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Optical Emission Spectroscopy Observations Of Fast Pulsed Capillary Discharge Plasmas

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Abstract. We present time resolved optical emission spectroscopic (OES) observations of a low energy, pulsed capillary discharage (PCD). The optical emission from the capillary plasma and plasma jets emitted from the capillary volume was recorded with with a SpectraPro 275 spectrograph, fitted with a MCP gated OMA system, with 15 ns time resolution. The discharge was operated with different gases, including argon, nitrogen, hydrogen and methane, in a repetitive pulsed discharge mode at 10-50 Hz, with, 10-12 kV pulses applied at the cathode side. The time evolution of the electron density was measured using Stark broadening of the H_β line. Several features of the capillary plasma dynamics, such as ionization growth, wall effects and plasma jet evolution, are inferred from the time evolution of the optical emission.

1. Introduction

Pulsed Capillary Discharges (PCD) are versatile transient plasma devices which are currently being used in different applications, including lasing in the extreme ultraviolet (EUV) [1], EUV and soft x-ray sources for lithography and microscopy [2, 3], and plasma jets production [13], among others. The transient behaviour and characteristic geometry of a PCD, a narrow open ends tube with a large aspect ratio, establishes natural conditions for the occurrence of the hollow cathode effect (HCE) [5], and the emission of plasma jets [6]. Electron beams emitted from the hollow cathode region (HCR) favor on-axis initiation of the PCD. Important issues in PCD investigations are the study of the plasma dynamics and the measurement of characteristic plasma parameters with time and space resolution. Time resolved optical emission spectroscopy is a suitable diagnostic to measure both, electron and density and temperature. The first is achieved by Stark broadening measurements of suitable transition lines and the second, by line intensity ratios or Boltzmann plots. OES also allows the dominant plasma species to be identified. This is important in order to evaluate potential applications of PCD as EUV and soft x-ray sources. We have performed OES observations of the capillary plasma, at different stages of the capillary discharge evolution, operating with different gases. Stark broadening of the H_β line was used to measure the time evolution of the electron density. Identification of Oxygen and Aluminium line emission allowed to identify the effect of capillary wall plasma in the electric breakdown phase of the discharge.

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2. Experimental Details

The experimental observations have been performed in a low inductance high voltage PCD device. The capillary is an alumina tube, 55 mm long, 1.6 mm internal diameter. The discharge was operated with different gases, including argon, nitrogen, hydrogen and methane, at pressures between 0.6 and 1.4 Torr in the HCR, in a repetitive pulsed discharge mode at 10-50 Hz, with, 10-12 kV pulses applied at the cathode side. The stored energy is less around 30 mJ per pulse. Characteristic current is of the order of 1 kA, in a 10 ns FWHM pulse. A schematic of the capillary assembly is shown in figure 1. Spectroscopic measurements were performed with a SpectraPro 275 spectrograph with a MCP gated OMA system. The system was operated in pulsed mode synchronized with the discharge voltage, allowing registration of spectra at different times during the plasma evolution. Time resolution was determined by a 15 ns integration time. Optical emission was observed axially, to investigate the time evolution of the capillary plasma, and at the capillary exit, transversal to the axis, to investigate plasma jets emitted from the capillary discharge, as shown schematically in figure 2. Electron beams were observed with a scintillator-photomultiplier arrangement, coaxial with the capillary, at the anode side [7]. Further details of the experimental set-up and OES arrangement have been published elsewhere [5].

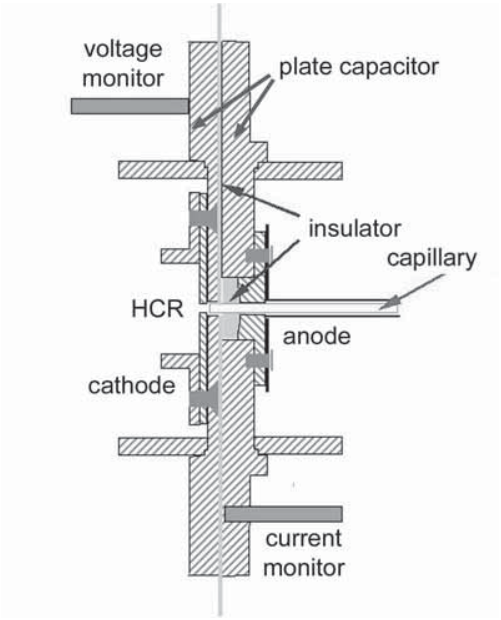


Figure 1. Capillary discharge assembly.

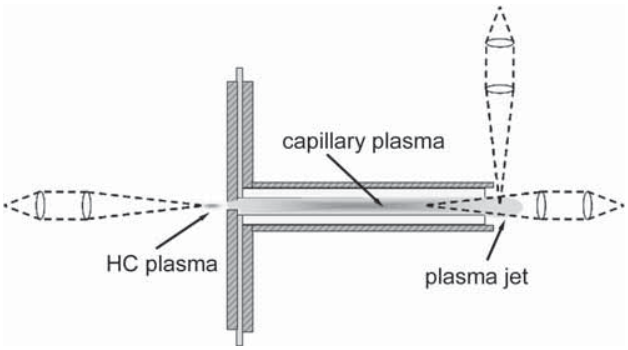


Figure 2. Plasma emission observation arrangement.

3. Results and Discussion

Figure 3 shows the voltage, HC emission and electron beam signals for an Argon discharge. Four distinctive phases are identified in the time evolution of the different signals, as defined in the figure. 1) the hollow cathode phase, 2) the ionization wave phase, 3) the electric breakdown and hot capillary plasma phase, and 4) the plasma expansion and jet emission phase. Phase 1 takes place before electric breakdown in the capillary, and correspond to the formation of a HCR plasma, due to the hollow cathode effect [7]. In phase 2, still before full electric breakdown in the capillary, a fast ionization wave propagates from the cathode towards the anode, along the capillary, giving rise to plasma formation. This has been establised by experimental observations

using capacitive probes along the capillary [7] and by a theoretical model of ionization wave generation [8]. This process is associated with a sharp increase in HC plasma emission and strong electron beam activity. Phase 3 corresponds to electric breakdown inside the capillary, with hot plasma formation, in association with a very fast, ∼10 ns, current pulse of kA level [9]. In phase 4 capillary plasma is expelled from the capillary, at the anode side, in the shape of a plasma jet [6]. Figure 4 shows the time evolution of Argon emission from the HCR, in the 460-500 nm band. $t = 0$ ns corresponds to electric breakdown. The intensity of the spectral emission follows clearly the light emission curve from the HC, seen in figure 3. The spectral lines correspond to ArII emission. Detailed analysis of the HCR plasma indicate that the characteristic electron temperatures and electron densities are in the ranges 1.4-1.8 eV, $10^{15} - 10^{16}$ cm^{-3}, respectively, which is produced by collisional processes involving electrons accelerated by the electric field leaking inside the HCR, with no additional heating [5].

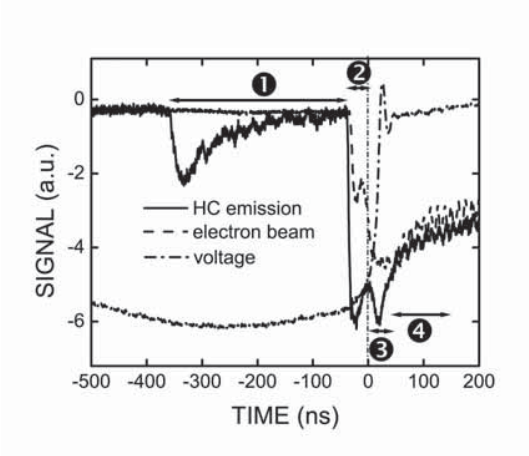


Figure 3. Time evolution of voltage, HC emission and electron beam signals, for an Argon discharge. $t = 0$ corresponds to electric breakdown in the capillary.

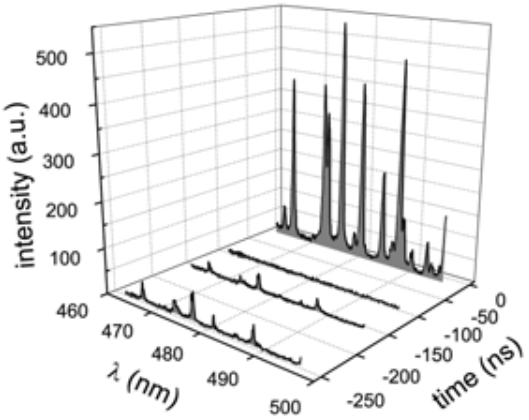


Figure 4. Time resolved Argon plasma emission from the HCR, during the hollow cathode and ionization wave phases.

Figure 5 shows axial observations of Argon emission, in the 430-470 nm band, during the ionization wave and hot capillary plasma phases. The emission intensity is orders of magnitude higher than that in the HC phase, as seen in figure 3. Figure 6 shows a time resolved spectrum, at a characteristic time which corresponds to peak current. Several ArII lines are identified. OII d AlII lines are also observed, which can be ascribed to emission from wall species ablated during the electric breakdown process. A point to note is that in this spectral band no emission lines corresponding to higher Argon ionization states exist, so the presence of ArII lines can not be taken by itself as an indication of a low temperature plasma at this phase.

Figure 7 shows the discharge current, together with the time evolution of the electron density, obtained from the Stark broadening of the H_β line [10], in Hydrogen discharges, at 0.75 Torr. It is seen that the electron density rises together with the current pulse, reaching a peak value close to $3 \cdot 10^{16}$ cm^{-3}, and later decays in a characteristic time scale of ∼80 ns, which corresponds to half of the peak value. The peak value is consistent with a fully ionized Hydrogen plasma, as the average initial neutral Hydrogen atom density is $\sim 2.5 \cdot 10^{16}$ cm^{-3}. Figure 8–a shows a synthetic spectrum of a carbon plasma, calculated using a Saha-LTE model [11], assuming a 4

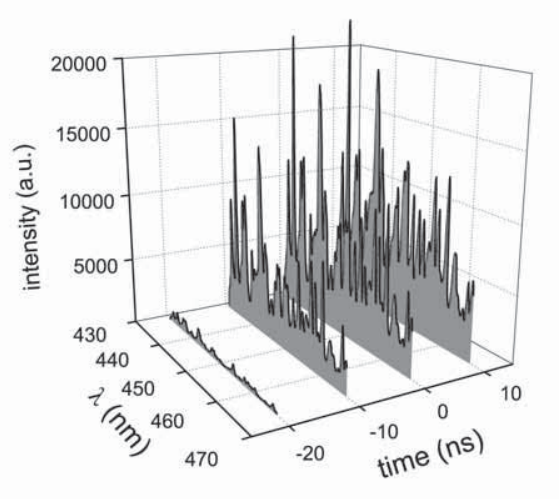


Figure 5. Time resolved Argon plasma emission from the capillary plasma, during the ionization wave and hot capillary plasma phases.

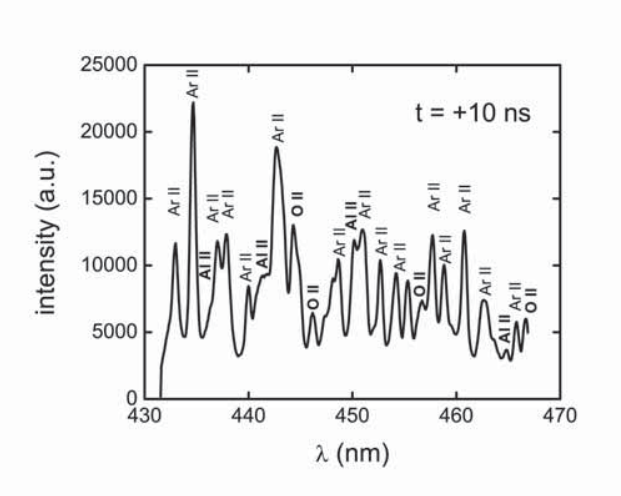


Figure 6. Time resolved Argon spectrum, corresponding to axial emission, 10 ns after electric breakdown.

eV, $3 \cdot 10^{16}$ cm^{-3} plasma. Under these conditions, the dominant lines in the spectral band correspond to CIII and CIV transitions. The relative line intensity matches reasonably well an actual spectrum corresponding to the axial emission of a methane capillary plasma, 10 ns after electric breakdown, shown in 8-b. At later times, greater than 80 ns after electric breakdown, the CIV lines almost disappear, giving place to CII lines, and very strong AlIII lines, from wall ablated species. An important point here is the fact that synthetic carbon emission spectra calculated under Saha-LTE equilibrium, assuming electron temperatures 0.5 eV either above or below 4 eV, result in relative line intensities which do not match the observed spectrum at 10 ns. Further estimations of the electron temperature in the case of an Argon plasma, using the Boltzmann plot technique, and assuming a partial local equilibrium model (pLTE), resulted in electron temperatures around 1.5 eV. The temperature was found to remain nearly constant for up to 500 ns after electric breakdown [12]. This is probably due to the fact that the temperature estimation relaies on ArII transitions, which might not satisfy adequately the conditions for pLTE.

Figure 9 shows the time evolution of the spectral emission from an Argon capillary plasma, recorded transversal to the capillary axis, at the capillary output, during the plasma expansion and jet emission phase. Maximum emission is achieved around 100 ns after electric breakdown, and later decays in a time scale of the order of 300 ns. A similar trend is observed in figure 10, which shows the time resolved H_β emission from a Hydrogen capillary plasma, recorded at different axial positions, beyond the capillary output. Again, maximum emission is achieved around 100 ns after electric breakdown and last for around 300 ns. The axial decay in plasma emission can be be attributed to plasma expansion in the low pressure region at the anode side. The Hydrogen spectra show also the presence of emission lines associated with OIII transitions arising from wall material [12]. Preliminary experiments reported elsewhere show that the capillary plasma jets can be used for thin film deposition, taking advantage of the wall ablation by using different materials at the anode end [13].

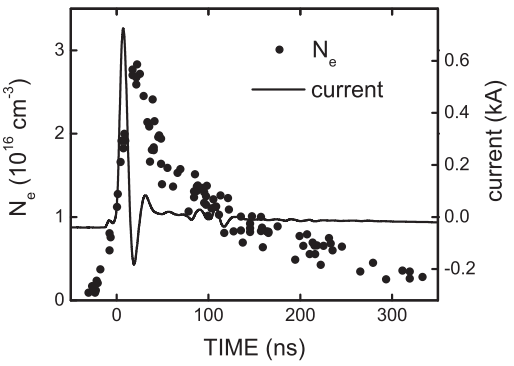


Figure 7. Time evolution of the electron density and discharge current.

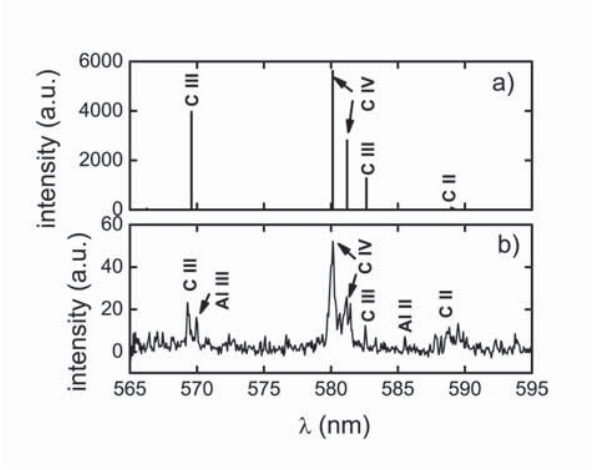


Figure 8. a) Synthetic spectrum of a carbon plasma, calculated using a Saha-LTE model, b) Methane emission spectrum, 10 ns after electric breakdown.

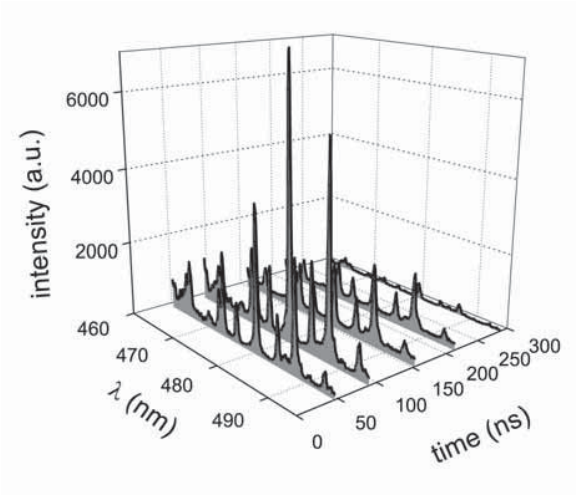


Figure 9. Time resolved Argon plasma emission at the capillary output, observed transverse to the capillary axis.

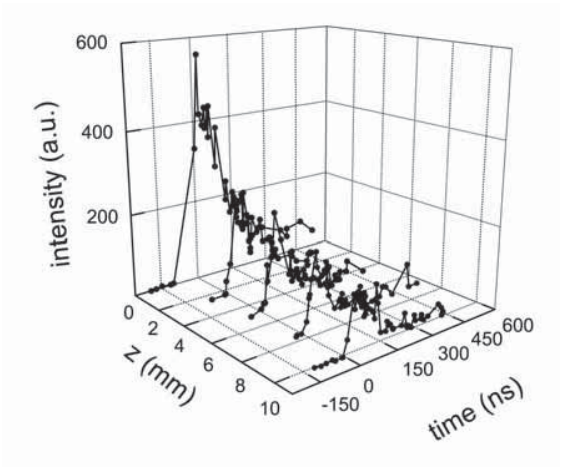


Figure 10. Time resolved evolution of the H_β line observed transverse to the capillary axis, at different axial positions.

4. Conlusions

We have performed detailed OES observations of the plasma emission in low energy, fast PCD. The overall features of the time evolution of the plasma emission are in agreement with the characteristic phases of a PCD, as established earlier using electron beam and capacitive probe measurements. We have measured the electron density, with time resolution, and inferred a characteristic electron temperature. Even though previous experiments confirm the effect of the HC electron beams in favouring on–axis discharge initiation, the presence of emission lines associated with capillary wall species, Aluminum and Oxygen, in the ionization wave, electric breakdown and hot capillary plasma, and plasma jet phases, indicates that the electron beam activity first, and the eV temperature capillary plasma later, ablate wall species, which

contribute to the overall plasma emission. These OES measurements confirm the unique features of the PCD, by which a low inductance design allows transient plasmas of a few eV temperature to be generated with a stored energy of less than 50 mJ per pulse. Operation with different gases has been demonstrated, which allows the PCD to be suitable as an EUV radiation source or a pulsed plasma device for thin film deposition. Further analysis of the spectral data is in progress to characterize better the PCD plasma.

Acknowledgments
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5. References

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