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ENERGETIC ION EMISSION IN A POSITIVE POLARITY NANOSECOND PLASMA OPENING SWITCH

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Abstract

We studied the emission of energetic ions from the plasma in a coaxial Plasma Opening Switch (POS) powered by a 300 kV, 15 kA, 90 ns positive polarity pulse. Fluxes lasting 2 - 3 ns of ions flowing radially onto the cathode were seen to occur at all axial locations of the switch plasma within 5 ns of the beginning of the upstream POS current. It is suggested the termination of this ion flux results from the formation of a cathode plasma that is consistent with our spectroscopic measurements. Later in the pulse, longer duration (100 ns) ion fluxes were observed radially, first appearing in the generator side of the switch plasma. Fluxes, 30 - 40 ns long of ions flowing axially towards the POS load at velocities $(2\pm1)\times10^{8}$cm/s were also seen. The dependence of the start time of the axial ion flow, of the ion velocities, and of the ion flux on the POS operation parameters were studied.

I. Introduction

Experimental studies of coaxial POS operated with a negative polarity for the central electrode showed a large increase of the ion current density at the cathode both in the nanosecond[1] and microsecond[2] regimes. The total ion current flow in the radial direction toward the cathode was measured to be ~(10-20)% and ~ 30% of the total POS current in the nanosecond and in the microsecond time scales, respectively. This residual ion current limits the rise in the POS resistance. Therefore, the investigation of the ion dynamics, especially of energetic ions, is extremely important for the improvement of the POS performance.

II. The Experimental Setup

The POS experimental setup is shown in Fig. 1. The plasma was injected radially outward through a 75% transparent anode by a gaseous (CH_4) plasma gun[3]. An LC-water-line generator with a positive polarity output pulse was used to deliver a 90-ns quarter period pulse with a peak current of (135±10) kA. An upstream vacuum inductance, 120 nH, was made by two aluminum tubes with outer and inner diameters 10 cm and 5 cm, respectively. A short-circuit coaxial inductance, 25 nH, served as the POS load. The POS upstream and downstream currents were measured by two Rogovskii coils.

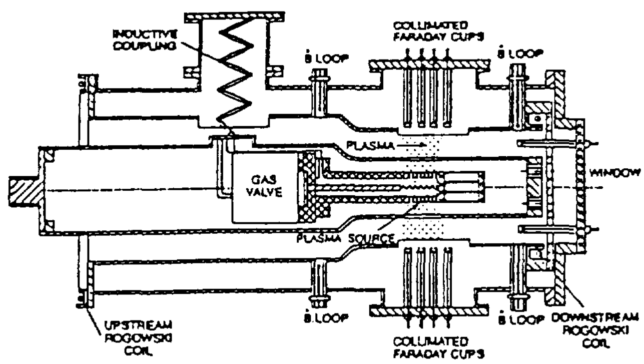

Fig. 1. The POS experimental setup

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The plasma electron density prior to the generator pulse was determined to be $(1.3\pm 0.5)10^{14}cm^{-3}$ at 0.5 cm from the anode surface from Stark broadening of H_α and H_β. The plasma average flow velocity, determined by Doppler shift of several ion species, was found to be $(1.5\pm0.5)10^6$cm/s. The electron density was found to be uniform in the azimuthal direction and over the 4-cm axial direction within 15%.

Varying the POS conduction times was achieved by changing the time delay, τ_d, between the discharge of plasma source and the generator. Typical waveforms of the upstream and downstream currents, and the POS current are shown in Fig. 2. The slow rise of the downstream current pulse was also observed in the previous studies[4] of a coaxial positive polarity POS.

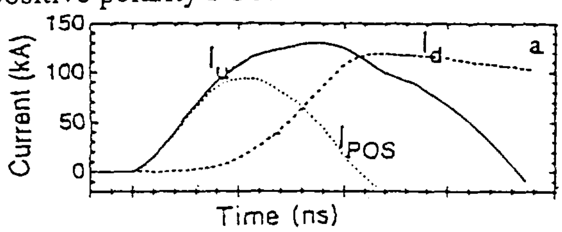

Fig. 2. Typical waveforms of the upstream (I_u), the downstream (I_d) and the POS (I_{POS}) currents.

The ion current density distribution in the radial direction at several axial positions along the POS axis was measured by two arrays of 4 Collimated Faraday Cups (CFC) with a transverse magnetic field. The CFC were placed in front of 1.4 cm wide slots in the cathode, at two opposite sides of the POS, and at axial distances of 1.7 cm from one another. The CFC could be radially translated to yield the ion radial velocities from Time of Flight (TOF) measurements. The current density and velocities of ions flowing in the axial towards the load were measured by four magnetically insulated CFC, azimuthally separated by 90°, and placed at the radial center of the POS interelectrode gap at various distances from the load side edge of the plasma.

III. Measurements and Data Analysis

3.1. Radial ion flow

The CFC signals in the two sides of the POS were similar to within the ±30% shot-to-shot irreproducibility. Based on these observations we assume in the estimates below azimuthally symmetric CFC signals over the entire plasma in the switch region. At distance of 1.5 cm from the cathode slots the signal exhibit two peaks, shown in Fig. 3. A short duration ion pulse, 2-3 ns long, appeared in almost all CFC within 5 ns from the beginning of the upstream current. The amplitude of these ion current spikes reached 40 A/cm^2. The decrease of the plasma density near the CFC by reducing the time delay τ_d, or by reducing the cathode slot width to 0.2 cm, resulted in the disappearance of the early ion spike, with less significant effect on the longer duration late ion signal.

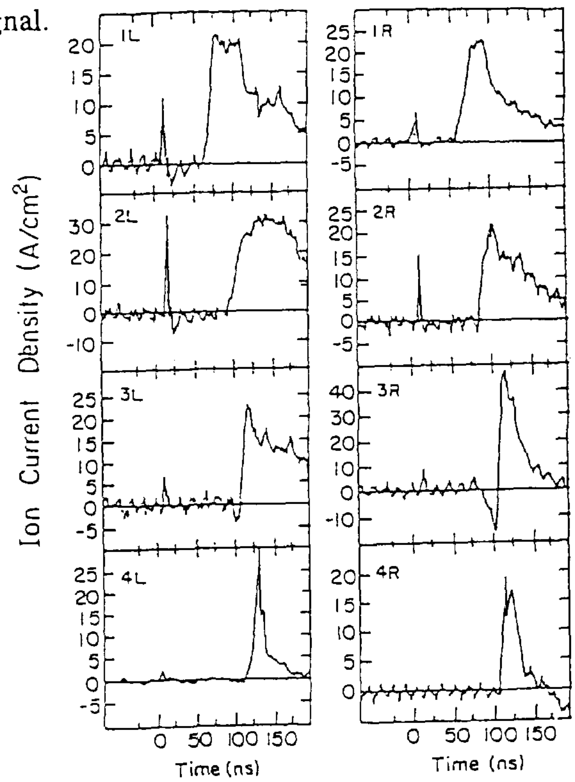

Fig. 3. The ion current density measured by two arrays of CFC at 4 axial locations and in both oppositive sides of the POS.

The start time of the longer-duration ion current was found to depend on the CFC axial position (see Fig. 4). This ion pulse began first at the generator side and later at the load side of the plasma. The axial propagation velocity of the ion-ejection zone during pulse are found to be $(8\pm1.5)10^7$cm/s and $(9.5\pm1.5)10^7$cm/s for the longer and shorter conduction times, respectively.

At 1.4 cm from the cathode slot the ion late signals has a relatively short time duration, while at larger distances the ion current was lower and lasted up to a few microseconds. The increase in the ion pulse

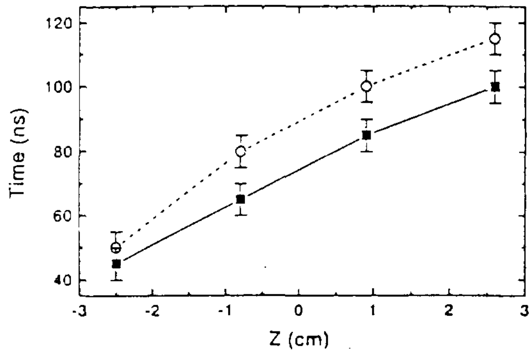

Fig. 4. The appearance time of the fastest ions, emitted in the radial direction for two operation regimes of the POS: 50 ns conduction time (solid) and 80 ns conduction time (dashed). The zero axial position correspond to the axial center of the POS plasma.

duration results from the differences in the ion velocities due to their different mass and charge. The radial velocity of the fastest ion component, averaged over 20 experiments for the same τ_d, was $(2.3\pm0.5)10^8$cm/s. Our spectroscopic investigations[3] of the plasma source showed that the plasma, formed from CH_4, consists of C and H atoms, protons, and CII-CIV ions. The fastest ion component is thus probably protons with energies (28±11) keV that is consistent with the POS voltage. The estimated total radial ion current rises in time to a maximum level of 5 kA, which is ≈ 5% of the current flowing through the POS.

3.2 Axial ion flow

In the upper half of Fig. 5 we present the current density of the ion flow propagated in the axial direction towards the shorts circuit end of the load. The reproducibility of the ion current density and the ion pulse duration was ±50% and ±30%, respectively. The flow of electrons co-moving with the ions was observed by the CFC without magnets and using a bias voltage of 100 V (see the lower half of Fig. 5). The ion axial velocity obtained from these TOF measurements was found to be similar in all axial locations, $(1.8\pm0.5)10^8$cm/s for the cases where the conduction times were ≤80 ns. The average peak density was (55 ± 20)A/cm^2, with a pulse FWHM of (30±10) ns. For longer conduction times, the ion axial velocity was found to be smaller, $(8\pm2)10^7$cm/s, and the signal duration increased with the axial distance. Based on the TOF data the time at which the ions left the load side of the plasma was found to be (60±15) ns when the POS conduction time was about 50 ns, which coincides with the rise of the downstream current.

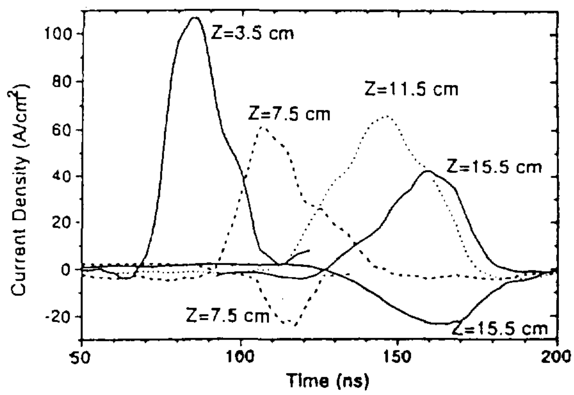

Fig. 5. Ion current density traces measured in a single discharge by 4 axially separated magnetically insulated CFC. The CFC are positioned between the plasma and the load.

IV. Discussion

Let us describe the process we believe is responsible for the short duration ion pulse collected at the CFC screen box. The same process is expected to occur near the cathode because it electrically is connected by plasma to the CFC screen boxes.

When a voltage is applied between the cathode and the anode, plasma electrons are drawn to the anode. As a result, electrons are drained from the vicinity of the cathode, and rising voltage falls mainly on the electron-free gap near the cathode. The ions in this region are drawn by the electric field to the cathode, and within an ion plasma period a space charge limited flow is established. At a certain intensity of the electric field, explosive emission occurs at the cathode, which forms plasma that serves as a source of electrons. This results in a space-charge limited bipolar flow with a low voltage drop that is characterized by a negligible ion flow.

The ion charge per unit are collected by the cathode during first 5 ns of the pulse is $Q_i=\int j_i(t)dt \approx 0.6$ nC/cm^2. The electron density near the cathode surface is $n_e \approx 4\times10^{13}$ cm^{-3} and the radial size of the region free of electrons at this time is estimated by $d=Q_i/en_e \approx 100$ μm. This electric field is sufficient to cause explosive emission at the cathode surface.

The formation of an electrode plasma was shown by our spectroscopic observations[3]. These measurements showed line emission of surface adsorbents (Si, O, C, H) and of electrode material (Al) within 50 ns after the beginning of the upstream current at 0.1 cm from the cathode surface (see Fig. 6). The electrode plasma radial velocity was determined

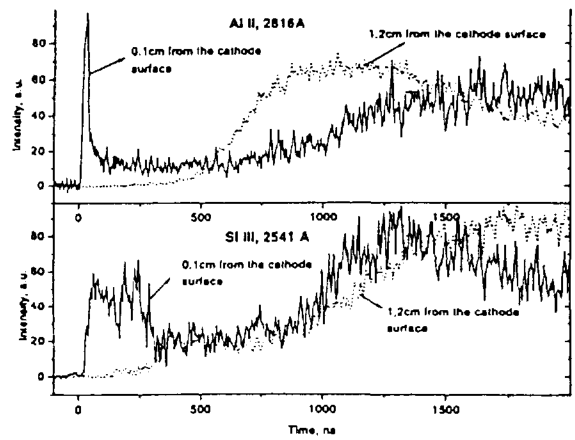

Fig. 6. Relative line intensities of AlII and SiIII ions at different radii from the cathode surface.

by the time interval between the appearance of the light at the different radii, $V_{pl} \approx (1.5\pm 0.5)10^6$cm/s. This suggests that this plasma was formed at the first few ns relative to the start of the upstream current.

The long duration ion current observed later in the pulse shows current densities that are higher that the plasma ion saturation current. Such long duration ion pulses were seen in nanosecond and microsecond POS experiments. Here, the long duration ion pulses were observed to be delayed with respect to the beginning of the upstream current. The delay time was found to depend on the axial position along the cathode with the axial propagation velocity being $\approx 10^8$cm/s, which can be interpreted as the propagation velocity of the ion emitting sheath[5].

The energetic ion flow in the axial direction towards the short circuit load is explained on the basis of the magnetic field evolution in the plasma[3]. The measurements described there showed a fast magnetic field penetration into the plasma and a formation of a narrow current layer at the load edge of the plasma. Only then the ion axial velocities become substantial.

These observations showed Z/M scaling for the ion velocities that allows us to conclude that the proton velocity at the load side edge of the plasma are $(1.5\pm0.4)10^8$cm/s, at t=75 ns. The proton velocity, presently obtained, is in agreement with this value.

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