**DEMETRA ACTIVITY REPORT 2016**

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## 1 Aim of the experiment and introduction

The DEMETRA experiment is dedicated to the modeling, development and test of RF structures devoted to acceleration with high gradient of particles through metal and dielectric devices. The team of the Laboratori Nazionali di Frascati (LNF) is involved in different research studies including the simulation and construction of RF structures performed in the framework of a INFN-LNF, SLAC (USA), KEK (Japan) and UCLA (Los Angeles) collaboration. A relevant fraction of the R&D was devoted to studies of new materials and manufacturing techniques to improve the maximum sustainable gradients in normal conducting RF structures operating at X-band (11.424 GHz), trying to minimize the breakdown and the dark current [1, 2]. Within 2016, the LNF team performed simulations [3, 4, 5], manufactured new RF devices and started characterization studies of new coatings based on transition metals oxides.

## 2 Copper technology & RF structures

High-brightness electron beams are required for a great number of applications, including advanced accelerators linear colliders, X-ray free-electron lasers (FELs), and inverse Compton scattering accelerators for research, compact or portable devices for radiotherapy, mobile cargo inspections and for security, biology, energy and environmental applications. The most successful device for producing such beams is a RF photo-injector gun. The latter has been undergoing a continuous evolution over the past 25 years achieving an always better emittance and higher currents. The present R&D in the cryogenic copper technology (working conditions 50 K) will enable a variety of new applications, including linear collider and free electron laser acceleration, thanks to accelerating gradients over twice the value achieved with competitive technologies.

As an example, in S band operation, the cryogenic copper technology allows to reach values of field gradient $> 250MV/m$. This level in turn permits over a factor of 25 of increase of the beam brightness [6, 7]. This new technology will permit compact and affordable new accelerators in many critical areas and interdisciplinary applications. Also for this reason in collaboration with SLAC we designed an innovative compact mode launcher with no RF multipolar fields, (see Fig. 1). In order to remove dipole and quadrupole modes from the standard radiofrequency photo-injector, a four-folded coupler has been designed. A $TM_{01}$ mode launcher has been chosen in order to power on axis a radiofrequency photo-injector in S-band or X-band. By this way, it is possible to remove the cavity coupler from the full cells, minimize the magnetic field on the coupling aperture and then the pulse heating and the breakdown rate of the RF structure. The novel, compact and symmetric launcher in Fig. 1 converts a $TE_{10}$ mode in a $TM_{01}$ mode. The design consists of four rectangular waveguides for power input and a circular one for output. A cut-off beam pipe and a couple of matching bumps, in order to minimize the reflected power, complete the design. The device has been optimized also to have EM fields at the output waveguide with equal phase and amplitude [8, 9, 10].

Following the international trend, we attempted to improve the performance of X-band structures also in terms of alternative manufacturing approaches to brazing such as the electroforming, or electron beam welding. In 2016, we dedicated time to design studies of linear accelerating standing wave (SW) structures to maximize the radio-frequency (RF) performance. In Fig. 2 we show a three cells X-band standing wave structure designed for breakdown study at high power. This structure has a rounded profile in order to increase the quality factor Q (for this structure Q $> 6\%$). In Fig. 2 we compare two designs for electroforming manufacturing. This approach has also been used to design a three cells W-band device at SLAC.

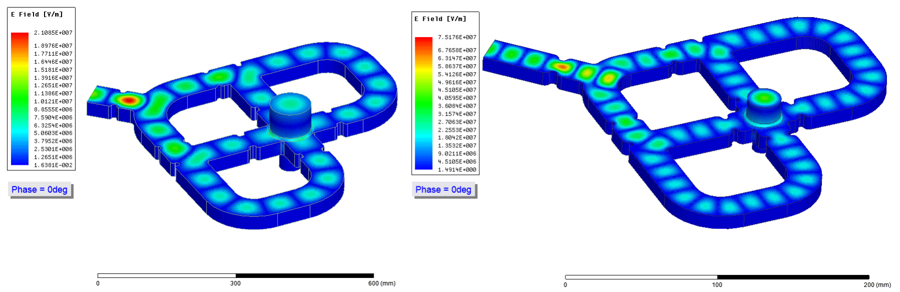


Figure 1: Symmetric and compact mode launchers designed in collaboration with SLAC and optimized to power the next generation of RF cryocooled photoguns with no multipolars fields. This new on axis symmetric coupler (as proposed by V. Dolgashev) that couples a TE10 rectangular mode to a TM01 circular mode has been simulated. The four symmetrized arms of the device also cancel dipolar and quadrupolar modes, allowing the operation with a high brilliance beam. The designs have been carried out for S-band (left) and X-band (right).

## 3 Breakdown studies

The design of accelerator components such as RF cavities suitable to minimize breakdown depends on materials, surface processing techniques, but also geometry so that it is necessary to understand and predict the breakdown behaviour of practical structures, but also identify alterntive materials highly performing in term of breakdowns.

Actually, after decades of studies and experiments the high-gradient RF breakdown phenomenon remains an open problem. A dedicated research and development has been launched in this field in the linear-collider community [11]. The activity of testing high-gradient RF sections at 11.424 GHz for the next generation of electron–positron linear collider is in progress, in particular to investigate breakdown mechanisms, which limit the high gradient performance of any RF structure [12].

The activity to design, construct and conduct high-power experimental tests on standing wave (SW) accelerating sections began at LNF in the framework of the collaborations with SLAC and KEK laboratories that dates back in the 90s. After that an intense technological activity has been always dedicated at LNF to design and manufacture X-band accelerating structures with different materials and methods. The motivation for the study of hard copper alloys came from results of the pulse heating experiments [12, 13]. Basically, from these experiment discs made of hard copper and hard copper alloys (CuCr, CuZr) had significantly less damage at 110 C while discs made of high-temperature annealed soft copper started to be damaged already at 50 C [14, 15]. Moreover, high power RF tests of a single-cell standing-wave structure made of soft copper, showed an excellent correlation with peak surface magnetic field and peak pulse heating temperature [15].

To improve high power performances, e.g. the discharge rate, fabrication procedures need to avoid heating of these devices at high temperature as it happens in conventional vacuum brazing

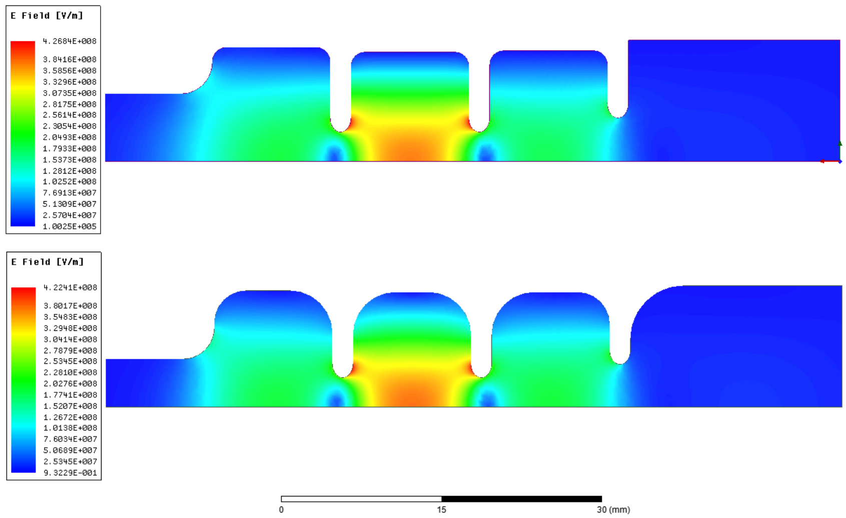


Figure 2: Comparison of the proposed layouts between two sections for an open X-band three-cells structure cavity designed for X-band breakdown tests and for electroforming manufacturing. Top: standard design for cell-to-cell brazing manufacturing; bottom: high radius fillet are manufactured as for open structures.

technique or using materials with a high fusion temperature. Moreover, for the standard brazing procedure a high temperature is required in order to obtain a joint with good mechanical and vacuum tight properties. Generally a temperature of at least $700-800\ ^\circ$C for copper is needed. However, this temperature modifies the morphological properties of the material, unavoidably affecting its quality in terms of RF performance. As a consequence, low temperature procedures (or hard bonding) started to be considered. Among the different possibilities we selected the Electron Beam Welding (EBW) procedure for our device. The main advantage of EBW is the low thermal energy transferred to the piece under manufacturing. In addition the method is characterized by the total absence of other metals generally present in the joint among cells, when the brazing process is used. The idea of using the Electron Beam Welding (EBW) technique is an interesting approach to the bonding of accelerating structure at low temperature. As a matter of fact, it has been already proved that hard copper is able to handle high power better than soft one. Since the high power RF tests of the hard-copper structures showed improvements over soft copper one, we have designed and fabricated a three cells standing wave copper structure operating at 11.424 GHz sealed with the EBW approach, that will be tested at SLAC in 2017. A photo of the first electron beam welded hard copper accelerating cavity manufactured at the LNF using the Italian technology is showed in Fig.3.

## 4 Metallic films

One of the goals of the DEMETRA project is to demonstrate the feasibility of accelerating gradients much higher than 130 MV/m using realistic accelerating structures and practical operating conditions. As underlined above, the main effects that limit the increase of the gradient in addition to the RF breakdown are the fatigue cracking due to pulsed surface heating and the dark current.

Modern accelerator technologies are enabled by the use of materials that match their demands. However, the new accelerators are highly demanding in term of material properties, in particular

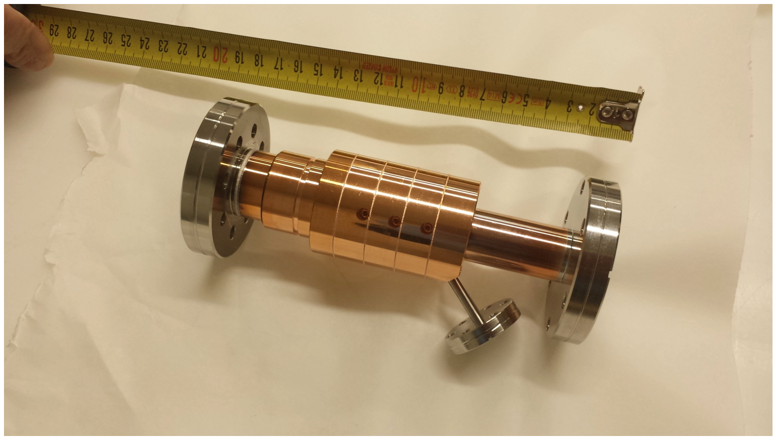

Figure 3: Photographs of the first electron beam welded hard copper accelerating cavity manufactured at the LNF using the Italian technology.

for breakdown phenomena. A way to go is certainly improving our understanding of the non-linear phenomena occurring during breakdowns in vacuum, although to increase the value of the applicable high frequency electromagnetic field we need also to identify new materials or alloys or improve performances of existing materials, e.g., taking advantage of nanotechnology.

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 advanced techniques combining a film deposition and precision electroforming new possibilities may open in this field. Adding a coating, of which we may control composition, internal stress, mechanical properties, roughness, etc., properties of a bulk material like the thermo-mechanical stability may be improved reaching values not attainable by uncoated materials.

With the present manufacture technology, for electric fields >100 MV/m breakdown phenomena are likely to occur, unavoidably damaging materials and devices. The breakdown phenomenon, which takes place in vacuum is affected by material properties and conditions existing at and/or adjacent to the surface. The scenario in which a breakdown may occur is far to be understood and not only field-electron emission. To find a solution to such extremely demanding applications we considered the possibility to coat copper (and other metals) with a relatively thick film to improve and optimize breakdown performances. The ideal coating material has to show comparable or superior mechanical and chemical-physical properties conductivity, mechanical resistance and chemical affinity. As we discussed in ref. [15], a high-conductivity Mo metallic coating made is an interesting option for high performance accelerator components. Although the Mo conductivity is lower compared to Cu, looking at the results of the Mo breakdown rate the application in high gradient accelerating structures is promising [16, 17, 18]

In 2016 we started to grow $MoO_3$ films on flat copper substrates with a roughness of 20-30 nm. The great interest towards molybdenum oxides is due to their mechanical resistance, good electrical conductivity and low field emission. Several films with different thickness (see Fig. 4) have been grown in collaboration with the Department of Physics of the University of Tor Vergata. Work is in progress within the DEMETRA collaboration and also outside (Napoli Federico II university) to characterize the properties of films and coated materials. In addition to the experimental approach we developed also an analytical model based on transmission line equations to evaluate the effective skin depth of thick coatings on copper. This tool allows a first evaluation of the quality factor of an RF device, of the electric field, and of the dissipated power in the coating layer. As showed in Fig. 5, different materials for the coating of a copper surface have been considered, such as SiC, TiN, Mo, and its oxides. At present, the best electrical performance can be achieved with transition metals like Mo [19].

Figure 4: Left: photograph of some samples of $MoO_3$ films growth on flat copper substrates and sealed in plastic bags after deposition; right: photograph of the sample on the evaporation HV chamber with the thickness gauge.

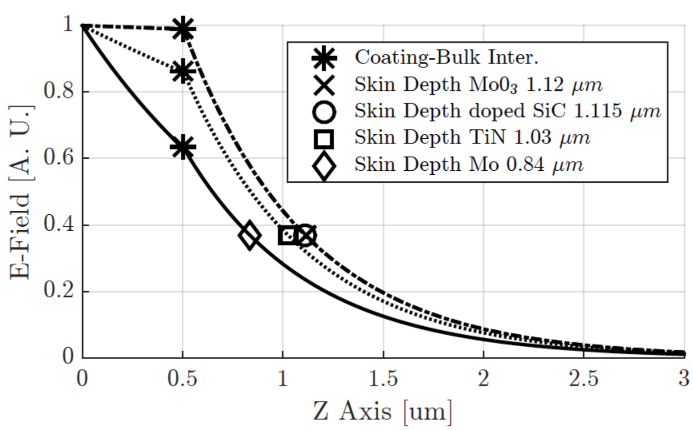


Figure 5: Comparison among the electric field profiles of a copper bulk coated with a layer 500 nm thick of $MoO_3$ (- - -), $SiC$ (-·-·), $TiN$ (····) and $Mo$ (——).

## 5 List of Conference Talks by LNF Authors in Year 2016

Include a list of conference talks by LNF authors.

1. A. Marcelli, Molybdenum oxides films: conductivity properties vs. work function, 13th International Conference on Atomically Controlled Surfaces, Interfaces and Nanostructures - ACSIN 13 (Rome, October 9-15, 2016).

**References**


1. Dolgashev, V. A., Gatti, G., Higashi, Y., Leonardi, O., Lewandowski, J. R., Marcelli, A., ... & Yeremian, D. A. (2016). High power tests of an electroforming cavity operating at 11.424 GHz. Journal of Instrumentation, 11(03), P03010.

2. Gatti, G., et al. "X-band accelerator structures: On going R&D at the INFN." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 829 (2016): 206-212.

3. Pompili, R., Anania, M. P., Bellaveglia, M., Biagioni, A., Castorina, G., Chiadroni, E., ... & Filippi, F. (2016). Femtosecond timing-jitter between photo-cathode laser and ultra-short electron bunches by means of hybrid compression. New Journal of Physics, 18(8), 083033.

4. R. Pompili, G. Castorina et al., Experimental characterization of the active plasma lens device (subm. 2016).

5. A. Brynes, G. Castorina, O. Frasciello, A. Marcelli and B. Spataro, Studies of geometric wakefields and impedances due to collimators, INFN-16-10/LNF, June 30, 2016.

6. A.D. Cahill, A. Fukasawa, R. Pakter, J.B. Rosenzweig, V.A. Dolgashev, C. Limborg-Deprey, S. Tantawi, B. Spataro, G. Castorina, RF design for the TOPOGUN photogun: A cryo-normal conducting copper electron gun. High Brightness Beam Workshop 2016 (Cuba, LAvana, March 28, 2016) submit to NIM-A (2016).

7. J.B. Rosenzweig, A. Cahill, V. Dolgashev, C. Emma, A. Fukusawa, R. Li, C. Limborg, J. Maxson, P. Musumeci, A. Nause, R. Pakter, R. Pompili, R. Roussel, B. Spataro, and S. Tantawi, Next Generation High Brightness Electron Beams From Ultra-High Field Cryogenic Radiofrequency Photocathode Sources, submit. to Phys. Rev. Special Topics - Accelerators and Beams (2016).

8. Chae, M. S., Hong, J. H., Parc, Y. W., Ko, I. S., Park, S. J., Qian, H. J., ... & Tang, C. X. (2011). Emittance growth due to multipole transverse magnetic modes in an rf gun. Physical Review Special Topics-Accelerators and Beams, 14(10), 104203.

9. G. Castorina, Design of a RF GUN with on-axis coupling and its feeding network (compact mode launcher with no multipolar component), Activity Report SPARC_LAB, 14/03/2016.

10. V. Dolgashev, High Gradient Acceleration Studies at SLAC, Seminar given at Laboratori Nazionali di Frascati INFN on 18/11/2016

11. http://clic-study.org/S

12. Dolgashev, V., Tantawi, S., Yeremian, A., Higashi, Y., & Spataro, B. (2012, June). Status of high power tests of normal conducting single-cell standing wave structures. In Conf. Proc. C100523: THPEA060, 2010 (No. SLAC-PUB-15117). SLAC National Accelerator Laboratory (SLAC).

13. L. Laurent, Pulse Heating Test Results, CLIC08 Workshop (CERN, 14-17 October 2008) Switzerland.

14. A. Dolgashev et al., Status of High Power Tests of Normal Conducting Single-cell Structures., EPAC08, Genoa, Italy, 2008.

15. Bini, S., Spataro, B., Marcelli, A., Sarti, S., Dolgashev, V. A., Tantawi, S., ... & Ruffino, F. (2013). Molybdenum sputtering film characterization for high gradient accelerating structures. Chinese physics C, 37(9), 097005.

16. Xu, Y., Spataro, B., Sarti, S., Dolgashev, V. A., Tantawi, S., Yeremian, A. D., ... & Parodi, R. (2013). Structural and morphological characterization of Mo coatings for high gradient accelerating structures. In Journal of Physics: Conference Series (Vol. 430, No. 1, p. 012091). IOP Publishing.

17. Marcelli, A., Spataro, B., Sarti, S., Dolgashev, V. A., Tantawi, S., Yeremian, D. A., ... & Cappuccio, G. (2015). Characterization of thick conducting molybdenum films: enhanced conductivity via thermal annealing. Surface and Coatings Technology, 261, 391-397.

18. G. Castorina, A. Marcelli, F. Monforte, S. Sarti, B. Spataro, An analytical model for evaluating the properties of metallic coatings, Cond. Matter (2016) doi:10.3390/condmat1010012

19. A. Marcelli et al. in preparation (2017)