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PLASMA FORMATION, EVOLUTION, AND DYNAMICS IN 100-1000 TW VACUUM-TRANSMISSION-LINE POST-HOLE CONVOLUTES *

D. V. Rose[ξ], D. R. Welch, T. P. Hughes and R. E. Clark
Voss Scientific, LLC, 418 Washington Street, SE
Albuquerque, NM, 87108, USA

W. A. Stygar
Sandia National Laboratories
Albuquerque, NM, 87187, USA

Abstract

Post-hole convolutes are used in high-power transmission line systems to join several individual transmission lines in parallel, transferring the combined currents to a single transmission line attached to a load. Magnetic insulation of electron flow, established upstream of the convolute region, is lost at the convolute due, in part, to the formation of magnetic nulls, resulting in some current losses. At very high-power operating levels, the formation of electrode plasmas is considered likely. This work examines the evolution and dynamics of cathode plasmas in the transmission-line/double-post-hole convolute configuration used on the Z machine. The results of these simulations suggest net current flow losses due to cathode plasma evolution in the vicinity of the post-hole convolutes of order 2 MA out of a total system current of ~18.5 MA, consistent with measurements.

I. INTRODUCTION

Vacuum post-hole convolutes [1-3] are a critical component in present and future high-power *z*-pinch drivers [4]. A post-hole convolute (PHC) is used to join several transmission lines in parallel, transferring the combined currents to a single transmission line attached to a load. Magnetic insulation is lost at positions inside the convolute due, in part, to the formation of magnetic-field nulls. Electron power flow current losses in the convolute region of transmission lines have been explored previously [1-3]. As electrical power levels for planned *z*-pinch facilities are increased, the formation of electrode plasmas represents an additional potential power-flow loss mechanism.

Several experiments have been carried out at other pulsed power facilities to investigate the formation and evolution of electrode plasma formation in high power, pulsed, magnetically-insulated transmission lines. [4,5] For example, at current levels of order 1 MA and voltages of 1 MV, cathode plasmas have been observed and measured on times scales of order 100 ns in millimeter-scale anode-cathode (AK) gaps with densities of order 10^{16} cm^{-3} and temperatures of ~3 eV. [4]

The 3D particle-in-cell (PIC) code LSP [6] is being used to study the dynamics of electrode plasmas in PHCs. The simulations use an explicit field-solver and particle advance for modeling the evolution of the dense plasmas. Simulations of the *Z* accelerator [7] double-post-hole convolutes (DPHC) and load region that include cathode- and anode-plasma formation in the vicinity of the convolute are being conducted. Potential electrical power loss in this region due to the presence of these plasmas is estimated. In addition, simulations of triple-post-hole convolute designs supporting future *z*-pinch accelerators [8] are planned.

II. SIMULATION MODEL

The energy-conserving PIC simulations are fully electromagnetic and use a cloud-in-cell model for the particles [9] to help minimize electrostatic fluctuations on the grid. This combination of models is numerically stable for time steps sufficiently small in order to resolve both electron-cyclotron and electron-plasma frequencies, ω_{ce}, $\omega_{pe} < 2$. The simulation geometry is essentially the same as described in Refs. [1,2], with the exception that the azimuthal coordinate encompasses an entire post-hole section (30 degrees).

A series of simulations has been carried out, and in order of increasing complexity are: (1) a "cold test" where particle emission is disabled which tests wave input and power coupling to the load, (2) an electron emission case where space-charge-limited (SCL) electron emission is

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ξ email: david.rose@vosssci.com

enabled from all cathode surfaces, and (3) the plasma emission case where both electron emission and plasma injection from the cathodes is enabled. For the case (3), which includes the creation and evolution of cathode plasmas, the simulations use three separate charged-particle species to represent electrons, neutral particles desorbed from the cathode surfaces, and ions produced from the ionization of the neutral particles. This scheme is part of a general electrode plasma model currently being developed [10]. In addition, a newly implemented adaptive particle management scheme is used to help control the total number of macro-particles in the simulations [11].

Electrons are emitted from the cathode using relativistically-correct, SCL emission model with a local electric field threshold of 240 kV/cm. This emission threshold is consistent with several published estimates for stainless steel and aluminum cathode materials [12].

The electrode plasma formation model assumes the desorption of a neutral, thermal, particle layer from a conducting surface. The desorption is initiated on a cell-by-cell basis once the local electric field exceeds the threshold set for SCL emission, although other criteria can be specified. The neutral desorption rate is selected to be less than or of order 0.5 monolayers-per-nanosecond, a typical contaminant desorption rate in pulsed power vacuum operating environments. (This rate is consistent with models of cathode plasma evolution [13] where leading edge of the expanding plasma must be sufficiently dense to allow SCL emission of electrons. This in turn gives an ion current returning to the cathode from the plasma that is of order of the SCL current.) Desorbed neutral particles are ionized within the first cell adjacent to the conducting surface. This technique allows charge conservation to be maintained in the PIC simulation and prevents the formation of sheaths along the conducting surface. The plasma self-similarly expands under the influence of local electric fields. This relatively dense ($n_p \sim 10^{15}$–10^{16} cm^{-3}) plasma can effectively act as a dynamic conducting boundary, with space-charge-limited emission of electrons occurring at the leading edge of the expanding plasma. The dynamic mechanisms governing the self-similar expansion and evolution of these plasmas are described elsewhere [10].

The simulations use a forward going voltage wave that drives a relatively simple transmission line circuit that is coupled to the PIC simulation grid. The forward going voltage wave used at the four input ``levels" in each simulation is shown in Fig. 1. This voltage wave was calculated from circuit simulations modeling the Z pulse forming line.

The simulation is terminated by a 2-cm inner radius coaxial transmission line. This section is coupled to a 1D imploding liner model. The liner model assumes a 2-cm initial inner radius, 2-cm long shell of mass 4.09 mg. The simulations presented here assume a 20:1 aspect ratio for the implosion, a value that is larger than the 10:1 aspect ratio typically obtained on Z [14]. This results in a delay in the time of peak power at the load relative to actual Z results, as shown in Fig. 1b). Additional simulations with a 10:1 aspect ratio are planned. It should be noted that despite following ~1016 cm-3 plasma densities, the grid size is of order 1 mm. Significantly finer resolution is at present not feasible.

III. SIMULATION RESULTS

We summarize the results of new PIC simulations of the Z machine DPHC using a 2-cm radius load with a 5-mm anode-cathode gap region immediately upstream of the load. Three simulations are described: a ``cold-test" in which the electromagnetic field solver is advanced without any particle creation, driving the load as a purely vacuum wave device. The second simulation includes SCL emission of electrons from cathode surfaces, as done in previous work [1,2]. The third simulation adds cathode plasma formation in the vicinity of the cathode plate holes in the convolute region. This plasma is liberated from the cathode surface once SCL emission is initiated (i.e., when the local electric field at the surface exceeds the threshold condition of 240 kV/cm). The plasma evolves initially from a fully ionized, electron-proton population one cell thick with a 3 eV thermal distribution. The cold-test simulation gives a peak load current, shown in Fig. 1, of about 18.5 MA, consistent with circuit models of Z. The peak electrical power of ~140 TW is also consistent with measured peak *x*-ray powers [14].

Electron power flow losses have long been recognized as a potential issue for power delivery efficiency in vacuum PHC systems. Previous computational studies of the Z DPHC have indicated that losses of order 100 kA result from the loss of magnetic insulation in the vicinity of the magnetic nulls [1,2]. Here, those estimates are confirmed in these simulations when the cold test results are compared with simulations that include electron emission from cathode surfaces. Figure 2 shows the load current from case (2) (electron emission). At peak power, electron current sheath currents flowing in the vicinity of the load are of order 70 kA, consistent with previous results.

These results are compared to a case where plasma desorption is modeled from the cathode holes in the convolute. The impact on the load current is observed at relatively early times and continues through to peak power as indicated in Fig. 2. At peak power, load current losses of over 2 MA result, roughly consistent with estimated current losses on Z [14]. This simulation indicates a number of areas where cathode plasmas can increase parasitic current losses upstream of the load. At early times (40 ns < t < 60 ns), plasma expanding from the cathode on the upstream side of post can cause premature diversion of the magnetically insulated electron flow approaching the post-hole region. This current loss mechanism is complex and dynamic, including the pulsed formation and detachment of relatively large electron vortices into the post-hole voids. A second loss phase, primarily occurring at later times (> 60 ns) involves rapid plasma expansion along the magnetic nulls. This brings the effective (electron emitting) cathode surface into closer proximity to the anode post, modifying the impedance of the convolute section and enhancing current losses.

Figure 3 illustrates the evolution of the highest density portions of the cathode plasma by plotting the ion density at 110 ns in the θ=0 plane (at the center of the post-hole). This figure shows the extension of the dense plasma ($>10^{14}$ cm^{-3}) through the magnetic null regions upstream of the posts. On the downstream side of the posts, the plasma from the inner edge of the cathode "holes" is deflected downward somewhat, resulting is less current losses to the downstream side of the posts relative to the electron-only case.

One way to visualize the enhanced losses due to cathode plasma evolution is shown in Fig. 4, which plots the electron energy deposition on the surface of the (anode) posts. Frames a) and b) of this figure are views of the upstream side of the posts while frames c) and d) are views of the downstream side of the posts. Frames a) and c) plot the energy deposition after 100 ns from the simulations that do not include cathode plasma emission while the simulation results that include cathode plasma emission are shown in frames b) and d). The most striking evidence of enhanced electron loss is shown on the upstream side of both posts in the case of plasma evolution (frame b). These regions coincide with the end of the magnetic null that connects the cathode plate (inner edge of the cathode hole) with the post (anode).

IV. SUMMARY

New 3D EM PIC simulations have been carried out to examine the impact of cathode plasma emission and dynamics in the PHC section of the Z accelerator. These simulations suggest enhanced current losses relative to previous electron power flow simulation models due to a number of effects including: partial gap closure immediately upstream of the post-hole region, as well as significant plasma transport in the vicinity of the upstream magnetic field nulls. Total loss currents of order 2 MA are observed at the point of peak load power, consistent with experimental current measurements.

The modeling techniques discussed here are currently being applied to 1-cm Z load configurations where a larger experimental dataset exists. These simulations are computationally more difficult due to the higher magnetic fields and the small AK gaps in the vicinity of the load. Preliminary results indicate similar current loss levels. Additional work needs to be carried out to examine the scaling of these current loss mechanisms for planned, higher-current Z pinch drivers [8].

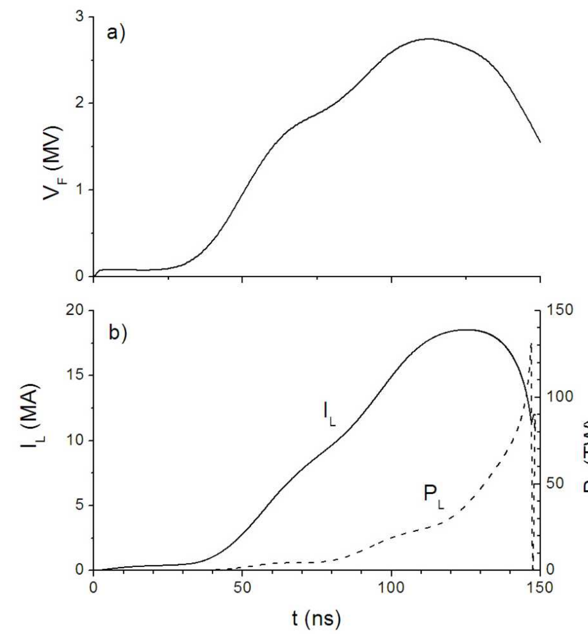

Figure 1 - a) Forward-traveling voltage waveform used at all four levels of the 2.5 Ohm convolute simulations. b) Load current and power as a function of time from a simulation without electron space-charge emission or plasma emission.

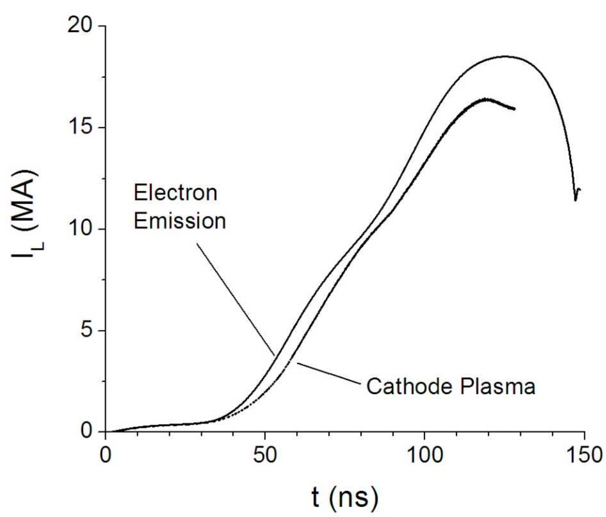

Figure 2 - A comparison of load currents as a function of time from two simulations that include electron emission. The lower curve represents a simulation that also includes the injection and dynamical evolution of plasma from the cathodes in the vicinity of the post holes.

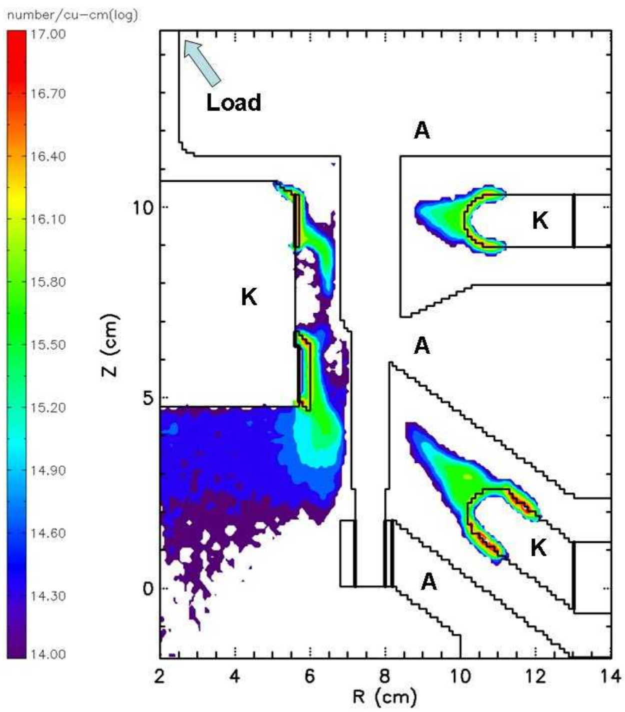

Figure 3 - Ion density (logarithmic contour levels between 10^{14} and 10^{17} cm^{-3}) at 110 ns from the simulation that includes cathode plasma emission. This slice is from the θ=0 plane, through the center of the posts. The anode and cathode sections are labeled "A" and "K", respectively. Power is feed from the right at r=14 cm. (Color figure)

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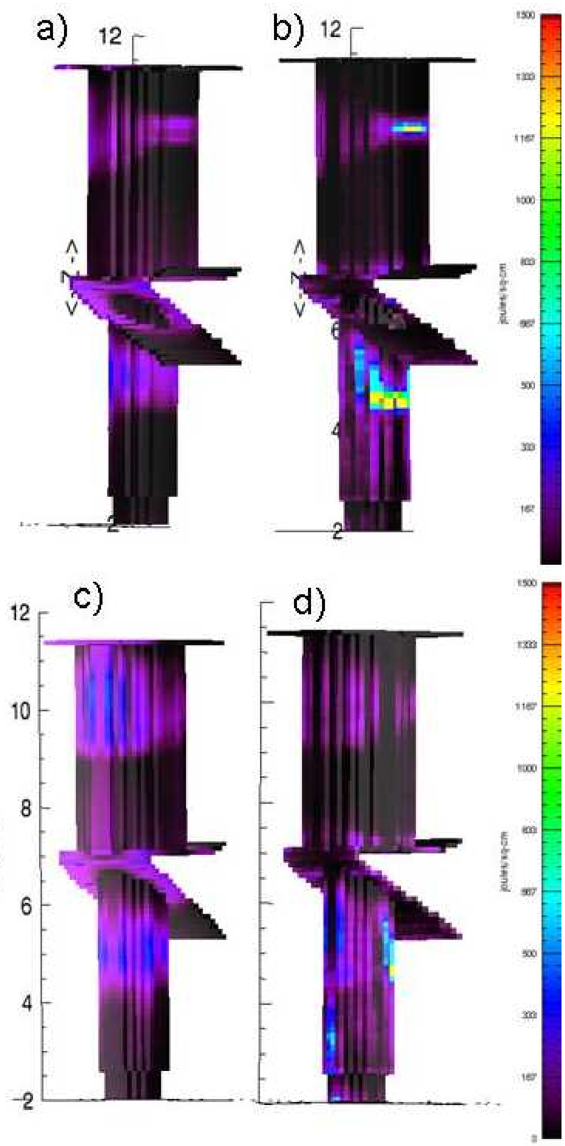

Figure 4 – Electron energy deposition after 100 ns on the posts. Frames a) and b) are views of the upstream side of the posts and frames c) and d) are views of the downstream (load) side of the posts. Frames a) and c) are from the simulation without plasma emission while frames b) and d) are from the simulation that includes cathode plasma emission. (Color figure)