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A Compact Ultrafast Capillary Plasma Discharge As an Intense XUV Source

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Abstract. A fast nanosecond capillary discharge for fast repetition rate operation has been designed and tested. Operated in Ar and Ar/He mixtures X-ray emission from ionization stages from Ar VIII to XII have been observed according to capillary dimensions and operating voltages. Intense electron beams are formed as a result of the transient hollow cathode effect. The emission characteristics are presented for capillaries of two lengths, 21 and 26 mm, and at three diameters, 0.8, 1.6 and 3.2 mm. In addition, time resolved observations allow comparison of theory and experiment of the emission in relation to the current and applied voltage. We find from the spectra a strong dependence on the capillary dimensions, capillary operating conditions such as voltage, gas mix and pressure, diameter and length with clear evidence of wall ablation under some conditions. This has important consequences on the long term reliability of the discharge. The energy output at 4.9 nm (Ar IX emission) and the in-band (13.5 nm 1%) is also presented.

1. Introduction

Pulsed capillary discharges have been studied as a possible source of EUV and soft X-ray radiation. More recent work has concentrated on the potential applications of the capillary dicharges as a 135 Å source for EUV lithography [1] and as a water-window x-ray microscope source at 28.9 Å. Also Laser operation have been shown to be possible in the extreme ultraviolet [2]. The range of time scales of the discharges, plasma volume, energy delivered to the discharge is very varied. Most of the discharges store tens, or more, of Joules and operate at currents which allow pinching of the plasma columns. I contrast our discharge operates at energies less than one joule and time scales of 10 ns [3]. The skin depth scale of our discharge is comparable with its diameter, so it does not show the characteristic pinching as the normal capillary discharges. Here, rather than pinching and forming a small hot plasma column, which is the mechanism commonly used in bigger diameter, the transient hollow cathode effect plays an important role in forming a low temperature precursor, through the generation of intense axially colimated high energy electron beam just prior to breakdown. This favor conduction on axis with minimal wall damage. The early non Maxwellian electron beam favors the ionization of higher states and bright EUV source is obtained.

We present typical spectra in argon discharges where ArVIII to ArX show the most prominent lines. Wall ablation is clearly observed from oxigen lines present in the spectra. This results combined with filtered diodes, XRD's and Faraday cups show the emission characteristics of intense electron beams and the plasma X-ray emssion.

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2. Experimental Description

Very fast discharges are possibles when the energy stored is an integral part of the experiment's electrodes [3], [4]. This configuration of low inductance, allows an approximately 20 ns half period current waveform and a maximum current of order 10 kA.

Two different capillary length have been used, 21 mm and 36 mm. A schematic diagram of the capillary discharge for the 21 mm case is shown in Fig. 1. We used three different internal diameter for each capillary length: 0.8, 1.6 and 3.2 mm, in all the cases the external diameter was 6.35 mm and made of alumina.

In the Fig. 1 we can see a parallel plate capacitor configuration of 1.6nF, which acts as the energy storage medium. Water is used both as dielectric and as coalant. A cooling agent is needed because of the high repetition rate possible with this cofiguration (up to 1 kHz). The capacitor was charged up in 1 μs with a fast IGBT based charger [8].

A differential pressure scheme is used in order to enhance spontaneous plasma formation in the hollow cathode region. This is achieved by pumping the cathode region through the capillary, allowing a pressure gradient to be established between the cathode and the anode.

The observations shown here were taken in Ar-He mixture. The helium presence prolongs the life-time of the capillary and improves the the spectral characteristics changing by the Ar/He ratio.



Figure 1. Experimental Set-Up. A schematic was put in front of a real picture of the capillary discharge.

A range of diagnostics have been used to meassure the electrical properties of the capillary and the emission characteristics. A groove at the anode region works as a Rowoski coil, voltage is measured with a resistive voltage monitor. Immediatly downstream the anode four pairs of permanent magnets bend the electron beam away from the detectors. Beyond the magnetic field we used the AXUV HS-5 diodes series [5] and a photoconducting diamond [6], with an appropriate filter, to see the temporal evolution of certain lines and to calculate the in band energy. At the same position that the diodes the GIMS (Grazing Incident Monochromator Spectrometer) spectrometer was the principal diagnostics for the species in the plasma [9]. It is based on Rowland circle system with a CCD interface. Time integrated emission spectrum in the ranges 20-300Å was possible. Emission intensity were estimated using the responsivities 0.25A/W for the diodes [5] and $4x10^{-4}$ A/W for the PCD [7].

3. Results and Discussion

In Fig. 2 we show important features of the capillary phenomenology for a discharge at 24 kV and 150 Hz in Ar/He using a 21 mm long and 1.6 mm inner diameter alumina tube. In the upper diagram, it is the current close to sinusoid after the first 5 ns with a half period of 20 ns. Maximum current is 4.8 kA for these conditions. The Faraday cup pin is slightly displaced off-axis so as not to obstruct the view of the filtered diodes downstream. The lower set of traces show the filtered diode response. As the aluminum filtered diode extends its response from 171 Å well into the longer EUV wavelengths, its signal is the longer lasting, starting with the bare XRD signal and extending well into the period of damped oscillating current. As will be seen below, from the spectrum integrated in time, the aluminum filter is sensitive to the lower ionization states of argon as well as oxygen impurities, while the titanium filter permits observation of the highest argon ionization stages, Ar X to XII, while the polycarbonate responds principally to Ar IX emission in the vicinity of 49 Å. If we consider the temporal evolution, the rising edges of filter signals show a clear tendency from longer to shorter wavelength as the plasma attains higher temperature. The width of the Ti-filtered diode and the polycarbonate filtered diamond detector is noticeably less, consistent with the duration of a hot plasma of approximately 4 ns duration.



Figure 2. Current and the temporal evolution of the filtered diodes.



Figure 3. The differents filters used in the experiment.

The Fig. 4 and 5 were taken at the same conditions than the electrical signal shown before. In Fig. 4 the dominant feature is the Ne-like argon 2p6-2p5.3s transition at 49 Å. Higher ionization states are seen when the voltage is increased, up to ArXII have been seen when the capillary is charged at 27kV. When the voltage is increased, O and Al lines appear in this region, showing erosion of the capillary wall. On observing Fig. 5, OVI lines are clearly visible. The most prominent argon line is 3s-4p transition from ArVIII at 159 Å.

The spectrometer covers 30-400 Å, but the emission beyond 250 Å falls off markedly and is not discussed here.

Intensity calculations on Fig. 6 show the intensity per pulse of some of the most interesting windows. For example, the He-like Ar lines at 49 Å are possible to see when a PCD is used with 2 μm of polycarbonate filter. Similarly the in band energy flux at 135 Å is possible to estimate usig a AXUV diode filtered with 100/200 Å of Si/Zr, which wavelength is of great interest to the EUV lithography comunity. In Fig. 7 the importance of the length and the diameter is establish. We can see that the smaller the diameter the more intense is the emission. Even though the life-time is reduced by at least one order magnitude. The best diameter to maximize





Figure 4. Ne-like argon lines are the most prominent.



Figure 5. O VI lines show that erosion of the capillary wall is present.

intensity/life-time is 1.6 mm. If we consider the 1.6 mm diameter and 21 mm length capillary, the total energy per pulse in the window 30-200Å integrated over 2π steradians is 11mJ. This result shows that the yield is 1/100 of the total initial stored energy.



Figure 6. Intensity calculated from the signal of the diodes.



Figure 7. Comparison of the differents lengths and diameters.

4. Conclusion

We have shown some preliminary results showing that this experiment may be used as a EUV radiation source. We have measured the soft X-ray output for two capillary lengths and three capillary diameters. The 1/100 efficiency, together with the high repetition rate could yield an output power as high as 10W. Wall damage remains a very important problem when the capillary is operated a high frequency and high voltage. Without doubt this will be a critical parameter to evaluate in the future. Shorter capillary, different gases and higher voltage are parameteres that in the future will be studied thoroughly to improve the spectral composition and the emitted intensity.

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