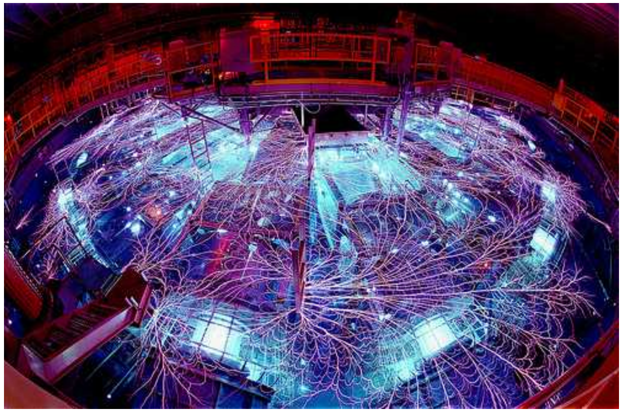
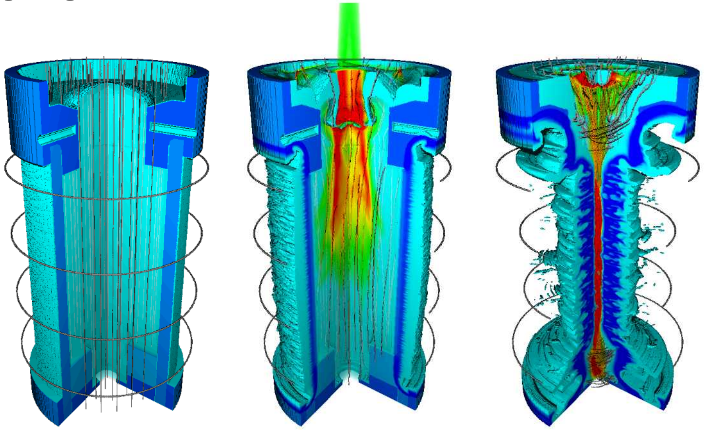
Streak Camera Applications on Z





Streak Camera Meeting
August 25th, 2014

David Bliss, Dan Dolan,
Tommy Ao, Chris Bourdon, Alan Carlson, Ross Falcon, Matthew Gomez,
Richard Hacking, Marcus Knudson, Greg Rochau, Dan Scoglietti

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

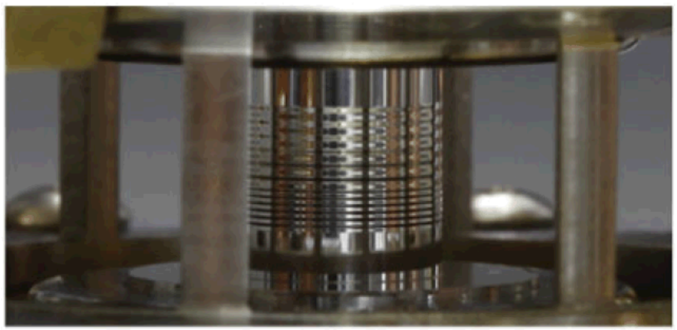
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Sandia National Laboratories

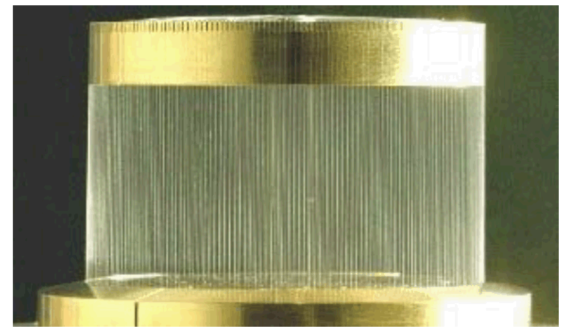
Z is a pulsed power machine that generates large currents, 26 MA. The resulting magnetic fields (>100 MG!) are used to drive high energy density physics experiments.

A wide variety of load configurations are studied on Z.

Cylindrical liners for
inertial confinement fusion



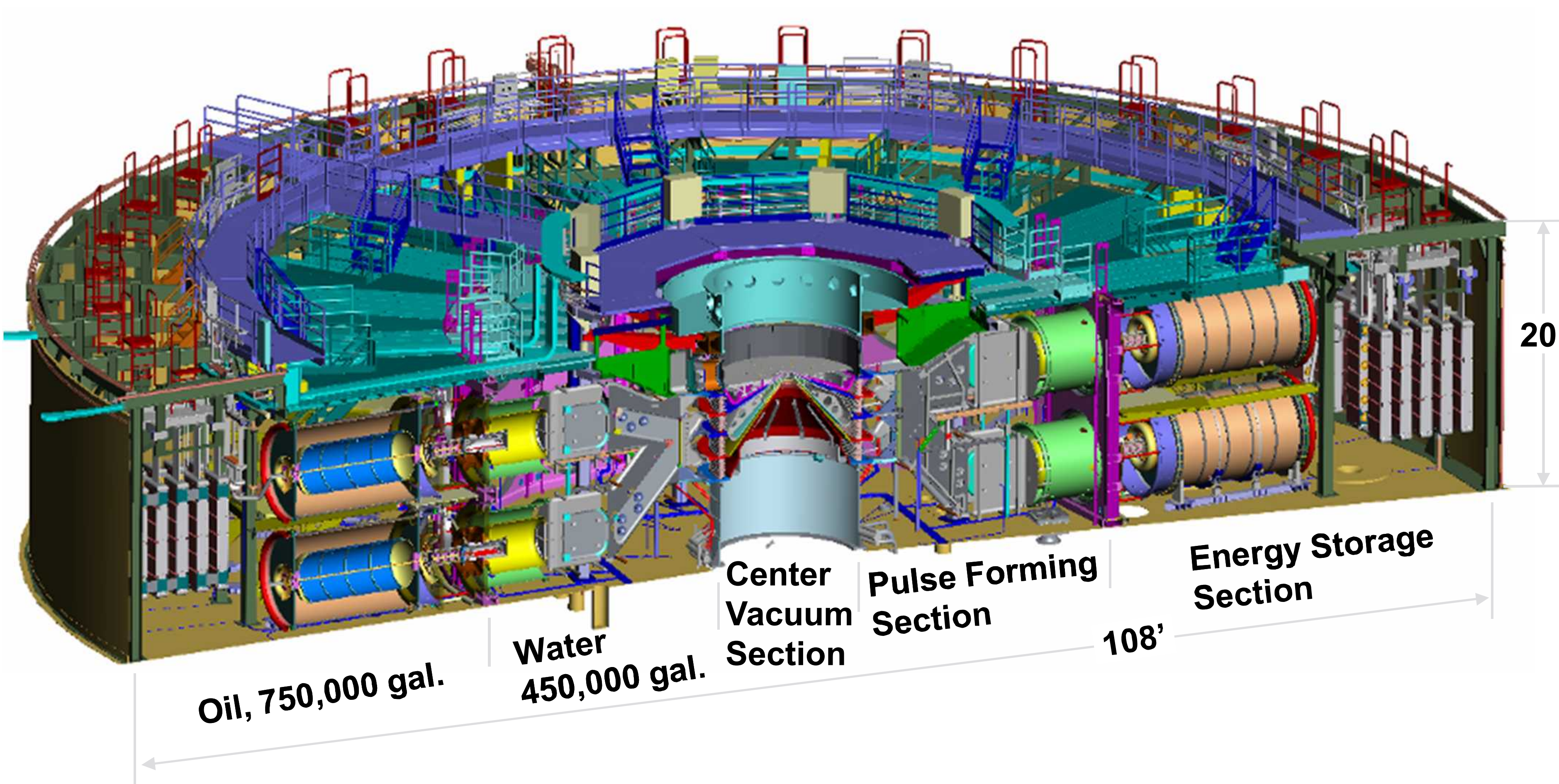
Wire arrays for
radiation effects science



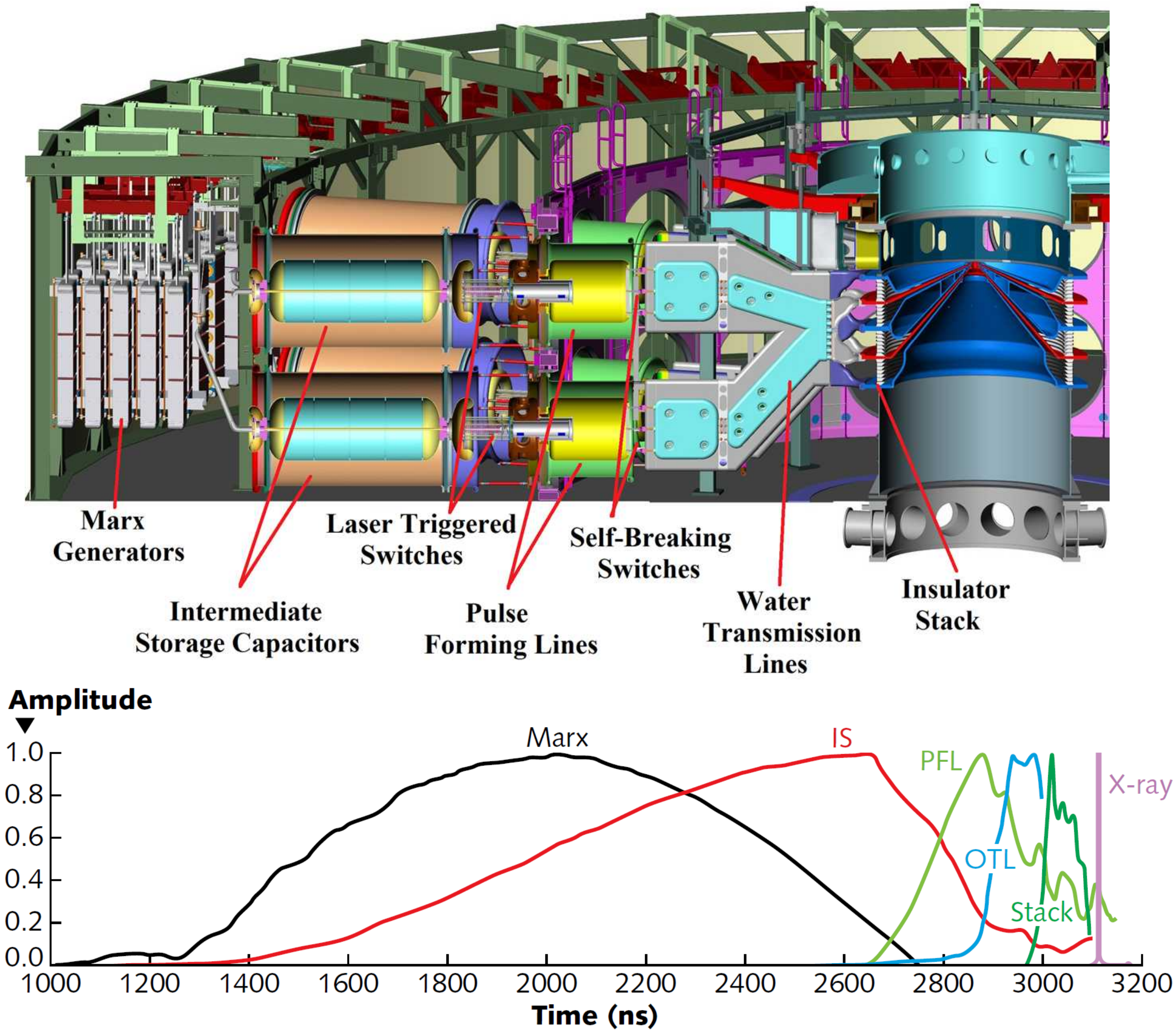
Flyer plates
and isentropic
compression
experiments to
measure dynamic
material properties

Cross sectional view of the Z-machine highlights the 36 individual modules and respective oil, water and vacuum sections.

Sandia National Laboratories



Z capacitors store 22 MJ of energy during a 2 minute charge. Pulse compression delivers ~3 MJ to the load in ~100-600 ns.



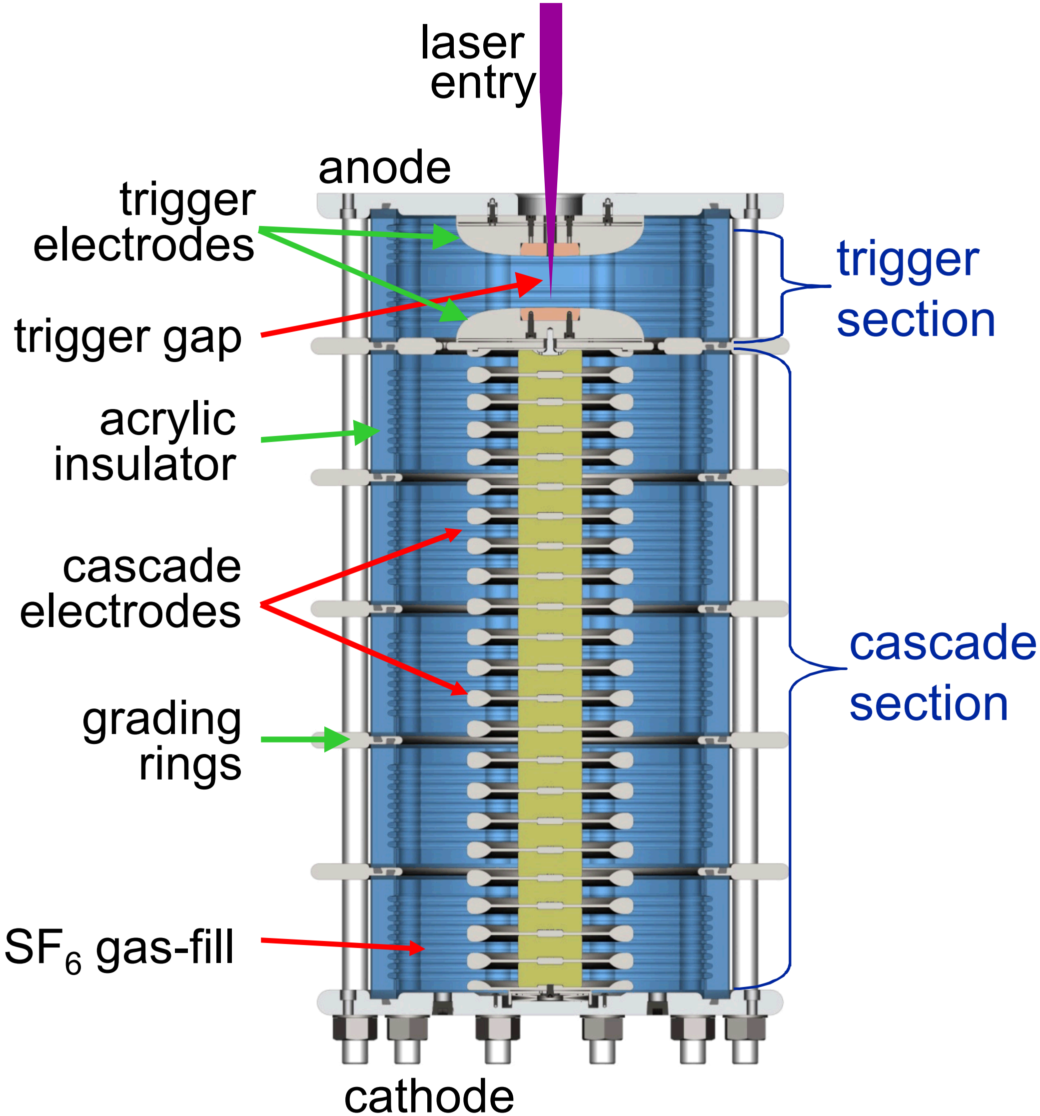
Streak cameras are used to diagnose both Z machine components and experiments fielded at the center.

- Visible streak cameras are used in two modes.
  1. Imaging of a line or a line averaged area, and
  2. Spectroscopy of a point on a surface or along a chord through a plasma.
- Streaked imaging examples
  1. Laser triggered gas switch closure
  2. Water switch closure
  3. Wire array dynamics
- Streaked spectroscopy examples
  1. Plasma density measurements in power flow gaps (Pulsed Power Science)
  2. Magnetic field measurements by Zeeman splitting of dopants (ICF)
  3. Temperature measurements of shocked materials (Dynamic Materials)
  4. Precision measurements of Hydrogen line shapes at White Dwarf photosphere conditions (Fundamental Science for Laboratory Astrophysics)

Z rocks the highbay!

Click image and then press CTRL+L*oop*, CTRL+F*ull* for Quicktime Movie

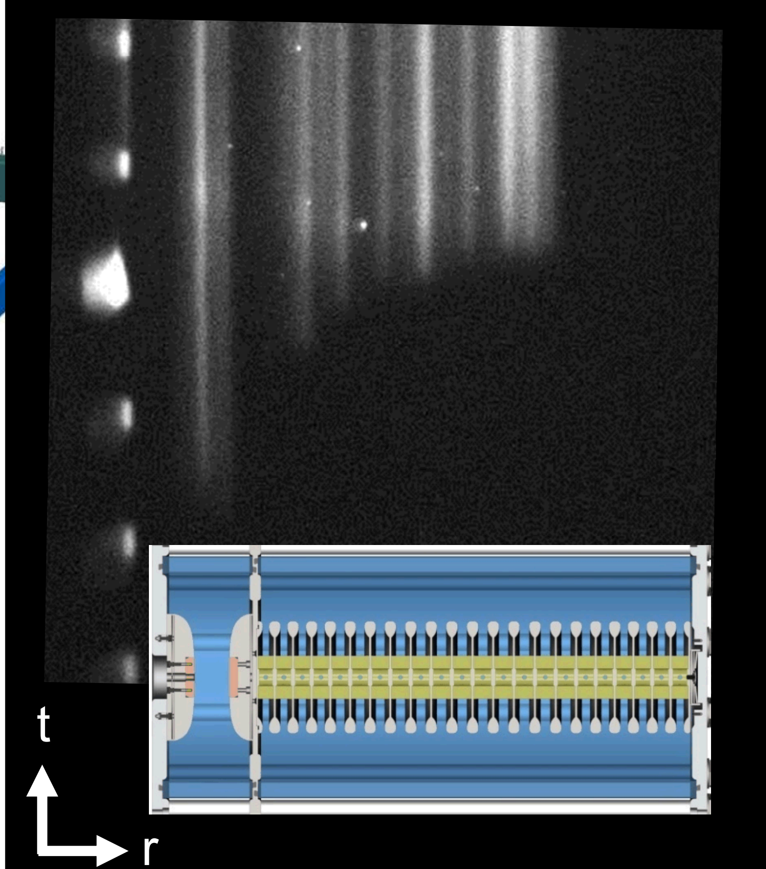
The laser triggered gas switch consists of two switches in series and is the last command fired component on Z .



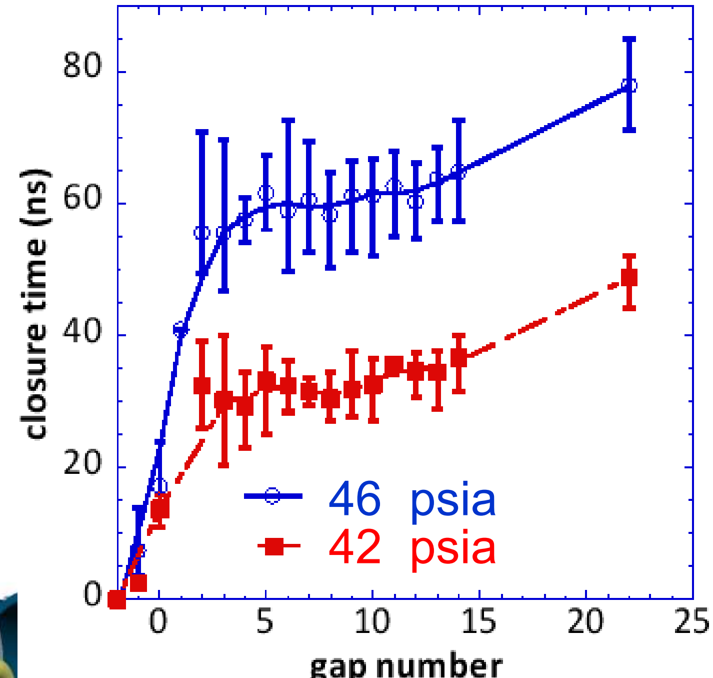
- The gas switch consists of two switches in series;
  1. a laser triggered switch,
  2. and a self break cascade switch.
- Closure of the cascade section relies on overstress from the trigger gap.
- The trade-off between pre-fire rate and timing jitter is balanced by adjusting the operating gas pressure.

The runtime of the laser triggered gas switch is dominated by closure of the first gaps in the cascade section.

Streak image of light emitted by LTGS during operation



Switch performance is a strong function of the SF_6 gas pressure.



Gap	Description
-2	Laser light arrives in trigger gap
-1	First visible light in trigger gap
0	Electrical closure of trigger gap
1	Visible light in first cascade gap

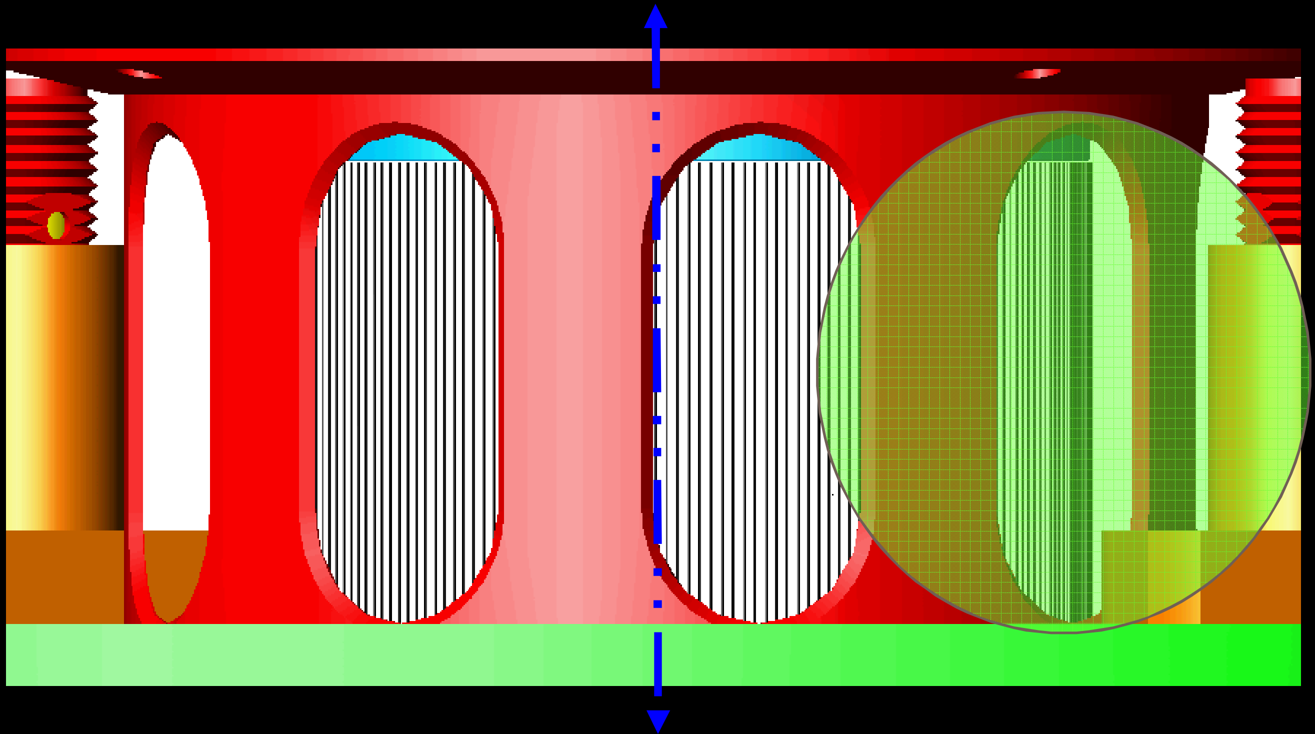
Z1311 Coverdale: Self Emission of a Large Diameter Copper Single Array

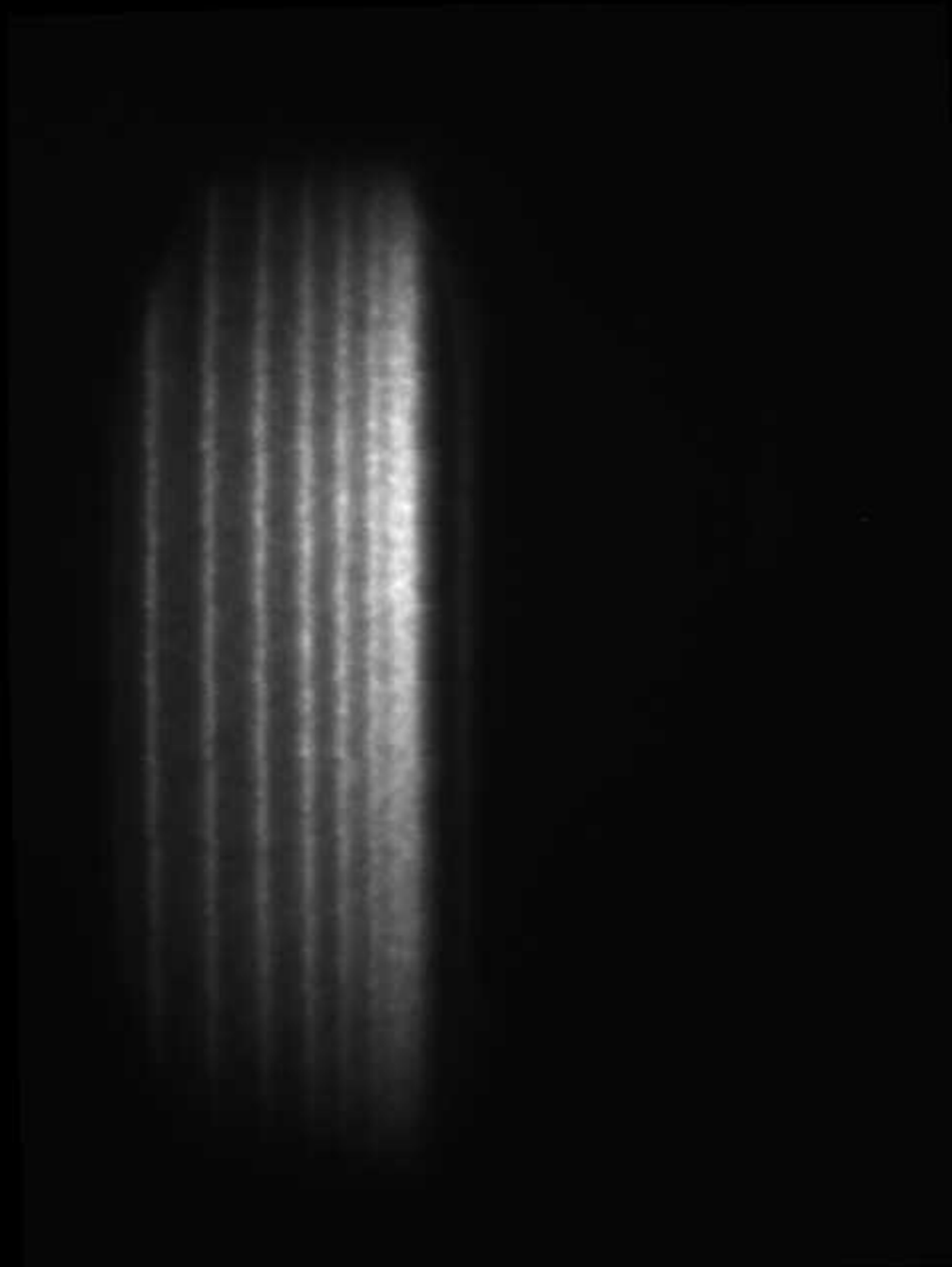
Material: Copper

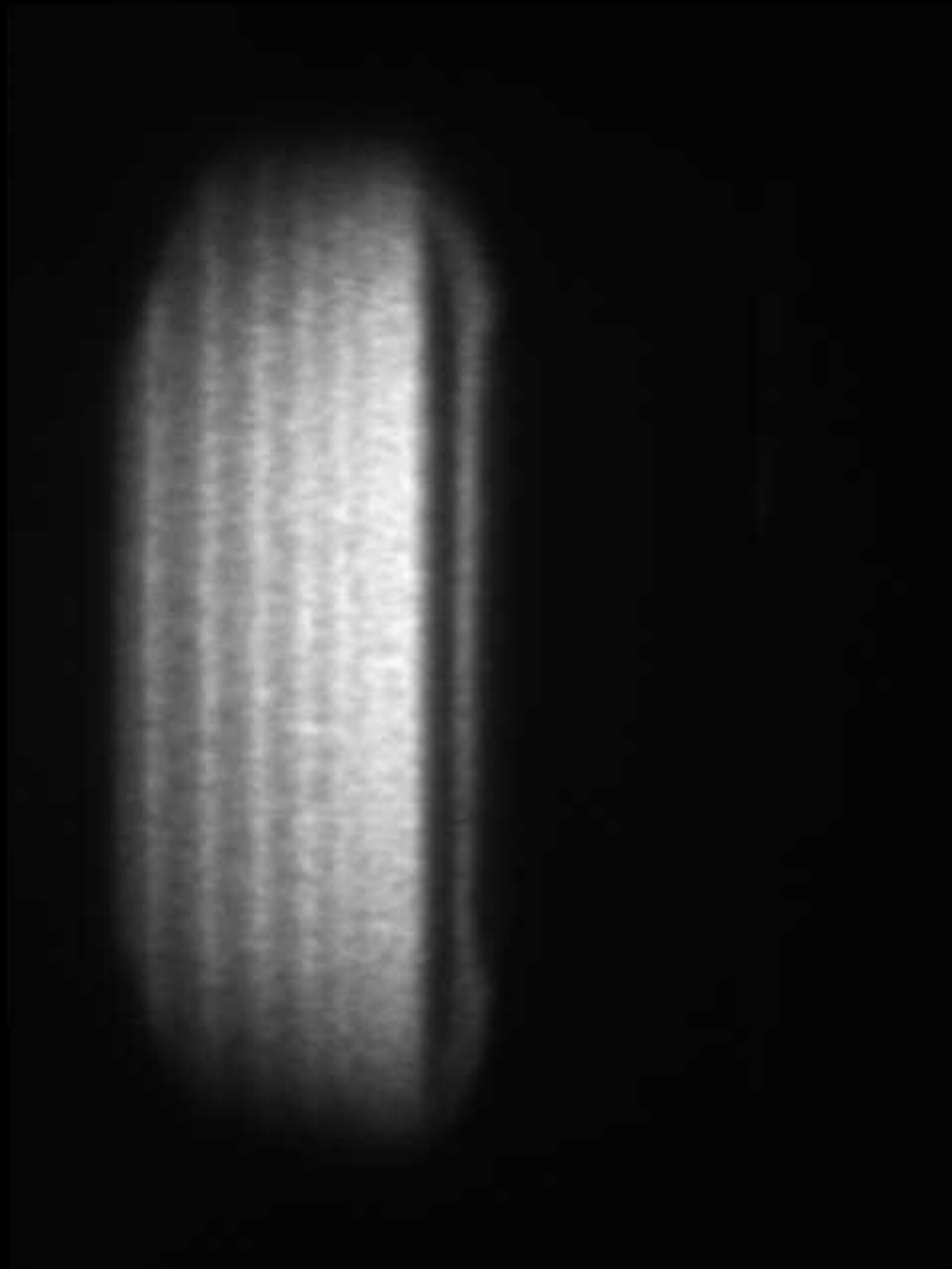
Array Diameter

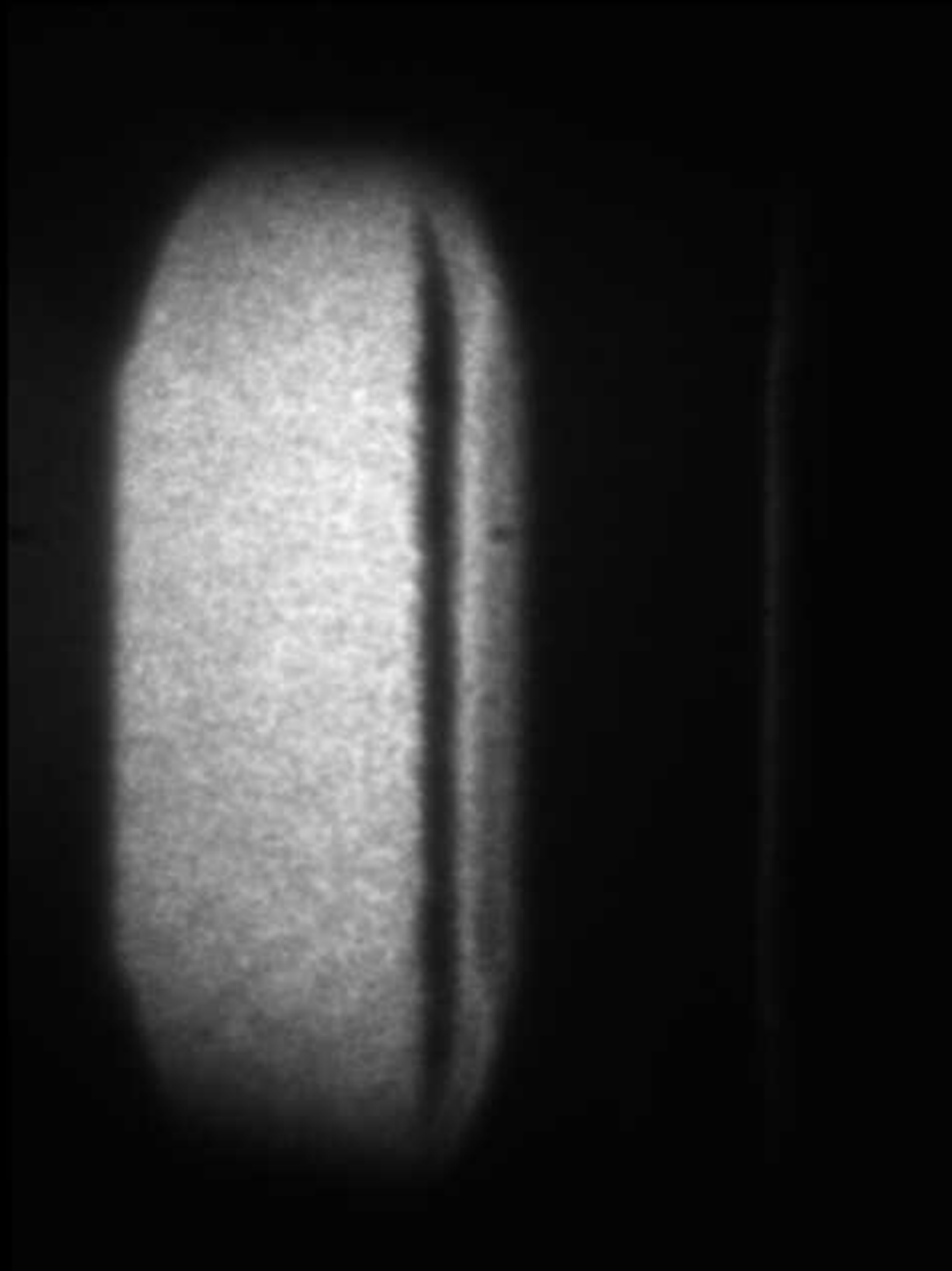
60 mm, 88 wires

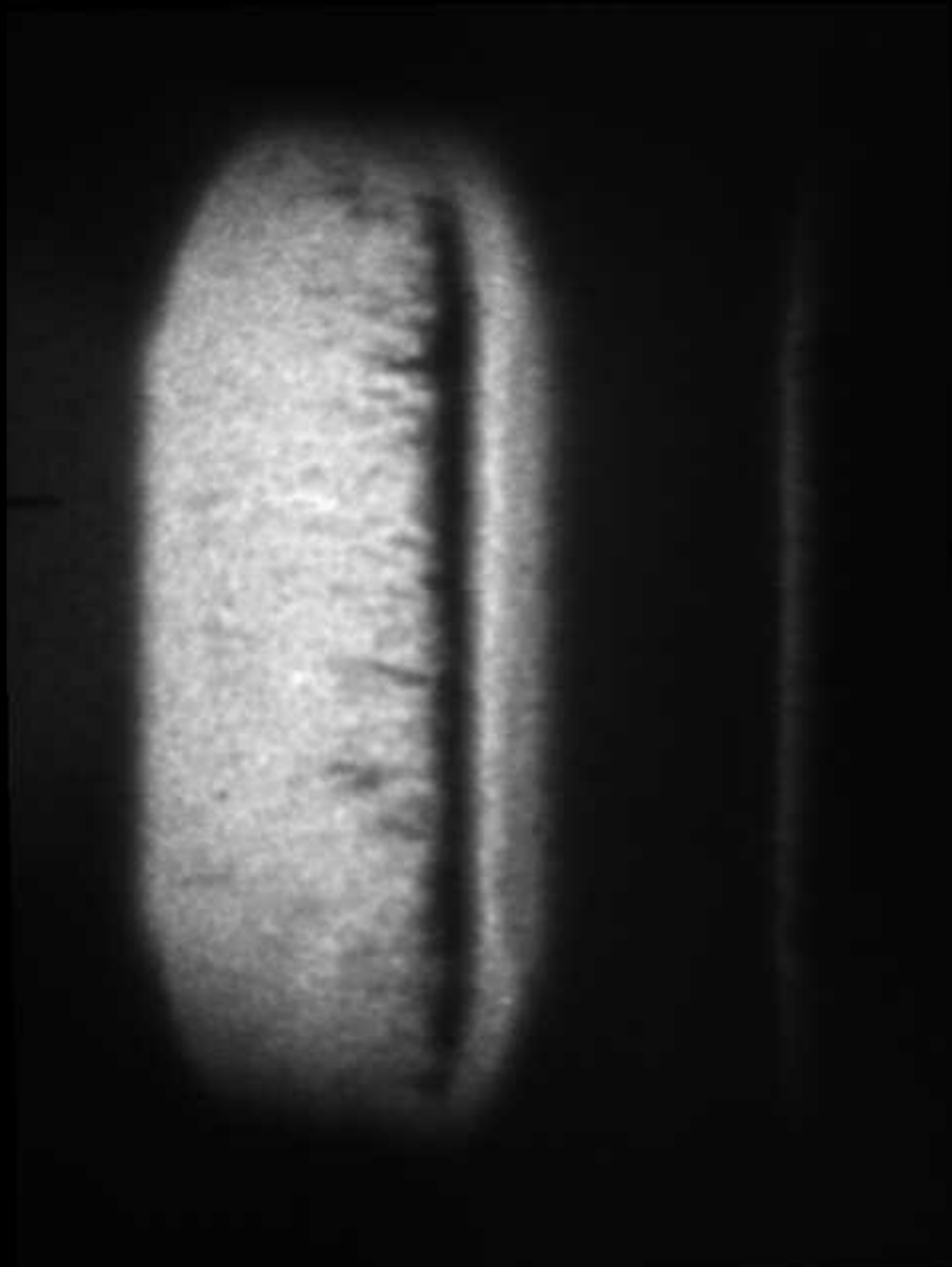
Wire Φ: 11.09 um





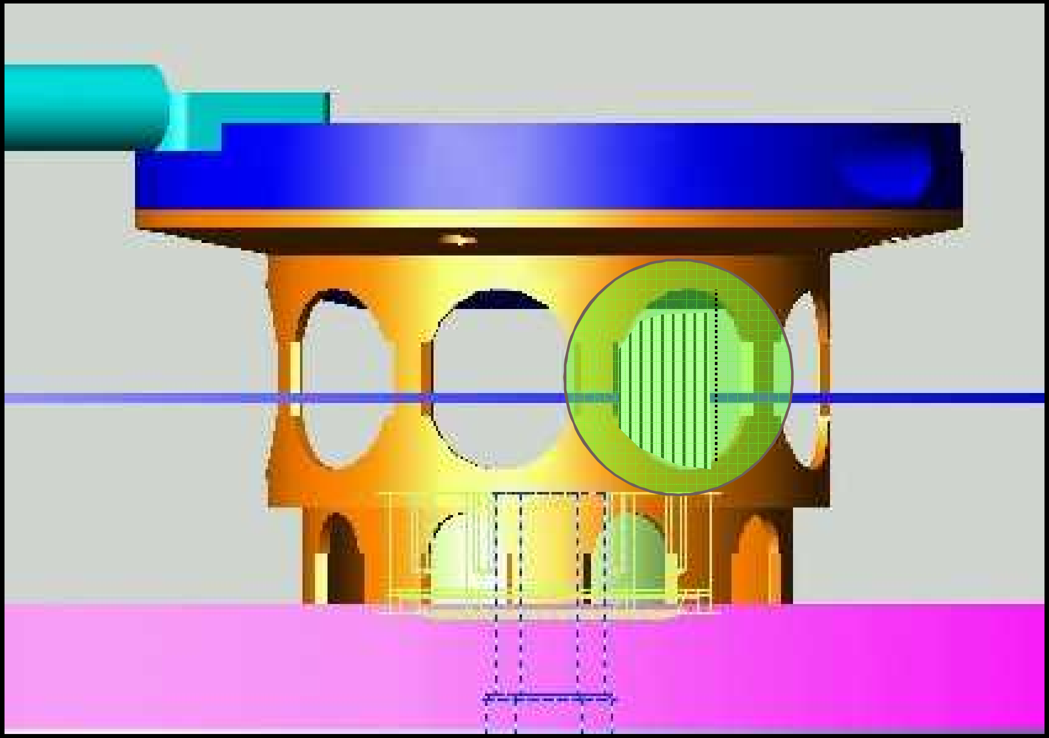


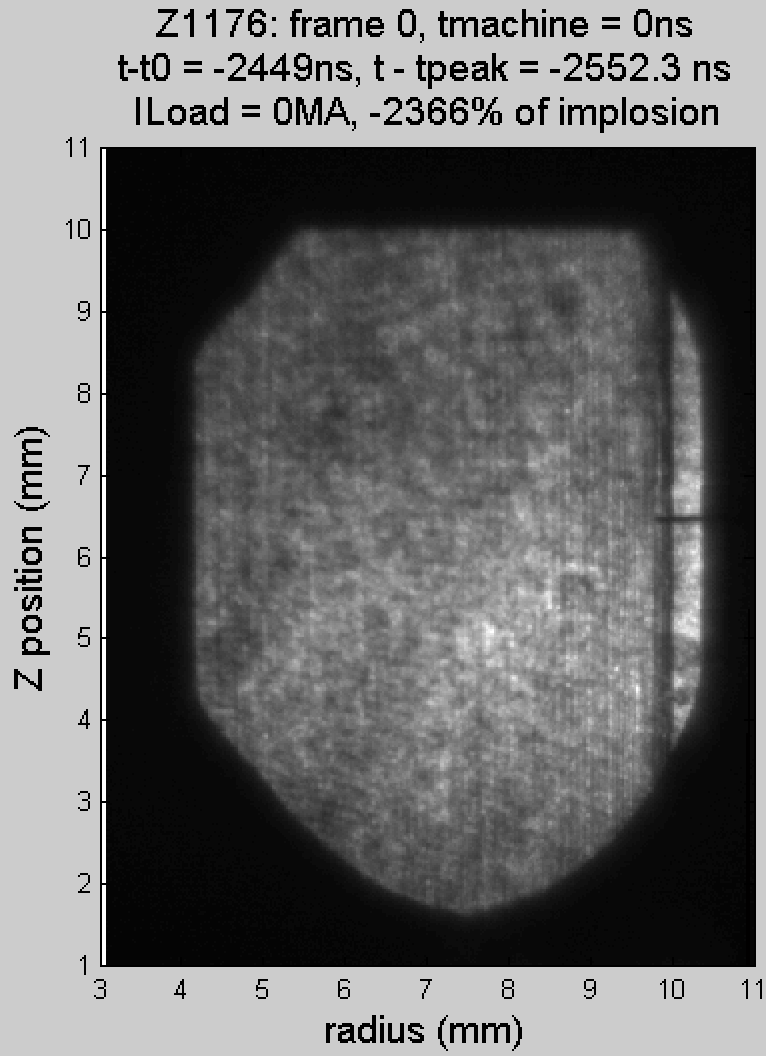




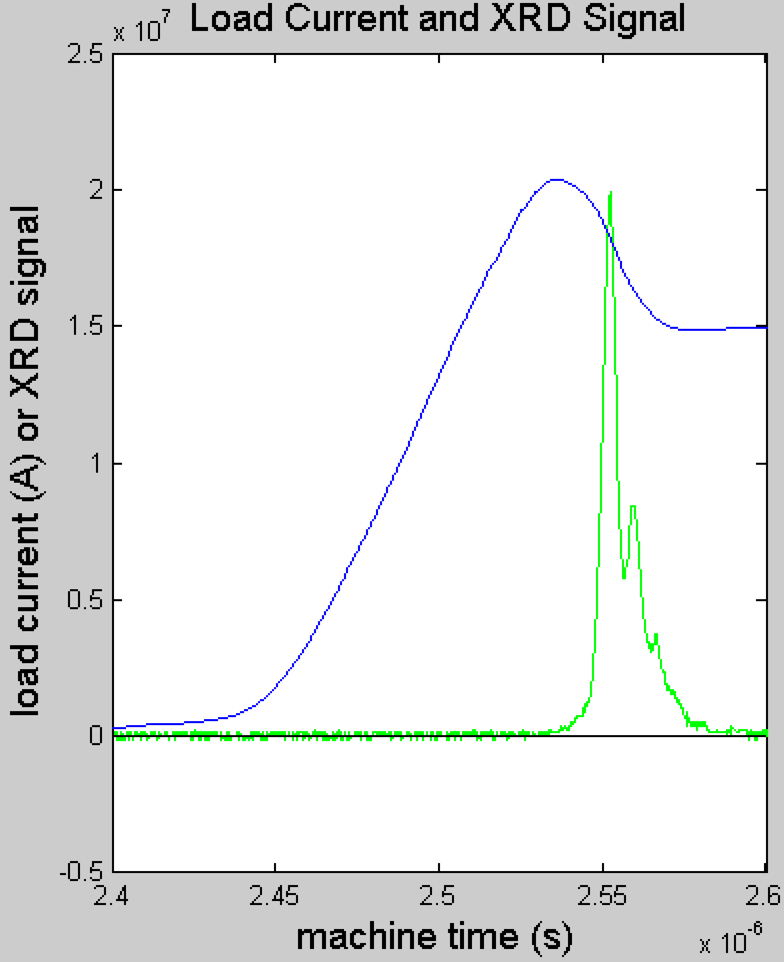
Z1176 Sinars: Laser Shadowgraph of a Single Tungsten Array

Material: W
Array Diameter: 20 mm, 300 wires
Array Height: 10 mm
Wire Φ: 11.5 um
Array Mass: 6 mg

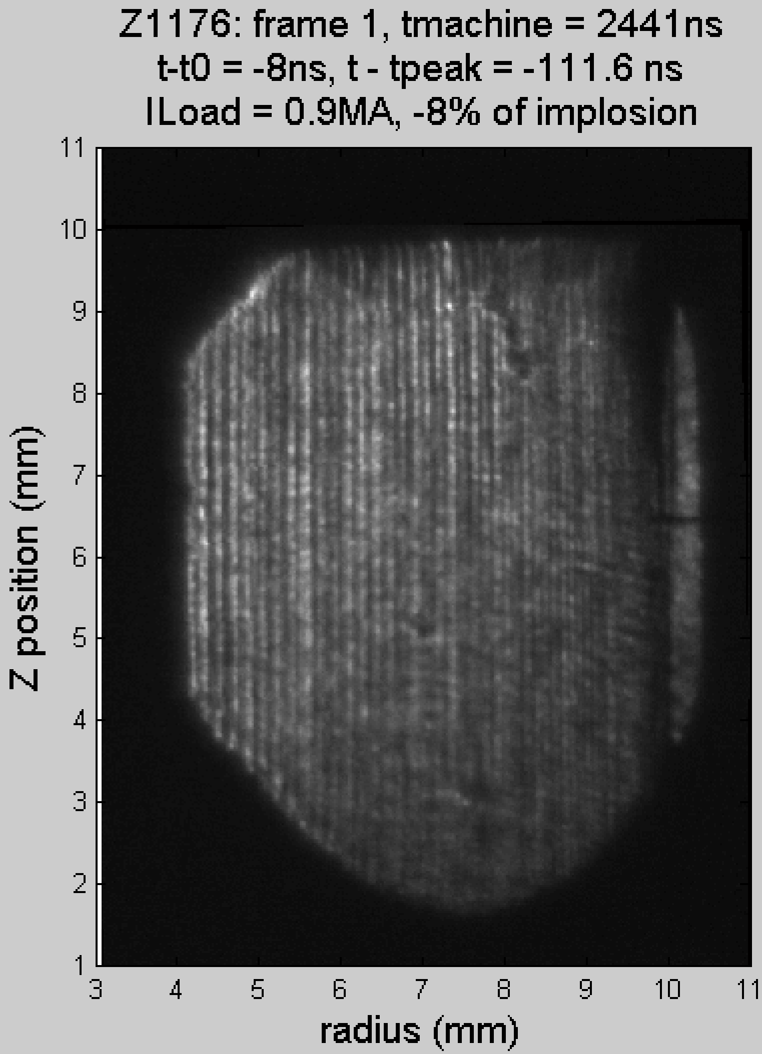


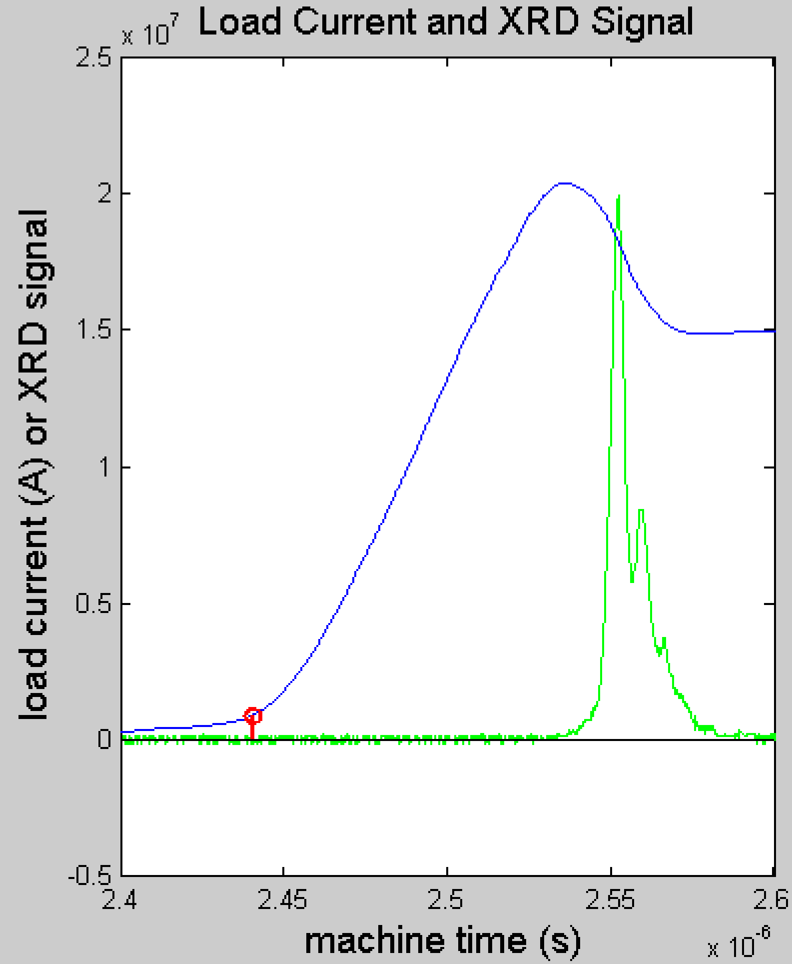


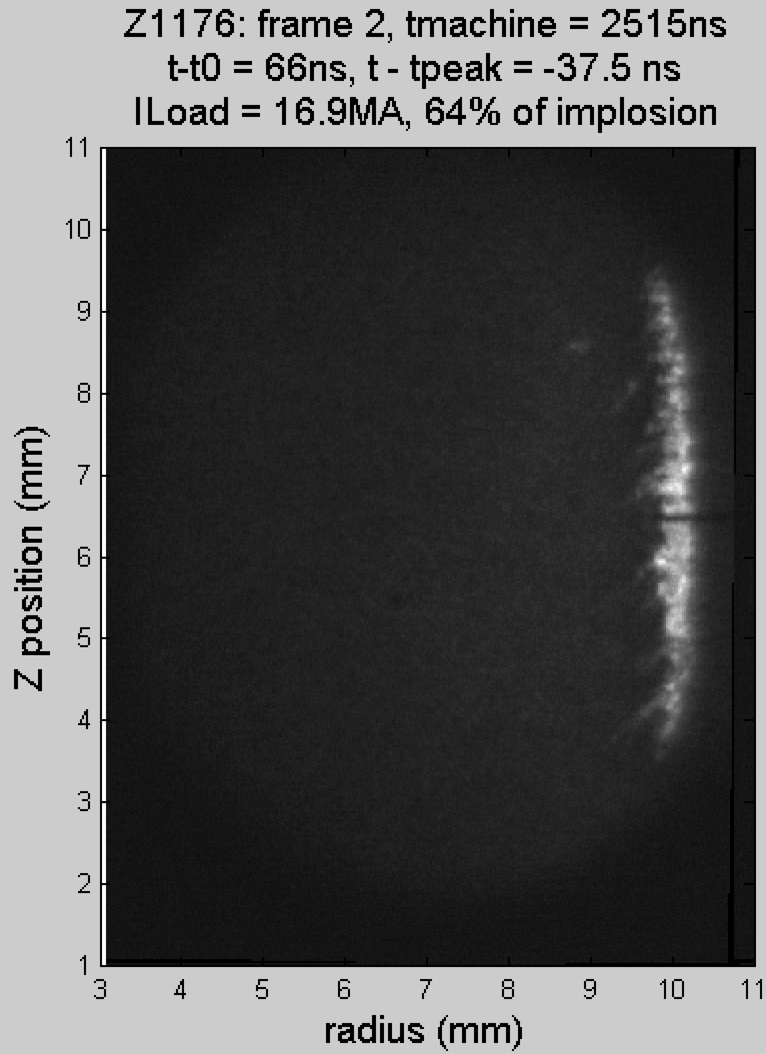
Z1176: frame 0, tmachine = 0ns
t-t0 = -2449ns, t - tpeak = -2552.3 ns
ILoad = 0MA, -2366% of implosion
Z position (mm)
radius (mm)

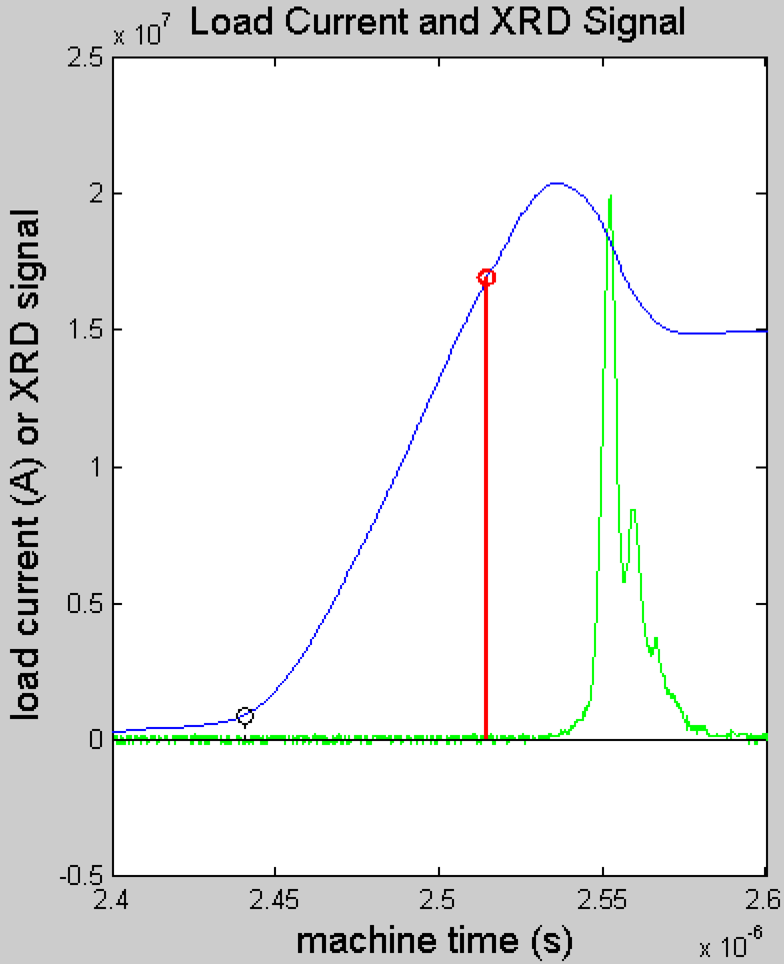


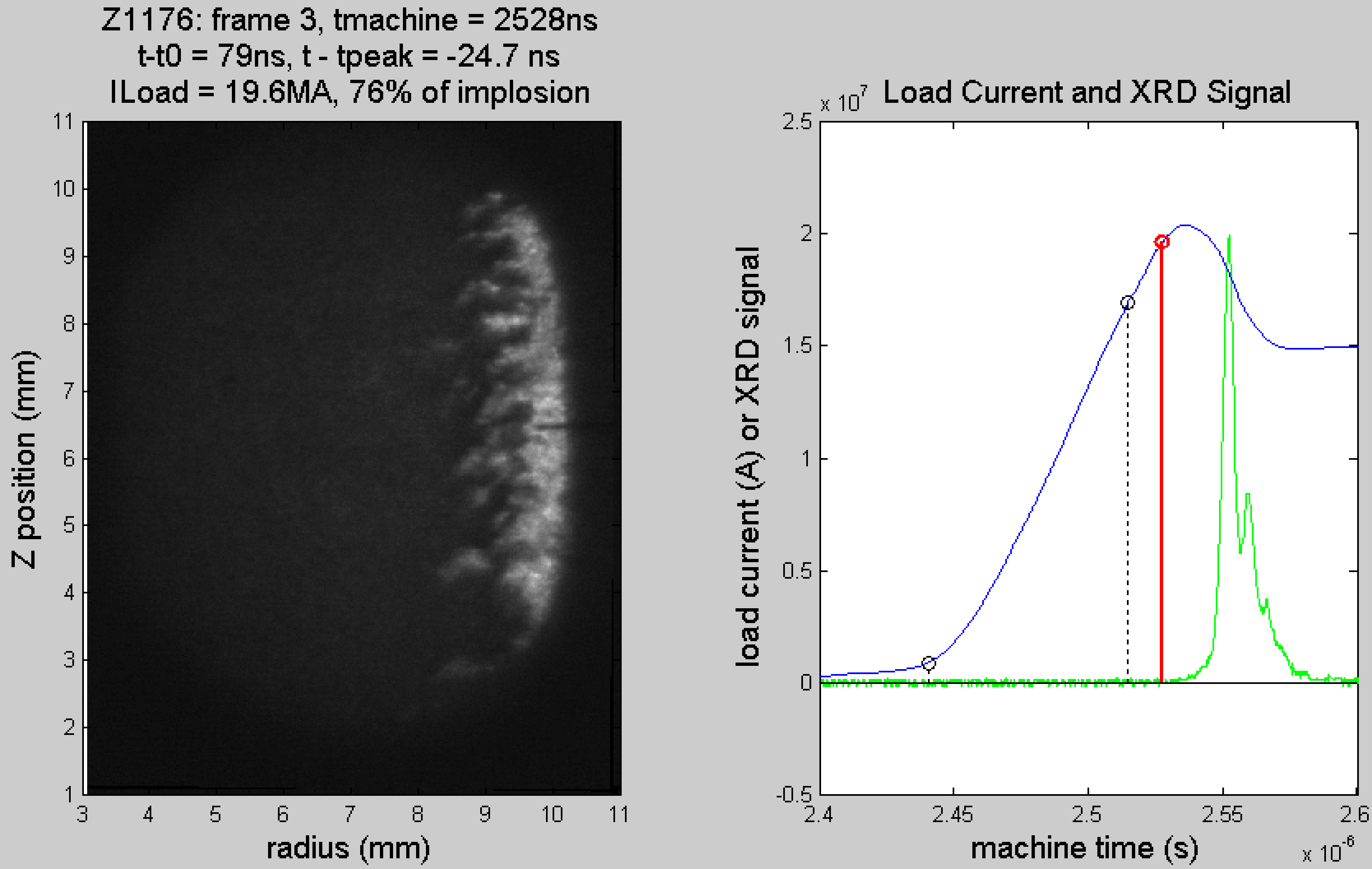
Load Current and XRD Signal
x 10^7
load current (A) or XRD signal
machine time (s)
x 10^-6


Z1176: frame 1, tmachine = 2441ns
t-t0 = -8ns, t - tpeak = -111.6 ns
ILoad = 0.9MA, -8% of implosion
Z position (mm)
radius (mm)
11
10
9
8
7
6
5
4
3
2
1
3
4
5
6
7
8
9
10
11

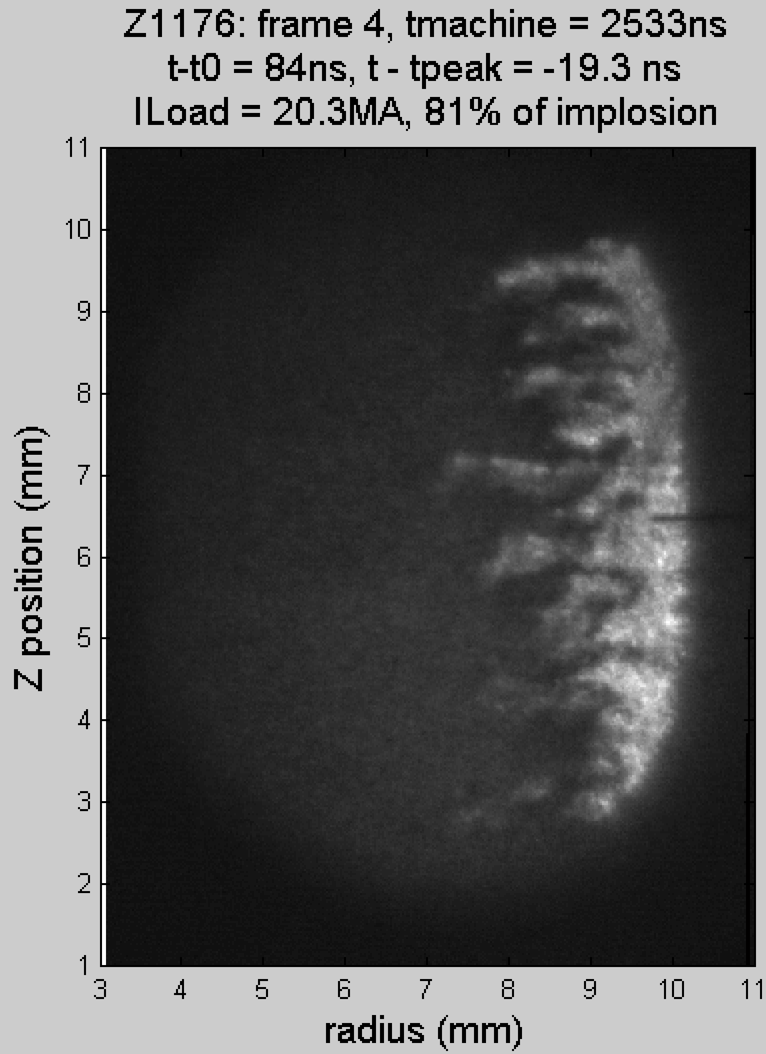

x 10^7
Load Current and XRD Signal
load current (A) or XRD signal
machine time (s)
x 10^-6
2.5
2
1.5
1
0.5
0
-0.5
2.4
2.45
2.5
2.55
2.6

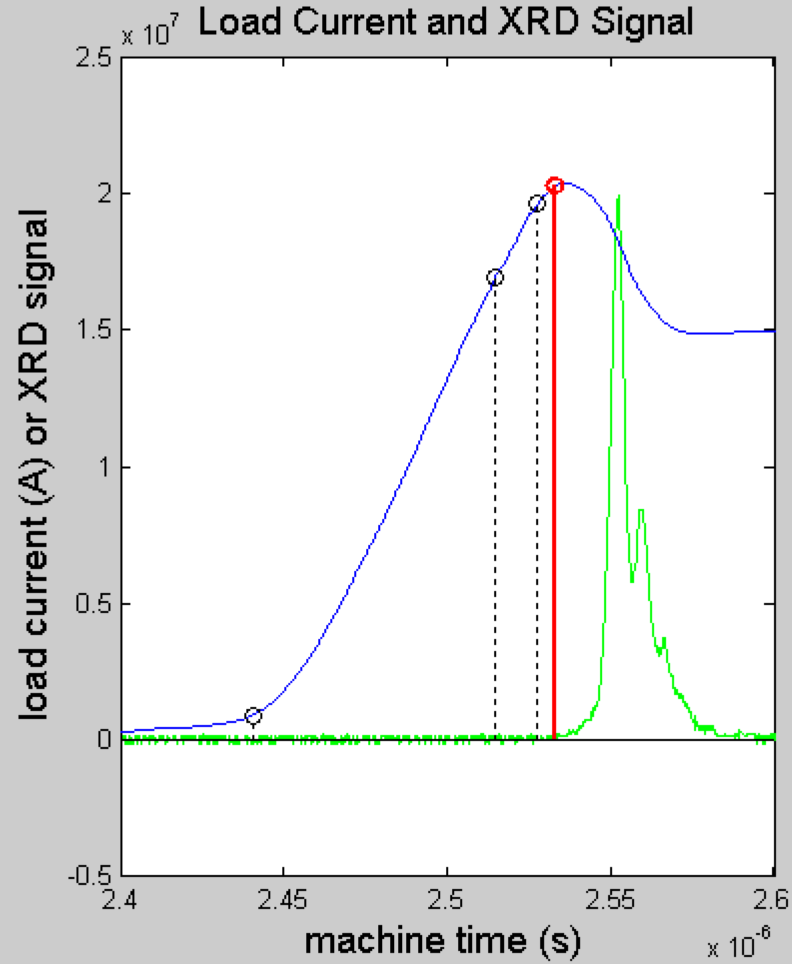

Z1176: frame 2, tmachine = 2515ns
t-t0 = 66ns, t - tpeak = -37.5 ns
ILoad = 16.9MA, 64% of implosion
Z position (mm)
radius (mm)
11
10
9
8
7
6
5
4
3
2
1
3
4
5
6
7
8
9
10
11

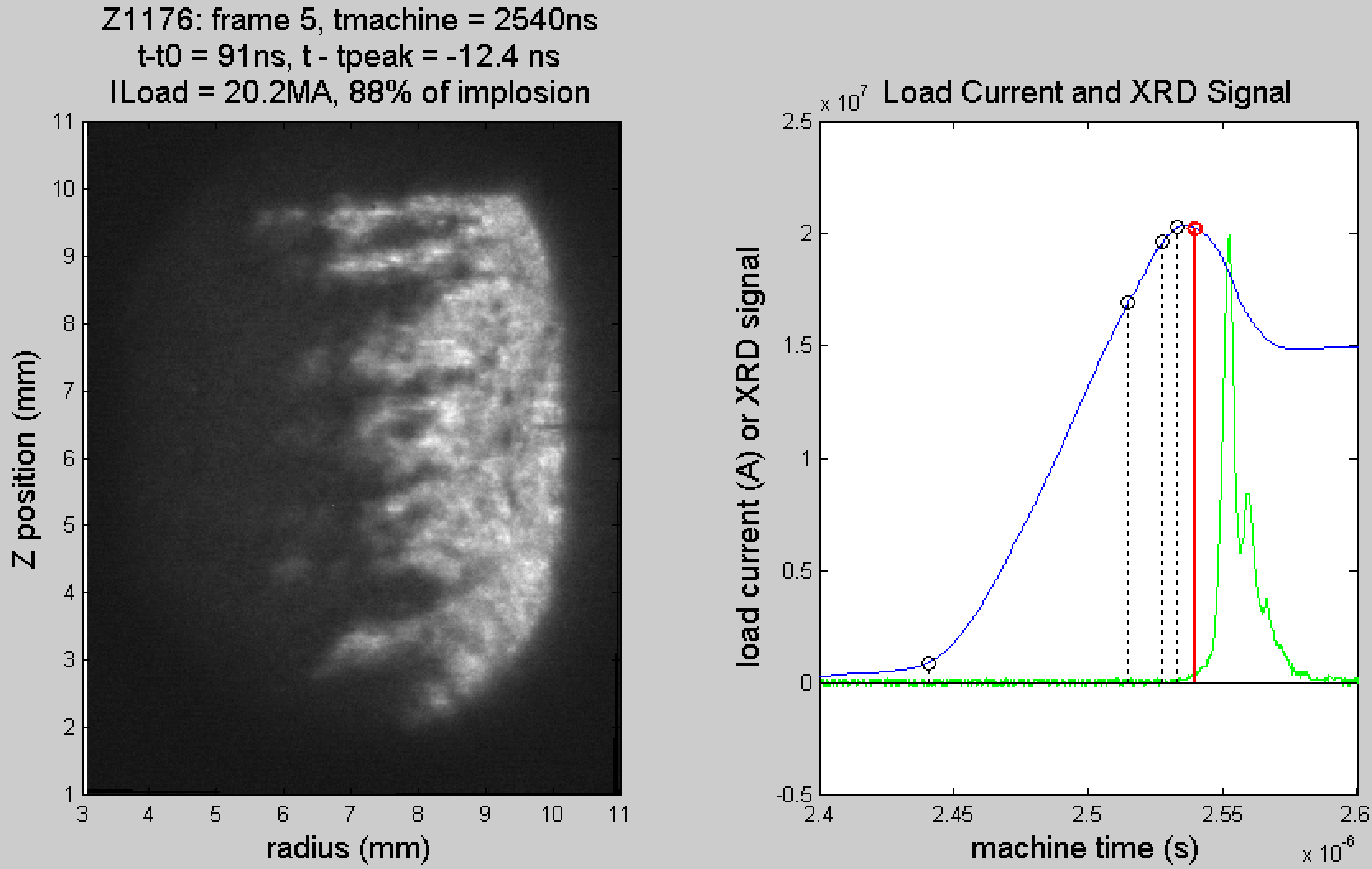

Load Current and XRD Signal
x 10^7
load current (A) or XRD signal
machine time (s)
x 10^-6
2.5
2
1.5
1
0.5
0
-0.5
2.4
2.45
2.5
2.55
2.6

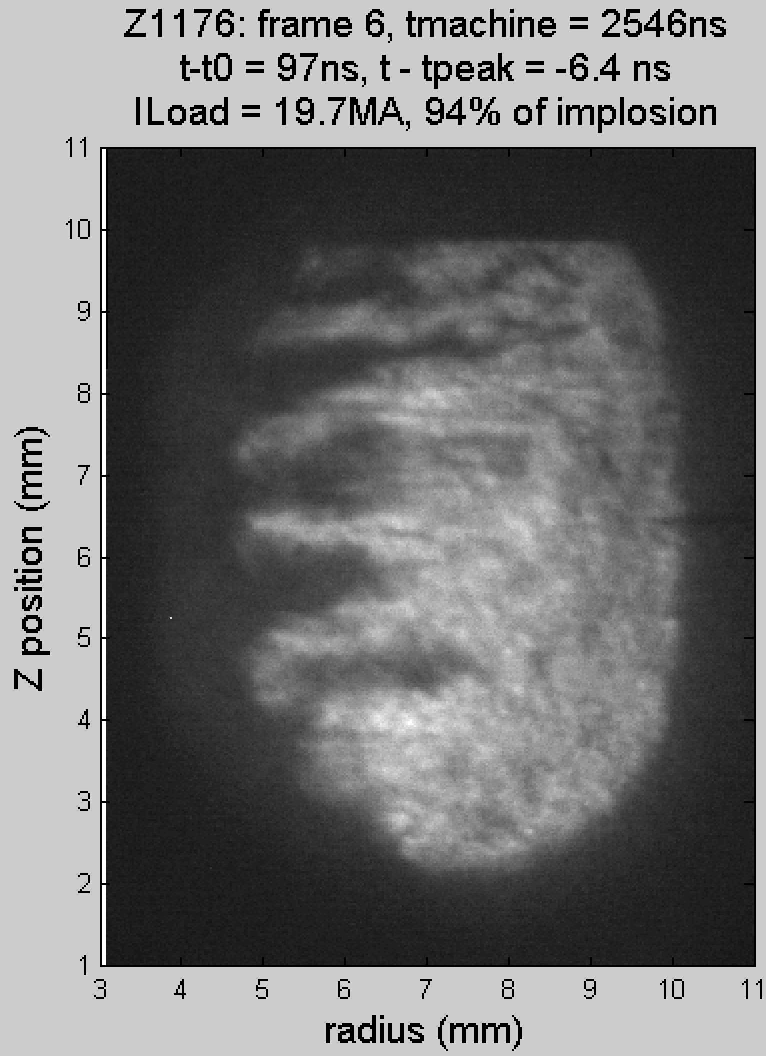


Z1176: frame 3, tmachine = 2528ns
t-t0 = 79ns, t - tpeak = -24.7 ns
ILoad = 19.6MA, 76% of implosion
Z position (mm)
radius (mm)
11
10
9
8
7
6
5
4
3
2
1
3
4
5
6
7
8
9
10
11
Load Current and XRD Signal
x 10^7
load current (A) or XRD signal
machine time (s)
x 10^-6
2.5
2
1.5
1
0.5
0
-0.5
2.4
2.45
2.5
2.55
2.6

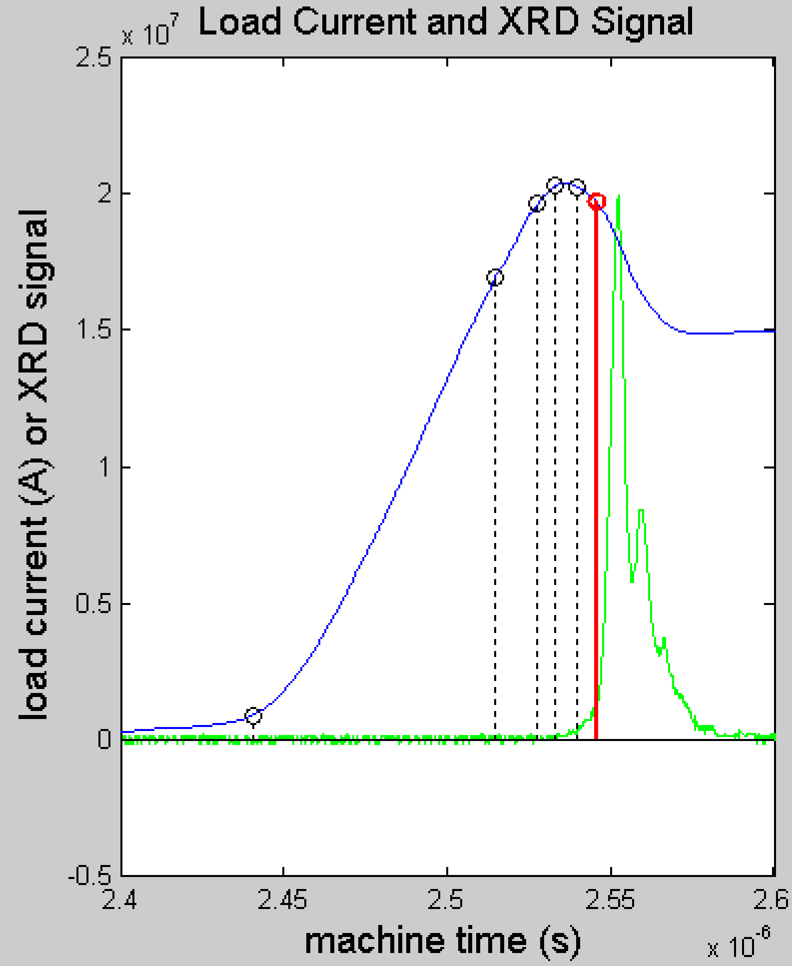

Z1176: frame 4, tmachine = 2533ns
t-t0 = 84ns, t - tpeak = -19.3 ns
ILoad = 20.3MA, 81% of implosion
Z position (mm)
11
10
9
8
7
6
5
4
3
2
1
3
4
5
6
7
8
9
10
11
radius (mm)


x 10^7
Load Current and XRD Signal
load current (A) or XRD signal
2.5
2
1.5
1
0.5
0
-0.5
2.4
2.45
2.5
2.55
2.6
machine time (s)
x 10^-6


Z1176: frame 5, tmachine = 2540ns
t-t0 = 91ns, t - tpeak = -12.4 ns
ILoad = 20.2MA, 88% of implosion
Z position (mm)
radius (mm)
Load Current and XRD Signal
x 10^7
load current (A) or XRD signal
machine time (s)
x 10^-6

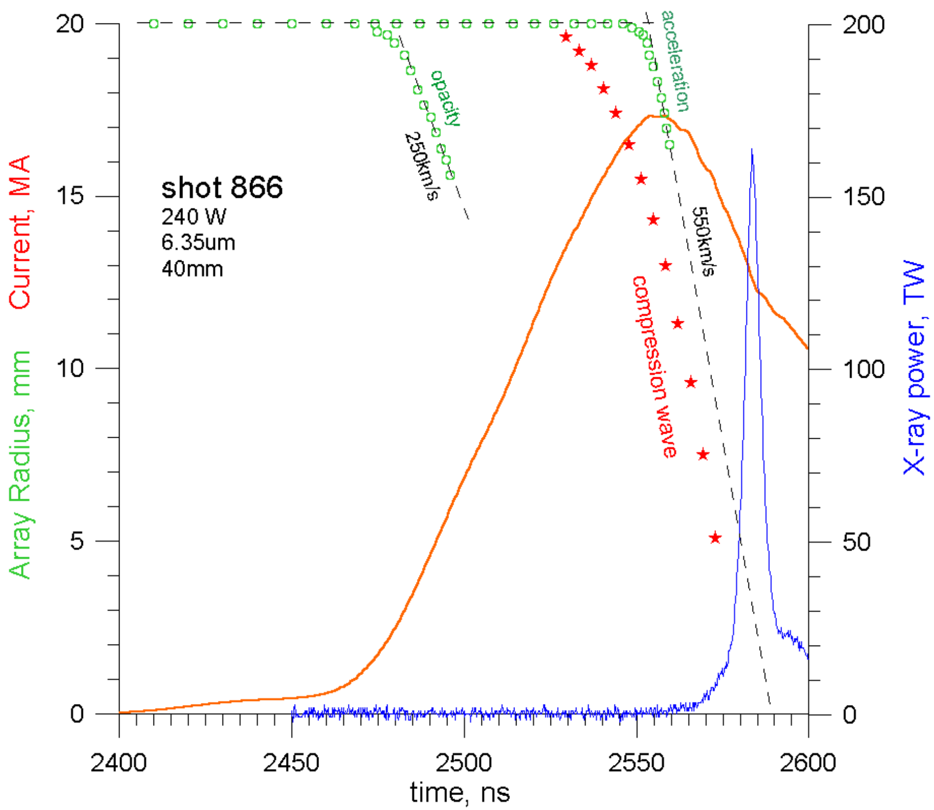


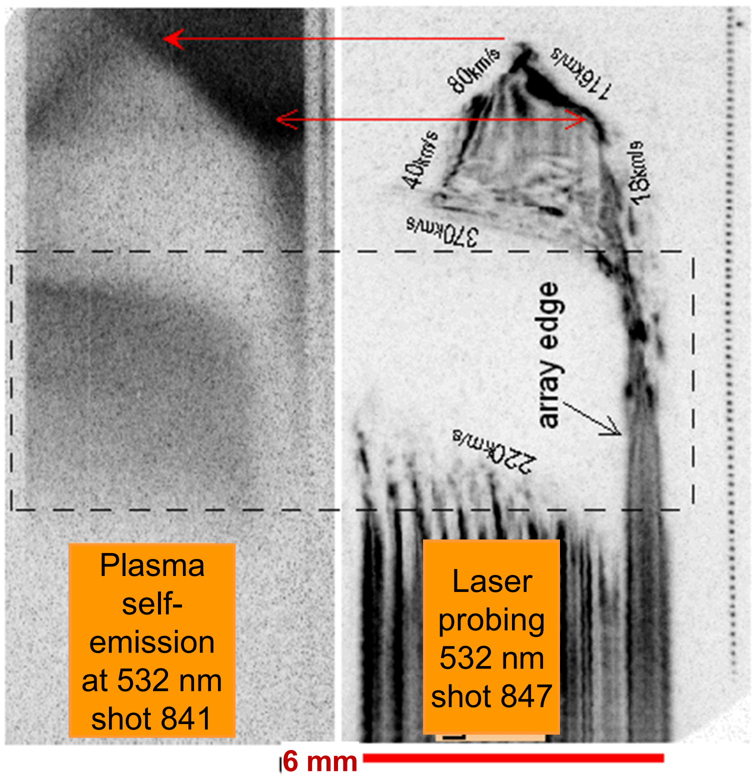
Z1176: frame 6, tmachine = 2546ns
t-t0 = 97ns, t - tpeak = -6.4 ns
ILoad = 19.7MA, 94% of implosion
Z position (mm)
radius (mm)



Load Current and XRD Signal
x 10^7
load current (A) or XRD signal
machine time (s)
x 10^-6

Streaked images of self emission and laser probing of wire array implosions show many details.

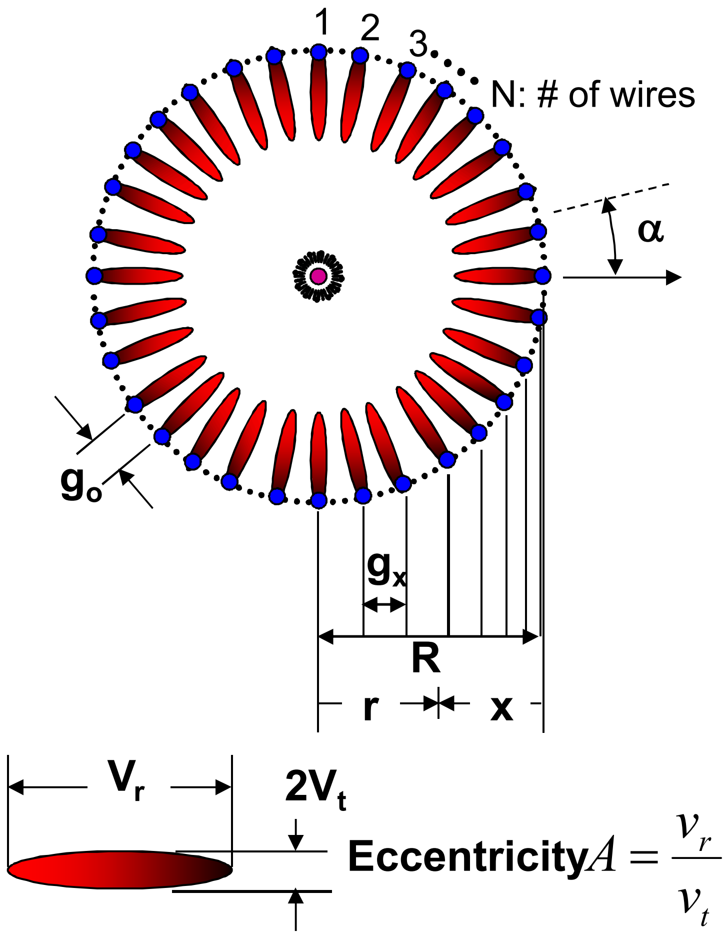




Shots 841, 847
PI: Christine Coverdale
Nested Stainless Steel Array

Wires: Φ = 10.2um SS
Outer Array: Φ = 55.0 mm, 104 wires
Inner Array: Φ = 27.5 mm, 52 wires

Interwire Gap Closure Model



Eccentricity $A = \frac{v_r}{v_t}$

Geometrical Parameters

$$g_0 = \frac{2\pi R}{N}$$

$$g_x = g_o \sin\alpha$$

$$x = R - r = R(1 - \cos\alpha)$$

$$\alpha = \cos^{-1}(1 - x/R)$$

The time it takes the opacity boundary to close the interwire gaps, where v_x is the velocity of the boundary.

$$t = \frac{g_x}{2v_x}$$

For asymmetric streaming, the apparent velocity is also a function of x

$$v_x = \left(v_r^2 \cos^2\alpha + v_t^2 \sin^2\alpha\right)^{\frac{1}{2}}$$

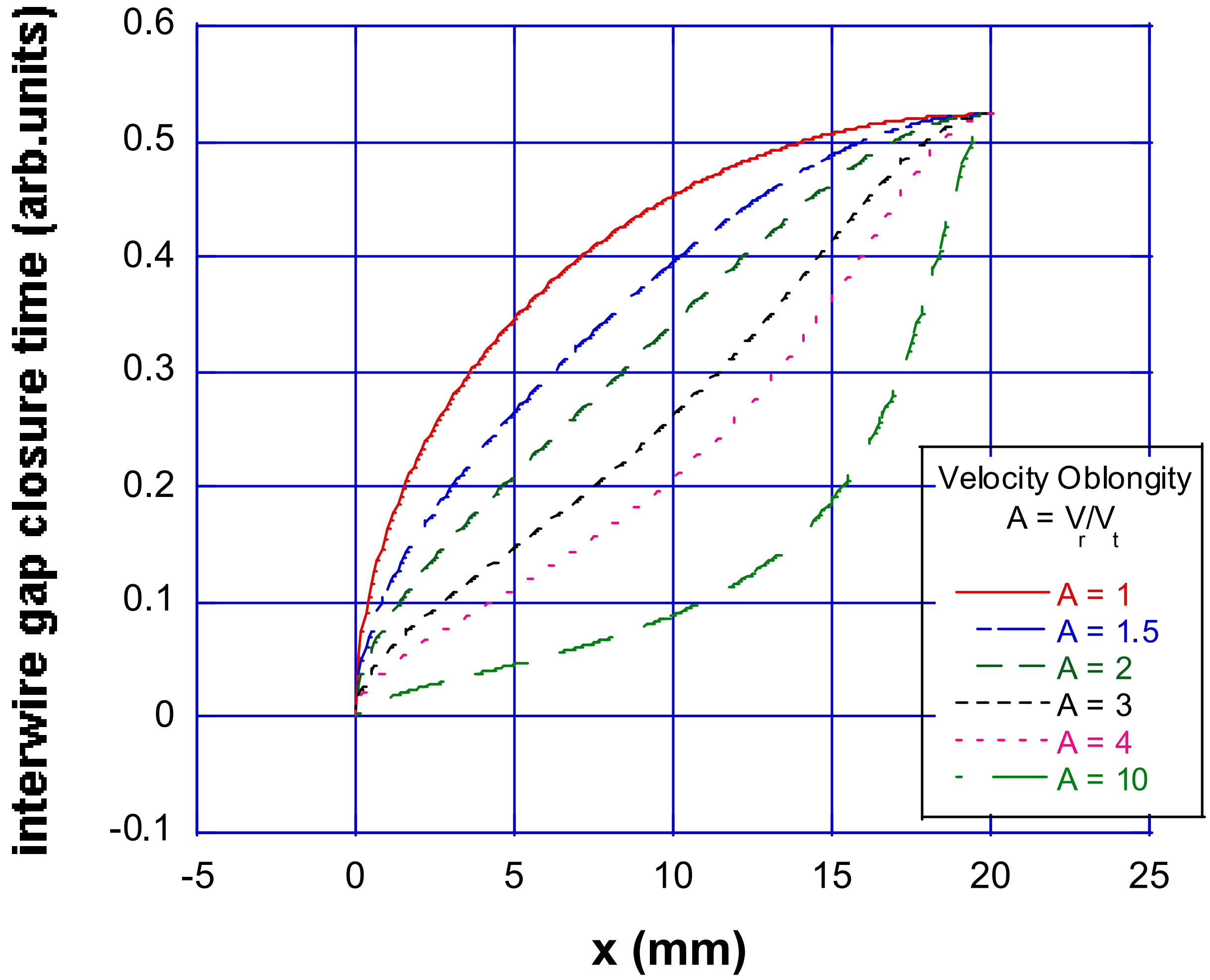
$$= v_t \left(A^2 \cos^2\alpha + \sin^2\alpha\right)^{\frac{1}{2}}$$

$$t = g_x \Big/ 2v_t \left(A^2 \cos^2\alpha + \sin^2\alpha\right)^{\frac{1}{2}}$$

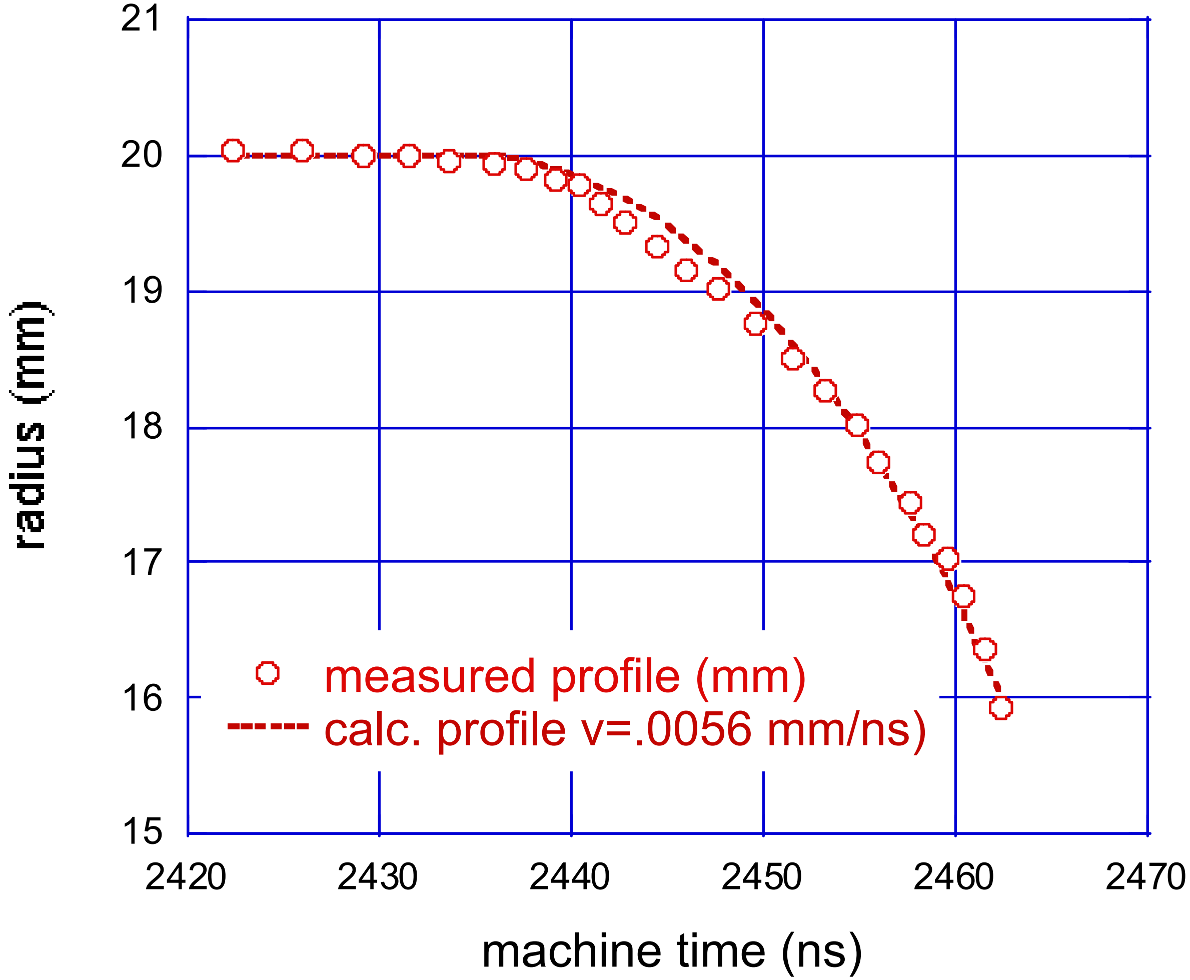
$$= g_o \sqrt{x^2 - 2R} \Big/ 2v_t \left(A^2 (R - x)^2 + x^2 - 2R\right)^{\frac{1}{2}}$$

The calculated interwire gap closure times show a strong dependence on the eccentricity of the streaming profile.

Sandia National Laboratories



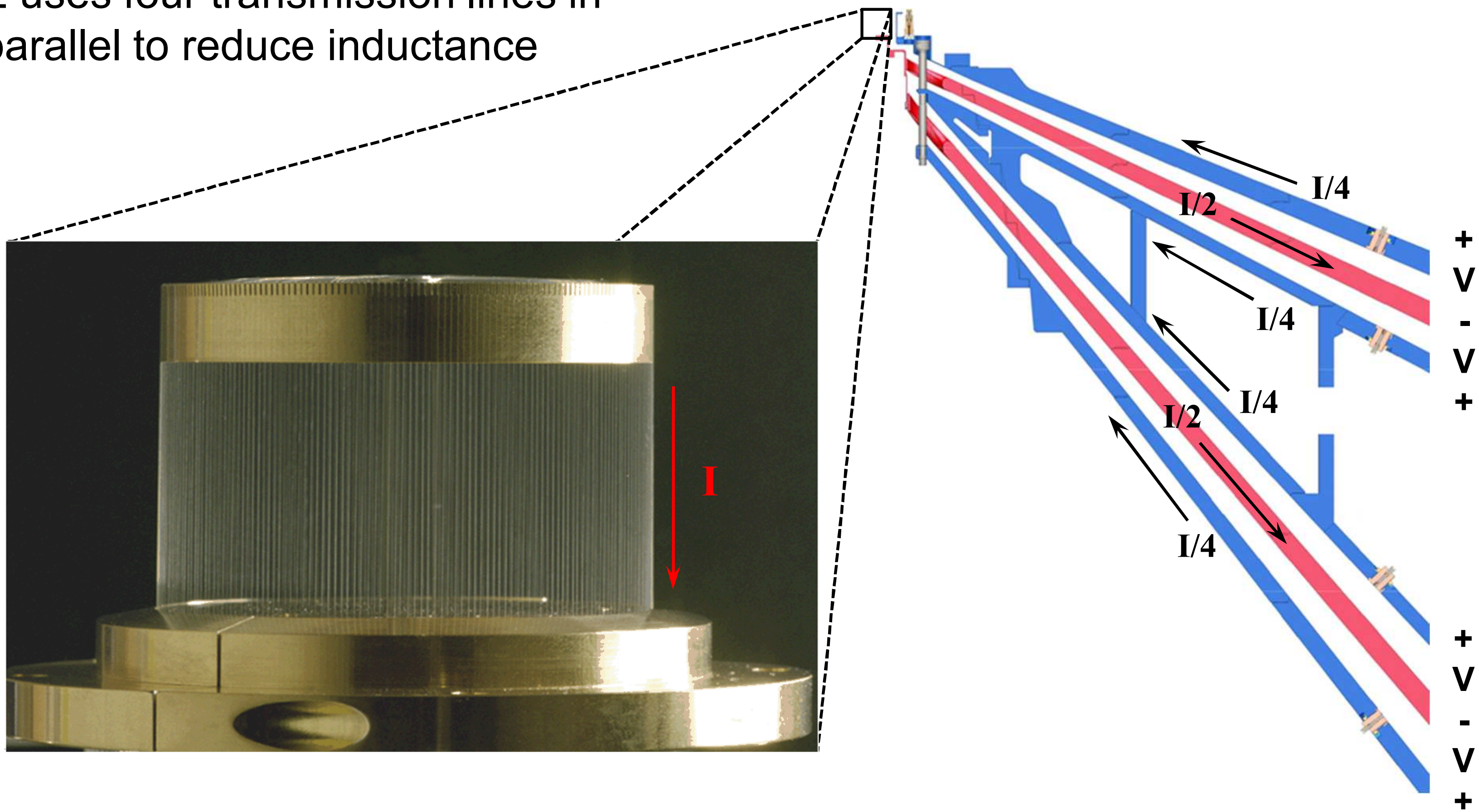
Fitting the experimentally measured opacity boundary with the model shows no streaming asymmetry is required.



A=1, No asymmetry included or needed!

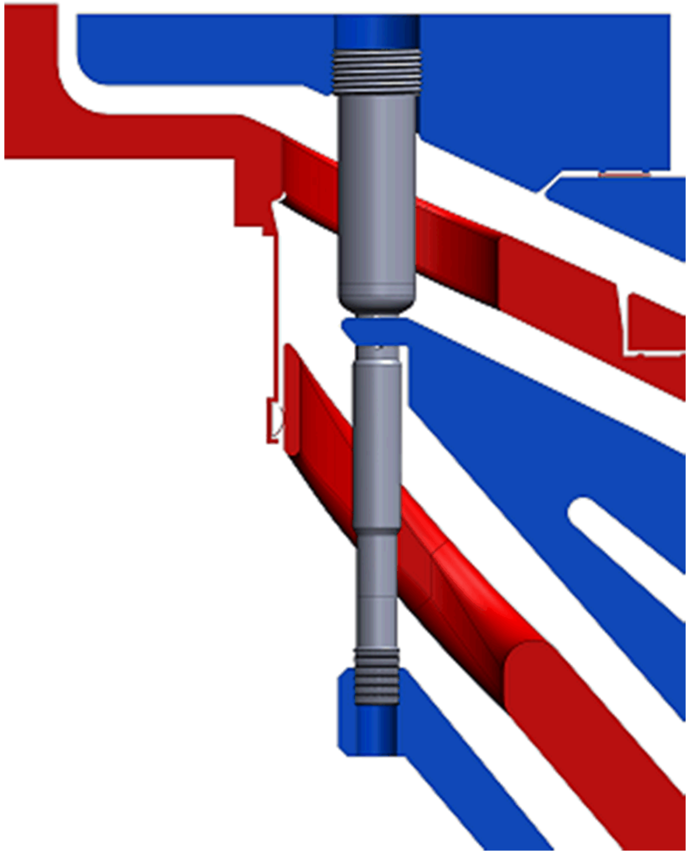
Low inductance transmission lines are required for high dI/dt current pulses

Z uses four transmission lines in parallel to reduce inductance

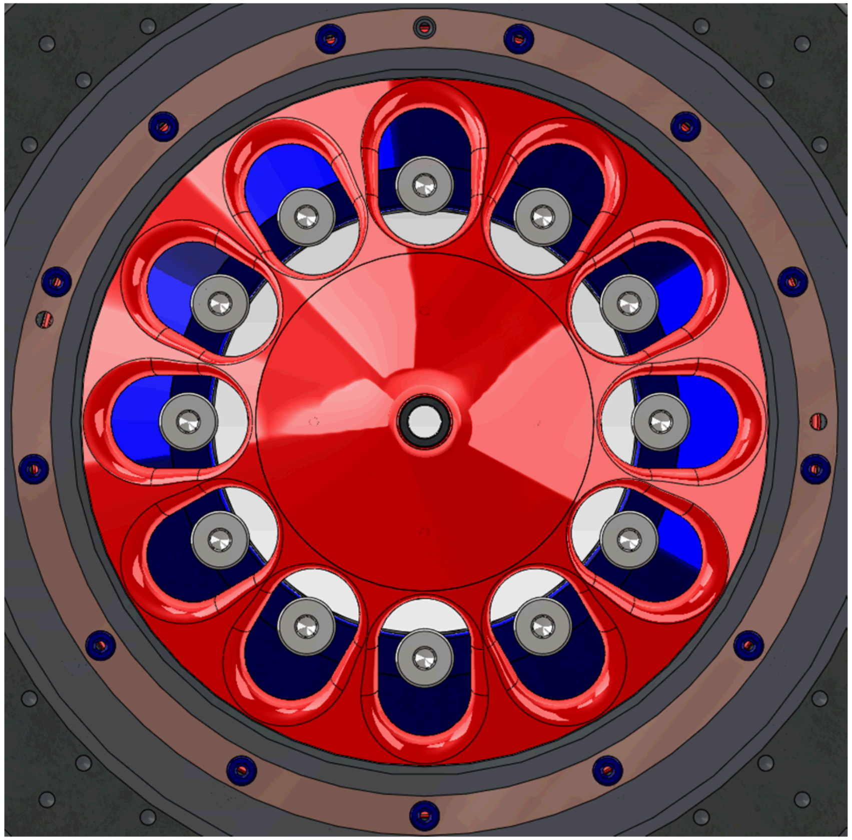


$V \sim L * dI/dt \Rightarrow V \sim 5MV, I \sim 25\ MA, t \sim 100\ ns$, so L_{total} is limited to ~20 nH

Post-hole convolutes are used to combine the current from several transmission lines into a single A-K gap



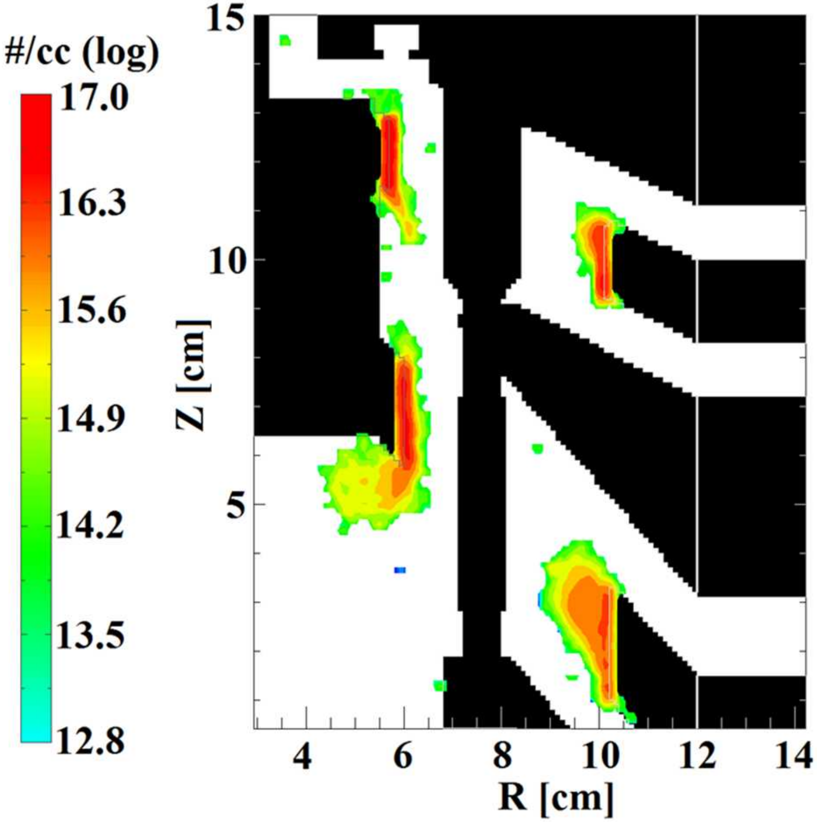
R-Z cross-section



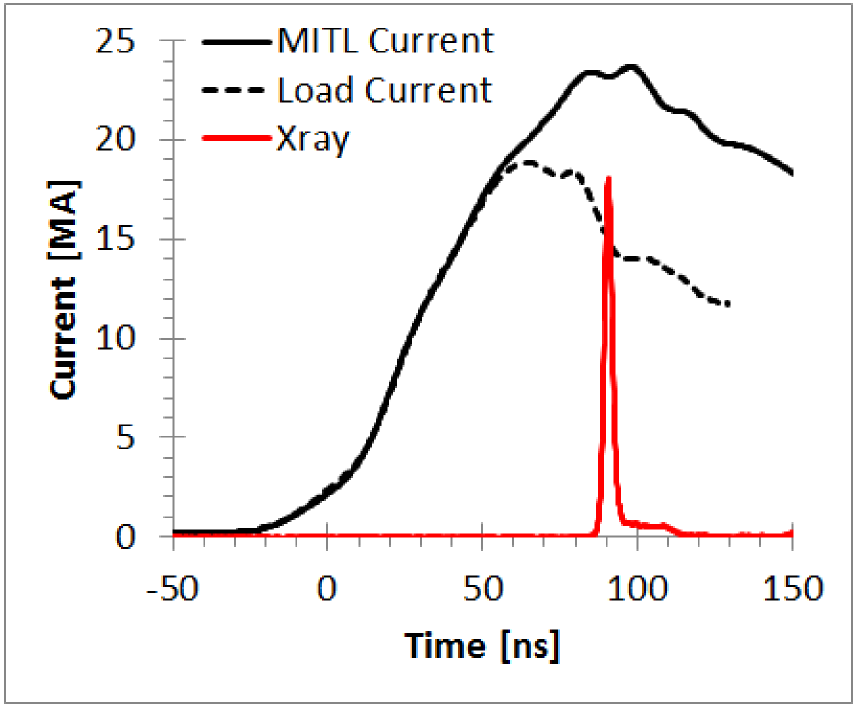
R-theta cross-section

Large current losses on the Z machine are attributed to plasma formation in the convolute.

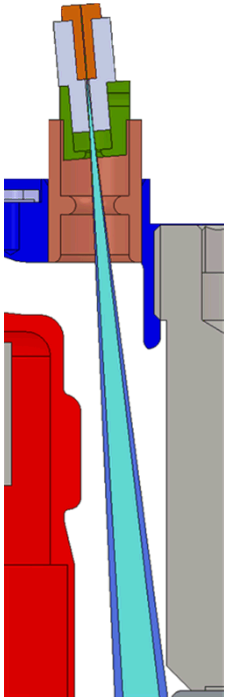
LSP Convolute simulation by D. V. Rose



Experimental data from large diameter wire array shot on Z

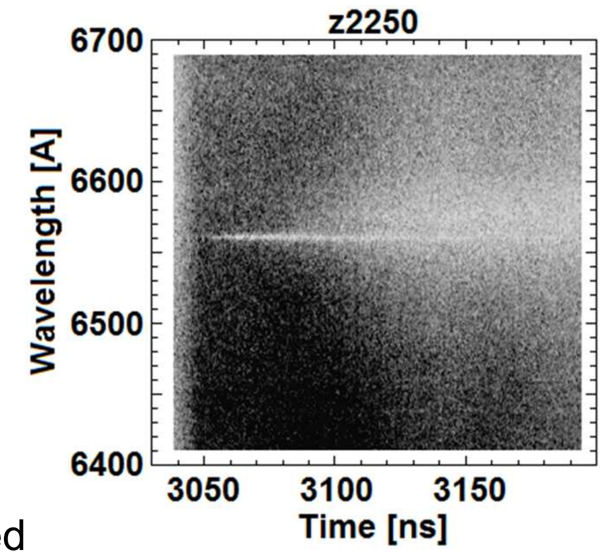


Previous measurements of the convolute plasma indicate a fast moving, high density, hydrocarbon plasma



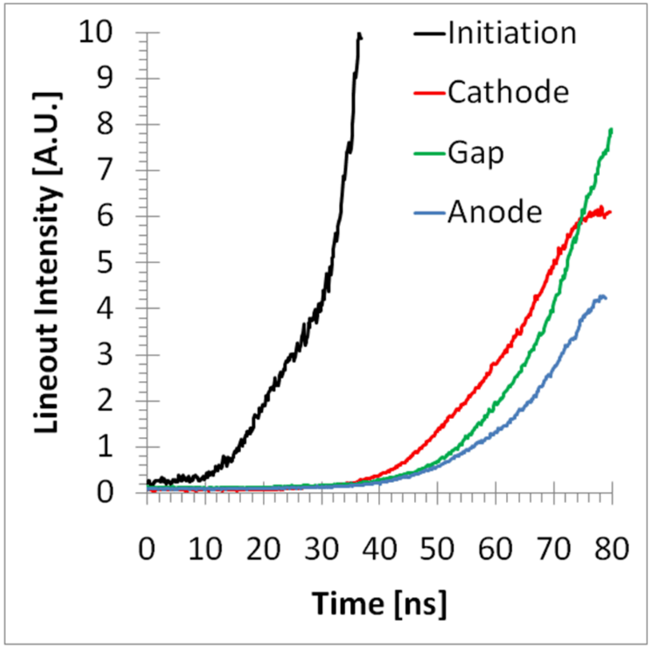
A fiber optically coupled probe was used to collect visible emission from the convolute

The spectrally and temporally resolved data consist of continuum emission with hydrogen and carbon absorption features

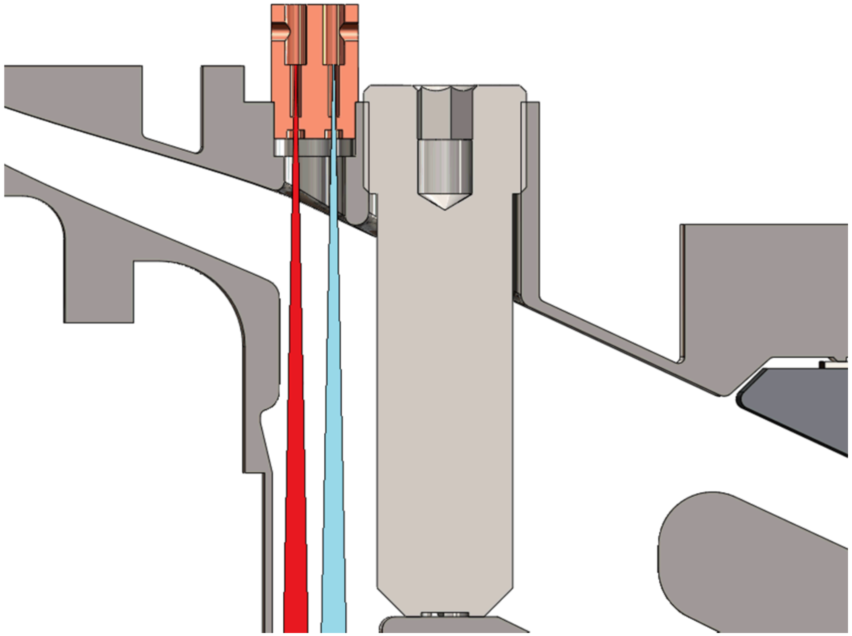


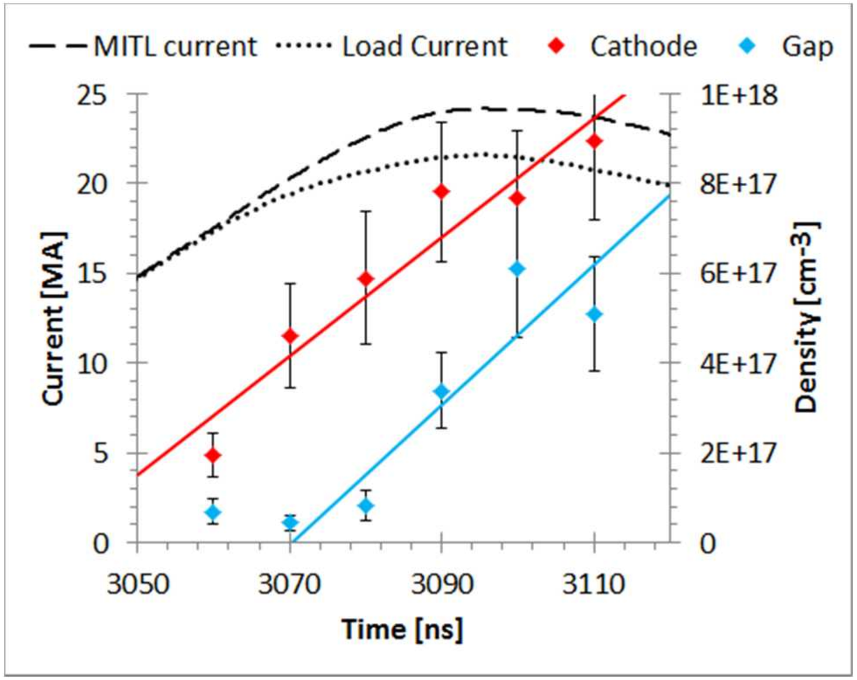
The H-alpha line profile was used to infer densities as high as 10^{18} cm^{-3}

Measurements from several shots were compared to estimate the plasma closure velocity based on continuum emission turn-on time



Spatially resolved measurements of plasma density in the convolute confirm high apparent closure velocities





The center to center distance for the two probes is ~ 4.4 mm

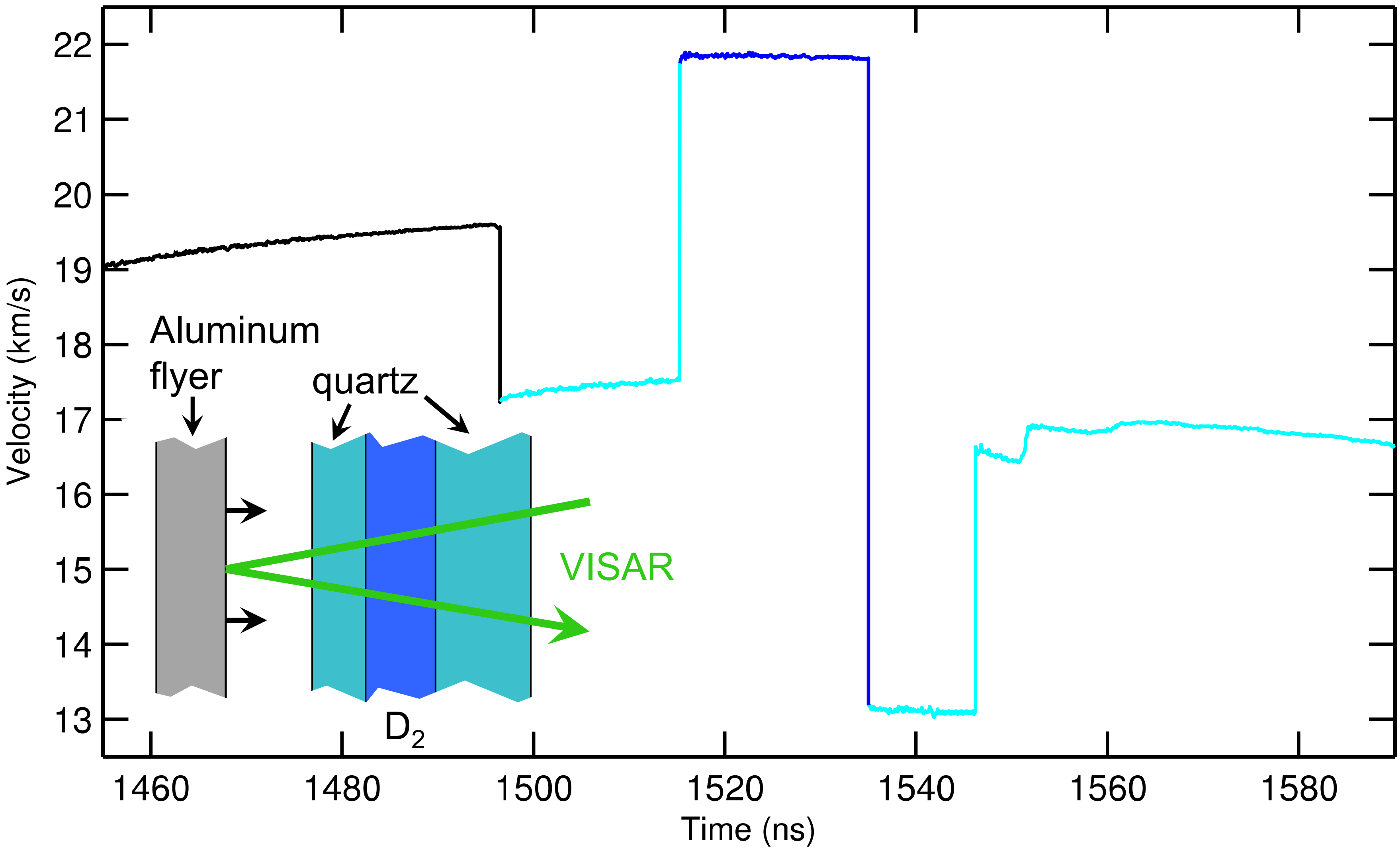
The density closer to the cathode leads the density in the gap by ~ 26 ns

The apparent closure velocity of the plasma is ~ 17 cm/μs

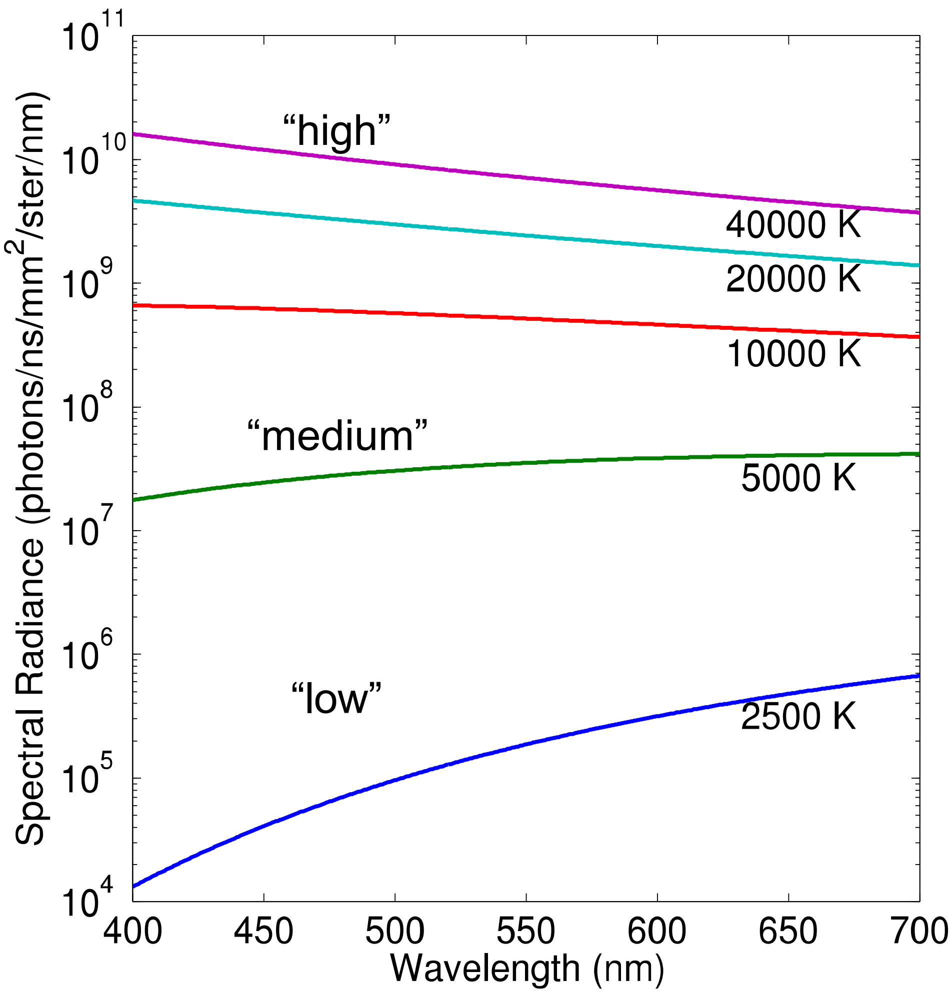
Measurement made on z2422

Temperature slides

VISAR was used to obtain precise flyer velocities and shock velocities in the D_2 and quartz



Streaked Pyrometry: Time dependent temperature measurement via blackbody emission from the sample.

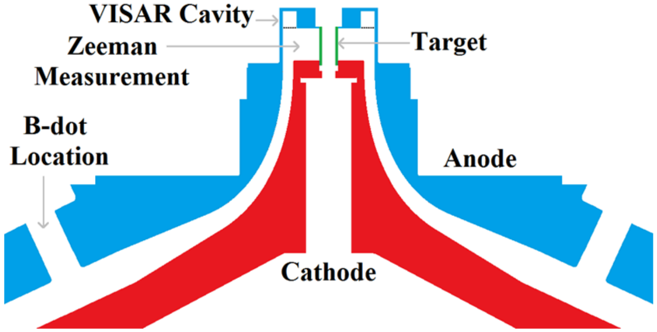


Planck's Blackbody Equation

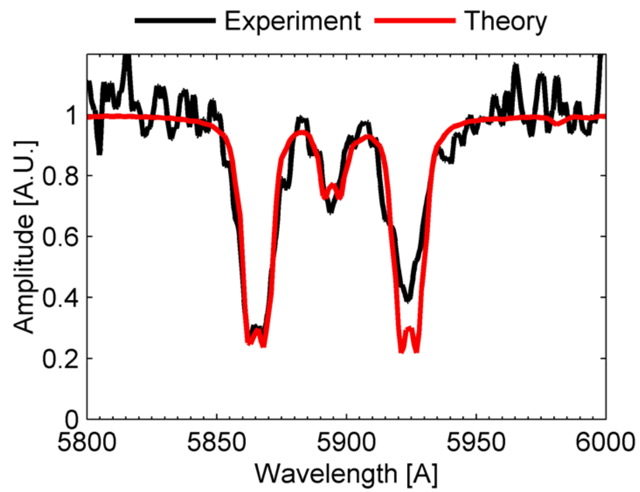
$$\frac{dL}{d\lambda} = \epsilon \times \frac{2hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)}$$

- High temperatures (>20,000 K)
  - -Minor spectral variation with T
  - -Ample signal levels
  - -Absolute calibration needed
- Moderate temperatures (<15,000 K)
  - -Modest spectral variation with T
  - -Reasonable signal levels
  - -Shape-based analysis feasible
- Low temperatures (<5000 K)
  - -Significant spectral variation with T
  - -Weak signals in the visible

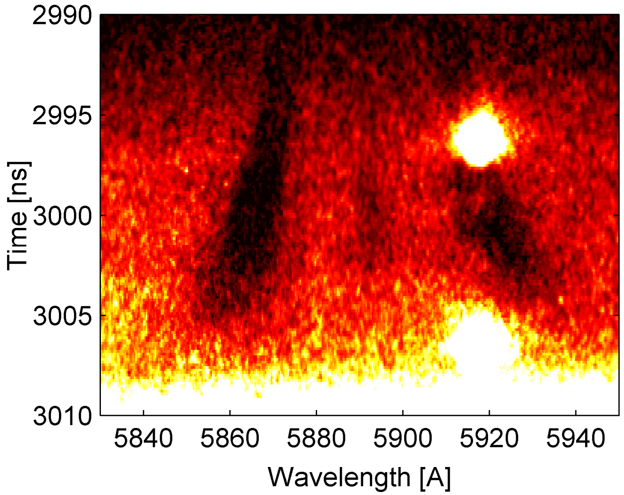
Sodium is used as a dopant to measure magnet field strength at the load via Zeeman splitting.



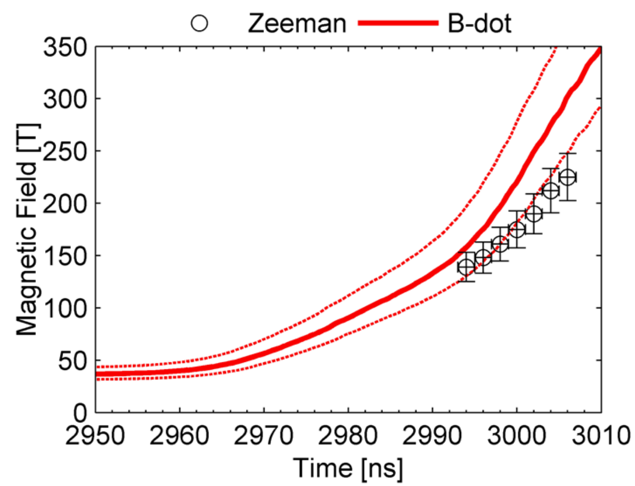
The load geometry fielded on a typical MagLIF experiment. B-dot measurements do not account for current losses at r < 6 cm.



Experimental spectrum averaged from 3000-3002 ns with the theoretically calculated spectrum, B = 180 T and a 25 degree angle between the magnetic field and diagnostic line of sight.



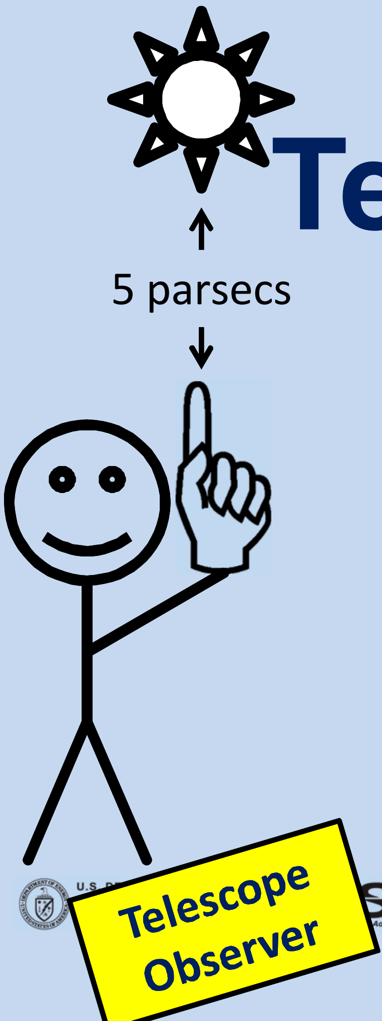
A streaked spectrum showing time-dependent Zeeman splitting in the sodium 3s-3p doublet.

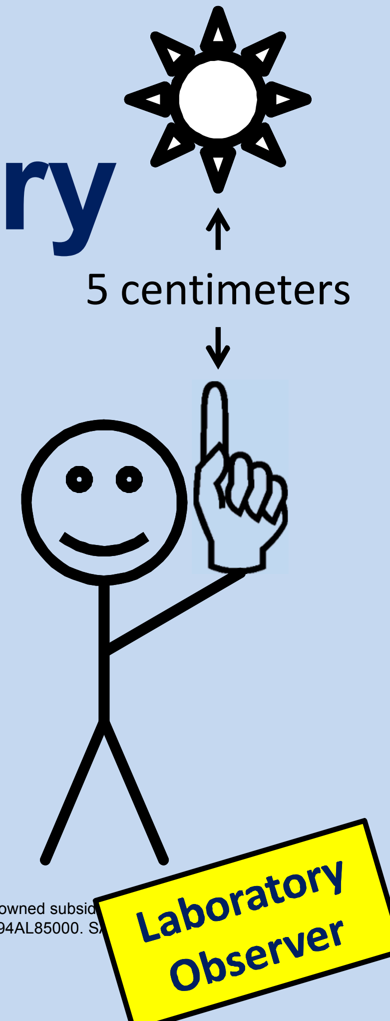


A plot of the magnetic field at the target surface measured spectroscopically and translated from the B-dot measurements.

Sandia National Laboratories

Creating and Measuring White Dwarf Photospheres in a Terrestrial Laboratory





Ross E. Falcon

University of Texas at Austin

Ph.D. Dissertation

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsid
Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. S

July 10, 2014 – Austin, TX

Nearly All Stars Are or Will Become White Dwarfs

- End point of stellar evolution for most stars, including our Sun
- Compact object
  - $\sim 2/3\ M_{\text{Sun}}$, $\sim 1\ R_{\text{Earth}}$
  - Electron degenerate core, stratified envelope
- Relatively simple
  - No nuclear fusion in core
  - Electron degeneracy pressure provides support against gravity
  - Star exponentially cools with time
  - Foundation for much more science

White Dwarf Atmospheric Parameters

- Effective temperature (T_{eff})
- Surface gravity (log g)
- Mass (M)
- Composition

Cosmochronology

Image: FORS, 8.2-m VLT Antu, ESO

Type Ia Supernovae

Illustration: David A. Hardy, PPARC

Asteroseismology

Nuclear Fusion

Intergalactic Distances

Dark Matter

Image: *NASA / A. Fruchter / STScI*

EOS

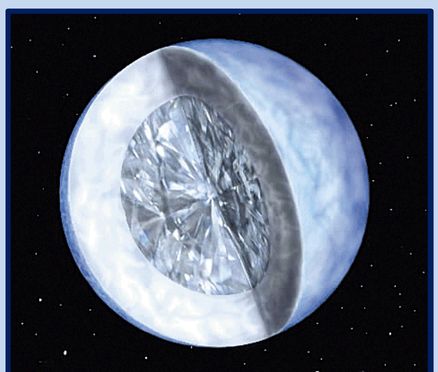
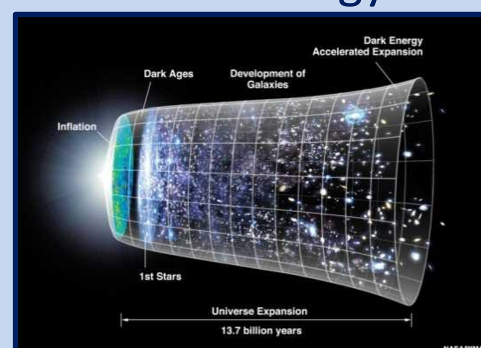


Illustration: Harvard-Smithsonian Center for Astrophysics/Travis Metcalfe, Ruth Bazinet

Dark Energy



Graphic: *NASA / WMAP*

Fit Spectral Lines to Infer WD Atmospheric Parameters

- Compare observed spectra with synthetic spectra from WD atmosphere models
- The *spectroscopic method* (see, e.g., Bergeron et al. 1992) is:
  - Precise
    - $\delta T_{eff}/T_{eff} \sim 5\%$
    - $\delta \log g / \log g \sim 1\%$
  - Widely-used; more than 30,000 WDs
    - Palomar-Green Survey
    - Sloan Digital Sky Survey
    - SPY
    - HETDEX

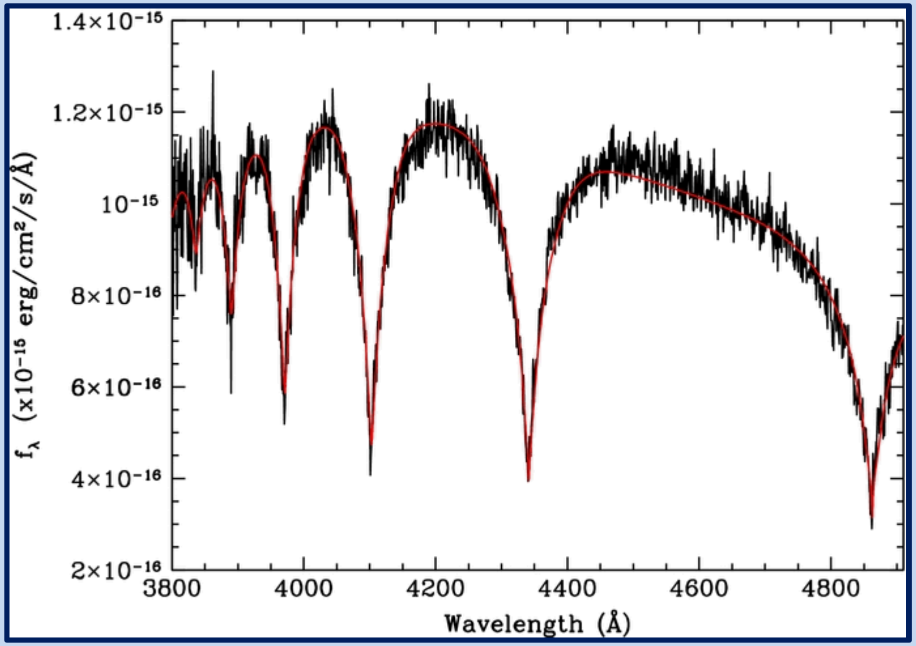
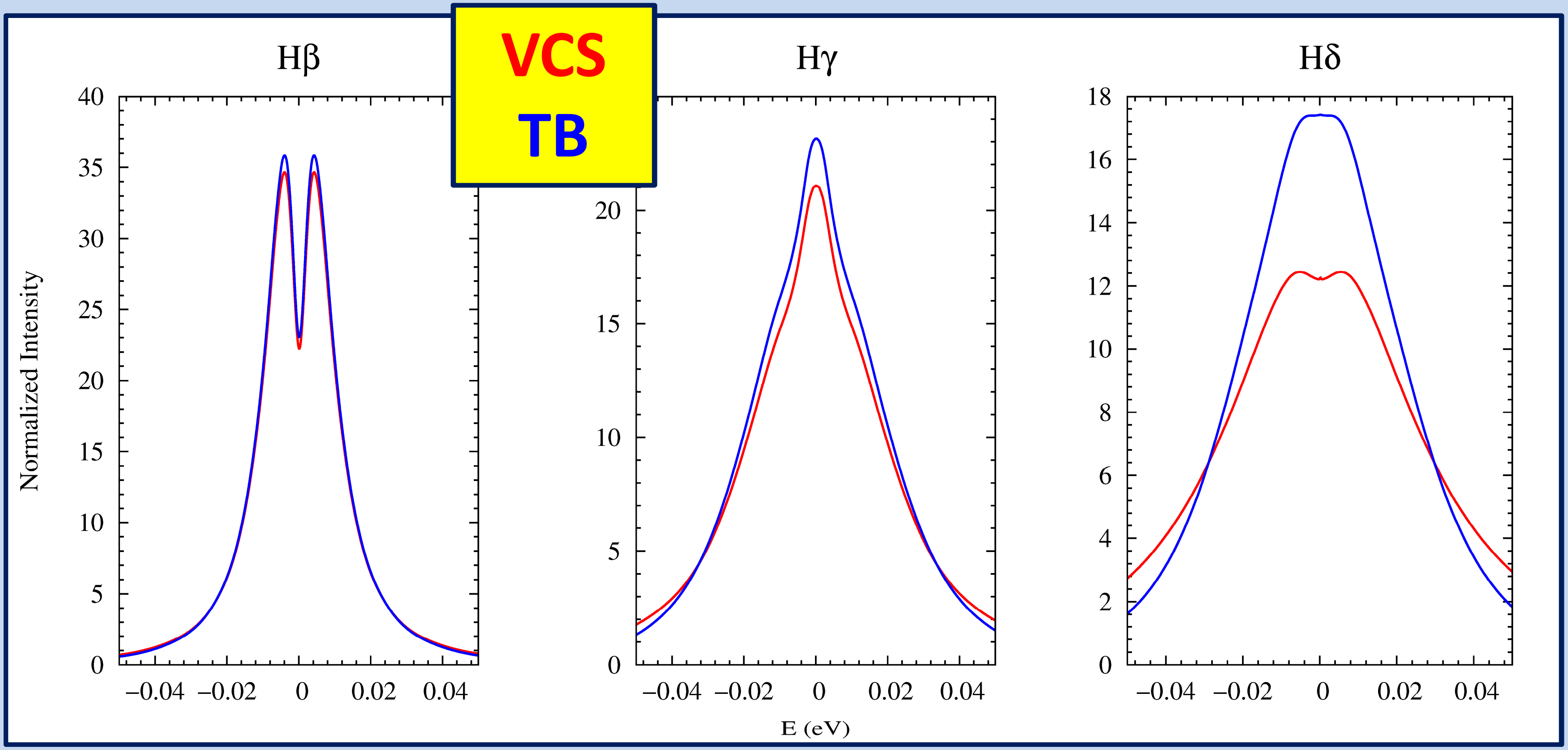


Figure from Hermes et al. (2011): KPNO spectrum of WD J1916+3938

Are the Line Profiles Used in WD Atmosphere Models Accurate?

- VCS and TB profiles disagree with increasing quantum number n and with increasing electron density n_e



Calculated at T_e = 1 eV and $n_e = 10^{17}$ cm^{-3}

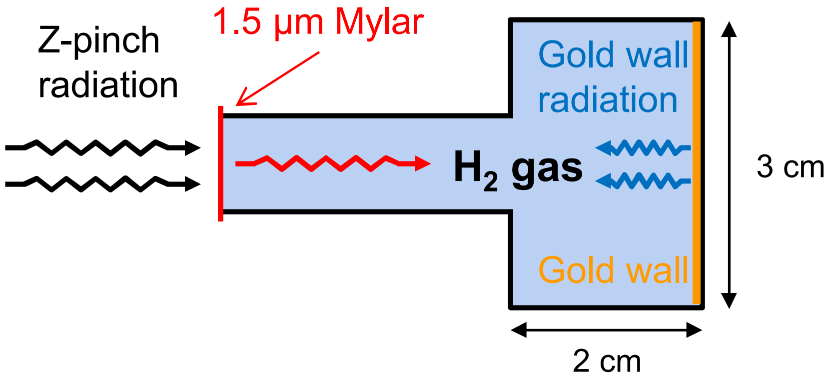
New Line Profiles Give Larger Inferred Masses

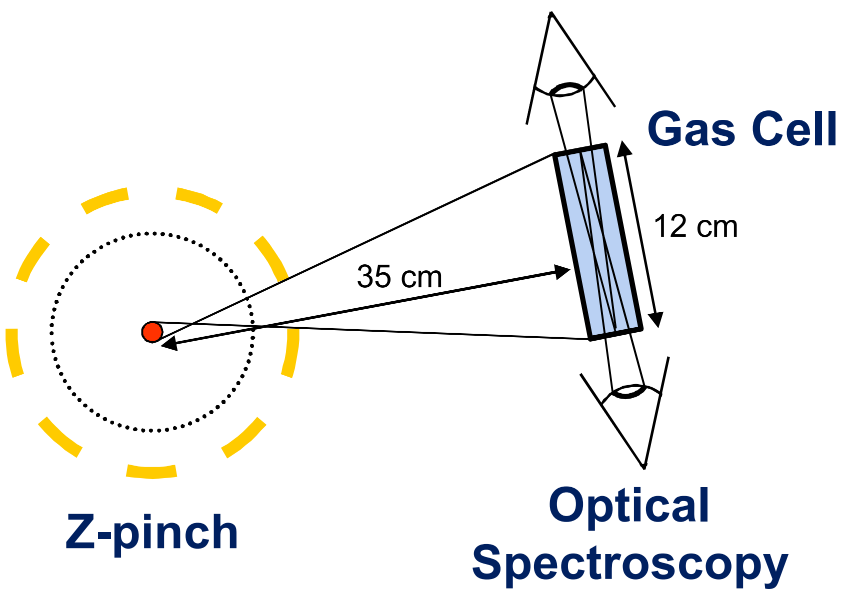
- New Stark broadened H line profiles (Tremblay & Bergeron 2009) result in systematic increases:
  - $\Delta T_{\mathrm{eff}} \sim 200 - 1000$ K
  - $\Delta \log g \sim 0.04 - 0.1$
  - $\Delta M \sim 0.03\ M_{\mathrm{sun}}$
  - For 250 WDs from the Palomar-Green Survey
- In WD community, Tremblay & Bergeron line profiles now replace Vidal, Cooper, & Smith (1973; VCS) profiles as tabulated by Lemke (1997)

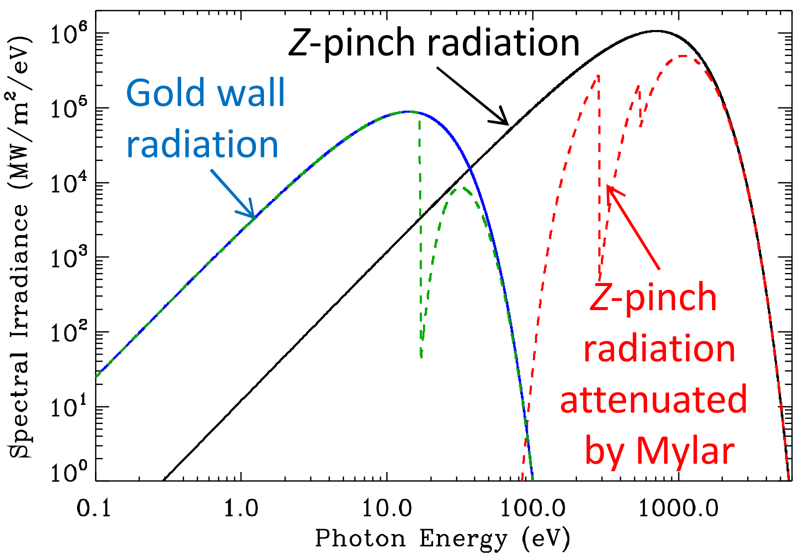
Investigation of White Dwarf Photosphere utilizes Z-pinch radiation to heat Au wall to excite H_2 gas.

- Z-pinch x-rays uniformly irradiate gold wall in gas cell
- Gold wall radiation couples well to hydrogen gas to heat through photoionization
- Total particle density set by initial fill pressure

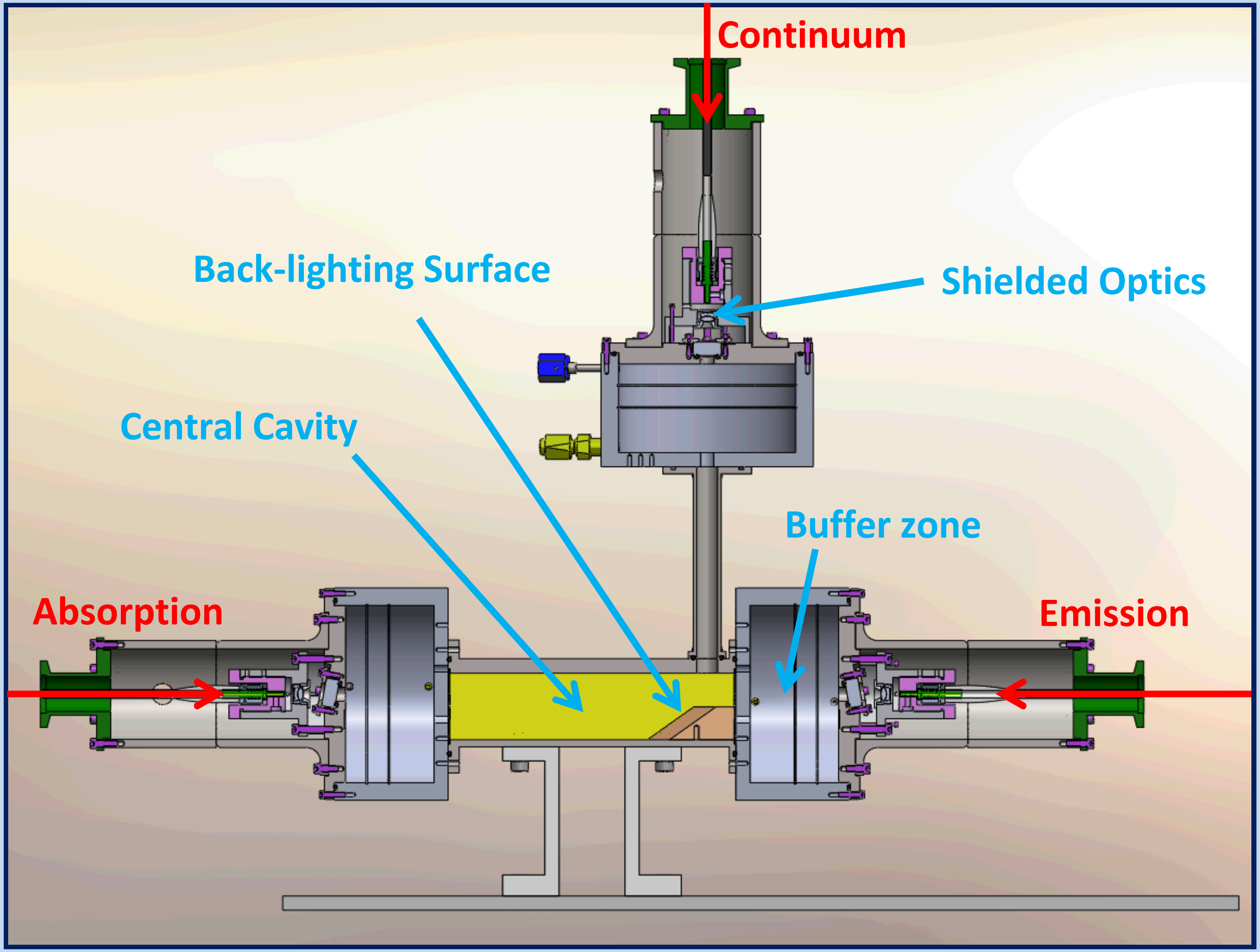
Cross-section of Gas Cell





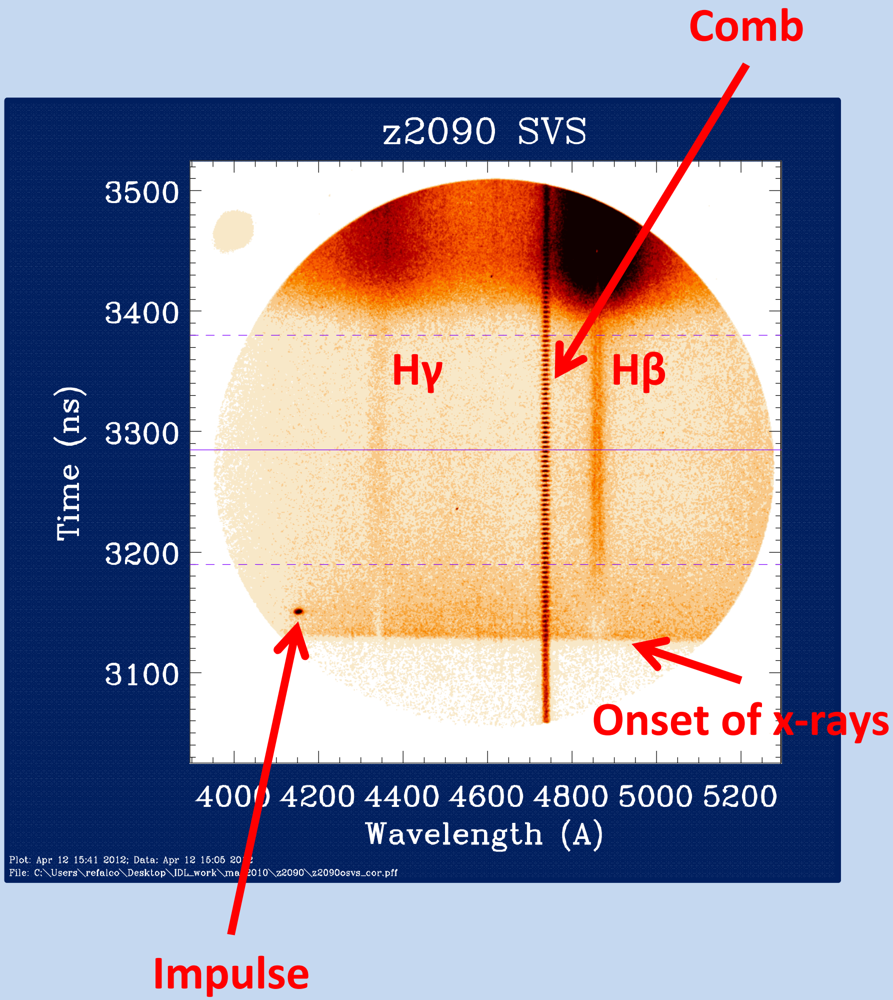


Back-lighting Surface Allows Absorption Measurements

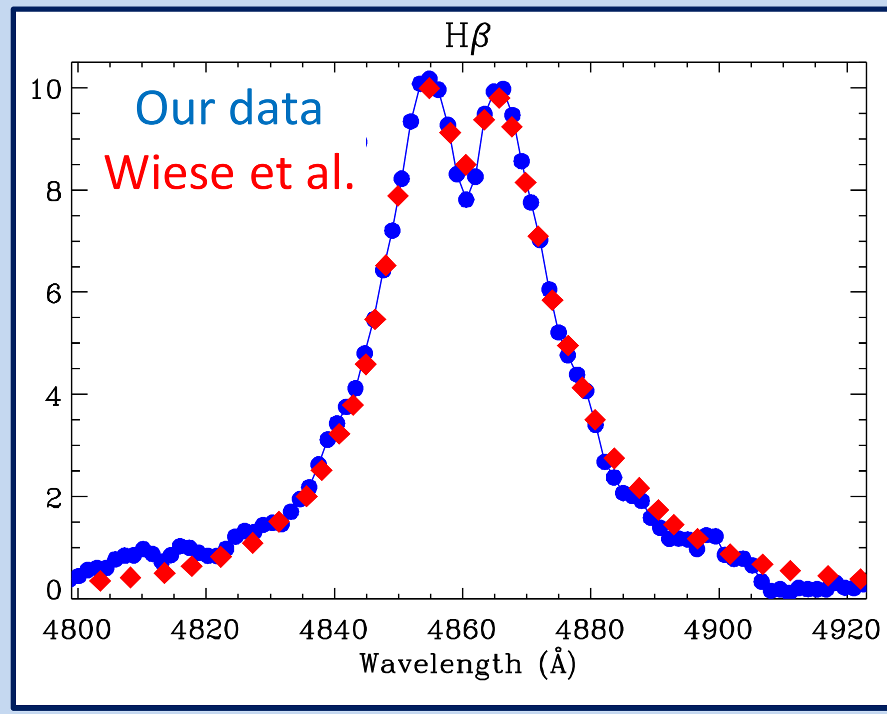



SF6 SUPPLY
MARX RETURN

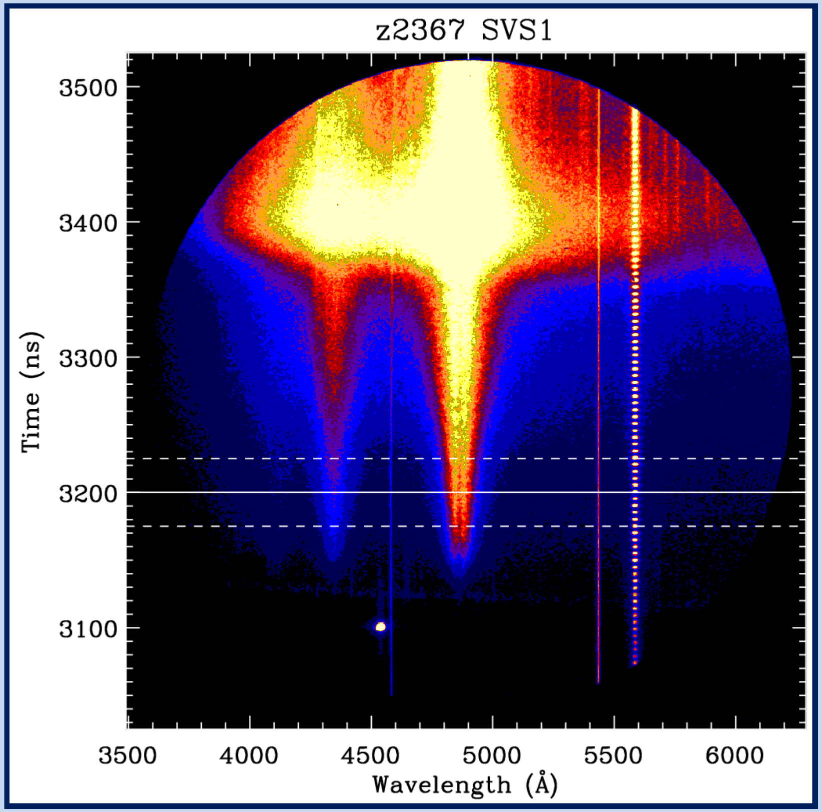
Hβ Emission Line Agreement with Wiese et al. Shows We Achieve Desired Conditions

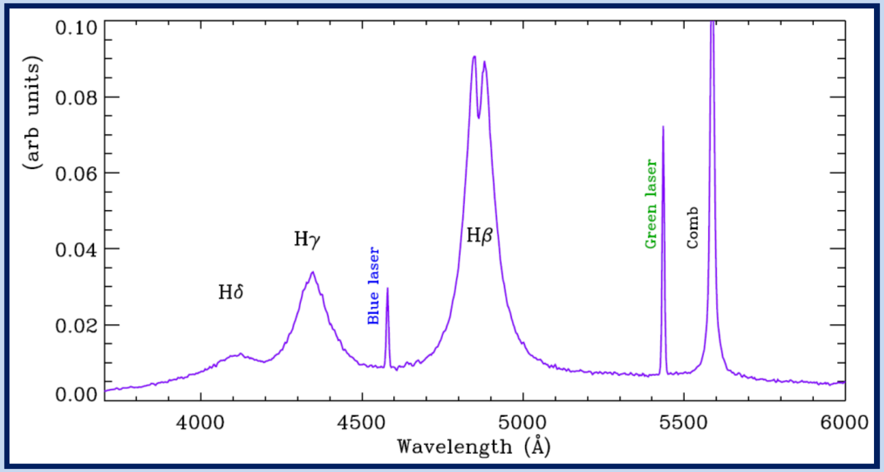


n_e = 5.7e16 cm^{-3}

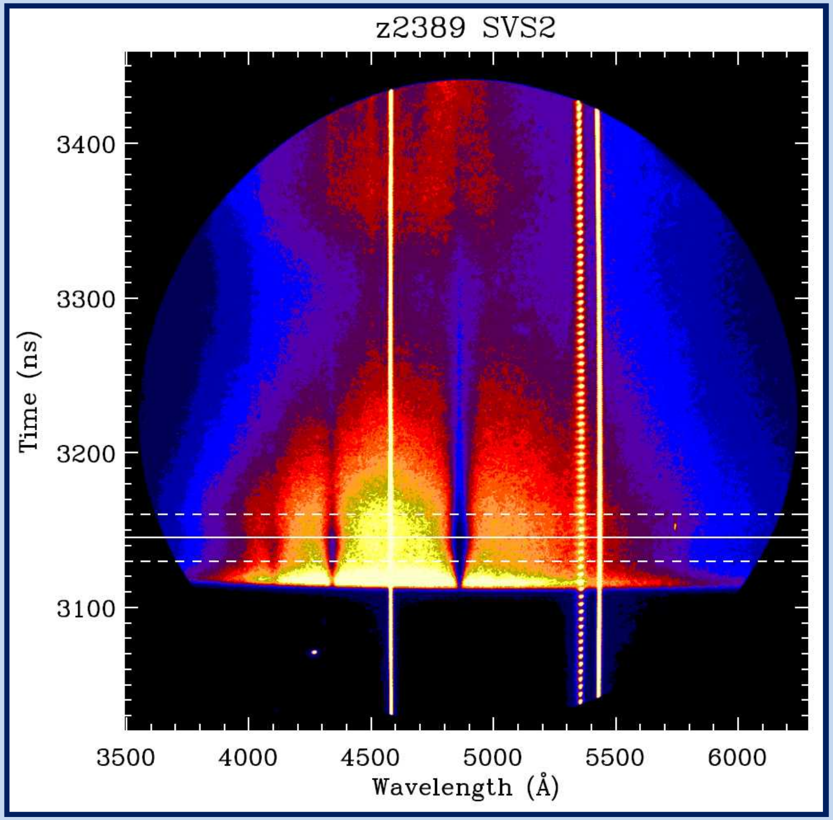


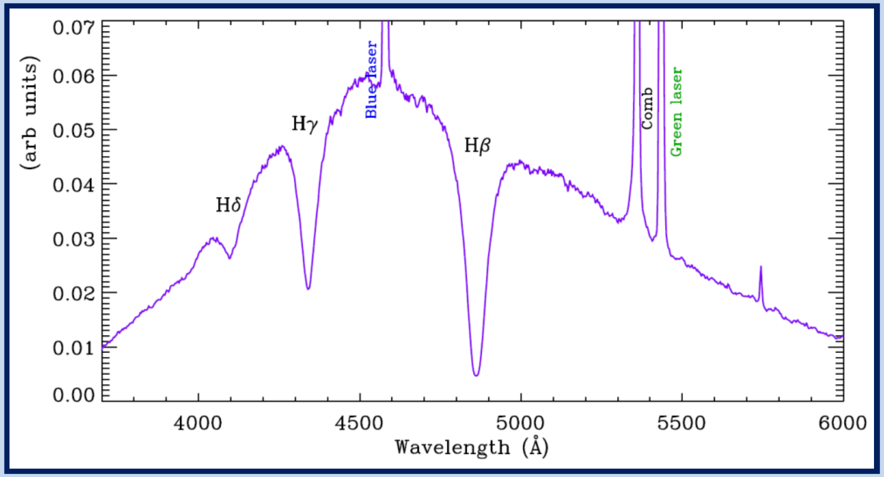
Emission



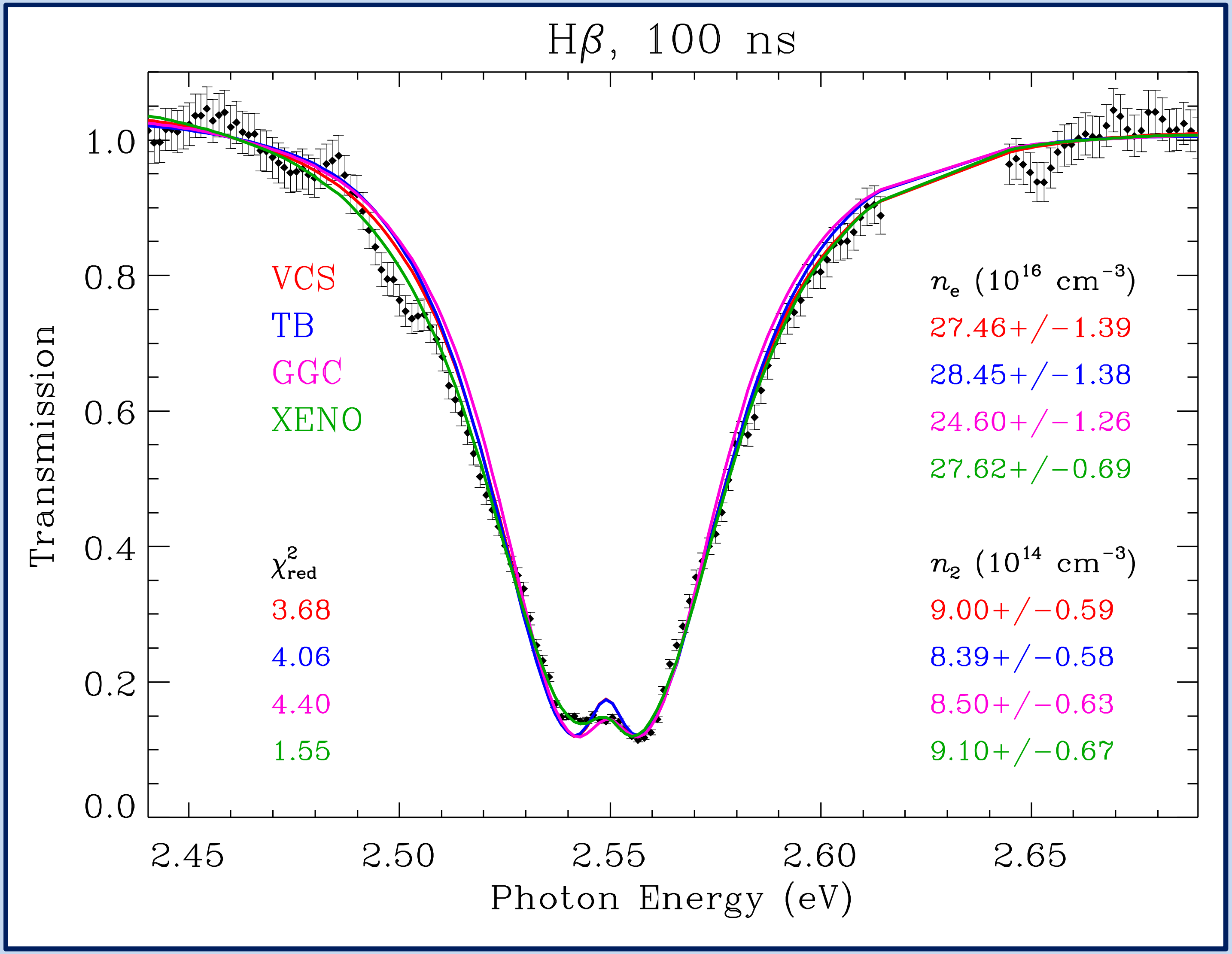


Absorption

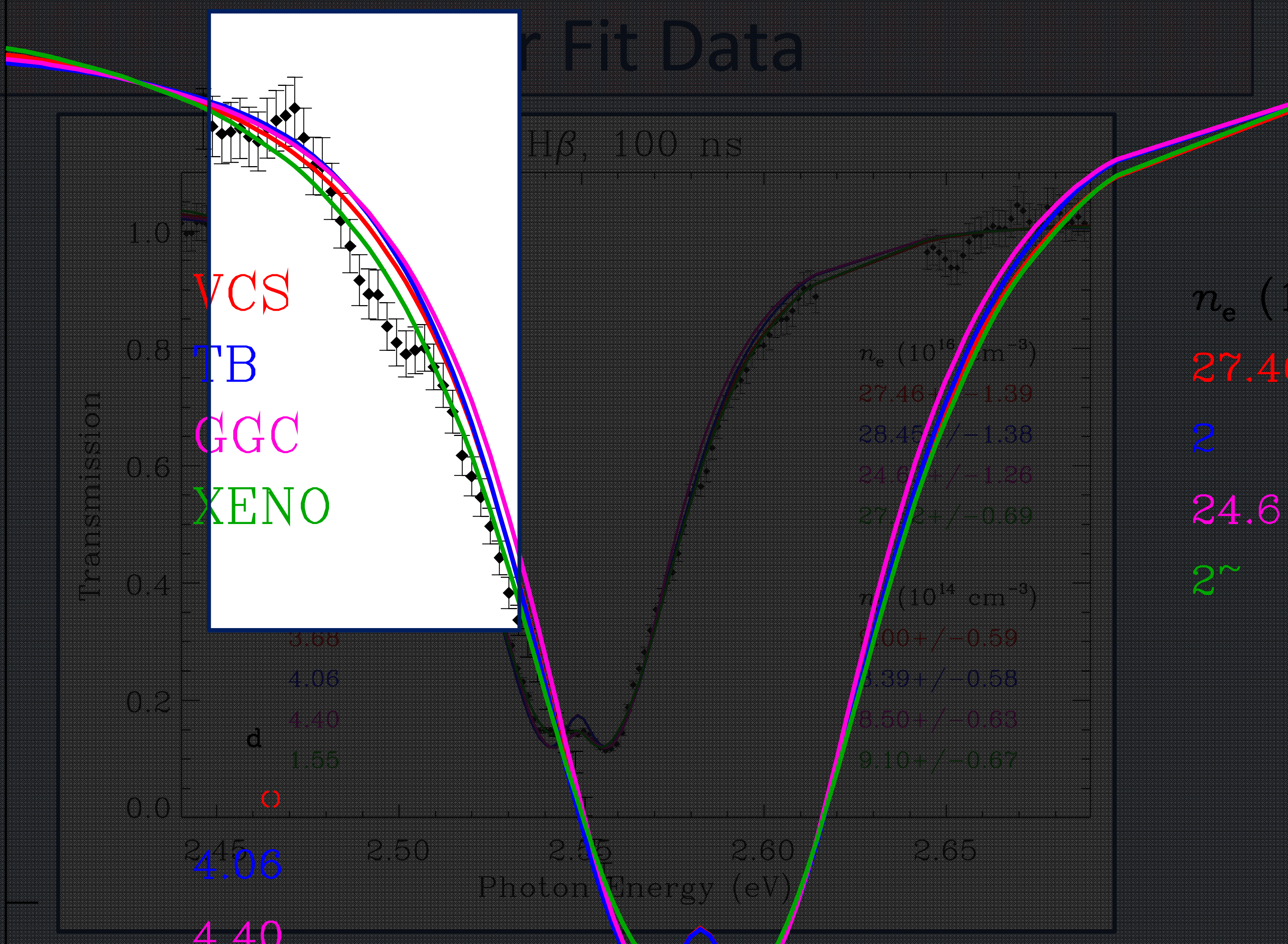




Xenomorph (Thomas Gomez) Profiles Better Fit Data

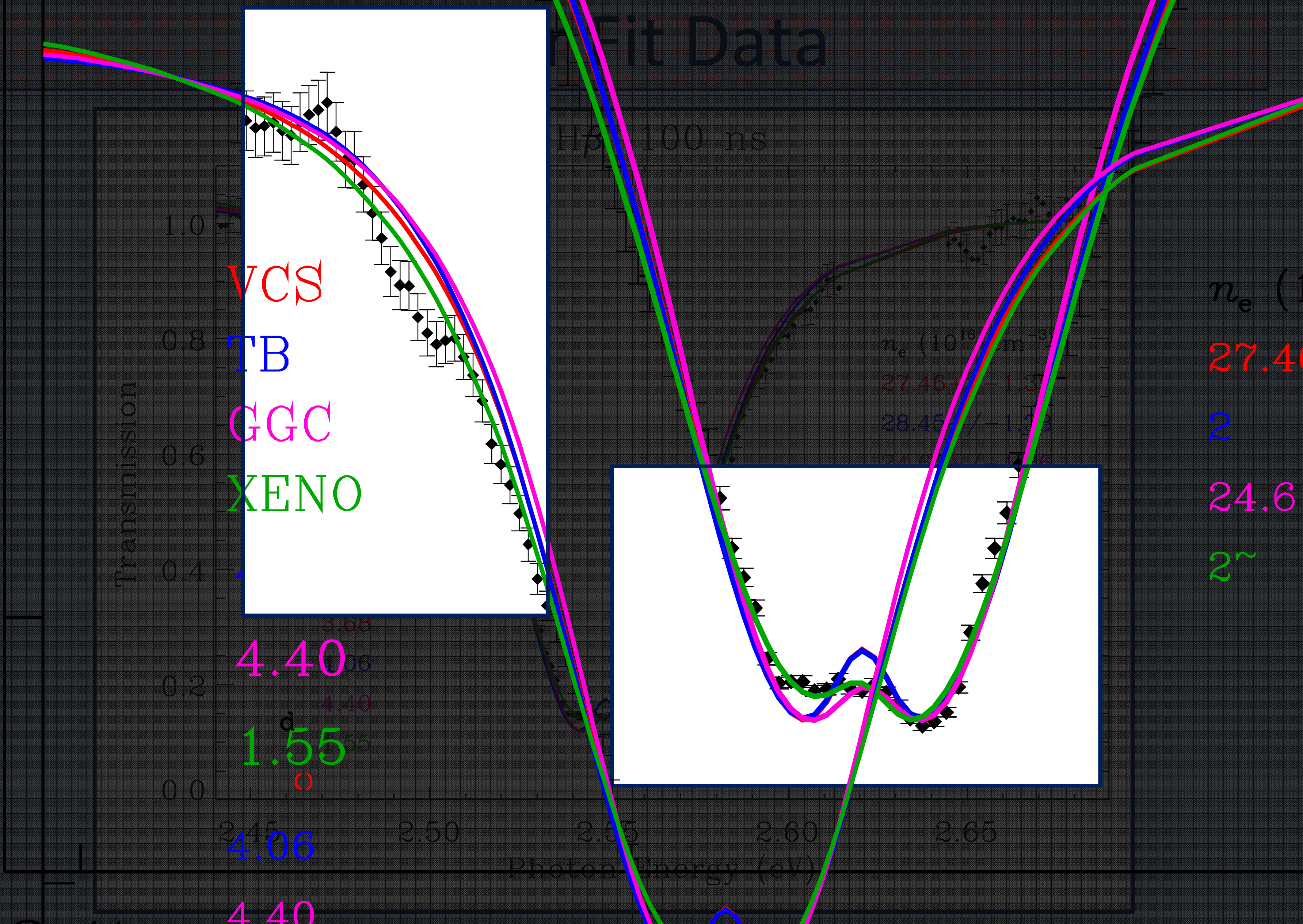


Xenomorph (Thomas Gomez) Profiles
r Fit Data



Xenomorph (Thomas Gomez) Profiles

Fit Data




DuPont™
Tyvek

Summary

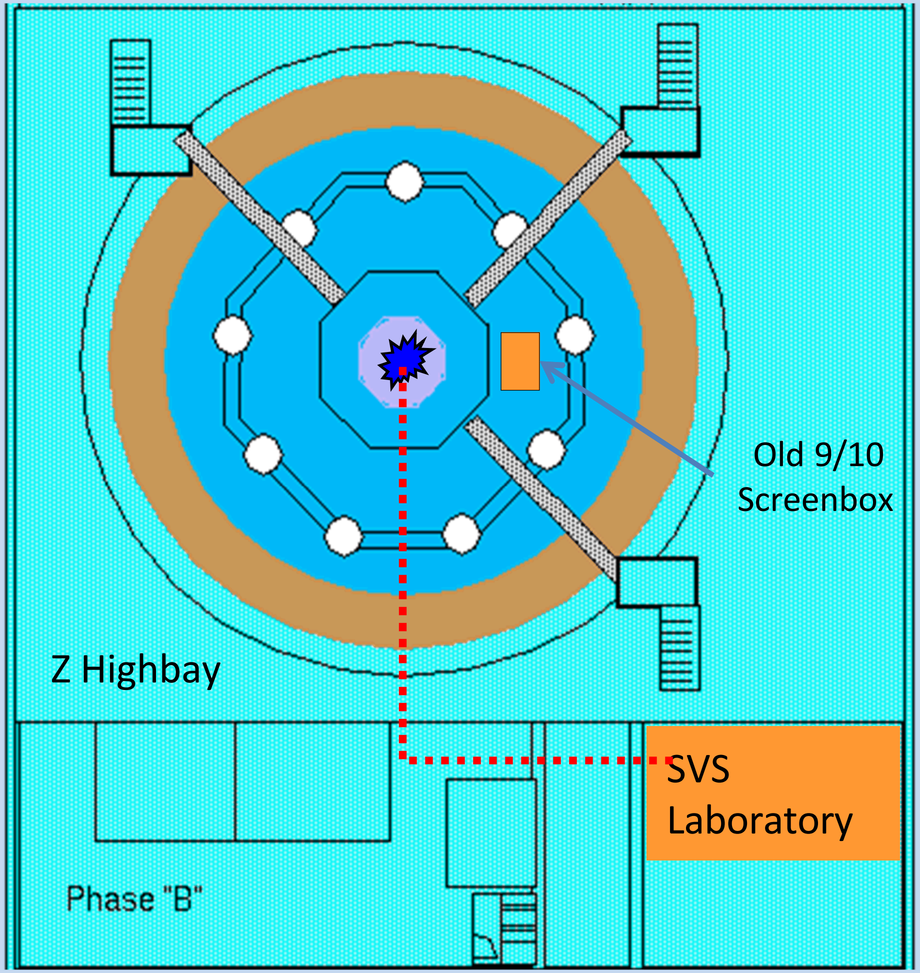
- Using gravitational redshifts, we measure a larger WD mean mass than that from the spectroscopic method
- We develop an experimental platform to probe WD photospheres
  - We measure relative line shapes and strengths of hydrogen plasmas

Conclusions (So Far) from Line Shape Comparisons

- Theoretical line profiles used in WD atmosphere models do not fit the detailed shape of our measured Hβ transmission at $n_e > 10^{17}$ cm^{-3}
  - They fit the width sufficiently to recover n_e
  - Line profiles with asymmetries (Xenomorph) fit best and should be tested in WD atmosphere models (since observed WD spectra also show asymmetric absorption lines)

- Assuming our Hβ transmission measurement is accurate, no theoretical line profile successfully calculates Hγ

- We measure better agreement between the relative calculations of Hδ and HY than we do between HY and Hβ
  - In other words, Hδ matches our measurements better when calculated using plasma conditions inferred from Hγ than from Hβ


Old 9/10
Screenbox
Z Highbay
SVS
Laboratory
Phase "B"

Recent experiments confirmed previous results and provided information about azimuthal symmetry of plasma

- Convolute plasma consists of hydrogen and carbon contaminants desorbed from the electrodes
- Plasma densities between 10^{16} cm^{-3} and 10^{18} cm^{-3} are observed in the convolute
- Apparent closure velocities on the order of 10s of cm/μs have been observed
- The convolute plasma appears to form symmetrically at each post