Implicit Collisional Three-Fluid Simulation of the Plasma Erosion Opening Switch

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Abstract—The plasma erosion opening switch (PEOS) has been studied with the aid of the ANTHEM implicit simulation code. This switch consists of fill plasma injected into a transmission line. The plasma is ultimately removed by self-electrical forces, permitting energy delivery to a load. Here, ANTHEM treats the ions and electrons of the fill plasma and the electrons emitted from the transmission-line cathode as three distinct Eulerian fluids—with electron inertia retained. This permits analysis of charge separation effects, and avoids the singularities that plague conventional MHD codes at low density. E and B fields are computed by the implicit moment method, allowing for time steps well in excess of the electron plasma period $\Delta t \gg \omega_p^{-1}$, and cells much wider than a Debye length, $\Delta x \gg \lambda_D$. Switch dynamics are modeled as a function of the driving electrical pulse characteristics, the fill plasma parameters, and the emission properties of the transmission line walls—for both collisionless and anomalously collisional electrons. Our low-fill-density ($n_e \leq 4 \times 10^{12}$ electrons/cm³) collisionless calculations are in accord with earlier particle code results. Our high-density computations ($n_e \geq 2 \times 10^{13}$ electrons/cm³) show the opening of the switch proceeding through both ion erosion and magnetic pressure effects. The addition of anomalous electron collisions is found to diffuse the driving B field into the fill plasma, producing broad current channels and reduced magnetic pressure effects, in some agreement with NRL experimental measurements.

I. INTRODUCTION

INDUCTIVE energy storage devices for pulse power can be significantly smaller and more economical than corresponding capacitive components. Opening switches allow for the inductive storage of energy in magnetic fields. Currents can then be switched from flow through the switch plasma to flow through a load. The plasma erosion opening switch (PEOS) was first introduced as a prepulse suppressor [1] on the transmission lines feeding diodes. More recently, it has been used for power-flow smoothing, high-energy switching, and power multiplication [2], [3]. The optimized use of plasma opening switches may determine the success of Sandia Laboratories' PBFA II light ion driver [4].

Earlier studies have presented a general theoretical model for the workings of the PEOS [5], and have given results from particle-in-cell (PIC) modeling [6], [7] for low-density plasma fill ($n_e \leq 4 \times 10^{12}$ electrons/cm³).

Also, the inclusion of anomalous collisions has been shown to have a significant effect on PIC simulation results [8]. Recently, the three-fluid ANTHEM code has been used to study switches at the higher electron densities ($n_e \sim 2 \times 10^{13}$), characteristic of recent PBFA II experiments [9]. Here, we present these high-density results in some detail, and describe new ANTHEM results from the inclusion of anomalous electron collisionality.

In Section II of this paper we describe two generic plasma opening switches and relate them to the units presently in use on PBFA II. Section III then outlines features of our implicit 2-D code. Section IV collects and discusses the results of simulation runs, in which we have varied the switch and drive pulse parameters and explored the effects of anomalous electron collisionality. Our observations are summarized in Section V.

II. GENERIC PLASMA OPENING SWITCHES

Fig. 1 provides a schematic of an idealized switch for PBFA II. Power is introduced at the generator "G," as electrons first flow along the cathode, pass up through the fill plasma, and return along the anode to the generator. This electron flow produces a B field directed into the page, and an inductive E field down toward the cathode. Prior to the arrival of the electromagnetic pulse, fill plasma is injected from guns through numerous holes in the anode. Plasma is injected, increasing the fill density, until a time when, from past experience, it is anticipated that the switch performance will be acceptable. At this point the driving B_z field is introduced. As it permeates the plasma, the internal electron flow is altered by a variety of processes until eventually the switch "opens" and this flow is diverted to the load "L."

The actual PBFA II switch is conical in form [10]. The fill-jet width is typically 6 cm at the anode where it enters, flaring to a greater width—characteristically 14 cm—at the cathode, where it is absorbed. The plasma density must drop off smoothly at the jet edges, left and right. However, we simplify the modeled situation and assume a homogeneous basically rectangular fill plasma measuring 8.5 cm from the cathode (y direction) and 14.0 cm in axial length (x direction). We simulate the arrival of power near the switch, by introducing B field at the left boundary of our test region at $t = 0$, and increasing it linearly over a 45-ns run-up time until the current I reaches a peak value of 3 MA. In PBFA II $B(r, t)[T] = 20I(t)[MA]/r[cm]$, which corresponds to a peak field

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Fig. 1. Idealized PBFA II PEOS. Power enters from the generator G , is shorted through the plasma until opening, and then passes to the load L .

of 3 T [30 kG] at the $r = 20$ cm cathode position. The ANTHEM mesh is presently Cartesian, so we set $B(x = 0, y, t) = B(r = 20, t)$. A 5-eV carbon C^{++} plasma has been assumed, along with a short-circuit load and perfectly conducting electrodes. We have further assumed that space-charge-limited emission of 5-eV electrons occurs along the electrodes originally in contact with the fill plasma.

The earlier simulations [6], [7] were more appropriate to the NRL Gamble I pulse power facility. For these, the fill plasma was typically 6 cm axially (x direction), and 1–2.5 cm in height from cathode to anode (y direction). The cathode radius was taken as 2.5 cm, the peak current was 0.1 MA, and the B field rose to a maximum value of 0.8 T. A shorter 5-ns run-up time was used to hasten the opening process for computational economy. Although most of our runs have examined the PBFA II switch, some results from simulations of the smaller switch will be mentioned here for comparative purposes.

III. THE COMPUTATIONAL MODEL

ANTHEM is an implicit 2-D plasma simulation code, based on a fixed Eulerian mesh. Its treatment of electron collisions is outlined in [11]. It calculates electromagnetic fields by the implicit moment method [12]–[15]. It follows the motion of either PIC simulation particles or multiple fluids across the mesh. For the present switch calculations, the code was configured to treat the fill-plasma ions, the fill-plasma electrons, and the cathode-emitted electrons as three distinct fluids. Anode-emitted electrons were added to the fill-plasma electron fluid. Electron inertia is retained, and the electron velocities are obtained from updates of the momentum equations for the electron components. We can, therefore, study charge separation effects that would be suppressed with more traditional single-fluid MHD modeling. The time step for calculations can be much larger than the electron plasma period ω_p^{-1} usually required with explicit fluid (or particle) advancement, because the E fields are computed implicitly [13].

Explicit PIC codes are subject to finite grid instability, which arises due to numerical aliasing of the particle information to the grid [13]. For an initially cold plasma with cells many Debye lengths across, this instability acts

in a few cycles to heat the background until the new Debye length equals the cell size. Thus, it was necessary to start the earlier PIC switch simulations [6], [7] at unrealistically high, kilovolt temperatures, rather than the 5-eV values actually characterizing switches. In ANTHEM, when particles are used to model the electrons, this instability is largely suppressed through use of the implicit fields [13]. Alternatively, when the electrons are treated as *fluids*, as in the present simulations, the instability is totally absent, and the background temperature can remain at the initial 5-eV value, until the plasma is compressed or collisionally heated.

The code computes a single B_z magnetic field component (into the page in Fig. 1) along with E_x and E_y electric field components. In accordance with the implicit moment method [11], [12], a set of auxiliary momentum equations is combined with Maxwell's equations to produce a single elliptic equation for a predicted B_z field. This is solved efficiently with a Chebyshev package requiring about 0.03 s/solve for our switch calculations. Given B_z , the momentum equations and Ampere's law yield predicted values for E_x and E_y . The true fluids are advanced through these predicted fields, and source corrections are obtained by comparison between the predicted sources and those actually achieved. These corrections are used subsequently to bring the true fields, and the predicted fields into accord [11], [12], [16], [17].

Given the advanced E and B fields, the plasma hydrodynamics is updated in two phases. In the first (Lagrangian) phase, the u_x and u_y velocities for each fluid are coupled by B_z , each electron velocity field is collisionally coupled to the ions [11], and all the velocities are modified in the advanced E fields and static pressure gradients. The cell walls are moved, and new component cell densities and temperatures are calculated. In the second (Eulerian) phase, the cell walls are slipped back to their original positions, successively for each fluid, and the fluid density, velocities, and temperature are advected across the walls by a spatially second-order Van Leer algorithm [12], [18], [19]. The update is completed with separate Joule heating and flux-limited thermal conduction calculations for both the emission electron, and the background electron components.

Relativistic effects were approximated by use of a velocity-dependent mass in the electron momentum equations, i.e., $m(v) = \gamma m_e$, $\gamma(v) = (1 - v^2/c^2)^{-1/2}$ with m_e the electron rest mass, and by the assumption $\partial\gamma/\partial t \approx 0$, along with a classical treatment of the electron temperatures, which generally remained below 60 keV. This bounds the maximum speed of electrons accelerated across the A–K gap by the speed of light, and it properly expands the gyroradii of relativistic electrons. But otherwise, this approximation is crude. A better relativistic fluid model is given in [20]. Similarly, one might expect that directed electron motion will be in some locations thermalized [21] by the gyromotion in B_z , thus requiring modeling through more complex pressure tensor than the scalar choice of our present fluid model [12]. For a more precise treatment

of both relativistic and pressure effects, we plan, in a future study, to advance relativistic particles, rather than the fluids, in our implicit fields.

The E fields, currents, and velocities were stored on the cell wall midpoints, the B_z elements were associated with the wall intersection points, and the densities, temperatures, and static pressures were retained at the cell centers. A 50×50 mesh was employed with dimensions $\Delta y = 0.17$ cm and $\Delta x = 0.55$ cm for the PBFA II modeling. The time steps were variable and with an upper limit set by a Courant condition determined from the fastest (hot-test) electrons. Thus, the initial Δt with 5-eV background electrons could be 300 times larger than at late times, when $\Delta t \leq \Delta y/c$, where c is the speed of light. The computational mesh is surrounded by ghost cells which overlay the conductors, which were assumed to be perfect. Inside the conductors the surface-parallel E field should be zero, so we set $E_x = 0$ in the ghost cells containing the cathode and anode. Normal to the electrode surfaces we set the emitted electron current to zero in Ampere's law until an extracting E -field threshold (either $E_y = 0$ or $|E_y| = 300$ keV/cm) is exceeded. Once emission is started at a given position x , it is continued, even if the field subsequently drops below the threshold. Thereafter, we provide enough electron emission current to drive the advanced, time level- $(m + 1)$, E_y to zero. Thus, once emission is started, the total current normal to the electrodes is $J_y^{(m+1)} = (1/4\pi)(E_y^{(m)}/\Delta t - c(\partial B_z^{(m+1)}/\partial x))$. Here, $E_y^{(m)}$ is the old E field following the current corrections [12] of the implicit moment method. Through Faraday's law this E -field rule provides the boundary conditions needed to solve the elliptic equation for B_z , leading to the complete advanced-field solution. The electron emission is then taken as $J_{ye} = J_y - J_{yeb} - J_{yi}$, with J_{yeb} and J_{yi} any background electron and ion current into the electrodes. This electron emission current is used as a source in the subsequent fluid update of each cycle.

IV. SIMULATION RESULTS

In the first application of ANTHEM to plasma opening switches [22] the wall-emission of electrons from the cathode was neglected. Low-density switching appropriate to NRL's Gamble I machine was examined. The initial fill density was 4×10^{12} electrons/cm³ for a C⁺⁺ plasma injected from the anode at 1.8×10^8 cm/s. At the anode, the boundary conditions were fully transmitting for this earlier study; i.e., all y derivatives on the fields were taken as zero. Since there was no emission, only two fluids, i.e., one for the ions and one for the electrons, were employed. With the absence of wall emission, the switch was calculated to open in *half* the time determined by earlier PIC calculations [7]. The principal and most interesting behavior was the development of shielding currents around the fill plasma. These appeared first on the generator side of the fill, then along the plasma bordering the cathode as the fill plasma was drawn away from this electrode, by the rising E and B fields. Eventually, the currents appeared along the load side of the fill

as switch "opening" began with B field advancing into the load region and current first passing through the load. For reference, in Fig. 2 we reproduce the evolving current vector fields and B_z contours from this earlier study.

Subsequently, while developing our emission algorithm, we performed a test in which all the background fill plasma was removed, except for a very high density quasi-neutral plasma region or reservoir (at 5×10^{14} electrons/cm³) in the three cells immediately adjacent to the bottom of the simulation area. This was provided to see if we could simulate cathode emission in an external E field without recourse to special boundary conditions. The implicit moment field treatment, the fluids, and the averaging procedures described in [12] permitted the introduction of the local high-density steep-gradient region that would be disallowed with conventional PIC modeling. A rising B field pulse, typical of Gamble I, was introduced at $t = 0$. This, in turn, created a rising inductive E field which drew electrons out of the dense plasma near the wall, while pushing the ions back toward the wall. By 380 ps the field had reached 0.61 kG at the generator, and produced the output of Fig. 3. We see that the E field has drawn the emitted electrons fully across the switch to the anode. The density of electrons and the electron flux are greater near the generator side of the cathode, because it has been exposed to the fields for a longer interval. The velocity vectors are very nearly vertical, but the electron flux $n_e v_e$ manifests strong elements running along the surface of the dense cathode plasma. The currents associated with this flux act to shield the interior of the dense plasma (just above the conductor) from the rising B_z . (All the plotted vector fields in this paper are self-scaled, with the display of vectors less than 1 percent of the maximum suppressed.) Fig. 3(c) verifies that both E_x and E_y are driven to zero in the dense plasma corresponding to a conductor. E_y rises in a space-charge-limited Child-Langmuir-like fashion beyond the dense plasma "cathode." The original Child-Langmuir analysis [23] was for steady-state emission in the absence of any significant magnetic field, so only approximate agreement can be expected. Fig. 3(e) displays details of the B_z gradients in the emission region. Fig. 3(f) indicates that the maximum emitted electron density is 10^{12} electrons/cm³ at the edge of the reservoir, with the ion density dropping by a 10^2 factor one cell above it. When the reservoir is eliminated (and again there is no background), but emission of our "third" fluid is turned on and our time-advanced $E_y^{(m+1)} = 0$ boundary condition is imposed at $y = 2.5$ cm in corresponding cells, essentially identical results are achieved. Having established this agreement, we proceeded to use the $E_y^{(m+1)} = 0$ boundary condition for all the simulations subsequently reported here.

Next, to check the effects of magnetic insulation, i.e., to see that a large B_z field could properly contain the electron emission, we ran the same problem, but with an initial bias B_z field of 0.5 T in the transmission line (and the $E_y = 0$ boundary condition). The results are collected in Fig. 4. In this case, emission proceeds, but the electrons

Fig. 2. Gamble I switch dynamics (for a 5-ns B_z linear rise from 0 to 0.8 T) in the absence of cathode emission and with a fully transmitting anode ($\partial E_x / \partial y = 0$). (a)–(d) B_z penetration history. (e)–(h) Evolving flux vectors $n_e v_e$. Times: (a), (e)—0.32 ns; (b), (f)—0.92 ns; (c), (g)—1.72 ns; (d), (h)—2.73 ns.

Fig. 3. Cathode emission in the absence of background ions. (a) Emitted electron density contours. High-density “wall” plasma simulating the cathode. (b) Electron flux $n_e v_e$. (c) E_y , E_x , and B_z profiles at $x = 3.3$ cm. (d) Corresponding electron velocity field. (e) Advancing B_z contours. (f) Corresponding electron and ion density profiles.

are largely entrained within a gyroradius of the cathode, as can be seen in Fig. 4(a), (b), (d), and (e). The vector flux plots, Fig. 4(b) and (d), display the $\mathbf{E} \times \mathbf{B}$ drift of these electrons. Fig. 4(f) shows that at 0.3 ns the peak density of the electrons at the cathode is about three times higher than when the bias field is absent. Together, Figs. 3 and 4 show that the model produces the anticipated emission in the absence of a bias B field, and that it provides significant magnetic insulation once B_z is sufficiently large.

It is interesting to make a direct comparison with earlier calculations. To accomplish this we modeled the 10^{12} electrons/cm³ simulation of [7]. Fig. 5 collects comparable ANTHEM and MASK [7] code output, showing the electron density at selected times. In each case, plasma was injected in through the anode at -1.8×10^8 cm/s.

The fill plasma had an equivalent 5.0-cm axial length (x direction) in the two studies, but the x axis is contracted in the plotted ANTHEM output. Emitted cathode electrons were added to the cold background fluid in the ANTHEM modeling, and inserted as additional particles in the MASK run. The E_x field was set to zero in the anode and cathode conductors. A zero E_y -field emission threshold was employed. The imposed B field rose to 0.8 T over 5 ns. At 0.4 ns there is a small disturbance of the plasma along the cathode. By 3.0 ns we see, in each case, significant cathode emission and the accumulation of notable plasma injection from the anode. A gap appears along the generator side of the fill plasma between the emitted electrons from the cathode and the injected plasma from the anode. The gap has cut across most of the fill plasma by 4.0 ns. In each computation, by $t = 5.0$ ns, electrons

Fig. 4. Wall emission in the presence of an initial 0.5-T B_z . (a) and (d) Emitted electron density contours at $t = 0.15$ and 0.30 ns. (b) and (e) Corresponding flux vectors showing magnetic insulation locking electrons within a gyroradius of the cathode. (c) B_z along the cathode at 0.2 ns. (f) Electron density profile at $x = 3.3$ cm.

Fig. 5. Comparison of ANTHEM, (a)–(d), and MASK, (e)–(h), calculations. In each case, current is streaming beyond the original fill plasma in a diagonal band toward the anode after 5.0 ns. Times: (a), (e)— 0.4 ns; (b), (f)— 3.0 ns; (c), (g)— 4.0 ns; (d), (h)— 5.0 ns.

are streaming in a diagonal band across the switch to the anode in the load region beyond the fill plasma. Thus, the implicit multifluid modeling has largely reproduced the earlier PIC results.

The explicit PIC calculations manifested finite grid instability which tended to heat the particles to a few

kiloelectronvolts in the time interval between 0.3 and 3.0 ns. No corresponding heating was active in the fluid modeling. Still, the overall results were in accord with the PIC computations. Recent measurements [24] indicate that the PBFA II fill-plasma density is close to 2×10^{13} electrons/ cm^3 . Also, the fill-plasma length at the cathode is currently three times greater for PBFA II. These conditions indicate that with a fixed number of cells, $\Delta x / \lambda_D [\sim (n_e / T_e)^{1/2} \Delta x]$ would be 13 times greater than in the earlier MASK run, suggesting a $(13)^2$ -fold increase in the level of finite grid heating, since $\lambda_D \sim T_e^{1/2}$, in explicit PIC calculations for PBFA II. This would invariably lead to nonphysical predictions. A 13-fold increase in the number of cells used in each direction could hold down the heating, but this remedy would be excessively expensive for any series of scoping runs. Consequently, thus far, explicit high-density PIC calculations have not been made.

Figs. 6 and 7 collect our B -field and flux-vector results from the application of ANTHEM to the idealized PBFA II switch. An injection velocity of -1.6×10^7 cm/s was assumed for this run with plasma loaded initially in the A–K region. Electron emission thresholds of 300 keV/cm were set at the cathode and anode. As the generator current begins to increase, induced electron currents are seen to rise on the generator side of the fill plasma and act to shield out B_z over several skin depths. The field penetrates most quickly along the cathode, but also more rapidly along the anode than in the center of the switch. Electrons for these shielding currents are drawn from near the cathode. Fig. 7 shows that initially (at $t = 14$ ns) they are more readily provided from the fill plasma (at progressively larger x) than from the cathode itself as emission. That is, the total current vector plots are generally little affected by the emission current contributions.

Fig. 6. B -field penetration across the PBFA II switch. (a)–(d) The field profiles at 0.1 and 4.3 cm above the cathode. (e)–(h) Corresponding B contours at $t = 14, 20, 24$, and 28 ns.

Fig. 7. Evolving emission current, background current, and total electron current from 14 to 28 ns. (a)–(d) Emission flux $j_e \equiv n_e v_e$. (e)–(h) Background flux $j_b \equiv n_b v_b$. (i)–(l) Total flux $j_e + j_b$.

As B_z penetrates the fill plasma along the anode, it provides magnetic insulation. This, in turn, moves the return point for electrons entering the anode to ever greater depths (larger x). This insulation of the anode was first described by Waisman *et al.* [6]. In agreement, we find that when the $\mathbf{v} \times \mathbf{B}$ terms are suppressed in ANTHEM, the more pronounced penetration of B_z near the anode ceases, and electrons enter the anode directly. This also occurs if we use a fully transmitting E_x -field boundary condition (i.e., $\partial E_x / \partial y = 0$) at the anode, as for the Fig. 2 runs.

Fig. 6(a)–(d) plots the B_z history along a line just above

the cathode, and along a second line crossing the center of the switch at $y = 4.3$ cm. These 1-D curves can be used to calibrate the accompanying B_z contour plots in Fig. 6(e)–(f). The removal of electrons from the cathode region (for their passage up the generator side of the fill) forms a gap in the electron density. Electrons cannot be supplied by the cathode until the emission threshold E field has been exceeded. This gap grows to the right as B_z enters it. By $t = 20$ ns, B_z in the gap has reached the load side of the plasma, and the switch begins to “open.” By $t = 28$ ns, B_z near the load has climbed to 80 percent of the drive field at the generator, and 80 percent of the drive

Fig. 8. Ion density development from 14 to 28 ns. (a)–(d) The development of an ion density gap near the cathode. (e)–(h) The ion velocity field. (i)–(l) The background electron n_b , emitted electron n_e , and ion charge density Zn_i density profiles along a cut at $y = 13.7$ cm.

current is passing through the load. The 20-ns conduction time is commensurate with some recent PBFA II shots, but low compared to an observed 35-ns conduction time on a recent optimal shot [25] which did, however, open in 7 ns. As the switch opens, the interior of the plasma remains shielded from the applied B field. Accordingly, after B_z appears in the load region, background electron flux runs back down the load side of the fill plasma from the vicinity of the anode to near the cathode as the right arm of a net U-shaped path. This net path is similar to the late-time current measurements by Weber *et al.* [25]. However, the experimentally measured current is distributed deep into the plasma at all times, rather than flowing only on the generator-facing surface as in these AN-THEM simulations. From 20 to 28 ns, the shielded plasma region rises from the cathode, and after 24 ns it also descends from the anode. This plasma expulsion from the electrodes is accompanied by erosion but enhanced by magnetic pressure effects.

Fig. 7 shows that at 14 ns the emitted electron flux is strong at both the generator and at the load side of fill plasma near the cathode where the B_z gradients are largest. At opening time ($t = 20$ ns), the emitted electrons shoot up the load side of the plasma, following a path that takes them to the right of the returning electron flux in the background plasma (that is acting to shield the bulk of the background from B_z). This continues at $t = 24$ ns. By 28 ns, when the switch is largely open, strong magnetic insulation of the emitted electrons is evident, manifesting a snake-like pattern in the emitted flux-vector pattern near

the cathode. The total flux at this time is dominated by a circulating current shielding a small central region of the background plasma from the external B field. Each of the individual flux vector fields displayed is self-scaled. In general, at these high background densities, the emitted flux is small compared to that of the background, as evident from the total flux plots. Thus, while one might expect to see significant mixing of the background and emitted fluids with possible two-stream instability, instead we find the emitted currents simply entrained near the fill-plasma surfaces—front, bottom, and load side. The inductive E fields must exceed 300 keV/cm in this problem to produce emission. Consequently, when emission is finally produced, its density (of order 10^{12}) is small compared to the 2×10^{13} electrons/cm³ background plasma.

The evolving ion motion is described in Fig. 8. The upper frames show that ion gaps develop along with the electron gaps, and that both reach the load side of the plasma by opening time, $t = 20$ ns. The lower set of frames shows that at $t = 20$ ns and $y = 13.7$ cm, density has dropped to 5×10^{12} cm⁻³ in the cathode gap, and 7×10^{12} cm⁻³ near the anode. The middle frames in Fig. 8 detail the ion velocity field. These frames show that the ions are propelled out of the lower gap towards the cathode. To a lesser extent, ions are also expelled from a later-forming ion gap toward the anode. Formation of the ion gaps is consistent with an ion erosion hypothesis [1], [5]. But at late times ($t \geq 24$ ns), density also accumulates in the background plasma adjacent to gaps, and rises to more than twice the initial background value. This is ev-

Fig. 9. (a) Electrostatic potential. (b) Voltage $V(x, y)$ at $t = 26$ ns.

ident from the 1-D density plots, Fig. 8(i)–(l). This second effect is due, as first explained in a diode context by Mendel [27], to the magnetic compression of background plasma by the $\mathbf{j} \times \mathbf{B}$ forces associated with the shielding currents. Both ion erosion and magnetic pressure effects thus characterize the final stages of our calculated collisionless opening process.

In Fig. 9 we present contour plots of both the electrostatic potential ϕ and the voltage V at $t = 26$ ns, when the switch is largely open. The potential serves only as a diagnostic in these calculations. It is found by inverting $\nabla^2 \phi = -\nabla \cdot \mathbf{E}$ with $\phi = 0$ boundary conditions at the conductors. The potential gradients are largest near the cathode where the electron emission is supplied. The voltage was computed from the nonconservative integral $V(x, y) = \int_{20.0}^y E_y(x, y) dy$. The maximum voltage and potential contours displayed are at ± 3.0 MV. The voltage is zero at the shorted load, and zero again just to the right of the expanded fill plasma.

The collisionless electrical characteristics of the switch are collected in Fig. 10. The linearly rising current out of the generator I_G is plotted, along with the load current calculated using B_z at $y = 0.1$ and $x = 17.0$ just beyond the fill plasma. We also plot the anode voltage $\Delta V = -\int_{20.0}^{28.5} E_y dy$ at this x position. The fill plasma still passes 20 percent of the current $I_P (= I_G - I_L)$ after the rapid opening phase.

Many other runs have been performed to characterize the collisionless performance of the PEOS. The results are summarized in Table I. The conduction times τ_{01} (time to the appearance of 20 percent of the drive field at the load) vary from 18 to 49 ns, as n_e goes from 10^{13} cm^{-3} to $2 \times 10^{14} \text{ cm}^{-3}$. τ_{01} was only slightly reduced when the fill-plasma length was reduced from 14 to 6 cm, indicat-

Fig. 10. Current and voltage history for the PBFA II switch. I_G generator current, I_L load current, $I_P = (I_G - I_L)$ plasma current, and $\Delta V = \int_{20.0}^{28.5} E_y dy$, the switch voltage.

TABLE I
PBFA II SWITCH CHARACTERISTICS AS A FUNCTION OF THE FILL-PLASMA DENSITY AND LENGTH (L_x)

Density (electrons/cm ³)	L_x (cm)	τ_{01} (ns)	τ_{02} (ns)
2×10^{14}	14	49	---
6×10^{13}	14	32	42
2×10^{13}	14	20	28
2×10^{13}	6	19	27
1×10^{13}	14	18	24

B_z at the load has reached 10 percent of the drive value by τ_{01} (the conduction time) and 80 percent of the drive value by τ_{02} , for an opening time $\tau_{02} - \tau_{01}$.

ing an opening process keying on the B field (or drive current) magnitude. The opening time $\tau_{02} - \tau_{01}$ was a minimum of 6 ns for our lowest presented fill density, 10^{13} cm^{-3} . No significant changes are observed when the background plasma drift speed is set to zero. At still lower densities of order $10^{12} \text{ electrons/cm}^{-3}$, the earlier PIC results are largely reproduced, as indicated previously.

Weber *et al.* [26] have reported the observation of broad channels of B -field penetration in the PEOS units at NRL. The plasma was 2.5 cm high and 6.0 cm long in these units. B_z decayed in a nearly linear fashion from its generator value to zero over an axially directed distance of 4 cm. (In more recent experiments, the region of linear decay covered 15 cm of a 30-cm plasma [28].) No significant y dependence for B_z was determined aside from the r^{-1} fall-off from the cylindrical geometry of the experiment, i.e., no gaps near the conductors were detected. Some broadening of the current channels may have occurred on the generator side of the fill plasma, due to the bell-shaped drop-off of density and consequent skin-depth thickening that must be expected at the fill-plasma edges. But this would not be sufficient to explain the general effect observed.

No direct data are available to establish the presence of broadened current channels in PBFA II switches. Still, it

Fig. 11. B_z evolution with active anomalous resistivity in the PBFA II switch. (a)–(d) $B_z(x, t)$ at $y = 0.1$ cm and $y = 4.3$ cm indicating a lengthened conduction time. (e)–(h) The total electron flux history. (i)–(l) B_z contours showing field penetration well beyond a skin depth.

appears that some additional mechanism is needed to explain the NRL experimental measurements. We have therefore considered the possibility that some form of anomalous collisionality [29] affects both the NRL and the PBFA II plasma erosion opening switches.

To probe the effects of anomalous collisionality in PBFA II, we have added the additional assumption that the electrons are scattered at the rates $\nu_\alpha = \min[\omega_{pi}(v_\alpha/c_{i.a.}), \omega_p]$, in which ω_{pi} is the ion plasma frequency, v_α is the drift speed of the component α (either background or emitted electrons), and $c_{i.a.} = (\kappa T_e/m_i)^{1/2}$ is the ion acoustic speed. The anomalous scattering was imposed by replacing the classical scattering rates in the momentum equations of [11] with the new anomalous rates. The dissipated kinetic energy was thermalized as effective Joule heating. With cold electron-ion (Buneman), ion acoustic, and lower hybrid instability, the maximum anomalous rate is usually taken [29] to be of order ω_{pi} . We explored the use of a higher limit, since preliminary calculations with a $\nu_\alpha \leq \omega_{pi}$ limit showed little deviation from our collisionless results.

Fig. 11 collects results for our collisional PBFA II switch at 2×10^{13} electrons/cm³ fill density. Clearly, the beginning of opening is delayed to 34 ns; opening is nearly complete after 45 ns. The region of B_z penetration is thickened to a depth of 6 cm at $t = 20$ ns, but penetration is still faster at the electrodes as in the collisionless case. The total flux plots show strong emission at the cathode associated with the sharp B_z gradients there. They also show a broadened current channel crossing the center of

the switch, and pronounced magnetic insulation of the electrons seeking entry to the anode.

In addition, we can report that when our anomalous collision rates are multiplied by an additional factor of 10, the y dependence of the B_z contours is largely eliminated, and B field penetrates in a ramp-like profile from the generator to the load side of the plasma fill after only 11 ns. By $t = 37$ ns, the generator B field is 2.6 T; in the load region B_z is 0.6 T. At $t = 45$ ns (at the generated current maximum) B_z at the load has risen to 1.5 T. The switch is 90-percent open by 53 ns. So the actual opening process is significantly delayed with such high resistivity. The calculated B -field ramps are, however, in good accord with the implications of the measurements of Weber *et al.* [26]. Instabilities that might produce high anomalous rates in PEOS switches are under investigation.

V. CONCLUSION

The implicit 2-D plasma simulation code ANTHEM has been used to examine the dynamics of plasma erosion opening switches for a variety of fill-plasma densities and sizes and for drive pulses typical of the Gamble I and PBFA II light ion accelerators. The implicit nature of the model has permitted its application in physical regimes previously inaccessible due to extreme computational expense. We have found that the low-density collisionless results are characterized by cathode emission and a diagonal flow of the emitted electrons across the transmission line, with magnetic insulation of the electrons at the anode that grows until it cuts off the current. Alternatively,

at PBFA II densities, the collisionless results (with a conventional 300 keV/cm threshold) are principally dominated by electron currents in the original background fill plasma, with the formation of plasma gaps near the cathode and anode due to erosion and magnetic pressure gradients. The electron flow across these gaps is ultimately constrained by magnetic insulation. We have obtained switch-timing agreement with experiment at the high fill densities. But full agreement with broad B -channel data may require the presence of strong anomalous electron collisionality, which requires further justification. New insights should continue to flow from extended collisional studies, and from new modeling using particle electrons. PIC electron modeling should provide a better relativistic treatment for large driving voltages and improved descriptions for plasma regions exhibiting multistreaming, as in the current channels, where finite electron gyromotions may contribute to B -channel broadening.

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REFERENCES

- [1] C. W. Mendel, Jr., and S. A. Goldstein, "A fast-opening switch for use in REB diode experiments," *J. Appl. Phys.*, vol. 48, pp. 1004-1006, 1977.
- [2] K. D. Bergeron and J. P. VanDevender, "Fast opening switch," in *Conf. Rec. Abstracts, 1978 IEEE Int. Conf. Plasma Science* (Monterey, CA), Paper 5D6.
- [3] R. A. Meger, R. J. Comisso, G. Cooperstein, and S. A. Goldstein, "Vacuum inductive store/pulse compression experiments on a high power accelerator using plasma opening switches," *Appl. Phys. Lett.*, vol. 42, pp. 943-945, 1983.
- [4] J. P. VanDevender *et al.*, "Decrease beam divergence in proof-of-principle experiment for the light ion beam fusion facility PBFA II," *Laser Particle Beams*, vol. 3, pp. 93-105, 1985.
- [5] P. F. Ottinger, S. A. Goldstein, and R. A. Meger, "Theoretical modeling of the plasma erosion opening switch for inductive storage applications," *J. Appl. Phys.*, vol. 56, pp. 774-784, 1984.
- [6] E. M. Waisman, P. G. Steen, D. E. Parks, and A. Wilson, "Switching of low density plasmas," *Appl. Phys. Lett.*, vol. 46, pp. 1045-1047, 1985.
- [7] J. M. Grossmann, P. F. Ottinger, J. M. Neri, and A. T. Drobot, "Numerical simulation of a low-density plasma erosion switch," *Phys. Fluids*, vol. 29, pp. 2724-2735, 1986.
- [8] J. M. Grossmann *et al.*, "Particle and fluid simulations of a PEOS," *Bull. Amer. Phys. Soc.*, vol. 31, p. 1444, 1986.
- [9] R. J. Mason and J. M. Wallace, "Implicit simulation of plasma opening switches," *Bull. Amer. Phys. Soc.*, vol. 31, p. 143, 1986.
- [10] R. J. Mason, "Simulated dynamics of plasma erosion opening switches," in *Proc. IEEE Conf. Plasma Sci.* (Washington, DC), 1987, Paper 3C9-10.
- [11] J. P. VanDevender and D. L. Cook, "Inertial confinement fusion with light ion beams," *Science*, vol. 232, pp. 831-836, 1986.
- [12] R. J. Mason and C. W. Cranfill, "Hybrid two-dimensional electron transport in self-consistent electromagnetic fields," *IEEE Trans. Plasma Sci.*, vol. PS-14, pp. 45-52, 1986.
- [13] R. J. Mason, "An electromagnetic field algorithm for 2-D implicit plasma simulation," *J. Comput. Phys.*, vol. 71, pp. 429-473, 1987.
- [14] R. J. Mason, "Implicit moment particle simulation of plasmas," *J. Comput. Phys.*, vol. 41, pp. 233-244, 1981.
- [15] R. J. Mason, "Implicit moment PIC-hybrid simulation of collisional plasmas," *J. Comput. Phys.*, vol. 51, pp. 484-501, 1983.
- [16] R. J. Mason, "Hybrid and collisional implicit plasma simulation models," in *Multiple Time Scales*, J. U. Brackbill and B. I. Cohen, Eds. New York: Academic, 1985, pp. 233-270.
- [17] J. U. Brackbill and D. W. Forslund, "An implicit method for electromagnetic plasma simulation in two dimensions," *J. Comput. Phys.*, vol. 46, pp. 271-308, 1982.
- [18] J. U. Brackbill and D. W. Forslund, "Simulation of low frequency, electromagnetic phenomena in plasmas," in *Multiple Time Scales*, J. U. Brackbill and B. I. Cohen, Eds. New York: Academic, 1985, pp. 271-310.
- [19] J. M. Wallace, J. U. Brackbill, and D. W. Forslund, "An implicit moment electromagnetic plasma simulation in cylindrical coordinates," *J. Comput. Phys.*, vol. 52, pp. 434-457, 1986.
- [20] D. C. Barnes, T. Kamimura, J.-N. Leboeuf, and T. Tajima, "Implicit particle simulation of magnetized plasmas," *J. Comput. Phys.*, vol. 52, pp. 480-502, 1983.
- [21] D. W. Hewett and A. B. Langdon, "Electromagnetic direct implicit plasma simulation," Lawrence Livermore Nat. Lab., Livermore, CA, Rep. UCRL-94591, Nov. 1986 (to be published in *J. Comput. Phys.*).
- [22] D. L. Youngs, "Time dependent multi-material flow with large fluid distortion," in *Numerical Methods for Fluid Dynamics*, K. W. Morton and M. J. Baines, Eds. London, England: Academic, 1982, pp. 273-285.
- [23] B. Van Leer, "Towards the ultimate conservative difference scheme. IV. A new approach to numerical convection," *J. Comput. Phys.*, vol. 23, pp. 276-299, 1972.
- [24] B. Van Leer, "Towards the ultimate finite difference scheme. V. A second order sequel to Godunov's method," *J. Comput. Phys.*, vol. 32, pp. 101-136, 1979.
- [25] D. Mosher, "Interactions of relativistic electron beams with high atomic-number plasmas," *Phys. Fluids*, vol. 18, pp. 846-857, 1975.
- [26] D. Mosher, private communication, Mar. 6, 1987.
- [27] R. J. Mason, J. M. Wallace, and K. Lee, "Implicit two-fluid simulation of electron transport in a plasma erosion opening switch," in *Proc. 6th Int. Conf. High Power Particle Beams* (Kobe, Japan), 1986, pp. 295-298; also in *Proc. 2nd Int. Topical Symp. Inertial-Confinement Fusion Research by High-Power Particle Beams* (Nagaoka, Japan), 1986, pp. 320-325.
- [28] C. D. Child, "Discharge from hot CAO," *Phys. Rev.*, vol. 32, pp. 492-511, 1911.
- [29] I. Langmuir, "The effect of space charge and initial velocities on the potential distribution and thermionic current between parallel plane electrodes," *Phys. Rev.*, vol. 21, pp. 419-435, 1923.
- [30] C. W. Mendel, Sandia Nat. Labs., private communication, Dec. 3, 1986.
- [31] M. A. Sweeney, G. A. Rochau, and T. Renk, Sandia Nat. Labs., private communication, Mar. 3, 1987.
- [32] B. V. Weber *et al.*, "Current distribution in a plasma opening switch," *Appl. Phys. Lett.*, vol. 45, pp. 1043-1045, 1984.
- [33] C. W. Mendel, Jr., and G. S. Mills, "Performance of a plasma-filled, series-field-coil ion beam diode," *J. Appl. Phys.*, vol. 53, pp. 7265-7273, 1982.
- [34] B. Weber *et al.*, "Plasma erosion opening switch research at NRL," *IEEE Trans. Plasma Sci.*, this issue, pp. 635-648.
- [35] R. C. Davidson and N. A. Krall, "Anomalous transport in high-temperature plasmas with application to solenoidal fusion systems," *Nucl. Fusion*, vol. 17, pp. 1313-1372, 1977.
- [36] S. A. Slutz, "Anode plasma ionization due to sheath heating in magnetically insulated ion diodes," *J. Appl. Phys.*, vol. 61, pp. 1288-1296, 1987.
- [37] C. L. Olson, "Ion beam divergence due to plasma heating in the amp-fion diode," *Laser Particle Beams*, vol. 2, pp. 255-272, 1984.