Characterisation of a Tungsten X-pin dense plasma

A Robledo-Martínez, A Villarreal-Garcia, L Miranda, and M R Hernández

Departamento de Ciencias Básicas, Universidad Autónoma Metropolitana, Av. San Pablo 180, Azcapotzalco, 02200 Mexico DF, Mexico.

E-mail: arm@azc.uam.mx

Abstract. An X-pin experiment using a load made of two 25-µm Tungsten wires was investigated. The X-pin is a plasma produced by a powerful (∼100 kA) current pulse that is applied to two or more slanted wires joined at the centre. The diagnostics employed included PIN diode detection, voltage and current measurement and pinhole X-ray photography. The results show that the X-rays emitted are initially thermal in nature and have energy ∼7.7 keV and afterwards there is harder, non-isotropic radiation that can be attributed to a plasma interruption. The radiography shows that there is formation of a jet of plasma at the moment of maximum compression.

1. Introduction

The Z-pin is a dense, magnetized plasma produced in gases and vapors of metallic fibers that experiences a strong compression due to its own magnetic field. Densities of $10^{17}$ to $10^{20}$ cm$^{-3}$ and temperatures in the range $10^3-10^5$ eV are typical of a Z-pin experiment [1]. The high density and temperatures thus produced are useful in the investigation of fusion plasmas and the physics of stellar interior [2]. In a multi-wire Z-pin experiments a powerful electric-current pulse of the order of 0.1-1 MA is applied to a set of parallel wires surrounded by high vacuum. The electric pulse vaporizes the wires and a plasma is created in the metallic vapor. Then the plasma is compressed by the magnetic pressure and at the moment of maximum compression an X-ray pulse, lasting tens of nanosecond, is produced. A variant of this technique employs a set of crossed wires joined at the center, hence the name: X-pin [3-6].

A Marx bank is a device used to generate high voltage, high current pulses with power supplied by a moderate-voltage low-current source. Its principle of operation is based in charging capacitors (slowly) in parallel and then discharging them in series. Typically, the capacitors are charged in about 1 minute and discharged in less than 1 µs. The charging current is of the order of tens of milliampere while the discharge current peaks at about hundred kA.

Fast pulsed-power generators comprising a Marx bank and a pulse-forming line were originally used as electron beam sources [7]. In this type of devices the Marx charges the line on a time scale of microseconds and then the line discharges onto a vacuum diode in order to apply an accelerating pulse lasting tens of nanosecond to the electrons. Later these generators were adapted to implode arrays of metallic wires for production of intense X-ray pulses. When the individual wire plasmas merge and implode under the effect of the magnetic pressure produced by the massive current pulse, a dense plasma is created which emits X-rays with energies of the order of 1-10 keV [8].

In pulsed power one of the configurations more often employed consists of a Marx generator feeding a transmission line for pulse forming purposes. In this configuration it is the line the one that feeds the load, not the Marx bank. The main advantage of this set-up is that the Marx is decoupled from the load allowing faster fronts to be employed. Several types of transmission lines are employed, the one using de-ionised water as insulation being one of the most popular [9].
The aim of this work is to produce fast pulses of X-rays using an X-pinch configuration of 25-µm Tungsten wires. The time resolved detection of the x-radiation using different filters helps to estimate the energy of the emitted radiation. The time-integrated X-ray photographs helps to visualize the plasma and learn how successful the pinching process was.

2. Experimental set-up

Figure 1 shows the schematics of the Z-pinch generator layout. The Marx bank is housed in a container made of cold-rolled 0.25-inch steel sheet with dimensions 1.2×1.0×0.7 m. The pulse-forming line (PFL), the transfer switch and the transfer line (TL) are inside flanged 19-inch stainless steel tubes. These are joined at the flanges by insulating diaphragms 2 inches thick. The total footprint of the ensemble Marx-line was 1.92 m². The vacuum chamber has 8 viewing ports, evenly spaced around its periphery, to incorporate different diagnostics. The inner conductor of both the PFL and the TL are cylindrical tubes with an outer diameter of 10 inches.

The spark gaps of Marx bank were pressurised with dry air to a working pressure of 3.0-3.7 bar. The spark gaps are triggered by applying an electrical impulse to the central trigger electrode; this distorts the field and causes breakdown between the two main electrodes. Once the gap has broken down, the voltage of the first capacitor is applied onto the next stage over-volting it and thus initiating a cascade of spark-gap operations that erect the Marx. When the pulse reaches the transfer switch, this self-triggers and transfers the current to the next section of line (TL) that feeds the load. A one-loop Rogowski coil protruding from the upper lid of the vacuum chamber was used to measure the load current.

In the present work the main parameters of the generator were as follows: the PFL and TL both had an impedance of 4.3 Ω, the Marx bank had 8 stages with a 1.6 µF each and maximum charging voltage was 55 kV. With these parameters a short circuit current of 140 kA was obtained in the preliminary tests at a charging voltage of 55 kV.

In order to detect the X-rays emitted by the plasma two PIN diodes were fitted to different viewports in the vacuum chamber, with identical radial distance from the center. The PIN diodes (Quantrad N-series) had a 250-µm deep intrinsic layer and were operated under a 300 V bias voltage. Each diode was fitted with a different transmission filter. These consisted of thin metallic films: in one case it was 125 µm aluminum and in the other a Titanium foil 12.5 µm thick plus a layer of aluminum 5 µm thick added to avoid fluorescence.

Figure 2 shows the combined response of the filter and the diodes as a function of incident photon energy. The response is obtained from the convolution of the absorbance of the silicon in the PIN with the transmission of the filter. Figure 2 shows that the Titanium-fitted diode is very sensitive in the photon energy interval 2.1-4.94 keV where the aluminum-fitted diode is not. In the interval 5.6-100 keV both are capable of detecting the photons within this energy range but will do that with different amplitudes in their output signals.
An X-ray pinhole camera was placed at one of the viewports of the vacuum chamber in order to take time-integrated radiographs of the plasma. It had a length of 15 cm which, when taking into account the radial distance (30 cm) from the center of the chamber to the flange it was fitted to, give a magnification ratio of 2:1. The pinhole had a diameter of 100 µm and was covered with an aluminum film 5 µm thick in order to prevent the light of the plasma from reaching the film. The film employed was conventional Kodak E-speed dental film.

3. Results

Figure 3 shows the signals obtained in a typical experiment X-pinch using two crossed 25-µm Tungsten wires. The graph shows the voltage, the current and the PIN-diode signals obtained in one of several shots realized in the lab. In the figure t=0 corresponds to the Marx’s activation.

The trace in panel (b) of Figure 3 (from voltage probe #1 in Figure 1) shows that when the Marx bank is fired at t=0, the PFL voltage begins to grow steadily in time and afterward experiences several oscillations due to the pulse travelling back and forth along the line. During the time interval t=0-0.28 µs the pulse induces a capacitive pulse of current at the load which can be clearly seen in the current signal. Then at t=0.28 µs the transfer switch closes and consequently the plasma current pulse rises very quickly with a rise-time of 75 ns and a peak value of 84 kA. When the current peaks, the plasma begins to emit X-rays as can be seen from the lower two panels in Figure 3. The difference observed in the signals is due to the fact that the otherwise identical diodes were fitted with different filters.
4. Discussion and conclusions

The X-pinch is a very dynamic plasma: it undergoes dramatic changes in its behaviour in the span of a few nanoseconds. Under normal circumstances, the response curves in figure 2 dictate that the signal detected by the Ti-fitted diode should always be larger than the signal of the other diode. This is the case of the larger peak of the Ti diode at $t=0.45 \, \mu s$ where it can be seen that the amplitude of the Ti diode is 1.6 times larger than that of the aluminum one. A comparison with the curves in figure 2 shows that this event matches photons having an energy of about 7.7 keV.

However, there are other peaks in the aluminum-diode’s signal that the titanium one does not detect. These we believe are produced by harder, anisotropic radiation produced by breaks in the plasma column. It is a well-known fact that the plasma column sometimes breaks and forms a mini-diode [10]. When this is formed the accelerating voltage for the electrons becomes the voltage of the transfer line that is of the order of 440 kV. This applied voltage can accelerate the electrons toward the anode where they emit X-rays. But if the mini-diode is not parallel to the axis of the electrodes then the emission can be strongly asymmetrical and one of the diodes detects more radiation than the other.

This is consistent with the results of Hass and co-workers [11] who found that in a tungsten X-wire experiment the X-ray high power peak observed was consistent with a Planckian-type spectrum with energy $\sim 5$ keV that is purely thermal in nature. This is followed by a break in the plasma and the gap created generates an e-beam that produces harder radiation: above 8 keV.

The radiograph in panel (a) of figure 4 shows that the plasma forms a jet extending to both sides of the point where the two wires join but also that it is more intense on the anode side. In fact, the processed image on panel (b) shows that the plasma has two fragments: one at the center, where the wires merge, and the other is the jet extending from the center to the anode. These type of jets have been observed by other researchers when the coronal plasma from both wires converges at the center [12, 13]. In the present case it is evident that the jet is stronger in the anode side of the A-K gap probably due to an electron beam that was emitted from the center of the pinch in the direction of the anode. The e-beam radiates due to the beam-target mechanism. This type of jet is of interest to astrophysicists as it can be used to simulate in the lab the ejection of stellar material.

References

[1] Haines M G 2011 Plasma Phys. Control. Fusion 53 093001
[2] Remington B A 2006 Rev. Mod. Phys. 78 755
[3] Ampleford D J et al 2015 IEEE Trans. Plasma Sc. 43 3344
[4] Shrestha I et al 2010 High Energy Density Phys. 6 113
[5] Pikuz S A, Shelkovenko TA and Hammer DA 2015 Plasma Phys. Rep. 41 291
[6] Pikuz S A, Shelkovenko TA and Hammer DA 2015 Plasma Phys. Rep. 41 445
[7] Nation J A 1983 High Power Relativistic Electron Beam Sources Applied Charged Particle Optics ed A. Septier, (N. York: Academic Press) pp. 171-206
[8] Pereira N R and Davis J 1988 *J. Appl. Phys.* **64** R1
[9] Mankowski J and Kristiansen M 2000 *IEEE Trans. Plasma Sci.* **28** 102
[10] Shelkovenko T A, Sinars D B, Pikuz S A and D A Hammer 2001 *Phys. Plasmas* **8** 1305
[11] Haas D, Bott SC, Ueda U, Eshaq Y and Beg F N 2007 *Proc. Pulsed Power Plasma Conf.* 639
[12] Beg F N, Ciardi A, Ross I, Zhu Y, Dangor AE and Krushelnick K 2006 *IEEE Trans. Plasma Sci.* **34** 2325
[13] Haas D M et al 2011 *Astrophys Space Sci.* **336** 33