NUCLEAAR

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1 Summary

NUCLEAAR is one of the projects of the Research and Development (R&D) section of the INFN Vth Committee, which addresses the scientific and technological challenges necessary to pushing forward the next research frontiers on accelerators. The developments are mainly oriented to technological and industrial applications of accelerators, of the future colliders, and of the next generation of accelerators after LHC, which at present is under discussion in the European Particle Physics Strategy Form.
In this context the aim of the NUCLEAAR project is the investigation of specific coatings to improve the performance of accelerating cavities. In order to design powerful and more compact accelerators, it is necessary to increase the intensity of the electromagnetic fields at which all accelerating devices operate. The present copper-based technology is limited by breakdown phenomena that damage the surface of the RF cavities operating at high electrical gradients (100-200 MV/m) for long time. Additional information on the NUCLEAAR experiment are available on the LNF website in three languages (ITA/ENG/Chinese) at the URL: http://w3.lnf.infn.it/ricerca/ricerca-tecnologica/nucleaar/.

2. Activity

In 2019 the activities of the NUCLEAAR experiment have been focused on the:

- Evaporation of flat and curved copper substrates;
- High electric field irradiations performed with high intensity THz radiation;
- Characterization of properties of coated films (electrical and optical experiments)
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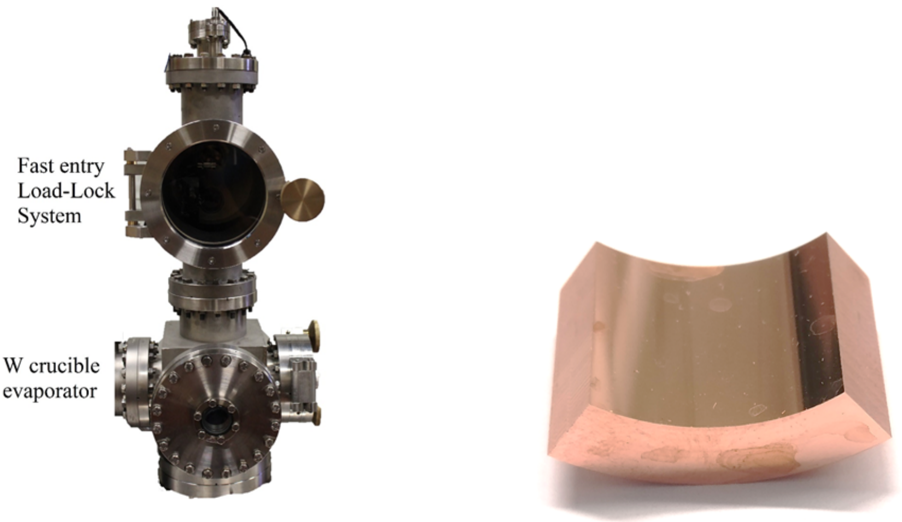

FIG. 1 – (left) HV evaporation chamber: in the upper part is placed the sample while in the bottom chamber is located the crucible filled with the oxide powder; (right) one small curved copper element with a thin coating of MoO_3. This is one of the sections that assembled together using the TIG welding allow to obtain a cylindrical cavity. The film in the internal side of each element has been evaporated on the copper surfaces with the high vacuum (HV) chamber shown in Figure 1 (left).

Evaporation of flat and curved copper substrates

For the preparation of a coated cylindrical cavity as expected in the 2nd year we manufactured several low roughness flat and curved copper substrates. After we started to develop a procedure to coat curved substrates. In Fig. 1 (left) a photograph of the evaporation chamber available in the LNF thanks to the cooperation with the Roma *Tor Vergata* university.
In the right of Fig. 1 a photograph of one of the four elements obtained from the manufacture of a cylinder of copper. The internal surface of each element was polished down to ~25 nm of roughness and after evaporated with a thin layer of MoO_3 (~100 nm).
The evaporation of other substrates will restart after the end of the analysis of the resistivity, annealing and reflectivity of the existing substrates and after the characterization of the assembling by TIG welding of the curved elements.

High electric field irradiations performed with high intensity THz radiation

To verify the damage induced by high electric field on copper and coated surfaces [MoO_3/Cu and MoO_3/Al], we performed irradiations experiments with a high intensity pulsed THz radiation using the THz Free Electron Laser at ISIR, the THz facility in Osaka (Japan) [May 18-22, 2019].
The THz generated from ISIR is able to induce an electric field gradient up to ~4 GV/m. We performed tests were performed on copper and aluminium samples, with and without MoO_3 coating. The analysis of the induced damage points out a strong dependence with the incident angle and the MoO_3 coatings showed a significant reduction of the damage induced by the THz pulses. In Fig. 2 is shown a typical damage pattern induced on copper.

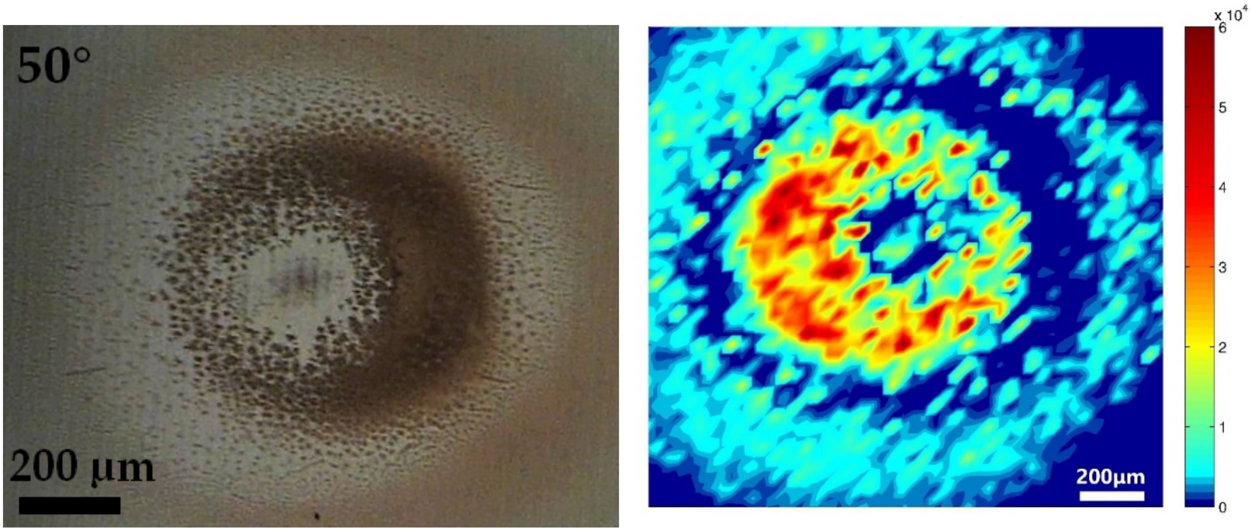

FIG. 2 – (left) Image obtained with the optical microscope of the damaged area on the copper surface. The damage is the result of 5000 pulses of THz radiation irradiating the surface at the incident angle of 50°. (Right) The same area on the left analyzed by Raman spectroscopy. The map in false colors shows the different distribution of copper oxide (Cu_2O) on the irradiated surface.

The planned experiments of damage to high electric fields to be carried out at Sapienza in the THz optical laboratory have been not yet performed for problems related to the Coherent laser system. Indeed, the installation of the TOPAS parametric amplifier was completed only at the end of 2019 and the test has been carried out only in January 2020. The optical system is now available and the first reflectivity experiments with copper substrates are planned.

Characterization of properties of coated films (electrical and optical experiments)

Experiments to measure the electronic transport have been carried out on five MoO_3 samples with different thicknesses prepared by thermal evaporation of MoO_3 as a function of temperature. In particular we attempted to measure three thick samples (from 150 to 700 nm of MoO_3) annealed and non-annealed. As an example, measurements on a thin sample (150 nm) annealed and not annealed (yellow pale transparent) show a measurable resistance for the annealed film while not annealed samples (almost disordered) exhibits an insulator behavior. The annealed sample is characterized by a relatively constant and slightly decreasing resistance vs. T probably due to the formation of a metallic layer. (see Figure 3) The coating appears as the combination of a transparent insulating layer overlapping a dark blue metallic layer. The analysis of the mechanism of transport of coatings is in progress.
Regarding the optical reflectivity experiments at Sapienza, it has been assembled a custom made THz Pulsed System (TPS) based in the reflection configuration (see Figure 4a). The layout uses the broadband THz radiation (0.1-3.5 THz) generated via photoconductive switches and can work both for THz emission and detection.

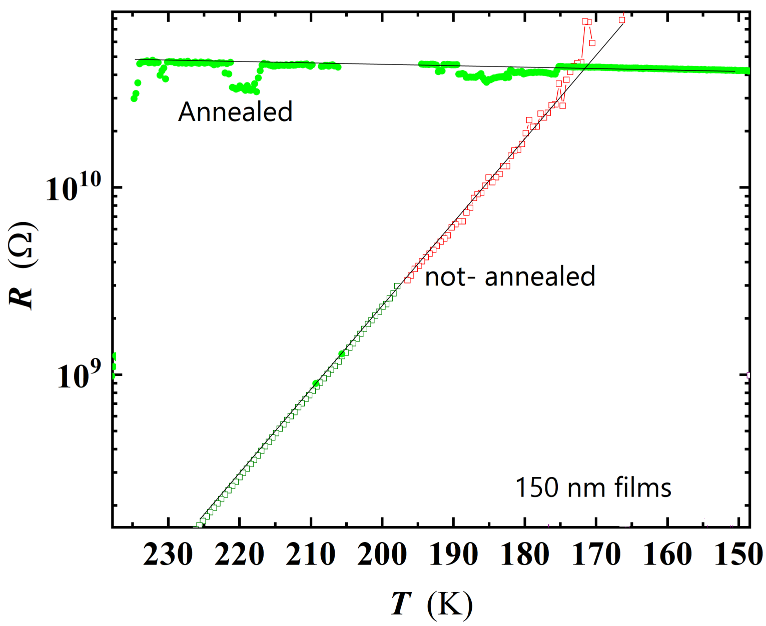

FIG. 3 – The resistance vs. temperature measured on films of MoO_3 prepared via thermal evaporation. Annealed and not annealed films clearly show a different conducting behaviour.

We use the mode-locked ultrafast laser (FemtoFiber NIRpro, Toptica) at 780 nm with the 100 fs temporal pulse width and the repetition rate of 80 MHz to illuminate a twin G10620-11 Hamamatsu PCAs. The femtosecond laser is split into two beams by a 50:50 beam splitter and each beam has 15 mW of average power. Dielectric mirrors deflect the beams towards the emitter and the PCA detectors. TPX made lenses are used to collimate and focalize the THz radiation. For the measurements the sample is aligned in the focus of the THz beam. The point-by-point spectral signal collection is obtained by scanning large area of the object with the 3D axes stage of Thorlabs. The reflected THz pulses are collimated and refocused on the PCA THz-detector again by TPX lenses. Simultaneously, the probe beam is used to gate the PCA THz-detector. The THz electric field as a function of time is measured with a delay line. The output signal from the THz-detector, extracted by a lock-in amplifier (Stanford, SR830), is transferred to the National Instrument acquisition card (NI 6361-BNC connector) allowing the data collection.

To measure the optical reflectivity of copper and films coted on copper we assembled at Sapienza the THz optical layout showed in Figure 4b and described above. The first tests was done and measurements of flat and curved copper surfaces and coatings are planned in the next weeks. At the same time also the experiments of damage to high electric fields (~ 4GV / m) on copper, and on coating of MoO_3 on copper and aluminum first carried out with the FEL ISIR in Osaka in May 2019 are planned to be performed in the near future. Indeed, at Sapienza, for problems related to the Coherent laser system, the installation of the TOPAS parametric amplifier was completed only at the end of 2019 and the testing carried out in January 2020. The completion of this optical system now ended and tests are in progress.

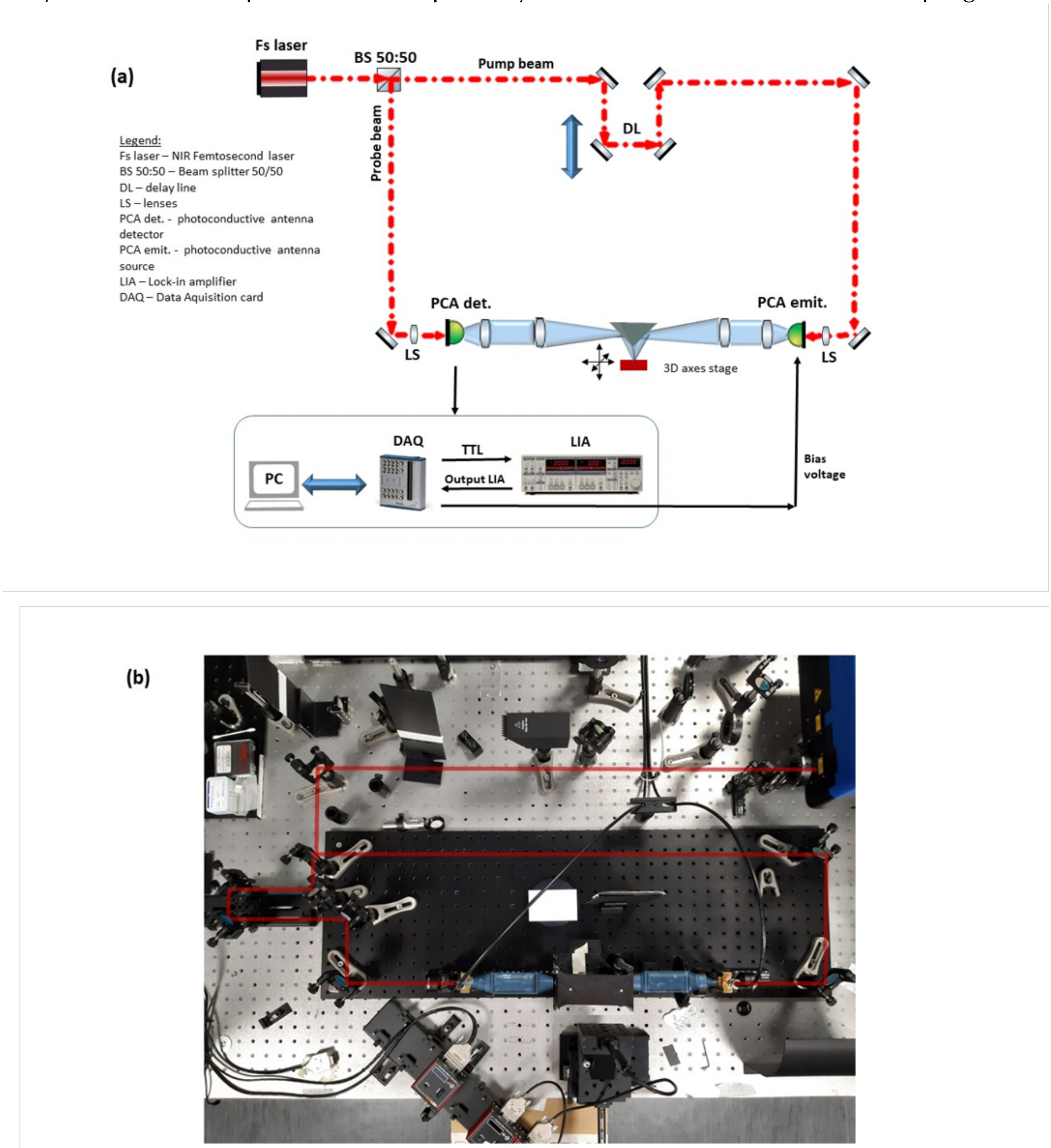

FIG. 4 – a) Layout of the THz Pulsed System based on the THz-TDS and working in the reflection configuration assembled at the THz laboarory at Sapienza university. It generates broadband THz radiation (0.1-3.5THz) for both THz emission and detection with the mode-locked ultrafast laser (FemtoFiber NIRpro, Toptica) at 780 nm, with 100 fs temporal pulse width and repetition rate of 80 MHz. TPX lenses are used to collimate and focalize THz radiation; b) Photograph from the top of the THz optical system described in panel a) and in the text.

3 List of Oral Presentations

S. Macis
Surface damage angular dependence of metallic systems by high gradient THz radiation
PIERS 2019, 17-20 June 2019 Rome, Italy

S. Macis
Thin conducting MoO_3 films on copper. A new opportunity for technological applications
10th Young Researcher Meeting, 18-21 June 2019 Rome, Italy

S. Macis
Thin conducting MoO_3 films on copper for technological applications
LIV Zakopane School of Physics, 21-25 May 2019 Zakopane, Poland

4 Publications

- S. Macis, L. Tomarchio, S. Tofani, J. Rezvani, L. Faillace, S. Lupi, A. Irizawa, A. Marcelli
  Angular dependence of copper surface damage induced by an intense coherent THz radiation beam
  subm. to Condensed Matter (2020) under review

- J. Scifo, A. Marcelli, B. Spataro, D. Hampai, S. Dabagov, S. Sarti, A. Di Trolio, R. Moscatelli, S. Macis, L. Faillace
  Molybdenum Oxides Coatings for High Demanding Accelerator Components,
  J. Instruments 3, 61 (2019)

- S. Macis, J. Rezvani, I. Davoli, G. Cibin, B. Spataro, J. Scifo, L. Faillace, A. Marcelli
  Structural Evolution of MoO3 Thin Films Deposited on Copper Substrates upon Annealing: An X-ray Absorption Spectroscopy Study
  Condensed Matter 4, 41 (2019)

- S. Macis, C. Aramo, C. Bonavolontà, G. Cibin, A. D'Elia, I. Davoli, M. De Lucia, M. Lucci, S. Lupi, M. Miliucci, A. Notargiacomo, C. Ottaviani, C. Quaresima, M. Scarselli, J. Scifo, B. Spataro, M. Valentino, P. De Padova, A. Marcelli.
  MoO_3 films grown on polycrystalline Cu: morphological, structural and electronic properties
  J. Vacuum Sci. Tech. A 37, 021513 (2019)

- A. Marcelli, M. Censabella, L. Faillace, M. Grimaldi, G. Keppel, S. Macis, C. Pira, J. Scifo, B. Spataro
  Nb superconductive thin film coating on flat Cu disks for high gradient applications
  INFN-19-15/LNF, July 16, 2019

- J. Scifo, A. Marcelli, B. Spataro, D. Hampai, S. Dabagov, S. Sarti, A. Di Trolio, R. Moscatelli, S. Macis
  TM oxides coatings for high demanding accelerator components
  INFN–19/3/LNF, January 18, 2019

5 Poster

SILS2019 Camerino - September 9-11, 2019

Tuning electronic properties of MoO_3 films on copper substrate: toward high efficiency cavities

S. Macis, S.J. Rezvani, G. Cibin, M. Lucci, I.P. De Padova, C. Bonavolontà, I. Davoli, A. Marcelli