Understanding the insulator conditioning process in fast plasma focus discharges

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Abstract. The presence of metallic deposition and oxides at the surface of insulators used in plasma focus discharges is expected to have a significant effect in the conditioning process that leads to neutrons and hard x-rays emissions. In this work, the atomic concentrations of the main elements present in these insulators are studied by energy dispersive x-ray (EDX) analysis. Preliminary results are presented. Surface oxidation was observed after the conditioning process. A significant concentration of metallic deposition from the anode is observed after a working cycle of a thousand shots.

1. Introduction
In the present, there is a renewed interest in the plasma community for the study of plasma focus discharges due to its potential as high intensity and compact source of fusion neutrons and x-rays. The plasma focus (PF) is a transient electrical discharge produced in an arrangement of coaxial electrodes separated by an insulator. The discharge is driven by a capacitive pulsed power generator through a spark-gap switch. During breakdown, a plasma sheet is formed over the insulator surface by a gliding discharge. It is well known that the efficiency for production of radiation in PF depends on a previous conditioning of the insulator. This process includes usually a series of high-pressure discharges. In spite of the intense research done on PF discharges, the breakdown phase has not been studied in full detail and, to the best of our knowledge; the physical mechanism behind the conditioning process has not been studied in detail. In this work, energy dispersive x-ray (EDX) analysis is used to study the atomic concentration of the deposited material on the insulator surface. The discharges were produced in the PF-400J device and the EDX analysis was carried out on alumina insulators just after the conditioning process and after a long-term working cycle.

2. Breakdown and role of the insulator
In PF discharges, the breakdown is triggered by fast transient discharges \((dV/dt > 1\ kV/\text{ns})\). Thus, the breakdown voltage can be two orders of magnitude higher than the breakdown voltage calculated from the Pashen's law\ [1]. The efficiency of the PF discharge for production of radiation depends, among other things, on the formation of a homogeneous plasma sheet during the breakdown stage\ [1]. The proper formation of the sheet is promoted by the existence of charge carriers in the space close to the insulator surface. Several techniques have been proposed to improve sheet formation, including use of a knife edge on the cathode plate, continuous pre-discharge and ionizing radiation\ [2, 3, 4]. A metallic
deposition along the insulator is also beneficial to the formation of the sheet. In effect, this fact has been proved by studies on Pyrex insulators, where the formation of metallic patches of diameter less than 10µm has been observed after long-term working cycles [3, 5]. The geometry and distribution of the patches on the Pyrex surface also influence the proper working of the discharge. Therefore, the insulator surface should be conductive enough to provide electrons for ionization, but without losing the insulating properties that allow the formation of high electric field gradients which are responsible of electron acceleration during breakdown. On the other hand, conditioning has been proposed to be cleaning of the insulator surface [1], but it is not clear if either removal or chemical modification is the main mechanism involved.

3. Experimental setup and study
The experiments were carried out using the PF-400J device [6]. This device is a capacitor bank with the following characteristics parameters: 880 nF, 27 kV, 38 nH short circuit inductance, 370 J, 300 ns quarter of period, 140 kA maximal current. The electrode configuration consists of an inner electrode of 1.2 cm diameter, and an outer electrode 2.6 cm diameter. Anode and cathode are made from stainless steel AISI 304. The alumina insulator has an effective length of 2.3 cm while the effective length of the anode is 0.7 cm. The discharges were operated in repetitive mode (~0.1 Hz) in hydrogen at pressures in the 3-25 mbar range. Emission of hard x-ray was monitored using a plastic scintillator (BC408) and a photomultiplier tube at 1.5m from the pinch.

Three alumina insulators were studied (A1, A2 and A8). Before the discharges, A1 and A2 were cleaned with methanol and tissue paper. A8 was subjected to an annealing process (2 h at 210 ºC) and then cleaned with methanol in an ultrasonic bath. Insulators A1 and A2 were studied under a discharge working cycle starting at 24mbar, and A8 starting at 25 mbar. After five shots, the pressure was decreased by around 2mbar consecutively. Conditioning of the insulator was assumed to be complete when the first hard x-rays signal was observed from the scintillator. The total number of shots for A1, A2 and A8 were 267, 36 and ~1000 respectively. Scanning electron microscopy (SEM) and EDX were performed in the system LEO 1420VP. The electron beam was operated at different acceleration voltages in order to study the atomic concentration of the insulator as a function of the information depth.

4. Results and discussion
Insulator A1 was used to compare conditioning and working cycle of the insulator. After conditioning, x-ray detection frequency ($R_{px}$) was observed to be dependent on the operational pressure. The operation pressure regime of the device is 9 to 11 mbar, with $R_{px}$ ranging from 40% to 80%. These values are consistent with previous characterizations of the device. Comparison of the conditioning process on insulators A1 and A2 showed a reasonable reproducible behavior. The first indication of a rapid compression of the plasma sheet (dip) appeared after 13 and 16 shots in A1 and A2, respectively. On the other hand, x-ray emission was detected on A1 and A2 after 32 and 40 shots, respectively. In figure 1, the EDX results for the insulator just after conditioning are shown. The insulator area under analysis was between 1 to 6 µm² with a maximal deep of around 1.1µm.

The effect of the PF discharges in the surface of the insulator during the conditioning process is clearly seen in figure 1(a), which shows a high concentration of oxygen and carbon compared with the virgin insulator. Despite the variations of carbon and aluminum concentrations, the concentration of oxygen is found to be almost uniform along the insulator, suggesting the increase of the oxidation state of the surface due to the discharges. This is also seen as the darker zone visible in the picture of the insulator after conditioning in figure 1(d). As shown in figure 1(c), the atomic profile of the anode corresponds to the main constituents of the steel: Fe, Cr and Ni. It is interesting to note that the metallic deposition is almost negligible after conditioning. Only small amounts (< 0.4%) of metallic deposition near the top-edge (figure 1(b)) of the insulator are observed using 30 kV in A2.
Figure 1. EDX analysis of insulator A2 after 36 PF-shots (a) and (b) and its respective anode (c). The atomic concentration of (a) oxygen (OKα), aluminum (AlKα) and carbon (CKα), and (b) iron (FeKα), nickel (NiKα), chromium (CrKα) and copper (CuKα) are shown as a function of the distance from the top-edge of the insulator. (c) Atomic concentration of the anode as a function of the electron energy. The lower concentration of carbon at low information depth (E < 20kV) is due to the methanol used for cleaning before the analysis. (d) Optical picture of the insulator before and after conditioning.

After a long-term working cycle, the effect of multiple discharges is the increase of the concentration of iron by an almost uniform metallic deposition from vaporization of the anode. As shown in figure 2(c), for a high information depth (30 kV) in A8, the iron concentration is similar to the highest values observed in insulator A2. Moreover, when decreasing the information depth (10 kV), Fe concentrations as high as 4% are observed along the insulator surface.

For both high (30 kV) and low (10 kV) information depths, the analysis of A8 show a similar behavior for the main constituents of the insulator (figures 2(a) and 2(b)). The correlation between the increase of the aluminum and oxygen signals and the decrease of the carbon signal is due to an effect of the x-rays bulk absorption, and indicates that the oxygen and aluminum atoms are bonded within the insulator bulk. Nevertheless, this is not observed in the area close to the top anode edge. This is an oxygen-rich and iron-free region, which is modified due to the proximity to the anode. The processes behind this phenomenon and their effects on the rupture and efficiency of the formation of the plasma sheet remain to be understood.

Figure 2. EDX analysis of insulator A8 (~1000 shots). Figure (a) and (b) show the atomic concentration of oxygen (OKα), aluminum (AlKα) and carbon (CKα) at 10 and 30 kV of beam acceleration voltage, respectively. (c) Comparison of the iron concentration at different electron beam voltage. (d) Image of insulator A8 after working cycle.

5. Final remarks and future work
Several questions arise from the present results. The role of carbon and oxygen during the conditioning process and its role on the efficiency for production of radiation should be understood. In addition, the effect of very small concentrations of metallic deposition on the breakdown should be studied. A systematic study, including verification of the present results, correlation of efficiency for radiation production with morphology and composition of deposition along the insulator, and characterization of the breakdown process is the next step in this research.
As preliminary conclusions, we can state that the chemical effect of PF-discharges during the insulator conditioning was successfully measured by EDX analysis. Low metallic deposition from the anode and surface oxidation were found along the insulators after the conditioning process. The spatial distribution of the related elements depends on the number of shots and the proximity to the top anode edge. Moreover, several questions arise from the present results. The role of carbon and oxygen during the conditioning process and their role on the efficiency for production of radiation should be understood. In addition, the effect of very small concentrations of metallic deposition on the breakdown will be systematically studied. Morphology and concentration analyses will be correlated with the efficiency for radiation production and the breakdown process in the next steps of this research.

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