SAND2007-4914C

REDUCTION OF ELECTRON FLOW CURRENT AND LOCALIZED ANODE ENERGY DEPOSITION IN TRANSITIONS FROM COAXIAL FEEDS TO A DISK

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Abstract

Many conceptual designs for fusion energy involve combining energy from a number of feed lines to a centrally located load. One such design with 70 coaxial lines (each delivering $I_a \sim 1$ MA at $V \sim 7$ MV) merging into a center disk has been shown to yield large ($I_e \sim$ 10-40 MA) electron flow currents. The combination of large electron flow currents, abrupt transitions, and magnetic nulls (inherent in this type of current-adder geometry) cause an extreme amount of energy to be deposited into localized areas of the anode. A revised design is proposed using 10 coaxial lines delivering $I_a \sim 7$ MA at $V \sim 9$ MV to provide improved magnetic insulation, hence lowering the electron flow currents. Unfortunately, it is shown that reducing the electron flow currents only provides part of the solution to the problem of localized anode energy deposition. Additional modifications to the geometry of the coaxial-to-disk transitions are also necessary to obtain results where reasonable anode temperatures are maintained. Computer simulations were used to examine these designs. The 3-D electromagnetic, particle-in-cell (PIC) code QUICKSILVER developed at Sandia National Laboratories was used for the numerical simulations.

I. INTRODUCTION

The current conceptual design for the Z-Pinch Inertial Fusion Energy (ZPIFE) driver is based on the addition of the current from a number of Linear Transformer Driver (LTD) modules. Each module drives a vacuum coaxial line. The coaxial feed lines converge radially into an annular disk that is connected to a conical Recyclable Transmission Line (RTL) at its inner radius. The configuration of this design is constrained by two decisions: the RTL must be a single-disk feed, i.e. not a triplate line with an extra inner conductor, and the conductors must enclose a sealed volume under vacuum. The second decision forces the coaxial lines to be coupled to a triplate disk configuration to close the volume and the first decision dictates that the triplate disk must be efficiently transitioned into a biplate disk. To this end, a large inductive cavity is used to direct the current down into the biplate disk. This conceptual design is illustrated in Figure 1.

The original concept uses 70 coaxial lines merging into the disk. Each of these lines delivers $I_a \sim 1$ MA at $V \sim 7$ MV. This conceptual design yields simulation results that include electron flow currents throughout the 3D structure ranging from 10 to 40 MA. As a result the design is very inefficient and the combination of the large flow currents and abrupt transitions from the feed coaxes to the disk cause an extreme amount of energy to be deposited in localized areas of the anode. This extreme amount of energy deposition causes significant damage to the anode ruining the possibility of achieving the desired frequency of operation ($f \sim 0.1$ Hz) and greatly increasing the operational cost of the ZPIFE design.

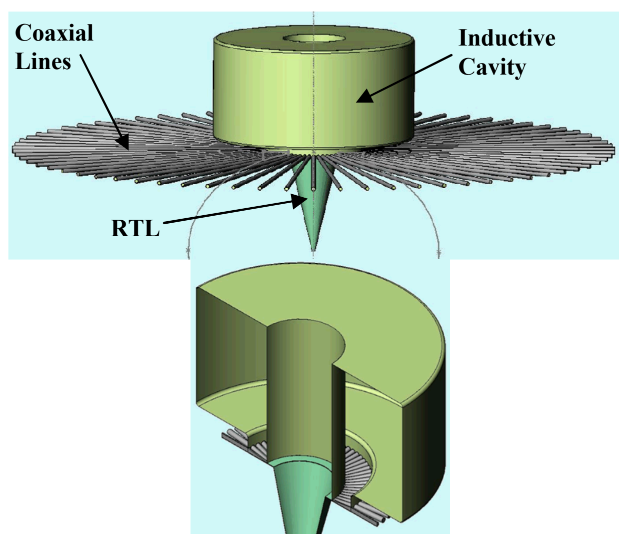

Figure 1. Conceptual design drawing of the ZPIFE driver including 70 coaxial feeds, RTL, and inductive cavity: a) exterior view and b) center-line, cut-away view.

After some initial analysis by T. D. Pointon, et al. [1], it was proposed that a revised design using fewer coaxial lines (with correspondingly higher current per line) would

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‡ Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

provide better magnetic insulation and therefore reduce the electron flow currents. The revised design uses 10 coaxial lines – each delivering $I_a \sim 7$ MA at V ~ 9 MV to ensure that a total of ~ 60 MA is delivered to the load.

Computer simulations are used to continue examination of this structure. The 3-D electromagnetic, PIC code QUICKSILVER [2] developed at Sandia National Laboratories is used for the numerical simulations. The capabilities of QUICKSILVER are especially well-suited to this problem since it has many features that were developed to model a variety of power flow issues in the Z and ZR accelerators.

II. SIMULATION SETUP

To avoid the necessity of generating a complex 3-D mesh, a simplified geometry is used to obtain simulation results. The simulations are done in cylindrical coordinates but the coaxial lines have a rectangular cross section in the ϕ-z plane. The ZPIFE structure uses 10 – 9 Ω rectangular coaxial lines feeding the inner disk MITL. Perfect symmetry is assumed for all 10 transmission lines so that the azimuthal extent of the simulations is from $\phi_{min} = 0$ to $\phi_{max} = \pi/10$ (1/20th of the overall structure). The disk-coax interface can be moved to smaller radius since there are fewer coaxial lines in this design of the ZPIFE structure. In the previous designs with 70 coaxial lines, the disk-coax interface was located at r = 5 m with 2.5 cm A-K gaps or r = 2 m with 1.2 cm A-K gaps. In the revised design with 10 coaxial lines, the disk-coax interface is located at r = 1 m with a 1.5 cm A-K gap for the disk and 3.4 cm gaps for the other three sides of the rectangular coax. The rectangular coax has uniform A-K gaps of 3.4 cm at the inlet (r = 1.3 m) but the bottom anode of the coax is tapered up closer to the cathode such that the A-K gap is 1.5 cm at r = 1 m. The inner disk is then linearly tapered to an A-K gap of 0.9 cm at r = 0.6 m. This new configuration is shown in Figure 2.

It is not practical to model the entire inductive cavity due to its large size [1]. A portion of the inductive cavity is modeled in 3-D, but the remaining inductance is modeled by a long (5 m) 1-D transmission line attached to the open end of the inductive cavity (at r = 1.2 m) and terminated with a large inductive load.

A matched 9 Ω, 5 m long transmission line is connected to the inlet (at r = 1.3 m) and is driven by a forward-traveling wave $V_f(t)$ using a source impedance of R = 0.7 Ω. The inner disk is attached to another long transmission line that models the rest of the inner disk and the RTL at r = 0.6 m. This transmission line is terminated with a fixed 1 nH inductive load, but this load can easily be replaced by a Z-pinch load. The parameters for the inner transmission line are computed from the r-z outline of the two conductors that form the RTL using the commercial IDL software package. The RTL is assumed to have inner and outer radii of r_0 = 5 cm and r_1 = 50 cm, and a height of 2 m. The A-K gap at r_0 and r_1 are g_0 and g_1, respectively. The RTL is connected to the 3-D geometry with a disk transmission line whose A-K gap is tapered linearly from the 3-D gap at r = 0.6 m to the gap at the outer radius of the RTL. Table 1 summarizes the radii and gaps used for the inner disk of the 3-D model and the RTL for the current 10-feed-line structure and for the two previous 70-feed-line structures.

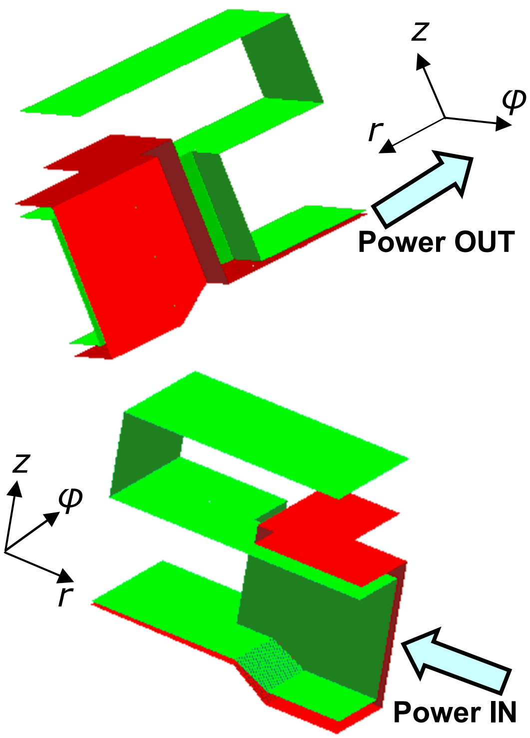

Figure 2. Three-dimensional QUICKSILVER simulation geometry for the ZPIFE driver with 10 coaxial feed lines.

Table 1. Radii and gaps for the inner transmission line.

	RTL				Disk @ r_{min}	
	r_0 (cm)	g_0 (mm)	r_1 (cm)	g_1 (mm)	r_2 (m)	g_2 (mm)
Figure 2	5	2	50	7.5	0.6	9
Geom. 1 †	5	2	50	10	4.6	25
Geom. 2 †	5	1.6	50	7.5	1.6	12

† From [1]

A simple analytic driving voltage, $V_{oc}(t) = V_0 \sin^2\omega t$, is used for the simulations. The peak amplitude of V_0 = 19.5 MV is chosen such that the current delivered to the load is approximately 60 MA and ω is chosen for a 200 ns pulse width (ω = 5π×10^6 rad/s).

III. PARTICLE SIMULATIONS

The two major areas where the original concepts for the ZPIFE driver showed problems in the initial simulations were large amounts of electron flow current, reducing the efficiency, and extreme energy deposition into localized areas of the anode. These areas will be a primary focus for the particle simulations for the revised structure. Time histories for the main currents and for the electron flow currents are shown in Figure 3. In the previous simulations, the electron flow current in the 3-D model was on the order of tens of mega amperes. Figure 3b shows that the electron flow current has been greatly reduced throughout the 3-D model due to the improvement in the magnetic insulation for each of the coaxial feed lines. This fact is reinforced in Figure 3a by the similarity in form and amplitude between the current input to the 3-D model, the current in the disk section, and the current delivered to the load. Figure 3a also shows that the inductive cavity is doing a good job of diverting most of the current into the disk section. The maximum current in the inductive cavity is only about 2-3 MA.

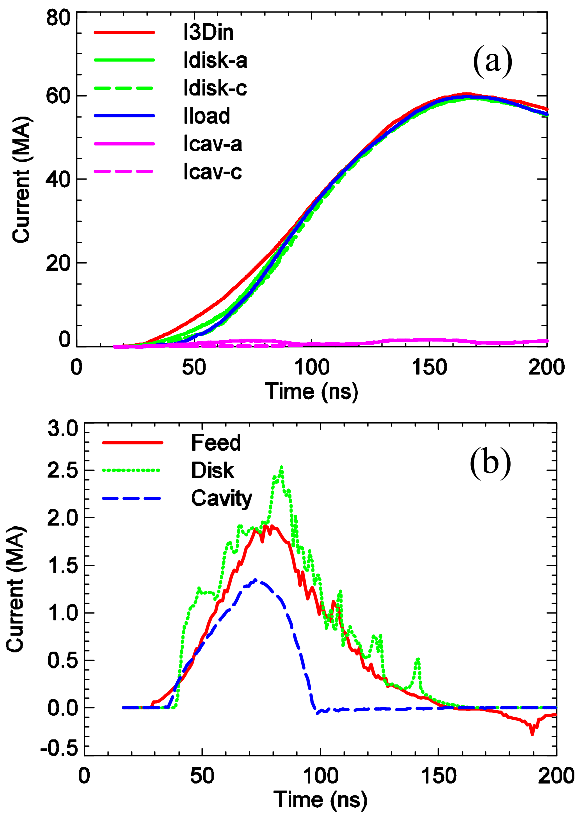

Figure 3. Time histories for the (a) current and the (b) electron flow current from the simulation of the revised ZPIFE structure.

Reducing the number of feed coaxial lines and increasing the current on each line reduced the electron flow currents but as shown in Figure 4, localized anode heating is still a problem with the revised ZPIFE structure. The apparent discontinuities in the anode temperature plots are due to the "stair step" approximation of the slanted anode conductor (several z values are being plotted so that the plot can include the entire anode).

The model used to predict the anode temperature increase is accurate for stainless steel up to T ~ 800°C. Above T = 800°C, the "temperature" from this model should only be considered a qualitative indicator of energy deposition [1].

In addressing the concern of energy deposition onto the anode conductor, anode energy deposition should definitely be limited such that the temperature of the anode conductor remains less than the stainless steel melt temperature of 1430°C. Ideally, energy deposition to the anode would be limited in a manner such that the temperature of the anode conductor remains less than 400°C. This temperature specification is made using the empirically-based temperature where impurities on the surface of the metal form a dense plasma on the anode causing the effective A-K gap to become smaller or breakdown completely [3].

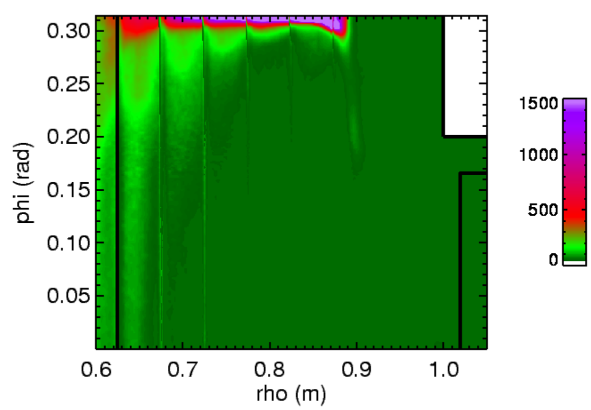

Figure 4. Contour plot of the transition region and the inner disk anode temperature ($T_{peak} \approx 9969$°C at (r, ϕ, z) = (0.8594, 0.3142, -0.1300)) at t = 200 ns for the revised ZPIFE structure.

The peak "temperature" for this simulation is $T_{peak} \approx$ 9969°C on a localized section of the anode along the centerline between adjacent coaxial feeds ($\phi = \phi_{max}$). This result is consistent with previous results for the original ZPIFE conceptual design with only a modest improvement in the peak anode temperature. However, anode heating is isolated to the region along $\phi = \phi_{max}$ whereas previous designs also included significant but less severe anode heating on the disk anode near $r = r_{min}$. The anode heating seen previously on the disk anode near $r = r_{min}$ was most likely due to the large electron flow currents propagating down the disk toward the load. The anode heating along $\phi = \phi_{max}$ however is due to the combination of the electron flow currents and a local minima of the magnetic field caused by the azimuthally asymmetric current distribution entering the disk region. The asymmetry of the current distribution is a result of the abrupt transition from the coaxial transmission lines to the disk geometry. The electron flow currents are significantly reduced, but the area over which the loss is occurring is also reduced since the transition is now at r = 1 m rather than r = 2 m or r = 5 m as in the previous simulations.

A couple of strategies for lowering the energy deposition to localized areas of the anode are investigated. The effect of lengthening the A-K gap at the loss region to increase the length of the magnetic null in the electric field direction is one of these additional strategies [4]. The gap lengthening strategy is implemented by expanding the A-K gap (by modification of the anode conductor) near $\phi = \phi_{max}$ (where the anode heating is most severe) using a simple, tapered trench. The specific configuration of this anode modification is detailed in Figure 5. In general, the results from using the gap lengthening strategy are very promising. The anode temperatures for the structure using this strategy are detailed in Figure 6. Figure 6 shows that the localized anode heating has decreased dramatically to $T_{peak} \approx$ 596°C.

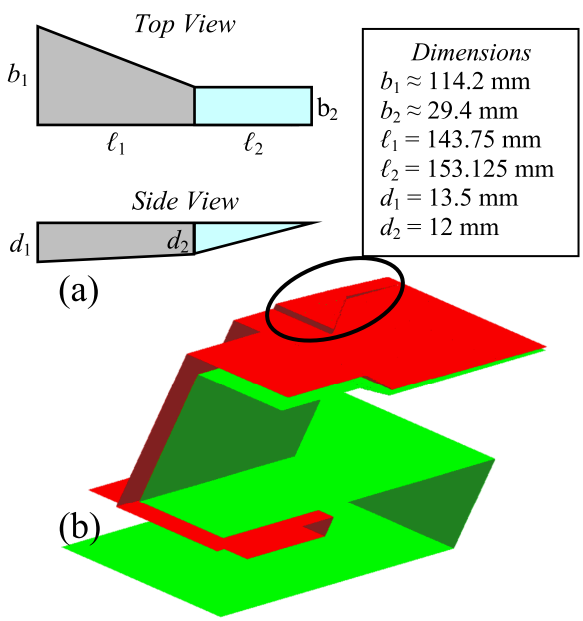

Figure 5. (a) Detailed schematic and (b) an upside-down view of the 3-D solid model showing the anode modifications used to lengthen the A-K gaps.

The second strategy for lowering the energy deposition to localized areas of the anode is to begin the transition from the feed coaxial line to the disk earlier by "morphing" the coaxial line from its normal profile to one that is flatter and wider so that the transition to the disk is more gradual. This more gradual transition will allow the currents in the transition region to be more azimuthally symmetric in the disk section since the coax-disk transition is distributed over a larger radial distance.

The 3-D geometry used for the QUICKSILVER simulations is illustrated in Figure 7. At the inlet, the coax has a square cross-section but the shape of the coax changes to a flatter and wider profile as it gets closer to the disk transition. The dimensions of the coax at the inlet (r = 1.3 m) and at the disk transition (r = 1 m) are listed and compared to the original 10-feed line structure in Table 2. The rest of the structure is scaled to match the feed coax as it connects to the disk transition. The transition from the square coax profile to the wider, flatter profile is realized with linear tapers due to time constraints. Ideally, the morphing of the coaxial line would be done more gradually with smooth edges and seamless transitions to minimize discontinuities.

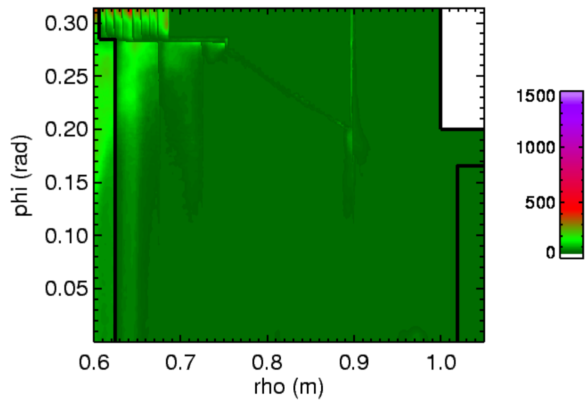

Figure 6. Contour plot of the transition region and the inner disk anode temperature ($T_{peak} \approx$ 596°C at (r, ϕ, z) = (0.6250, 0.3142, -0.1278)) at t = 200 ns for the revised ZPIFE structure with the anode modifications used to lengthen the A-K gaps in Figure 5.

Table 2. Dimensions and A-K gaps for the feed transmission line for the original 10-feed-line geometry and for the morphing 10-feed-line geometry.

	Inlet (r = 1.3 m)				Transition (r = 1 m)			
	w_{a0} (cm)	h_{a0} (cm)	g_0 (cm)	g_{b0} (cm)	w_{a1} (cm)	h_{a1} (cm)	g_1 (cm)	g_{b1} (cm)
Orig.	40.0	40.0	3.4	3.4	40.0	36.62	3.4	1.5
Mor.	23.2	23.2	2.0	2.0	60.0	18.0	7.5	1.5

† w_a ≡ anode width, h_a ≡ anode height, g ≡ A-K gap for top and sides, g_b ≡ A-K gap for bottom

Figure 8 shows that the localized anode heating is still a problem with this structure near $\phi = \phi_{max}$. The peak temperature for this structure is $T_{peak} \approx$ 7592°C. This is an improvement over the unmodified 10-feed line structure which has $T_{peak} \approx$ 9969°C. The anode heating is localized in an area very close to $\phi = \phi_{max}$ so this structure is an excellent candidate for lengthening the A-K gaps in the area where the anode heating is most severe. The A-K gap lengthening for this structure is achieved by using a geometry like that shown in Figure 5 but with the following dimensions: $b_1 \approx$ 47.9 mm, $b_2 \approx$ 29.2 mm, ℓ_1 = 75 mm, ℓ_2 = 159.375 mm, d_1 = 13.5 mm, and d_2 = 12 mm.

Figure 9 shows the anode temperature contour plot for this structure. The contour plot of the anode temperature shows that the combination of the morphing feed line and lengthening the A-K gap is very effective in lowering the energy deposition into the anode. The peak temperature for this configuration is $T_{peak} \approx 443°C$.

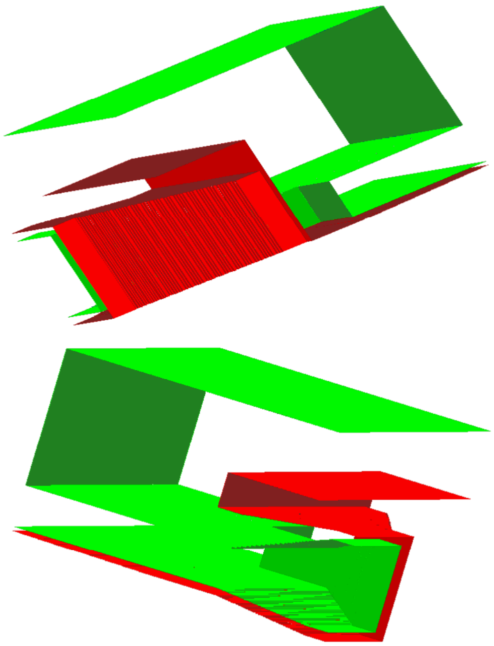

Figure 7. Three-dimensional QUICKSILVER simulation geometry for the ZPIFE driver with 10 morphing coaxial feed lines.

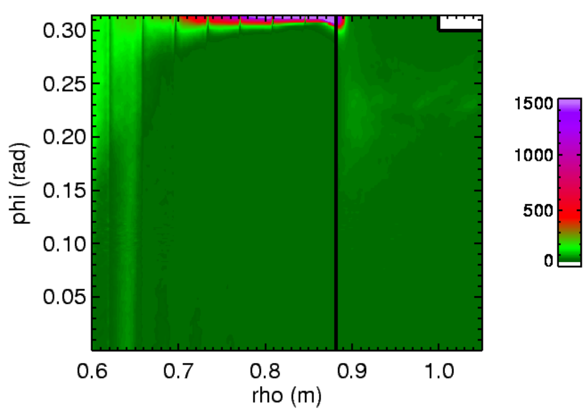

Figure 8. Contour plot of the transition region and the inner disk anode temperature (Tpeak ≈ 7592°C at (r, ϕ, z) = (0.8687, 0.3142, -0.08925)) at t = 200 ns for the revised ZPIFE structure with the morphing coaxial feed.

IV. CONCLUSION

The simulation results show that switching to a 10-feed line structure (versus a 70-feed line structure) yields a vast improvement in (lowering of) the electron flow current. Unfortunately, this reduction in electron flow current only translates into a modest improvement in the energy deposition on the anode in the transition and disk regions since the transition region area is reduced by at least a factor of two by the new location of the transition radius (r = 1 m). Two different methods of reducing this energy deposition were attempted. Lengthening the A-K gaps provides more than a factor of 16 reduction in the peak local deposition. Making the transistion from the coaxial feed line to the disk section more gradual yielded approximately a 24% reduction in the peak local deposition and the combination of the two methods yields a 22.5 fold reduction in the peak local deposition. Anode temperatures as low as ~ 440°C have been achieved in simulations using these methods. Even better results may still be possible by moving the disk transition out to larger radius and/or by using more complex geometries with smoother conductor surfaces and transitions.

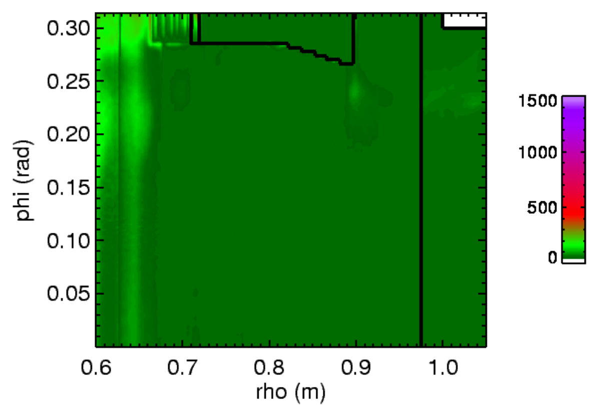

Figure 9. Contour plot of the transition region and the inner disk anode temperature ($T_{peak} \approx 443°C$ at (r, ϕ, z) = (0.7188, 0.3142, -0.0900)) at t = 200 ns for the revised ZPIFE structure with the morphing coaxial feed and the anode modifications to lengthen the A-K gaps.

V. REFERENCES

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