New Compact Hohlraum Configuration Research at the 1.7 MA Z-pinch Generator

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MOTIVATION

- **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. From another point of view, a pulsed power offers much more efficient energy coupling than lasers.**

- **In this presentation, we report on the first proof-of-the principal experimental demonstration at the UNR 1.7 MA Zebra generator of the full configuration of new compact hohlraum design with a central target and tailored shine shields as jointly proposed by the Sandia National Laboratories and the University of Nevada, Reno [B. Jones, M. Cuneo, D. Ampleford, C. Coverdale, E. Waisman, R. Vesey, M. Jones, A. Esaulov, V. Kantsyrev, A. Safronova, K. Williamson, A. Chuvatin, L. Rudakov. Physical Review Letters, v. 104, 125001 (2010)].**

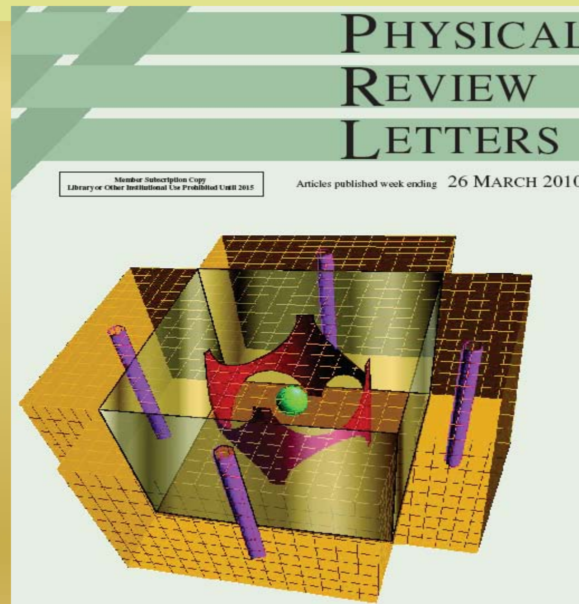
New hohlraum concept for radiation physics and ICF is based on PWA application

Important problems to be solved:

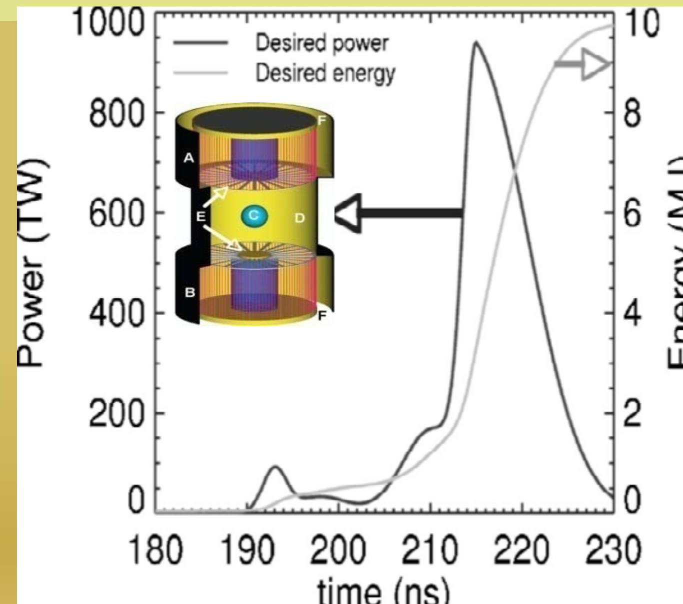
- equal current redistribution in magnetically decoupled parallel-driven compact Z-pinches without yield/power loss [*Phys. Plasmas, v.21, 031204 (2014)*]
- maximize x-ray power/yield while keeping mm-scale source size [*publications in 2005-2014*]
- study of anisotropy of output radiation [*Phys. Plasmas, v.20, 070702 (2013)*]
- x-ray pulse shaping (application of Triple PWA, DPWA with induced axial B_z , or combined multi-material DPWA) [*J. Phys., 244, 032030 (2010); PRE , v. 84, 046408 (2011)*]

- The *new proposed hohlraum concept** is based on application of planar wire arrays (PWAs) in compact cavities to drive a hohlraum and a capsule.

- Much smaller hohlraum is needed compared with double-ended scheme, and more compact and cheaper generator will be used.



New proposed hohlraum concept
T_{rad} ~ 90 eV* (24 MA at Z)



Double-ended concept T_{rad}~70 eV
M. Cuneo *et al*.,PRL,88, 215004(2002)

* B. Jones, M. Cuneo, D. Ampleford, C. Coverdale, E. Waisman, R. Vesey, M. Jones, A. Esaulov, V. Kantsyrev, A. Safronova, K. Williamson, A. Chuvatin, L. Rudakov. Physical Review Letters, v. 104, 125001 (2010)

INTRODUCTION

- **This presentation reports on the joint success of two independent lines of multi-year research efforts.**
- **First of them is the strong improvement in energy efficiency of pulsed-power systems, which started in early 1980s with O. Zucker's experiments at the NRL. Successful continuation of this approach was the Load Current Multiplier (LCM), proposed by A. Chuvatin [A. Chuvatin *et al.*, Rev. Sci. Instrum., v. 76, 063501 (2005)] in collaboration with L. Rudakov and B. Weber from the NRL.**
- **Our UNR group in collaboration with A. Chuvatin (and support from the SNL) participated in the design of the new 100 ns LCM unit and led the effort of its integration into the Zebra (almost doubled current load *I* from 0.9 to 1.7 MA with plasma loads).**
- **Independently, from 2005 we've led the development of innovative sources, such as planar wire arrays (PWAs) [V. Kantsyrev *et al.*, IEEE Trans. Plasma Sci., v. 34, 194 (2006)]. PWA turned out to be an effective radiator [V. Kantsyrev *et al.*, HEDP, v. 5, 115(2009)] even though the physical mechanism of efficient magnetic energy conversion into radiation still remains unclear.**

INTRODUCTION (continued)

- **New results on PWAs were obtained, as well as on the comparison with planar foil liners – some promising alternative to wire arrays [V. Kantsyrev *et al.*, Phys. Plasmas, v.21, 031204 (2014)]. The anisotropy of power/yield from PWAs was investigated [V. Kantsyrev *et al.*, Phys. Plasmas, v.20, 070702 (2013)], multistep precursor formation and radiation from PWAs was studied [A. Safronova *et al.*, HEDP, v.7, 252 (2011)], and the possibility of x-rays pulse shaping was shown [K. Williamson *et al.*, Phys. Plasmas, v.17, 112705 (2010)].**

- **Pioneered at UNR, the PWA Z-pinch loads have later been tested at the SNL on the Saturn generator (*I* = 3-6 MA), on GIT-12 machine in Russia (*I*=3 MA), and on the QiangGuang-1 generator in China (*I*=1.5 MA), always successfully.**

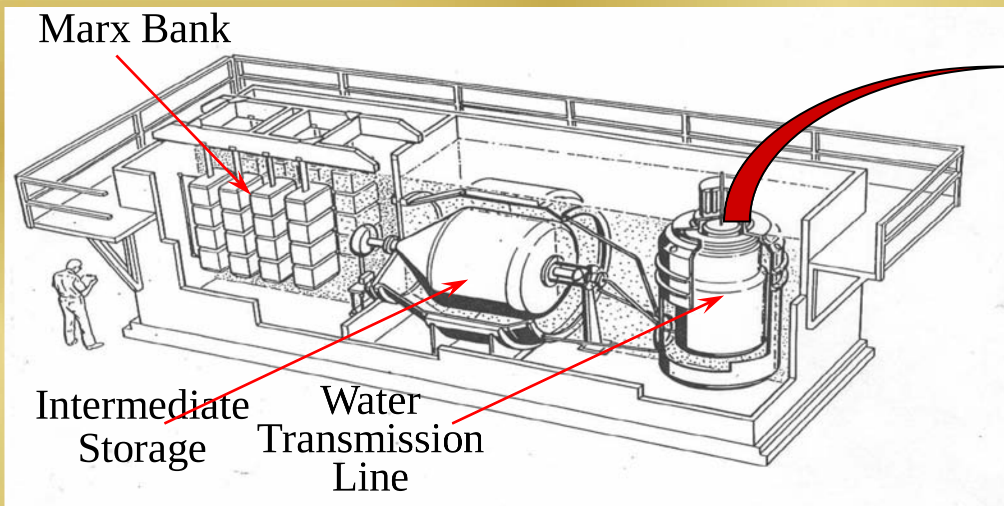
INTRODUCTION (continued)

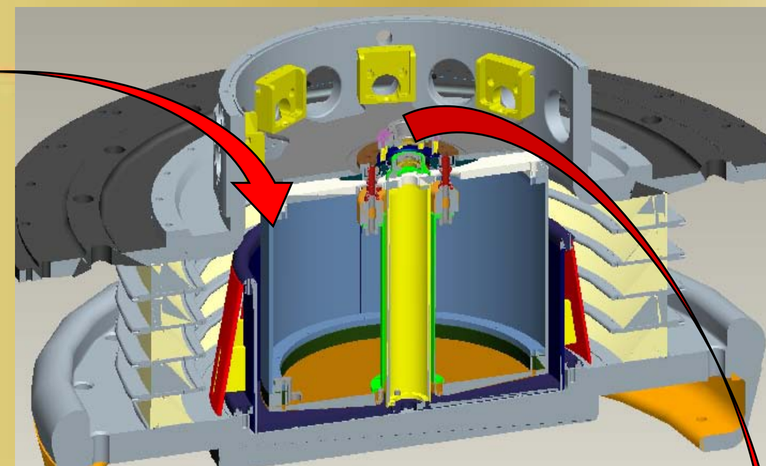
- **In 2014, we successfully tested different PWAs (single – SPWA, double – DPWA) in collaboration with University of Michigan on the UM LTD generator MAIZE for the first time (see first results in talk by N. Jordan *et al*., this Conference session 7, Aug. 05, and in future DPP 2014 presentation by A.S. Safronova *et al*.).**

- **The two innovative approaches mentioned in the beginning were used in combination to produce a new concept of compact hohlraum radiation source for ICF, as jointly proposed by SNL and UNR [B. Jones et al., PRL, v. 104, 125001 (2010)], and demonstrated first experimental results with simplified design at Zebra/LCM in coordination with B. Jones, M. Cuneo and R. Vesey from the SNL [V. Kantsyrev *et al*., Phys. Plasmas, v. 21, 031204 (2014)].**

The Increased Current at UNR Zebra Without Changing Generator Architecture

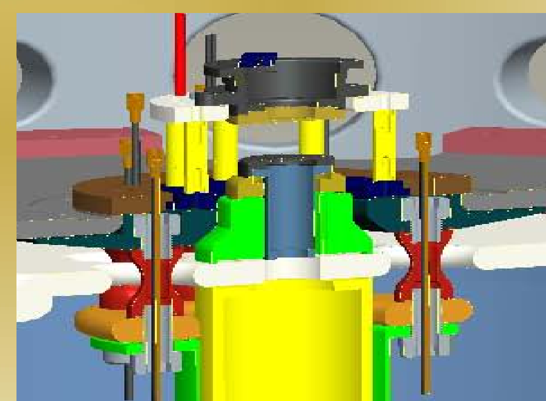
V. Kantsyrev, A. Chuvatin (Ecole Polit.,France), L. Rudakov (Icarus Inc.), M. Cuneo (SNL),
A. Astanovitskiy, R. Presura, W. Cline, A. Safronova, A. Esaulov, K. Williamson, G. Osborne,
I. Shrestha, M. Weller, V. Shlyaptseva, B. LeGalloudec, V. Nalagala, S. Batie





LCM 2011 -2013 version

Marx Bank → Intermediate Storage → Water Transmission Line → Vacuum Chamber with LCM and load

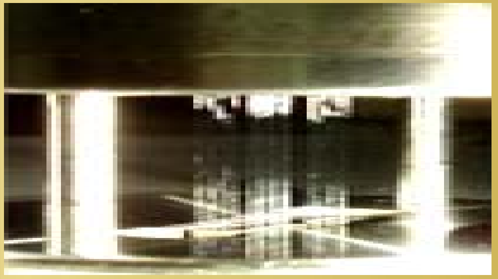


UNR/NTF Zebra in 2011-12: current 0.9 MA in standard mode and up to 1.7 MA (wire arrays) and 1.9 MA (short circuits) with *Load Current Multiplier* (LCM*); current rise-time 100-110 ns; impedance 1.9 Ω; initial stored energy ~150 kJ

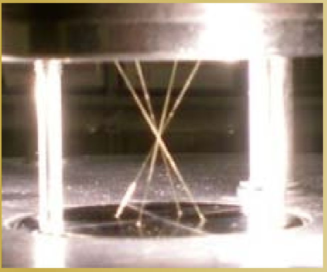
* A.S. Chuvatin, V. L. Kantsyrev, L.I. Rudakov *et al*, Physical Review, S.T. Accelerators and Beams, v. 13, pp. 010401-1÷8 (2010).

Maximize x-ray power / yield while keeping mm-scale size of PWA , planar foil or X-pinch x-ray sources in experiments on the UNR Zebra/LCM generator

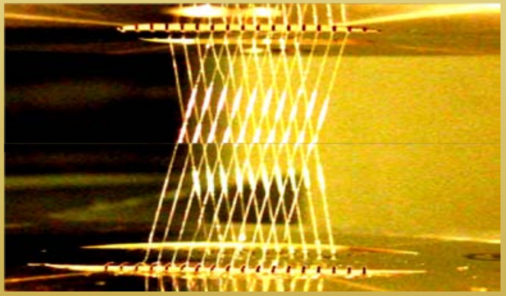
Double planar wire array (DPWA)
Most powerful source, useful for pulse shaping



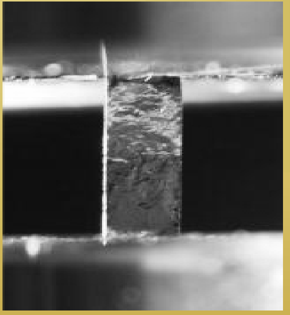
Triple planar wire array (TPWA)
Wire rows are imploded independently. Useful for pulse shaping



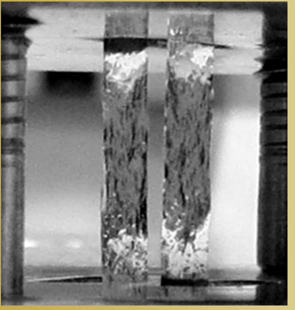
X-pinch
Useful as a test point source



DPWA with skewed wires (DPWA sk)
Generated induced axial B_z that mitigated MRT instabilities and useful for pulse shaping



Single Planar Foil (SPF)



Double Planar Foil (DPF)

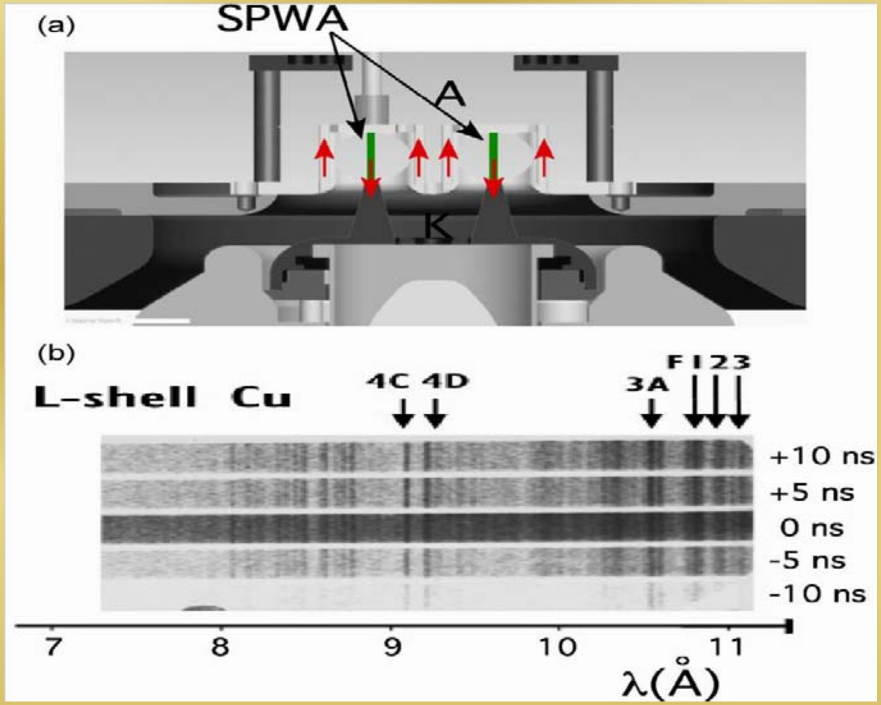
Maximize x-ray power / yield while keeping mm-scale size of PWA , planar foil or X-pinch x-ray sources in experiments on the UNR Zebra/LCM generator (continued)

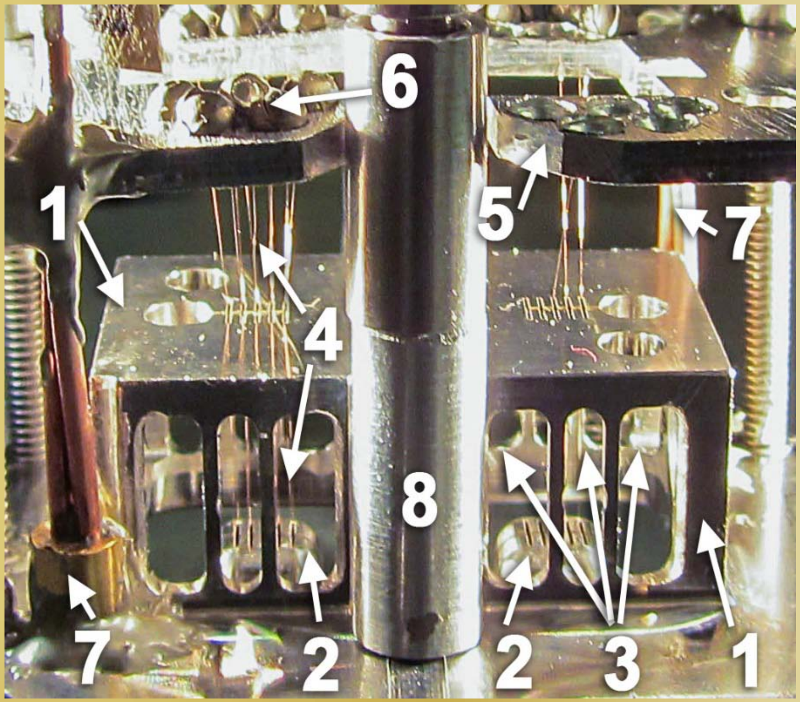
- **Compact, mm-scale, DPWA and TPWA demonstrated: larger resistive energy (>30 kJ/cm) and power (> 1TW/cm) gain, highest current scaling (~ $I^{1.8 \div 2}$) among all loads tested at university scale generators, anisotropy of power/yield regarding wires rows, and the possibility of radiation pulse shaping.**

- **Planar foil sources (Al SPF and DPF) have shown yields which are close to PWAs results, and smaller axial Te and Ne gradients. Work is in progress [V. Kantsyrev *et al.*, PoP, v.21, 031204 (2014)].**

- **Radiation yield E_T is larger than the magnetic field work E_k ($E_T \sim 6$ -10 E_k).**

Current redistribution experiments on the UNR 1.7 MA Zebra/LCM generator: parallel-driven PWA Z-pinches





Two magnetically decoupled SPWAs (left) and DPWAs (right) Z-pinches.

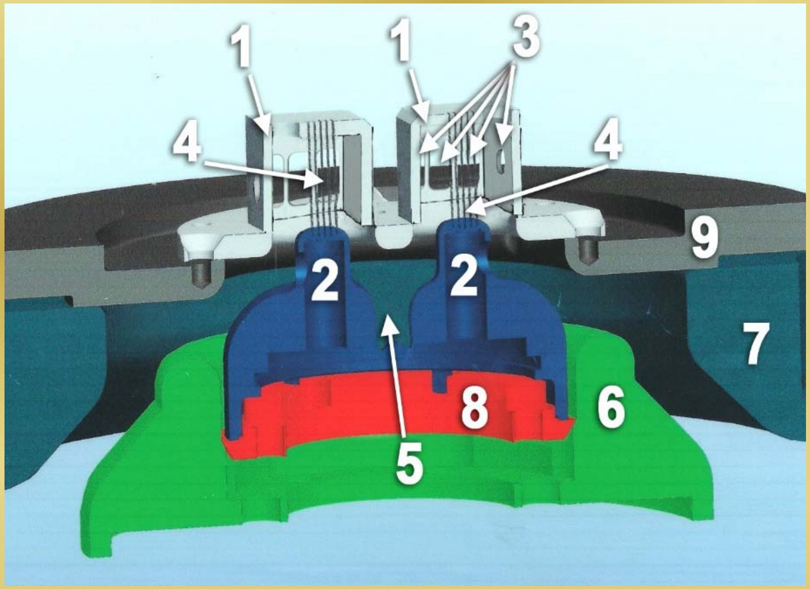
Design of twin SPWAs "in cavities" loads (viewed parallel to the planes of the SPWAs). Currents around the cavities and through the planar arrays are indicated with arrows*. Time-gated L-shell spectra for a Cu planar array in one of the cavity. Te = 400 eV. Times are relative to the peak x-ray power.

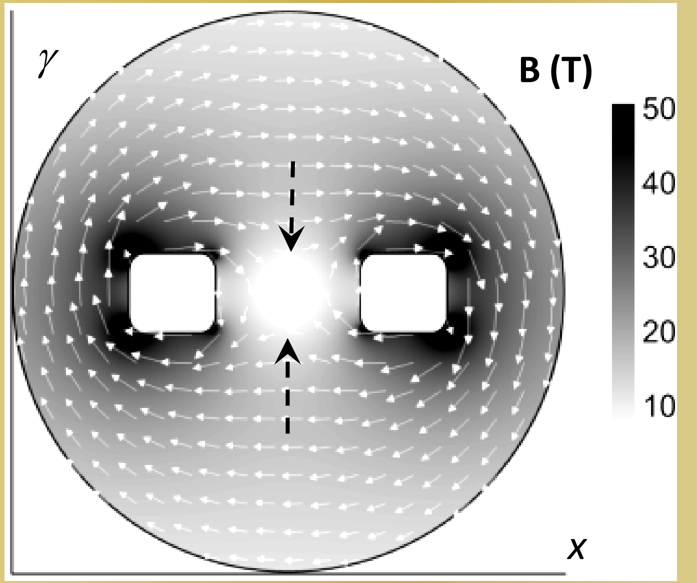
Decoupled DPWAs being driven in parallel.** 1.Cavities for W DPWA sources. 2. Top parts of cathode (cathode stalks). 3. Cavities side windows for diagnostics access. 4. W wires. 5. Support for wires weights. 6. Top wires weights. 7. Micro-B-dots for measuring currents in cavities. 8. Load-supporting rods that are removed before shot.

*J.L. Giuliani, F. Beg, R.M. Gilgenbach, V.L. Kantsyrev et al, *IEEE Trans. Plasma Sci.*, v.40, 3246 (2012).

**V. Kantsyrev, A. Chuvatin, A. Safronova, L. Rudakov *et al.*, Phys. Plasmas, v. 21, 031204 (2014).

Design of a cathode-anode gap for avoiding a loss of the magnetic insulation at magnetic null region





A nearly zero magnetic field region might be formed between two vertical electrode stalks at the top of the cathode beneath the central hohlraum cavity that can lead to unwanted discharge in anode-cathode gap. We mitigated the risk of arcs forming at this magnetic null by removing the central part of the cathode (arrow 5 in left figure)*. The simulation show high symmetry of magnetic field in A-C gap.

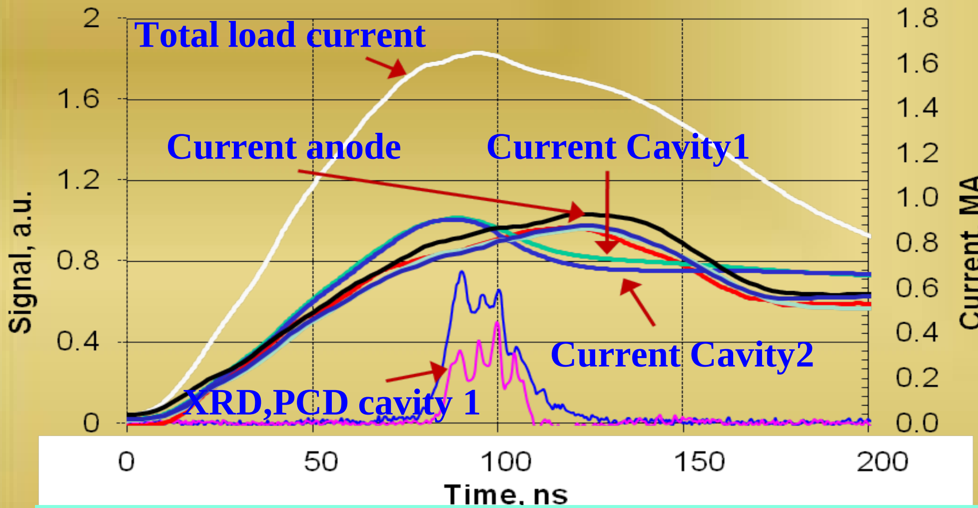
Cutaway of connection of anode and cathode of magnetically decoupled DPWA sources to the top of the LCM. 1. Cavities for W DPWA sources with windows. 2. The cathode with two stalks electrodes. 3. Cavities side windows for diagnostic. 4. W wires. 5. The central hole of the cathode. 6, 7. Top parts of the LCM: cathode and anode sides of the magnetically insulated transmission line (MITL). 8. The cathode's connector . 9. The anode plate.

*V. Kantsyrev *et al.*, Phys. Plasmas, v. 21, 031204 (2014).

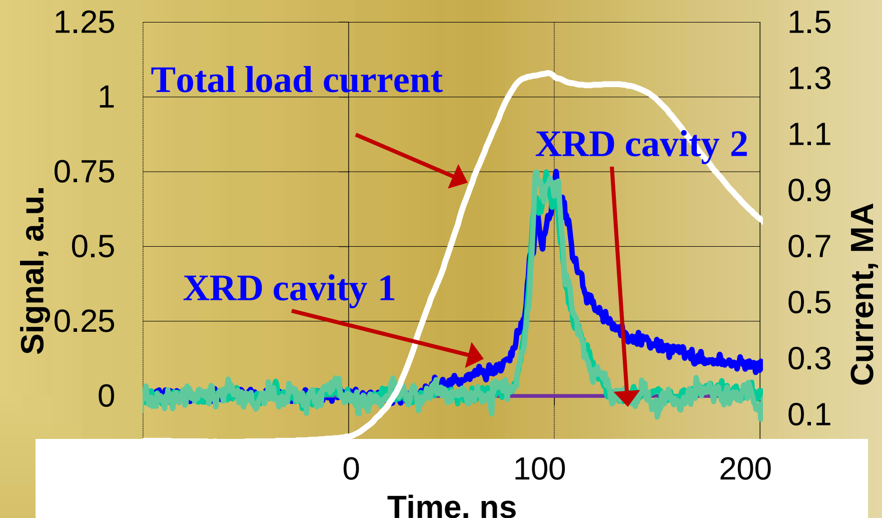
Direction and intensity *B* (in Tesla) of the magnetic field lines in (*X*,*Y*) azimuthal plane, which is positioned in the middle of a cathode-anode gap (parallel to the bottom plate of the central cavity in Fig.1, section through the vertical cathode stalks that connect to each DPWA). The view is from the top. Current was 1.6 MA. The region of nearly zero B is marked by arrows.

Driving in parallel two magnetically decoupled compact Z-pinches was experimentally demonstrated with equally redistributed currents

- The current in each cavity was measured to be at least 0.75 – 0.82 MA .



Currents VS sub-keV / keV bursts. Cu DPWAs Sh. 2485

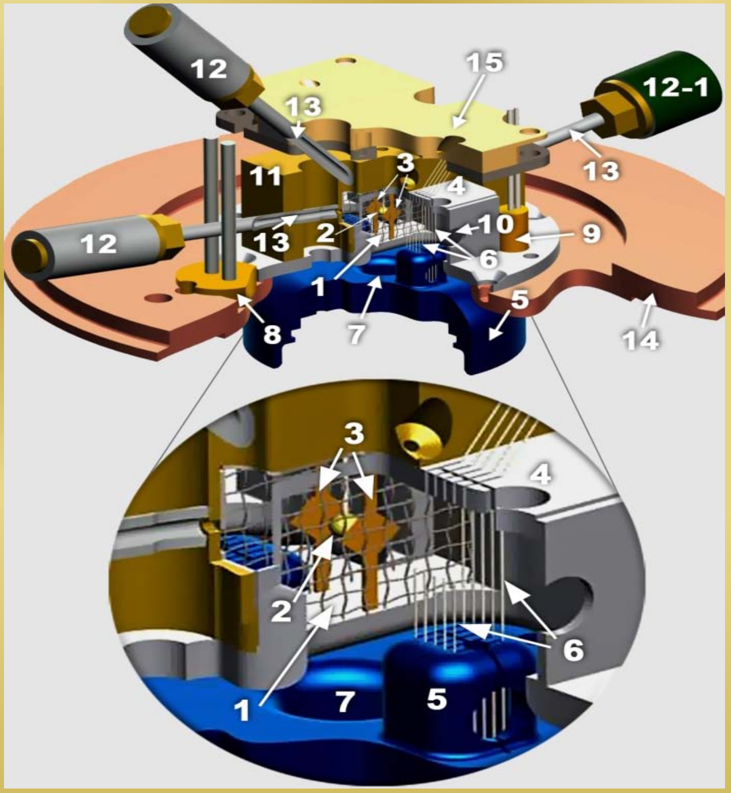


Synchronized sub-keV (XRD) emission from cavities was shown. W DPWAs Sh. 2798 .

- While current is redistributed in two cavities, the kinetic energy $\Delta L\, I^2/2$ released at stagnation should be in each cavity 1/4 and total E_Σ in two cavities is 1/2 of energy compared to the case when full current of 1.6 MA flows in one load of the same geometry

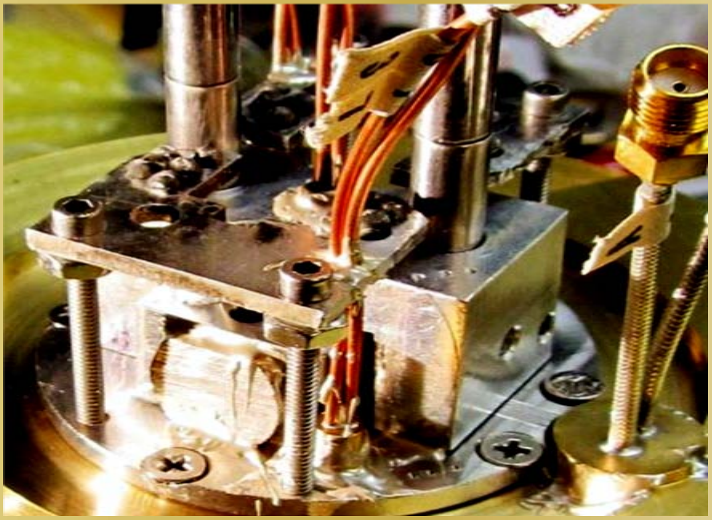
- However the total yield from two cavities E_Σ was at least 80-85 % compared to the total yield E_T from one PWA with the same geometry at 1.6 MA (plasma radiated as a resistor?)

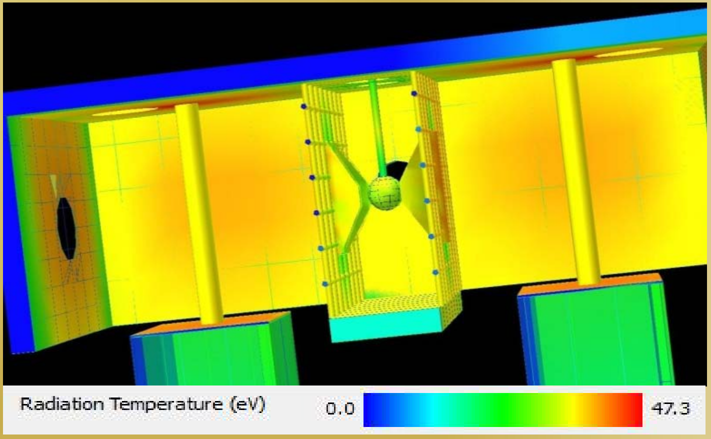
The new compact hohlraum in full configuration with two magnetically insulated DPWA parallel-driven x-ray sources, central target and tailored shine shields



The cutaway of a new compact hohlraum.

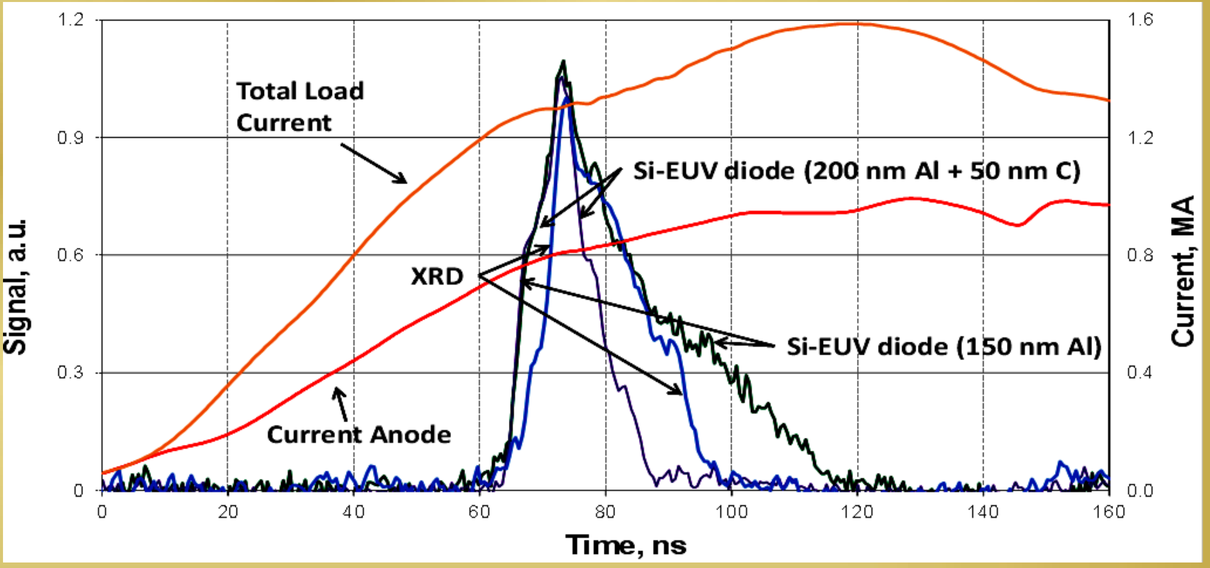
1. W (Au) central cavity with two grids at sides. 2. Re-emission target. 3. Tailored shine shields to provide a more symmetric temperature distribution on the re-emission target.4. One of two cavities for W DPWA sources. 5. The cathode with vertical electrode stalks . 6. W wires. 7. The central hole of the cathode. 8. Micro-B-dot for total load current. 9. Micro-B-dot for one of the source current. 10. Diagnostics window for measuring DPWA burst 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.





Predicted distribution of radiation temperature T_R in hohlraum using modified view-factor code VisRaD (PRISM Co.) (the anisotropy of DPWA emission was considered). The acrylic spherical (ϕ=1.5 mm) target T_R is ~ 38.7 eV on the side target surface.

Results of Zebra/LCM experiments involving new compact hohlraum configuration with two magnetically insulated DPWA x-ray sources, re-emission central target, and tailored shine shields



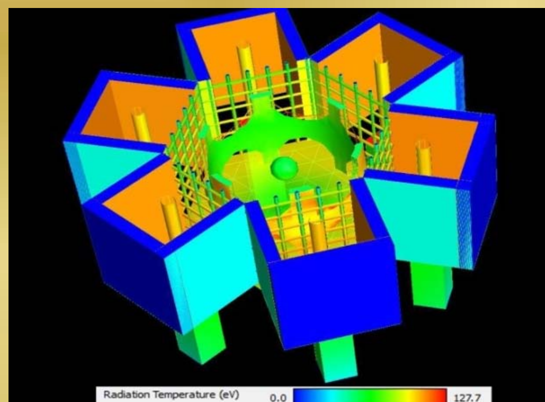
W DPWAsources: 5 x 5 ,7.62 μm wires in each source cavity, inter-row gap Δ=3mm. Shot # 3256.

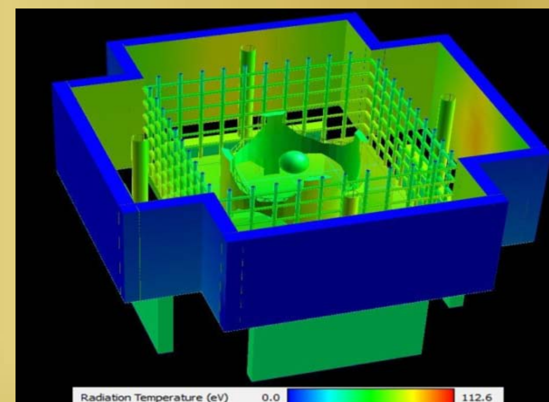
Experimental estimation of radiation temperature T_R of acrylic re-emission target in central cavity was performed assuming blackbody radiation sources in hohlraum by comparison of signals from cross calibrated filtered Si-diodes AXUVHS5 (XRD signal shows emission from a DPWA source in a spectral region > 0.2 keV). There were altogether four shots with a new configuration.

Experimental plastic target T_R varied in the range 37 ± 3 eV in comparison with ~ 38.7 eV from VisRaD code simulation.

Future application of new compact hohlraum configurations with multi - PWA x-ray sources at multi-MA facilities

- **Below is comparison of new indirect drive design with VisRad modeling (end-on view) with six DPWAs (left) and four SPWAs (right). The sources' plasma columns at final stagnation stage are shown. The central cavities were separated from the sources by Au grids (initial 70% transmission). The central target is surrounded by similarly shaped Au tailored shine shields in both schemes. Better symmetry of hohlraum exposure is obtained for 6-sources scheme.**





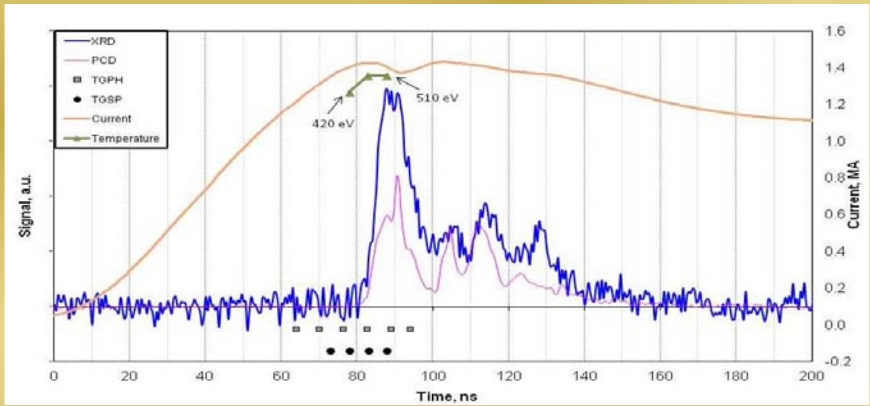
- **At 20 MA (Z-SNL generator scale), the 6-source scheme's (target T_R = 85 eV) x-ray power flux ($\sim T_R^4$) should be 1.3 times higher than that in the 4-sources one (target T_R = 80 eV). In addition, DPWA sources will provide possibility of radiation pulse shaping. Calculation was made with modified code VisRaD (the anisotropy of DPWA emission was considered) based on yield and power scaling: $E \sim I^{1.7-2}$, $P \sim I^{1.3-1.5}$ [*,**, ***].**

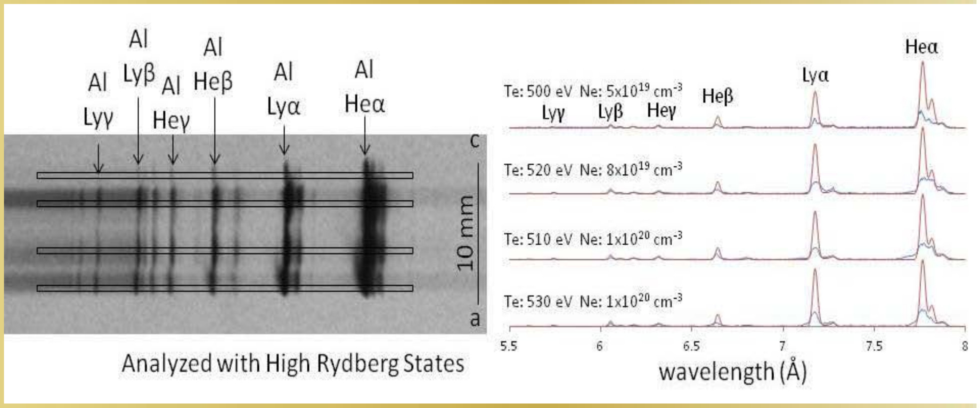
- **A new scheme with parallel-driven Z-pinches is a significant advance in terms of driver requirements compared to a double-ended cylindrical pinch scheme (the scheme with parallel driven pinches could be more efficient by a factor of ~ 4.5 in terms of energy requirements*). Then, energy requirements 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.**

*** B. Jones *et al.*, Phys. Rev. Lett., v. 104, 125001 (2010); ** K. Williamson *et al.*, AIP Conf. Proc., v. 1088, 141 (2009); *** V. Kantsyrev *et al.*, HEDP, v. 5, 166 (2009).**

Future opportunity for improvement of the novel hohlraum design

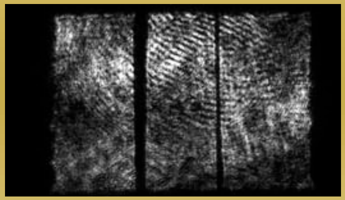
- **It might be useful to employ a double flat planar foil instead of DPWA at currents of more than 30-50 MA, because at such current wire arrays (cylindrical or planar) might be transformed into foils.**

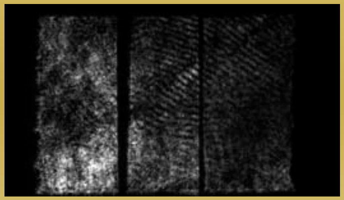


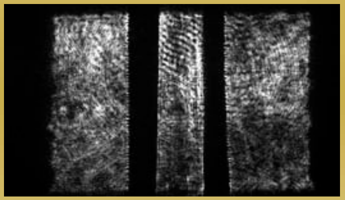


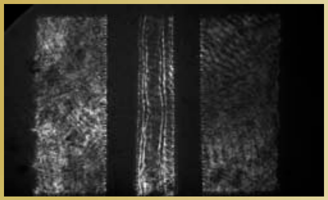
<u>At the left</u> is radiation output from Al double foils (width – 5 mm, inter-foil gap - 3 mm, foils thickness of 1.8 μm, anode – cathode gap = 10 mm). Shot # 3246. XRD and PCD – signals from detectors in sub-keV (> 0.25 keV) and keV (>0.8 keV) spectral region respectively vs load current. In green is time dependence of T_e. <u>At the right</u> is 1D spatially resolved, time integrated spectra

23 ns **26 ns** **32 ns** **35 ns**









Laser shadowgraphy images, time is after current start. View is along foil planes.

*** V.V. Shlyaptseva, V.L. Kantsyrev, A.S. Safronova *et al.*, Int. J. Mod. Phys.: Conf. Ser., 36 (2014), *in press*.**

Future opportunity for improvement of the novel hohlraum design (continued)

- **The Al double planar foil successfully imploded and generated powerful radiation bursts. The T_e of Al DPF was estimated to be: average $T_{e\ DPF}$ = 515 eV (I =1.5 MA) that is similar for Al DPWA. The Al DPF showed a radiation yield near 14-16 kJ /cm at current 1.4 -1.5 MA, which is close to Al DPWA. For future experiments with multiple Z-pinch sources at multi-MA generators, DPF sources can be used instead of DPWAs due to easy load maintenance.**

- **Also, the highest yield/power on SNL-Z was obtained with W (atomic number Z_a=74) wire loads. Experiments on Zebra have shown that more than W load's yield and power can be obtained from a gold (Au, Z_a=79) PWAs*. VisRad simulation has demonstrated, that x-ray power flux from Au PWAs might be ~1.3 times higher than with W in a new hohlraum design*. Thin W flat foils will be extremely brittle. In contrast, even sub-μm flat Au foils are reliable and strong. It will be important for application of a new hohlraum with Au sources due to an increase of yield and power.**

*** V.V. Shlyaptseva, V.L. Kantsyrev, A.S. Safronova *et al*., Int. J. Mod. Phys.: Conf. Ser., 36 (2014), *in press*.**

CONCLUSION

❖ 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 that will enhance the hohlraum design and address 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 a 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.

ACKNOWLEDGMENTS

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