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Two Dimensional RMHD Modeling of Effective Ion Temperatures in Recent ZR Argon Experiments

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Abstract. Radiation magnetohydrodynamic *r-z* simulations are performed of recent Ar shots on the refurbished Z generator to examine the effective ion temperature as determined from the observed line width of the He-γ line. While many global radiation properties can be matched to experimental results, the Doppler shifts due to velocity gradients at stagnation cannot reproduce the large experimentally determined width corresponding to an effective ion temperature of 50 keV. Ion viscous heating or magnetic bubbles are considered, but understanding the width remains an unsolved challenge.

INTRODUCTION

During the past few years the capability to drive gas puff z-pinch loads has been demonstrated on the refurbished Z generator at Sandia National Laboratories [1]. Three recent Ar shots (Z2559-Z2561) were reported by Jones, *et al*., [2] using an 8 cm diameter, 2.5 cm length, double-shell nozzle. The Marx charging of 85 kV and plenum pressures for the separate shells were the same for all experiments. The initial density profile had a outer-to-inner shell mass ratio of 1:1.6 and a total mass loading of 1 mg/cm. The measured K-shell yields, peak K-shell powers, and pulse widths were impressively similar with average values of 330 kJ, 27 TW, and 7.9 ns, respectively. Analysis is continuing on these shots. In [2] a two zone core-blanket model for the plasma at the time of peak power was developed to best match three observed ratios of H-like to He-like lines. The best fitting model has a 1.4 mm radius core of electron temperature (T_e) = 2.4 keV and ion density (n_i) = 6.7×10^{19} cm^{-3}. The blanket extends out to 4 mm radius with T_e = 0.11 keV and n_i = 2.5×10^{19} cm^{-3}. A separate analysis in [3] examined the current losses in the Z refurbished generator. A circuit model was coupled to a two dimensional radiation-magnetohydrodynamic (RMHD) simulation code and the current losses were varied to best match global properties of the experiments, namely the MITL and feed currents, the K-shell yield, the K-shell and total power pulse shapes, and the line to continuum fraction of the K-shell emission. It was found that including current losses in the feed section as well as the convolute could satisfactory reproduce the constraining data. The calculated load current, which is not directly measured, peaks at ~14 MA and drops to ~10 MA at stagnation. The analysis in Ref. [3] is a follow-up to pre-shot calculations of Ref.[4] designed to determine, among several choices, the optimal total mass loading and initial density profile.

The objective of this brief article is to use results from the best matching RMHD simulation in [3] to compare with experimental data other than the global properties mentioned above. In particular, a companion article in this Conference Proceeding by Apruzese, *et al.,* [5] notes that the observed broad width of the Ar He-γ line (14 eV) requires a Doppler broadened component with an effective ion temperature (T_i^{eff}) of 50±10 keV (not necessarily thermal), even after accounting for instrumental, opacity, and Stark broadening. The He-γ line was chosen for this analysis because it is isolated and unaffected by satellites. Large line widths have been observed before and the extant literature on this topic is presented in [6]. The cause of this phenomenon remains somewhat controversial due to many possible contributing effects: purely thermal, turbulence, vorticity, or directed motion. A RMHD simulation in [6] found that the time variation of T_i^{eff} observed from a Ne gas puff on a small 500 kA pulsed power generator at the Weizmann Institute of Science [7] could be explained by steep velocity gradients at stagnation and the resultant Doppler shifts. In this case T_i^{eff} decreased from ~4 keV at 6 ns before peak power to 0.5 keV at 4 ns after. Given this agreement between experiment and simulations, it is natural to determine if the simulation of [3] could also explain the T_i^{eff} = 50 keV at peak power on the much larger (~15 MA) Z generator.

SIMULATIONS AND RESULTS

The two dimensional (*r,z*) RMHD code Mach2-TCRE was used for the simulations in [3]. The MHD component is performed by Mach2, while the collisional-radiative ionization kinetics is handled in a three dimensional table look-up. Further details including the radiative transport with references are provided in [3]. The RMHD model used in [3] and in this study is different that of [6] in that an Ar atomic table is used instead of a Ne one and the radiation transport is improved to self-consistently treat non-local absorption. Fig.1 displays the ion density, electron temperature and radial velocity at three times around peak power (t = 0 ns). For comparison, the density and temperature of the two-zone model at peak power from [2,5] are shown. The MHD simulations have about the same central density at t = 0 ns as the core of the two-zone model, but the temperature is much higher over the region of the blanket. One can see rapid changes in the plasma from the MHD model during these times.

The simulations provided, at each time step, the computational grid and, for each cell, the thermal ion and electron temperatures, radial velocity, and populations of the upper and lower states of each spectral line of interest. This information can be post-processed to calculate synthetic spectra for the He-γ line. Consider a set of parallel rays perpendicular to the z-axis that cover the entire plasma volume. Along each ray the radiative transfer equation is solved using a frequency grid that covers a chosen radiative transition and is sufficiently dense to resolve Doppler shifts of a few km/s. Since the populations for the He-like ground and He-γ levels are known from the simulations one can readily calculate the emissivity and absorptivity at each frequency. In each cell the vector velocity is projected onto the ray and the line profile of the emissivity and absorptivity are Doppler shifted from the at-rest line center. The result of summing the resultant He-γ intensities over the plasma for three times is shown in Fig.2. The effective ion temperature is determined from the FWHM of the synthetic line profile:

$$\text{FWHM} = 2\sqrt{\ln 2}\sqrt{2k_B T_i^{eff} / m_i}\,(E_o / c)$$

where k_B is the Boltzmann constant, m_i is the ion argon mass, E_o is the line center energy (3875 eV), and c is the speed of light. The effective Doppler width (=FWHM) is displayed in the middle panel of Fig.2 along with the observed He-γ profile for shot Z2560 at +0.4 ns. Clearly the calculated effects of Doppler shifts due to the velocity gradients of the simulation do not account for the observed much wider line width at the time of peak power.

The same procedure employed to calculate T_i^{eff} from synthetic spectra at t = 0 ns can be performed throughout the stagnation. The result is shown in the upper section of Fig.3. One sees that early in the stagnation the simulated T_i^{eff} due to Doppler shifts is many tens of keV, and exceeds the one measured value of 50 keV. By t = 0 ns the simulated T_i^{eff} has decreased to ~19 keV, at least a factor of two below the range of observed value. Also in Fig. 3 we have the thermal ion (T_i) and electron (T_e) temperatures from the simulation. These two plasma temperatures were determined by averaging over the plasma volume weighted by the K-shell radiative power. This has the effect of estimating the temperature of the K-shell emitting regions. The sharp increase in T_i at -9 ns represents the thermalization of the implosion kinetic energy. As the stagnation proceeds the ion and electron temperatures equilibrate. The small increase of T_e throughout stagnation reflects the loss of electron energy through collisional excitation and subsequent radiation.

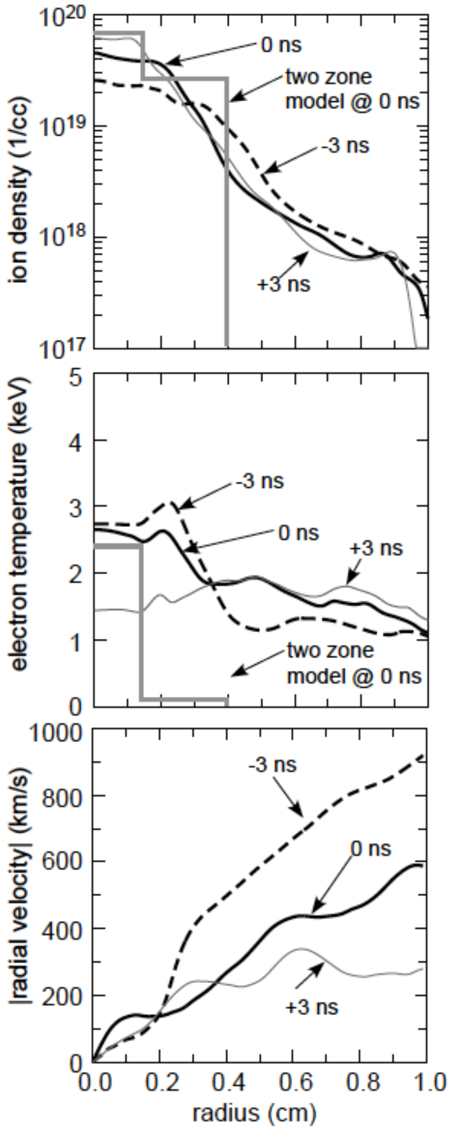

Fig.1 Ion density, electron temperature, and velocity as a function of radius from the simulations at -3 ns before, at, and +3 ns after peak power. These curves result from averaging along the axial direction. The density and temperature of the two zone model [2,5] are the straight lines.

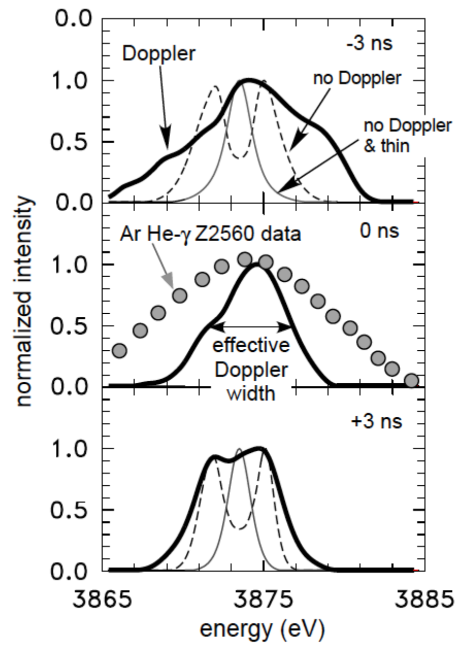

Fig. 2 Synthetic Ar He-γ line profiles from the simulations at the same times as in Fig.1. The middle panel shows the observed He-γ profile for Z2560 at 0.4 ns after peak power. The effects of radiation transport on the line profile when the Doppler shifts are neglected (dashed line) and, in addition, when opacity is neglected (light line) are shown in the top and bottom panels. In all cases the synthetic and observed profiles are normalized to a peak of unity.

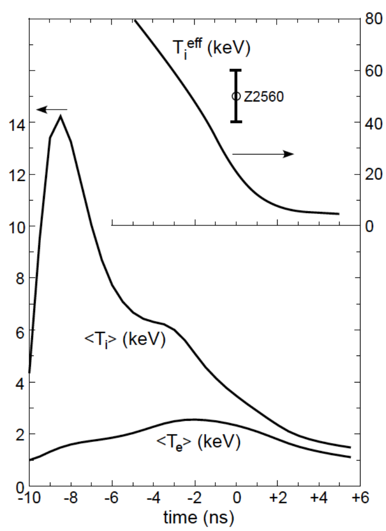

Fig. 3 Effective ion temperature and thermal ion and electron temperatures from the simulations during stagnation. The data point for Z2560 is noted.

DISCUSSION

The large 14 eV width of the He-γ line in Z2560 is not explained solely by Doppler shifts from radial velocity gradients based on our RMHD simulations, in contrast to the case of Ne in [6]. This may arise from a number of factors stemming from the approximations used in our simulation. First, the He-γ emission in the experiments may be generated from regions of the plasma with different densities and temperatures than the regions of the plasma responsible the bulk K-shell emission. This scenario would not be consistent with the TCRE approach used to model the ionization kinetics because this approach assumes the emission from the He-γ line is determined from the opacity in the bulk K-shell emitting He-α line. Second, our two dimensional (*r,z*) model implicitly implodes to a central axis. If the stagnation is not symmetric, *i.e*., is 3D, one may have parcels of plasma passing through the axis at high speed. If this is the case one has to understand how the He-like ionization stage is reached without thermalization of the directed radial velocity. There is also the possibility of vorticity and turbulence, though the velocities in these features would need to be near transonic. Another possibility is ion viscous heating as proposed by Haines [8,9]. From the simulations we find near stagnation $n_e \sim 8\times10^{20}$ cm^{-3}, $\overline{Z} \sim 17$, $T_e \sim 2$ keV, and $T_i^{eff} \sim 20$ keV. The magnetic Prandtl number is the ratio of the ion kinematic viscosity to the resistive diffusivity, $P_{r,mag} = \nu_{ii} / (c^2\eta / 4\pi)$, where η is the resistivity. The above numbers give a magnetic Prandtl number of ~6. According to Haines [8] this is a slightly viscous pinch. If $T_i \sim 4$ keV is used instead of T_i^{eff}, then $P_{r,mag}$ is only ~0.1 and the pinch is resistive. For the viscous pinch with $I \sim 10$ MA, $\ell = 2.5$ cm, a pinch duration of 5 ns, a radius r ~0.4 cm and mass $\mu = 1$ mg/cm from, then the enhanced energy deposition due to ion viscous heating [9] is

$$E_{enhanced} \sim R_{enhanced} I^2 \Delta t = (\frac{\ell}{2\mu^{1/2}c^3}\frac{I}{r}) I^2 \Delta t \sim (0.1\Omega)(10\ \mathrm{MA})^2 (5\ \mathrm{ns}) \sim 50\ \mathrm{kJ}$$

This formula for the enhanced energy is the same for the enhanced energy in the magnetic bubbles model of Velikovich, *et al.,* [10]. If this energy were all put into the K-shell emitting ions their temperature rise would only be ~5 keV. Adding this to the ion thermal temperature is far short of the observed 50±10 keV from the He-γ line. On the other hand if only the K-shell core properties from [5] are used (r ~0.14 and $\mu = 0.27$ mg/cm) the temperature rise would be >100 keV. The case for or against ion viscous heating or magnetic bubbles to explain the large effective ion temperatures is not clear. The problem of large line widths in z pinches is as yet unsolved and remains challenging.

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