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Determination of implosion dynamics and plasma energetics in Z pinches

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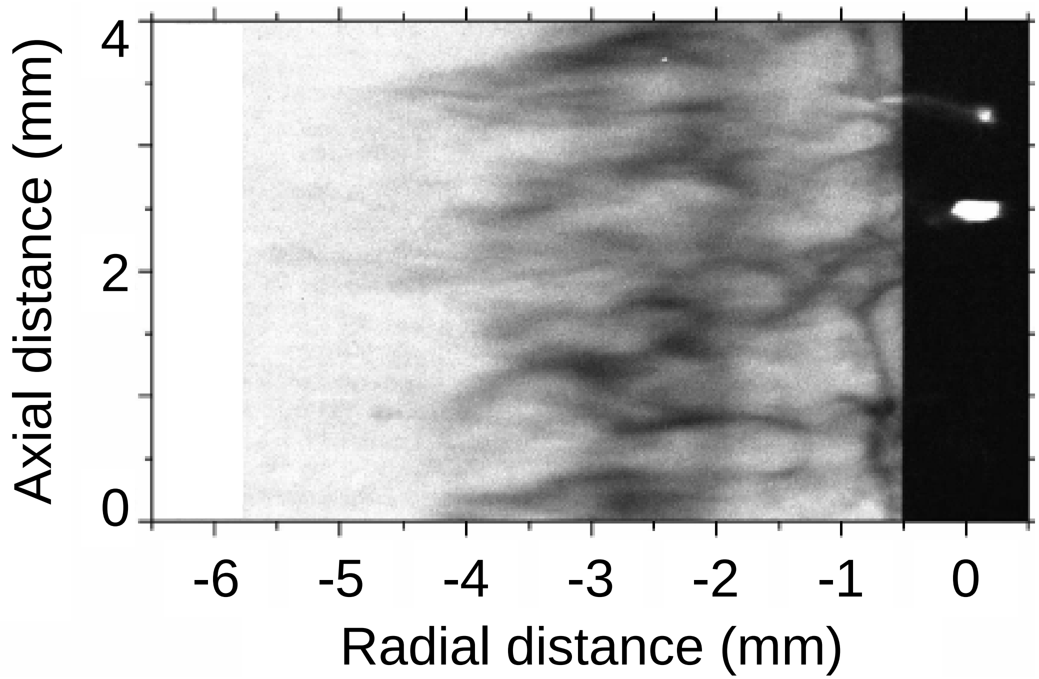
Motivation for studying ion velocities

- Essential z-pinch physics can be studied quantitatively, including structure and energy coupling
- Spectroscopic study of low- to mid-Z plasmas is linked to K-shell source development
- Applications to ICF-relevant loads
  - Doping of tungsten wires with low-Z tracers
  - Low- to mid-Z needed to mitigate opacity on high current drivers

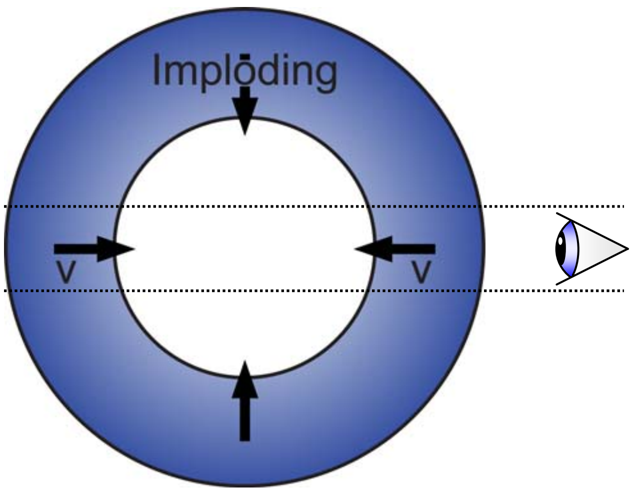
Imploding plasma structures were studied by various methods recently

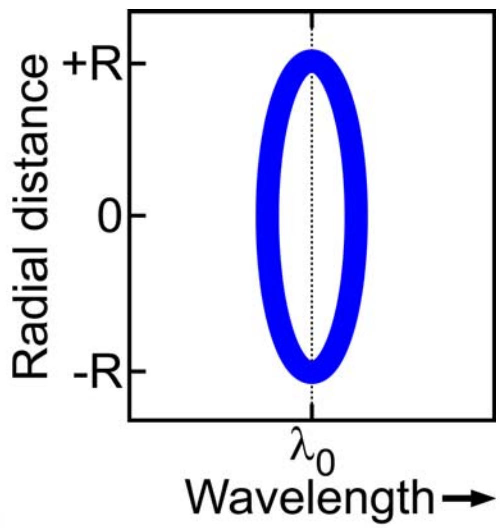
- Radiography
  - D. B. Sinars *et al.*, Phys. Rev. Lett. **93**, 145002 (2004).
- X-ray imaging
  - B. Jones *et al.*, Rev. Sci. Instrum. **77**, 10E316 (2006).
- Electrical measurements
  - M. E. Cuneo *et al.*, Phys. Plasmas **13**, 056318 (2006).

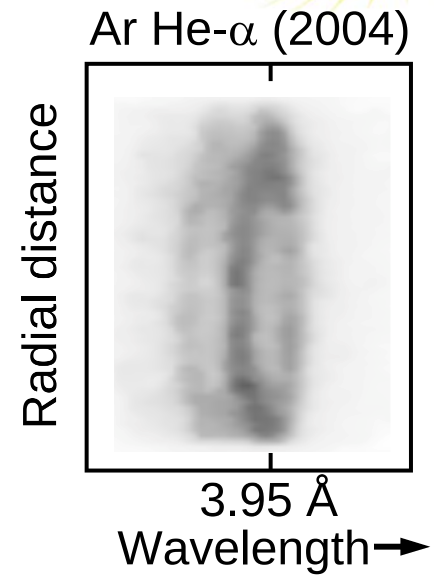


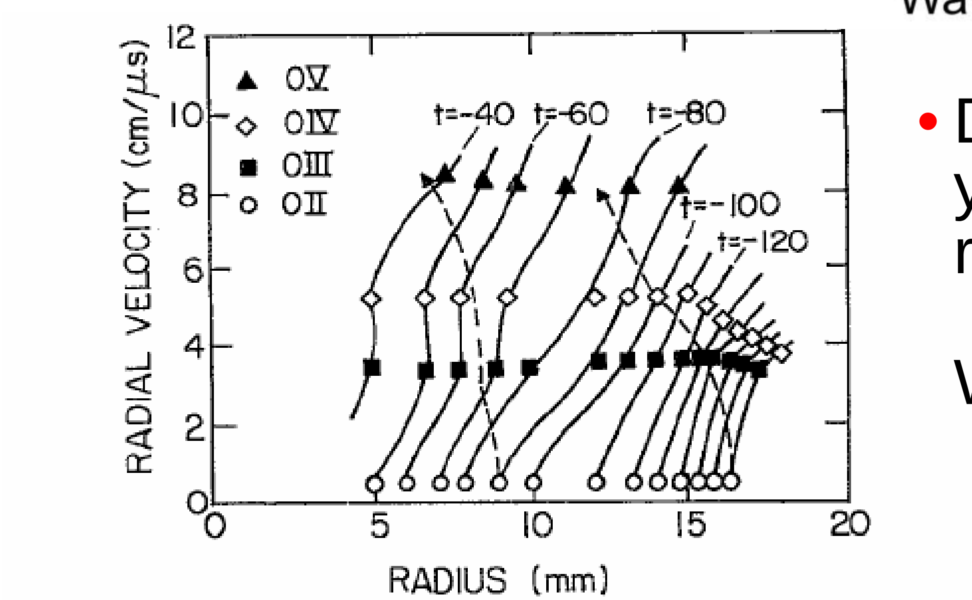
- For detailed particle velocity distributions, including discrimination between isotropic and directed components, using the Doppler effect is essential

Doppler splitting and broadening have been used to determine the ion velocity in gas puff z pinches









- Doppler effect observation has yielded the evolution of the radial ion velocity profile

Weizmann Institute (1995)

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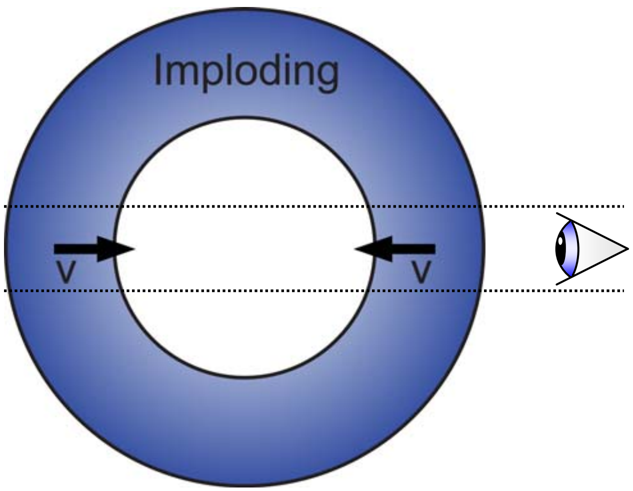
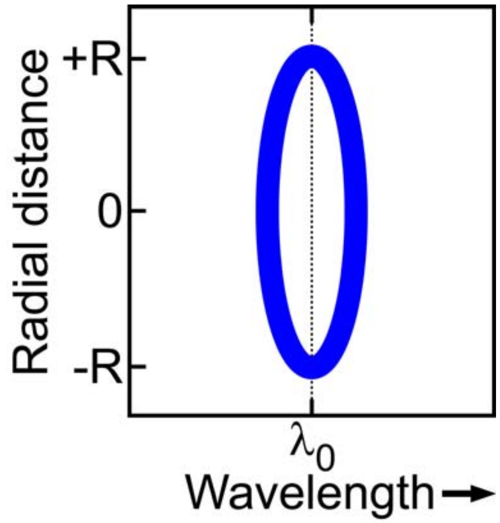
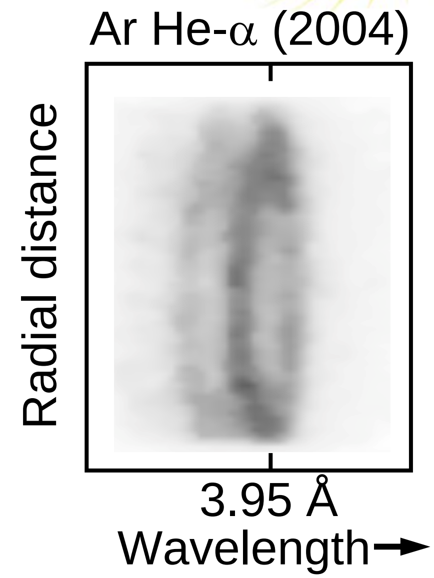
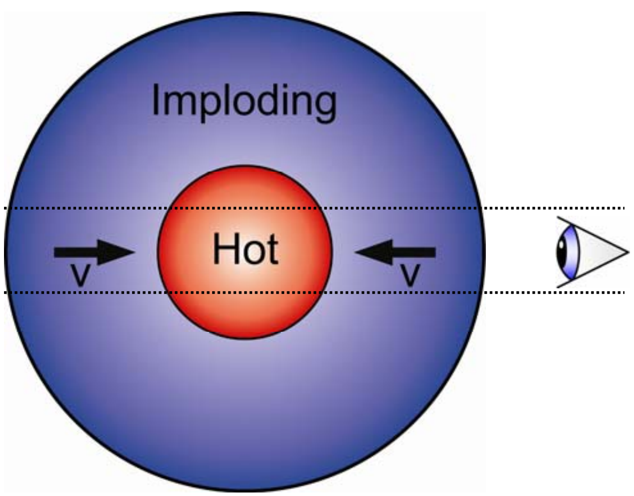
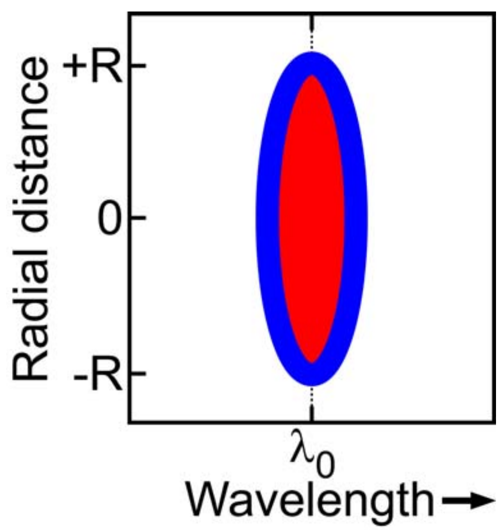
With wire arrays, a hot plasma on axis is formed early, which makes observations of Doppler splitting difficult











- Self emission from wire array precursor or stagnating plasma fills in the Doppler split line profile

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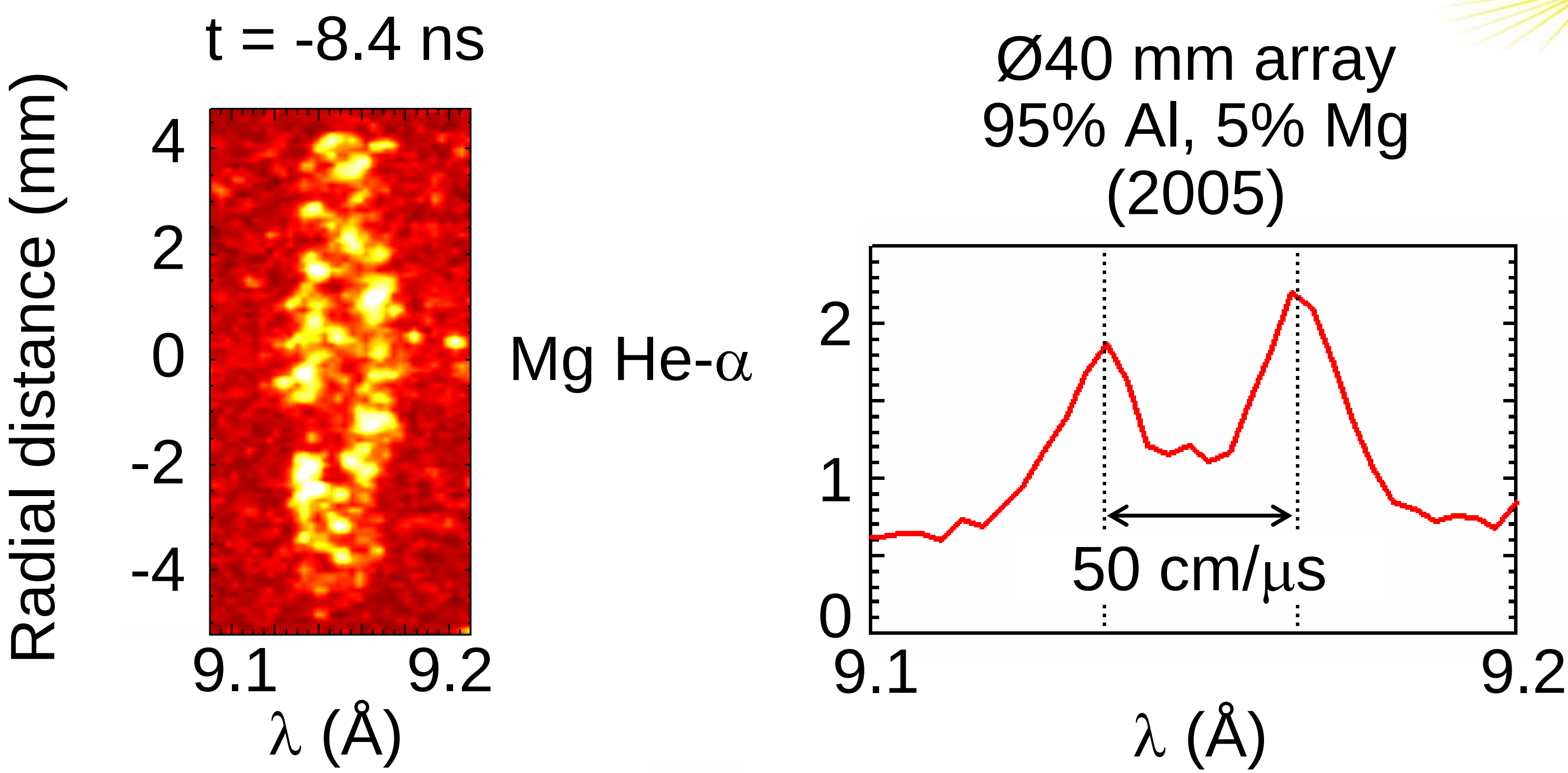
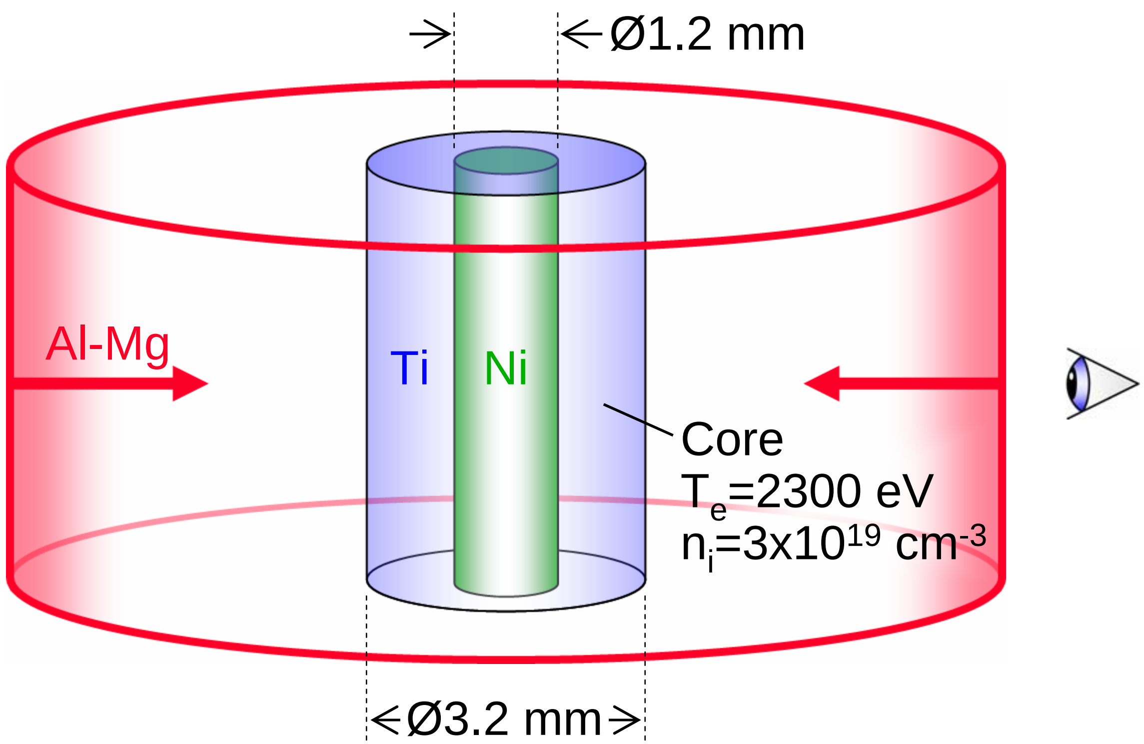
1) Use of Doppler splitting in implosions of large diameter, low-Z wire arrays, with minority ions

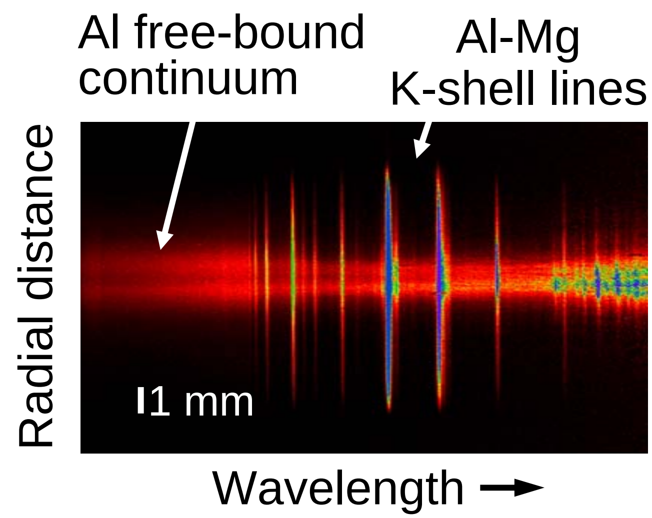


- Mg lines are optically thin at early times

2) Pre-filling the region on axis with other species allows for observation of Doppler splitting in the imploding shell

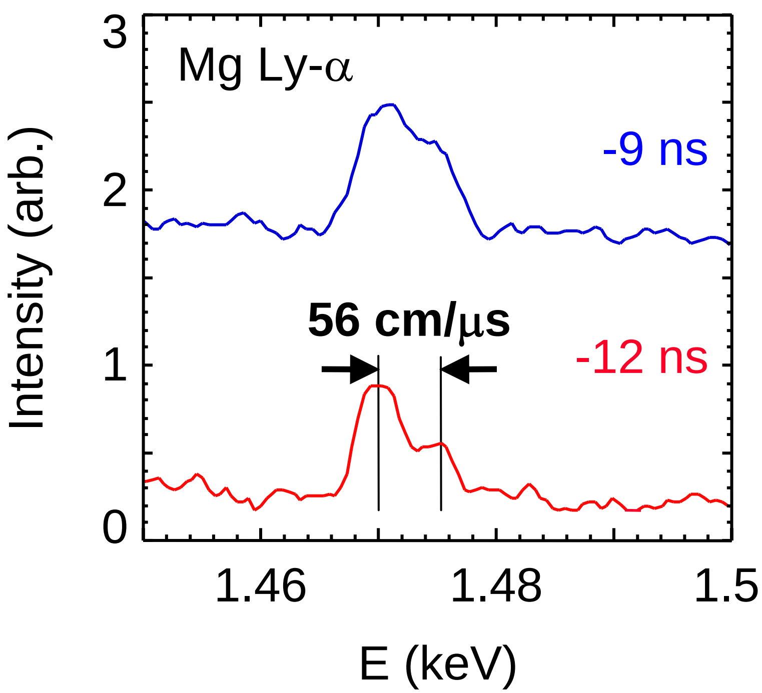
- Nested array: Al-Mg outer, Ni-Ti inner (2006)
- Analysis of the spectroscopic data yielded the structure of the pinch, densities, and temperatures
  - Collisional-radiative model, radiation transport in discrete zones
  - Line shape calculations (Stark, Doppler)



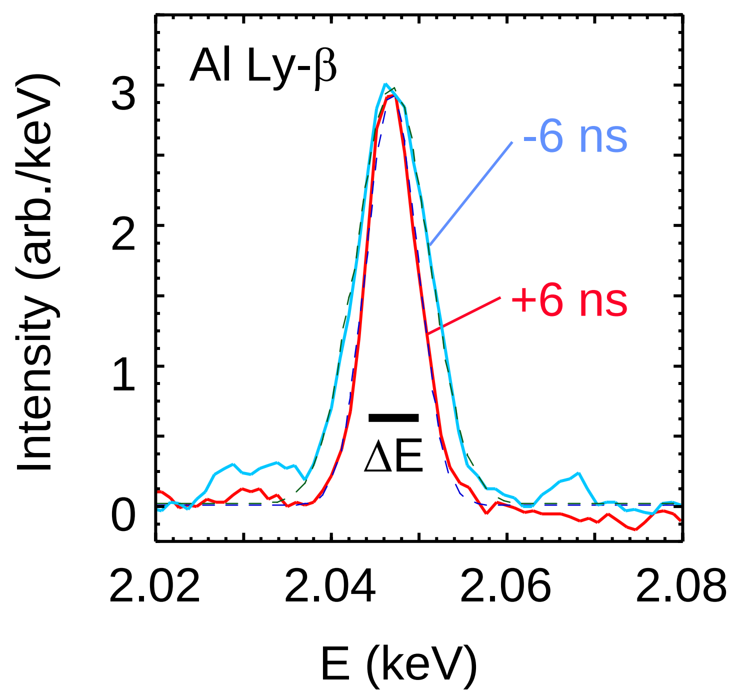


Doppler splitting observed in imploding Al-Mg shell, unobscured by emission from on z-pinch axis

- Implosion velocity inferred prior to peak x-rays



- Observed decrease in line width after implosion may indicate ion energy loss (analysis in progress)



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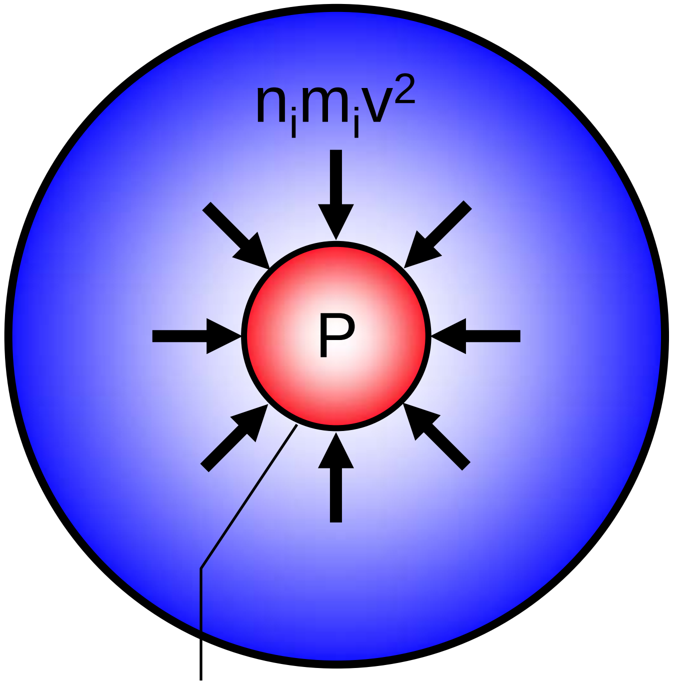
Inference of plasma properties allows the physics of pressure balance at stagnation to be considered



Ni-Ti core rises to a diameter of Ø3.2 mm

- At stagnation, mass accretes in the core, rising by ~10x, while the core density is approximately constant
- It appears that pressure balance is maintained
  - $P = n_e T_e + n_i T_i = n_i m_i v^2 + B^2/8\pi$
  - It is seen that the kinetic pressure dominates unless 12 MA flows in the core
- Measurement of plasma n, T, v profiles will allow for studying the energy balance
  - Compare $N m_i v^2/2$ + estimated PdV work to the total radiation emitted from the core

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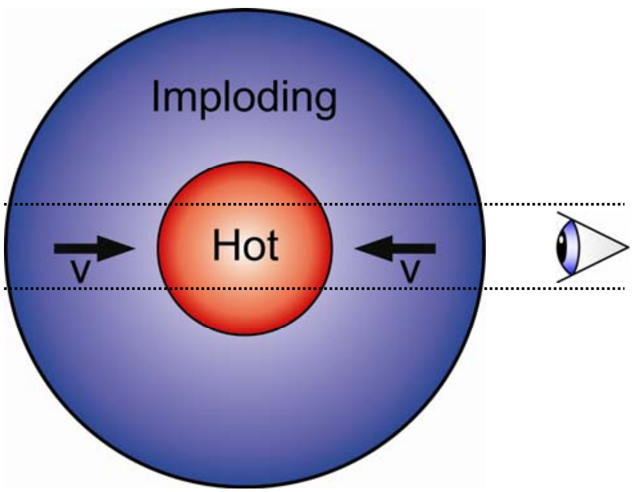
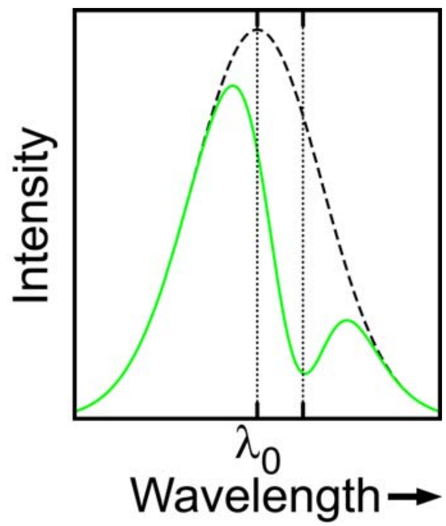
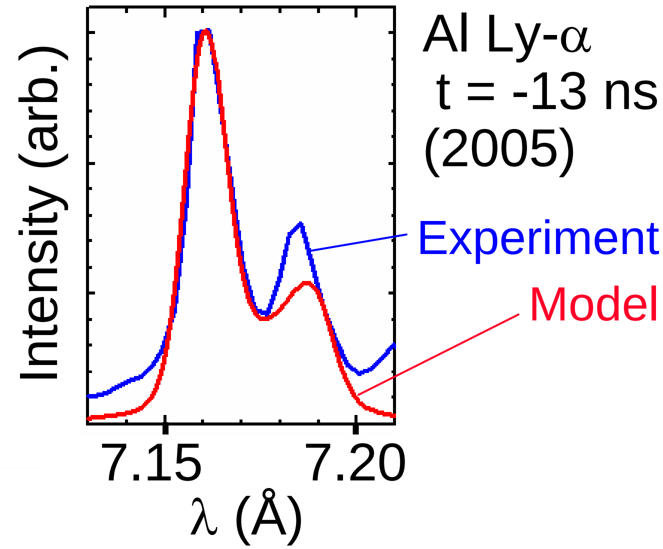
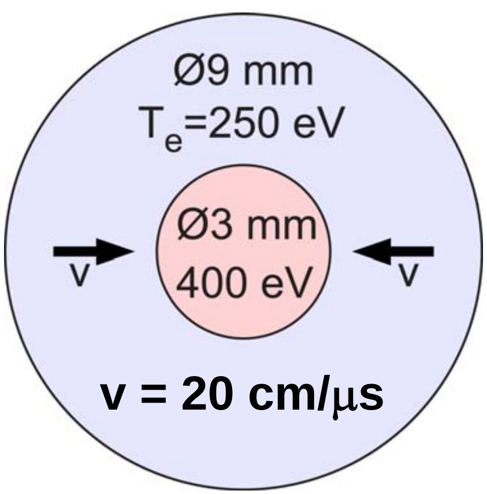
3) Use of the core radiation to backlight the imploding plasma

- Doppler-shifted absorption line seen in large-mass Al wire array









- Velocity of the compact wire array is relatively low at this time
  - 6 mg/cm, Ø20 mm load relevant to ICF
- Ion velocities in the core are also determined
- Spectroscopy yields T_e, mass, n_i, radii, and the velocities of the various regions

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Summary

- Three ways were demonstrated for diagnosing particle velocities in the wire array implosions
- A new quantitative picture for the small-mass loads:
  - Less participation of Al outer array material in the core
  - Al outer array material reaches the core late
  - Narrow Ni core surrounded by Ti core (n_i, T_e, radii are determined)
  - Al-Mg velocities are measured
  - All are used in 2D MHD nested array modeling (E. Yu, 2006)
- For the large-mass loads, the detailed radial structure seen spectroscopically quantitatively adds to the picture developed from other diagnostics (Cuneo, Sinars, Bliss, 2001-2005)
  - The relatively low velocity measured spectroscopically together with T_e, n_i in the core and in the imploding plasma can be used to constrain 3D MHD implosion modeling (R. Lemke, C. Jennings, 2007)
  - Comparisons to radiography will be useful

Future work

- Optimize the spectroscopic instruments (resolution, imaging)
- Use dopant and alloy techniques (demonstrated on Z) to:
  - Control the opacities
  - Perform local observations (study structure)
  - Study velocities from different viewing directions
- Ion velocity distribution and plasma structure measurements for small diameter ICF-relevant, low-Z arrays (Be, Al, C)
- Take advantage of K-shell source development shots to study important z-pinch stagnation physics
- Magnetic field measurements