Characterisation of a fast microcapillary discharge plasma using a compact multi-deflector Thomson parabola ion analyser

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ABSTRACT

A compact Thomson parabola ion analyser has been developed and tested on a fast microcapillary plasma discharge. The discharge cell comprises a circular parallel-plate capacitor (1 – 2 nF) with a 50 micron sized hole in the dielectric and a somewhat larger hole in one of the electrodes, which acts to hold off the voltage before self-breakdown in vacuum. The cell capacitance is pulse charged to about 10 kV in about 50 ns. Self-breakdown proceeds via a surface discharge over the dielectric exposed in the electrode hole and through the microcapillary in the dielectric. The current in this discharge rises to about 20 kA in 1 ns. The ions in the plasma outflow are predominantly single and doubly charged species from the dielectric and have energies in the range 1-10 keV

INTRODUCTION

Previously we have reported on the development of a compact fast microcapillary discharge apparatus which is a source of EUV [Engel *et al.* 1999a] and energetic ion emission [Engel *et al.* 1999b]. An ion probe operating in the time-of-flight mode was used to resolve the ion velocities, but did not measure the charge or mass of the ions. This paper describes the results of using a gated Thomson parabola to detect the ion species present in the plasma outflow.

EXPERIMENT

In short the microcapillary discharge setup consists of a 9 cm diameter circular parallel plate capacitor with a small hole in the dielectric and a larger hole in the ground electrode, figure 1. Using an 80 μm thick Mylar ($C_{10}H_8O_4$) dielectric foil the capacitance of the cell is typically ~2 nF. In the experiments reported here an optional Al back plate was inserted in between the Mylar and the brass back electrode. The electrode with the hole connects to a vacuum chamber evacuated to $<10^{-3}$ mbar. The cell capacitance is pulse charged to about 10 kV in about 70 ns. Self-breakdown proceeds via a surface discharge over the dielectric exposed in the grounded electrode hole and through the microcapillary in the dielectric. The initial diameter is roughly 80 μm but increases with the number of shots on the cell.
A time-resolving Thomson parabola analyser (TPA) has been described before [Rhee 1984]. In the magnet holder there are four gaps (gap space δ=3 mm, gap length L=10 mm and BL~130 mT, EL~130 V) where the parallel magnetic, B, and electric fields, E, are applied. The four deflected beams fall on the four quadrants of a MCP where they are detected. The recording medium is photographic film (HP5 Plus 400). Four beam collimation apertures of 600 μm diameter were placed in front of the gaps. The TPA

utilises a four-quadrant, micro channel-plate (MCP) image intensifier as a high-speed shutter, figure 1. The gating pulse on the MCP is ~15 ns (FWHM) with an amplitude of 5.5 kV. The ion detection efficiency of a MCP in the energy range 2-20 keV is almost constant ~ 60% but is rapidly decreasing for lower energies e.g. [Oberheide et al 1997]. An electrical probe operated in the time-of-flight (TOF) mode was used to measure the ion flow at a distance of 13.5 cm from the discharge cell. On the discharge cell a current probe together with a coaxial voltage divider [Pfeiffer 1986] are used to monitor the discharge current and hold-on voltage respectively of the microcapillary. The current monitor was described earlier [Choi & Favre 1994]. A fast oscilloscope was used to record the signals from the current and voltage monitor and the electrical probe.

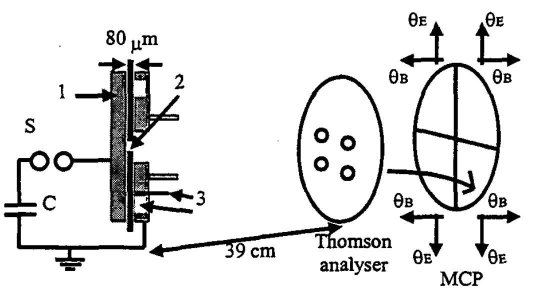

Figure 1: Schematic of the microcapillary setup with a time resolvable Thomson parabola analyser. C is a capacitor bank of 6nF charge by the HV power supply. S is the spark gap operated in air at atmospheric pressure. 1: Brass electrodes, 2: Mylar dielectric with the microcapillary (not to scale), 3: Groove and co-axial cable used to detect the magnetic flux change in the groove.

RESULTS

The current in the discharge increases to > 10 kA in about 1 ns, hence the rise time is > 10^{13} A/s, figure 2 (A). The subsequent evolution of the signal can be approximated with an under-damped oscillation from the discharge of a capacitor in a RL (resistance, inductance) circuit. The mean values of the resistivity, ρ, and inductance during the first oscillations of the discharge are $\rho \sim 0.15$ mΩcm and L~0.2 nH. Using Spizer's formula [Spizer 1962] for the plasma resistivity of a fully ionised plasma the electron temperature is estimated to be >100 eV in the initial plasma.

The ion current detected by the electrical probe positioned 13.5 cm downstream from the cell is shown in figure 2 (B). Also shown is the expected ion current at the position of the Thomson parabola analyser assuming a self-similar expansion.

The probe does not discriminate between ions but records the total current intercepted by the solid angle of the probe at the mircrocapillary. The TPA results allow the ion species in the late stage of the flow to be determined, i.e. when the plasma plume expansion has become inertial. Ions are first detected at the MCP (situated 6 cm behind the TPA) after about 1.6 μs and can be followed up to around 3.5 μs where the energy of a typical ion is to low to be efficient recorded by the MCP (<2 keV). For a particle with velocity, v, the deflections in an idealized field system for the TPA are [Rhee 1984]:

$$(1-A)\quad \tan\theta_E = \frac{ZeEL}{Amv^2} \qquad (1\text{-B})\quad \tan\theta_B = \frac{ZeBL}{Amv},$$

where Z is the ion charge, A the ion mass number, e the electronic charge and m the unit nucleon mass. It can be seen from (1-A) and (1-B) that a straight line crossing the origin of the deflection coordinates is a constant velocity line:

$$(2)\quad v = \frac{EL}{BL}\tan\alpha .$$

Here α is the angle to the electric deflection axis of the line, see figure 3. Figure 3 is a schematic diagram of the photograph of a MCP quadrant in the experiment. The MCP was gated at a time where the plasma plume flows in between the magnets of the TPA. The deflected ions fall on a straight line corresponding to a constant velocity going through origin marked by neutrals/radiation both of which do not experience deflection.

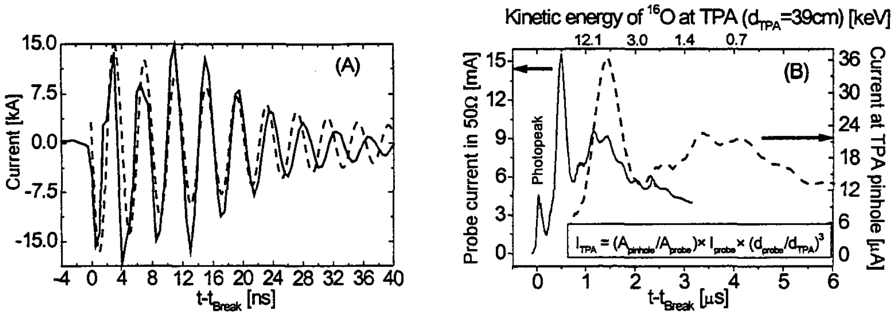

Figure 2: Microcapillary with 80μm thick Mylar dielectric. **(A):** Experimental current (solid line) in cell and calculated current (broken line) expected for a capacitor discharge in a RL series circuit (C=1.4nF, L=0.2nH, R=0.02Ω). **(B):** Current collected by electrical probe at 13.5 cm from cell (solid line) and scaled to the position of the Thomson Parabola Analyser "TPA" (broken line).

Since the time of the gating is known, the velocity of the ions, v, can be calculated. For the analysis presented here the values of BL and EL were measured independently whereby the angle α is determined from (2). This allows us to make the projection onto the magnetic axis for each of the ion spots on the film and hence the mass to charge ratio A/Z of the ions can be found, typical results of which are shown in figure 4. Also shown in figure 4 is the deflection expected for an ion with the velocity in the given measurement.

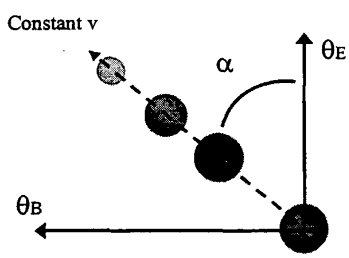

Figure 3: Schematic showing how the developed film of a quadrant from the MCP typically look.

CONCLUSION

Typical ions identified in the plasma from the microcapillary are C+, C++ and O++. We ascribe these ions to be originating from the dielectric of the discharge cell. In the spectroscopic measurements [Engel *et al* 1999a] CV and OV ions were observed in the initial breakdown plasma along with ions from the metal electrode.

Following time evolution of the charge distribution in the TPA measurement is seen tahat greater variety of ionisation stages are present at early times i.e. in the first part of the expanding plasma plume. This is to be expected as the lower density and temperature at the front can cause the ionisation stage to freeze in during the evolution of the plasma [Anders 1997].

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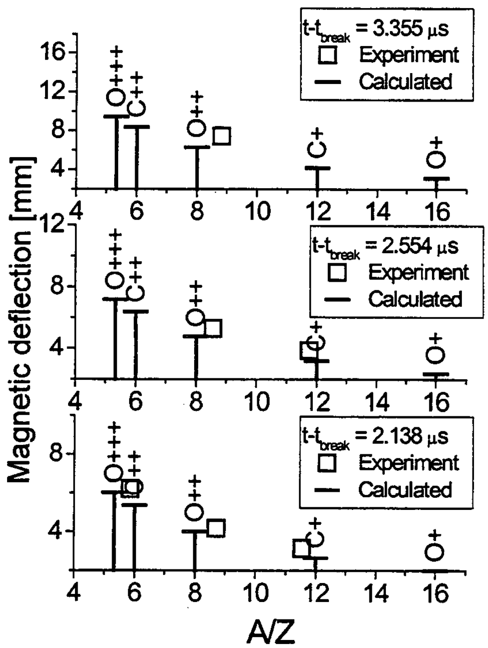

Figure 4: Charge and mass resolved deflection for ions in a microcapillary discharge with a Mylar dielectric at various times after break-down. Charging voltage ~9kV.

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