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ANTHEM SIMULATION OF PLASMA OPENING SWITCHES

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ABSTRACT

Plasma Opening Switches have been examined numerically with the aid of the ANTHEM plasma simulation model. A generic bi-cylindrical switch is studied. The switching of generator pulses ranging from 50 ns to 1 μ sec is reviewed, for a variety of plasma fill lengths and densities, and for a range of resistive loads.

INTRODUCTION

The Plasma Opening Switch (POS) is a pulsed power element used in conjunction with modern inductive storage techniques. Ordinarily, the POS consists of plasma injected between the anode and cathode of a bi-cylindrical transmission line. At first, electrons from a Marx generator run down the cathode to the fill plasma region, take a short circuit path across the plasma to the anode, and then run back along the anode to the generator. Over time, electrical forces push the fill plasma out of the transmission line, breaking the current path. Then the electrons pass down along the cathode to the load.

We have studied a the generic POS shown in Fig. 1. The cathode radius is 8 cm, the anode is at 10.5 cm. The full length of the switch is 50 cm. The injected plasma is doubly ionized carbon, injection velocities from 0 to 10 cm/ μ sec have been employed. The plasma fill width ranges from 5 to 30 cm in our simulations. The fill density has ranged from 4×10^{17} to 6×10^{17} cm⁻³. The cathode and anode absorb all the plasma striking them. The generator supplied a 1 MV pulse that would rise to 1 MA in the absence of a load over either 50, 100, 300 or 1000 ns (1/ μ sec). The maximum magnetic field established at 1 MA is 3 T (30 kG) at the generator end of the cathode. These conditions are typical for experiments with POSs around the world.¹ The NRL GAMBLE II machine (with a 2.5 cm cathode) pushed on its plasma with a similar

magnetic field at its early operational 300 kA current level, as did Sandia Laboratories PBFA II accelerator (with its larger ~ 20 cm cathode) in recent experiments at a maximum 3 MA.

CALCULATIONAL PROCEEDURES

Calculations were performed with the ANTHEM implicit simulation code[2]. ANTHEM is a multi-fluid/PIC model. For its present application separate electron and ion fluids were employed to represent the background electrons and ions constituting the fill plasma, and a third electron fluid was introduced to model the emission. The solution for electric and magnetic fields is obtained implicitly from Maxwell's equations by the Implicit Moment Method[2-4]. Thus, in ANTHEM the electric and magnetic fields are advanced by

$$E^{(m+1)} = E^{(m)} - 4\pi e \Delta t j^{(m+1)} + c \Delta t \nabla \times B^{(m+1)}$$

$$B^{(m+1)} = B^{(m)} + c \Delta t \nabla \times E^{(m+1)}$$

with time-advanced currents, $j^{(m+1)} = j[E^{(m+1)}]$, determined from a set of auxiliary moment equations[2].

In our simulations the $\mathbf{v} \times \mathbf{B}$ term was treated implicitly[2]. The plasma resistivity[4-6] was set to zero. Changes were made so as to base the code on momenta rather than velocities, so that electron relativistic effects could be included. A low emission threshold[5-6] (10 V/cm) for electrons was selected. A circuit representing the switch and inductive store is shown in Fig. 2. The drive voltage ΔV_G was set at a constant 1 MV. The generator inductance L_G was set at 50, 100, 300 and 1000 nH for corresponding pulse rise times of 50, 100, 300 and 1000 ns, respectively. Most of the runs were made for a resistive load R_L of 1 Ohm. The peak generator current in the absence of switch plasma was, therefore, 1 MA. The variable switch resistance R_s was calculated by the code

GENERAL POS OPENING CHARACTERISTICS

A schematic of interesting POS regimes is provided in Fig. 3. The PBFA II accelerator at Sandia National Laboratory produces a short generator pulse (50 - 100 ns). Switches for PBFA

It must open into a 7 to 10 Ohm load, e.g. a barrel diode for light ion inertial confinement fusion. Maximum current to this load should be about 4 MA, yielding a 28 MV voltage drop across the load. The Los Alamos TRILMASTER program seeks to implode thin foils over a 2-5 μsec time scale. For this application a POS would have to conduct large currents for several microseconds and then open in a fraction of a microsecond. Our simulations have begun to explore both regimes. Runs have been made for the lower left corner of Fig. 3. R_L from 0 to 25 Ohms have been used. Generator pulses have ranged from 50 to 1000 ns, yielding opening times ranging from 17 ns to 1.6 μsec for various plasma fill densities and lengths.

In general, switch opening is calculated to occur via three competing mechanisms[7]. Opening goes by: a) density gap formation at the cathode, b) magnetic insulation at the anode, and c) magnetic field advection through the fill plasma. These three effects are evident in the Fig. 4a density plots, and accompanying Fig. 4b magnetic field evolution history. These figures give results from a simulation for $3 \times 10^{13} \text{ cm}^{-3}$ fill density, a 50 ns drive pulse (i.e. $L_G = 50 \text{ nH}$), $R_L = 1 \text{ Ohm}$, and a fill plasma length along the cathode of $L_r = 20 \text{ cm}$. This POS conducts for 43 ns (when 5% of the drive field is measured at the load), and then opens (so the load measurement is 85 % of the drive) by 63 ns.

a) The cathode gap: Figure 4a shows that at 30 ns a gap of density has penetrated along the cathode to the 12.5 cm point. By 61 ns this gap is evident in the ions all the way to the back of the original fill plasma, i.e. beyond 30 cm. The cathode gap is associated with the pushing of a magnetic piston along the cathode. At 43 ns this just reaches the back of the original fill plasma. In Fig. 5b the lower plots are contours of magnetic field at 30, 43 and 64 ns; the upper plots give axial cuts of the magnetic field profiles at the $r = 8, 8.5$ and 10.5 cm . The lowest intensity curve at the generator is the $r = 10.5 \text{ cm}$ result. Some ions are propelled into the cathode as the gap forms. This is an erosion like process, as first reported by NRL workers. But ions are also lifted off the cathode by magnetic pressure effects associated with the currents shifting back toward the generator at points higher than the mol gap level.

b) Anode magnetic insulation: Magnetic field also penetrates along the anode. In Ref. 7 we

showed that this was related to a the presence of a finite $\nabla \times \mathbf{E}$, when $E = 0$ in the conducting anode, while $\mathbf{E} \simeq -\mathbf{v} \times \mathbf{B}/c$ in the plasma just below the anode. Faraday's Law then predicts B-field growth and penetration. Once field has penetrated along the anode to the back of the fill plasma, instead of directly entering the electrode, the electron flow is diverted to the back (load side) of the fill plasma. The resultant current running just below the anode produces a magnetic pressure gradient ($\mathbf{v} \times \mathbf{B}$ force), which pushes plasma away from the anode. Thus, we observe early anode plasma gap formation. In the narrow ($\Delta r = 2.5$ cm) switch examined here the push of plasma up from the cathode can close the anode gap. The plasma is found to slosh up and down in the center of the switch. Early anode opening is followed by slower cathode opening, and then anode closure. The current sheet marches across the switch near the cathode. After early penetration near the anode, a second current sheet forms near the generator side of the plasma. This moves across to join the cathode sheet, achieving a near vertical path at about 44 ns. The vertical sheet can march no further toward the load, because the plasma in the load region is tenuous. So the switch opens, i.e. current passes back into the cathode wall and directly to the load.

c) Magnetic advection: Reference 7 showed that even if the ions are rendered immobile (with non physically high mass) magnetic field can penetrate 15 cm of a 10^{13} cm $^{-3}$ fill plasma in roughly 50 ns. The field is carried along with the stream of cathode emitted electrons. This effect is still active at 3×10^{13} cm $^{-3}$, but weaker since the emission electrons are moving more slowly (calculation indicates that more than 150 ns is needed for magnetic field to penetrate 20 cm of fill). In the Fig. 4 calculational run the advection effect competes with field penetration along the electrode gaps.

The insert in the lower corner of Fig. 4b shows the response of "probes" placed at $r = 8$, $z = 0$, the generator I_G , and at $z = 37$ and $z = 50$, the load (at cathode and anode). The probes record $I(MA) = r(cm) \times B(T)/20$. Note the weak foot on the load probes near $t = 37$ ns. This is due to the early anode field penetration. When the probe current rises quickly between 43 and 64 ns the $dI_G/dt \neq 0$. For the switch the load current rises to about 90% of the drive value

at 64 ns, for a temporary period of efficient current transfer to the load.

PARAMETER STUDIES

Numerous simulation runs were made to study the dependence of POS opening on experimental parameters. Figure 5 shows how opening varies with the plasma fill length L_z . The "I"s are data from specific runs. By "conduction time" we mean the time when 5% of the drive field is achieved at the load. The "opening time" is when 85-90% of the drive field reaches the load probes. Figure 6 collects results for a switch filled with plasma at 3×10^{13} electrons/cm³ density and driven by our standard pulse with a 50 ns rise time ($L_G = 50$ nH). The calculated dependence on length is nearly linear, $\tau_{cond} \simeq \tau_{open} \simeq L_z$. The inserted sub-figures show that with 30 cm of fill plasma opening starts gradually with a precursor foot, which appears at 37 ns and grows gradually until 70 ns. The field then grows rapidly at the load over the next 5 ns to 75% of the drive value. By contrast, the field for the 5 cm plasma grows cleanly in a single process over 13 ns to nearly 100% of the generator current. Sandia Laboratory selected a 4 cm plasma as optimal in their recent PBFA II experiments, possibly because of the this cleaner operation for shorter switches. Detailed examination of the computer runs shows that opening via the anode and cathode processes is simultaneous in the shorter switches, while with longer fill plasma the anode opening occurs first, followed later by break open of the cathode gap. The circled data for $L_z = 20$ was obtained for a wider switch ($\Delta L_r = 8$ instead of 21.5 cm). We were surprised to find that break out of the cathode gap takes longer, when there is additional space above the cathode to relieve the compressional effects of the magnetic piston running toward the load along the cathode.

Generally, as density is increased with the 50 ns drive pulse, the tendency for break through of a cathode gap persists. Figure 6 for 20 cm of fill plasma shows that $\tau_{cond} \sim \tau_{open} \sim n_e^{-1/2}$. The inserts show that the low density (4×10^{12}) switch opens cleanly to the full drive current. At 10^{14} electrons/cm³ the iond probes (lower 2 curves) collect only 68% of the drive current. So, the extra plasma in the switch for either greater lengths or higher densities reduce the switch

efficiency.

With longer drive pulses the denser switch can open cleanly, however. Under a 300 ns generator pulse the 20 cm POS with 10^{14} density can conduct for 160 ns and open in 10 ns to about 60% of the drive current.

Figure 7 shows that $\tau_{cond} \simeq \tau_{open} \simeq \tau_{drive}^{2/3}$ for the 20 cm switch at 3×10^{13} electrons/cm³. So, a generator pulse that would rise to 1 MA in 1 μ sec will, in fact, be conducted for only 325 ns. Higher densities are needed for longer conduction times. Under a 1 μ sec generator pulse a 20 cm plasma at 10^{15} electrons/cm³ is calculated to conduct for 615 ns and open in 40 ns. Figure 8 collects the density dependencies with this longer 1 μ sec driver. They are weaker, i.e. $\tau_{cond} \simeq \tau_{open} \simeq n_e^{1/3}$. So, a density exceeding 6×10^{15} is needed for a 1 μ sec conduction time.

Finally, we look at load effects. Figure 9a collects the calculated current and voltage characteristics of the generic switch with 20 cm of 3×10^{13} fill plasma under the 50 ns generator pulse. With a 1 Ohm load ($R_L = 1$) voltage at the load rises to only 60% of the driving 1 MV at about 70 ns. With $R_L = 5$ Probes near the load report voltage doubling. However, current through the load (lower two $I(t)$ curves) peaks at only 30 % of the generator current. Figure 9b shows the magnetic field and electron and ion density configurations in this POS at 94 ns, well after opening with the 1 Ohm load. In the low resistance case a significant density trough prevails in the ions (lowest contour plots) 0.5 cm above the cathode and across its full length. While with the 5 Ohm load, a density peak remains near $z = 20$ cm at late times. A current sheet continues to pass up through this sheet as an alternate path to the path through the load. This is evident from the cluster of B-field contours crossing the switch vertically from $z = 20$ to 25 cm, and shielding the load region from B field penetration, as evident from the B field cuts displayed in the upper right corner of the figure.

CONCLUSIONS

We have demonstrated the the implicit techniques embodied in the ANTHEM code can have great value in the modeling of plasma opening switches. General characteristics of the

POS have been categorized for moderate densities. Scaling rules have been developed for the dependence of the switch's conduction time on the fill plasma length, density and on the drive pulse duration. Our calculations indicate that the POS shows much promise as a useful pulsed power element for long time scale switching into moderate impedance loads. Much additional experimental and simulational work will be needed to realize this potential.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5

Fig. 6

Fig. 7

Fig. 8

1 Ohm

5 Ohms

Fig. 9a

1 Ohm

5 Ohms

Fig. 9b