Characterization of X-ray Events in a Vacuum High Voltage Long-gap Experiment

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***Abstract*— The High Voltage Padova Test Facility (HVPTF) is an experimental device for the study of HV insulation in vacuum, in support of the realization of the prototype of a neutral beam injector for ITER, named MITICA. The facility investigates the physical phenomena underlying voltage holding in vacuum, in particular the mechanisms causing breakdowns and the electrode conditioning process. At HVPTF, inside a high vacuum chamber, two stainless steel electrodes, separated by a few centimetres gap, can achieve HV values for a maximum potential difference of 800 kV. During the voltage conditioning of the electrodes, current MicroDischarges (MD) and high energy X-rays are observed and analysed. In this work, we present a characterization of the MicroDischarge dynamics occurring during the conditioning process, with the aim to gain information on the reason of the growing difference between the current contributions measured by the two electrodes. The analysis will be performed thanks to two new X-rays detectors recently installed: a LYSO and a $LaBr_3(Ce)$ scintillating crystals. The new diagnostics indeed provide the fine dynamics of a single MD, recording energy and time of each single detected X-ray. In particular, we compare the MicroDischarge dynamics at the beginning and at the end of the conditioning process and we try to give a preliminary interpretation of the observations.**

***Index Terms*—Vacuum breakdown, voltage holding, large gaps, X-rays spectra.**

I. Introduction

This work has been carried out in the framework of ITER [1], the international experimental facility, currently under construction in Cadarache (France), aiming at demonstrating the technological and scientific feasibility of thermonuclear fusion as a convenient energy source. ITER is a tokamak and it requires additional heating systems to reach high plasma temperatures and to sustain fusion conditions: among them, two neutral beam injectors (NBI) will be installed. In order to validate the ITER NBI design and address the outstanding issues related to its demanding requirements, a full-scale prototype named MITICA (Megavolt ITER Injector & Concept Advancement) will be developed in Padova (Italy) [2].

The occurrence of voltage Breakdown (BD) in ITER can possibly cause damages to the internal surfaces and the production of electromagnetic radiation. Moreover, these events can heavily affect the voltage holding capability of the system, jeopardizing the achievement of the -1 MV voltage in the beam source. The source is, in fact, directly facing the vacuum vessel (at ground potential), in a surrounding gas of about 10^{-5} Pa during the voltage conditioning, or about 0.02 Pa during the operation.

The HV holding in high vacuum is a technological challenge affecting the operation of different physics experiments e.g. particle accelerators. Despite many studies have been carried out in the last century [3], the physical mechanisms behind the phenomenon are not well understood, in particular those regarding vacuum breakdown between long gap (from a few centimeters to meters) electrodes [4].

With the aim to investigate this topic and to provide possible solutions to improve MITICA voltage holding, a specific device, the High Voltage Padova Test Facility (HVPTF) was developed. Its main applications are the test of MITICA components (e.g. high voltage insulators) and the investigation of the physical aspects underlying vacuum insulation [5, 6]. This contribution mainly deals with this latter aspect, presenting new analyses of X-rays spectra produced during the voltage conditioning of the electrodes.

II. Experimental setup

A stainless steel cylindrical vacuum chamber, 2.4 m long, with a 1.2 m diameter, hosts two stainless steel electrodes (in Fig. 1). In the experimental sessions analyzed in this work, the negative electrode is a sphere with a 40 mm diameter and the positive one is a plate with a 108 mm diameter. The gap between them is set to 33 mm. The operating pressure is about $4 \cdot 10^{-5}$ Pa. The electrodes are connected to two Cockcroft Walton power supplies, polarizing each electrode up to ±400 kV to ground, for a maximum of 800 kV potential difference between the electrodes. The vacuum chamber is at ground potential.

The voltage conditioning of the electrodes is realized by means of an automatic procedure, symmetrically operating on both power supplies. A chain of voltage cycles is obtained during each session, since the voltage rises and drops several times before reaching a saturation value. Further details about the procedure are described in [6].

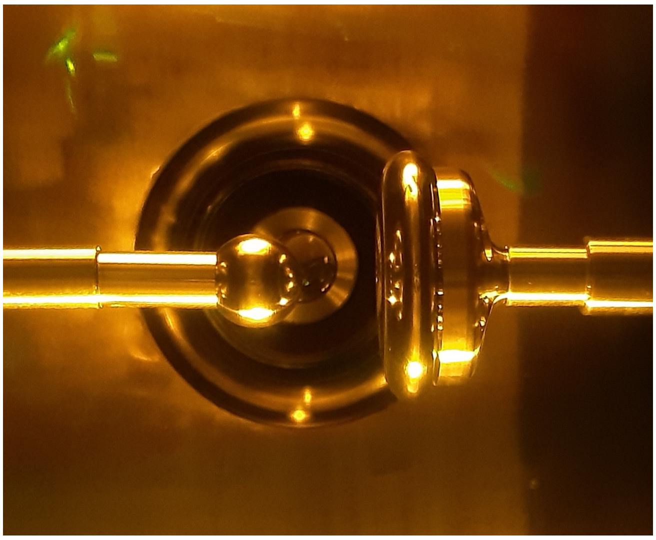

Figure 1: Photo of the electrodes inside the vacuum chamber: the sphere (40 mm diameter) is the negative electrode and the plate (108 mm diameter) is the positive one. The gap between them is set to 33 mm.

The available signals are the voltage applied to the positive and the negative electrodes, V_+ and V_-, and the relative collected currents, respectively I_+ and I_-, along with the gas pressure signal, p. They are sampled together at 100 Hz.
During the conditioning process of the electrodes, current MicroDischarges (MD) are observed to occur, associated to a global increase of gas emission (in particular H_2 and CO_2 from the Residual Gas Analyser) and a large amount of X-rays.

The study of the currents collected by negative and positive electrodes, in order to acquire information about the physical phenomena affecting the voltage holding, is difficult for two main reasons. The first of them is technical, namely, currents are sampled with a time resolution of 100 Hz, which is too low for fast dynamics to be noticed. The second is the fact that current measurements are the result of different contributions that cannot be distinguished: they include interactions between the electrodes or between a single electrode and the vacuum chamber, and it is not possible to discriminate arriving electrons from leaving ions.
High rate X-ray detectors provide information on both these aspects, by measuring the energy of the collected electrons and by detecting single events.

During the past experimental campaigns, the system was unable to well process the high X-ray rates, produced during electrodes conditioning. Currently, the problem has been partially overcome by the installation, at 1 m from the device window, of two new scintillators, characterized by very small sized crystals. This, so to reduce the efficiency, giving the possibility to distinguish each single event, up to a maximum rate of some MHz. Moreover, a new digitizer, characterized by shorter dead time and bigger memory has been installed. A description of the LYSO and the LaBr detectors and of their energy calibration can be found in [7].

III. Experimental Results

Figure 2 (top) shows the time evolution of the currents collected by the positive and negative electrodes during the voltage conditioning. A rescaled time window of 3 seconds has been used in order to highlight the time scales at stake. The associated X-ray events, recorded by the LYSO and $LaBr_3$(Ce) detectors, are presented in the following spectrograms i.e. the energy spectra in time (the color code corresponding to the X-ray counts is in a logarithmic scale). The total voltage between the electrodes is at 465 kV (see the magenta curve). The presence of events with energy overcoming that established by the accelerating voltage is due to a pile-up effect.
It can be observed a clear relation between the current spikes, hereafter MicroDischarges (MD), and the full energy X-rays signals. The main contribution to the total number of X-rays detected is provided by the half-energy events, namely those involving one electrode and the vacuum chamber. In any case, experimental evidence [6] suggests that MD realize the conditioning of the electrodes and, thus, our study focuses on the MD phenomenon.

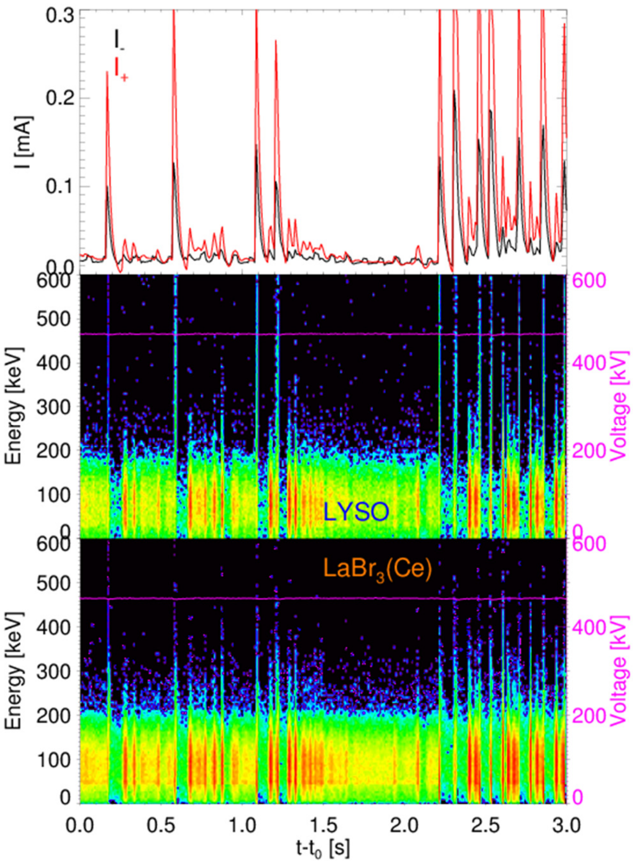

Figure 2: On the top, black and red curves represent negative and positive electrode currents respectively. In the central and bottom figures, the X-ray spectrograms obtained by the two X-ray detectors data are shown (the color code refers to the X-ray counts in a.u.). The magenta curve is the total voltage between the electrodes; X-ray energies overcoming it are affected by pile-up. The time line has been rearranged for ease of viewing (#1910111214).

In Figure 3, X-rays generated by a single MD event are shown. A time window of 10 ms around the MD is selected, in order to ease the viewing of the times and, thus, of the dynamics.
Figure 3a shows data collected by the old detector, a EJ-228 organic scintillator in polyvinyl toluene, with the aim to compare its output with that provided by the new devices, at

similar experimental conditions (at stage II). This system is not fast enough to process so high event rates: more than 97% of the events are recorded at the full-scale energy value (at about 18350 keV, not visible in the figure). The full-scale measure has no physical meaning, but states that the system was flooded. This entails that the data of our interest (up to 600 keV, in the figure) are affected by a distortion: the majority of the events were lost or recorded with delay. This effect probably hide the fine dynamics revealed by the new detectors.

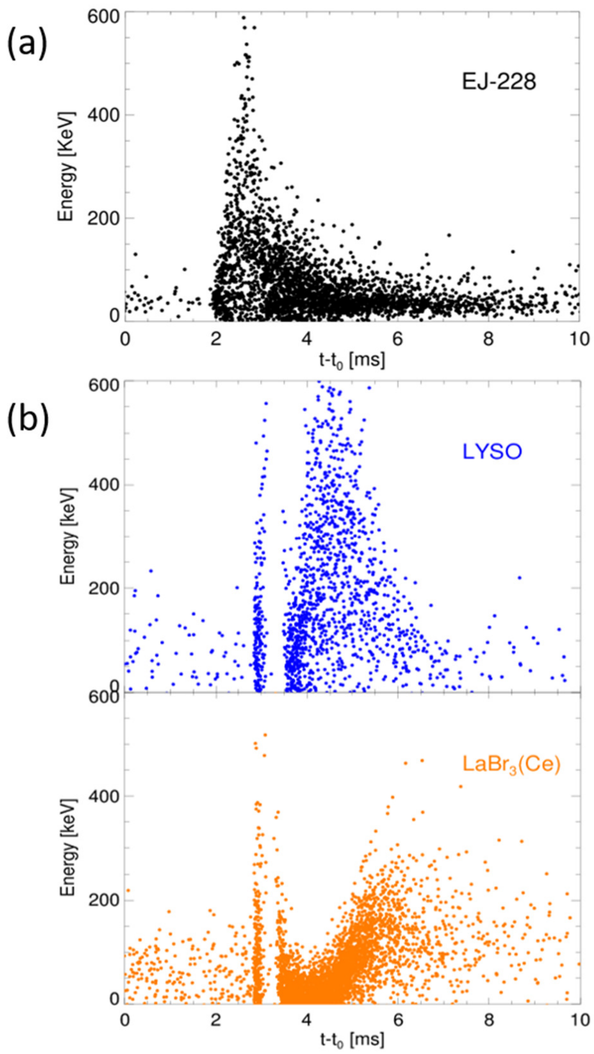

Figure 3: X-ray events generated by a single MD are shown: a) data from the old scintillator EJ-228 (#1705040750); b) data from the new scintillators, LYSO and LaBr (#1910111214). The time line has been rearranged for ease of viewing.

Regarding to Figure 3b, indeed, the high time resolution of the new acquisition chain (small detectors + fast electronics + data acquisition system) allows to distinguish three main different phases within the spike event. In the first phase, lasting fractions of a *ms* (0.1 - 0.2 ms), X-rays of different energies are generated, up to the maximum value provided by the accelerating voltage. In the second phase, lasting 0.4 - 0.5 ms, the events are very rarefied, with a count rate comparable to the background one. During the third phase, characterized by a strong recovery of the X-rays (lasting 3 – 4 ms), the energy distribution of the events, despite being well reproducible for all MD, exhibits a clear difference between the two detectors.

At present, we cannot state which of the two scintillators provides a more realistic picture of the energy-time distribution of X events in this phase.

A preliminary tentative interpretation of the MD internal dynamics suggests that the first train of events is generated by the primary electrons leaving the cathode and hitting the anode. For the electrons impact, some gas is emitted by the anode, ionized and generating a small plasma; then particles diffuse, producing the X events recorded in the third phase. The clear disagreement between data provided by different detectors in this last phase has to be further investigated.

The possibility to visualize in detail the X-rays produced during the MD events, besides the study of the dynamics internal to the MD, can be used to better investigate the conditioning mechanism, by comparing different stages of the process.

It has been observed 0, indeed, that the maximum current value collected by the positive electrode not always corresponds to that collected by the negative one, neither during MD: a third electrode i.e. the vacuum chamber, is involved. In particular, during the conditioning process, the relation between the two current values evolves in time.

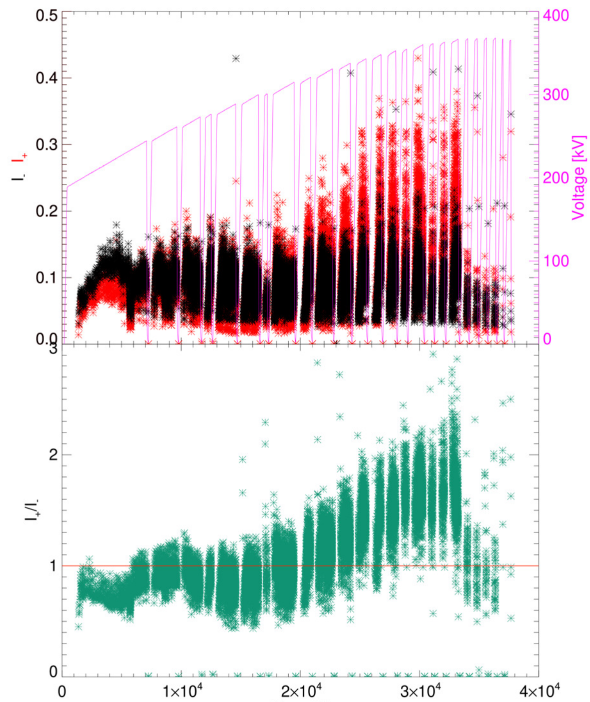

Figure 4: Complete conditioning process (#1705040750) realized during a single operation day: on the top, the maximum value of current measured by positive (red) and negative (black) electrodes during MD events, in time; the magenta curve represents the voltage between the electrodes. On the bottom, the time evolution of the rate between I_+ and I_- contributions.

In Figure 4, the maximum MD values of the current collected by positive (red) and negative (black) electrodes are observed on the top, and their ratio (pine green) on the bottom. The ratio $R = I_+/I_-$, evolves from an initial stage of $R \leq 1$ (stage I), to a gradual increase of the rate till $R \approx 2$ (stage II). Finally, when the conditioning process cannot improve further and the voltage achieves a saturation value, the R parameter drops to $R \approx 1$ (stage III). This last observation suggest a suitable practical method to understand when the system achieves its maximum and, thus, the electrodes conditioning can stop. The clear modification of the currents behaviour (the transition from stage 2 to stage 3) and the R parameter warn in real time that the operator can stop to increase the voltage between the electrodes in the HVPTF device.

The study of the time evolution of the conditioning process can bring new insights to understand its mechanisms.
With this aim, LYSO data of a "typical" MD event (obtained by a sum of 7 single events) from the initial conditioning stage have been compared with those from the named stage II. Unfortunately, in the campaign under study, with the new detectors, the conditioning process stopped before achieving stage III, thus the associated events are missing; moreover, the LaBr scintillator was not available during stage I, thus only LYSO data are shown.
In Figure 5, on the top, data measured during stage I are shown, on the bottom those from stage II. For both stages, X-rays distribution in the energy-time plane is visualized, obtained by rescaling in time and summing 7 single MD events, with the aim to emphasize the common features. The pine green curves represent the dynamics of the X-ray counts (an average over the 7 MD events). In the spectrograms (on the right), the color represents the number of X-ray counts: it is worth noting MD events exhibit completely different dynamics at the initial and at the advanced stage. In particular, at the initial stage of the conditioning process (when the voltage between the electrodes is not so high i.e. 260 kV in our example), the X-ray distribution consists of a peak of events with all energies, followed for 1-2 ms by events at lower energies. On the contrary, at stage II, the distribution in time is characterized by the 3 phases described earlier in this section.

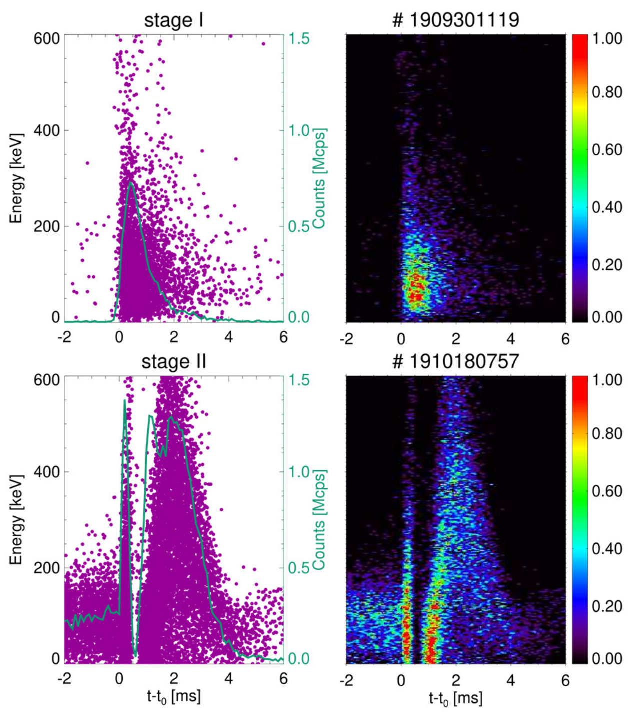

Figure 5: X-ray events are shown in the energy-time plane (violet points); the green line represents the time evolution of the counts per (micro-)second. The same information is visualized in the spectrogram, where the color represents the counts number (in Mcps) that emphasizes the most populated regions. The top pictures refer to stage I, the bottom ones to stage II.

The comparison of the different dynamics of X-rays from MD at I and II stages could help to shed some light to the physical processes occurring during the conditioning. At stage I, X-rays produced by the primary electrons are observed, followed by those from secondary electrons emission and back acceleration towards the anode. At stage II, the higher electrons energy extracts a greater gas amount from the anode, allowing the development of a plasma between the electrodes. This plasma could create collisional conditions causing a reduction of the high energy X-rays component for half a *ms*. The increase of I_+ with respect to I_- in this stage (see Figure 4) could be associated to an additional current component from secondary electrons collected by the anode from the plasma, while part of the ions would be lost on the vacuum chamber.

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Conclusion

The HVPTF experiment investigates the voltage holding phenomenon in vacuum. The new scintillators recently installed in the device are characterized by a very high time resolution, and, thus, allow us to analyze in detail the MicroDischarge dynamics. Though in the near future, measurements data will improve by including the attenuation of the energy spectrum due to the device window or the scintillator itself, excluding pile-up contributions and using known radiation sources for energy calibration, the main effort will be required for the physical interpretation of the measurements. The observations reported in this work, indeed, have given some hints for the interpretation of the MicroDischarge dynamics, but further data analysis and theoretical evaluations are required to provide a more reliable picture of the phenomenon.

Acknowledgments

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