Abstract. Peak x-ray powers as high as 280±40 TW have been generated from the implosion of tungsten wire arrays on the Z Accelerator at Sandia National Laboratories. The high x-ray powers radiated by these z-pinches provide an attractive new driver option for high yield inertial confinement fusion (ICF). The high x-ray powers appear to be a result of using a large number of wires in the array which decreases the perturbation seed to the magnetic Rayleigh-Taylor (MRT) instability and diminishes other 3-D effects. Simulations to confirm this hypothesis require a 3-D MHD code capability, and associated databases, to follow the evolution of the wires from cold solid through melt, vaporization, ionization, and finally to dense imploded plasma. Strong coupling plays a role in this process, the importance of which depends on the wire material and the current time history of the pulsed power driver. Strong coupling regimes are involved in the plasmas in the convolute and transmission line of the powerflow system. Strong coupling can also play a role in the physics of the z-pinch-driven high yield ICF target. Finally, strong coupling can occur in certain z-pinch-driven application experiments.

1. INTRODUCTION

Recent progress with fast z-pinches (implosion time short compared to magnetohydrodynamic (MHD) instability growth rates) has opened the possibility of achieving high yield inertial confinement fusion (ICF) in the laboratory. Arrays of 240 tungsten wires, 7.5 µm in diameter, have been imploded on Sandia's Z accelerator, producing 1.8±0.25 MJ of x-rays at a peak power of 210±30 TW [1]. Experiments on Sandia's Z accelerator to reduce the magnetic Rayleigh-Taylor (MRT) growth rate by using nested wire arrays have achieved x-ray powers of up to 280±40 TW in a 4 ns radiation pulse and a total radiated energy of 1.75±0.2 MJ. [2]. The most complete high yield ICF target design yet published [3] requires two 8 MJ, ~1000 TW z-pinches driven by a 60 MA peak current. Given that the x-ray output for z-pinch experiments on a variety of drivers has been found to scale with current, I as, I^2, this performance level seems achievable.

The high x-ray powers achieved at Sandia appear to be a result of using a large number of wires in the array which decreases the perturbation seed to the magnetic Rayleigh-Taylor (MRT) instability, minimizes precursor plasma generation, and allows merger of plasmas from adjacent wires prior to implosion. Success in scaling z-pinch x-ray output power and energy to the level required for high yield fusion will require a deeper understanding of the fundamental physics processes, the ability to simulate these processes, and experiments to validate the models. To date, experimentally observed x-ray output is consistent with calculated yields from two-dimensional (2-D) radiation-MHD simulations [4], however, three-dimensional (3-D) simulations are required to confirm the wire number scaling hypothesis and study the scaling to higher pinch currents. Sandia is developing a 3-D radiation-MHD code to simulate the implosion physics and x-ray output scaling of wire arrays [5]. We must also assemble accurate and detailed models and databases for conductivities, opacities, constitutive responses and equations of state (EOS) for all the materials present in a high yield z-pinch target. In particular, z-pinch-driven fusion has some unique requirements for conductivities (electrical and thermal) and opacities for the materials (mostly metals) that form the wire array and the transmission lines that supply the current to the z pinch.

The parameter space spanned by high yield z-pinch-driven ICF is shown in Figure 1 on a plasma map covering many orders of magnitude in temperature and density. Here, the straight line $\Gamma = E_{pot}/E_{kin} = 1$ separates the ideal and strongly coupled states of a hydrogenic plasma ($z=1$). The figure also shows the regime where electron Fermi degeneracy is important and lines of constant pressure. Note that subsequent figures in this paper contain the same reference lines for strong coupling, Fermi degeneracy, and constant pressure. The various curves on this figure show the phase space evolution of the powerflow system, wire
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
array and fusion capsule for high-yield ICF conditions. We note that the strong coupling plays a role in many of these plasmas, as will be discussed in more detail in the following sections.

Figure 1 – Density and temperature diagram of astrophysical and laboratory plasma phenomena in comparison with the regimes found in z-pinch-driven high yield ICF. Lines depicting boundaries of strong coupling, $\Gamma=1$, Fermi degeneracy, $\Theta_e=1$, and $r_s/a_B=1$ (Wigner cell radius equal to Bohr radius) are shown. The curved lines are phase space trajectories of various components of the z-pinch target, that are individually displayed and discussed in subsequent figures.

2. Z-PINCH PHYSICS

When an axial current ($z$-current) is passed through a cylindrical plasma, an azimuthal magnetic field is created and the resulting JXB force implodes the plasma towards the cylindrical axis of symmetry. The equilibrium pinches of the 50s and 60s were designed to directly heat and confine deuterium and tritium at fusion conditions, but failed to reach fusion conditions due to MHD instabilities. Fast z-pinches, driven by modern pulsed power generators, are designed to produce thermal x-radiation that can be used for indirect drive ICF. This pulsed power technology implodes z-pinches in ~100 ns, thereby avoiding most MHD instabilities. With these fast z-pinches, the current is applied rapidly, and the magnetic pressure quickly implodes a cool plasma, resulting in a supersonic implosion time. During the implosion, the main energy reservoir is the ion kinetic energy. Final heating occurs from the shock heating of the ions, continued PdV work and ohmic heating. The stagnated plasma can efficiently radiate, depending on the atomic number of the wire material.

The Z accelerator at Sandia National Laboratories stores 11.4 MJ of energy in the capacitor bank, the capacitors release their energy in about 1 $\mu$s, the energy is compressed in space and time in pulse forming and transmission line sections, and is finally delivered as a 20 MA current to the wire array. X-ray output from the imploded z-pinch plasma has been up to 1.9 MJ in a 6 ns pulse (15% electrical efficiency and a factor of 167 temporal power compression).
To date, simulations of z-pinch implosions, stagnation and radiation generation have been performed with 2-D radiation-MHD codes. In 2-D axisymmetric calculations, the pinch is typically modeled as a shell with zone-to-zone random density perturbations of specified amplitude. These perturbations are the seed to the MRT instability that develops in a typical bubble-and-spike structure that results in a broadening of the plasma sheath as the shell implodes, thereby broadening the radiation pulse, and limiting the x-ray power.

Figure 2. Phase space diagram showing the implosion of a plasma shell with an initial 1 eV temperature to stagnation on axis when the plasma becomes a hot, dense x-ray radiator. The reference lines are defined in Figure 1. The curve that is hotter at 1.e20 density represents a MRT “bubble”, while the cooler curve represents a “spike”.

The phase space diagram of such a 2-D simulation for the implosion of a tungsten plasma is shown in Figure 2. We see that distributing the wire array mass into a 1 mm thick, azimuthally symmetric plasma shell results in a low density initial condition; the plasma is assumed to have a 1 eV temperature. Strong coupling does not appear to play a role for such a plasma implosion. However, the opacity and emissivity of the hot dense plasma when the pinch stagnates on axis is a significant physics issue that requires further study. Furthermore, the source of the density perturbation that is presumed to be caused by the breakdown and early time instability of the individual wires in the array is not modeled. Therefore, 3-D simulations of the initiation of the individual wires in the array, and their merger into an imploding plasma are required.
2.2 Wire initiation and merge

As described above, understanding the initiation and merger of individual wires in the array is important in determining the viability of scaling z-pinch performance to high yield ICF conditions. Three-dimensional effects related to wire array implosions include: 1) density perturbations that seed the magnetic Rayleigh-Taylor instability; 2) acceleration of coronal plasmas that surround the wires, forming a precursor plasma on axis; and 3) acceleration of arrays where the plasmas never merge, or retain distinct wire cores. Simulations to model these phenomena require a 3-D MHD code capability, and associated databases, to follow the evolution of the wires from cold solid through melt, vaporization, ionization, and finally to dense imploded plasma. Strong coupling plays a role in this process, the importance of which depends on the wire material and the current time history of the pulsed power driver. Electrical and thermal conductivities, as well as consistent EOS information is important in the proper calculation of initiation and merger, and this data is required for states encompassing the entire evolution of the wire: solid, liquid, vapor, and plasma.

![Figure 3](image.png)

Figure 3 – Phase space diagrams illustrating the initiation of a single wires of aluminum and tungsten, respectively. Note that the tungsten wires were assumed to be preheated to 3000 degrees Kelvin. The curves with hot plasma at lower densities represent the coronal plasma, while the core plasma remains cooler and denser.

Figure 3 traces the evolution of single wires of aluminum and tungsten from solid through plasma state as modeled in recent 1-D ALEGRA simulations. The curves with hot plasma at lower densities show the density-temperature history of a Lagrangian tracer particle in the outer coronal plasma, while the other curves represent a tracer particle at the wire core. It is interesting to note that in these simulations the aluminum corona evolves to a state where it follows a line of constant pressure. The tungsten plasma appears to expands less and the core stays strongly coupled for longer period of time. The calculated radial mass distribution for the aluminum wire is in good agreement with recent data from Cornell University [6]. This indicates that the simulations contain adequate physics models. The challenge now is to study the initiation process in two- and three-dimensions for a single wire, and then in 3-D for a wire array.

2.3 Powerflow issues

The transfer efficiency of electrical current from the pulsed power driver to the array must remain high throughout the power pulse in order to drive an efficient implosion. Conductor magnetohydrodynamics,
Joule heating, magnetic field diffusion and material deformation are important in determining the powerflow efficiency at the 10 MA/cm current densities found in a high yield z-pinch accelerator.

Recent simulations [7] demonstrate that the formation and expansion of plasma into the anode-cathode gap is a strong function of the electrical conductivity of the electrode material. The fidelity of these simulations depends largely on an accurate knowledge of the material resistivities over the wide range of temperatures and densities found in Figure 4. By comparing with experimental data, these simulations have shown that the standard conductivity model found in the SESAME library [8] is not very accurate for this parameter range, often differing from the data by several orders of magnitude. We have recently developed a modified Lee-More [9] algorithm that smoothly blends into the standard Lee-More results outside this regime, but is modified to give good agreement with recent data for Cu, Al, and W from experiments performed by DeSilva [10]. A set of constant-temperature conductivity curves for copper calculated by this algorithm is shown in Figure 5.

![Phase space diagram showing the evolution of the powerflow conductor material at fixed Eulerian positions. The curve on the right is for material within the initial conductor boundary, while the other curve is for a point just inside the vacuum gap.](image)

These accurate resistivities are important in both powerflow and wire initiation simulations.
3. PHYSICS OF Z-PINCH-DRIVEN ICF

Sandia is presently pursuing two high yield ICF target design concepts [11], as illustrated in Figure 6: the z-pinch-driven hohlraum (ZPDH) is the primary concept and the dynamic hohlraum (DH) is the backup concept. In the ZPDH concept, two pinches indirectly illuminate a hohlraum cavity that contains the fusion capsule. The relatively large gold-coated hohlraum absorbs and reemits the z-pinch x-ray energy, symmetrizing the flux to the fusion capsule. In the DH concept, a single pinch collides with a central foam cylinder containing the fusion capsule. The collision generates a radiation pulse that grows stronger as the pinch continues to implode. It remains to be determined whether sufficient time-dependent radiation symmetry on the fusion capsule can be obtained with this simpler and more efficient z-pinch configuration.

Figure 6. Schematic of high yield ICF target concepts: z-pinch-driven hohlraum (left) and dynamic hohlraum (right). The sphere at the center of each target is the fusion capsule containing the deuterium and tritium fuel.
3.1 The role of strong coupling in hohlraum physics

Strong coupling is not much of an issue in hohlraum physics for either high yield target concept. In the z-pinch-driven hohlraum, the vacuum hohlraum contains primarily classical plasmas. Even in the dynamic hohlraum, the low-density foam surrounding the fusion capsule never reaches the strong coupling regime, and the converter shell is also primarily classical, as seen in Figure 7. Adequate models of hohlraum wall and foam opacities are the most important physics for this part of the target design.

![Figure 7. Phase space trajectories of foam, beryllium capsule shell, solid D-T fuel and gaseous D-T spark plug for dynamic hohlraum high yield ICF target.](image)

3.2 High yield capsule implosions

Various regions of the high yield fusion capsule definitely pass through the strongly coupled plasma regime, as seen in Figure 7. In particular, the cryogenic DT ice in the main fuel layer remains in a strongly coupled state throughout much of the capsule implosion. As the ice is compressed by the target implosion there is a modest rise in temperature and a strong increase in density. The initial compression of this layer comes close to reaching the conditions found at the Jovian core. As the target continues to implode, this fuel layer is further compressed and undergoes shock heating. We see that the fuel passes through the conditions found at the solar center and even surpasses these conditions for a short time, before disassembling.

The equation of state of the deuterium and tritium in the target at these extreme conditions is also a significant issue for high yield fusion. Recent data from researchers at LLNL [12] suggest that deuterium might be more compressible than previously thought due to molecular disassociation. If this increased
compressibility is confirmed, then the fuel in the ICF target will be easier to compress and the yields will be higher for a given energy driver.

4. Application experiments in the strong coupling regime

Sandia has recently developed a cryogenic target capability for studying the deuterium EOS, both on the hypervelocity launcher [13] and on the Z accelerator. If data can be obtained with an experimental precision of about 1% at these facilities, then the EOS curve for deuterium will be further constrained. We plan to carry out several experimental campaigns to study the deuterium EOS over the next two years. The Z/Beamlet backlighter will be useful in these experiments when it becomes operational next year.

5. SUMMARY

Pulsed-power-driven z pinches are powerful sources of thermal radiation that are an attractive option for high yield inertial confinement fusion. The z-pinch wire arrays are three-dimensional, and require a three-dimensional modeling capability. The success of modeling these z-pinch targets is predicated upon having adequate models and databases for resistivities, opacities, EOS, constitutive responses, and the like. The required models and databases span a parameter space that includes regions of strong coupling. Experiments will be performed on the Z accelerator to help generate data that can validate some of the required models.

Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

References