Time-resolved Electron Beam and X-ray Emission from a Neon Plasma Focus

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Abstract

The paper reports the results of an analysis directed towards the complete description of the temporal evolution of the electron beam emission and the identification of the phenomena involved in the electron emission processes in a 3 kJ/14 kV Mather-type plasma focus operated in Neon in the 1.5-5.5 mbar range.

The electron beam was extracted through the anode and passed through a drift tube along which the electron current was measured using a fast derivative Rogowski coil coupled to an appropriate RC passive integrator. The X-ray emission in the 0.5-40 keV range was monitored using a soft X-ray spectrometer. A scintillator-photomultiplier detector was employed for photon energies above 70 keV. A computer-controlled CCD pinhole camera was used to capture X-ray images of the focusing area.

Several electron emission periods and mechanisms corresponding to different plasma phenomena i.e. pre-focus emission, pinch emission, emission by instabilities and turbulence, secondary and late plasma compressions, etc. were identified and discussed. The study of the electron beam output with respect to the operating pressure showed that the electron beam production reaches an optimum (in terms of total current and shot-to-shot reproducibility) at 4 mbar Neon pressure.

1. Introduction

From the early experiments performed with plasma focus devices, a strong electron emission coming from the pinch area was observed. The electron beam interaction with the metallic electrode structure was proposed as the source of the hard X-ray emission [1, 2]. The observed energy was much in excess of the discharge voltage. Various acceleration mechanisms were proposed and discussed for these energetic particle beams [2, 3].

Recent technological and industrial applications, such as electron beam pumped lasers, microlithography and micro-electro-mechanical systems (MEMS), as well as medical and microbiological processes, require intense pulsed particle and radiation sources. Successful experiments have shown that plasma focus devices can be used as electron beam sources for microlithography. Lithography of less than 0.5 μm feature size was already demonstrated using electron beams emitted from the plasma focus [4].

The electron emission is the primary source for higher energy X-rays, which originate due to the strong electron bombardment of the open-end of the central electrode (anode).

Since the emission mechanisms for photons above 10 keV from the plasma focus are related to the anode bombardment, the discharge parameters, the electron and X-ray emissions have to be correlated, in order to deepen the understanding of the plasma phenomena involved. The photon emission in the 10-40 keV range is suitable for deep microlithography and MEMS.

2. Experimental set-up

The experiments were carried out on the NIE-SSC-PFF device [5], under the following operating conditions: charging voltage-14 kV, energy stored in the capacitor-3 kJ, Neon gas filling pressures-1.5-5.5 mbar.

During the experimental campaign, the following diagnostics were used simultaneously, with a recorded sampling of 1 ns: resistive high voltage probe, derivative Rogowski coil for the current derivative and the discharge current, minimum pinch radius detector, two-channel soft X-ray detector with different filtering (24 μm aluminised Mylar and 24 μm aluminised Mylar plus 10 μm copper), scintillator-photomultiplier detector for hard X-rays, and derivative Rogowski coil (via an RC passive integrator) for electron-beam current. A CCD pinhole camera was used to capture X-ray images of the focusing area.

The electron beams were extracted through an electron drift tube. The voltage along the tube was maintained constant at the value of the high voltage plate potential.

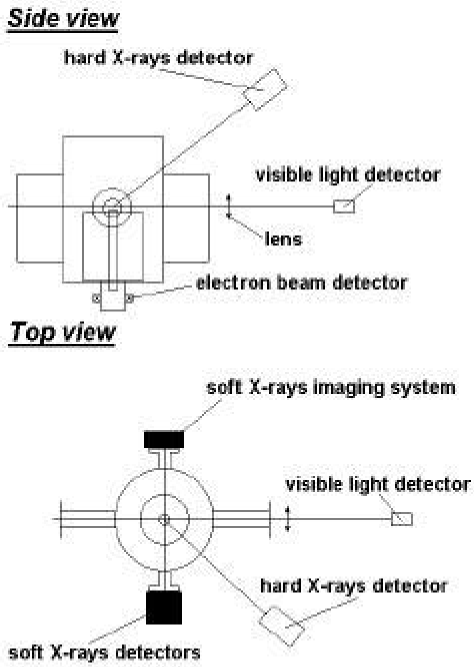

Fig. 1: Schematic diagram of the experimental set-up.

The schematic diagram of the experimental set-up is shown in Fig. 1.

3. Electron Beam Emission

The electron emission from the Neon plasma in our 3 kJ dense plasma focus device exhibits several emission periods and peaks. The amplitude of these peaks and the instant when these emissions start vary with the filling pressure. The peaks are separated for discharges at some pressures and overlap for some others.

The first emission period (Fig. 2-A) can be separated into two parts.

The first one, which is not seen clearly separated for all the discharges, is a 20-25 ns interval (Fig. 2-time lens detail). After a 5-8 ns slow increasing current corresponding to the pre-focus emission (Fig. 2-A1), during the next 15-20 ns, some 3-6 sharp peaks appear, with 3-4 ns FWHM (Fig. 2-A2). There is no clear indication whether the peaks are related to burst-type emission, or to some plasma oscillations. Since the neon pinch lifetime is within this range, the origin of these electrons is ascribed to the pinch itself. The penetration of the magnetic field causes the anomalous resistivity and consequently, an extremely high electric field appears in the plasma diode. At the instant when the first $m=0$ instability occurs, the characteristics of the signals change. The result is a sharp, but almost constant increase in the beam signal.

The second part of the first emission period exhibits a higher peak of 75-150 ns FWHM (Fig. 2-A3). This can be related to the persistence in front of the anode of a turbulent and relatively dense plasma after the instant when the instabilities destroyed the plasma column. This plasma contains a high amount of impurities, mainly copper coming from the anode due to the electron bombardment. This pulse, which at higher operating pressures reaches the highest amplitude, exhibits a slow-rising leading edge followed by a rounded shape peak. The decay time is longer than the overall rise time and, at higher pressure, increases up to 1 μs, due to overlapping with later pulses. This peak is caused by instabilities-related emission. As the filling pressure increases, the amplitude increases at first, and then it decreases. The peak value of the electron current depends on the pressure and also on the overall pre-pinch dynamics.

All the phenomena occurring during the pinch phase have a strong axial symmetry. Therefore, during the first emission period, most of the electrons are emitted mainly on-axis. The anode bombardment is not very strong, hence the higher energy X-ray emission is not very intense.

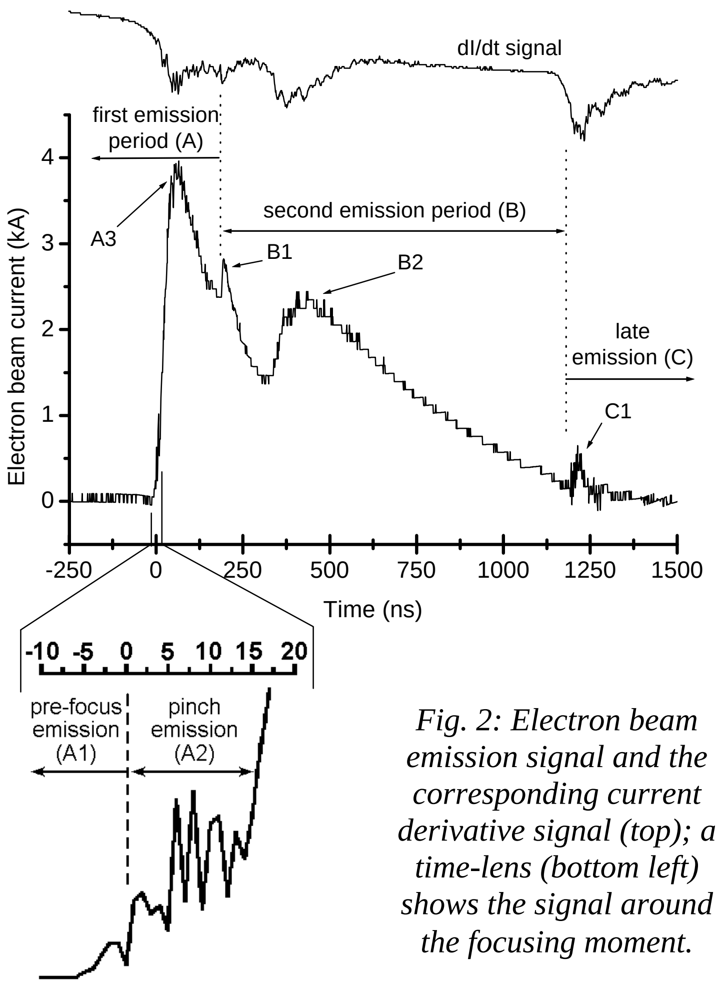

Fig. 2: Electron beam emission signal and the corresponding current derivative signal (top); a time-lens (bottom left) shows the signal around the focusing moment.

After the first emission period, at low operating pressures, some discharges feature either no detectable electron beam emission, or, eventually, some very late peaks (0.9-1.3 μs later). This emission (Fig. 2-C) is also related to a strong current derivative dip. This could be due to another plasma sheath collapsing because of the high amount of energy remained in the electrical circuit. The minimum radius detector does not see this sheath. The explanation of this late electron peak is that the plasma dynamics for the earlier stages (i.e. breakdown, axial and radial acceleration) was not good enough.

For the other discharges, which usually exhibit high values for the first electron peak (associated with a good pre-pinch dynamics), a second strong emission period is recorded (Fig. 2-B). At low operating pressures, this emission occurs either 200-300 ns after the first peak (as a sharp peak-Fig. 2-B1) or later, at 450-500 ns (as a rounded peak-Fig. 2-B2). There are also some discharges exhibiting both peaks, with 200 and 500 ns delay with respect to our time reference. As the pressure increases, these time intervals decrease down to ~100 ns and ~350 ns respectively. At this instant the plasma is strongly impurified, mainly with copper coming from the electrodes. The current derivative signals show strong compressions correlated with these peaks.

The amplitude of the second emission period peaks (Fig. 2-B1 and B2), which are wider than the A3 peak, is also high, and is almost constant, regardless of the operating pressure. The explanation is that the remaining plasma filaments are compressed again, once or even twice, in front of the inner electrode. The result is a very turbulent, relatively dense plasma, which emits strong electron beams. Due to the strong turbulence and the lack of symmetry, the emission is not only on-axis, but also off-axis. Therefore, a very strong electron bombardment appears, and the result is an intense X-ray emission, with energies above 20 keV. This emission can be seen on the soft X-ray channels (filtered PIN diodes) or, if the energy is above 70-80 keV, on the scintillator-photomultiplier detector.

When the operating pressure is higher than 2.5 mbar, the electron emission peaks start to overlap, giving the image of a single peak with a slow decreasing trailing edge. The electron current reaches its maximum during the first emission period (Fig. 2-A3 peak).

4. Electron Beam Optimisation

The graphs presented in Fig. 3 contain the amplitude of the average signals and the electron beam charge plotted against pressure.

If either the amplitude or the charge of the electron beam current is taken as the optimisation parameter, the 4 mbar Neon represents the optimum pressure value for electron beam generation. Consequently, our dense plasma focus device can be used as an electron beam source when operated at 14 kV/ 3 kJ in 4 mbar Neon gas. This is an unexpected result, for some other works indicate that these operating conditions of this machine represent also the optimised values for soft X-ray emission [6].

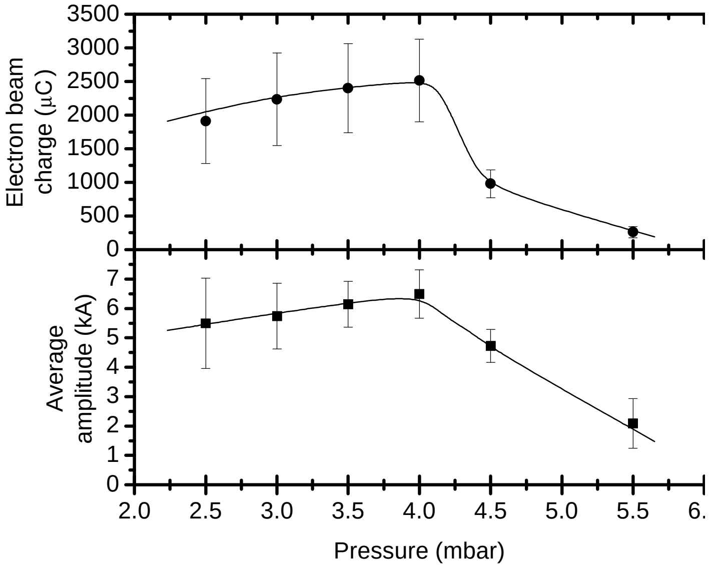

Fig. 3: Electron beam charge and electron beam current versus pressure.

5. Conclusions

Many plasma phenomena are involved in the electron beam emission from a plasma focus device.

The electron emission exhibits very strong correlations with the main discharge current derivative signal, i.e. with the plasma general dynamics. The early stages during the operation of the device (breakdown, axial and radial acceleration) have a decisive influence to the electron beam emission. If this dynamics is not very good, the energy remaining in the electrical circuit gives rise to secondary plasma compressions. Due to the increasing amount of impurities and lack of symmetry, a very turbulent compressed plasma can be created.

References

[1] J. W. Mather, in *Methods of Experimental Physics*, edited by H. Griem and R. Lovberg, Academic Press, New York, Vol. 9, Pt. B, p. 187 (1971).
[2] M. J. Bernstein, Phys. Fluids, **13**, 2858 (1970).
[3] B. A. Trubnikov, Sov. J. Plasma Physics, **12**, 490 (1986).
[4] P. Lee, X. Feng, G. X. Zhang, M. H. Liu and S. Lee, Plasma Sources Sci. Technol., **6**, 343 (1997).
[5] S. Lee, T. Y. Tou, M. A. Eissa. A. V. Gholap, K. H. Kwek, S. Mulyodrono, A. J. Smith, Suryadi, W. Usada and M. Zakaullah, Am. J. Phys., **56** (1) (1988)
[6] M. Liu, *PhD. thesis*, Nanyang Technological University, Singapore (1996).