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Radiation Symmetry in Z-Pinch Driven Systems for Inertial Confinement Fusion

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Indirect-drive inertial confinement fusion with z-pinch sources shares many of the same requirements as laser-driven targets with regard to pulse shaping, radiation symmetry, and fuel preheat. This paper briefly presents the simulation techniques, results, and comparisons with experimental data concerning radiation symmetry in z-pinch driven vacuum hohlraums. As an example, calculations are presented for recent single- and double-ended hohlraum experiments to measure symmetry with self-backlit foam balls.

1. Introduction

Capsule radiation symmetry is a crucial issue in the design of z-pinch concepts for high-yield inertial confinement fusion; high convergence capsules typically require <1-2% fluence asymmetry. For double-ended hohlraum schemes [1,2] such as the one shown in Figure 1, capsule symmetry is influenced by power imbalance of the two z-pinch x-ray sources, and by hohlraum effects (geometry, time-dependent wall albedo, and wall motion). Two- and three-dimensional (3D) viewfactor models have been used to design hohlraums that optimize the capsule radiation symmetry for near-term experiments and for high-yield targets [3]. Two-dimensional (2D) radiation-hydrodynamics (RHD) models have also been used to study the coupling of z-pinch energy to surrogate capsules via hohlraum absorption and re-emission, in reasonable agreement with foam ball burnthrough data from the 20-MA Z machine at Sandia National Laboratories [4].

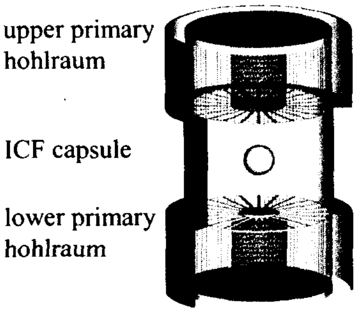

Fig. 1 Double-ended z-pinch driven hohlraum schematic

2. Computational Methods

Simulations of radiation symmetry in double-ended z-pinch hohlraums have relied on the complementary methods of viewfactor and radiation-hydrodynamics. Viewfactor codes model radiation transport among emitting/absorbing surfaces. The equation for radiation transfer among all the N surface elements in the problem can then be cast in matrix form, where the matrix has N^2 elements and is generally dense. The OPTSEC routine calculates geometric form factors and visibility factors in three dimensions and then integrates over azimuth to produce 2D axisymmetric form factors. The geometry is currently static, but time-dependence is introduced through a prescribed z-pinch power history P(t), and an iterative solution for effective radiation temperature, Tr(t), and albedo $\alpha(t)$ for each element, which relies on parameterized albedo results from a series of 1D Lasnex [5] RHD runs. This approach is much faster than an in-situ RHD calculation, but is only applicable to the pulse shapes modeled in the Lasnex albedo simulations. OPTSEC is often run in an optimization mode, where the time-dependent simulation described above is a single function call, with the results measured against a specified set of optimization rules and objectives. Variables to be optimized are typically parameters describing the hohlraum geometry, and the objective is to minimize time-integrated radiation asymmetry or particular Legendre modes at a capsule.

The Lightscape [6] commercial lighting simulation package allows a large number of surface elements to adequately define complex 3D geometry. A progressive refinement solution method is used; at each step a given surface element distributes its energy to all the other elements in the problem. Thus, form factors are recalculated at the price of computing time, but storage is minimized. All reflecting surfaces are assumed to be diffuse, but primary sources (e.g. the pinch) may have a non-Lambertian angular distribution of flux. Automatic mesh refinement based on local gradients in incident flux is performed as the simulation proceeds. The albedo for each wall element is specified based on offline calculations and does not change during the simulation. Lightscape is useful for modeling the effects of 3D features (e.g. beryllium spokes, diagnostic holes, off-center capsules, azimuthally-asymmetric pinch output, etc.) in our hohlraums.

Lasnex 2D axisymmetric RHD simulations include a moving pinch source with a prescribed output power history, ablation of wall material to consistently model wall motion and albedo, multigroup radiation treatment, and capsule ablation/implosion. A Lagrangian mesh with occasional rezoning allows fine resolution of the near-surface region of hohlraum walls to accurately model the radiation absorption and re-emission. These simulations are semi-integrated because we do not perform the magnetohydrodynamic pinch calculation self-consistently, but this approach does allow measured or hypothetical pinch output histories to be specified. Because the main physics goal of this simulation is to model the transport of radiation and its interaction with the hohlraum and capsule, this approach is useful.

3. Foam Ball Symmetry Simulations: Single Pinch Configuration

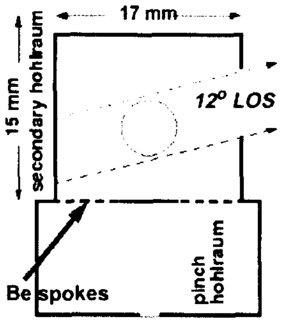

Fig. 2 Single-sided drive foam ball hohlraum geometry.

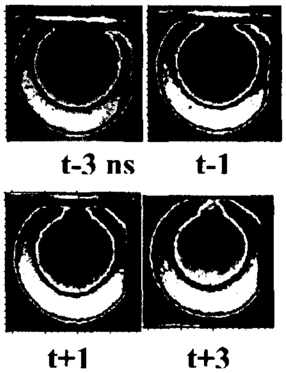

Fig. 3 Experimental x-ray images of foam ball at four times.

Time-resolved measurements of the asymmetric burnthrough of a low density CH foam ball have been made for a single-pinch version of the hohlraum geometry presented in the preceding sections [7]. Figure 2 shows the geometry schematically. A 5-mm diameter foam sphere of initial density 40-60 mg/cc is backlit by the hohlraum wall emission and viewed with a gated-microchannel-plate x-ray pinhole camera filtered to transmit primarily $\geq$250 eV photons, at a spatial resolution of approximately 150 μm. Figure 3 shows experimental x-ray images of the foam ball at various times relative to the peak secondary hohlraum temperature.

Figure 4 shows a snapshot from a Lasnex 2D multigroup RHD calculation for this configuration [3], which includes the effects of z-pinch source motion during its implosion, hohlraum wall motion due to ablation, shine shield expansion, and foam ball ablation and shock propagation. To compare directly with experiment, the simulations are postprocessed to superimpose the hohlraum wall emission and the foam ball self-emission profiles along the experimental line-of-sight, to produce a filtered time-gated synthetic x-ray image. As in the experimental analyses, lineouts are taken at various polar angles and the 30% edge radius is identified. Figure 5 shows an example comparison of the change in edge position versus polar angle for various times, for a postprocessed Lasnex simulation (120 TW peak power, 55% spoke transmission) and as measured. The profiles in general are dominated by P_1 due to the single-sided drive; P_1 coefficients approach 50% at the time of peak drive. The excellent agreement between the measured and calculated foam ball asymmetry demonstrates the usefulness of this type of simulation, but truly validated simulations will require simultaneous measurements of pinch power, primary and secondary hohlraum temperatures, and foam ball burnthrough on the same shot. Sensitivity to assumed pulse shape, source motion, non-Lambertian source, etc. is currently being explored computationally.

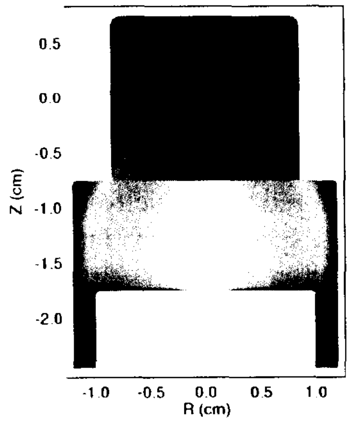

Fig. 4 Radiation temperature plot for Lasnex simulation near peak pinch power.

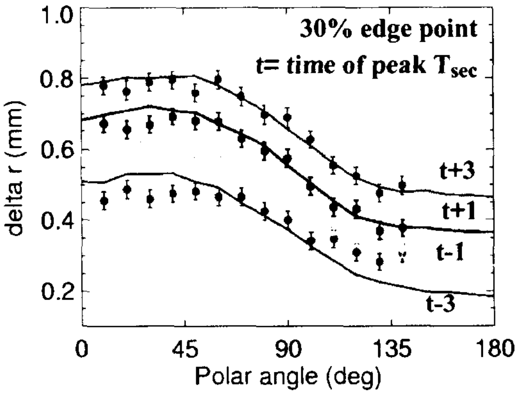

Fig. 5 Lasnex results vs. measured foam ball burnthrough radius change.

4. Foam Ball Symmetry Simulations: Double Pinch Configuration

With the development of single-sided power feed, double-pinch hohlraum configurations on Z [2], experiments in a much more symmetric radiation environment are possible. Figure 6 shows a temperature snapshot from a Lasnex hohlraum model of this shot configuration, including the imploding x-ray sources, double primary hohlraums, inter-primary power feed, and foam ball at the center of the secondary. Figure 7 shows synthetic foam ball burnthrough profiles for the case of 40 TW peak power per pinch, which when compared with Figure 5 indicate the level of symmetry improvement. Calculated time-dependent flux asymmetry Legendre modes 1 through 8 are in the ±5% range during the main power pulse, dominated by P_1 and P_2, with smaller time-integrated values. With a 15-mm long secondary, the calculations predict a slightly pole-hot drive, manifested in the

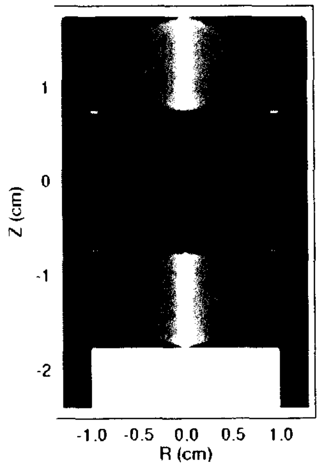

Fig. 6 Lasnex model of double-pinch hohlraum.

faster burnthrough at 0° and 180° seen in the profiles. Further improvements are possible by tuning the secondary hohlraum geometry, as predicted using the OPTSEC 2D viewfactor optimization procedure. Recent Z experiments captured eight self-backlit foam ball images per shot, spaced at 2 ns intervals to map out more of the ablation history. Burnthrough profiles are being extracted to compare with the simulations.

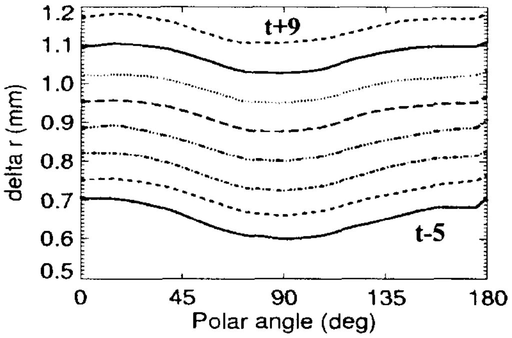

Fig. 7 Calculated burnthrough radius change in double-pinch hohlraum.

5. Laser X-Ray Backlit Targets

Z experiments are now using the recently commissioned Z-Beamlet laser in point-projection mode [8] to backlight capsules and symmetry targets. At the 75 eV drive accessible in Z double-pinch hohlraums, a 2-mm diameter, 60-μm thick CH shell has sufficient opacity at 4-12 keV backlighting energies to provide a reasonable convergence ratio diagnostic. Large diameter (4-5 mm) targets designed for high sensitivity as a symmetry diagnostic have been fabricated and await testing on Z: thin (15-30 μm) Ge-doped plastic shells for limb distortion and low-density (20-40 mg/cm^3) SiO_2 foam spheres for imaging of the ablatively driven shock. For the asymmetry levels predicted by OPTSEC, Lightscape, and Lasnex, the response of an implosion capsule or symmetry target at the center of the secondary hohlraum will provide the most precise measurement of upper-lower pinch power imbalance, a key concern for double-pinch configurations.

6. Conclusions

Computational tools have been specifically developed and adapted for studying radiation symmetry and its effects in z-pinch driven vacuum hohlraums. Benchmarking tests are underway with self-backlit foam spheres in single- and double-pinch hohlraums at the 15% asymmetry level; more stringent tests at the several percent level using laser x-ray backlit implosion capsules, thin shells, and silica foam spheres have begun. Beyond Z, the 2D time-dependent viewfactor optimization code has predicted optimum configurations providing adequate symmetry for the implosion and ignition of a 400 MJ capsule on a dual 60-MA, 1200 TW z-pinch machine, with integrated simulations under development.

References

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