Dynamics of a z-pinch x-ray source for heating ICF relevant hohlraums to 120-160 eV

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AUG 17 2000
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Abstract

A z-pinch radiation source has been developed that generates 60 ± 20 kJ of x-rays with a peak power of 13 ± 4 TW through a 4-mm diameter axial aperture on the Z facility. The source has heated NIF (National Ignition Facility)-scale (6-mm diameter by 7-mm high) hohlraums to 122 ± 6 eV and reduced-scale (4-mm diameter by 4-mm high) hohlraums to 155 ± 8 eV -- providing environments suitable for indirect-drive ICF (Inertial Confinement Fusion) studies. Eulerian-RMHC (radiation-hydrodynamics code) simulations that take into account the development of the Rayleigh-Taylor instability in the r-z plane provide integrated calculations of the implosion, x-ray generation, and hohlraum heating, as well as estimates of wall motion and plasma fill within the hohlraums. Lagrangian-RMHC simulations suggest that the addition of a 6 mg/cm^3 CH_2 fill in the reduced-scale hohlraum decreases hohlraum inner-wall velocity by ~40% with only a 3-5 % decrease in peak temperature, in agreement with measurements.

PACs numbers: 52.58.Ns, 52.55.Ez, 52.25.Qt

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I. INTRODUCTION

In typical configurations for indirect-drive ICF (inertial confinement fusion), a high power pulse of laser or x-ray energy is absorbed in a high-Z enclosure (hohlraum) that surrounds a spherical shell (capsule) containing DT (deuterium-tritium) fuel. The hohlraum walls are heated in an ever increasing *multi-phase* drive to a temperature of up to 300 eV [1, 2], which emit soft x-rays that freely traverse the region between the walls and capsule. The early three phases of the drive consist approximately of a ~ 85 eV *foot* pulse having a ~ 10 ns duration, followed by a *first-step* pulse at ~ 120 eV for ~ 2 ns and a *second-step* pulse at ~ 155 eV for ~ 1 ns [3, 4]. The x-rays are absorbed by the low-Z material of the capsule shell (the ablator). As the x-rays are absorbed, they generate a time-sequenced series of shocks of up to ~ 150 Mbars that accelerate the converging shell with a controlled inflight aspect ratio and a nearly Fermi-degenerate fuel-compression. A hot spot forms at the center of the capsule due to the shock heating and the following compression, which results in ignition of the DT fuel.

This indirect-drive ICF concept is the main approach toward achieving thermonuclear ignition and burn in the U.S. National Ignition Facility (NIF) [5], currently under construction and scheduled to be completed about 2006. The NIF will provide a hohlraum input power of up to ~ 600 TW and be capable of heating ICF ignition-scale hohlraums to radiation temperatures of up to ~ 300 eV. Two existing U.S. research facilities - the Omega laser at the University of Rochester [6] and the Z-facility at Sandia National Laboratories [7] - are currently employed in pre-NIF hohlraum experiments to test various aspects of the indirect-drive ICF concept. The Omega hohlraums are used to generate high-temperature short-pulses in small-scale hohlraums, while Z can be used for complementary studies involving lower-temperature longer-pulses in full NIF-scale hohlraums.

Application of pulsed-power generators like the Z-facility to this pre-NIF ICF effort was first suggested in 1995 [8] after it was discovered [9] that the use of very large numbers of wires enabled the generation of high x-ray power from annular wire-array z pinches. This wire-number discovery represented a breakthrough (10, 11) in controlling z-pinch instabilities and was a major step forward in z-pinch load design for large pulsed-

power generators [12-15]. Combined with the conversion of the PBFA-II generator to a z-pinch driver [7], the successful application of this breakthrough on Z [16] reopened interest in the field of fast z-pinches [17] as x-ray sources for fusion [18, 19]. At Sandia National Laboratories, for example, three hohlraum concepts that take advantage of the high x-ray powers generated with this new pulsed-power capability are under development to investigate the feasibility of z-pinches to drive ICF targets [18-22]. They are referred to as the *z-pinch driven* [23, 24], the *dynamic* [25, 26], and the *static-wall* hohlraum [27]. To date, the large-volume *z-pinch driven* hohlraum has developed a temperature of 95 ± 5 eV in a 17-mm diameter by 15-mm high hohlraum, when heated by radiation generated external to a single pinch [28]. The energy-efficient *dynamic* hohlraum, which uses radiation generated internal to a radially converging target heated by the imploding wire array, has developed temperatures ranging from 80 to 180 eV as the diameter of a 10-mm high hohlraum compresses from 5 to 1.6 mm [22]. And the *static-wall* hohlraum, which combines features from both concepts, has developed a temperature of 130 ± 7 eV in a NIF-scale hohlraum (6-mm diameter by 7-mm high) [29], again when heated by x-rays from a single pinch.

In this later concept, the hohlraum is placed above a cylindrical target in a z-pinch on the Z generator (Fig. 1). The x-rays are produced in the target located inside a nested array of wires [30]. In this arrangement, the imploding arrays, composed of tungsten wires, form a plasma shell [16] that acts as an annular radiation case as it strikes the target. A fraction of the x-rays produced in the target by the conversion of the array kinetic-energy into thermal energy at the array-target interface is trapped in the target by the high atomic-number case. Radiation flows from the interior of the hot target through an REH (radiation entrance hole) into the hohlraum, whose walls remain relatively static.

In this manuscript we discuss the z-pinch implosion, x-ray production, and hohlraum heating generated from such a target on Z that is capable of heating NIF- and reduced-scale hohlraums to temperatures required for the *first-* and *second-step*, respectively. The manuscript shows that the peak temperature, measured for either hohlraum, driven by the single-sided geometry of Fig. 1 scales according

to the Planckian relation and is consistent with static radiosity-code [31] calculations. The measured temperatures give credibility to the measured x-ray power flowing axially from the target. These target configurations are also under development as sources of high-brightness x-rays for high energy-density physics experiments.

Three-temperature E-RMHC (Eulerian-radiation-magneto-hydrodynamic-code) simulations [32-34] provide insight into the underlying dynamics. The simulations take into account the development of the magnetically-driven RT (Rayleigh-Taylor) instability in the r-z plane of the imploding tungsten load, x-ray generation as the tungsten plasma strikes the target, and radiation transport to the hohlraum. These fully-integrated simulations suggest the hohlraums remain relatively free of z-pinch plasma until after final stagnation occurs and are thus useful environments for ICF experiments. Moreover, such hohlraums could also be driven by two co-linear z pinches to improve the temperature uniformity within the hohlraum (one from the bottom, as shown in Fig. 1, and another, not shown, from the top) [27]. This geometry would provide a suitable environment [35] for studying the implosion of 2-mm diameter capsules being developed for NIF [36]. In this case, the capsule would be positioned at the center of the hohlraum, between the two z-pinchers. The temperature drives within the hohlraums then would provide environments in which to better understand the dynamics of hohlraums, capsule ablator burn-through rates, and shock propagation velocities using NIF-relevant pulse shapes and hohlraum sizes prior to the completion of NIF [9, 35].

The E-RMHC and an Lagrangian-radiation-magneto-hydrodynamic-code (L-RMHC) [37] simulations indicate that during the useful heating time of the hohlraum, the wall implodes inward 0.3-0.6 mm, and would alter the temperature field on a potential capsule were it to be placed within the hohlraum. The simulations suggest, however, that the addition of a low-opacity foam fill within the hohlraum substantially retards the motion. The simulated temperature reduction with increased foam density for the reduced-scale hohlraum agrees with that measured and is also reported on here.

In the remainder of this manuscript, Section II first reviews the experimental arrangement and diagnostics used. Section III then discusses the z-pinch x-ray source, including the simulated implosion dynamics, the subsequent target compression, heating, x-ray generation, and plasma flow through the REH. Section IV discusses the resulting hohlraum temperatures measured, as well as the simulated temperatures

and inward radial expansion of the hohlraum wall. In this section, closure of a diagnostic hole within the hohlraum is given special attention. It is principally through this aperture that the wall temperature of the hohlraum is measured. Section V provides a brief summary.

II. EXPERIMENTAL ARRANGEMENT

Figures 1A and 1B show a side-on and end-on (axial) view of the experimental layout, respectively. They indicate the direction of the power flow into the wire-array load from the Z generator, the nested wire arrays, the target, the 4-mm diameter REH between the target and the hohlraum, and the NIF-scale hohlraum. Figure 1E illustrates the size of the reduced-scale hohlraum. Figure 1A indicates the location of one of the two current (B-dot) monitors [38], which are located at a 60-mm radius and separated by 180 degrees. These monitors measure the current flowing to the load.

The wire arrays in Fig. 1 are made of tungsten, have a length of 10 mm, and are mounted at diameters of 40 and 20 mm. The outer and inner arrays are composed of 240 and 120 wires, and have total masses of approximately 2 and 1 mg, respectively. This configuration has been found to generate high powers when the wires stagnate on axis without a target [30]. High numbers of wires help ensure that the resulting plasma shell acts as a more uniform radiation case for radiation inside the target and develops high x-ray power when impacting the target [9, 16, 39-41]. The target is a solid CH_2 cylinder of TPX (poly [4-methyl-1-pentene]) foam [42, 43] with a density of 14 mg/cm^3 and small ($6 \mu\text{m}$) cell size. The diameter of the target is 5 mm. The target foam is extended into and tamps the REH to reduce closure resulting from the early radiation heating generated during the initiation and Joule heating of the imploding wire-array plasma, and the impact of the outer array on the inner. The slope of the wire-array glide plane, between the inner array and the target, is set to 3 degrees (Fig. 1D) to prevent premature sliding of tungsten plasma across the REH, which would block the radiation generated in the target from reaching the hohlraum [34]. To minimize the effect of variations in the magnetic pressure acting on the imploding array, the current-return surrounding the load is solid except for a 3-mm diameter hole, which permits the radiation external to the target to be monitored. To minimize the effects of the magnetic perturbation on the outer wire array arising from this

diagnostic hole, the hole is covered by two vertical 250- μm -diameter beryllium wires spaced 1-mm apart (Fig. 1C). Recent 2D simulations, however, show that the wires should have little effect on the magnetic field topology.

Importantly, the use of the low-density foam target decreases the radial extent of the final pinch at stagnation by roughly two, relative to that measured for targetless (bare) pinches (Fig. 2). The target likely acts to mitigate the RT instability much like the inner array does when impacted by the outer one in the nest. Because of the radial-size reduction, similar x-ray powers are generated through a 3-mm-diameter REH when using the foam target as are generated during a bare pinch viewed through a 6-mm-diameter REH (Fig. 2). Application of this target to the present experiment (with the 4-mm diameter REH) enables both the NIF-scale and reduced-scale hohlraum to be heated by the same axial power, and thus permits the reduced-scale hohlraum to be driven to a higher temperature.

The hohlraums are thin-walled (25.4- μm thickness) gold cylinders measuring 6 mm in diameter by 7 mm in height (Fig. 1A), or 4 mm in both diameter and height (Fig. 1E). In the NIF-scale hohlraum, a 3-mm diameter diagnostic hole is centered 2.5 mm below the hohlraum's top cover. In the reduced-scale hohlraum, a 2-mm diameter diagnostic hole is centered 1.15 mm below the top cover and tamped by a 10-mg/cm³ TPX disk of 0.5-mm thickness to retard aperture closure. The interior of the NIF-scale hohlraum is left empty. For the reduced-scale hohlraums, the temperature is examined when the hohlraum is left empty as well as when filled with 6 and 14 mg/cm³ TPX foam.

The temperature of the inside hohlraum wall, midway between its bottom and top, is measured with two independent diagnostics, each of which views the interior through the diagnostic hole described above, but at $\pm 20^\circ$ about the normal to the aperture in the horizontal plane (Fig. 1B). A correction to the measured temperatures for the reduction in hole size due to plasma closure is applied to both diagnostics. In one diagnostic, the temperature is measured using a set of twelve silicon-diodes mounted downstream from a transmission-grating-spectrometer. The diodes are positioned to be sensitive to x-rays in discrete energy channels ranging from 100 to 600 eV [23]. Using this diagnostic, the temperature is taken as a weighted average of the individual brightness temperatures from each channel. In the other diagnostic, a brightness

temperature is determined from a total-energy bolometer [44] and filtered x-ray diodes (XRDs) sensitive to x-rays in four discrete channels covering a similar energy range [45]. In this diagnostic, the temperature is defined by one of the XRD signals (typically the channel with the lowest-energy sensitivity) normalized by the total energy measured in the bolometer. Over the range of temperatures measured here and in other static-wall configurations (where the load and target were adjusted to produce temperatures in a lower range of 55-120 eV [1]), the temperatures determined from the two diagnostics agree to 2% on average with a shot-to-shot variation of $\pm 4\%$ (Fig. 3). In Fig. 3, the abscissa corresponds to the temperature uncorrected for hole closure. Plasma closure of the diagnostic hole is measured with a multi-filtered fast-framing pinhole camera, sensitive to x-rays in four discrete spectral channels covering 100 to 600 eV [46]. The four filters are 12.7- μm Be, 5- μm parylene-n (CH) plus 0.1- μm Al, 1- μm Ti, and 1- μm Cr foil. For the temperatures discussed here, a correction for the reduced hole size based on an average of an effective area [47] from these images is used. This correction increases the peak temperature by 15 to 26% depending on hole size and hohlraum fill.

On one of the reduced-scale hohlraum shots (with a 6 mg/cm³ foam fill), an active SBO (shock-break-out) diagnostic [37] was fielded to confirm, by an independent method, that the brightness-temperature technique outlined above provided credible peak temperatures. This SBO diagnostic used the measured timing difference between the loss of reflected laser light from an aluminum step plate having two well defined thicknesses: 113 and 215 μm . The bottom surface of the two-step plate was mounted atop the hohlraum and directly heated through a 2-mm diameter hole in the hohlraum. The arrangement is illustrated in Fig. 1F and discussed in detail in Reference 37.

The radiation produced external to the target was monitored by a suite of off-axis diagnostics that viewed the source through a small hole in the current return can (Fig. 1C). These diagnostics included a total-energy bolometer, a filtered XRD set, and filtered fast-framing pin-hole cameras. Additionally, on some shots the hohlraum was removed and the power exiting the REH was measured by a further suite of on-axis diagnostics [22, 25, 48]. For these measurements, Lambertian emission at the REH was assumed. In these shots, the size

of the diagnostic apertures viewing the target through the current return varied. The variations were expected to minimally impact the quality of the implosion and resulting axial power.

III. X-RAY SOURCE

A. Array Implosion Dynamics

Simulations of the imploding wire arrays using the Screamer circuit code [49, 50] and a baseline 2D E-RMHC model [34] are illustrated in Fig. 4. In Screamer, the Z generator is modeled as a set of transmission lines driven by a measured voltage source. The circuit model also includes voltage-dependent transmission-line loss near the z-pinch load. The implosions of the arrays and target are handled with an 0D model that calculates the acceleration and collision of infinitesimally-thin plasma shells consistent with the drive circuit and the increasing load inductance. The driving force is the magnetic pressure, $P = B^2 / 2\mu_0$, where the magnetic field B is related to the current I and shell radius r , all functions of time, by $B = \mu_0 I / 2\pi r$. The current is assumed to flow only on the outer shell in an array of shells (which are assumed to represent the arrays and target slices at discrete radii). When two shells collide, momentum is conserved and the mass of the inner shell is accrued to the outer one, which continues to accelerate inward to the next collision (resulting in a discontinuity in velocity and kinetic energy at the time of the collision [Fig. 4C]). In contrast, the E-RMHC simulations lump the details of the generator into an external circuit model consisting of an equivalent voltage source, inductance and resistance elements, and the load (Fig. 1A). The circuit elements produce a current that matches the current flowing in the load, as represented by the Screamer calculations, up to the time of peak current. In the E-RMHC calculations, the detailed physics of the load are modeled in cylindrical geometry. The wire arrays are assumed to start as annular shells of tungsten plasma that have a temperature of 1 eV. The outer shell is given a random perturbation in its density, which provides a seed for the generation of the RT instability. The simulation includes: (1) magneto-hydrodynamic modeling of the RT instability in r - z , including the contact discontinuities at the electrode boundaries, (2) resistive magnetic field diffusion, (3) non-equilibrium radiation diffusion, electron-ion coupling and thermal conduction, (4) SESAME tabular equations of state, opacities, and electrical resistivities [51], with (5) the radiation magneto-hydrodynamic mesh coupled self-consistently to the external circuit.

In both models, the simulated current flowing in the load up to its peak value of ~ 21 MA at 220 ns is in excellent agreement with that measured (Fig. 4A). The decrease in the rate of current rise for times greater than 150 ns (and the rapid fall off later) arises from the monotonically increasing inductive loading on the generator as the arrays begin and continue to converge radially (Fig. 4C). In Screamer, the outer array collides with the inner at 211 ns, the combined arrays impact the target at 227 ns (with a kinetic energy of 660 kJ), and final stagnation of the arrays on axis (with the swept-up target) occurs near 233 ns. The change in current (Fig. 3A) and associated discontinuity in the rate of change of current (Fig. 4B) near 211 ns, 227 ns, and 233 ns are due to the loss of radial kinetic energy (Fig. 4C) (and the corresponding decrease in the rate of change in the load inductance) when the outer array impacts the inner one, the combined arrays impact the target (first strike), and the load stagnates on axis, respectively. In contrast to the sharp discontinuities calculated with the infinitesimally-thin arrays in Screamer, the variation in the current and its rate-of-change in the E-RMHC model are both more gradual and physical, owing to the finite thickness of the plasma shells and associated current distribution within them. The rate of change of the E-RMHC current shown in Fig. 4B is in approximate agreement with the measurements.

The spread in the leading-edge of the imploding shell calculated in the E-EMHC model and shown in Fig. 4D corresponds to the locations of the upper-most spike and bubble shown in the 2D plots of Fig. 5. The axial locations of these two features closest to the REH are indicated by the arrows in the 230-ns plot of Fig. 5. The radial evolution of this hot, highly-emissive leading edge in the model agrees with the half-width-half-maximum of measured radial lineouts of the plasma emission prior to stagnation. After stagnation, however, the experimental radiating plasma re-expands, in contrast to the model whose mass-averaged diameter continues to converge. The modeled radius reaches its minimum ~ 4 ns after stagnation and remains relatively small at ~ 0.5 mm. The associated current-weighted diameter tracks the mass-averaged diameter up to stagnation and then moves to even smaller diameters. The higher current measured after stagnation relative to that modeled in Fig. 4A is consistent with the larger pinch radius measured, and hence the lower inductive loading relative to that modeled.

These comparative differences are similar to those noted with the implosion of aluminum arrays [52] on the Saturn generator [53]. There, the differences were attributed to a higher emissivity used in the simulation

than was physical and/or the 3D nature of the implosion near stagnation. The higher emissivity radiatively cools the imploding plasma, thus permitting the plasma to reach higher radial compressions in the calculation. In contrast, 3D effects (not included in this model) may be expected to soften the experimental implosion, reducing the effective radial compression [54]. Such effects are observed experimentally as stagnation is approached in the on-axis fast-framing pinhole camera images, where a flute-like r - θ instability having a mode number of 6 ± 2 in the x-ray emission can be seen [55]. The origin of these effects likely relates back to the formation of the plasma shell during the wire-plasmas expansion phase and to other azimuthal asymmetries present in the load configuration, and is under active investigation.

B. Target Implosion Dynamics

The peak of the calculated off-axis x-ray power pulse occurs at 234 ns (Fig. 6A). It corresponds to the time when the RT bubbles stagnate on-axis (234-ns plot of Fig. 5), and is referred to as the time of stagnation in the following figures. In this baseline E-RMHC model, the random density perturbation used to seed the RT instability in the outer shell has been chosen so that the off-axis radiated power pulse matches those measured in experiments for a pinch without an axial target [34]. Using this perturbation (random fluctuations in density varying $\pm 6\%$ seeded into each 0.1mm x 0.1mm zone), the shape of the calculated off-axis power is bracketed by that measured (Fig. 6A). In Fig. 6A, Shot Z441 corresponds to the solid return can conditions of Fig. 1 with the small monitoring diagnostic aperture (Fig. 1C), whereas Z438 used 18 foam-filled vertical slots of 4-mm width. The slots provide a greater sensitivity to the radiation arising from the first strike of the plasma on the target at ~ 227 ns, as observed. Additionally, the shape of the calculated off-axis power pulse agrees well with the measured shapes generated from other target configurations [34], providing consistency with the perturbation value used. The measured pulse width of 2-3 ns is qualitatively consistent with that expected from the calculated ~ 1 -mm thick sheath (Fig. 4D) stagnating on-axis with the calculated velocity of ~ 0.4 mm/ns. In Fig. 6A, the measured powers are scaled to that simulated, and the relative timing shifted so the signals overlay. The absolute value of the measured power is uncertain owing to the magnitude of the plasma closure of the diagnostic aperture.

It is estimated to be 160 ± 50 TW, where a large part of the uncertainty arises from the estimated aperture size during closure.

Figure 6B shows a comparison of the associated modeled and measured (without a hohlraum present) on-axis x-ray power for Shot Z438, using the timing established by the comparison of Fig. 6A. The error bars shown in the figure represent the estimated 1-ns timing uncertainty and the $\pm 15\%$ uncertainty in measuring the axial power. The peak axial power averaged over four similar shots is 13 ± 4 TW. The peak occurs 2 ± 1 ns prior to stagnation. Here the uncertainties refer to the RMS shot-to-shot variation. In the baseline model shown, the first (and lower) peak is associated with the radiation generated at the first strike and that of the second (and higher) peak with final stagnation. The time of the first radiation peak (which occurs ~ 3 ns before stagnation) is in reasonable agreement with the measured first-strike radiation time of 2 ± 1 ns. The calculated risetime (10-90%) of the first peak of 2.4 ns is also in reasonable agreement with the measured risetime of 2.8 ± 0.2 ns. The measurements exhibit, however, only one peak corresponding to the first strike, with only a change in slope observed shortly after stagnation. Moreover, the magnitude of the measured first-strike peak is approximately double that simulated at first strike, but similar to that calculated at stagnation. The origin of the differences in the axial power between the experiment and model is not yet understood.

In the baseline model, a fraction of the current has been assumed to be flowing in the target prior to the plasma first strike [34]. The current reduces the expansion of the target and reduces calculated radiation risetimes. This *ad hoc* assumption reconciles some important observed features such as pulsewidths and radiation powers from similar experiments, but needs to be viewed with caution since not all the observed results are in agreement with the model. In another model (which assumes a smaller initial perturbation by a factor of six and which does not use the assumption of magnetic field in the target) the first-strike power is increased significantly, occurs slightly later, and gives better agreement with that measured. This model, however, produces off-axis powers significantly in excess of those measured (and is not discussed further here). The lack of a second axial radiation peak at stagnation in the measurements may arise from 3D effects, such as the azimuthal asymmetries mentioned at the end of the last section [55], which would reduce the efficiency of converting the stagnating plasma into x-rays [54]. Alternatively, the REH may be closing faster or more tungsten plasma may be sliding across the REH, blocking radiation flow exiting the target, than is calculated.

The overall energetics of the implosion calculated in the baseline model is illustrated in Fig. 7. Although the features shown are those of the baseline model, they also qualitatively represent those that would be seen in other models. The upper dashed curve in Fig. 7 is the tungsten kinetic energy in a simulation without a target present and the lower thin solid curve shows the simulation of the tungsten kinetic energy for the baseline model. The difference between these two curves prior to ~233 ns (just before the time of stagnation) indicates energy that has been deposited by the circuit into the load and which is available for creating kinetic energy in the foam target, internal energy in the tungsten and foam, and radiation energy. The thick solid curve shows the internal energy in the foam, with the step between 210 ns and 225 ns representing energy deposited in the foam due to radiation produced by the collision of the outer array with the inner. After this time, the kinetic energy of the tungsten begins its conversion into internal energy during the first-strike process. The internal energy rapidly rises, with the subsequent generation of radiation exiting the REH (lower thin solid curve). The internal energy and tungsten kinetic-energy show an inflection at 232 ns, corresponding to the peak of the radiated energy at first strike (Fig. 6B) and the start of the 2D bubble stagnation on axis (Fig. 4D and Fig. 5 at 232 ns). The stagnating bubbles begin to inhibit radiation flow, originating in the lower portions of the target, from reaching and exiting the REH. Between this time and final stagnation at 234 ns, kinetic energy continues to be delivered by the radial acceleration of the tungsten and target (Fig. 4C), but is balanced by its loss to internal and radiation energy. As stagnation is finally approached, the kinetic energy is rapidly converted to internal and radiation energy, giving rise to the second peak in the power radiated axially. This radiation peak is closely followed by the peak in the internal energy and off-axis radiation power, all of which occur at the time of stagnation. In contrast to the difference between the measured and simulated axial power distributed with time, the 47 kJ radiated axially in the simulation is in agreement with the 60 ± 20 kJ measured 2 ns after stagnation. This correlation is illustrated for Shot Z438 as the dash-dot-dot curve in Fig. 7.

In Fig. 8, three snapshots of density and radiation temperature are shown at times during the rise of the axial radiation pulse, which illustrate the basic conditions and mechanisms seen in the simulations. At 225 ns, a radiation-induced shock ("c" in Fig. 8) has penetrated to ~0.5 mm accompanied by the radiation wave generated by the collision of the two arrays. Further out, at ~2.5 mm ("b" in Fig. 8), the leading edge of the imploding tungsten impacts the foam and begins the generation of a much larger shock and radiation wave. The main body

of the combined tungsten shell is still between 3.5 mm and 0.6 mm ("a" in Fig. 8). Its two-component structure is the result of the impact of the outer array on the inner one. Three nanoseconds later, at 228 ns, a strong shock develops at the tungsten-foam interface (at ~ 2 mm) and radiation penetrates to the center of the foam with temperatures between 65 and 90 eV. Finally, at 230 ns, a very strong shock develops at ~ 1.5 mm just ahead of the tungsten-foam interface, and radiation uniformly fills the foam to a temperature of ~ 145 eV. Unique to these target configurations is the feature of a penetrating radiation front well ahead of the generating shock, which always remains just ahead of the tungsten-foam interface. The tungsten plasma shell forms an imploding hohlraum wall surrounding the target, and is also a partial energy source for radiation held within. It is the radiation within the CH_2 target that heats the above positioned *static-wall* hohlraum (Fig. 1A).

C. Axial Material Flow Through the REH

Figure 5 illustrates (1) the evolution of the bubble-spike structure of the converging tungsten plasma shell, (2) its subsequent interface with the foam target and its compression, (3) the expansion of the tungsten and foam through the REH, (4) the beginning closure of the REH, and (5) the subsequent motion of the wall of the NIF-scale hohlraum in the baseline model. Figure 9 plots the associated axial flow of the tungsten and foam after the first strike. At 229 ns the upper tungsten spike of Fig. 5 sweeps just past the aperture of the REH. At this time the $\mathbf{J} \times \mathbf{B}$ force begins to push the tungsten vertically through the REH at the rate of ~ 0.2 mm/ns for the duration of the implosion. This rate is about half that of the radial convergence (~ 0.42 mm/ns) of the leading edge of the tungsten in the foam. By the time of stagnation (234 ns), the tungsten has vertically traversed the 0.8-mm thick REH and extended about 0.2 mm into the hohlraum, for a total vertical displacement of ~ 1 mm.

The radiation generated when the outer array hits the inner array creates an early-time heating of the foam target (Figs. 7 and 8), causing it to expand through the REH (Fig. 5). The interface between the expanding foam and the vacuum within the hohlraum is also plotted in Fig. 9. By the time the tungsten plasma first strikes the foam (~ 227 ns), the hot outer radii of the foam have expanded ~ 1 mm beyond the REH. Over the duration of the implosion, this region of the foam continues to expand at the rate of ~ 0.25 mm/ns. When the first radiation-induced shock begins to stagnate on the axis at ~ 230 ns (Fig. 8), a hot axial jet of foam is produced, the top surface of which then rapidly expands along the axis at a velocity of ~ 0.4 mm/ns (Fig. 9). By the time of

stagnation (234 ns), the foam jet has caught up with the slower expanding foam at the larger radii. (Relative timing of these effects indicated by the simulation may not be dependable, however, since the experimental evidence generally indicates a period of about 1-3 ns between peak axial radiation and stagnation, compared with the 0.5 ns period in the baseline model simulation.) At this time, the foam-vacuum interface has reached a height of ~3 mm above the REH into the hohlraum. Although Fig. 9 shows that the foam has expanded a considerable distance into the hohlraum, its density throughout the hohlraum is low, typically $1 \cdot 10^{-3}$ g/cm³ or less (Fig. 10).

The target plasma blowing through the aperture helps tamp the REH and reduce its radial closure (Fig. 5). The effect of this tamping can be seen when the calculated radial motion of this gold-vacuum interface is contrasted with that calculated midway up the hohlraum wall (Fig. 11). At stagnation, the material interface of the REH has converged inward by ~0.2 mm, whereas the interface of the gold wall with the vacuum within the hohlraum has increased by ~0.6 mm. The associated 2/3rds optical depth at this time is 0.4 mm and the temperature of this surface is the one being measured by the off-axis diagnostics (Fig. 1A), which views the inner hohlraum wall through the diagnostic hole.

III. HOHLRAUM TEMPERATURES

A. Diagnostic-Hole Closure

Figure 12 plots the reduction in the radius of the 3-mm diameter diagnostic hole measured for the NIF-scale hohlraum as a function of time. Also plotted is the reduction of the 2-mm-diameter hole observed for the reduced-scale hohlraum. In this case, the measurements were made both when the hohlraum was empty and when filled with 6 mg/cm³ of CH₂ foam. For all reduced-scale-hohlraum measurements, the aperture was tamped with a 0.5-mm thick disk of 10 mg/cm³ foam (Fig. 1E). Zero time corresponds to the time of measured peak power in the hohlraum diagnostics (~ 233 ns in Fig. 6). The data points correspond to the mean, and RMS variation about the mean, of the closure measured from the four different images. Shown in addition is the radial closure measured for the lower-temperature experiments at zero time, corresponding to the data of Fig. 3. In this case, the uncertainty corresponds to the variation in the average of the means. In general, the radial closures measured near zero time are similar. They vary from 0.2-to-0.3

mm, and are independent of hohlraum temperature within the shot-to-shot variation. The approximate independence of closure with temperature suggests that the general radiation produced from the current flow through the wire plasma during implosion, and the early heating (Fig. 7) that arises when the outer array strikes the inner array, dominate hole closure at this time. In contrast, the closure rates measured for the reduced-scale, higher temperature hohlraums (0.05-0.069 mm/ns) are significantly faster than for the NIF-scale lower-temperature hohlraum (0.028 mm/ns), as would be expected. The smaller initial closure for the foam-filled hohlraum also suggests that the foam itself may inhibit the transport to the hole of low-energy x-rays generated during the implosion.

Over the limited duration of the diagnostic sensitivity (~ 4 ns), approximately centered about the measured time of peak hohlraum temperature, the decrease in radius scales linearly with time, for all measurements (Fig. 12). The area thus decreases quadratically with time. The extrapolation of this dependence outside the measured range for the two different sized holes is used in the next section to correct the measured temperature. This extrapolation to early time suggests that the hole begins to close 5-to-10 ns prior to the peak of the measured temperature.

Figures 13A-D and 13E-H illustrate the mass isodensity contours associated with the hole closure calculated for either hohlraum size. The contours are logarithmically spaced with four contours per decade. The calculations were done with a 2D Eulerian code in r - z geometry, with single-temperature radiation diffusion [47]. The initial conditions are shown in Figs. 13A and 13E, where a planar temperature source was assumed to be located just left of the hole. The source was taken to be a composite of the early-time heating calculated by the baseline E-RMHC model for times less than ~ 230 ns (where the hohlraum temperature diagnostic was insensitive to the radiation field and unable to measure the temperature) followed by that measured for the given configuration (as illustrated in Fig. 14 for the NIF-scale hohlraum). In Figs. 13F-13H, the interface between the gold and the foam tamper is meaningful. In Figs. 13B-13D, the interface of the material blow-off into the vacuum, however, is largely arbitrary and dependent on the density selected. By the end of the E-RMHC early heating (Figs. 13B and 13F) both holes have undergone significant changes in their original geometries. Though the material for the plugged hole has expanded, the foam-gold interface has remained relatively constant, while the gold has expanded into the open hole.

Figures 13C and 13G show the two holes just before peak temperature. Figures 13D and 13H show the two holes at late time where the unplugged hole is filled with gold, but the plugged hole still maintains an interface between the foam and gold.

One-dimensional L-RMHC calculations indicate that, with the radiation fields measured here, the foam plug burns through rapidly (~ 0.5 ns) and the temperature measured on its exterior differs by less than ~ 2 eV relative to its interior [56]. In the single-temperature E-RMHC calculation it is the location of the gold-foam interface that defines the aperture of the closing hole with the foam tamper. The corresponding percentage area left open is plotted in Fig. 15. This calculated percentage is in agreement with that measured. For the open hole without the tamper, the radius at which the optical depth exceeds unity is used to provide a qualitative estimation of the radius to which the hole has equivalently closed down. Alternatively, the effective area calculated for this hole as seen through one of the hard-energy filters of the camera (the Cr filter) provides an upper estimate of the closure. Both calculations are shown as the slant-marked area in Fig. 14. Like the estimate for the tamped hole, they are in qualitative agreement with that measured. The calculated areas provide confidence in the experimentally measured ones, which are used to correct the measured temperature for either hohlraum size. In Figs. 13B and 13C, the arrows correspond to the radii associated with the two estimates. Comparison of the location of the arrows in Fig. 13C with the position of the gold-foam interface of Fig. 13G indicates that the addition of the foam tamper helps retard the closure. This conclusion is reinforced when the results of Figs. 13D and 13H are contrasted. In Fig. 13D the hole is completely closed (and has been closed for ~ 2 ns), whereas in Fig. 13H the hole still is partially open.

B. Measured Temperatures

Figures 14 and 15 plot the uncorrected temperature based on the total power radiated through the diagnostic hole for the empty NIF-scale and reduced-scale hohlraums associated with Shots Z441 and Z514, respectively. Illustrated also in these two figures is the simultaneously measured effective area of the hole. The corrected temperature based on the quadratic extrapolation of this reduced hole area with time is also shown. The large hohlraum reaches a peak temperature of 122 ± 6 eV and the smaller hohlraum reaches a peak temperature of $\sim 165 \pm 8$ eV, within ~ 1 ns following the peak of the axial radiation (Fig. 16). For the larger

hohlraum, the calculated hole-closure estimate suggests that the quadratic extrapolation is underestimating the closure after the time of peak temperature (Fig. 14). Thus, for the NIF-scale hohlraum the corrected temperature is likely underestimating the actual temperature past its peak. On the other hand, the pinhole-camera measurements and calculations of the tamped hole suggest that this hole has completely closed ~ 10 ns after the peak in the uncorrected temperature is reached (Fig. 15). A significant radiation signal, however, is measured beyond this time. The calculated closure does not take into account reemission from the gold plasma or foam closing the hole. Moreover, by this time the target plasma has had ample time to penetrate the hohlraum and begin exiting the hole. The change in slope that occurs in the uncorrected temperatures 2-3 ns beyond their peaks in both Figs. 14 and 15 is likely a manifestation of such processes. Earlier experiments support this conjecture [29]. In these experiments, images from fast-framing pinhole cameras viewing the exit of the diagnostic normal to the axis of the hole show plasma exiting the hole consistent with these time scales. Thus, beyond a few ns after the peak in the uncorrected temperature, the corrected temperature is likely no longer reflecting the actual temperature of the hohlraum wall. It is the peak in the corrected temperature shortly following the peak in the uncorrected temperature that is referred to as the peak temperature T of the hohlraum.

The relative peak temperatures measured for either size hohlraum are consistent with the Planckian relation $T \propto A^{-1/4}$ (Fig. 17). Here and in the figure, A corresponds to the hohlraum surface area. The measurements are also consistent with the absolute value of the expected temperature (solid curve in Fig. 17) calculated from a radiosity code [31] that uses the measured average incident power of 13 TW and wall albedo of 0.8 (estimated for these conditions [29]).

Figure 18 plots the measured peak temperature of the reduced-scale hohlraum as a function of the density of the foam filling its interior. Shown also in Fig. 18 are the temperatures calculated using either the baseline E-RMHC [34] or an L-RMHC [37] model. In the L-RMHC model, the source x-ray power exiting the REH is adjusted to be consistent with the average 13-TW measured. In this L-RMHC model, the array and target dynamics are not calculated. Sub-micron zoning is used in the hohlraum wall, however, to enable the hydrodynamics of the wall motion to be adequately described. In the E-RMHC modeling, which included the array and target dynamics, the zone size was limited to 20 μm owing to the complexity and subsequent time

length of the simulation. In this case, the E-RMHC modeling provides only an upper bound on the hohlraum temperature, because the energy extracted from the x-ray source in driving the hydrodynamic motion of the walls is underestimated.

In Fig. 18, the E-EMHC simulations correspond to the peak temperature calculated (which occurs at the time of stagnation in the baseline model) scaled by a factor of 0.79 to fit the data points. The relative decrease in the calculated temperature of 5% and 12% with increased density of 6 and 14 mg/cc is consistent with the measurements, respectively. The measured shot-to-shot variation of $\pm 3\%$ about the scaled temperature is also approximately consistent with the shot-to-shot variation of the measured incident axial and associated off-axis power of about $\pm 30\%$. As expected, the baseline-model calculations overestimate the measured temperature. On the other hand, the wall temperature calculated with the fine-zoned L-RMHC model (solid curve) is in agreement with that measured, providing confidence in the temperatures measured as well as with the model. Moreover, the slight time delay calculated (between the peak of the power heating the hohlraum and its peak temperature) with increasing density of the hohlraum fill is in agreement with that measured (Fig. 16). This model shows that at the time of peak temperature the gold wall has expanded radially by only 0.31, 0.19, and 0.11 mm for the 0, 6, and 14 mg/cm³ density fills, respectively (Fig. 19). The associated rate of wall expansion is 0.14, 0.078, and 0.053 mm/ns, respectively. The radial expansion shown in Fig. 19 for the L-RMHC model is somewhat less than that calculated by the E-RMHC model, because in the L-RMHC model the early-time heating is not included. The calculated expansion rates, however, are similar for the empty hohlraums in either model. The calculations suggest that these expansion rates can be significantly reduced with the addition of the fill. The 6 mg/cm³ fill, for example, reduces the calculated wall velocity $\sim 40\%$, with only a 3-5 % calculated reduction in peak temperature.

The measured temperatures scale is supported by the measured time difference for a radiation-driven shock to break out of the two-step witness plate of Fig. 1F. This difference was measured when the hohlraum was filled with 6 mg/cm³ foam for Shot Z515 (Fig. 18). The 4.1 ± 0.1 ns measured time difference, when coupled with a L-RMHC model simulation of the shock-break-out, suggests that the peak temperature of a Planckian radiation field at the surface of the plate is 146 ± 3 eV [37]. This temperature, measured at the upper

surface of the hohlraum, is consistent with the 150 ± 8 eV wall temperature measured midway along its height [37]. Temperatures decreasing by ~ 10 eV from the midpoint to the top with a vacuum fill are calculated [35].

IV. SUMMARY

A z-pinch load having a cylindrical target centered on axis has been developed that produces 60 ± 20 kJ of x-rays with a peak power of 13 ± 4 TW through a 4-mm diameter REH on the Z facility. The REH is axially positioned above the target. The peak in the on-axis power exiting the REH occurs 2 ± 1 ns prior to the peak in the off-axis radiation pulse (stagnation), and is associated with the impact of the tungsten plasma on the target (first strike) and its subsequent compression and heating to generate x-rays prior to final stagnation. The x-rays are confined by the opacity of the tungsten wall of the converging wire-array plasma and flow from the target through the REH. With this source, NIF-scale and reduced-scale hohlraums have been heated to temperatures of 122 ± 6 and 155 ± 8 eV, respectively. These temperatures are characteristic of those required of the *first-* and *second-step* pulse necessary for ICF ignition and propagation burn. The increase in temperature measured with the reduced-scale relative to the NIF-scale hohlraum, from these z-pinch generated x-rays, is consistent with that expected from the Planckian relation. The result complements that which showed the temperature of the NIF-scale hohlraum as a function of x-ray power from a z-pinch to be also consistent with the Planckian relation [29].

The RMHC models provide insights into the dynamics of the wire-array implosion, target compression, heating, x-ray generation, and plasma flows, and the subsequent heating and motion of the hohlraum wall. The modeling suggests that the impact of the outer array on the inner generates a low-level radiation pulse that gives rise to ~ 30 eV radiation temperatures within the hohlraums that lead to diagnostic hole closure rates of ~ 0.02 mm/ns for the ~ 15 ns prior to first strike. After first strike, the closure rates increase to 0.02-0.07 mm/ns and are in agreement with those measured. The upper end of these measured rates is within a factor of two of the ~ 0.14 mm/ns calculated motion of the gold-vacuum interface within the hohlraums. The calculations show that the wall motion can be significantly reduced by the addition of low-density foam without a significant drop in hohlraum temperature, as measured. Using a 6-mg/cm^3 CH_2 fill, for example, reduces the calculated wall motion by $\sim 40\%$ and the associated hohlraum temperature by only

3-5%. The simulations also suggest that the hohlraums remain relatively free of z-pinch plasma until after stagnation occurs. The plasma fill that does occur is principally that of the low-opacity foam with densities typically of the order of 10^{-3} g/cm³.

Combined with the measured temperature profiles, the simulations indicate that such hohlraums as those used in these experiments show promise as useful environments for studying the characteristics of ICF relevant hohlraums under *first-* and *second-step* temperature conditions. Moreover, when driven by two co-linear z-pinchs to improve the temperature uniformity within the hohlraum (as discussed in Refs. 27, 29, and 35) such hohlraums should provide suitable environments for also studying the implosion of ICF capsules.

ACKNOWLEDGEMENTS

Profs. J. S. DeGroot and M. G. Haines are thanked for useful discussions; Drs. M. K. Matzen, and J. L. Porter are thanked for their vigorous programmatic support; Dr. R. A. Vesey is thanked for evaluating the effect on temperature loss through the foam tamper; J. C. Armijo, S. S. Dropinski, T. L. Gilliland, D. E. Hebron, D. O. Jobe, S. E. Lazier, J. S. McGurn, J. F. Seamen, D. Schroen-Carey, J. A. Torres, and the Z crew are thanked for their dedicated technical support; Lastly, Dr. W. A. Stygar is thanked for his careful review of the manuscript and T. L. Cutler for her technical editing.

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*Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94AL85000.

FIGURE CAPTIONS

1. Schematic of experimental arrangement illustrating (A) side-on view with NIF-scale hohlraum, (B) end-on view, (C) off-axis diagnostic aperture, (D) 3-degree anode glide plane, (E) reduced-scale hohlraum, and (F) shock-break-out diagnostic with reduced-scale hohlraum.
2. FWHM of radial linout across REH x-ray image and measured axial power for (A) a bare pinch with a 5.8-mm diameter REH, and (B) a 14 mg/cm³ 5-mm diameter foam target with a 3-mm-diameter REH. The load geometry is that of Fig. 1 except the diameters of the outer and inner arrays are 35 and 17.5 mm, respectively, and the AK gap is 3 mm.
3. Uncorrected temperature measured by the bolometer-XRD system (BXS) relative to the uncorrected temperature measured by the transmission-grating spectrometer (TGS) as a function of the uncorrected BXS temperature. Mean (dotted line) and RMS variation are 1.02 ± 0.04 .
4. Screamer and/or baseline E-RMHC model of the (A) load current, (B) rate of change of the load current, (C) radii and array kinetic energy of the annular arrays, and (D) radius of the mass-weighted tungsten annulus (dashed curve) and radii of the leading edge of the bubble and spike corresponding to the location of the arrows in the 230-ns plot of Fig. 4. Shown also in (A), (B), and (D) are data from Shots Z438, and Z385. The associated on- and off-axis radiation power pulses for Z385 are shown in (D). The dotted lines in the figures link the times when the outer array collides with the inner array (at 211 ns), the combined arrays impact the target (at 227 ns), and the combined arrays plus target stagnate on the z axis (at ~234 ns).
5. Log density plots of the imploding tungsten plasma and foam target, showing the expansion of the gold walls of the NIF-scale hohlraum in the baseline E-RMHC model. The two arrows in the 230-ns plot correspond to the axial location of the bubble and spike whose radii are plotted in Fig. 4D.

6. (A) Off-axis and (B) on-axis radiated power measured and simulated in the baseline E-RMHC model. The off-axis measurements are normalized to the simulated peak power.
7. Energy partition in the baseline E-RMHC model showing the tungsten kinetic energy (second-to-top thin solid curve), the internal energy of the foam target (thick solid curve), and the axial radiated energy (bottom thin solid curve). Shown also is the simulated tungsten kinetic energy without the target (dashed curve) and the measured axial radiated energy for Shot Z438 (dash-dot-dot curve).
8. Density and radiation-temperature radial profiles midway along the axis in the target as a function of three discrete times in the baseline E-RMHC model. The shaded area corresponds to tungsten. "a", "b", and "c" point out the radial location of the tungsten annulus, the tungsten-foam interface driven shock, and the radiation-driven shock, respectively.
9. Axial location of the leading edge of the tungsten-foam interface (solid curve), foam-vacuum interface at $r=1.8$ mm (dash-dot curve), and foam-vacuum interface at $r=0$ mm (dashed curve) in the baseline E-RMHC model with the NIF-scale hohlraum. Positive z values are inside the hohlraum. Values less than negative 0.8 are inside the foam target. Shown as the shaded region is the axial extent of the REH. The arrows marking 227, 230, 232, 234, and 235 ns refer to the interface plots of 227, 230, 232, 234, and 235 ns in Fig. 5, respectively.
10. Typical foam plasma density inside the plume expanding into NIF-scale hohlraum at three axial locations in the baseline E-RMHC model.
11. Radial expansion of the gold-vacuum interface (material surface) and the 0.66 optical-surface midway up the hohlraum wall, and the gold-foam interface in the REH relative to the initial surfaces in the baseline E-RMHC model, for the NIF-scale hohlraum.

12. Measured radial closure of the hohlraum diagnostic hole for the NIF-scale hohlraum (Z441 and Z386), the empty reduced-scale hohlraum (Z514), and the 6 mg/cm³ foam-filled reduced-scale hohlraum (Z515). Zero time corresponds to the peak in the hohlraum temperature.
13. Mass isodensity contours of the hole closure calculated for (A-D) the 3-mm-diameter open hole in the NIF-scale hohlraum, and (E-H) the 2-mm diameter tamped hole in the reduced-scale hohlraum. The contours are logarithmically (base 10) spaced with four contours per decade. In the plots a, b, c, and d correspond to densities of 10⁻¹, 10⁻², 10⁻³, and 10⁻⁴ g/cm³, respectively. Zero time corresponds to the peak in the hohlraum temperature.
14. Measured uncorrected and corrected (for hole closure) NIF-scale hohlraum temperatures for Shot Z441 (solid curves). Shown also connecting with these temperatures is the baseline E-RMHC model calculation of the early heating (dashed curve). Over the range 228-234 ns, the measured percentage open area of the hole is indicated (solid curve), with the shaded region representing the measured RMS variation among the four energy filters. The slanted shaded area corresponds to the estimated percentage open area calculated from the Eulerian code.
15. Measured uncorrected and corrected (for hole closure) reduced-scale hohlraum temperatures for Shot Z514 (solid curves). Over the range 232-238 ns, the measured percentage open area of the hole is indicated (solid curve), with the shaded region representing the measured RMS variation among the four energy filters. The estimated percentage open area calculated from the Eulerian code is also indicated.
16. Measured (data points) and L-RMHC modeled (solid curve) time difference between the time of peak axial power and peak hohlraum temperature, for the reduced-scale hohlraums. Shown also is the measured time difference for the NIF-scale hohlraums.

17. Measured peak hohlraum temperature as a function of the hohlraum surface area (data points) for the two size hohlraums. Shown also is the Planckian scaling relation normalized by that calculated for the reduced-scale hohlraum.
18. Measured peak hohlraum temperature as a function of hohlraum foam-fill density, for the reduced-scale hohlraum (data points). Shown also are the L-RMHC (solid curve) and the scaled baseline E-RMHC modeled temperatures (dashed curve).
19. L-RMHC modeled wall motion (corresponding to the interface between the gold plasma and vacuum or foam) as a function of the density of the hohlraum foam fill, midway along the length of the reduced-scale hohlraum wall.

A. Side-On View

B. End-On View

Fig 1

A. Bare Pinch (REH= 5.8mm)

B. Foam Target (REH= 3mm) (14 mg/cc 5-mm diam.)

Fig. 2

Fig 3

Fig. 4

Fig 5

Fig 6

Fig 1

Fig 8

Fig 9

Fig. 10

Fig 11

Fig 12

3-mm Hole

2-mm Hole

Fig 13

Fig. 14

Fig 15

Fig 16

Fig 17

Fig 18

Fig 19