SAND2008-5766C

2D Radiation MHD K-shell Modeling of Single Wire Array Stainless Steel Experiments on the Z Machine

J.W. Thornhill[a], J. L. Giuliani[a], J. P. Apruzese[a], Y. K. Chong[a], J. Davis[a], A. Dasgupta[a], K. G. Whitney[b], R. W. Clark[b], B. Jones[c], C. A. Coverdale[c], D. J. Ampleford[c], M. E. Cuneo[c], and C. Deeney[d]

[P]Plasma Physics Division, Naval Research Laboratory, Washington DC 20375
[b]Berkeley Research Associates, Beltsville Maryland 20705
[c]Sandia National Laboratories, Albuquerque NM 87545
[d]National Nuclear Security Administration, Washington DC 20585

Abstract. Many physical effects can produce unstable plasma behavior that affect K-shell emission. Such effects include: asymmetry in the initial density profile, asymmetry in power flow, mass flow out the boundaries, thermal conduction at the boundaries, and non-uniform wire ablation. Here we consider the effect of asymmetry in the radiation field as a contributing mechanism for generating non-one-dimensional plasma behavior that affect K-shell power and yield. To model this effect, we have incorporated into the MACH2 MHD code a self-consistent calculation of the non-LTE population kinetics utilizing ray trace based radiation transport. Such 2D methodology is necessary for modeling the enhanced radiative cooling that occurs at the anode and cathode ends of the pinch during the run-in phase of the implosion. This enhanced radiative cooling is due to reduced optical depth at these locations producing an asymmetric flow of radiative energy that leads to substantial disruption of large initial diameter (>5 cm) pinches and drives 1D into 2D fluid (i.e., Rayleigh-Taylor like) flows. The effect of this 2D behavior on K-shell power and yield is investigated by comparing 1D and 2D model results with those obtained from a series of single wire array stainless steel experiments performed on the Z generator.

Keywords: wire array Z pinch, gas puff Z pinch, K-shell radiation, MHD, implosion.
PACS: 52.58.Lq, 52.65.Kj, 52.59.Qy, 52.30.Cv

INTRODUCTION

The 20 MA current levels of the Z generator at Sandia National Laboratories [1] have made possible the production of 125 kJ of K-shell photons exceeding 4.9 keV from titanium wire arrays [2], 60 kJ over 6.9 keV from stainless steel [3], and 30 kJ over 8.6 keV from copper wire arrays [4]. The recent refurbishment of the Z generator [5] should increase the peak current level and potentially lead to increased production of photons in the energy ranges just mentioned. However, because the short circuit current profile of the refurbished Z machine peaks ~10-15 ns later than the original generator, achieving this goal will require new load designs that can be successfully imploded from larger initial diameters in order to take advantage of higher but slightly longer rise time drive currents and energy of the refurbished Z machine. Larger diameter loads are inherently more susceptible to instability development and they typically have larger gap spacing between wires; both conditions make it difficult to quantify the larger diameter's effect on K-shell yield production. Empirical K-shell scaling formulations have been developed [6] that allow one to extrapolate a given load design's performance on the original Z machine to the different mass and energy conditions available on the refurbished Z machine. However these formulations are of limited utility when trying to predict the performance of a new larger diameter load design on the updated Z machine when the design was never experimentally benchmarked to the original Z generator.

Another analytic tool available for gaining insight into how the multidimensional effects inherent to large diameter loads affect K-shell emission is a 2D radiation-MHD hydrodynamics code that can reasonably model the ionization dynamics and radiation transport that takes place in a hot, K-shell-radiating plasma. We employ such a model in this investigation to help quantify the deleterious effect of unstable plasma behavior on producing K-shell emission. Specifically, this effect is investigated by comparing 1D and 2D model results with measured values taken from a series of single wire array stainless steel Z experiments.

EXPERIMENTS AND MODEL

The modeled experiments are 55 mm diameter, 2 cm length, stainless steel, single wire array loads that were imploded on the Z machine. There are three shots modeled: Z122 (900 μg/cm, 140 wires), Z121 (1093 μg/cm, 170 wires), and Z89 (1350 μg/cm, 210 wires). These loads produced 65 kJ, 55 kJ and 45 kJ of K-shell emission, respectively.

The magnetohydrodynamics (MHD) model used in this investigation is the MACH2 two-dimensional code [7] that has been modified to include the tabular collisional radiative equilibrium (TCRE) model [8] for treating the equation of state and radiation transport of the 2D plasma. MACH2 is a resistive MHD simulation code with three components of velocity and magnetic field but only two spatial dimensions. In this investigation the calculations have only toroidal field and in-plane velocities. The code solves for both ion and electron internal energies and it uses magnetically inhibited Spitzer diffusion and conductivity coefficients. In order to improve resolution, especially near the time of stagnation when most of the K-shell photons are emitted, a moving grid is employed. This grid moves in a quasi-Lagrangian fashion such that the original radial grid that was uniformly distributed over 3.5 cm radius has been compressed to a uniform distribution over ~1 cm radius by the time of stagnation. There are 96 radial and 96 axial grid points used in the calculations. An external driving circuit model for the Z generator is coupled to the simulation by using the magnetic energy equation to determine the Poynting flux through the input boundary. This net power addition and the current determine the simulation voltage.

The TCRE model is a computationally efficient and reasonably accurate method for modeling the ionization dynamics and radiation transport of K-shell emitting Z-pinch plasmas. The radiation source function for the model is obtained from a self-consistent collisional radiative equilibrium (CRE) calculation, not by making an *ad hoc* assumption that it is Planckian as is assumed in three-temperature LTE diffusion methods. Accurate line opacities and radiation transport are employed, and optically thin radiation is allowed to freely escape rather than diffuse. It uses a table look-up method that updates local equation of state information based on a knowledge of the plasma's electron internal energy, ion temperature, ion density, and the volumetric radiative power (W/cm^3) and opacity of a strong radiating line. A self-consistent determination of radiative power and electron internal energy depends on local plasma conditions as well as line photo-excitations that are affected by radiation generated in remote plasma regions. Consequently, a ray-trace transport of radiation is executed whenever the local plasma parameters change enough to warrant an update of the radiation field.

The circuit model for the Z generator that is used in these simulations is shown in Fig. 1, while Fig. 2 gives an example of the initial ion density profile used in the calculations. It is an *ad hoc* profile in the sense that even though we could not properly model the wire ablation physics (requires a 3D rad-MHD model), this profile does reproduce two important features of the implosion: 1) reasonable agreement with the experimental implosion times and 2) the mass is swept up in a snow plow fashion in a time that is commensurate with Lebedev's rocket model [9]. Note, the stainless steel (SS) plasma is modeled as an Fe plasma. This should be a reasonable approximation since Fe is the major constituent of SS (72% Fe, 19% Cr, 8% Ni, 1% Mn, < 1% Si and other elements) and the other constituents have atomic numbers close to that of Fe (26).

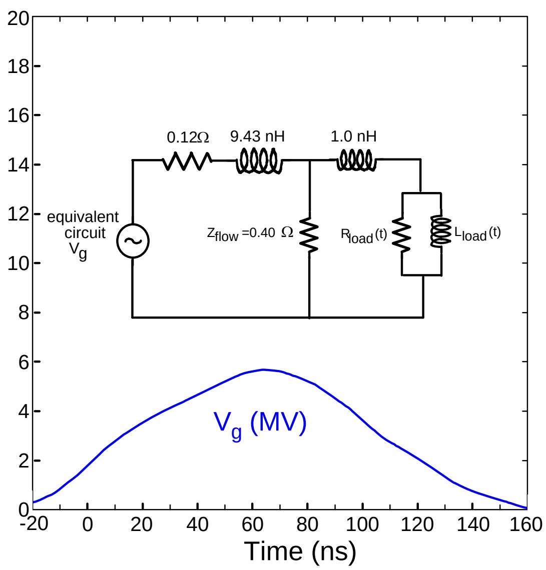

FIGURE 1. Equivalent circuit model of the Z machine.

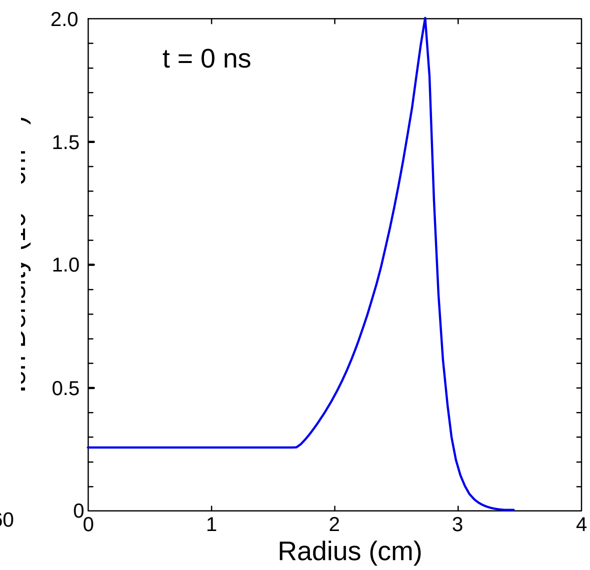

FIGURE 2. Initial density profile used in the simulation of shot Z89.

RESULTS

Fig. 3 compares 1D, 2D and experimental K-shell radiative power and yield for shot Z89. The experimental current profile is also shown in this figure. The 1D and 2D current profiles (for clarity are not shown) are nearly identical to the experimental profile for times up to 100 ns, after which they drop more precipitously with time. The total powers (not shown) were 510, 92, and 160 TW for the 1D, 2D and Z89 experiment, respectively. As one would expect from an idealized calculation, the 1D total radiative power and K-shell power are substantially larger than the observed values. The 1D K-shell yield is a factor of 5 larger that obtained in the experiment (242 kJ vs 45 kJ). What is most surprising about the results displayed in this figure is that the 2D K-shell power and yields are comparable to the experimental values. It is a surprising result because there was no initial perturbation applied to the initial density profile to instigate 2D behavior that could readily account for the substantial power and yield differences between the 1D and 2D calculations.

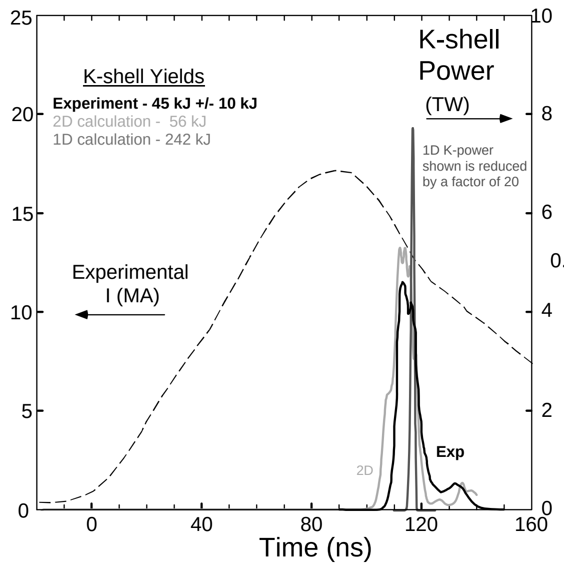

FIGURE 3. Experimental, 1D and 2D calculated K-shell powers and yields for shot Z89. The measured current profile for Z89 is also displayed.

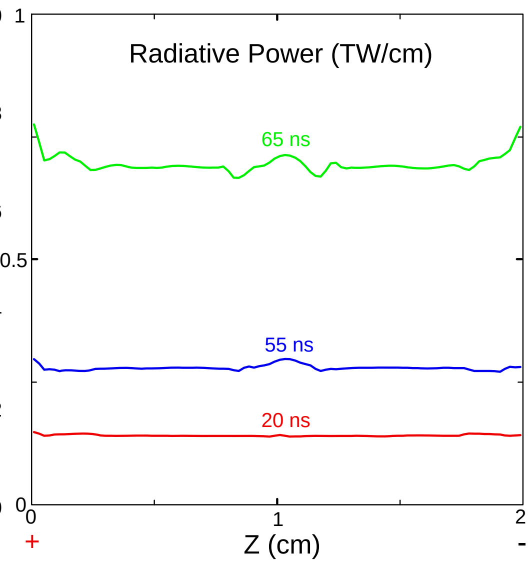

FIGURE 4. 2D calculated radiated power (TW/cm) as a function of axial position and time for shot Z89. Powers are summed over radius (+ is anode and – is cathode).

Though there was no initial perturbation included in the 2D calculation there is enough asymmetry in the radiation field to eventually disrupt the pinch. This asymmetry is largely due to the modeled vacuum boundary conditions at the anode and cathode ends of the pinch. This boundary condition results in a reduction in optical depth at these locations that leads to more radiative cooling than is present in most of the interior of the pinch. Fig. 4 illustrates this enhanced radiative cooling at the boundaries by displaying the total radiative power as a function of axial position during several early plasma run-in times. This asymmetry in the radiation field produces density and temperature gradients that eventually disrupt the pinch as the implosion progresses. The largest optical depth in the plasma occurs at the midplane (z = 1 cm) and produces a slightly larger temperature there which also produces an enhanced radiative power relative to most of the other axial locations.

Contour plots of the ion density and the K-shell power at the time of peak K-shell emission (115 ns) in the simulation of shot Z89 are shown in Fig 5a and 5b, respectively. These two figures illustrate the disorganized structure of the K-shell emitting plasma and they also show that regions of high plasma density somewhat correlate with the locations of highest K-shell power.

As mentioned earlier shots Z121 and Z122 were also modeled. The calculated powers and yields for these two shots were also comparable to the experimental values. The yields for shots Z121, Z122, and Z89 were 65 [46], 55 [55], and 45 [56] kJ, respectively. The calculated yields are shown in brackets. The calculations did not show the same decrease in K-shell yield with increasing mass trend that was observed in the experiments.

Accounting for most of the relevant physics that gives rise to unstable plasma behavior that affect K-shell emission would require a 3D rad-MHD model for which nearly all the asymmetric effects are correctly modeled (e.g. boundary conditions, power flow, initial density and breakdown conditions, and radiation field). In the work presented here only asymmetry in the radiation field was considered and it may or may not be one of the dominant competing mechanisms that produce unstable plasma behavior that affects K-shell emission. However, regardless of the source of the instability development, it is likely that a mitigation scheme that reduces this behavior should lead to increased K-shell yields.

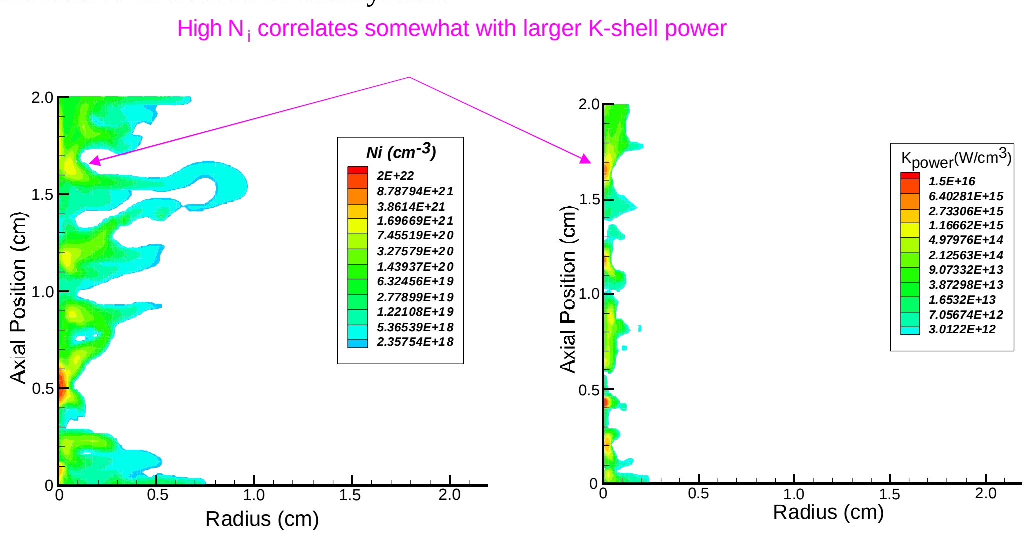

FIGURE 5. Ion density (a) and K-shell power (b) contour plots at the time of peak K-shell emission (115 ns) in the 2D calculation for shot Z89.

We investigated such schemes by performing 2D calculations for two different profiles: 1) a uniform fill and 2) one similar to the double-puff with central jet profile [10,11] measured at the midplane. It is believed that the large density peak on axis exhibited in the second profile is responsible for the substantial increase in argon K-shell yields achieved on the Decade Quad generators [10,12]. Both profiles are initially one-dimensional with only radial dependence, and both were normalized to a 55 mm diameter cylindrical geometry and 1350 μg/cm. The K-shell yields and powers calculated for the uniform fill profile were comparable to those observed and previously calculated for the 1350 μg/cm load, Z89. However, the results for the structured profile were much improved. The K-shell power was a factor of ten larger and the yield was increased a factor of three over the previous calculation for Z89. This result in conjunction with the experimental success of the double-puff with central jet configuration is encouraging for pointing out a promising design direction for future K-shell-emitting wire array experiments.

CONCLUSIONS

In the work presented a 2D rad-MHD model that is capable of reasonably modeling the equation of state and radiation transport present in a hot, K-shell-emitting Z-pinch plasma was employed to simulate stainless steel single wire array experiments performed on the Z generator. It was theoretically demonstrated that the two-dimensional radiation field can be a contributing mechanism for causing large diameter wire arrays to become unstable during the implosion process. This radiation-driven non-1D behavior was calculated to significantly reduce the K-shell emission below that achievable in a 1D simulation.

The reduction of the adverse effects of unstable plasma development on K-shell yield from large diameter loads (whether these effects be instigated by asymmetries in the radiation field, power flow, boundary conditions, initial density profiles, etc) will require new load designs. Here we theoretically demonstrated that the initial density profile that leads to substantial improvement in argon K-shell yields on Saturn and Decade Quad would also improve stainless steel K-shell yields on the Z machine.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy/NNSA.

REFERENCES

1. R.B. Spielman, *et al*., Phys. Plasmas **5**, 2105 (1998).
2. C. Deeney, *et al*., Phys. Plasmas **6**, 2081 (1999).
3. B. Jones, *et al*., J. Quant. Spectrosc. Radiative Transfer **99**, 341 (2006).
4. C. Coverdale, *et al*., "Dynamics of copper wire arrays at 1MA and 20 MA generators," in *Dense Z-Pinches*, J. Chittenden, Ed. AIP Conf. Proc. **808**: AIP New York, 2006, pp. 45-48.
5. D.H. McDaniel, *et al*., " The ZR Refurbishment Project," in *Dense Z-Pinches*, J. Davis, C, Deeney, and N.R. Periera, Ed. AIP Conf. Proc. **651**: AIP New York, 2002, pp. 23-28.
6. J.W. Thornhill, *et al*., IEEE Trans. Plasma Science **34**, 2377 (2006).
7. R. E. Peterkin, Jr., *et al*., J. Comput. Phys. **140**, 148 (1998).
8. J. W. Thornhill, *et al*., Phys. Plasmas **8**, 3480 (2001).
9. S. V. Lebedev, *et al*., Phys. Plasmas **9**, 2293 (2002).
10. J.S. Levine, *et al*., Phys. Plasmas **13**, 082702 (2006).
11. H. Sze, *et al*., Phys. Plasmas **14**, 056307 (2007)
12. R. J. Commisso, *et a*l., Proc. 16^{th} IEEE Pulsed Power Conf., 1773 (2007)