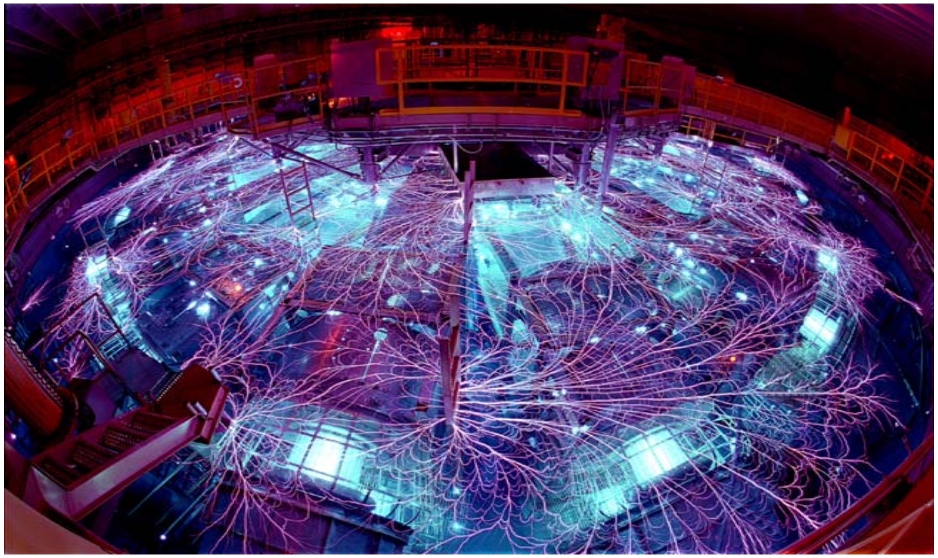
SAND2006-5729C

Z-Pinch Research on the 20-MA Z Accelerator



C. Deeney

Presented by

Dillon McDaniel
Sandia National Laboratories

In collaboration with

D. J. Ampleford, J. E. Bailey, D. E. Bliss, C. A. Coverdale, M. E. Cuneo, C. J. Garasi, B. Jones, S. V. Lebedev, P. D. LePell, T. A. Mehlhorn, J. L. Porter, C. L. Ruiz, D. B. Sinars, D. F. Wenger

1st Euro-Asian Pulsed Power Conference
Chengdu, China, Sept. 21, 2006

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.

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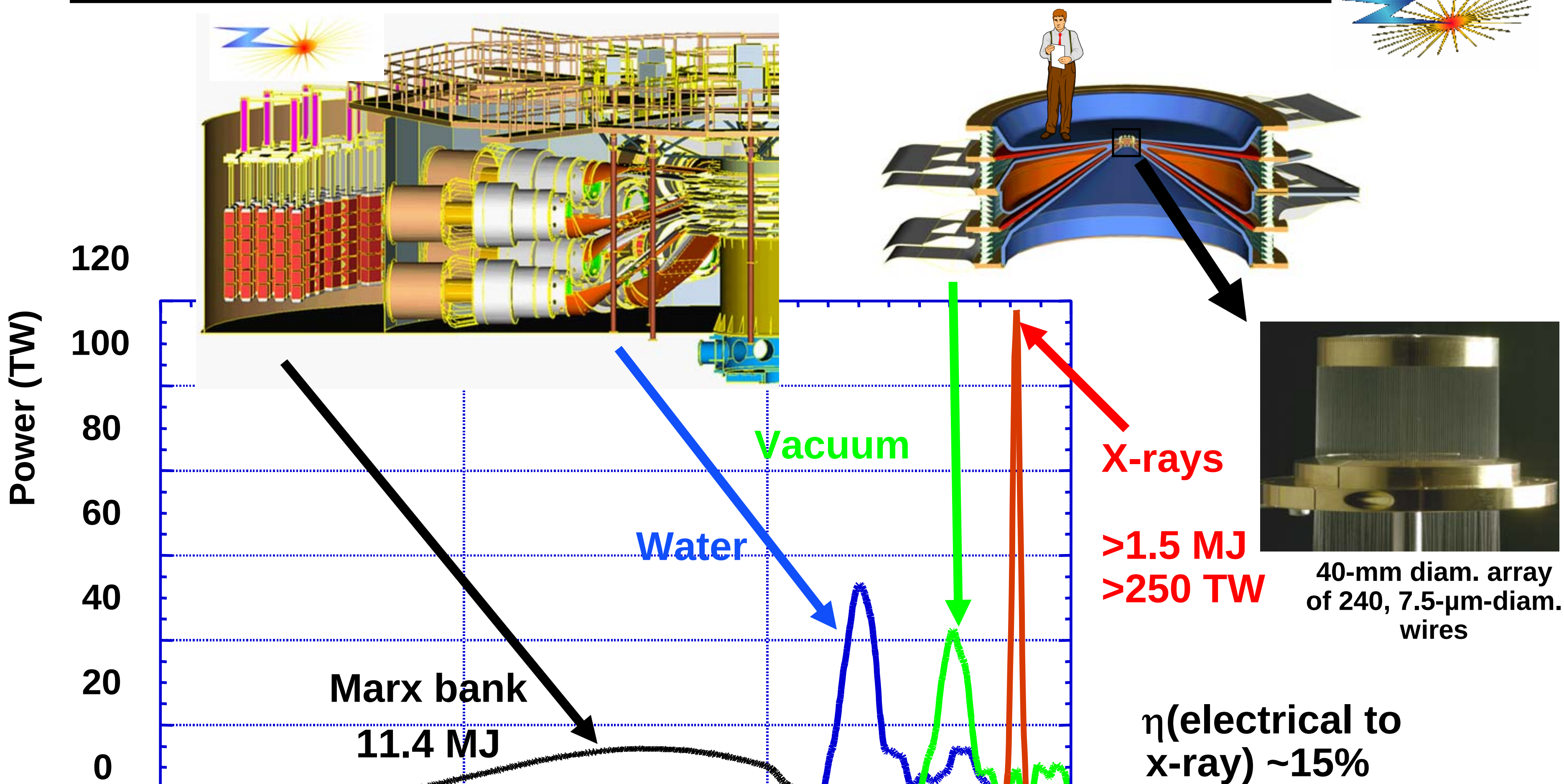
Sandia's Z machine delivers up to 20 MA to an imploding load



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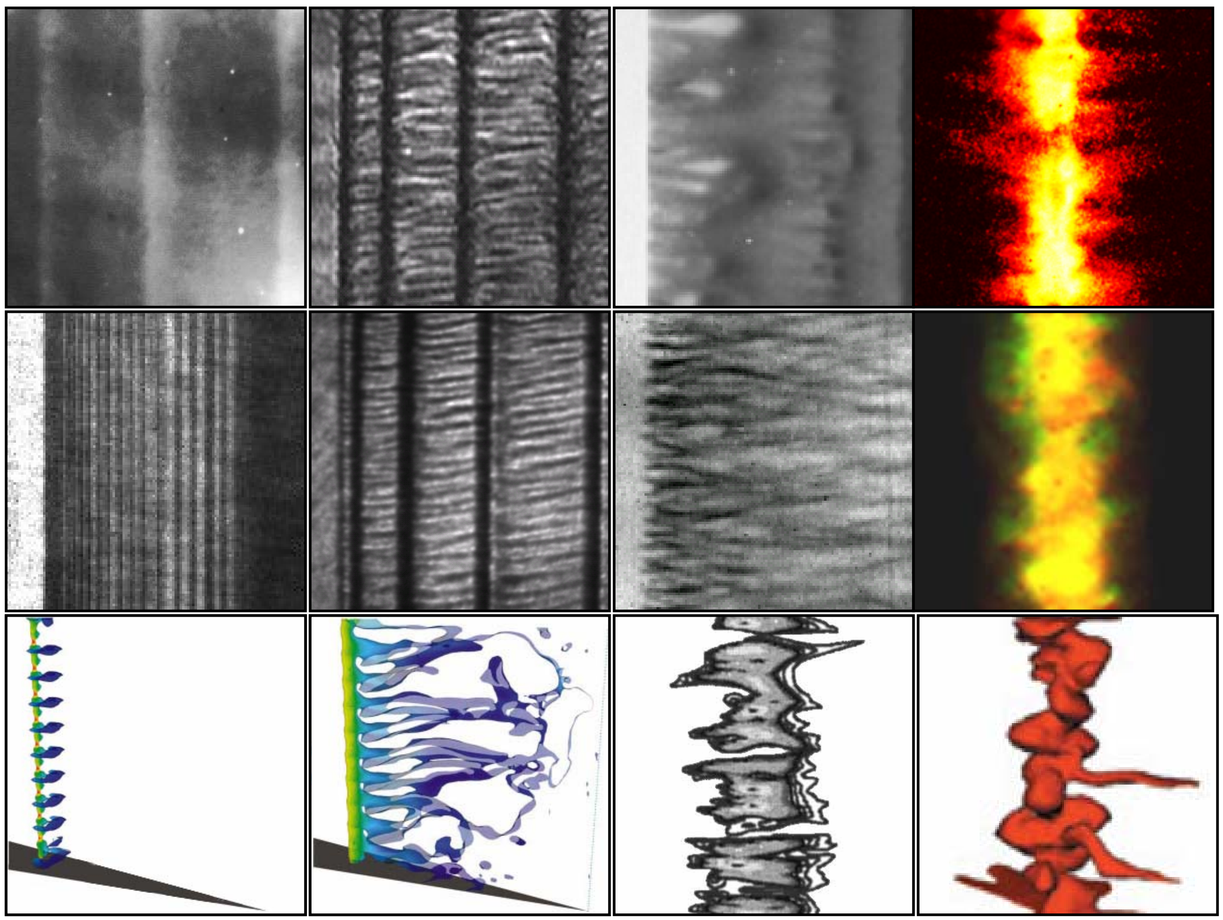
Z-pinch implosions exhibit rich dynamics

Initiation | Ablation | Implosion | Stagnation

1 MA

20 MA



Experiment

Modeling

3D MHD

2D r-z MHD

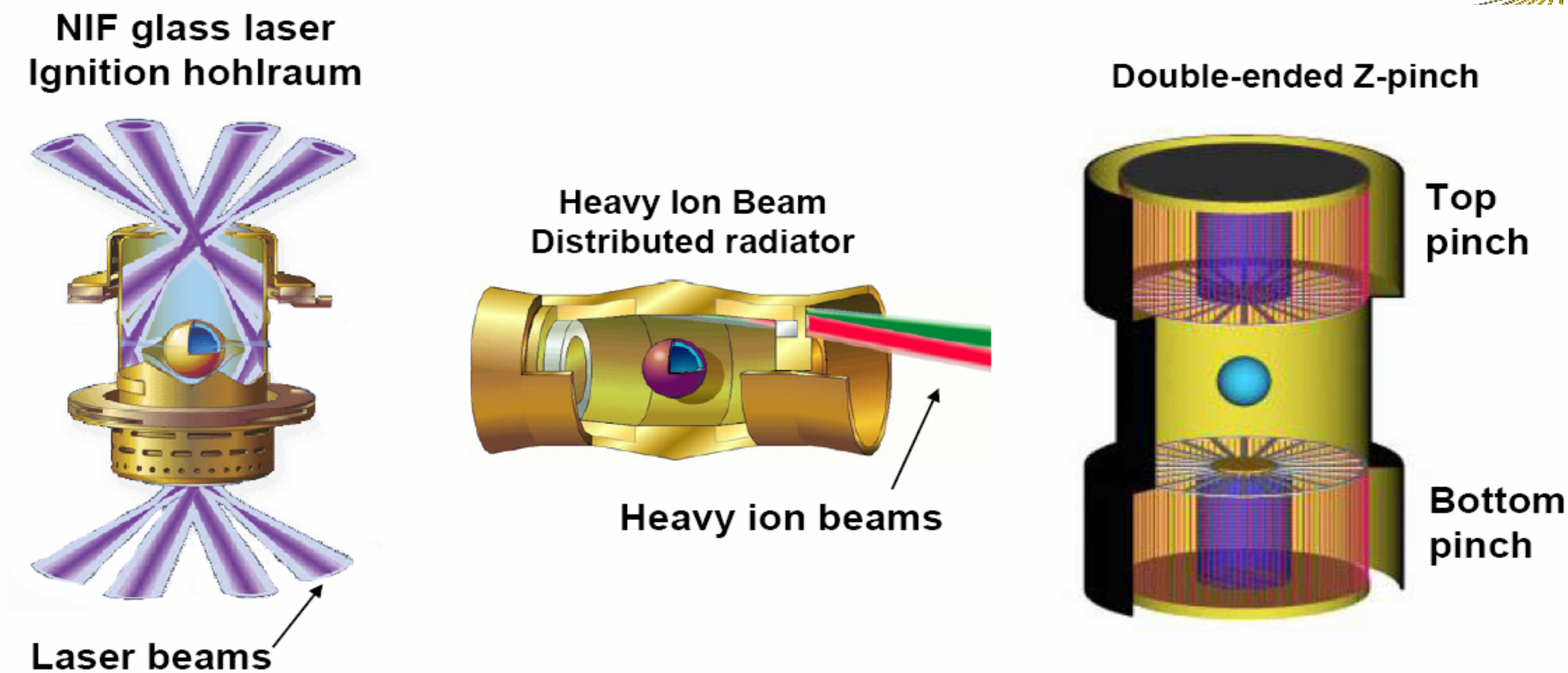
3D MHD

Experiments at Z study a variety of phenomena

- Z-pinch sources are relevant for
  - Inertial confinement fusion (ICF)
  - K-shell x-ray sources
  - Basic plasma physics research
- Magnetically driven flyer plates and isentropic compression are also areas of research at Z

- Studies with z-pinch research are tied to the four main phases of a z-pinch, and include
  - Initiation of wires
  - Ablation of the wires
    - Precursor formation
  - Implosion dynamics
    - Growth of instabilities
  - Stagnation physics
    - Heating and opacity

One application of z-pinch x-ray sources is inertial confinement fusion



- **The high ~15% conversion efficiency from wall-plug input energy into x rays could facilitate pulsed power drive of high-yield capsules (yield > 200 MJ)**

M. K. Matzen *et al.*, Phys. Plasmas **12**, 055503 (2005)

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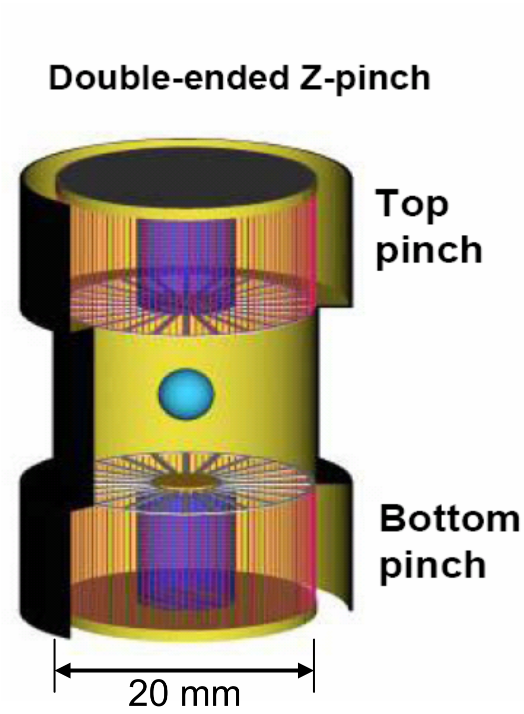
Z-pinch-driven ICF is currently studied on the Z machine



J. H. Hammer, *et al.*, Phys. Plasmas **6**, 2129 (1999)

- **ICF studies on Z use compact Ø20 mm, 300-wire arrays to heat hohlraums for indirect drive capsule implosion**
- **NIF-scale capsules (~2 mm diameter) are presently used in experiments on Z**
- **High-yield z-pinch facility would use ~5 mm diameter cryogenic capsules**
- **Challenges for z-pinch ICF research:**
  - **Hohlraum design to achieve capsule symmetry**

    R. A. Vesey *et al.*, Phys. Rev. Lett. **90**, 035005 (2003)
  - **Z-pinch power optimization and radiation physics**
  - **Radiation pulse shaping**

    M. E. Cuneo et al., Phys. Plasmas **13,** 056318 (2006)

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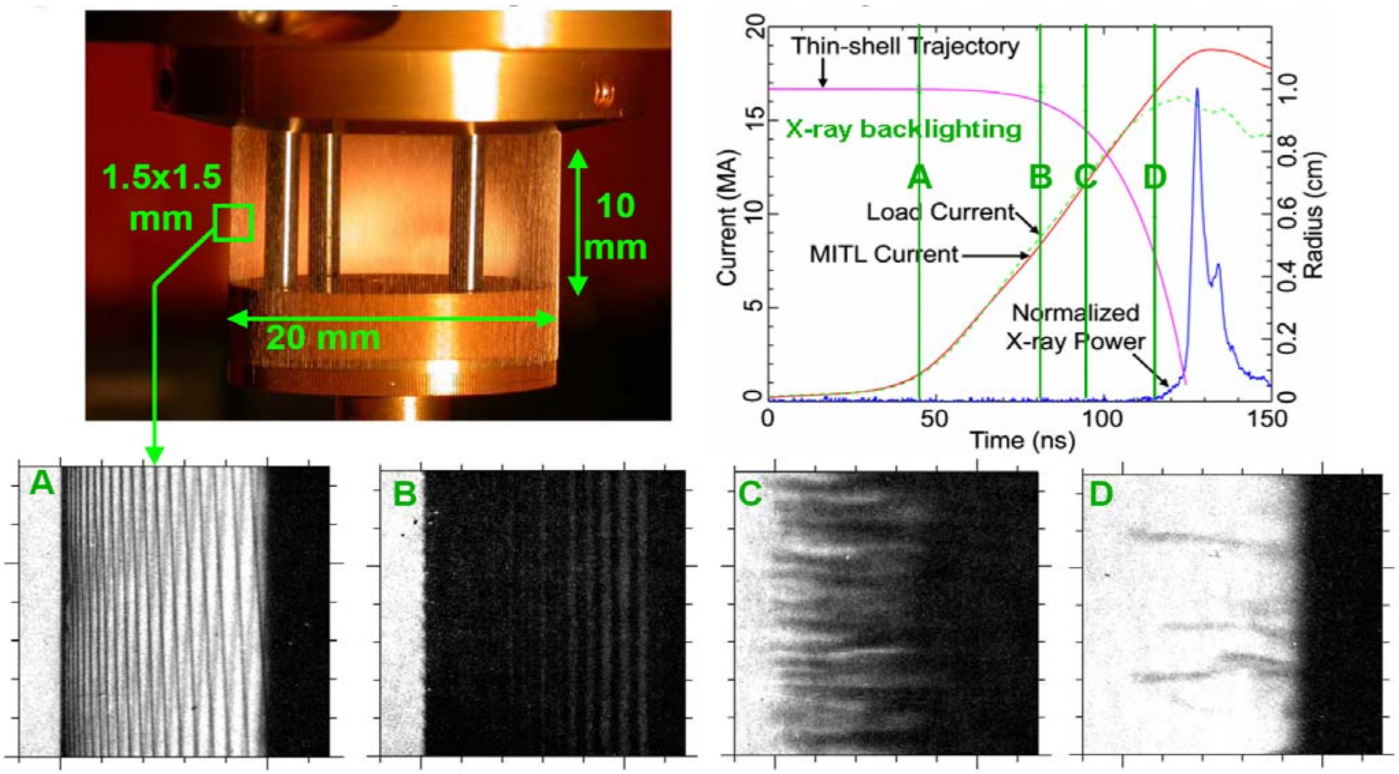
1.865 keV backlighting has been used to study the early stages of wire-array z-pinch implosions

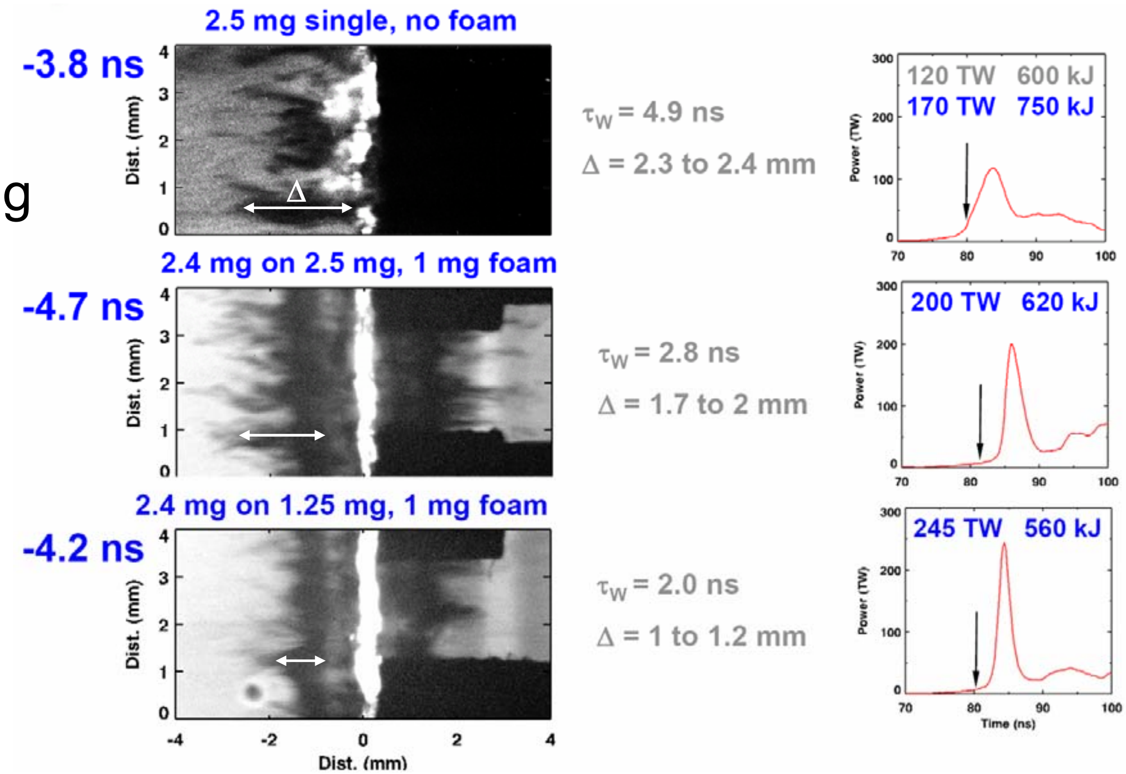


- Wire ablation pre-fills the interior of the wire array with plasma
- Magnetic Rayleigh-Taylor (MRT) implosion instability creates trailing mass

D.B. Sinars et al., Phys. Rev. Lett. **93**, 145002 (2004)

Correlation between pulse width and mass distribution is seen in single and nested arrays

6.151 keV backlighting



- **Shape of x-ray power pulse may be determined by the distribution and velocity of mass thermalizing on axis**
- **Nesting arrays provides a technique for controlling MRT implosion instabilities**

Courtesy of M. E. Cuneo, D. B. Sinars *et al*., to be published

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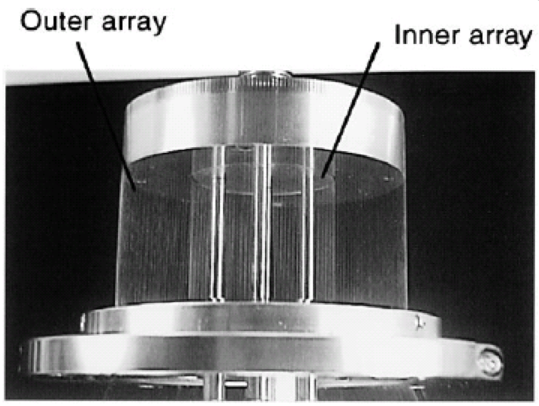
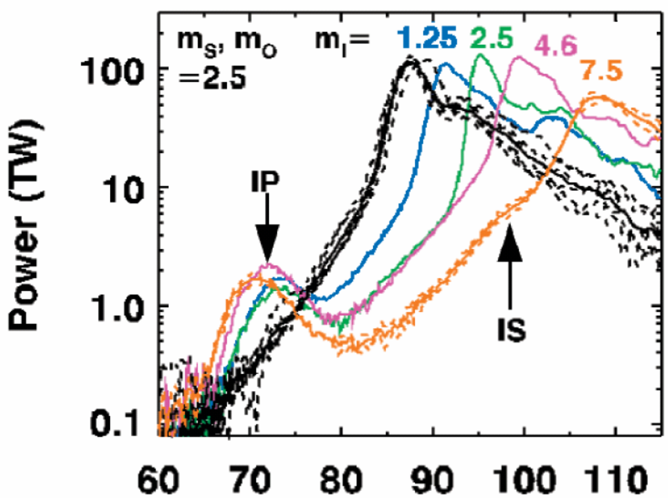
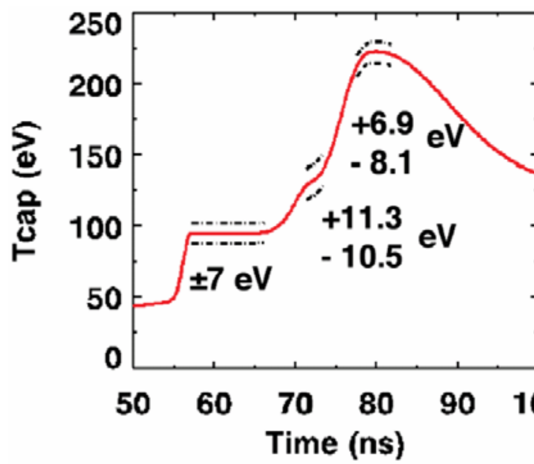
Nested wire arrays can provide pulse shaping for ICF capsule drive

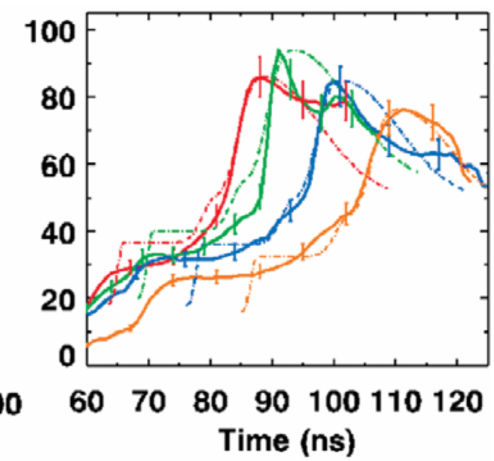




Radiation drive for high-yield z-pinch ICF design



Scaled drive pulses on Z



IP – Interaction pulse between outer and inner wire arrays provides 1st shock

IS – Inner strike on precursor or foam provides 2nd shock

Stagnation provides 3rd shock

M. E. Cuneo *et al.*, Phys. Rev. Lett. **95**, 185001 (2005)

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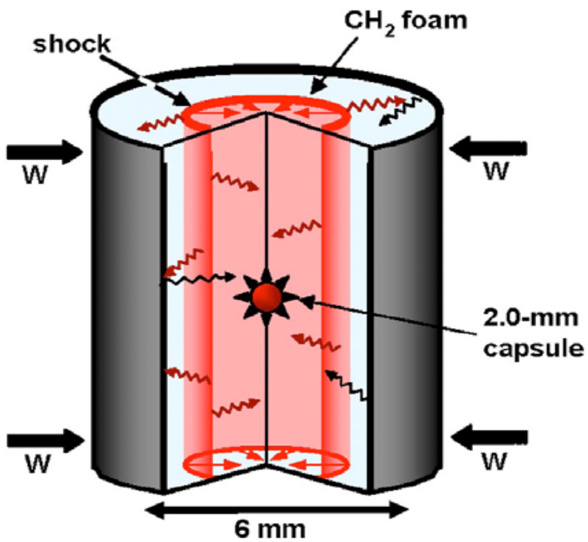
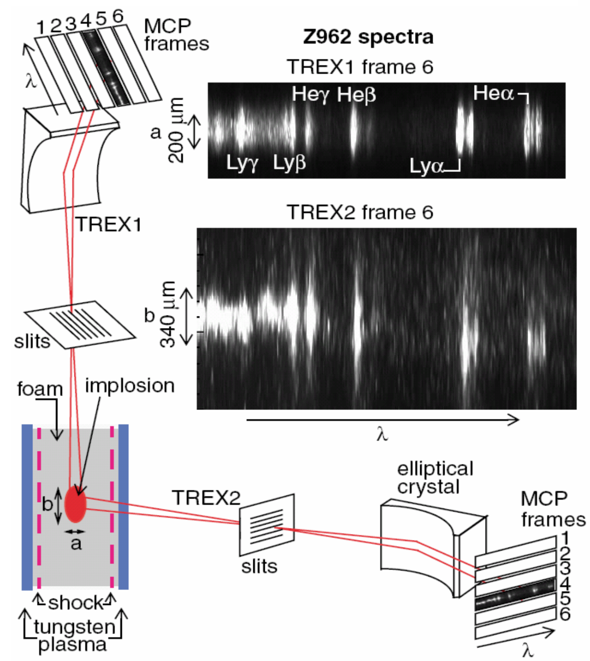
Dynamic hohlraum concept has produced thermonuclear fusion neutrons on Z

Z-pinch dynamic hohlraum





- **Annular tungsten z-pinch drives radiating shock and captures radiation**
- **>2 x 10^{11} neutrons produced in Z experiments**
  - C. L. Ruiz *et al*., Phys. Rev. Lett. **93**, 015001 (2004)
  - New York Times article, April 8, 2003
- **Capsule conditions diagnosed by tomographic spectroscopy**
  - J. E. Bailey *et al.*, Phys. Rev. Lett. **92**, 085002 (2004)

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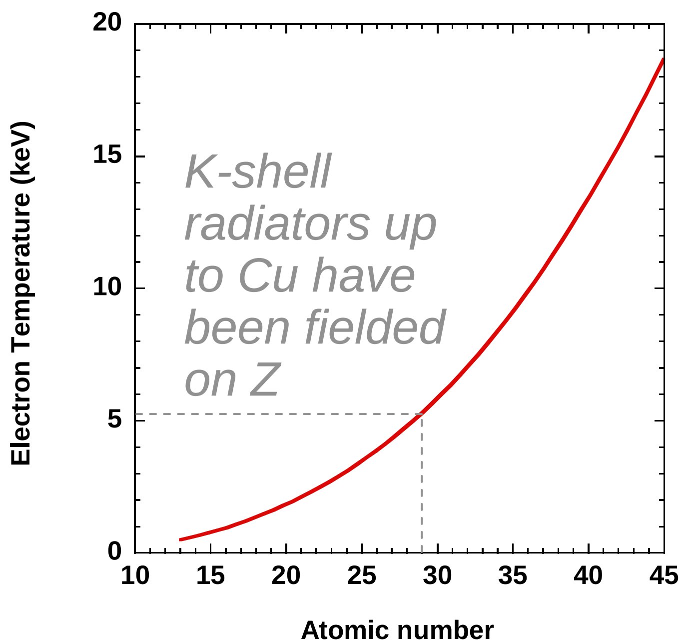
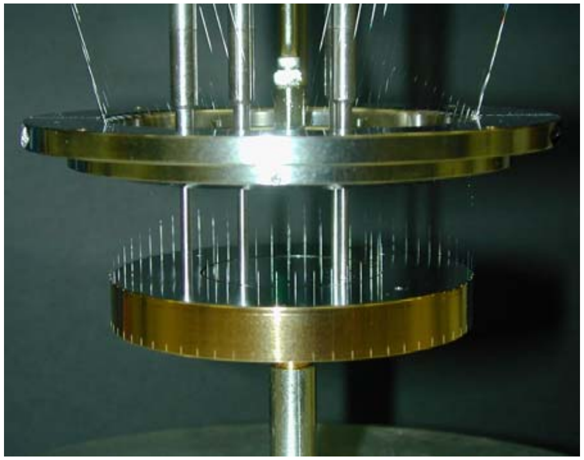
K-shell sources study a different parameter regime—higher temperature than ICF loads

- ICF loads are typically designed to achieve local thermodynamic equilibrium
- K-shell sources are non-LTE

- Plasma conditions necessary to produce significant K-shell dictate large diameters
  - High temperatures and densities





70 mm outer dia., nested array

Typically large diameter, low wire number nested arrays as compared to ICF loads
- 70mm on 35mm, 64 on 32 wires (IWG = 3.44 mm)

Wire number effects impact output
- **Optimal wire number** ***(M. Mazarakis, Plasma Dev. Operations 13, 157 (2005); C.A. Coverdale et. al., Phys. Rev. Lett. 88, 065001 (2002))***
- **Field asymmetries** ***(J. Chittenden, private communication)***

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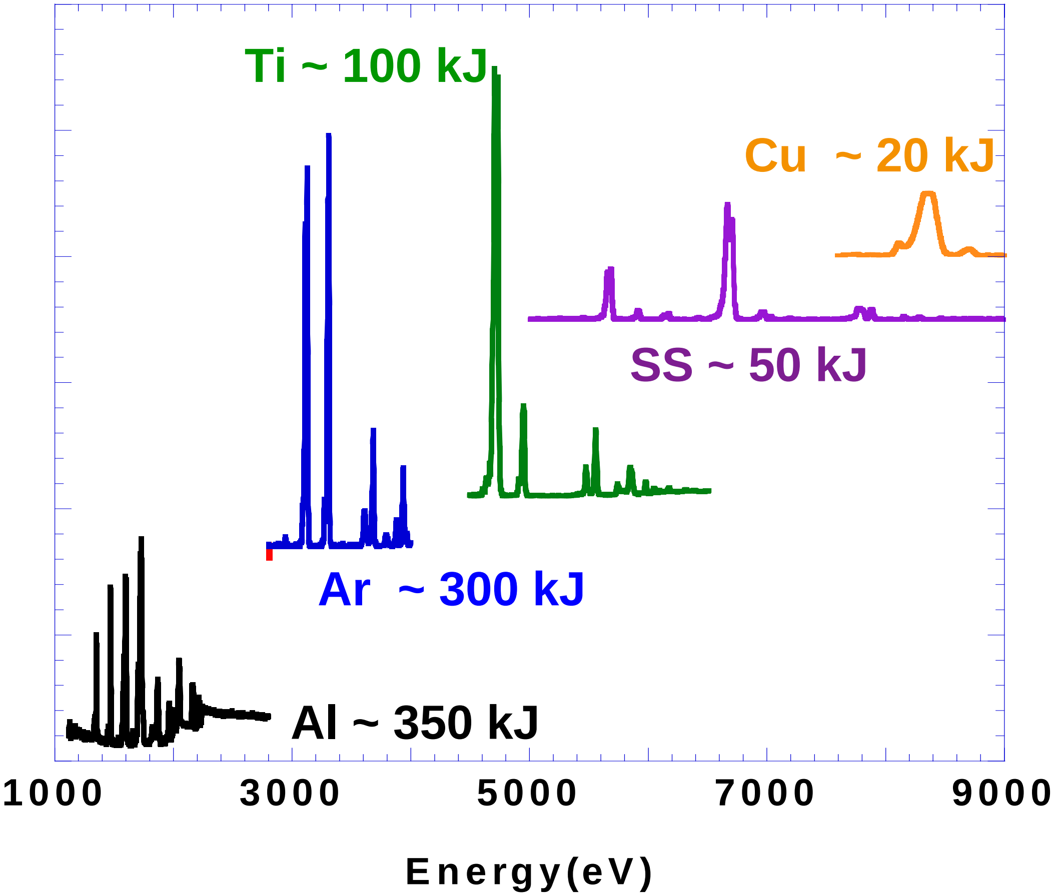
Z machine allows K-shell radiation studies at a range of soft x ray energies



- These are peak outputs
  - Other configurations fielded have produced different x-ray fluence

- Al: 40mm on 20mm nested
- Ar: 8cm nozzle, double shell
- Ti: 50mm on 25mm nested
- SS: 55mm on 27.5mm nested
- Cu: 60mm on 30mm nested

C. Deeney *et al*., Phys. Plasmas 6, 2081 (1999)
H. Sze *et al*., Phys. Plasmas 8, 3135 (2001)
B. Jones *et al*., J. Quant. Spec. 99, 341 (2006)
C.A. Coverdale *et al*., JRERE 20-1 (2002)

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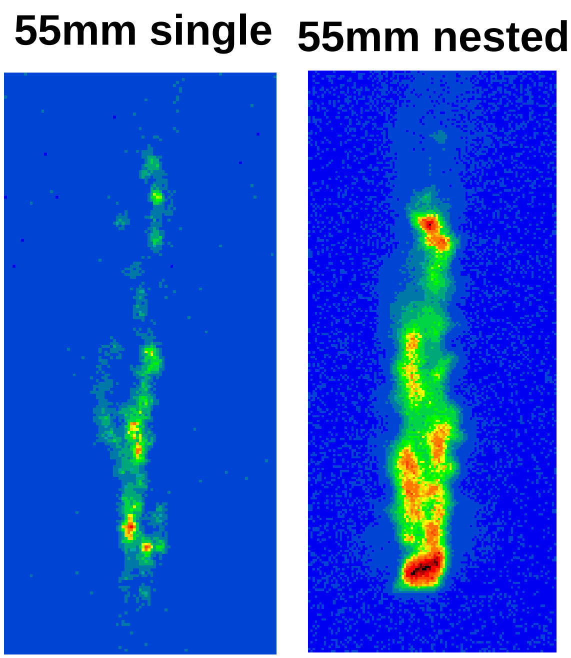
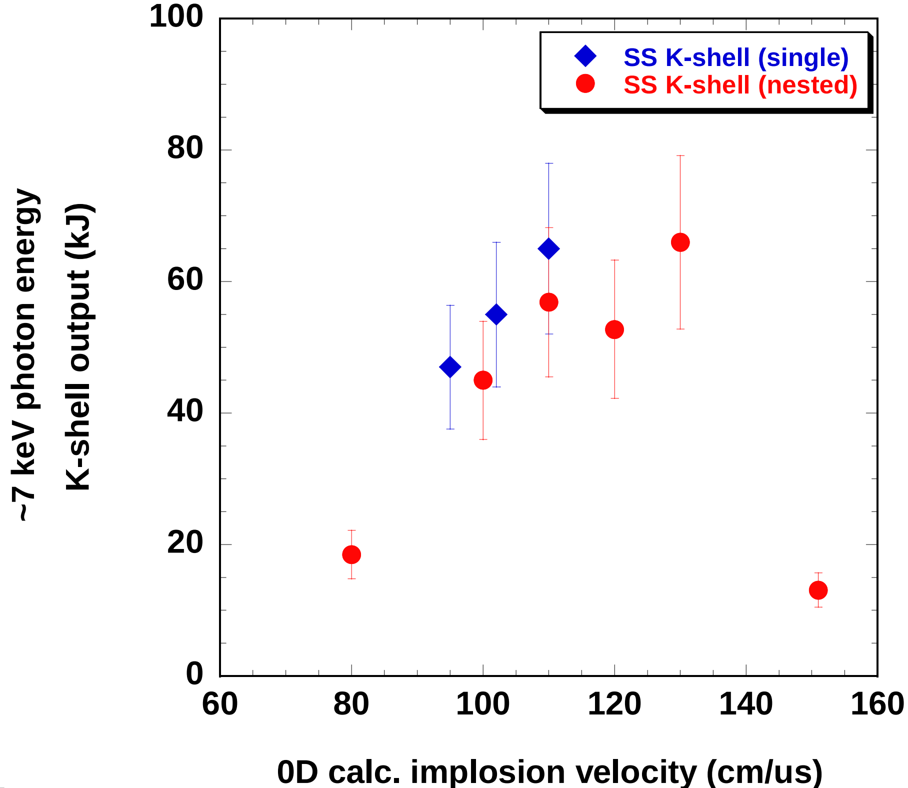
Comparisons between load configurations show effects on radiated output

Stainless Steel K-shell images near peak radiation





- Intense regions present in both configurations; less pronounced with nested
- Softer x-ray images show less structure, wider pinch

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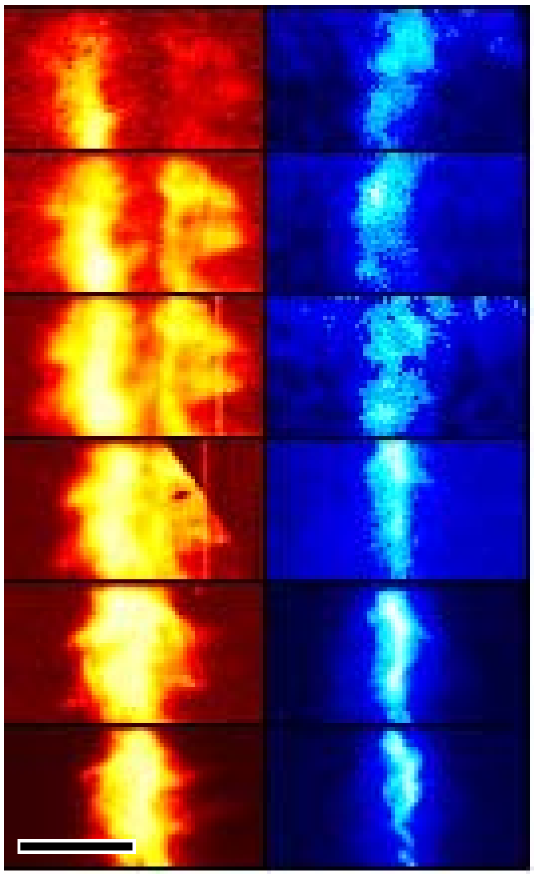
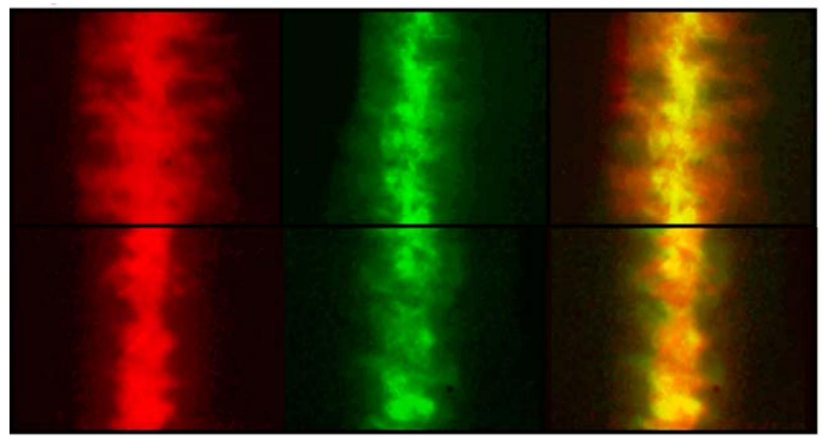
K-shell sources can be used to study the dynamics near stagnation for soft and hard x-ray energies





- Instability
- Hot, dense column emitting K-shell on axis with colder material still imploding
- Observed structure varies with atomic number

B. Jones *et al*., Rev. Sci. Instrum. (2006)

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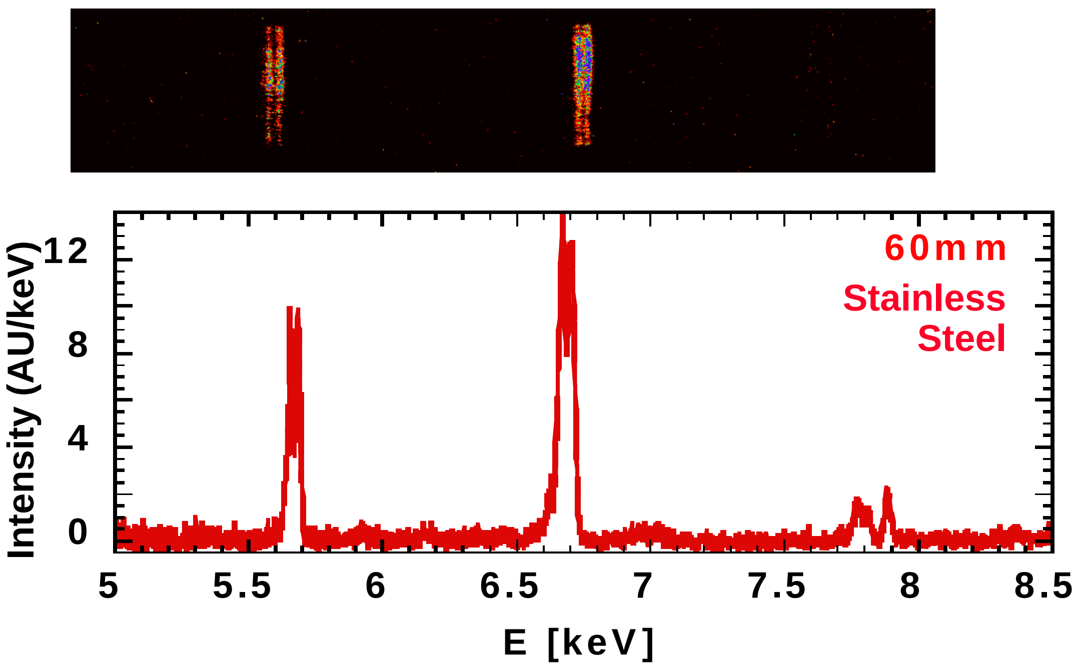
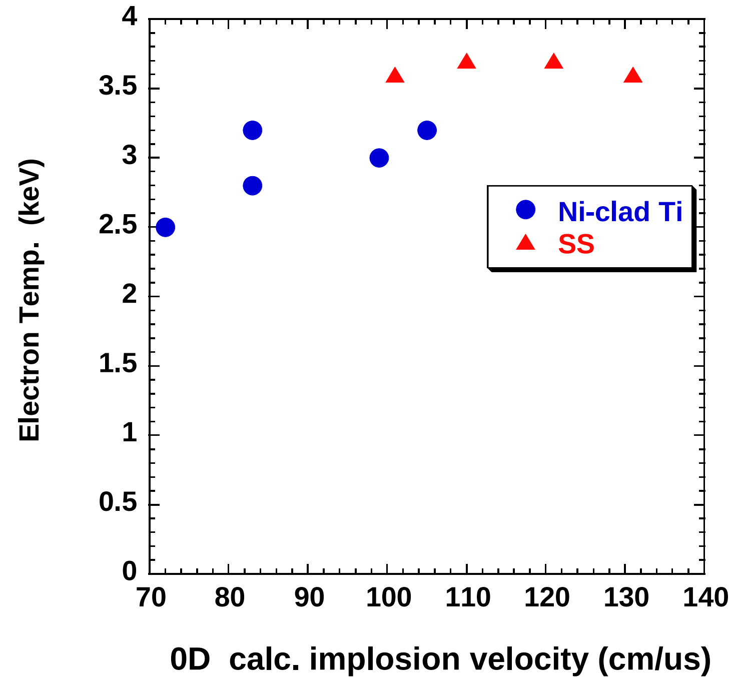
K-shell sources offer opportunities to study plasma conditions through spectroscopy

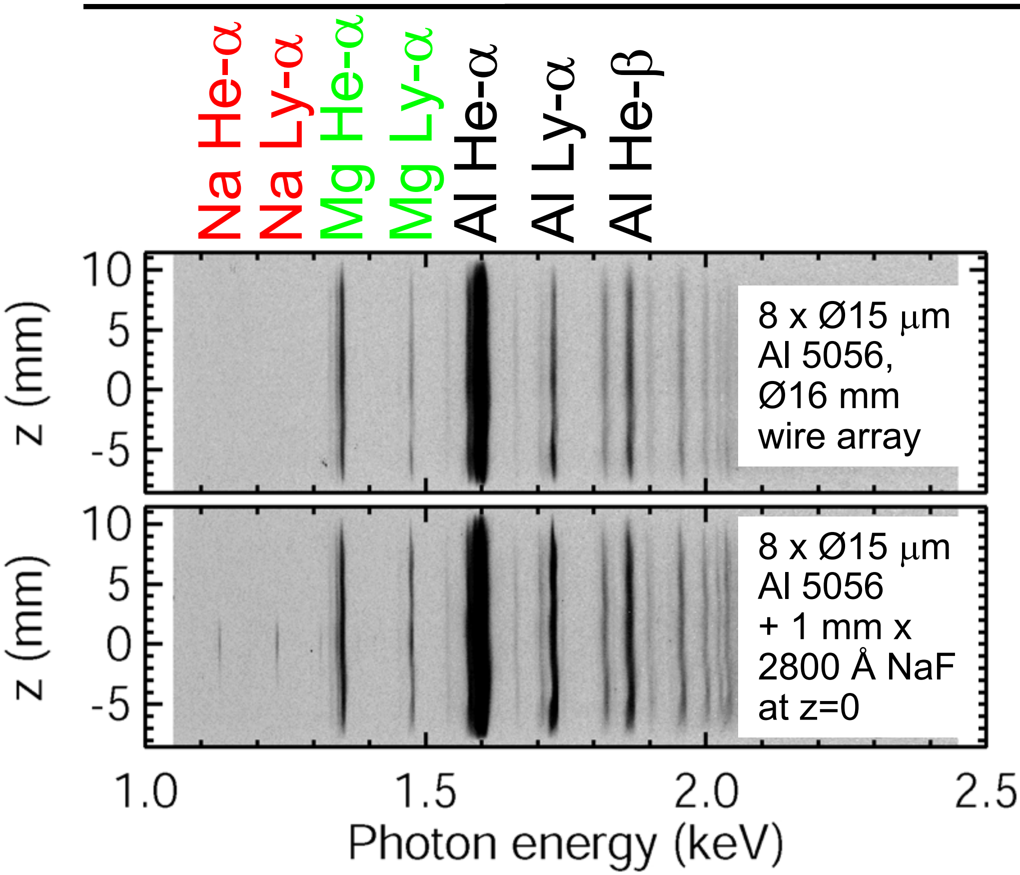
Time integrated spectroscopy can be used in conjunction with pinch size and K-shell power to infer electron temperature and ion density
(J.P. Apruzese et. al., J. Quant. Spectrosc. Radiat. Transfer 57, 41 (1997))

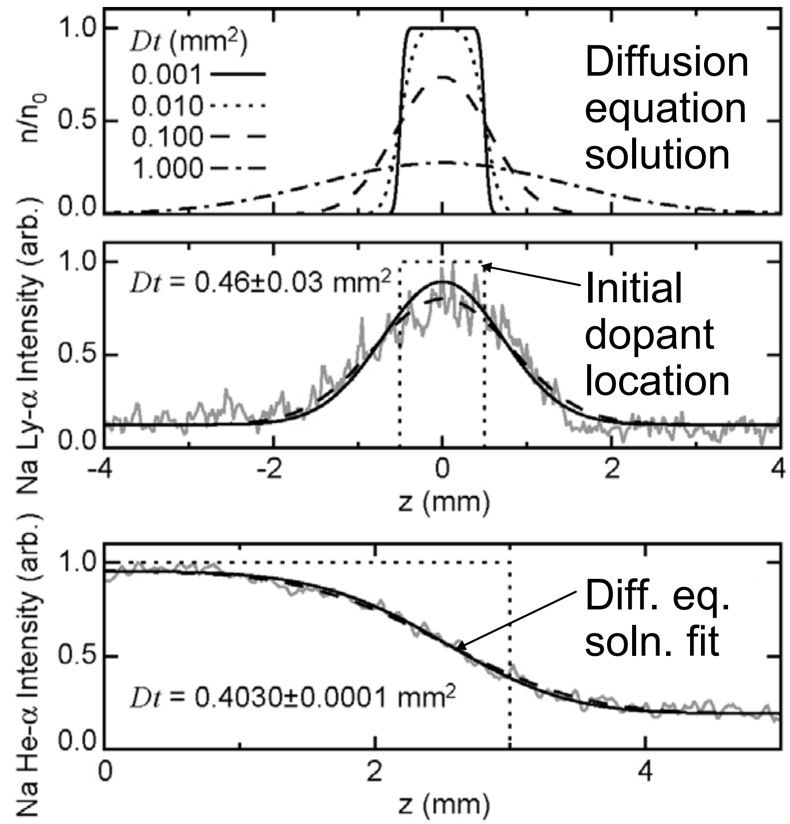




Opacity plays a role, especially for lower Z materials

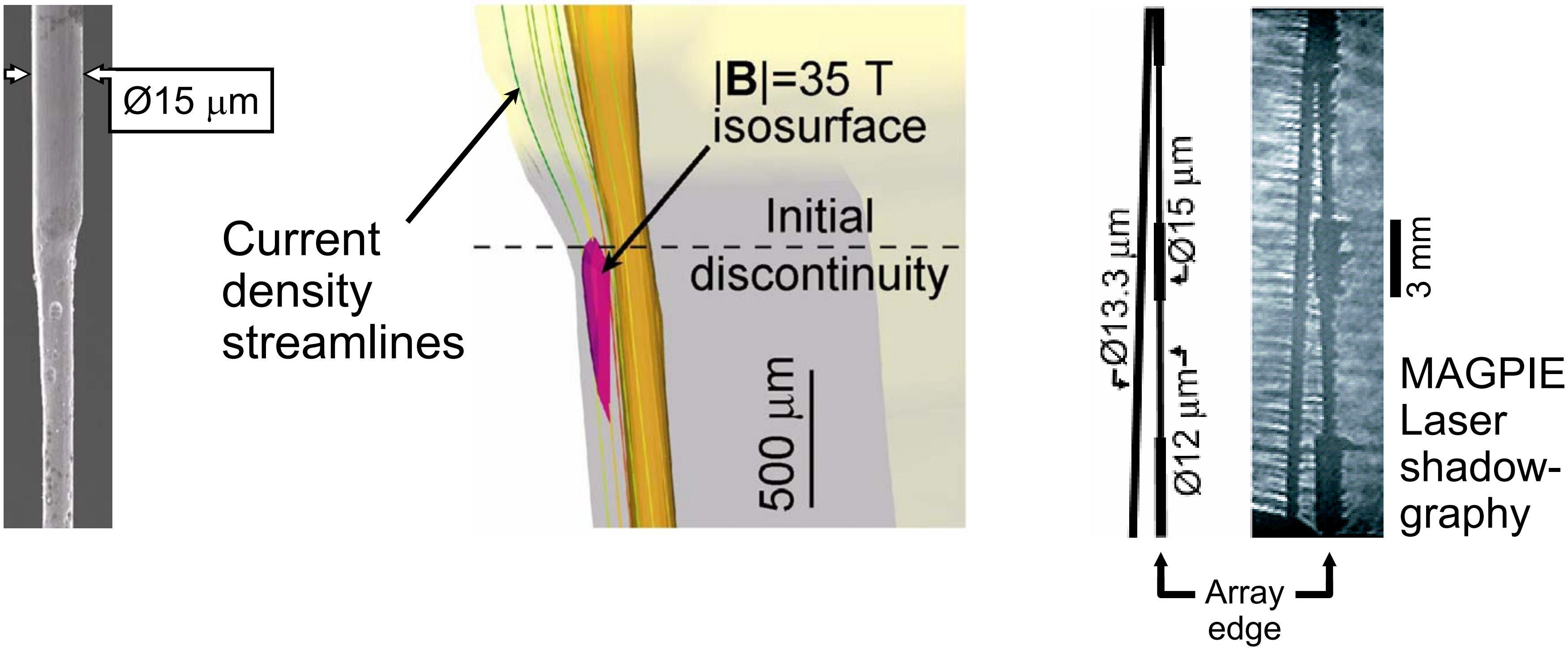
Particle transport in dense z-pinches is studied with localized dopant tracers





- NaF coated Al/Mg wires shot on 1 MA Zebra at UNR
- Na K-shell spectroscopy shows axial diffusion of material, perhaps indicating plasma turbulence

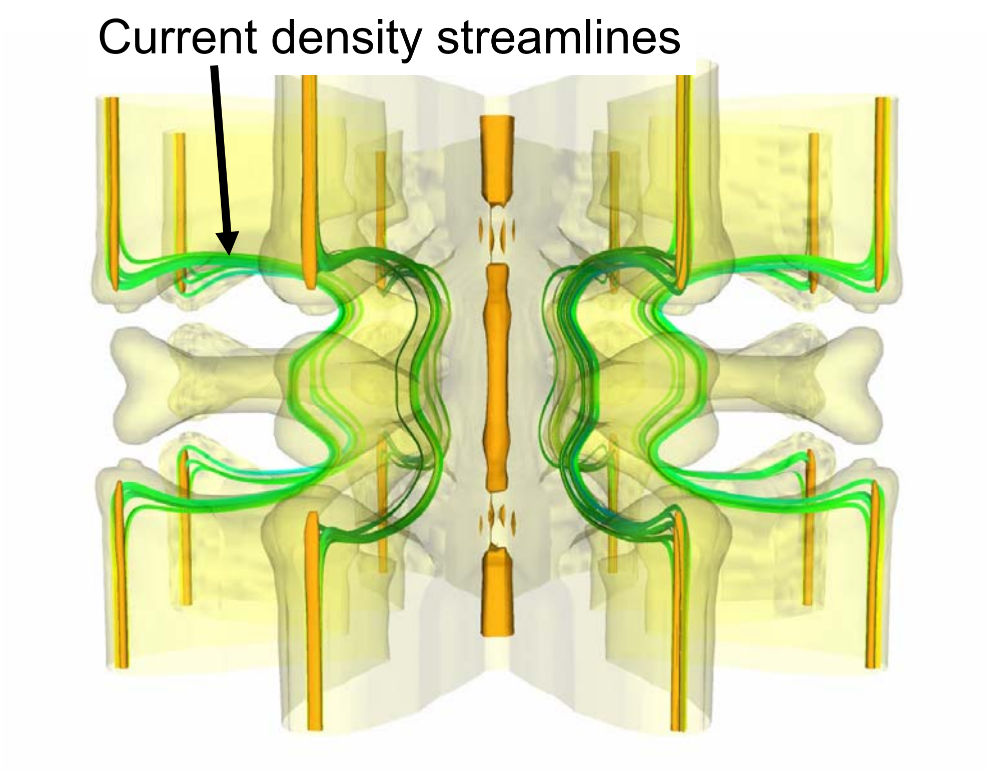
Z-pinch instability evolution studied in university experiments with seeded perturbations



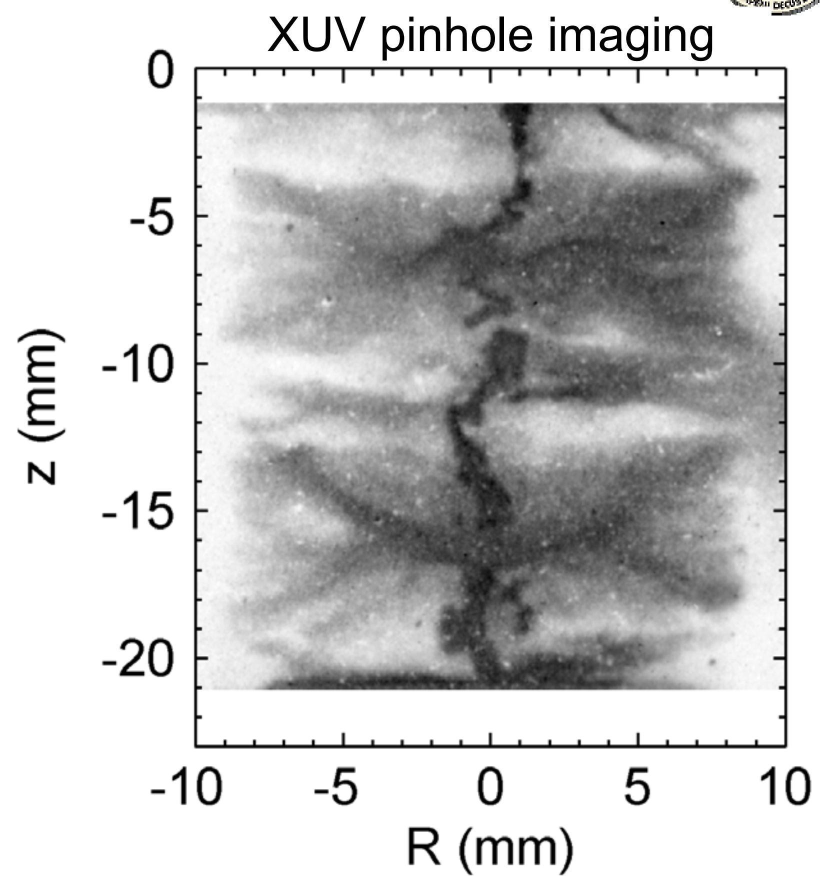
- **Wires etched at Sandia to seed controlled initial perturbations**
- **ALEGRA-HEDP 3D MHD modeling predicts enhanced j x B at discontinuities in wire radius (C. J. Garasi)**

B. Jones *et al.*, Phys. Rev. Lett. **95**, 225001 (2005)

Seeded instabilities initiate MRT bubble implosions in 1 MA MAGPIE experiments

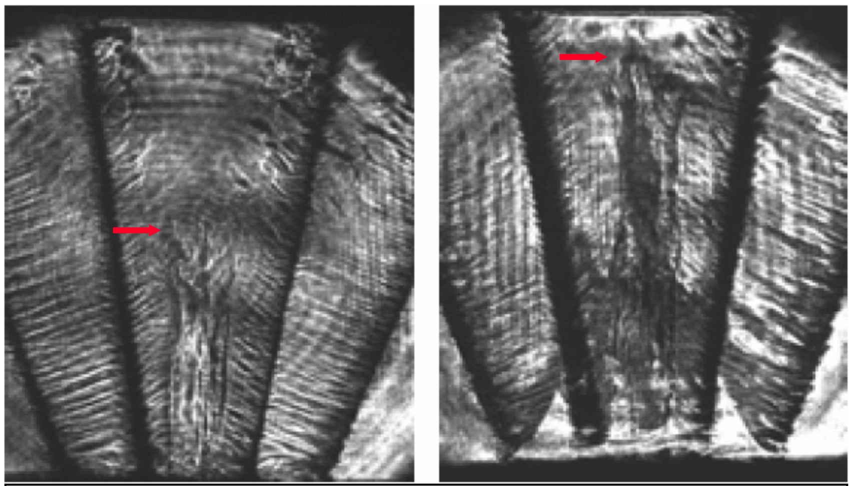


3D MHD ALEGRA-HEDP model
(C. J. Garasi, Sandia)



B. Jones *et al.*, Phys. Plasmas **13**, 056313 (2006)

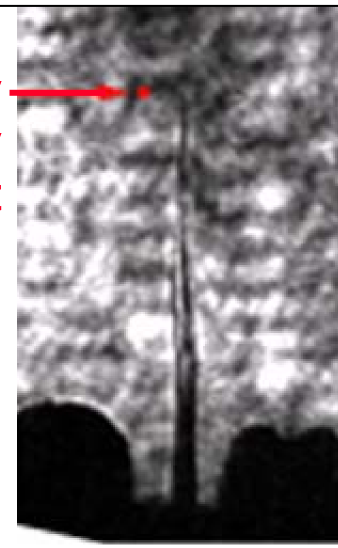
Lab astrophysics and z-pinch dynamics studied in jet production from conical arrays



1 MA array physics experiments at University of Nevada, Reno
D. J. Ampleford, V. V. Ivanov, V. L. Kantsyrev, A. S. Safronova *et al*.

1 MA laboratory astrophysics experiments at Imperial College
D. J. Ampleford, S.V. Lebedev, S.N. Bland, S.C. Bott, J.P. Chittenden, A. Ciardi *et al*.

Laboratory wire array jet



- **Zippered precursor formation in conical array**
- **Axial velocity of ablated flow creates high Mach number jet exiting anode**
- **Jet interaction with plasma side-wind or other materials studied at Imperial College, related to astrophysical jet interactions**

D. J. Ampleford *et al*., Astrophys. & Sp. Sci. **298**, 24 (2005).
S. V. Lebedev *et al.,* Astrophys. J. **564**, 113 (2002).

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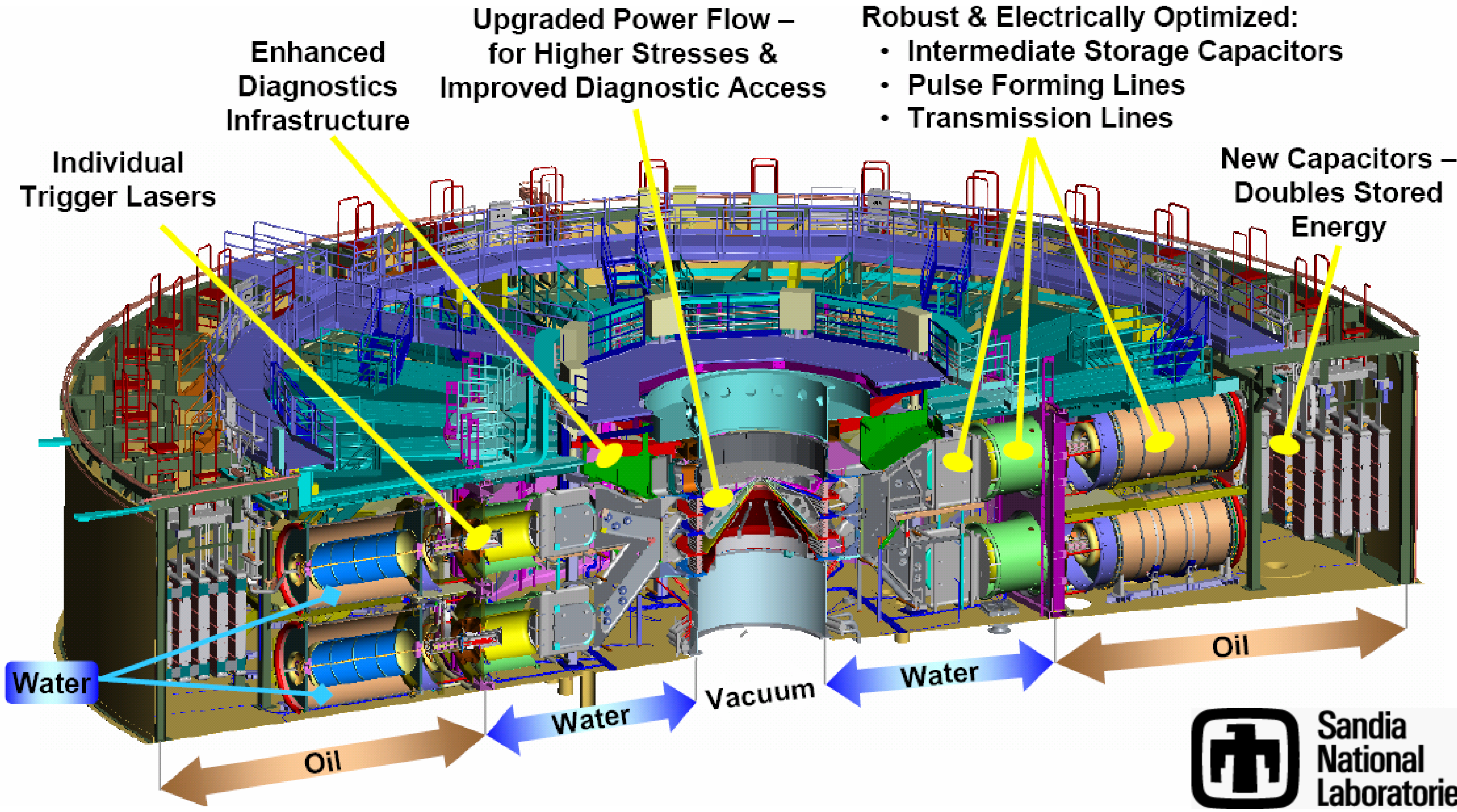
Z Refurbishment underway, 26 MA capability in 2007



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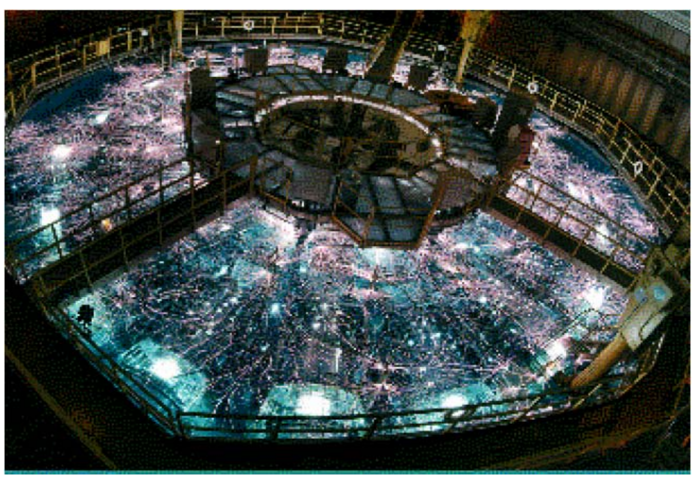
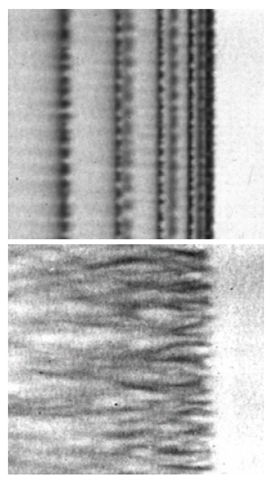
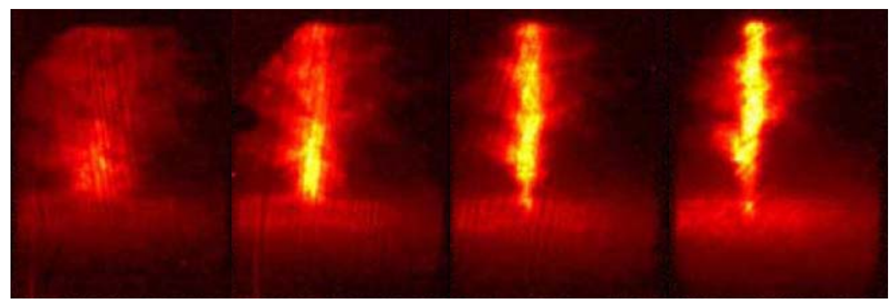
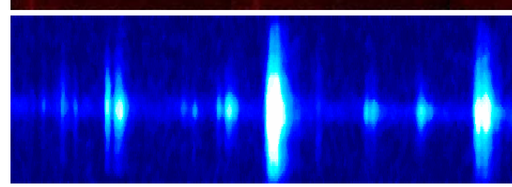
Summary

- Z machine's 20 MA, 100 ns current pulse drives z-pinch implosions
- Wire array z pinches are the world's brightest soft x-ray source
  - >1.5 MJ, >250 TW radiation production achieved
  - High efficiency ~15% wall-plug electrical input to x-ray output
- Inertial confinement fusion is studied at Sandia using z-pinch sources to drive capsule implosions
- Z-pinch applications range from K-shell radiation studies to astrophysics
- Enhanced capability with 26 MA ZR in 2007

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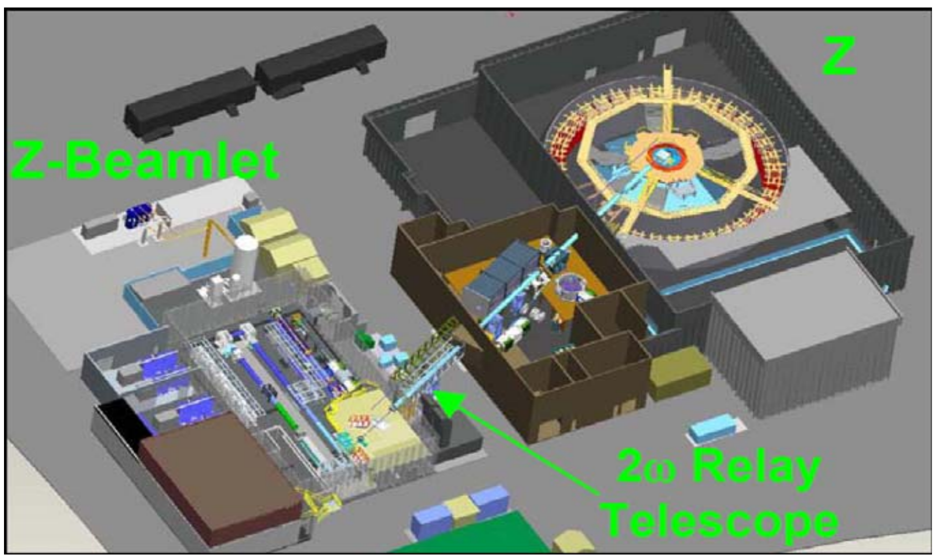
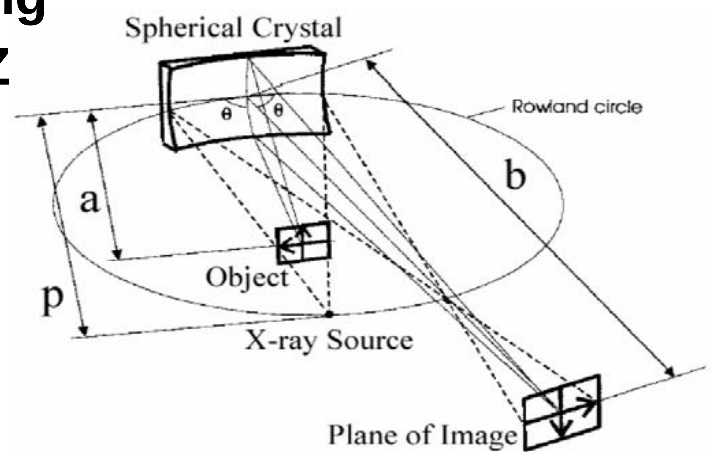
The x-ray sources for radiography on Z are made using the Z-Beamlet Laser

- Z-Beamlet resides in a separate facility to the south of Z. The beam travels 75 m via a relay telescope to a final optics assembly on Z
- In a single 0.3-1.5 ns pulse, the laser can deliver up to 1.5 kJ of 527-nm light to a target in a 50-200 μm spot (>10^{15} W/cm^2 on target) to produce ~0.1-10 J of x rays for backlighting
- Curved-crystal imaging implemented on Z



P. Rambo *et al*., Appl. Opt. **44**, 2421 (2005).



D.B. Sinars *et al*., Rev. Sci. Instrum. **75**, 3672 (2004).

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