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RADIATION ENVIRONMENTS PRODUCED BY
PLASMA Z-PINCH STAGNATION ON CENTRAL
TARGETS.

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Radiation environments produced by plasma z-pinch stagnation on central targets

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A goal of pulsed-power technology is the development of an intense, megajoule level source of soft x-rays for use in high-energy density physics experiments. Since 1980 experimental facilities, theoretical concepts, computational tools, and diagnostics have been developed that place pulsed-power at the threshold of performing experiments of great interest to the applied physics community. In this paper the "Flying Radiation Case" approach will be presented and its predicted performance on Sandia National Laboratory's Z-Machine [M. K. Matzen, Phys. Plasmas **4**, 1519 (1997)] will be described. The effects of instability growth in the plasma during the implosion, its reassembly on a central cushion, and the plasma interactions with shaped electrodes are considered.

I. INTRODUCTION

A goal of modern pulsed-power technology is the development of an intense, high-energy density x-ray source by converting the energy of a magnetically imploded plasma into radiation and material internal energy. An intermediate-term goal is to obtain a source with which experiments on radiation transport, opacity, equation of state, and implosion physics may be performed. Ultimately, with a multi-megajoule source it is envisioned that fusion experiments will be possible.

The past two decades have been characterized by an increase in the total energy, E_{rad} , radiated by z-pinches, as well as an increase in peak radiated power, P_{rad} . In 1980-81, the Black Jack V machine at Maxwell Laboratories and the Python machine at Physics International produced approximately 0.16 MJ of radiated energy with a power of 4 TW¹. By 1988 the Shiva Star² machine at the Phillips Laboratory produced 0.95 MJ of energy with $P_{rad} = 5$ TW. In 1991 the Los Alamos inductive store machine Pegasus II generated 0.28 MJ, with a power of 0.9 TW. In Russia in 1993, the Angara V machine produced 0.075 MJ at 25 TW and 0.120 MJ at 3 TW³. The Los Alamos high-explosive driven system Procyon produced 1.5 MJ with a power of 3 TW in 1994. Finally, in 1996 the Saturn machine at Sandia National Laboratory generated 0.4 MJ with a power of 85 TW⁴, and was followed this year by 1.8 MJ at 210 TW on the Z-Machine⁵. The relative suitability of a specific technology for applications experiments depends on the requirements for the experiment. In addition to total energy and peak power, parameters of importance may include: details of the radiated spectrum, the time dependence of the radiated power, the experimentally available volume, the time scale during which specific parameters are realized, and the accessibility of the source. Nevertheless, the energies and powers currently available place pulsed-power technology at the threshold of useful and exciting applications.

Initial attempts to produce pulsed-power driven radiation sources used bare z-pinches in which high Z plasmas were formed from cylindrical foils, wire arrays or gas-puffs. Conversion of implosion kinetic energy of the plasma into thermal energy and radiation during stagnation on axis produced the x-ray source. Bare pinches, which are intrinsically unstable, produce non-uniform implosions, a broad spread in implosion velocity and relatively low power. Furthermore, the hohlraum surrounding a bare pinch tends to have large surface areas and an A-K gap leading to the vacuum transmission line. These features result in significant radiative losses and low

temperatures. The Flying Radiation Case (FRC) concept⁶, shown schematically in Figure 1 was developed to circumvent these problems. The central, optically thin cushion, which may contain internal, cylindrical shells of high Z material, acts as a reassembly layer for the unstable, imploding plasma. It also acts as the hohlraum, thereby eliminating losses associated with the A-K gap. As a result, the FRC can produce higher hohlraum temperatures and radiative powers than the bare pinch.

The operation of the FRC involves three stages. During the implosion, stored electrical energy is converted into the magnetic and kinetic energy of a high Z driver-plasma. The backside of the driver-plasma is magnetically Rayleigh-Taylor unstable, and perturbations which may be present initially, or which arise during the implosion, will grow⁷. These effects are further augmented by the $1/r$ dependence of the magnetic field and the current density in the plasma. If the perturbations are of sufficient amplitude, or if the ratio of plasma shell thickness to run-in distance is small, the instabilities may disrupt the driver. Even when disruption does not occur, multi-dimensional effects spread the sheath radially, and reduce the implosion velocities compared with strictly one-dimensional (1-D) implosions leading to reduced radiated power and plasma temperatures.

The second stage begins when the driver-plasma impacts the cushion, and implosion kinetic energy is converted into thermal energy through the formation of converging shocks in the cushion. During the process, a diverging shock is also set up in the driver-plasma, leading to radiative losses from the system. The material for the cushion and its density are chosen so that it becomes optically thin to radiation from the converging shock. The supersonic radiation front is set up by the shock and heats the central hohlraum.⁸ Physical arguments and two-dimensional (2-D) magnetohydrodynamic (MHD) calculations indicate that an imploding driver plasma will tend to reassemble when it impacts a cushion material. Thus, the cushion can lead to a more nearly homogeneous central radiation environment than would be obtained from the implosion of a simple plasma which stagnates on axis.

The third stage consists of shock reflection on axis and subsequent disassembly of the FRC. The outward moving reflected shock further heats the cushion by as much as a factor of two. Radiation continues to flow through-out the optically thin cushion, and additional energy is delivered to targets located in it or in an end hohlraum. Disassembly results when the reflected

shock reaches the contact discontinuity between the cushion and the driver-plasma. This corresponds to the onset of disassembly of a bare pinch.

II. HOHLRAUM TEMPERATURES PRODUCED BY A BARE PINCH AND AN FRC

A simple model may be used to estimate the temperature produced in a vacuum hohlraum surrounding a bare pinch and to compare it with the temperature produced by an FRC. The model does not include directly the magnetic field which drives the implosion; instead, it uses a plasma velocity at the onset of the pinch for the bare implosion and at impact with the cushion for the FRC. The "hohlraum" in the FRC example is the region inside of the contact discontinuity between the imploding plasma and a central cushion. For the bare pinch, the hohlraum consists of the stationary cylindrical return conductor of radius R_w and axial height ℓ , the two electrode walls and the (open) A-K gap to the vacuum transmission line. Both models will be followed below through hydrodynamic disassembly.

In a one-dimensional model of a bare pinch, the imploding plasma stagnates on axis producing an outward moving shock wave. Thermal radiation from the shock heated plasma is the source of radiated power filling the hohlraum. Disassembly of the pinch is regarded as beginning when the outward-moving shock reaches the surface of the plasma. Denote the radius of the pinch by R_p and the velocity of the imploding plasma at its surface by $v_o(R_p)$. The Hugoniot relations in the strong shock limit may be used to show that the temperature behind the shock is

$$T_p = \frac{v_o(R_p)^2}{2 C_{V,p}} \quad (1)$$

where $C_{V,p}$ is the plasma's heat capacity. Radiation produced by the pinch fills the hohlraum, and is partially reflected and absorbed by the walls. Radiation is also lost through the A-K gap leading to the vacuum transmission line. Assume that a fraction α (the albedo) of the incident radiation is reflected or re-emitted as the front propagates into the wall. Then the rate of change of the energy E_{vac} in the vacuum resulting from these processes is

$$\frac{dE_{vac}}{dt} = \dot{E}_p + \alpha \sigma T_w^4 A_w - \sigma T_w^4 A_w - \sigma T_H^4 A_{ak}$$

Here A_w is the area of the hohlraum wall (the cylindrical return conductor and the electrodes), T_w is the wall temperature (assumed to be uniform) and $\dot{E}_p$ is the luminosity of the pinch. The last term on the right side represents losses through the A-K gap, whose area is denoted by A_{ak} . For simplicity, it is assumed that $T_w \approx T_H$. Next, we set $\dot{E}_p = \sigma T_p^4 A_p$, where A_p is the radiating area of the pinch, take $A_{ak} = \pi(R_w^2 - R_o^2)$ where R_w is the radius of the return conductor, R_o is the initial radius of the plasma and $R_w - R_o = h$. In steady-state (1) can be solved for T_w :

$$T_w^4 = T_p^4 \frac{A_p}{A_w(1-\alpha) + A_{ak}} = T_p^4 \frac{R_p}{R_w} f(R_o, R_w) \quad (2a)$$

$$f(R_o, R_w) = \frac{1}{(1-\alpha) \left[1 + \frac{R_w^2 + R_o^2}{2\ell R_w} \right] + \frac{R_w^2 - R_o^2}{2\ell R_w}} \quad (2b)$$

The first term in square brackets on the right side of (2b) is the wall contribution associated with the outer cylindrical return conductor. The second term in square brackets arises from the electrode walls. Finally, the last term in the denominator arises from losses through the A-K gap.

Using (1) and (2) the hohlraum temperature produced by a 1-D, bare pinch can be related to the implosion plasma velocity at pinch:

$$T_H = \frac{v_o^2(R_p)}{2 C_{Vp}} \left[\frac{R_p}{R_w} f(R_o, R_w) \right]^{1/4} \quad (3)$$

Clearly, $R_w > R_o$, so an overestimate of the hohlraum temperature is given by (3) in which R_w is replaced by R_o . This shows that the hohlraum temperature in the bare pinch is a function, primarily, of the degree of convergence R_o/R_p (since the velocity at stagnation is also a function of these variables). There is an additional, though weaker, dependence on the albedo and the size of the A-K gap.

The hohlraum temperature in the FRC is the temperature inside the contact discontinuity. Define the initial radius of the cushion by R_c . Then the source temperature in the FRC prior to shock reflection in the strong shock limit is⁶

$$T_{frc} = \frac{v_o^2(R_c)}{2 C_{V,c}} g(\rho_c/\rho_f) \quad \text{with} \quad g(\rho_c/\rho_f) = \frac{1}{\left[1 + \left(\frac{\rho_c}{\rho_f} \frac{\gamma_c + 1}{\gamma_f + 1}\right)^{1/2}\right]^2} \quad (4a)$$

where $C_{V,c}$ is the heat capacity of the cushion, and the factor $g(\rho_c/\rho_f)$ depends on the properties of the imploding plasma and the cushion. It should be noted that the impact velocity for the FRC is defined at a different radius in (4) than it is in the bare pinch model (1).

Next, consider the heating associated with the outward passage of the reflected shock. Denoting the effective gamma of the material behind the reflected shock by γ_c' , the temperature in the strong shock limit is⁶

$$T_{frc}' = \frac{3\gamma_c' - 1}{\gamma_c'} \left[\frac{v_o^2(R_c)}{2 C_{V,c}} g(\rho_c/\rho_f) \right] \quad (4b)$$

where the quantity in square brackets is given by (4a).

Equations (3) and (4) may be used to compare the 1-D hohlraum temperature T_{frc} produced in the FRC with the temperature T_H produced by a bare pinch surrounded by a fixed wall. A simple limit results when the initial load radius is large compared with the A-K gap $R_o \gg h = R_w - R_o$, and when $R_w \approx R_o \approx \ell$. For typical plasmas currently used in z-pinch experiments we expect $1 < \gamma < 5/3$ in both the plasma and the cushion. For simplicity, assume that $\gamma_c \approx \gamma_f$ and that $\rho_c < \rho_f$. It then follows that

$$\frac{T_{frc}}{T_{bare}} \approx \frac{3\gamma_c' - 1}{\gamma_c'} \frac{C_{V,p}}{C_{V,c}} \left[\frac{v_o(R_c)}{v_o(R_p)} \right]^2 \left[\frac{R_w}{R_p} \left\{ 2(1 - \alpha) + \frac{h}{\ell} \right\} \right]^{1/4} \quad (5)$$

The temperature ratio associated with the first shock in the FRC is obtained by omitting the first factor on the right side of (5). This factor varies from 2.17 when $\gamma_c' \approx 1.2$ to 2.4 when $\gamma_c' \approx 5/3$.

Consider the other factors on the right side of (5). For high-Z radiation loads, the imploding plasma will be partially ionized. Radiative pre-heat of the cushion will also result in partial ionization of its outer layers. Thus, for a simple, unstructured cushion we may take $C_{V,p}/C_{V,c} \approx 1$ for order of magnitude estimates. The last factor in (5) represents wall losses and gap losses. Using an albedo $\alpha = 0.2$, a ratio of A-K gap width to load height $h/\ell \approx 0.25$ and a convergence ratio of 20:1, this factor is approximately to 2.5. The velocity ratio appearing in (5) is the most problematical. If z-pinchs were strictly 1-D, the magnitude of the velocity at pinch would be greater (possibly by a factor of as much as two) than the velocity of impact for the FRC. However, 1-D models greatly overestimate the velocity to be used in approximations such as (1). Two-dimensional effects tend to produce substantial deviations from ideal behavior by the time the imploding plasma has reached a convergence of as little as 2:1 to 4:1. Partial saturation of the instability growth in the imploding plasma prior to impact with the cushion (typical convergence ratios of 5:1 to 10:1) can produce velocities $v_o(R_c)$ for the FRC that may not be too different from simple 1-D estimates. Two-dimensional calculations suggest that a value of 2/3 is not unreasonable for this factor. Collecting the approximations above suggest that

$$\frac{T_{frc}}{T_{bare}} \approx 2.5 \times \left(\frac{2}{3}\right)^2 \times 2.5 > 2 \quad (6)$$

According to this model, comparable performance for a bare pinch and an FRC would require that pinch velocities be as much as 2.5 times greater than the impact velocity at the cushion's initial radius.

III. RADIATION-HYDRODYNAMIC MODEL OF THE FRC

The simple model from the previous section is useful for order of magnitude estimates, but cannot be expected to reproduce quantitative results for real materials, particularly when the cushion is optically thin. The principle, quantitative features of the FRC can be seen in a 1-D, radiation-hydrodynamic (i.e., not MHD) evolution of an imploding plasma as it impacts an unstructured cushion. Although the model does not include magnetic field effects, the results are

in qualitative agreement with more detailed calculations. The radiation-hydrodynamic model includes tabular equations of state for the plasma and the cushion, models shock formation and propagation, and includes radiation transport in a flux-limited, three temperature diffusion approximation.⁹ The densities, temperatures and velocities are characteristic of those that would be produced by the Sandia Z-Machine.

The initial model consists of a tungsten plasma imploding on a central cushion. The initial conditions represent a simple spatial average of conditions obtained from more detailed 2-D radiation-magnetohydrodynamic models. In particular, the initial radial distribution of the imploding tungsten is characteristic of the sheath thickness obtained from perturbed 2-D simulations. The initial conditions are as follows. The tungsten plasma has an outer radius of 0.7 cm, a thickness of 0.25 cm, a uniform density of $2.2 \times 10^{-3} \text{ g/cm}^3$, and is moving inward radially with a uniform velocity of 52 cm/ μs . The radiation and material temperatures in the tungsten are 33 eV. The CH cushion is initially uniform with an outer radius of 0.29 cm, a density of 0.02 g/cm³, and a uniform pre-heat of 3 eV. The initial 3 ns run-in prior to impact results in radiative pre-heat of the cushion's outer layers. The density (solid curve), radiation temperature T_R (dotted curve) and material temperature T_e (dash-dot curve) are shown in Figure 2a shortly after impact. The supersonic radiation front has separated from the shock and is moving into the cushion, pre-heating it. About 7 ns later (Figure 2b) the radiation front is approaching the axis, the shock is at $r = 0.14 \text{ cm}$ and the contact discontinuity between the tungsten, and the cushion has moved to $r = 0.19 \text{ cm}$. The radiation temperature is spatially uniform between the front and the contact discontinuity with $T_R \approx 90 \text{ eV}$. The shock reaches the axis at about $t = 236 \text{ ns}$ and is reflected, heating the cushion to temperatures in the range 150 - 200 eV. Figure 2c shows the structure at $t = 239 \text{ ns}$ when the reflected shock is at $r = 0.05 \text{ cm}$. Disassembly occurs when the reflected shock reaches the contact discontinuity, giving a minimum radius for the hohlraum of about 0.08 cm. Finally, the time evolution of T_R and T_e on axis are shown in Figure 2d. The radiation and material temperatures do not couple until late in time ($t > 240 \text{ ns}$). During shock formation radiation temperatures of about 350 eV and material temperatures of about 600 eV occur in a small portion of the cushion, but drop rapidly as the material expands. The stand-off time between arrival of the radiation front and the shock front on axis is about 6 ns.

A series of calculations which include magnetic fields and the external pulsed-power drive, and which include spatial variations in the initial velocity, density and temperatures of the materials show essentially the same results.

IV. PRELIMINARY MODELS FOR THE Z-MACHINE

The total radiated energy and power available on the Sandia Saturn and Z-Machines, as well as recent improvements in radiation load designs¹⁰, indicate that these machines are ideal facilities upon which to test the FRC concept. Furthermore, a 2-D Eulerian radiation-magnetohydrodynamic code is available which has been used successfully to model quantitative aspects of bare pinch implosions on these machines.¹¹ We use this code to model the FRC. The calculations use a single loop external circuit containing an experimentally measured, time dependent voltage wave form $V(t)$, and a system resistance, $R = 120\text{ m}\Omega$, and inductance, $L = 10.24\text{ nH}$, (measured to the back side of the initial radiation load) to represent the Z-Machine. The voltage wave form, and the resulting current in the imploding load for a bare pinch experiments, are shown in Figure 3. The radiation load parameters were chosen from a typical experiment (Shot 26) for which 2-D code results and experimental data are in excellent agreement. The load consists of a 2 cm high, 4 mg tungsten wire array with an initial radius of 2 cm. The calculations, which include the electrode glide-planes, a central cushion and an axial end hohlraum, start about 212 ns into current delivery to the wire array. Data and models for the bare pinch can be found elsewhere.¹²

The first model shows the evolution of an unstructured FRC consisting of a 0.02 g/cm^3 , CH cushion with initial radius 0.29 cm which contains an axial end hohlraum (radius 0.21 cm and length 0.5 cm) which is also filled with CH at the same density. The model at $t = 212\text{ ns}$ is shown in Figure 4a. By $t = 225\text{ ns}$ the tungsten plasma has begun to reassemble on the central cushion (Figure 4b). Shock formation in the CH establishes converging and diverging shock waves. The former moves supersonically toward the axis, reaching it at about 226 ns, as shown by contours of T_R in Figure 4c. It should be noted that the contact discontinuity between the tungsten and the CH has not moved significantly by this time, and that the radiation front shows only slight deviations

from cylindricity despite the evidently more severe structure seen in the vicinity of the contact discontinuity. In particular, we note the absence in the radiation field of the small scale features which show up in the density. Radiation flow into the end hohlraum has also started by this time. Finally, Figure 4d shows the tungsten plasma at 237 ns, corresponding to the main pinch. The open regions near the axis in the cushion, which do not contain contour lines, represent compressed CH at temperatures of 200 - 250 eV.

Figure 5 shows T_R and T_e versus time at a representative point on axis in the central hohlraum, and at the end of the axially located hohlraum. The radiation temperature in the pre-shocked central hohlraum increases gradually from about 120 eV to 170 eV. The shock arrives on axis about 5 ns after the arrival of the radiation front. The radiation temperature in the FRC increases to 200 eV to 250 eV during shock reflection, with disassembly beginning at about 240 ns. The radiation front, which moves to the right at 40 cm/ μ s, reaches the end of the axially located hohlraum at $t = 236$ ns, producing a temperature there of about 100-120 eV. The spatial variation in the radiation field at any instant is quite small in both the axial and radial directions. As the tungsten plasma moves off the right hand electrode, a shock is driven axially into the end hohlraum with a velocity of about 15 cm/ μ s, arriving at the end about 12 ns after the arrival of the radiation front. Finally, when the bulk of the plasma pinches, an axial jet forms and moves into the end hohlraum at about 22.5 cm/ μ s. Design modifications are being explored to eliminate the axial jet.

V. TWO-DIMENSIONAL RADIATION-MAGNETOHYDRODYNAMIC MODEL OF A STRUCTURED FRC

The unstructured model discussed in Section IV illustrates the effects of instabilities on the FRC's performance. An issue of concern is the presence of instabilities even after the imploding plasma has assembled on the cushion. Clearly, these features cannot be wholly removed by impact, since momentum and current inhomogeneties, for example, are set up in the cushion by the reassembly process itself and these represent seeds for subsequent instability growth. Several modifications to the simple FRC may be made to reduce these effects (Figure 6). The addition of a

high density, high-Z coating on the outer surface of the cushion, with a mass comparable to that of the imploding plasma, helps the reassembly process, and produces an additional delay between the convergent shock front and the radiation front. It also produces a more nearly 1-D pinch in the cushion. The addition of internal shells may also have an effect on the central hohlraum temperature and stand-off time between the shock and radiation front. Further gains may be possible using contoured electrodes to add spatial power compression during the implosion. Contoured electrodes also produce axial flow in the plasma which may help suppress instability growth.¹³

A simple structured FRC starts with the model in Section IV, with the addition of a coating of tungsten on the outer surface of the cushion. As a first step, the total mass of the layer was chosen to be equal to that of the imploding plasma, 4 mg, with a density of 0.11 g/cm^3 . A finer mesh is needed to resolve the outer tungsten layer, the formation of the shock waves and the supersonic radiation front in the cushion. At this time a calculation of the full configuration is not possible due to computer time constraints, and a representative strip is chosen. The other material properties are taken directly from the axial strip $0.75 \text{ cm} \leq z \leq 1.00 \text{ cm}$ in the full model at $t = 220 \text{ ns}$. For this model, the current wave form obtained from the full model has been used to drive the implosion. Figure 7a shows the initial grid and the axial strip from which the structured FRC input is taken. The initial density contours are shown at $t = 220 \text{ ns}$ in Figure 7b. The subsequent evolution of the tungsten plasma shows partial reassembly in the cushion ($t = 225 \text{ ns}$, Figure 8a), and subsequent instability growth during the pinch (Figure 8b and 8c). At the last time, a substantial fraction of the initial cushion volume is open.

The radiation temperature in the central hohlraum in this model starts at about 130 eV and reaches nearly 200 eV prior to the arrival of the main shock on axis. Furthermore, the iso-density contours indicate that the central hohlraum remains open longer than in the simple unstructured model. The increase in end hohlraum temperature should scale roughly as the increase in the central temperature as long as the central hohlraum remains open. Thus, the added tungsten reassembly shell should give an increase in the end hohlraum temperature of about 30%, or $T_R \approx 125 - 150 \text{ eV}$. The tungsten coating on the cushion is partially effective in suppressing

instability growth arising during the implosion, essentially reproducing the temperatures obtained in the 1-D calculation of the unstructured FRC.

Calculations have shown that the addition of an embedded tungsten shell, with normal density of 19.2 g/cm^3 (inner radius 0.1 cm, thickness 200 μm) running from $0.85 \text{ cm} \leq z \leq 1.0 \text{ cm}$, is effective in shielding the inner portion of the central hohlraum. The imploding plasma-cushion material stagnates on this layer forming an internal hohlraum with an essentially fixed inner radius of 0.1 cm. During this process, radiation from the plasma between $0.75 \text{ cm} < z < 0.85 \text{ cm}$ which stagnates on axis continues to fill the internal hohlraum. This is shown most dramatically by comparing Figure 9 with Figure 8c, both of which occur at the same time. The internal reassembly layer has stopped the bubble originally located near $z = 0.95 \text{ cm}$, while the plasma in the left portion of the FRC continues to stagnate on axis. The region between the internal reassembly layer and the axis constitutes an internal hohlraum that is protected from the instability effects of the imploding plasma. During the calculation the massive tungsten shell remains essentially intact, apart from a layer of low-density ablated material along its inner surface. The calculations indicate that massive, internal reassembly layers can be effective in arresting the further development of magnetic instability growth, at least on time scales of interest for applications experiments.

The calculations above have not been optimized, either with respect to the coating material, its composition or its initial radius and mass. Further modifications to the structured FRC may also produce even higher temperatures, or keep the central hohlraum open for a longer period.

VI. APPLICATIONS AND SUMMARY

With the goal of performing high-energy density physics experiments pulsed-power facilities have been developing the experimental, theoretical and computational capabilities to produce intense, high-energy x-ray sources. To perform the range of experiments of interest to the applications community, these sources must be high energy (MJ level), high temperature ($> 100 \text{ eV}$), high power (10's of TW and greater), and uniform over dimensions of at least a few mm. In

addition, some experiments require long pulses (100's of ns) and relatively large volumes ($> 0.1 \text{ cm}^3$).

With these controlled conditions experiments will be possible to measure equations of state, opacities, radiation flow as well as applications of interest to ICF. For example, calculations¹⁴ are being used to design an experiment studying radiatively driven shocks in an aluminum target in the central cushion of an FRC on the Z-Machine.

With the advent of the Z-Machine and radiated energy and power of 2 MJ and 210 TW respectively, a facility is now available with which to develop controlled radiation environments for applications experiments. Calculations predict that a Flying Radiation Case driven by the Z-Machine holds promise in producing usable (i.e., predictable and controllable) radiation environments of 200-220 eV for 7 ns in the cushion, and 150 eV for 15-20 ns in an end hohlraum, with typical volumes of order 0.1 cm^3 . If these experiments show promise, there will be interest in building the next generation of pulsed-power machines to reach even more extreme conditions.

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Figure Captions

Figure 1. Schematic representation of a Flying Radiation Case, showing an imploding plasma and an unstructured central cushion. Radiation from the pinch can be used to fill an end hohlraum (left), or can escape from an axial aperture (right).

Figure 2. 1-D radiation-hydrodynamic model of an FRC, showing density in g/cm^3 (solid), T_R (dotted) and T_e (dot-dash) in keV. (a) 3 ns after the plasma impacts the cushion (First strike); (b) formation of the hohlraum by the supersonic radiation front; (c) final heating of the cushion by the reflected shock. (d) T_e (dotted) and T_R (solid) on axis versus time.

Figure 3. Experimentally measured voltage wave form, and calculated current wave form for a bare pinch (Shot 36) on the Z-Machine.

Figure 4. Evolution of an unstructured FRC with an end hohlraum. Iso-density contours of the tungsten plasma in the r - z plane at: (a) $t = 212$ ns; (b) $t = 225$ ns; and (d) $t = 237$ ns. (c) shows iso-contours of T_R at $t = 226$ ns just as the radiation front reaches the axis.

Figure 5. T_R (solid curve) and T_e (dotted curve) versus time on axis ($r = 0$ cm and $z = 1.0$ cm) in the central hohlraum, and T_R (dashed-dot curve) and T_e (dashed curve) versus time in the end hohlraum ($r = 0.1$ cm and $z = 2.4$ cm).

Figure 6. Modifications to the simple FRC to enhance the temperature, volume and duration of the central hohlraum.

Figure 7. Model of an FRC containing a tungsten reassembly layer on the outer surface of the cushion. (a) tungsten iso-density contours for the full problem at $t = 220$ ns; (b) tungsten iso-density contours for an axial strip taken from the grid in part (a) which include a tungsten reassembly layer at the start of a fine-zoned calculation.

Figure 8. Evolution of the tungsten plasma for the structured FRC in Figure 7; (a) $t = 225$ ns; (b) $t = 229$ ns; and (c) $t = 235$ ns.

Figure 9. Tungsten density at $t = 235$ ns for a structured FRC as in Figure 7, which also includes an internal, solid density, tungsten reassembly layer. Comparison with Figure 8c shows that this structure effectively halts the growth of large scale instabilities on timescales of interest and protects a portion of the internal hohlraum.

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Fig 1

Fig 2a

Fig 2b

Fig 2c

Fig 2d

Fig 3

Fig 3

Fig 4a

Fig 4b

Fig 4c

Fig 4c

Fig 4d

Figs

Fig 6

Fig 7a

Fig 7b

Fig 8a

Fig 8b

Fig 8c

Fig 9

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