Dynamic Characteristics of X-pinch Experiments Conducted in a Small Capacitive Generator: Refractive Optical Observations.

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Abstract. Among the dense plasmas configurations of interest for applications as a portable intense source of X-rays, the X-pinches are the most attractive by their brightness, source size, short duration and space localization, being particularly reproducible when they are conducted with fast pulsed power generators. In recent time, several characteristics of the dynamics and emission have been reproduced in compact generators (typically capacitive generators) of low current rise-rate (less than 0.5 kA/ns). In this work, a preliminary characterization of the dynamic of X-pinch plasma conducted in a small capacitive generator is reported. In order to obtain the plasma dynamics and quantitative information of the plasma density, the dark field Schlieren technique and interferometry were implemented. The experiments were carried out on the multipurpose generator (1.2 µF, 345 J, 47.5 nH, T/4=375 ns and Z=0.2 Ω in short circuit) capable to produce currents up to 122 kA with 500 ns quarter period, when a charging voltage of 24 kV and metallic X-pinches are used as load. The electrical behavior of the discharge and the X-ray emission are monitored with a Rogowski coil and filtered PIN diodes respectively. For the refractive optical diagnostics a 532 nm frequency-doubled Nd-YAG laser was used. As from a single Schlieren record per shot, a sequence with the time evolution of the plasma is constructed. From the images, a similar dynamic of X-pinches conducted in fast generators of high current is observed, where structures such as coronal plasma, plasma flares and plasma jets are identified. The plasma dynamics observed from a VUV gated pinhole image system is compared with registered dynamic with refractive optical techniques.
1. Introduction

Several dense transient plasmas configurations have been explored to produce small size (µm) and short durations (ns) X-ray sources: plasma focus [1], vacuum spark [2, 3], X-pinches [4], among others [5]. In particular in the X-pinch configuration, two (or more) thin metallic wires are arranged between two faced electrodes forming a ‘X’ shaped configuration with only one contact point at the crossing of the wires. This kind of configuration has captured the attention of different research groups because of its brightness, source size, short duration and space localization, being particularly reproducible when fast pulsed power generators are used [5]. The application of a current pulse across the wires results in the ablation of the wire surface by Joule effect creating a hot and low-density coronal plasma surrounding a cold and dense wire core. The current bulk flows by the coronal plasma where the plasma experiences a local self-induced magnetic field, which serves to locally confine and pinch the plasma toward the axes of the individual wires. Moreover, as a result of the current flow along leg of the X-pinch, a distribution of global magnetic field in all space is produced, which presents a greater intensity in the region close to the cross point of the wires. Thus the X-pinch dynamics is governed by the characteristics of the precursor plasma and its interaction with the global magnetic field. The strong global magnetic field at the cross point of the wires compresses the plasma on axis, forming a hot and dense micro-pinch. Under these conditions, the plasma yields an intense and small soft X-ray source of short duration ideal for studies and applications, as for instance, for applications to high-resolution radiography of biological specimens [6]. The X-pinch hot spot has been widely studied, in contrary to the low-density coronal plasma research which has not been in the priorities of the scientific community, particularly in the low current generators. Characterization of the coronal plasma has been performed with complementary techniques such as interferometry and time-resolved self-emission imaging or dark-field Schlieren [7, 8].

In this direction and considering the encouraging results reported in previous work using our compact capacitive generator [9], we report preliminary characterization of the plasma dynamics using refractive optical diagnostics, which are contrasted with those obtained with time-gated self emission pinhole images in the VUV range.

2. Experimental set-up

The X-pinch experiments shown here were conducted with a multipurpose generator, whose electrical characteristics are reported in reference [9, 10]. The generator is capable to deliver currents about 122 kA, with quarter period of 500 ns when a 24 kV charging voltage and metallic X-pinches load is used. Two different materials were diagnosed, aluminum wire of 25 µm for the self emission pinhole images and tungsten wire of 13 µm for the refractive optical diagnostics.

Three types of X-pinch assemblies were tested, which were determined by the electrode configurations available, as experience is gained in the assembling technique. In Figure 1(a) and Figure 1(b) the X-array is formed with two wires hanging in parallel connecting the electrodes by the edge of the apertures. Then, a conical metallic stopper is introduced in the lower aperture (anode) fixing and pressuring the wires against the electrode. At the first scheme, the upper free ends of the wires are twisted in 360° while the second one in 180°, with only one touch point. In Figure 1(c) the X-array is formed introducing both ends of a single wire through holes available in the upper and lower electrodes. After that, the upper electrode is rotated a little bit more than 180° forming an X. In the three assemblies, the inter-electrodes spacing is 10 mm.

In order to map the plasma structures linked to dynamics of the coronal plasma, namely; instabilities, precursor plasma, plasma flares and subsequent plasma jet formation, the dark-field Schlieren technique and interferometry were implemented. For the Schlieren technique a circular stopper of 0.7
mm was placed at the focal point of a lens of 300 mm of focal length, allowing a minimum detectable angular deflection of 0.001 radians. To the characterization of the plasma density, a Mach-Zehnder interferometer was implemented, in which only a section of the X-pinch (almost complete) was imaged on the CMOS detector in order to obtain a better spatial resolution. For this purpose a lens of focal length \( f = 250 \text{ mm} \) was used, which led to magnification of \( m = 2.1 \).

![Schematic representation of X-array assembly:](image)

Figure 1: Schematic representation of X-array assembly: (a) Two parallel wires rotated 360°, (b) Two parallel wires rotated 180°, and (c) Only one wire rotated 180°.

In a first stage, only dark-field Schlieren technique for twisted X-pinch (rotated at 360°) was implemented. In a second stage, where one of the electrodes is rotated 180° to form the X-array, both diagnostics, Schlieren and interferometry were available simultaneously. In all refractive optical diagnostics a 532 nm frequency-doubled Nd-YAG laser was used. In Figure 2, a schematic of the experimental set-up is shown, including the additional diagnostics such as filtered PIN diode and filtered PCD detector. For the Schlieren diagnostic only (without interferometry), the experimental setup is similar, but in this case the reference beam is blocked. Additionally, a gated imaging system based on a four-stripe MCP camera coupled to a vertical pinhole array of 50 µm/each was implemented. The pinhole array was assembled 26 cm away from the plasma and 14.8 cm in front of the MCP detector, resulting in a plasma image of magnification 0.58 over each stripe.

### 3. Experimental results

Figure 3 shows a sequence of dark-field Schlieren images which was built with single records per shot, for Tungsten wires of 13 µm and charge voltage of 24 kV. From Fig. 3(a) to Fig. 3(d) the X-pinches were formed with the rotation of the two parallel wires in 360°, as shown in Figure 1(a). From the image sequence is easily recognizable a coronal plasma around each wire, which is present from an early stage of the discharge along the entire wire. Furthermore, we observed plasma flares that migrate from the coronal plasma close to the cross point region which feed a central plasma column. It should be noted that this central plasma column is longer than the distance between the cross-point of
the wires and the intersection point of last observable plasma jet (from the Schlieren technique) with the symmetry axis.

This could lead one to believe that only a portion of coronal plasma is ejected toward the axis and feeds the plasma column. Nevertheless, from the pinhole image sequence in the VUV range (Figure 4), it is possible observe how the coronal plasma, according to how it is coming to the symmetry axis, is shaping the upper end of jet like plasma structure. On the other hand, the plasma characteristics that migrates from the furthest regions of the X-pinch, where the global magnetic field is lower, presents density gradients that are not solved for the Schlieren optical system.
In Fig. 3(e), a plasma column gap of approximately 1.2 mm in the micro-pinch region is observed. This gap is responsible for the appearance of the diode effect, which produces a strong electric field that accelerates the electrons against the virtual anode, producing an intense hard x-ray pulse.

![Figure 2: Experimental set-up for dark-field Schlieren, interferometry and complementary diagnostics.](image-url)
Figure 3: (a–d) Schlieren sequence of 13 μm Tungsten X-pinches for the wires assembly of fig 1(a); (e) Schlieren recording for 13 μm Tungsten X-pinches using the wires assembly of fig 1(b).
The interferometry diagnostic presented at this work was implemented on a 13 µm Tungsten X-pinch. The X-pinch is formed with the assembly of wires shown in Figure 1(c). Figure 5 shows an example of a simultaneous record of a Schlieren and plasma interferogram in an early stage of the discharge. In order to characterize and improve the spatial resolution at the region around of the cross point of the wires, an interferometric optical system with higher magnification was implemented (m=2.1). The time is taken with respect to the discharge onset time.

It is important to point out that in this experimental stage, the laser stability was affected by the electromagnetic noise, which resulted in the record of low-contrast interferograms due to the intensity variations of the laser. For this reason and in order to use the obtained information, we decided to apply techniques of digital image processing on the original interferogram. Frequency filtering techniques to isolate the carrier frequency were used, with which a synthetic interferogram is constructed. Subsequently this interferogram is decoded to obtain both the interferometric phase and the areal density. The entire process is shown in the picture sequence of Figure 6.

Figure 4: Pinhole image sequence (for the same shot) in the VUV spectral range, for a typical shot of Al X-pinch of 25 µm.

Figure 5: Dark-field Schlieren and interferometry simultaneously of 13 µm Tungsten X-pinch.
From the decoded information it is possible recognize consistencies between the information recorded both the Schlieren and at the interferogram, in particular those that account for the existence of a low-density coronal plasma around of wires and a jet-like plasma at middle plane. However, the interferogram does not show an opaque structure corresponding to the dense core at the centre of the each wire as other authors have reported in studies of this kind [5, 7, 8]. This effect could be due to the beam diffraction at the thin and dense plasma structure, as it is observed between the X-pinch arms. It should be pointed out that in dark-field Schlieren records of the X array (without plasma) before the generator triggering, the diffraction effects were not observed. For a deep characterization of the plasma density in X-pinch experiments conducted with the "multipurpose generator", an extensive interferometric study is necessary.

4. Remarks and conclusions

A preliminary set of refractive optical observations, on different X-pinch configurations have been conducted. The plasma dynamics observed from Schlieren diagnostics are compared with the dynamics registered by means of a gated VUV pinhole image system. From the diagnostics set employed and experimental results obtained, an approach to the plasma dynamics on X-pinch experiments carried out in a small capacitive generator of low current can be summarized as following: (i) Experiments with metallic wire conducted on the multipurpose generator showed similar characteristics to those observed in higher currents and high current rate generators (≥10^{12} A/s), namely: density modulation along the wire and migration of precursor plasma because of the global magnetic field (similar dynamics). (ii) From the four-frame MCP diagnostic, a plasma jet and a tiny compressed structure with high emission of soft X-ray were observed at the crossing point of the wires. (iii) From the Schlieren sequence, flare-like plasma structures coming from the coronal plasma are observed, particularly from the regions close to the cross point of the wires, where the global magnetic field is higher. At later times, a clear break of the plasma structure at the cross point of the wires is observed, leaving a gap that form virtual electrodes, where an intense electric field is formed.
Further experiments with complementary diagnostics are being designed in order to characterize the dynamics of the cross-point region of the wires, with a special interest in the characteristics of the micro-pincher in the successive bursts of the hard X-ray during the rise current, as is reported in [9].

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