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Received by OSTI

AUG 0 4 1988

LA-UR--88-2029

DE88 014425

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SUBMITTED TO: The Proceedings of the 7th International Conference on High-Power Particle Beams, Beams'88, July 4-8, 1988 Karlsruhe, FRG.

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SIMULATION OF PLASMA EROSION OPENING SWITCHES

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ABSTRACT

Recent progress in the modeling of Plasma Erosion Opening Switches is reviewed, and new results from both fluid and particle simulation compared. Three-fluid simulations with the ANTHEM code for switches on the NRL GAMBLE I machine and the SNL PBFA II machine have shown strong dependence of the opening dynamics on the anode structure, the threshold for electron emission, on the possible presence of anomalous resistivity, and on advection of the magnetic field with cathode emitted electrons. Simulations with the implicit particle-in-cell code ISIS confirm these observations, but manifest broader current channels – in better agreement with GAMBLE I experimental results.

INTRODUCTION

The PEOS is an important element in inductive storage, permitting the accumulation of energy in a vacuum transmission line over the long conduction time characteristic of the charging circuit (say, a Marx bank), and opening fast enough to drive a light ion ICF load, or a diode for radiation simulation with efficiency. A basic understanding of PEOS plasma dynamics is needed, if we are to use the switch optimally, or design *a priori* improvements.

Since the Beams'86 conference, when the first ANTHEM simulation[1] of the PEOS was presented, much progress has been made. ANTHEM is an implicit plasma simulation code[2], which has principally been run in a three-fluid mode. The background ions and electrons are treated as the first two fluids. Emission electrons serve as the third. It calculates time advanced current sources implicitly for use in Maxwell's equations. With it, global problems on meshes with cells much larger than a Debye length can be simulated, using time steps much larger than the smallest local plasma period. More recently the implicit ISIS code[3] has been used to search for effects that might be missing in a fluid description of the switches. Results from both of these codes are presented in this paper.

THE MODELING

An idealized PEOS is shown in Fig. 1. For GAMBLE I the switch typically had a C^{++} fill plasma 2.5 high by 6.0 cm long at a density of 3×10^{13} electrons/cm^3 at 5 eV initial temperature. All our calculations have been for a short-circuit load. The generator pulse rose linearly from 0 to 100 kA over 50 ns, corresponding to a maximum magnetic field at the cathode of 8 kG. The magnetic skin depth was approximately 0.1 cm, and the Debye length was 0.005 cm at 1 keV. For PBFA II the cathode radius was 20 cm the anode was at 28 cm and the plasma length was from 4 to 14 cm. Its generator pulse rose from 0 to 30 kG. Traditional explicit codes would require cells matching the Debye length. Our implicit simulations can model the Fig. 1 configuration with a 50×50 mesh. Time steps are set by a Courant condition on the fastest electrons. Thus, a typical global run can be completed in about 2 to 4 hours of CRAY XMP time.

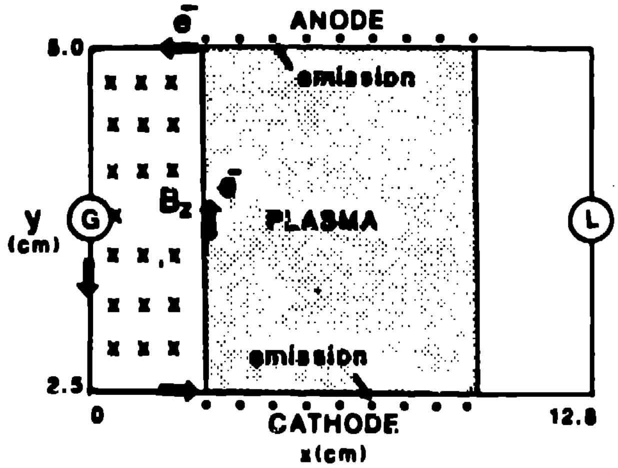

Fig. 1.

RESULTS

In Ref. 1 one of us showed how magnetic field rapidly penetrates along the cathode when electron emission was absent. Enhanced field penetration was absent along the anode for a transmitting boundary, where $\partial E_z/\partial r = 0$ (with E_z the axial, E_r the radial and B_θ the azimuthal electric and magnetic field components).

Reference 4 showed that with a large (300 keV/cm) emission threshold, E_{th} (measured one cell above the cathode surface), a fast gap developed along the cathode of an idealized PEOS for the PBFA II accelerator at the Sandia National Laboratory. After 20 ns this gap reached the load side of the fill plasma, and then rapid opening of the switch followed, with magnetic field at the load rising to the drive value in 6 additional ns. In this large E_{th} regime currents are induced along the underside of the plasma gap, as electrons first flow toward the generator, and then up along the generator side of the fill plasma toward the anode. Magnetic pressure helps to open the cathode gap in conjunction with ion erosion – the acceleration of ions in the electric field of the gap toward the cathode. In this mode of operation magnetic field penetration of the plasma fill is minimal. The diamagnetic currents act to keep B within a few skin depths of the surface. To bring about significant magnetic field penetration of the fill plasma, large anomalous collision rates (approaching the plasma frequency, ω_p) were required.

Next, ANTHEM was used[5] to examine GAMBLE I experiments[6], but with a zero emission threshold. Electrons were immediately supplied at the cathode surface, whenever needed to maintain $E_r = 0$ there (in regions initially exposed to fill plasma). Also, comparisons were made between results for solid ($E_z = 0$) anodes and transparent $\partial E_z/\partial r = 0$) structures. Switches with a closed anode manifested an accumulation of magnetic field near the anode, magnetic insulation of the electrons there – that had also been seen in the earlier PBFA II simulations[2], and a slow penetration of the field along the anode into the load region. With an open anode, no favored field penetration at the anode was observed in calculation. Slow gap formation at the cathode was noted, and magnetic field managed to penetrate 6 cm of 6×10^{13} cm^{-3} fill plasma for the GAMBLE I switch in 50 ns. The current sheets crossing the fill plasma were thin (1 - 2 cm), but could be broadened to match the GAMBLE I data with the introduction of anomalous collisions at a maximum rate no larger than $0.1\omega_p$.

More recently, the field penetration observed in the GAMBLE I simulations[6] was explained in the context of new, $E_{th} = 0$ simulations done for PBFA II[7]. The earlier calculations had, in fact, been conducted in cartesian geometry. The Ref. 7 results were from cylindrical calculations. Actually, few differences were seen in cylindrical versus cartesian runs. In simulations for 10^{13} cm^{-3} fill density, it was determined that $\mathbf{v}_d = c(\mathbf{E} \times \mathbf{B}/|B^2|)$ drift just above the cathode created a deflection of emitted electrons toward the load, creating an excess of positive charge near the electrode. Eventually, this pulled the path of the emission electrons back toward the generator surface of the fill plasma. But, it also started enhanced erosion of the ions (and, therefore, also the plasma electrons) toward the cathode, with accompanying formation of a density gap and field penetration along the cathode. It was noted that magnetic field was entrained on the emitted electrons, so that emission "painted" those regions of the fill crossed by the emission current channel. The channel would move through 10 cm of 10_{13} cm^{-3} fill plasma in 40 ns, leaving "penetrated" magnetic field in the plasma regions above the gap. The delivery of B_θ obeyed

$$\partial B/\partial t = -\partial(v_z B_\theta) - 1/r\partial(r v_r B_\theta)/\partial r + \ldots ,$$

which follows from Faraday's law, and $\mathbf{E} = -\mathbf{v} \times \mathbf{B}/c + \ldots$, and which mimics the equation for the advection of electron density. When the ion mass was made infinite in simulation tests, penetration by advection continued, but no cathode gap was formed. Then, field penetration to the load took longer, 60 ns (versus 40 ns with finite mass ions and cathode gap formation). Thus, two modes of switch opening were observed: (a) slow opening along a solid anode ($E_z = 0$), and (b) fast opening through a cathode gap (with $E_{th} = 0$). [Even faster opening had been seen for large E_{th} in Ref. 2, but this is now thought not to be physical.]

The conduction times of 35 ns and the rapid opening at the cathode over an additional 5 ns in our PBFA II simulations is consistent with experimental results on the Sandia accelerator. However, the current channels remained thinner (1 - 2 cm) than expected from the earlier GAMBLE I data. We have, therefore, run nearly comparable simulations on the ANTHEM (fluid) and ISIS (PIC) codes to see if particle simulation can predict broader current sheets. The results are collected in Figs. 2 and 3.

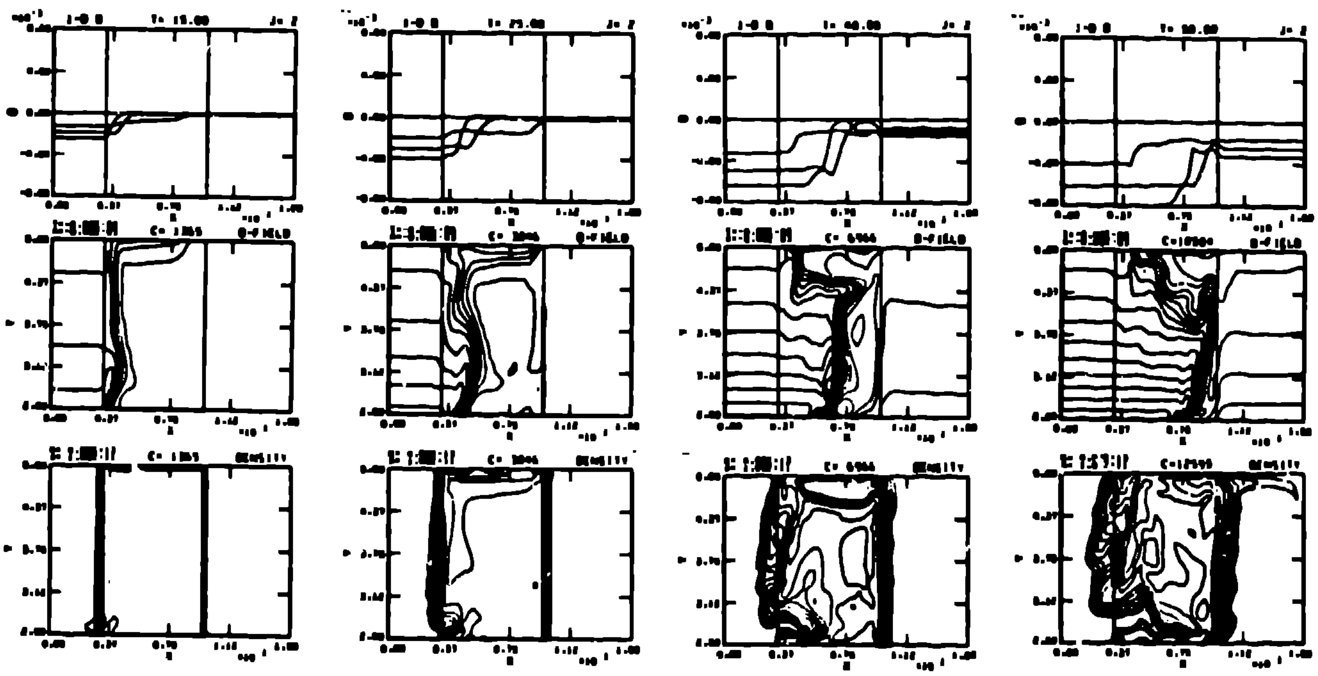

Fig. 2

The Fig. 2 ANTHEM simulation is for the GAMBLE I switch at 2×10^{13} electrons/cm^3. The load is at 15.0 cm. From left to right the times are: 15, 25, 40 and 50 ns, into the rising pulse. The top row shows B_θ cuts at r = 2.5, 3.75 and 5.0 cm, respectively. The middle row gives corresponding contours of magnetic field. The bottom row collects contours for total electron density, ranging logarithmically from 10^{11} cm^{-3} to 2.4×10^{13} cm^{-3}. One sees accumulation of magnetic field near the anode, the narrow channel for $\partial B_\theta/\partial z$ gradients and emission current, the formation of a cathode gap in the electrons, and magnetic insulation of the electrons entering the gap at a late period of the 50 ns pulse.

The Fig. 3 ISIS results were for a 45 ns pulse and $n_e = 3 \times 10^{13}$ cm^{-3}. They employed a 130(z)× 30(r) mesh. The results are collected in pairs showing magnetic field contours and electron particle plots for: upper pair, t = 15 and 25 ns; lower pair, 40 and 50 ns. Corresponding to the ANTHEM gap in electron density contours near the cathode, a very similar gap is evident in the ISIS particle plots. Anode accumulation of magnetic field is clear in both simulations. Also, both ISIS and ANTHEM show corresponding magnetic insulation of the electrons above the cathode. However, the magnetic plots indicate much broader (3 - 6 cm) B_θ transitions and current channels in the ISIS runs.

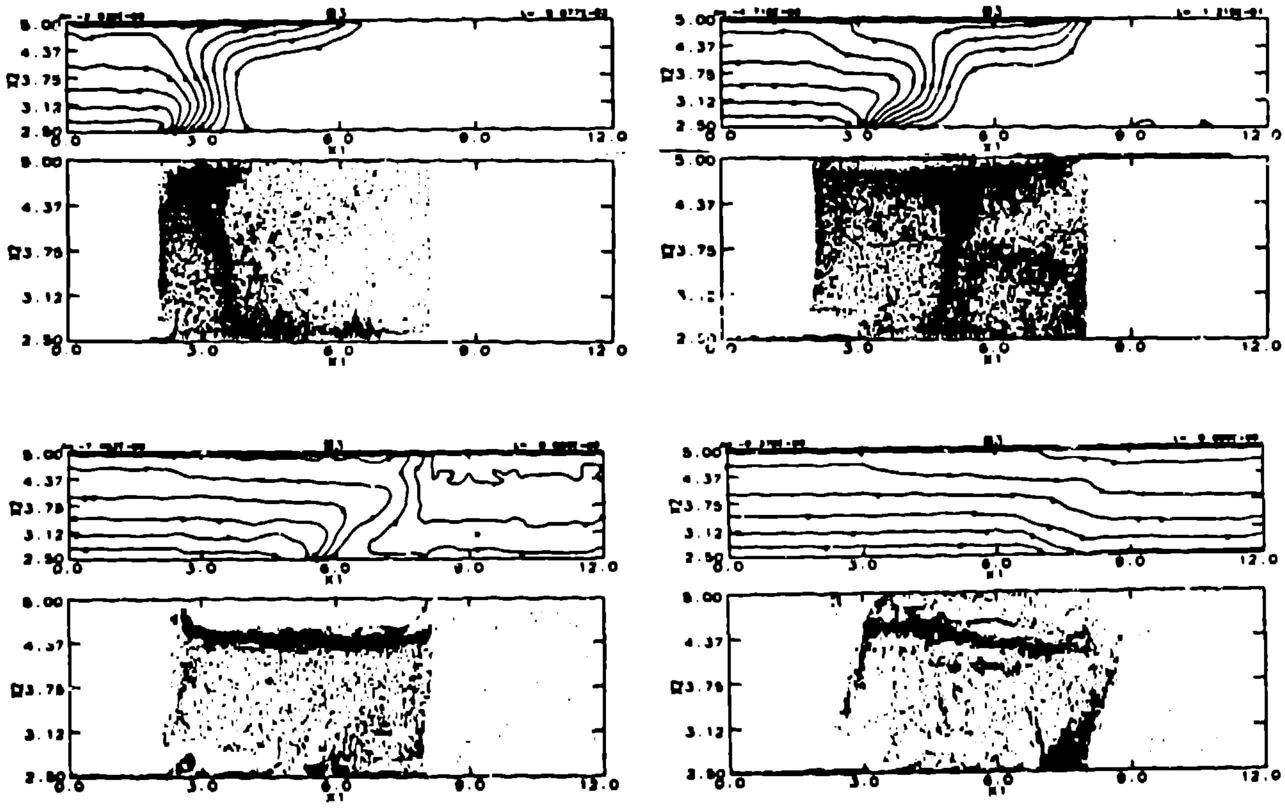

Fig. 3

Work is now underway to isolate the origin of the wider current channels seen in the PIC simulations. Numerical differences in the ANTHEM and ISIS implicit models are under scrutiny. But, broader collisionless shock structures (with associated plasma precursors), and better replication of the electron gyro effects under particle modeling are the anticipated explanations for the improved agreement with experiments manifested by the ISIS simulations.

CONCLUSIONS

Much has been learned about the dynamics of the PEOS since the last Beams conference. Advection with the cathode emission electron stream has emerged as an important mechanism for the field penetration of switch plasmas. The need for anomalous resistivity is still uncertain, but implicit collisionless particle simulations agree with available magnetic field probe data. Further analysis and comparison of the fluid simulations, particle simulations and the data now promise to provide a comprehensive understanding of PEOS phenomenology.

ACKNOWLEDGEMENTS

We acknowledge stimulating discussions with J. Paquin, J. Wallace, and D. Winske at LANL, J. Mendel, J. Quintenz, and M. A. Sweeney at SNL, and J. M. Grossmann and P. F. Ottinger at NRL. This work was performed under the auspices of the U.S.D.O.E.

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