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PEOS technology scaling to the long conduction time (~> 200ns) and 10-20 MA current levels required by the 10X machine is discussed. The approach taken is to employ the results of the electromagnetic numerical modeling we have performed for conduction times of 50 to 80 ns in constructing the functional dependence of the switch operation on its physical parameters. BLACKJACK 5 and ACE PEOS experiments as well as results from fully electromagnetic particle in cell simulations are compared with the heuristic ion piston model. Implications of this analysis on switch length, radius and density for the 10X machine are given.

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PEOS LONG CONDUCTION TIME THEORY

E. Waisman
D. Parks
P. Steen
A. Wilson

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PEOS LONG CONDUCTION TIME THEORY

E. Waisman, D. Parks, P. Steen, and A. Wilson

VG 1 General program overview.

VG 2 The objective is to discuss how PEOS technology scales up to the long conduction times ($\gtrsim$ 200 ns) and 10 to 20 MA currents required by the 10X machine.

The approach is to employ the results of the electromagnetic numerical modeling we have performed for conduction times of 50 to 80 ns, in constructing the functional dependence of the switch operation on its physical parameters.

We compare the BLACKJACK 5 and ACE PEOS experiments, as well as the E&M simulations, with a heuristic model: the ion piston mechanism.

Implications of this analysis on switch length, radius and density for the 10X machine are given.

VG 3 A schematic representation of the particle electromagnetic model is shown. Ions and electron self-consistent trajectories are followed in a planar mesh of length > ℓ, and height DR, where ℓ is the part of the computational grid occupied at t=0 by the initial carbon neutral plasma, of ion density N and injection velocity v. DR represents the A-K gap. The total length of the mesh includes, besides ℓ, sections to the left and right of it initially empty of particles.

The input (upstream) side is driven by V_{oc}, the open circuit voltage of BLACKJACK 5 shot #1057 in most cases, coupled by a L-Z circuit with L and Z constant in time (upstream inductance and line impedance, respectively). The output side (downstream) is a L-Z circuit, where L is the downstream inductance to the load, and Z is the time dependent magnetic limited impedance of a ring e-beam diode.

VG 4 Shown in this viewgraph is the comparison with the experiment of the electromagnetic simulation using the actual length and gap of shot PEOS BLACKJACK 5 1057, i.e., ℓ = 18.1 cm and DR = 4.2 cm. The density and injection velocity of the C^+ plasma in the simulation were $N = 4 \times 10^{12}/cm^3$ and V_p = 10 cm/μs, respectively. This density, for the given switch size, is near the limits of what these calculations can treat in reasonable computing times, even at relatively low resolution.

Agreement between the E&M simulation and experiment is semiquantitative (we remark that the actual density distribution is only known to order of magnitude accuracies in the experiments). The simulation shows, for this density of $4 \times 10^{12}/cm^3$ of C^+, shorter conduction time than the observed one, and the presence of a "numerical" foot for the load current. No evidence of loss of magnetic insulation or sizable switch current after opening is observed in the simulation. Perhaps this difference between simulation and experiment is due to: (i) In the calculations no geometric details such as corners, convolute posts, etc. in the vacuum section between switch and local are considered. (ii) We used a simplified impedance model which, upon the load getting to a voltage ~ 100 kV, goes from 8 Ω to about less than 1 Ω in 5 ns. The experimental observation shows Z ~ 1.5 to 2 Ω at that stage.

At this point of the talk a video cassette was shown of ion density, electron density, and magnetic field profiles, obtained from the E&M calculation for a switch of length ℓ = 9 cm and with all other parameters the same as in the previous viewgraph. The images show the formation of a current channel at early times and the formation of an ion piston (snowplow) at times before opening.

VG 5 Shown in this viewgraph is the definition of T_c and T_o, conduction and opening time, respectively, for the E&M simulations.

Such definition is necessary because we observe a "numerical" foot in our calculated load currents, that we conjecture is due to spurious numerical diffusion, consequence of discretization errors.

VG 6 Numerical scaling studies were done by keeping V_{oc}, total inductance (upstream + switch + downstream) constant, and using the same load model. The plasma length, density, and gap were changed, as indicated in the viewgraph; also R $(R_{anode} + R_{cathode})/2$ was varied -- since our geometry is planar, R only enters in the relationship between current and magnetic field in the circuit-boundary conditions. Also the injection velocity was changed from 10^6 to 10^7 cm/s, and we consider two cases, identical in all other respects, differing by charge state, i.e., C^+ and C^{++}. In total about 20 different cases were run for times between 30 and 80 ns.

VG 7 Scaling of the numerical simulations follow the indicated functional dependence. Later in the sequence of viewgraphs we explain the ion piston model.

VG 8 This viewgraph shows schematically the differences in load turn-on between theory and experiment.

VG 9 In this viewgraph the formulation of numerical diffusion is introduced. It is shown that the "numerical diffusion time" is proportional to the number of macroparticles (typically 10^9 to 10^{10} electrons or ions) per computational cell. These effects seem to be bothersome, but not to overwhelm the physics studied: for the case shown before, simulation of shot #1057, the diffusion time is of the order indicated in this viewgraph, i.e., somewhat larger than the calculated conduction time.

VG 10 The equations describing a 1-D leaky ion piston are introduced. Here μ is mass/unit of the plasma area, ρ its volume mass density, x is the position of the ion piston front; x = 0 at the initial edge of the switch, M is the ion mass. The "leakiness" is represented in equation (2) in the term μ/τ, τ is the characteristic time that an ion of mass M would take to traverse the colissionless length c/ω_p, if accelerated by the force $eB\dot{x}/c$, where $\dot{x}$ is the velocity of the ion piston front. Equation (4) is the circuit equation valid for the conduction phase, i.e., the time it takes for the ion piston to reach the end of the switch, that is to go from x=0 to $x=\ell$; g is the A-K gap.

VG 11 The predictions of the ion piston model are shown in this viewgraph. With T_c the conduction time, $B(T_c)$ the magnetic field at that time (upstream, since for $t \lesssim T_c$ the load current is zero), and ℓ the switch length.

The observations of ACE and BLACKJACK 5 in comparable geometry (same cathode radius, same length and same plasma timing) seem to obey this prediction. We remark that this prediction about BT_c agrees much better with the observations than the threshold current model, which would have predicted equal currents for both cases, irrespective of the factor of three in conduction-time of ACE with respect to BLACKJACK 5.

VG 12 The NRL model scaling of the peak switch magnetic field ($\alpha\ I_{sw}/r_c$) with switch length L_{sw} is compared with BLACKJACK 5 and the recent ACE PEOS experimental data. The linear scaling predicted by that model is shown to be poor.

VG 13 The scaling of magnetic field (I_{sw}/r) with the average ion piston velocity (L_{sw}/r) where T_c is the conduction time is shown. The prediction of the model is good, indicating that the model can be utilized for extrapolating to the long conduction times needed in the 10X machine.

VG 14 This viewgraph illustrates a *comparison of the upstream* current vs time between experiment, shot #1235, the ion piston model and a constant inductance assumption for the duration of the conduction phase. The experimental load current is shown to indicate when the conduction phase is over — turn-on of load. The density shown $N_{carbon} = 1.04 \times 10^{12}/cm^3$, is the one which gives the best fit to the experiment using the ion piston model, such as to have the ion piston front reach the downstream end of the plasma at T_c. L-DOT = dL/dt effects are seen to be significant.

VG 15 Conclusions are self-explanatory.

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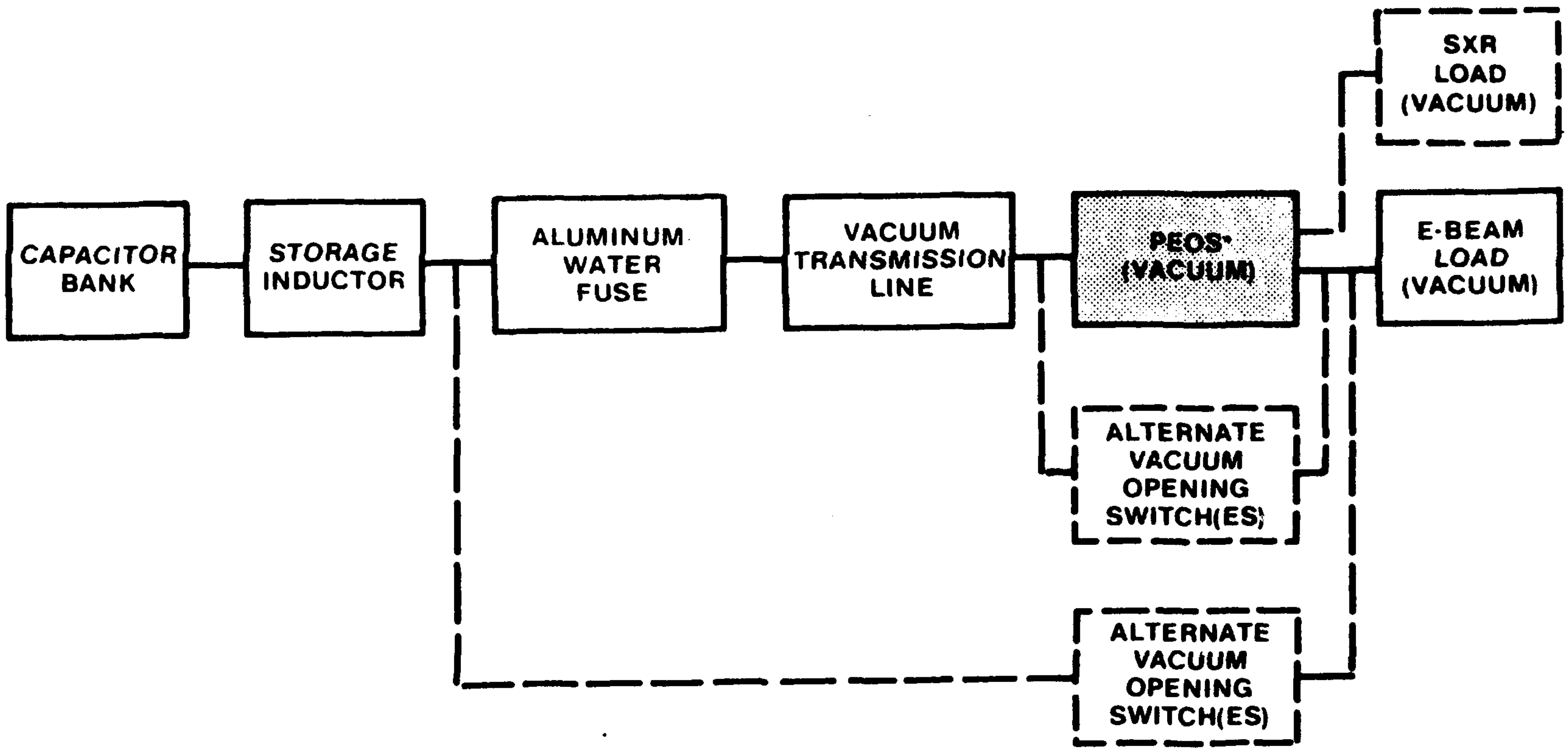
DNA LARGE AREA BREMSSTRAHLUNG SOURCE (LABS) PULSER SYSTEM OPTIONS



*PLASMA EROSION OPENING SWITCH

Viewgraph 1

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OVERVIEW

- PEOS SCALING FOR LONG CONDUCTION TIMES (>200 ns)
- NUMERICAL MODELING IN 50 TO 80 ns CONDUCTION REGIME. DEPENDENCE WITH PHYSICAL PARAMETERS AND COMPARISON WITH BLACKJACK 5 RESULTS
- IMPLICATIONS FOR FUTURE TECHNOLOGY

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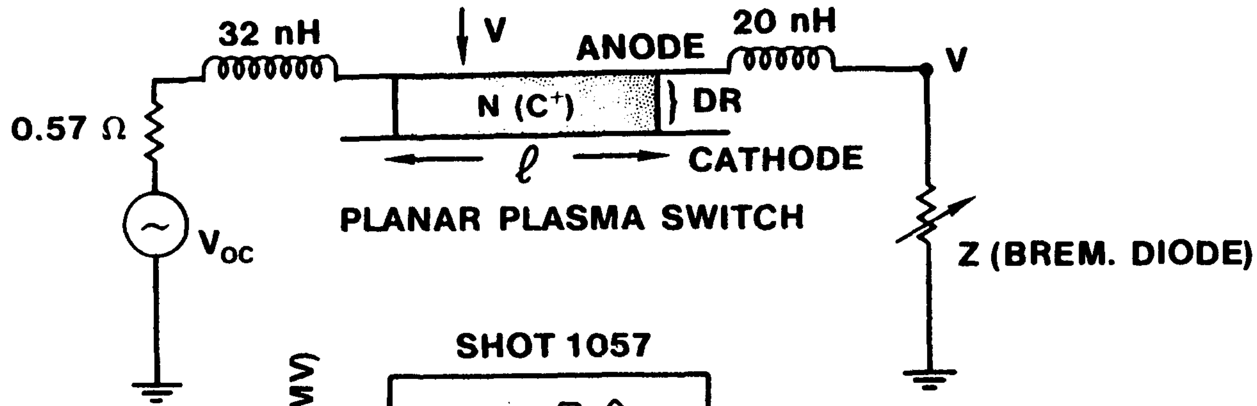
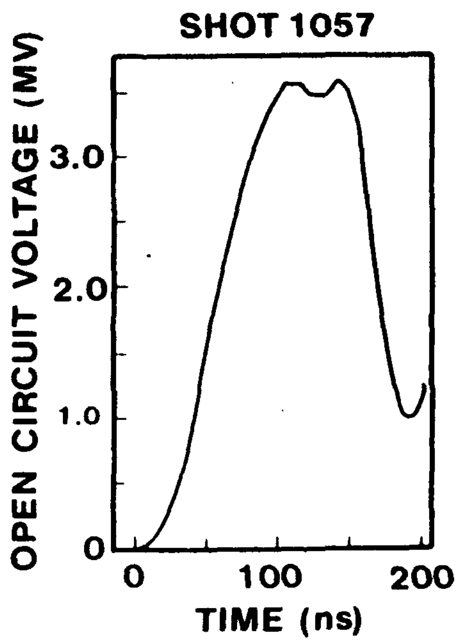
SCHEMATICS OF LUMP CIRCUIT FOR BLACKJACK 5 PEOS ELECTROMAGNETIC PARTICLE SIMULATIONS





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Viewgraph 3

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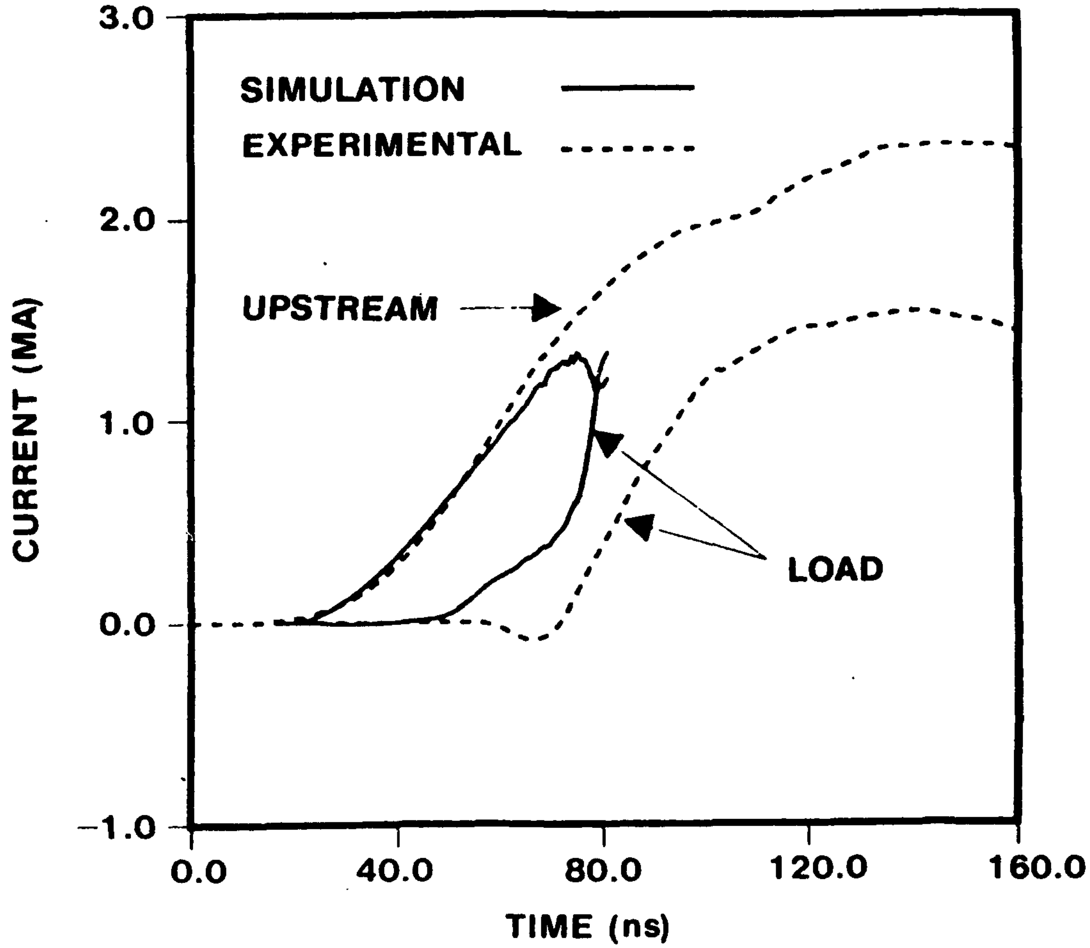
BLACKJACK 5 PEOS SHOT 1057

$N = 4 \times 10^{12}/cm^3 \quad V_p = 10\ cm/\mu s$



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Viewgrapn 4

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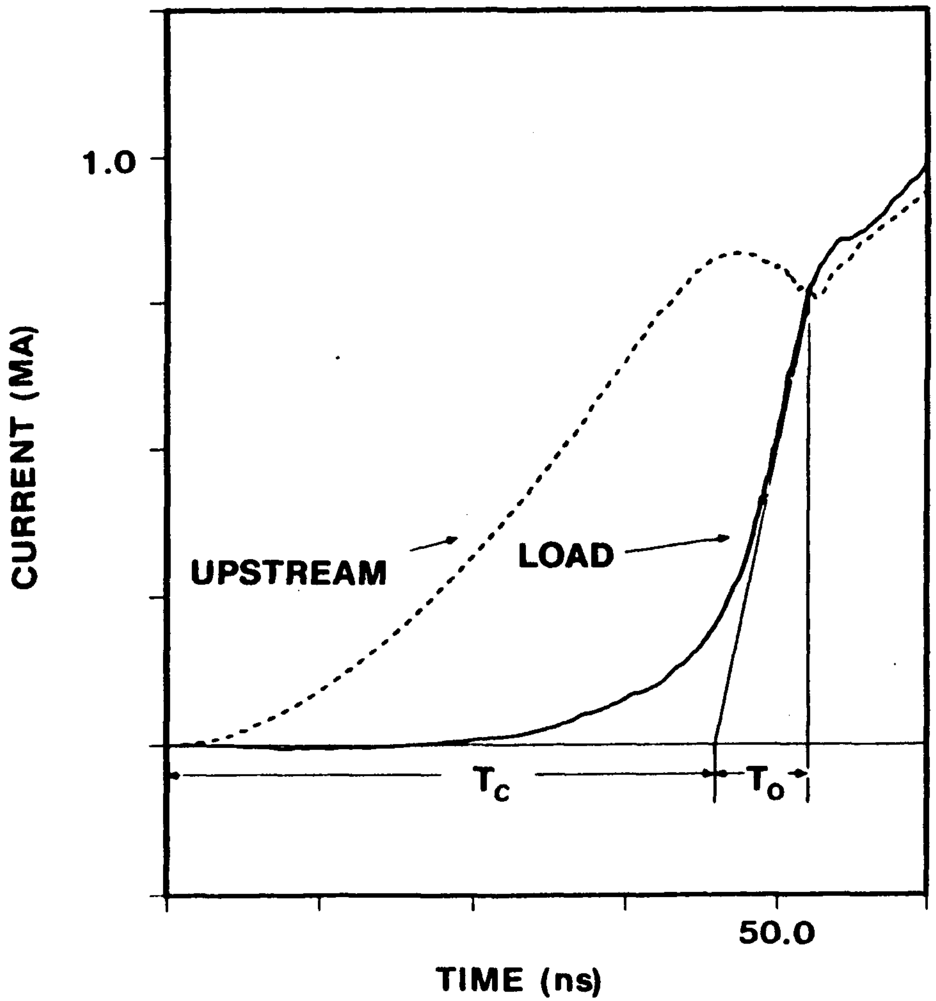
DEFINITION OF T_C AND T_O



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Viewgraph 5

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NUMERICAL SCALING STUDIES

- OPEN CIRCUIT VOLTAGE, LOAD AND INDUCTANCE CONSTANT
- SIZE (ℓ AND R): VARIED BY FACTORS OF 4
- DENSITY: 1 TO 8 x $10^{12}/cm^3$ C^+
- GAP: FROM 1.6 TO 4.2 cm
- INJECTION VELOCITY: 10^6 AND 10^7
- CHARGE STATE: C^{++} VERSUS C^+

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NUMERICAL SCALING RESULTS

- WITHIN "NUMERICAL EXPERIMENT UNCERTAINTY" SCALING FOLLOWS FUNCTIONAL DEPENDENCE OF ION PISTON MODEL

  $$T_c \,\alpha\, (\ell R)^{1/3}/\rho^{1/6} \text{ AND } I\,(T_c) \,\alpha\, (\ell R)^{2/3}/\rho^{1/3}$$

  IF CURRENT α t^2

- NO DEPENDENCE ON GAP, INJECTION VELOCITY, CHARGE STATE

- OPENING TIME RELATIVELY INSENSITIVE TO PARAMETRS (10 TO 20 ns) SHORTER, AS EXPECTED, FOR HIGHER B

- LACK OF AGREEMENT WITH ION PISTON MODEL IN ABSOLUTE TERMS

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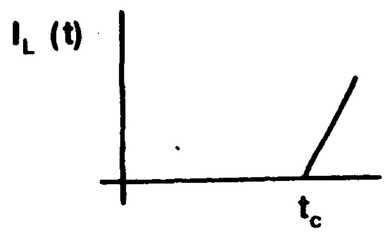
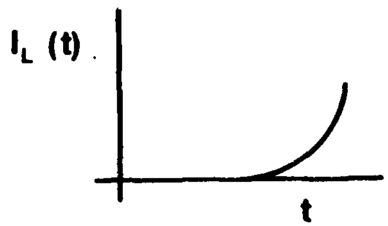
THEORY EXPERIMENT DIFFERENCES

- EXPERIMENT



I_L TURNS ON ABRUPTLY

- THEORY



I_L TURNS ON GRADUALLY

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NONPHYSICAL NUMERICAL EFFECT

- **NUMERICAL COLLISIONS**

  $\nu_{COLL}/\omega_p \sim 1/2\pi N_C$

  $N_C = n\,[\lambda_D^2 + (\Delta x)^2]$

  $\approx$ NUMBER OF PARTICLES IN GRID SQUARE

- **NUMERICAL MAGNETIC DIFFUSION**

  $t_d = 4\pi\sigma/c^2\ L^2$

  $\sigma = \omega_p^2/4\pi\nu_{COLL} = 1/2\ N_C\ \omega_P$

  $t_d = 2\pi N_C \omega_P\ L^2/c^2 = 2\pi N_C/\omega_P\,[L/c/\omega_P]^2$

  $56\ \text{ns} < t_d < 225\ \text{ns}$

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ION PISTON ONE-DIMENSIONAL MODEL (IN QUASI-PLANAR FORM)

- $d/dt\ \mu\dot{x} = B^2/8\pi$
- $d\mu/dt = \rho\dot{x} - \mu/\tau$
- $1/2\ (eB\dot{x}/Mc)\ \tau^2 = d \sim \omega_p/c$
- $d/dt\ LI = V_{DIODE}\ \ t < T_c$

WHERE

$L = L_o + \Delta L$, AND $(\Delta L)\ I = gBx/c$

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SCALING PREDICTED BY ION PISTON MODEL

- FOR $I = \alpha t^n$ (UPSTREAM CURRENT)

$$B\,(T_c)\;T_c/\ell = \sqrt{\rho}\;\sqrt{4(n+1)\;(n+2)\pi}$$

- IT SEEMS TO EXPLAIN ACE AND BLACKJACK 5 PEOS EXPERIMENTS, I.E., FOR SAME ℓ AND ρ (APPROXIMATELY)

BT_c (ACE)	BT_c (BLACKJACK 5)
4.8×10^{-3} Gs	3.1×10

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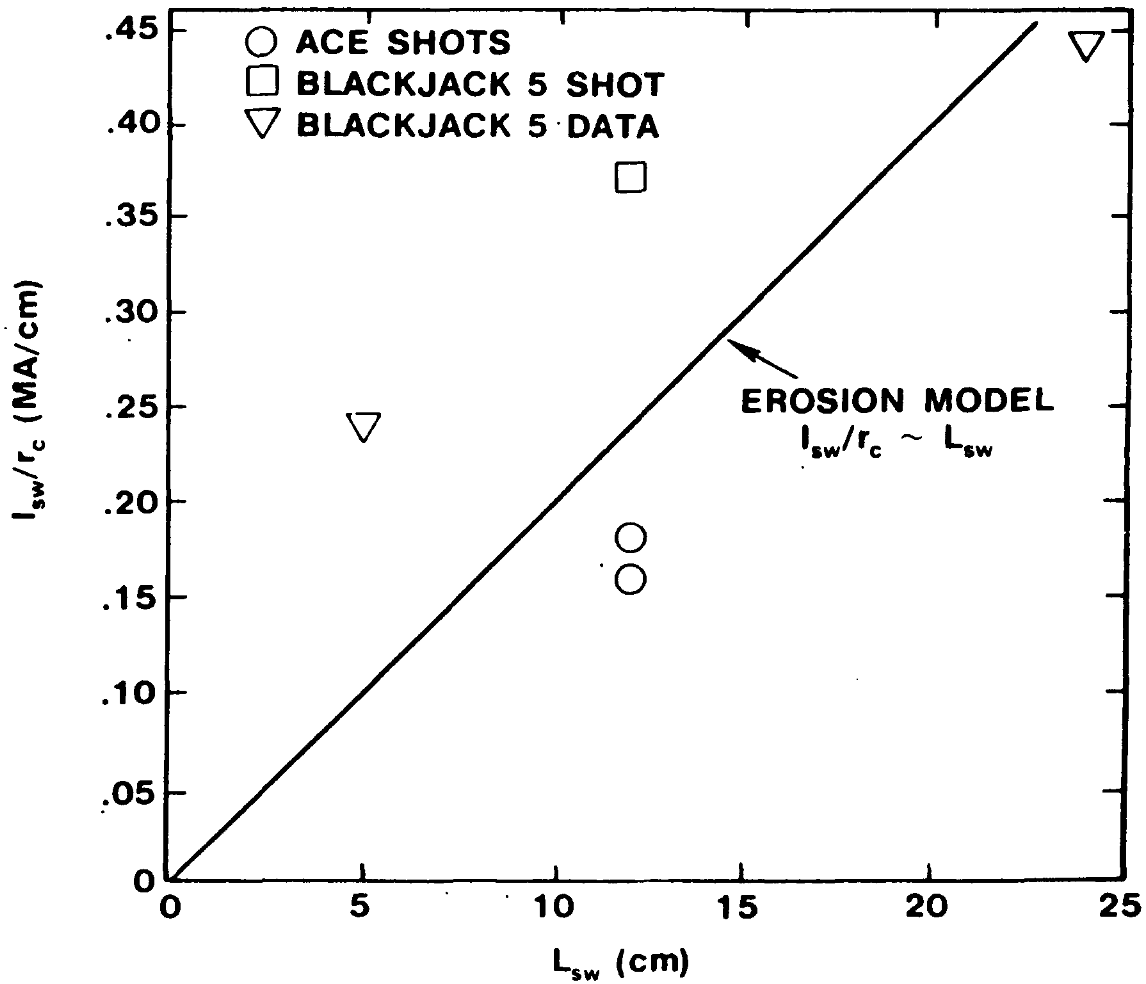
EXPERIMENT — NRL MODEL COMPARISON



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Viewgraph 12

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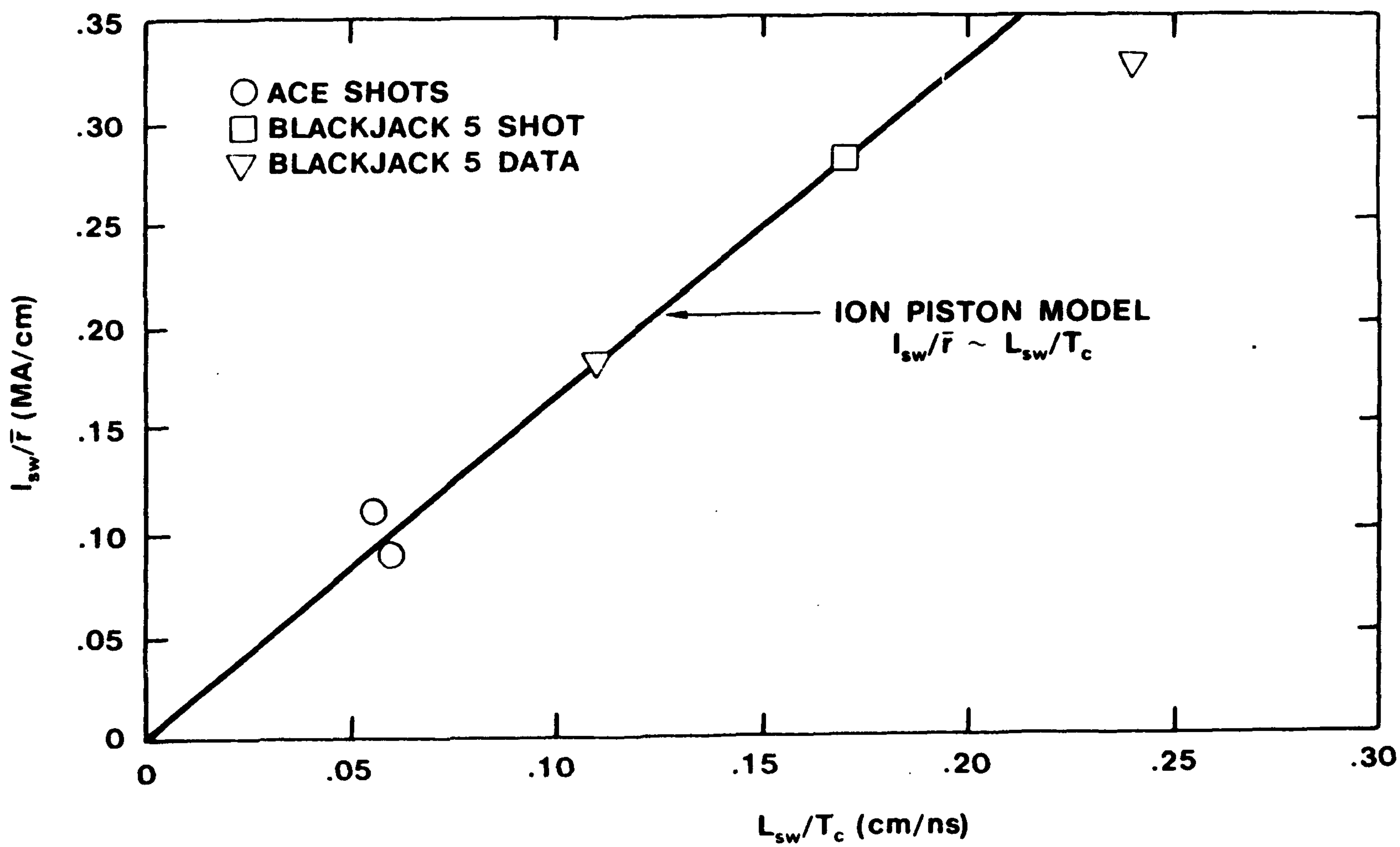
EXPERIMENT — ION PISTON MODEL COMPARISON



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Viewgraph 13

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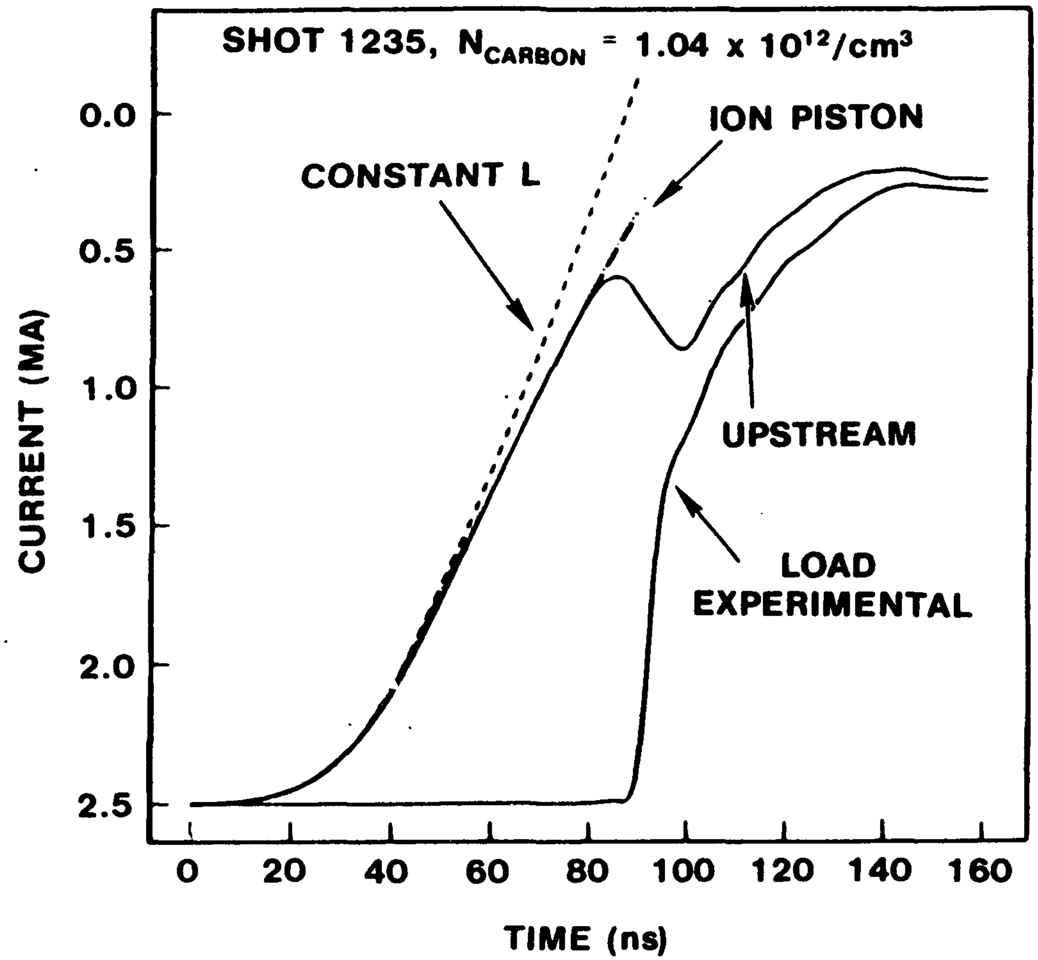
EFFECT OF L-DOT



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Viewgraph 14

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CONCLUSIONS

- FUNCTIONAL DEPENDENCE IMPLIED BY ELECTROMAGNETIC SIMULATION AND ION PISTON MODELS INDICATES THAT FOR THE 10X MACHINE WE REQUIRE:
  - HIGH DENSITY $N \sim 10^{14}/cm^3$
  - LARGER SWITCH SIZES $\ell \sim 20$ TO 40 cm AND RADIUS >30 cm
- SMALL CATHODE BLACKJACK 5 AND ACE EXPERIMENTS INDICATE THAT THE PEOS IS ALREADY IN THIS DENSITY REGIME
- PRESENT FIRST PRINCIPLE MODEL NEEDS MODIFICATION TO TEST THIS REGIME
- FURTHER VALIDATION OF SCALING WITH N, ℓ AND SWITCH RADIUS IS ESSENTIAL

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PLASMA EROSION OPENING SWITCH EXPERIMENTS AT MAXWELL LABORATORIES

PRESENTED AT

DNA ADVANCED PULSED POWER REVIEW
LAS VEGAS, NEVADA
MARCH 31 - APRIL 1, 1987

PRESENTED BY

W. RIX

P. DAVIS, M. GERSTEN, N. LOTER, J. RAUCH,
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