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X-ray Power Increase from Symmetrized Wire-Array z-Pinch Implosions

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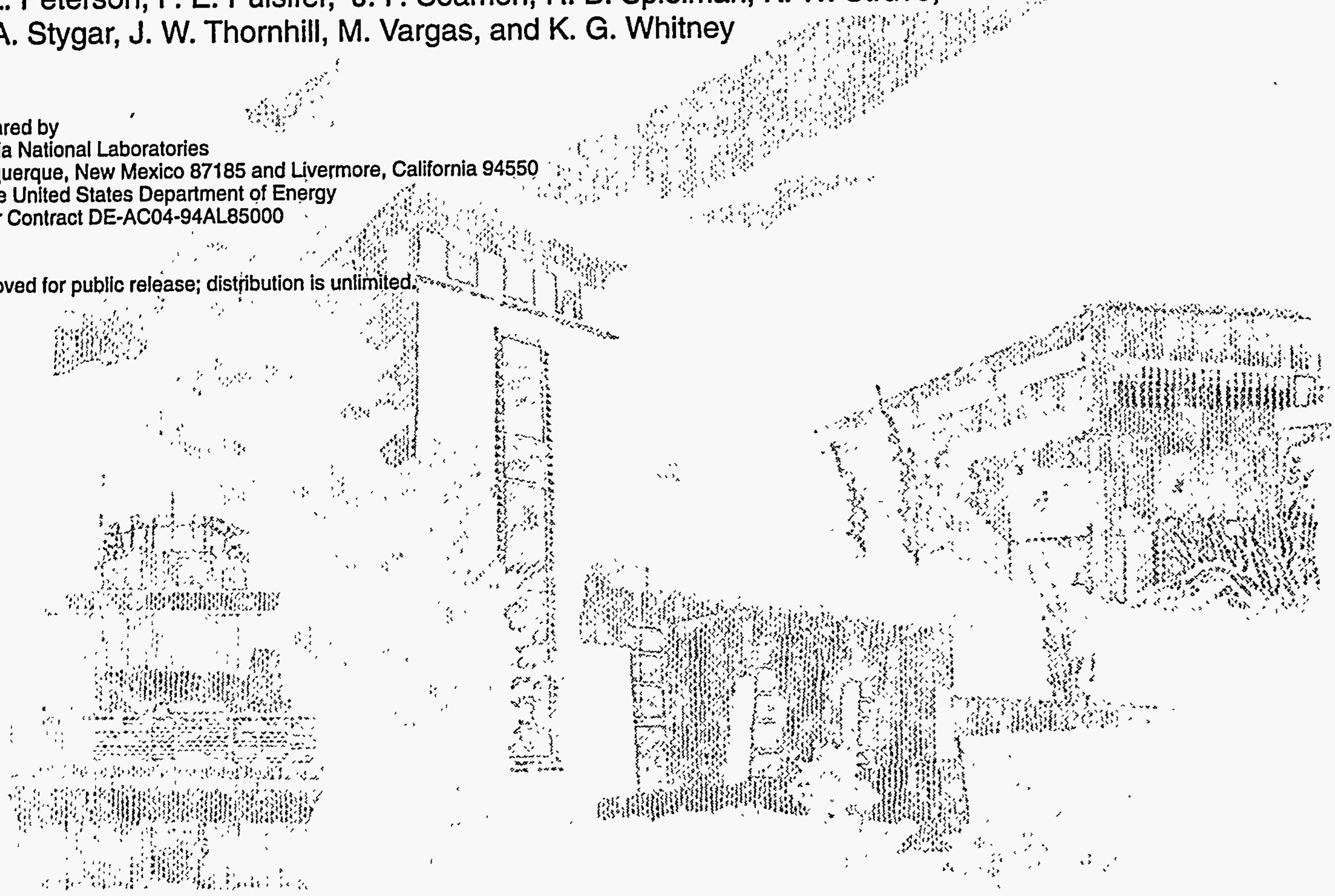

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Abstract

A systematic experimental study of annular aluminum-wire z-pinches on the Saturn accelerator shows that, for the first time, the measured spatial characteristics and x-ray powers can approach those of two-dimensional, radiation-magneto-hydrodynamic simulations when large numbers of wires are used. Calculations show that the implosion begins to transition from that of individual plasma wires to that of a continuous plasma shell, when the circumferential gap between wires in the array is reduced below 1.4 +1.3/-0.7 mm. This calculated gap coincides with the measured transition of 1.4 ±0.4 mm between the observed regimes of slow and rapid improvement in power output with decreasing gap. In the plasma-shell regime, x-ray powers in excess of a factor of three over that generated in the plasma-wire region are measured.

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X-ray Power Increase from Symmetrized Wire-Array z-Pinch Implosions

I. Introduction

Maintaining cylindrical symmetry in z-pinch implosions is an important element of plasma-radiation-source (PRS) load design. Ideal implosions require an annulus with perfect axial and azimuthal uniformity. The additional requirement of low mass, typically less than 500 μg/cm for fast drivers such as Sandia's Saturn accelerator [1], makes fabricating the ideal cylinder challenging. The high-symmetry, low-mass trade-off has historically led to the choice of gas jets, low-density foams, or thin foils over cylindrical-wire arrays for z-pinch loads. Thin foils have demonstrated similar peak power performance to that reported on here [2]. However, these thin foils were expensive and difficult to fabricate, which has precluded their routine use on Saturn.

Data [3-8] and analyses [9] suggest that reducing azimuthal asymmetries, such as the granularity introduced by discrete wires, leads to improvements in implosion quality. Here, implosion quality refers to high radial compression in the PRS required to (1) generate high thermal x-ray power for achieving high temperature in hohlraums, (2) achieve excitation of high-atomic-number K-shell x rays for nuclear-radiation-effects studies, and (3) provide a testbed for phenomenological studies of such sources with one- and two-dimensional computer codes.

Because of the potentially significant benefits derivable from the improved symmetry using wire arrays, we systematically studied experimentally and theoretically the dynamics of aluminum wire implosions as a function of the gap between wires while keeping the array mass fixed for two load geometries on Saturn. Aluminum was chosen for the large existing database and because array mass, radius, and implosion-time constraints for maximum radiation output could be easily maintained over a large range of gap spacing.

The experimental arrangement was that of Ref. 10 and, in general, was similar to Ref. 11, except for the number of wires used in the array and the diagnostics employed. One load geometry consisted of a 615- to 656-μg array of wires positioned at a radius of 8.6 mm whose wire number was varied from 10 to 136, and the other geometry consisted of an 820-μg array positioned at a radius of 12 mm whose wire number was varied from 13 to 192. Eight current return posts were positioned at 17- and 27-mm radii for the small and large radius loads, respectively. For both load configurations, 20-mm wire lengths were used. About 7 MA with a ~ 35-ns 10-to-90% rise time flowed through the load. Radiation detectors included a bolometer, arrays of filtered x-ray diodes (XRDs) and photoconducting detectors (PCDs) covering x-ray energies from 200 to 7000 eV, a time- and radius-resolved

KAP crystal spectrometer covering 150 to 3500 eV, and two time-resolved x-ray pinhole cameras having x-ray sensitivities above 200 and 1000 eV.

The detailed measurements made with these detectors are summarized in this paper and correlated with numerical simulations in the xy plane using a particle-in-cell magnetohydrodynamic code (MHC) [12] and in the r-z plane using a two-dimensional (2D) multi-photon-group Lagrangian radiation magnetohydrodynamic code (RMHC) [13], a 2D three-temperature Eulerian RMHC [14], and the 2D MACH2 RMHC [15]. The Lagrangian RMHC calculations for a 1-mm axial length permitted detailed comparisons with the measured radiation. The Eulerian calculations modeled the entire axial length prior to compression. The Eulerian RMHC permitted the simulations to be reliably extended beyond peak compression. Measurements of our large-wire-number implosions were highly reproducible and correlate well with the simulations. These correlations permit, for the first time [13], detailed studies of PRS phenomenology to be made without the complications of gross instabilities and significant asymmetries.

II. xy Characterization

As the number of wires in either radius load is increased, the quality of the pinch is monotonically improved as determined by (1) the inductive current notch at the time of implosion (0 ns in Fig. 1), (2) the radial compression ratio, and (3) the radiation rise time, pulse width, and peak power [10]. As an example, Fig. 2 illustrates the significant reduction in rise time (from 48 to 2.3 ns) and in pulse width (from 60 to 3.2 ns), and the associated increase in power (from 0.7 to 5 TW) that occurs for one of the K-shell x-ray detectors when the number of wires is increased from 10 to 90 for the small radius load. Moreover, when the data from the various radiation detectors is plotted as a function of the circumferential gap between the wires, as illustrated in Fig. 3 for the total power, the data from the two radial scans appear to fit a single curve dependent on gap alone. This figure shows that not only does the total x-ray power increase with decreasing gap, but that below a gap of about 1.4 mm, the increase in power with decreasing gap becomes rapid—almost as if a transition between two different states of implosion is occurring. This transition from slow to rapid power increase at 1.4±0.4 mm is observed in all x-ray channels. Over the 6- to 0.4-mm range in gap explored, the associated total energy measured increases by about 60%. This increase is somewhat more than the increase in the calculated kinetic energy imparted to the implosion at stagnation due to the factor of two increase in the measured compression ratio.

Using the measured current and a 1D-Lagrangian RMHC, the dynamics of a single-wire plasma, starting from the solid state, was calculated and used as input to the xy code simulation. This simulation allows the merging and compression of the wire plasma to be tracked as illustrated in Fig. 4A and 4B, for a 10- and 40-wire load configuration, respectively. These simulations show that the plasma of each wire will remain localized and will *never* merge with its neighbor until stagnation is reached provided that (1) the plasma from the adjacent wire does not merge before the system begins to implode (Fig. 4A), and (2) the current in a single wire is high enough to generate self-pinching. Thus, the shot-to-shot

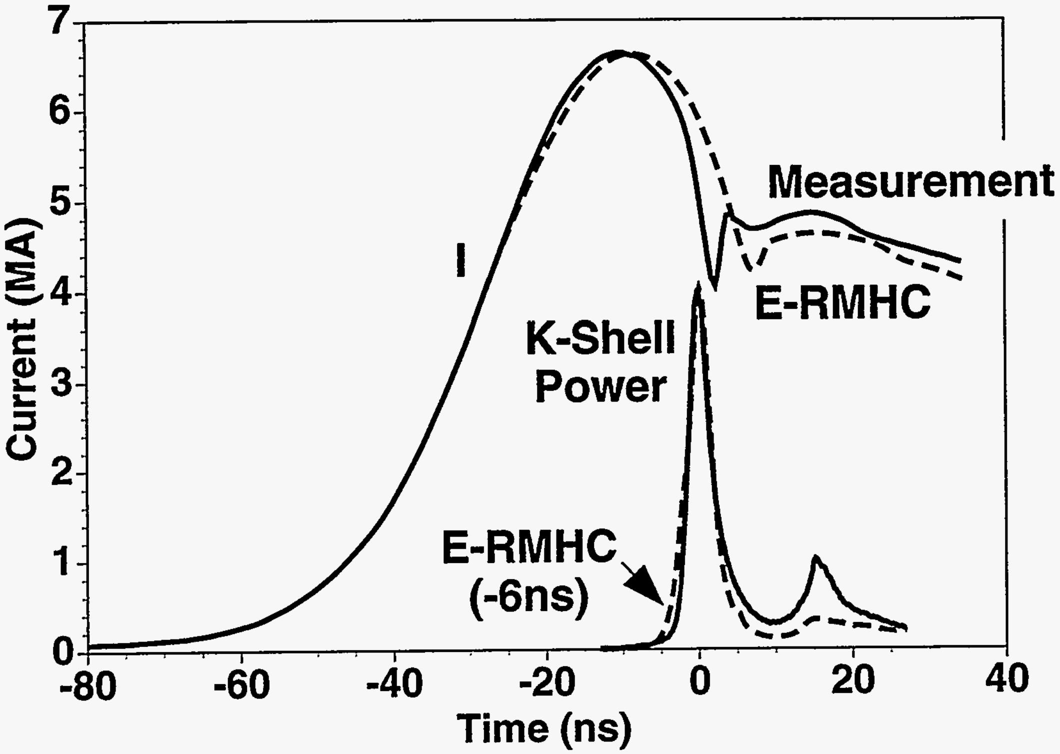

Figure 1. Comparison of measured (solid) current with Eulerian RMHC simulation (dashed) showing associated experimental K-shell and the RMHC total relative powers.

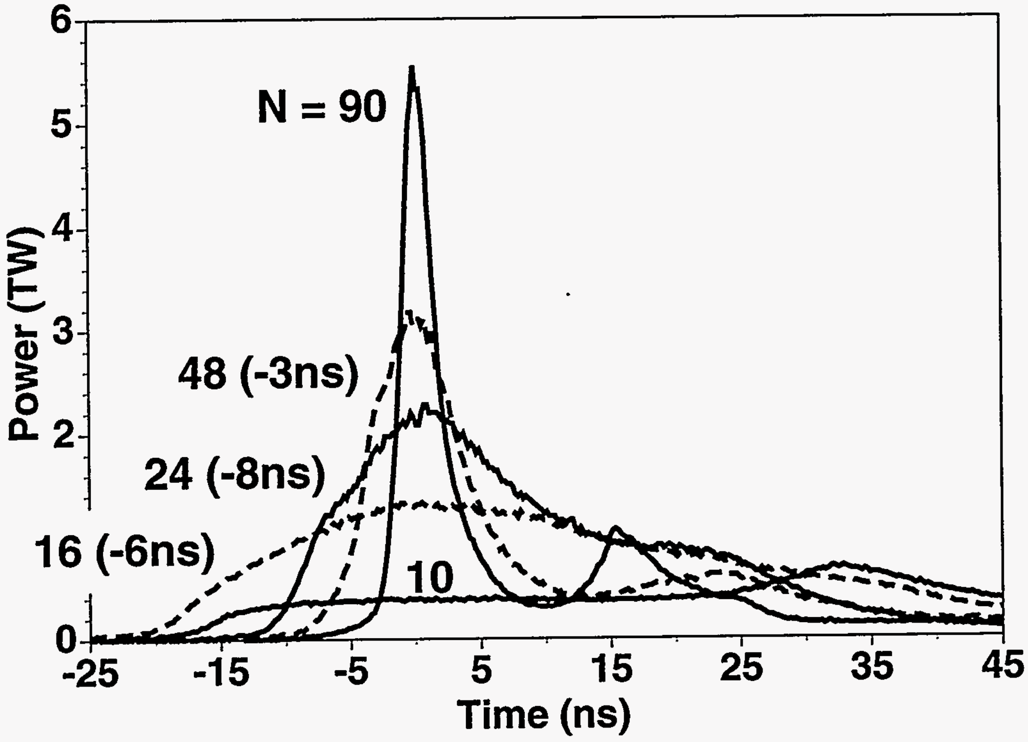

Figure 2. K-shell power versus wire number. Times in parenthesis show shift required to align time of peak power.

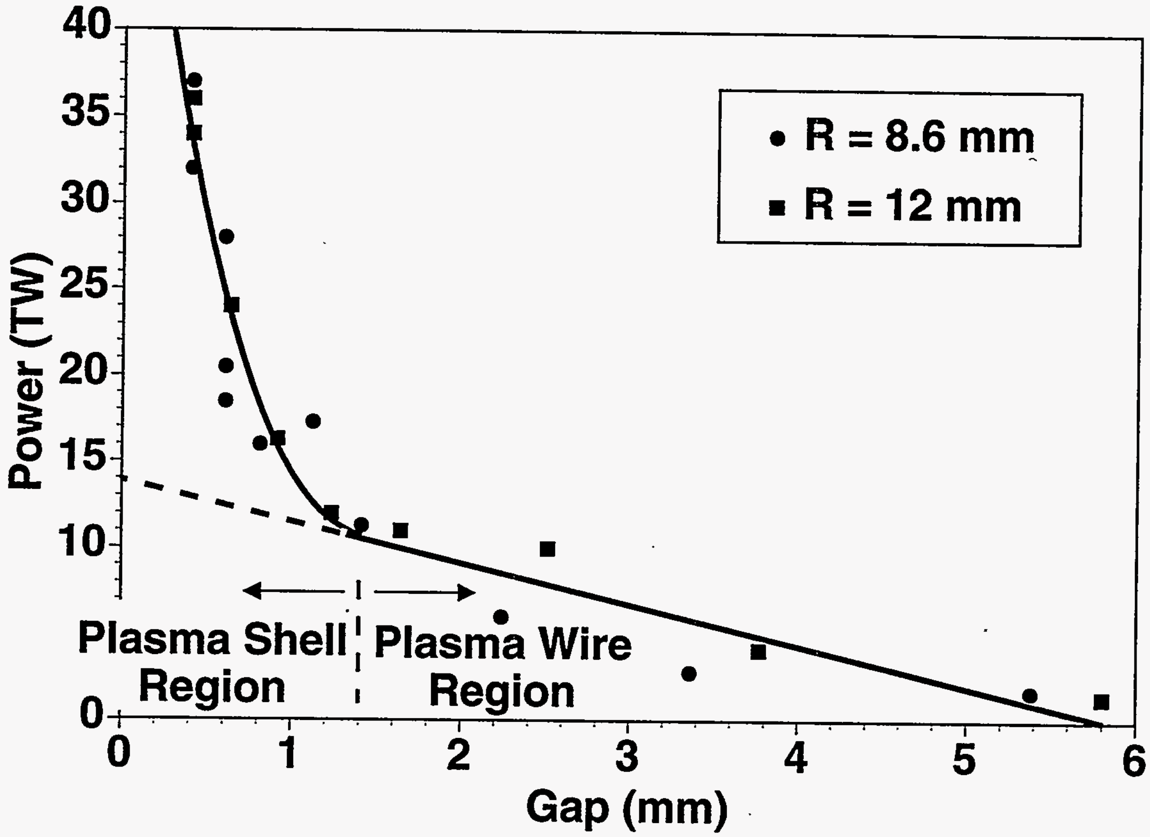

Figure 3. Total x-ray power versus wire gap.

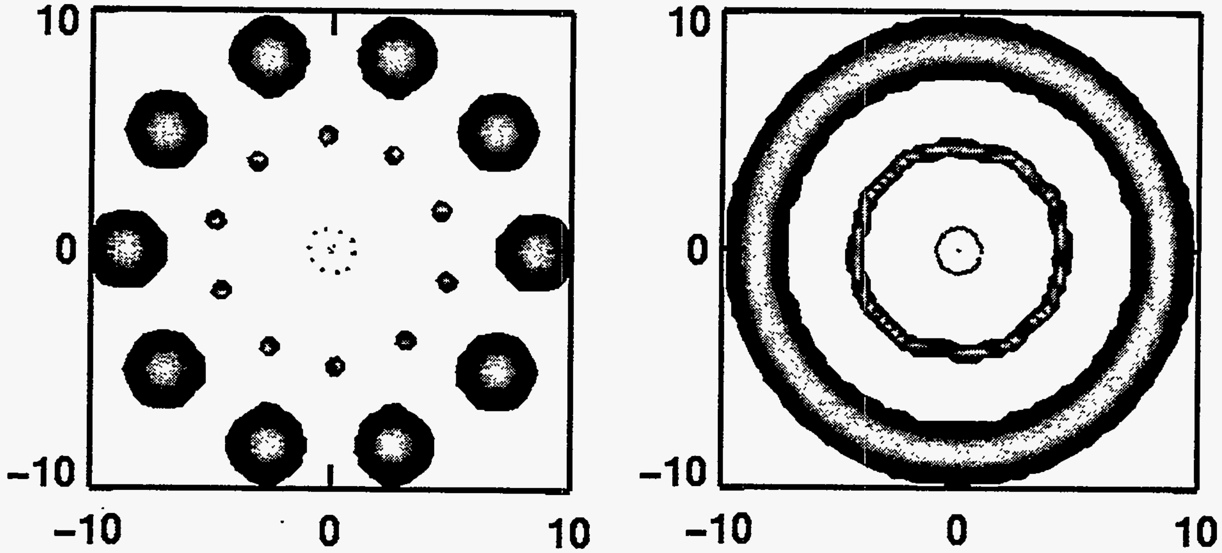

Figure 4. x,y simulation in mm units of (A) 10- and (B) 40-wire implosions at 86, 11, 3, and 0 ns before stagnation for small radius load.

time-dependent radiation output and low-power characteristics of the historically large-gap wire implosions are likely due to the random nature and shearing [8] of self-pinched wires and the straggling of the wire plasmas as they approach stagnation.

Importantly, these simulations show that only when the gap is reduced below 1.4 +1.3/-0.7 mm do the wires begin to merge to form an annular shell that remains a shell throughout the implosion process (Fig. 4B). This calculated merge point of ~ 1.4 mm coincides well with the measured transition between the regimes of slow and rapid increase in power with decreasing gap. It is also consistent with the measurements made with the fast-framing x-ray pinhole camera, which showed that even for gaps as small as 1.4 mm, the individual wires were seen to implode as separate entities until just before peak compression, whereas the high-power small gap shots showed the formation of a well-defined plasma shell. Moreover, the calculations also show an improvement in the merger with decreasing gap that helps explain the continued improvement in implosion quality with decreasing gaps below 1.4 mm (Fig. 3).

III. r-z Characterization

Figures 1 and 5A compare the current and total x-ray power measured for a 90-wire, 0.6-mm gap load with that simulated in the r-z plane by the Eulerian (E) and the Lagrangian (L) RMHCs, respectively, when small initial random density perturbations are assumed. The comparisons show that the behavior of such nearly azimuthally symmetric 90-wire loads can almost coincide with that calculated in the r-z plane using small (~ 5%) values for an axial perturbation. However, the connection between the azimuthal symmetry and the seeding of axial perturbations has not yet been determined.

Such azimuthally-symmetric implosions exhibit a clear first compression followed by a second weaker-compression/expansion phase (measurements in Figs. 5A and 5B). Additionally, prior to the first compression, Rayleigh-Taylor bubble/spike structure are observed with short 1.1±0.1-mm wavelengths in agreement with all the 2D RMHC simulations, which merge into longer 3.4±0.4-mm wavelengths. The longer wavelengths appear to seed a 2.9±0.6-mm sausage instability after the first compression. These instabilities are seen along with a second implosion in the Eulerian RMHC model (Fig. 1) that simulates the entire 20-mm length. This model used an adjustment to the electron-radiation energy coupling to generate the Fig. 1 results.

Analysis of the free-bound and K-shell line spectra shows that the pinch has a gradient structure composed of a hot core surrounded by a cooler plasma [16], in qualitative agreement with the 1D and 2D models. The electron temperature in the core reached temperatures of 1.4±0.2 keV and 1.0±0.2 keV at the first and second compression (Fig. 5C), respectively, with temperatures of 0.4 keV being measured in the surrounding plasma at peak compression. Although higher spectral resolution is needed than was available in order to draw more definitive conclusions, an analysis of the emission spectra in these experiments suggests that the K-series lines are Doppler broadened. The ion temperatures that are

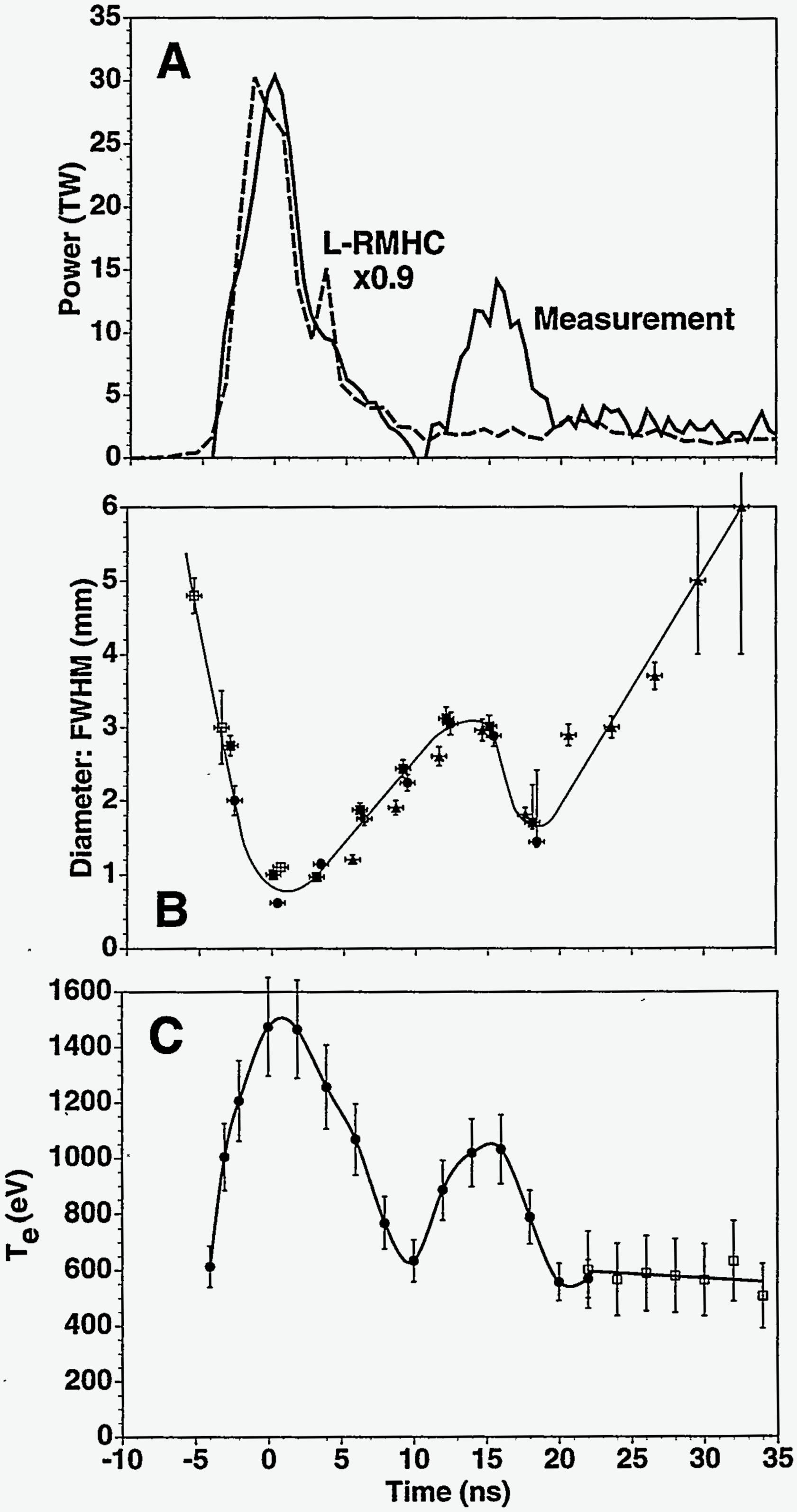

Figure 5. (A) Comparison of measured total power with Lagrangian RMHC simulation; (B) Measured radial diameter; (C) Measured core electron temperature

inferred from the widths of these lines, after a correction for line opacity is made, are in excess of ~ 20 keV. Such inferences are consistent with the 1D and 2D simulations of the experiments.

IV. Conclusions

We have shown that reducing azimuthal asymmetry by reducing the circumferential wire gap has provided significant gains in the radiated x-ray power with its limit not yet reached. However, other asymmetries like those generated by the predicted and observed Rayleigh-Taylor and sausage instabilities may ultimately limit what can be achieved for single-shell wire array loads. Meanwhile, the higher power performance already demonstrated using this small-gap technique with high-wire-number tungsten loads [17,18] on Saturn may well be adequate to achieve 125-eV vacuum-hohlraum temperatures on PBFA-Z [17,19] and ignition-relevant ICF physics on the proposed X-1 accelerator [20-22].

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