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J. H. Hammer, M. Tabak, S. Wilks, J. Lindl,
P. W. Rambo, A. Toor and G. B. Zimmerman
Lawrence Livermore National Laboratory
Livermore, CA 94551 USA

J. L. Porter, Jr.
Sandia National Laboratories
Albuquerque, NM 87185-1191, USA

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HIGH YIELD INERTIAL FUSION DESIGN FOR A Z-PINCH ACCELERATOR[1]

J. H. Hammer, M. Tabak, S. Wilks, J. Lindl, P. W. Rambo,
A. Toor and G. B. Zimmerman
Lawrence Livermore National Laboratory
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J. L. Porter, Jr.
Sandia National Laboratories,
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Abstract

In this paper we discuss design calculations for high yield inertial fusion capsules, indirectly driven by a double-ended z-pinch-driven hohlraum radiation source. The z-pinches are imploded by a high current (~ 60 MA) accelerator while enclosed within a hohlraum. Radial spoke arrays and shine shields isolate the capsule from the pinch plasma, magnetic field and direct x-ray shine. Our approach places minimal requirements on z-pinch uniformity and stability, usually problematic due to magneto-Rayleigh Taylor (MRT) instability. The hohlraum smooths the radiation field at the capsule, even in the presence of large millimeter scale inhomogeneities of the pinch and the high-spatial-frequency perturbation of the spoke array. The design requires simultaneity and reproducibility of the x-ray output to 5-10%, however. Reproducibility at this level may be achievable based on experience with the Z and Saturn accelerators. Recent Z experiments also suggest a method for generating the required x-ray pulse shape, through implosion of a multi-shell z-pinch. X-ray bursts are calculated and observed to occur at each shell collision. Variation of shell masses and radii allows considerable latitude for creating the desired pulse shape. For the design considered, a capsule absorbing 1 MJ of x-rays at a peak drive temperature of 210 eV is found to have adequate stability and produces 400 MJ of yield. A larger capsule with slightly longer drive and similar peak temperature absorbs 2 MJ with a yield of 1200 MJ.

1. INTRODUCTION

We consider an indirect drive inertial fusion design driven by z-pinch x-ray sources. The sources must drive the hohlraum to sufficient radiation temperature with an appropriate pulse shape and symmetry. The design, sketched in Figure 1 is motivated by recent experiments on the Saturn and Z pulsed power accelerators, where high power x-ray production from imploding wire-array z-pinches has been achieved [1]. At 20 MA, the Z accelerator produces up to 2 MJ of x-rays with a peak power of 290 TW, and pulse widths as short as 4 ns. For our ICF targets, of order 16 MJ will be necessary, requiring a higher power driver. We must also find a means of providing the correct pulse shape, which entails heating the hohlraum to ~100 eV for 20 ns before the main drive. Other recent experiments on Z [2],[3] demonstrated a pulse shaping technique: multiple shells. In these experiments, the imploding wire array impacted on foam shells or an internal wire array, with a burst of x-ray emission at each impact. The concentric wire array experiment was close to a hydrodynamic scale of the ICF pinch design, and produced timing and contrast similar to our calculations below. We discuss the scaling of pinch x-ray production and pulse shaping in greater detail in Section 2. The successful development of the z-pinch-driven hohlraum [1],[3] is also important for our concept. A Z-pinch-driven hohlraum has an imploding pinch within a hohlraum with a narrow annular power feed. Radiation temperature in the hohlraum is set by a balance between emitted power and losses to the wall and power feed gap. Adequate x-ray coupling and drive symmetry in the secondary hohlraum is also critical. Modeling of the coupled hohlraums, the current-return spokes separating the hohlraums, as well as static and time-dependent view factor calculations evaluating symmetry are discussed in Section 3. ICF capsule scaling [4] predicts ignition of capsules at 210 eV with adequate margin against Rayleigh-Taylor instability if they are

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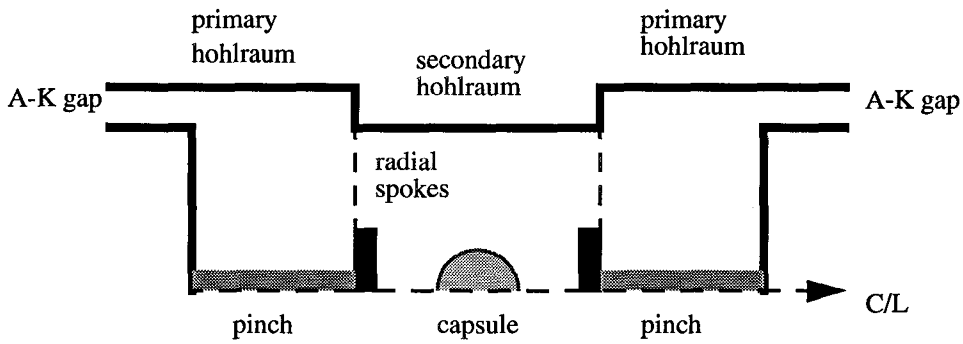

FIG 1. Target geometry for z-pinch driven hohlraum ICF concept

sized to absorb 1MJ or greater. This criterion is well matched to the hohlraum energetics for the ~60MA driver. We discuss the capsule design in Section 4.

2. Z-PINCH DYNAMICS AND PULSE SHAPING

The x-ray output for experiments on a variety of drivers has been found to scale as I^2, consistent with most of the energy imparted by **JxB** forces undergoing conversion to x-rays. At 60 MA, this scaling would give ~18 MJ of x-ray yield. Our concept employs a pinch geometry and driver approximately scaled from 2cm diameter implosions on Z. The current rise time and implosion velocity are comparable to the Z experiment, but at approximately 3 times the current. The shortest pulses observed for 2cm diameter Z wire arrays is ~6 ns, while our ICF concept requires ~10 ns drive for the main pulse. The observed efficient conversion of magnetic energy to x-rays is consistent with 2D radiation magnetohydrodynamic calculations [5],[6], but ab initio pinch calculations that accurately predict the pulse duration are not yet possible. The pulse duration and the energy release depend on instability growth. Instability levels depend on the pinch initiation which remains poorly understood. In 2D, axisymmetric calculations, the pinch is typically modeled as a shell with zone-to-zone random density perturbations of specified amplitude. The source of the density perturbation is presumed to be the breakdown and early-time instability of the wire array which may involve 3D effects not modeled. The most unstable modes of the imploding pinch are predicted to be axisymmetric magneto-Rayleigh Taylor instabilities, which can be included in the 2D calculations. Typically, a perturbation level chosen in the range of 0.5 to a few percent with 50-100 micron zones can reproduce the experimental pulse width and give axial structure with mm wavelength scales as seen in framing images at stagnation. The pulse width, determined predominantly by the radial extent of bubble-spike structures, may vary by a factor of ~2 as the perturbation is varied from 0.5% to 5%. The codes predict smaller radial extent of the x-ray "hot spots" than observed and 3D structure is also often evident at stagnation. Our ability to accurately model pinch x-ray generation for future, higher current accelerators is therefore clearly limited. On the other hand, for similar current rise times, initial pinch radii and implosion velocities to Z experiments, it is plausible that the pinch dynamics and hence pulse duration will be similar for larger drivers. This is consistent with our 2D radiation MHD calculations with perturbations similar to those chosen to match Z x-ray output pulse widths. The z-pinch load used for simulations of our ICF concept consists of multiple concentric shells. The initial configuration has 2 inner shells extending from $0.330\text{cm} < r < 0.348\text{cm}$, and $0.400\text{cm} < r < 0.418\text{cm}$ at density 0.8 g/cc, and a distributed outer shell between $0.418\text{cm} < r < 1.110\text{cm}$ at average density 0.0147g/cc. With a Z-like current rise time of 100ns and current peak of 63 MA, a simulation with 2% random density seed in the outer shell produces a total yield for 2, 1cm long pinches of 17.5 MJ (16 MJ within the time of interest), with a pulse width of 5 ns and peak power of 2100 TW. An identical simulation except at 1% perturbation gave the same energy out with 2400 TW peak power and 4.5 ns pulse width. A 1% perturbation with different random seed again gave very similar energy out but with 1800 TW peak power and 6 ns pulse width. At 10% perturbation, the pulse width is 6 ns with peak power of 2000 TW and 20 MJ radiated in the time of interest. These compare with a 1D result where the total emission is 14 MJ (13MJ in the time of interest) with peak power of 4000 TW and pulse width of 1.7 ns. The more efficient emission for an unstable pinch appears due to the conversion of additional magnetic energy through the degrees of freedom added by the instability,

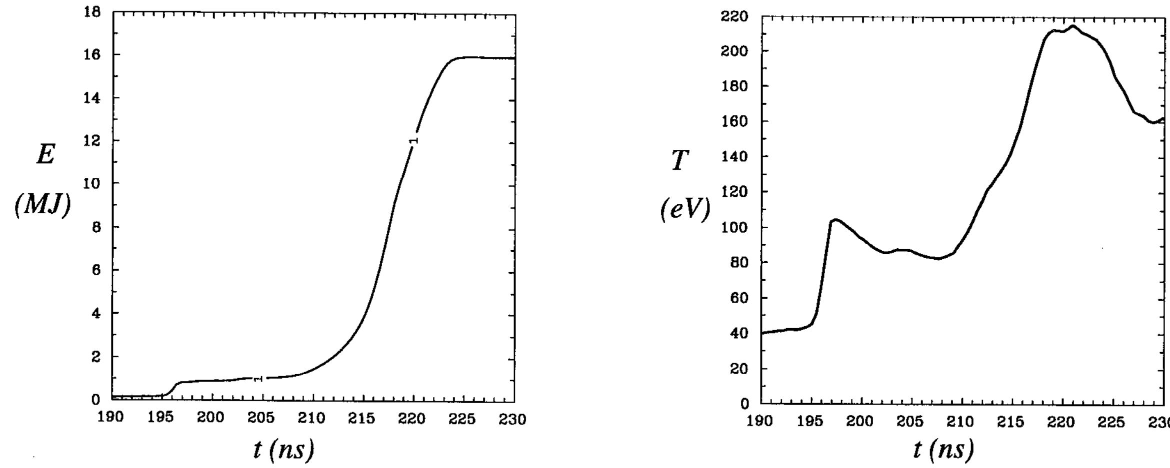

FIG. 2 Pinch x-ray energy release and secondary hohlraum temperature

and by convection of the stagnating plasma that brings hot plasma to the pinch surface where it can radiate more effectively. The increased implosion velocity of plasma in the bubbles is also advantageous for x-ray production. The simulations employ low atomic number pinch constituents (LiD) to minimize radiation trapping within the pinch observed in 1D simulations. We speculate that higher Z pinches will also radiate effectively due to the convective effect.

3. HOHLRAUM ENERGETICS AND SYMMETRY

On Z, hohlraum temperatures of 145 eV have been obtained[3]. For a wall loss dominated hohlraum, i.e., assuming the power feed gap can be kept small, and assuming the pulse duration remains the same, the radiation temperature scales as $T \sim (E/A)^{0.3}$, where E is the energy release and A is the wall area[4]. If E varies as I^2, then $T \sim I^{0.6}$, giving hohlraum temperatures of 280 eV at the 60 MA level for the same size hohlraum as fielded on Z, i.e. 1.2 cm radius and 1 cm length. Power feed inter-electrode gaps as small as 1.5 mm have been successfully employed, admitting a peak electrical power of 40 TW with pulse duration of 100 ns. The power feed provides a substantial sink for hohlraum x-rays, so it is critical to maintain a small gap to reach high hohlraum temperatures. It appears that the magnetic pressure (~0.6 MB on Z) plays a role in preventing plasma closure, an effect that we also observe in simulations at higher current. Coupling to a secondary hohlraum containing a capsule will lower the temperature due to transport inefficiencies and increasing the total wall area. We find detailed calculations with Lasnex[7] predict secondary temperatures of 210 eV or greater for 16 MJ of x-ray energy release. Figure 2 shows the result of a 2 dimension hohlraum calculation with the nominal design geometry: 1.25 cm radius primary hohlraums, 1 cm in length with 2 mm power feed slots on each end of a 1.6 cm long, 1 cm radius central hohlraum. The power feed slots are 4 mm long in the simulation. The pinch is modeled as a planckian x-ray source, at time-varying radius determined from a 1D pinch calculation and with emitted energy as shown in Figure 2, scaled from a 1D calculation to a total yield of 16 MJ. The peak power is 2360 TW. The primary and secondary hohlraums, with 50%-50% Au-Gd walls to minimize wall losses, are separated by shine shields 400μm thick, 0.45 cm in radius and a radial spoke array extending between the shine shield and the hohlraum wall. Efficient transmission through the spoke array separating the primary and secondary hohlraums is clearly critical. 2D radiation MHD calculations, treating the spokes as a periodic array of parallel, current-carrying rods exposed to the pinch magnetic field and hohlraum x-ray environment predict adequate transmission for 2 different spoke array designs. A 21-spoke array of 960μm diameter, 0.88 g/cc LiD rods gave transparency ~ 50% during the foot of the pulse, rising to near 100% at the peak of the drive. A 9 spoke array of 500μm diameter Au rods gives more nearly constant transmission in the range 70-80%. The hohlraum calculation shown in Fig. 2 links to the Au spoke calculation for the time-dependent transmission and absorption of the spoke array. Recent Z experiments give qualitative evidence that the spoke array func-

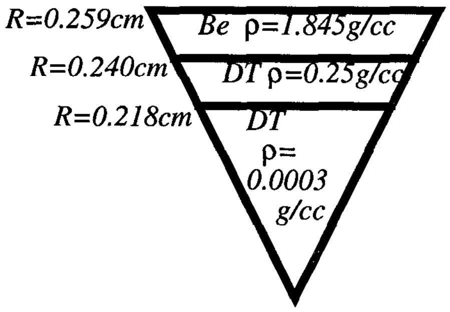

FIG. 3. 1 MJ Capsule

tions as required without degrading pinch performance. Subsequent experiments will employ a secondary hohlraum for quantitative measure of transport.

We have also done 3D view factor calculations to explore the effects of pinch asymmetries, time dependent wall albedo and the non-axisymmetric perturbations due to the spoke array. Large, few millimeter scale spatial fluctuations in the pinch x-ray emission are found to have negligible effect on x-ray flux uniformity at the capsule, even if the fluctuations are assigned random 3D directions for preferential shine. Time-dependent, axisymmetric calculations with variable wall albedo and neglecting the spoke array gave time-averaged symmetry for P_2, P_4 and higher Legendre moments at the capsule less than 2%, as required for a symmetric implosion. For the time-dependent case, the shine shield radius and central hohlraum length were chosen as in the design described in Section 2. The greatest sensitivity is to P_1 caused by power imbalances between the pinches. Left-right power balance to 7% or better is required to remain below 2% flux asymmetry. Static 3D calculations with a 24 spoke array showed negligible flux perturbation at the capsule, and analogous calculations for 8, 500μm diameter spokes showed 2% flux asymmetry.

4. CAPSULE DESIGN

We have designed a capsule driven by the z-pinch driven hohlraum, shown in Figure 3, with a Be ablator and a cryogenic fuel layer containing 3.6 mg of DT. Driven with a pulse shape similar to that shown in Figure 2. with a peak drive temperature of 210 eV, the capsule absorbs 1MJ and yields 400 MJ in 1D simulations. We have evaluated stability against RT modes through a series of 2D calculations. We find the most unstable mode during the capsule implosion is Legendre mode $l \sim 60$ with growth factor of 400. At ignition, the dominant mode fed through to the hot spot has $l \sim 20$ with growth factor 350. These growth factors are similar to those found for the NIF point design [4]. At comparable surface roughness of a few hundred Angstroms, these capsules should have similar or slightly greater ignition margin than the NIF point design, since the converged capsule dimensions are ~ a factor of 2 larger than for NIF. We have also evaluated a capsule that absorbs 2MJ with drive times and capsule radii scaled by a factor of 1.26 at similar peak temperature. The 2MJ capsule has a 1D yield of 1200 MJ and readily fits within the hohlraum used to drive the 1MJ capsule.

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