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UNIVERSITY OF NEVADA •Reno

Status of Planar Wire Array Work at UNR Zebra and SNL Saturn

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8h International Workshop on The Physics of Wire Array Z-Pinches (April 8, 2009, La Jolla Shores Hotel, La Jolla, CA)

Sandia National Laboratories

MOTIVATION

- **Effective conversion of magnetic energy to soft x-ray radiation, reducing the source size while maintaining output E_T, shaping of radiation pulse, and understanding of the coupling mechanism of the magnetic energy to Z-pinch plasma are critical for minimization of the radiation energy necessary to ignite Z-pinch-driven Inertial Confinement Fusion (ICF) [1-4].**

- **The single (with cascade-type implosion as multilayered nested array [4]) and double planar wire arrays (SPWA and DPWA) that were placed in the center of the z-pinch chamber and studied as a radiation source, were found to be a possible path to resolving these issues. Experiments were performed in 2005-2008 on 1 MA, 100 ns generator "Zebra" [4-6].**

- **In 2007 and 2008, the first experiments with SPWA were performed on 3-5 MA SNL generator "Saturn"[7, 8] with participation of the UNR scientific team.**

- **The fast imploded compact cylindrical wire arrays (CCWA) were tested on Zebra in 2006-2007 and have shown comparable E_T and P_{subk} with SPWA [5].**

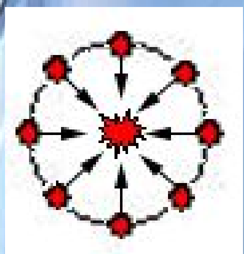
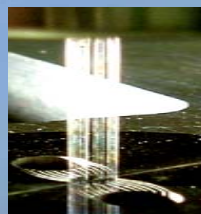
- **X-ray spectroscopy and imaging of the PWAs supported by a set of theoretical codes represents a unique tool to study radiative and implosion characteristics of wires and planes, from different materials in particular.**

1. M. Cuneo *et al*, Phys. Rev. Lett. 95, 185001 (2005). 2. R. Vesey *et al*, Phys. Plasmas 14, 056302 (2007).
3. C. Deeney *et al*, Phys. Rev. Lett. 81, 4883 (1998). 4. V. Kantsyrev *et al*, IEEE Trans. Plasma Sci. 34, 194, and 2295 (2006).
5. V. Kantsyrev *et al*, High Energy Density Phys., 3, 136 (2007). 6. V. Kantsyrev *et al*, Phys. Plasmas, v.15, 030704 (2008)
7. B. Jones *et al*, Sandia Report SAND2007-6337. 8. B. Jones *et al*, Sandia Report SAND2008-6166.

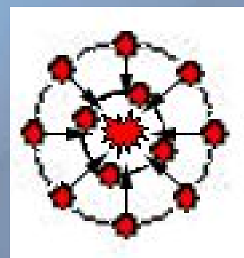
Wire Arrays Imploded at 100 ns generators (UNR - Zebra, C.U. – Cobra)

Single-Step Precursor Formation

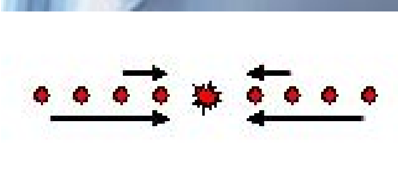
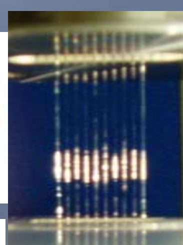
Precursor formed in one location coincides with the stagnation plasma column position

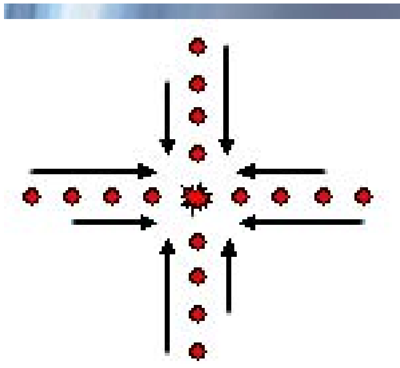
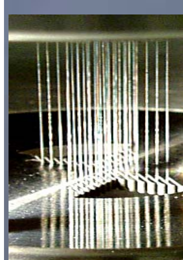
Compact Cylindrical Wire Array (CCWA)-”Zebra” and “Cobra”




Nested Cylindrical Wire Array (NCWA)-”Cobra”

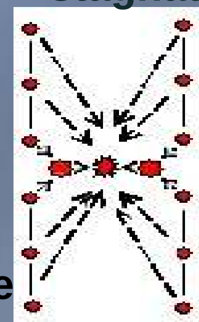
Single Planar Wire Array (SPWA)-”Zebra”

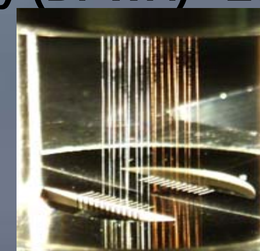
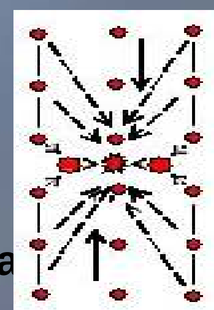
Cross Planar Wire Array (CPWA)-”Zebra”

Multi-Step Precursor Formation

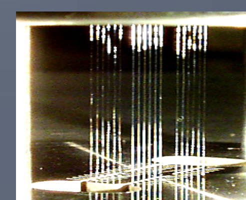
Precursor formed in several locations, some of which do not coincide with the stagnation plasma column position



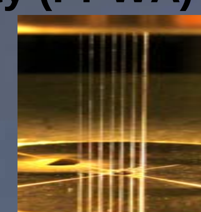
Double Planar Wire Array (DPWA)-”Zebra”

Triple Planar Wire Array (TPWA)-”Zebra




Prism-like Planar Wire Array (PPWA)-”Zebra”



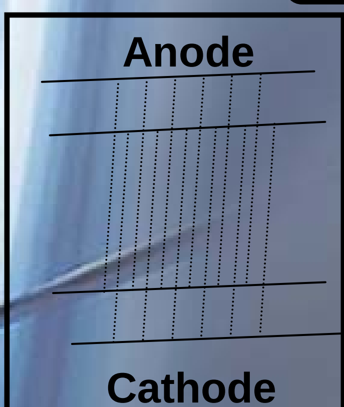
Planar Wire Arrays

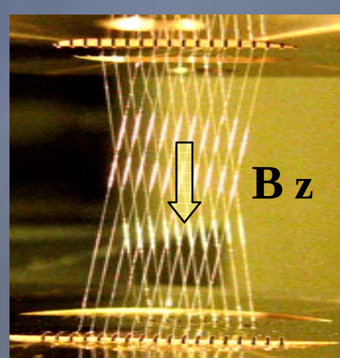
PWA with Open Magnetic Configurations

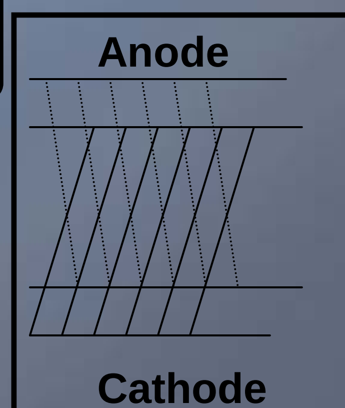
- Single
- **Double**
  Best radiator
  - **Straight Wires**
  - **New - Skewed Wires**
    B_z - RT mitigation
- Triple
- Cross

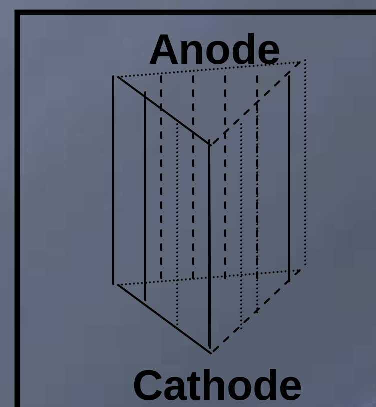
PWA with Closed Magnetic Configuration

- **New – Prism-like**
  Effective pulse shaping

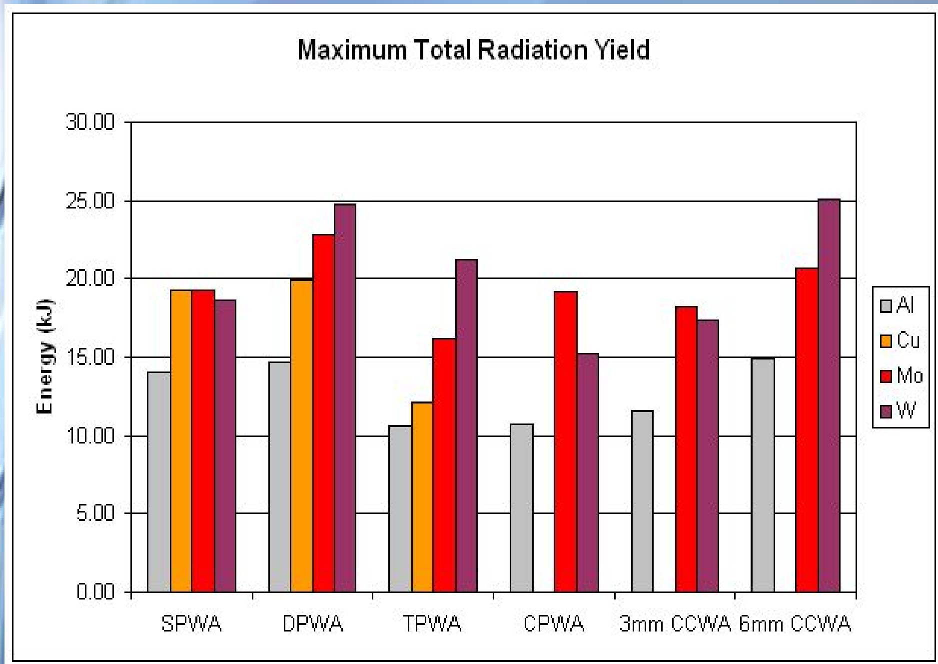


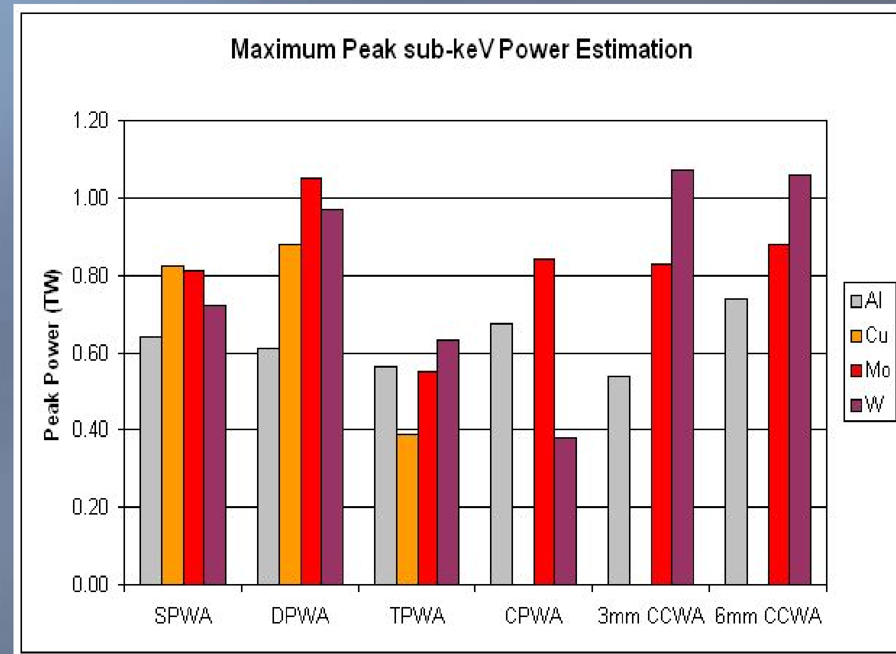






Radiation characteristics of compact planar and cylindrical loads at Zebra generator experiments





I. The DPWA is the best x-ray radiator tested at 0.8-1.4 MA: combination of larger resistive energy / power gain, small mm-scale size, weaker opacity effects with peak current rising, possibility of radiation pulse shaping. Scaling of yield / power with peak current was found near quadratic.

II. Radiation yields E exceed that from kinetic energy conversion E_K (E_K < 4-6 kJ) in 3-5 times, and mechanism of energy coupling is enhanced resistivity of the strongly inhomogeneous plasma (may be strongly resistive Hall plasma). During implosion / stagnation different mechanisms dominate (experimental comparison of DPWA and CCWA).

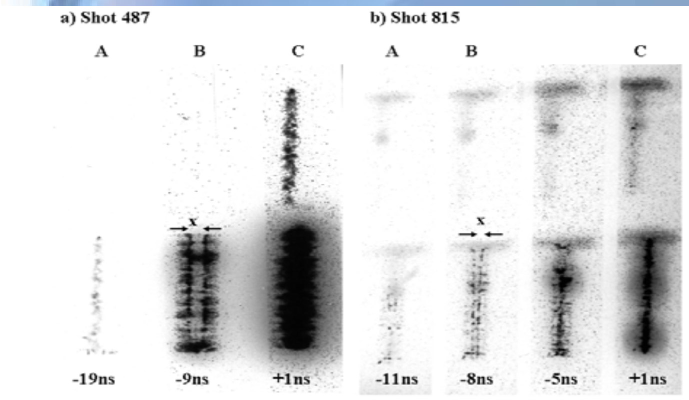
III. Asymmetry of sub-keV radiation was observed for SPWA.

Multi-planar wire array implosions

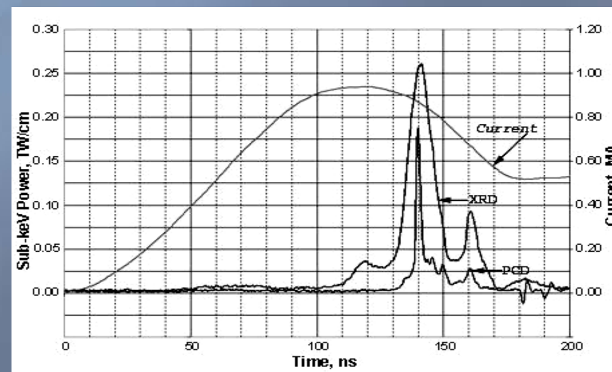
The possibility of radiation pulse shaping was demonstrated.
Significant part of radiation was associated with bright spots.

DPWA* - two-step precursor formation, independent implosion of wire rows made from different materials, T_e~ 1.2 keV, N_e>10^{20} cm^{-3}

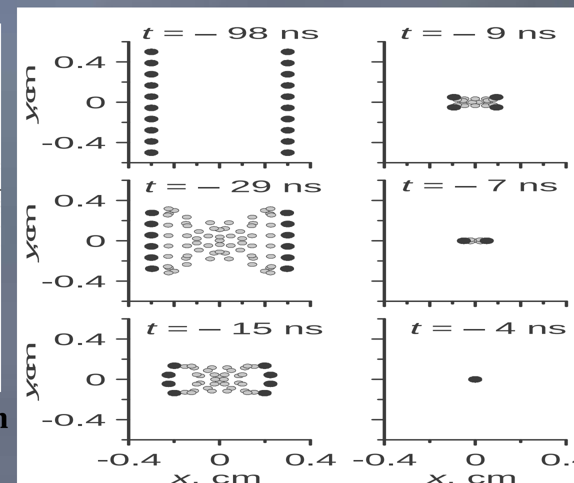
The Wire Ablation Dynamics Model(WADM) simulation.**



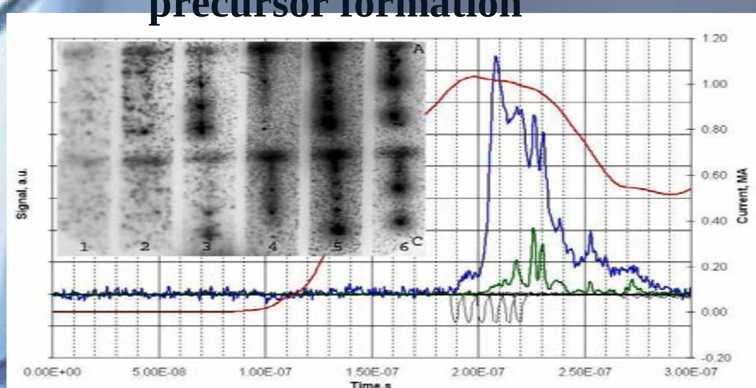
a) # 487, Al, DPWA, Δ=6 mm, D=9 mm,
b)# 815, Mo DPWA, Δ=3 mm, D= 4.9 mm



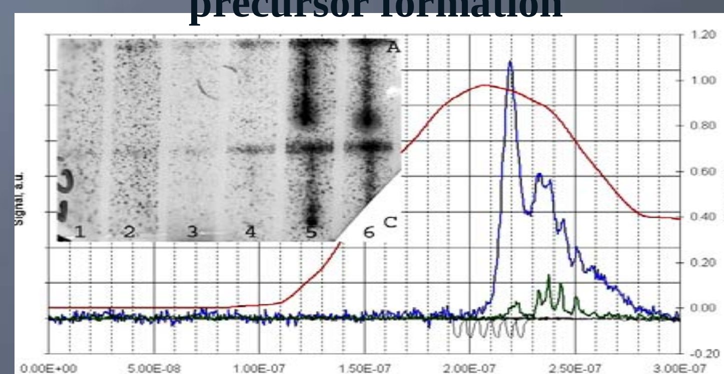
 # 1029, Mo/Al DPWA, Δ=6 mm, D=6.3 mm



Triple-PWA Mo/Al/Mo implosion. Multi-step precursor formation



Cross-PWA Mo implosion. Multi-step precursor formation



*** V. Kantsyrev *et al*, Phys. Plasmas, v.15, 030704 (2008)**
**** A. Esaulov *et al*, AIP Conf. Proc. 1088, p. 45-48 (2009).**

Most uniform final plasma was observed among all PWAs.
No enhanced x-ray yields / power in comparison with another PWA.
In SPWA where two central wires were removed (central gap= 3 IWG) the decreasing power and yields were observed.

3D MHD simulations of SPWA*

As seen from 3D MHD modeling SPWA implosion process is more complicated than just cascade-type way (shown by Wire Dynamics Model).

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

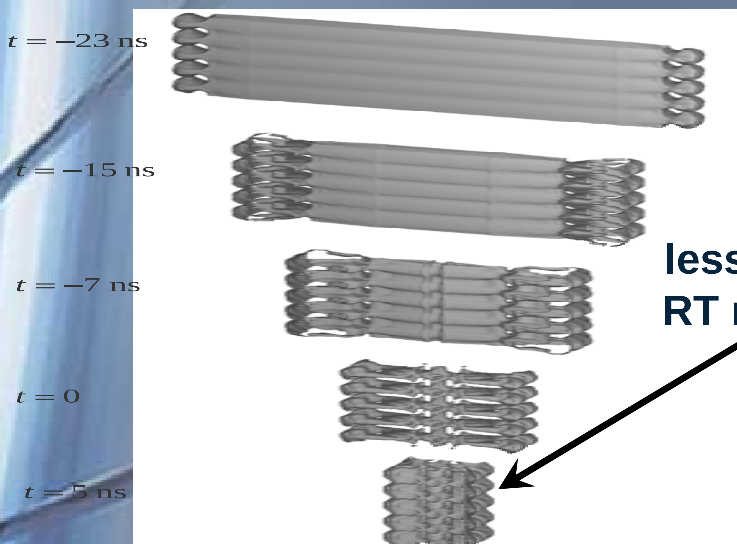
- **the inner wires ablate significantly later as compared to the outer wires****
- **the inner wires do not implode until the outer wires are destroyed by RT-instability****

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)

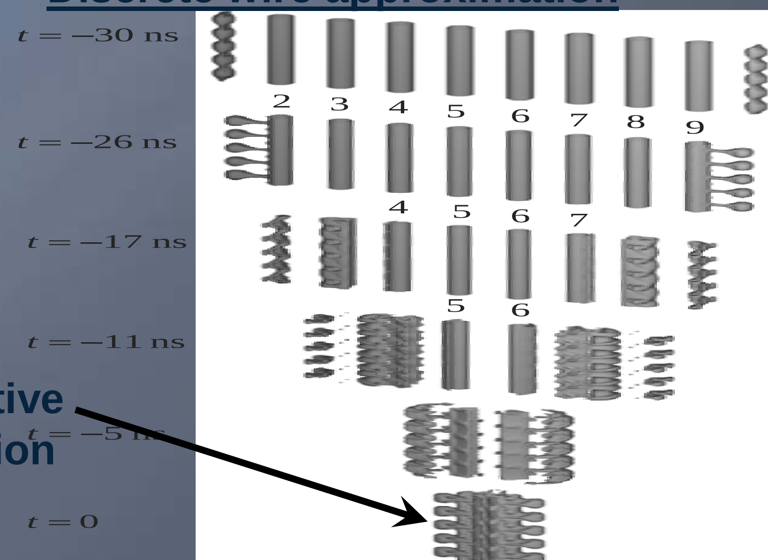
Uniform strip approximation



less effective RT mitigation

more effective RT mitigation

Discrete wire approximation



* **A. Esaulov *et al*, Phys. Plasmas 15, 052703 (2008)**

We continue extensive studies of L- and K-shell radiators using PWAs at 1MA and present diagnostically important L-shell lines and Te from modeling

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16S 42.36 59.99 72.68	17 Cl 35.21 49.34 59.21	18 Ar 29.76 41.38 49.20
19 K 25.49 35.23 41.56	20 Ca 22.08 30.39 35.59	21 Sc 19.32 26.50 30.83	22 Ti 17.04 23.32 26.97	23 V 15.15 20.68 23.80	24 Cr 13.55 18.47 21.16	25 Mn 12.20 16.60 18.95	26 Fe 11.03 15.00 17.06 400	27 Co 10.03 13.62 15.44	28 Ni 9.15 12.42 14.05 400	29 Cu 8.39 11.38 12.84 500	30 Zn 7.72 10.46 11.78 500	31 Ga 7.12 9.64 10.84	32 Ge 6.59 8.92 10.01	33 As 6.11 8.27 9.28	34S e 5.69 7.69 8.62	35 Br 5.31 7.17 8.03	36 Kr 4.96 6.70 7.51
37 Rb 4.65 6.27 7.03	38S r 4.36 5.88 6.59	39 Y 4.10 5.53 6.20	40 Zr 3.86 5.20 5.84	41 Nb 3.64 4.91 5.51	42 Mo 3.44 4.63 5.21 1400												

Legend (29 Cu):
- Ne-like, 4A, λ(Å) → 8.39
- Ne-like, 3C, λ(Å) → 11.38
- Ne-like, 3G, λ(Å) → 12.84
- max Te (eV) → 500

Convex KAP crystal (2d=26.63Å), R=51 mm
Convex α-Quartz (2d=6.687 Å), R=102 mm

- X-pinches still show the record Te (~2.5 keV) from K-shell plasmas on Zebra.
- For PWAs, K-shell satellite lines were observed indicating Te < 1000 eV.

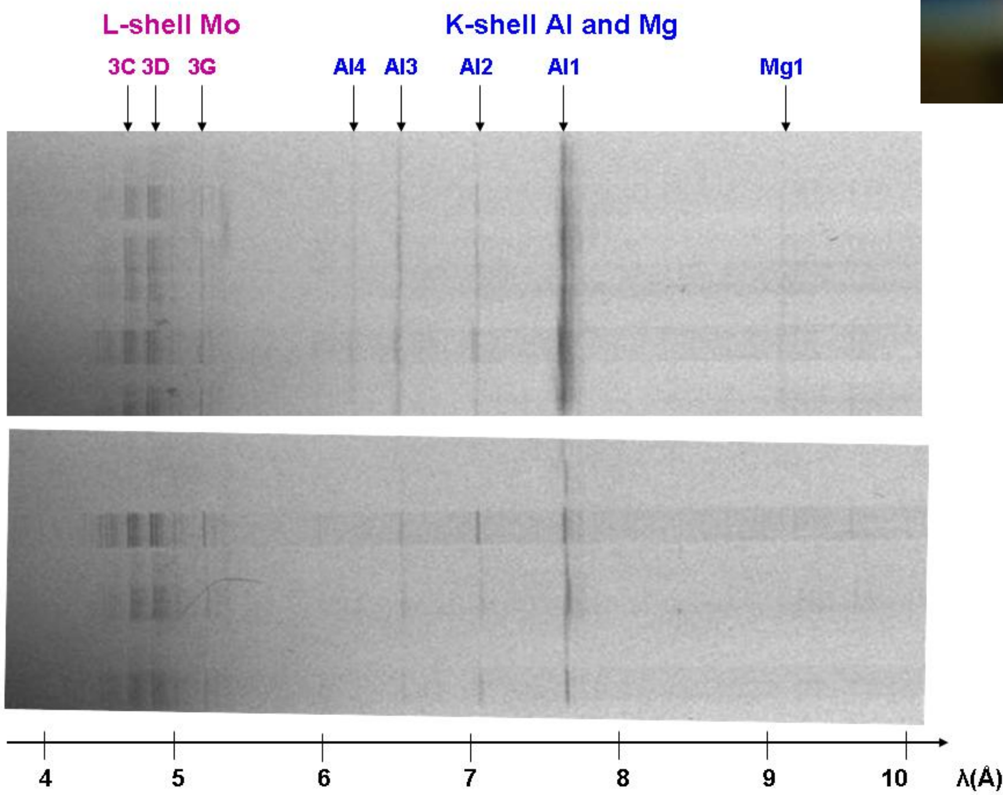
Studies of radiation from Combined Single Planar Wire Arrays (SPWA) on 1 MA Zebra at UNR

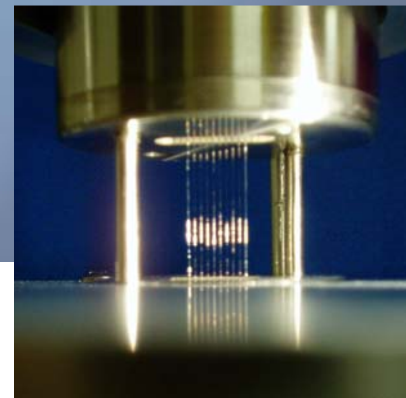
Shot N	Number of wires	Compos.	Configur.	Wire ϕ (μm)	Mass of load (μg)	Al mass (%)	Bolo (kJ)
802	15	Al/Mo/Al	IIIIIIIIIIIIIII	15/7.62/15	140	13	15.8
803	14	Mo/Al/Mo	IIIIIIIIIIIIII	7.9/15/7.9	139	13	16.6
782	10	Al/Cu/Al	IIIIIIIIII	17.8/10.16/17.8	143	18	14.1
808	14	Al/Cu/Al	IIIIIIIIIIIIII	10/10.16/10	183	5	14.1
757	10	Cu/Al/Cu	IIIIIIIIII	10.16/17.8/10.16	143	18	11.3

- For modeling of uniform Mo planar wire arrays, see Yilmaz *et al*, JQSRT 109, 2877 (2008)
- Extensive research on implosion dynamics and precursor studies of Cu cylindrical wire arrays on Zebra was led by Christine Coverdale which provided important information and test-bed for codes to be used for Cu planar wire array studies

K-shell Al and Mg spectra (both time integrated and time-gated) were much more intense for Al/Mo/Al than for Mo/Al/Mo planar wire arrays

Time integrated
spatially resolved

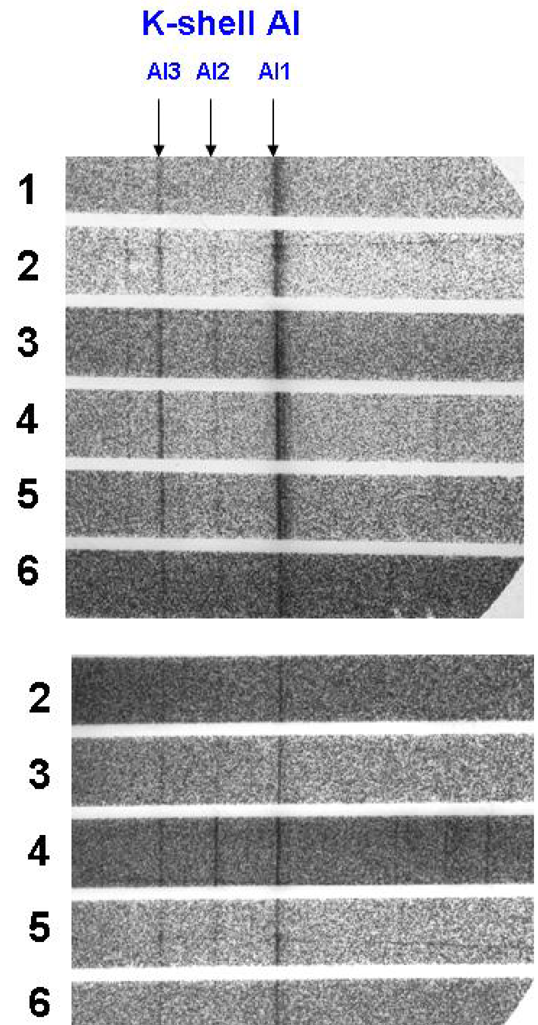




Shot 802
Al/Mo/Al

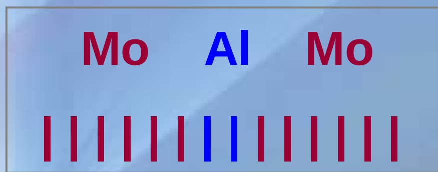
Shot 803
Mo/Al/Mo

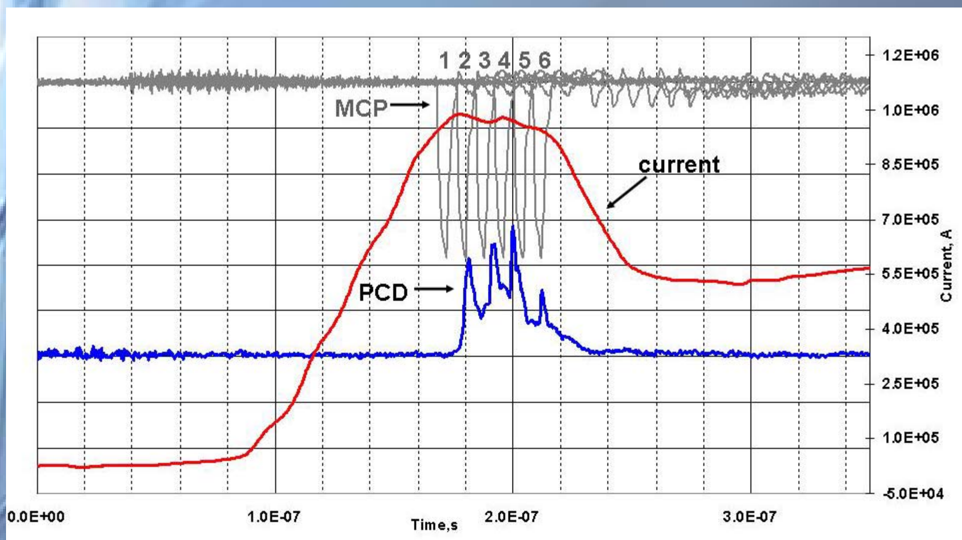
Time-gated
spatially integrated

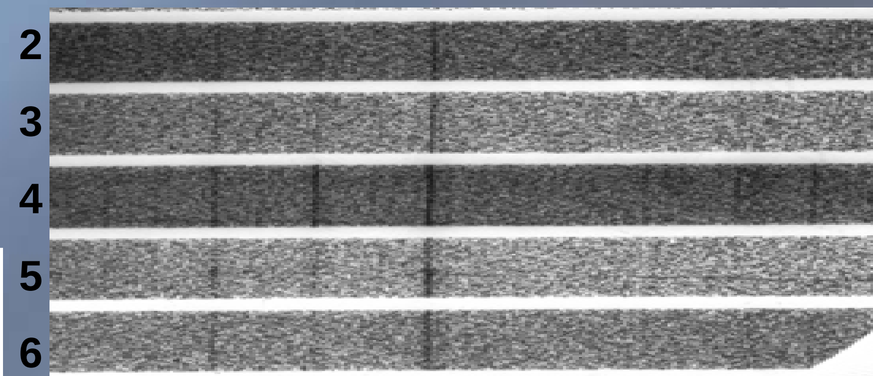


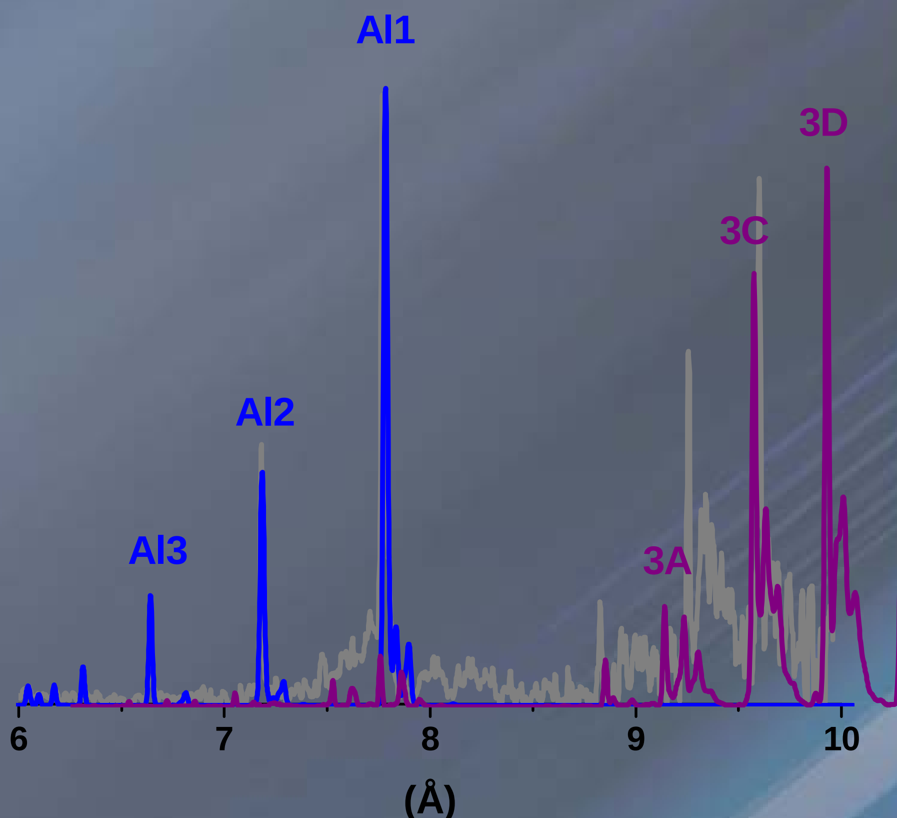
For more about the study of Mo SPWA with Al tracer wires , see Safronova *et al*, HED 3, 237(2007)

Mo SPWA with Al tracer wires (shot 803). Time-gated spectra . Maximum Te from both L-shell Mo and K-shell Al are reached at stagnation (N4). Note two different temperature plasma regions.









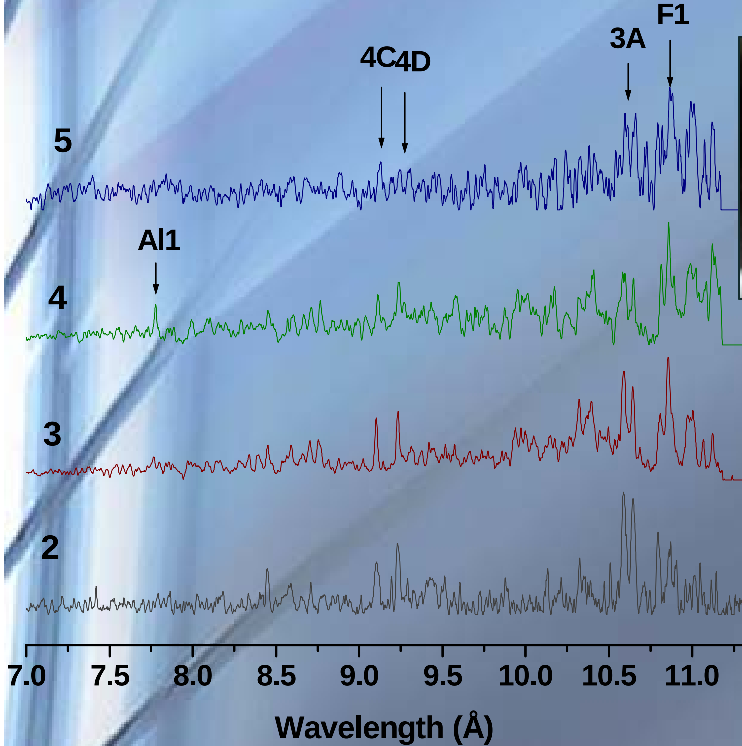
N4

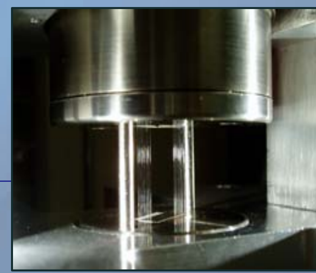
L-shell Mo: Te= 1200eV, Ne=5x10^{20} cm^{-3}

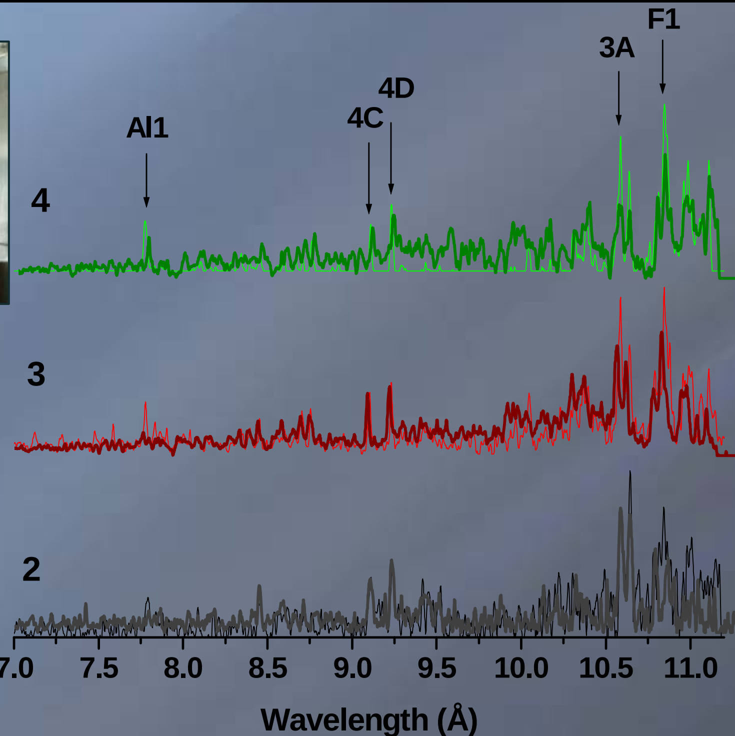
K-shell Al: Te=400 eV, Ne=5x10^{20} cm^{-3}

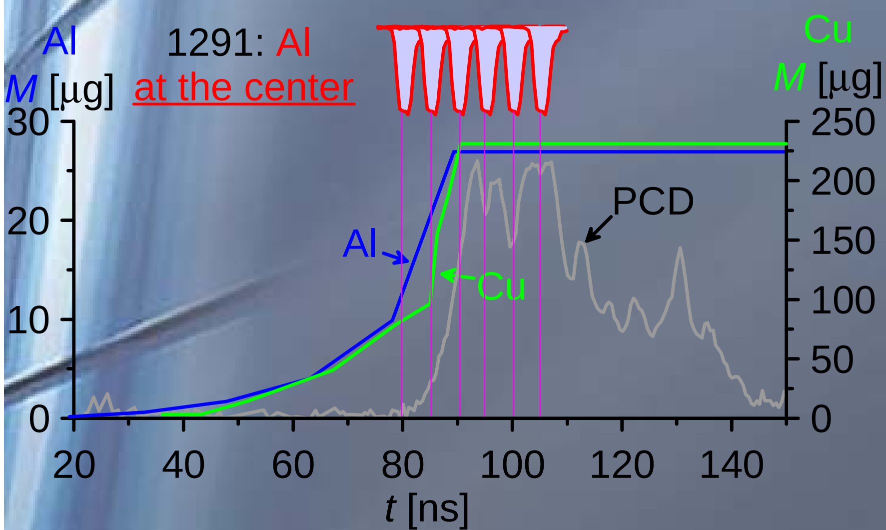
Safronova *et al*, Proceedings of APiP09 conference, March 22-26, 2009

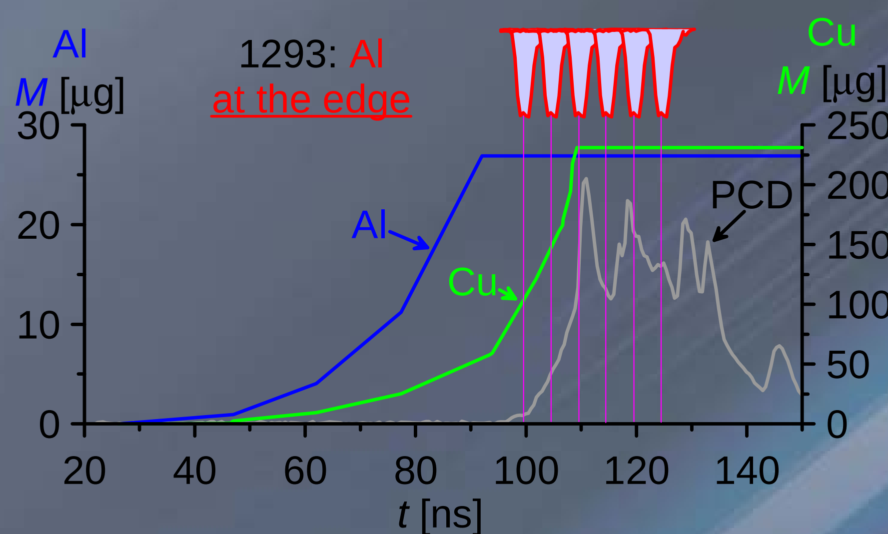
Studies of implosions of DPWA from Cu DPWA with Al tracer wires





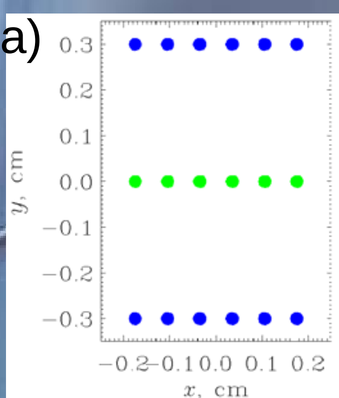




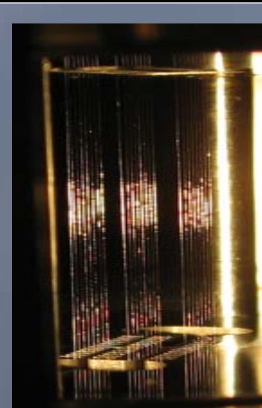


Triple PWA
(spectroscopy+imaging+implosion dynamics)

Shot #	Material # Wires	Diameter (µm)	Linear Mass (µg/cm)	Al (%)	Implosion Timing (ns)	Bolo Max (kJ)
1261	Mo/Mo/Mo 6/6/6	7.9/7.9/7.9	90	-	91	16.2
1262	Mo/Al/Mo 6/6/6	7.9/15/7.9	89	32	93	16.9
1263	Al/Mo/Al 6/6/6	15/7.9/15	87	65	97	13.1

a)


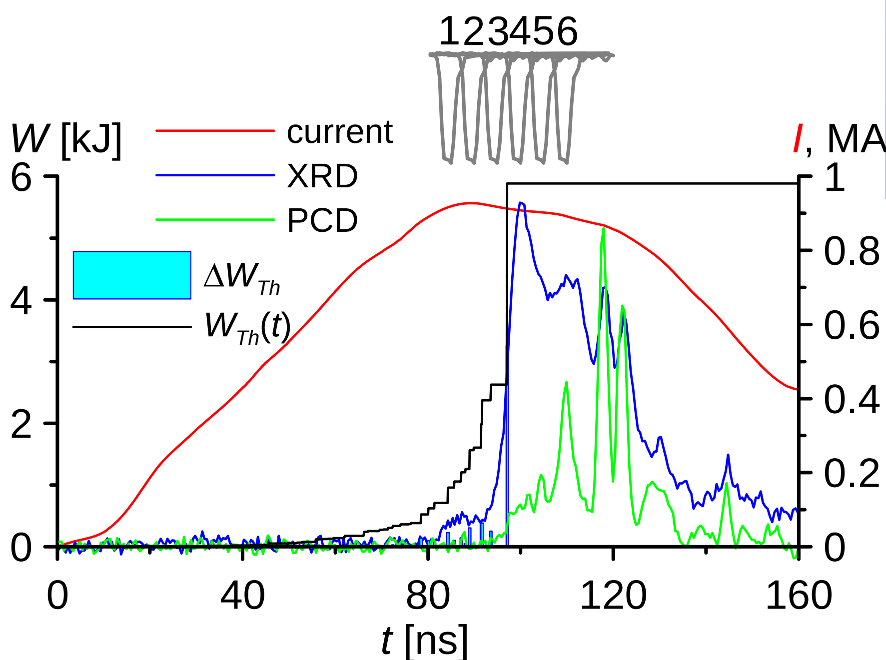
Mo
Al
Mo

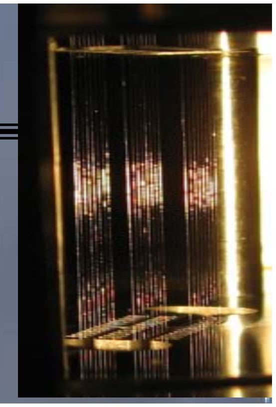
b)


a) Top view of example of triple planar wire array.

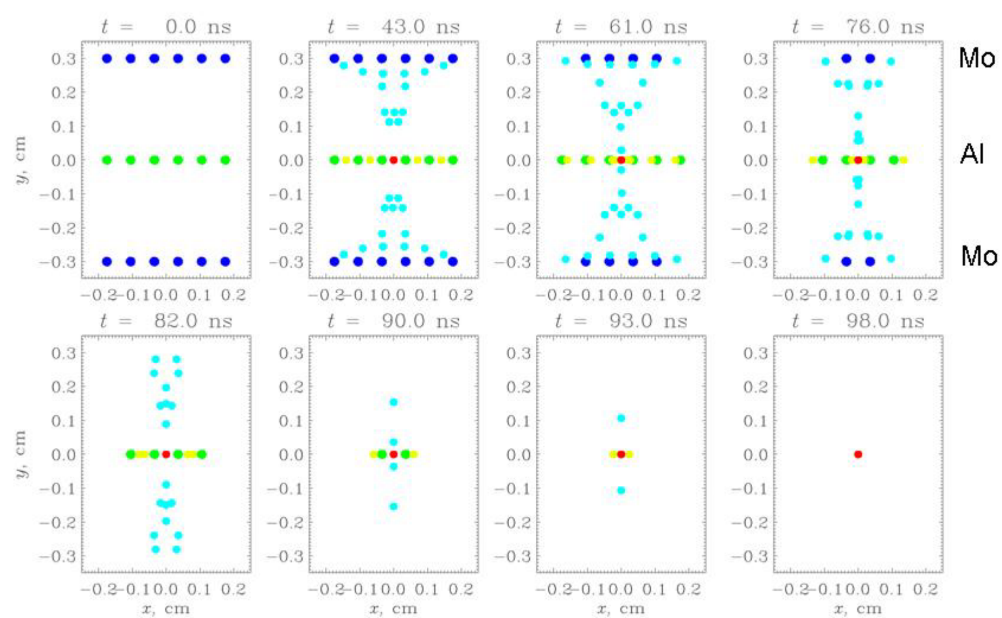
b) Picture of side view of triple planar wire array.

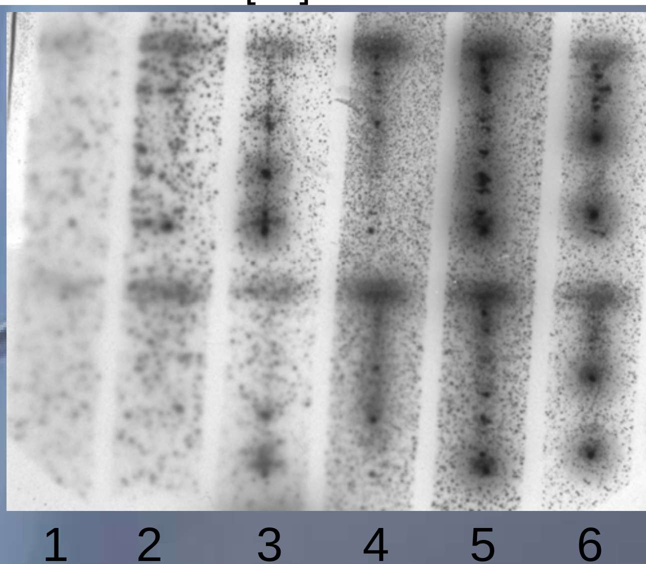
WADM can model mixture of materials





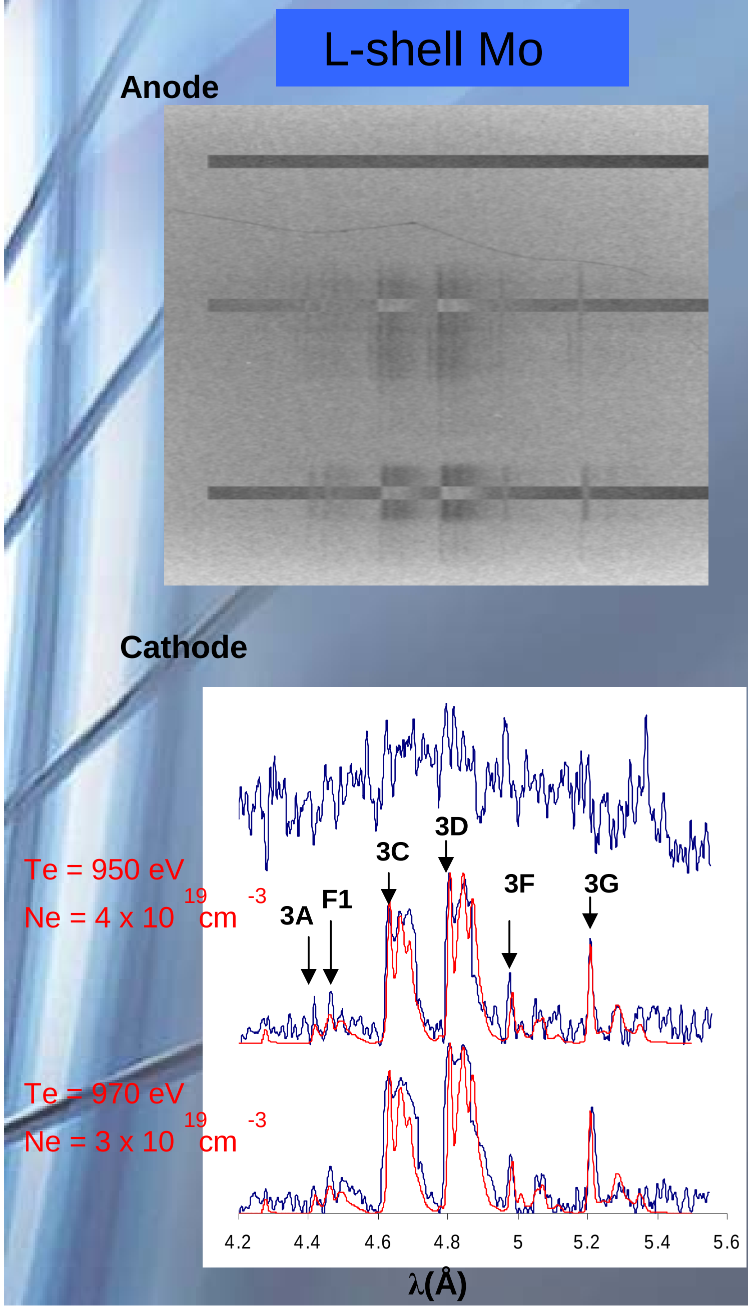
Implosion dynamics: shot # 1262

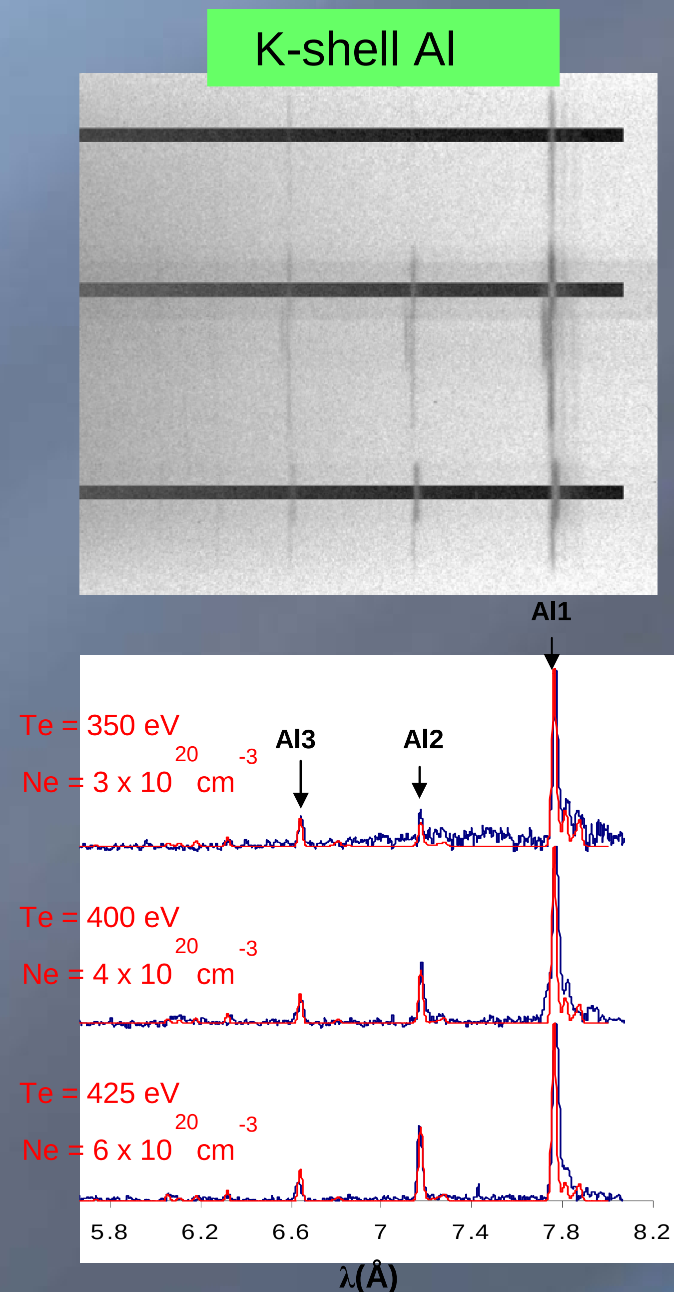


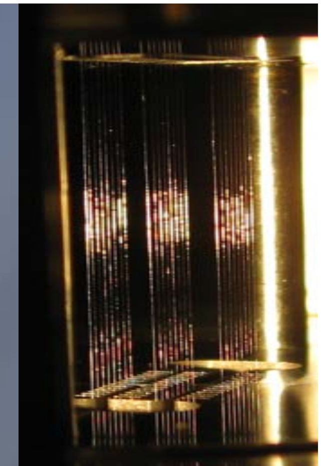


WADM calculations, see Esaulov *et al*, HEDP (in print, 2009)

Modeling of axially resolved spectra of L-shell Mo and K-shell Al show gradients in Te and Ne and two different plasma regions



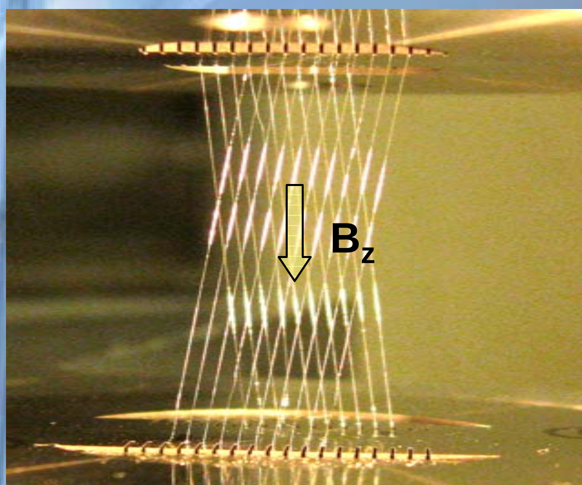




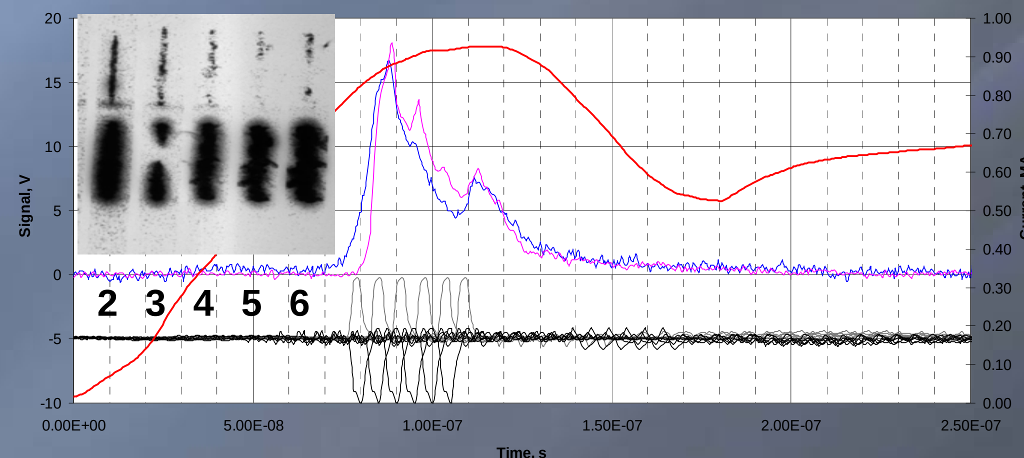
Note: no Mg lines - no opacity?

Double planar array with skewed wires - method to mitigate RT instabilities and to provide more effective X-ray generation?

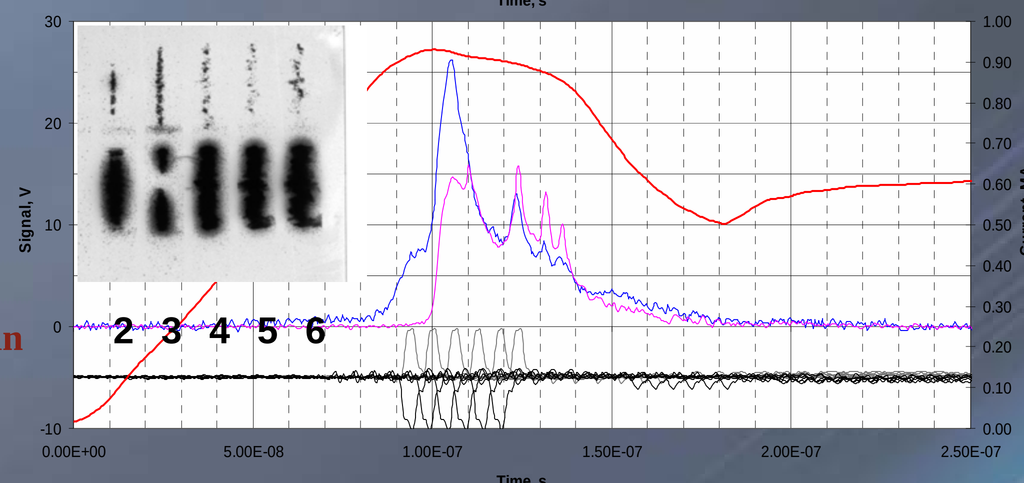
Wires twisted along a curved surface of cylindrical wire array are suggested to create an initial axial magnetic field Bz, to decrease of the magneto-Rayleigh-Taylor instabilities, and possibly to reach a higher pinch compression ratio and to provide more effective X-ray generation *.



A)



B)



Al DPWA with skewed wires.

Angle between wires 16^0. Φ_w=10 µm,N_w=10

A)# 1632, Δ=3 mm. B)# 1630, Δ=6 mm.

Strip 3# was with damage at a center.

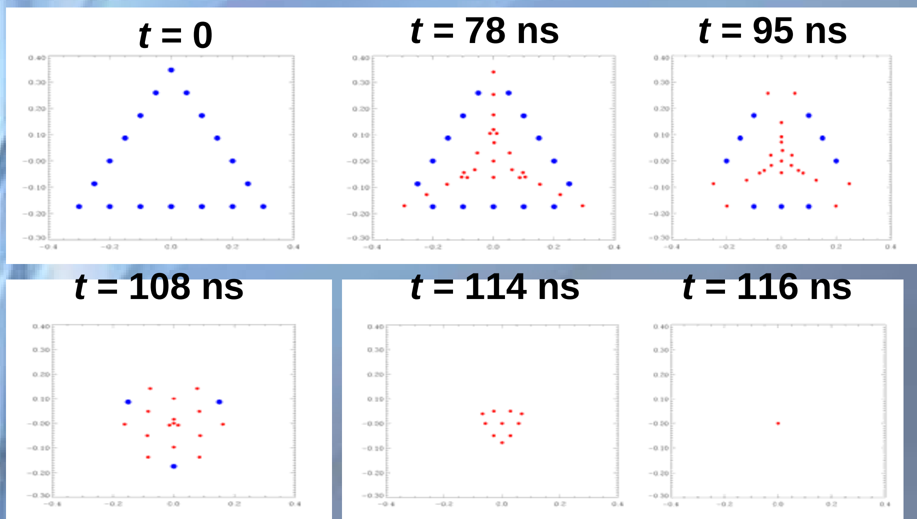
Maximum Te ~380 eV which is slightly higher than in standard DPWA (Te ~360 eV) , and maximum Ne 8×10^{19} cm^{-3} was lower by a factor of 2.

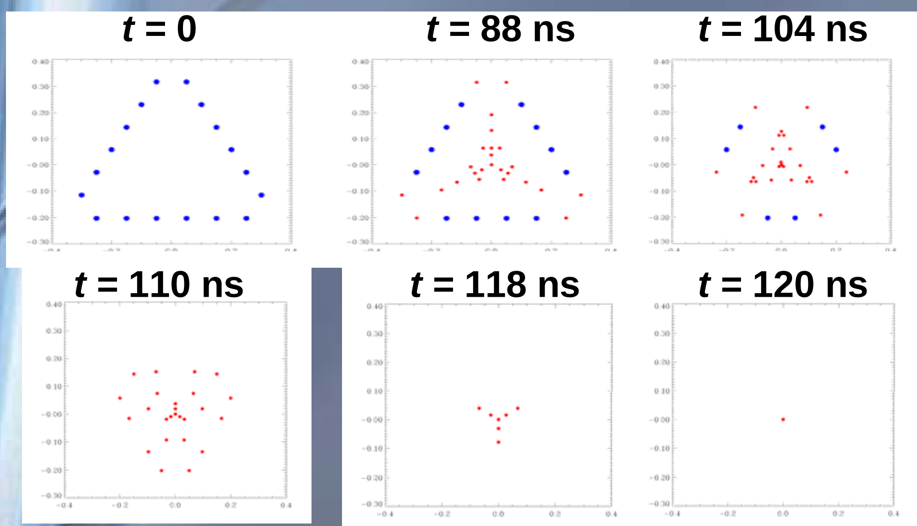
Possibility of radiation pulse shaping.

***Chandrasekhar S., Hydrodynamic and Hydromagnetic Stability. Oxford:Clarendon Press (1961); Rudakov L,and Sudan R., Phys. Reports, v. 283, 253 (1997); Volkov N. et al., Bull. Am. Phys. Soc., v. 42, 2051 (1999); Lebedev S. et al., Plasma Phys. Control. Fusion, v. 47, B465 (2005).**

Different implosion of prismatic planar array with and without corner wires

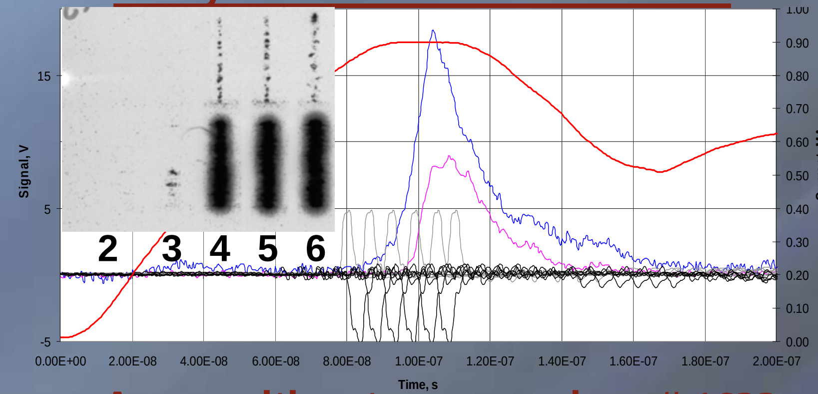
Possible radiation pulse shaping by removing corners wires.



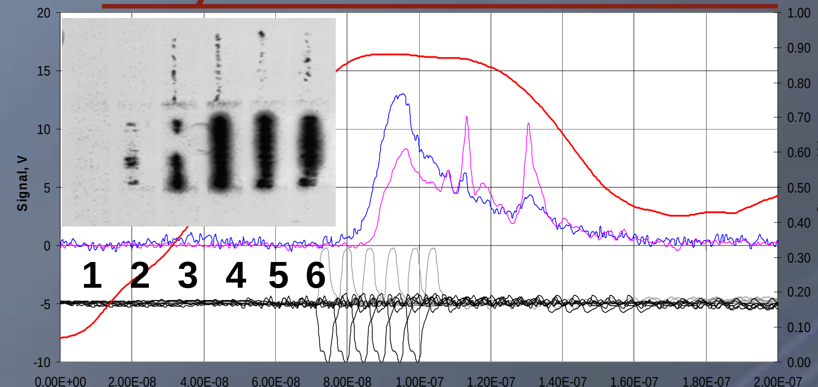


The Wire Ablation Dynamics Model (WADM) simulation. Blue dots are initial wires positions, red dots are low density ablation plasmas

Array with corners wires #1631



Array without corner wires # 1633



Prismatic arrays with Al wires.

Φ_w=17.8 μm,N_w=18 or 15, d=1 mm.

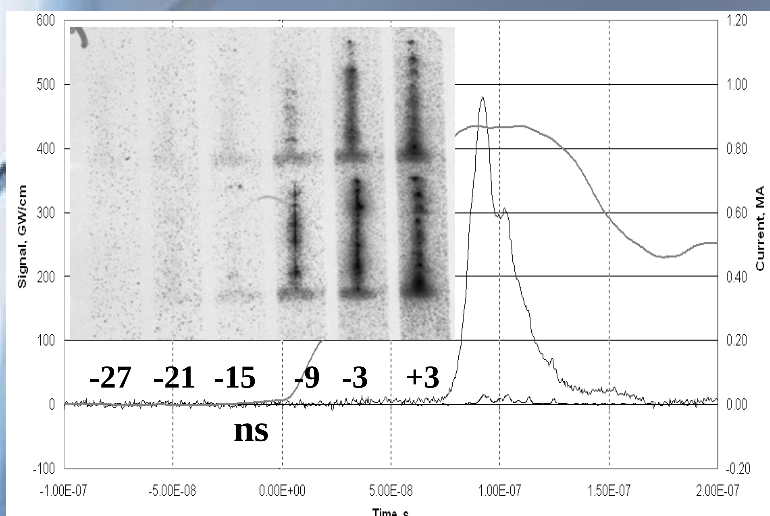
Strip 3# was with damage at a center.

Total yield was the same and power (in sub-keV) was 0.7 as of Al DPWA. Possibility of radiation pulse shaping ?

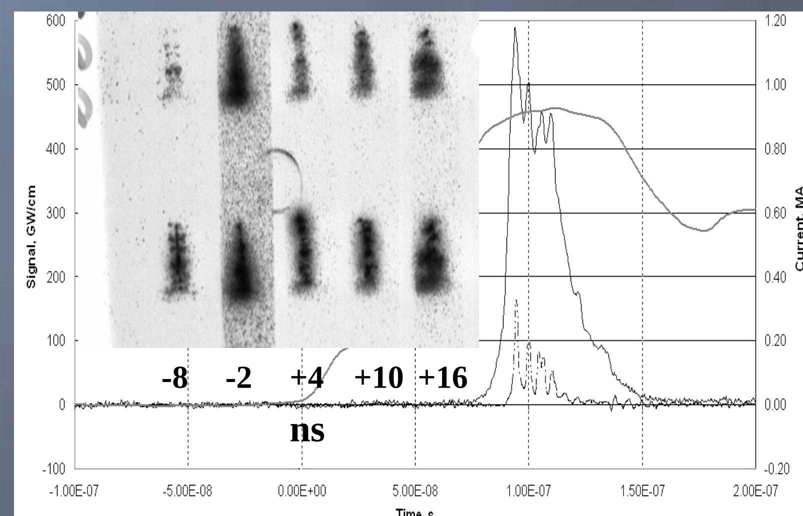
Scaling of radiation parameters with the anode-cathode gap (AC_{gap})

- A comparison of E_T (kJ/cm) and P_{subkeV} (TW/cm) for the AC_{gap} =1 or 2 cm was performed for W SPWA and DPWA (one Al wire tracer in each row) with constant linear-mass density.
- The radiation scaling coefficients (ratio $E_{T\ 1cm}$ / $E_{T\ 2cm}$ = $K_{1>2}$ and $P_{subkeV\ 1cm}$ / $P_{subkeV\ 2cm}$ = $N_{1>2}$) were determined from averaged values for at least two identical shots fielded at each AC_{gap}.
- The SPWA performed much better at 1cm than at 2cm ($K_{1>2}$ = 1.27 and $N_{1>2}$ =2.7).
- The DPWA loads also radiated significantly higher at AC_{gap}=1cm ($K_{1>2}$ = 1.4 and $N_{1>2}$ =1.3).

X-ray time-gated images showed different structure of imploded plasma for 1 and 2 cm AC gap. For example, W DPWA with AC_{gap}=1 cm formed some conical-like structure at stagnation stage that is distinct from column-like picture for AC_{gap}=2 cm. Experiments and data analysis are in progress.



+16

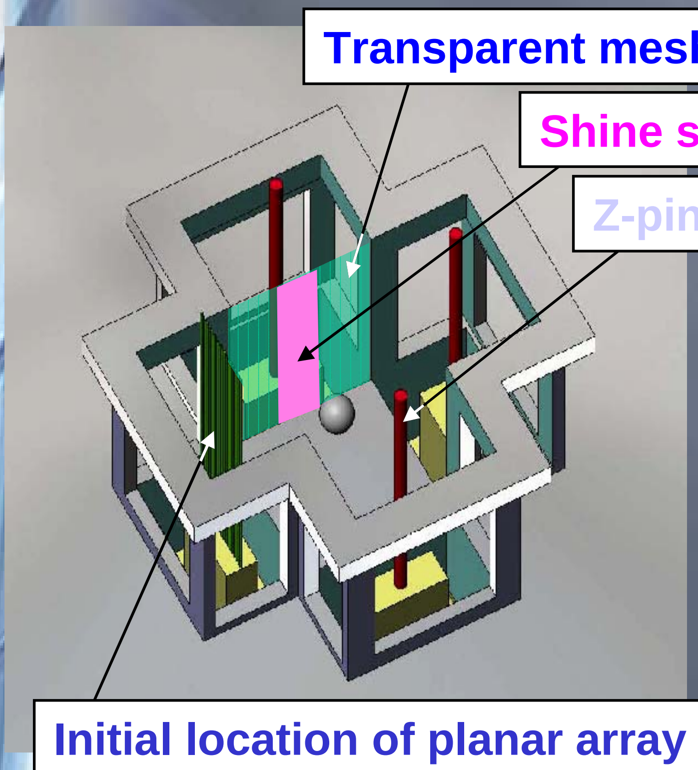


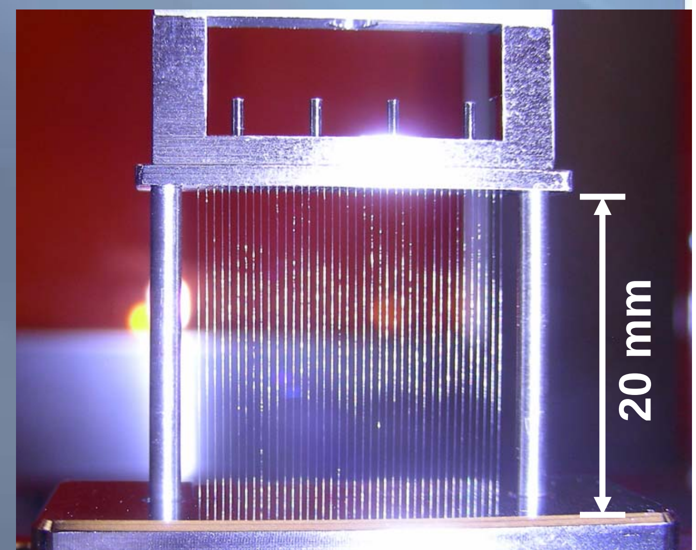
DPWA, W+Al(5056), N=8 (one Al wire on end of each row), d=0.7, Δ=3mm, W Φw=7μm, Al Φw=17.8μm.

Shot #1602, ACgap = 2 cm (left). Shot #1599, ACgap = 1 cm (right).

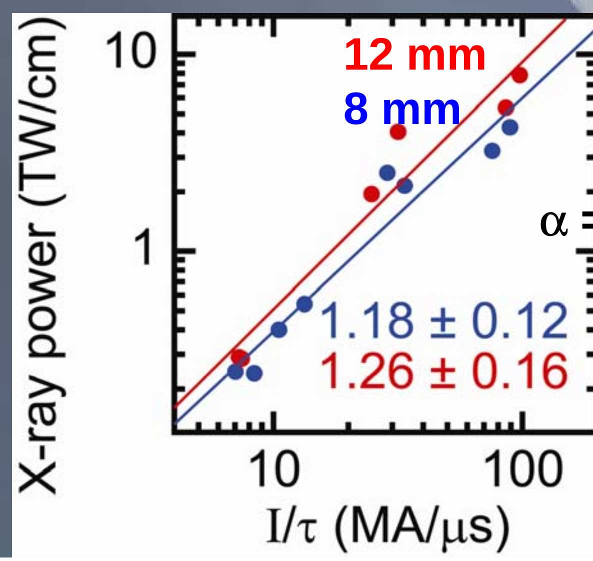
Images at the top in 1 keV, and at the bottom in 3 keV regions. Frames duration is 3 ns, interframe interval is 6 ns. The anode is at the bottom.

Planar arrays are being explored for a more compact x-ray source geometry

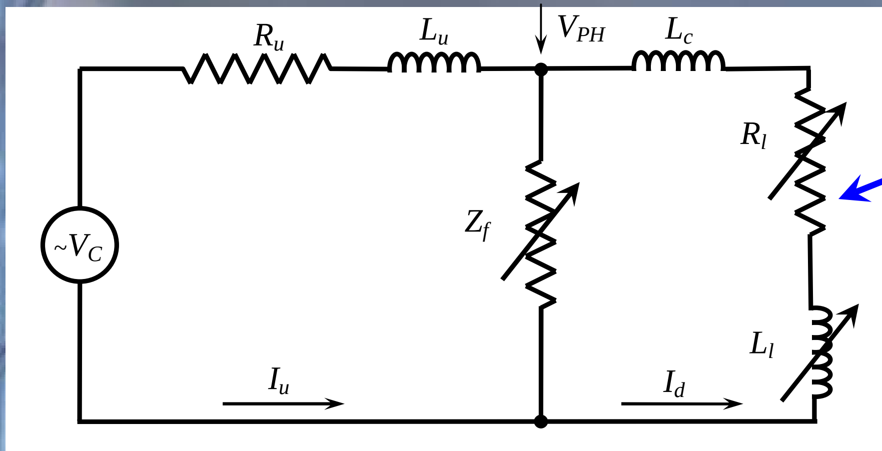




$$P \propto (I/\tau)^{\alpha}$$

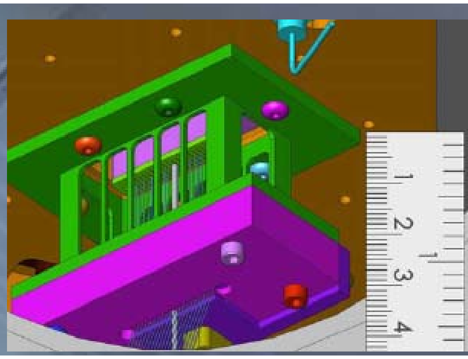


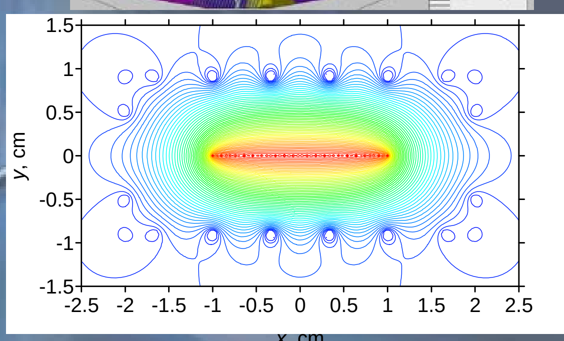
Saturn load design



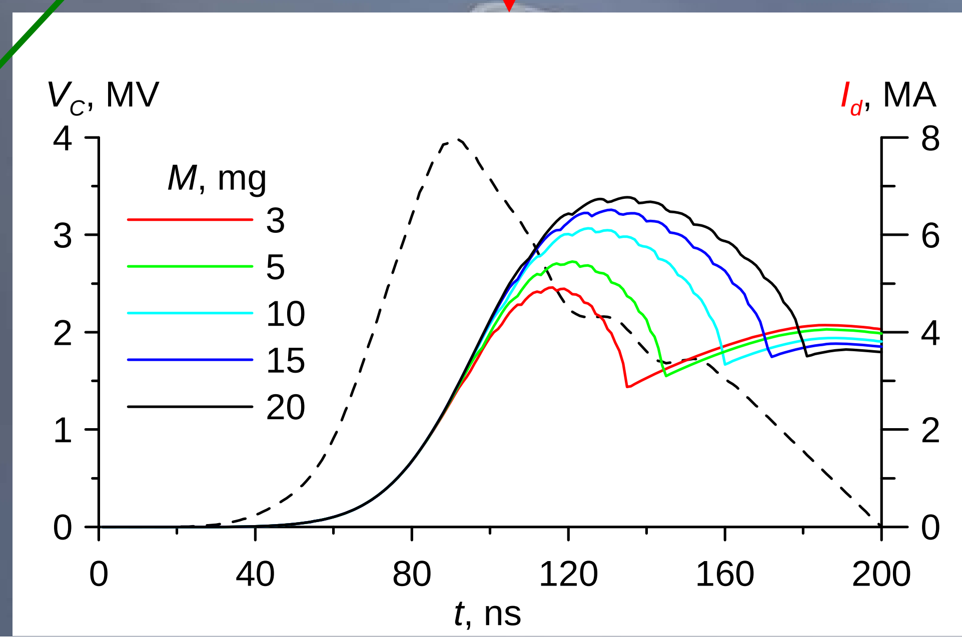
Full circuit simulations

Rectangular box return current design





Load mass & size scan



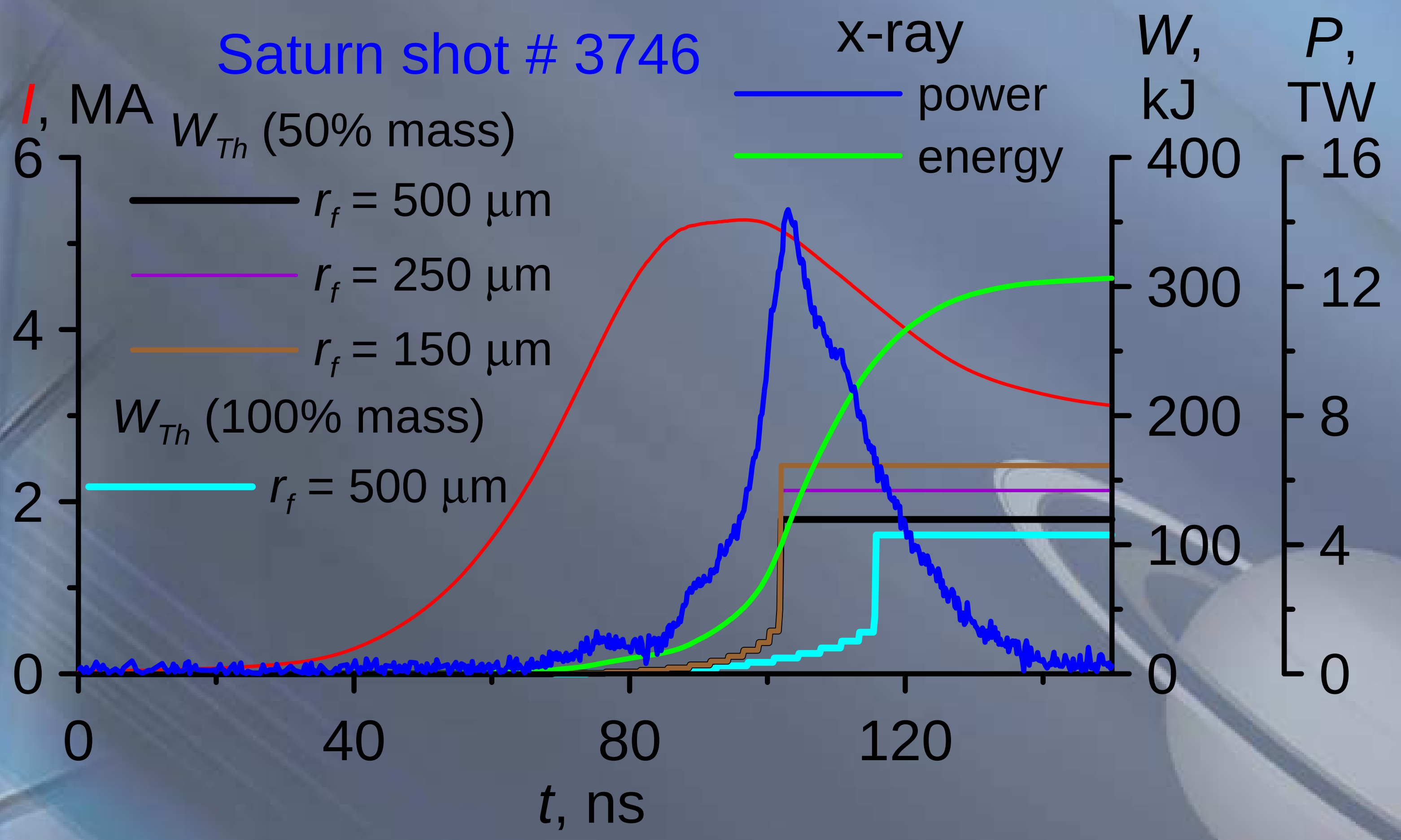
Implosion characteristics and details of loads

Shot number	Wire material	Array height, h (mm)	Array width, W (mm)	Wire number	Wire diameter (μm)	Array mass (mg/cm)	Design implosion time
3744	W	20	8	16	40.60	3.987	Nominal
3745	W	20	12	24	23.50	2.004	Nominal
3746	W	20	12	24	23.50	2.004	Nominal
3747	W	20	8	16	40.60	3.987	Nominal
3748	Al 5056	20	20	40	30.50	0.789	Nominal
3752	W	20	20	40	11.43	0.790	Nominal

Shot number	Peak power (TW)	Yield in prepulse (kJ)	Yield to peak power (kJ)	Peak power $\times$FWHM (kJ)	Yield to back of FWHM (kJ)	Total yield (kJ)	Calculated coupled energy (kJ)
3744[i]	8.3	16.6	100.2	160.2	162.2	245.3	93
3745[i]	10.5	18.0	140.4	230.4	236.9	298.7	108
3746[i]	15.3	23.0	120.6	242.4	247.0	326.2	108
3747[i]	6.1	14.0	87.8	134.5	143.0	206.8	72
3748	11.5	24.2	138.6	209.3	217.7	287.3	145
3752[i]	13.2	0.5	189.5	215.0	274.6	352.5	135
3753	4.5	0.9	16.8	57.3	46.3	114.6	47
3754	7.2	3.1	30.4	98.2	92.6	155.2	34
3755	4.3	3.5	19.8	45.8	43.4	123.3	48
3756	6.2	3.8	27.2	70.8	61.2	126.8	38

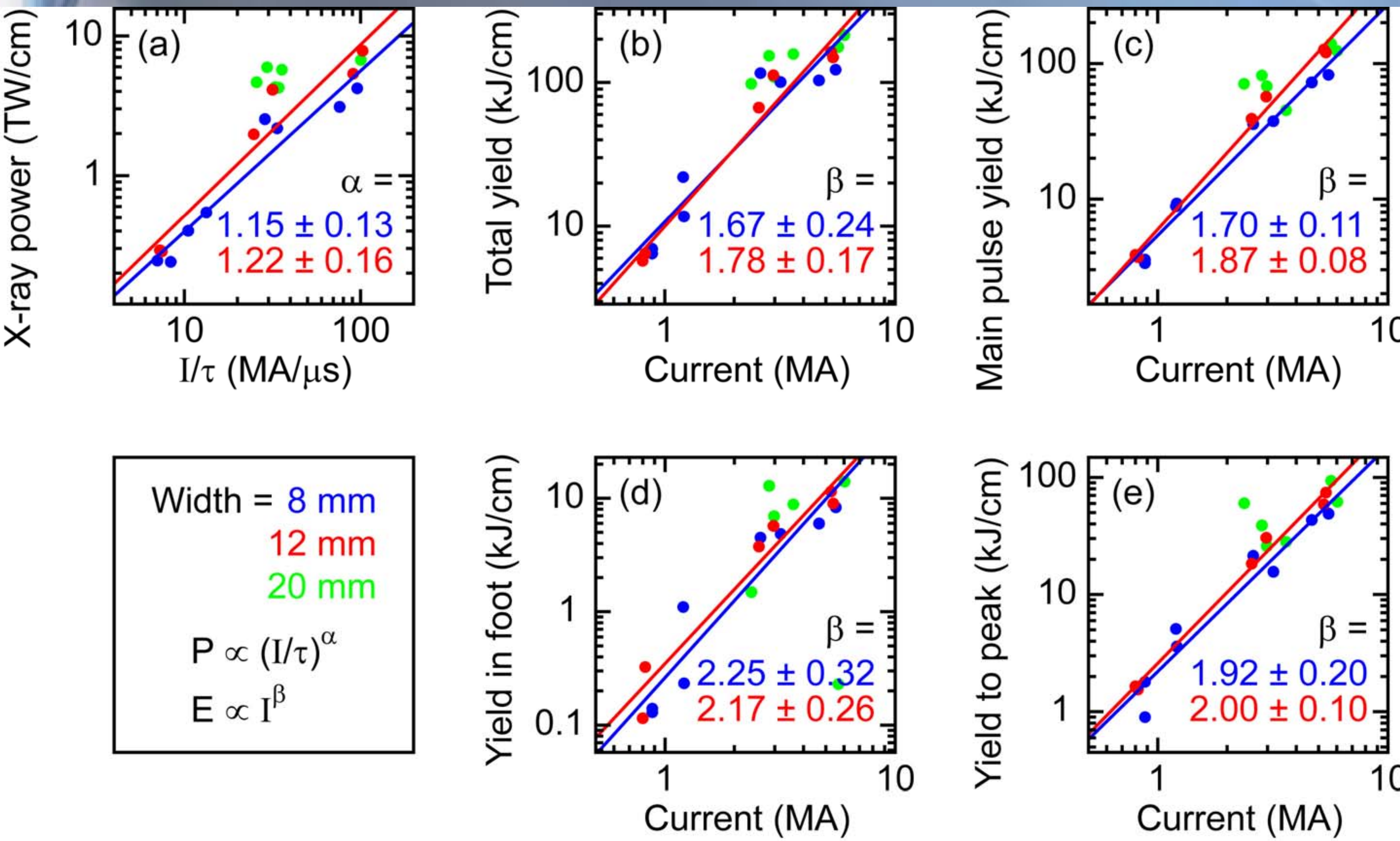
Jones *et al*, SAND2008-6166, Tables 2.1 and 3.2

Saturn data processing



Total radiated energy in the main pulse (> 300 kJ) *is almost twice as higher as the most optimistic estimations for the thermalized kinetic energy* (~ 160 kJ)

PWA experiments on Saturn (two series) and on Zebra provide data for scaling of planar wire array power and yield



B. Jones *et al*, SAND2008-6166, Fig. 3.1

CONCLUSION (PWA work on Zebra at UNR)

- The DPWA was found to be the best x-ray radiator tested recently at University scale, 100 ns generator. It is characterized by combination of such properties as large resistive energy and power gain, small, mm-scale size, and the possibility of radiation pulse shaping. Also, an important feature of the DPWA is the easy diagnostic access observation to plasma implosion and stagnation stages.

- The simulations indicate the upper boundary estimation for thermalized kinetic energy Ek < 2-4 kJ. The total radiation yield E_T (25 kJ from W DPWA and CCWA) exceeds the inductive energy change Ek by at least a factor of 4-5, and another mechanism of plasma heating different from thermalization of Ek might dominate in these experiments (it could be the resistivity of a strongly inhomogeneous plasma generated throughout the implosion).

  - New types of planar wire arrays, double planar array with skewed wires and prismatic planar array, were successfully begun applied for optimization of X-ray generation.

- X-ray spectroscopy and imaging of the PWAs supported by a set of theoretical codes proved to be a unique tool to study radiative and implosion characteristics of single and multiple wires and whole wire planes, of the combined PWAs in particular.

CONCLUSION (PWA work on Saturn at SNL)

- **The Single Planar Wire Array compact loads of the widths 8–20 mm have been successfully tested, demonstrating high x-ray powers > 15 TW and yields > 320 kJ, which are significantly higher than maximum 7 TW and 150 KJ power and yield from the compact cylindrical arrays at the same machine.**
- **In the current range 0.8–3 MA (~100 ns rise time) x-ray power from single planar arrays scales with current almost quadratically** $P \propto I^{1.8\text{–}1.9}$
- **The evidences of anomalous heating of z-pinch plasma created by imploding planar wire arrays have been found both in 1–1.4 MA experiments on Zebra facility as well as in 3 – 5 MA experiments at Saturn.**
- **New concept of z-pinch driven vacuum hohlraum that implements planar wire array load design has been proposed.**

B. Jones *et al*, Sandia Reports SAND2007-6337 and SAND2008-6166

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