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Investigation of plasma dynamics in cylindrical, nested, and linear wire arrays in the 1-MA Zebra generator

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Abstract

Dynamics of the ablation and implosion stages in cylindrical, nested, and linear wire arrays were investigated in the 1-MA Zebra generator. Plasma bubbles arise in breaks on the wires in the beginning of implosion. The leading edges of the bubbles carry material with the speed >250 km/s. In linear wire arrays plasma cascades to the center of the array from wire to wire. In nested arrays, the implosion begins in the external cylinder. The plasma bubbles then hit the plasma columns in the internal cylinder and collapse to the center. The regimes of ablation and implosion in the wire arrays with different mutual magnetic fields are compared. Two-step implosions were observed in double nested arrays. Implosion begins on the outer array. Next, the imploding plasma hits the inner circle and collapses to the center of the array. Rescaling of perturbation was observed in linear and nested arrays. Triple wire arrays demonstrate shortening of the generated x-ray pulse, increase of power, and smoothing of plasma instabilities.

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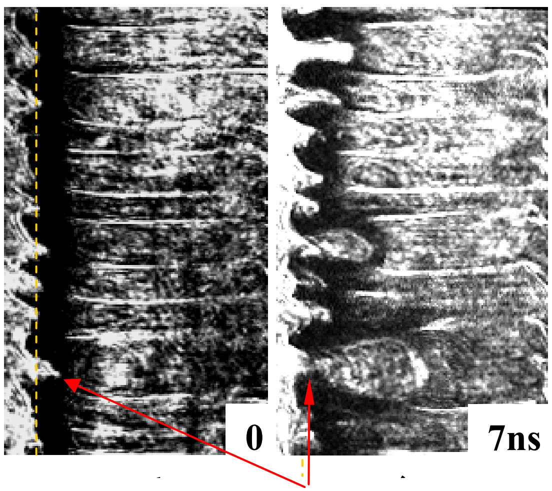
Implosion bubbles indicate breaks in wires and present mass transport in cylindrical wire arrays

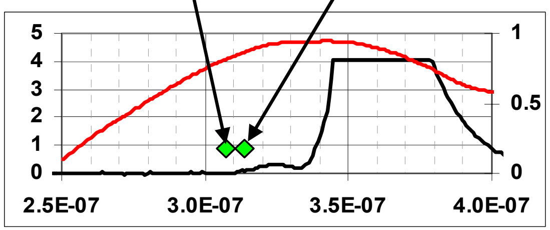
#511

Axis



1 mm

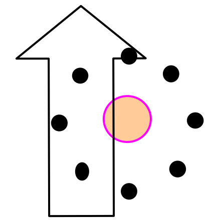
Bubbles are blown when the wire core is broken



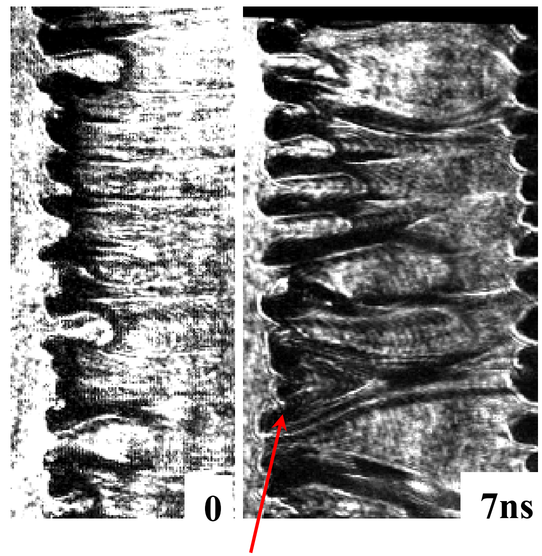
Bubbles arise at 20-25ns before the x-ray pulse

Al 8 x 15 µm wire arrays

Bubbles are blown in different time



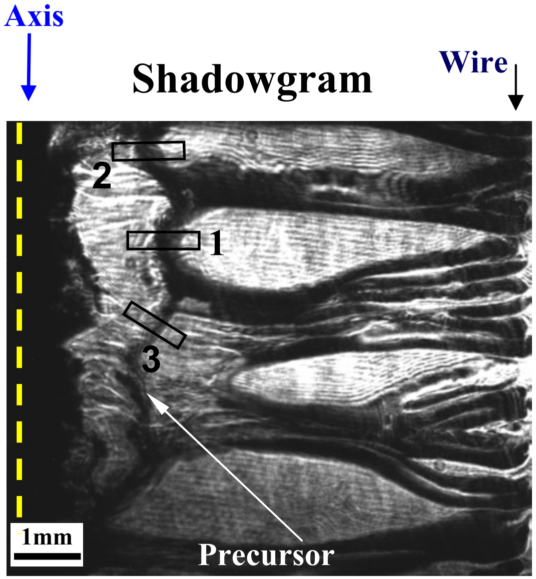
#514

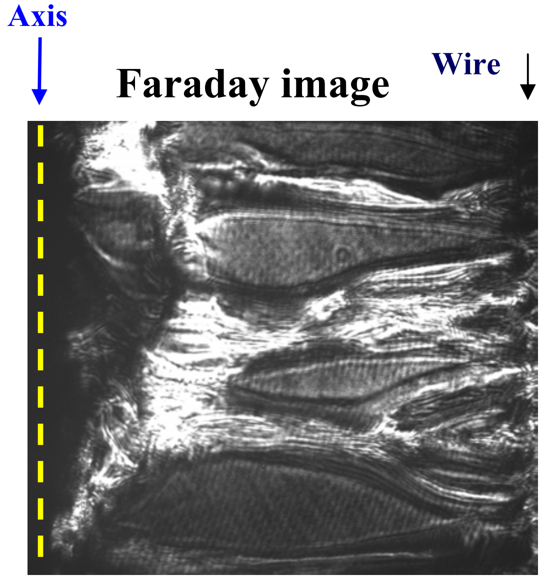


Typical after bubble "fingers" on the edge of the wire array

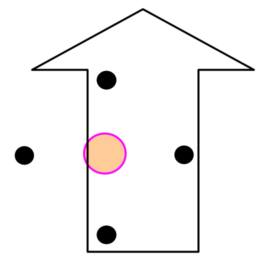
V. Ivanov et al., "Dynamics of mass transport and magnetic fields in low wire number array z-pinches", Phys. Rev. Lett. 97, 125001 (2006)

Plasma bubbles hit and sweep the precursor

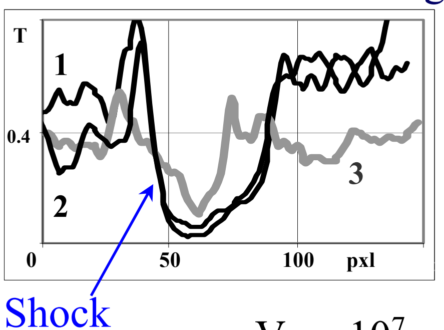




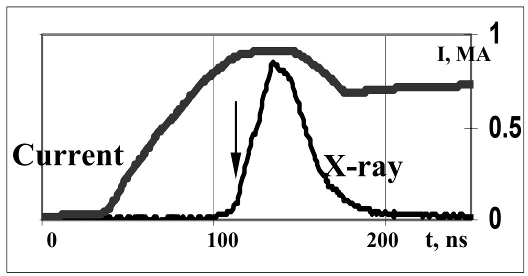
Al 4 x 20 μm wire array



Outlines from the rectangles 1-3



Timing



#541

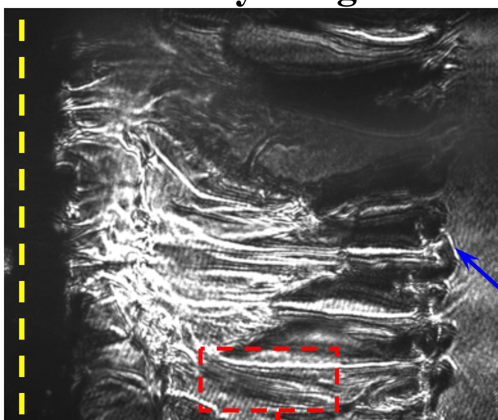
$V_A \sim 10^7$ cm/s if $N_e = 10^{19} cm^{-3}$, B =0.3MG

Bubbles with $V_{buble} \geq 3 \cdot 10^7$ cm/s produces shock in the precursor

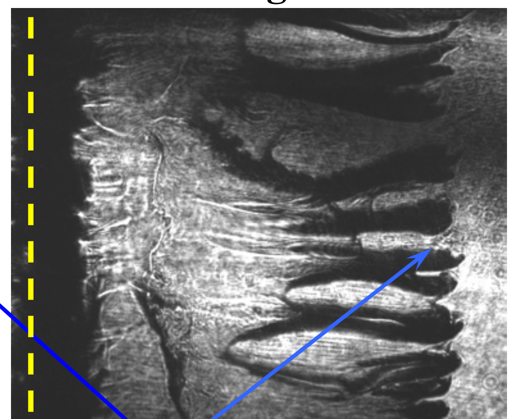
Current switch back to the initial position of the wire

Al 4 x 20 µm wire arrays

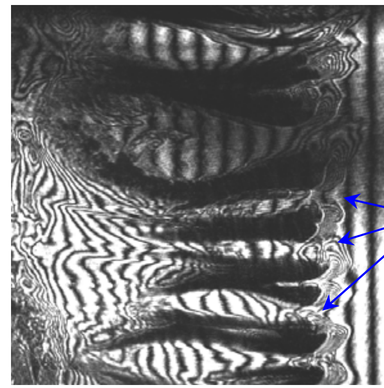
Faraday image



Shadowgram

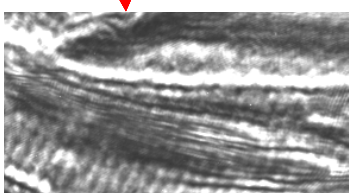


Interferometry

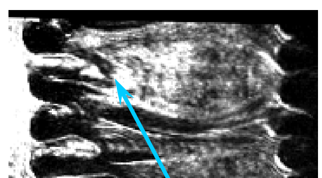


$N_e \sim 10^{19}\ cm^{-3}$

Faraday effect in breaks on the wire.
α=2°, **I > 0.1 MA**

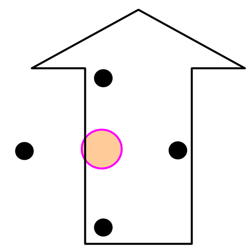


Filamentary structure of current



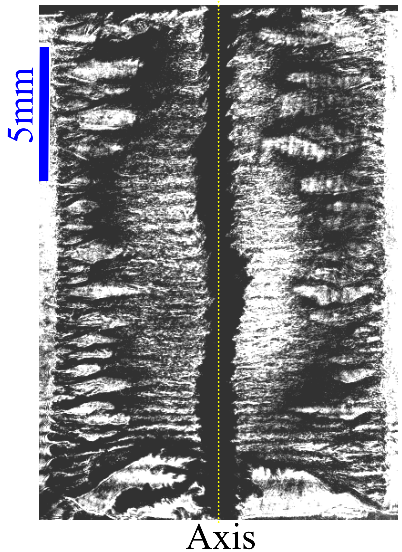
#514

Secondary bubble

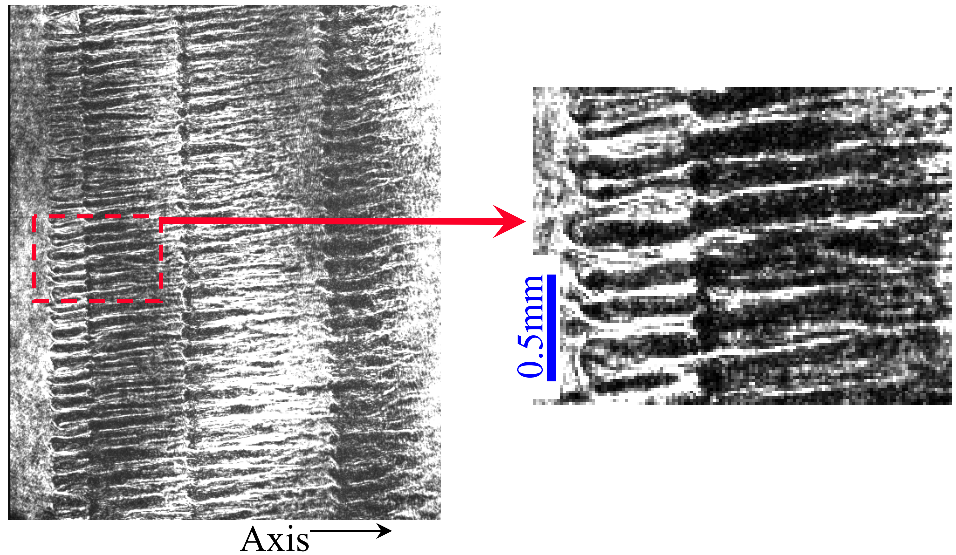


Bubbles are smaller and more regular in multi-wire arrays

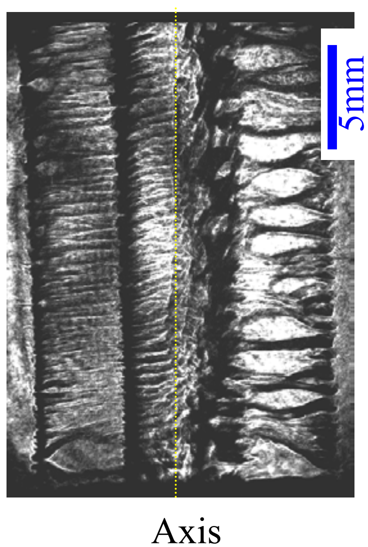
#653. **W** 4x**12** μm



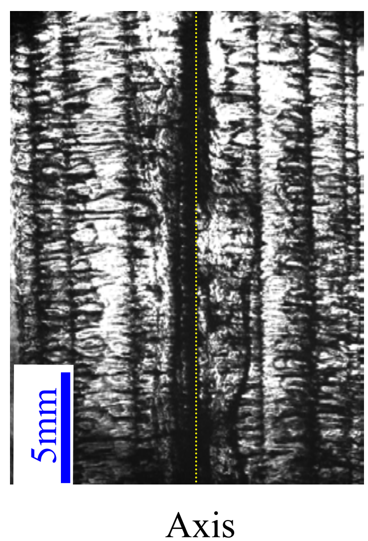
#687. **W** 16x**4.3** μm



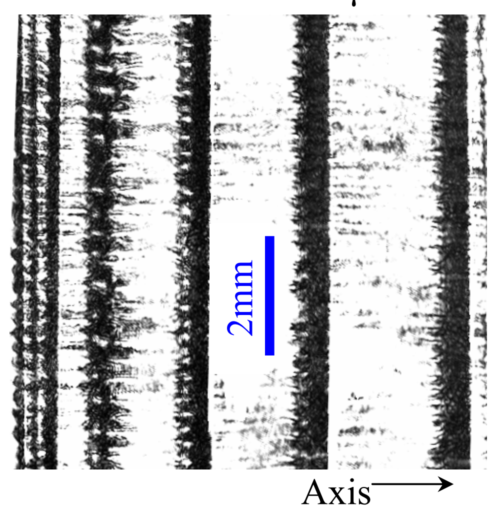
#541. **Al** 4x**20** μm



#506. **Al** 16x**10** μm

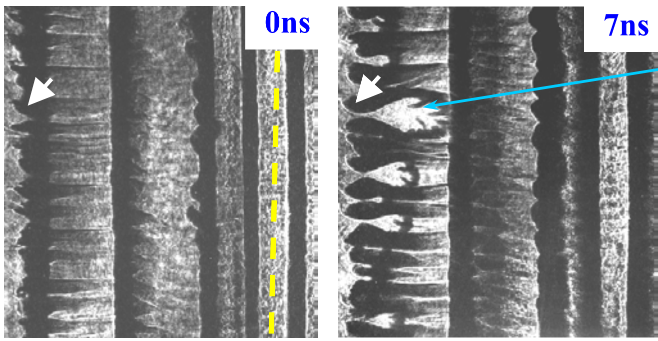


#663. **Al** 24x**10** μm



Implosion Dynamics in Linear Wire Arrays

#650. **Al 8x18μm** Two-frame shadowgram

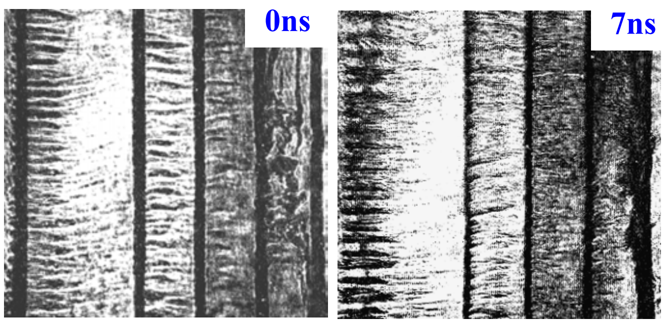


Flares in bubbles

2211122

$V > 2.7 \cdot 10^7$ cm/s

Two-frame shadowgram W 10x5μm



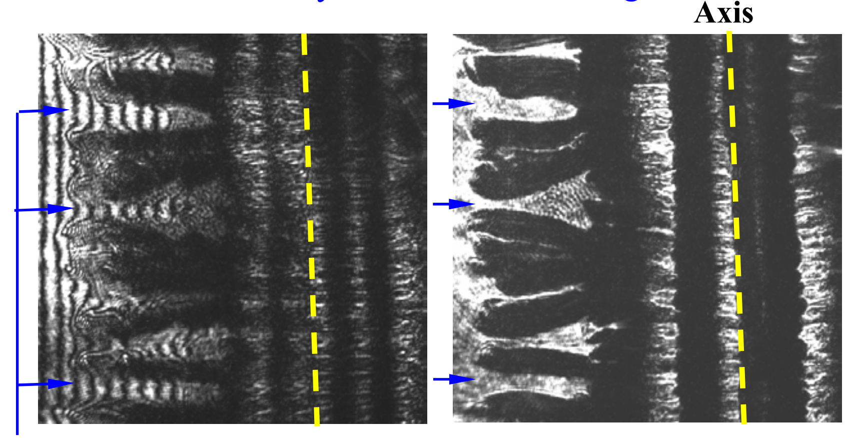
Shot 683

2111112

Dense plasma is absent in wire breaks

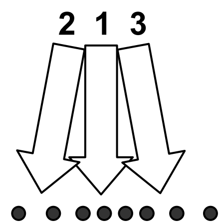
Al 6x20 μm (22322)

Interferometry Shadowgram



$N_e < 4 \cdot 10^{18}$ cm^{-3}

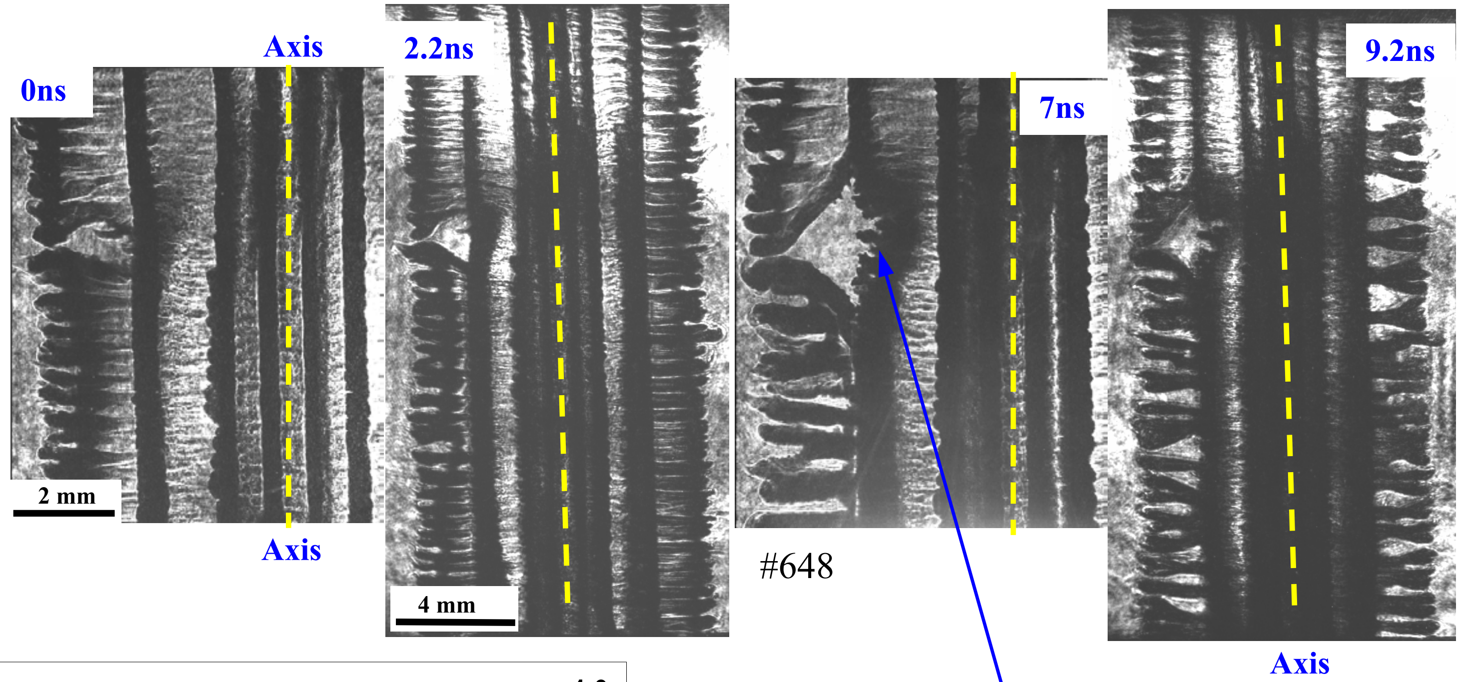
#665

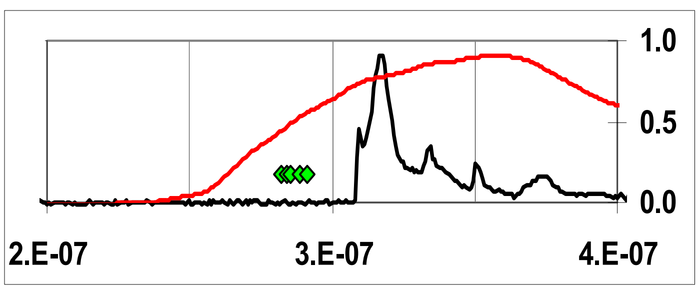


* - see also V.V. Kantsyrev et al., IEEE Trans. Plasma Sci., 34, 2295 (2006)

Cascade Implosion in Linear Wire Arrays

Four-frame shadowgram of implosion in Al 8x18 µm linear load (2211122)



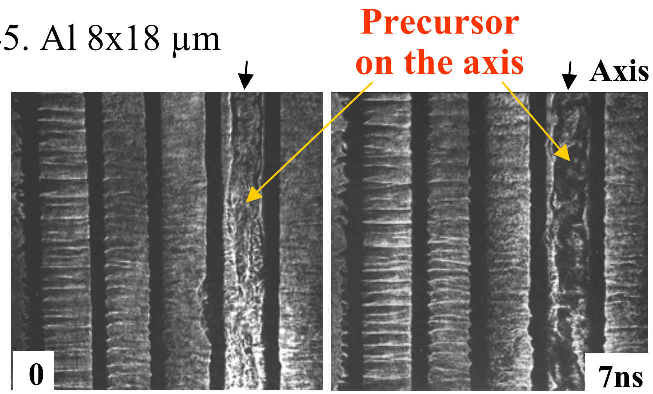


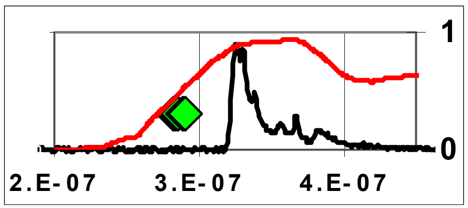
Magnetic Rayleigh-Taylor Instability

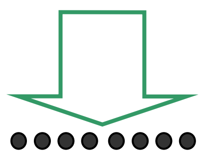
Ablating plasma does not move to the axis of the linear array with an enlarged central gap

Equidistant linear arrays

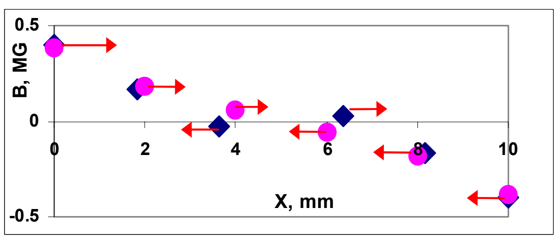
#645. Al 8x18 μm







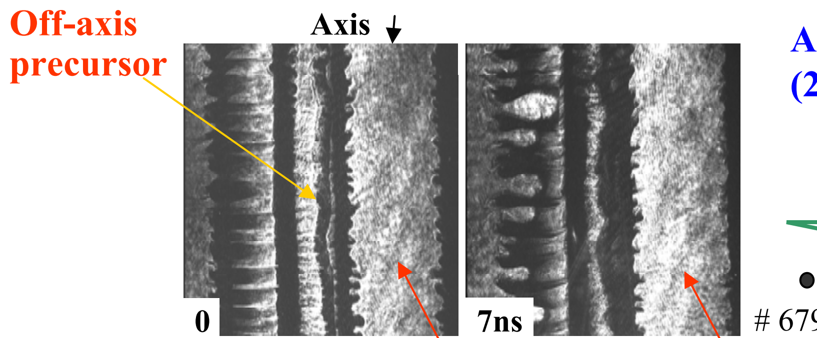
Mutual **jxB** force in linear 6-wire arrays



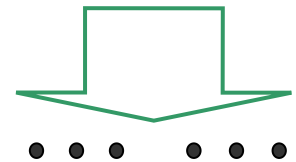
● Mutual magnetic field in the equidistant linear wire array

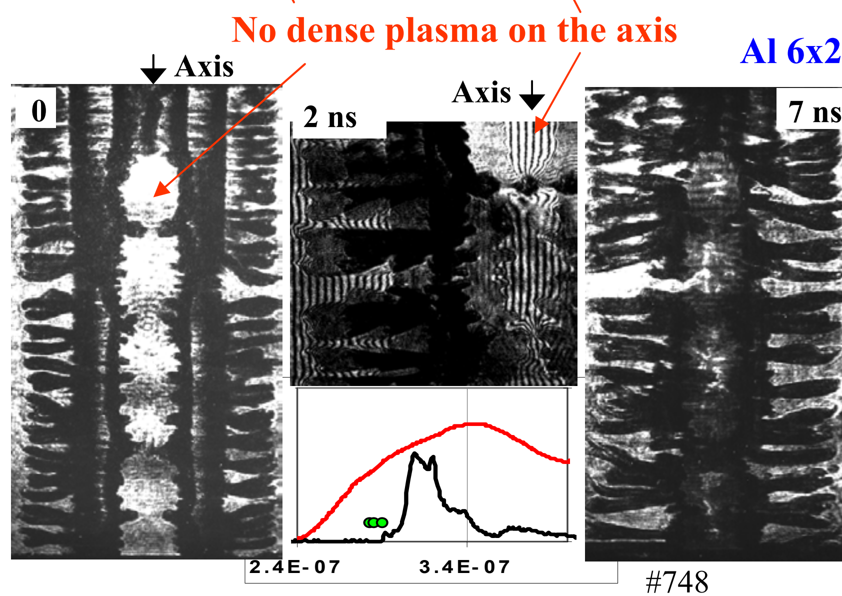
◆ In the array with the enlarged central gap

The central gap is enlarged



Al 6x20 μm (22322)



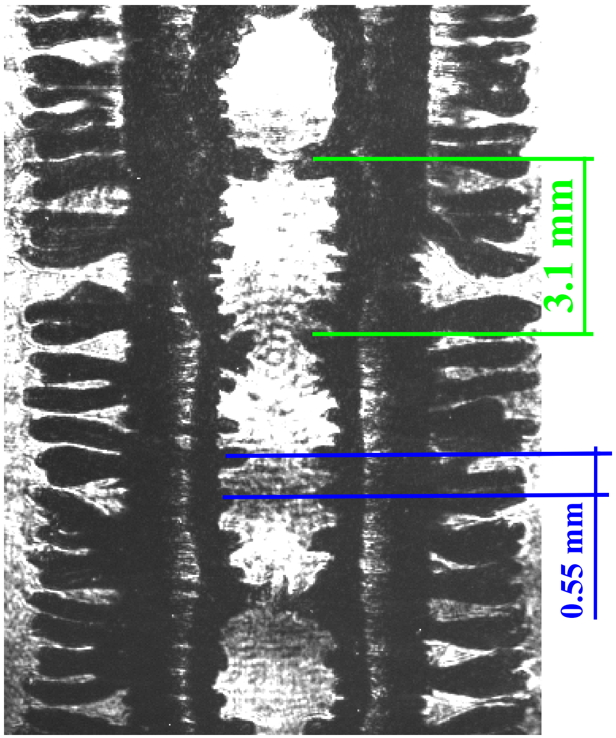


Al 6x20 μm

A **jxB** force confines plasma. Ablating plasma does not penetrate to the center.

Instabilities in Linear Arrays

Magnetic Rayleigh-Taylor Instability



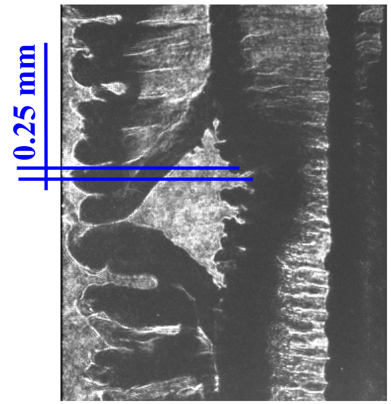
$$\lambda_{MRTI} \approx 2\pi \frac{Kc}{\omega_{pi}}, \quad \text{K=10-20*}$$

$$\omega_{pi} = \sqrt{\frac{4\pi \cdot n_i e^2 Z^2}{m_i}}$$

For Al plasma column Ø 0.5 mm:
$n_i \sim 1 \cdot 10^{20}$ cm^{-3}, Z~1-2

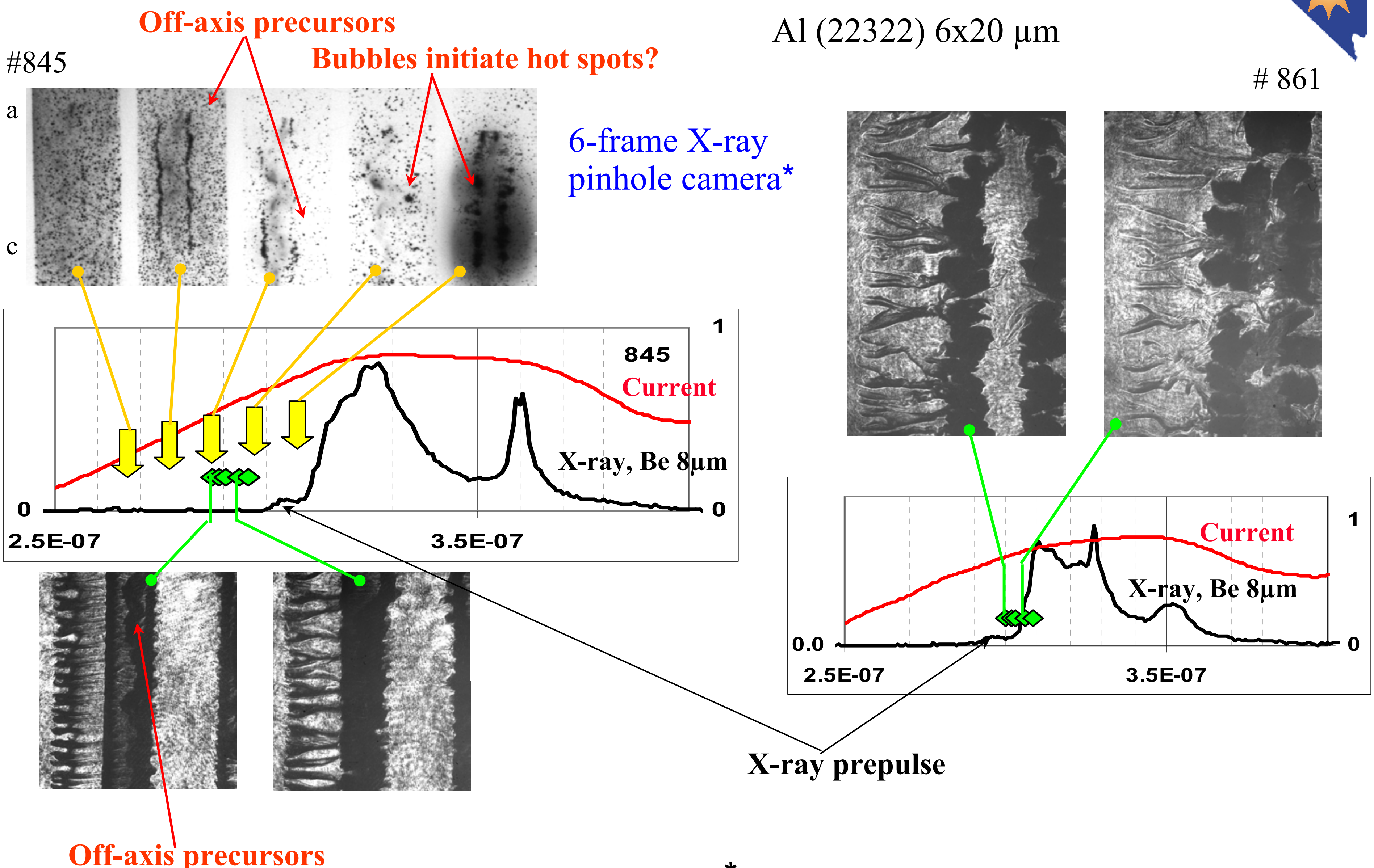
$\omega_{pi}=(2.5\text{-}5)\cdot 10^{12}$, λ_{MRTI} = 0.18-0.75 mm

Change of the instability scale



* - V.I. Sotnikov *et al.*, Phys. Plasmas 9, 913 (2002)

Implosion of the Array with the Enlarged Central Gap



* - X-ray core diagnostics developed by V. Kantsyrev

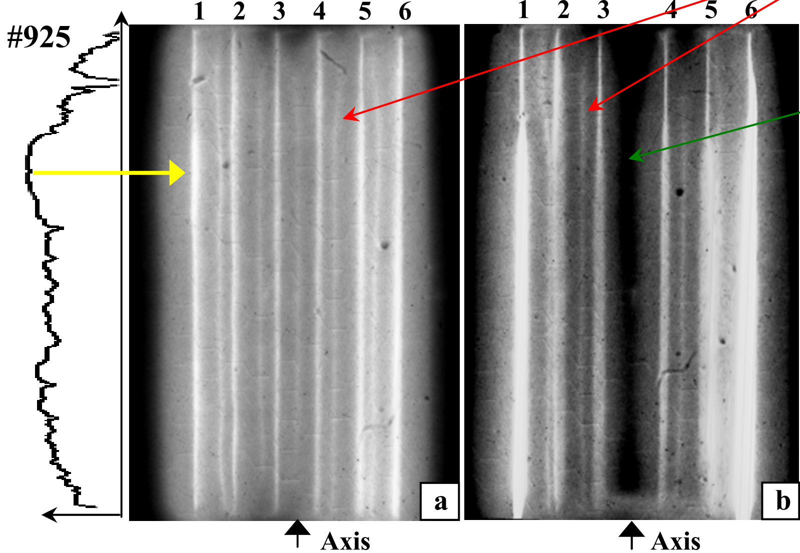
The intensified CCD shows formation of plasma on the early stage

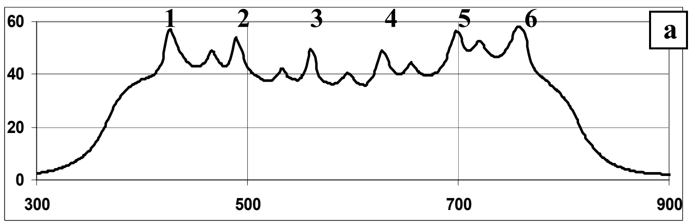
UNIVERSITY OF NEVADA •Reno

Optical images of linear arrays

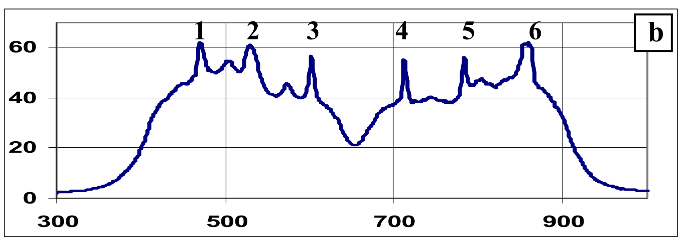
Off-axis precursors

No plasma on the axis





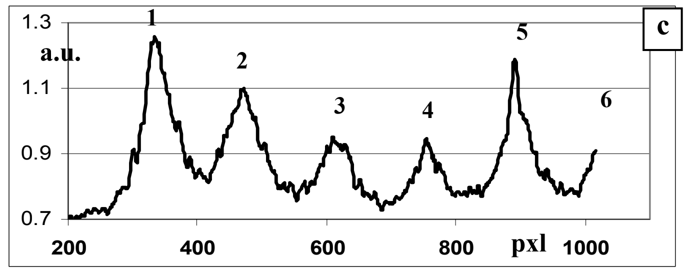
#925, equidistant linear Al 6x20 µm, +20ns

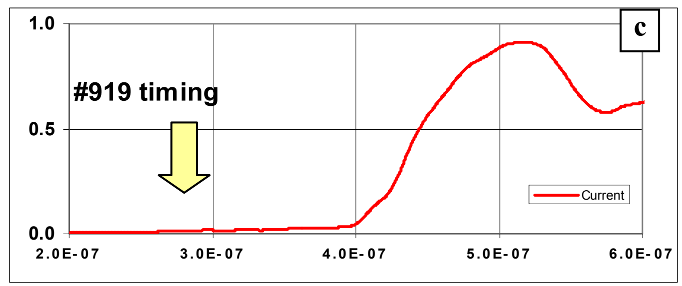


#922, Linear 22322, Al 6x20 µm, +10ns

Plasma arise on the current prepulse

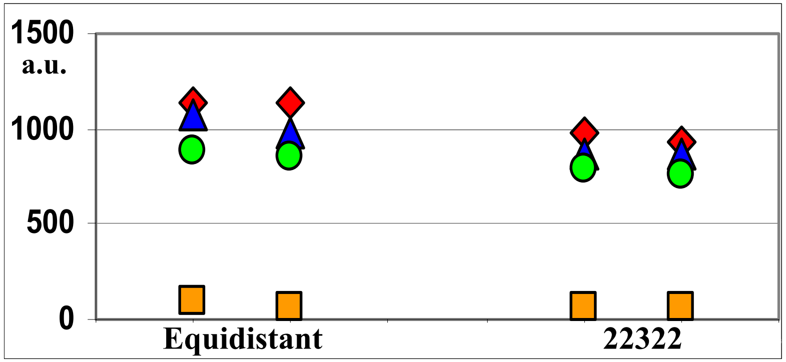
#919, equidistant Al 6x20um, –80ns.





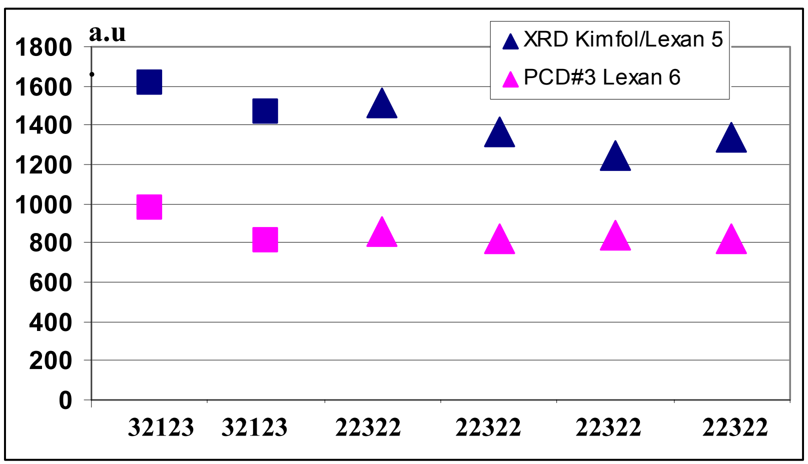
X-ray yield is smaller in arrays with the enlarged central gap

Arbitrary X-ray yields was integrated from PCDs and the XRD in one series of shot:

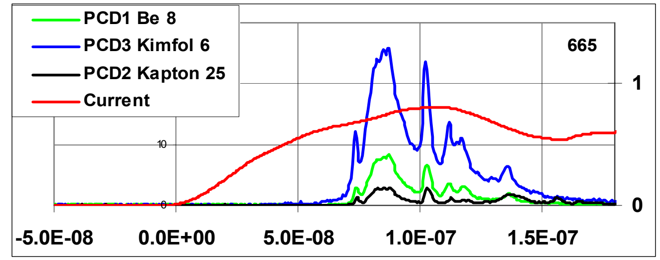


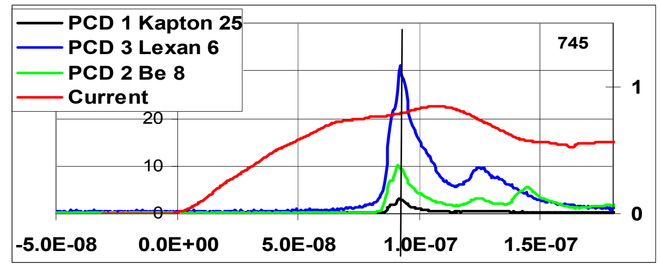
◆ – XRD, 6-µm kimfol; ▲ – PCD, 8-µm Be;

● – PCD, 6-µm kimfol; ■ – PCD, 25-µm kapton.

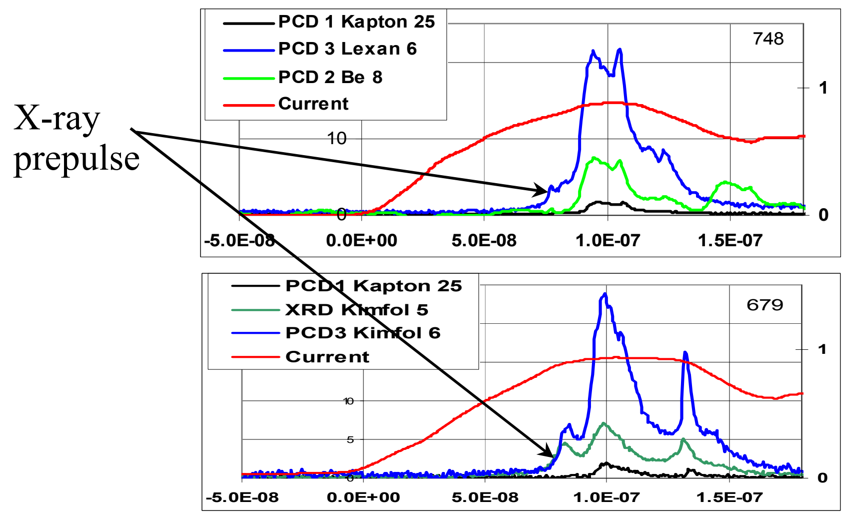


Equidistant linear arrays, Al 6x18µm



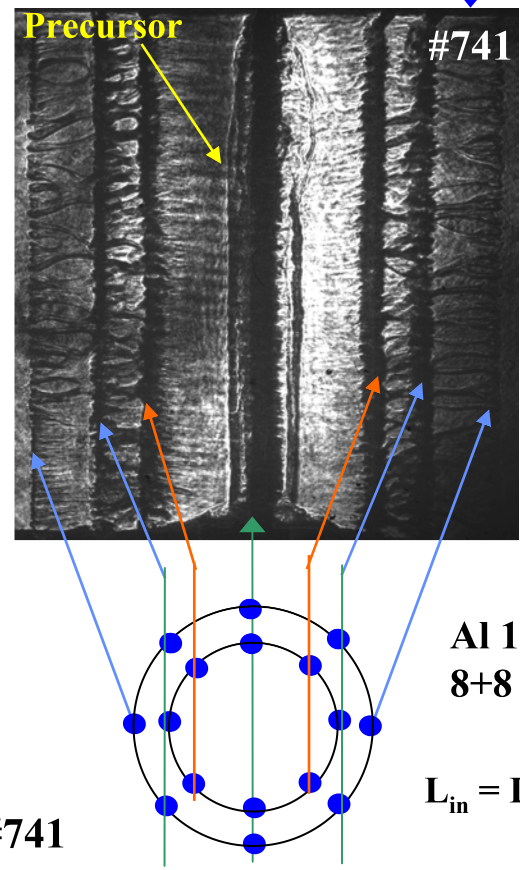


The central gap is enlarged (22322), Al 6x18µm



Nested Wire Array Experiments in the Zebra Generator

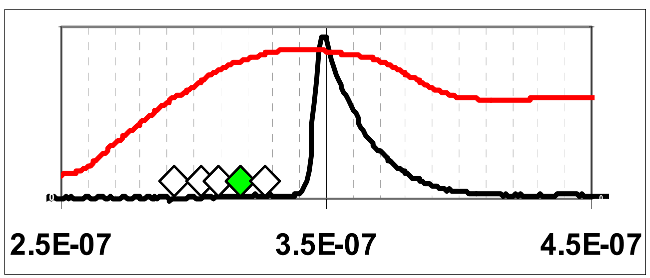
1. Implosion begins on the external cylinder. Bubbles hit wires of the internal cylinder (the current transfer mode*)



Al 16/12mm, 8+8 x 10μm

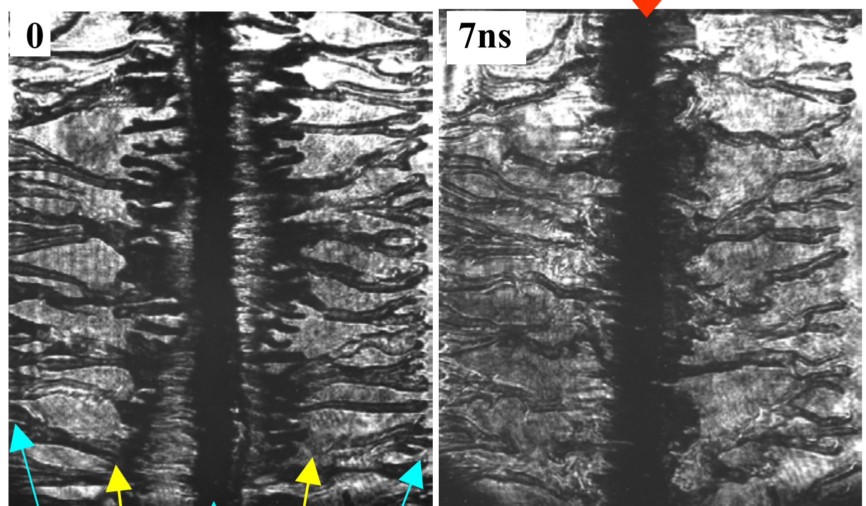
$L_{in} = L_{out} = 2$ cm

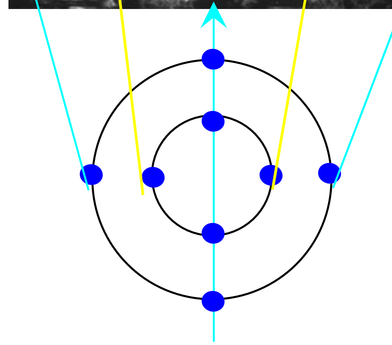
#741



2. Implosion begins on the internal cylinder

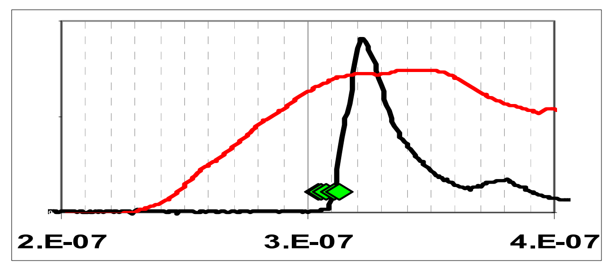
3. The internal cylinder collapse





#746

Al 16/8mm
4+4 x12μm



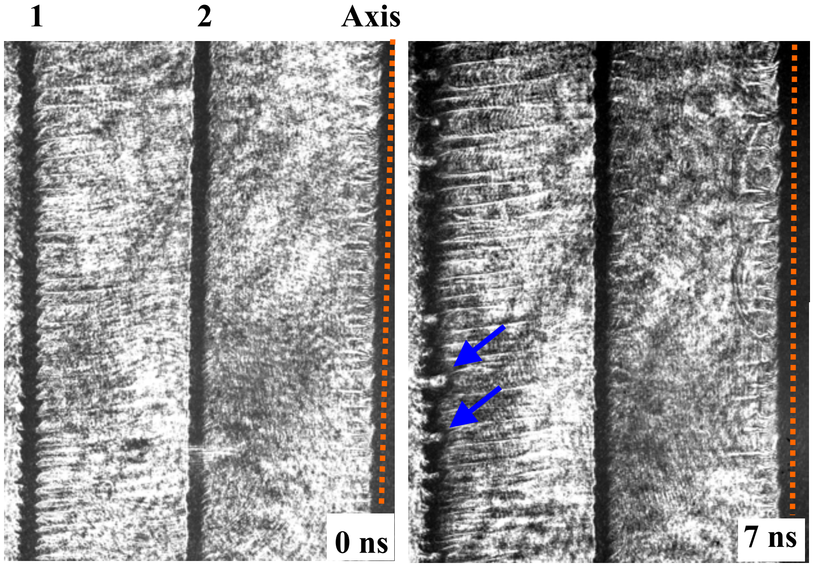
* - S.V. Lebedev et al., PRL 84, (2000).

S.N. Bland *et al.,* Phys. Plasmas 10, 1100 (2003)

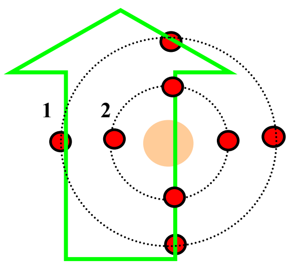
Cascade Implosion in Nested Wire Arrays

Two frames of shadowgraphy

#842



Al 4+4 x 12μm, Ø16/8mm

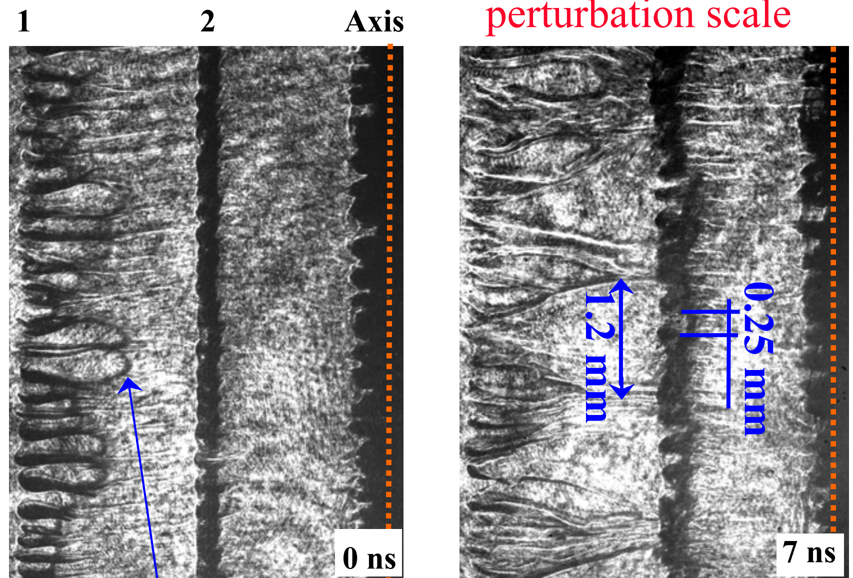


$L_{in} = L_{out} = 2$ cm

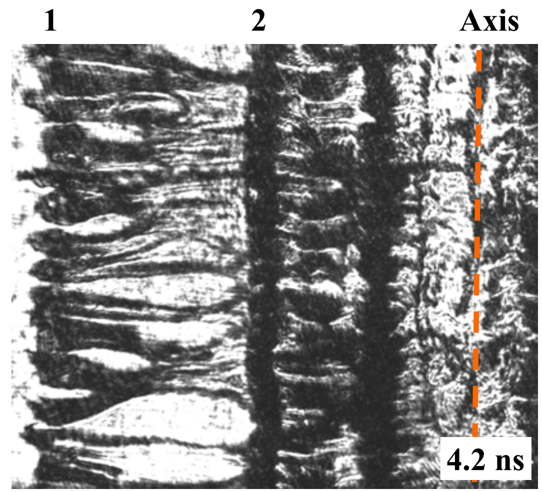
Three frames of shadowgraphy

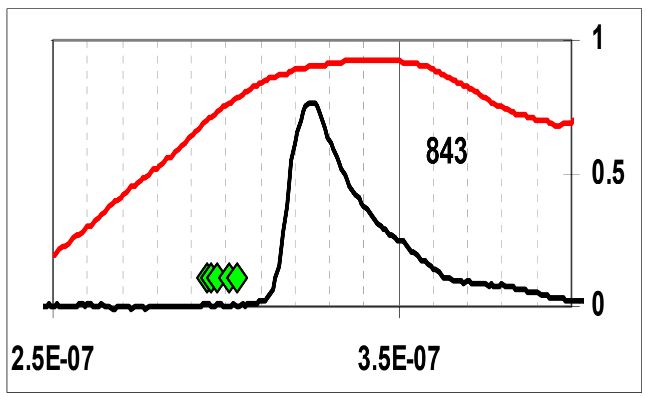
#843 Al 4+4 x12μm

Change of plasma perturbation scale



$V = 4.5 \cdot 10^7$ cm/s



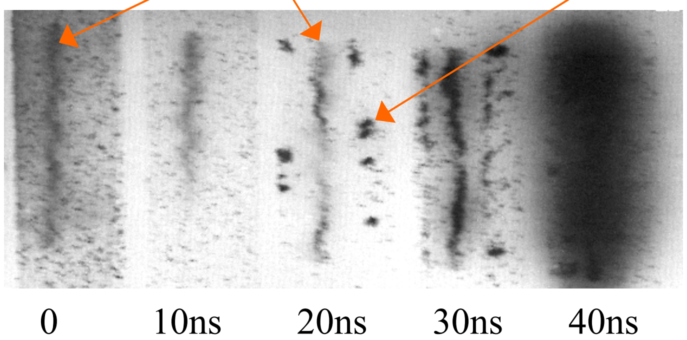


Implosion bubbles from the outer wires initiate hot spots on the inner wires of the nested array

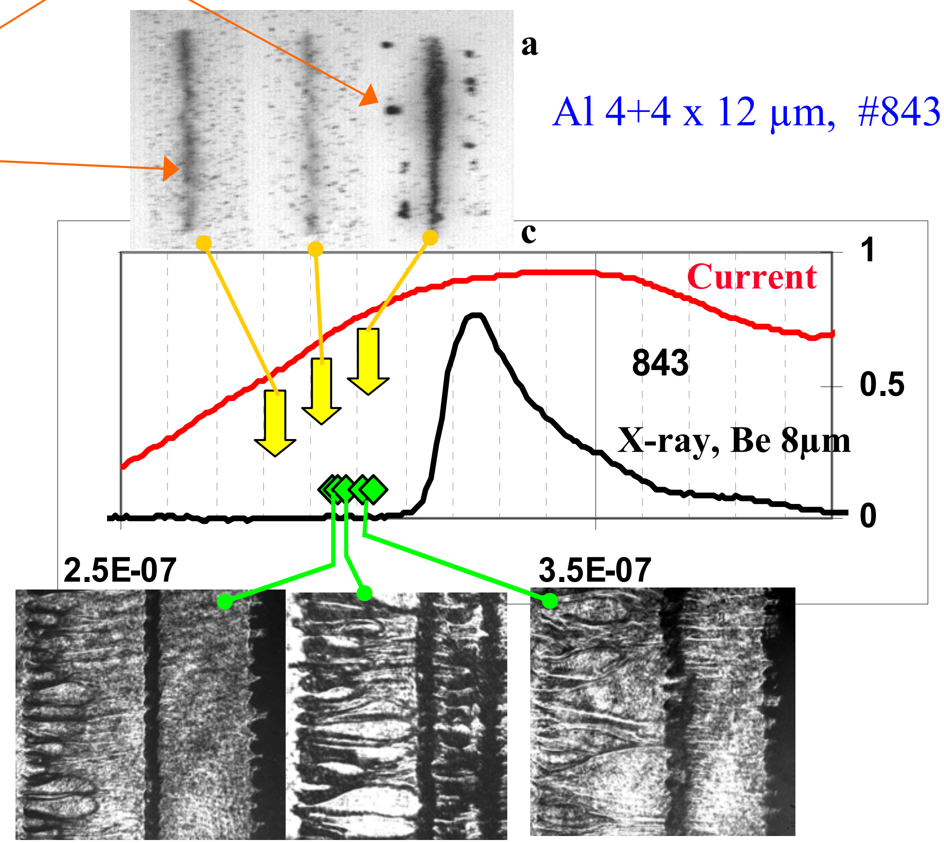
6-frame X-ray pinhole camera*
Be 9 μm + Mylar 3 μm

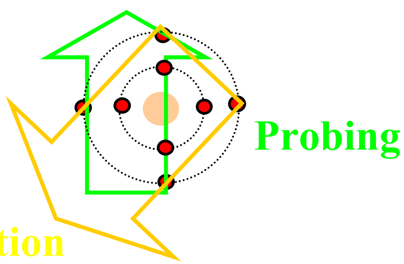
Bubbles initiate hot spots

Precursor



Al 4+4 x 12 μm, Ø16/8 mm, #841



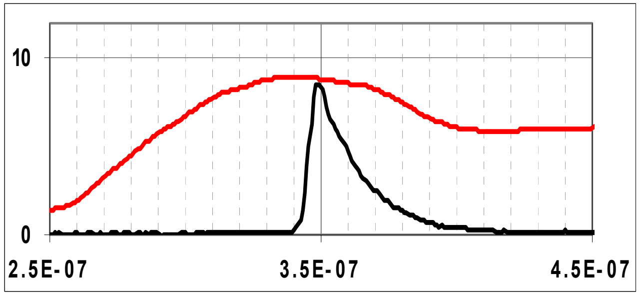


* - X-ray core diagnostics developed by V. Kantsyrev

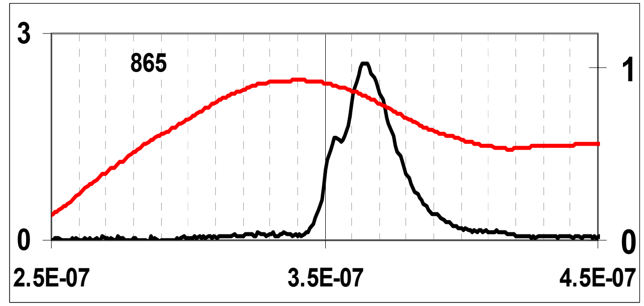
Nested loads provide good implosion with low azimuthal symmetry

PCD, Be 8 µm

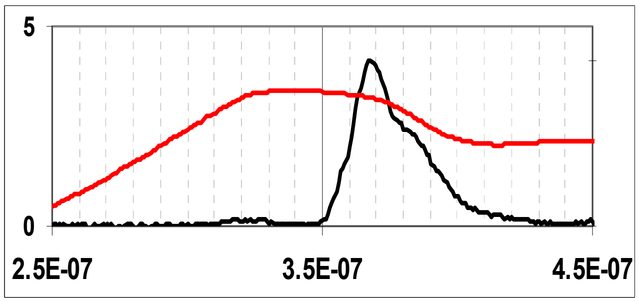
Al 8+8 x 10µm, 16/8mm, 33 µg/cm



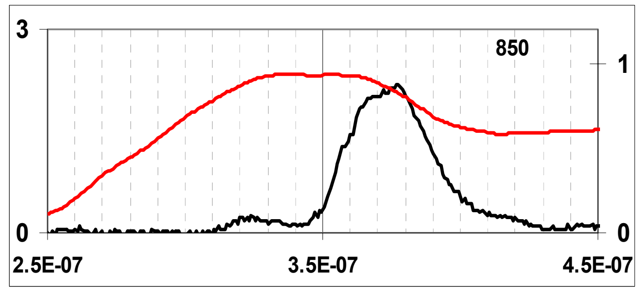
Al 16 x 10µm, 33 µg/cm



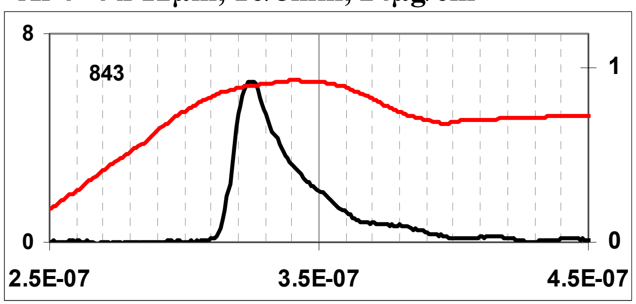
Al 4+4 x 20µm, 16/8mm, 66µg/cm



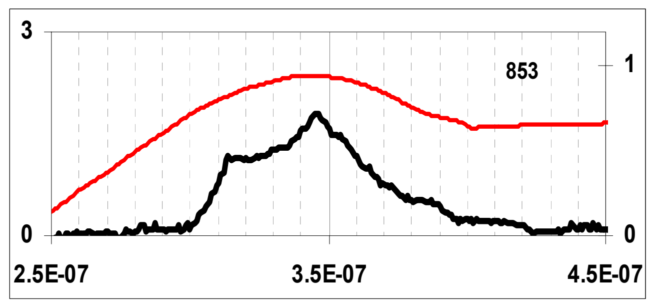
Al 8 x 15 µm, 37 µg/cm



Al 4+4 x 12µm, 16/8mm, 24µg/cm

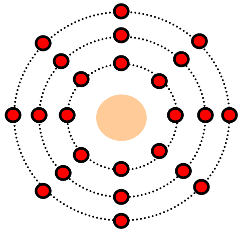


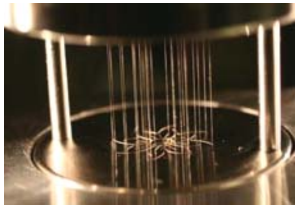
Al 4 x 15 µm, 19 µg/cm



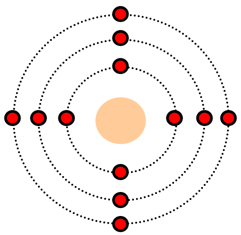
Triple wire arrays produce a maximum of power and a shortest x-ray pulse

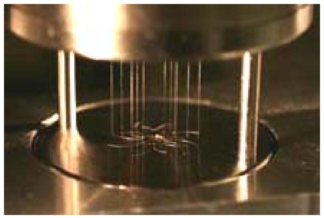
Triple nested array 16/12/8 mm, Al 8+8+8 wires, 10 µm

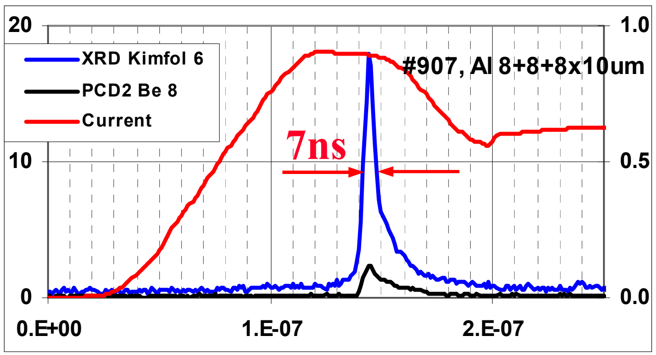


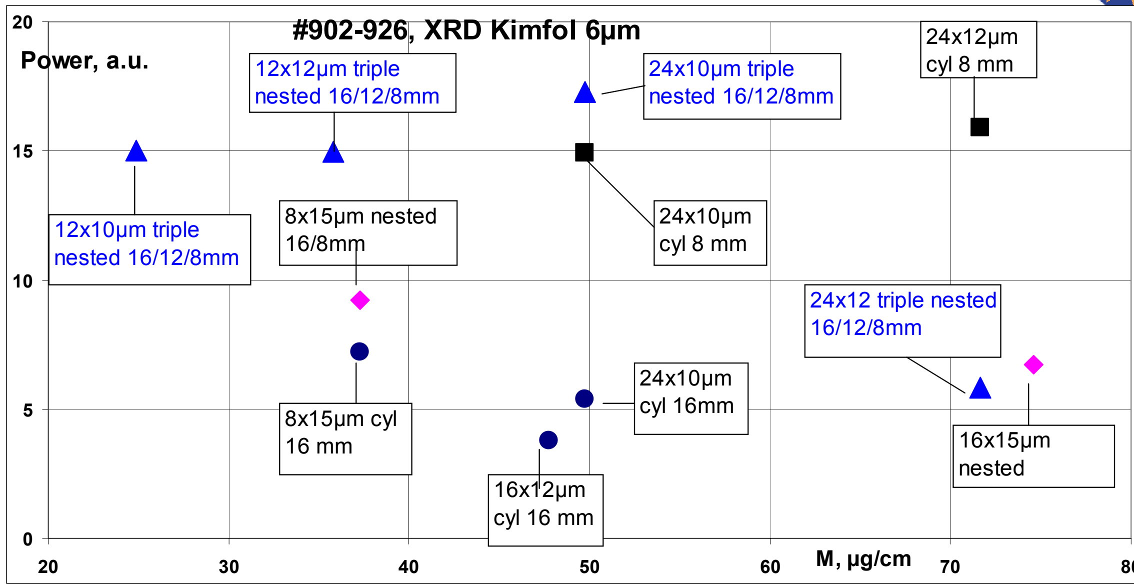


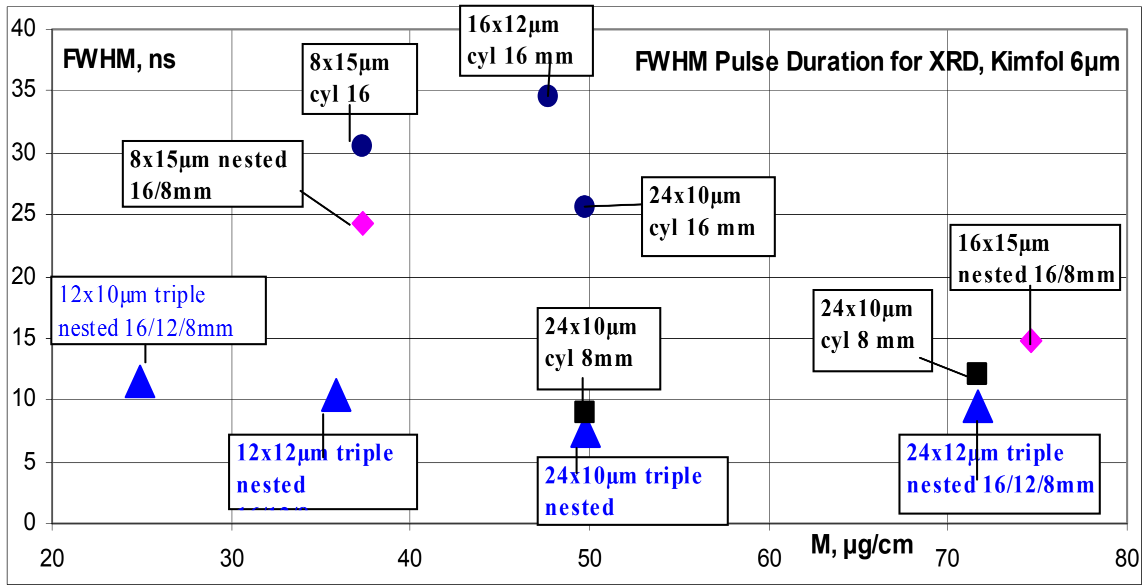
Triple nested array 16/12/8 mm, Al 4+4+4 wires, 12 µm



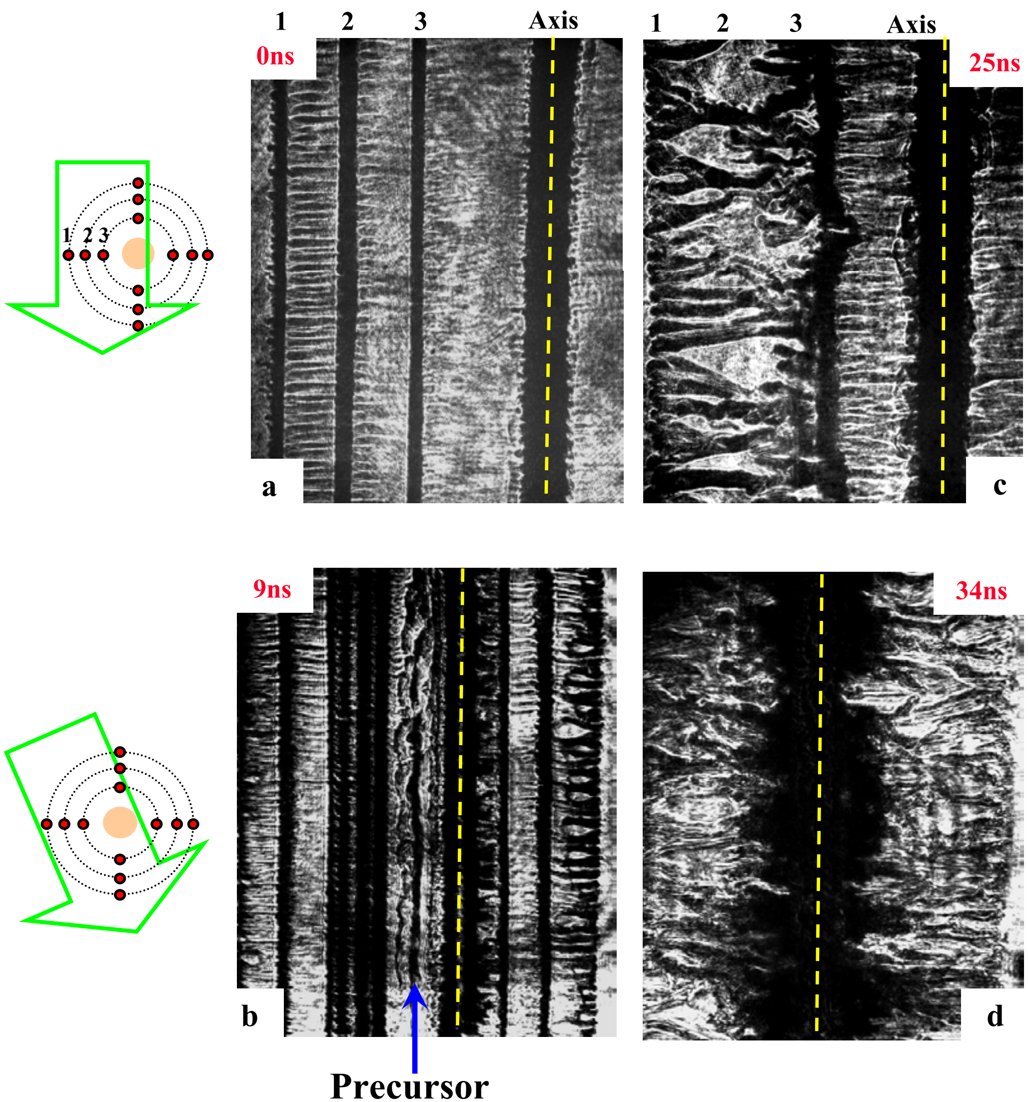




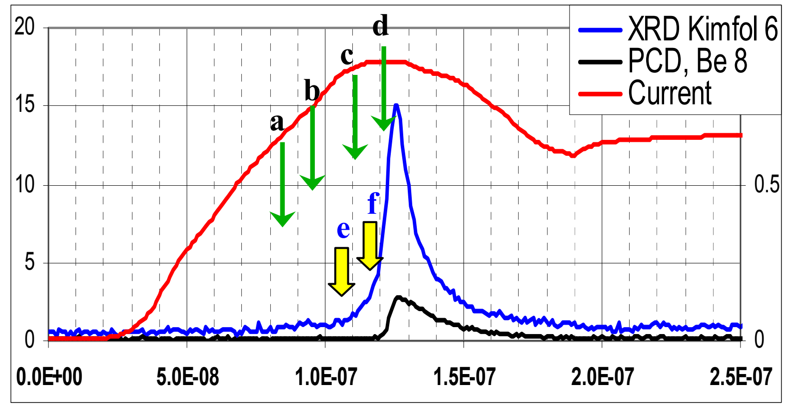




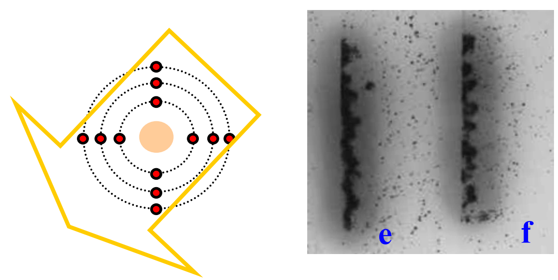
Cascade Implosion in Triple Nested Wire Arrays



#909, Al 16/12/8mm, 4+4+4 x 12 µm,

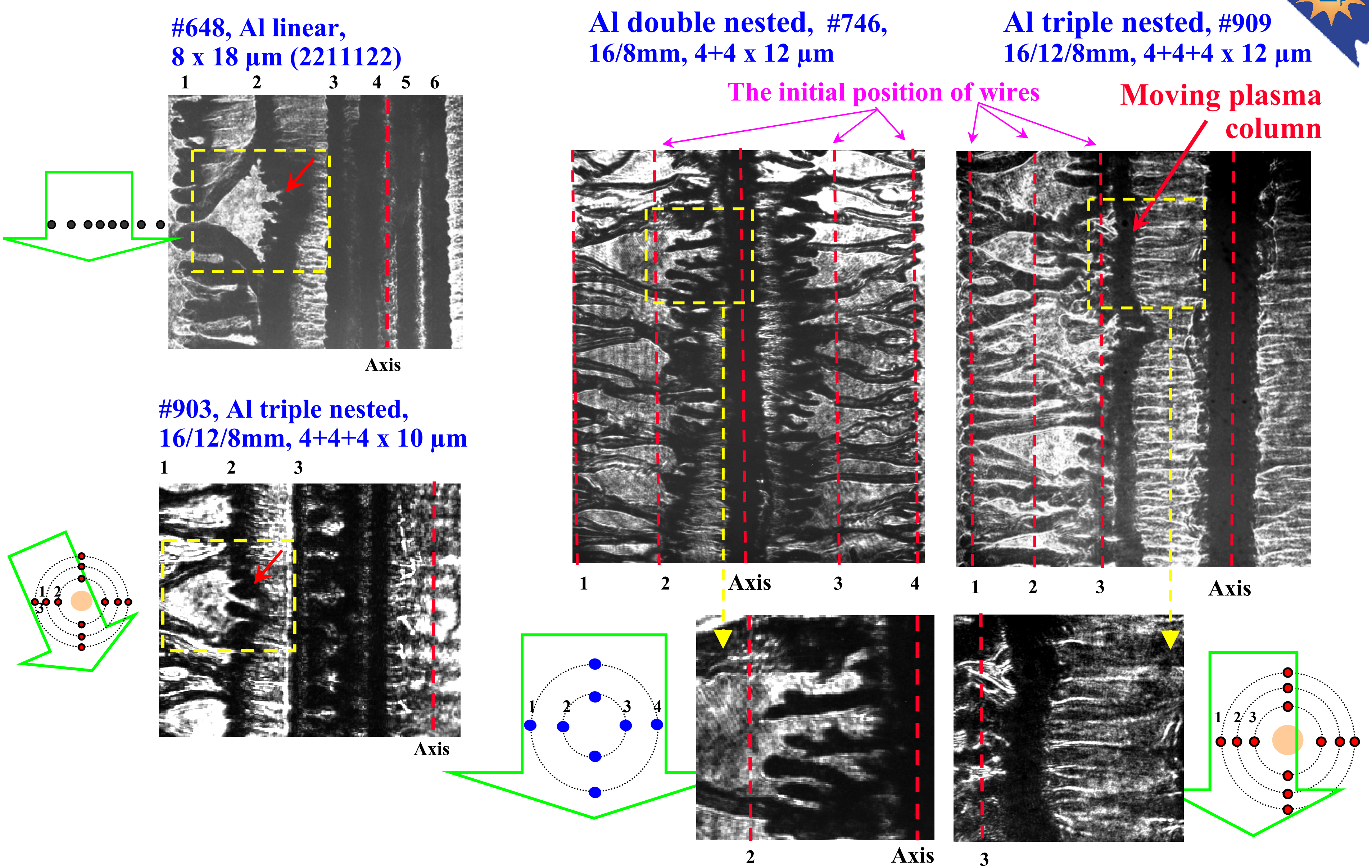


No hot spots in triple wire arrays



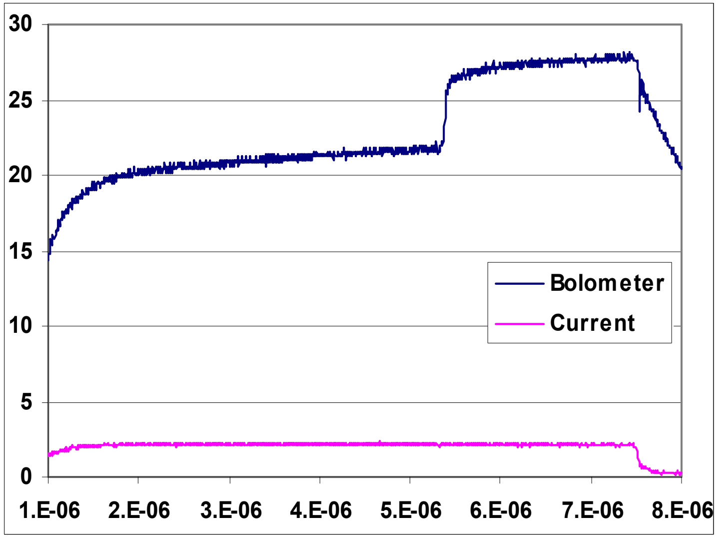
6-frame X-ray pinhole camera
Be 9 µm + Mylar 3 µm

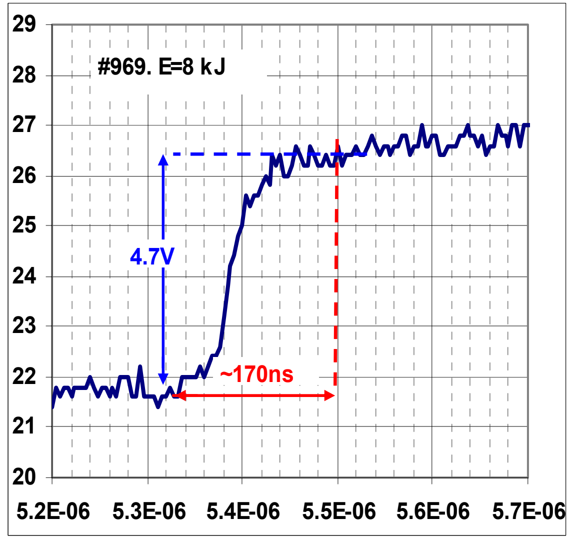
Triple loads demonstrate smoothing of the MHD instability

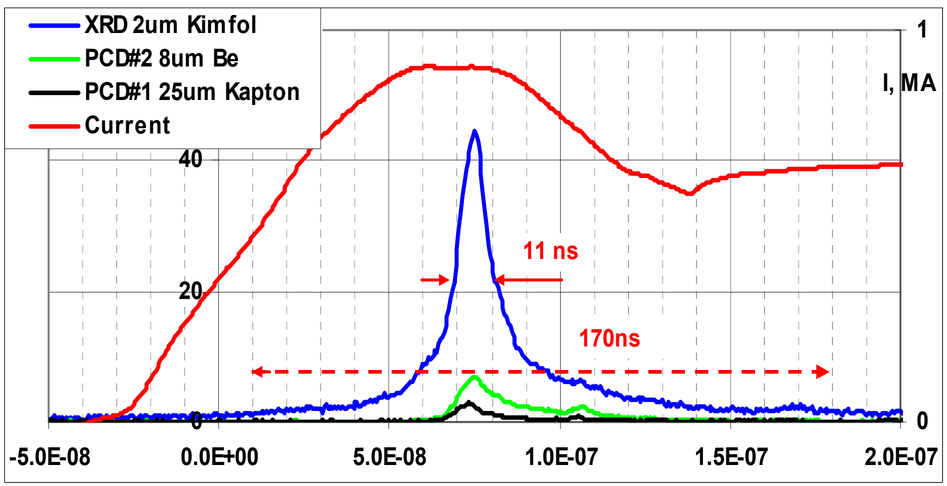


Measurements of Soft X-ray Power

#969, Al 16/12/8/6mm, 3+3+3+3 x 12µm







XRD, Kimfol 2 µm/ Ni Bolometer:

P_{peak}=0.34 TW

Conclusions

- Bubbles in the plasma streams present a mechanism of mass transport in low-number wire arrays. The speed of material $\geq 3\cdot 10^7$ cm/s was measured in the wire array implosion.
- Bubble dynamics in linear wire arrays differ from dynamics in cylindrical arrays. Implosion begins on the edge wires. Current moves with the leading edges of bubbles. Implosion cascades from wire to wire. In linear arrays with the enlarged central gap plasma does not penetrate to the center during ablation stage.
- In nested arrays with equal wire length implosion begins on the outer array. The outer array collides with the inner array. Rescaling of perturbation was observed in linear and nested arrays. Nested arrays produce shorter and more powerful x-ray pulses compare to cylindrical wire arrays but with smaller energy. Triple nested arrays produce the shortest soft x-ray pulse with maximum power.
- Bubbles could initiate hot spots on the inner wires in nested and linear arrays.

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