SAND2008-1227C

Experimental Studies of Implosion Characteristics and Radiation Properties of Planar and Cylindrical Wire Arrays and X-pinches

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2008 Stewardship Science Academic Alliances (SSAA) Symposium
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Washington, DC
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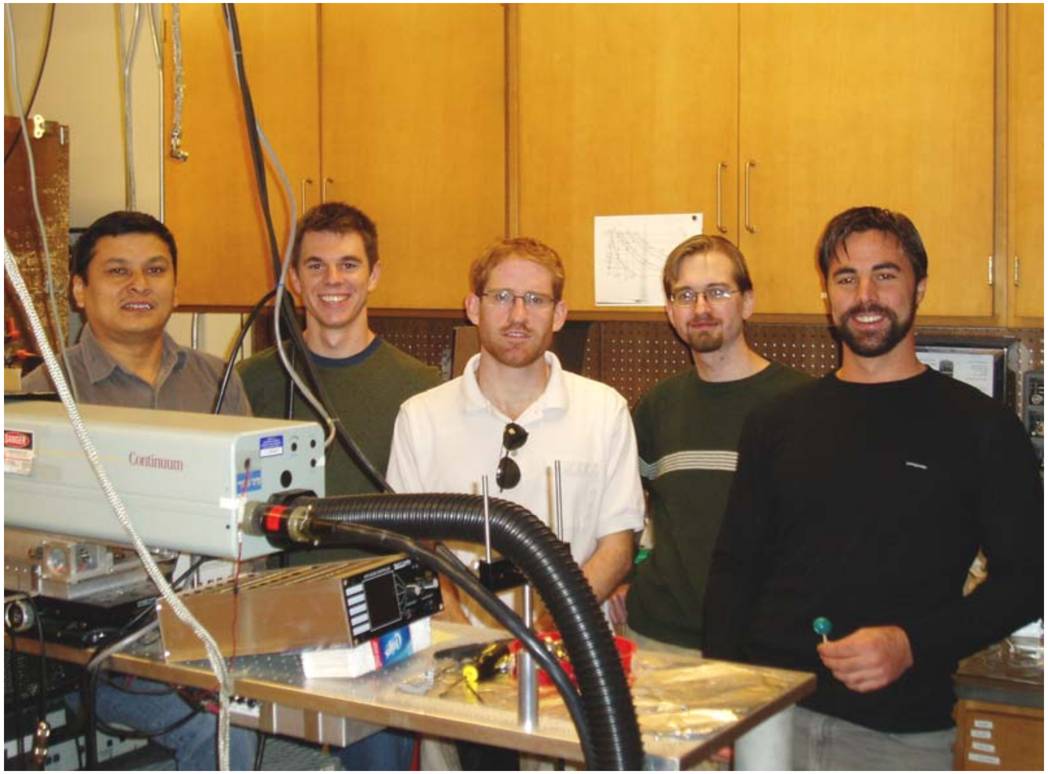
Grant DE - FC52- 06NA27586

The UNR Physics students involved in planar wire arrays, compact cylindrical arrays, and nested arrays research on 1 MA, 100 ns z-pinch generators



I. Shrestha, M. Henry, M. Weller, G. Osborne, K. Williamson

Four graduate and one undergraduate students at Physics Department (Plasma Physics and Diagnostics Laboratory) are working on this experimental research and collaborating with Nevada Terawatt Facility, Sandia National Laboratories, and Cornell University scientists.

UNR, Plasma Physics and Diagnostics Laboratory research in 2006-2007 (in collaboration with Theoretical Plasma Spectroscopy Group)

Main direction of experiments useful for minimization of the radiation energy necessary to ignite Z-pinch-driven Inertial Confinement Fusion (ICF), are:

- Better understanding of the coupling mechanism of the magnetic energy to the plasma;
- Studies of new Z-pinch loads to increase conversion of magnetic energy to soft x-ray radiation (including scaling of radiated energy and power with the peak load current);
- Reducing source size while maintaining output; Shaping of output radiation pulse.

Nevada Terawatt Facility "Zebra"
1 MA, 100 ns, 1.9 Ω generator

1. Development and testing of Load Current Multiplier (SNL Grant, joint with Ecole Polit.).
2. Study of uniform and combined from different materials new multi-planar wire arrays loads:
   - Single Planar Wire Array (SPWA),
   - Double Planar Wire Array (DPWA),
   - Triple Planar Wire Array (TPWA),
   - Cross Planar Wire Array (CPWA), and

     Compact Cylindrical Wire Array (CCWA)
3. Z-pinch electron beam generation study (*see presentation of I. Shrestha et al)

Cornell Center of Excellence "Cobra"
1 MA, 100-250 ns, 0.35 Ω generator

1. Study of uniform and combined from different materials wire arrays:
   - Nested Cylindrical Wire Array (NCWA)
   - Compact Cylindrical Wire Array (CCWA)
2. Z-pinch electron beam generation study *

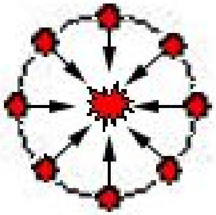
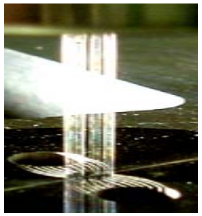
Sandia National Laboratories
Saturn 3 MA 100 ns generator

UNR experimental and theoretical support of the SNL single planar wire array performance and scaling at multi-MA levels on the Saturn generator.

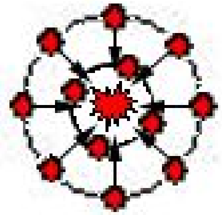
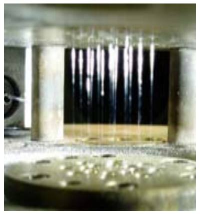
Multi-planar, and Cylindrical Wire Array Plasma Formation at 1 MA, 100 ns generators

Single-Step Precursor Formation

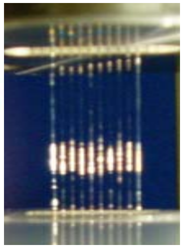
Precursor formed in one location coincides with the stagnation plasma column position

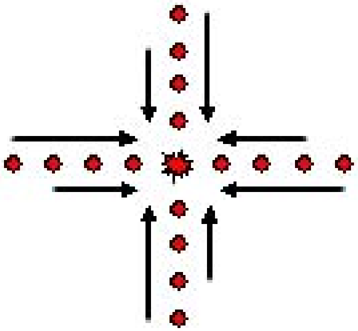
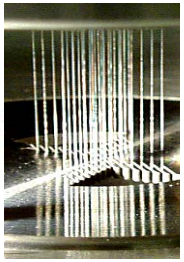
Compact Cylindrical Wire Array (CCWA)-”Zebra” and “Cobra”
Ek = 5-6 kJ

Nested Cylindrical Wire Array (NCWA)-”Cobra”
Ek = 5-6 kJ

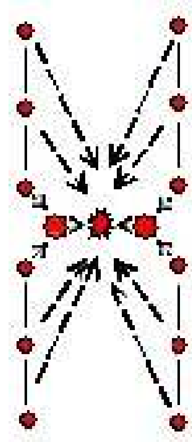
Single Planar Wire Array (SPWA)-”Zebra”
Ek = 3-4kJ

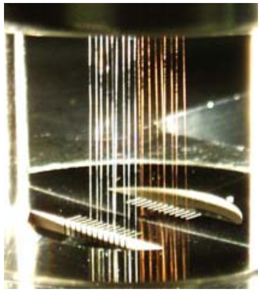
Cross Planar Wire Array (CPWA)-”Zebra”
Ek = 6 kJ

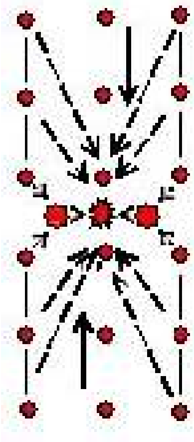
Multi-Step Precursor Formation

Precursor formed in several locations, some of which do not coincide with the stagnation plasma column position

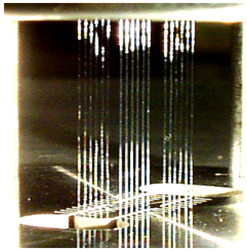


Double Planar Wire Array (DPWA)-”Zebra”
Ek = 4-5kJ



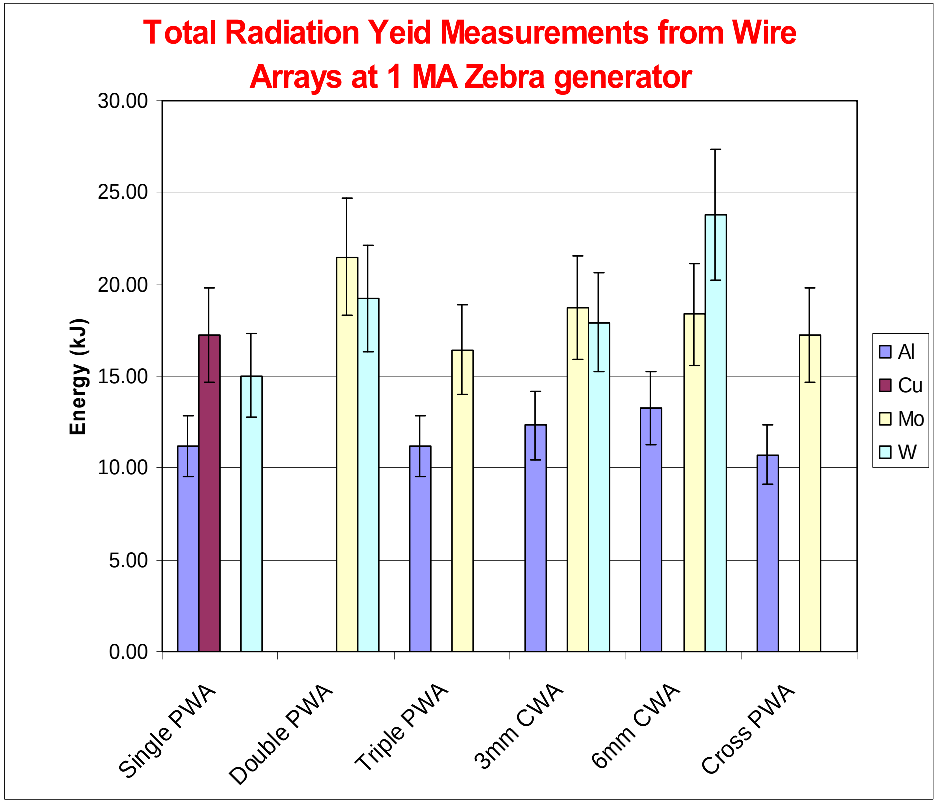


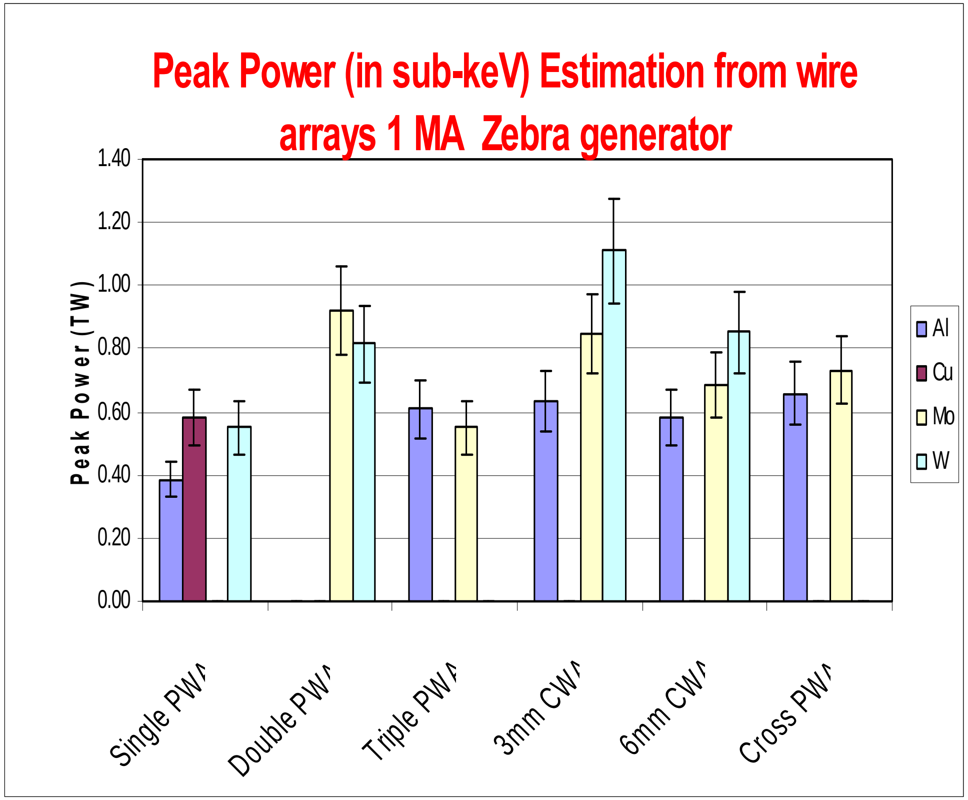
Triple Planar Wire Array (TPWA)-”Zebra”
Ek = 5-6 kJ



E_k – estimated kinetic energy ($\Phi_{fin.pinch}$ =100 μm)

Radiation characteristics of Z-pinch loads at 1 MA Zebra generator





For all tested loads radiation yields exceed the converted kinetic energy

Wire Dynamics Model (WDM) versus 0D Model for planar arrays*

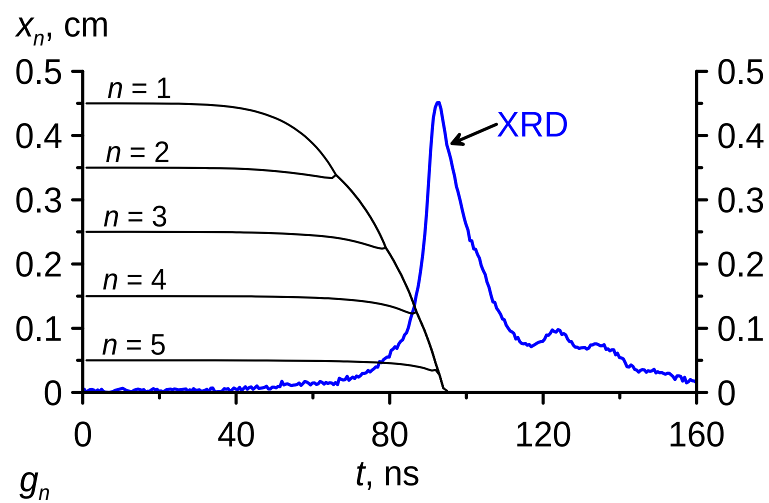
0D-model assumes EVEN current partition. WDM accounts for UNEVEN partition, that affects: array implosion dynamics and ablation dynamics of the array wires

Effects due to UNEVEN current partition are:

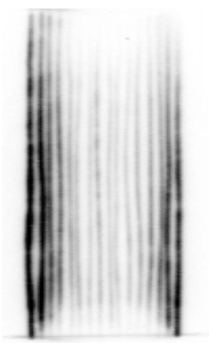
- **absent for cylindrical arrays (0D is used)**
- **moderate for nested arrays (limited use of 0D)**
- **very strong for planar arrays (WDM is needed)**

Implosion trajectories and sub-keV radiation pulse →

WDM simulations of SPWA

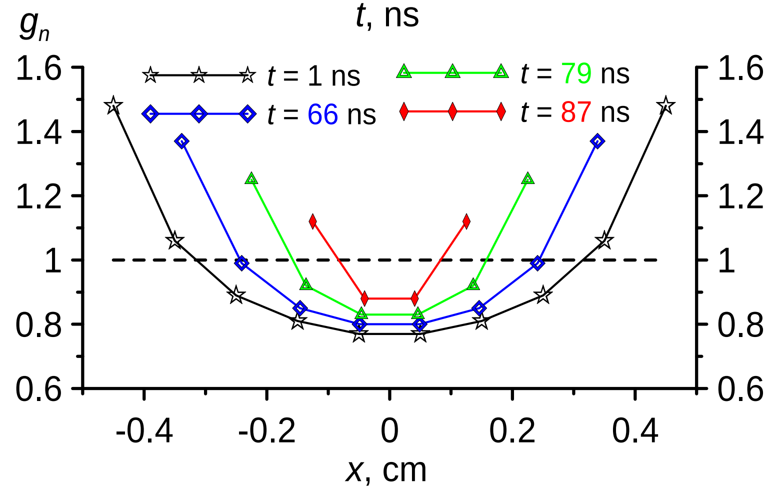


WDM has been used successfully in our experiments to estimate load implosion times



Dynamic current partition

$$g_n = \frac{NI_n}{I_\Sigma}$$ →



ICCD camera optical image of W SPWA, shot #1251 (10 ns).

***A. Esaulov et al., Physics of Plasmas, 13, 120701-4 (2006).**

3D MHD simulations of SPWA*

Wire ablation and implosion dynamics in planar geometry is very different from cylindrical arrays:

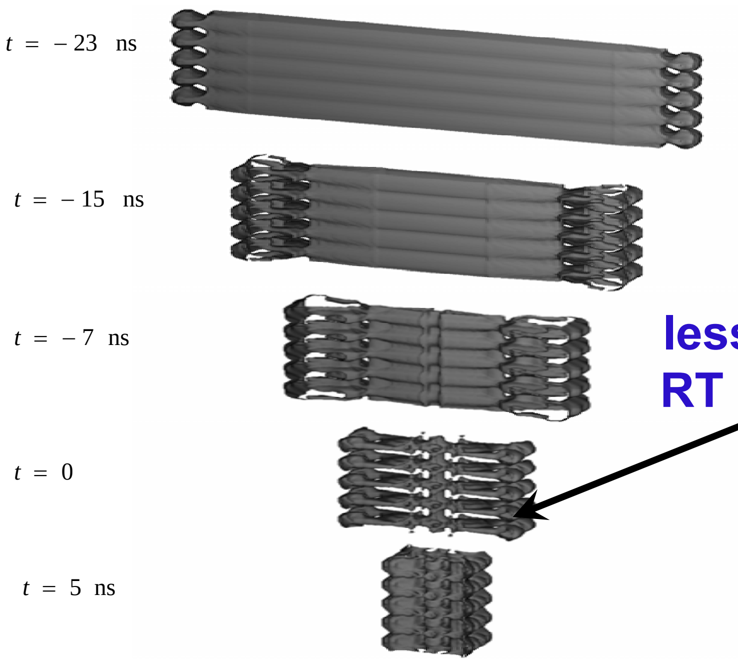
- the inner wires ablate significantly later as compared to the outer wires
- the inner wires do not implode until the outer wires are destroyed by RT-instability

Initial conditions for the MHD simulations:

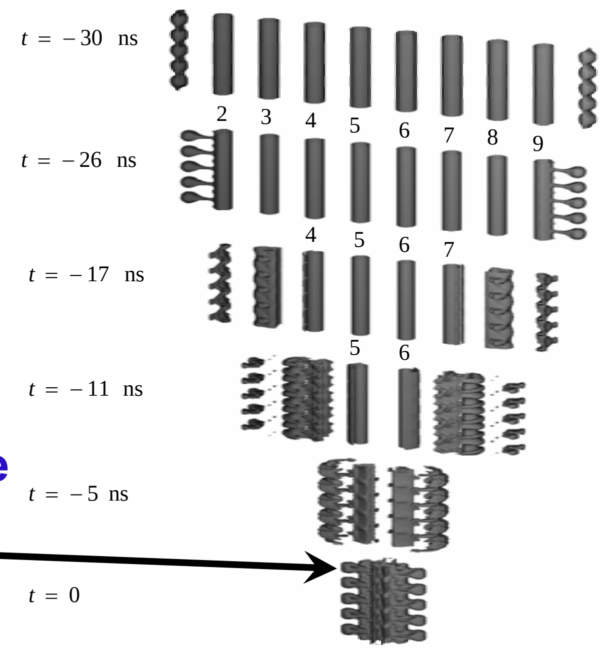
strip approximation (early wire ablation, inter-wire space is pre-filled with ablated plasmas)

discrete wires approximation (very late ablation, no pre-fill) with ablated plasmas)

Uniform strip approximation



Discrete wire approximation

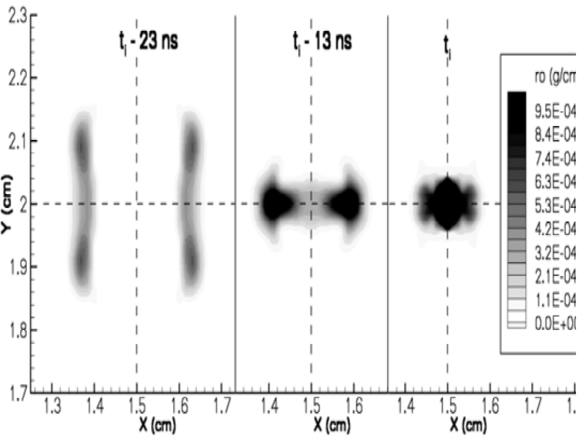


less effective RT mitigation

more effective RT mitigation

*A. Esaulov et al., Phys. Plasmas (2008), submitted

Mo DPWA implosion on Zebra generator (two-step precursor formation and the possibility of radiation pulse shaping were demonstrated)



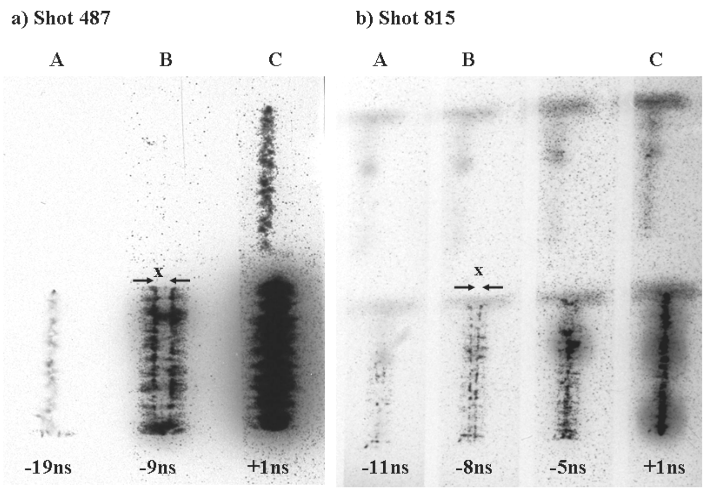
A B C

The MHD modeling* of Mo DPWA implosion (view from the top of a DPWA).

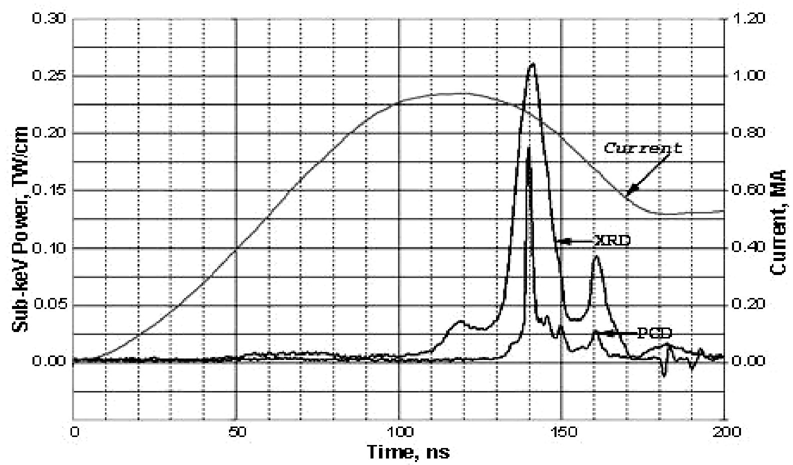
The stage A corresponds to a beginning of wires cascade motion (first from outside).

The stage B shows bright radiating double plasma columns formation. The stage C is a stagnation phase.

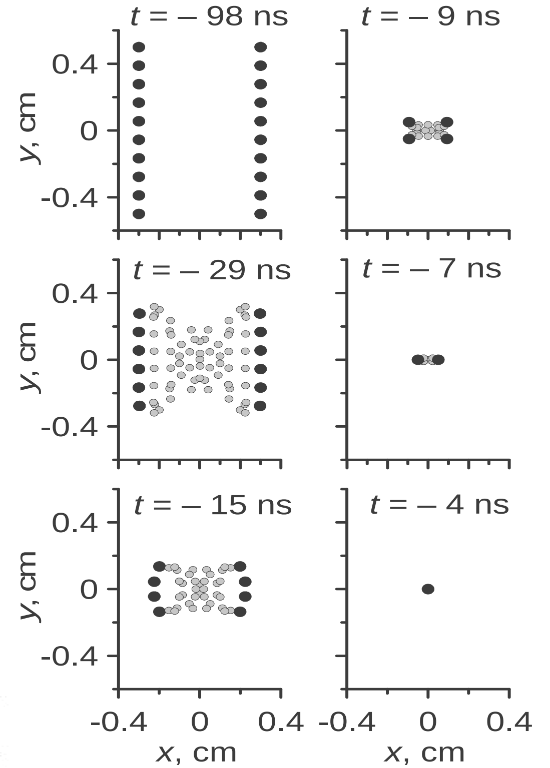
*** A. Chuvatin et al., IEEE Trans. Plasma Sci., v.33 (2) (2005).**



a)# 487, Al DPWA, Δ=6 mm, D=9 mm, x ≈2 mm; b)# 815, Mo DPWA, Δ=3 m x ≈1.2 mm. Observation is along arrays planes.E cf; top 3 keV, bottom 1 keV.



 # 1029, Mo/Al DPWA, Δ=6 mm,



The Wire Ablation Dynamics Model *(WADM) simulation of implosion (view from the top of a DPWA). Shot # 487: Al wires, D = 10 mm, Δ=6 mm.

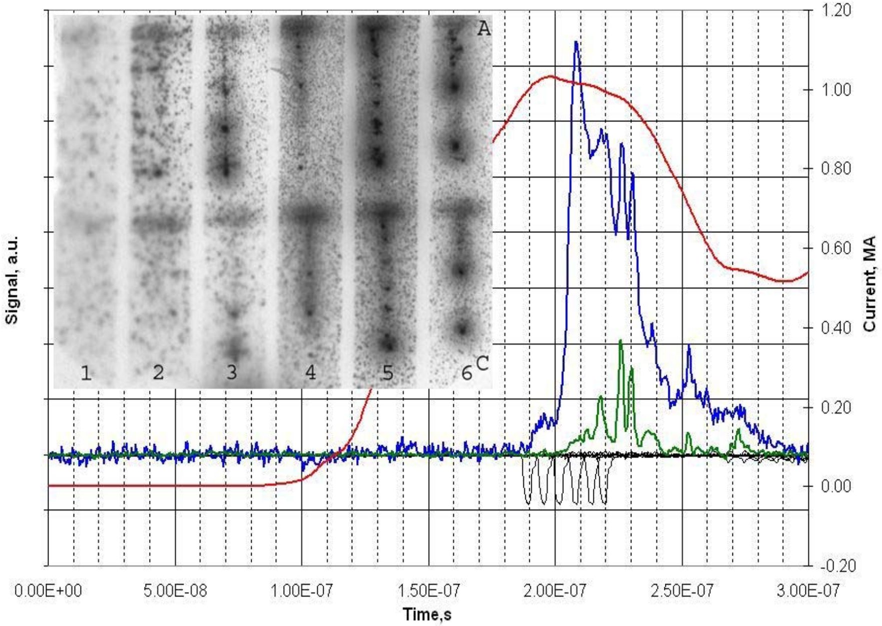
Black dots – parent wires.

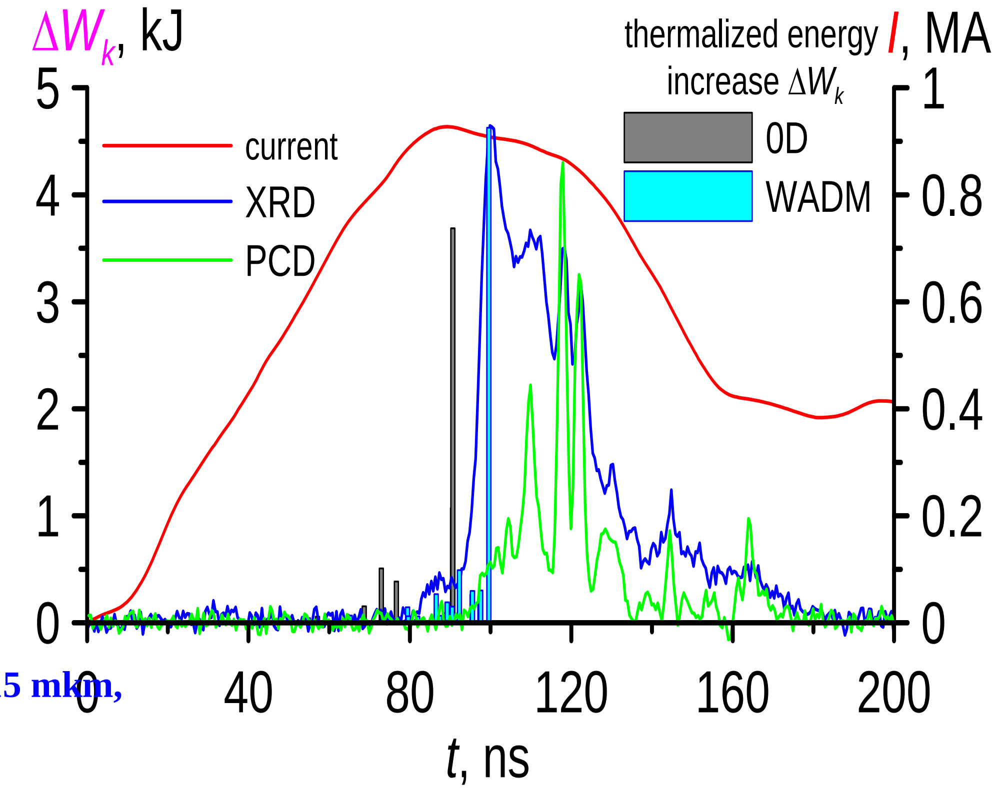
Grey dots – ablated plasma.

*** A. Esaulov, PoP, submitted.**

Combined TPWA Mo/Al/Mo implosion

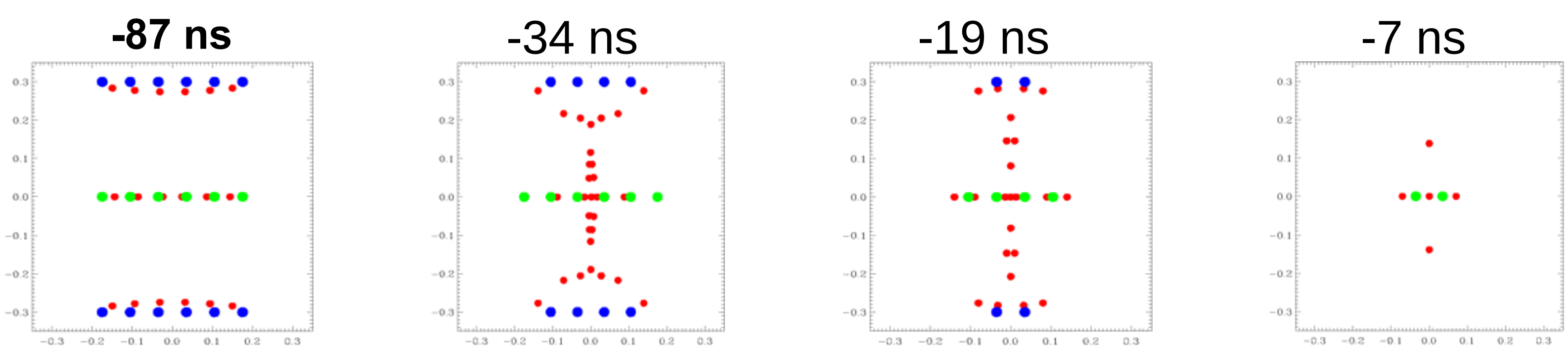
Significant part of radiation was associated with hot spots. Prepulse formation was observed.





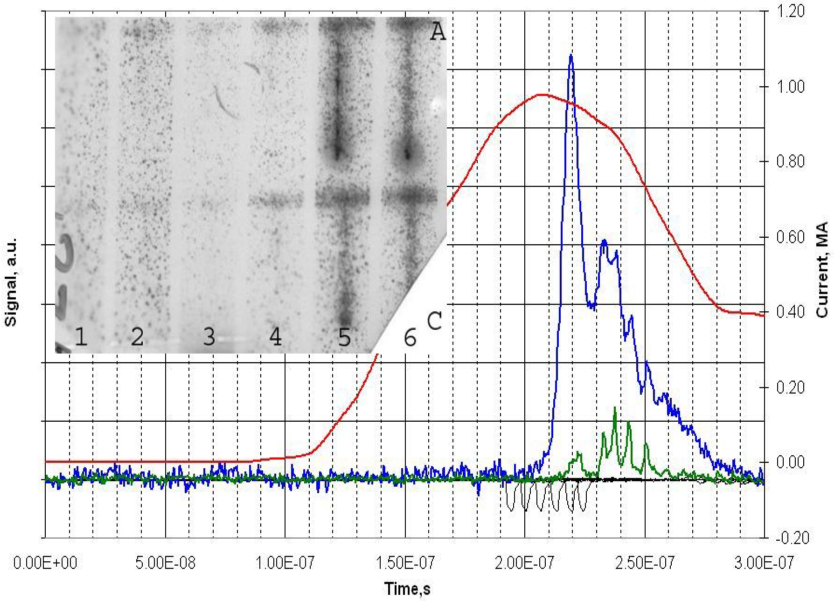
#1262 Al, D=3.5 mm,Δ=2x3 mm, d=0.7mm, Φw=7.9/15 mkm, N=6/6/6 Anode – top. t=3 ns,
Δt= 6 ns, E_{cf} at the top 1.3 keV, at the bottom 4 keV.

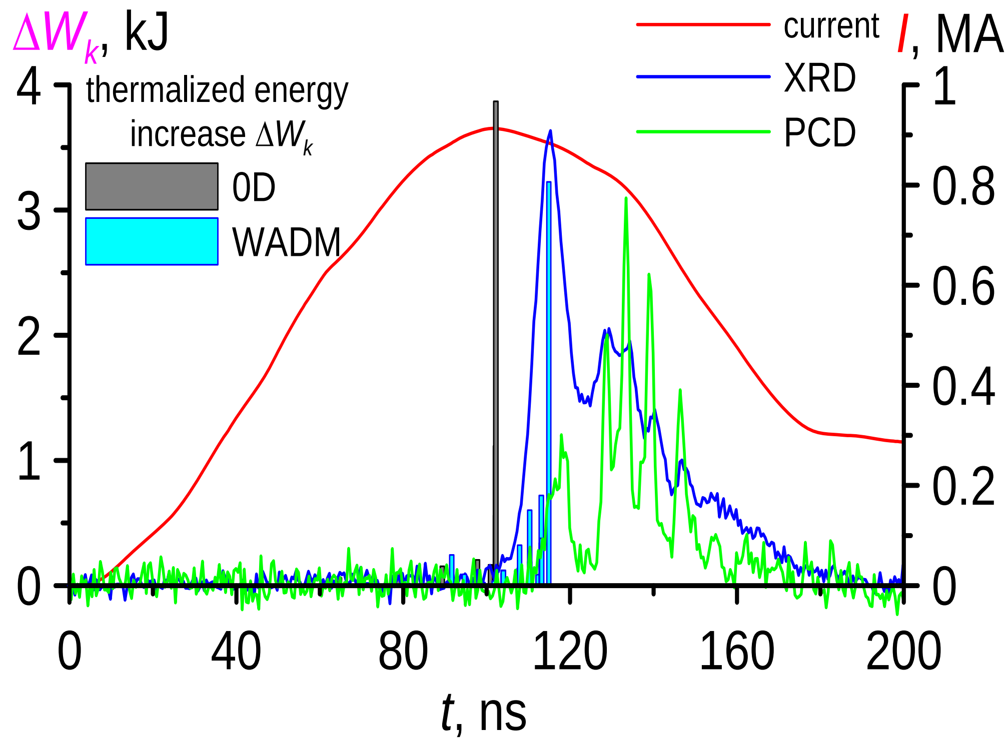
1262
Mo
Al
Mo



CPWA may provide increasing conversion of kinetic energy into main radiation pulse

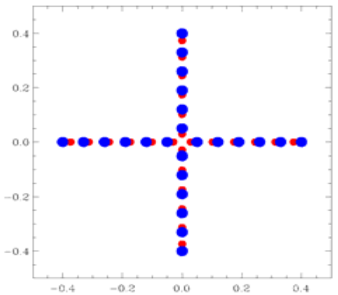
Most uniform plasma column structure was observed among all PWA



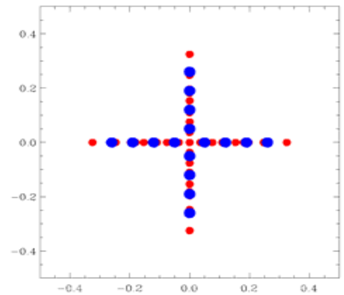


 # 1270 Mo D=7.7 mm, d=0.7 mm,
Φw=8.6 mkm, N=12/12. Anode – top. t=3 ns,
Δt= 6 ns, Ecf at the top 1.3 keV, at the bottom 4 keV.

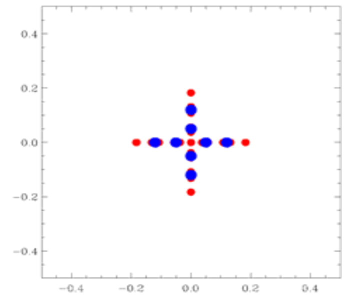
-102 ns



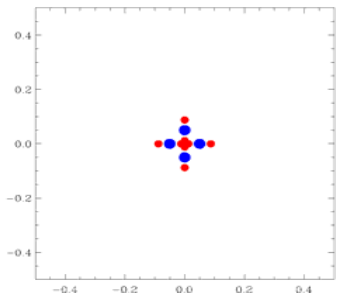
-34 ns



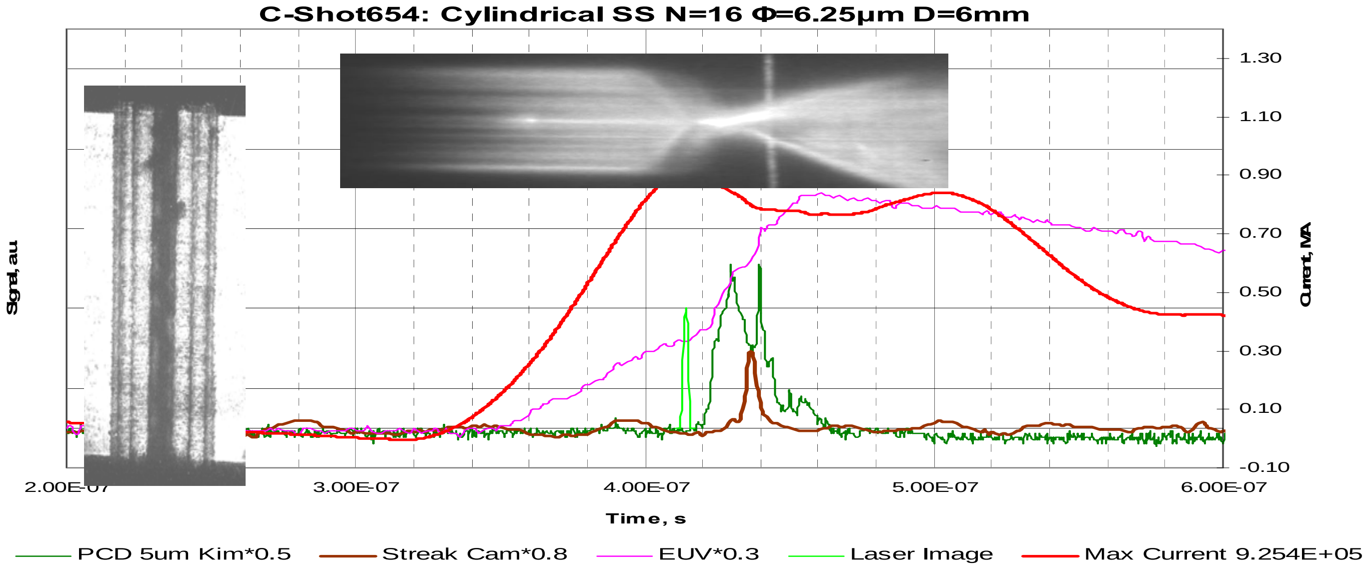
-14 ns



-5 ns



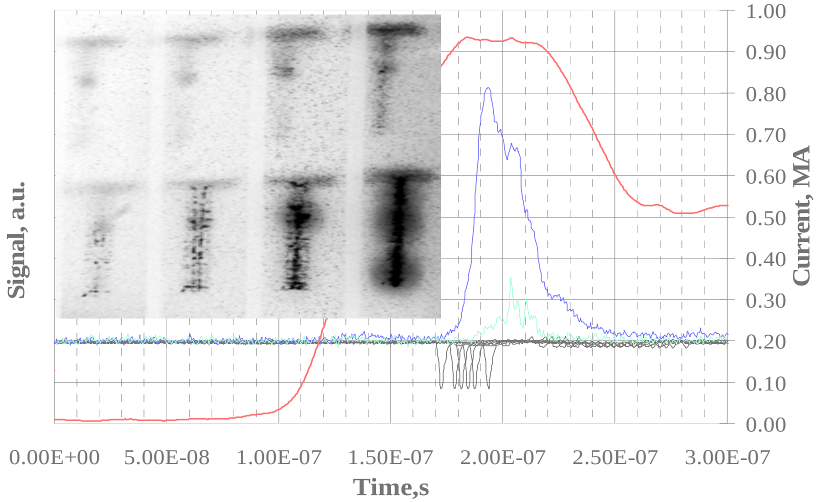
Compact stainless steel wire arrays radiate more energy and more in the first x-ray radiation burst than any nested arrays studied on 1 MA Cobra generator



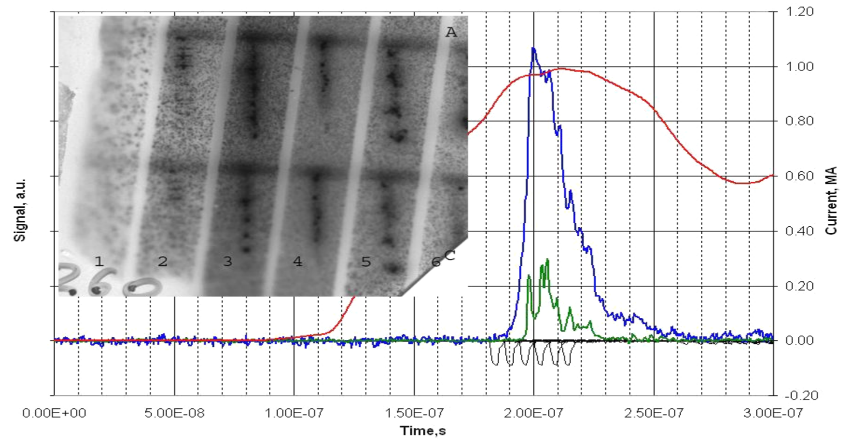
		Sub-keV Yield (A.U.)	Sub-keV Peak Power (A.U.) in first radiation peak
Stainless steel	single compact (Φ=6 mm, N=16, M=78μg)	1	1
Stainless steel	nested (Φ=6/13 mm, N=8x8, M=78μg)	0.8	0.6
Stainless steel (outer) Al (inner)	nested (Φ=6/13 mm, N=8x8, M=73μg)	0.7	0.5
Stainless steel (inner) Al (outer)	nested (Φ=6/13 mm, N=8x8, M=73μg)	0.6	0.4

More information of nested and compact cylindrical wire arrays studies on Cobra generator see in presentation of K. Williamson et al

Mo DPWA and CCWA implosions on 1 MA Zebra generator: different implosion features at early stages and same plasma heating mechanism at final implosion stage?



 # 815, Mo DPWA, Δ=3 m. Observation is along arrays planes. E cf: top 3 keV, bottom 1 keV.



 # 1260 Mo CCPWA, D=3 mm, N=24. Anode – top. E_{cf} : top 1.3 keV, bottom 4 keV.

Double precursor columns seen just 10 ns before main x-ray burst.

For Mo DPWAs E_{Tmax}=22-23 kJ, $P_{subkmax}$ =0.9-1 TW, T_{emax}~1.0-1.3 keV, N_{emax}~10^{21}cm^{-3}

Traling mass features seen 10 ns before main x-ray burst

For Mo CCPWA E_{Tmax}=21-22 kJ, $P_{subkmax}$ =1 TW, T_{emax}~1.1-1.2 keV, N_{emax}~10^{21}cm^{-3}

Despite different implosion dynamics of DPWAs and CCWAs they formed plasma with similar characteristics. Yields exceed that from kinetic energy conversion.

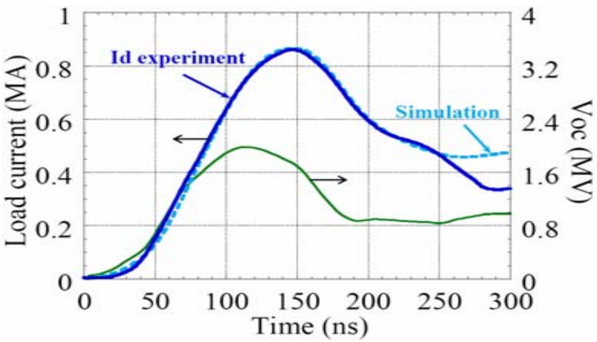
Same plasma heating mechanism at final implosion stage?

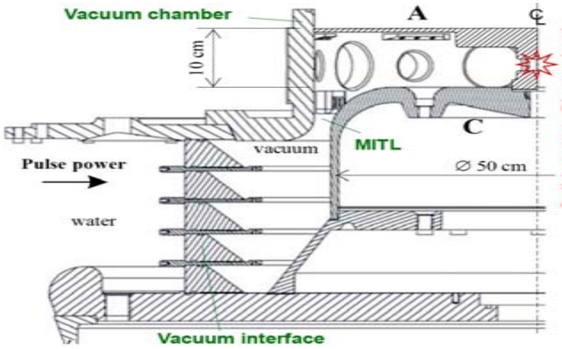
Does enhanced resistivity play a significant role?

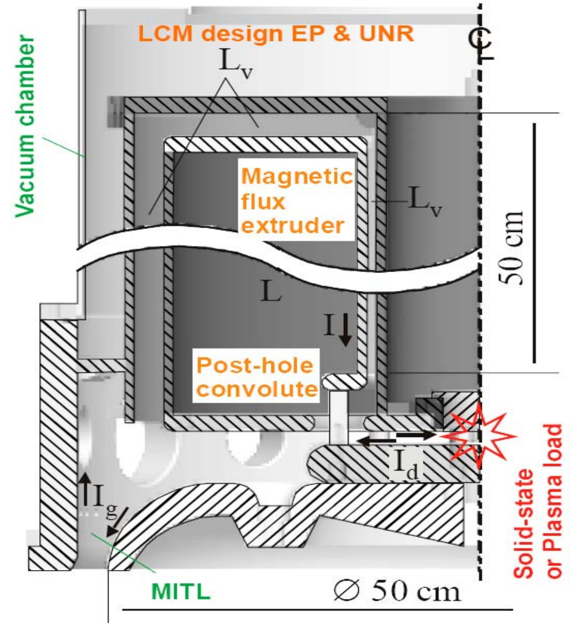
Load Current Multiplier (LCM)

A. Chuvatin (Ecole Polit.,France);V. Kantsyrev (UNR);L. Rudakov (Icarus Inc.);M. Cuneo (SNL); A. Astanovitskiy, W. Cline, R. Presura, A.Safronova, A. Esaulov, K. Williamson, I. Shrestha, F. Yilmaz, G. Osborne, T. Jarrett, B. LeGalloudec, V. Nalagala (UNR); T. Pointon, K. Mikkelson (SNL)

Load Current Multipliers (LCM) is a new concept theoretically formulated in 2005
LCM improves generator-to-load energy transfer efficiency without changing generator architecture
The concept validated by 2007 on long-pulse low voltage generators in France and Russia (> 50 nH, < 300 kV, ~ 1 μs): demonstrated current increase from 4.5 to 8 MA







Standard output hardware of Zebra @ UNR

Nominal generator operation:

Open-circuit voltage Voc ≤ 2 MV, load current Id ≤ 1 MA

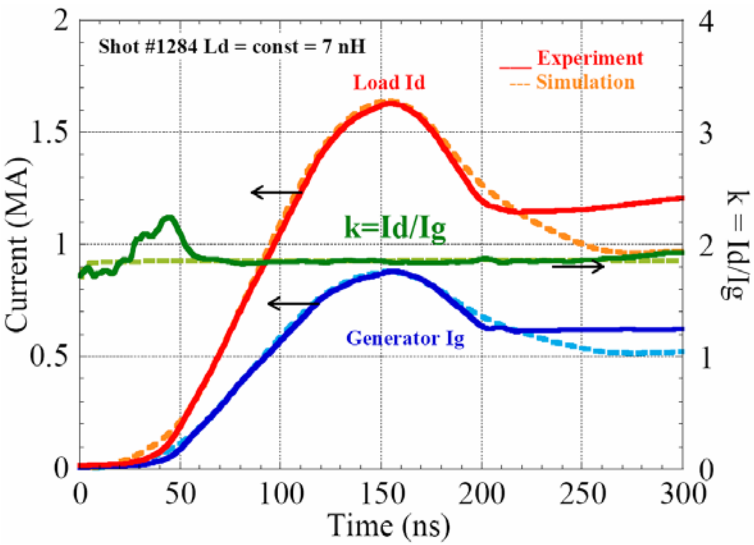
Joint experimental campaign June2007 and Oct2007 @ UNR
University of Nevada Reno - Ecole Polytechnique (France) - SNL

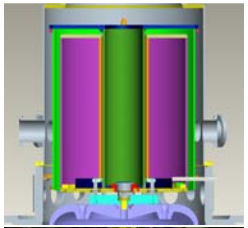
Objective: Validate the concept on a short-pulse high voltage generator at UNR (1.9 Ohm, 100 ns, Voc ~ 2 MV)

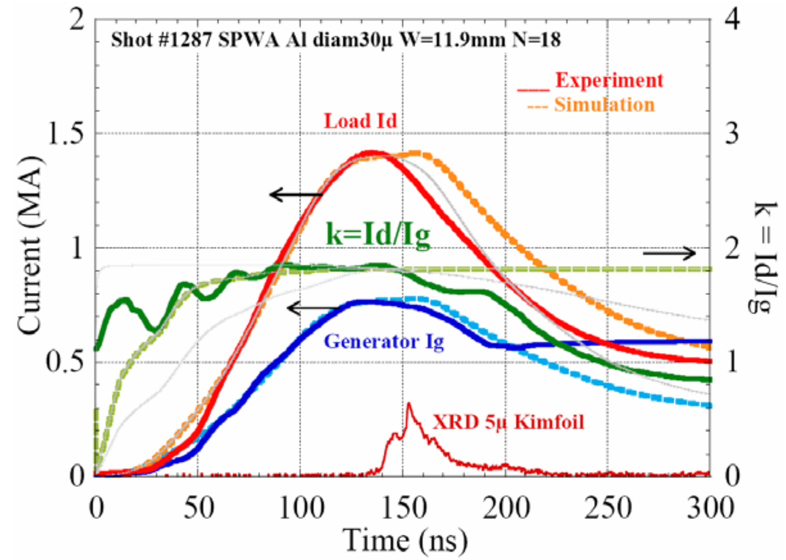
Joint LCM experiments June2007 and Oct2007

Shot #1284 (LEFT): 6 mm diameter rod, constant load inductance Ld ≈ 7 nH

Load current amplitude increased from nominal 0.8-0.9 MA to 1.62 MA in this shot, ± 0.05 MA uncertainty/ assymetry







Shot #1287 (RIGHT): z-pinch SPWA, 18 Al wires, 30 μ diameter, width = 11.9 mm

In this SPWA shot: Generator current is lower due to non-nominal Zebra operation, NOT DUE TO LCM

- Load current multiplication coeff. κ = Id/Ig ~ 1.8 ±0.1 at peak current, close to theory/simulations
- => lossless LCM design: MITL's and PHC at high electric fields (> 1 MV/cm) and plasma radiation
- SPWA κ drops below κ^{theor} after first XRD peak w/o current assymetry => pinch resistance of 0.1-0.2 Ohm

First LCM concept validation at 100 ns, high Voc, constant-inductance and z-pinch loads

Demonstrated 1.6 MA load current makes UNR's Zebra generator the highest-current university pulse-power in the world

CONCLUSION

- **Plasma formation and implosion features of different multi-planar wire arrays, compact cylindrical wire arrays, and low-wire number nested wire arrays (NWA) of the small size (3-13 mm) were studied on the 1 MA, 100 ns UNR Zebra and Cornell COBRA generators.**

- **The possibility of radiation pulse shaping by varying geometry and materials of DPWA and TPWA was demonstrated.**

- **Highest radiation yields and power were observed for DPWA and CCWA.**

- **Despite different implosion dynamics of DPWA and CCWA they formed at stagnation a plasma with similar characteristics.**

- **For all tested loads radiation yields exceed conversion kinetic energy. New theoretical model on the coupling mechanism of the magnetic energy to the Z-pinch plasma is needed.**

- **First Load Current Multiplier (LCM) concept validated at 100 ns, constant-inductance and z-pinch loads. Demonstrated 1.6 MA load current makes UNR's Zebra generator the highest-current university pulse-power machine.**

ACKNOWLEDGMENTS

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