SAND2007-1860C

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

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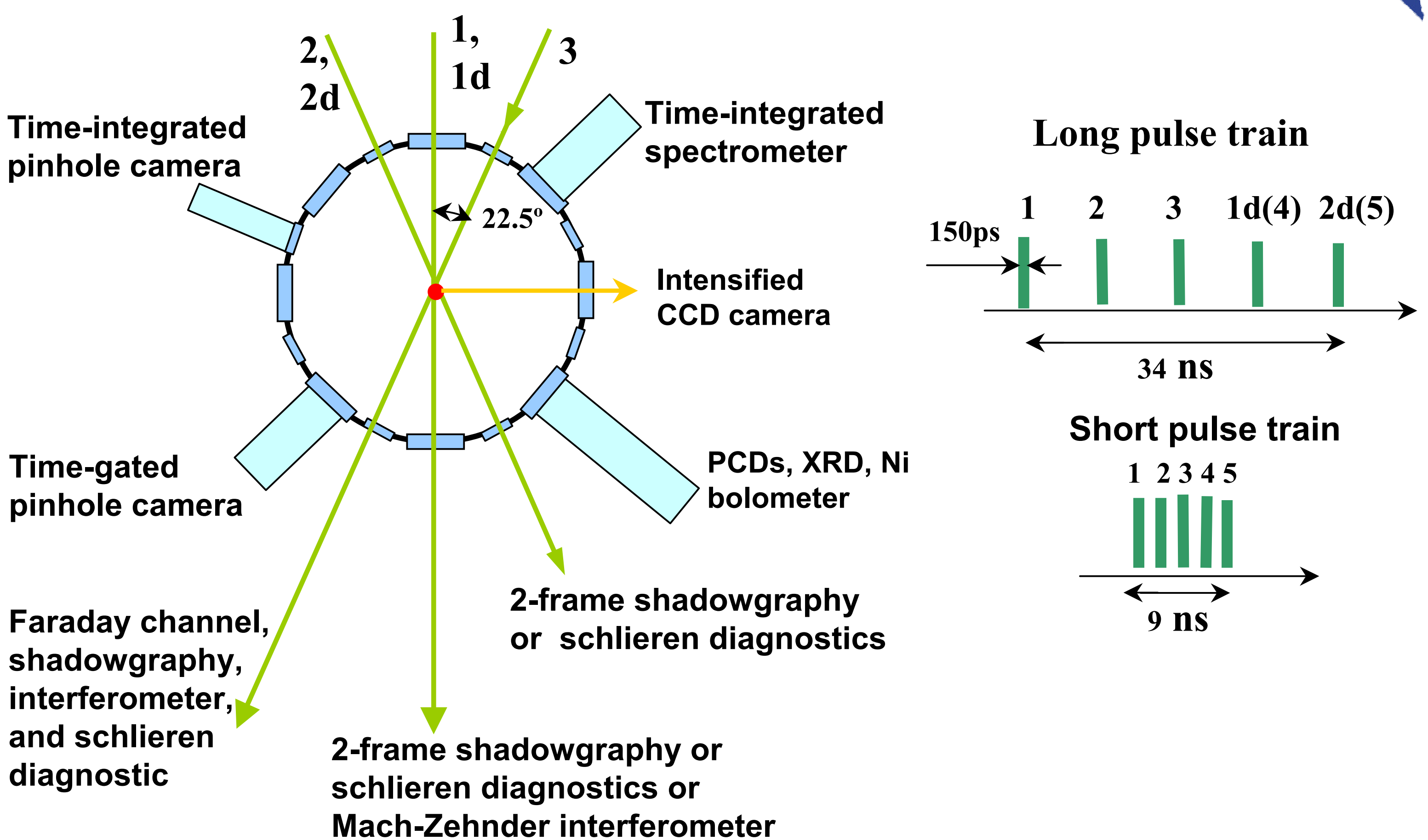
Content

1. Implosion dynamics in low-wire-number cylindrical arrays.
2. Cascade implosion dynamics in linear arrays.
3. Implosion and x-ray production in nested and star-like loads.
4. Comparison of soft x-ray power generated by different loads in the Zebra generator

Plasma Diagnostics on the Vacuum Chamber of Zebra

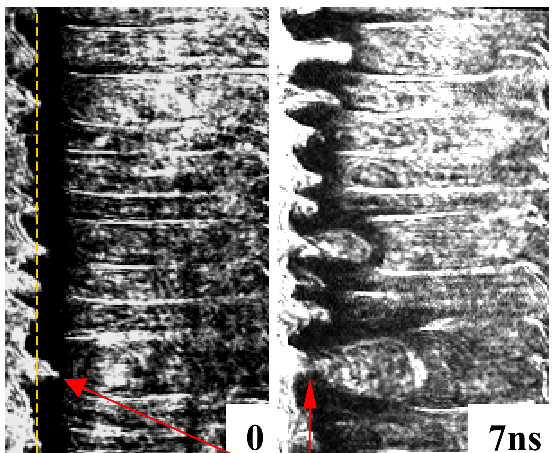
Three optical delay lines



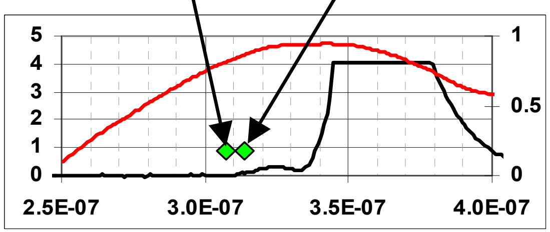
Implosion bubbles indicate breaks in wires and present mass transport in cylindrical wire arrays

#511

Axis



Bubbles are blown when the wire core is broken



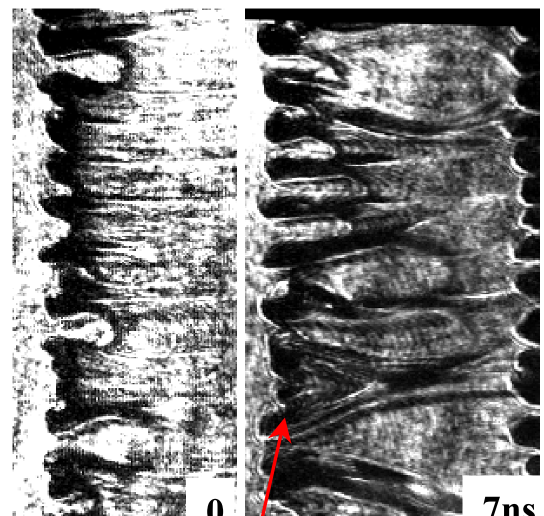
Bubbles arise at 20-25ns before the x-ray pulse

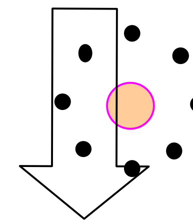
1 mm

Al 8 x 15 μm wire arrays

Bubbles are blown in different time

#514

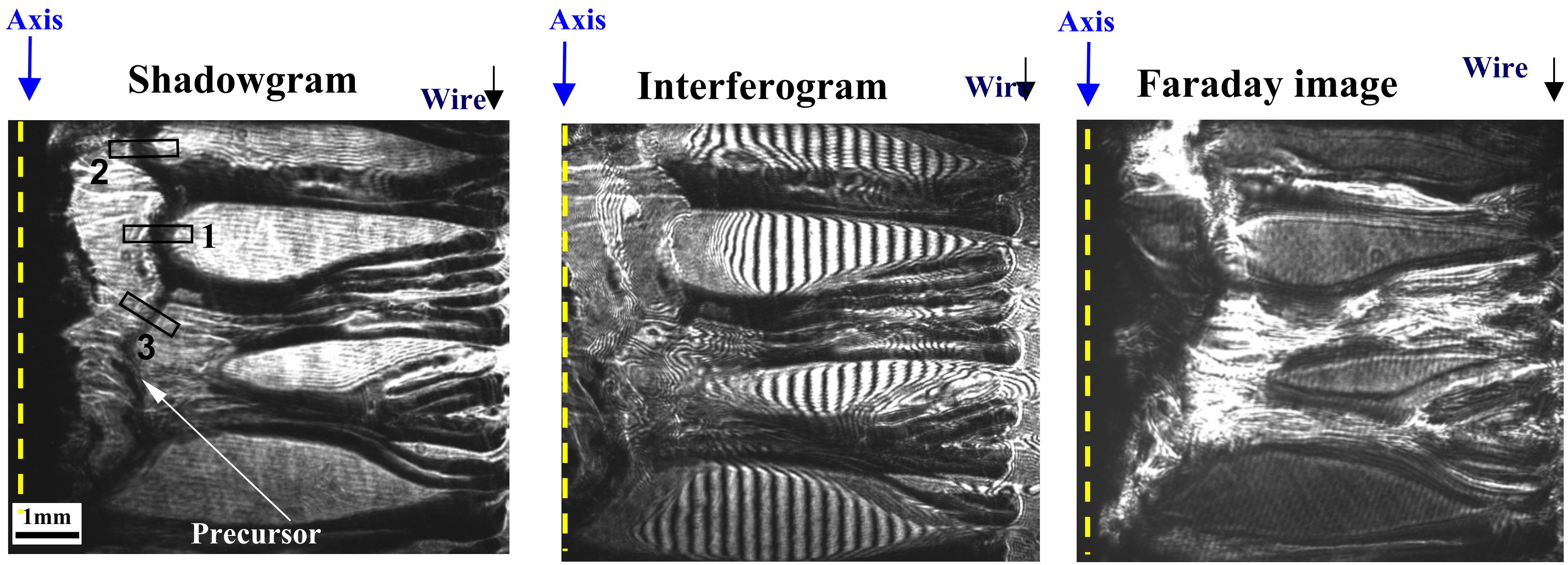




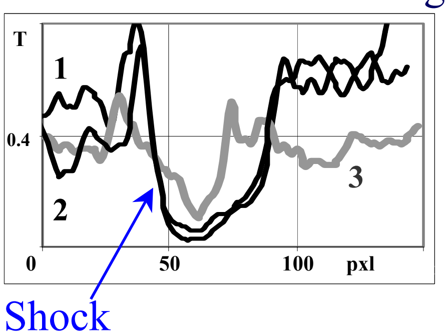
Typical after bubble "fingers" on the edge of the wire array

V. Ivanov et al., Phys. Rev. Lett. 97, 125001 (2006)
C. J. Garasi et al., Phys. Plasmas, 11, 2729 (2004)
B. Jones et. al., Phys. Rev. Lett. 95, 225001 (2005)
S.V. Lebedev et al., Plasma Phys. Contr. Fusion, 47, A91 (2005)

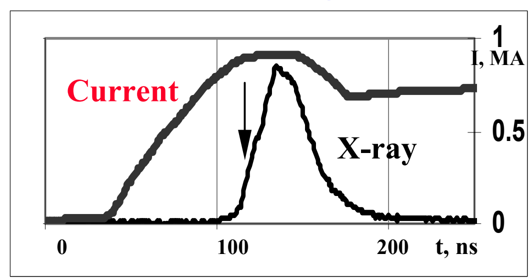
Plasma bubbles hit and sweep the precursor



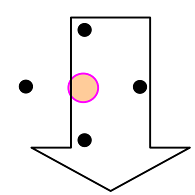
Outlines from the rectangles 1-3



Timing



Al 4 x 20 µm wire array



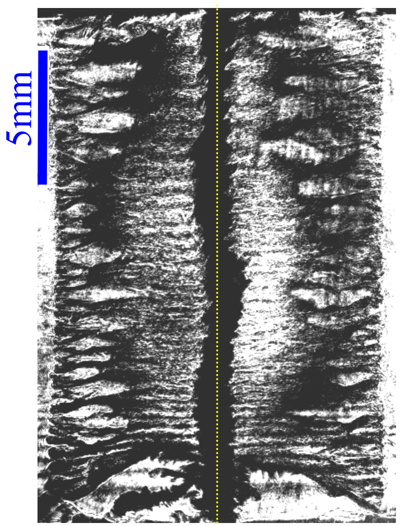
$V_A \sim 10^7$ cm/s if $N_e = 10^{19}$cm^{-3}, B =0.3MG

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

V. Ivanov et al., Phys. Rev. Lett. 97, 125001 (2006)

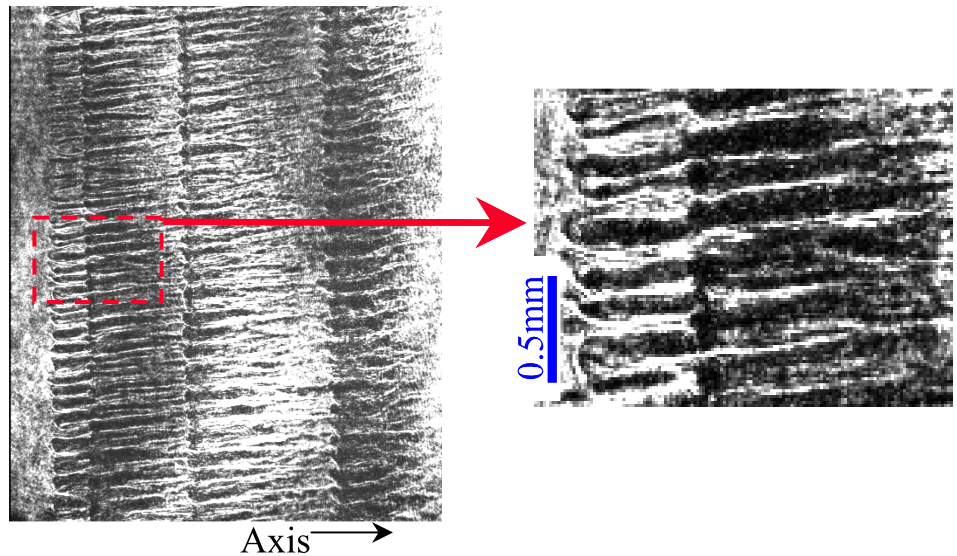
Bubbles are smaller and more regular in multi-wire arrays

#653. **W** 4x**12** μm



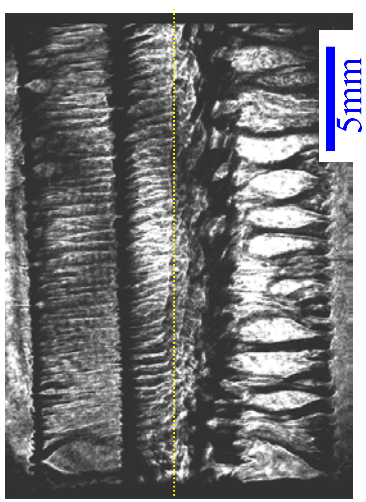
Axis

#687. **W** 16x**4.3** μm



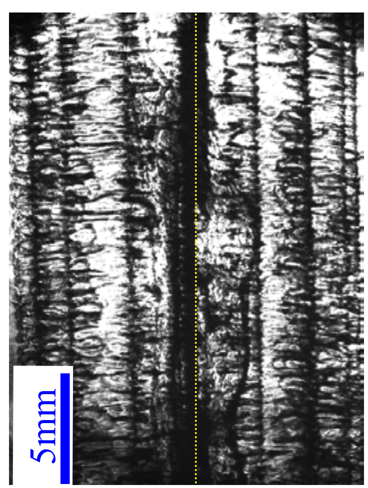
Axis

#541. **Al** 4x**20** μm



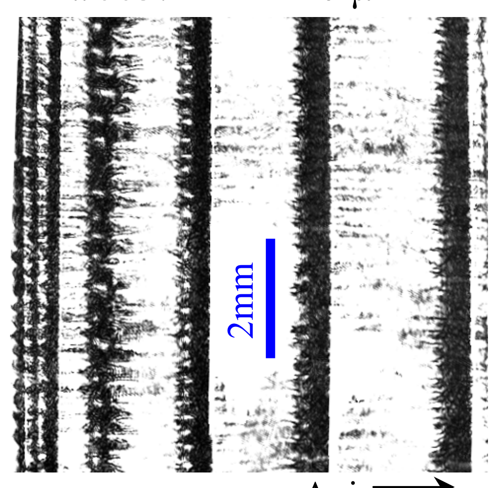
Axis

#506. **Al** 16x**10** μm



Axis

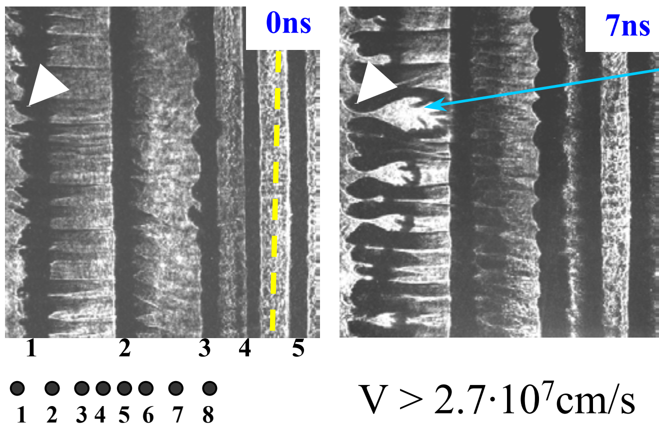
#663. **Al** 24x**10** μm



Axis

Implosion Dynamics in Linear Wire Arrays

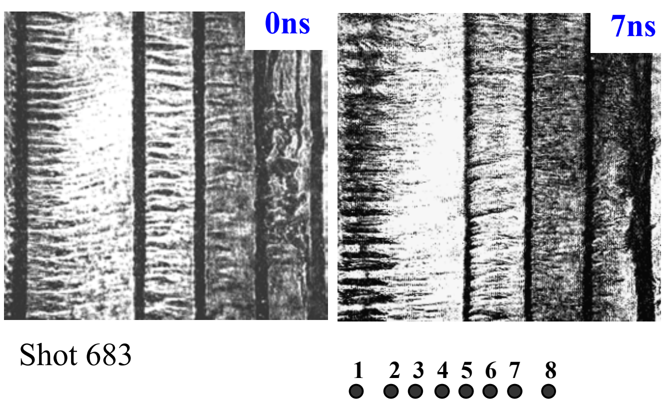
#650. **Al 8x18μm** Two-frame shadowgram



Flares in bubbles

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

Two-frame shadowgram W 10x5μm

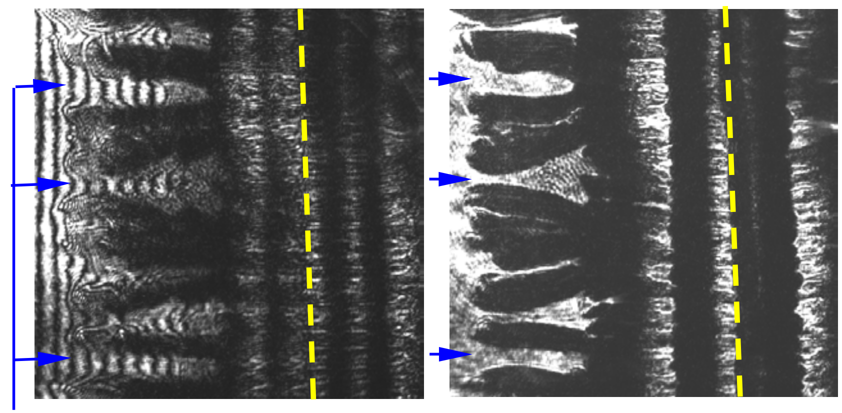


Shot 683

Dense plasma is absent in wire breaks

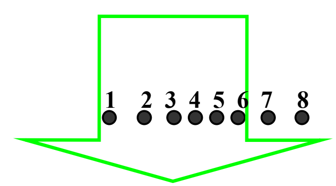
Al 6x20 μm (22322)

Interferometry Shadowgram



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

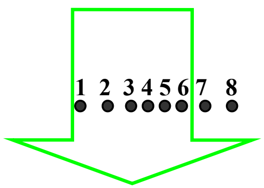
#665

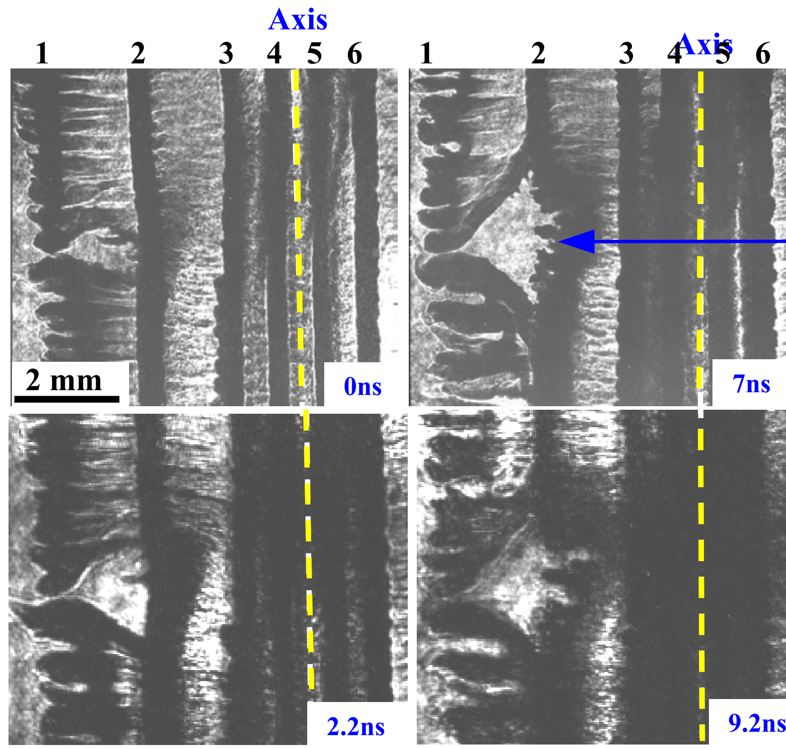


* - see also V.V. Kantsyrev et al., IEEE Trans. Plasma Sci., 34, 2295 (2006)

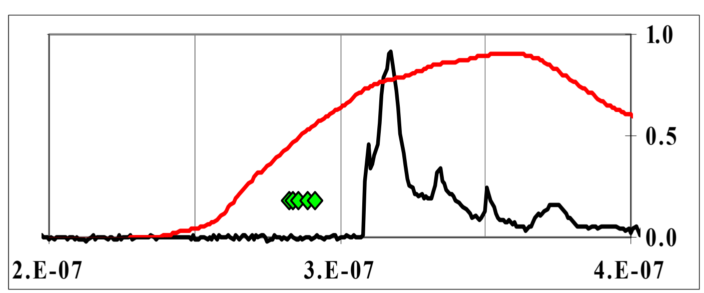
Cascade Implosion in Linear Wire Arrays

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





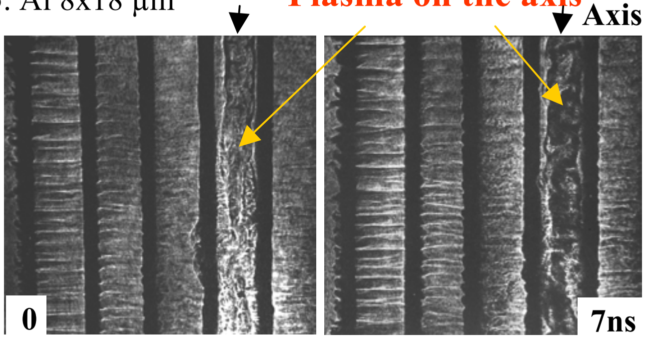
Magnetic Rayleigh-Taylor Instability



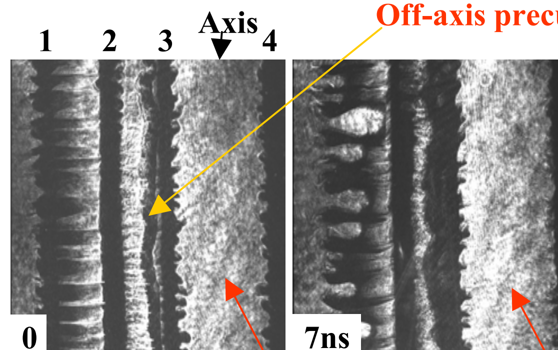
Ablating plasma does not move to the axis of the linear array with an enlarged central gap

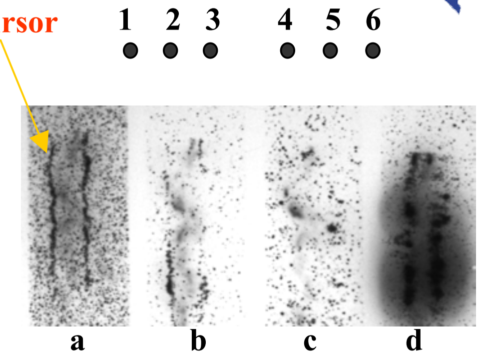
Equidistant linear arrays

#645. Al 8x18 μm



The central gap is enlarged. Al 6x20 μm (22322)



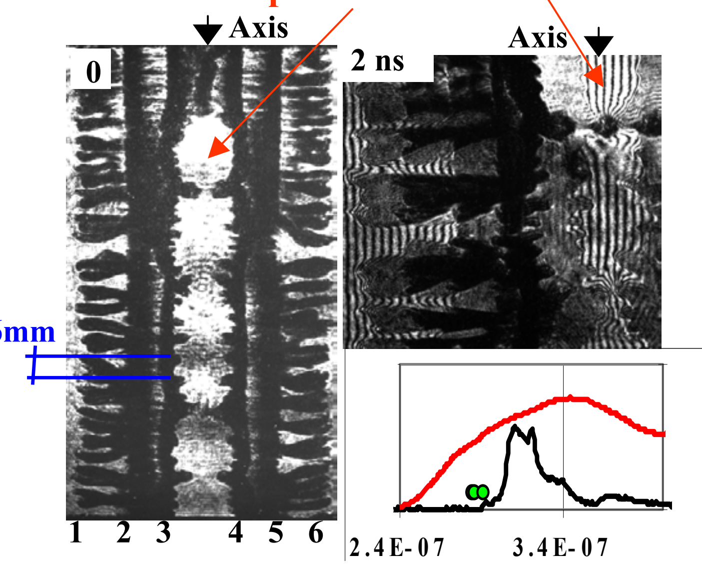


Be, 15μm

$$\lambda_{MRTI} \approx 2\pi \frac{Kc}{\omega_{pi}}, \text{ K=10-20*}, \quad \omega_{pi} = \sqrt{\frac{4\pi \cdot n_i e^2 Z^2}{m_i}}$$

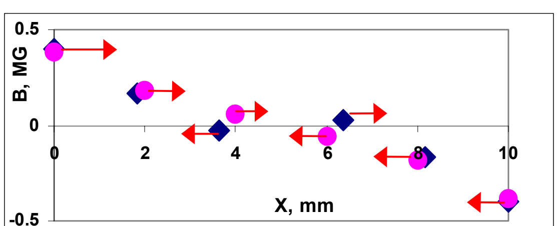
For Al plasma column Ø 0.5 mm:
$n_i \sim 1\cdot 10^{20}$ cm^{-3}, $Z\sim 1$-2
$\omega_{pi}=(2.5$-$5)\cdot 10^{12}$, λ_{MRTI} = 0.2-0.7mm

No dense plasma on the axis



Al 6x20 μm

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



● Mutual magnetic field in the equidistant linear wire array

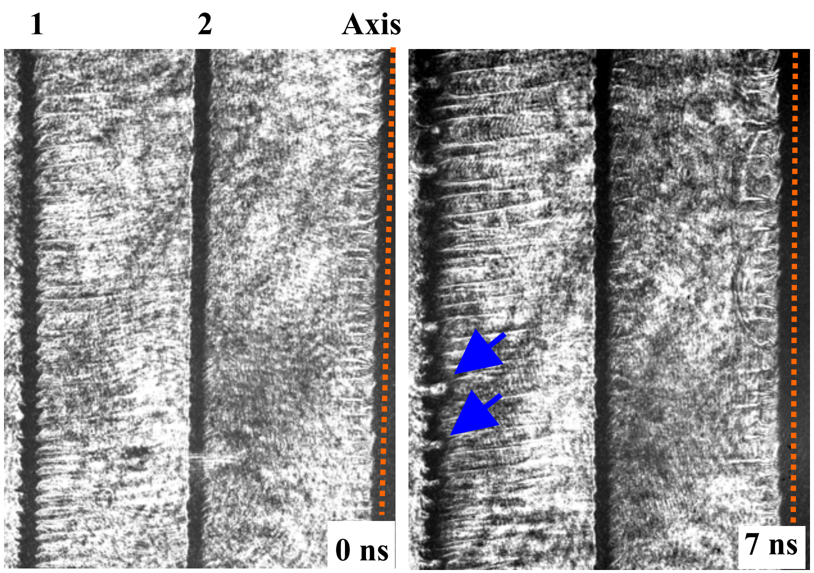
◆ In the array with the enlarged central gap

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

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

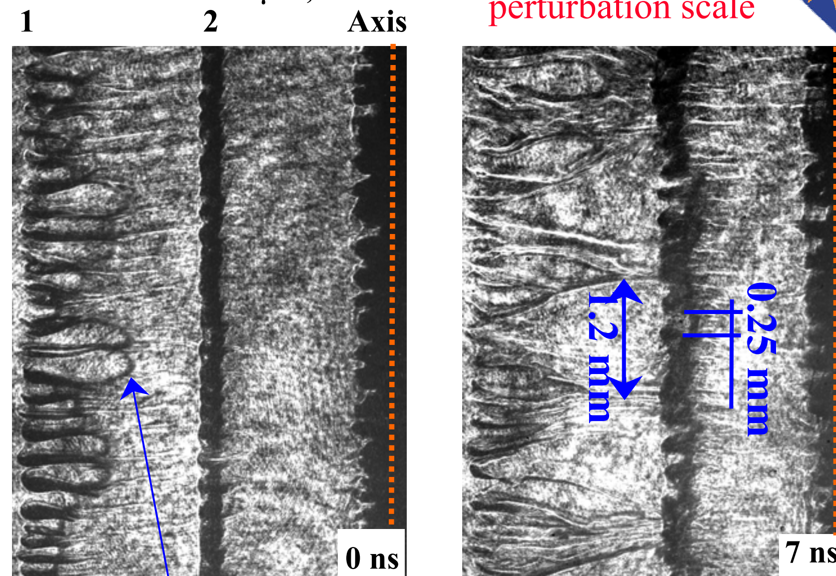
Cascade Implosion in Nested Wire Arrays

#842. Al 4+4 x 12µm, Ø16/8mm

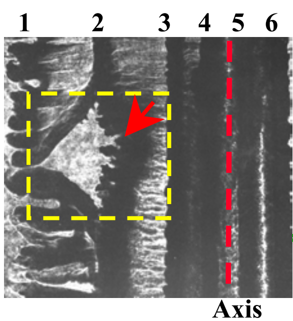


#843. Al 4+4 x 12µm, Ø16/8mm

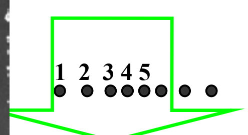
Change of plasma perturbation scale

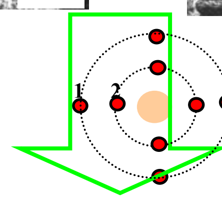


V =4.5·10^{7}cm/s

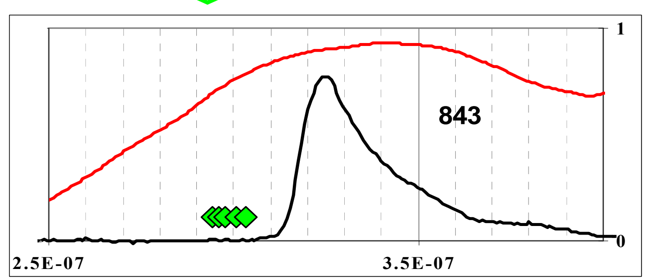


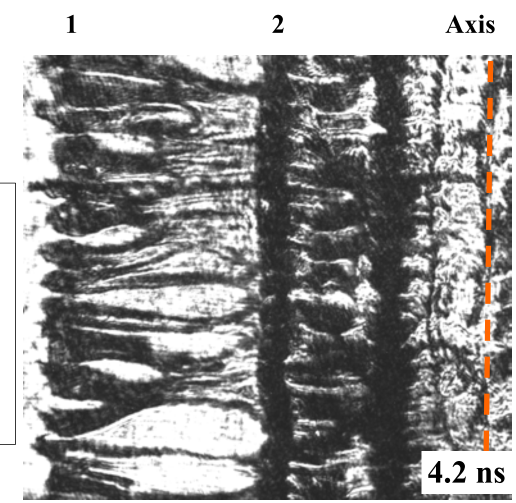
Linear, 8x18µm

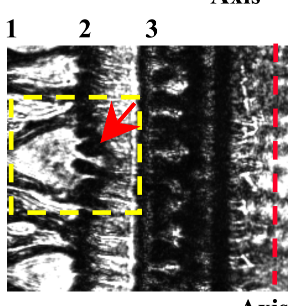




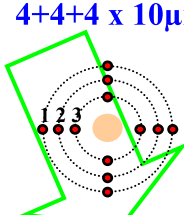
$L_{in} = L_{out} = 2$ cm*







Triple, 16/12/8mm, 4+4+4 x 10µm



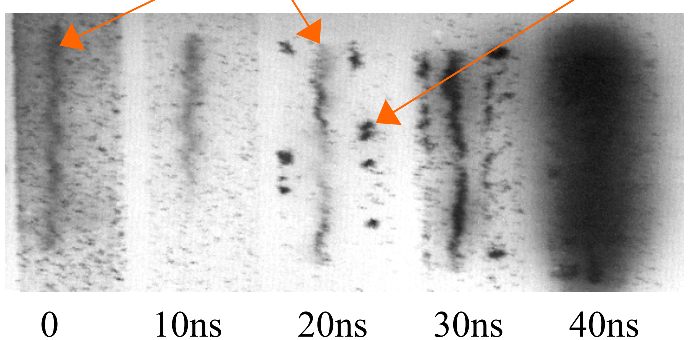
Two regimes: S.V. Lebedev et al., PRL 84, 2000.
S.N. Bland *et al.,* Phys. Plasmas 10, 1100, 2003

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

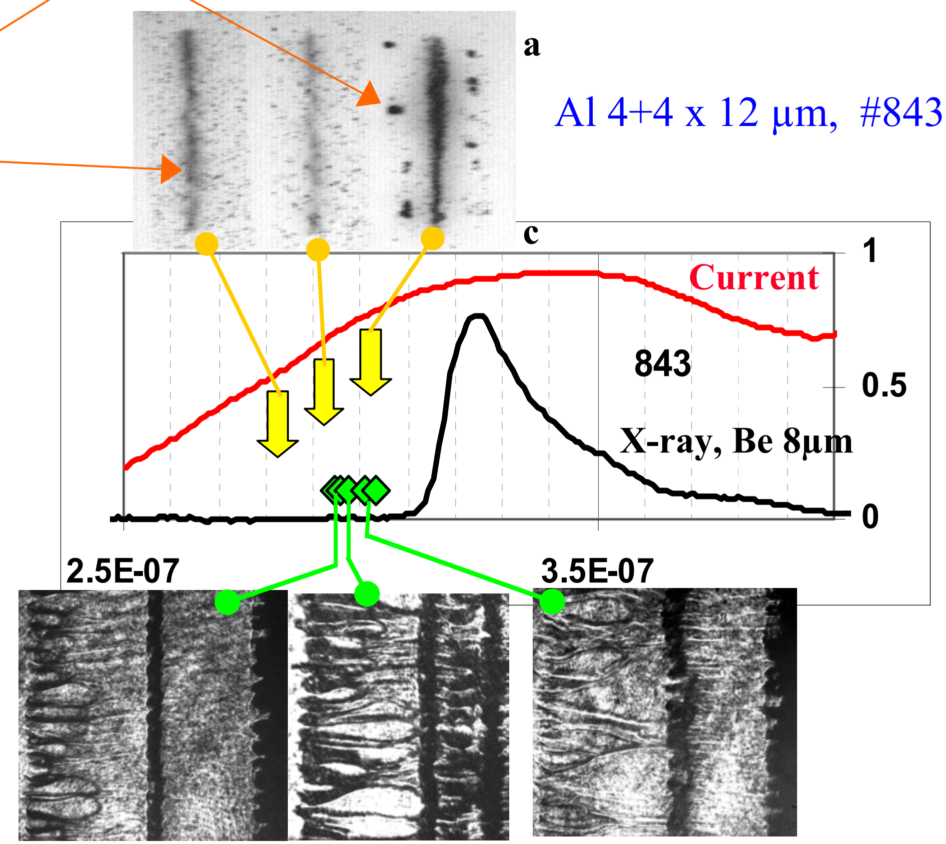
6-frame X-ray pinhole camera*
Be 9 µm + Mylar 3 µm

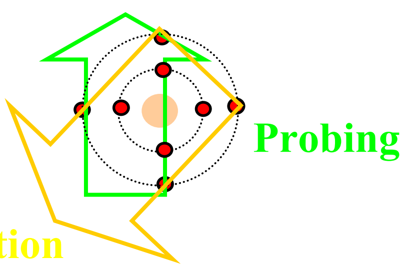
Bubbles initiate hot spots

Precursor



Al 4+4 x 12 µm, Ø16/8 mm, #841

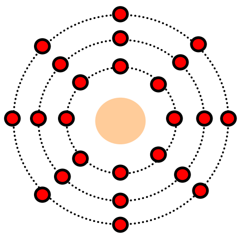


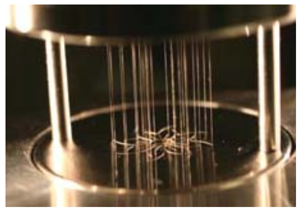


Nested loads provide good implosion with low azimuthal symmetry

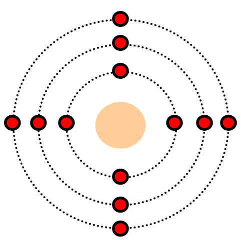
Triple wire arrays produce a maximum of power and a shortest x-ray pulse

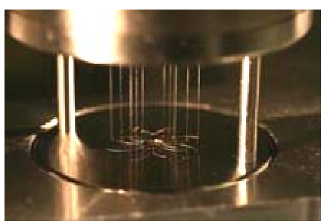
Triple nested array 16/12/8 mm, Al 8+8+8 wires, 10 µm

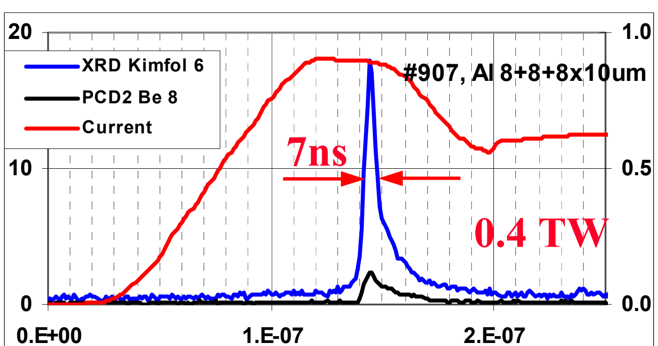


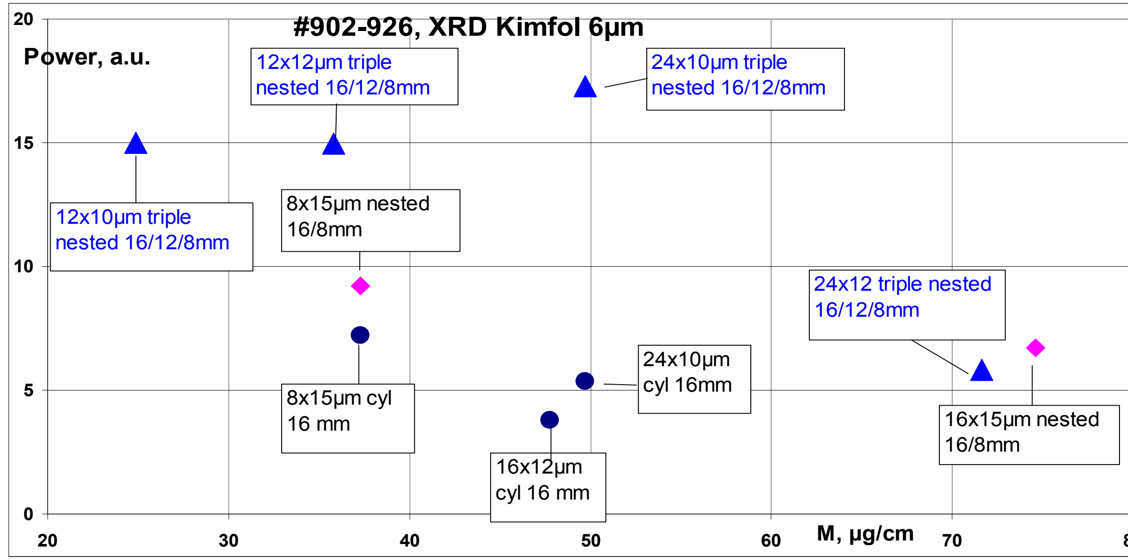


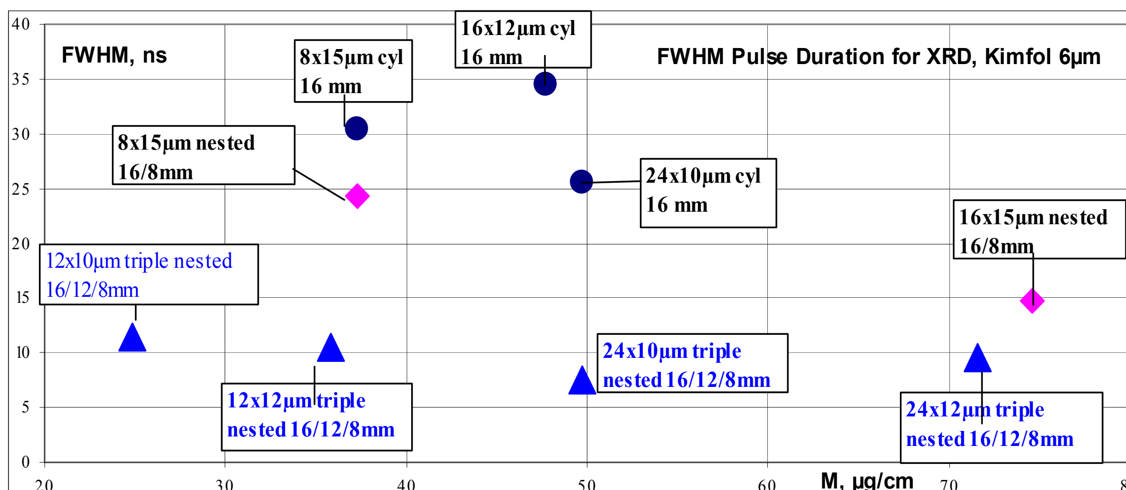
Triple nested array 16/12/8 mm, Al 4+4+4 wires, 12 µm



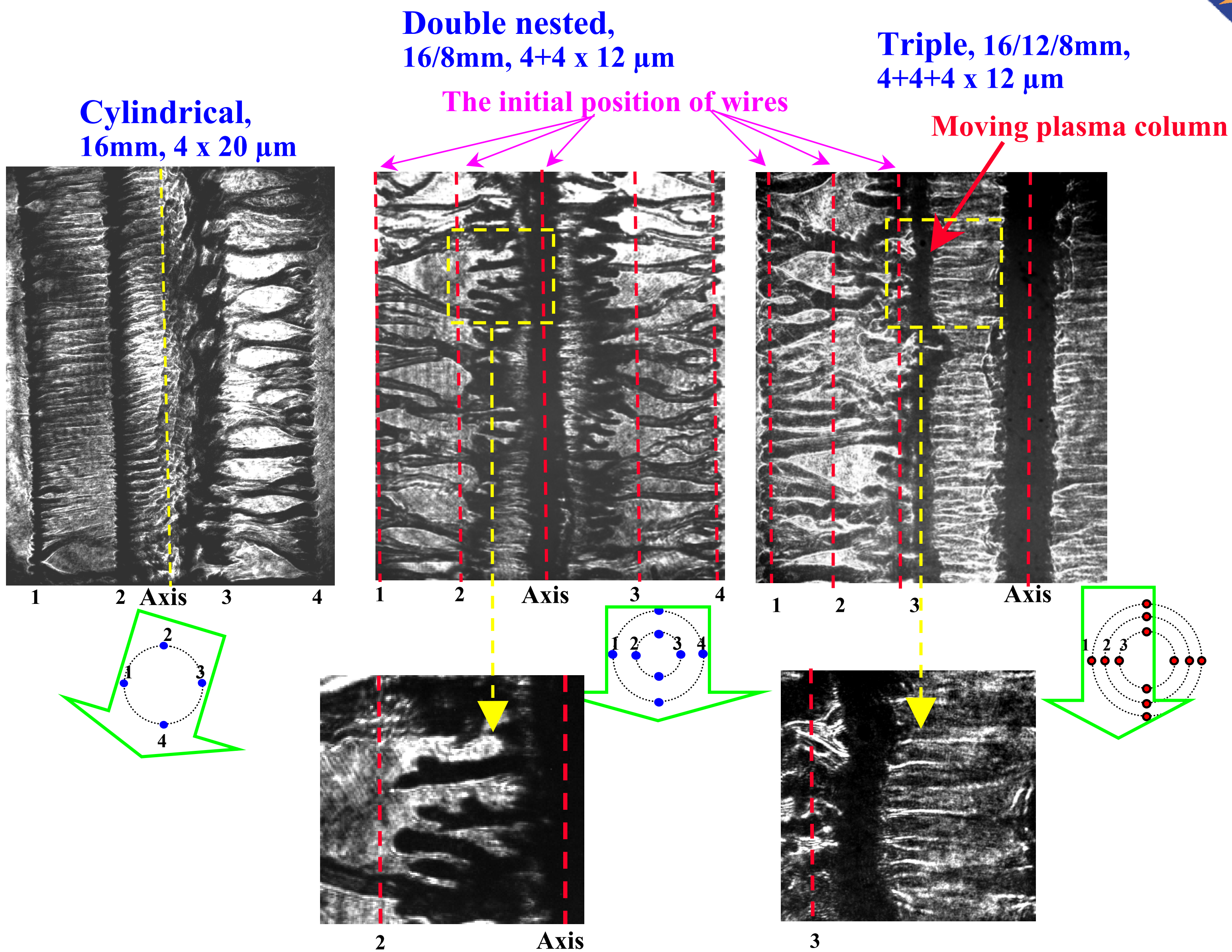






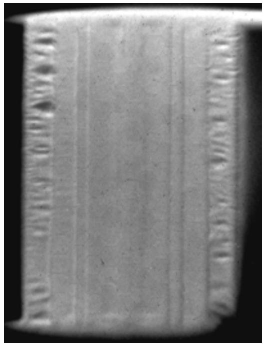


Triple loads demonstrate smoothing of the MHD instability



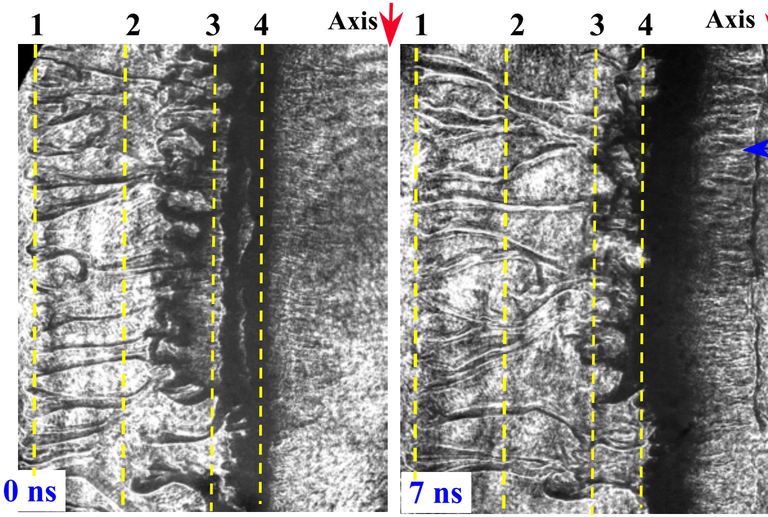
“Star”-like wire arrays present smoothing of instabilities

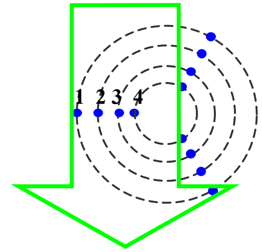
#976, Al 16/12/8/6mm, 6+6+6+6x 12µm



ICCD

#967, Al 16/12/8/6mm, 3+3+3+3 x 12µm

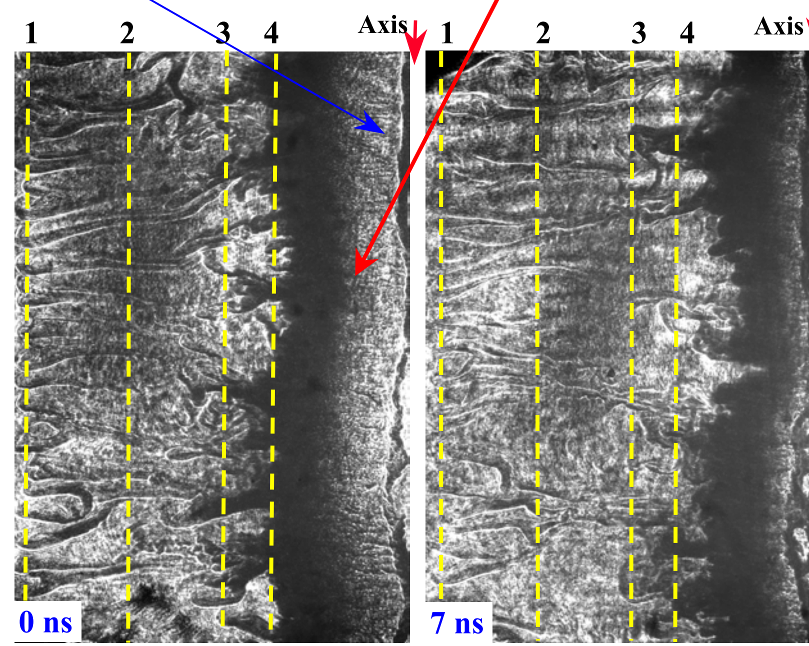




#980, Al 16/12/8/6mm, 3+3+3+3 x 12µm

The leading edge of the moving plasma column is smooth

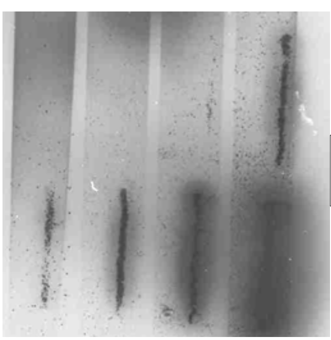
Shock



No hot spots

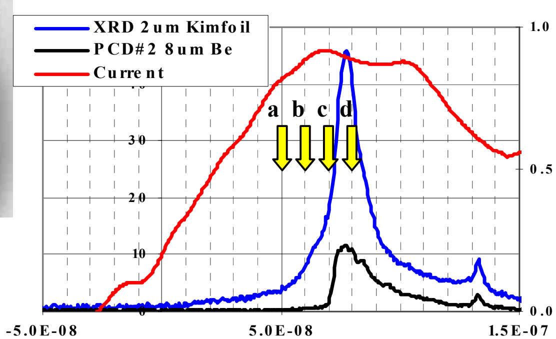
Mylar, 110 µm

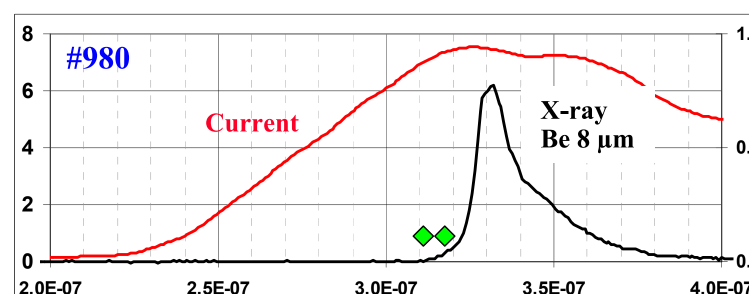
Be, 15µm



a b c d

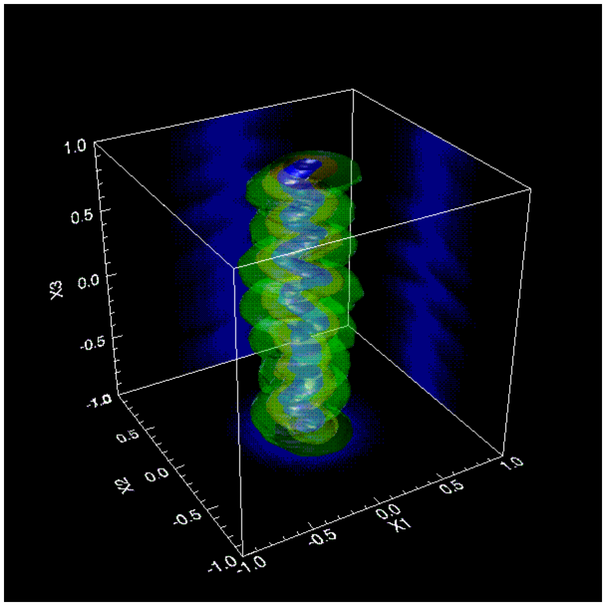
#982, Al 16/12/8/6mm, 3+3+3+3 x 12µm

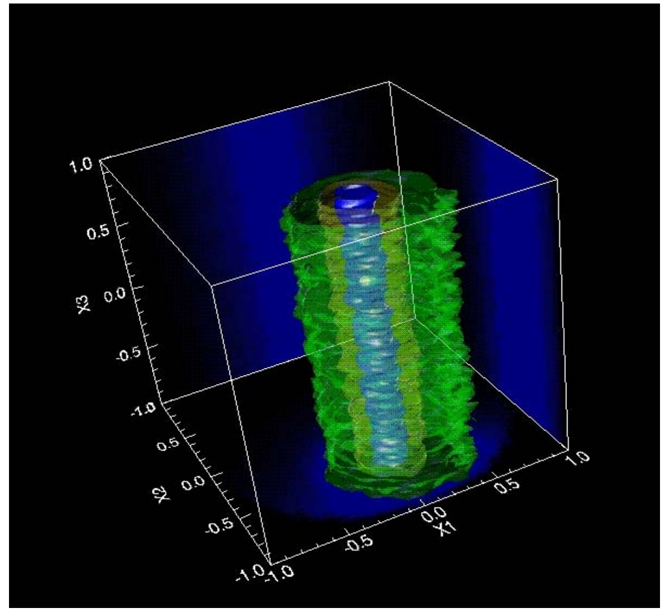


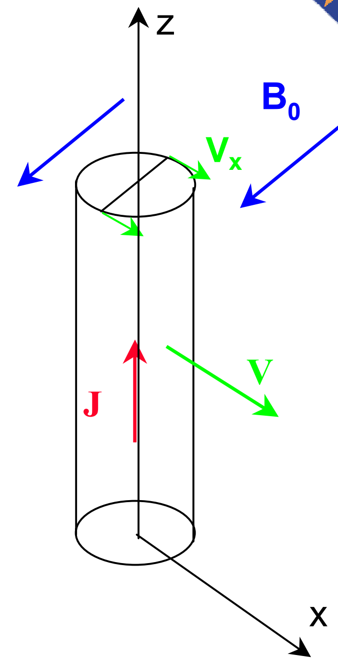


Stabilization of the plasma column crossing the magnetic field*

$B_0 = 0$ **t = 90** $B_0 = 0.3$







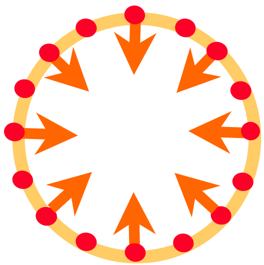
- In the presence of external magnetic field B_0, plasma column experiences drift motion due to the $J \times B_0$ force;

- Flow shear connected with the plasma drift motion across the axial direction can suppress development of sausage and kink instabilities.

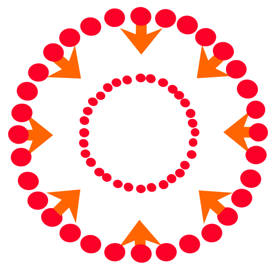
* - V.I. Sotnikov *et al.*, presented in ICOPS 2004

“Star”-like wire arrays demonstrate directed implosions with smoothing of instabilities

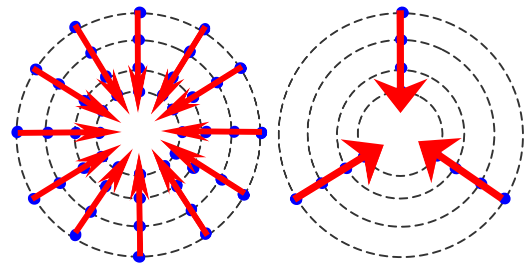
Cylindrical array



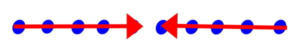
Nested array



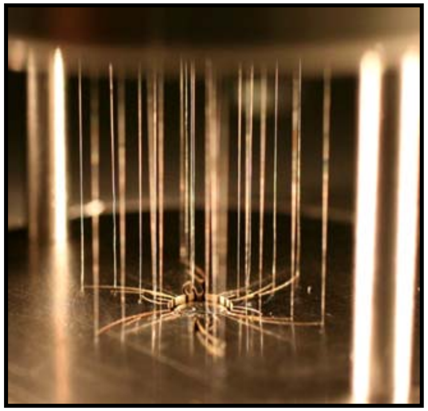
“Star”-like loads

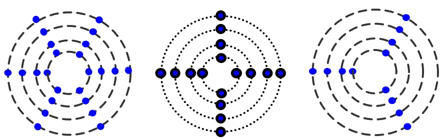


Is a linear array a member of this class?



Nested quadruple* load, 24wires, Ø16/12/8/6 mm



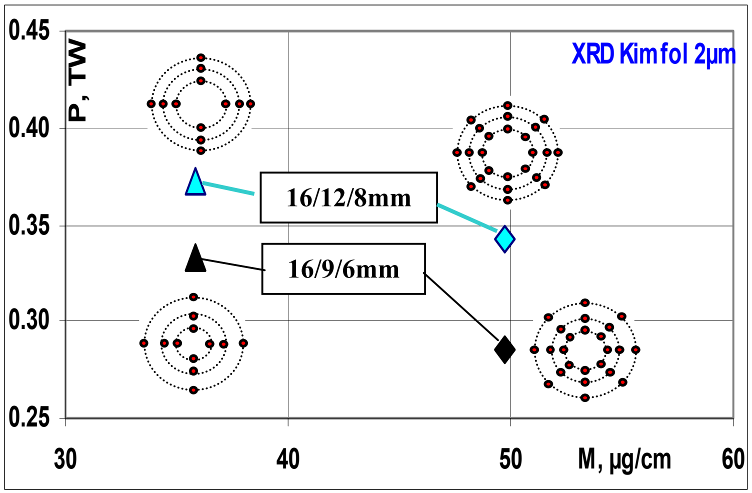


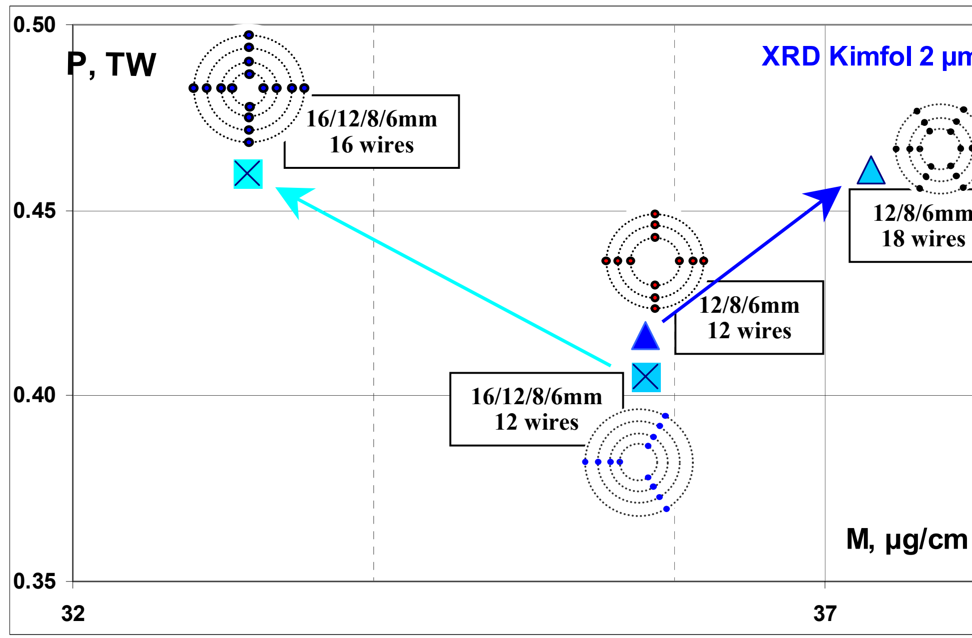
Parameters for optimization

1. A number of wires in the ray;
2. A number of rays in the “star” (azimuthal homogeneity);
3. Mass scaling;
4. Wire spacing;
5. Diameter scaling;
6. Material;
7. Optimization for K-shell radiation.

* - Design of A. Astanovitskiy

Wire spacing azimuthal symmetry influences to plasma dynamics and radiated x-ray power

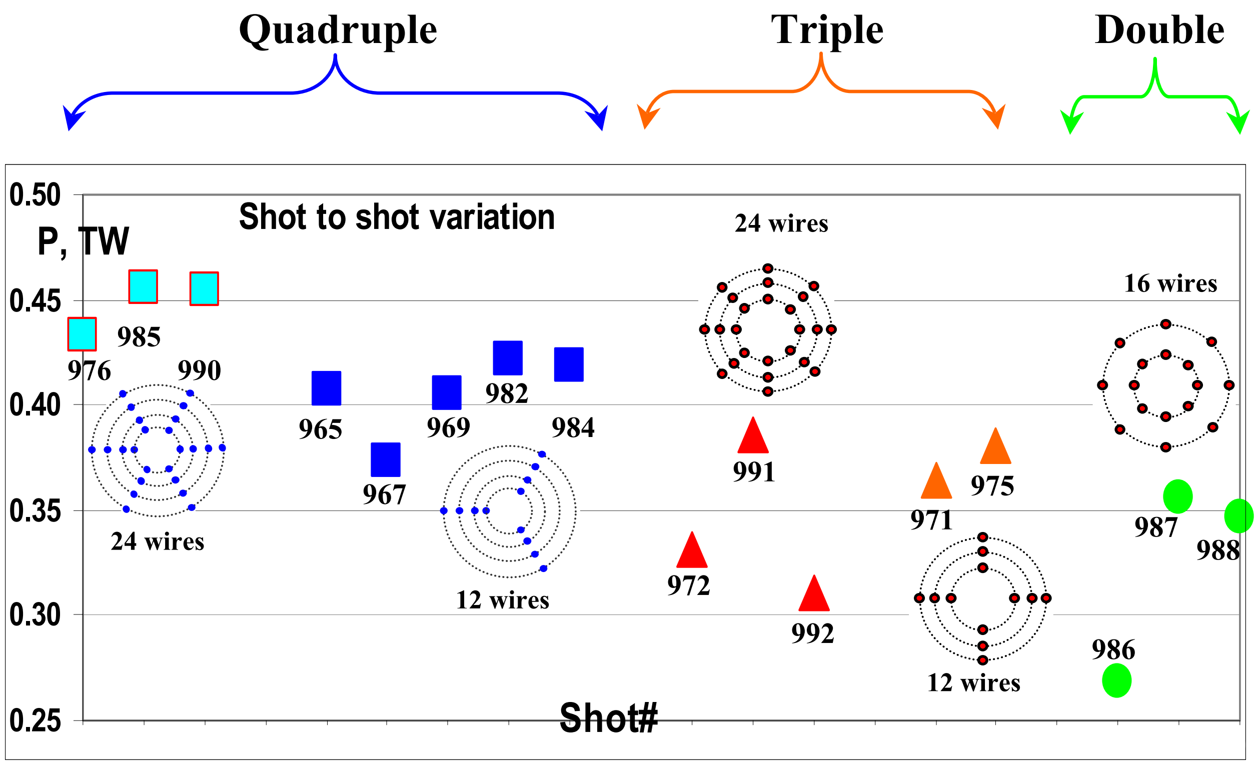




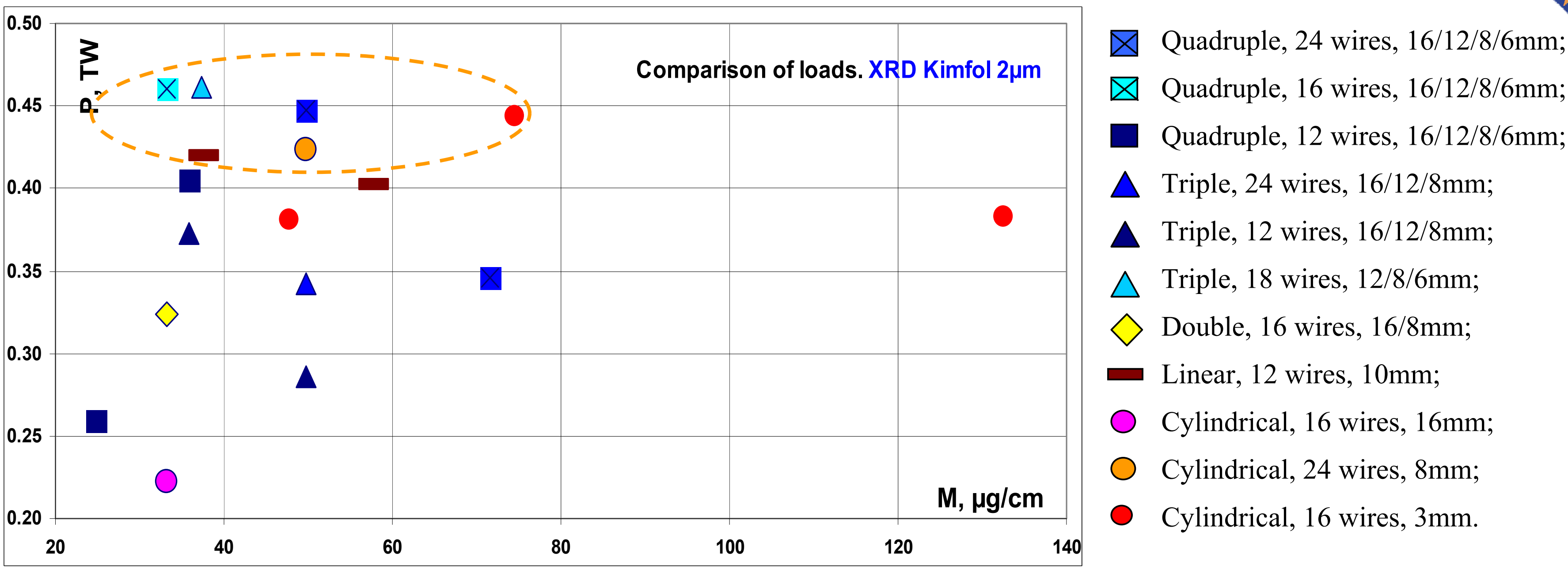
MHD simulation could help to optimize wire spacing

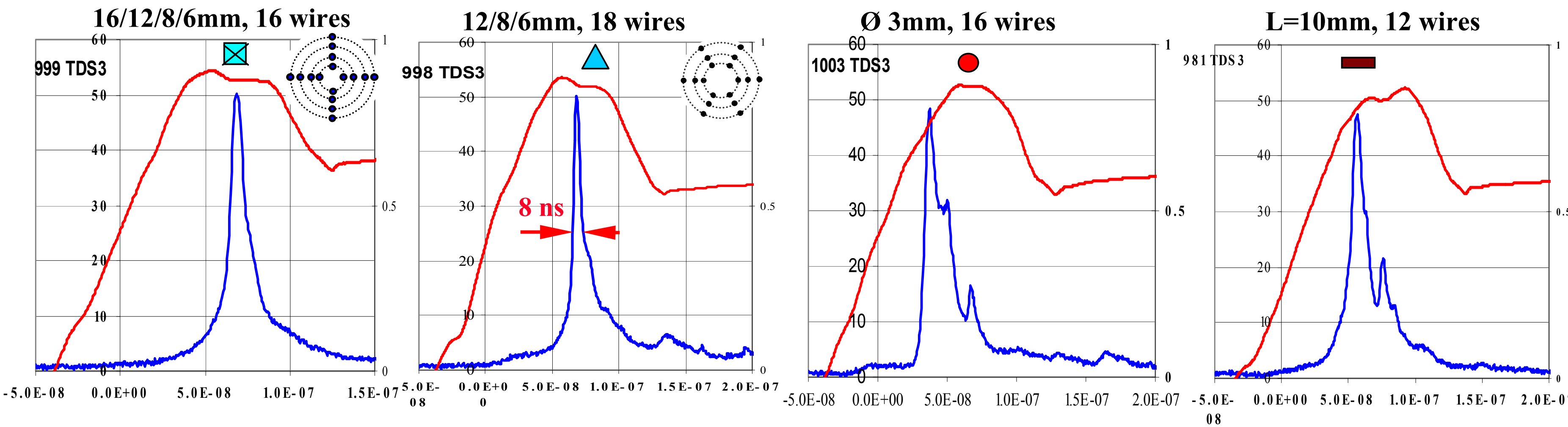
- **Improved azimuthal symmetry increases radiated soft x-ray power in star-like loads.**
- **Compact star-like wire array produces larger x-ray power.**

Shot to shot reproducibility and soft x-ray power increases with a number of cylinders



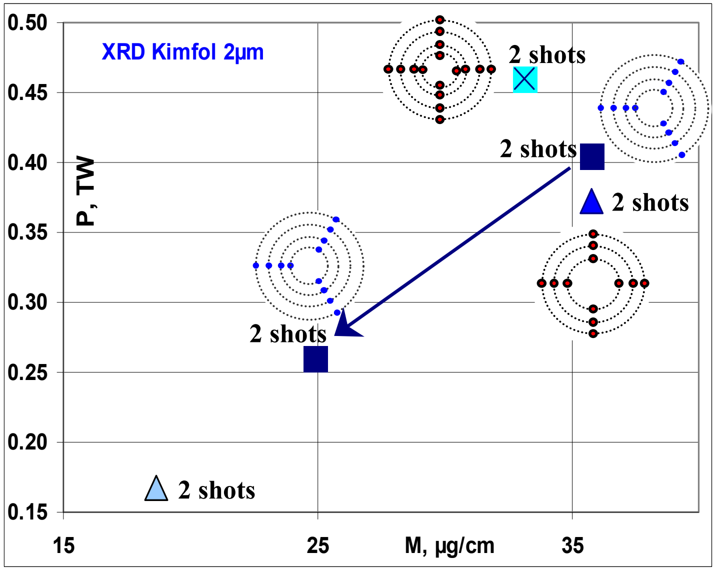
Comparison of Loads in the Zebra Generator

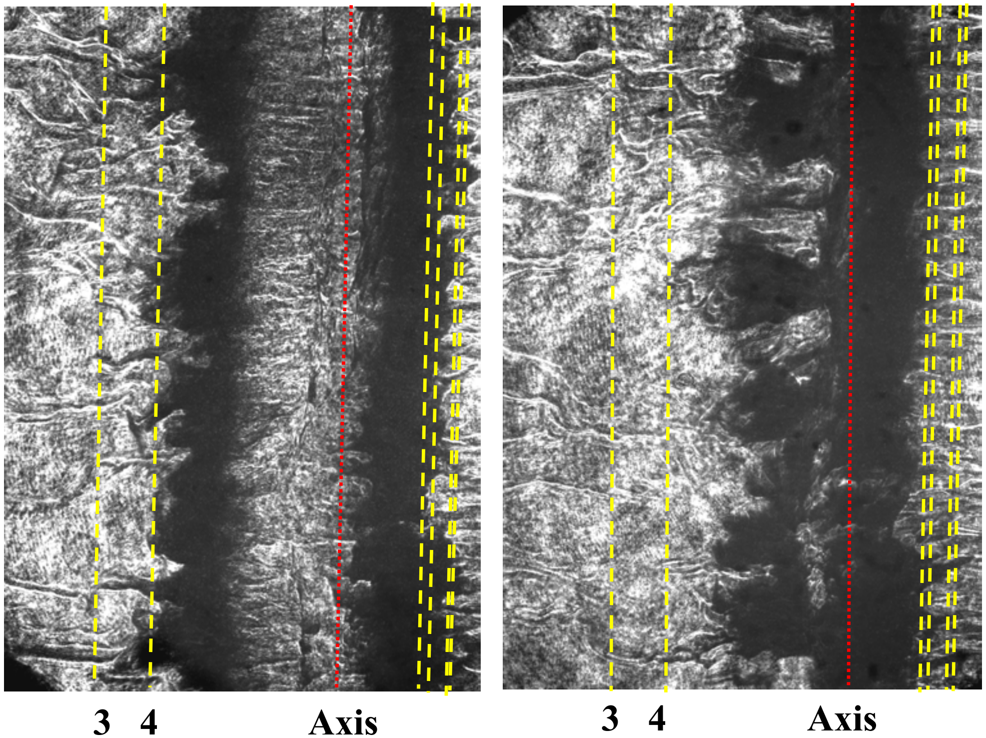




Power of the soft x-ray pulse fall in light loads

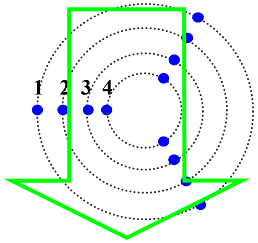
MHD instability breaks the leading edge of the moving plasma column



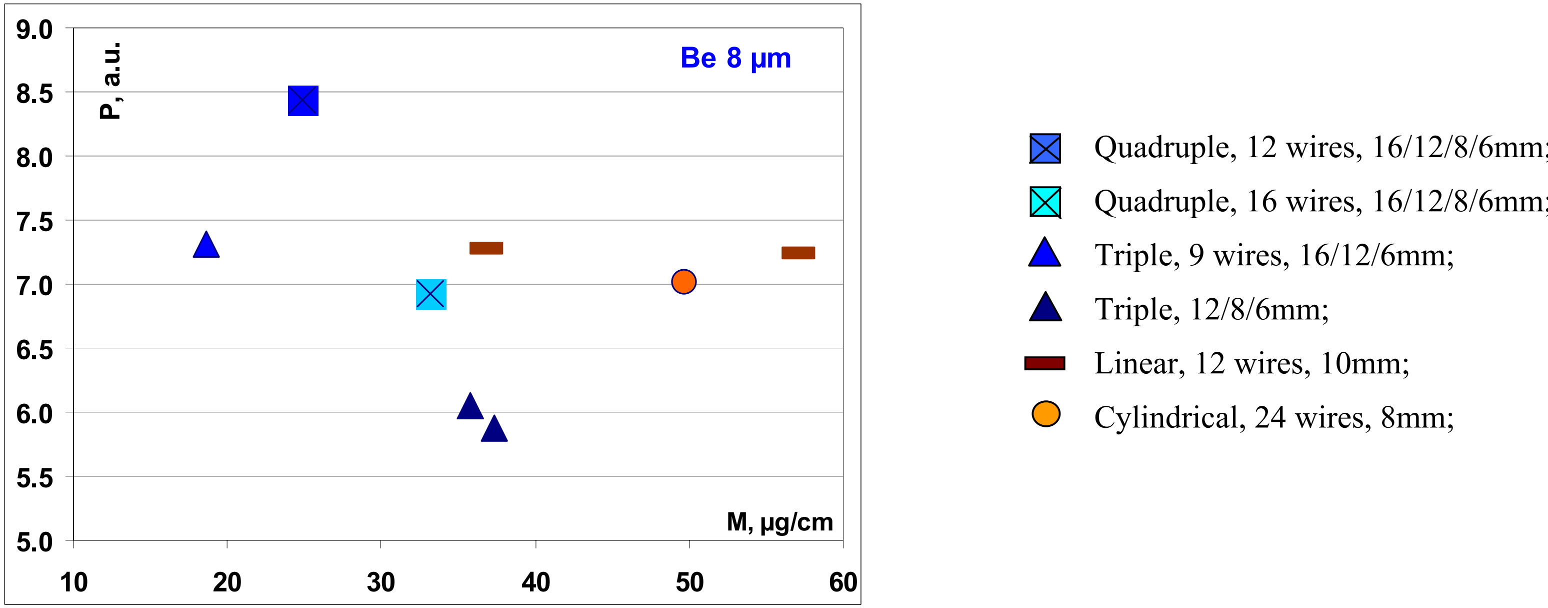


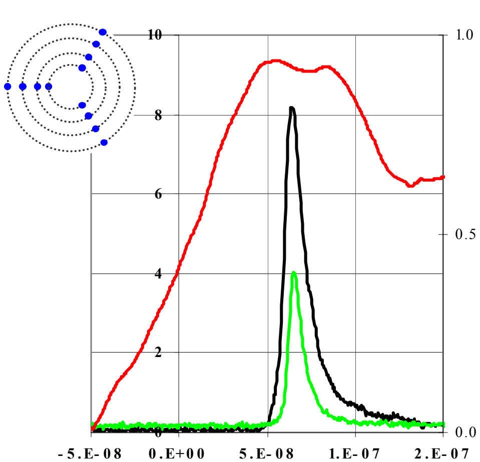
Bubbles and MHD instability are not smoothed because of larger speed and kinetic energy per unit mass

993. Al 12 wires, 10µm
16/12/8/6mm

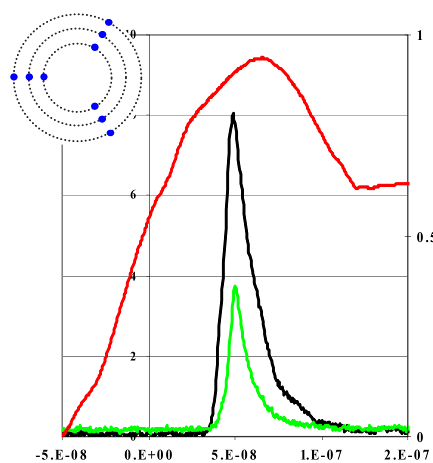


Light star-like loads are good radiators of K-shell x-ray

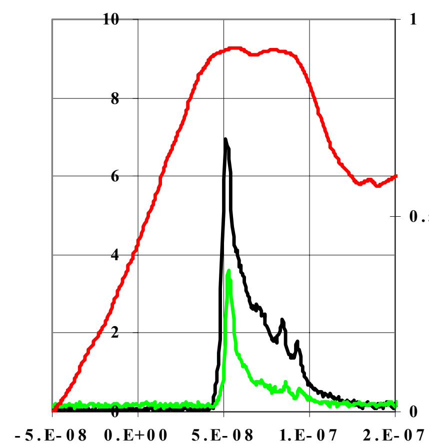




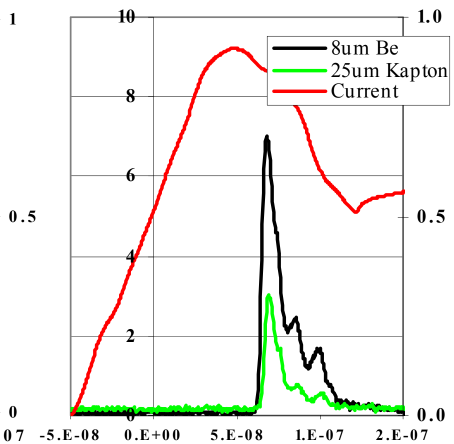
16/12/8/6mm, 12 wires



16/12/6mm, 9 wires

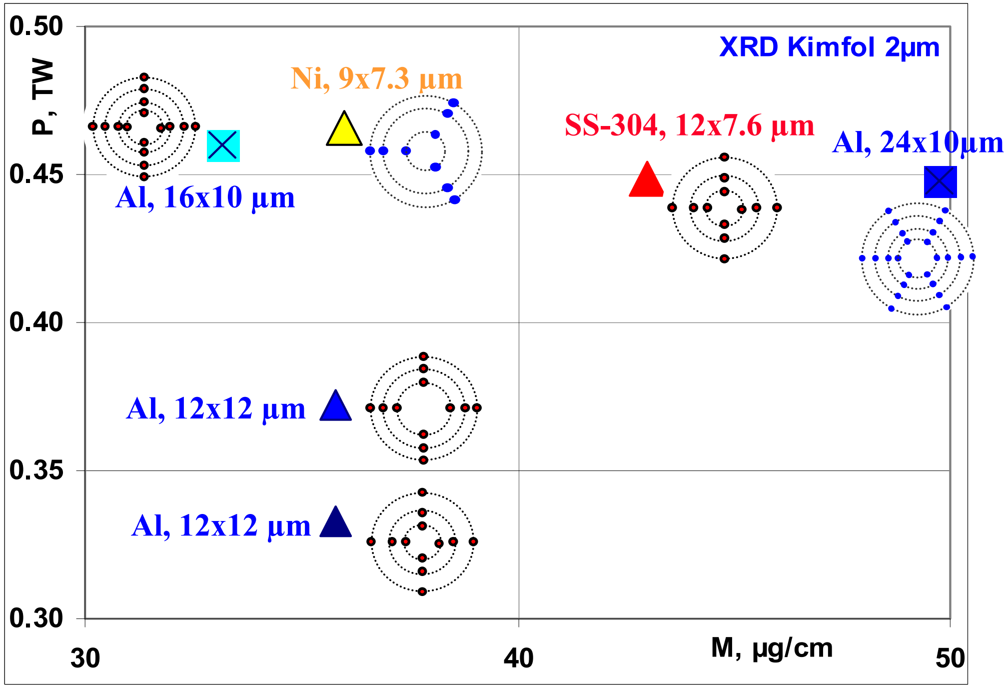


Linear, 12 wires



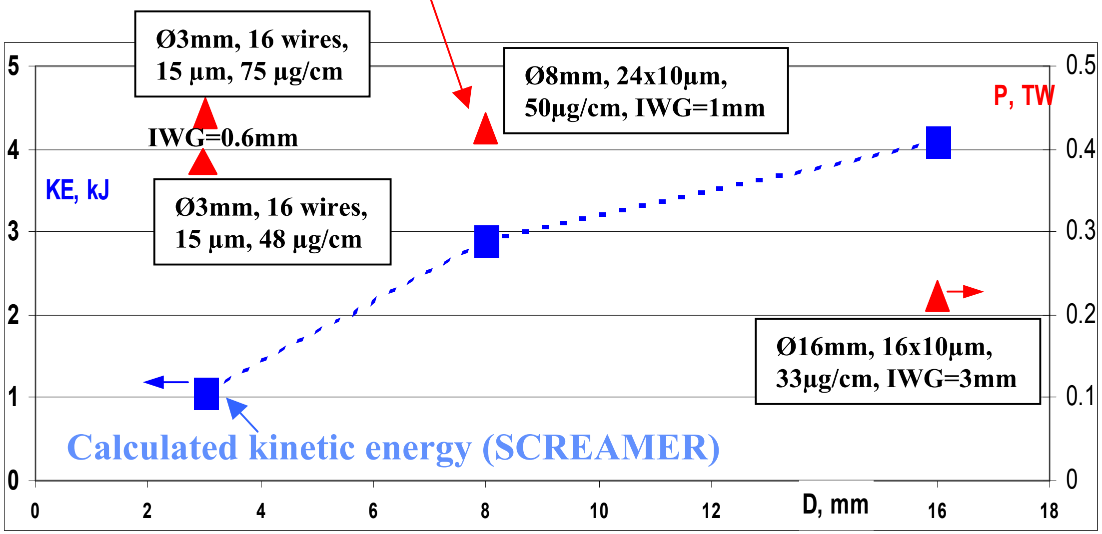
Ø8mm, 24 wires

Stainless steel and Ni star-like wire arrays produce larger soft x-ray power than Al loads

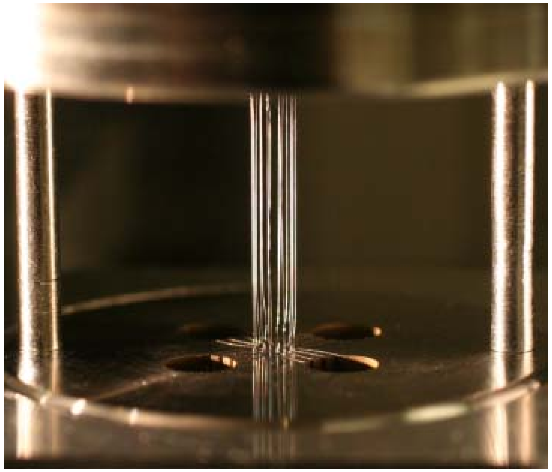


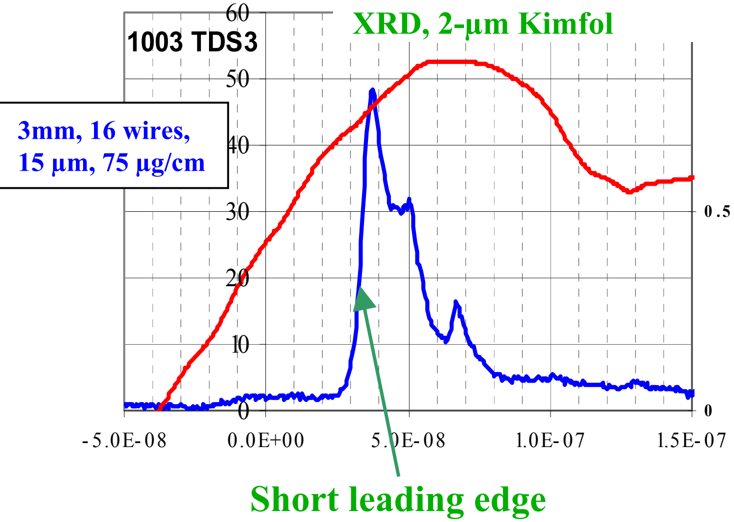
Calculated kinetic energy falls in 3-mm loads but radiated power increases

Radiated peak power (Ni bolometer/XRD with a 2-µm Kimfol filter)



Cylindrical, 16 wires, Ø3 mm





1. Does 0-D calculation return right kinetic energy?
2. Is inter-wire gap important?
3. Can microturbulence play a role in the soft x-ray production and form a short rising edge?

Conclusions

1. Different types of loads were tested in the 1-MA Zebra generator. Star-like, compact cylindrical, and linear wire arrays radiate the largest soft x-ray peak power.
2. Smoothing of MHD instability was observed in star-like loads during cascade implosion. This could be linked to efficient production of soft x-ray radiation. High level of MHD instability in light star-like loads correlates to the fall of radiated x-ray power. Light star-like loads are good radiators of the K-shell x-ray.
3. Very compact cylindrical loads produce a powerful soft x-ray pulse despite smaller calculated kinetic energy. More experiments are needed to investigate mechanisms of implosion in compact arrays.