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ROLE OF PLASMAS IN THE OPERATION OF A SELF MAGNETICALLY PINCHED DIODE *

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Abstract

The self magnetic pinch (SMP) diode is being developed as an intense electron beam source for high-power x-ray radiography. The diode is comprised of a ~1-cm diameter, hollow cathode with a rounded tip from which a high-current electron beam is emitted. The beam self focuses in its own magnetic field as it propagates across a ~1-cm vacuum gap where it deposits its energy onto a planar high-atomic-number bremsstrahlung target. Heating of the anode by the beam quickly provides an ion emitting plasma and bipolar diode operation. The dynamics of expanding electrode plasmas can affect the impedance lifetime of the diode. Realistic modeling of such plasmas is being pursued to aid in the understanding of the operating characteristics of these diodes as well as establishing scaling relations for reliable extrapolation to higher voltages. Here, a hybrid particle-in-cell code is used to study the evolution of electrode plasmas in the SMP diode for a nominal 6-MV voltage and different anode-cathode gaps. The impact of the intense ion beam on the cathode surface can lead to enhancement of the cathode plasma production and faster diode impedance loss.

I. INTRODUCTION

The self magnetic pinch (SMP) diode[1,2] is being developed as an intense electron beam source for high-power x-ray radiography.[3] The diode is comprised of a ~1-cm diameter, hollow cathode with a rounded tip from which a high-current electron beam is emitted. After exceeding the critical current[2]**Error! Bookmark not defined.** the beam self-focuses in its own magnetic field as it propagates across a ~1-cm vacuum gap where it deposits its energy onto a planar high-atomic-number target producing a bright source of bremsstrahlung radiation. The intense electron bombardment quickly heats the anode producing a plasma of mostly hydrocarbon contaminants and subsequent backstreaming energetic ions which in turn strike the cathode. The evolution and dynamics of expanding electrode plasmas has long been recognized as a limiting factor in the impedance lifetimes of high-power vacuum diodes.

Realistic and accurate modeling of the production and evolution of such plasmas is being pursued to aid in the understanding of the operating characteristics of these diodes as well as establishing scaling relations for reliable extrapolation to higher voltages. In typical pulsed power diodes with large area cathodes, electrode plasma velocities are of order 1--3 cm/μs.[4] For diodes with sub-cm cathode radii, the effective speed associated with the rate of impedance loss can be much larger.[5] Here, we examine the effects of electrode plasma motion in high power SMP diodes. Simulations with the LSP particle-in-cell (PIC) code demonstrate that a rapid acceleration of a low density cathode plasma is possible with intense bipolar flow. This effect can lead to an increase in both ion and electron currents above that of bipolar Child-Langmuir. Energetic anode ions impact the cathode and enhance the rate of cathode plasma production. This feedback is a possible mechanism for rapid impedance loss in the SMP diode.

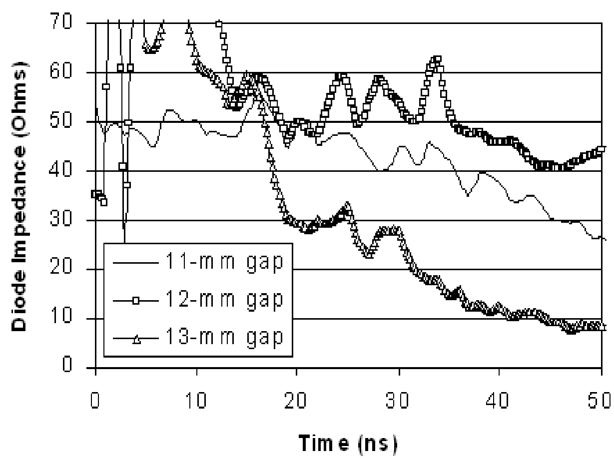

Figure 1. The measured SMP diode impedance on RITS-6 for 11, 12, and 13 mm AK gaps is plotted versus time.

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Here, we examine the SMP diode fielded on the RITS-6 pulsed-power accelerator at Sandia National Laboratories. With a 52 Ohm magnetically insulated transmission line (MITL) feeding the diode, the SMP diode nominally produces 150-kA current with 6-MV voltage. The measured SMP diode impedance is extremely sensitive to changes in the AK gap, *g*, as shown in Fig. 1 which plots time-dependent impedance ($Z_d = V_d / I_d$, where V_d is voltage and I_d is the current in the diode). As seen in the figure, smaller gaps start out with smaller Z_d as expected from Child-Langmuir current scaling $I_{CL} \sim V_d^{3/2}/g^2$, but experience a steady fall. The larger gaps initially have a higher Z_d, but after a short 10-15 ns period, the Z_d rapidly falls. For a 12-mm gap, Z_d remains relatively flat for 40 ns with a slow fall. The range in behavior is found for only a 20% variation in *g*. Understanding this behavior requires accurate modeling of high density electrode plasmas.

In Sec. II, simulations of the RITS-6 geometry with various models for electrode emission of charged species and plasmas are presented with comparison to data. Conclusions are discussed in Sec. III.

II. SIMULATION OF THE SMP DIODE AT NOMINAL 6 MV

To improve understanding of the SMP diode behavior, simulation techniques must be capable of accurately modeling the production and evolution of dense plasma evolving from the tip of an annular cathode and from the anode. The LSP simulation code makes use of a plasma injection technique that minimizes sheath formation at the injection plane via a programmed ionization of an injected neutral gas at the emitting electrode surfaces. The cathode surface cells are first given a 150-kV/cm electric field threshold for space-charge-limited (SCL) emission of electrons. On the anode, surface cells are permitted to emit protons if the surface temperature rise exceeds some threshold. The metal surface (aluminum in these simulations) is heated by cathode electron impact. We assume ΔT = 200 K in these simulations. If the surface cell has exceeded these thresholds, the neutral particles are injected with a given flux and temperature (1 eV) from that cell surface. In our simulations, all H neutrals randomly transition to an e-H+ pair within 2 cells (0.006 cm) of the surface. If dense ionized plasma is injected directly, a strong nonphysical sheath will form between the electrode and the plasma. The plasma flux is an input parameter here, 0.0625 ML/ns, where ML is a monolayer with 10^{15}-cm^{-2} areal density. This flux produces a peak plasma density at the cathode surface of order 3 x 10^{16} cm^{-3}. The plasma is not injected until the cell has exceeded the surface electric field (or temperature rise on the anode) threshold for SCL emission. Additionally, LSP has the option of injecting additional material in proportion to the flux of impacting high energy ions from the anode. In this case, plasma is injected with weight $w_p = w_{imp}\gamma_p$ where w_{imp} and γ_p are the impacting ion weight and stimulated plasma yield, respectively. We also assume an initial number of surface monolayers N_{ML} of 20 in all simulations; once deplete plasma formation ceases.

A. Simulations of bipolar SMP diode operation

We first examine the SMP operation with purely bipolar flow of electrons and protons from the surfaces shown in Fig. 2. The AK gap, g, is varied from 9 to 15 mm. SMP operation on RITS-6 typically shows the diode impedance holds up reasonably well in the 12--13-mm gap range but falls rapidly outside this range. The simulation results are not as dramatic with purely bipolar flow. As *g* increases, the diode impedance increases from 41--57 Ω with total current decreasing from 140--117 kA. The ion current increases linearly with 1/*g* carrying roughly 10% of the total current. There is little in these electrical signals to indicate impedance cliff edges in *g* as observed in experiment.

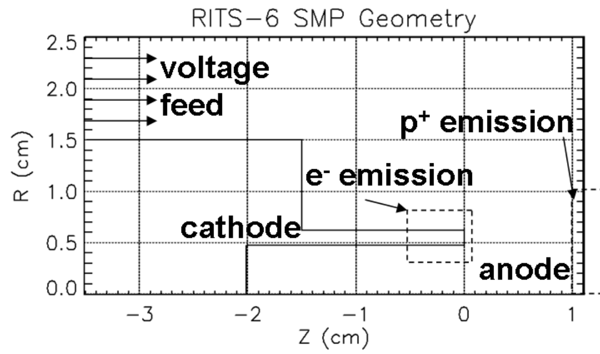

Figure 2. The LSP simulation geometry for the SMP diode simulations is shown. An incoming wave is injected at the upper left. Regions of SCL emission of electrons from the cathode and protons from the anode are outlined. In plasma simulations, plasma is also injected from these regions.

The position at which the ions strike the cathode can be important however. We know that an energetic proton can have a stimulated yield of >> 100 for both neutrals and electrons. This potentially increases the plasma production on the cathode allowing excess material to flood the gap. We see in Fig. 3 the proton density 20 ns into the simulations with *g* = 9, 11, 13 and 15 mm. The radial extent of proton emission increases with *g*. Protons in the 9-mm gap case do not pinch quickly enough to avoid significant impact of the cathode. The intermediate gaps minimize proton deposition on the cathode face. The 15-mm gap case shows protons striking the cathode face that originate from the anode center where the electron beam has pinched. These ions are accelerated within roughly an 18 degree angle for all gaps. Thus, energetic protons strike deeper inside the cathode hole for smaller gaps. Bipolar simulations at *g* = 11 mm with other ion species (C+--C4+) show that larger mass-to-charge ratio ions will strike the cathode face from a smaller radius. The dependence is fairly weak, but an increasingly higher temperature for ion turn-on at the anode is required to avoid cathode face impact with heavier ions.

We have thus identified a possible mechanism that could explain the reason why the SMP cathode must be annular as well as the narrow window of AK gaps that operate reliably. Ion impact on the cathode face could cause enhanced flow of plasma across the gap by providing a greater and more energetic supply of plasma. Anode pre-heating to clean adsorbed contaminants might offer a greater range of operation for the SMP AK gap particularly at small *g*.

B. SMP simulations including electrode plasma

We test the ion impact theory with a series of LSP simulations with plasma injection coupled to proton impact. The stimulated yield of neutrals from the impact of a multi-MeV ion can be high, $\gamma_0 >> 1000$, with yield γ_0 scaling with the electronic stopping power. Using the stopping power scaling from 1-MeV K+ ion measurements on clean stainless steel, we can expect 6-MeV proton stimulated neutral gas yields in excess of 100.[6] Carbon ions at 6-MeV energy will have even higher yields. A similar scaling from measurements of proton stimulated electron yield $\gamma_e = 148$ at 28 MeV to 6 MeV gives γ_e=690[7] half with energies above 20 eV---sufficient to ionize most gases. Thus, with both direct ionization by protons and secondary electron ionization, a good percentage of the desorbed gas will be quickly ionized. In these simulations, we attempt to model this stimulated emission by assuming a "plasma yield" γ_p = 100-1000 ion/electron pairs per anode proton impact in the region near the cathode tip (within 5 mm including the inner edge).

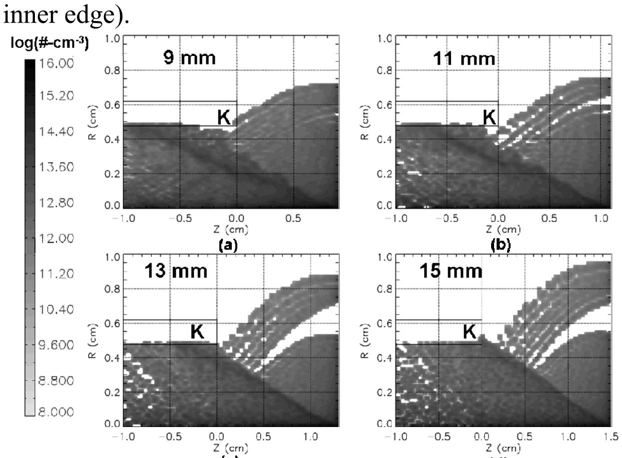

Figure 3. The proton densities are plotted for the (a) 9-mm, (b) 11-mm, (c) 13-mm and (d) 15-mm AK gap simulations after 20 ns for the bipolar flow simulations.

We examine a case that we expect to have rapidly decreasing impedance (9-mm AK gap). In these simulations, we assume a constant plasma injection rate of 0.0625 ML/ns. We again use the 200 K ion emission threshold. With γ_p =1000, the stimulated plasma rapidly results in an impedance collapse (2 Ω/ns). The simulation with γ_p = 100 shows a much more modest initial impedance loss of roughly 0.25 Ω/ns although this rate increases in time. Typically this impedance loss is accompanied by a larger percentage of the diode current carried by anode ions. The ion current increased to 30% of the total in the γ_p = 1000 simulation. The ion current in the γ_p = 100 simulation is roughly half that by 20 ns but increasing. This trend will further reduce the dose with less electron current striking the converter at an already reduced voltage. The simulation with the larger yield exhibits two strong plasma plumes that jet from the K face and inner surfaces. The γ_p = 100 simulation shows a less obvious plasma motion with an only slightly declining impedance of roughly 48 Ω up to 20 ns although the impedance loss accelerates at later times.

As the AK gap increases, fewer protons strike the cathode face. For γ_p = 100, impedance histories are compared from simulations with 9, 11 and 15-mm AK gaps in Fig. 4. As expected for larger gaps, because the flux of anode protons striking the K face is relatively small in the first 25 ns, the impact of the stimulated plasma was small for the *g* = 11 mm and 15 mm with little loss of impedance. This contrasts with the 9-mm AK gap result which had impedance falling to 37 Ω by 25 ns. The ion current was significantly less with the larger AK gap as well.

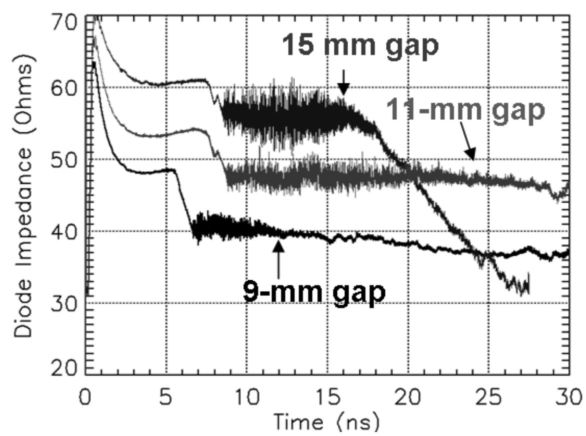

Figure 4. The Z_d for the 9, 11 and 15 mm gap simulations including plasma injection are plotted. The plasma injection included a .0625 ML/ns constant flux plus a stimulated plasma yield from proton impact of 100.

Due to the evolution of plasma, the anode protons in the 11-mm simulation eventually begin striking the cathode face after 25 ns. This case was run out just past 30 ns where the impedance begins to fall at a faster rate due to the increased influx of plasma. Beyond 31 ns, the simulation accuracy degraded due to beam pinching and subsequent under-resolution of the electron cyclotron frequency ω_{ce}. The impedance history in the 11-mm simulation compares very closely with that of the experiment in Fig.1. In the *g* = 15 mm simulation, the Z_d

start out the highest, but soon after the plasma production is enhanced by proton impact, Z_d essentially collapses as observed in experiment for g = 13 mm. Thus, proton impact on the front face of the cathode given a sufficient yield of plasma can lead to an increasingly more rapid loss of diode impedance.

As seen in Fig. 5, the simulations also show that as Z_d falls, the fraction of current being carried by the ions increases to 16% compared with 10% with purely bipolar flow. The reason for the larger ion flow is that the plasma brings the cathode potential closer to the anode surface near the axis than calculated in the bipolar flow simulation. This movement enhances the ion current drawn from the small radius beam spot. During this rapid movement in which the effective gap is reduced to order 1 mm (roughly 3 mm in the bipolar flow simulation), the diode impedance changes only 10-40% because the surface area of ion and electron emission has decreased as well.

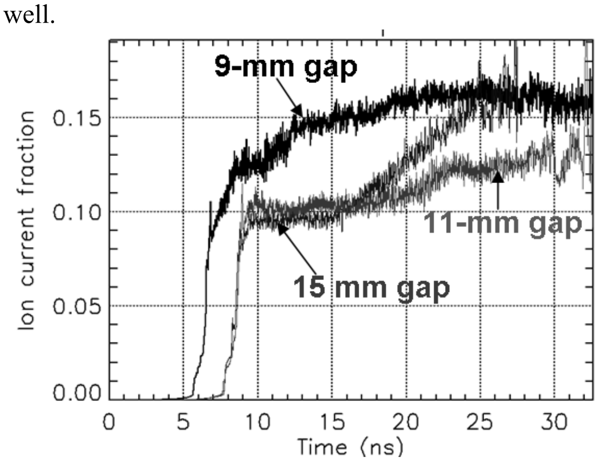

Figure 5. The fraction of current in protons for the 9, 11 and 15 mm gap simulations including plasma injection with γ_p = 100 is plotted.

III. SUMMARY

We have examined the role of bipolar flow and plasma evolving off electrode surfaces. The SMP diode exhibits a narrow window of stable AK gap operation. The anode quickly becomes a source of ions as its temperature rises due to electron bombardment. LSP simulations with a temperature threshold for proton emission at the anode show that these anode protons strike the front face of the annular RITS-6 cathode for AK gaps < 11 mm and > 13 mm roughly consistent with the window of stable experimental operation. In the case of smaller AK gap, the proton emitted at larger radius strike the cathode face. This radius is sensitive to threshold temperature with larger radii turning on with smaller temperature threshold. These protons could be eliminated by heating the anode white hot to remove most weakly bound surface material. LSP also calculates that protons emitted near the axis for larger AK gaps will strike the cathode face. It is not obvious how to affect their trajectories since these protons basically follow the electron beam space charge backwards. For intermediate AK gaps, essentially all protons end up inside the cathode annulus striking the inner surface.

Permitting a feedback of proton impact to plasma injection flux does show a strong dependence of impedance behavior on AK gap length. In simulations with a large plasma yield from proton impact of 1000, an LSP simulation with 9-mm AK gap which allows proton strikes on the K face resulted in a rapid loss in impedance due to plasma crossing the gap from that region. The ion current fraction increased to 30 % due to this plasma that when coupled with the voltage drop would compound the loss in bremsstrahlung production at the target. Plasma emerging from with the cathode hole doesn't provide such a rapid impedance loss. An 11-mm simulation was in good agreement with the impedance behavior of a comparable RITS-6 shot. The impedance in both simulation and experiment showed a stable 20 ns window with a more rapid fall beyond 25 ns. In the simulations, the fall was the result of a slow increase in proton flux on the cathode face and increased plasma injection.

These coupled simulations offer some explanation for the narrow AK gap operational window observed for SMP diodes as well as possible remedies. Cathode geometries can be designed to limit proton impact by increasing the radius or making them more annular. Boiling off contaminants on the anode with vigorous heating could also limit the proton strike particularly for smaller AK gaps.

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