Density Redistribution in a Microsecond-Conduction-Time Plasma Opening Switch

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The first measurements of the line-integrated electron density in a coaxial microsecond-conduction-time plasma opening switch during switch operation are presented. Current conduction is observed to cause a radial redistribution of the switch plasma, with a large decrease in axial line density over most of the radial extent of the switch. A local reduction in line density of more than an order of magnitude occurs by the time opening begins. It is hypothesized that this density reduction allows the switch to open by an erosion mechanism. Initial numerical modeling efforts have reproduced the principal observed results.

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Pulsed power generators that use inductive energy storage techniques offer potential benefits for producing TW and higher electrical power pulses [1]. Applications for such generators include inertial confinement fusion and the production of intense x-ray pulses. A plasma opening switch [1] (POS) allows the use of vacuum inductive storage for the generation of such high power pulses. A POS consists of plasma injected between two conductors in vacuum, through which current flows, storing magnetic energy in the circuit. At some point, depending on the details of the POS and the driving current, this conduction phase ends and the switch opens, transferring energy to a load. Over the past decade much attention has been directed toward microsecond-conduction-time POS development [2-7]. This technology has promise for the development of compact, multi-TW, multi-MA generators. In experiments to date switches have conducted MA-level peak currents for $\sim 1\ \mu s$ before opening in tens of ns [4-6]. Magnetic probe measurements (discussed below) show that large-scale translation of the current-carrying plasma toward the load does not occur, indicating a relatively high ($\sim 10^{15}$-10^{16} cm^{-3}) plasma density. This high density makes the observed, rapid opening of the switch difficult to explain. We report here the first quantitative, nonperturbing, *in situ* measurements of the plasma electron density during POS operation. The electron density is measured using heterodyne-phase-detection HeNe interferometry. These measurements indicate that the plasma mass is rarified during the conduction phase. Based on these observations, we propose a mechanism by which current conduction is limited and opening occurs.

A schematic of the experiment, on the Hawk generator [8], is shown in Fig. 1. The coaxial switch geometry comprises a 5-cm-radius center-conductor cathode and an array of twelve axial anode rods at a radius of 7.5 cm. A short-circuit load is located 25 cm beyond the switch. Plasma is injected by eighteen flashboards positioned at an 18-cm radius. Each flashboard consists of an array of surface discharges across a carbon-coated insulator. A mask outside the anode rods shields all but the 8-cm-long switch region from the injected plasma. The flashboards are typically pulsed 1 to 2 μs before the generator is fired. Electrical diagnostics include sets of dB/dt loops at the generator and at the load. In the absence of opening, the generator drives 720 kA through the switch in 1.2 μs.

The details of the interferometer will be presented in the future [9] and are only summarized here. An acousto-optic modulator splits a 10-mW cw HeNe laser beam into two beams with a 40-MHz relative frequency shift. A scene beam is directed through the switch region in the axial direction, parallel to the cathode (see Fig. 1). A reference beam traverses an equal path length outside of the vacuum system before combining with the scene beam at the beam splitter. The intensity of the combined beam exhibits a 40-MHz beat signal whose phase depends on the relative phase shift between the two beams. The zero-crossing times of the beat signal are used to determine the time-varying phase shift of the scene beam, from which the line-integrated density $\int n_e\,dz$ is calculated. Several null tests were performed to verify that the measured phase shift is caused by material in the switch region [9]. These tests showed a small spurious phase shift leading to an apparent negative density when the switch opens. This effect gives a measurement limit of less than 2×10^{15} cm^{-2}, or 2° of phase shift. Neutrals are not expected to affect significantly the phase shift be-

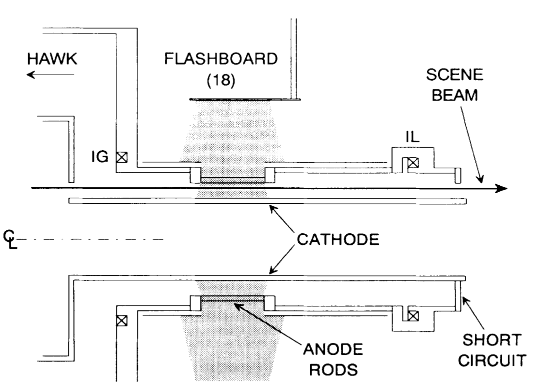

FIG. 1. The Hawk POS geometry, showing the scene beam path and the generator (IG) and load (IL) current monitors.

cause the densities required are too high: The phase shifts from neutral C and H are 27 and 80 times lower, respectively, than those from free electrons at the HeNe wavelength. Before each shot the flashboards alone are fired and the density is evaluated for comparison with shots where the POS plasma conducts current.

Typical data are shown in Fig. 2. On this shot the switch current rises to 660 kA in 900 ns before the switch opens, i.e., before current is delivered to the load. The detected portion of the scene beam was located radially 1.5 ± 0.05 cm from the cathode surface, and azimuthally between two anode rods. At about 350 ns into the conduction phase on this shot, the line density departs abruptly from the flashboard-only behavior. Rather than increasing, the line density decreases somewhat until just before the switch opens. At that time it decreases sharply. During opening, the line density is less than the measurement limit of 2×10^{15} cm^{-2}. This represents a decrease of over an order of magnitude relative to the value of 350 ns. Later, the line density increases again, eventually rising to a level exceeding 10^{18} cm^{-2} for tens of μs. When the switch opens, an inductive voltage appears across the switch gap. We believe that the late-time density increase reflects enhanced electrode plasma formation due to bombardment by energetic particles accelerated by the switch voltage.

Measurements at other radii, except those within a few mm of either electrode, are qualitatively similar to those in Fig. 2; the line density departs from the flashboard-only value early in the conduction phase and decreases until opening occurs. At 0.25 cm from the cathode the line density increases relative to the flashboard-only case during the first few hundred ns. It then decreases, but remains finite at opening. At 0.1 cm from the anode the line density increases sharply toward the end of the conduction phase. The results are similar at different azimuthal locations relative to the anode rods.

Line densities as a function of radius are summarized in Fig. 3 for a series of shots similar to the one in Fig. 2. Line densities are shown for two times, early (300 ns) in the pulse and just before opening (900 ns), and compared with data from flashboard-only shots at the same times. At the beginning of the generator pulse (0 ns, not shown) the line density is higher at the cathode because of stagnation of the injected plasma and/or secondary plasma formation due to bombardment of the surface by the injected plasma. At 300 ns there is little effect of current conduction other than a further increase in line density at the cathode. This may be indicative of the explosive-emission cathode plasma. By the time of opening, current conduction through the plasma has greatly altered the line density profile. Conduction causes an approximately fourfold line density reduction over most of the radial extent, relative to that at the same time on flashboard-only shots, and a twofold reduction relative to that at 300 ns. The latter comparison confirms that the initial plasma has been redistributed. Since the interferometer integrates along the axis, and the same results are observed at different azimuths, this redistribution must be associated with radial displacement of the plasma. These measurements indicate that plasma is pushed out to the anode radius. Plasma may also be pushed into the cathode, accumulating closer than the minimum observed distance of 0.25 cm. The lowest line density immediately prior to opening occurs most frequently at 1.5 ± 0.1 cm from the cathode; opening presumably occurs at this location. We believe that the minimum occurs here, rather than at the cathode, because of the much higher initial line density at

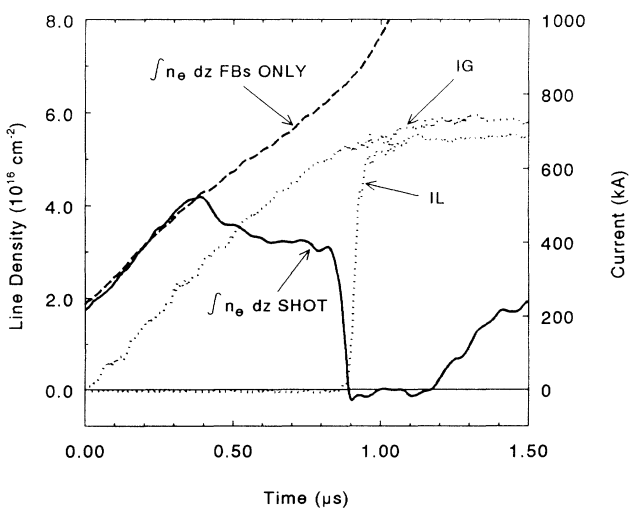

FIG. 2. The electron line density at 1.5 cm from the cathode during a shot on Hawk. The line density ($\int n_e dz$, FBs) when the flashboards alone are fired is shown for comparison. The generator (IG) and load (IL) currents are also shown.

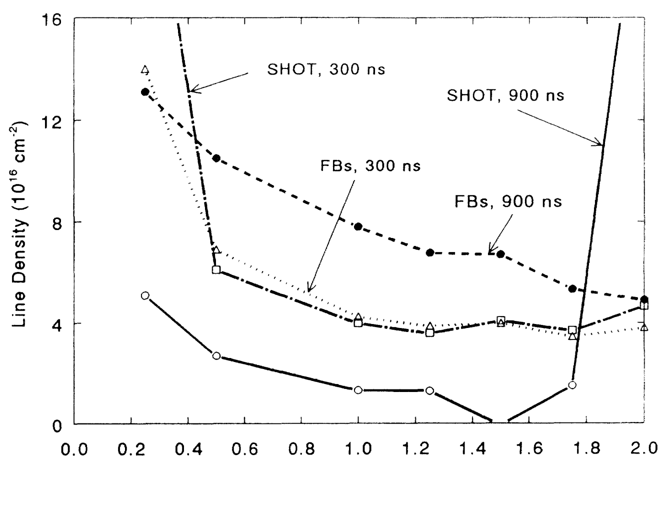

FIG. 3. Electron line density as a function of radial position, early in the conduction phase and just before opening. Flashboard-only data are shown for comparison.

the cathode (Fig. 3). Fast framing photography of POS plasmas has shown a decrease in visible light emission near the center of the switch gap at the end of the conduction phase [10,11].

In previous experiments, current flow in the switch region was diagnosed with arrays of dB/dt loops immersed in the switch plasma [12]. These measurements indicate that current is conducted across the switch in a broad (4 to 8 cm wide), predominantly radial channel that propagates toward the load as the conduction phase progresses. At opening, the center of the current channel is located near the load end of the 8-cm-long switch aperture. This translation is consistent with calculations of the center-of-mass hydrodynamic translation of a C^{++} switch plasma, using the current wave form and measured electron line density. The observed radial plasma displacement toward the anode and cathode can be explained by a relatively small axial ($j_z/j_r \sim 10\%$) tilt or bend in the current streamlines, which would not be resolved by the magnetic probe measurements. We believe that the axial component of the current streamlines arises from a combination of the radial dependence of the magnetic field and the radial variation of the initial plasma line density. A radial variation of B^2/n will result in a radial variation of the axial displacement, and thus a bend in the current streamlines.

Hydrodynamic motion of the switch plasma was modeled with the ANTHEM two-fluid code [13]. The measured electron line density profile at 300 ns was divided by 8 cm to get an average local density. To reduce computation time, the plasma mass and length and the current rise time were reduced. A 4-cm-long, H^+ plasma was assumed, with a current rise time of 200 ns. This rise time was chosen to provide the same calculated center-of-mass translation as the experimental parameters. Results are shown in Fig. 4. Figure 4(a) shows electron density contours at 210 ns, corresponding to the time of switch opening in the experiment. The current streamlines follow these contours—mostly radial, but bowed. The plasma has been displaced toward the load end of the switch region, albeit in a narrower channel than indicated by the magnetic field measurements. We believe that the observed current channel width could be reproduced by incorporating anomalously enhanced resistivity in the modeling [14]. More importantly, the slight bending of current streamlines has led to a radial density redistribution, with a density minimum at 1.7 cm from the cathode. This compares well with the results in Fig. 3. Figure 4(b) shows the calculated time history of the axial line density at this radius. (Note that because of the reduced length of the switch aperture in the computation the initial line density is a factor of 2 less than the experimental value.) A sharp decrease is seen at the end of the conduction phase, which compares well with the results in Fig. 2.

The ultimate opening of the switch, causing voltage generation and current transfer to the load, occurs in a (relatively short) few tens of ns. Similar results were obtained in Refs. [2-7]. The observed reduction in the line density by more than an order of magnitude at 1.5 cm from the cathode may allow the switch to open by enhanced erosion [15] of the switch plasma. Erosion occurs when the ion current drawn from the switch plasma exceeds the saturation value. A vacuum gap D forms at a rate given by $dD/dt = j_i/en_e - v_D$, where v_D is the ion injection velocity perpendicular to the cathode and j_i and n_e are the line-integrated ion current density and electron density. Effective switch gap opening rates are inferred from similar shots with diode loads [6]. Based on magnetic insulation arguments and electrical data from these experiments, gap opening rates of ~ 5 cm/μs and switch gaps at opening of a few mm are inferred. Faraday-cup measurements [12] indicate that the ion current is on the order of 20% of the total current at the time of opening. At the line density of 4×10^{16} cm^{-2} measured at 300 ns (Fig. 3), j_i/en_e is about 0.4 cm/μs, which is far too small to explain the observed opening rate. However, at the reduced electron line density at the end of the conduction phase of 2×10^{15} cm^{-2} (the interferometer measurement uncertainty), j_i/en_e exceeds 10 cm/μs. This rate may well exceed the ion injection velocity and can explain the observed rapid opening.

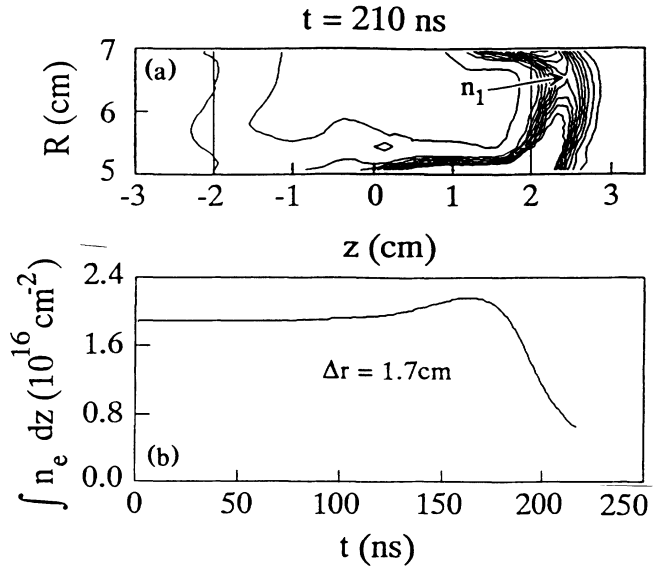

FIG. 4. ANTHEM code predictions: (a) Electron density contours at the end of the conduction phase. The vertical lines indicate plasma location. The electron density at n_1 is 1.3×10^{16} cm^{-3}. The density rises to over 4×10^{16} cm^{-3} near the cathode. (b) Axial line density at 1.7 cm from the cathode.

In conclusion, line-integrated electron density measurements during POS experiments have shown new features of plasma dynamics relating to the conduction and opening mechanisms in a POS. Current conduction causes a reduction in line density during most of the conduction phase and over most of the plasma radial extent. The global density reduction during the conduction phase indicates that current conduction in this experiment is limited by hydrodynamic motion, as suggested in Ref. [5]. Even though the magnetic force is primarily in the axial direction, it is the radial redistribution of the switch plasma that controls conduction. This is supported by fluid code computation. We hypothesize that opening occurs in a two-stage process: a slow line density reduction by radial $\mathbf{j}\times\mathbf{B}$ forces followed by rapid gap formation by erosion of the rarified plasma.

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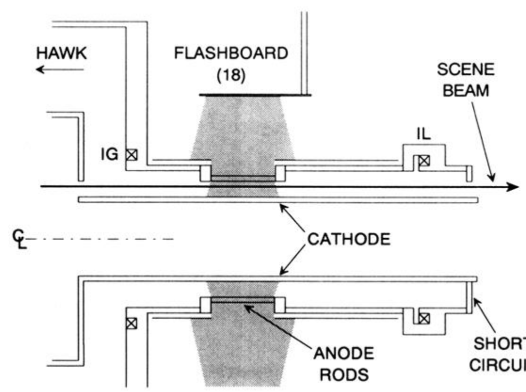

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