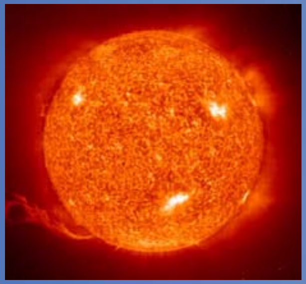
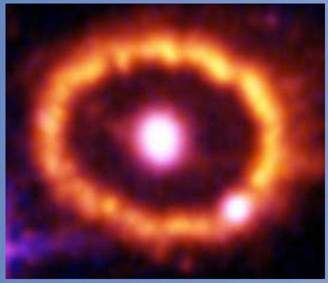
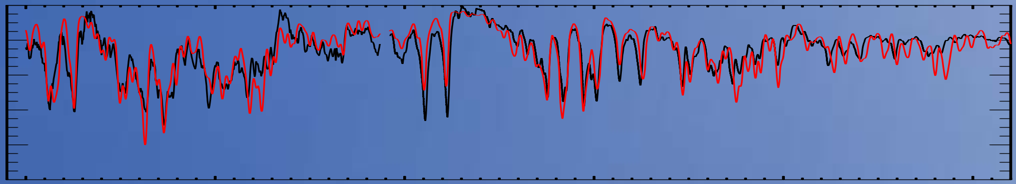
28 July 2009

# *Laboratory Astrophysics on the Z Pulsed Power Facility*

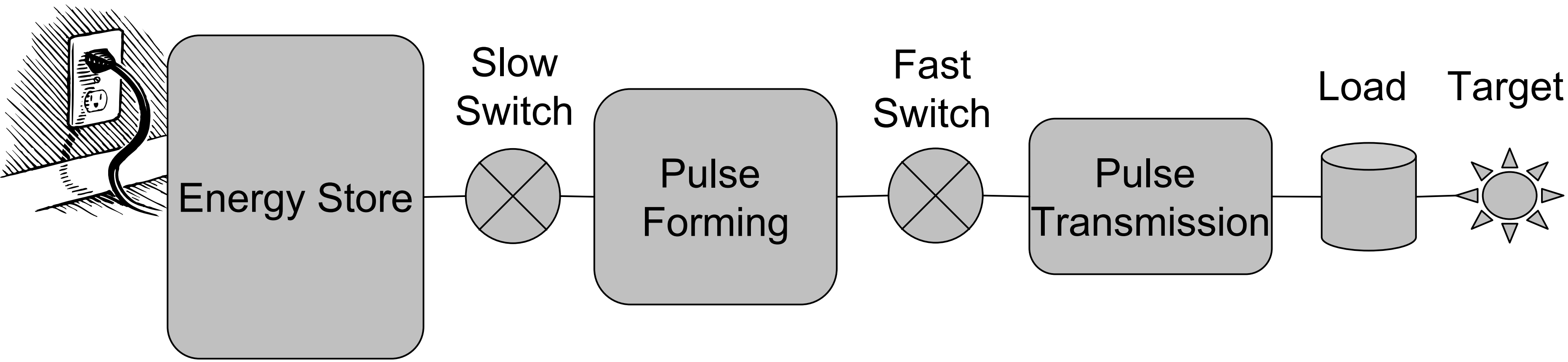





**Gregory A. Rochau**

Workshop on Science with High-Power Lasers and Pulsed Power

Sandia is a multiprogram 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.

# Pulsed power is the temporal compression of electrical energy to produce short bursts of high power.




Low Electrical Power
Up to $10^7$ J – $10^6$ W

High Electrical Power
Up to $10^7$ J – $10^{14}$ W

[ Take the equivalent energy required to operate a TV for a few hours (1-2 MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~15 TW). ]

…S T Pai & Qi Zhang, “Introduction to High Power Pulse Technology,” World Scientific Publishing Co., Singapore, 1995.

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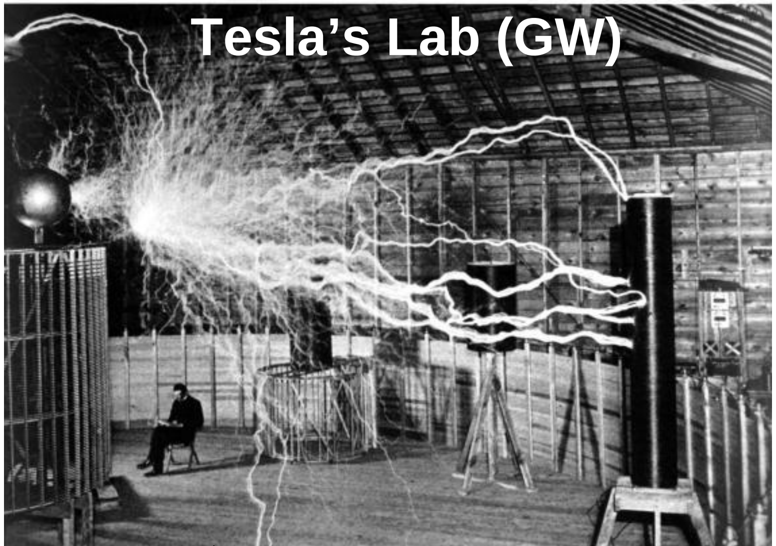
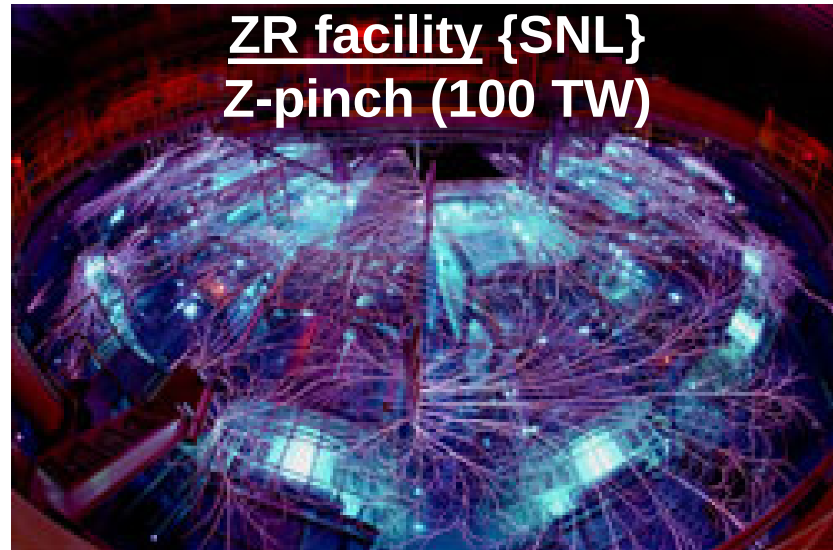
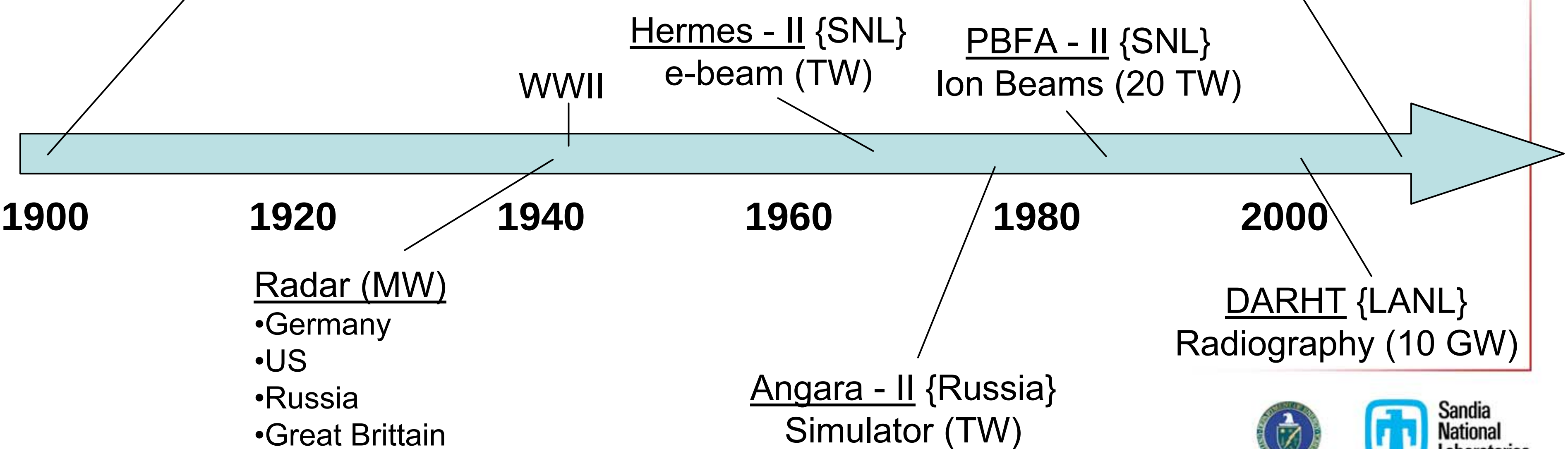
# Pulsed power has been investigated for over a century.

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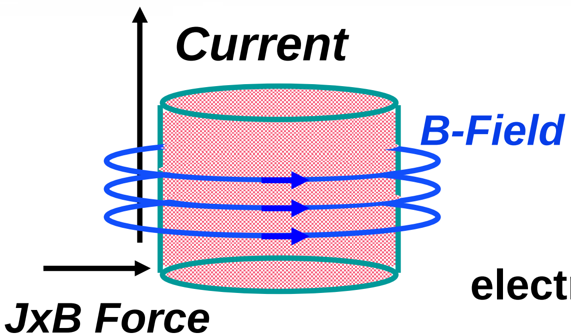
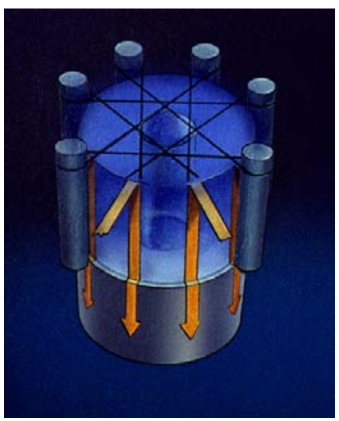
# Z-pinch implosions effectively convert electrical energy into radiation

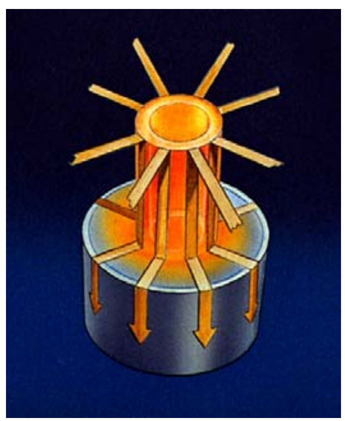



kinetic and electrical energy → internal (shock heating) → x rays

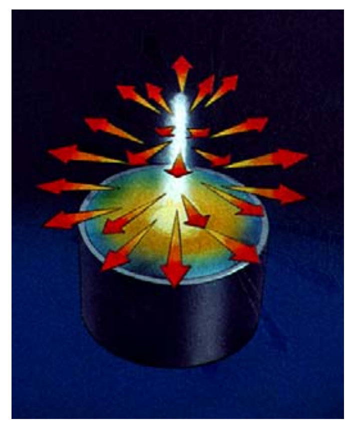
electrical energy → kinetic energy



Initiation



Implosion



Stagnation

- Z-pinch loads
  - Gas puffs
  - Foils
  - Low density foams
  - wire arrays
- $E_{x\text{-}ray} \approx 0.15\ E_{electrical}$

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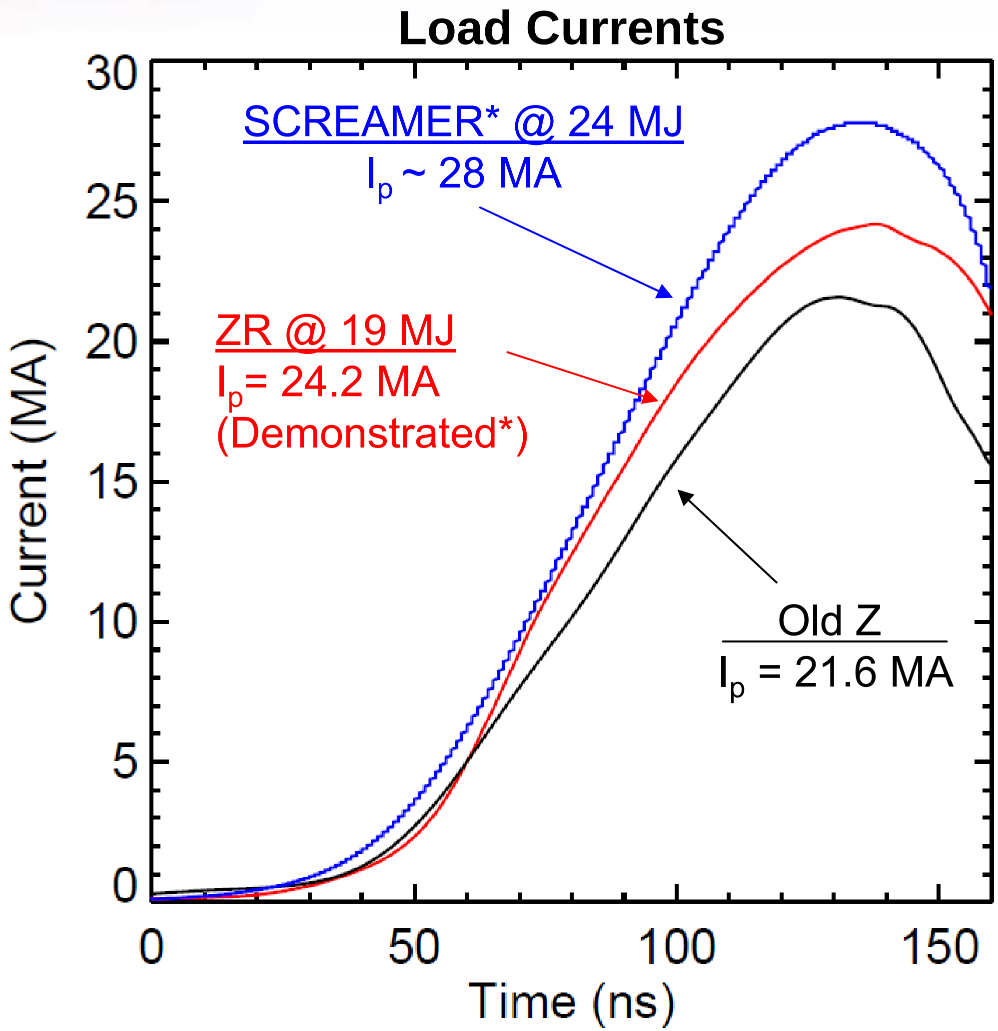
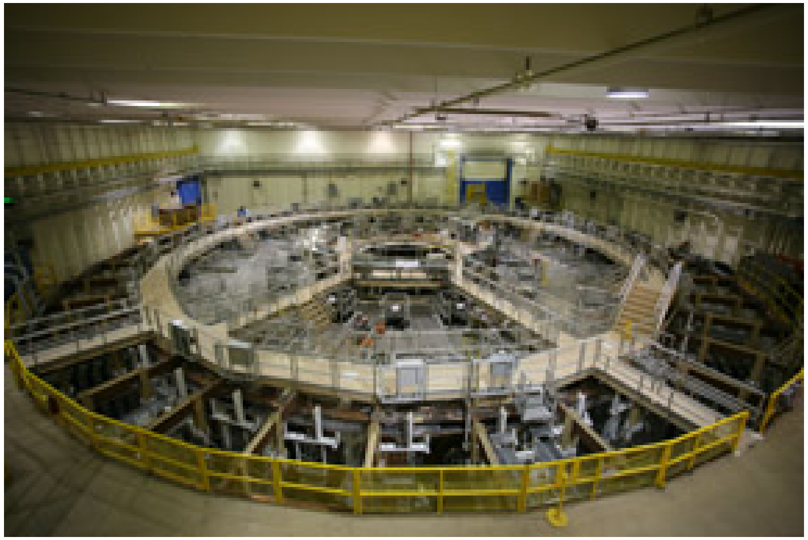
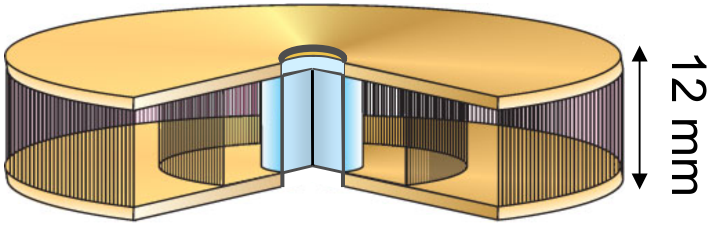
# The refurbished Z facility delivers world-record currents to Z-pinch loads






*50% increase in Electrical Energy

*Predicted 100% increase at full capacity

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# The Z facility has an extensive suite of standard diagnostics

**X-ray Power and Energy**

| | |
|---|---|
| Filtered X-ray Diodes (XRDs)………………. | < 4 keV Power |
| Photo-Conducting Diamonds (PCDs)………. | > 1 keV Power |
| Silicon Diodes (TEP)……………………….. | Broad-band Power |
| Bolometers……………………………............ | Broad-band Energy |

**X-ray Spectroscopy**

| | |
|---|---|
| Elliptically Curved Crystals…………………… | 0.7-10 keV Time-gated |
| Convex Curved Crystals……………………… | 0.7-10 keV Time-integrated |
| Spherically Curved Crystals………………… | 0.7-10 keV Time-integrated |
| Transmission Crystals………………………… | > 10 keV Time-integrated |

**X-ray Imaging**

| | |
|---|---|
| Filtered Pinhole Cameras……………………... | > 0.7 keV Time-gated |
| Multi-layer Mirror Pinhole Cameras………… | 0.277±0.003 keV Time-gated |

**X-ray Backlighting**

| | |
|---|---|
| Point-projection……………………………… | two-frame @ ~1kJ ea. |
| 1 or 2-color Monochromatic Imaging............. | two-frame @ ~1kJ ea. |

**Fiber-Based Velocity Interferometry (VISAR)**

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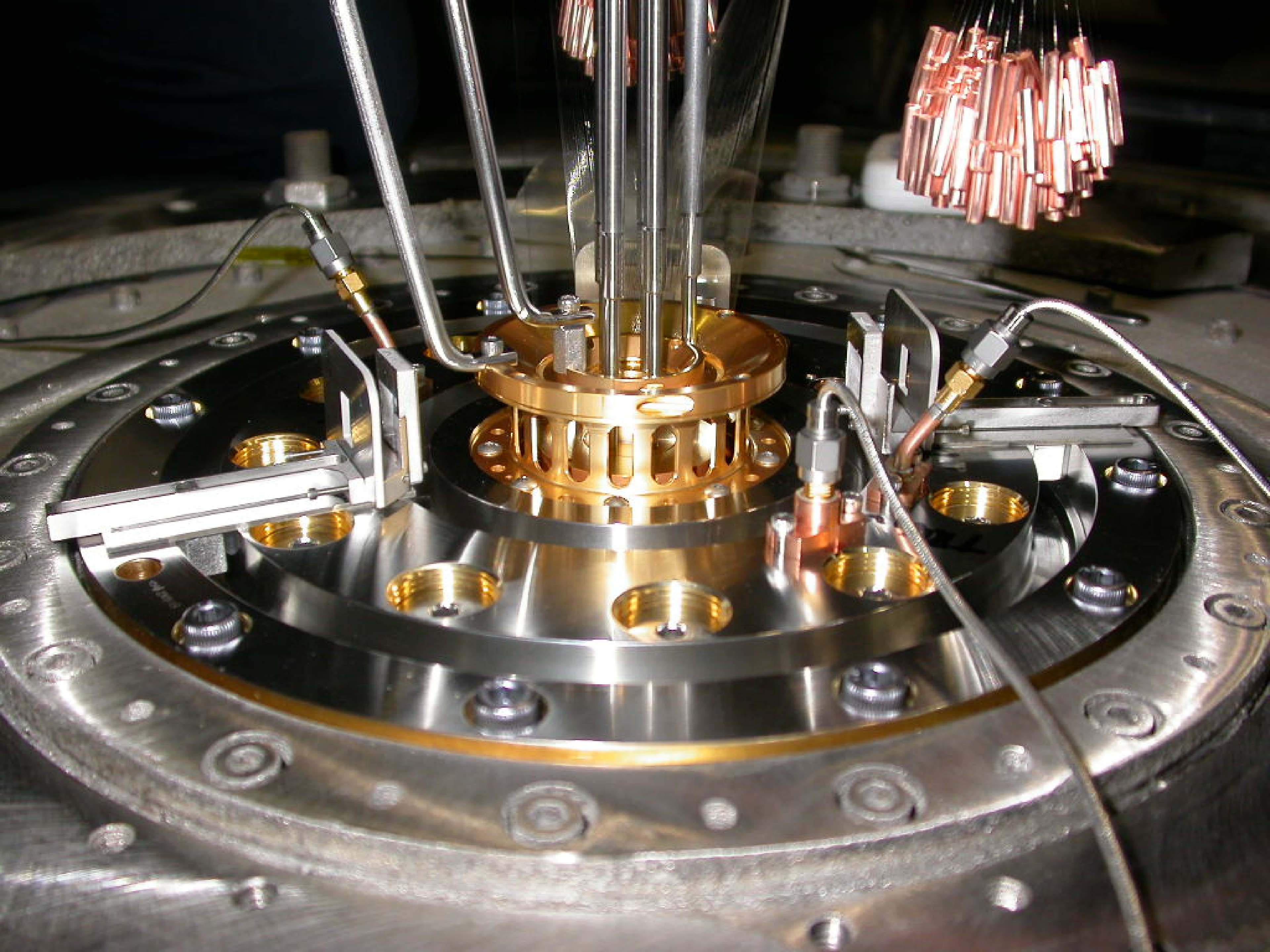
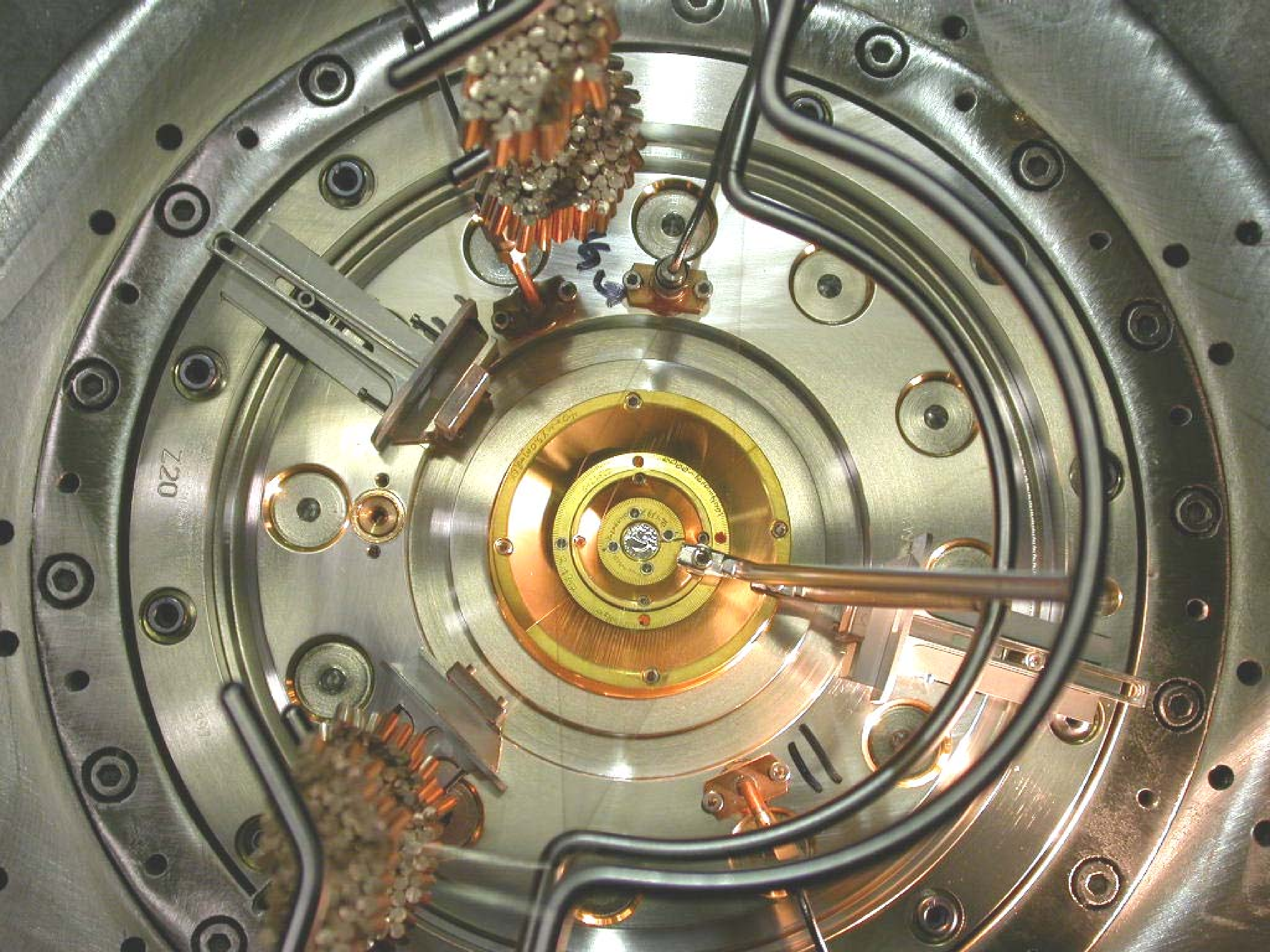
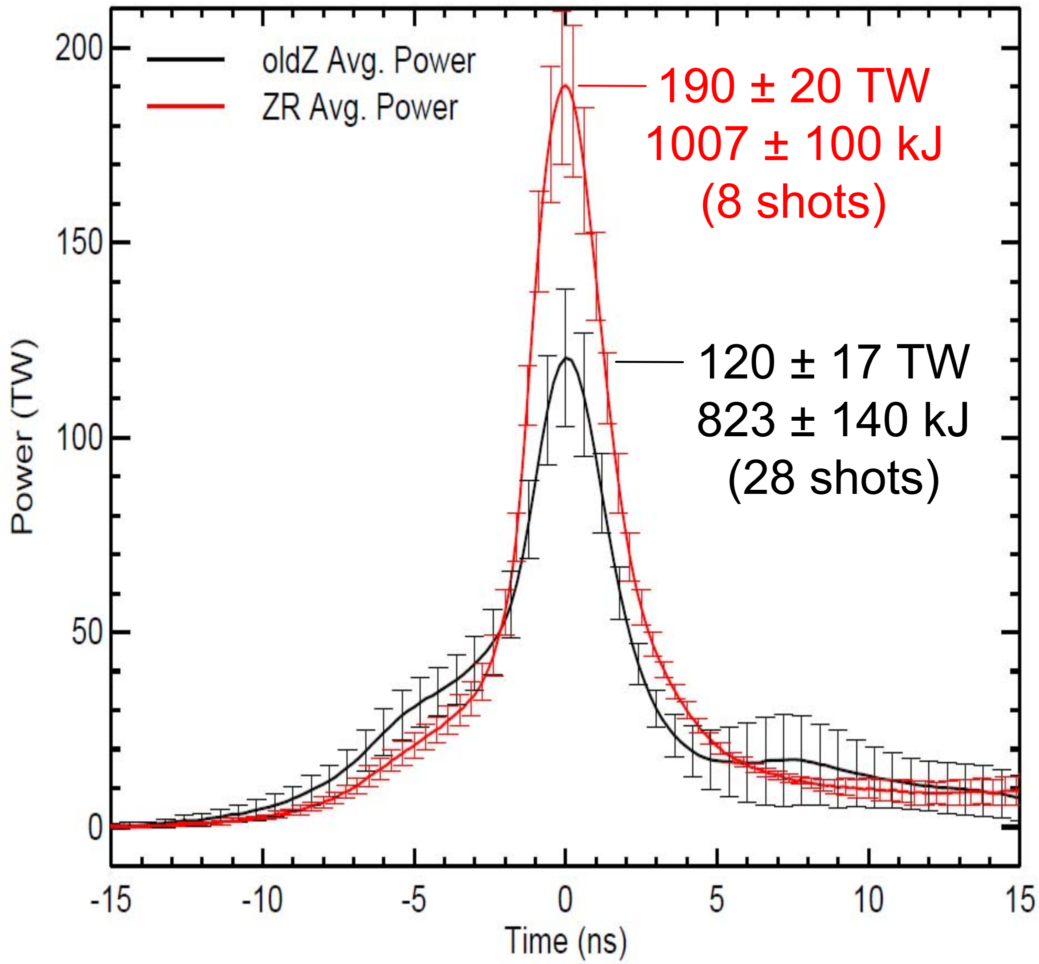




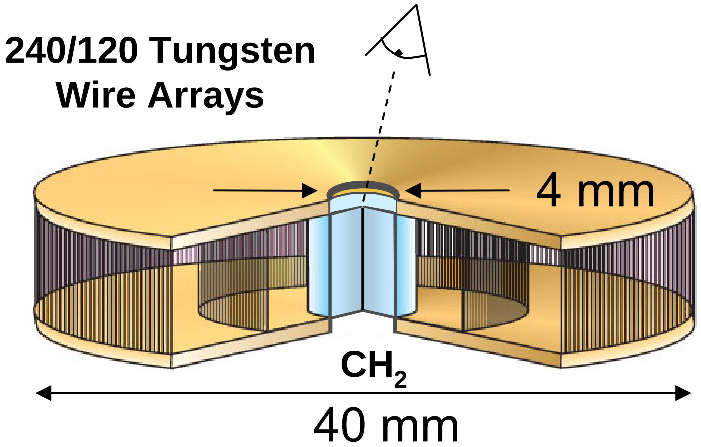
# The Z-pinch Dynamic Hohlraum (ZPDH) is an energetic and reproducible x-ray source.

**Radial Power on Z and ZR**




## ZPDH Source

- $I_p$ > 21 MA
- 18 radial slots (x-ray exit holes)
- 1 axial aperture
- High internal temperature

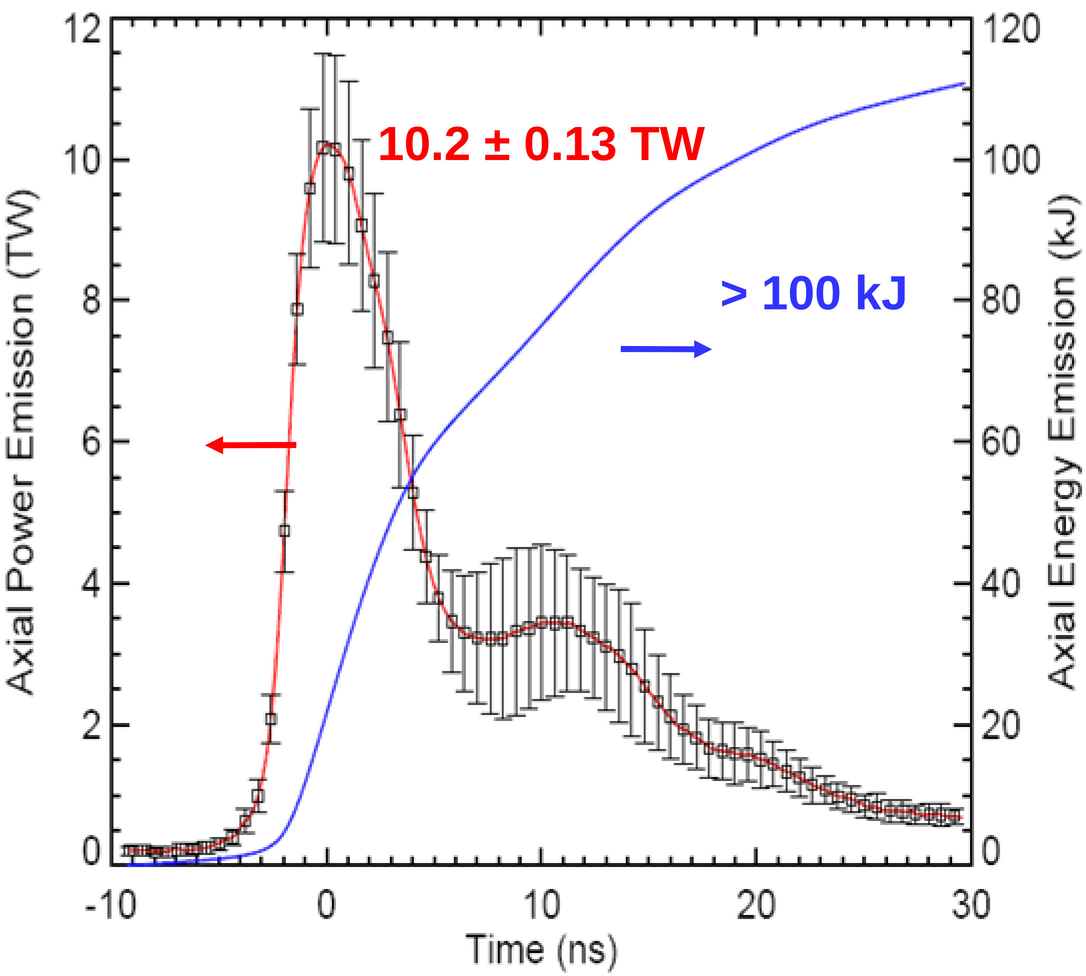




Sanford et al., POP 9 (2002)
Bailey et al., POP 13 (2006)
Lemke et al., POP 12 (2004)
Slutz et al., POP13 (2006)
Rochau et al., PPCF 49 (2007)

# The Z-pinch Dynamic Hohlraum (ZPDH) is an energetic and reproducible x-ray source.

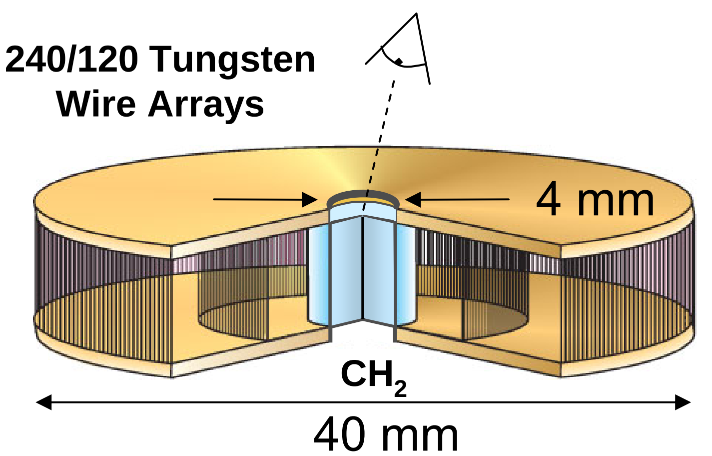
**Axial Power and Energy on Z**




*Axial power not yet conclusively measured on ZR

## ZPDH Source

- $I_p$ > 21 MA
- 18 radial slots (x-ray exit holes)
- 1 axial aperture
- High internal temperature





Sanford et al., POP 9 (2002)
Bailey et al., POP 13 (2006)
Lemke et al., POP 12 (2004)
Slutz et al., POP13 (2006)
Rochau et al., PPCF 49 (2007)

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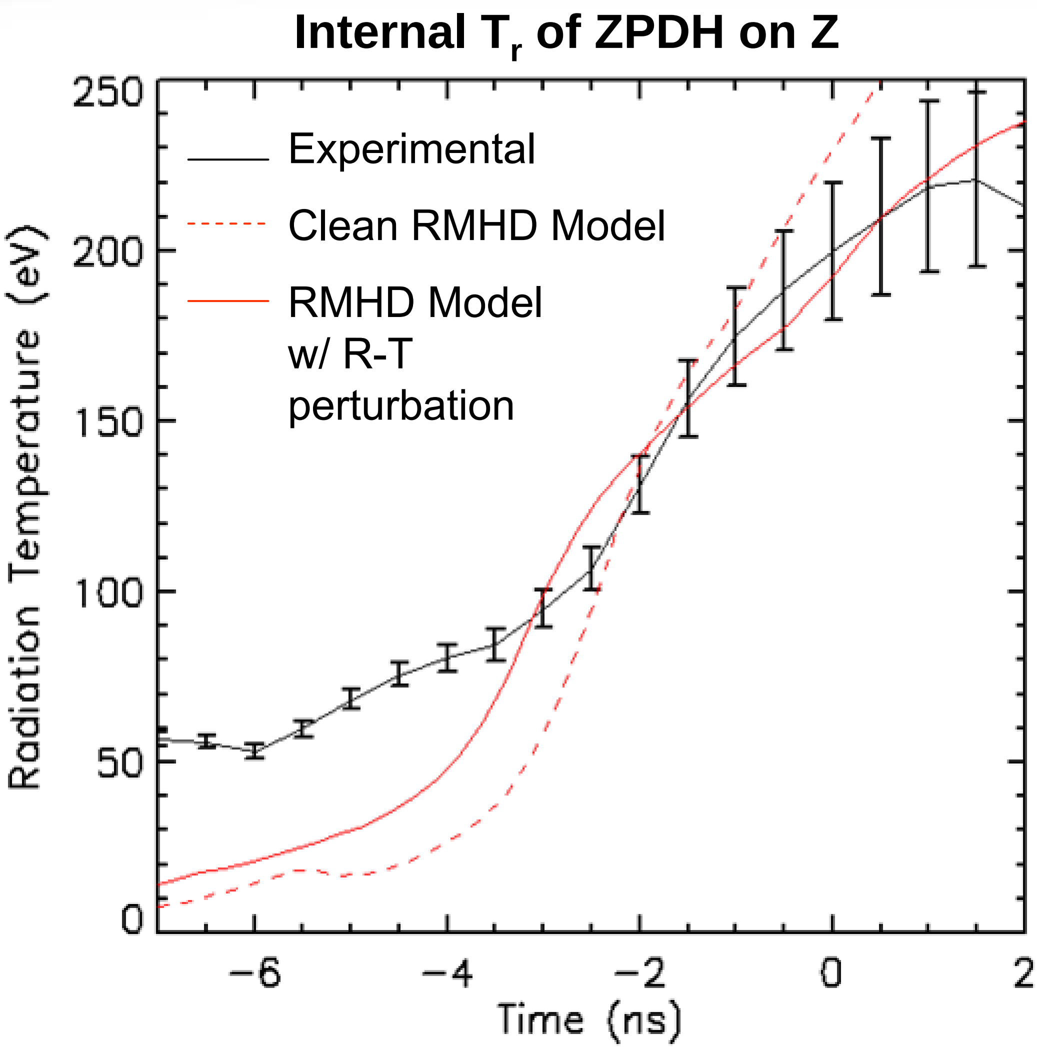
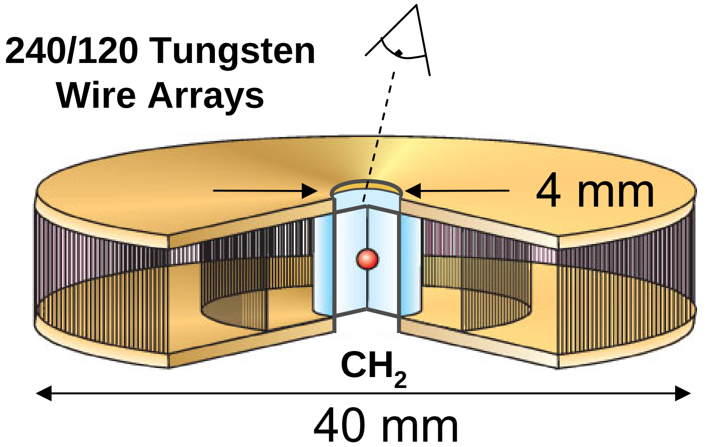



## ZPDH Source

- $I_p$ > 21 MA
- 18 radial slots (x-ray exit holes)
- 1 axial aperture
- High internal temperature

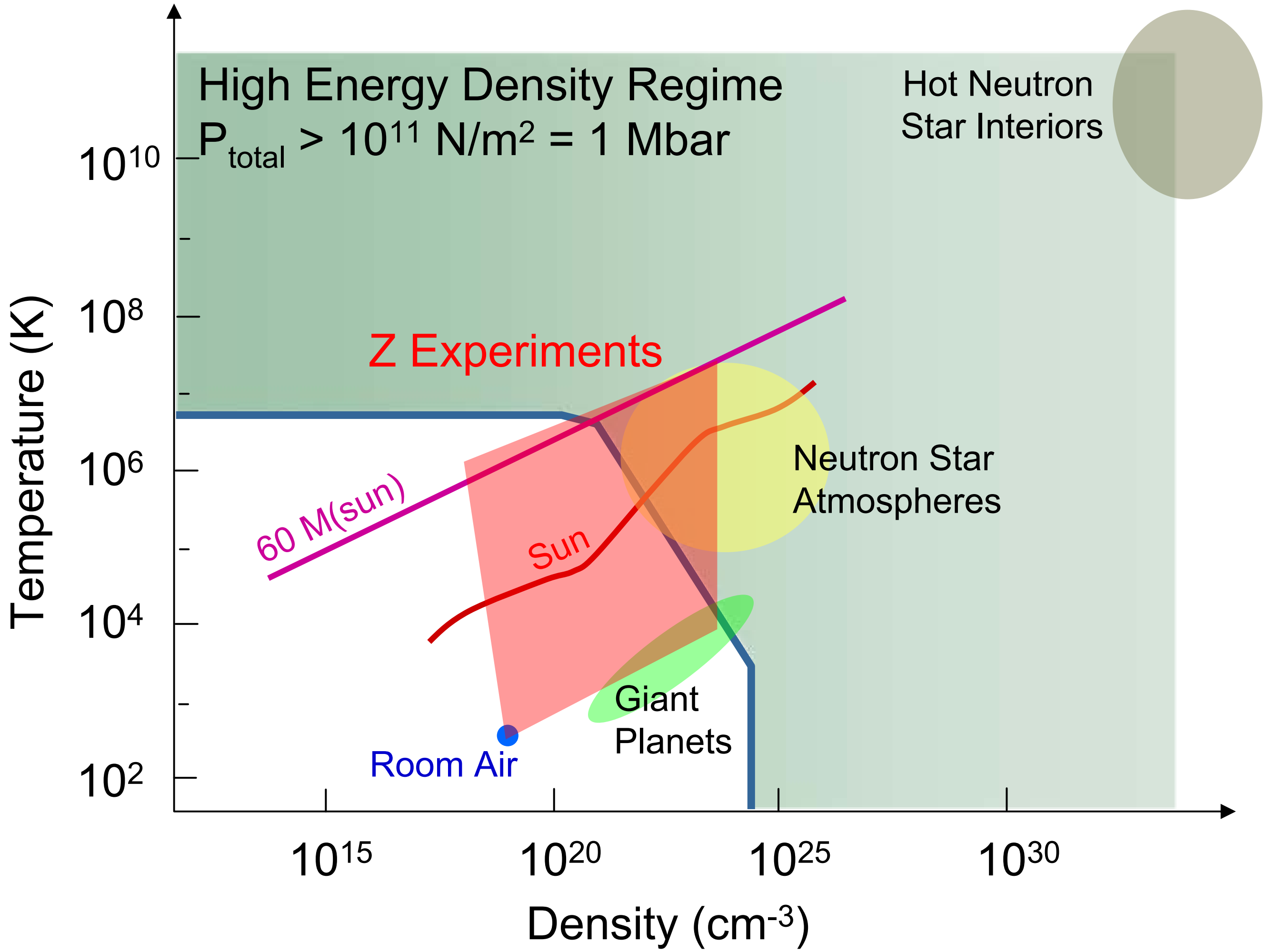




Sanford et al., POP 9 (2002)
Bailey et al., POP 13 (2006)
Lemke et al., POP 12 (2004)
Slutz et al., POP13 (2006)
Rochau et al., PPCF 49 (2007)


*Internal $T_r$ not yet measured on ZR

# The Z facility provides a wide range of energy densities – Flexibility for Lab Astro

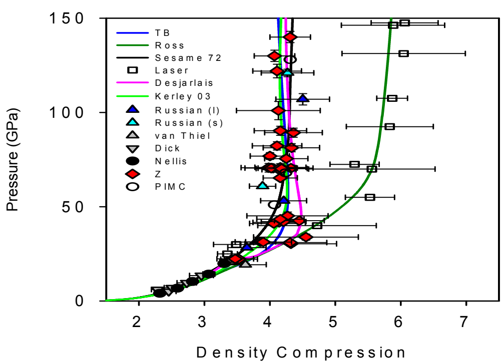


# Z provides multiple platforms for a variety of laboratory astrophysics experiments.

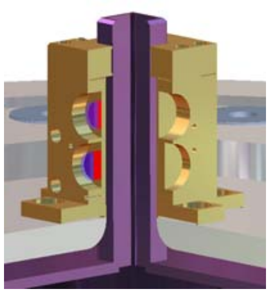
## EOS

**$D_2$ EOS relevant to giant planet interiors.**

Reduced VISAR data




B- Driven ICE & Flyer Plates

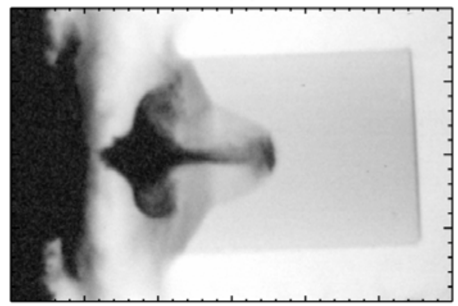


Knudson et al., PRL 87 (2001)

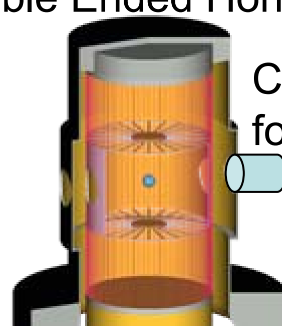
## Rad Jets

**High resolution imaging of radiation driven jets**

Backlit image



Double Ended Hohlraum



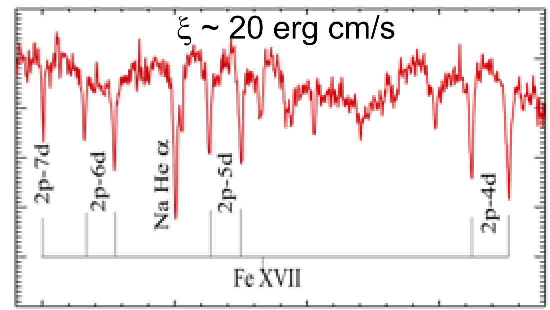
$C_{15}H_{12}O_4$ foam

Bennett et al., RSI 77 (2006)

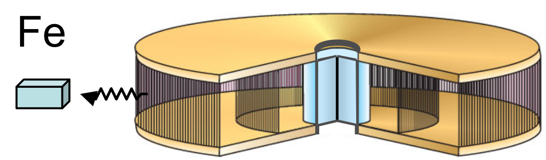
## Photoionized Plasma

**Rad dominated plasmas relevant to accretion objects**

Fe absorption




Wire-Array Z-Pinch Source

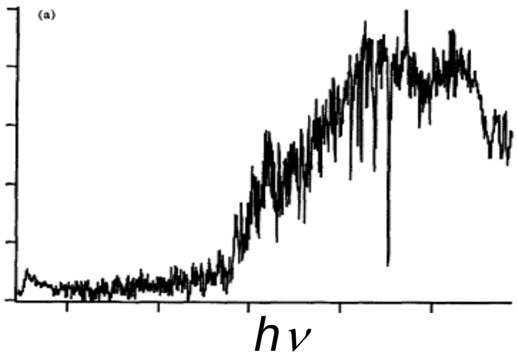



Foord et al., PRL 93 (2004)

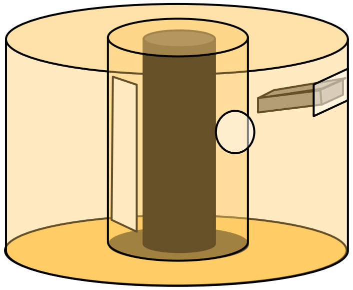
# Z provides multiple platforms for a variety of laboratory astrophysics experiments.

## Stellar Envelope Opacity

**Opacity of Fe in envelope around Cepheid Variable stars.**



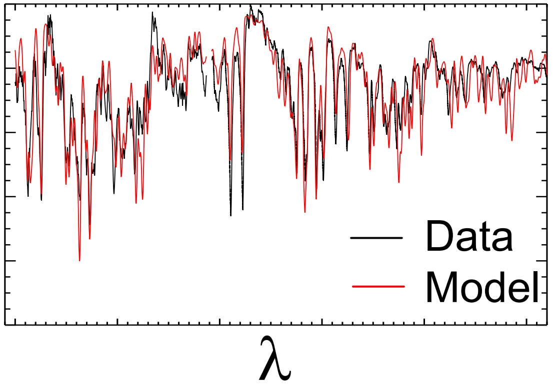

Saturn Z-pinch Secondary Hohlraum



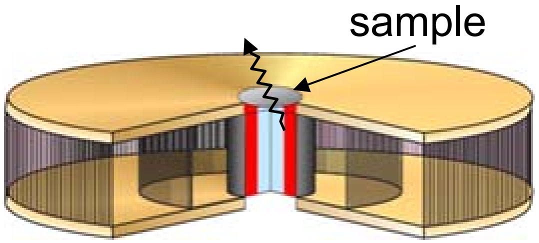
Springer et al., JQSRT 58 (1997)

## Solar Interior Opacity

**Opacity of Fe at the boundary between the solar radiation and convection zones.**




Z-pinch Dynamic Hohlraum

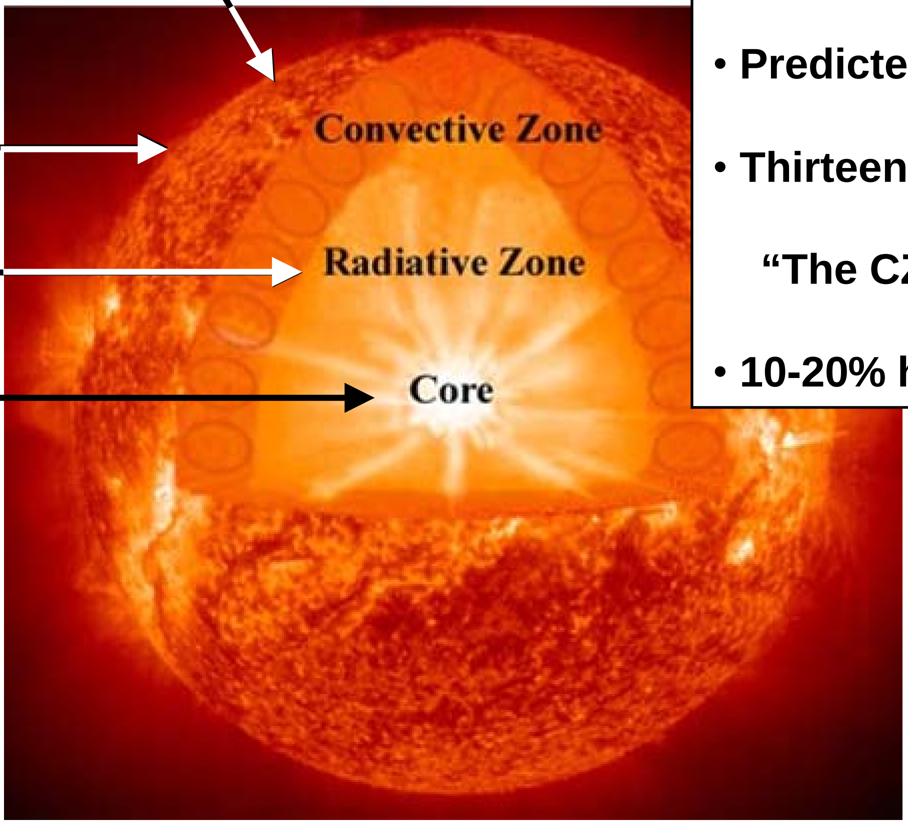



Bailey et al., PRL 99 (2007)

# An astrophysical issue: The ‘CZ problem’

| T(eV) | $n_e$ (cm$^{-3}$) | $r/R_0$ |
|---|---|---|
| 54 | $1\times10^{22}$ | 1.0 |
| 182 | $9\times10^{22}$ | 0.713 |
| 1360 | $6\times10^{25}$ | 0 |

Solar model : J.N. Bahcall et al, Rev. Mod. Phys. 54, 767 (1982)




- measured boundary $R_{CZ} = 0.713 \pm 0.001$
- Predicted $R_{CZ} = 0.726$
- Thirteen $\sigma$ difference

“The CZ problem”

- 10-20% higher opacity?

**Transport depends on opacity, composition, ne, Te**

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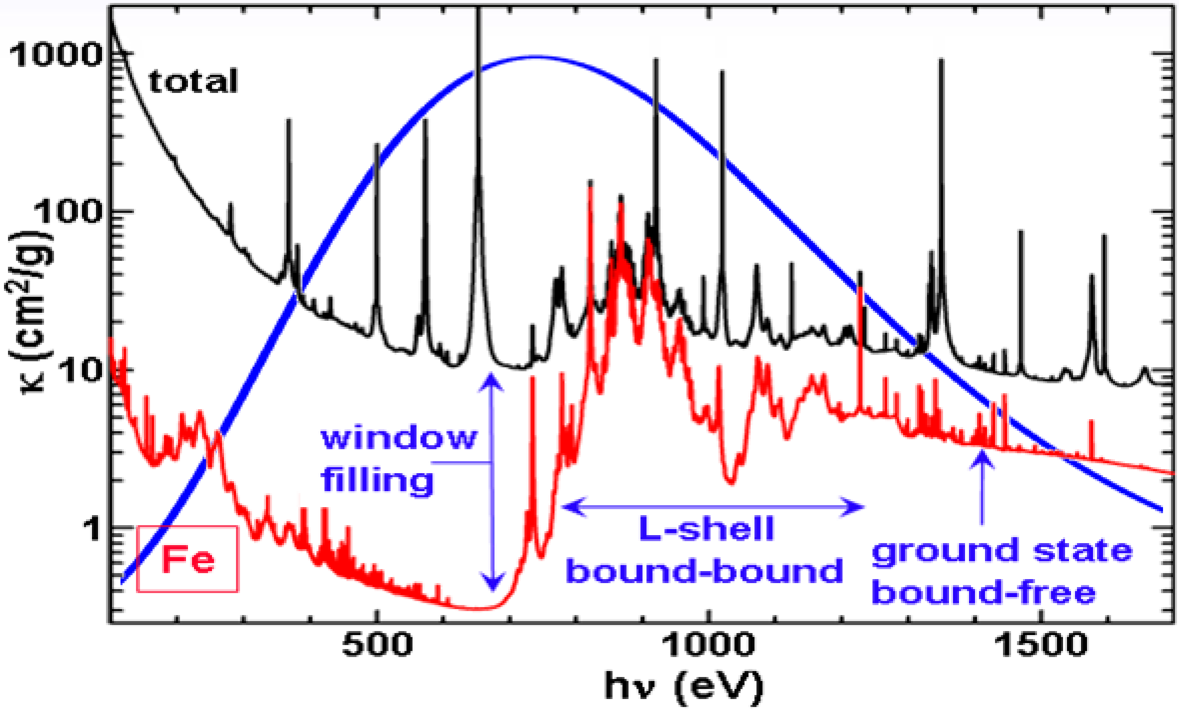
# Definition of a laboratory astrophysics experiment to address the 'CZ problem'




- **Base of solar convection zone: $T_e$ ~ 193 eV, $n_e$ ~ $10^{23}$ $cm^{-3}$**
- **Most important elements: O, Ne, Fe**
- **Fe is the most complex and therefore the most suspect**
- **Fe charge states: +16, +17, +18 ( Ne-like, F-like, O-like)**
- **Photon energy range hν ~ 700-1400 eV**
- **Atomic processes: L-shell bb transitions and bf transitions**

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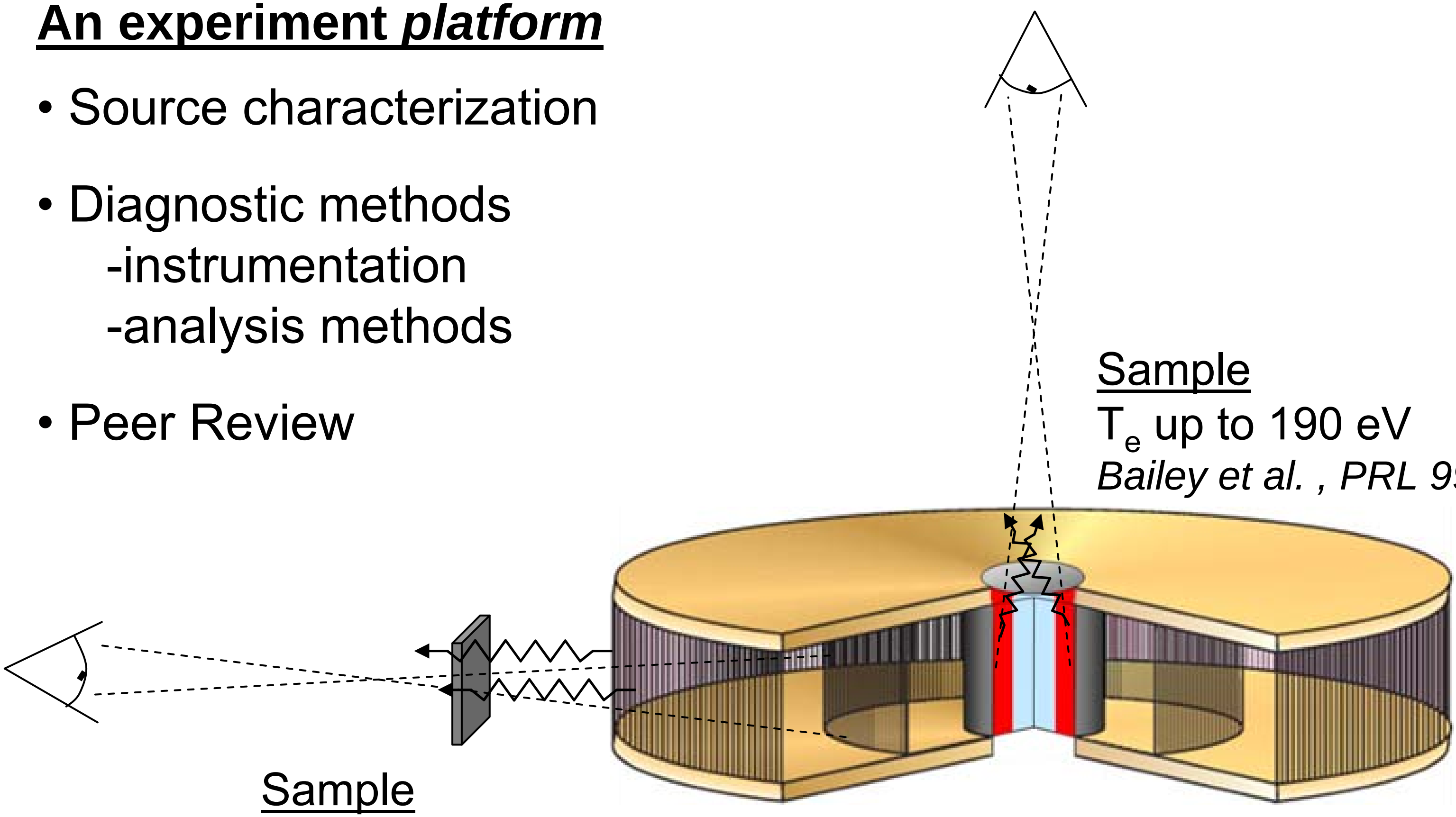
# The Z-pinch Dynamic Hohlraum (ZPDH) provides a *platform* for high temperature opacity experiments.

**An experiment *platform***

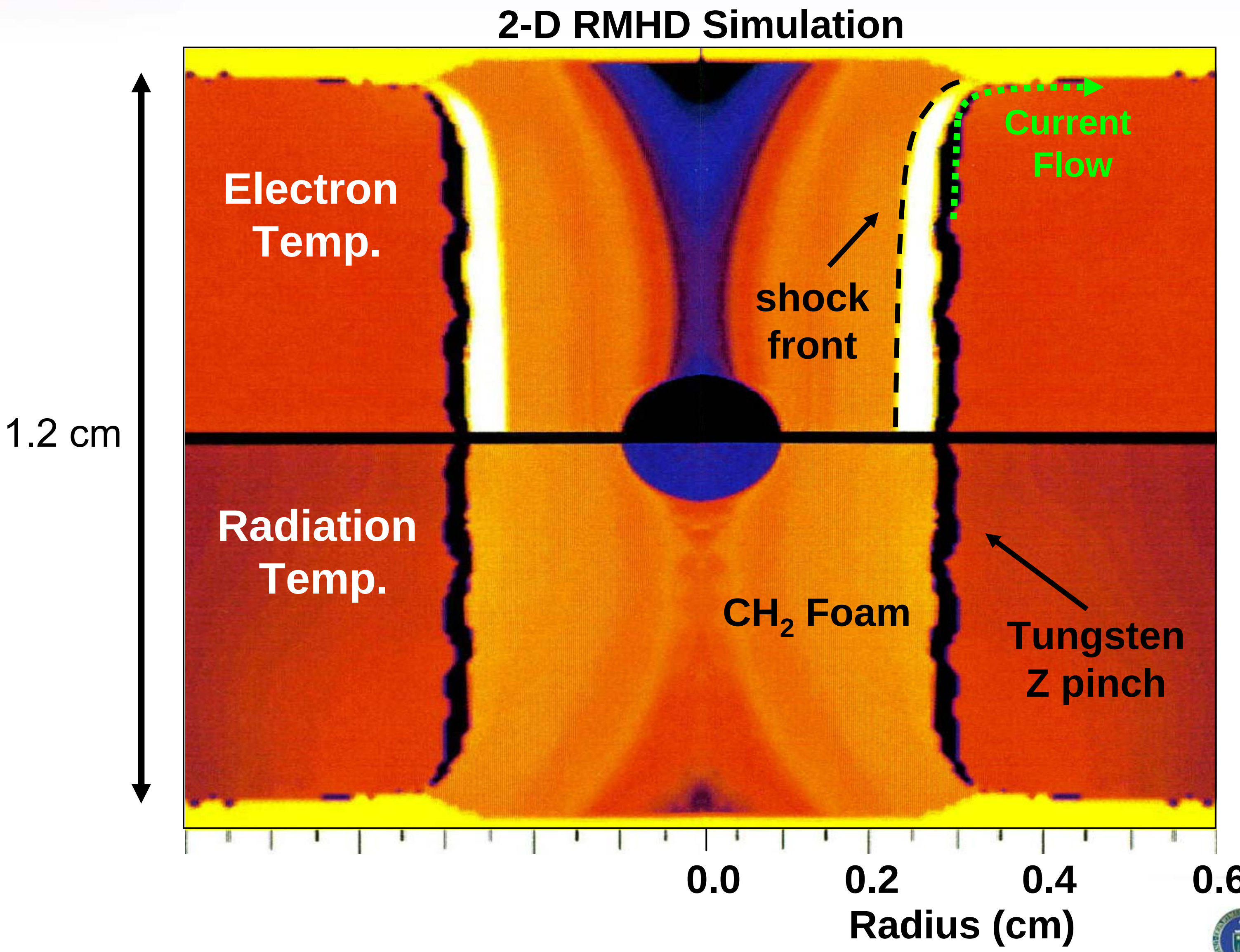
- Source characterization
- Diagnostic methods
  - -instrumentation
  - -analysis methods
- Peer Review



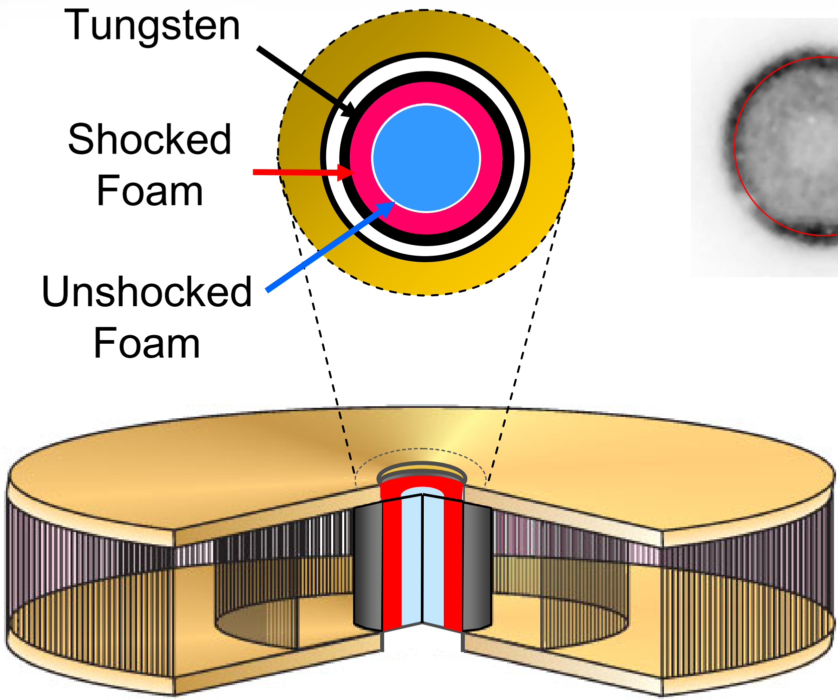
Sample
$T_e$ up to 190 eV
*Bailey et al. , PRL 99 (2007)*

Sample
$T_e$ up to 50 eV
*Rochau et al., PRE 72 (2005)*
*Bailey et al., JQSRT* 81 (2003)

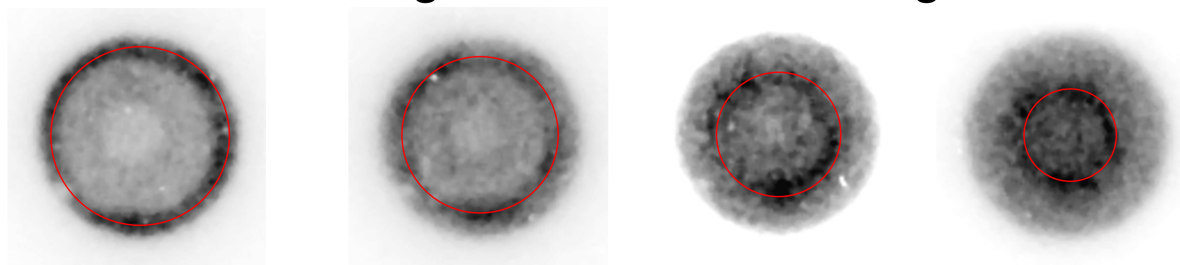
# The Dynamic Hohlraum is formed by an imploding Z pinch, and heated by a strong radiating shock.

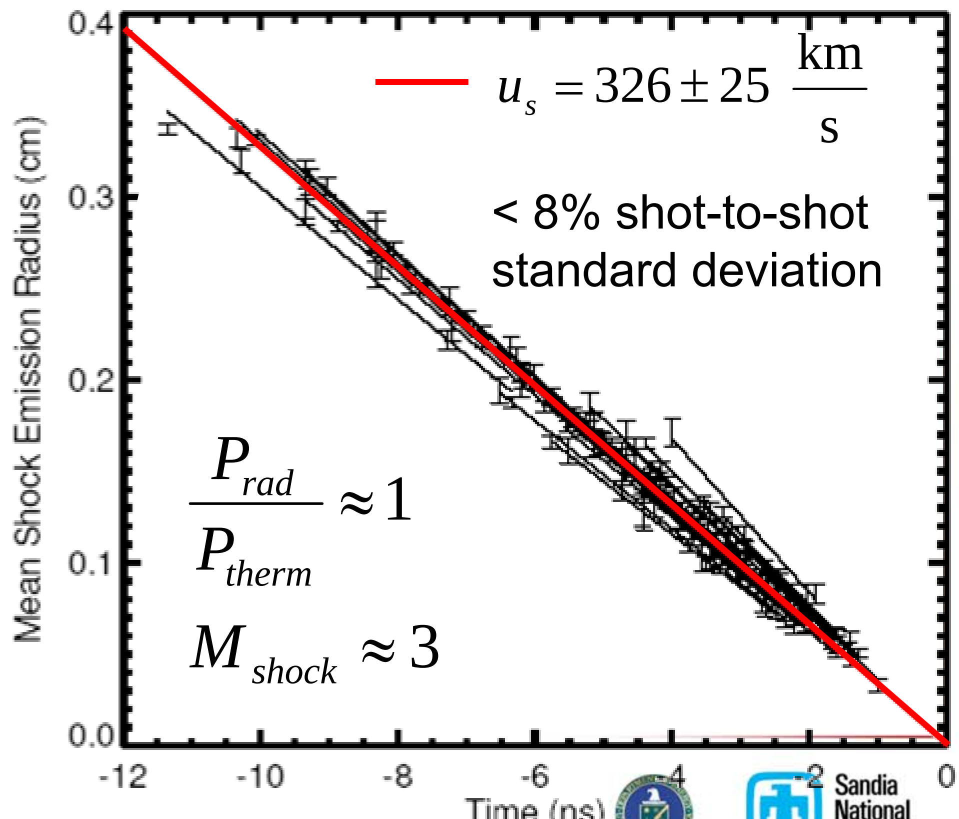


# A reproducible radiating shock is the source of x-ray energy for the Z-pinch dynamic hohlraum.




**Framing Pinhole Camera Images**






Radiating Shock Image
SNR 1987a

Rochau et al., PRL 100 (2008)

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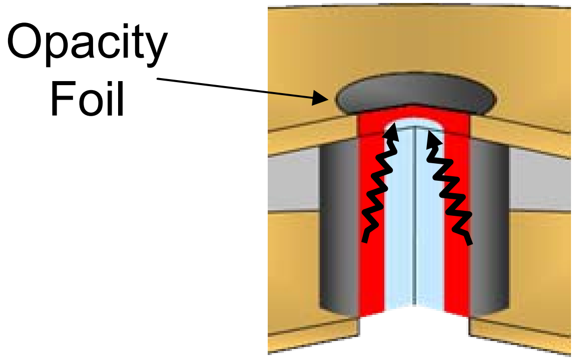
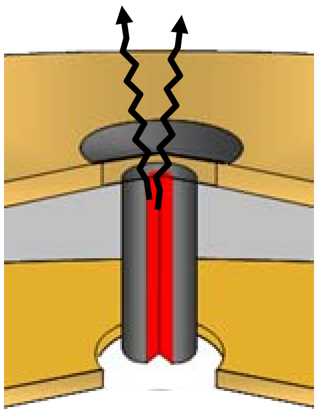
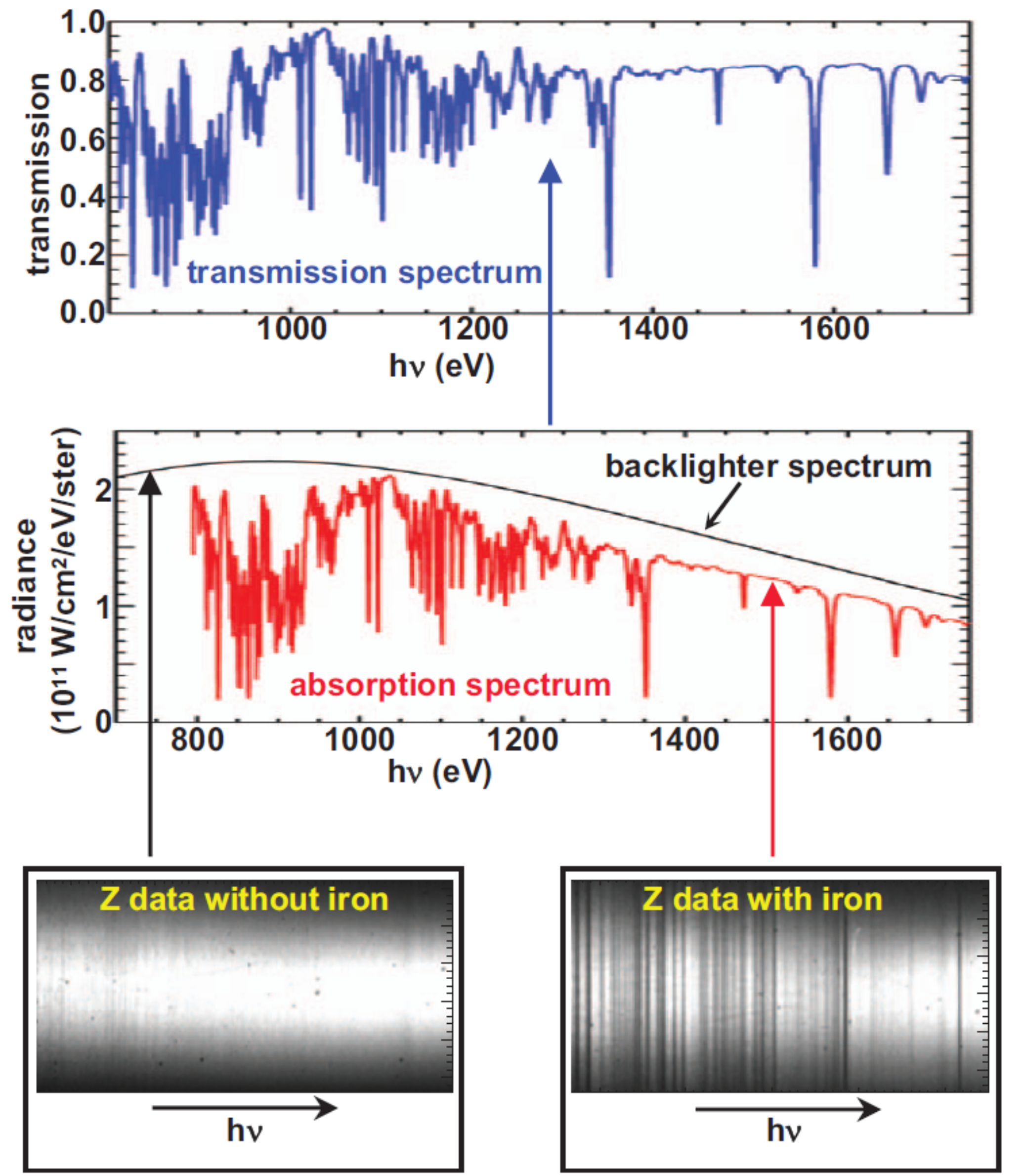
# The ZPDH shock is used to drive and backlight opacity experiments at $T_e$ > 150 eV.

Foil is heated during the ZPDH implosion



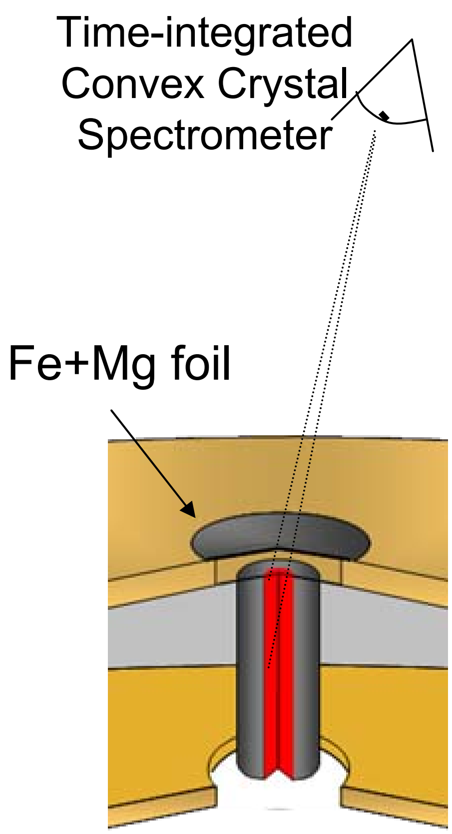

Foil is backlit at shock stagnation

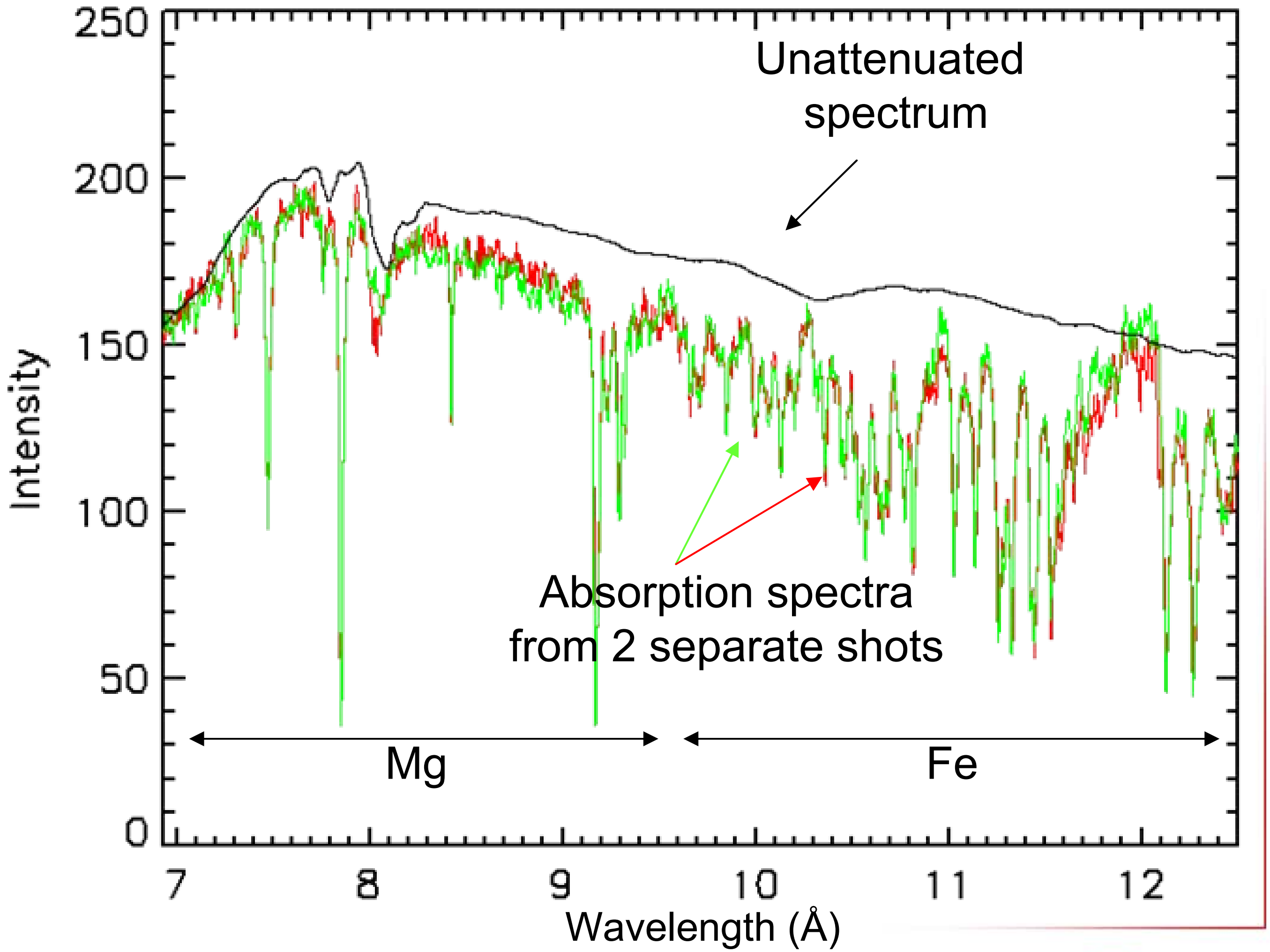




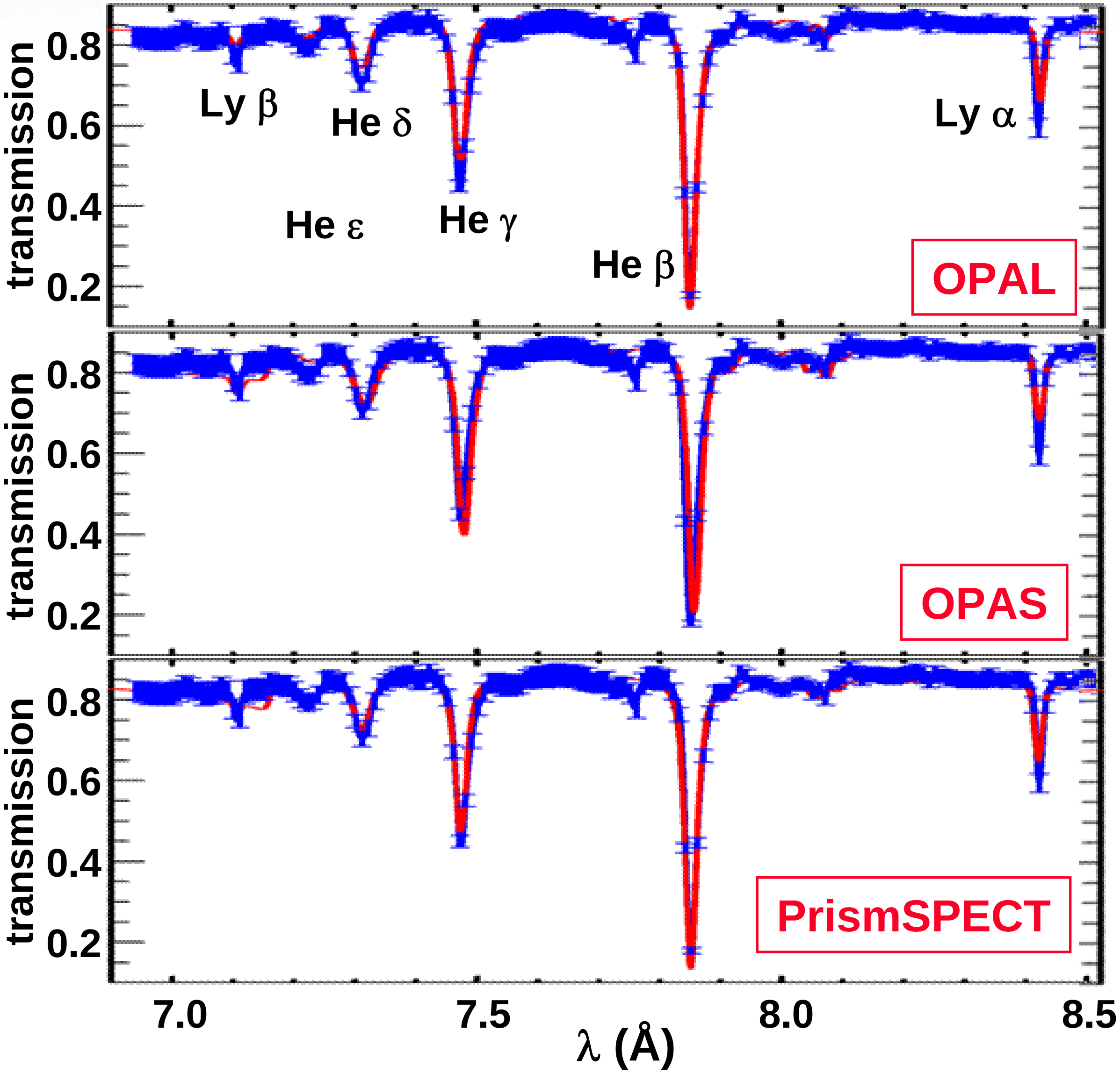

Bailey et al., POP 16 (2009)

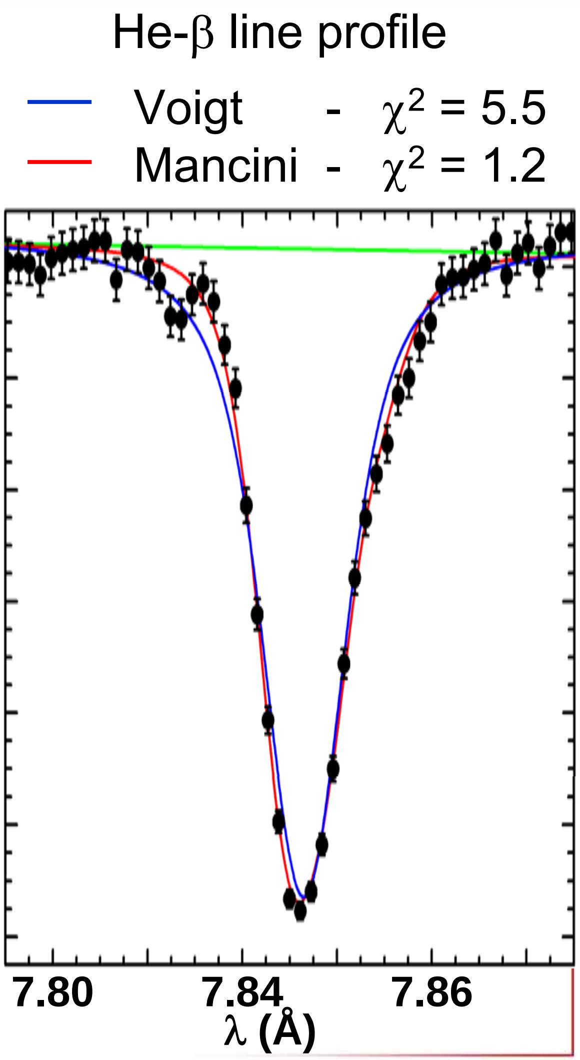
# Opacity measurements require reproducibility in source power (heating) and spectrum (backlighting).



# Mg K-shell spectra indicate $T_e$ = 156 eV and $n_e$ = 7*10$^{21}$ cm$^{-3}$.

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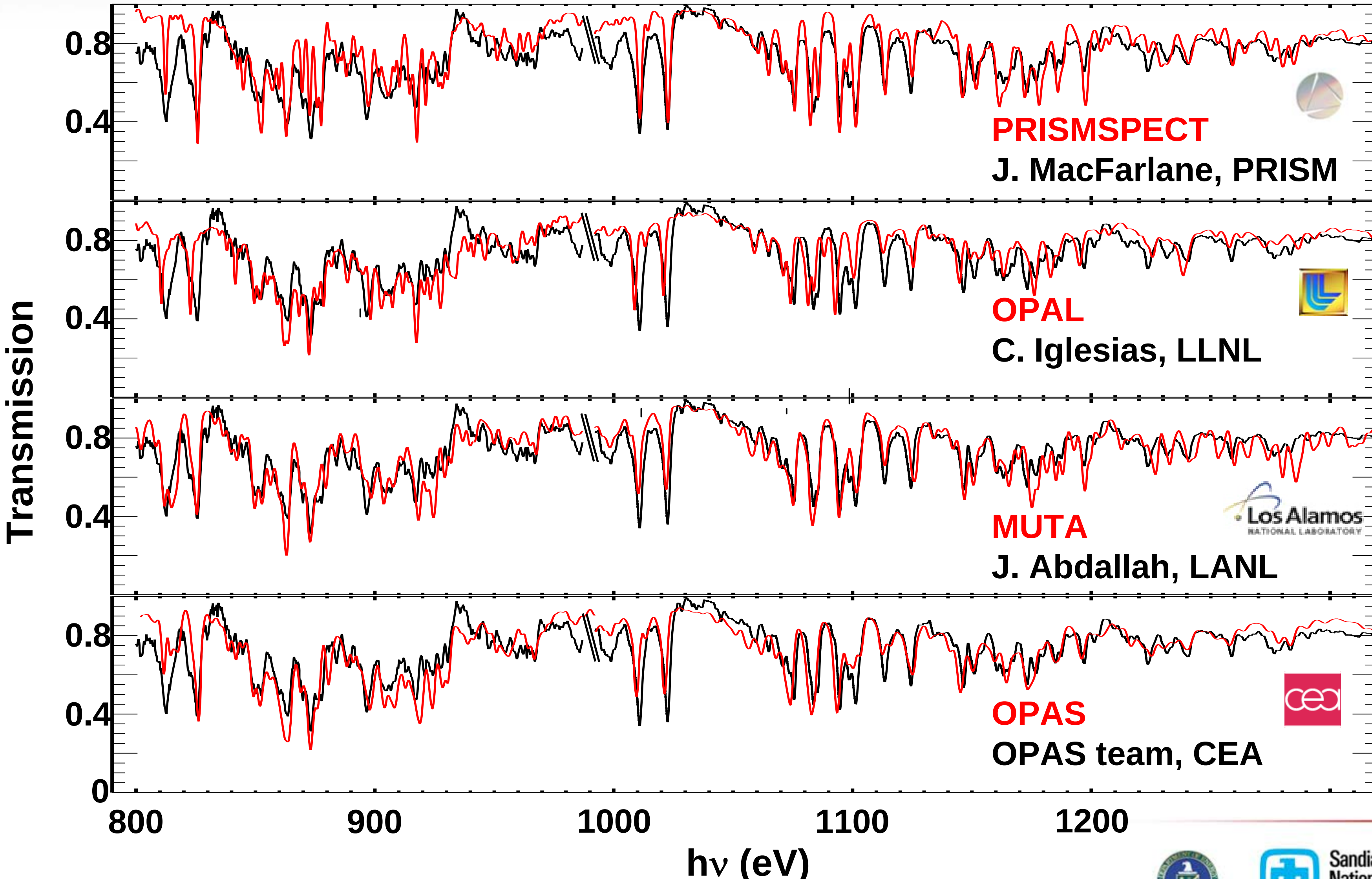
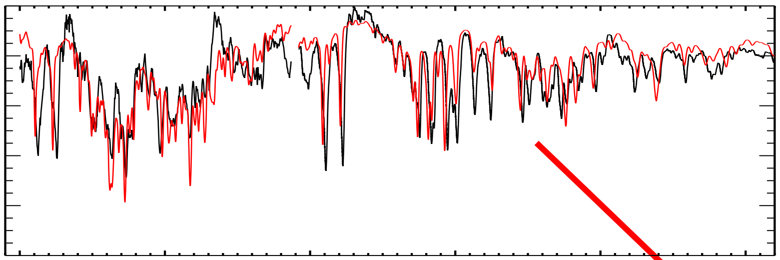
# The measured Fe transmission compares well with models from LANL, LLNL, CEA, and PRISM.



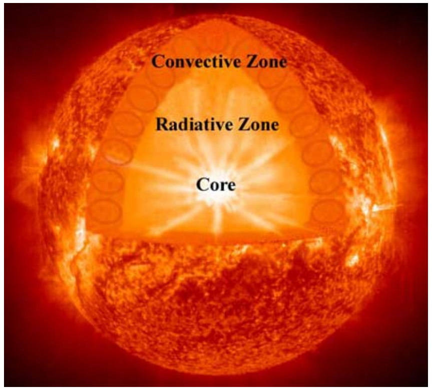

Bailey et al., PRL 99 (2007)

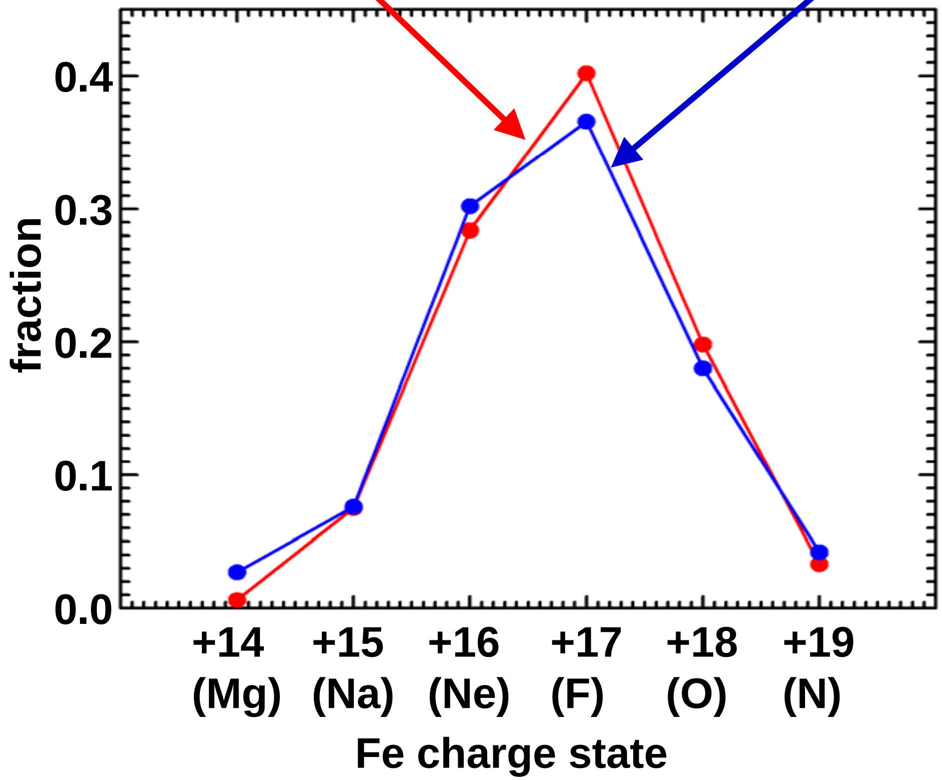
# Z experiments reproduce the iron charge states at the Solar CZ boundary

**Z conditions**
**156 eV, 7 x $10^{21}$ $cm^{-3}$**



**Solar CZ boundary**
**193 eV, 1 x $10^{23}$ $cm^{-3}$**

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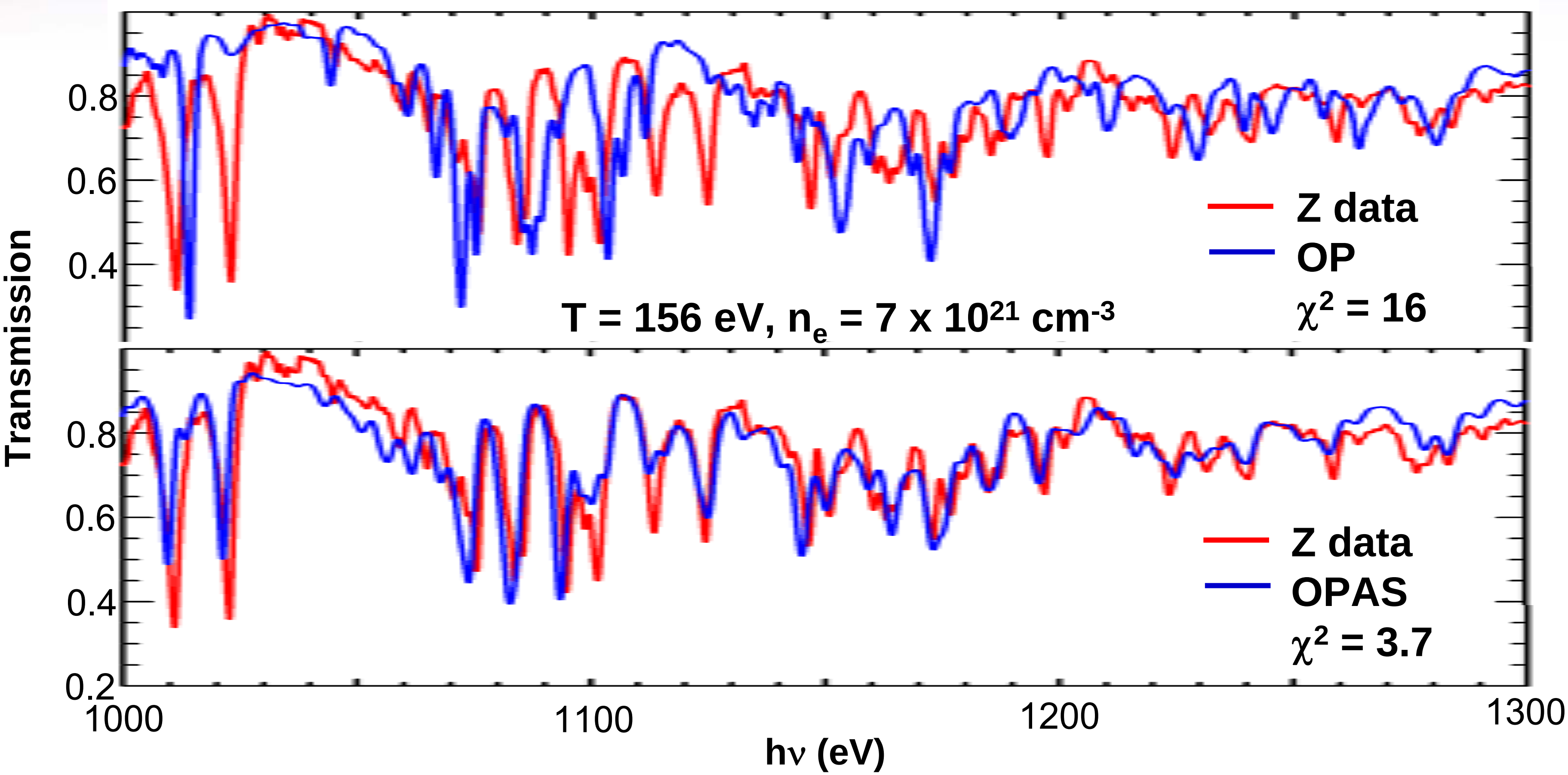
# The OP model used in solar research predicts Fe L-shell opacity that is too low at Z conditions




- OP Rosseland mean is ~ 1.5x lower than OPAS at Z conditions.
- If this difference persisted at the exact CZ conditions, it would solve the CZ problem

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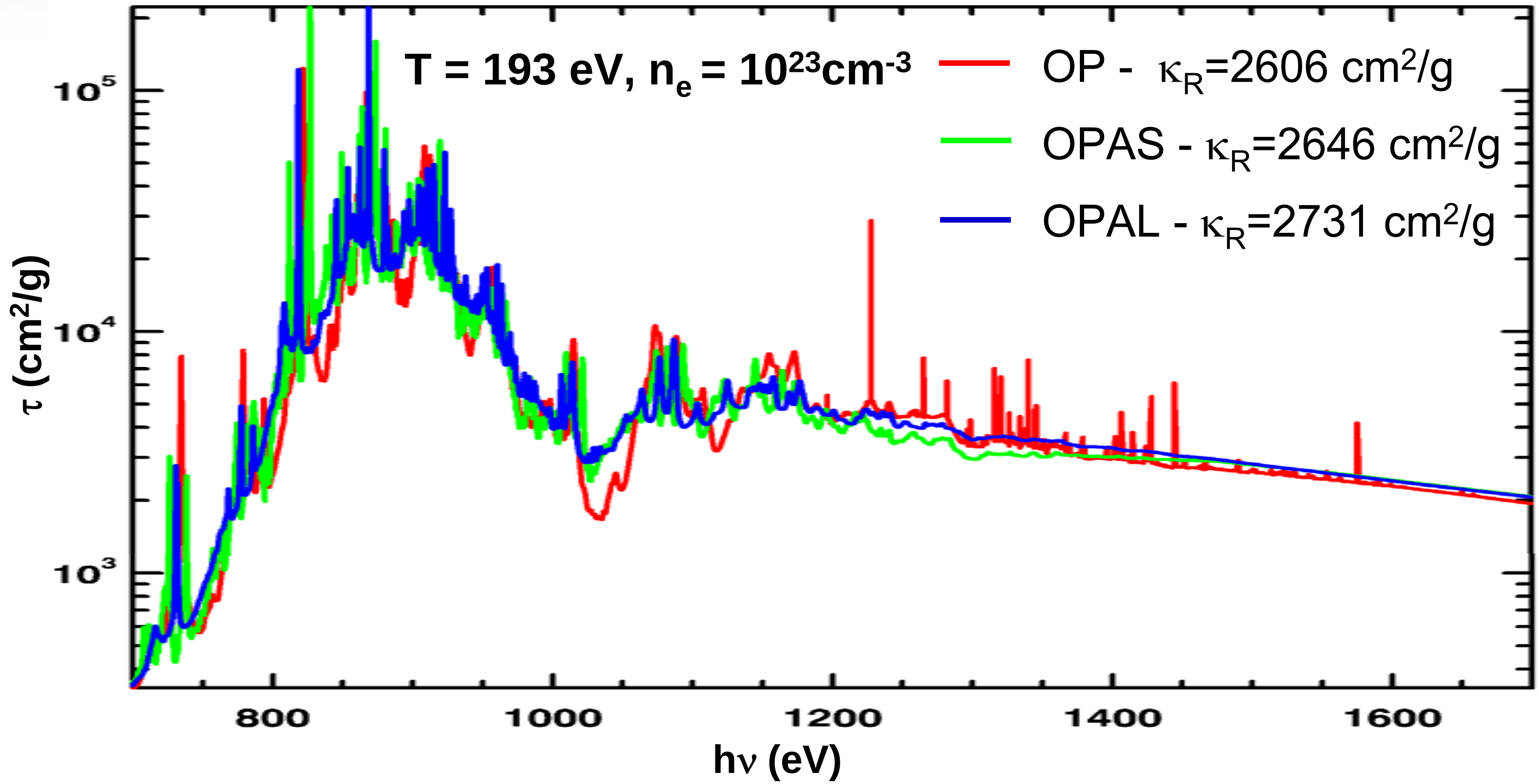
# Discrepancies at Z conditions raise a caution flag for solar opacities

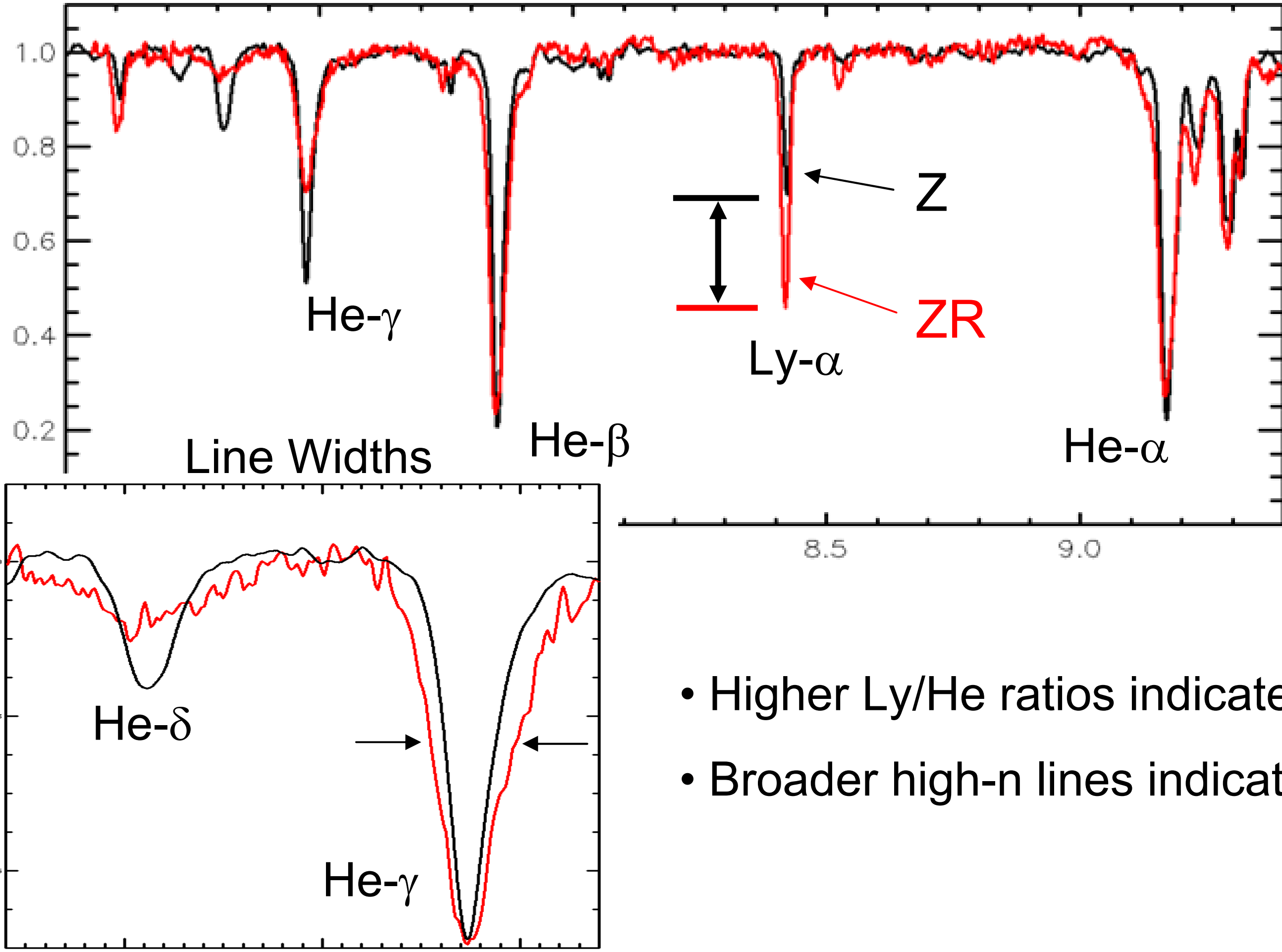


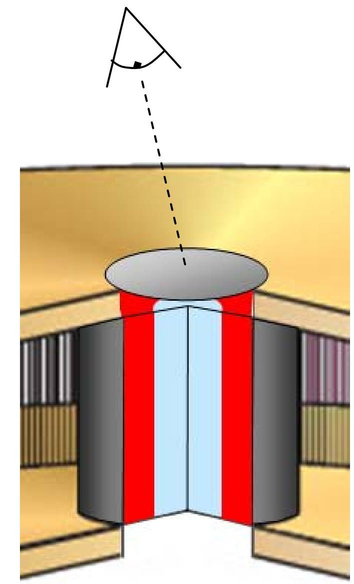

**At the base of the convection zone (T=193 eV, $n_e$=$10^{23}$cm$^{-3}$):**

- **Iron frequency-dependent opacities possess some differences.**
- **Rosseland mean opacities are not significantly different, even though they disagree at Z conditions.**

# The higher power ZPDH on ZR heats opacity foils to ~20% higher temperatures than achieved on Z.

Mg K-shell absorption from a Mg/Fe foil



- Higher Ly/He ratios indicate ~20% increase in $T_e$
- Broader high-n lines indicate ~300% increase in $n_e$

Preliminary comparisons indicate $T_e$ ~ 190 eV, $n_e$ ~ $3x10^{22}$ $cm^{-3}$

# Pulsed power sources are gaining recognition as effective drivers for laboratory astrophysics

2010 Joint OFES-NNSA HEDLP grants for laboratory astrophysics related to Z:

-Mancini et al., UNR, Photo-ionized plasmas (Accretion disks)

-Pradhan et al., OSU, Laboratory Tests of Stellar Interior Opacity Models

-Bailey et al., SNL, Laboratory Tests of Stellar Interior Opacity Models

-Frank et al., IC, Astrophysical Jets

# Extra Slides

# Many People and Institutions Contribute

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**Swarthmore College**

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**Ohio State University**

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**Weizmann Institute, Israel**

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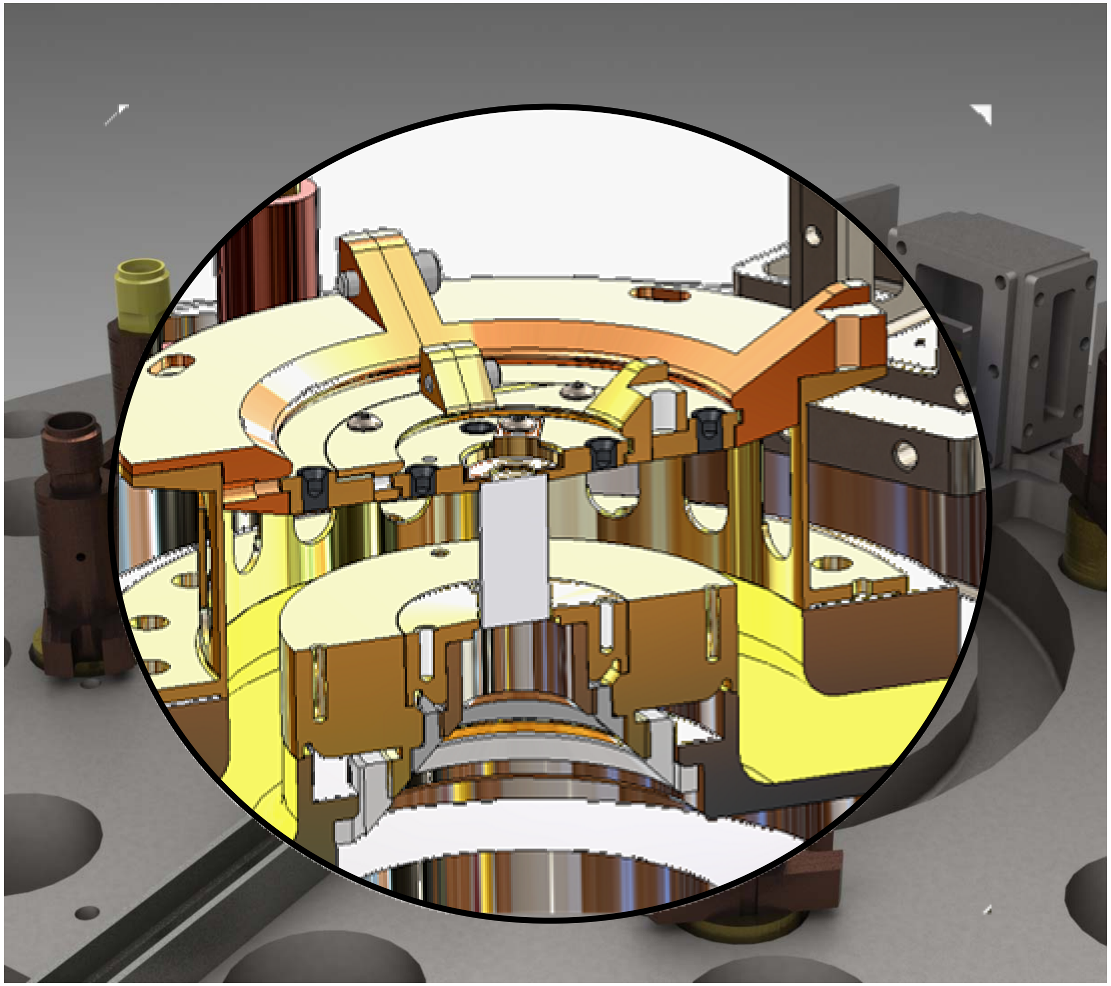
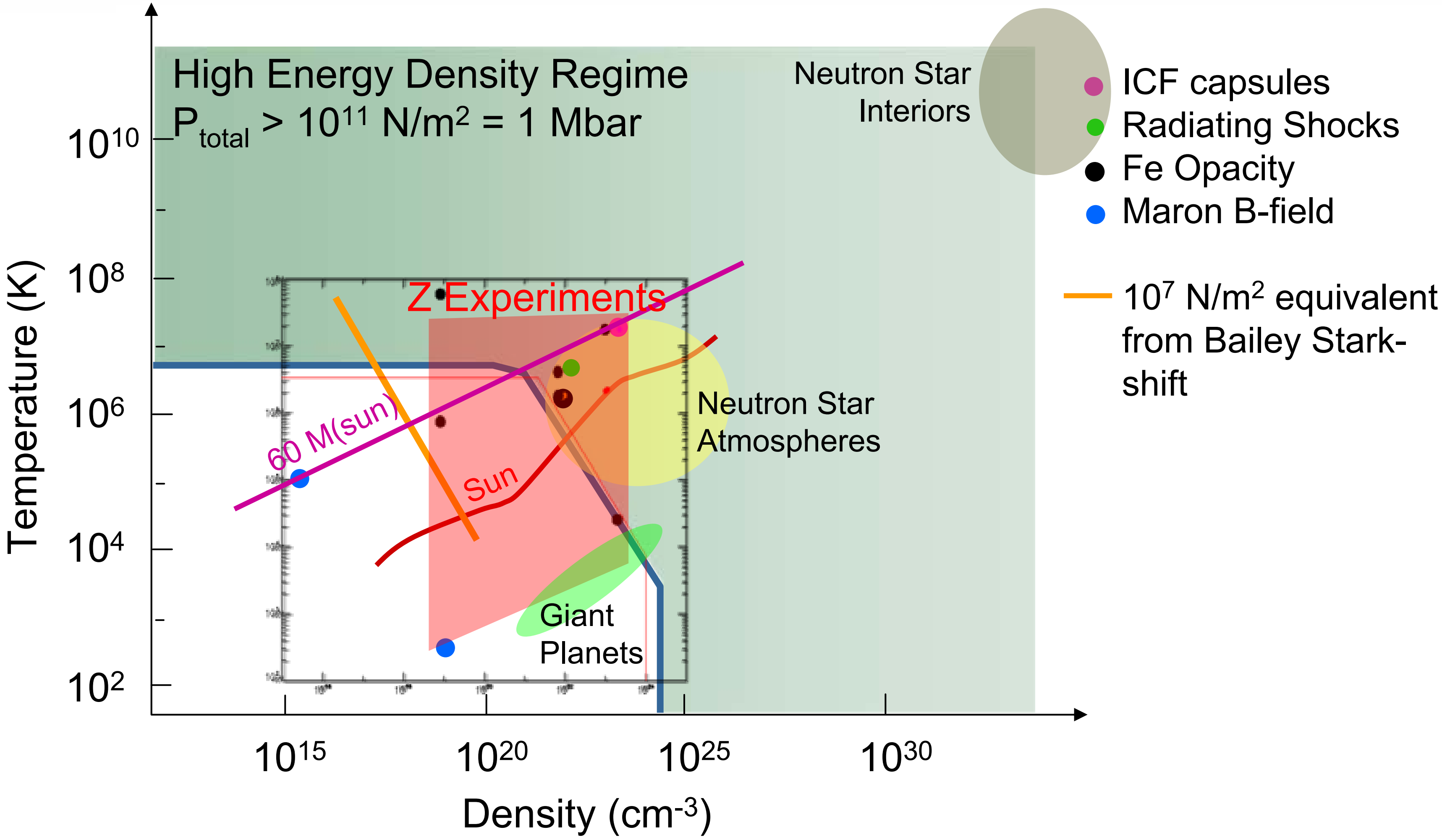
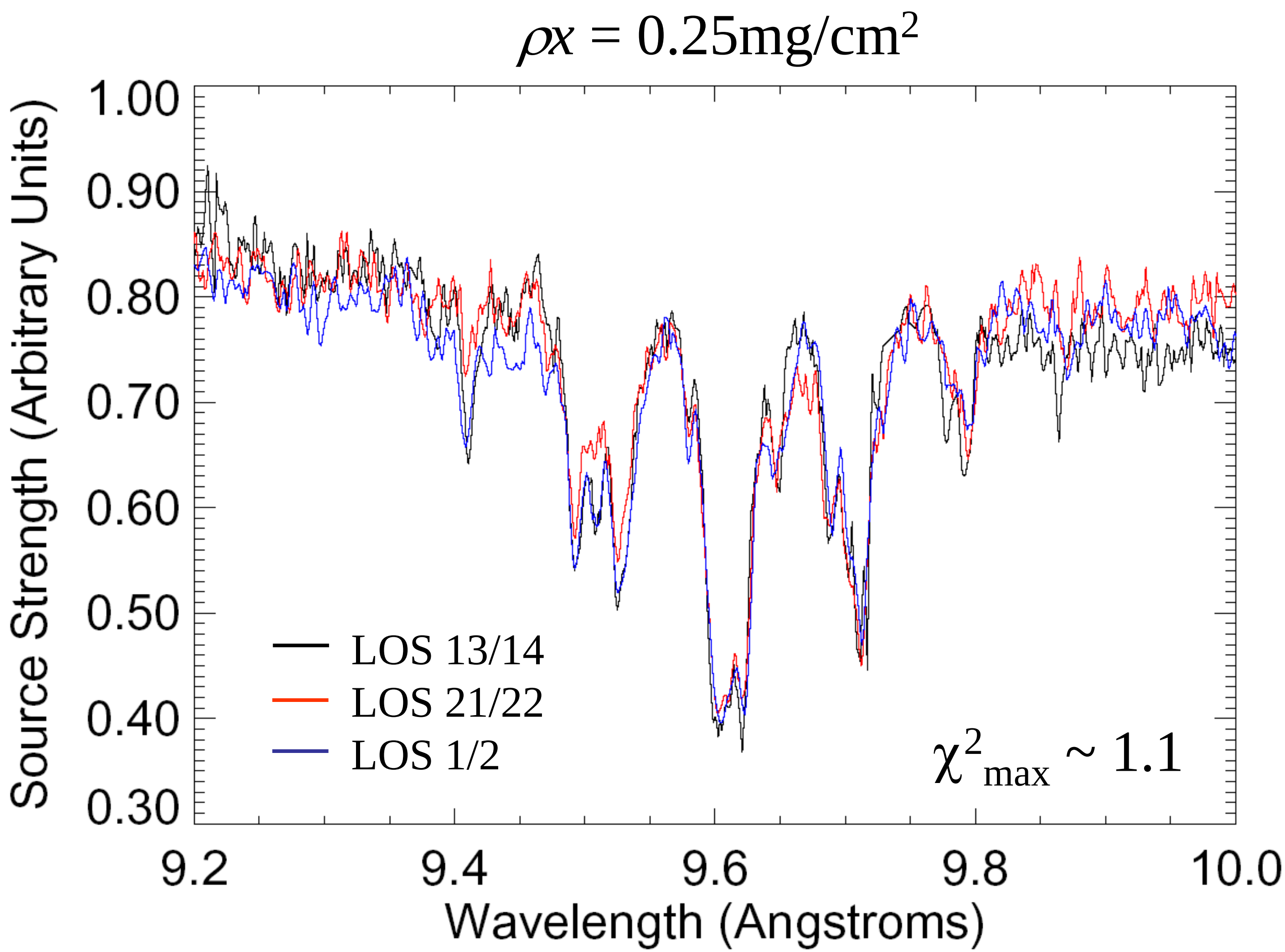
# The anatomy of a Z-pinch source



# The Z facility provides a wide range of energy densities – Flexibility for Lab Astro

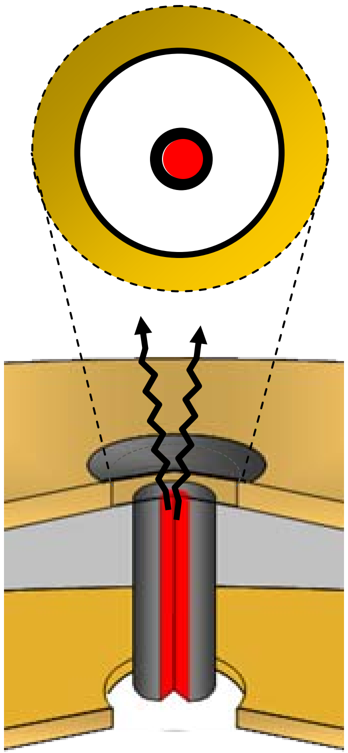


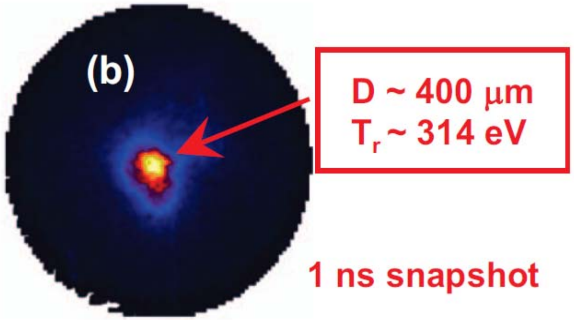
# Mg foils at three azimuths show a consistent radial x-ray energy.

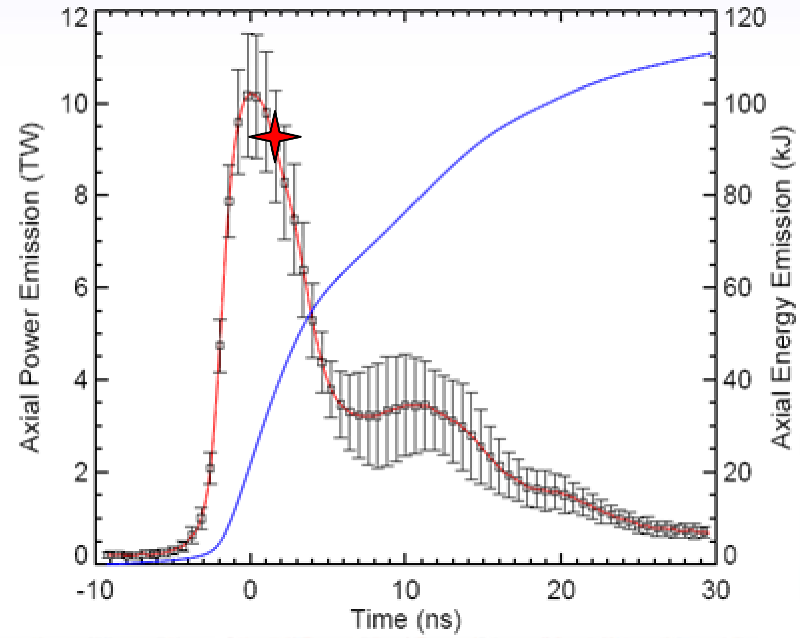


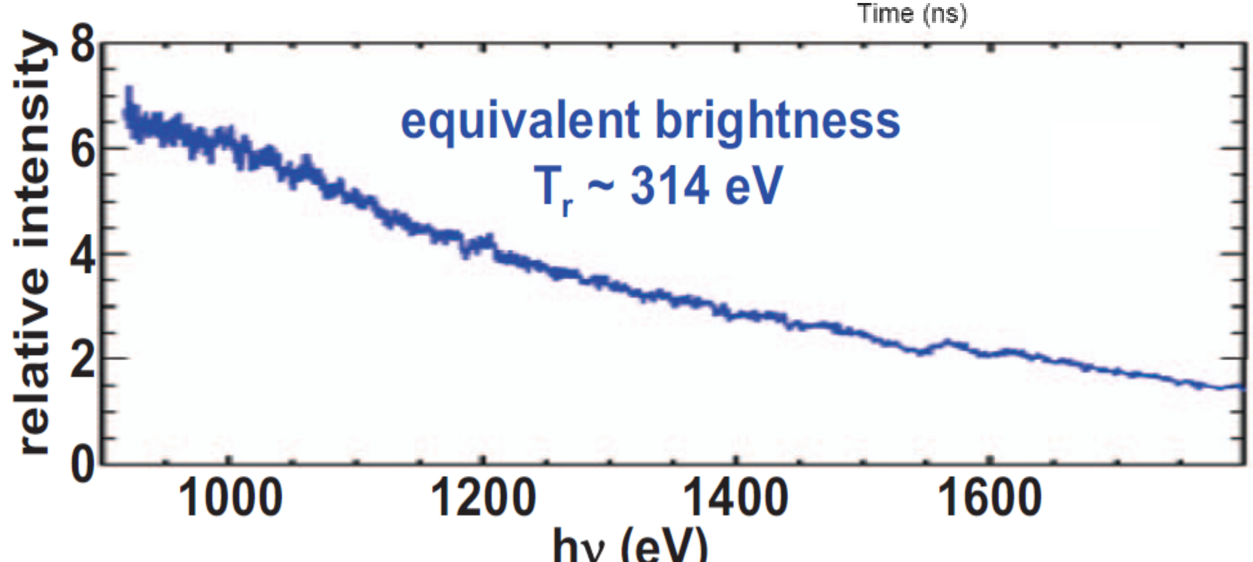

Rochau, Ph.D. Thesis (2003)

# The shock stagnation makes a bright, featureless, continuum backlighter.



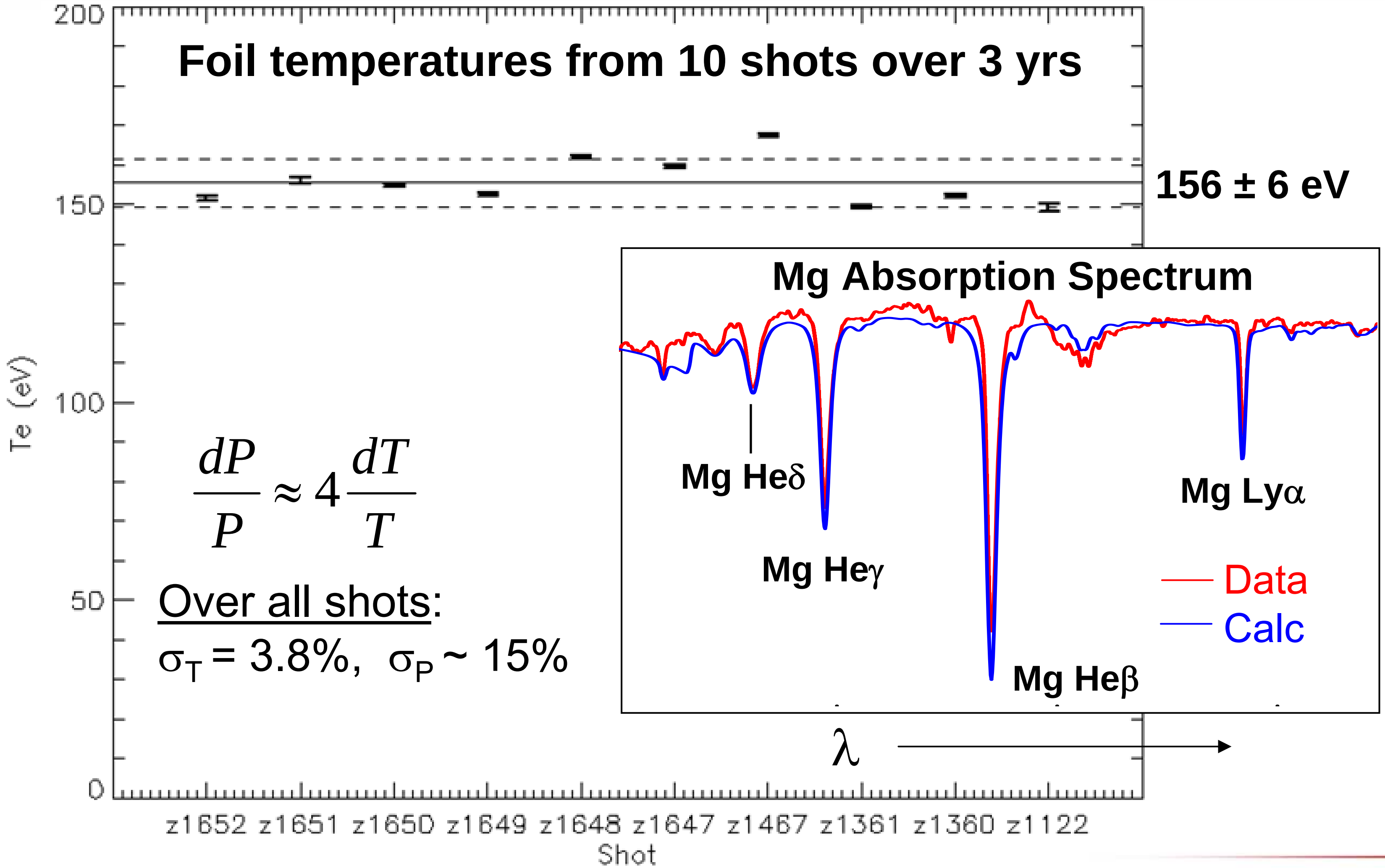



Bailey et al., POP 16 (2009)

# Sample electron temperatures are reproducible to < 4%.




$$\frac{dP}{P} \approx 4\frac{dT}{T}$$

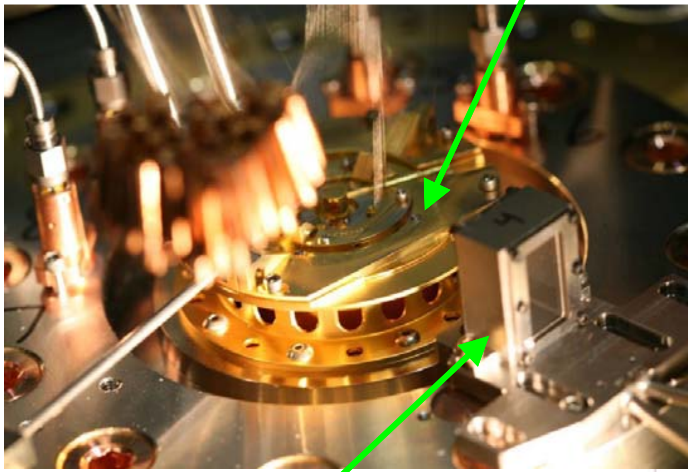
Over all shots:

$\sigma_T = 3.8\%$, $\sigma_P \sim 15\%$

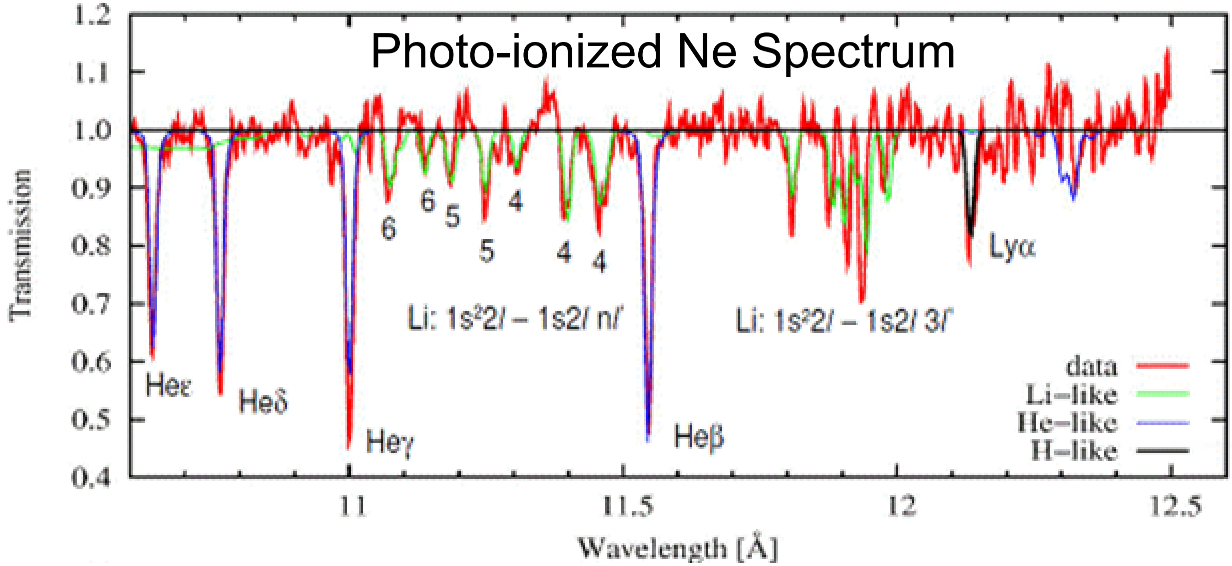
# Photo-ionized plasma research is a success story for external user experiments on Z

- Initial work by M. Foord and R. Heeter:
  Fe at ξ ~ 20 erg cm/s
  *Foord et al., PRL 93 (2004)*
- Stockpile Stewardship Academic Alliances Grant:
  R. Mancini, 2007-2009
  Ne at ξ ~ 4-10 erg cm/s
  *Hall et al., Astro. Space Sci. 322 (2009)*
- High Energy Density Laboratory Physics Grant:
  R. Mancini, 2010-2012

Z-pinch Source



Neon Gas Cell

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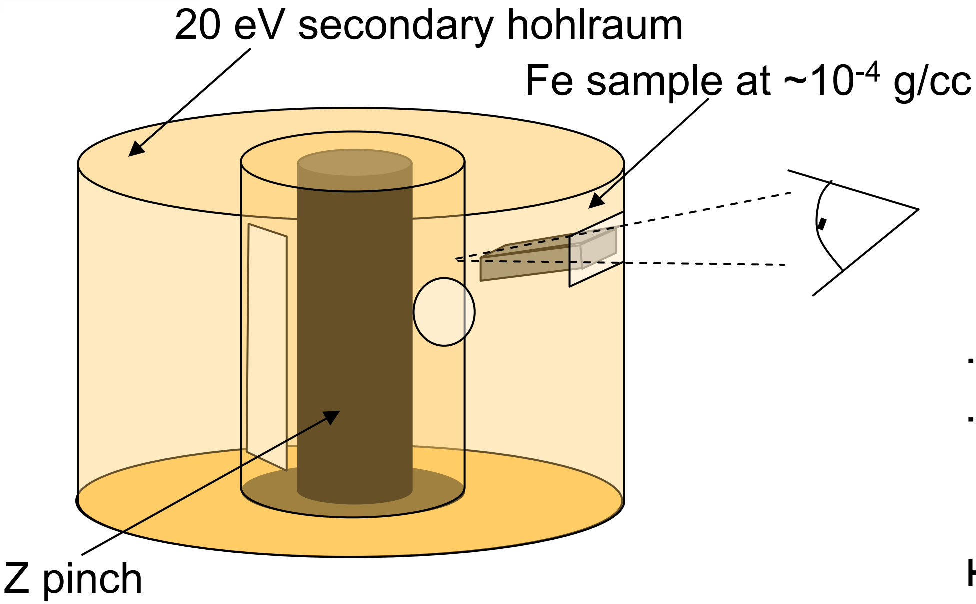
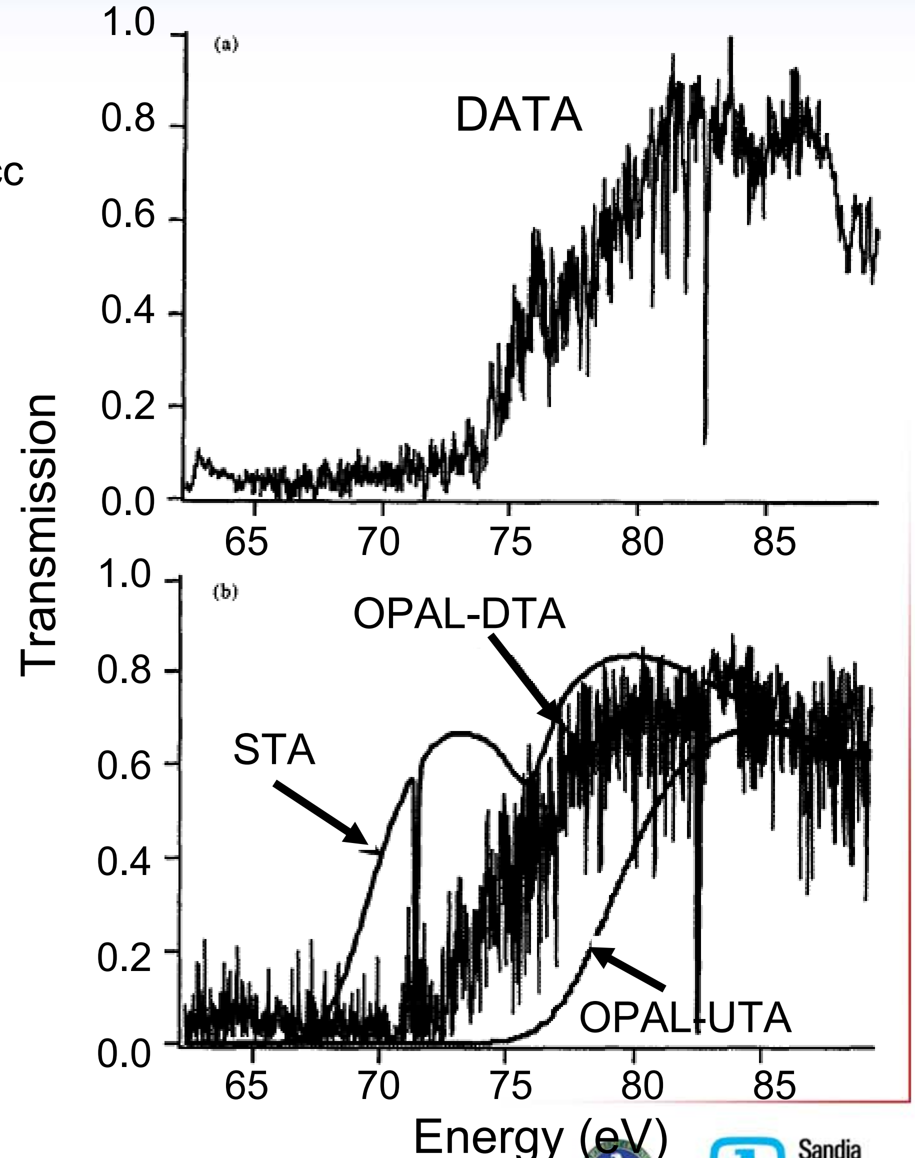
# Measurements of Fe at $T_e$ ~ 20 eV benchmarked opacity calculations for stellar envelopes.




- Detailed line-by-line treatment is required to match even the bulk transmission.

- Critical temperature and density regime for Stellar envelopes.
  - Rogers and Iglesias, Science 263 (1994)

Springer et al., JQSRT 58 (1997)

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