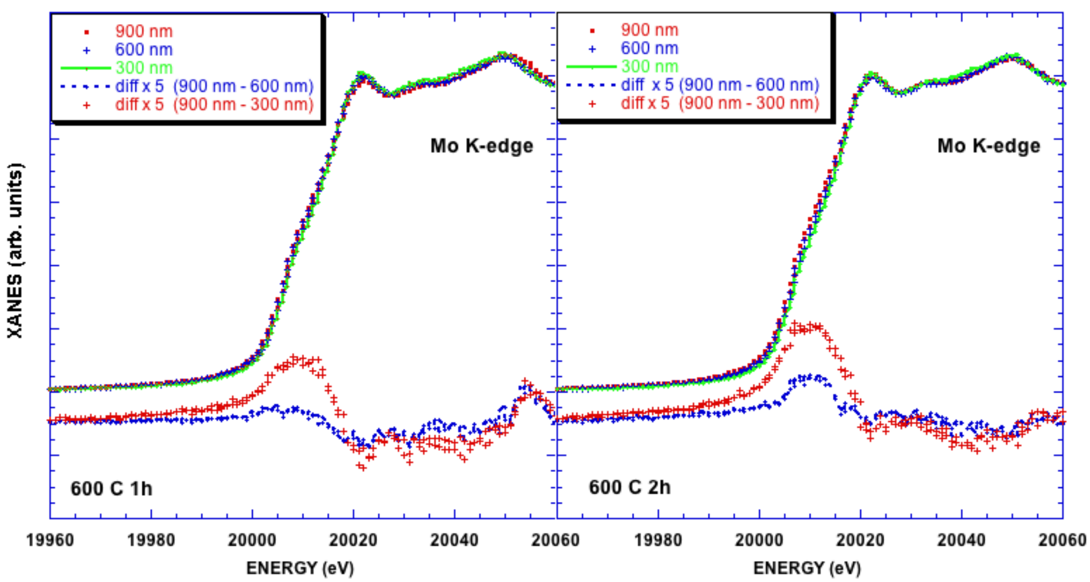

Figure 2: Comparison among XANES spectra of Mo coatings with different thickness and annealing temperature at the Mo K-edge and differences (enhanced by a factor 5) among these normalized spectra. Data show that both structure and morphology of these films are affected by the sputtering process and the thermal annealing.

We growth several Mo films at room temperature by using the RF magnetron sputtering technique on glass and sapphire substrates and the deposition parameters were optimized addressing the growth of almost oxygen free Mo layers. We also combined FIB imaging, to visualize at high spatial resolution the morphology of these Mo films and to accurately measure their thickness, with transport experiments to evaluate the resistivity [16, 17, 18, 19]. The characterization of the chemical properties of the coated films has been carried out also at the Diamond Light Source (UK) with the XANES (X-ray Absorption Near Edge Structure) and the XRD (X-Ray Diffraction) techniques, i.e., to evaluate the degree of crystallinity, identify different ordered phases and probe local structure and electronic properties [20, 21, 22, 23]. As an example, in Fig. 2 we show the comparison of the XANES spectra of different coatings at the Mo K-edge and the differences among normalized spectra in the edge region. The differences (enhanced by a factor 5) point out that the structure and morphology of these films are affected by the thermal annealing procedure [24]. The

Mo coatings we growth exhibit a resistivity less than one order of magnitude higher than the Mo bulk and comparable with that of bi-layer MoOx films (105 cm) growth with different crystalline phases. Work is in progress to enhance the conductivity of these multiphase films characterized by percolative phenomena, critical processes for which the dimensionality is a relevant parameter, tuning both growth parameters and post treatment processes [25, 26] The achieved results show that the combination of magnetron sputtering and post-deposition annealing is a suitable method to grow homogenous Mo coatings that could be used for RF cavities working at high frequencies.

In cooperation with SLAC different imaging techniques have been considered to evaluate and to understand the damage induced by breakdowns after operation of RF structures at high gradient. Visible images shown in Fig. 3 clearly show that gold coating is removed in the regions of the high-electric field while no obvious pulse heating damage occurs on the plating. The result is very surprising after the observation of the massive pulse heating damage of the copper coating.

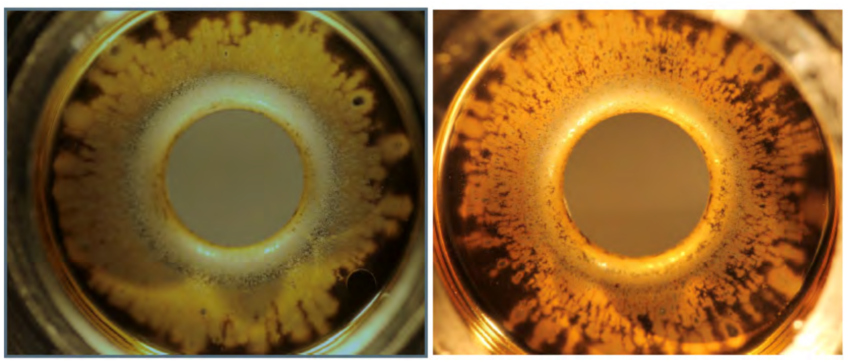

Figure 3: Images of the autopsy of an electroformed three cells Au structure: left) the image of the high gradient side of the center cell; right) the image of the high gradient side of the end cell. The removal of Au from the surface due to multiple breakdowns is evident in the region of the highest-electric field.

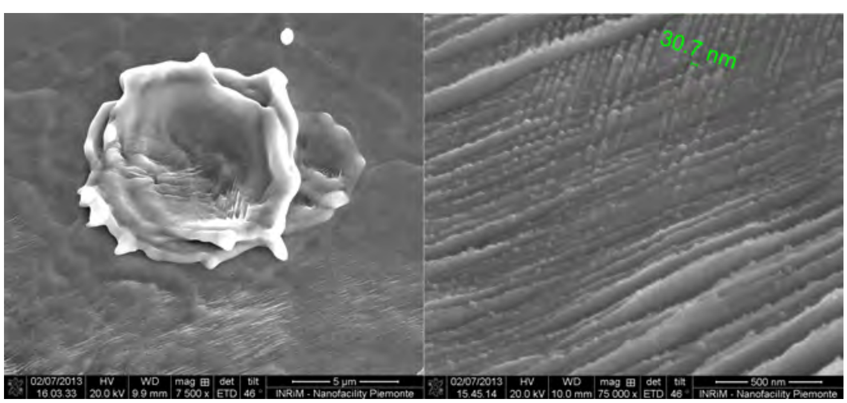

Figure 4: Details of the surface of a cavity exposed at SLAC (courtesy of V. Dolgashev). left) an isolated defect consisting in a molten Cu crater showing the texture ascribed to thermal fatigue; right) a magnified view of texture at the nanometer scale induced by the cyclic pulsed heating.

To clarify at the submicron scale of the observed phenomena, investigations are currently being made in collaboration with the LNL to understand the mechanism of RF breakdown by using electron and ion microscopies. The possibilities offered by nm resolution SEM-FEG coupled to the capability to investigate with Focussed Ion Beams (FIB) sub-surface regions under the RF debris may shed new light on this challenging issue, see Fig. 4.

This complex issue and the underlying mechanisms could be addressed applying the most modern x-ray imaging techniques to obtain 2D and 3D images of RF devices or section of these devices at high spatial resolution trying to reconstruct the induced damage and to understand the mechanism and the consequence of the breakdown phenomena. For 3D imaging we sectioned an iris made in copper. Indeed, for its size and thickness we had to reduce it in order to allow the collection of x-ray images. A photograph of the iris on the sample holder inside the high-resolution computed tomography (CT) system is shown in Fig. 5. Because of the high x-ray absorption cross section of copper the results obtained are still not satisfactory, but preliminary results point out that there is room for improvement and, in the future, using optimized and powerful industrial devices, in the future a reconstruction of small metallic devices is in principle possible.

Figure 5: Photograph of the copper iris of a high-gradient cell installed on the sample holder for the X-ray CT scan to investigate the induced internal damage of components undergoing high-gradients (courtesy Labormet Due).

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