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Anode Plasma Dynamics in an Extraction Applied-B Ion Diode: Effects on Divergence, Ion Species and Parasitic Load*.

J. B. Greenly, R. K. Appartaim, J. C. Olson

Laboratory of Plasma Studies, Cornell University, Ithaca, N.Y. 14853 USA

Analysis of data from the LION (1.2MV, 300kA, 40ns) extraction applied-B diode [1] allows a number of inferences regarding the effects of anode plasma dynamics on ion beam divergence, ion species composition, and diode impedance and power coupling. In-gap emission spectroscopy and beam diagnostics [1] have been used to investigate the mechanisms which determine anode plasma dynamics and its effects on diode performance. The two dominant features of anode plasma dynamics observed on LION are (1) expansion away from the solid anode surface and into the accelerating gap during the beam pulse, and (2) evolution of the composition of the plasma during the pulse, with a strong increase of both neutrals and high charge states of heavier ion species during the latter part of the pulse. A previous paper [1] has presented the data that support conclusion (2). In this paper, we present data characterizing the plasma expansion, and suggest a possible picture of the mechanism of the plasma dynamics that could produce these basic features.

Figure 1 shows anode plasma spatial extent as a function of time for typical LION diode regimes, as derived from streak photography of anode plasma light, and diode impedance evolution with time. The model used to relate diode impedance to the effective anode location on the gap is that of Desjarlais [2], assuming that the effective anode surface where the electric field vanishes (space-charge limited emission) is the "edge" of the anode plasma, and that magnetic flux fully penetrates the plasma. A set of diode current-voltage characteristics for LION derived from this model are shown in Figure 2.

The assumption of flux penetration is central to the arguments to follow. The diode characteristic is strongly modified, especially at high ion current density enhancement, and strong heating of the plasma may occur. Flux penetration would occur under a number of scenarios: if the plasma edge moves across the field by motion of neutral particles with subsequent ionization as has often been proposed, or if the effective resistivity is high enough for the rising magnetic field due to compression of the insulating flux toward the anode by the diamagnetic cathode electron flow to penetrate. The necessary resistivity may be supplied by neutral collisions, or by anomalous processes such as fast EMHD penetration. Krall [3] has considered lower hybrid drift turbulence as a dissipation mechanism, and there may be others. Whatever the mechanism, if rising field penetrates on a time scale of a fraction of the diode current risetime, a substantial amount of energy would be dissipatied in the plasma. For parameters typical in a LION pulse, penetration of a 1T field on a 10 ns timescale results in $>10^8$ W dissipated in the plasma. Radiation and conductive and convective loss to the anode surface would absorb most of this power, heating the solid surface. Furthermore, during penetration there will be a magnetic field gradient in the plasma and hence a force on the plasma which will tend to compress it toward the anode during the current rise. On the other hand, if penetration is nearly instantaneous, almost no force and no heating would occur. Thus a measurement of the magnetic field in the anode plasma would be a very valuable input into understanding the dynamics of the plasma and its possible influence on diode performance.

In Fig.1, we see that the anode motion inferred from the model assuming penetration tracks with but exceeds the motion inferred from plasma light. This is not surprising, since the latter is certainly only a lower limit: if the effective anode occurs at a plasma density which has luminosity below the threshold of streak sensitivity, the streak data will underestimate the plasma thickness. The velocity of compression of flux surfaces toward the anode during current rise is ~10cm/μs, so if the field was strongly excluded by the plasma, it would be very difficult to explain the plasma expansion during the current rise, yet the impedance model would require even greater expansion if flux was excluded. Thus the similar expansion inferred from both model and streak data gives some degree of confidence that the magnetic field does penetrate the plasma on a time scale shorter than the current risetime. Unfortunately, these considerations do not give enough information to estimate the actual penetration rate or consequent force or power dissipation on the plasma.

Figure 1 shows a characteristic evolution of the plasma thickness that was universally observed on LION. The plasma expands rapidly, at >5cm/μs for the first ~10-20ns of the beam pulse. Expansion then slows or even stagnates for ~20 ns through the main current rise to peak beam power. Then, as the diode voltage and current decline, rapid expansion resumes, at a rate that can approach 10cm/μs in highest current shots with strong parasitic load. This resumption of expansion is coincident with the increase of strong neutral emission lines in the plasma, as well as lines of high charge states of ions such as carbon and oxygen [1]. In the remainder of this paper, we outline a model of, or more properly a set of questions about, the anode plasma dynamics which may explain these observations, and briefly indicate some implications of this model for overall diode performance. To summarize the observations to be explained, the LION data have shown:

1) Initial fast expansion of the anode plasma.

2) early high energy (cathode) electron loss, which peaks during the interval of fastest current rise, then nearly disappears after peak power. The electron loss is nearly the same in parasitic and nonparasitic regimes.

3) a stagnation of plasma expansion during fastest current rise to peak power.

4) rapid plasma expansion as current falls to the end of the pulse, somewhat faster in strong parasitic load regime.

5) during current fall, rapid increases in neutrals and high ion charge states within 0.5mm (diagnostic resolution) of the plasma edge, but not beyond into the gap.

The proposed model contains the following elements:

1) The initial fast expansion of the plasma is an outstanding question. The initial sources of plasma may be cathode loss electron-induced desorption, dielectric breakdown due to charge deposition, surface flashover driven by the applied electric field, etc. Whatever the source, the rapid expansion requires a strong heating of the vaporized anode material to a velocity of 5 cm/μs, requiring >10eV energy for at least some component of this material. This heating may be due to a combination of previously proposed mechanisms, e.g., by cathode electron bombardment, instability of diamagnetic surface current flow in the plasma[2], or dissipation due to conduction of the ion beam current back to the surface through the plasma. However, it appears difficult to reach the necessary velocity by thermal means. One simple alternative which has not been considered is suggested if one assumes that the initial efflux of plasma from the surface is very weakly ionized. When this material extends 1 μm above the solid surface, until the electrons exceed 5x1013/cm3 density and 1eV temperature, the Debye shielding length is longer than the plasma thickness. This means that the gap electric field penetrates this layer. Even if space-charge limited ion flow is already taking place, reducing the field to zero at the solid surface, the voltage drop across this 1μm is >10V. If the neutral density is much larger than the ion density, the substantial rate of charge exchange could produce a fast neutral flux that can move into the gap at the observed velocity. Also, if the layer is very nonuniform, localized "blobs" of plasma with ions accelerated in this way could move across the magnetic field by polarization drift. In either case, the acceleration that causes plasma expansion would come not from heating, but from electrostatic force on the plasma ions.

2) After the initial fast expansion phase, the plasma does exclude the electric field except in a thin sheath, but neutrals can still be transported from the solid surface through the anode plasma and then ionized at or beyond the effective anode surface in a fraction of the pulse length. Collisional equilibration time of neutrals with plasma ions (including elastic collisions and charge exchange) is short compared to ionization time by the low energy

plasma electrons, and neutrals can acquire the necessary velocity to traverse the ~mm thickness of the plasma in times shorter than the pulse length.

3) The key element of this model is that there exists an avalanching ionization mechanism just outside the plasma edge, driven by trapped electrons originating from neutrals ionized as they pass through the edge. When an ionization occurs in the gap near the edge, the resulting ion is extracted in the beam, and the electron is accelerated toward the anode. Electrons originating in this way are well trapped in the electric and magnetic fields of the gap and the magnetic field in the plasma, in orbits which remain in the neighborhood of the plasma edge. The energy of these electrons depends on their point of origin: the further out in the gap, the higher the energy. For example, with 1kA/cm2 at 1MV, the average energy of electrons born in the first 0.1mm away from the plasma edge (assuming that the space charge of these electrons does not strongly perturb the gap electric field) is about 1.4 keV, and the distribution ranges up to 15keV. The CV lines observed in LION late in the pulse confirm the presence of a substantial population of at least 300eV electrons. This population has much larger cross section for ionization of neutrals and ions than the MeV cathode electrons, and an ionization avalanche can result, limited by the rate of loss of these electrons to the anode. Welch [4] has carried out simulations that show this avalanching.

To understand the dynamics of these electrons, a fundamental condition in the diode must be recognized. The amount of charge extracted in the beam (~1014 electron charge/cm2 in 30ns) is much larger than the amount of net polarization charge (~1012/cm2, positive near the anode, or negative near the cathode) which produces the electric field in the gap. Thus in a time of <1ns, if a significant fraction of the ion current were being supplied by particles ionized in this avalanche, enough electrons would be left in the trapped layer to neutralize the entire positive anode charge layer. This cannot happen, or the electric field would collapse in the gap. Thus these electrons must be lost rapidly, with sub-ns lifetime. This loss could be driven by collisions with plasma ions and neutrals, but collisions are unlikely to be fast enough to detrap >100eV electrons in <1ns. Field fluctuations due to either instability or static spatial nonuniformity could detrap these electrons. Even with a short electron trapping time, the net positive space charge layer at the plasma edge would be partially neutalized, which would enhance ion current density. The electron detrapping fluctuations would have further consequences, including enhancement of ion divergence. The LION data indicating suppression of cathode electron loss late in the pulse places some upper limit on the magnitude of these fluctuations, since it appears that these very high-energy electrons remain well trapped in the gap.

4) The stagnation of plasma motion near peak power could be due to a near balance between the expansion mechanisms and the combination of magnetic compression of the plasma and erosion by ion extraction.

In summary,the basic mechanism of anode plasma expansion which appears consistent with all the LION data is production of particles, mostly neutrals, at the solid surface, which collisionally acquire high enough velocity to arrive at the plasma edge, and which then ionize by avalanche driven by the trapped electrons produced by ionization, resulting in the production of plasma beyond the edge, and the propagation of that edge into the gap.Thus rapid plasma expansion and the simultaneous appearance of lines of both neutrals and highly ionized states could all be consistent.

One of the many open questions related to this scenario is why some diodes exhibit complete impedance collapse at the end of the pulse, and others such as the LION diode do not. Impedance model analysis similar to that for LION, carried out with data from several diodes including the small SABRE diode on GAMBLE II[5] which all tend to collapse to zero voltage and large current at the end of the pulse, all indicate that the diode operating point at peak power falls to the right of the peak of the diode characteristic with finite plasma thickness. Such a point for G(amble)II is indicated on Figure 2. This case is chosen because the diode voltage at peak power, gap and magnetic field were all nearly identical to the LION parameters, while the diode area was half that of LION, so the GII point can be plotted on this figure (with doubled current). It is remarkable that the points for LION and GII lie on nearly the same characteristic, with a plasma thickness of about 0.15 of the gap, or 1mm, at about the same time in the pulses, but GII produced four times the current density of LION. Within the Desjarlais model [2], this is a simple consequence of finding the intersection of this diode characteristic with the generator load line. The fact that GII then evolves to zero impedance while LION remains nearly constant to the pulse end must be a consequence of plasma dynamics, and the model would suggest that one important factor may dominate. The GII point corresponds to much stronger diamagnetic field compression than LION. For these points, the model gives 25% of the gap magnetic flux within the anode plasma for LION, but 45% for GII. In both cases, the anode plasma expands rapidly after peak power, and the velocity of expansion appears to be similar. However, the larger diamagnetic compression in GII results in 85% of the insulating flux within the anode plasma by the time the plasma thickness has reached 2 mm, and 95% at 2.5 mm near the end of the pulse, whereas in LION the corresponding numbers are 40% at 2mm and 48% at 2.5 mm. A fundamental factor not yet mentioned here is the expansion of the cathode plasma into the gap. On LION this proceeds at about 2-3cm/µs, not enough to collapse the LION gap, but enough at the same velocity after 50 ns to lose the remaining 5% of the flux in GII and short the gap. Thus, assuming the same plasma expansion velocity history for both diodes, by the end of the pulse GII has lost almost all of the insulating flux into the anode plasma and the impedance collapses, while LION maintains insulation.The same plasma expansion histories may result in qualitatively different impedance histories depending upon the degree of ion current density enhancement that can be driven by a pulsed power driver with a particular diode. High enhancements lead naturally to impedance collapse. If penetration of the rising magnetic field into the plasma dissipates substantial energy, the evolution to high enhancement would also drive the ablation of surface material into the plasma and exacerbate impedance collapse and generation of parasitic ions.

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Figure 1

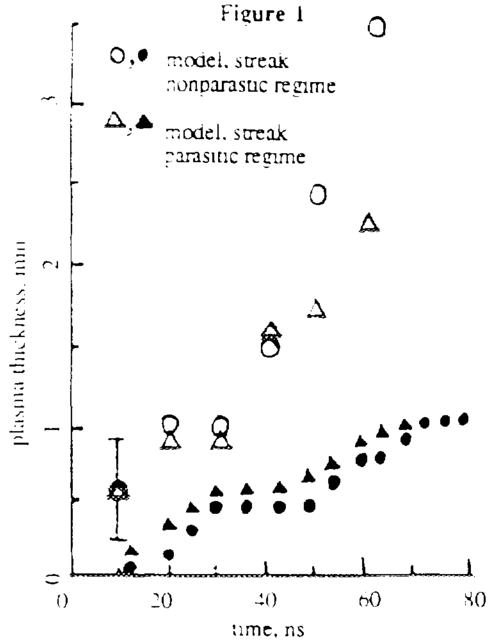
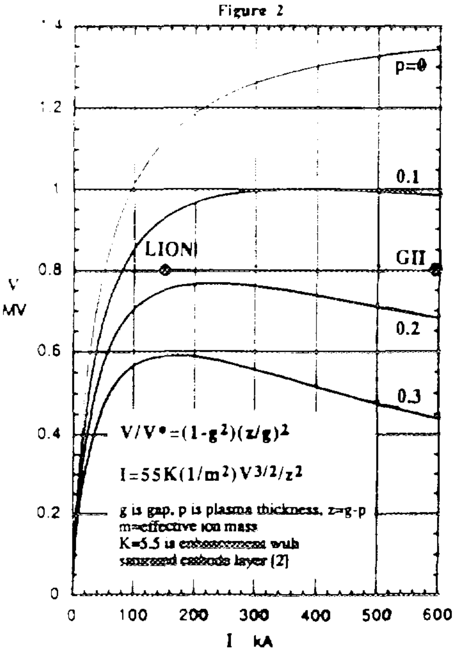


Figure 2



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