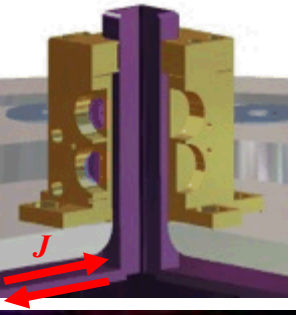
SAND2014-15940PE



Diagnostic Capabilities for Planetary Science Experiments on Z

T. Ao, D. H. Dolan, and C. T. Seagle

Sandia National Laboratories

Sandia National Laboratories

Exceptional service in the national interest

Fundamental Science with Pulsed Power: Research Opportunities and User Meeting

July 21-23, 2014

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

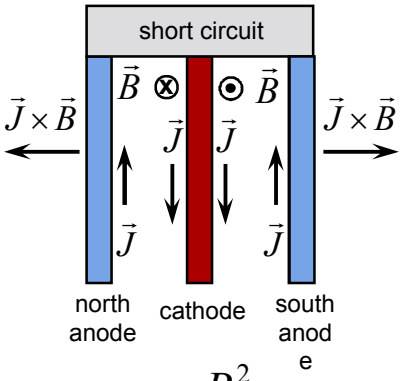
Outline

Sandia National Laboratories

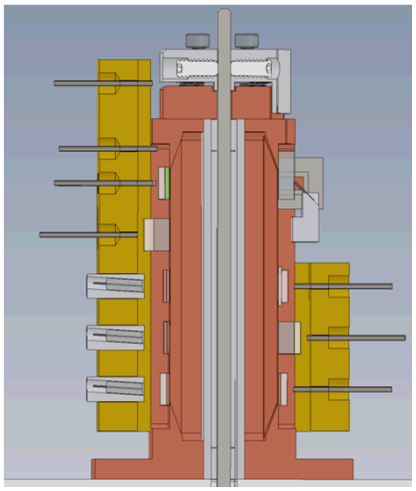
- Z – DMP (Dynamic Material Properties) experiments
  - Planar
  - Cylindrical
- Velocimetry
  - VISAR (Velocimetry interferometry for any reflector)
  - PDV (Photonic Doppler velocimetry)
- Streaked Visible Spectroscopy (SVS)
  - Pyrometry (emission)
  - Reflectance
- X-ray
  - Radiography
  - XRTS (X-ray Thomson scattering)
- Future developments

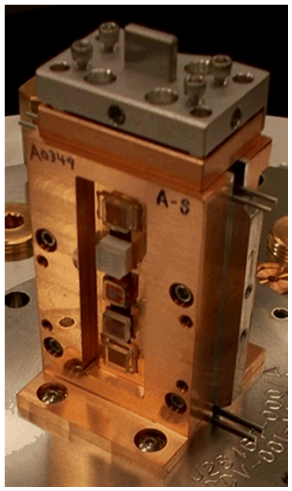
Z – Planar experiments

- Coaxial load[1]
  - Cathode stalk surrounded by anode panels
  - Dual pressures possible on north and south panels
  - Enclosed magnetic fields
  - More sample locations
  - Optimal for (flyer plate) shock compression

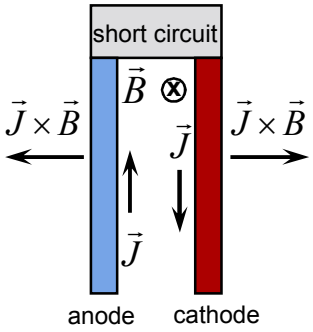


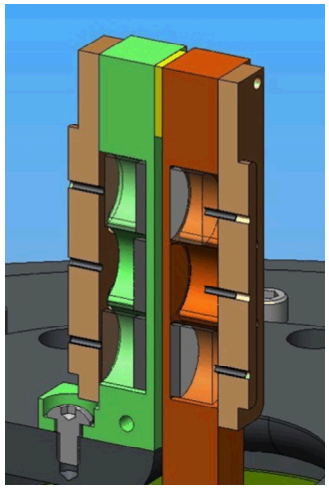
$$P = \frac{B^2}{2\mu_0}$$





- Stripline load[2]
  - Identical pressure on both cathode and anode panels
  - Higher current density and pressure
  - Open magnetic fields
  - Optimal for high-pressure ramp compression



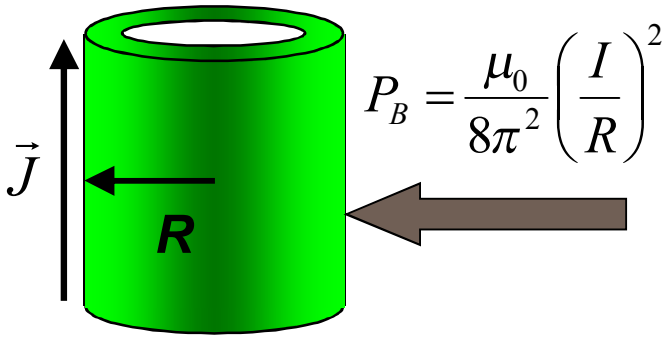


[1]M. D. Knudson *et al.*, J. Appl. Phys. **94**, 4420 (2003)

[2]R. W. Lemke *et al.*, Int. J. Impact Eng. **38**, 480 (2011)

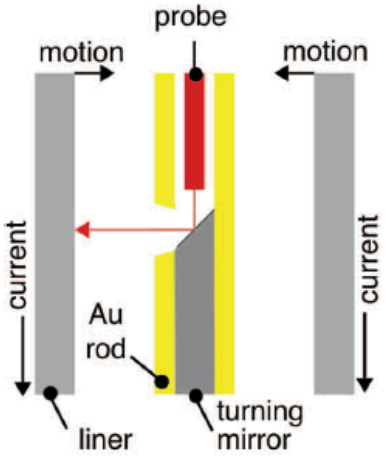
Z – Cylindrical experiments

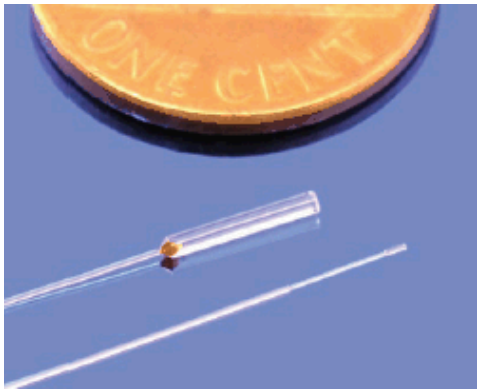
- Cylindrical implosion reaches extreme pressure states[1]
  - Current pulse shaping creates ramp-wave compression
  - Quasi-isentropic compression to 20 Mbar



$I = 20$ MA
$R = 1$ mm
$P_B \approx 64$ Mbar

- Diagnostics are challenging
  - Limited space
    - Miniature probes
  - Velocities well beyond 10 km/s

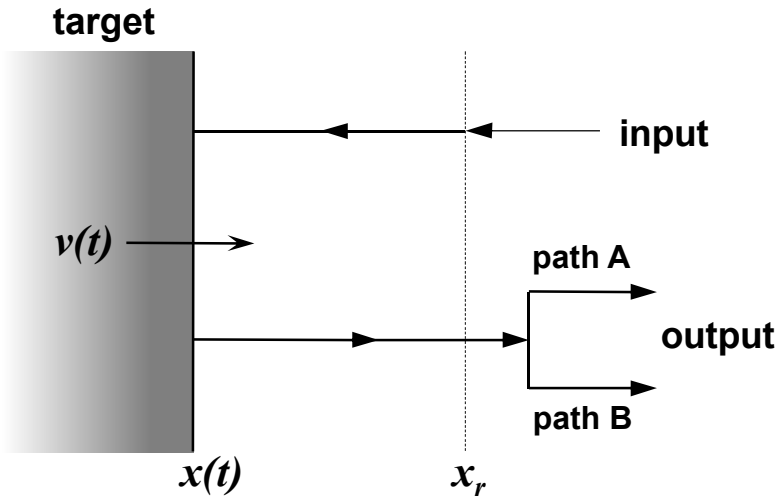




[1]R. W. Lemke *et al.*, AIP Conf. Proc. **1426**, 47 (2012)

VISAR
(Velocimetry Interferometry System for Any Reflector[1])

- Doppler shifted light from a moving target split along two different paths
  - i.e. reference leg and delay leg of interferometer
- Measured signal[2]: $s(t) = aI_A(t) + bI_B(t) + 2\sqrt{abI_A(t)I_B(t)}\cos[2\pi F(t)]$
  - Fringe shift directly proportional to target velocity: $F(t) = \frac{\Phi(t) - \Phi_i(t)}{2\pi} \approx \frac{v}{K}$
- Details of operation
  - Sensitive to intensity variations of reflected target light
  - Requires additional system to resolve fringe jump ambiguities

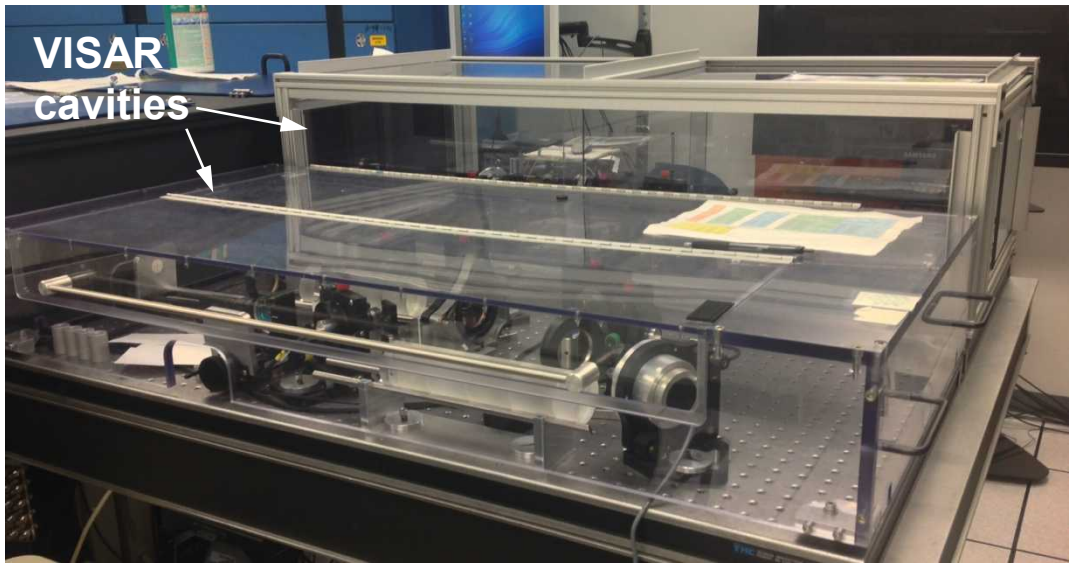


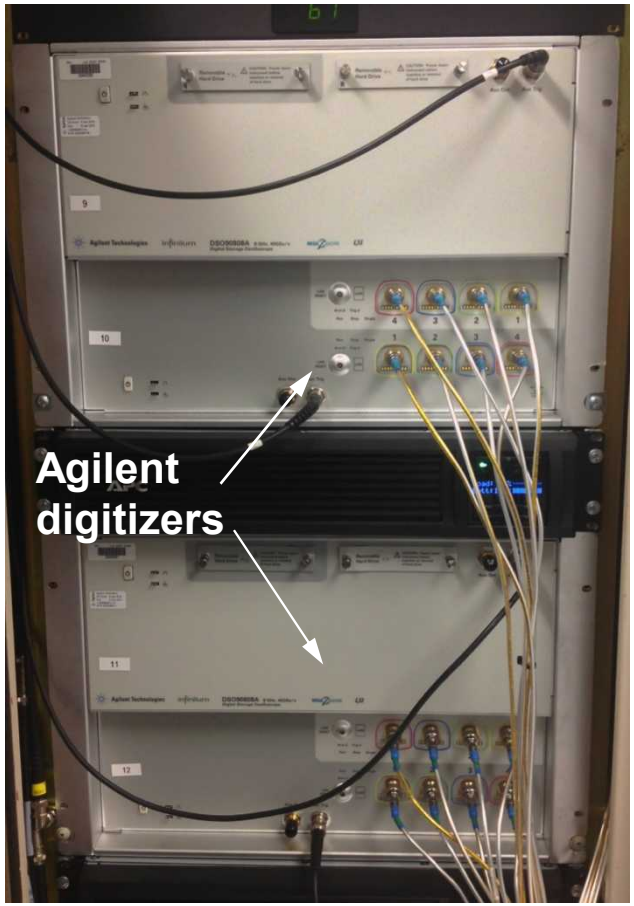
[1]L. M. Barker and R. E. Hollenbach, J. Appl. Phys. **43**, 4669 (1972)

[2]D. H. Dolan, SAND2006-1950 (2007)

VISAR capabilities on Z

- Two VISAR systems (fast push-pull[1])
  - Each system dual VPF: (0.229 – 11.28) km/s/f; (0.932 – 14.52) km/s/f
  - Total of 38 channels, 3 GHz detectors
  - Agilent digitizers: 8 GHz, 40 GS/s (25 ps resolution)
  - Timing characterization
    - < 200 ps uncertainty between VISAR channels
    - ~ 200 ps uncertainty to machine time
  - Pulsed laser: 532 nm, 5 us, ~20 kW

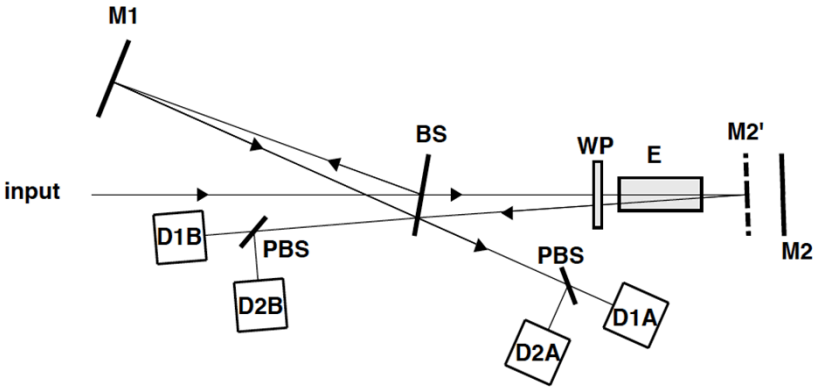


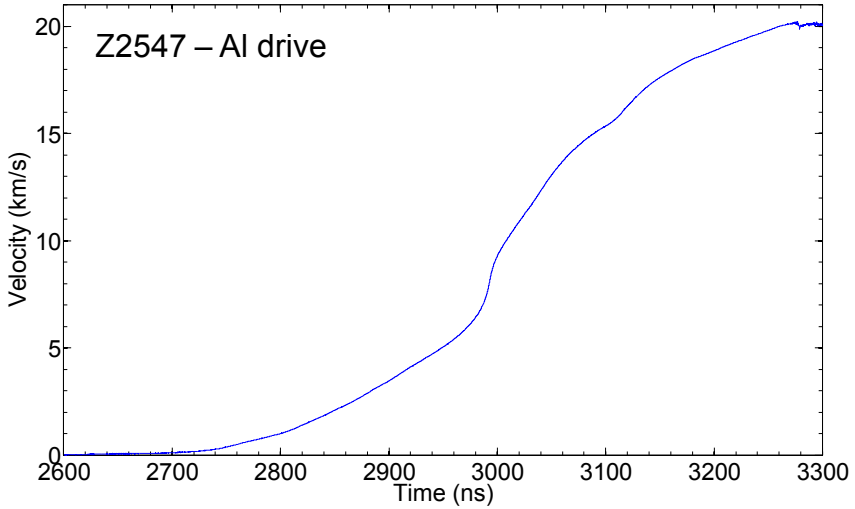


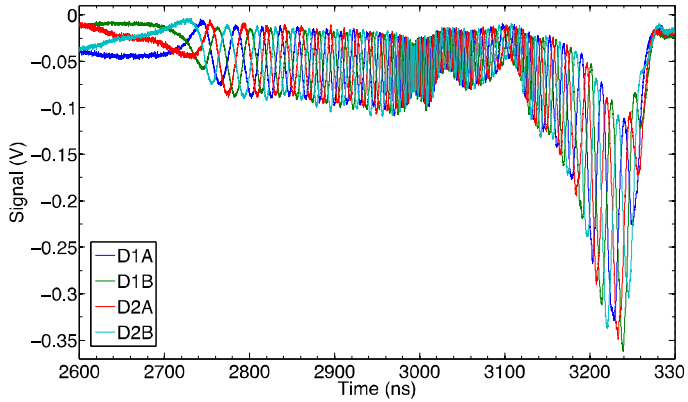
[1]B. Marshall, NSTec-STL (2004)

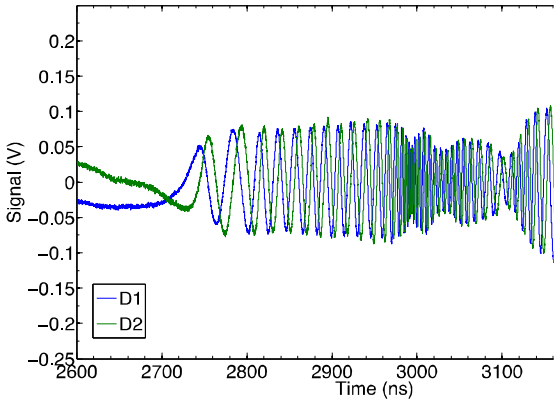
VISAR is the primary and most established diagnostic for Z – DMP experiments

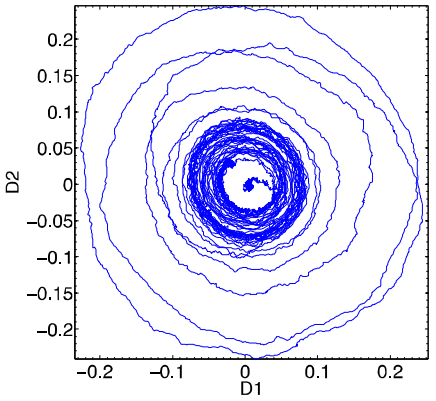
- Push-pull VISAR[1,2]
  - 4-channels: D1A, D1B; D2A, D2B









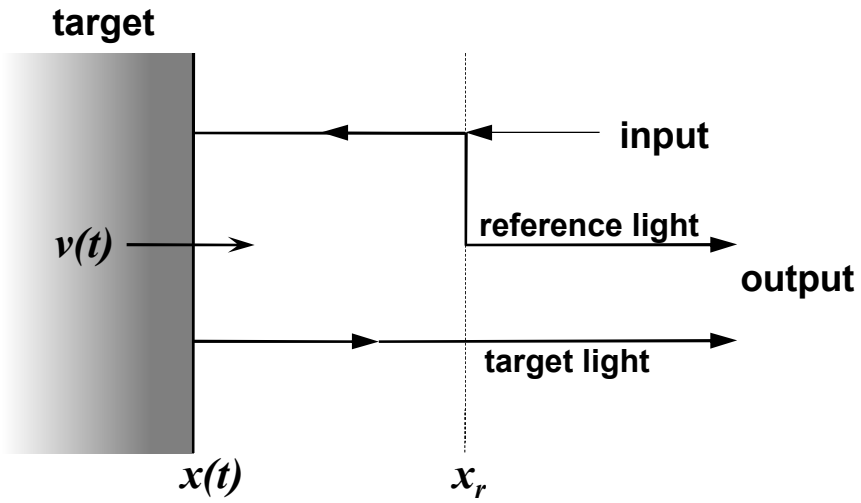


[1]W. F. Hemsing, Rev. Sci. Instrum. **50**, 73 (1979)

[2]D. H. Dolan, SAND2006-1950 (2007)

PDV (Photonic Doppler Velocimetry[1])

- Doppler shifted light from a moving target combined with unshifted light
  - "Heterodyne velocimetry"
- Measured signal[2]: $s(t) = aI_R(t) + bI_T(t) + 2\sqrt{abI_R(t)I_C(t)}\cos\left[\Phi(t_i) + 4\pi\frac{x(t) - x(t_i)}{\lambda_0}\right]$
  - Beat frequency proportional to velocity: $B = \frac{2v}{\lambda_0}$
- Details of operation
  - Readily available components
    - Infrared fiber-based (1550 nm)
    - Fast detectors; GHz digitizers
  - Insensitive to intensity variations of reflected target light
  - Resolve multiple velocities
  - Simple assembly and operation
  - Lack of intrinsic delay time

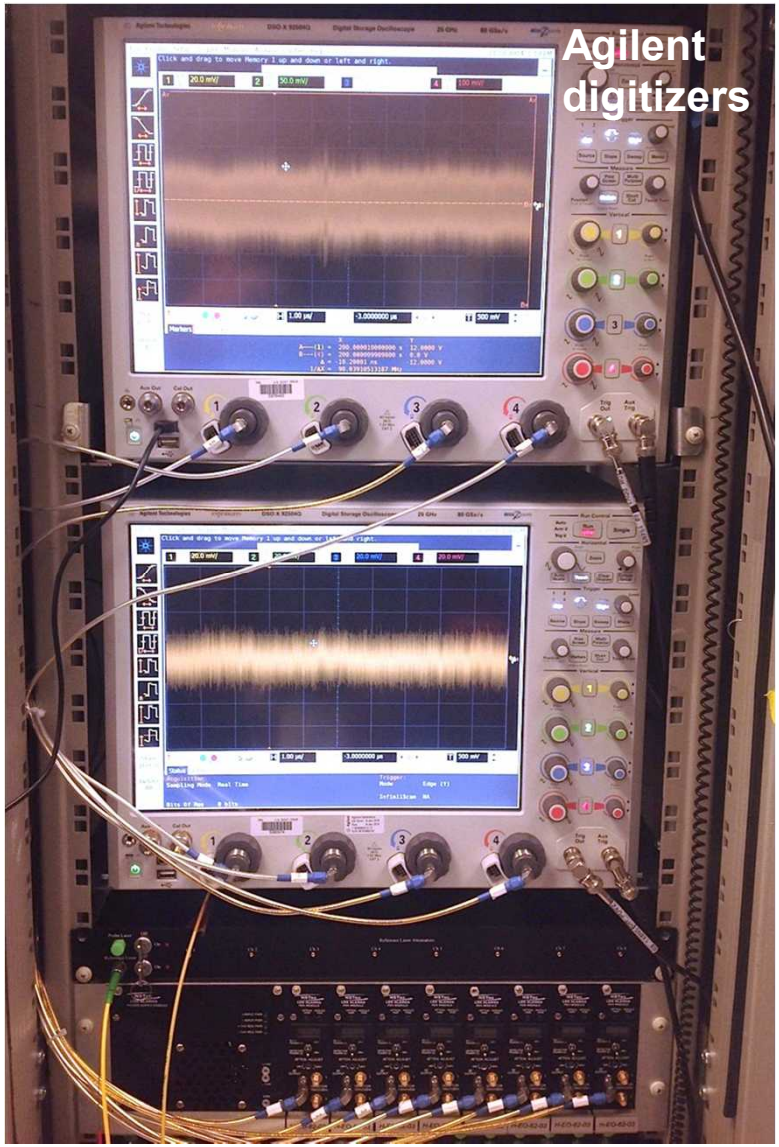


[1]O. T. Strand *et al.*, Rev. Sci. Instrum. **77**, 083108 (2006)

[2]D. H. Dolan *et al.*, Rev. Sci. Instrum. **81**, 053905 (2006)

PDV capabilities on Z

- Electrical bandwidth
  - Eight 20 GHz Miteq detectors
  - Two (4 channel) 25 GHz Agilent digitizers at 80 GS/s (12.5 ps resolution)
    - Covers up to 19.4 km/s
- Fiber lasers (1550 nm, CW)
  - One amplified laser at fixed wavelength
    - Tunable seed + EDFA or 2 W system
  - Several adjustable reference lasers
    - 25-50 mW output
    - Fast tuning over 1550-1551 nm
- Other
  - Wavelength monitoring to ~ 0.1 pm
  - Timing characterization
    - < 100 ps uncertainty between PDV channels
    - ~ 200 ps uncertainty to machine time



Velocity-frequency mapping of PDV

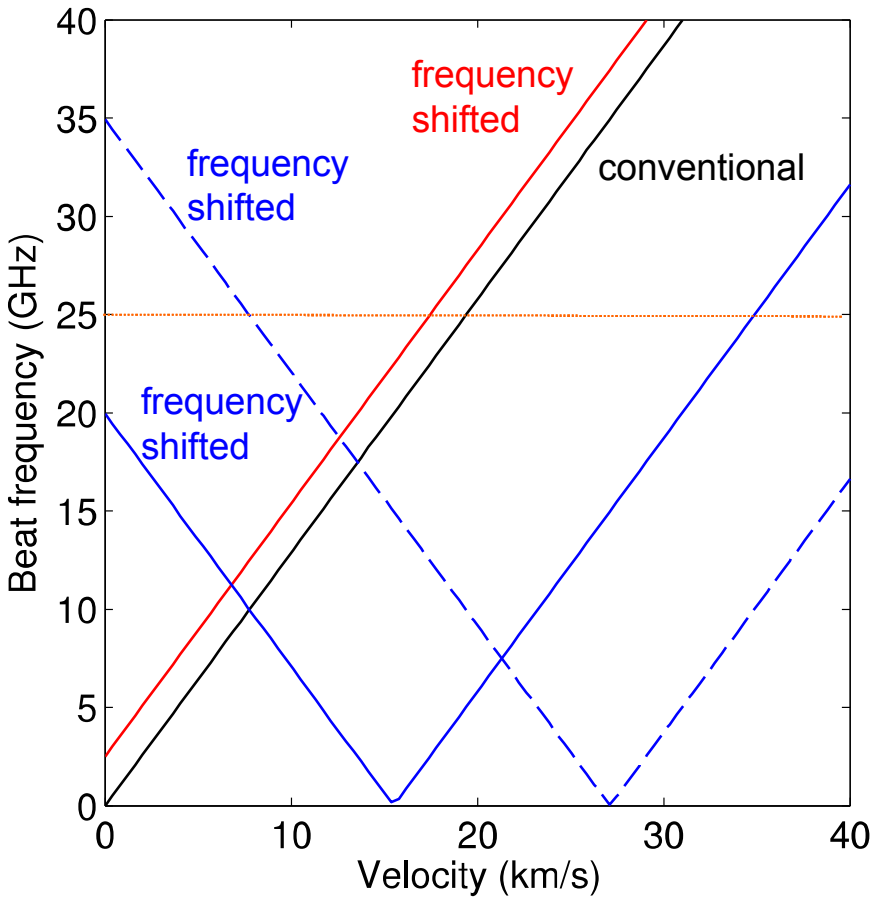
- Conventional PDV
  - No motion, no beating
    - Not currently used at Z
  - Velocity limited by bandwidth
    - 1 km/s requires 1.29 GHz at 1550 nm
    - 40 km/s requires 51.6 GHz!

$$B = \frac{2v}{\lambda_T}$$

- Frequency shifting PDV[1]

$$B = \left| \frac{2v}{\lambda_T} + c_0 \left(\frac{1}{\lambda_T} - \frac{1}{\lambda_R} \right) \right|$$

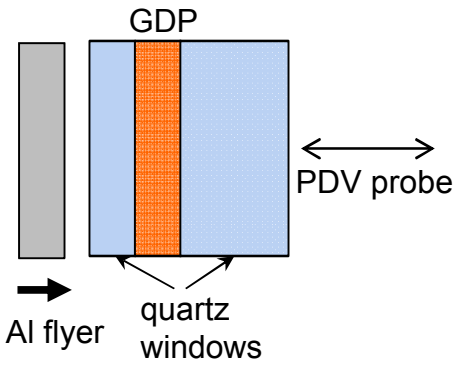
  - Red reference
    - Unambiguous mapping
    - Preferred configuration
  - Blue reference
    - Greater coverage
    - Issues near f=0
    - May require precise wavelength monitoring

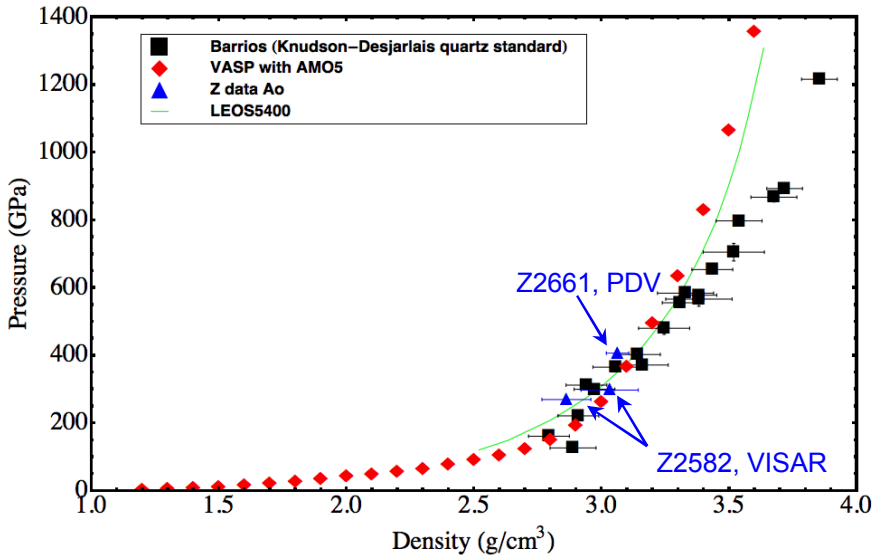


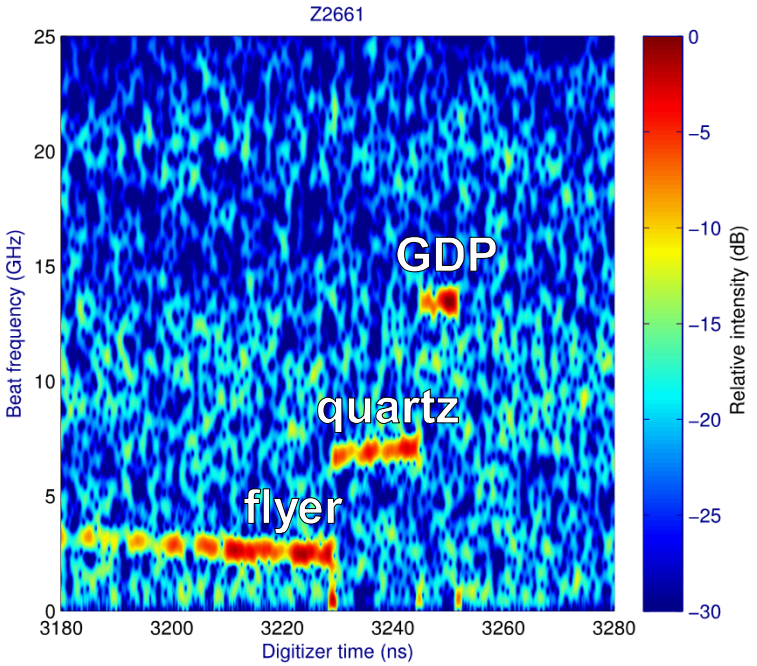
[1]T. Ao *et al.*, Rev. Sci. Instrum. **82**, 023907 (2011)

PDV acquired high fidelity EOS data of GDP

- Glow Discharge Polymer (GDP) EOS critical for ICF capsule design
  - Previous measurements insufficiently accurate (10%)[1]
    - GDP absorbs VISAR 532 nm light
  - PDV 1550 nm light penetrates GDP
    - Enables 1.5% accurate measurements at 4 Mbar
- Velocities based on beat frequency shift from offset frequency (35.148 GHz)
  - Flyer velocity: 25.4 km/s (2.44 GHz)
  - Quartz velocity: 32.9 km/s (7.2 GHz)
  - GDP velocity: 37.6 km/s (13.4 GHz)





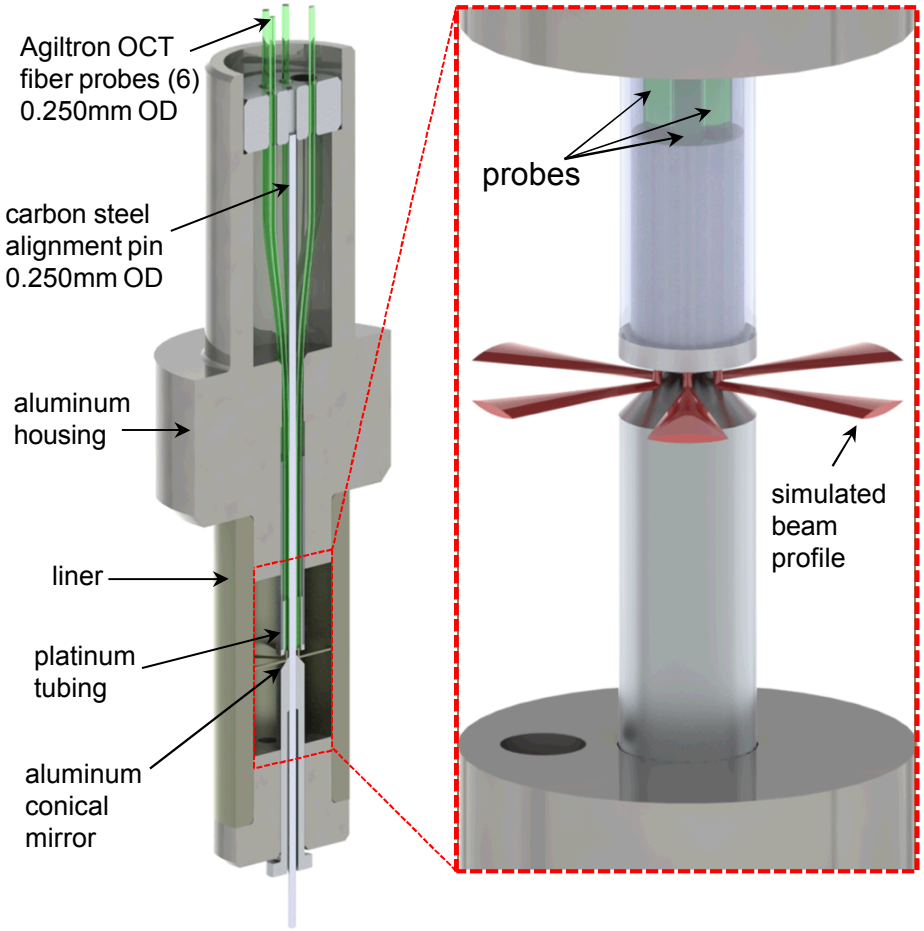


[1]M. A. Barrios *et al.*, J. Appl. Phys. **111**, 093515 (2012)

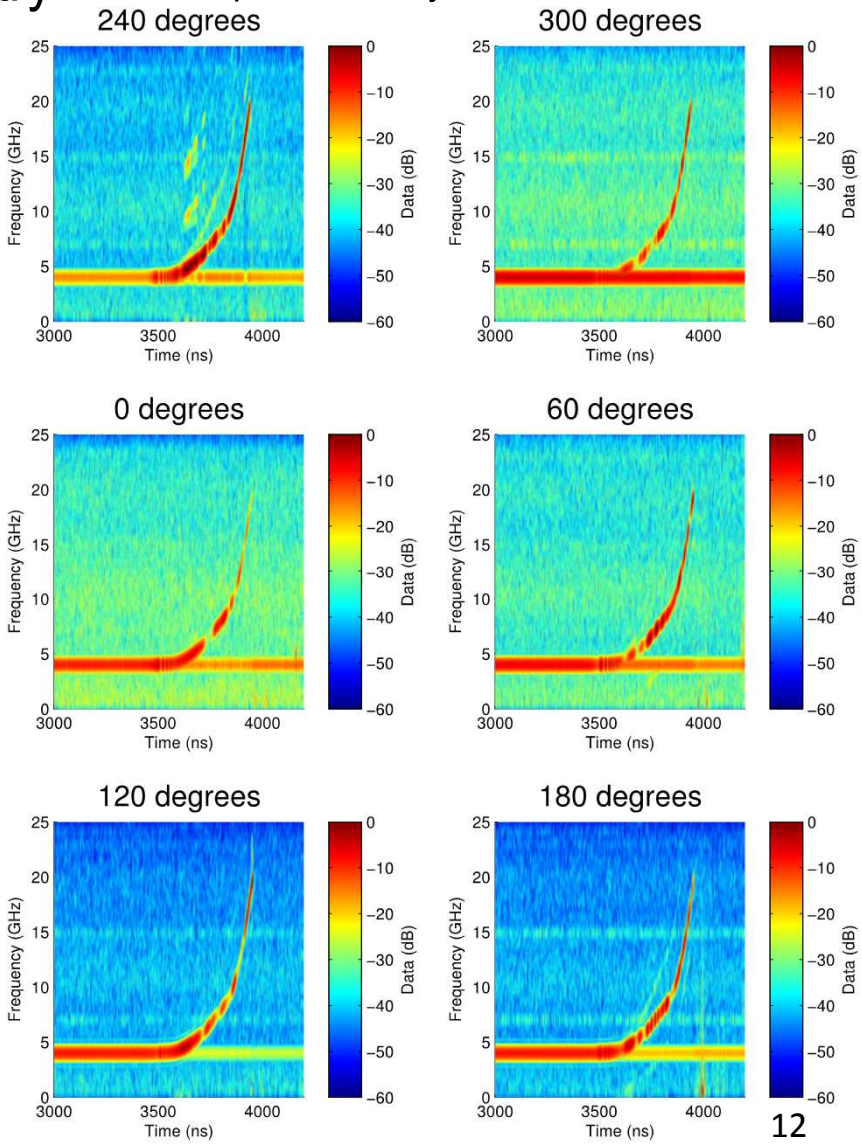
PDV measured implosions of cylindrical liners[1]

Sandia National Laboratories

- Multi-point design evaluated symmetry
  - Measurement every 60 degrees
  - Al drive of Ta liner
    - 7.3 Mbar peak pressure



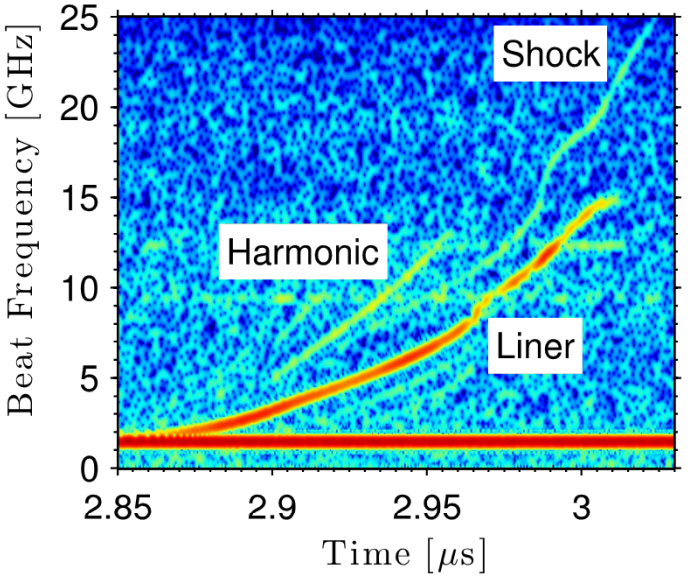
peak velocity = 11.5 km/s

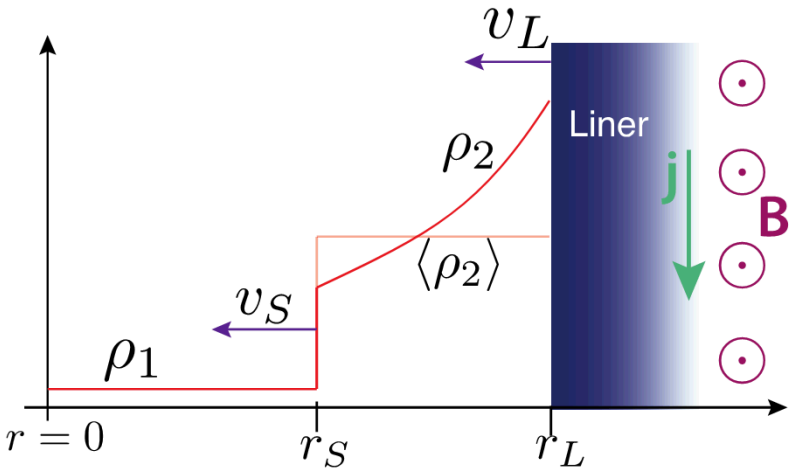


[1]D. H. Dolan *et al.*, Rev. Sci. Instrum. **84**, 055102 (2013)

PDV measured shock wave of liquid deuterium filled in hollow liner

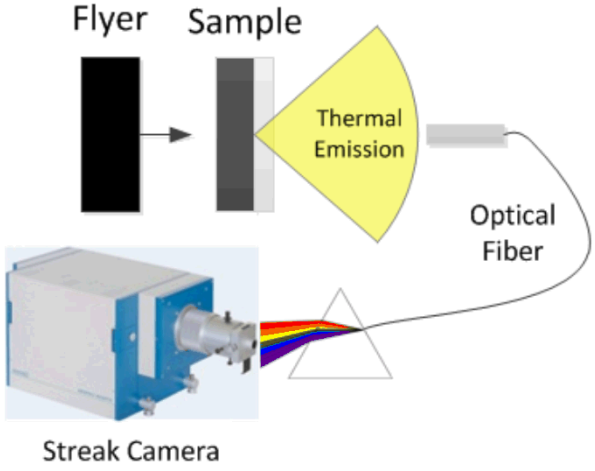
- Be liner filled with liquid D_2 (4 K)
  - PDV probe immersed in liquid
  - Survived condensation
- Magnetic drive launches ramp wave in liner which becomes shock wave in liquid
  - Liner reflection
  - Shock reflection (initially weak)
- Shock grows stronger and its reflectance increases
  - Eventually light cannot reach liner
- Window corrections are complicated
  - Ambient refractive index unknown
  - No steady state

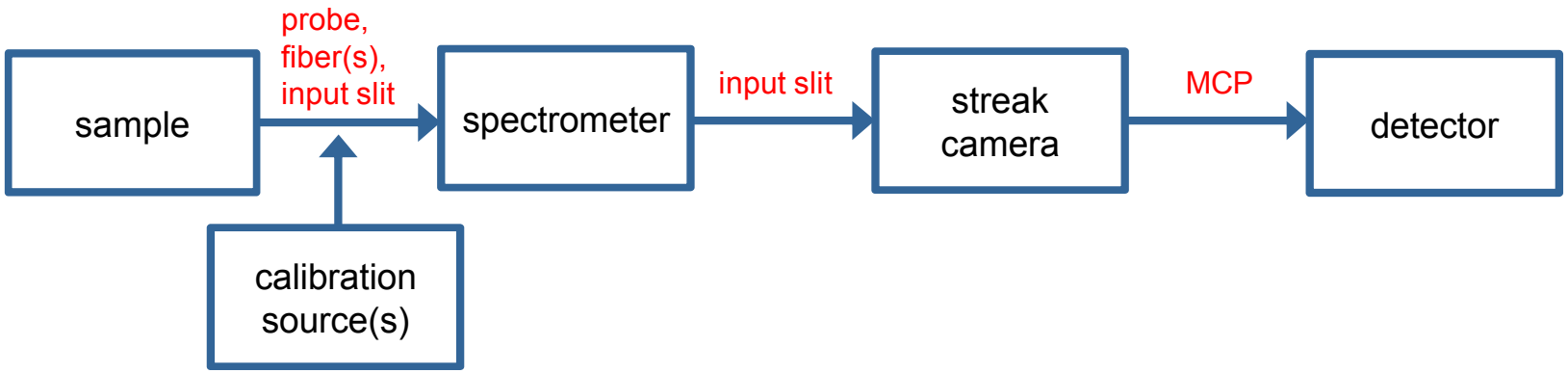




SVS
(Streaked Visible Spectroscopy[1])

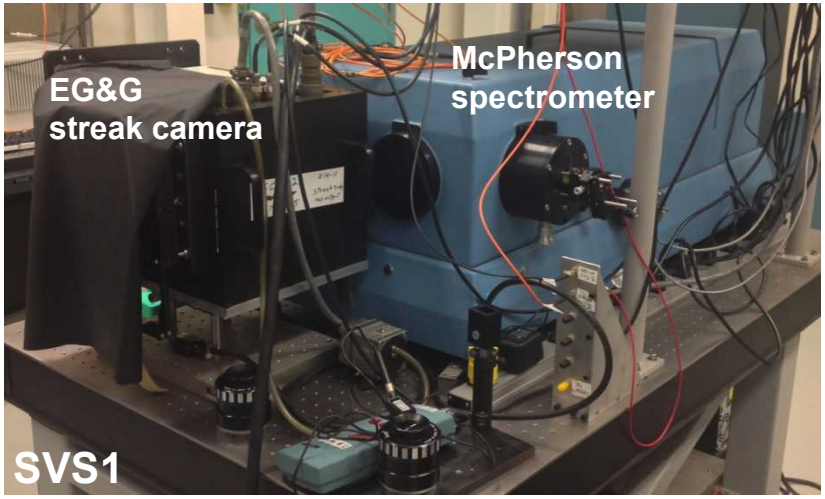
- Time-resolved optical spectroscopy
  - Fiber probe collects sample radiation
  - Spectrometer disperses light horizontally
  - Streak camera disperses line image vertically
    - Photons -> electrons -> photons
    - Another round of conversion at MCP
  - Detector acquires 2D image
    - Wavelength vs time
  - Image intensity controlled by items in red
    - Opening slits degrades resolution
    - Increasing gain adds image noise



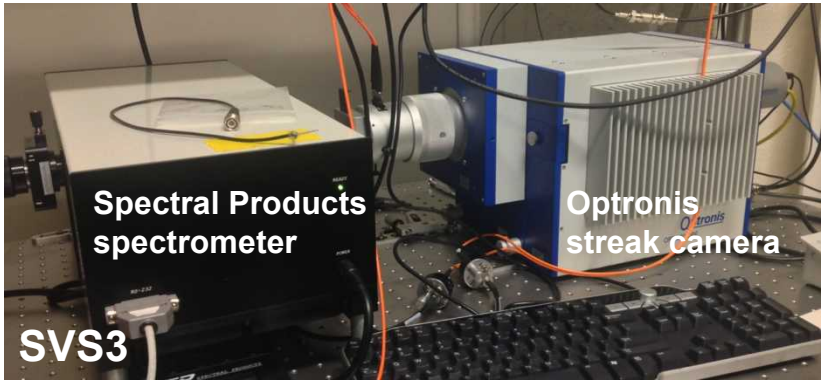


SVS capabilities on Z

- SVS1 and SVS2
  - Two EG&G streak cameras
    - Time window: < 100 – 500 ns sweep
  - Two McPherson (2061) spectrometers
    - Spectral range: 425 – 750 nm
    - Gratings: 150, 300, 600, 1200 gr/mm
  - Film coupled



- SVS3
  - Optronis (SC-10) streak camera
    - Time window: < 100 – 2000 ns sweep
  - Spectral Products (DK240) spectrometer
    - Spectral range: 425 – 850 nm
    - Gratings: 50, 150, 300, 600 gr/mm
  - CCD coupled

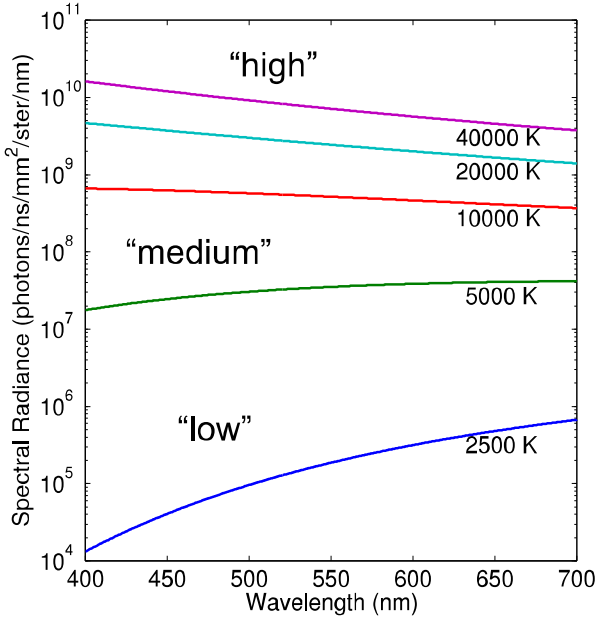


SVS pyrometry[1]

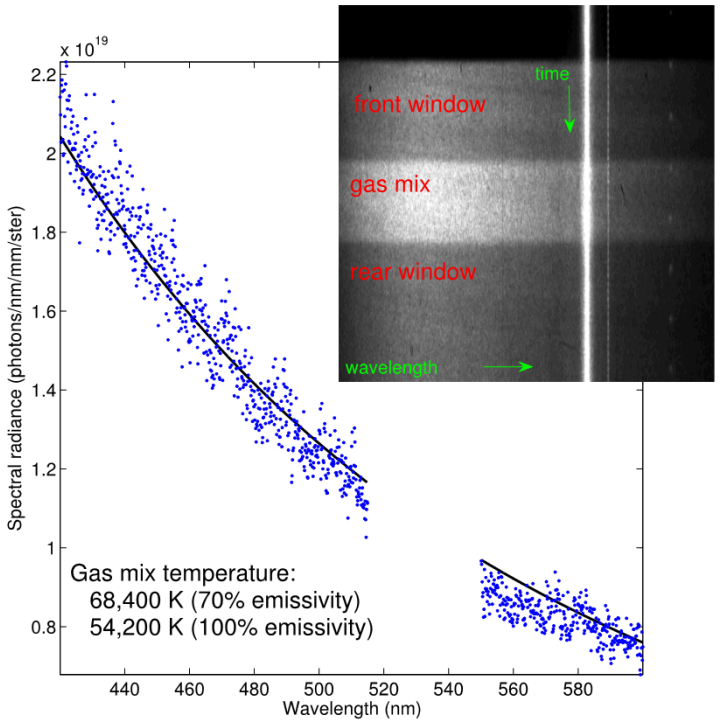
- Temperature inferred from measured radiance and emissivity

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

- Three general domains
  - High: >12,000 K (several eV)
  - Medium: 5000-10,000 K
  - Low: < 5000 K



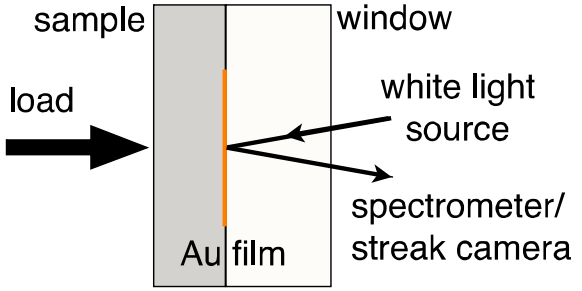
- Al flyer impact of quartz gas cell (Z2295)
  - Ethane-xenon gas mixture
  - Calibrated against quartz standard
  - Plenty of light
  - Absolute calibration needed
  - Emissivity important

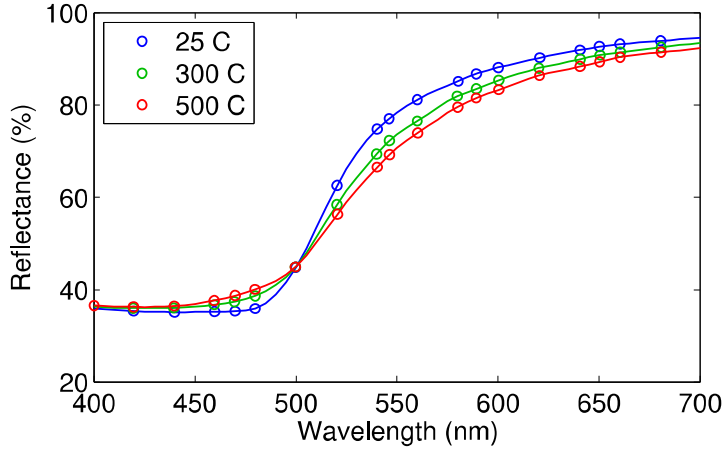


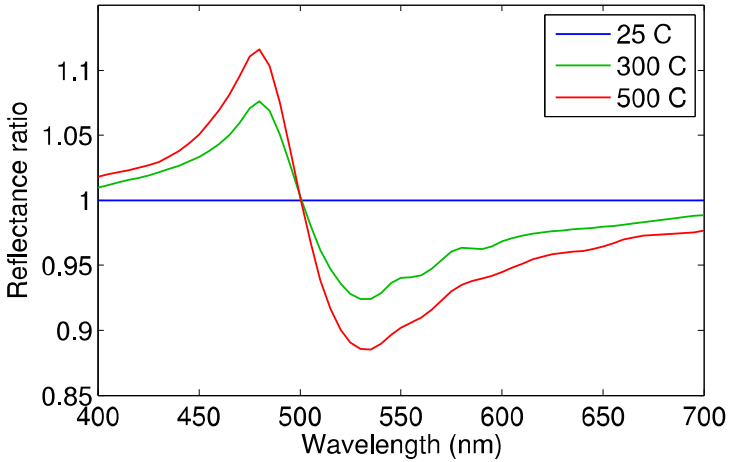
[1]G. A. Lyzenga *et al.*, J. Chem. Phys. **76**, 6282 (1982)

SVS reflectance thermometry[1]

- Better suited for ramp wave measurements (<1000 K)
- Optical properties change with temperature
  - Reflectance spectrum changes indicate temperature shift
- Signal levels controlled by light source, not sample temperature
  - Can operate at very low temperatures (<100 C) with ns resolution
- Embedded gold film serves as a standard gauge
  - Thin film (300 nm) provides quick thermal equilibrium
  - Chemically stable



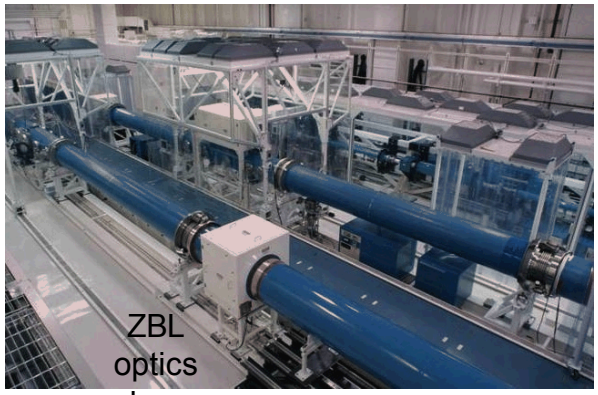


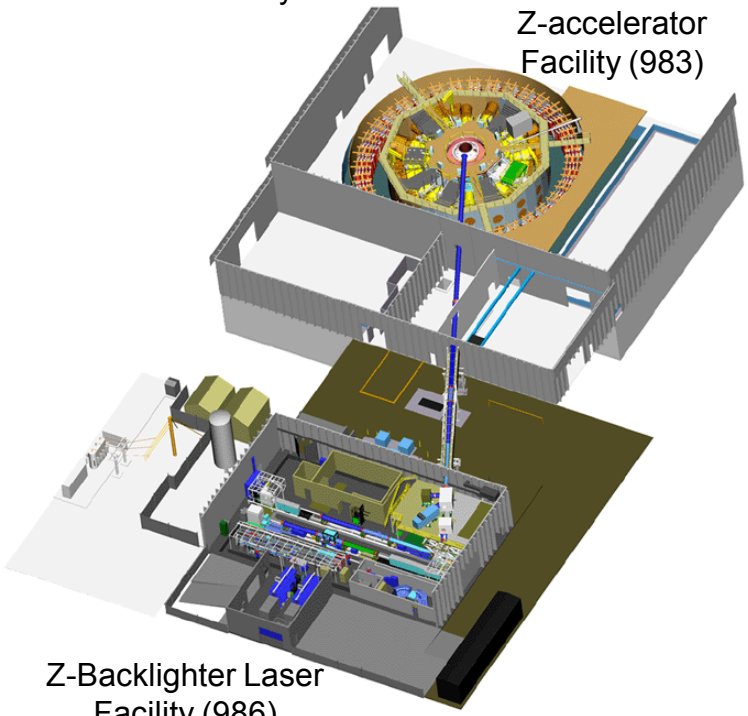


[1]D. H. Dolan *et al.*, SAND2013-8203 (2013)

X-ray capabilities on Z

- Z-Backlighter Laser (ZBL)[1]
  - Housed in building next to Z Facility
  - Beam transported ~ 200 feet to Z center section
  - 2ω (527 nm) light, ~ 10^{12} W
  - Multi-kJ beams: up to 4 kJ in 4 ns
- X-ray radiography
  - 2-frames of ZBL to irradiate metal foils
    - Si: 1.865 keV, Mn: 6.151 keV
    - Up to 20 ns separation
  - Monochromatic crystal imaging
- X-ray Thomson scattering
  - Single frame of ZBL to irradiate a metal foil
    - Mn: 6.181 keV
  - Focusing spectrometer with spatial resolution[2]



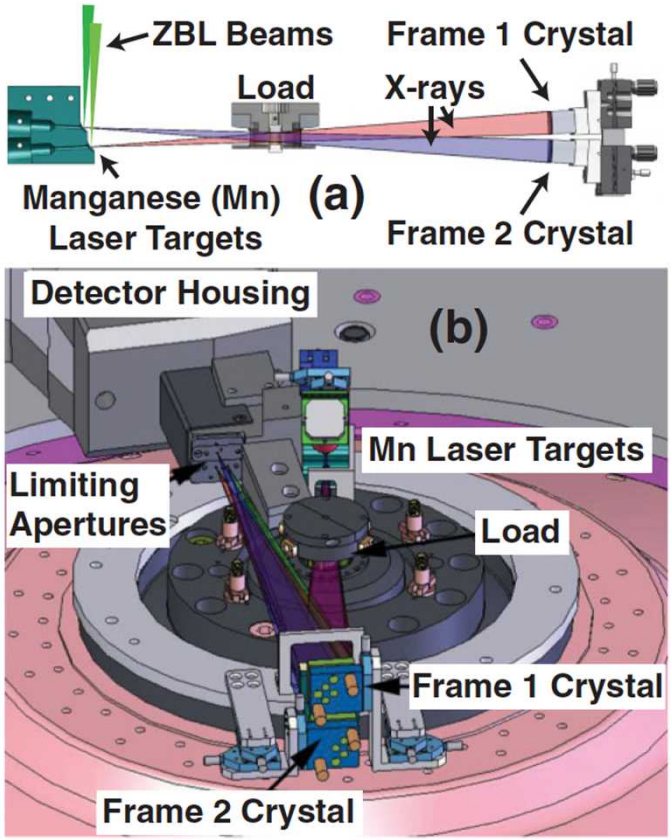


[1]P. K. Rambo *et al.*, Appl. Opt. **44**, 2421 (2005)

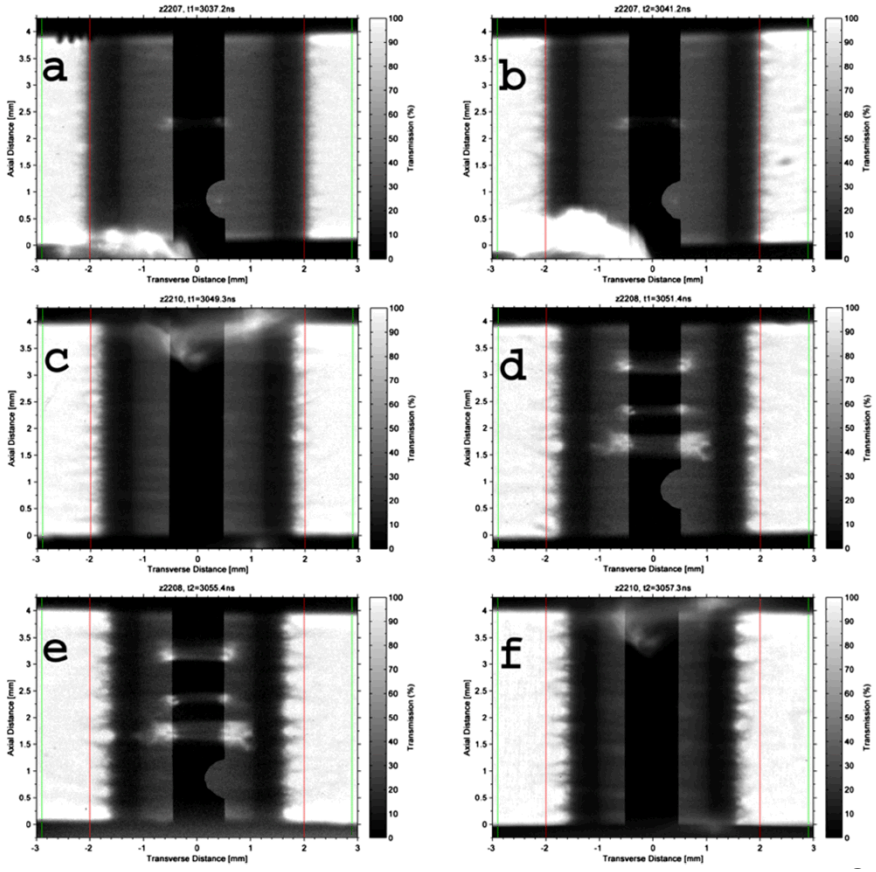
[2]D. B. Sinars *et al.*, J. Quant. Spec. Rad. Transf. **99**, 595 (2006)

X-ray radiography

- 2-frame 6.151 keV monochromatic backlighting[1]
  - ZBL: Two ~1 kJ, 527 nm, 1 ns beams irradiated Mn targets



- Solid liner implosion for multi-Mbar shockless compression[2]
  - Cylindrical Be liner
    - 900 μm thick, 2.0 mm inner radius
  - Ramp compression: 2.4 Mbar, 300 ns

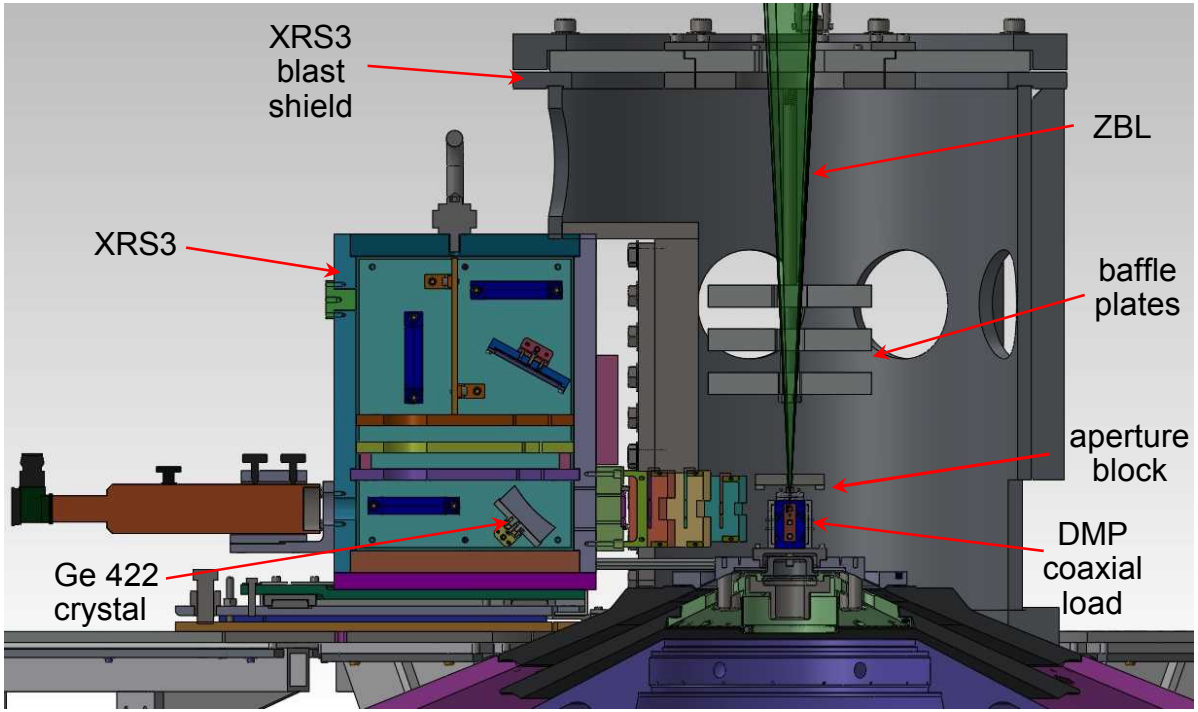


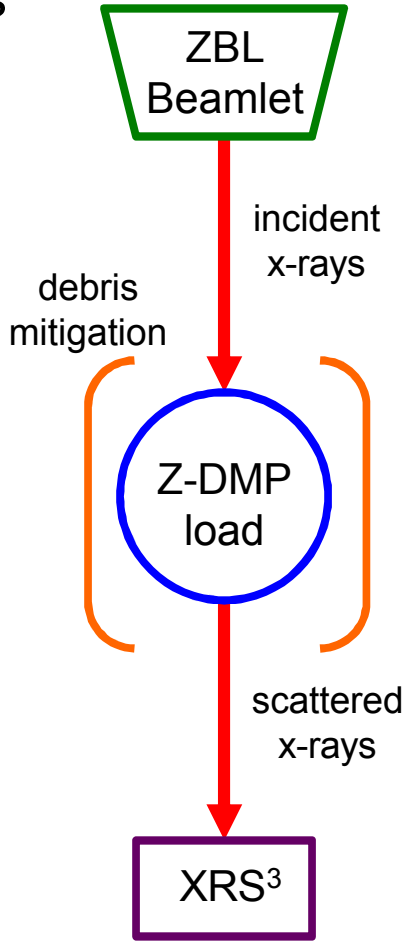
[1]R. D. McBride *et al.*, PRL **109**, 135004 (2012)

[2]M. R. Martin et al., Phys. Plasma **19**, 056310 (2012)

XRTS
(X-ray Thomson Scattering[1])

- 3 key components to XRTS on Z-DMP experiments[2]
  - ZBL produce quasi-monochromatic x-rays (6.181 keV)
  - Z-DMP load generate warm dense matter state
  - Detect x-rays with spectrometer (XRS3)



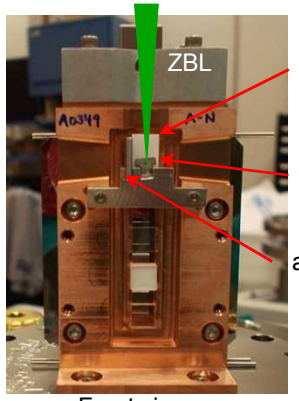


[1]S. H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009)

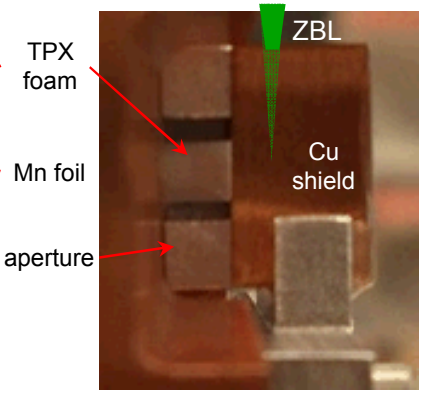
[2]T. Ao *et al.*, J. Phys. Conf. Ser. **500**, 082001 (2014)

Measured XRTS data from ambient & shocked TPX (CH_2) foam, and Mn x-ray source

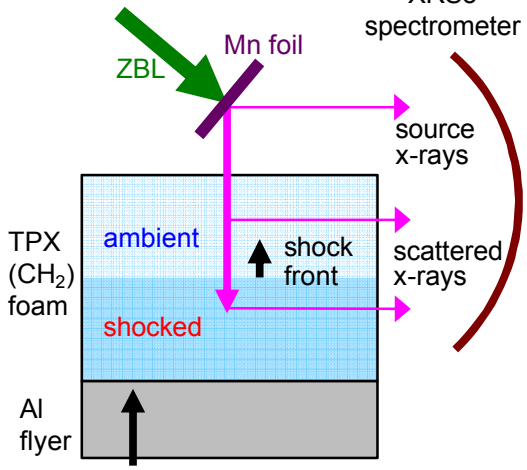
- Al flyer (25.4 km/s) impacted TPX foam (0.2 g/cc)
  - Uniform, long-lived, well-defined shocked TPX foam (0.75 Mbar, 0.52 g/cc)
  - In-situ comparison with ambient state
  - Characterized Mn x-ray probe source spectrum for x-ray scattering comparison

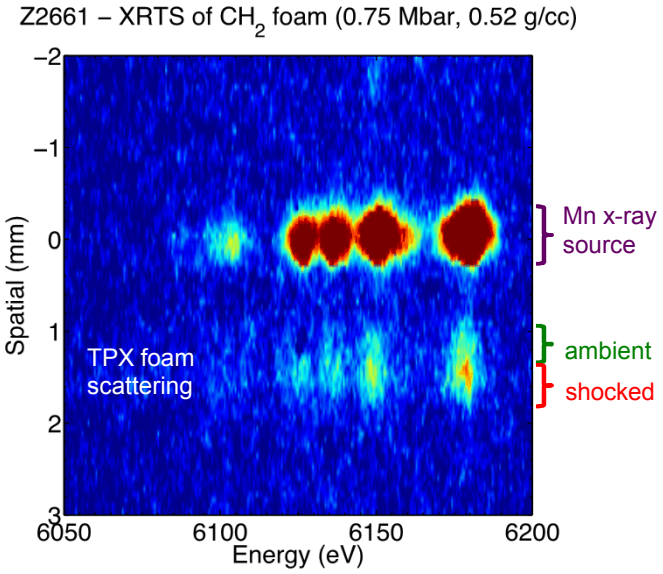


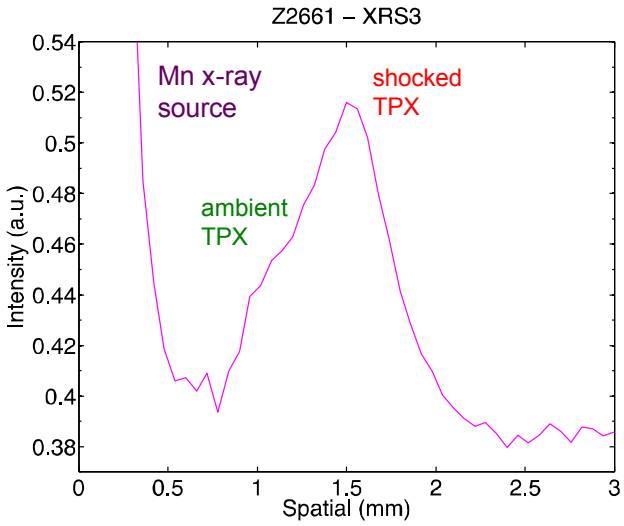
Front view



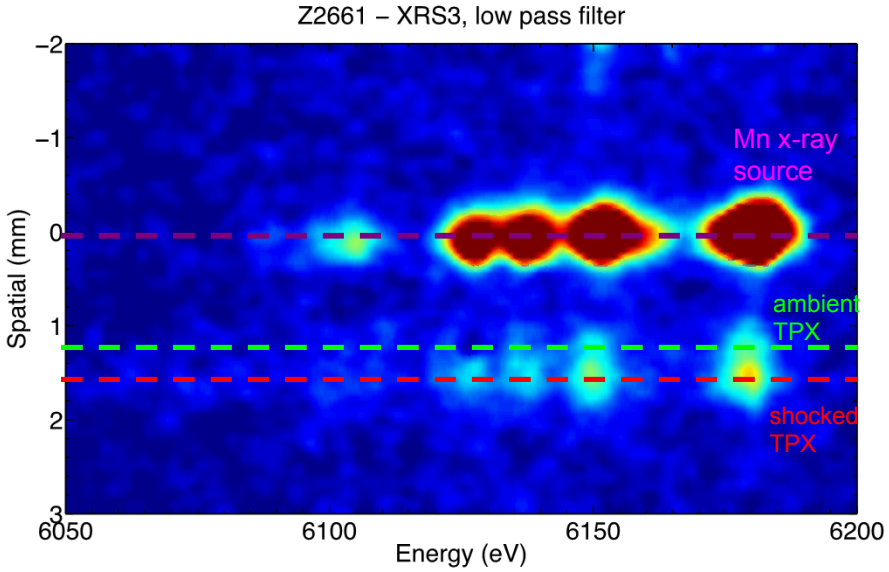
XRS3 view (90° scattering)

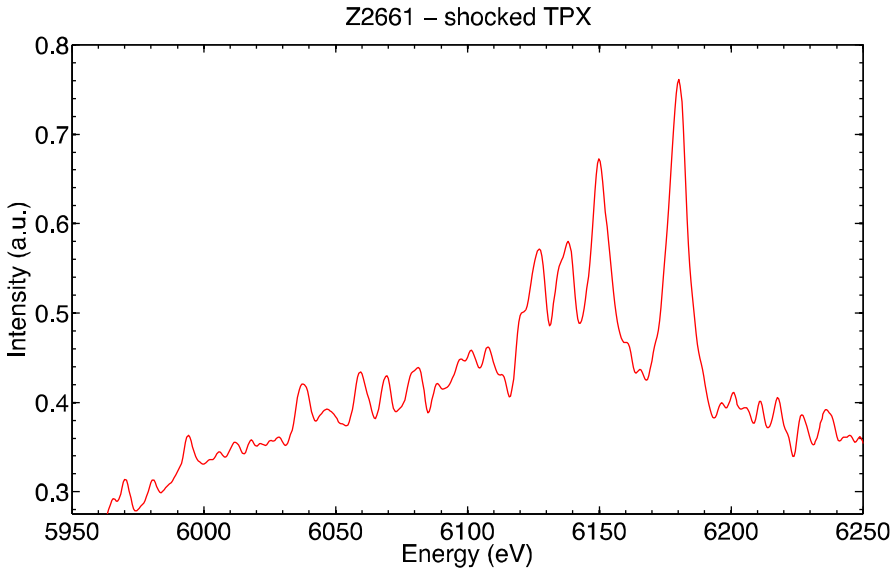


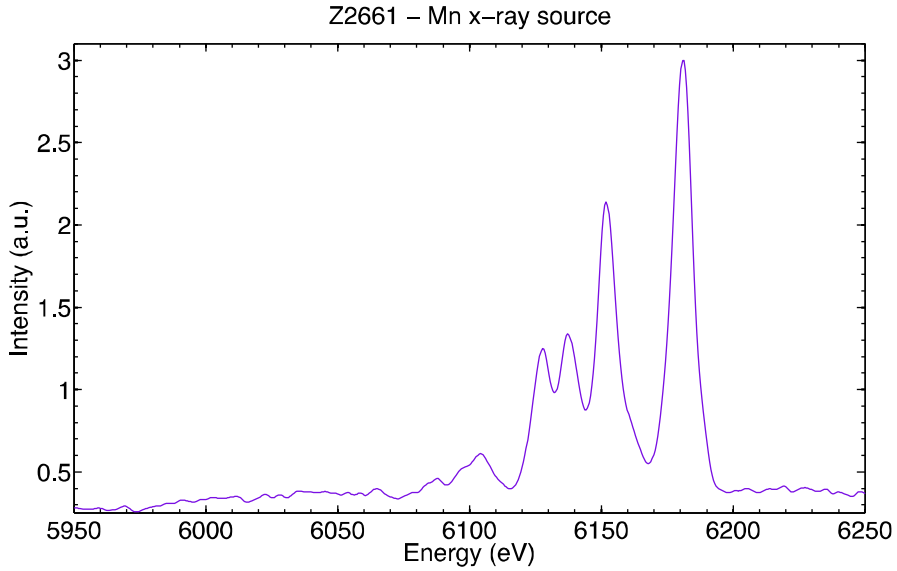


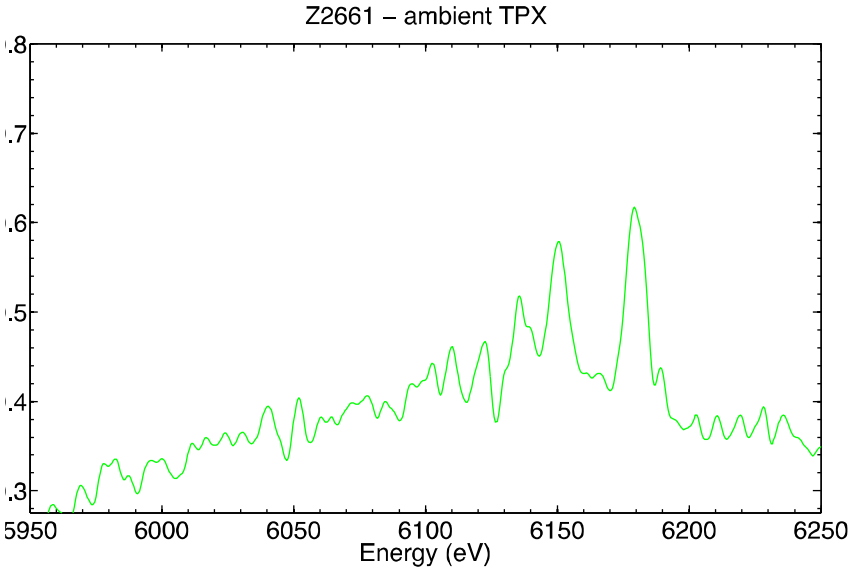


XRTS data with high spectral resolution









Future developments

Sandia National Laboratories

- Spatially-resolved velocimetry
  - Line-VISAR or Line-imaging ORVIS
  - Multiplex-PDV
- Time-resolved spectroscopy
  - Wavelength-conversion of optical to infrared
- Phase identification
  - X-ray diffraction
- Dielectric properties
  - Ellipsometry