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Phys. Rev. E **90**, 063101 — Published 2 December 2014
DOI: 10.1103/PhysRevE.90.063101

Study of a new compact hohlraum configuration with parallel planar wire array X-ray sources at the 1.7 MA Zebra Generator

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A new compact Z-pinch x-ray hohlraum design with parallel-driven x-ray sources is experimentally demonstrated in a configuration with a central target and tailored shine shields at 1.7 MA Zebra generator. Driving in parallel two magnetically-decoupled compact double planar wire Z-pinches has demonstrated the generation of synchronized x-ray bursts that correlated well in time with x-ray emission from a central re-emission target. Good agreement between simulated and measured hohlraum radiation temperature of the central target is shown. The advantages of compact hohlraum design applications for multi-MA facilities are discussed.
PACS numbers: 52.58Lq; 52.59.Qy; 32.30.Rj; 52.70.La
Keywords: Z-pinch, hohlraum, Planar Wire Array; X-ray Source, Inertial Confinement Fusion.

Interest in indirect drive of fuel capsules for ICF studies has led to the development and application of the world's most powerful laser facility, NIF [1]. From another side pulsed power offers much more efficient energy coupling than lasers [2]. In this paper, we report the first proof-of-the-principle experimental demonstration of the full configuration of new compact hohlraum design as jointly proposed by the Sandia National Laboratories and the University of Nevada, Reno [3]. The new design enhances efficiency over prior pulsed power driven concepts [2]. This approach is based on application of multiple compact Z-pinch planar wire array (PWA) x-ray sources surrounding a central hohlraum cavity with capsule/target and tailored shine shields (to provide a more symmetric temperature distribution on the capsule/target) (Fig.1). Modeling has shown [3] that a much higher radiation temperature for a given energy input can be achieved (compared to a double-ended design [2]). The resolution of several important problems in the realization of the new hohlraum design has already been achieved. The possibility of PWAs x-ray pulse shaping was demonstrated [4, 5], the anisotropy of PWA radiation output was studied [5], the maximizing of PWA radiation yield and power while keeping mm-scale source dimensions have been shown [5, 6]. Recently, using a simplified compact hohlraum design (without capsule/target and tailored shine shields) equal current redistribution in several magnetically decoupled Z-pinch PWAs driven in parallel without radiation yield and power loss was achieved [7]. The experiment was performed at the UNR 100 ns Zebra machine, which current I was increased from 0.9 to 1.7 MA by incorporating a new Load Current Multiplier (LCM) device [8] in the generator without changing its architecture. Zero magnetic field was observed in the central hohlraum cavity positioned between cavities with PWA sources [7]. Both latter results are important because the application of decoupled loads might lead to a loss of the magnetic insulation with unwanted discharge in the anode - cathode gap. Indeed, the preliminary analysis has shown [7] the formation of a nearly zero magnetic field region between two vertical electrode stalks at the top of the cathode directly beneath a hohlraum central cavity (Fig. 1).

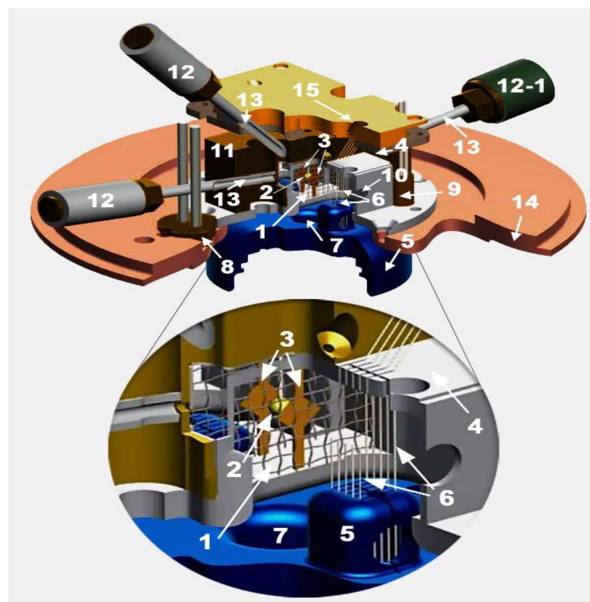

Fig. 1(color online). The cutaway of a new compact hohlraum. 1. Central cavity with two grids at sides and four W (gold coated) walls. 2. Re-emission target in the middle of central cavity. 3. Tailored shine shields in the central cavity to provide a more symmetric temperature distribution on the re-emission target.4. One of two cavities for W DPWA sources. 5. The joint cathode with two vertical electrode stalks at the top. 6. W wires of DPWA. 7. The central hole of the cathode. 8. Micro-B-dot for total load current measuring. 9. Micro-B-dot for one of the source current measuring. 10. Diagnostics window for measuring DPWA radiation parameters. 11. EUV diodes holder.12.Filtered EUV diodes for central cavity diagnostics. 12-1. Filtered EUV diode or pinhole camera. 13. EUV collimators. 14. Anode plate. 15. Support for wires weights.

On the other hand, using of the LCM allows us to reduce voltage between electrodes while increasing total load current [8, 9]. In the present work, the risk of arcs forming at this magnetic null was mitigated by removing the central part of the cathode [7] under the nearly zero magnetic field region (Fig. 1).

First experiments in which the entire configuration of this new compact hohlraum design was performed at the UNR 100 ns, 1.7 MA Zebra /LCM generator with the load consisting of two magnetically decoupled Z-pinch double planar wire array (DPWA) x-ray sources driven in parallel. DPWA sources were used due to much better pulse shaping properties compared with single PWAs [3, 4]. Cutaway (Fig.1) showing a structure of an assembled new compact hohlraum configuration with re-emission target in the middle of central cavity, two tailored shine shields, two cavities with x-ray sources, and radiation and current diagnostics.

Hohlraum design modeling that used the view-factor code VisRad (PRISM Computational Sciences [10]) shows promise in implementing experiments with new hohlraum design on the 1.7 MA Zebra/LCM generator. While fully integrated rad-hydro simulations will be useful to develop a better understanding of the hohlraum physics, view factor modeling is a valuable design tool, allowing us to iterate rapidly on experimental design and to demonstrate the feasibility of the concept for hohlraum and ICF studies on a 1-2 MA university-scale pulsed power platform. The hohlraum had the inner dimensions of 28.5 x 12 x 10 mm (central cavity dimensions were 4.5 x 12 x 10 mm). The anode-cathode gaps were 3 mm. The central cavity was separated from the source cavities by stainless steel grids with initial 70% transmission. The inner wall surfaces of each x-ray sources stainless steel cavities were coated with gold (thickness – 0.2 μm) for better soft X-ray re-emission. The side walls of the central cavity were made of gold-coated W plates. Two tungsten DPWA sources consist of two wire rows (5 wires in each row with inter-wire distance 0.7 mm) with inter-row gap 3 mm. W wire diameter was 7.62 μm. The central hohlraum cavity has a re-emission acrylic spherical target with diameter of 1.5 mm placed in the middle of this cavity on a polyethylene holder (Fig.1). Two concave diamond-shaped shine shields (made from stainless steel foil) were placed between the target and the sources closely to grids' surface.

Currents were measured with calibrated micro-B-dots (PRODYN Techn. Inc., NM, USA). The current in each source cavity was measured to be at least 0.75-0.8 MA for maximum total load current I ~ 1.65 MA.

The radiation characteristics of DPWA W sources were measured with basic Zebra generator diagnostics through a hole in the end plate of the hohlraum. To reduce the effects of hole closure on the source temperature and the pinch power measurements, the size of diagnostic windows in cage walls was 2-4 mm and distance between the plasma and the detectors was more than 1 m. Diagnostics included bare Ni bolometers (0.01 – 5 keV region), filtered x-ray diodes (XRD) measuring radiation in sub-keV region (> 0.2 keV), and photoconducting detectors (PCD) sensitive in keV region (> 0.8 keV). Only shots with maximum x-ray peak position deviation of ± 10 ns with respect to the current maximum were selected for analysis. The average peak power in the sub-keV region (>0.2 keV) of the source in each cavity was found to be P_{DPWA} = 0.65 TW. Driven in parallel, these Z-pinch sources showed similar simultaneous x-ray bursts with nearly equal amplitudes. The synchronized simultaneous sub-keV (>0.2 keV) x-ray bursts from cavities are shown in Fig. 2A. The deviation of the interval between the peaks of sub-keV bursts in cavities was found to be ± 0.9 ns. That can be explained by a simulation that demonstrated high symmetry of magnetic field in inter-electrode gaps (Fig.2 B). This together with the experimental data suggests uniform current delivery to each DPWA x-ray source, and robust reproducibility of such plasma radiation sources.

The central cavity hohlraum environment was analyzed by cross-calibrated AXUVHS5 diodes (Opto Diode Co. CA, USA) with different integrated filters: Al (thickness is d = 150 nm, cut-off energy E_{cf} = 17 eV), Al/C (d = 200/50 nm, E_{cf} = 37 eV), Si/Zr (d = 100/200 nm, E_{cf} = 65 eV), or Cr/Al_2 (d = 100/200 nm, E_{cf} = 300 eV). All diodes (Fig.1) registered radiation from central cavity through tungsten-carbide collimators (with inner diameter of 1 mm). The

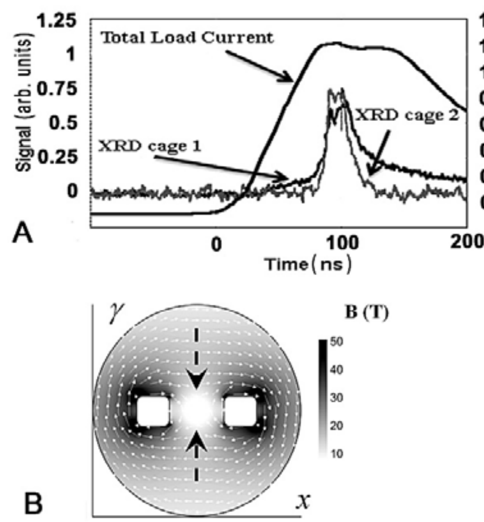

FIG. 2. A. Comparison of XRD sub-keV signals from two cavities (cages) with W DPWA sources vs total load current. Shot 2798. B. Direction and intensity B (in Tesla) of the magnetic field lines in (X,Y) azimuthal plane, which is positioned in middle of cathode-anode gap (parallel to bottom plate of central cavity in Fig.1, section through the vertical cathode stalks that connect to each DPWA). The view is from the top. Current was 1.6 MA. The region of nearly zero B is marked by arrows.

larger size of collimators' opening allowed the reduction of the effect of diagnostic holes closure. The two collimated EUV diodes (at the left in Fig.1) can register radiation from only the same spot (1.1 mm diameter) on the side surface of re-emission target. The initial alignment (before placing the load in generator chamber) was made with a He-Ne gas laser and microscope. The third calibrated, filtered EUV diode (if utilized) that observed same spot on a opposite side of the target, was used for estimation of a non-uniformity of the target re-emission in different directions. For more data, a pinhole camera or a spectrometer might be use instead of third diode.

Experimental estimation of the re-emission target surface radiation temperature T_R was performed by comparing pairs of signals from different cross-calibrated Si-diodes assuming the existence of blackbody radiation sources in cavities. Experiments with the same type of re-emission target without and with shine shields were performed for comparison. The experimental T_R of re-emission target without shine shields was around 45-55 eV (for different diode pairs) in comparison to T_R~38 eV at the point closest to the W source, and 33 eV on the side target surface from VisRad simulations. The T_R was in reasonable correlation with VisRad modeling. The predicted non uniformity of T_R distribution on target surface was estimated about 15%. In addition, we compared the two source scheme with a single-sided drive hohlraum (one W DPWA source with current 1.6 MA and power 1.1 TW, without tailored shine shields). In this case, the maximum T_R will be 42 eV at the point closest to the W source. But the asymmetry of the temperature distribution will be 35-38% compared with 15% in a hohlraum with two wire arrays sources.

The uniformity of the distribution of T_R on the target surface was improved significantly with the application of tailored shine shields between the sources and a target (Fig.1). Also, we are taking into account that the W DPWA is an anisotropic x-ray source [5] (typical ratio K=1.2 of power radiated along wire rows to one emitted orthogonal to planes was measured in our new Zebra tests) and maximum radiation is emitted in the direction parallel to the wire planes [5]. In this particular scheme a proper design of shine shields was applied to use the anisotropy to increase the radiation flux at the target surface. Modeling with modified VisRad showed that T_R will be 35.3 eV at the point closest to the shield and 38.7 eV on the side target surface. The maximum non uniformity of the T_R distribution on target surface in the scheme with tailored shine shields was estimated to be 9%.

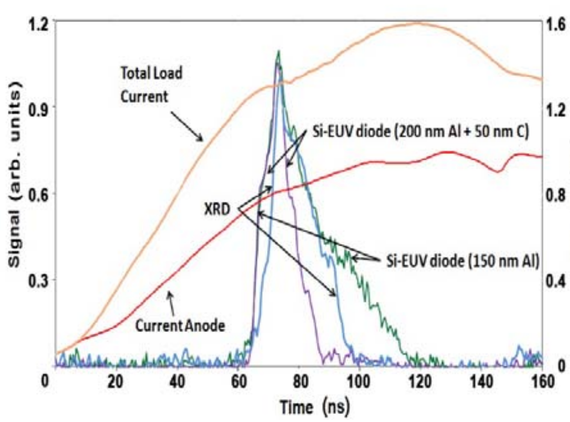

FIG. 3 (color online). Comparison of sub-keV (XRD signal) emission from one of the W DPWA sources with EUV bursts from the acrylic re-emission target in two wavelength regions (two differently filtered Si-diodes signals) vs total load current and anode plate current. Shot # 3256.

Altogether there were four experiments with a new full configuration with central target and tailored shine shields. Diode signals were shown to have the same amplitude (Fig.3) for illustrative purposes.

Experimental T_R of a re-emission target with shine shields was measured to be T_R =37 ±3 eV (for different diodes pairs) in comparison to T_R~38.7 eV at point on side target surface in VisRad simulation. Hence, simulation shows good agreement with the results of the first experiments on a re-emission target T_R measurement with the full configuration of this new hohlraum design. The EUV bursts in different spectral regions from the target correlated well with sub-keV emission (XRD signal) from the DPWA sources (Fig.3) especially in the leading edge. At the same time, the signals' trailing edges were shorter in a harder region (>37 eV) than in softer region (>17 eV).

The results of experiments and simulations of the new compact hohlraum configuration look encouraging, especially given the synchronicity and symmetry of sub-keV bursts from the sources.

We might expect better symmetry of hohlraum exposure on a larger multi-MA machine just because it would be averaging over more sources in a multi-pinch geometry. Now that we have demonstrated the ability to field hohlraums driven by multiple pinches, and the ability to model them with a view-factor code, we can confidently use this simulation tool to improve the design. The configuration of 6 or more pinches proposed by A. Chuvatin and V. Kantsyrev to reach better symmetry of hohlraum exposure, and shown in Fig. 4 (A), seeks to do this by using DPWAs. The application of scheme Fig. 4A, instead of the primary one [1] (Fig. 4B) with four single planar wire arrays (SPWAs), will lead to the increase the radiation flux in the central cavity. This is made possible by the more compact DPWA (compared to the SPWA) where row planes are directed toward the central target.

In the VisRad simulation of these schemes we consider a pulsed power driver delivering on SNL - Z generator scale. The hohlraums were made of Au, and the wire arrays from W; total current I=20 MA (I =3.3 MA at scheme A and I = 5 MA at scheme B in each source cavity). The basic data for W sources were: average P_{DPWA} =0.65 TW at I = 0.75 MA, SPWA power P_{SPWA} =12 TW at I = 6 MA [1]. The current scaling of planar array sources' power is estimated to be $P \sim I^{1.3\text{-}1.8}$ [3, 6, 11]. Figures on the conservative end are $P \sim I^{1.3}$ for P_{DPWA} = 7.5 TW per source (6-source scheme) at I = 3.3 MA, and P_{SPWA} = 10 TW (4-source scheme) per source at I = 5 MA. The VisRad simulation demonstrated T_R ~ 85 eV (2 mm diameter target), taking into account DPWA source anisotropy K_{DPWA}=1.2 for 6-source scheme, and ~ 80

eV for 4-source one (K_{SPWA}=1.2). Hence, in 6-source scheme, the x-ray power flux (~T_R^4) might be 1.3 times higher than that in the 4-source one. In addition to the increase in power flux the use of DPWA will provide the radiation pulse shaping possibility [4]. Time-dependent anisotropy [5] also might be used for effective radiation pulse shaping [4, 11]. The uniformity of the T_R distribution at the target surface with shields (that have not yet optimized) was 5-7 %. It can be reduced to 1.5% by optimization of shine shields shape [3].

A new hohlraum scheme with parallel-driven Z-pinches is a significant advance in terms of driver requirements compared to a double-ended cylindrical pinch scheme [12],

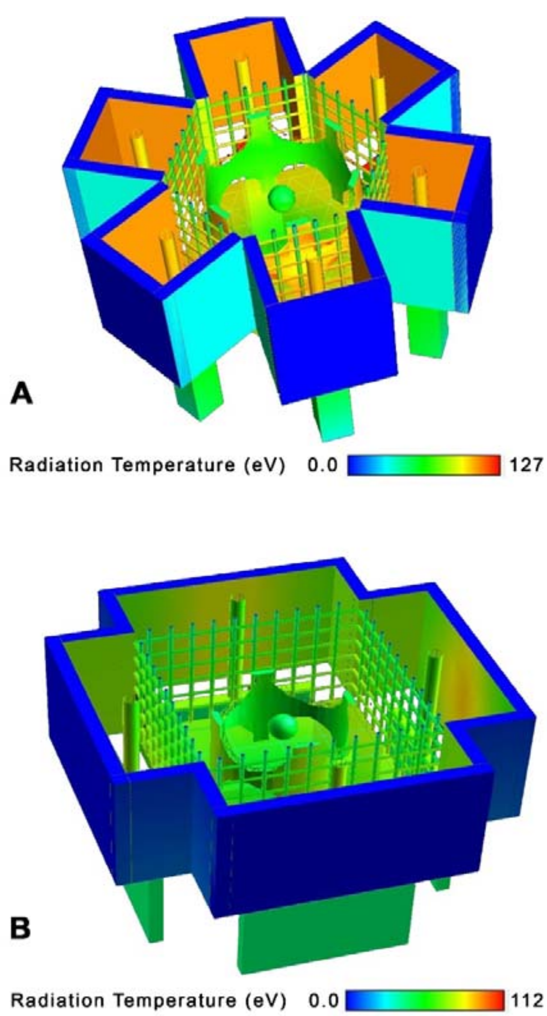

FIG.4 (color online). Comparison of new indirect drive configurations in VisRad modeling (end-on view) with six DPWAs (A) and four SPWAs (B). The sources' plasma columns at final stagnation stage are shown together with the top cathodes surfaces (top covers are not shown). The central cavities were separated from the sources by Au grids with an initial 70% transmission. The central plastic target is surrounded by similarly shaped Au tailored shine shields in both schemes. The minimal gap anode-cathode was 2 mm. A) DPWA has initial inter-row gap Δ = 2.5 mm and width D_d = 2.5 mm, height H_d=10 mm. Each source cavity has the width W_d = 6.5 mm, length L_d=6.5 mm, H_d=10 mm. B) SPWA has D_s = 12 mm, H_s=10 mm. Each source cavity has W_s=5 mm, L_s=16 mm, H_s=10 mm.

because even the geometric arguments from Ref. [3] show that the scheme with parallel driven pinches could be more efficient by a factor of ~ 4.5 in terms of energy requirements. Then, energy requirements directly translate to the size of the Z-pinch generator, so this would make a significant impact on size and cost of a future pulsed-power driven ICF facility. Also, there is further opportunity for improvement and optimization of the novel hohlraum design. In particular, it might be useful to employ double flat planar foil sources instead of DPWAs [7] at currents of more than 30-50 MA, because at such current any wire arrays (cylindrical or planar) may be transformed into foils because the required diameter of wires will increase and the inter-wire gap will shrink. Note, that the highest yield and power from SNL Z generator were obtained with thin wire (4-5 μm diameter) loads made from W (atomic number Z_a=74) [12]. Experiments on Zebra demonstrated that even more than a W load's yield and power can be obtained from a gold (Au, Z_a=79) PWA [13]. VisRad simulation has shown, that x-ray power flux might be ~1.3 times higher than with W in new hohlraum design with Au sources and central target [13]. Preparation of thin W flat foils is difficult because such W loads will be extremely brittle. In contrast, even sub-μm flat Au foils are very reliable and strong [7]. It will be important with application of a new multi-source hohlraum design due to an increase in radiation yield and power and much simpler Au foil loads preparation compared with W.

In summary, the first proof-of-principle experimental demonstration of the full configuration of a new compact hohlraum design with parallel-driven Z-pinch sources, central re-emission target, and tailored shine shields (to provide a symmetric temperature distribution on the target) was achieved. New results and a code that is validated by experiments allow the further studies enhancing the hohlraum design and addressing hohlraum physics. The present data demonstrate that new multi-z-pinch hohlraum configurations are realizable. Numerical simulation shows good agreement with measured radiation temperature of re-emission target around 30-40 eV and demonstrates the possibility of application of a new multi-source compact hohlraum design for multi-MA ICF review experiments.

This work was supported by DOE/NNSA under Cooperative Agreements DE-NA0001984, DE-FC52-06NA27586, and in part by DE-NA0002075 and DOE/SNL Grant 681371. Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract No.DE-AC04-94AL8500.

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