SAND2011-4018C

THE STUDY OF ABLATION AND IMPLOSION DYNAMICS IN CLOSELY COUPLED NESTED CYLINDRICAL AND STAR WIRE ARRAY Z PINCHES

D. Papp, V. V. Ivanov, A. Haboub, A. A. Anderson,
S. D. Altemara
University of Nevada, Reno, Reno, NV 89507, USA
B. Jones
Sandia National Laboratories, Albuquerque, NM 87110
J. P. Chittenden
Blackett Laboratory, Imperial College, London SW7 2BZ, UK

Presented at the 8th international conference on Dense Z-pinches,
Biarritz, France, June 5-9, 2011

Abstract

Plasma dynamics in cylindrical closely coupled and star wire arrays at ablation and implosion stages were studied. Nonprecursor ablation regime was studied and radiative properties were compared with the regular ablation regime with precursor. The $j \times B$ force in star arrays and in nested cylindrical arrays with closely located wires can be inverted. In latter, the local magnetic field at the wires is stronger, and plasma from the inner wires does not ablate to the center, and the array implodes in the non-precursor regime. In some star array configurations with large number of wires, the inner wires ablate not to the center but within the rays, and do not form a precursor on the axis. This mode of implosion was observed in star and planar wire arrays. In closely coupled nested cylindrical arrays, the inner and outer cylindrical arrays are of equal wire numbers, with 0.5-1mm radial separation between the inner and outer wires. Calculations using the inductance method show initial outward $j \times B$ forces acting on the inner array, which also prohibits early plasma accumulation on the axis. This may also suggest that pairs of wires merging before imploding to the center. In contrast to this, ablation starts at the outer wires, and the plasma of these wires implode into the inner wires which stay at their original position. This behavior is similar to the cascading mode in star arrays. Ablation to the center is partly suppressed, and the ablated plasma forms a weak and late precursor.523nm and 266nm laser shadowgraphy shows cascading features in the ablation stage. The better plasma penetration of the UV light permits the resolution finer details, while the same region at 532nm probing appears as a mass of non-penetrable plasma. The development of a two-frame 266nm UV-probing allows investigation of the dynamics of ablation implosion in areas opaque for regular probing at 532nm. ________________________________

* Work was supported by the DOE/NNSA under UNR grant DE-FC52-06NA27616. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Motivation

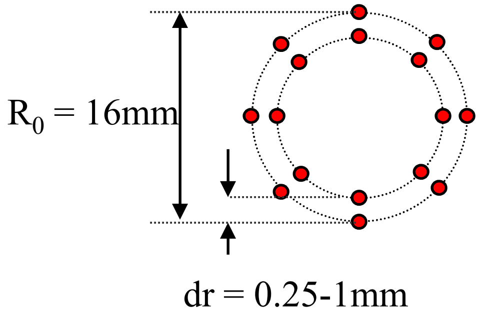
Study the role of precursor in stabilizing the pinch

Closely coupled nested cylindrical arrays have a very short distance between the inner and outer arrays (1mm or less)

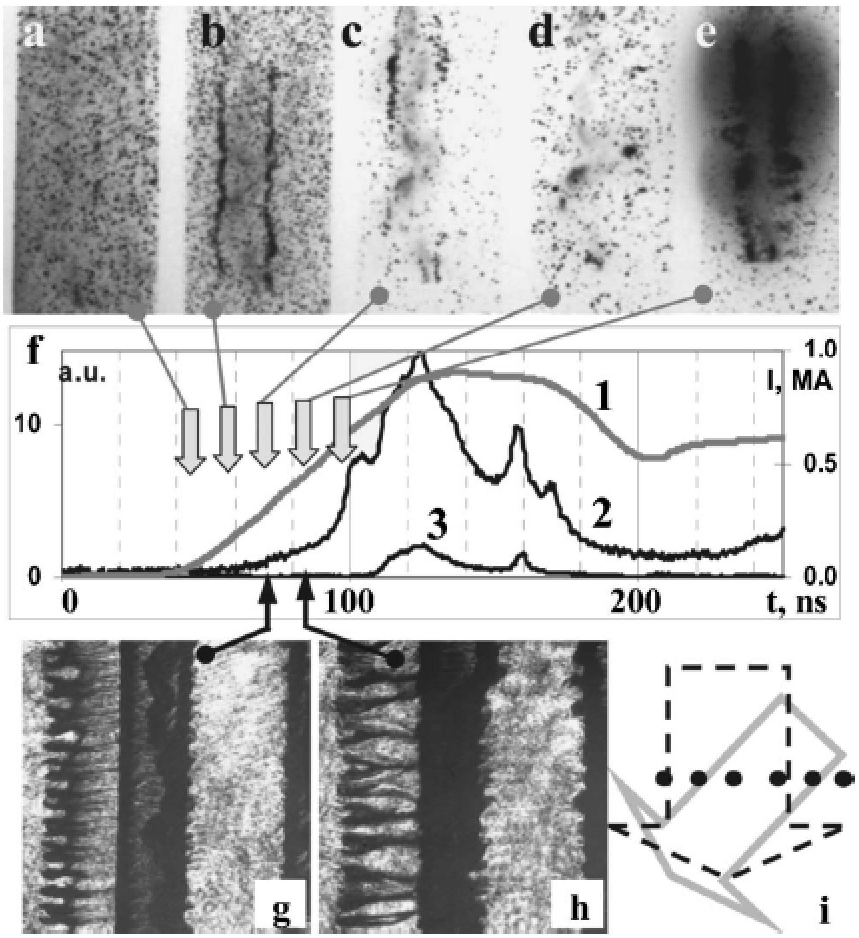
Calculations predict outward ablation on inner wires

Similar calculations for star arrays are in agreement with observations on the presence of precursor

- Determine under what conditions would non-precursor implosion happen
- Investigate effects on X-ray yield
- Study the interaction within wire pairs

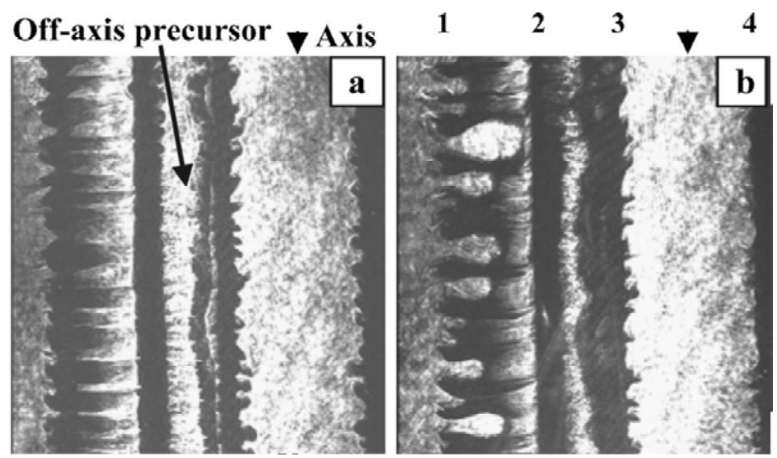


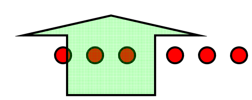
Non-precursor array configurations are possible in linear arrays*



6x20µm Al linear array

- Linear arrays with equidistant spacing have central precursor
- Linear arrays with large central gap have no precursor on the axis
- The loads provide 5-10% lower X-ray yield and bolometer energy compared with equidistant linear arrays
- The precursor might have stabilization effect





*:Ivanov, V.V. et al., Physics of Plasmas **14** (2007), 032703

In CCN arrays inductance model predict the merging of wire pairs during ablation phase

A 2D inductance model* was implemented in MATLAB. A wire array is modeled as current loops consisting of a wire *i* and a return current backpost *k*.

The voltage drop is the same over each loop. In an inductive load it is determined by the rate of change of magnetic flux over each wire loop:

$$V = \frac{\partial \Phi_{ik}}{\partial t} = \frac{\partial \Phi}{\partial t} = const \quad \Rightarrow \Phi = const$$

The total flux through a current loop *ik* is the sum of the contribution of all possible loops:

$$\Phi = \Phi_{ik} = \sum_{j=1}^{Nw} \sum_{m=1}^{Nb} L_{ik,jm} I_{jm}$$

The mutual and self-inductances $L_{ik,jm}$ of wire-backpost loops can be calculated:

$$L_{ik,jm} = \frac{\mu_0 h}{2\pi} \ln\left(\frac{r_{im} r_{jk}}{r_{ij} r_{mk}}\right) + \frac{\mu_0}{4\pi}\left(\ln\frac{2h}{r} - 0.75\right)\delta_{ij} + \frac{\mu_0}{4\pi}\left(\ln\frac{2h}{r} - 0.75\right)\delta_{km}$$

This result in a system of linear equations of $N_w \times N_b$ size. Wire currents are recovered by summation of the relevant loop currents.

The code was benchmarked by an approximate formula for nested arrays**, and by comparing to another implementation of the same method†

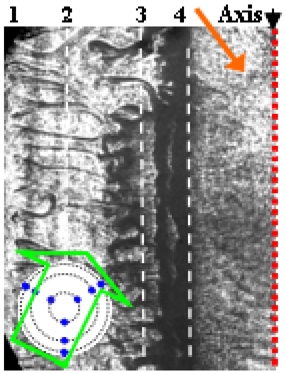
*:Davis et al., Appl. Phys. Lett. **70**, 170 (1997)

:Velikovich et al., Phys. Plasmas **9, 1366 (2002)

†:S. N. Bland, Imperial College, London, personal communication

Star arrays can implode with or without precursor

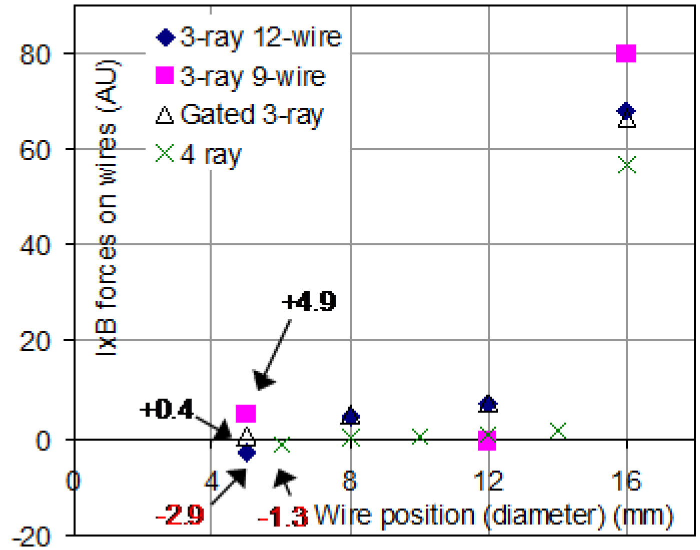
No precursor

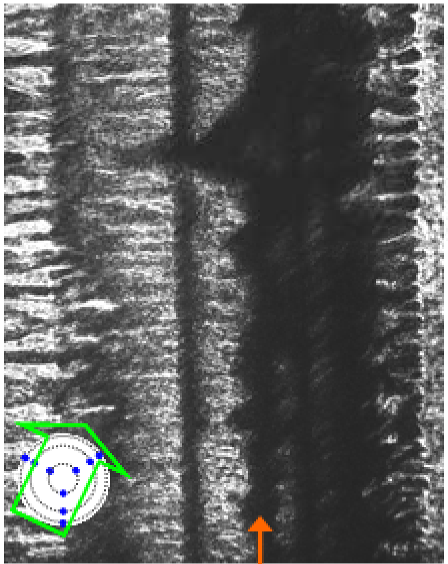


3-ray 12-wire Al star Ø16/12/8/6mm

I×B force calculations are in qualitative agreement with the observations

I×B forces on the wires in star arrays. Negative force on the inner wires - no precursor

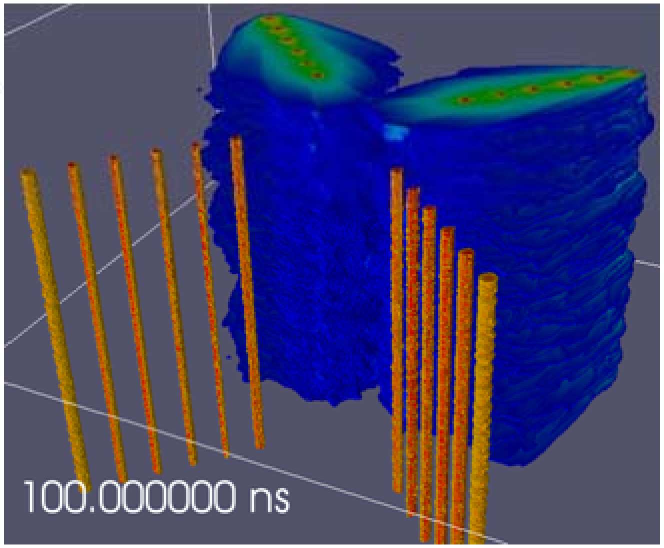




Precursor on axis

3-ray 9-wire SS star Ø16/12/5mm, #1715

GORGON3D simulation by J.P. Chittenden from Imperial College, London shows no ablation-stage precursor in a 4-ray star



In closely spaced nested arrays the model predicts the merging of wire pairs during ablation phase

Current distribution was calculated for closely coupled nested arrays

Assumption: current flows in discrete 400µm diameter wire cores

Determining I×B forces gives qualitative guidelines for implosion behavior

Forces on the inner wires directed outward

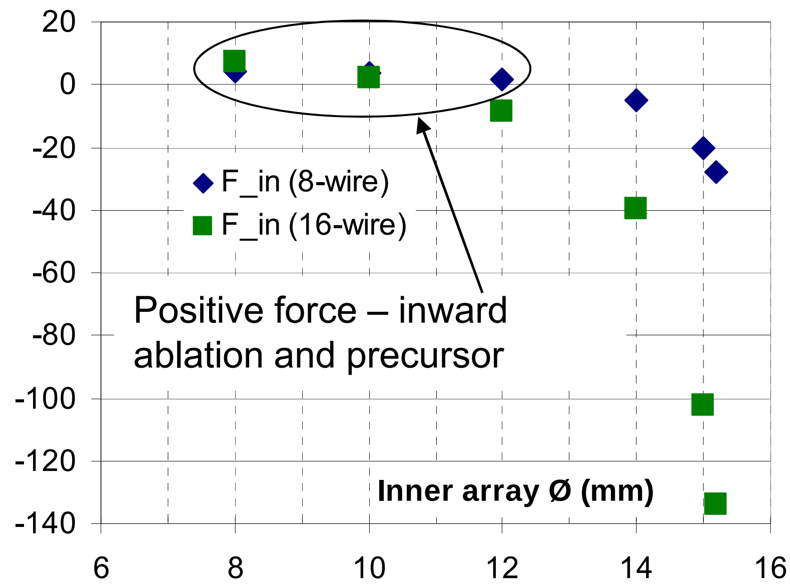
Inner and outer wires should ablate toward each other, then merge in ~50ns

Config	Wire #	I_in	B_in	B_out	F_in	F_out
14/16mm	8	0.44	-18	32	-40	89
15/16mm	8	0.45	-45	55	-102	151
14/16mm	16	0.36	-5	21	-5	33
15/16mm	16	0.38	-20	31	-19	47
16mm	8			11		27
16mm	4			9		47

Current distribution, B field (in T) and I×B forces (kN) on the wires in nested and regular cylindrical arrays for 1MA total current

Using some approximations, local magnetic field dominates over the global one when

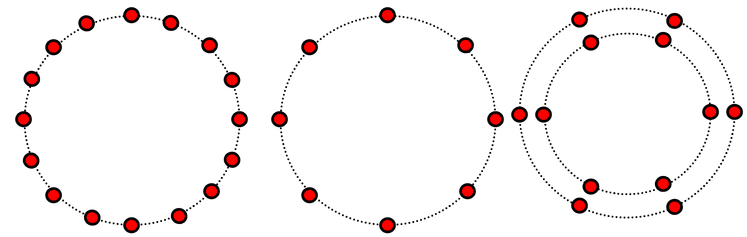
$$dr \leq 2 \cdot R_0/(N_{wires}-2)$$



I×B force (AU) on the inner array wires, in nested cylindrical loads with 8 and 16 wires

Different cylindrical and nested configurations were investigated

Shots			Configuration	Load Ø, mm	Wire #	Wire Ø,µm	Mass µg/cm	Predicted Precursor
2386	2387	2394	Cylindrical	16	8	17.8	52.5	Yes
2399			Cylindrical	16	16	12.7	53.5	Yes
2395	2396		Closely sp.	14/16	8	17.8	52.5	No
2400			Closely sp.	15/16	8	17.8	52.5	No
2388	2390	2393	Closely sp.	14/16	16	12.7	53.5	No
2385	2391	2392	Closely sp.	15/16	16	12.7	53.5	No
1338	1341		Cylindrical	16	6	17.8	39.4	Yes
848	849	850	Cylindrical	16	8	15.0	37.3	Yes
865	1237		Cylindrical	16	16	10.0	33.2	Yes
1343	1350		Nested	8/16	6	17.8	39.4	Yes
1342			Nested	8/16	12	12.0	35.8	Yes
986	987	988	Nested	8/16	16	10.0	33.2	Yes
1064	1066		Nested	8/16	8	15.0	37.3	Yes
1344	1347	1353	Closely sp.	14/16	6	17.8	39.4	No
974	978		Closely sp.	14/16	8	15.0	37.3	No
1164	1238		Closely sp.	15.2/16	8	15.0	37.3	No
1348	1352		Closely sp.	15/16	12	12.0	35.8	No
1346	1351		Closely sp.	15.5/16	12	12.0	35.8	No
1345	1349		Closely sp.	15.5/16	16	10.0	33.2	No
966	968		Closely sp.	14/16	16	10.0	33.2	No
1068	1170	1241	Closely sp.	15.2/16	16	10.0	33.2	No

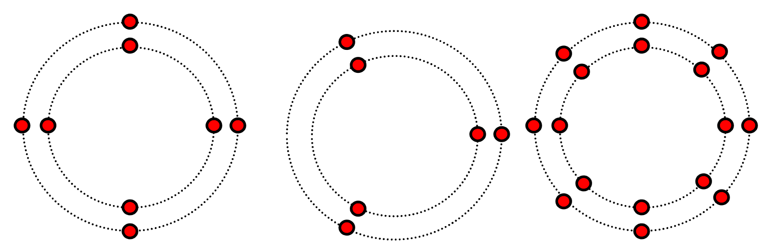


Regular and nested cylindrical arrays with 6-16 wires were investigated in several campaigns

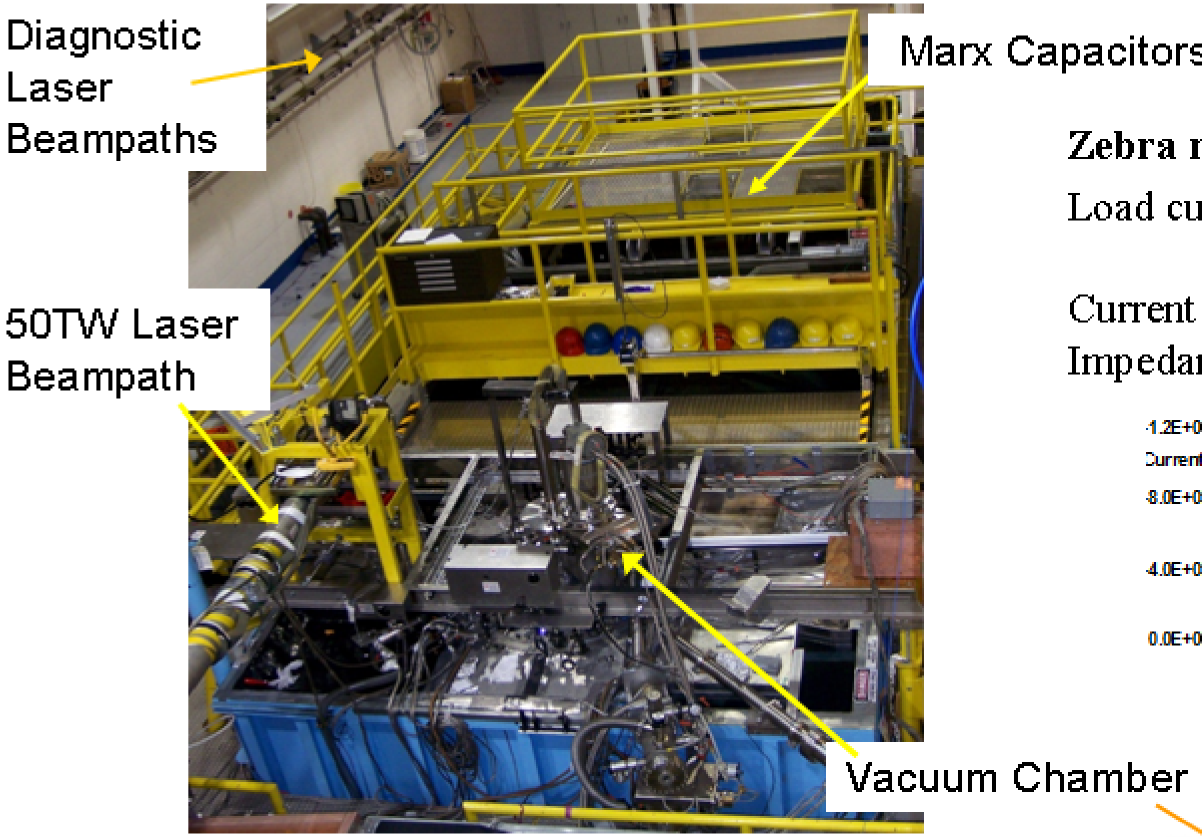
Cylinder spacing in nested arrays was varied from 0.25 to 1mm

The earlier experiments (up to shot #1353) used different current return setup

Loads #2390-2400 were not optimized for implosion time

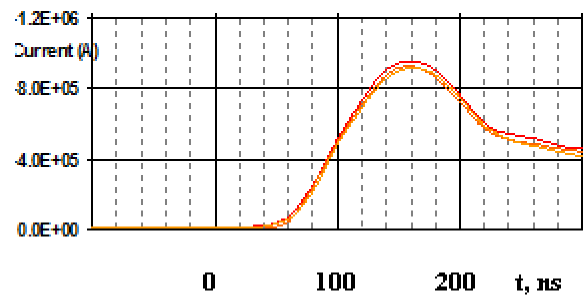


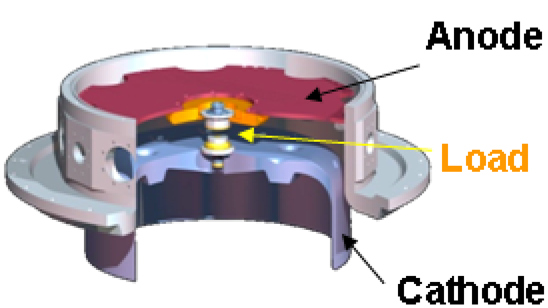
1MA Zebra generator at UNR

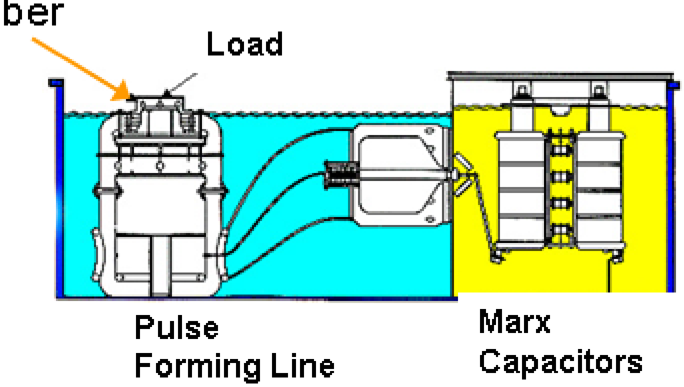


Zebra regular operation:

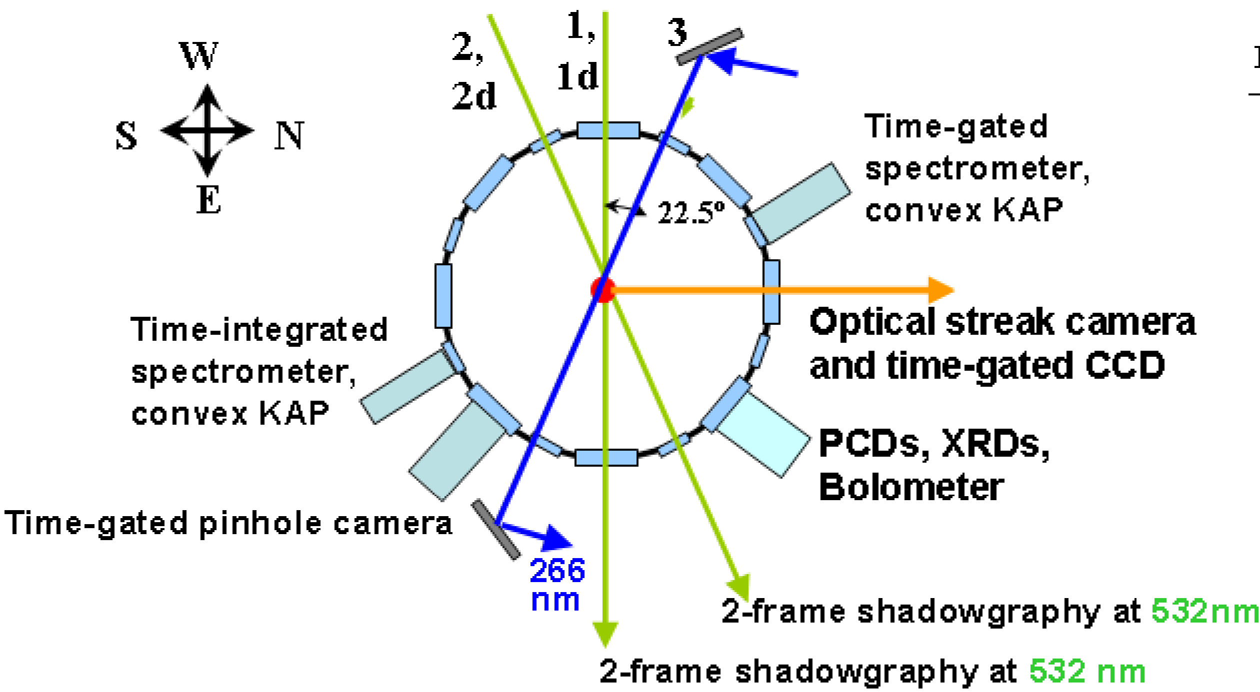
Load current 1 MA
1.7MA with a doubler
Current rise time 80 ns (10%-90%)
Impedance 1.9Ω

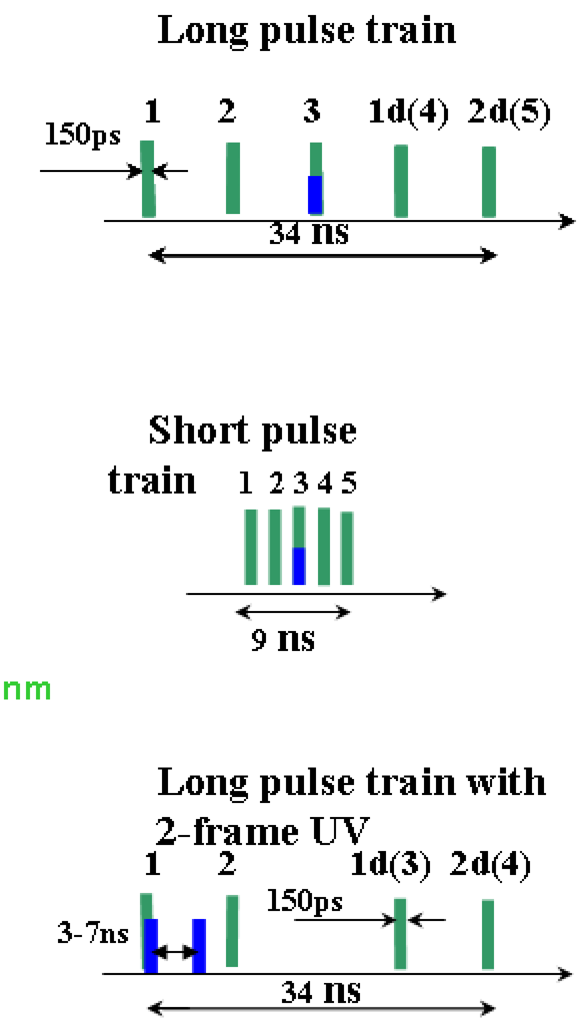






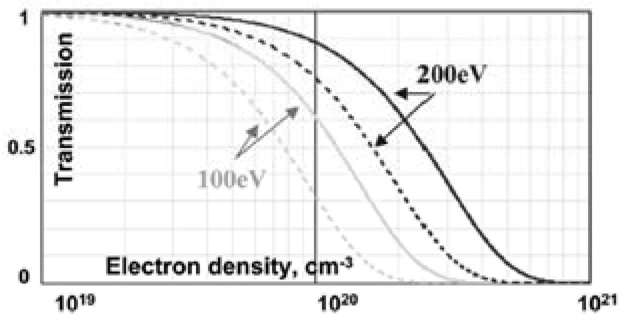
Diagnostics setup



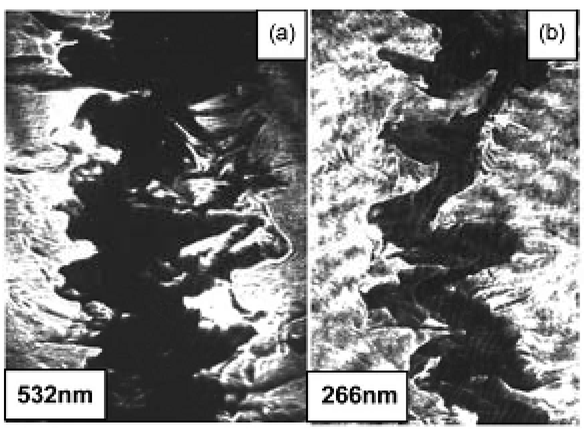


Shadowgraphy at 532nm and 266nm

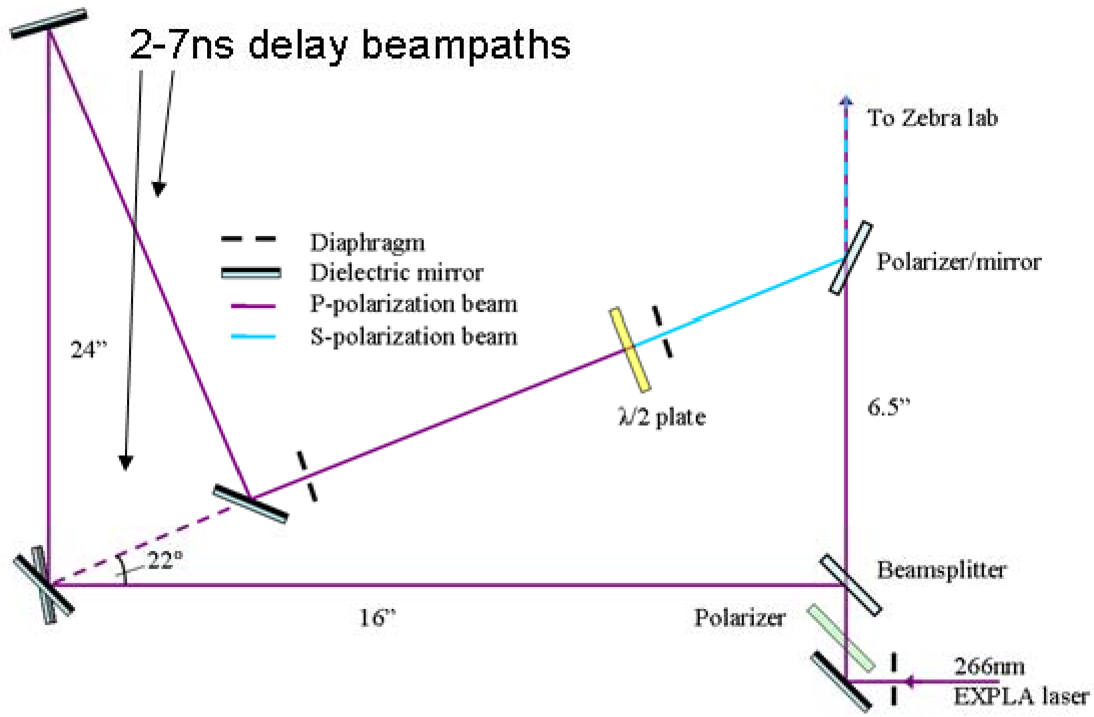
A delay channel was developed for 2-frame UV (266nm) shadowgraphy



*Transmission in a plasma, for 532nm (dashed) and 266nm (solid line) probing**



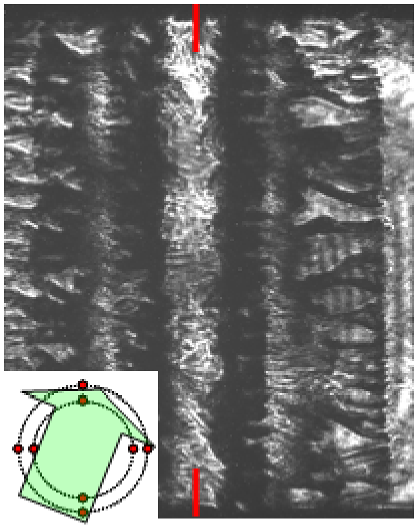
*Lower absorption of UV reveals details in denser plasma**



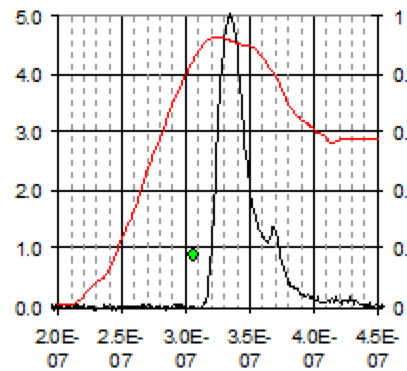
UV delay channel scheme

*:Ivanov, V.V. et al., IEEE Trans. Plas. Sci. **38**, 574 (2010)

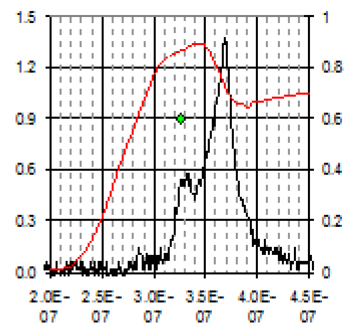
In low wire number closely spaced nested arrays, there is no plasma on axis until late implosion stage

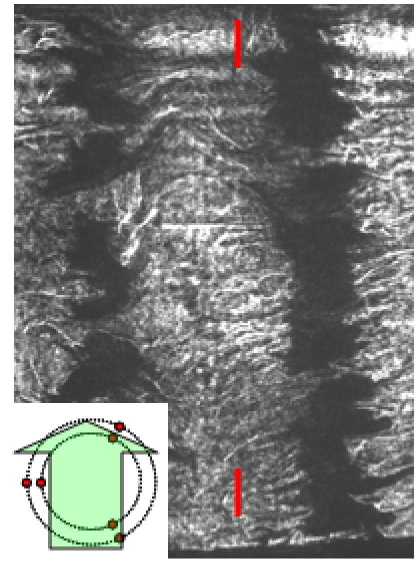


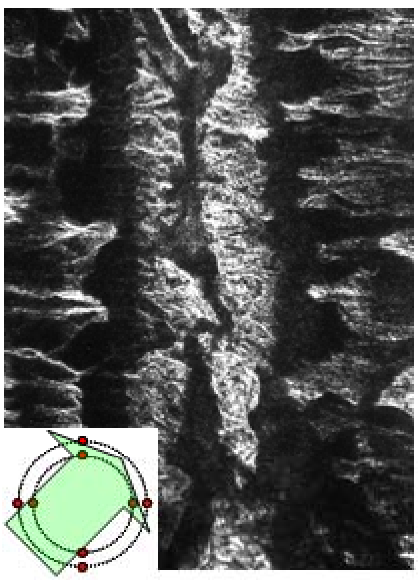
#978, 8x15um, 14/16mm load

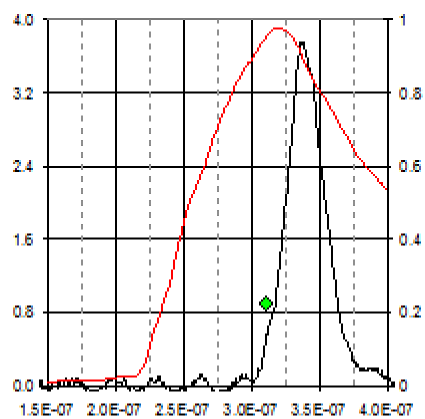


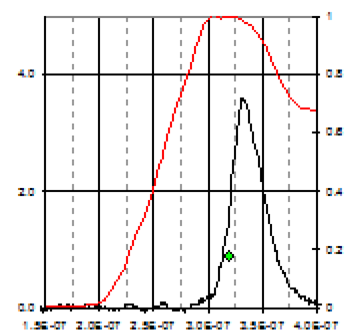
#1344, 6x15um, 14/16mm load



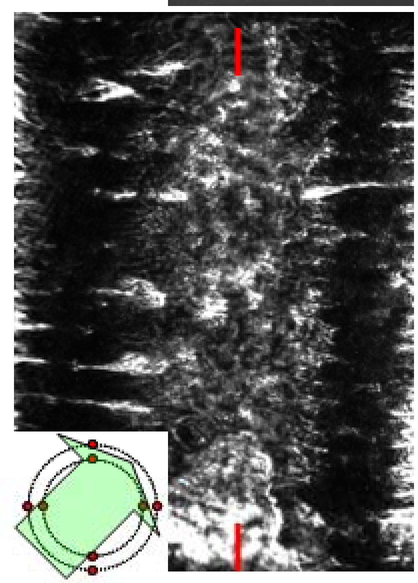








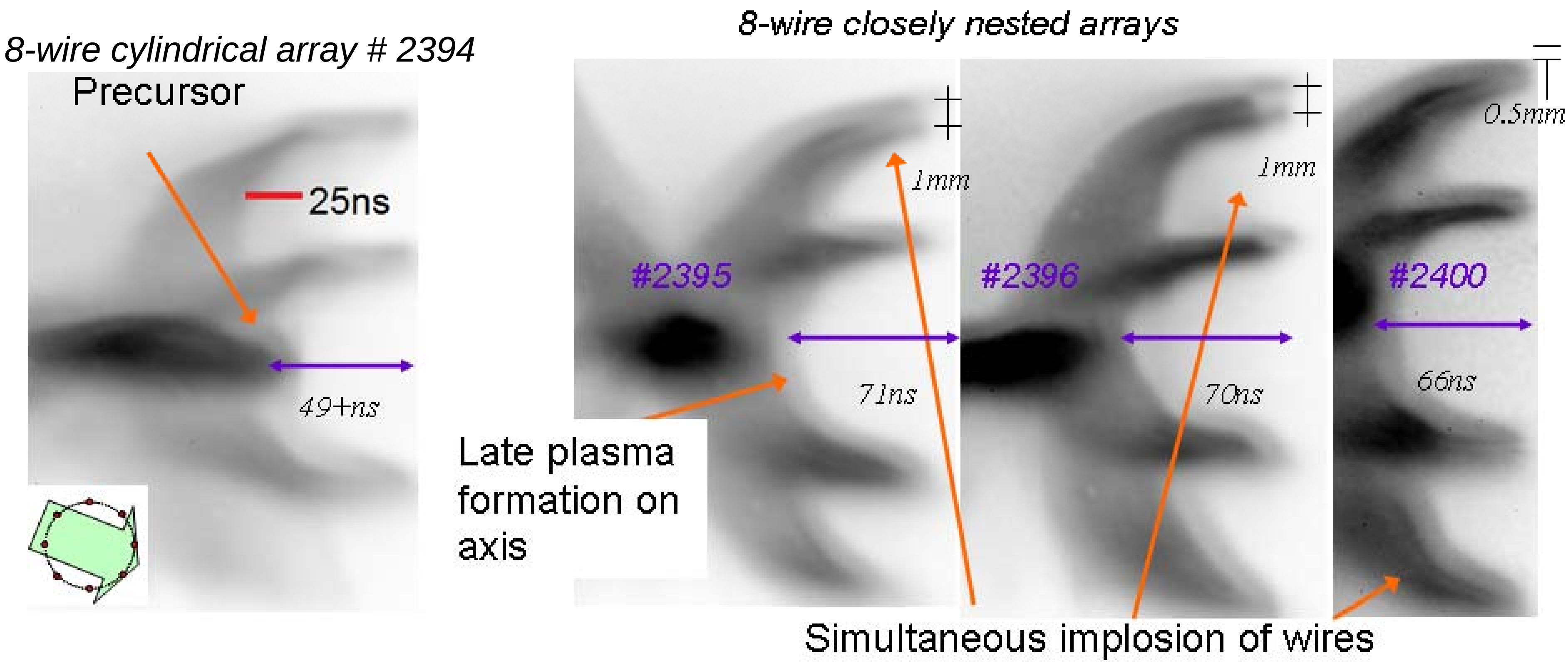
#2396, 8x17.8um 15/16mm load



#2400, 8x17.8um 14/16mm load at 130ns (left)

Plasma accumulates on axis just before implosion

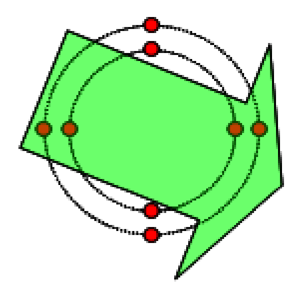
Streak camera shows this late plasma on the axis in 8-wire closely spaced arrays



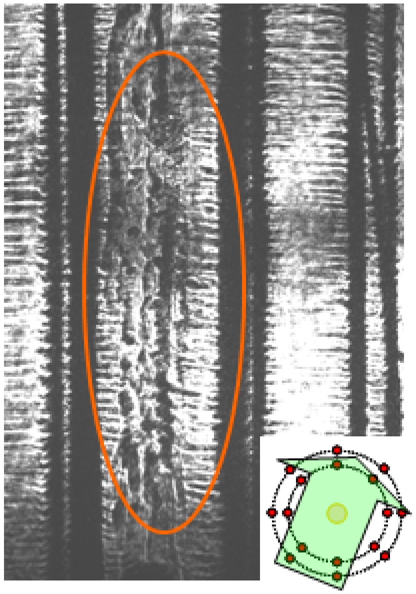
Plasma formation on axis is minimally ahead of the main pinch

Two-wire structure appears to be preserved during implosion

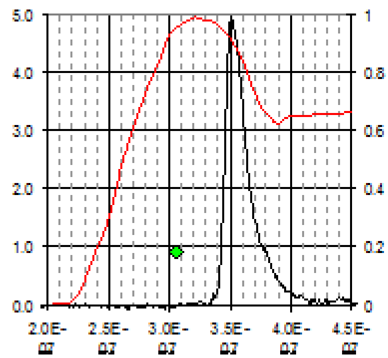
Inner wires do not move outward and merge early



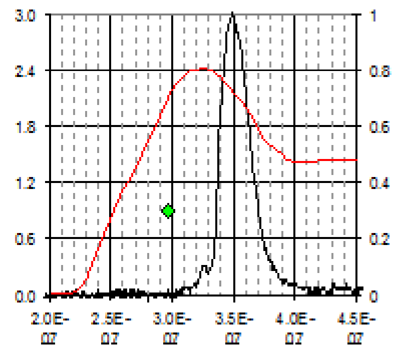
Precursor is found in 12-16 wire closely spaced nested arrays, despite dominating local B-fields

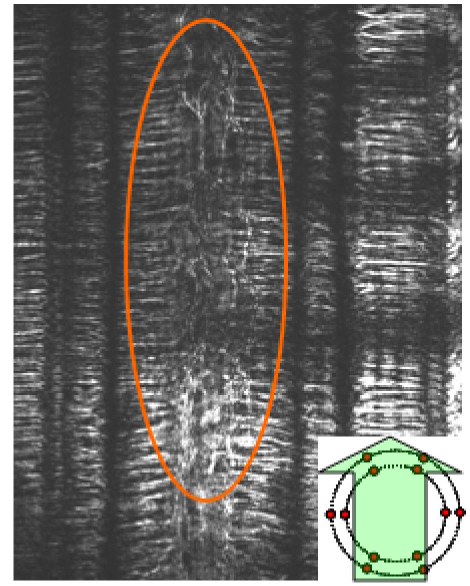


#966, 16x10μm,
14/16mm

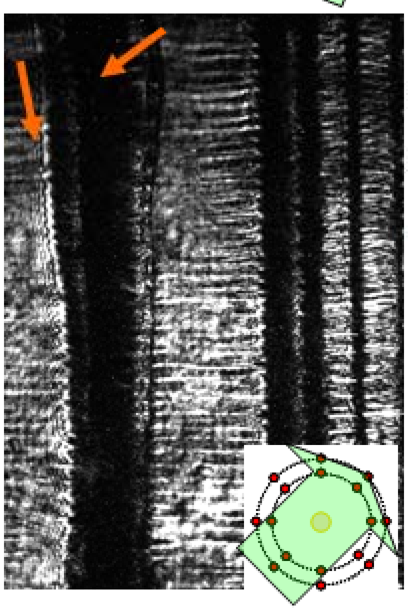


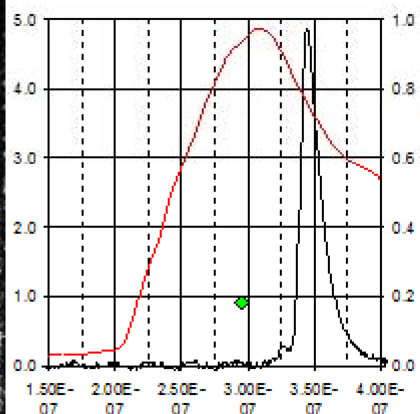
#1352, 12x10μm,
15/16mm



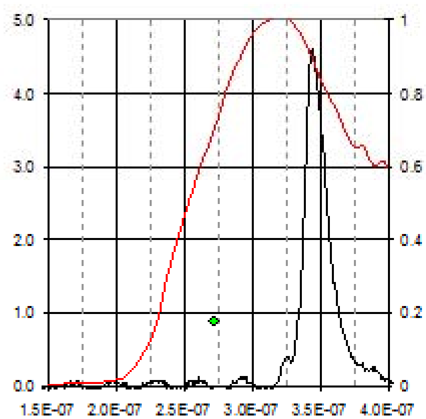


532nm probing cannot resolve ablation features of closely located wires

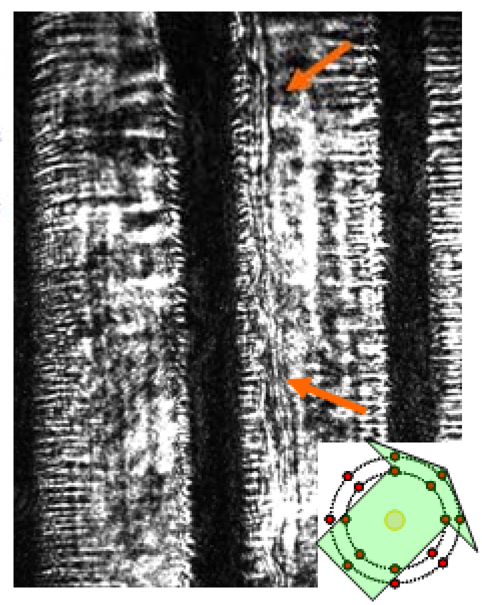




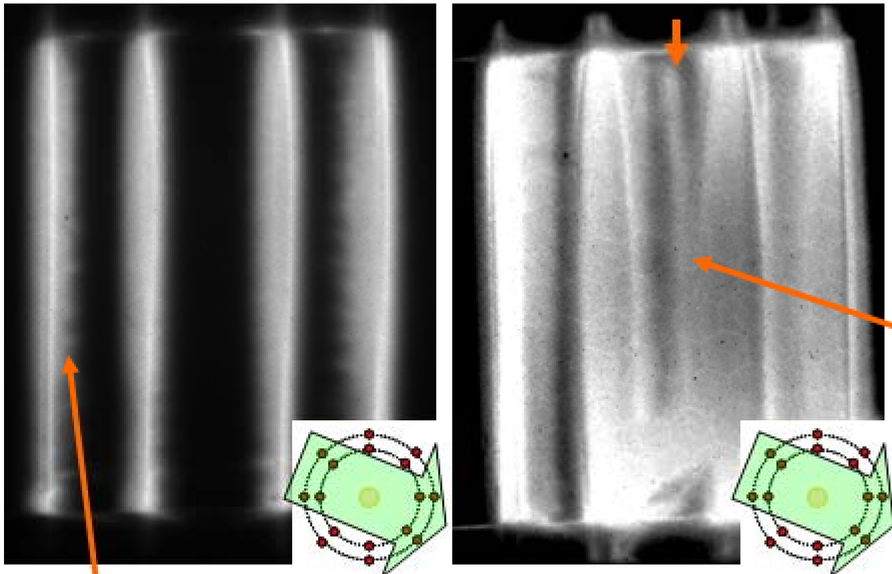
#2393, 16x12.7μm,
14/16mm



#2391, 16x12.7μm,
15/16mm



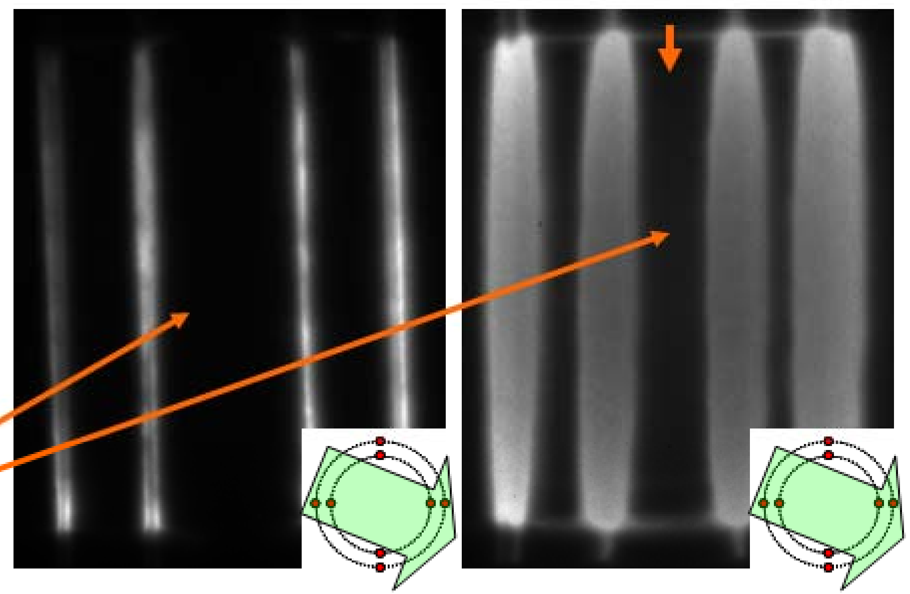
ICCD imaging shows precursor in 16-wire closely coupled arrays



16-wire 15/16mm loads in the early and late ablation stage, #2391 (left) and 2385 (right)

Precursor on axis

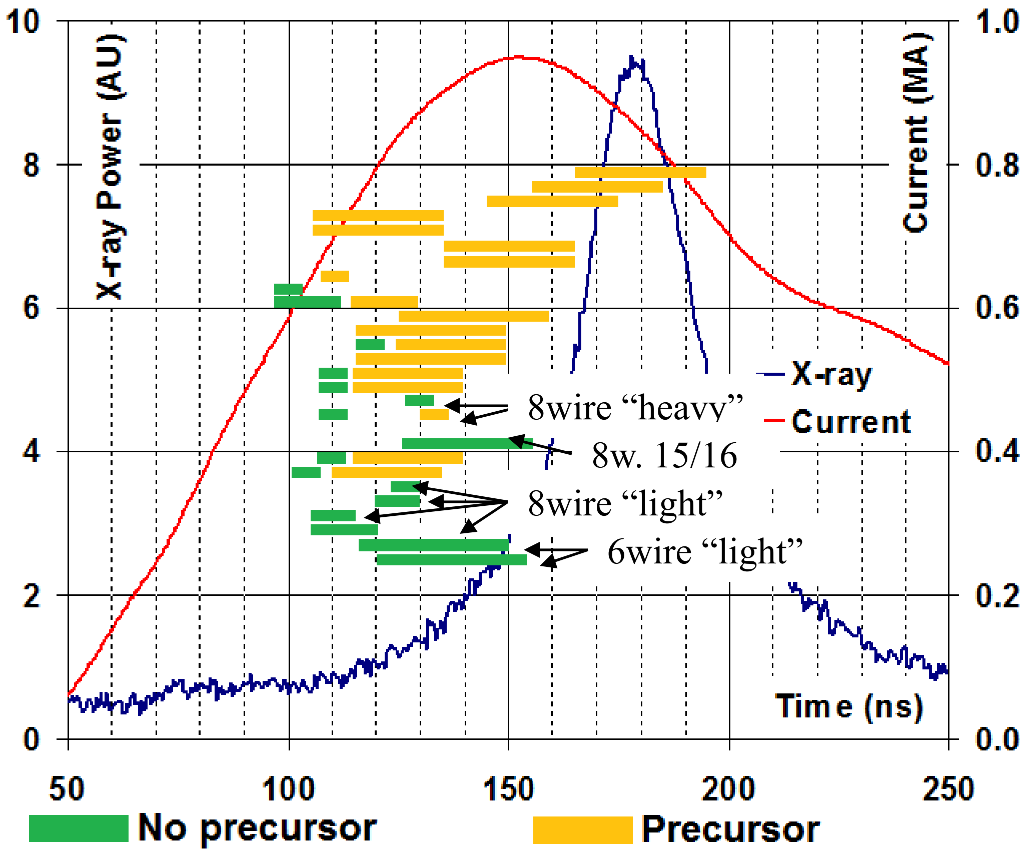
Inward ablation



8-wire loads during ablation stage, #2399 (15/16mm) and #2396 (14/16mm)

No precursor on axis

Presence of precursor depends on number of wires in the closely nested arrays



Presence of precursor on shadowgraphy frames. Current and soft X-ray pulse is the average for shots #2385-2400 (heavy loads)

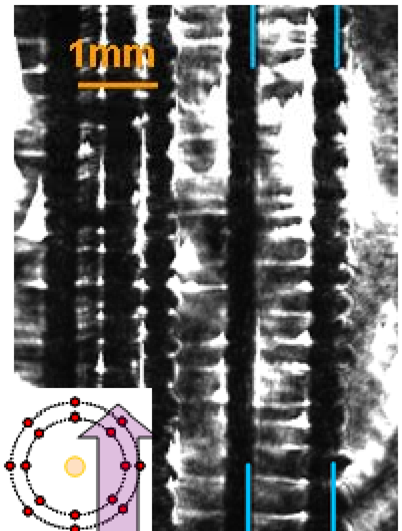
No discernible effect of wire spacing

Shadowgraphy shows precursor formation in 12 and 16-wire loads

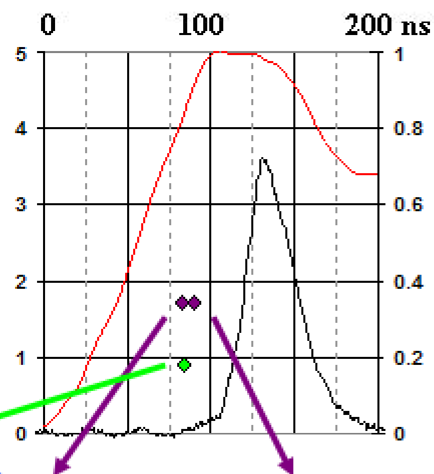
Only a single low wire-number load had plasma on axis before the wire mass imploded

Calculations has the highest outward forces on low wire-number arrays

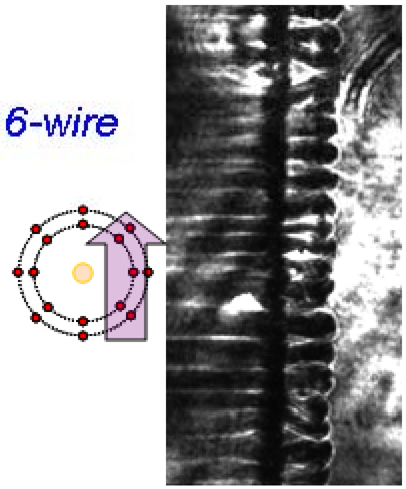
UV probing resolves details and makes the ablation process clear



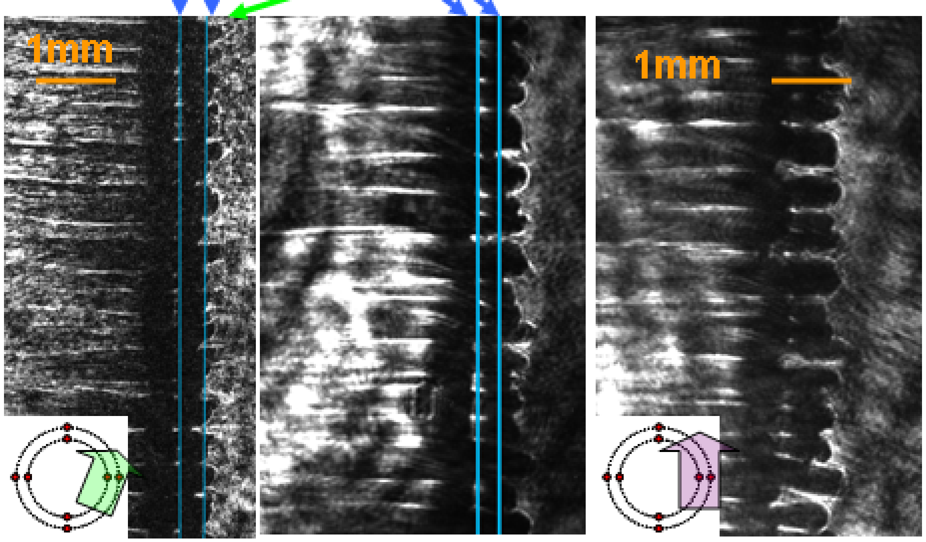
UV shadowgram of wire ablation, #2390, 16-wire 14/16mm



UV, #2392, 16-wire 15/16mm



Original wire positions



UV probing resolves the details in the wire plasma

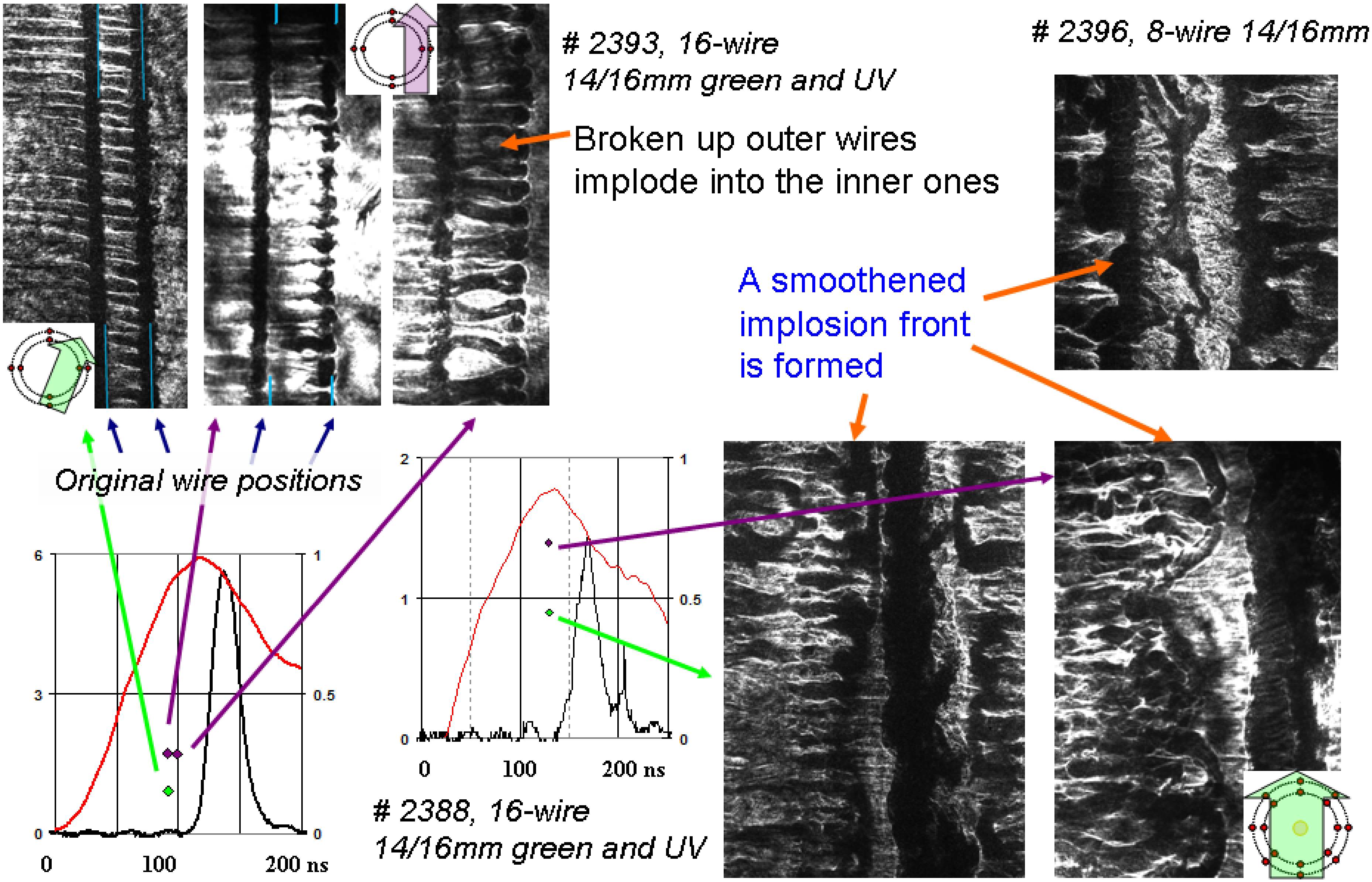
Outer wires break up while inner wires still ablate

Plasma from wires ablates to the center

No outward ablation or movement on inner wires

Green, UV and delayed UV shadowgrams, #2400, 8-wire 15/16mm

Cascading similar to star arrays are present



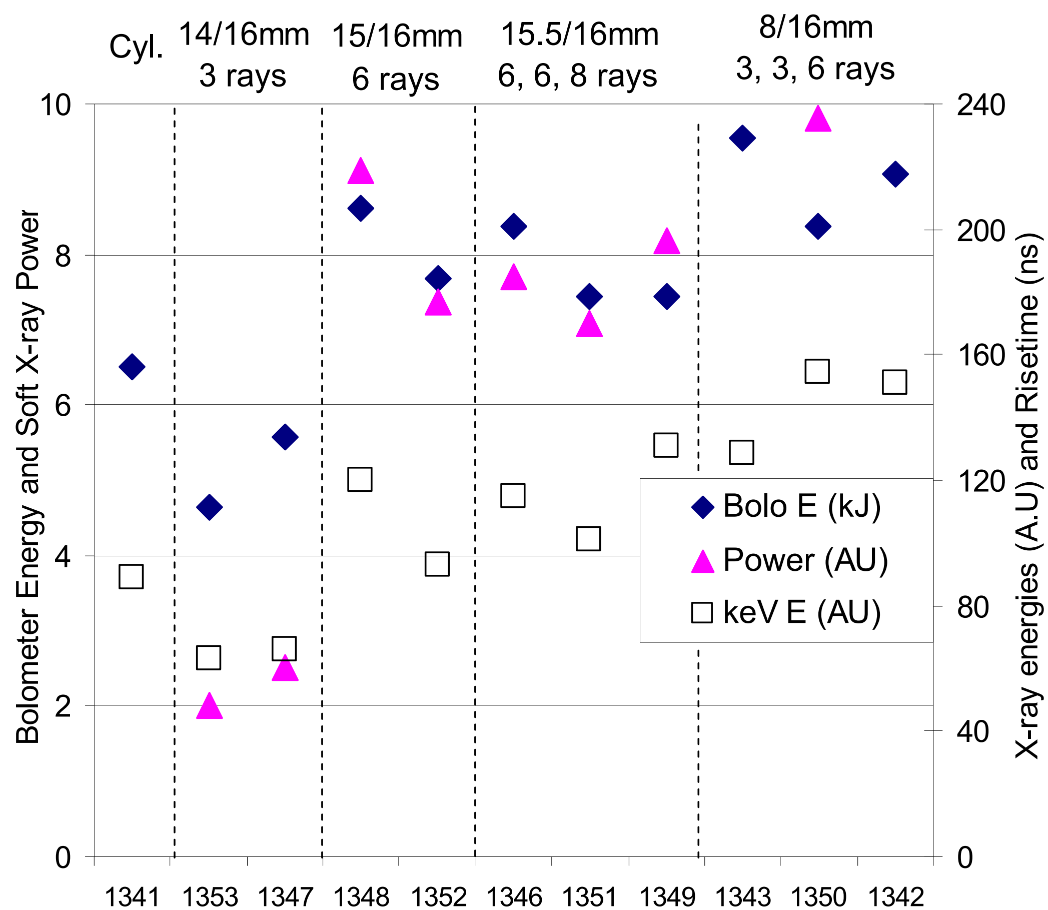
Quality of closely spaced loads is between cylindrical and regular nested arrays

6 and 3-ray arrays with large wire gap showed similar yields

3-ray (star) arrays with close wires preformed poorly

6 and 8-ray closely spaced loads with 0.25 and 0.5mm wire gap had similar yields

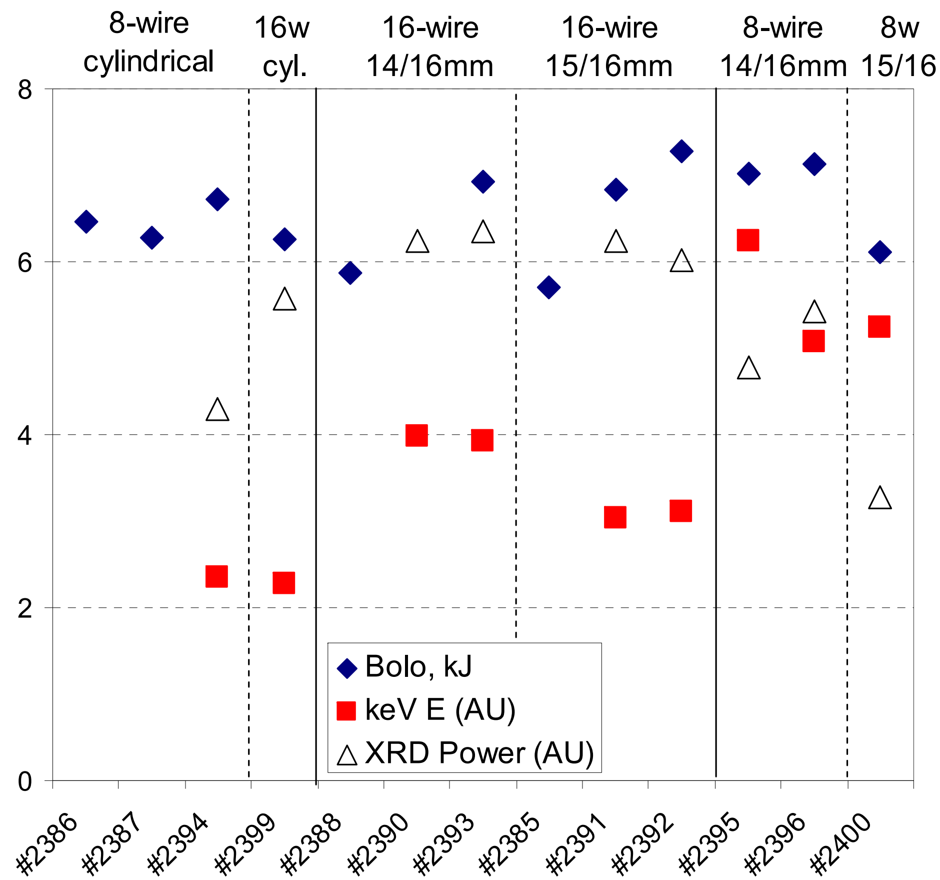
15% lower total energy and 30% lower hard X-ray energy than large-gap nested arrays



Hard X-ray yield is significantly improved in closely coupled nested vs. cylindrical arrays

16-wire closely spaced vs. cylindrical:
- Similar soft X-ray energies
- 50% max soft X-ray power
- 50% higher hard (keV) X-ray energy
- 3x higher rise rate

8-wire vs. 16-wire closely coupled:
- Similar soft X-ray energies but larger variance
- 30% less maximum power
- 50% higher hard X-ray energy
- 6-wire loads showed opposite result



The improvement in implosion quality can be credited to cascading - the smooth plasma front mitigates instabilities

There is a precursor in the 16-wire loads – no definite conclusion on the stabilization effect

There are two effects in cylindrical arrays with closely spaced wires

In cylindrical arrays, high number of wires improve implosion quality

There is an optimal inter-wire gap for keV X-ray yield, 0.7-2.2mm in case of Al wires

If the wires are closer than ~0.7mm, the implosion quality drops

Al arrays with 0.78mm inter-wire gap closely followed the 0D implosion trajectories

At the closest distances, the inter-wire gap is in the order of wire core diameter (0.25mm for Al)

Within these distances local magnetic field dominates

Sanford, T.W.L., PRL **77,** 5063 (1996)

Coverdale, C.A., PRL **88**, 065001-3 (2002)

Lebedev, S.V., PRL **85,** 98 (2000)

Summary and conclusions

Implosion of closely spaced nested arrays was studied

Low wire number arrays imploded without precursor

The keV X-ray yield of closely coupled nested arrays was between the yield of cylindrical and regular nested arrays

Two-frame 266nm shadowgraphy channel resolved ablation details

No outward ablation or plasma flow - predicted by calculations – was seen

More complex physical models are necessary to describe the ablation of closely spaced nested arrays

Work was supported by the DOE/NNSA under UNR grant DE-FC52-06NA27616. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.