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Measurement and modeling of the implosion of wire arrays with seeded instabilities

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Imperial College

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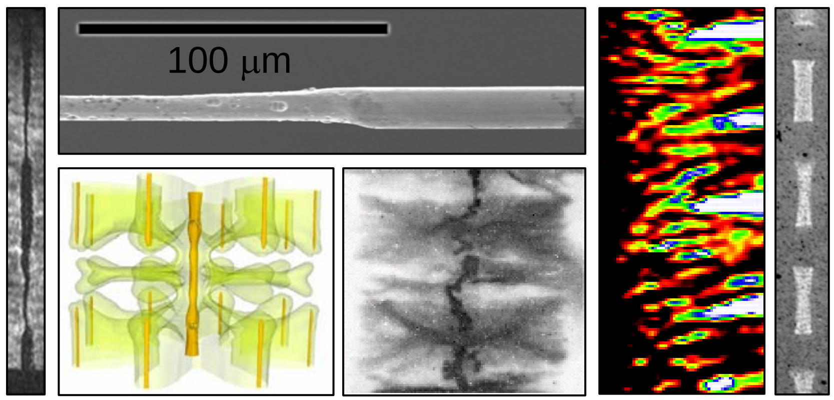
Mission Research Corp.



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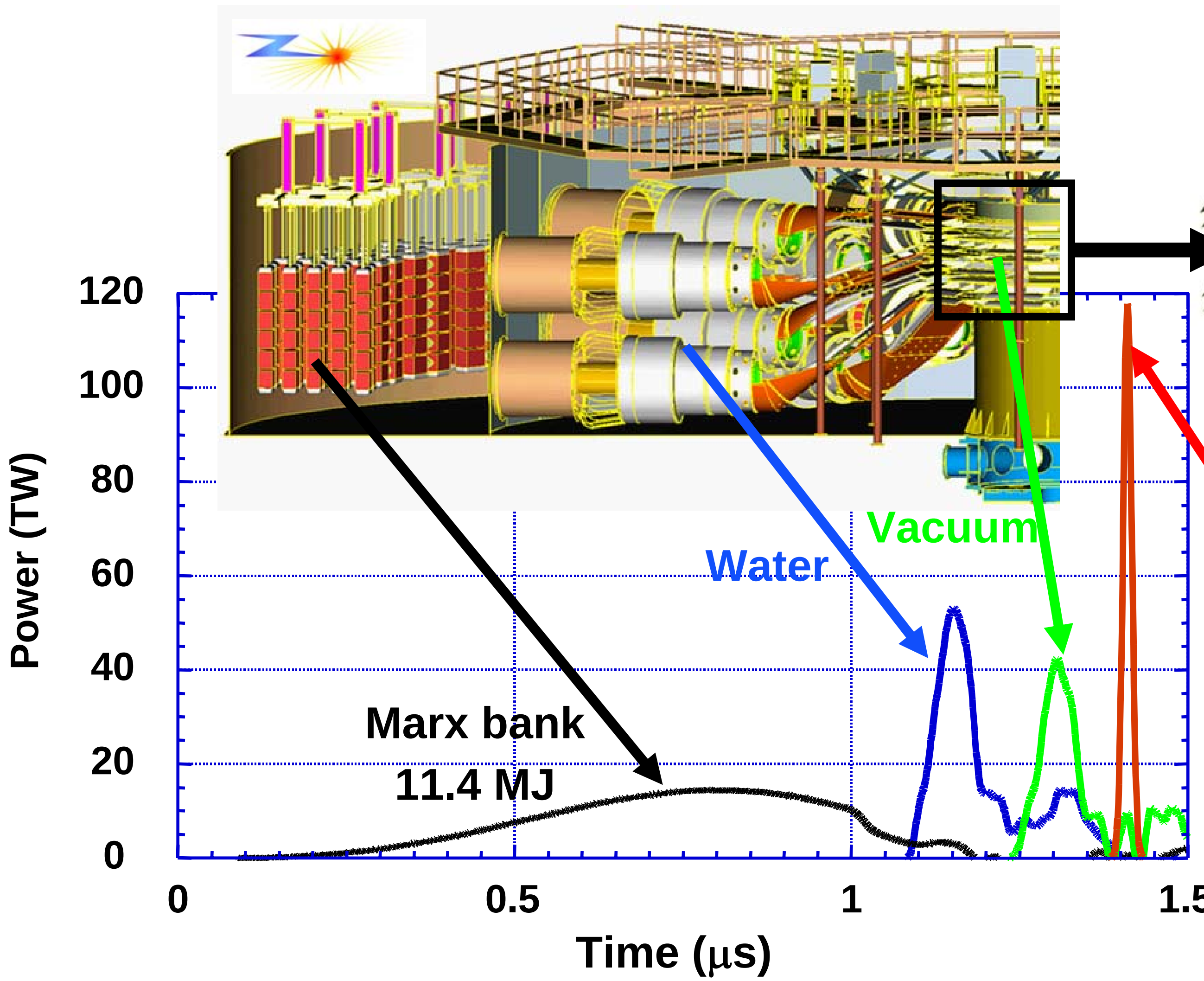
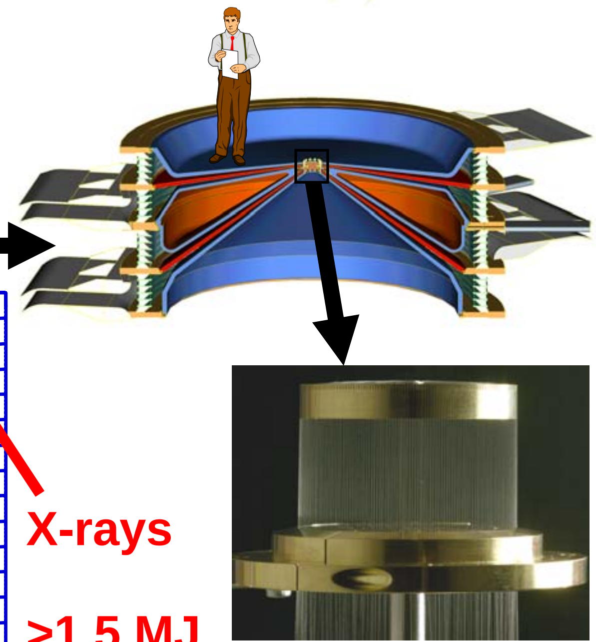
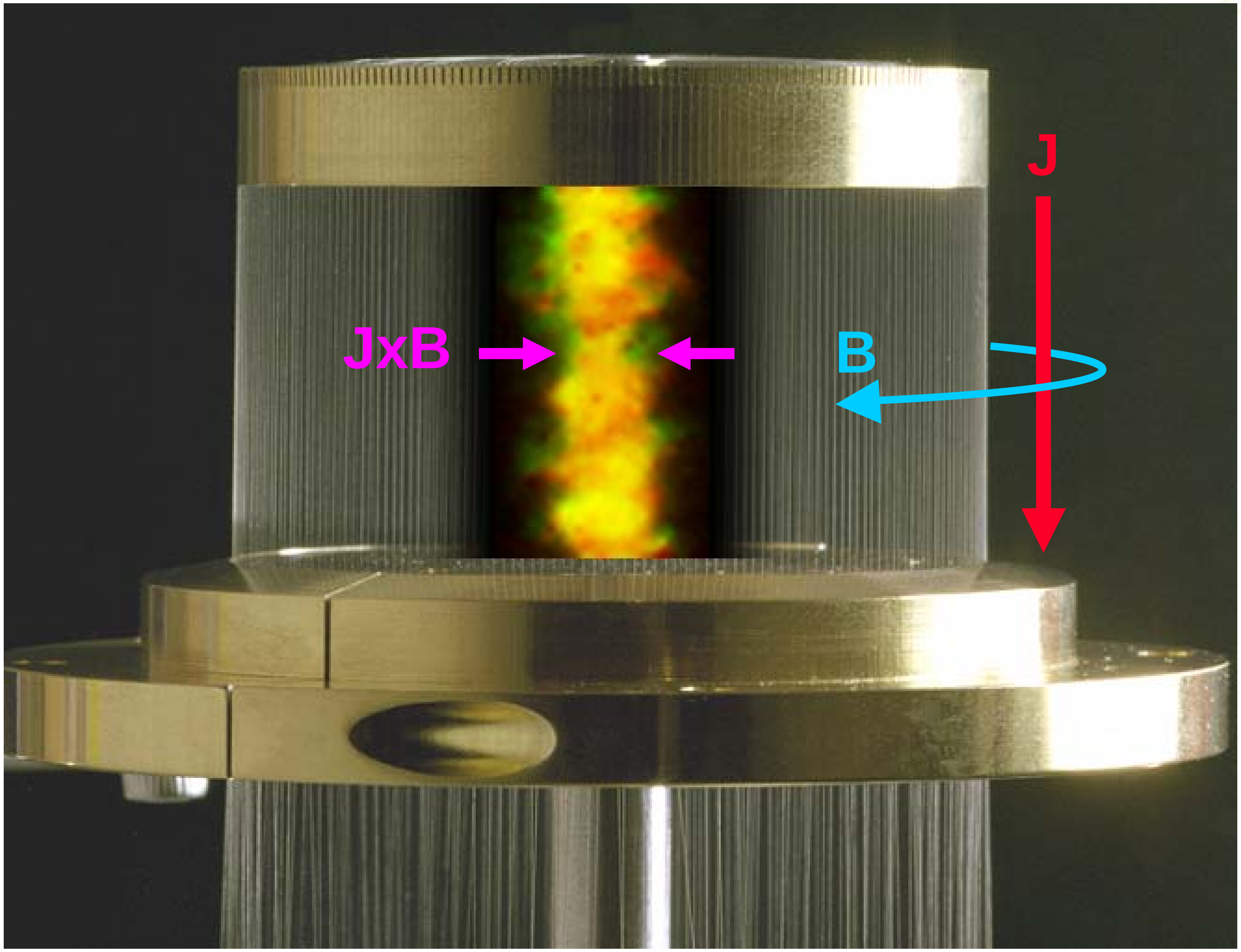
Sandia's Z machine produces world-record soft x-ray powers





J x B pinches wire array into a dense, radiating plasma

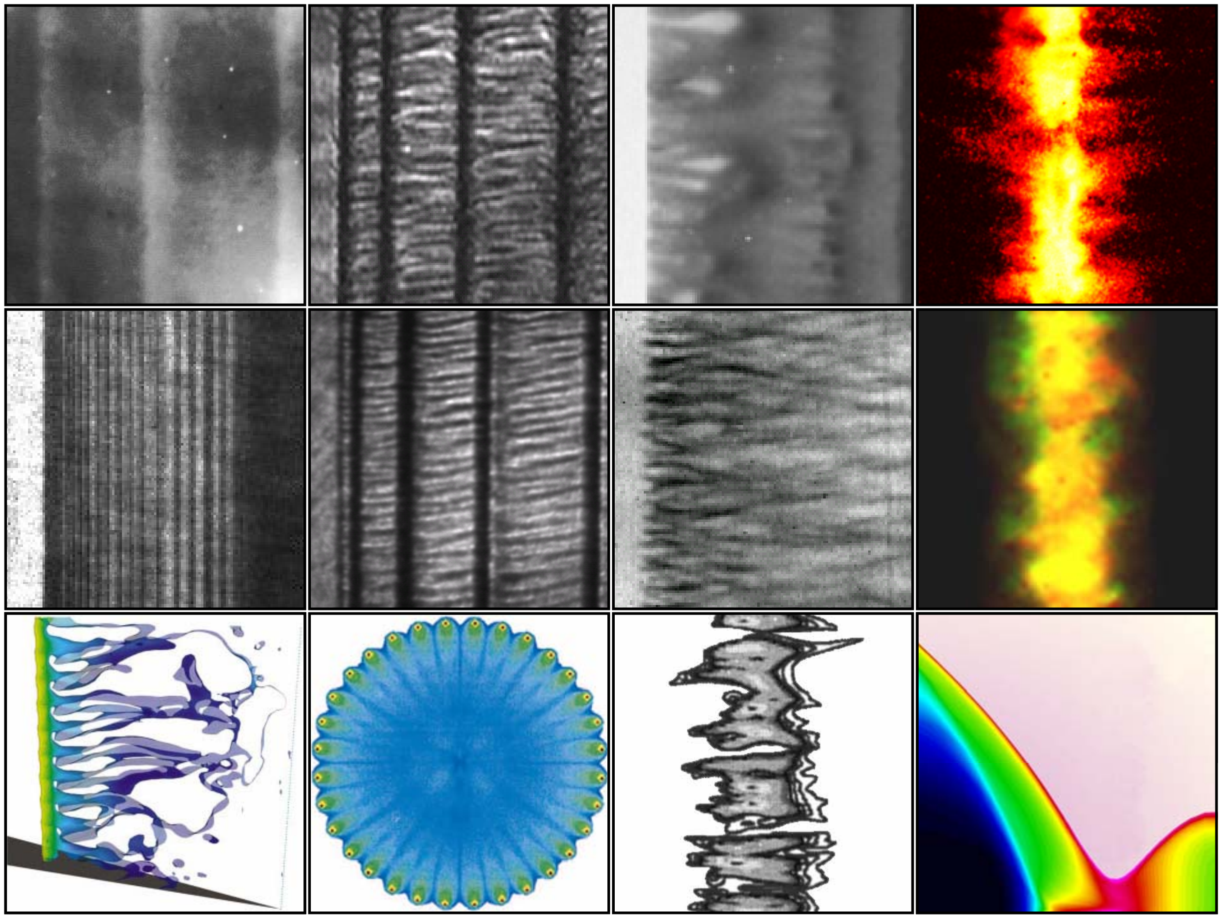


Wire array z-pinches do not implode as a simple shell

Expanded core-corona | Ablation | Implosion | Stagnation

1 MA

20 MA



Experiment

Modeling

3D MHD | 2D r-θ MHD | 2D r-z MHD | 1D RMHD

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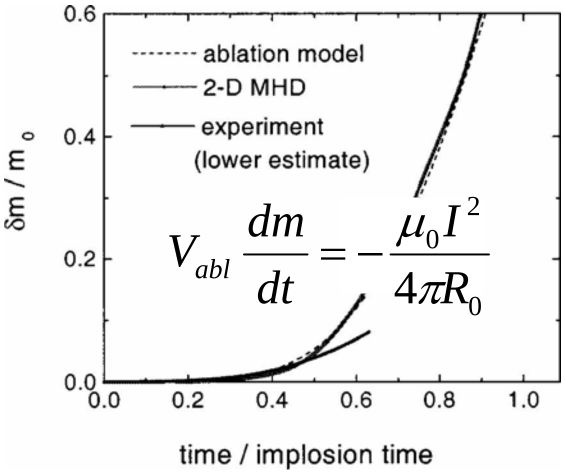
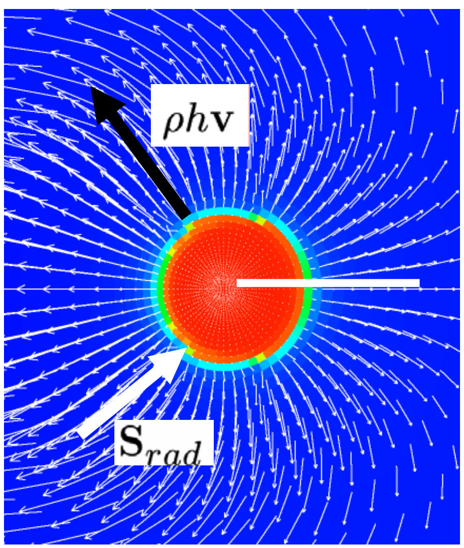
Instabilities appear during the wire ablation phase

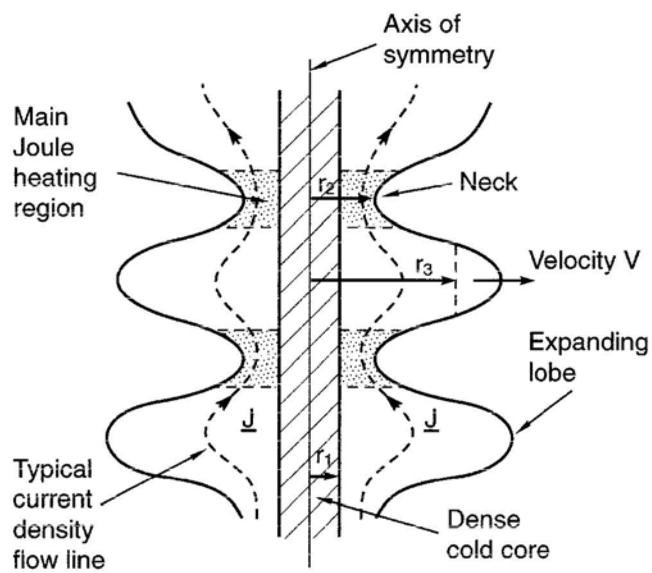


S. V. Lebedev *et al.*, Phys. Plasmas **8**, 3734 (2001).



E. P. Yu *et al.*, DPP05 C03.6

- Ablation rate is understood through an analytic rocket model and 2D r-θ MHD
- m=0 coronal instability and **j** x $\mathbf{B}_{global}$ results in ablating flares—what determines the characteristic λ?
  - MHD favored mode with ka~1
  - Electrothermal instability (Haines)



M. G. Haines, IEEE Trans. Plasma Sci. **30**, 588 (2002).

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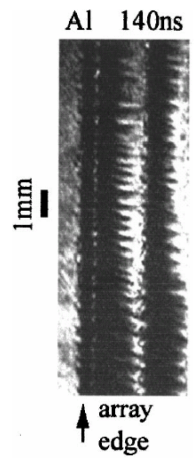
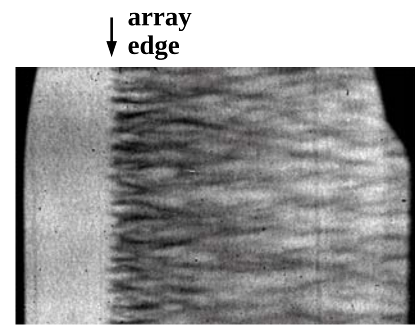
3D structure impacts x-ray production in wire array z-pinches

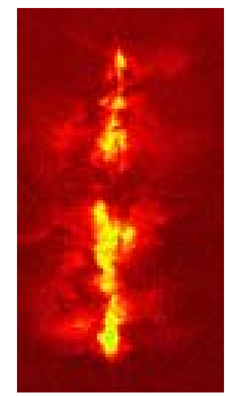
- Instabilities in wire plasma lead to 3D structure at implosion
  - Non-uniform wire ablation early in time leads to radial flare formation
  - Magnetic Rayleigh-Taylor type implosion instability seeded by flares
  - Trailing mass may impact current path
  - 3D structure in stagnated pinch likely impacts x-ray generation and transport



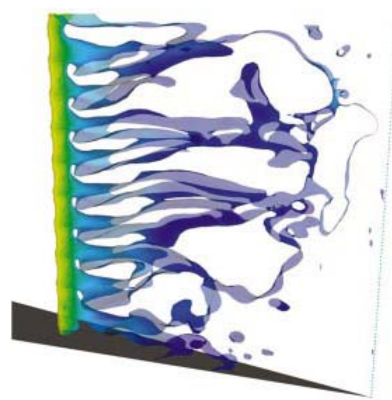
Wire ablation; Lebedev *et al.*, Phys. Plasmas **8**, 3734 (2001).



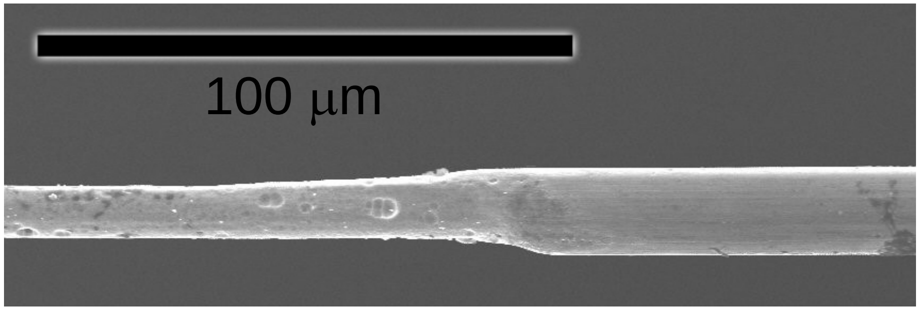
Stainless steel wire array on Z at 13.9 MA; D. B. Sinars *et al.*, Phys. Plasmas **12**, 056303 (2005).

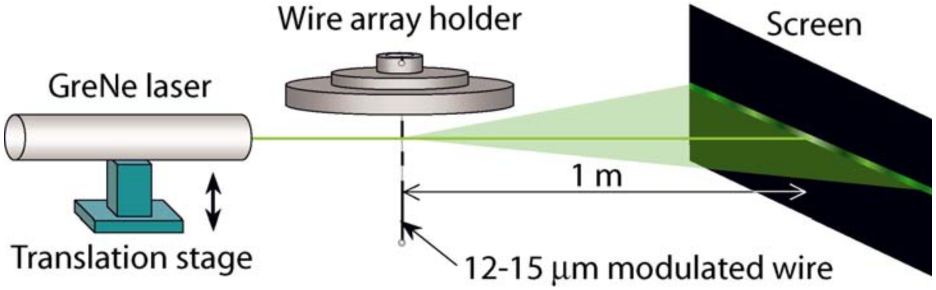

Al/Ni/Ti wire array on Z near peak x-ray power

- *Ad hoc* perturbations are seeded in 3D MHD simulations to reproduce phenomenological structure
  - C. J. Garasi *et al.*, Phys. Plasmas **11**, 2729 (2004).
  - J. P. Chittenden *et al.*, Plasma Phys. Control. Fusion **46**, B457 (2004).



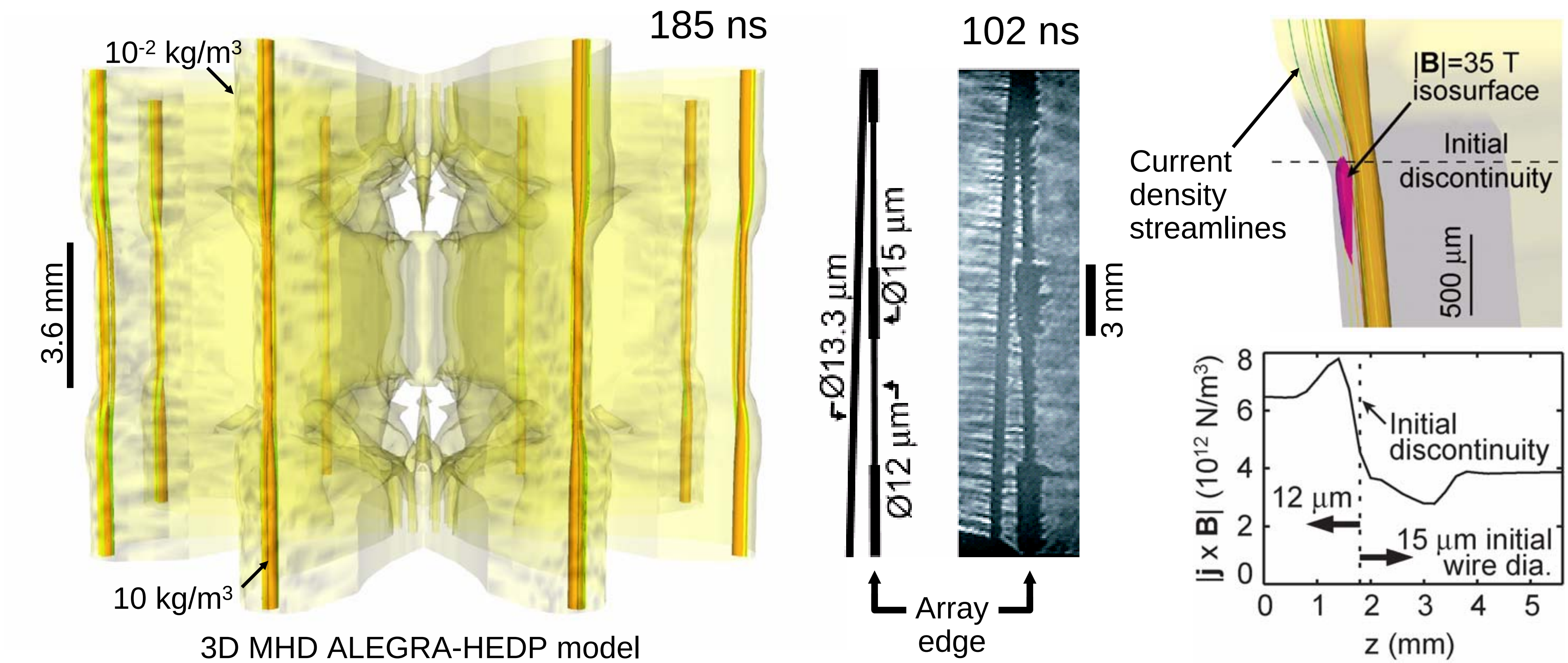
Mass perturbations are seeded by modulating wire radius





- Extruded Ø15 μm Al 5056 wires are chemically etched at MPCL/Sandia to have 20% modulation in radius with controlled axial wavelength
  – B. Jones *et al*., Rev. Sci. Instrum. **75**, 5030 (2004).
- Aligned in wire arrays to ±100 μm with laser diffraction
- Allows seeded perturbations in z-pinch mass/length
  – Investigate radial flare formation
  – Implosion RT-type instability growth studies
  – X-ray pulse shaping by tailoring the profile of the imploding mass
- Seeded perturbations have been employed in laser plasmas
  – e.g. H. F. Robey *et al*., Phys. Plasmas **8**, 2446 (2001).

Coronal modulation enhances |j x B| at wire discontinuities



- Enhanced magnetic field in thinner core regions constricts coronal plasma, leaving imprint of modulated structure
- Non-uniform current path near discontinuities in coronal plasma radius causes local magnetic field enhancement

– B. Jones *et al.*, accepted in Phys. Rev. Lett. (2005).

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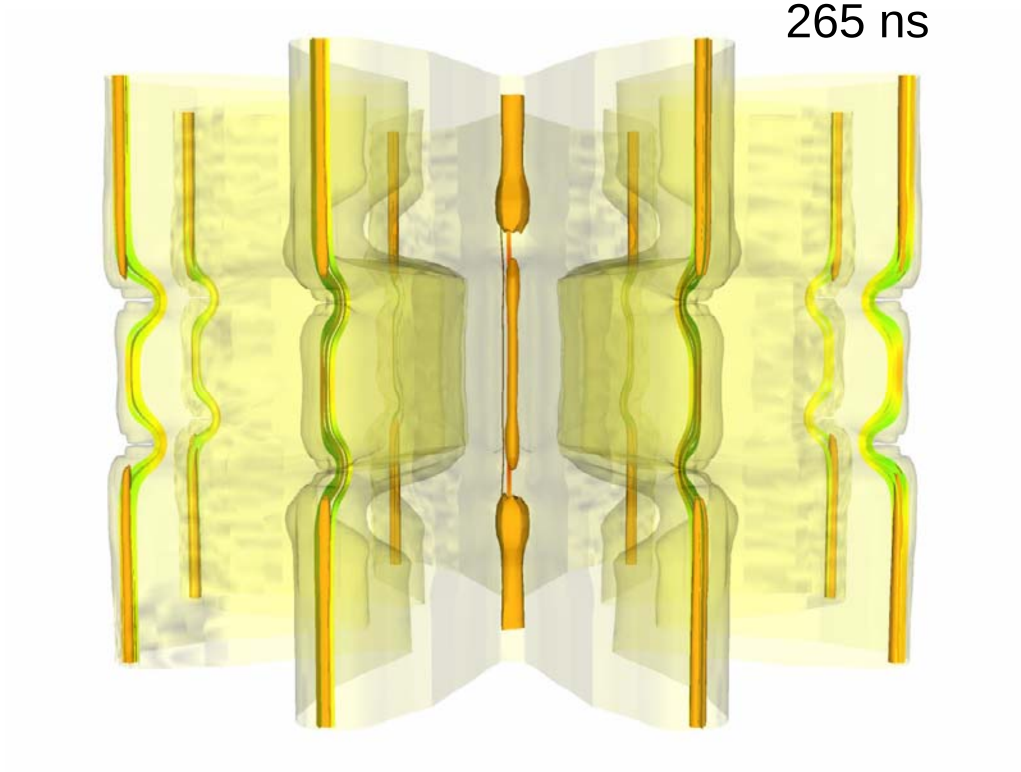
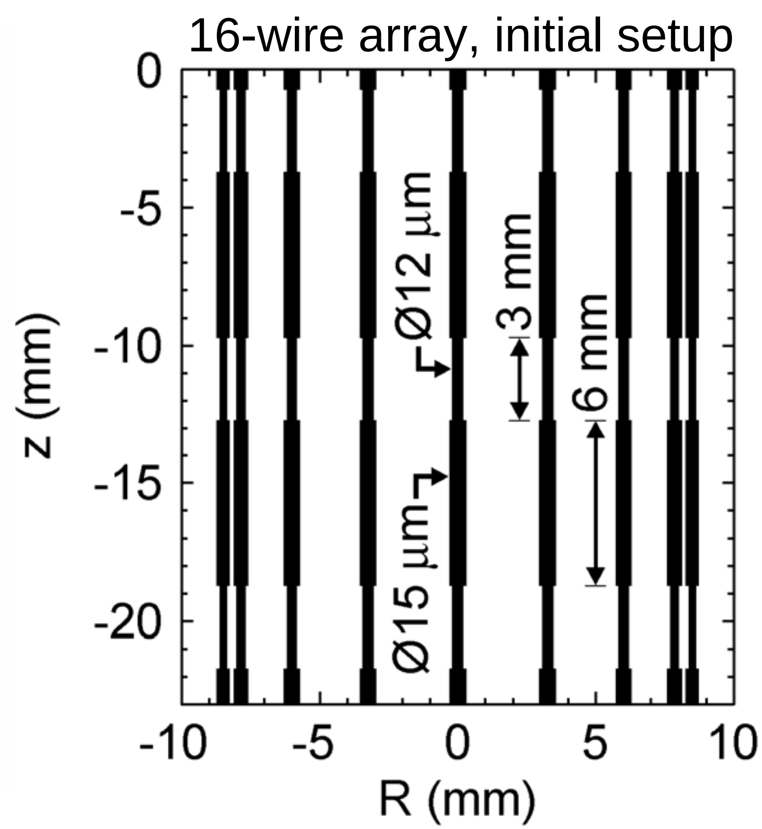
Magnetic bubbles form at the discontinuities in wire radius





- Local |**j** x **B**| enhancement at wire radius discontinuities enhances ablation, breaks wire cores, and initiates bubble implosion at discontinuities
- Bubble formation seen in both MHD model and experiment

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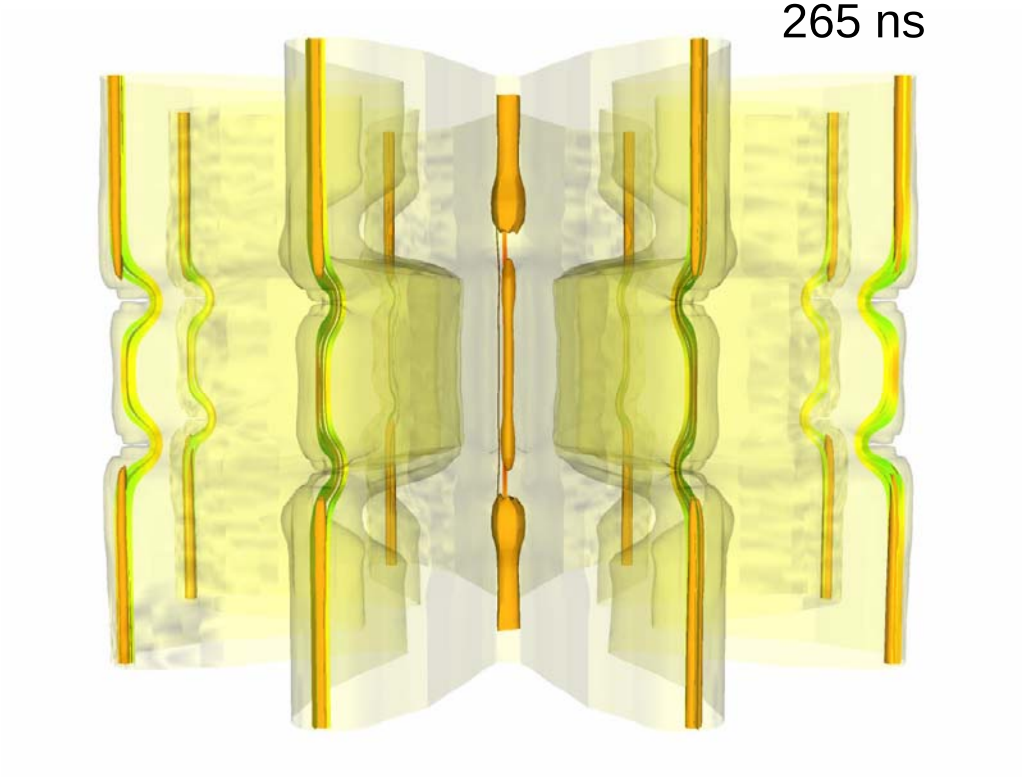

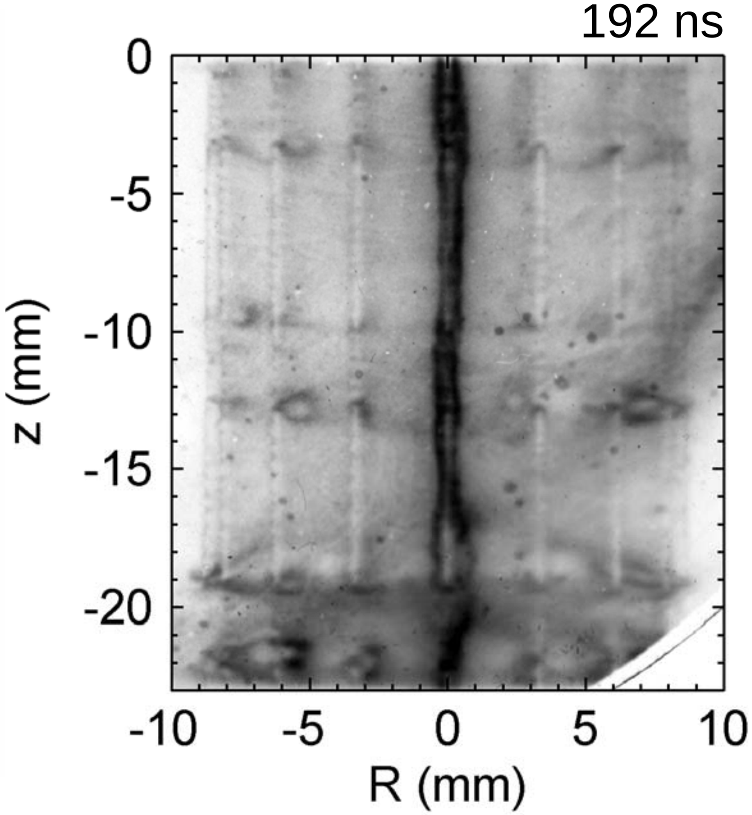

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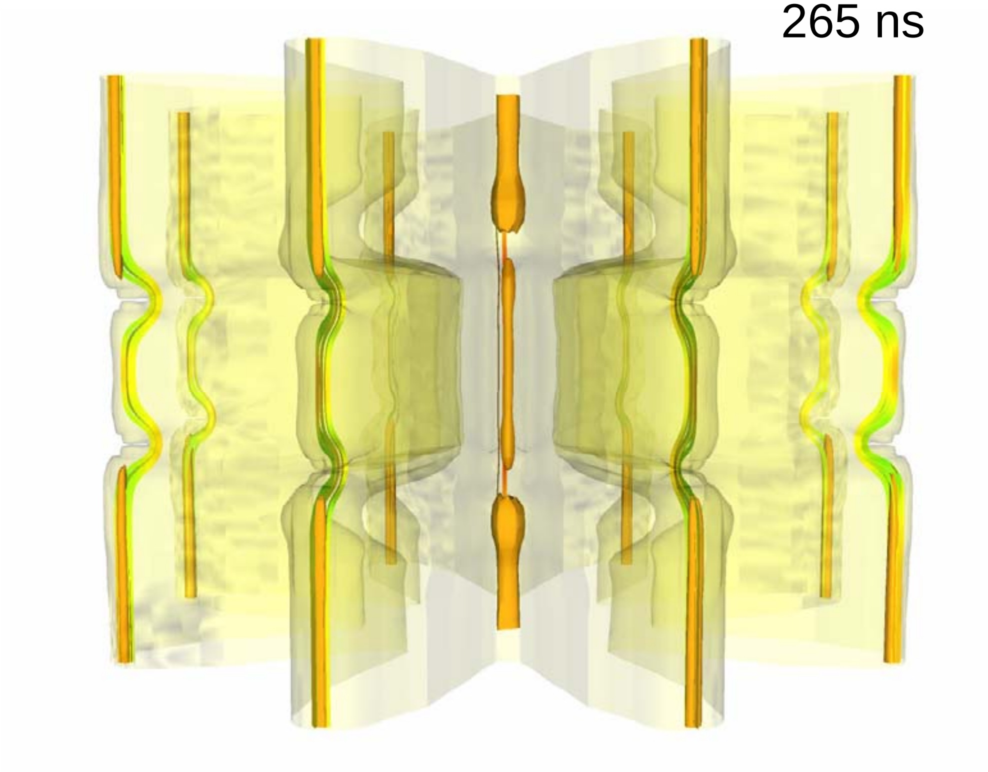

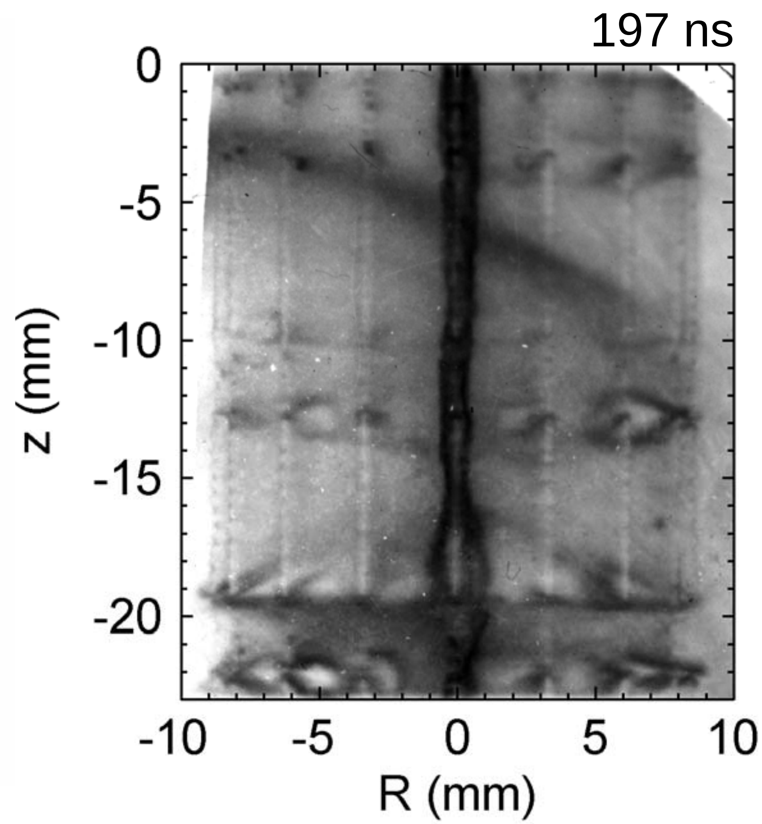

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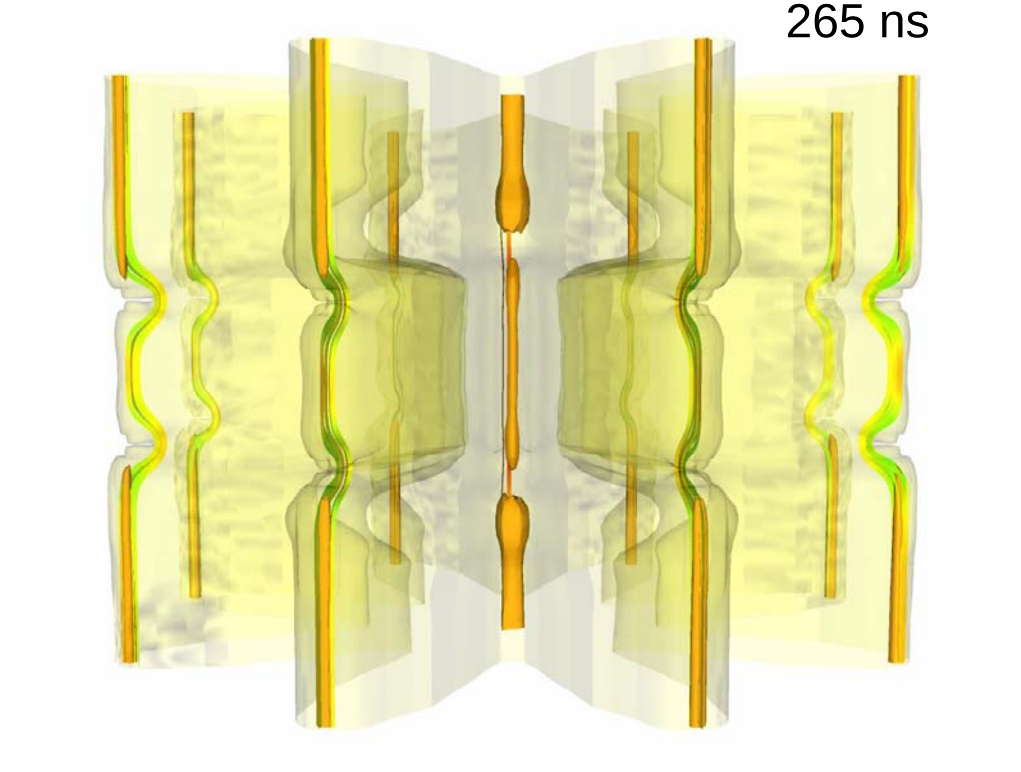

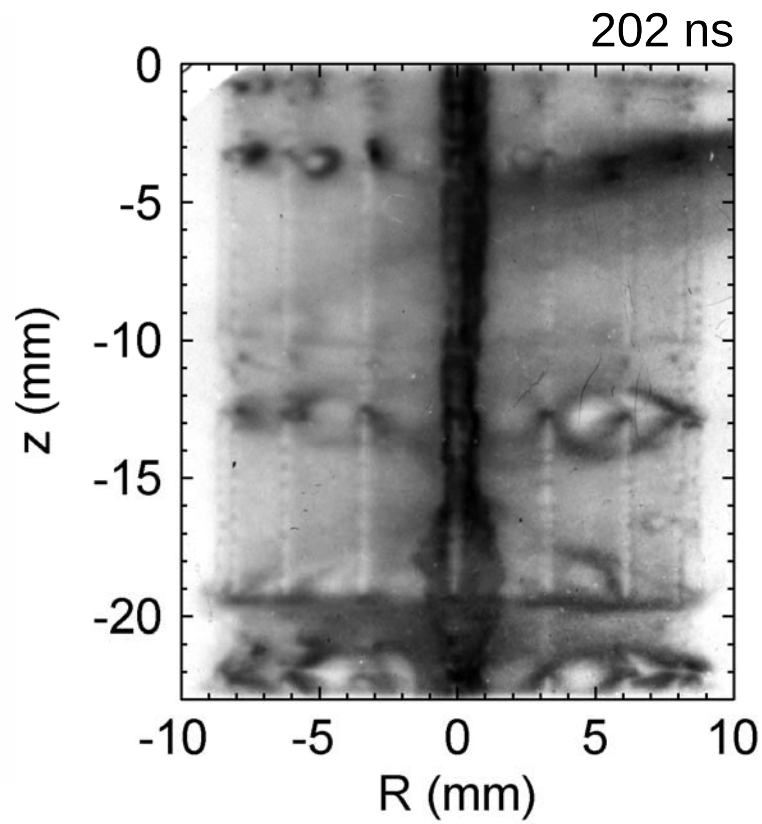

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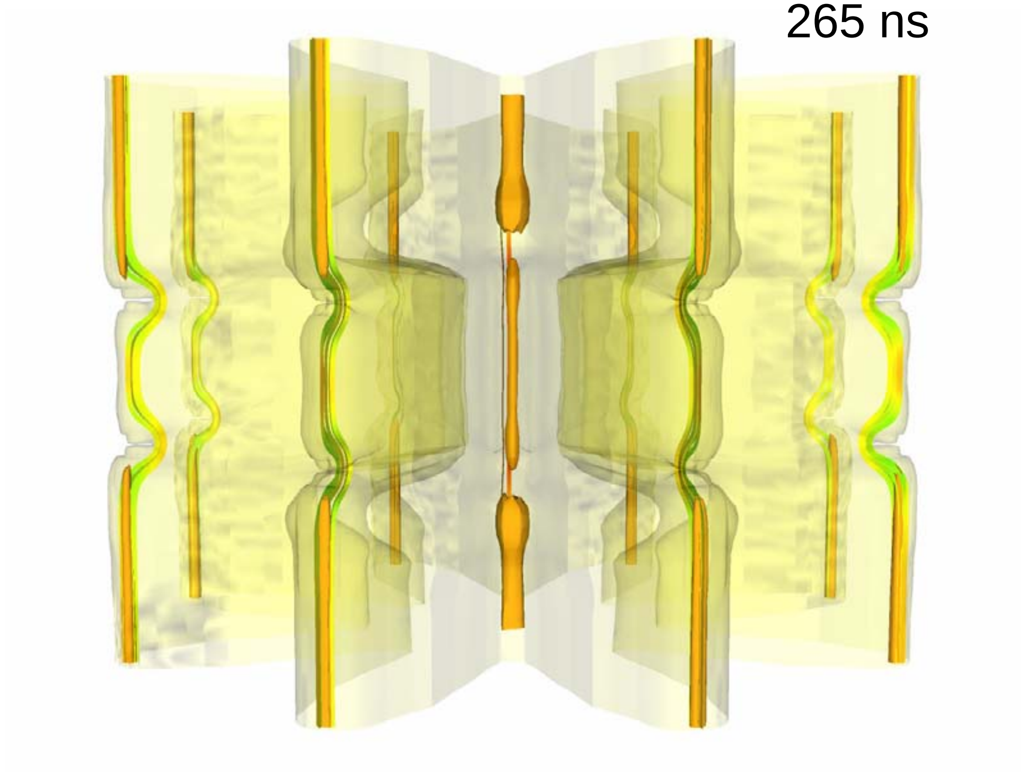

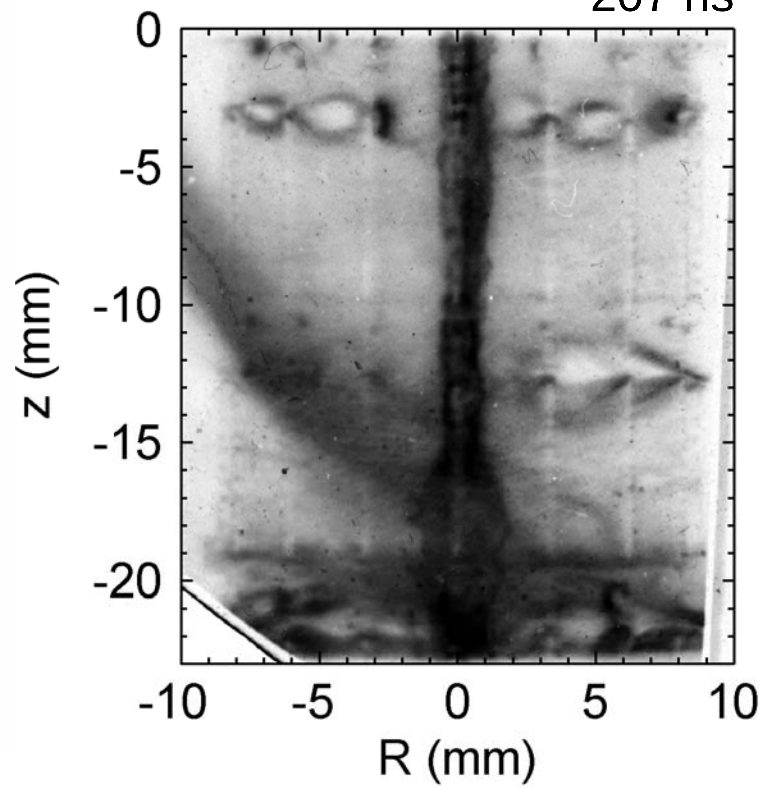

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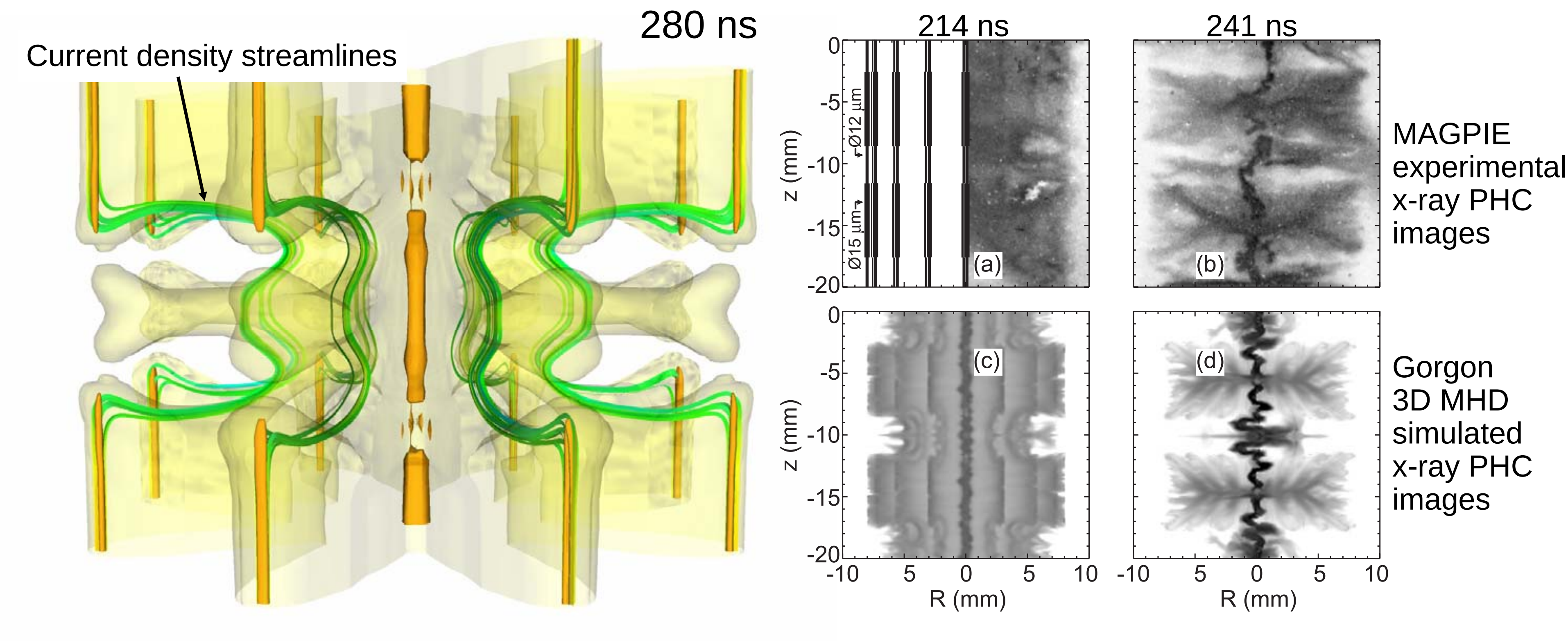
Correlated gaps form as magnetic bubbles implode



- Gorgon MHD model includes short-wavelength perturbations
- Same physics may explain trailing spikes in standard array
- Measurement of magnetic field in the gaps is needed to determine the actual current path

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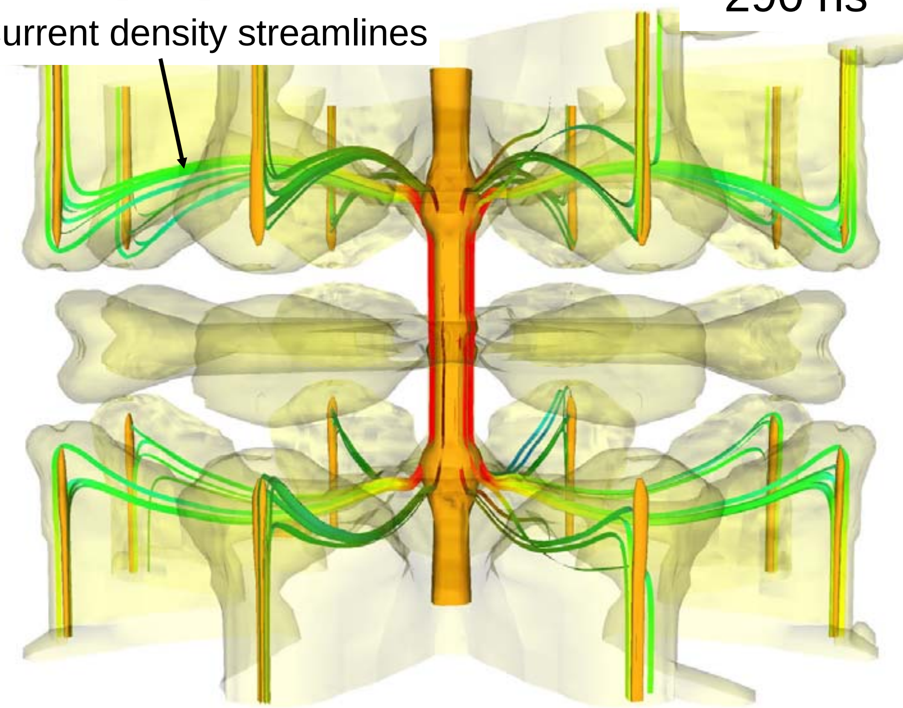
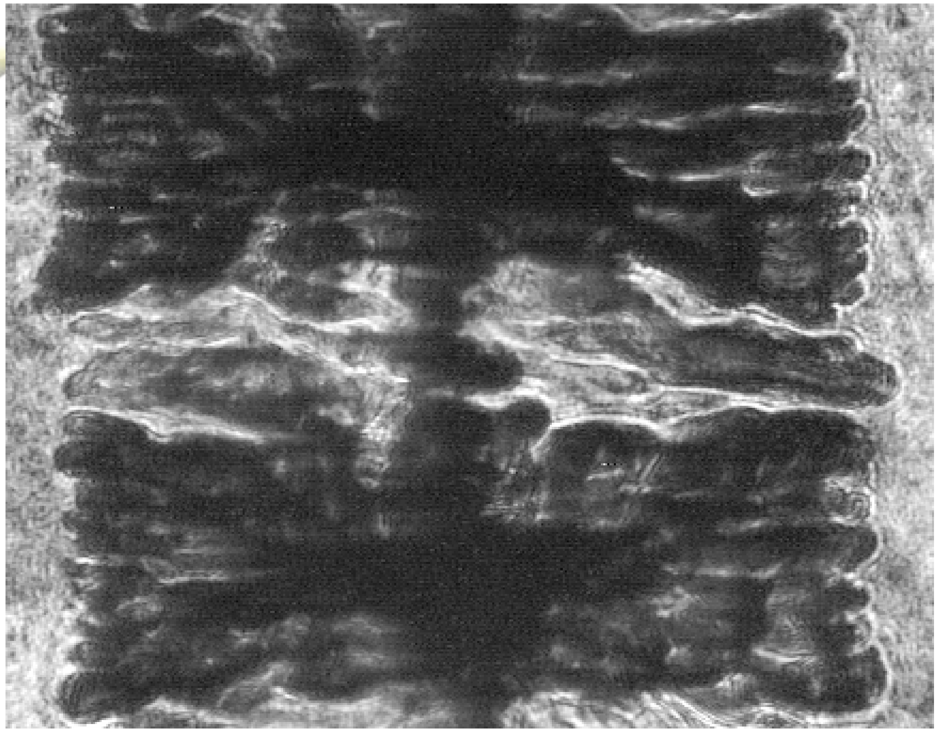
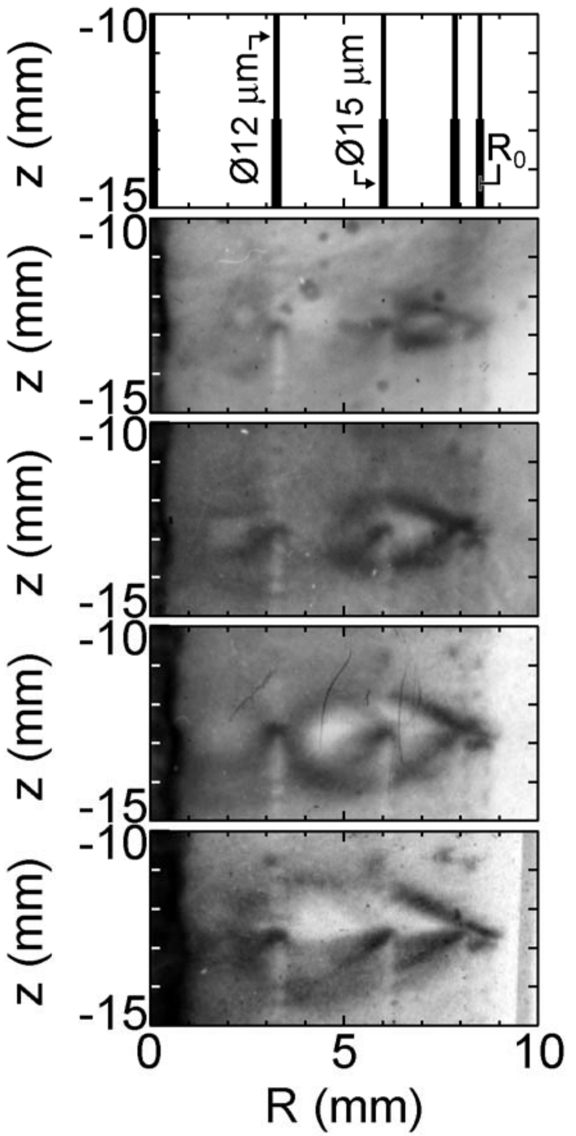
Correlated gaps form as magnetic bubbles implode

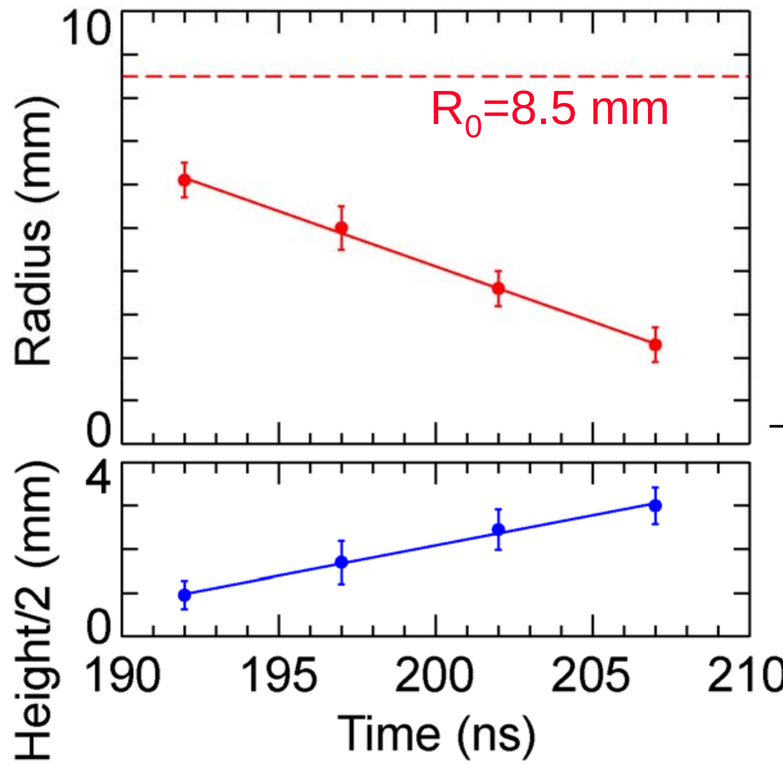




- Same physics likely explains trailing spikes in standard array
  - Standard wire array shows similar ~2 mm bubble size on MAGPIE
- Measurement of magnetic field in the gaps is needed to determine the actual current path

Bubbles are observed to implode rapidly—driven by j x B?





Fit results –

v = 25.5 ± 3.6 cm/μs

R = R_0 at
t = 182.8 ± 1.9 ns

R = 1 mm at
t = 212.2 ± 3.4 ns

v = 13.9 ± 3.4 cm/μs

H = 0 at
t = 185.0 ± 2.7 ns

- 20-25 cm/μs bubble implosion velocity
- Bubble blown from a point, rather than expanding spherically like a blast wave
- **j** x **B** would accelerate bubble, but snowplow of prefill decelerates it

$$F = \frac{d}{dt}(mv) = \dot{m}v + m\dot{v} = \frac{\mu_0 I^2}{4\pi NR}$$

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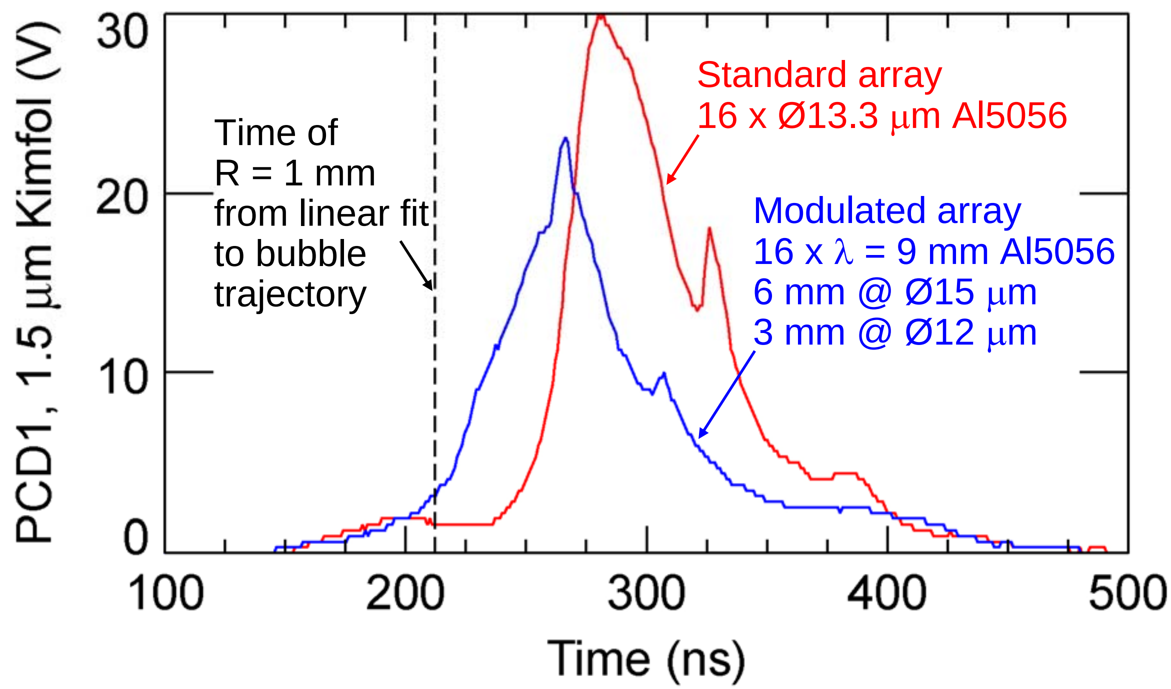
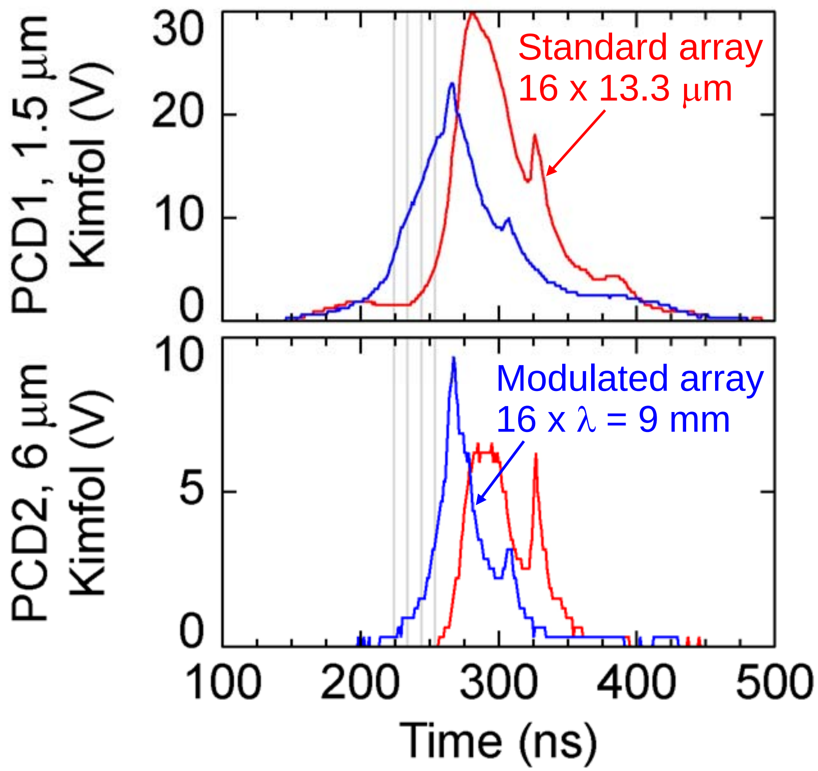
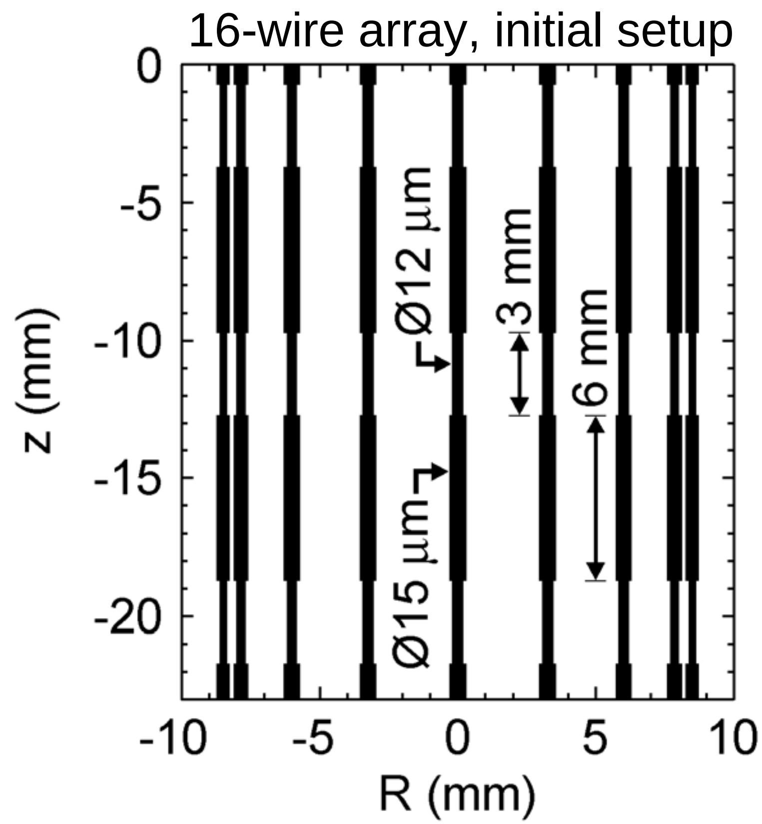
Bubble collision on axis determines start of x-ray rise



- Comparison of modulated with standard array of same mass
- Similar initial rise of precursor radiation
- Start of main x-ray rise corresponds to collision of imploding bubbles with the precursor (see also V. V. Ivanov, BP1.121)
- X-ray pulse shaping by tailoring the arrival of mass on axis

X-ray pulse shape determined by assembly of mass on axis





- Peak power is similar to standard wire array
- Stagnated pinch may be hotter with lower mass
- Bubbles from discontinuities zipper on axis into a dense pinch—likely similar mechanism in standard array

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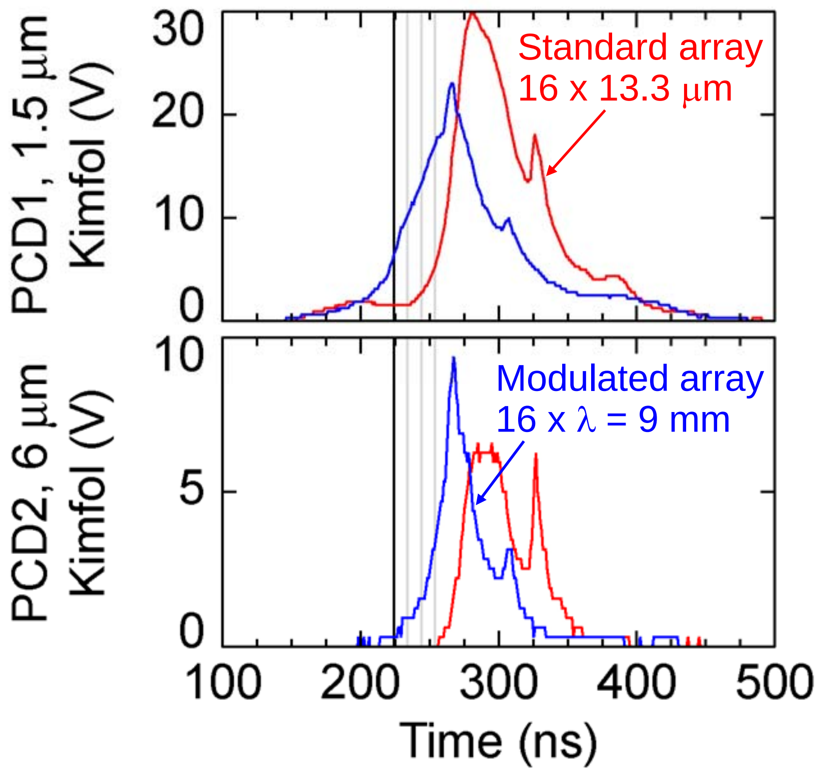

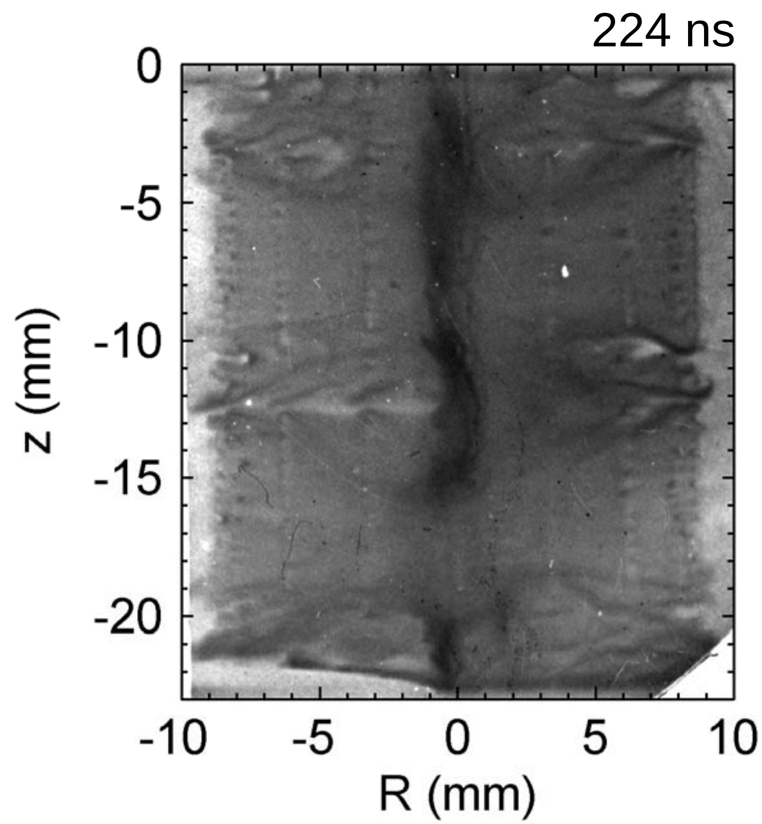

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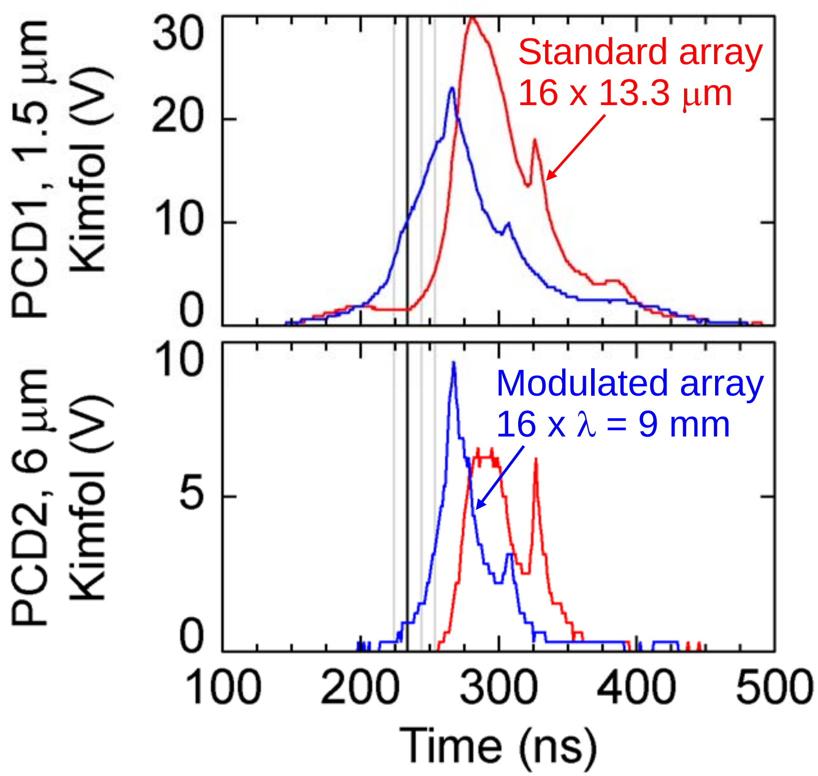

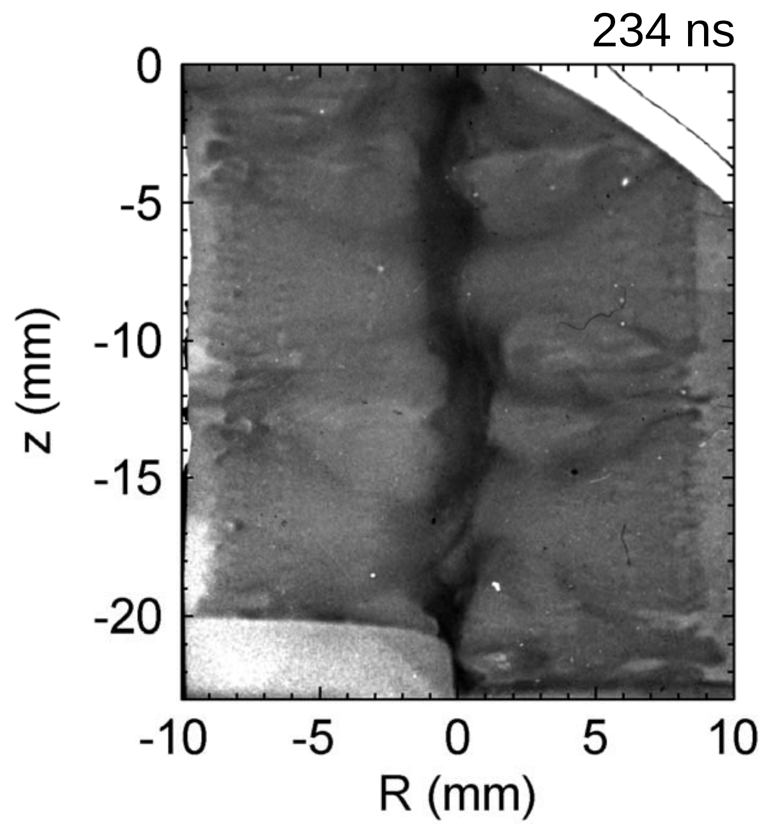

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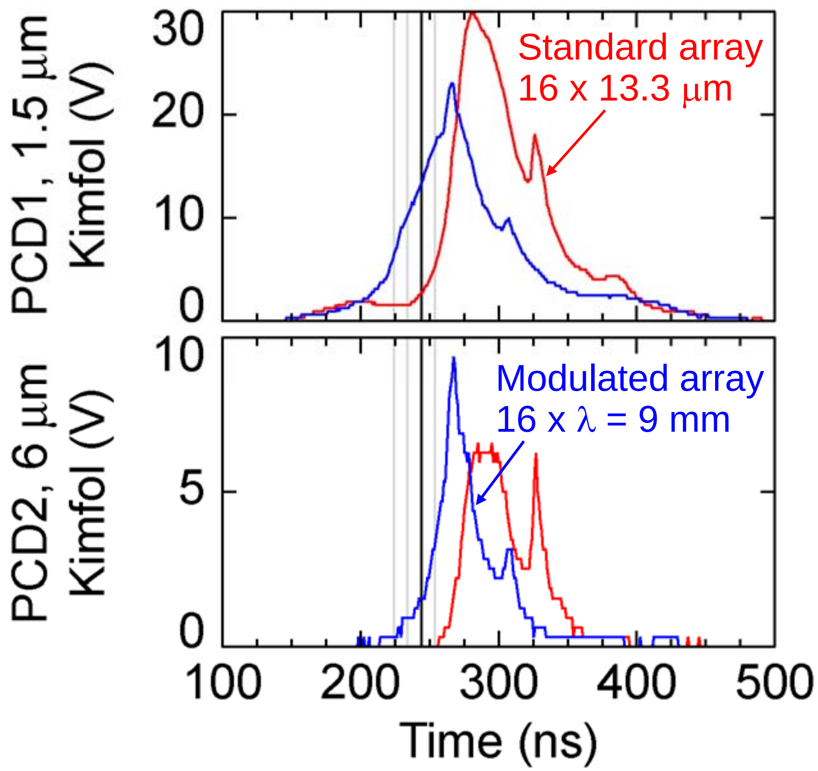

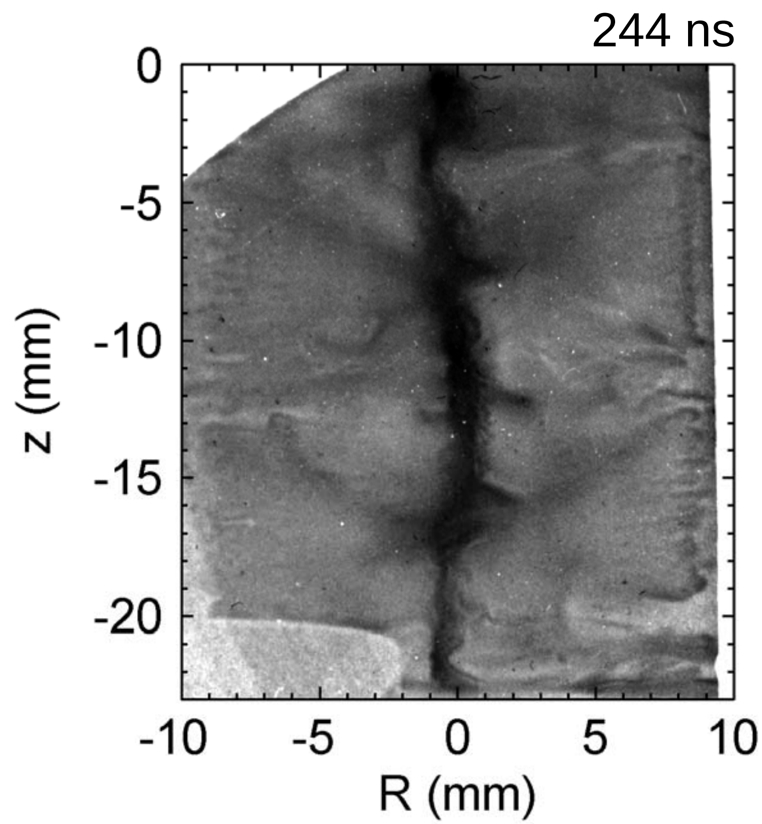

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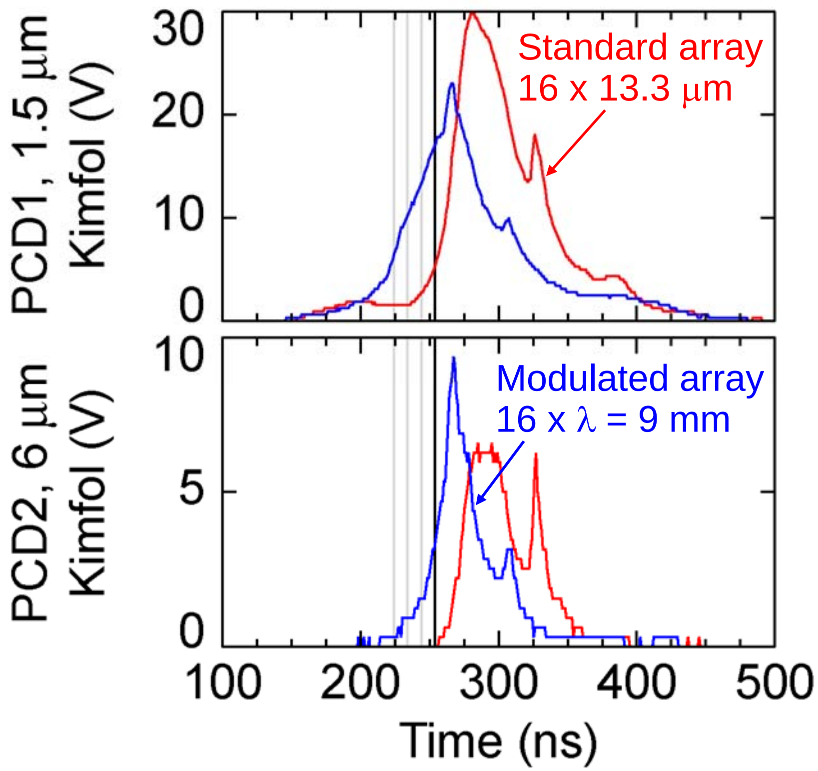

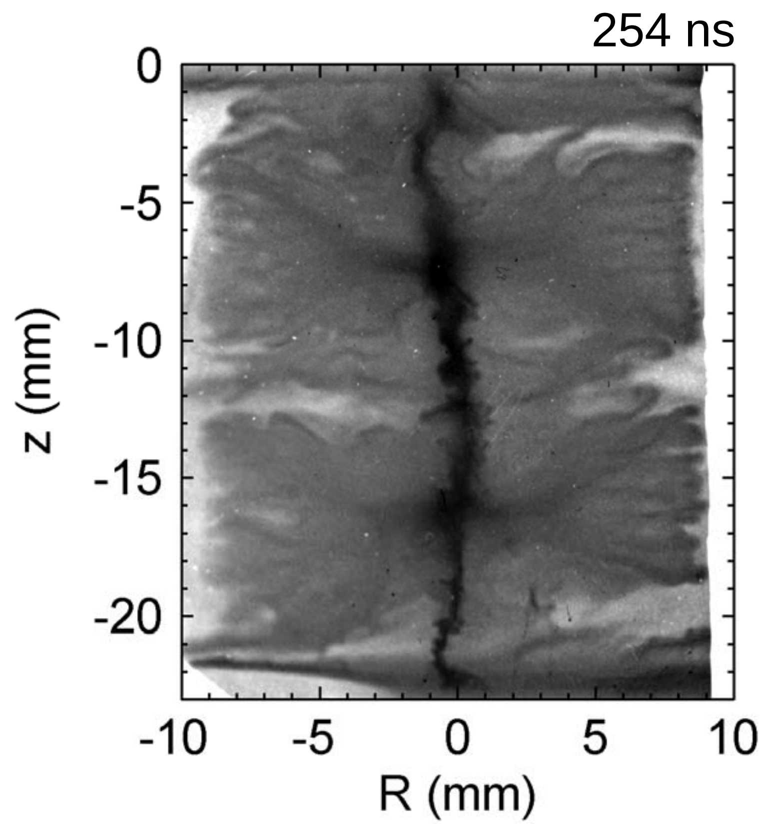

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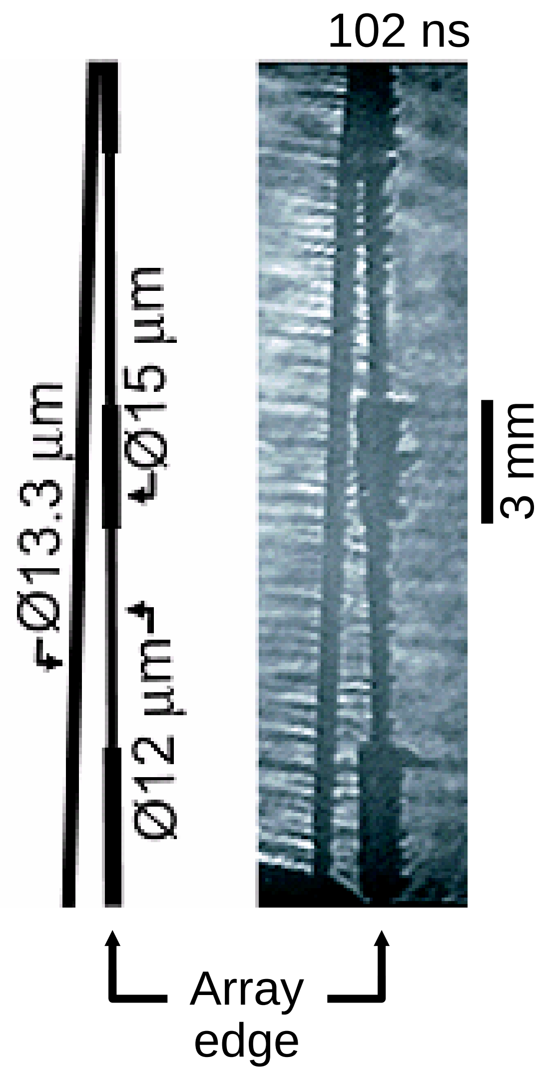
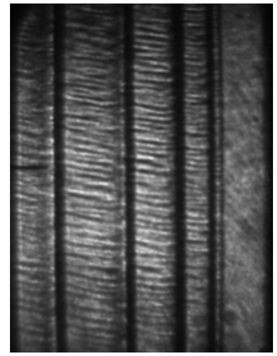
Natural short-λ mode is superimposed on long-λ perturbation



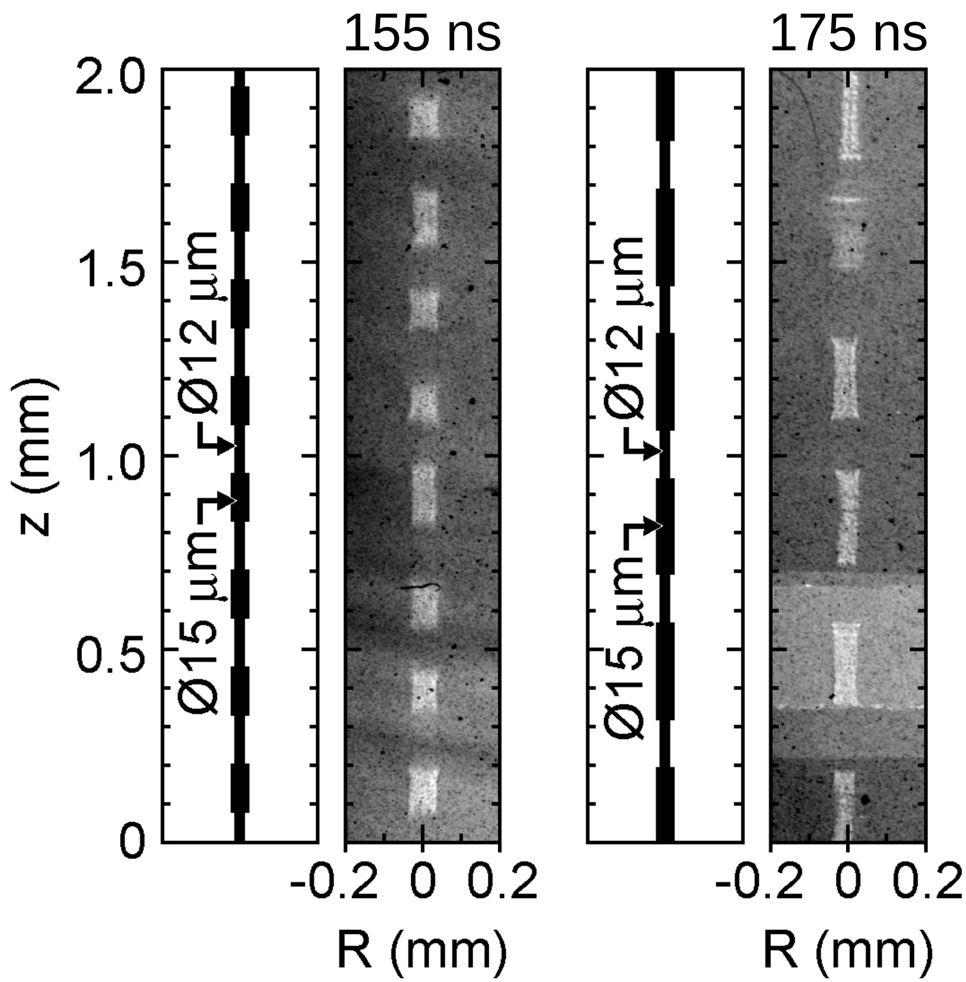
Stainless steel wire array on the 20 MA Z machine—G. Sarkisov, D. Bliss *et al.*



Aluminum wire array on the 1 MA MAGPIE driver

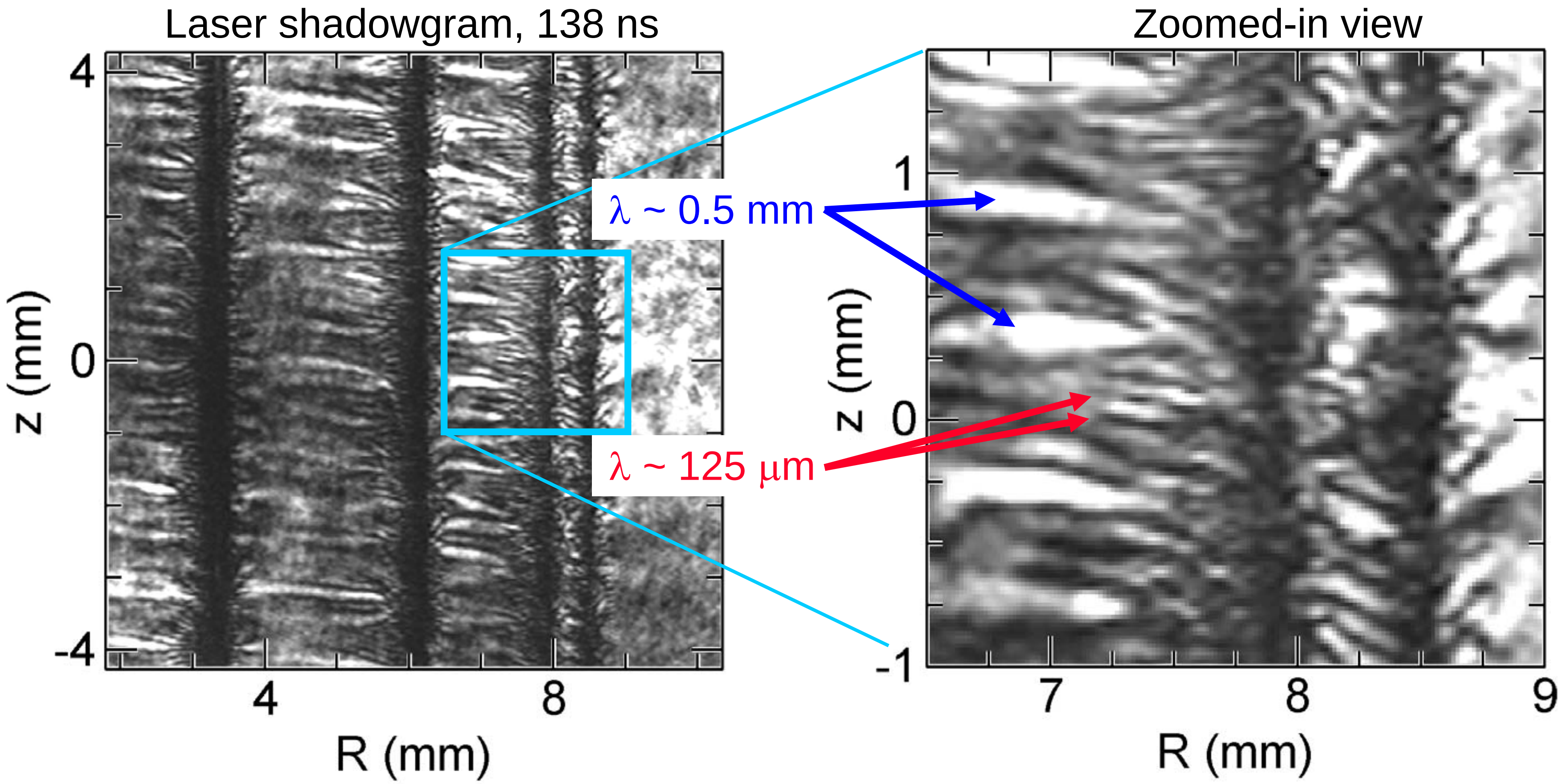
- Radial flares of ~0.5 mm wavelength (in Al) are seen early in time on all machines due to axially non-uniform wire ablation
- In experiments with longer wavelength seeded perturbations, the ~0.5 mm natural mode is seen superimposed
- What will happen if we seed λ < 0.5 mm? Will seeded and natural modes compete?
  - M. R. Douglas, C. Deeney, and N. F. Roderick, Phys. Plasmas **5**, 4183 (1998).
  - D. Ryutov and A. Toor, Phys. Plasmas **5**, 22 (1998).

Wire core evolution is dominated by seeded perturbation



- Mass ablated from thick segments < initial mass of thin segments—faster ablation rate near thinner wire core?

Short wavelength perturbations compete with natural mode



- Corona is impacted by seeded features, but signature of natural mode also appears superimposed
- Natural ~0.5 mm flare mode determined by coronal physics?

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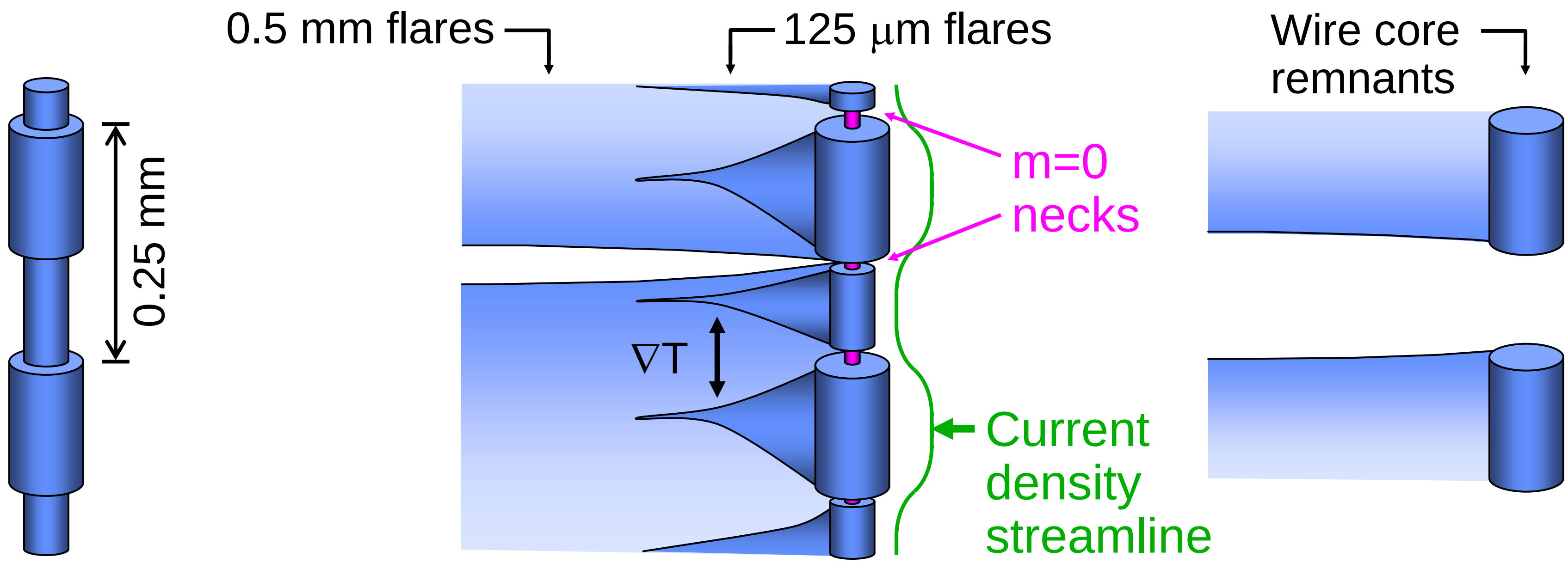
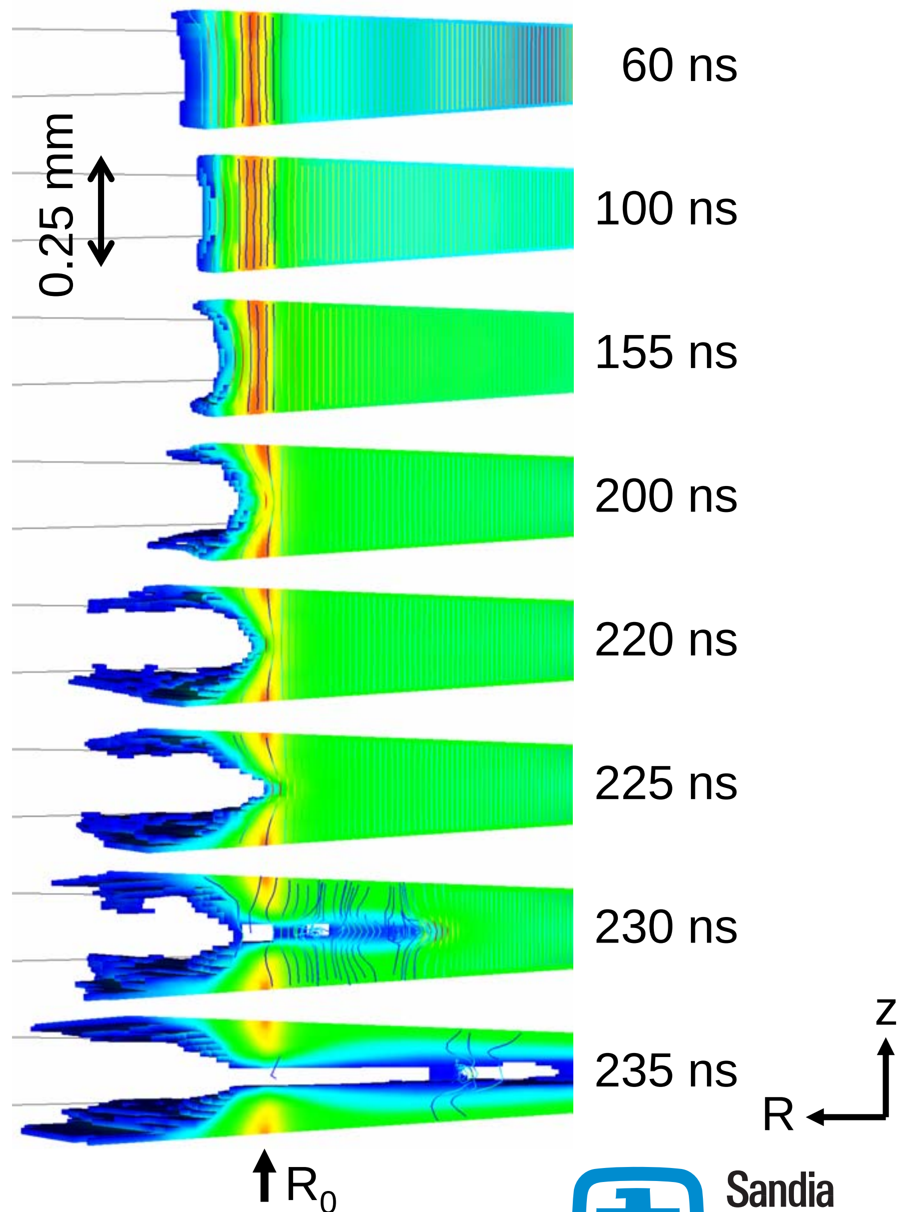
Possible mechanism for observed behavior with short-λ seed



- Per the longer wavelength seeded features, discontinuities in the wire lead to enhanced **j** x **B** and local necking regions
- Material flows axially out of the pinched necks, is pushed in radially by global **B**, forms radial flares with 125 μm period
- Thermal conduction in the ablated plasma shorts out the small-λ seeded mode and produces λ~0.5 mm jets
  - M. G. Haines, Phys. Rev. Lett. **47**, 917 (1981).

3D MHD Gorgon model simulates wire core break-up

- Modulation of corona in response to seeded perturbation is seen again
- Thinner core section ablates/implodes earlier, leaving thicker wire core sections at late time
- Current stream lines press against thinner core—faster ablation rate?
- 125 μm wavelength flares are not reproduced—higher resolution needed?



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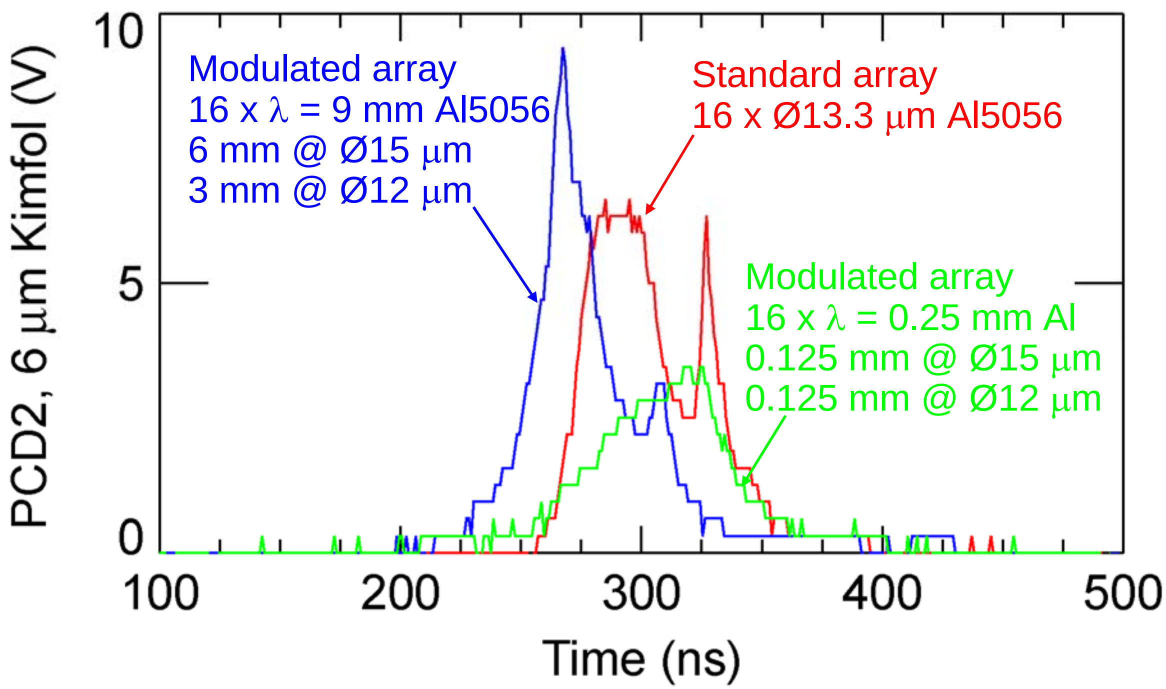
Short-λ perturbations dramatically compromise x-ray pulse

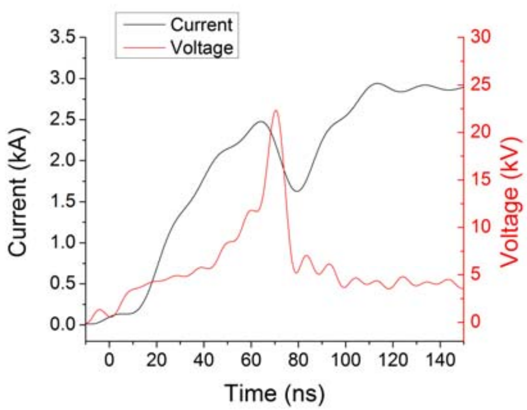


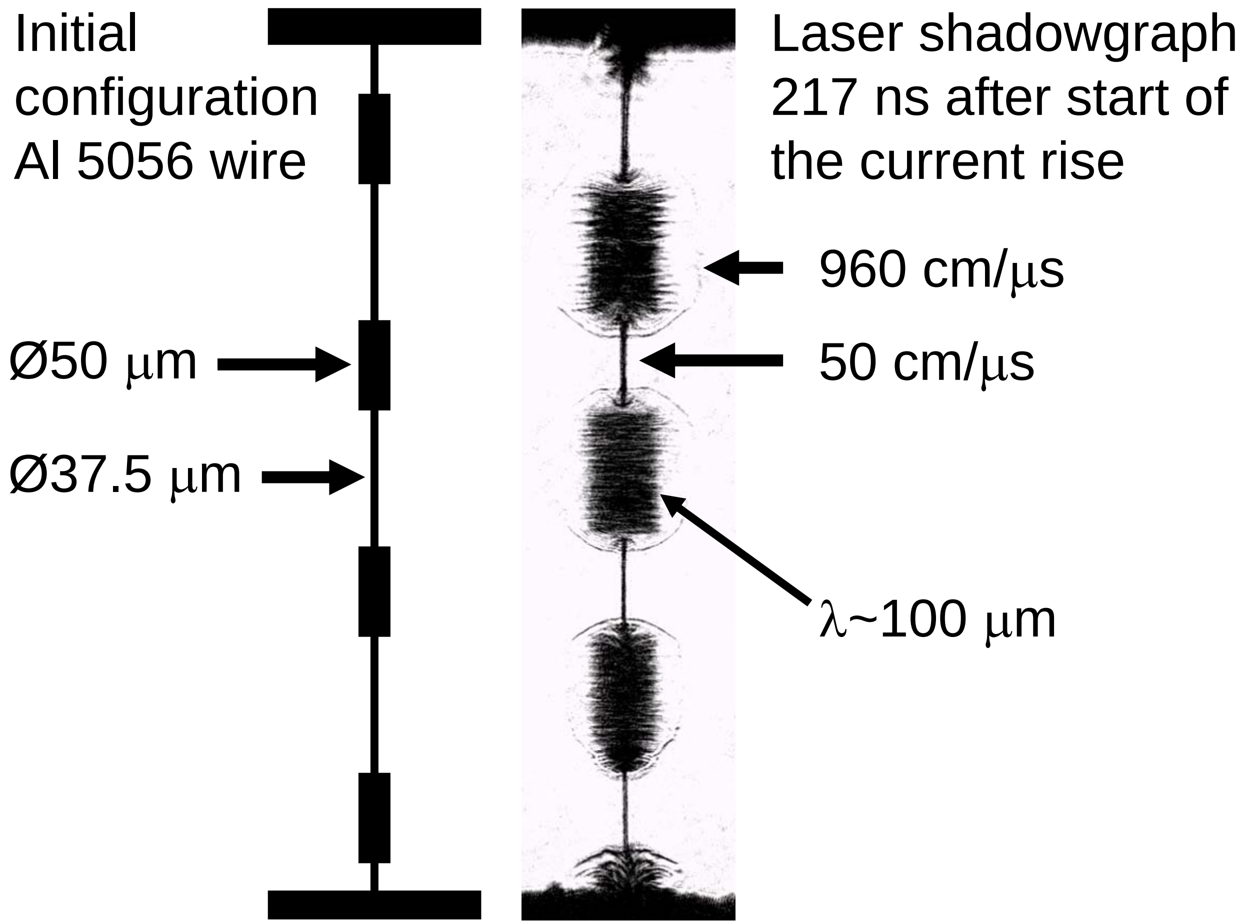
- In short-wavelength seeded instability case, current may be shunted out of wire cores, leading to a late implosion
  - Remaining wire core sections were not expanded at normal levels
  - m=1 instability seen at early time in precursor column on axis
- Smaller perturbation amplitude needed to test the concept of competing modes to reduce RT radial extent

Single wire experiments show opposite modulation trend

Shot specifications

V_{peak} = 26.0 kV
I_{peak} = ~8 kA
t_{peak} = 72.0 ns
dI/dt = 49.3 A/ns

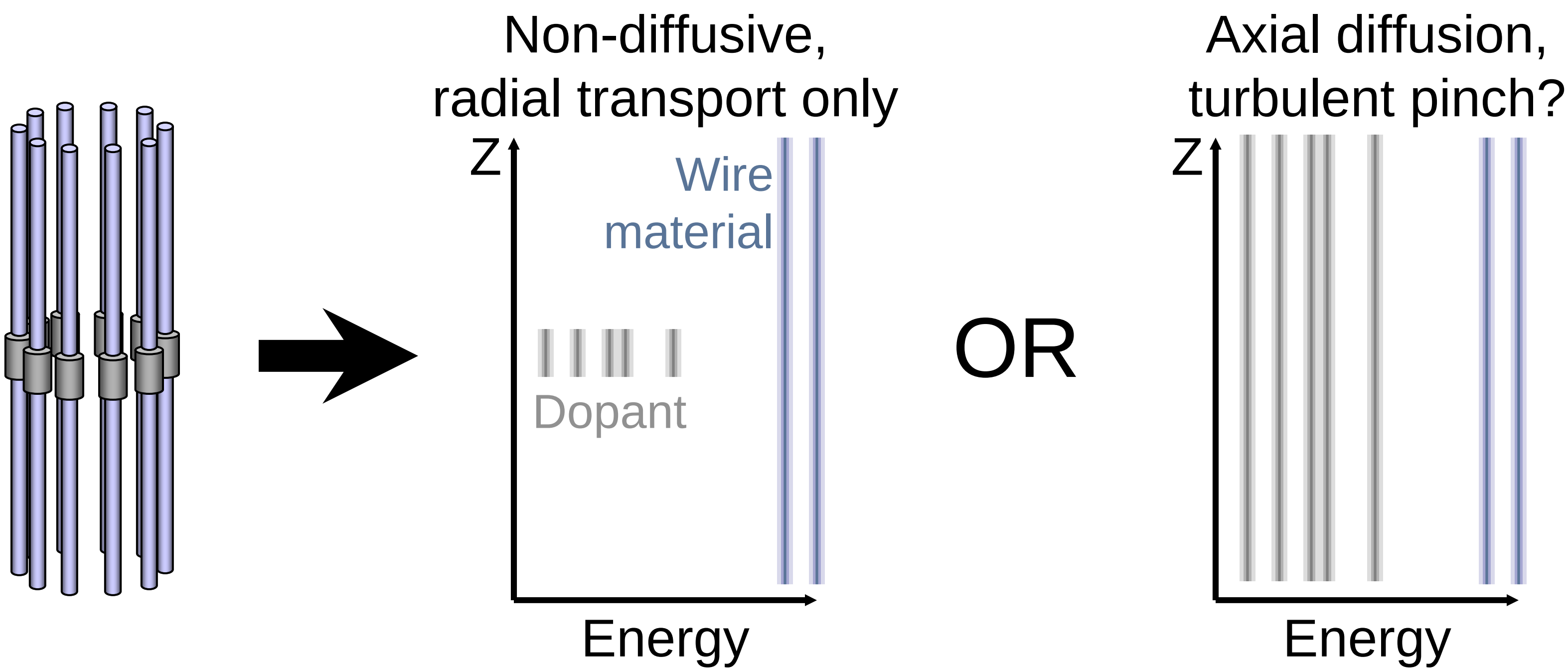




- Thin wire sections have large corona, opposite of wire arrays
- Different breakdown mechanism? Role of global B field?

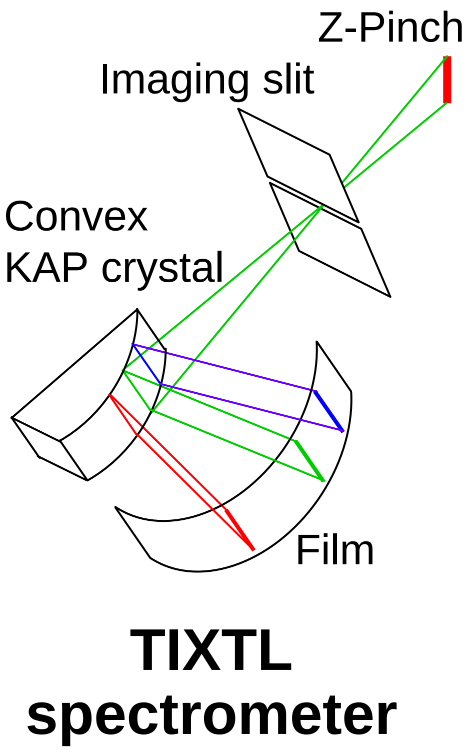
Courtesy of David Chalenski,
Harold Barnard, Bruce Kusse

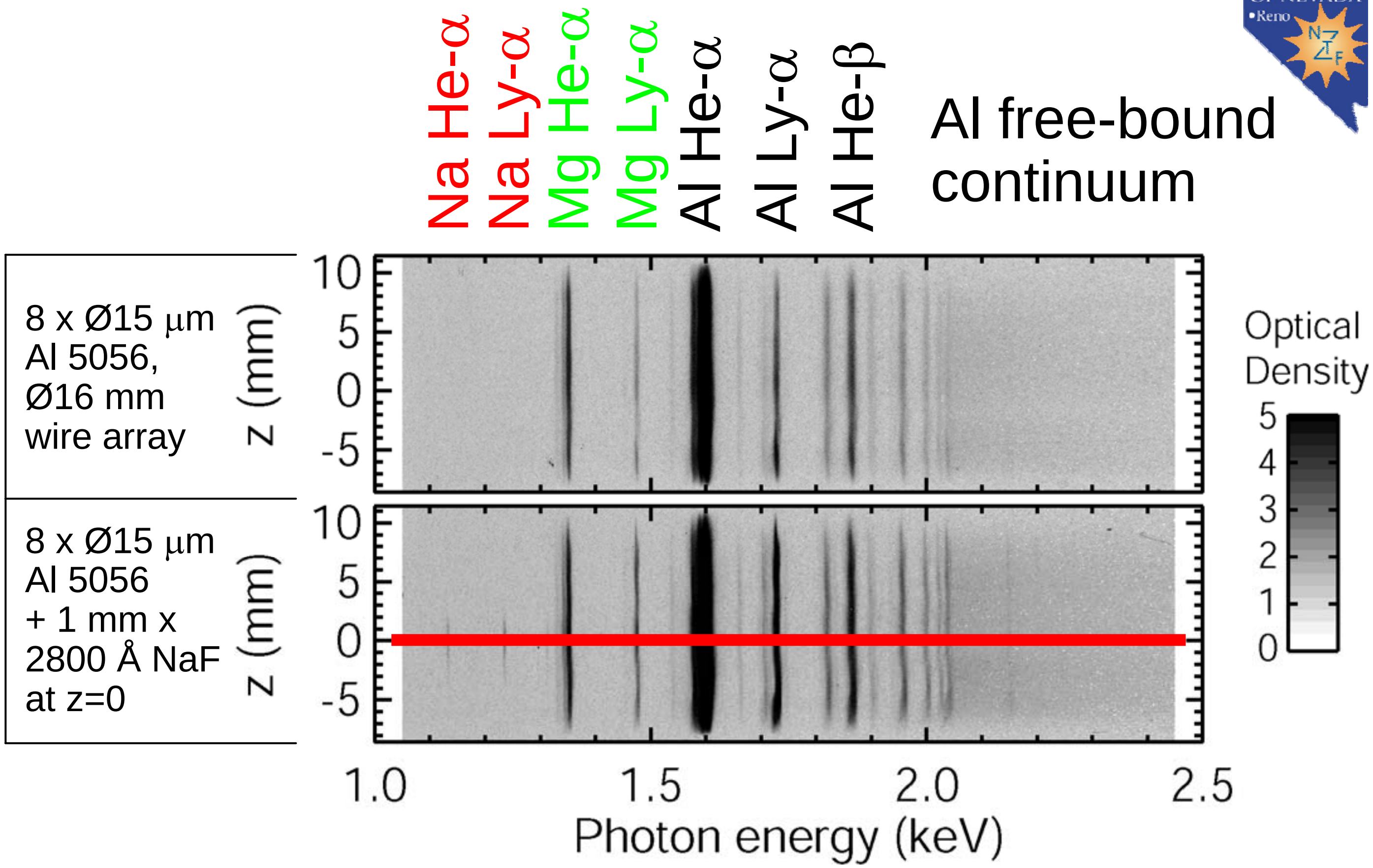
Localized dopant bands for particle transport studies



- Particle transport may be a quantitative signature of turbulence affecting z-pinch energy balance
- Localized dopants coated on wires at MPCL/Sandia
- Wire array experiments at UNR/NTF-Zebra 1 MA generator
- Localized NaF dopants previously used with laser plasmas
  - Y. Al-Hadithi *et al.*, Phys. Plasmas **1**, 1279 (1994).
  - K. B. Fournier *et al.*, JQSRT **71**, 339 (2001).

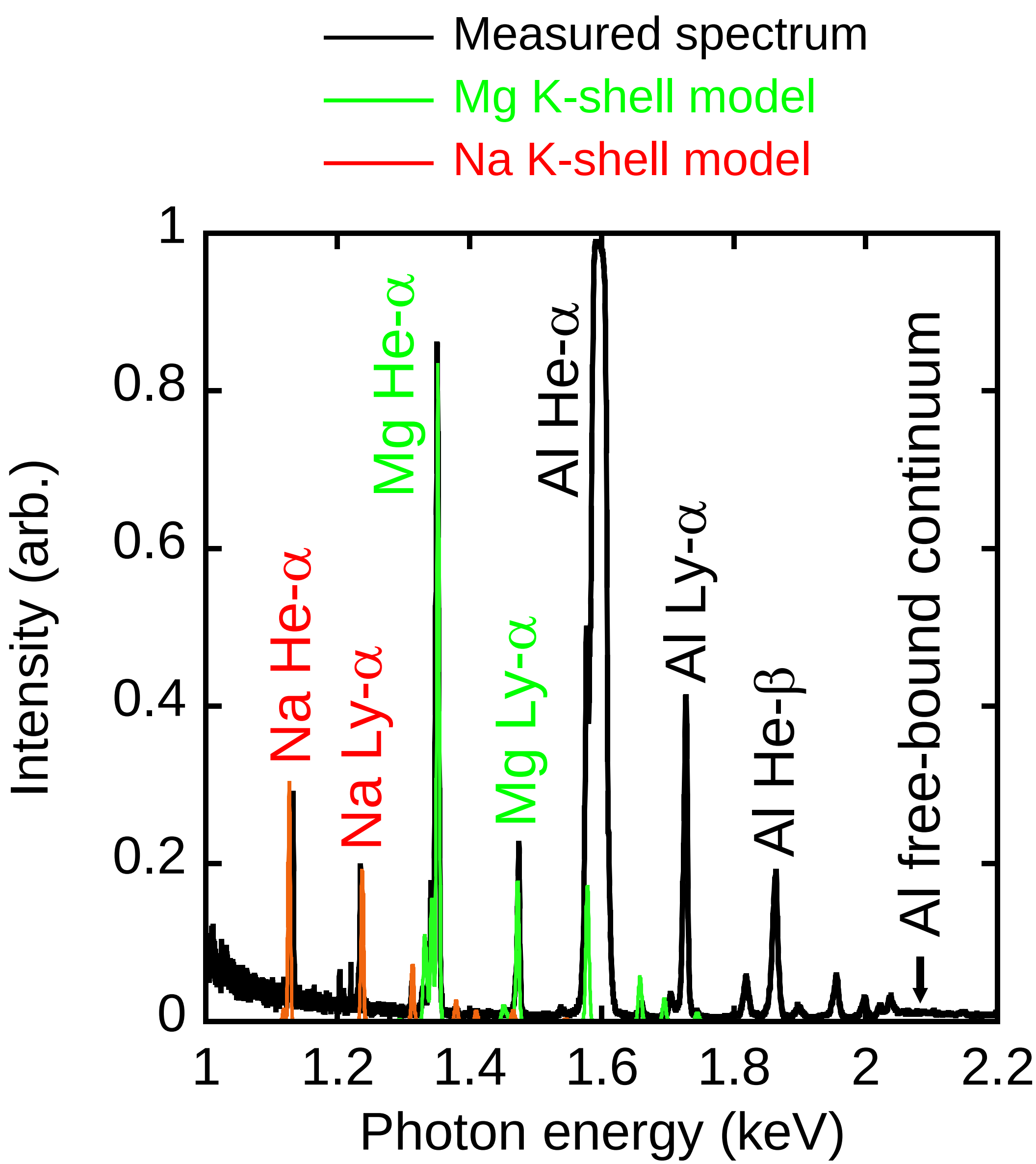
Localized Na K-shell emission observed on 1 MA Zebra driver





- Dopant coatings previously increased K-shell yield by mitigating opacity effects in wire array z-pinches
  – C. Deeney *et al.*, Phys. Rev. E **51**, 4823 (1995).

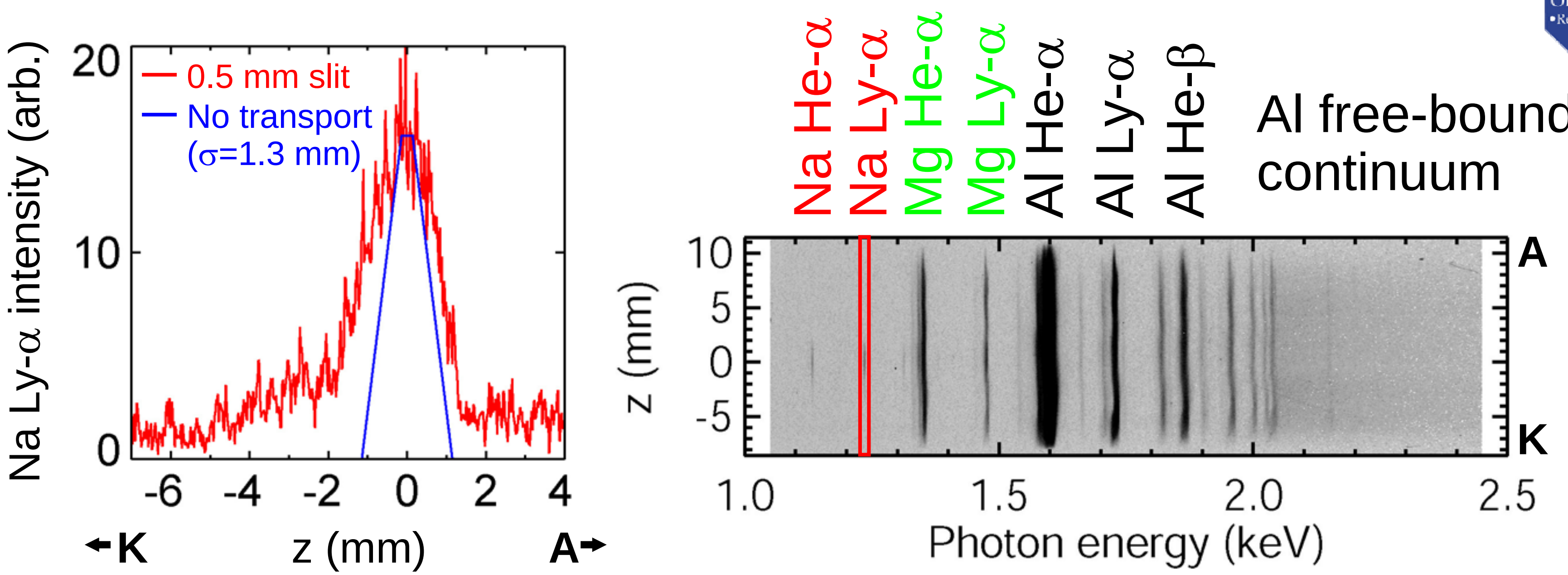
Atomic physics modeling provides plasma n_e, T_e diagnosis



- K-shell CRE models for Mg, Na have been developed at UNR
- $n_e \sim 2 \times 10^{20}$ cm^{-3}
  $T_e \sim 280$ eV
  inferred from comparison with both Mg and Na lines
- Low-Z doping of tungsten wires may allow spectroscopic measurement of plasma parameters

In collaboration with Alla Safronova and Victor Kantsyrev (UNR)

Na dopant is transported axially in the z-pinch plasma



- DEF film data converted to exposure using Henke tables
- Axial lineout taken over full width of the Na Ly-α line
- Emission is peaked near initial NaF band location
- Material has spread in axial direction (TIXTL can resolve this)
- An additional tail of material is transported in the direction of the cathode?

Summary

- Seeded perturbations offer a technique for exploring the role of 3D structure in wire array z-pinches
- MHD simulations with well defined initial perturbations allow study of instability growth without *ad hoc* assumptions
- Modulations in wire radius have linked current path discontinuities with seeding of RT bubbles
- Main x-ray pulse rise is due to collision of bubbles on axis assembling to form the stagnated z-pinch
- Many interesting research possibilities
  - Short-wavelength modulations and interaction with radial flares
  - Physics of magnetic bubbles
  - X-ray pulse shaping for ICF applications
  - Initiation studies with modulated single wires