Soft X-Ray Emission from a Plasma Focus of Hundreds Joules

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Abstract. Emission of soft X-ray in plasma focus devices with energy over 1kJ have widely been reported [1-3]. However, the research in devices with lower energy (<1 kJ) have not been received the same attention. We present results on the study of soft X-ray in plasma focus device PF-400J (176-539 J, 880 nF, T/₄ ≈ 300 ns) [4-6] operated in Hydrogen to 7 mbar of pressure. The temporal and spectral soft X-ray characteristics are investigated by means filtered PIN BPX-65 diodes. Temporal correlations between soft X-ray signals and hard X-ray are performed.

1. Introduction
The plasma focus (PF) device is a known source of dense transient high temperature plasmas, and it has been studied since late 50's. A plasma focus is a particular pinch discharge in which a high pulsed voltage is applied to a low pressure gas between coaxial cylindrical electrodes. The central electrode is the anode which is partially covered with a coaxial insulator. In the pinch phase, beams of ions and electrons, and ultra-short (< 100ns) X-ray and neutron (using Deuterium gas) pulses are generated. Particularly the electron beam collision with the anode top side surface generates copious hard X-ray emission. The Plasma Focus device can be used as high-intensity and short duration X-ray source.

The Thermonuclear Plasma Department of the Comisión Chilena de Energía Nuclear has constructed two very small plasma focus. The PF-50J (160 nF capacitor bank, 20-35 kV, 32-100 J, rise time ~150 ns) [3-6], and the PF-400J (880 nF, 20-35 kV, 176-539 J, rise time~300 ns). The very low energy of this devices (32 to 539 J) allow repetition rate between 1 to 0.1 Hz. So, a compact (~0.5 m³) and cheap devices are obtained, this allows easy modification in wide parameter range.

The principal aim of this work is to characterize the soft X-ray emission and correlationate it with hard X-ray emission.

2. Experimental Setup
The experiments were performed in PF-400J device which is powered by a 880 nF capacitor bank operating up to 30 kV(~400 J). An external inductance of 40 nH is obtained. Typical current pulse at 30 kV is 141 kA peak with ~ 300 ns quarter period. The device was operated to 28 kV (345J) with Hydrogen at pressure of 7 mbar. The electrode system consist of a Cu anode, 12 mm radius and 28 mm length, and eight Cu cathode rods, symmetrically arranged in a 27 mm radius circle.
The Voltage is measured at the base plate of the plasma focus electrodes by a resistive divider, and current by a Rogowski coil at the capacitor bank.

An array no collimated of five filtered PIN diodes (BPX-65), radially located to 100 mm from upper end of the anode, were used to monitor soft X-ray emission from plasma and anode simultaneously. These detectors were normalized against each other by masking each with an identical filter (Al of 10 µm). The PIN diodes response is between 0.5 and 30 keV. A combination of filters were used to look at different spectral windows within 0.8-10.0 keV region. Three diodes, to 90º from anode axis, were used with 10 µm Aluminium, 12.5 µm Titanium and 3 µm Silver plus 23 µm Mylar respectively. The others diodes, to 30º from anode axis, were used with 7.5 µm Nickel and 7.6 µm Copper. The response of PIN diodes with different filters are shown in the figure 1. Hard X-ray is detected using a scintillator-photomultiplier system, radially placed to 223 cm away from anode tip. The scintillator BC408 accoupled to photomultiplier PHOTONICS XP-2262/B were used.

3. Experimental Results

Figure 2 show a typical signals at compression time for a shot with Hydrogen at 7 mbar and a voltage charge of 28 kV. It shows oscillograms of voltage, current derivative, hard x-ray measured radially with photomultiplier+scintillator combination, three radial filtered PIN diodes and two filtered PIN diodes to 30º.

![Figure 1. Response of PIN diodes with different filters used.](image-url)
4. Discussion ad Conclusions
The X-rays emitted from hot plasmas of Hydrogen is bremsstrahlung type. Line radiation and recombination are always present due to impurities such as carbon, nitrogen and oxygen. In plasma focus devices, the main source of line radiation is the interaction of the electron beam from the focus region with the anode, which is made of copper. The dominant line radiation are $K_\alpha$ and $K_\beta$, which are between 8 and 9 keV approximately. The x-ray detectors are not collimated, so the signals include x-ray emission from plasma and from anode edge.

Roughly, the soft (diodes to 30° and 90°) and hard (radial photomultiplier) x-ray signals are in time correlation with peak voltage and dip of time derivative of the discharge current (FIGURE 2). Soft x-ray are generally emitted in two or three short pulses arising from the pinch and post-pinch phases of the discharge. Typical 4-10 ns half-width x-ray pulses, as shown by the PIN diode signals, are observed. Particularly the signals, in FIGURE 2 ($D_{90^\circ}$, $D_{30^\circ}$), show two periods of emission separated by 5 ns approximately. The start of first period coincide with the start of pinching phase (V or dI/dt signals) and reach the peak in about 6 ns. The time peak of this period coincide with the start of hard X-rays detection (PM signals) associated with electron beams.

The diode with the Al (10 µm) filter show a transmission band between 0.75 y 1.56 keV, which corresponds to the L shell of Copper (anode). Due to this fact, it is not possible to establish if the X-ray signal in diode is owing to emission from the pinching plasma or emission from the anode being hit by lower energy electrons.

To 30° the diodes solid angle permit to observe inside the hollow anode, about 10 mm under the top end of the anode. This diodes, masked with Copper and Nickel filters, record higher intensity than the radial diodes, about eight times bigger. This difference probably is due to x-ray radiation.
provenance from the wall inside hollow anode. The diodes $D_{30º}$ and $D_{90º}$ in Figure 2 show a complex history of the X-ray emission. In the first peak the diode filtered with copper shows a bigger intensity than the diode filtered with Nickel, both to $30º$. This mean that the x-ray emission is dominated by anode emission in region of 8.33 to 8.96 keV due to electron beam bombardment, this region is coincident with specific line $\text{K}\beta_1$ (8.904 keV) of copper. At this time we have electron beams near to 9 keV at least. Simultaneously, the low intensity of signals in diodes to 90º indicate that the x-ray emission is dominated by plasma emission principally with contribution of low energy electron beams probably. The diode filtered with Al (to 90º) record a bigger signals than the others diodes to same angle, filtered with Ti and Ag+My. This is due to the low energy window of Al between 0.75 and 1.56 keV. The signals too show a similar intensity of diode with Ti and diode with Ag+My, then the emission is lower than 3.35 keV. In the second period the hard x-ray signal decrease (in module) with the signals diodes to 90º, while the diodes to 30º maintain intensity. This mean that the plasma is cooling and there are electron beams of low energy (< 8.33 keV). Owing to the superposition of radiation coming from plasma and anode is not direct to obtain the plasma temperature with the diodes signals.

In conclusion, we have presented preliminary measurements of X-rays emission in a plasma focus device, PF-400J, operated to 7 mbar of hydrogen and a bank energy of 345 J (28 kV). These preliminary observation indicate that there is a plasma with two or three period of weak x-ray emission, in correlation with pinch phase, with a half-width time of 4 to 10 ns which have energy lower than 3.37 keV. The electron beams have sufficient energy to excite K lines of cooper anode, at least of 9 keV. The photomultiplier signals indicate the presence of more energetic electron beams in correlation with the soft x-ray.

The next step is to identify the x-ray emission region using a pinhole camera with others filters combination, in hydrogen, to correlate with PIN diodes. In future, too, we want to work with gas mixtures (Hydrogen+Argon or Nitrogen) and gas puff mode.

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