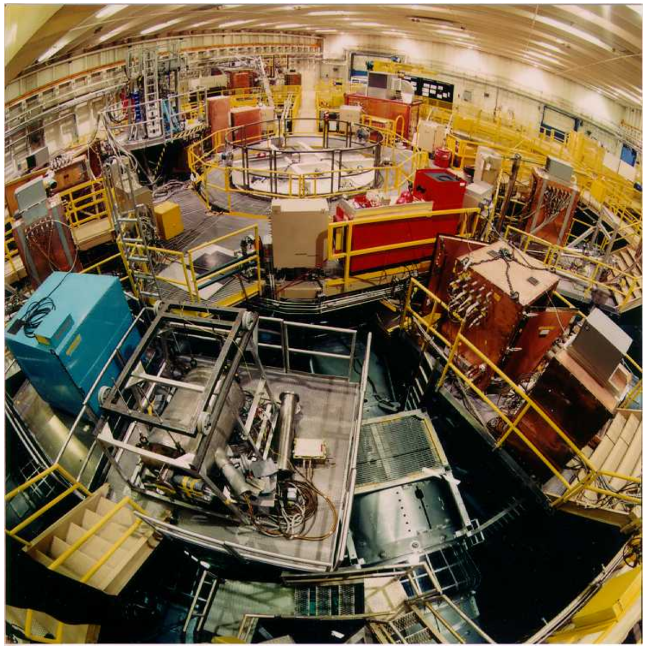
SAND2007-4203C

Operational Experience in Fielding the Z Diagnostic Suite in the Harsh Environment of the Z-Facility at Sandia National Laboratories

International Workshop on ITER-LMJ-NIF Components in Harsh Environments

Aix-en-Provence, France

June 27, 2007



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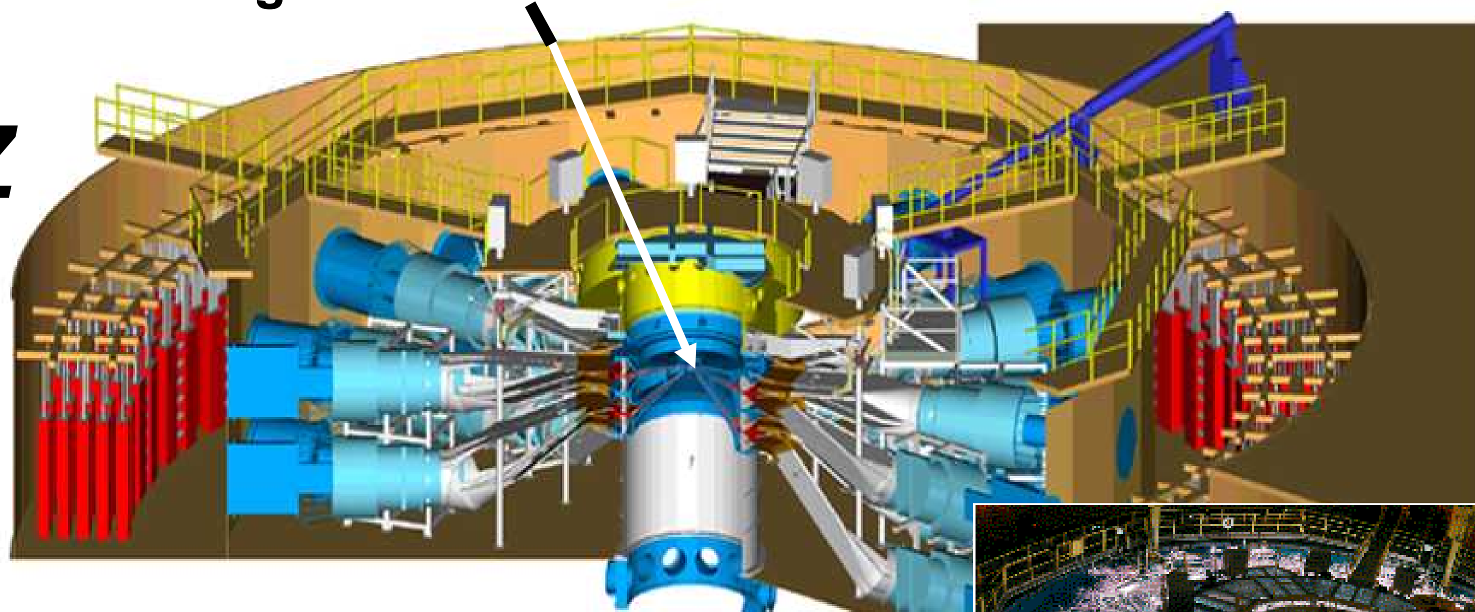
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

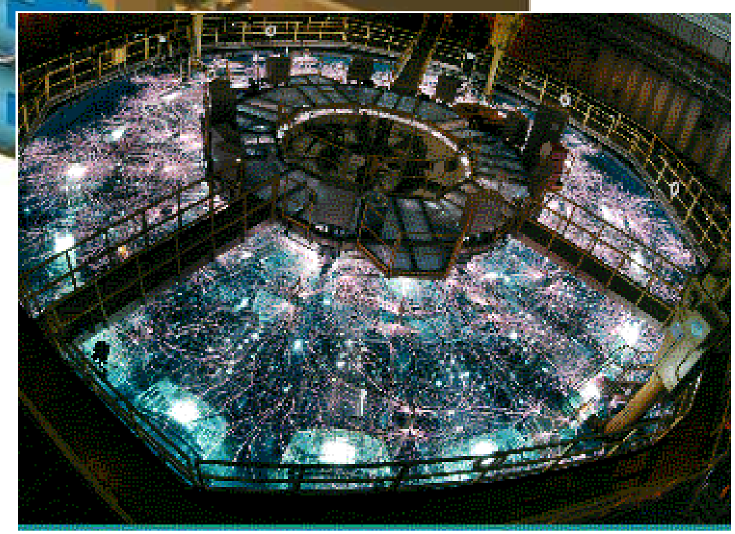
The Z pulsed-power accelerator provides efficient time compression and power amplification for inertial confinement fusion (ICF) research

Target Chamber

Z



11.5 MJ stored energy
19-20 MA peak load current
40 TW electrical power to load
100-250 TW x-ray power
1-1.8 MJ x-ray energy

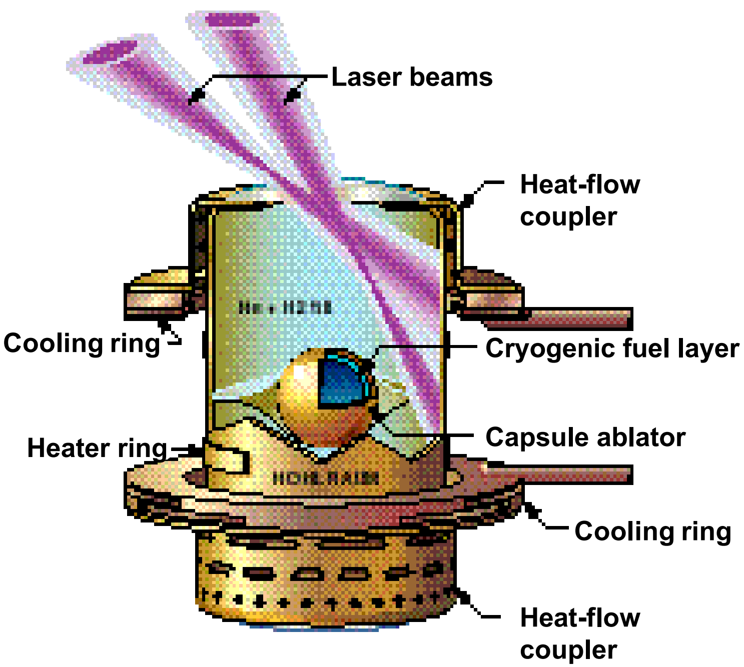


The Z facility is a challenging environment for developing and fielding x-ray, γ-ray, and nuclear diagnostics

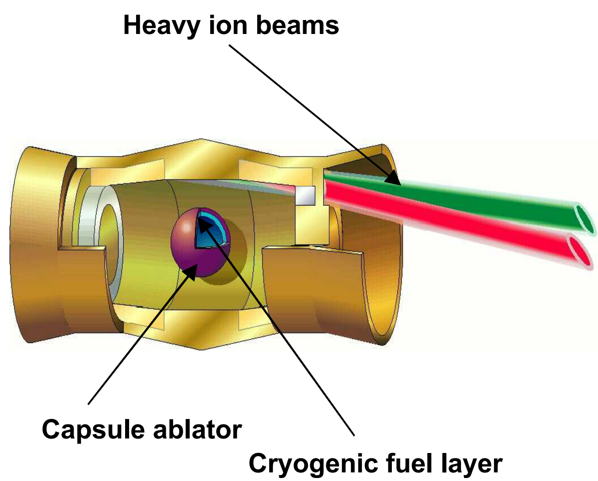
Debris field	Large amounts of debris of various sizes requires extensive baffle arrangements and fast closure valves
EMP background	Electric fields of ~ 1 MV/m
X-rays: 100 eV to 3 keV	1.6 MJ and 200 TW
X-rays: 1 keV to 10 keV	50-150 kJ and 10-30 TW
γ-rays: 30 keV to ~ 5 MeV	75 rads at 1 m in 5 ns pulse yielding 1.5 x 10^{10} rads/s
Neutrons: ~ 2.45 MeV	2.6 x 10^{11} neutrons/4π produced in dynamic hohlraum capsule experiments
Neutrons: ~ 2.45 MeV	3.7 x 10^{13} neutrons/4π for D_2 gas puff z-pinch on Z at 18 MA

Hohlraums may be driven with a variety of radiation sources including lasers, heavy ions, and Z-pinches

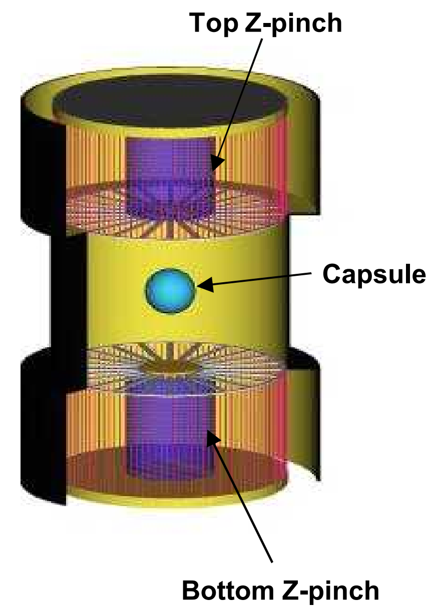
NIF Laser Ignition Hohlraum



Heavy Ion Hohlraum

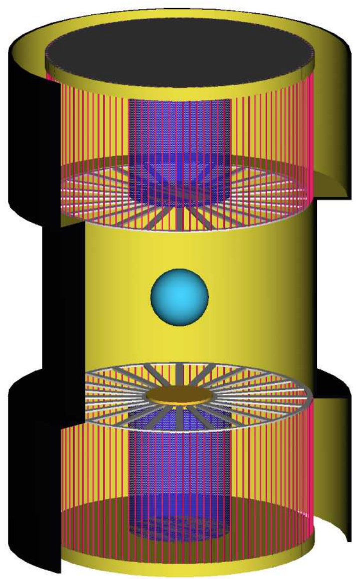


Double-Ended Z-pinch Hohlraum



Two complementary approaches to Z-pinch-driven fusion are being studied at Sandia

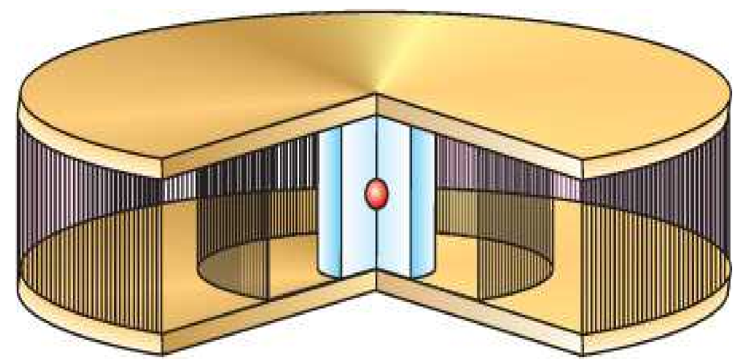
Double-ended hohlraum



Key issues

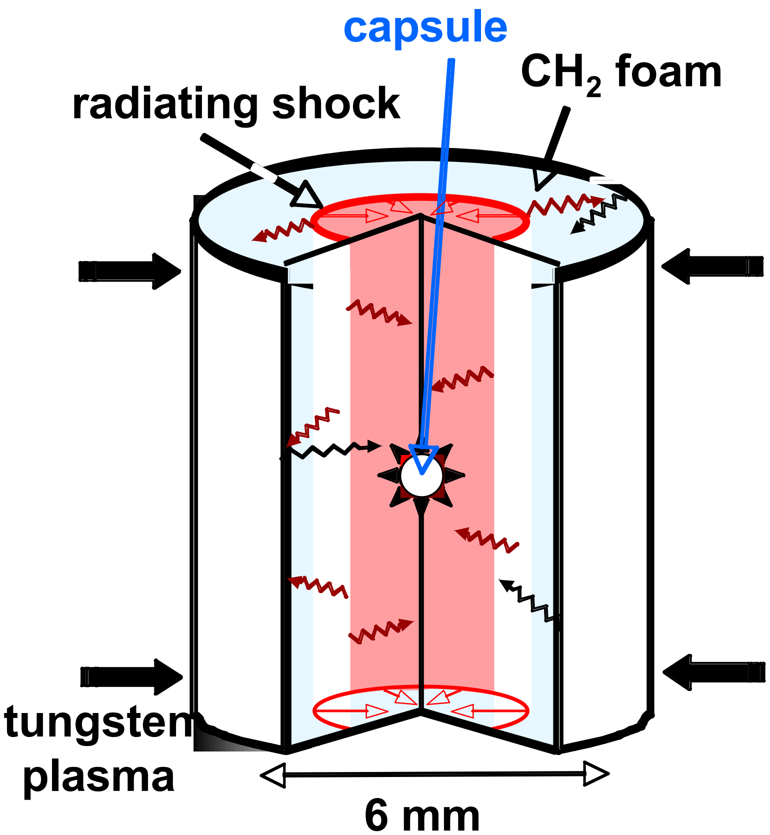
- hohlraum energetics
- radiation symmetry
- pulseshaping
- preheat
- capsule implosions

Dynamic hohlraum



R. J. Leeper et al., Nuclear Fusion 39, 1283 (1999).

Dynamic hohlraums efficiently couple x-rays to capsules



- Z-pinch plasma impacts foam converter
  - The impact launches shocks in foam and tungsten
  - The foam shock is a main radiation source
  - The z-pinch confines the radiation
  - Capsule heated mainly by re-emission from tungsten hohlraum wall

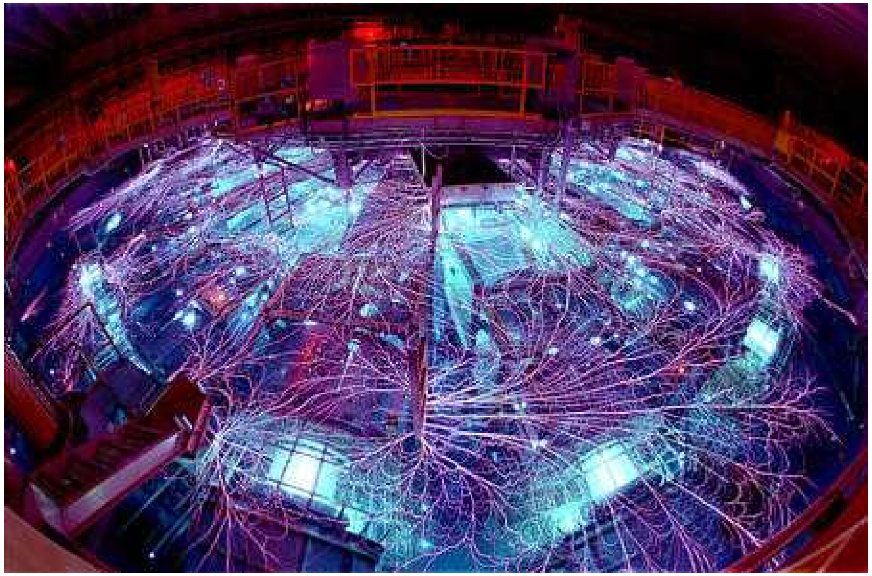
physics issues:

1. interior diagnostics
2. symmetry
3. radiation production
4. radiation transport
5. radiation confinement
6. preheat

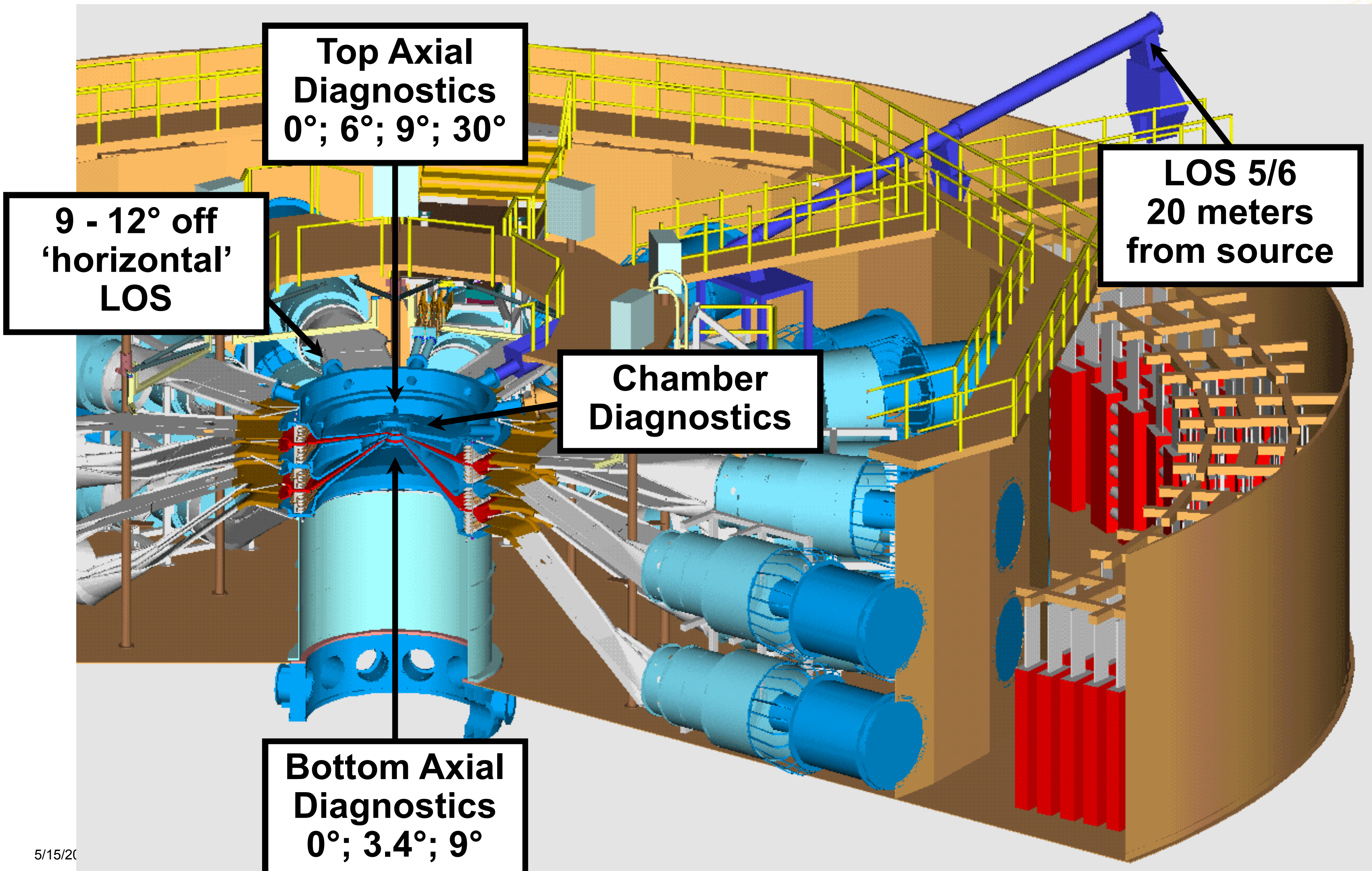
J. E. Bailey et al., Phys. Rev. Lett. 89, 095004 (2002).

Inertial confinement fusion (ICF) research on Z require extensive diagnostic suites

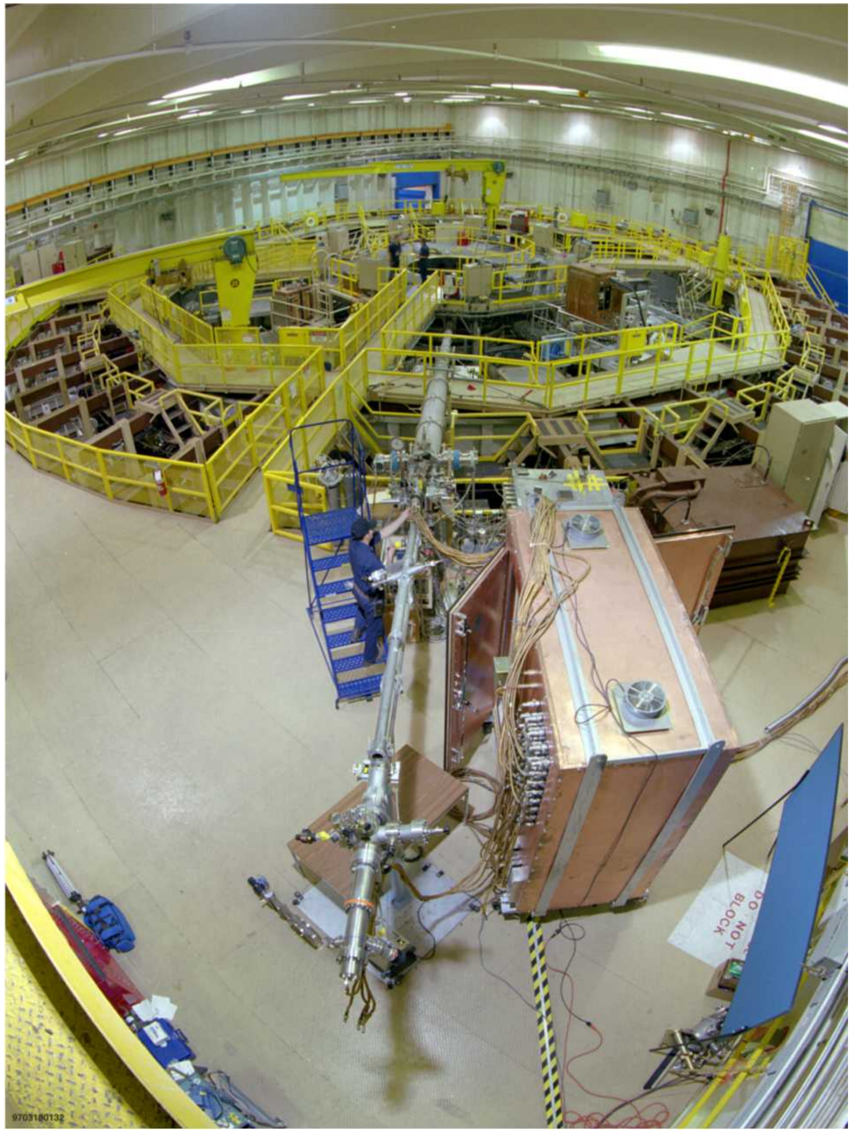
- X-ray fluence and flux diagnostics
- X-ray imaging diagnostics
- X-ray backlighting diagnostics
- Time-integrated and time resolved spectroscopy diagnostics
- Shock physics based diagnostics
- Neutron detector systems



The arrangement of diagnostics on Z take advantage of the available solid angle



Eleven lines of sights are located around Z at a vertical angle of twelve degrees from the horizon

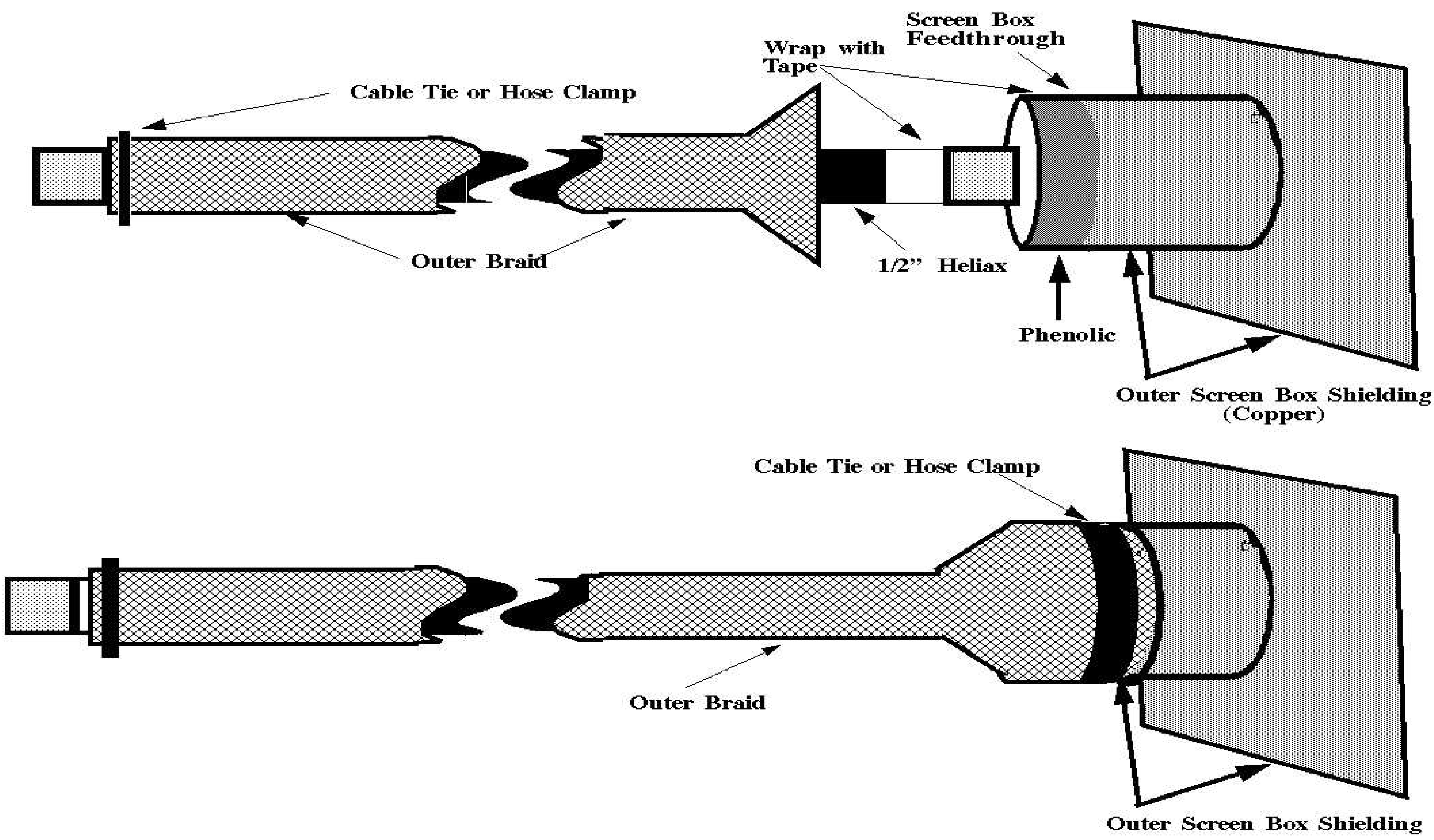


Axial measurements on Z make use of the the Z axial diagnostic package

Coaxial cable runs on Z are located on a high EMP environment

- Digitizers are located in screen boxes arranged azimuthally around Z's central vacuum chamber
- The cables used are typically 6.7 m of Andrew LDF4-50A 1.3 cm Heliax cables using "N" Type connectors
- Inside the screen box is a 2.4 m run of RG9914
- Special care is taken to minimize noise on the cable runs by installing an outer steel braid to the Heliax cable runs and securing one end to the "N" connector at the diagnostic and attaching the opposite end to the screen box feedthrough
- The connector at the screen box feedthrough is isolated electrically by wraps of electrical tape
- The braid is then mechanically attached to the feedthrough housing and thus creates a triaxial cable run
- The combination of Heliax and RG9914 cables creates a cable run to allow signals recording in excess of 4 GHz, which exceeds the digitizer recording capability
- Fast signals are primarily recorded using the TDS684 and TVS645 with a sample rate of 200 ps/sample

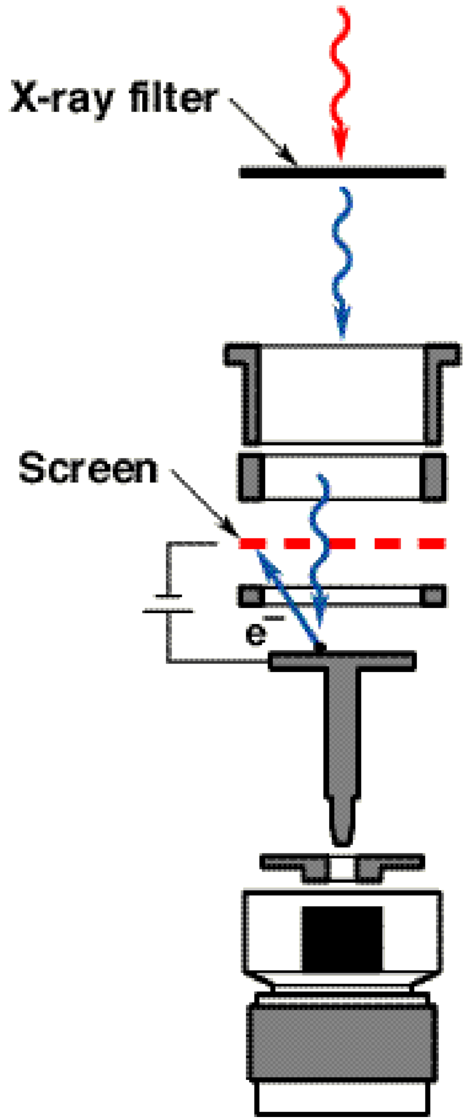
Noise on Z cable runs is minimized by installing an outer steel braid on Heliax cables and securing one end to the "N" connector at the diagnostic and the other end to the screen box feedthrough



X-ray fluence and flux diagnostics are used to characterize the z-pinch source and hohlraum temperature

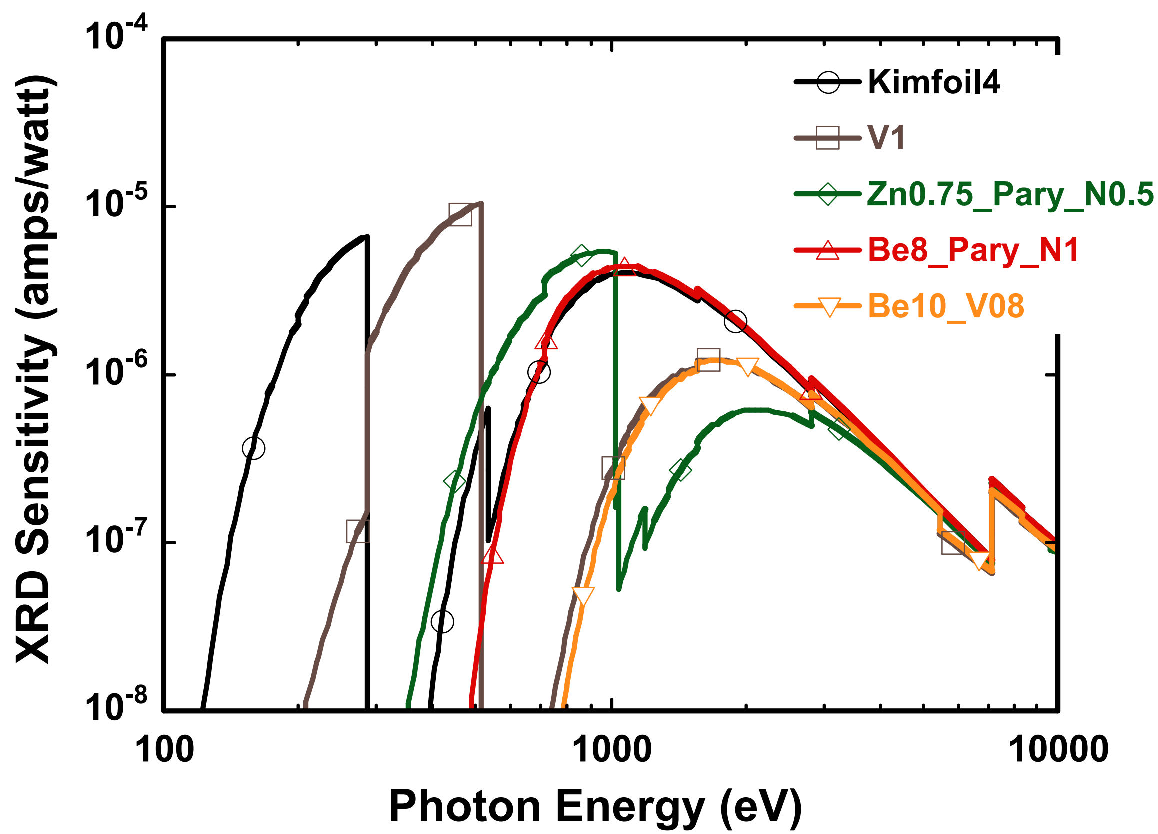
DIAGNOSTIC	QUANTITY OBSERVED	USED TO OBTAIN
XRD Array	145 eV To 2.5 keV X-rays	Source Temperature
Bolometer	Few eV To 2 keV X-rays	Total X-ray Yield
Soft X-ray Calorimeter	Few eV To 2 keV X-rays	Total X-ray Yield
Transmission Grating Spectrograph (Time-Resolved)	50 eV To 2 keV X-rays	Continuum Measurement of Source Temperature

Filtered x-ray diodes (XRDs) are used to primarily measure the soft x-ray flux from the source

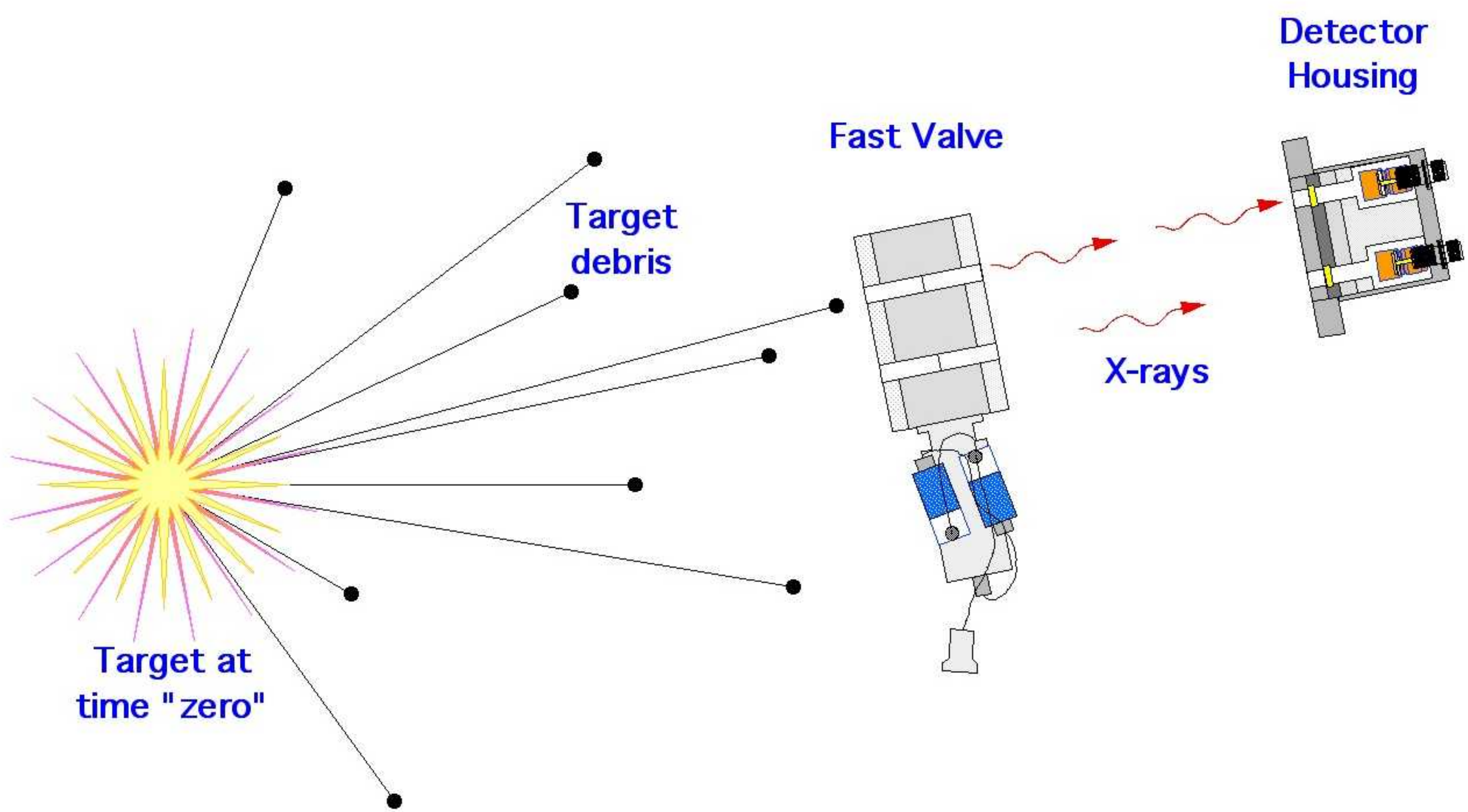


- XRD Photocathodes: Vitreous carbon
- Time resolution: ~ 500 ps fwhm
- Bias voltage: -1000 volts
- Spectral coverage: 140 eV - 2.5 keV

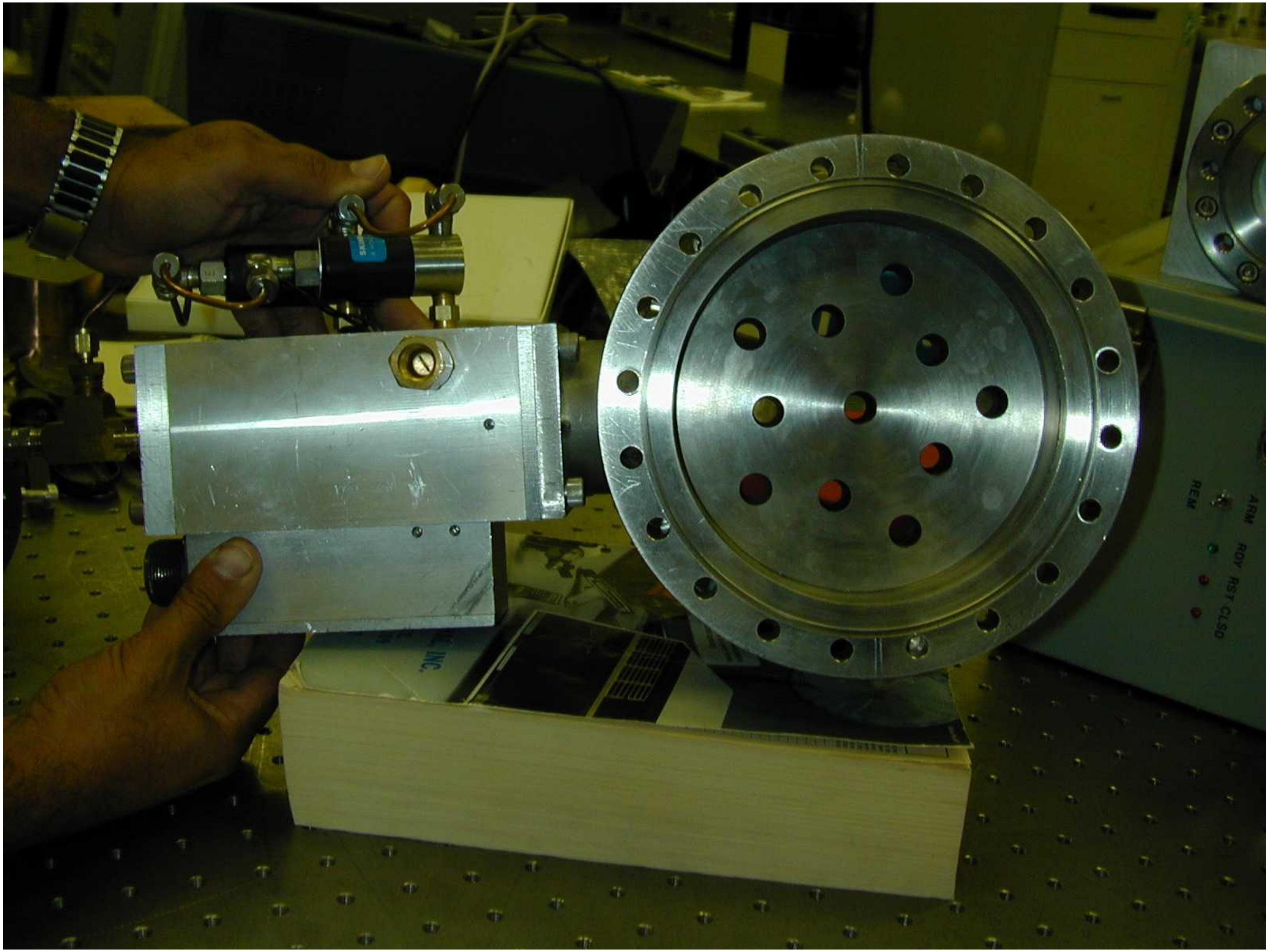
Predicted XRD Responses with carbon photocathodes



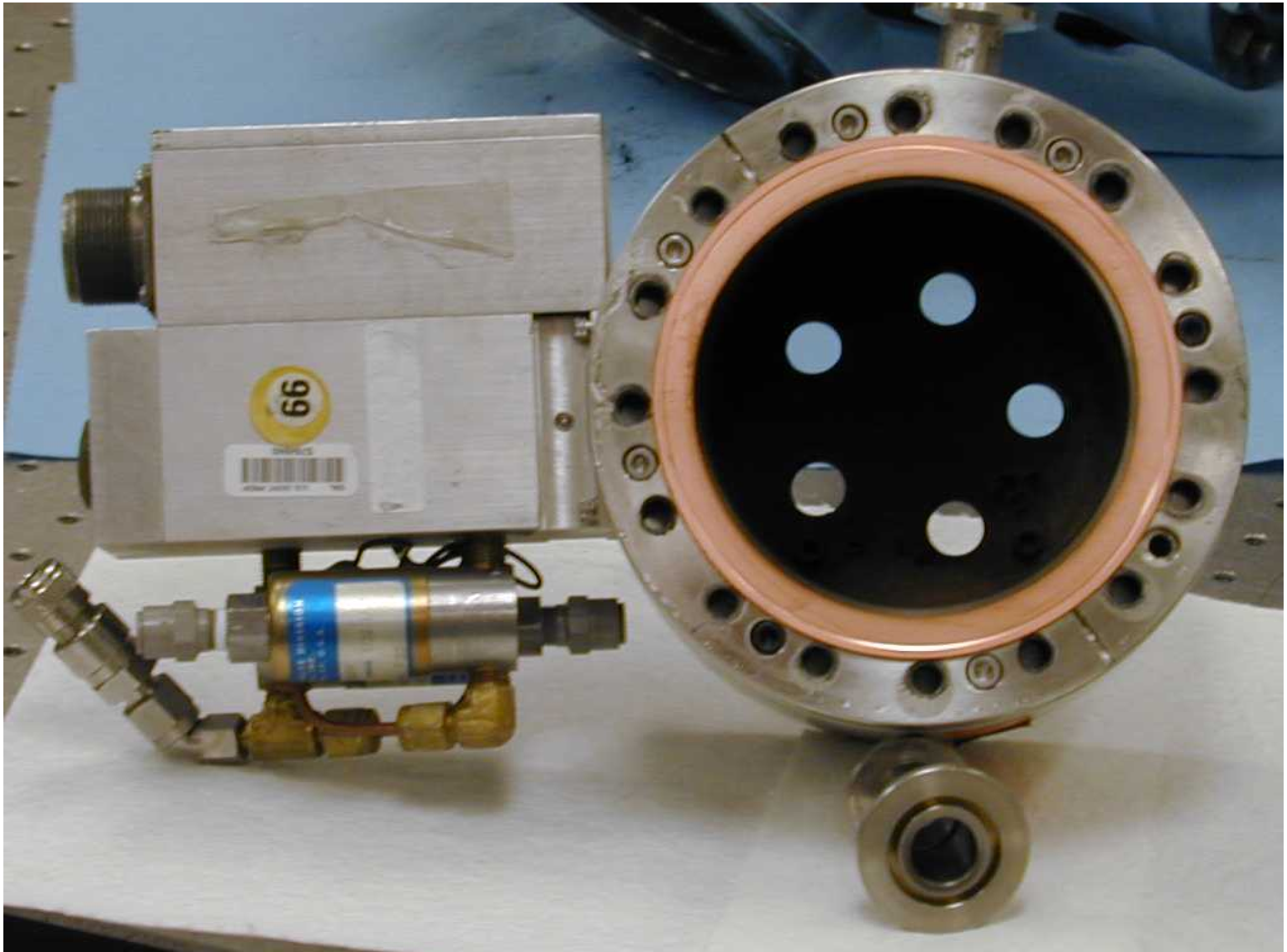
Fast closure valves are used to protect diagnostics from target debris on Z



An eleven-port Z fast valve is shown in this photograph

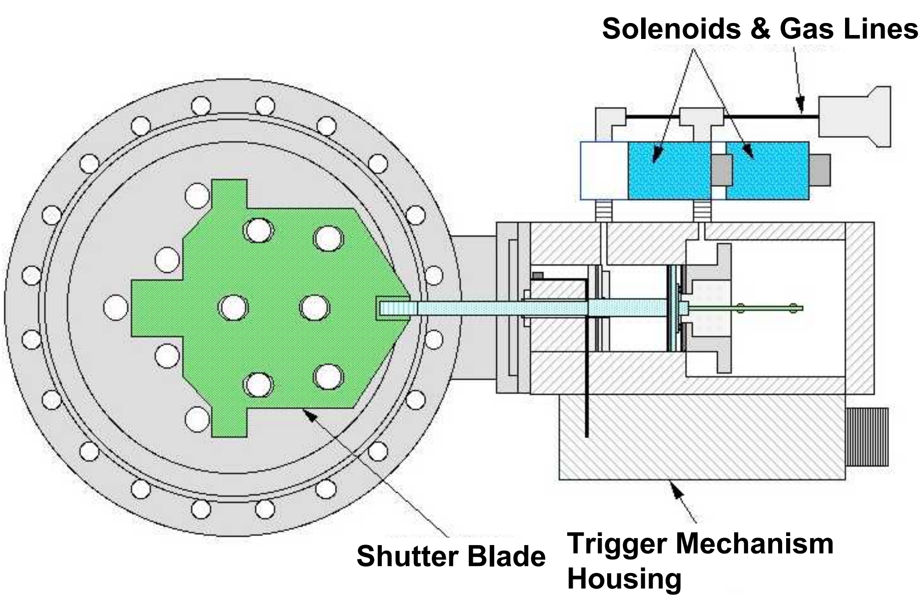


A five-port Z fast closure valve is shown in this photograph

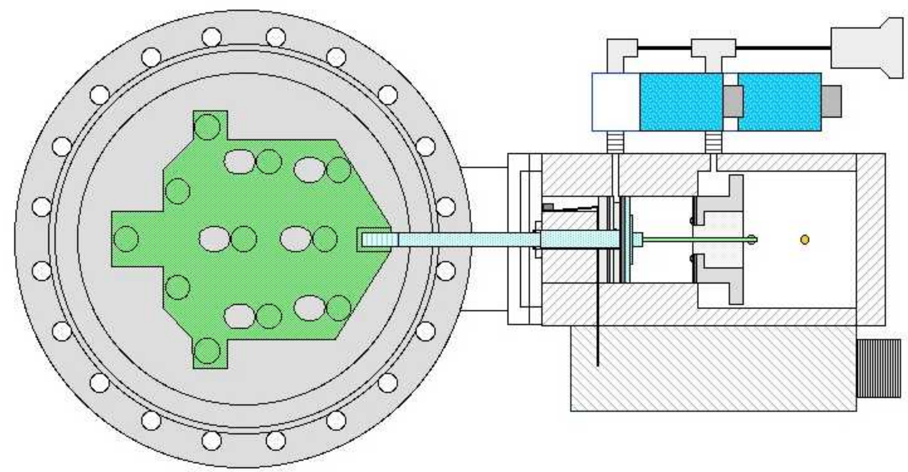


Schematic of eleven port fast valve showing open and closed positions

Open Position



Closed Position

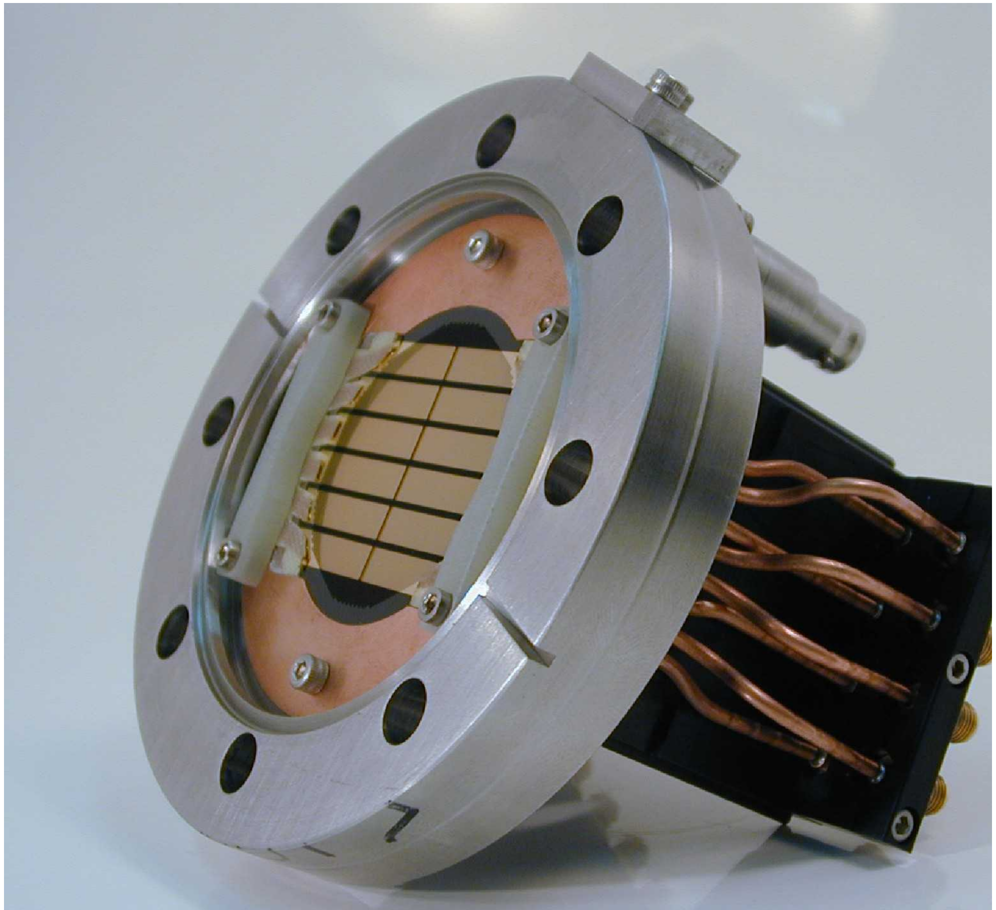


- The Z fast valves operate at typical nitrogen pressures of 160 psi
- The valves can be operated in Close-Open-Close (C-O-C) and Open-Close Modes (O-C)
- In the C-O-C mode, the time to close a 3 mm x 28.2 mm slit is ~ 0.10 ms and a 11-port set 12.7 mm diameter apertures in ~0.2 ms
- In the O-C mode, the time to close a 11-port set of 12.7 mm diameter apertures is ~ 0.8 ms

Imaging diagnostic techniques are core to quality measurements in ICF research

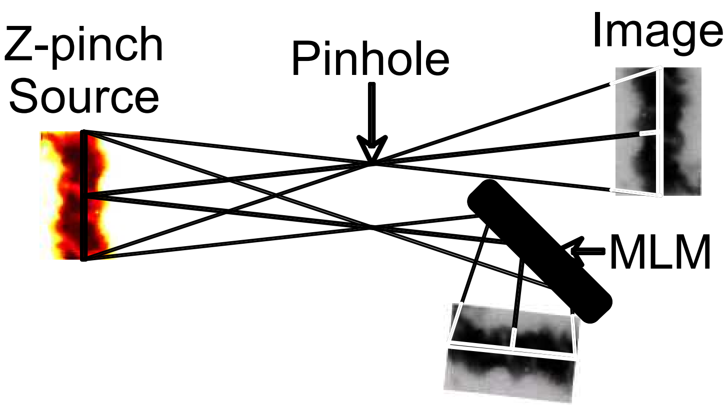
DIAGNOSTIC	QUANTITY OBSERVED	USED TO OBTAIN
X-ray Pinhole Camera (Time-Integrated)	30 eV To 10 keV X-rays	Source Image
X-ray Pinhole Camera (Time-Resolved)	30 eV To 10 keV X-rays	Source Image
Streaked Fiber Arrays (Time-Resolved)	100 eV To 3 keV X-rays	1-D Filtered Source Image
Z/Beamlet Laser Backlighter	1.865 keV To 10 keV X-rays	Absorption Image

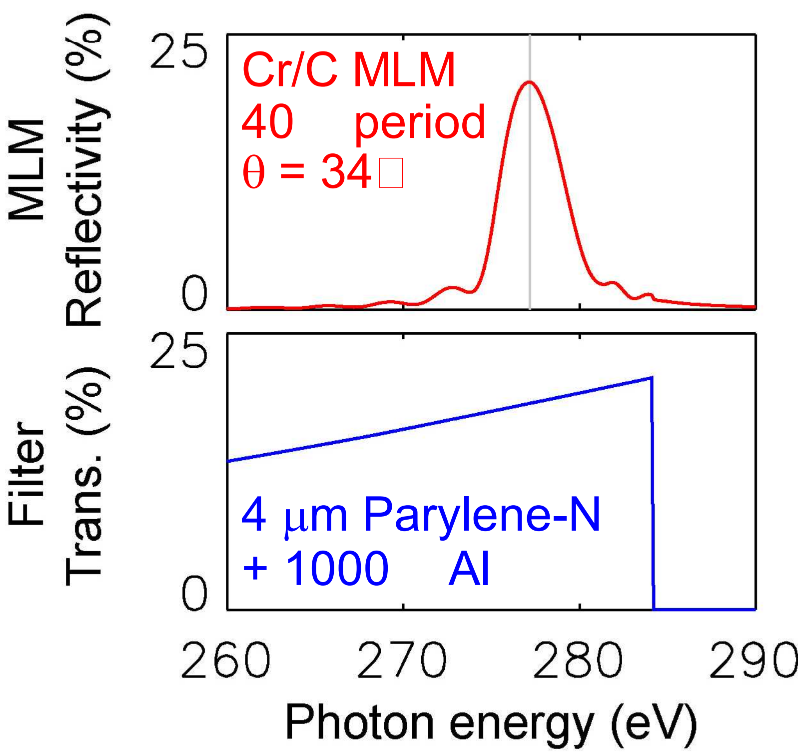
The actual microchannel plate detector systems used for imaging and spectroscopy are shown here



- Multiframe
- MCP's: 50 mm diameter
- MCP Gate times: ~0.8 - 5 ns

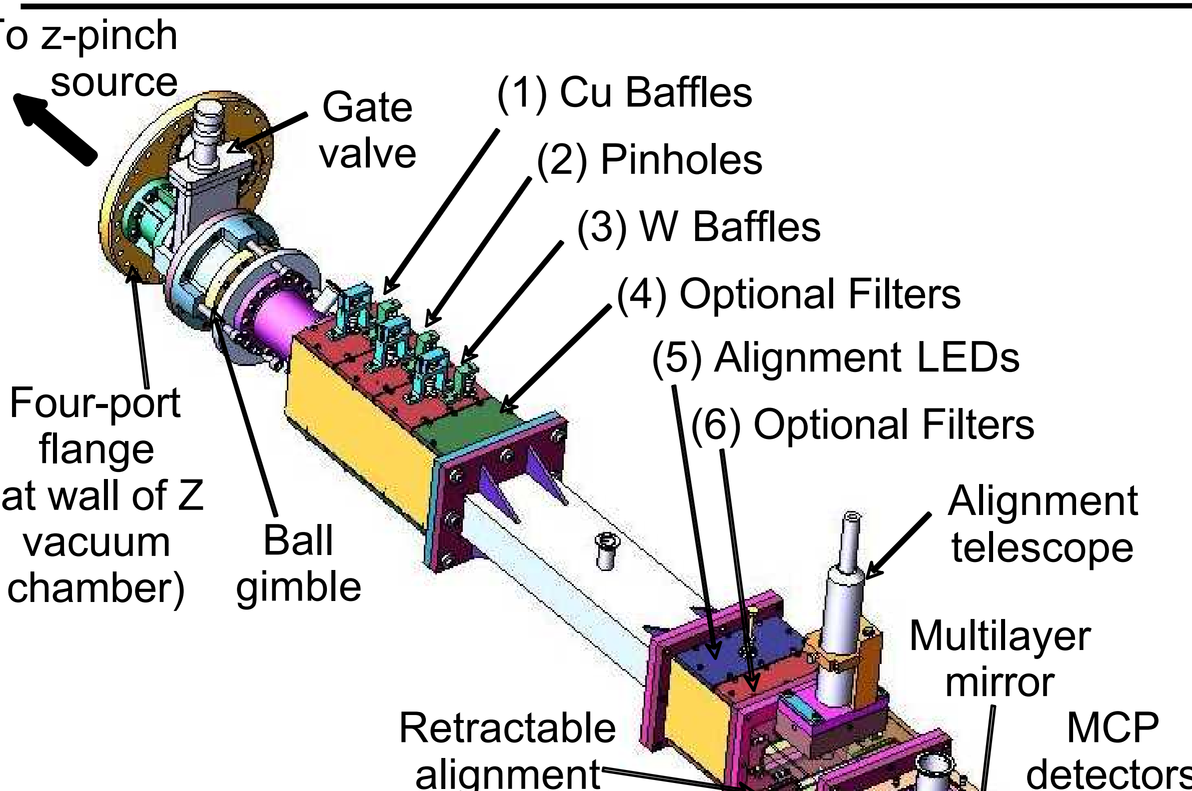
Multilayer mirror (MLM) pinhole camera produces monochromatic images

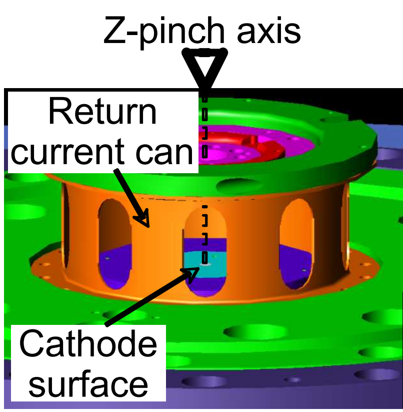




- **Pinhole images are reflected from planar Cr/C multilayer mirror (MLM)**
  - **Calculated 20% peak reflectivity, ~5 eV photon energy bandwidth**
  - **34° grazing angle allows shielding of detector from hard x-rays**
- **Thin filter blocks UV/visible light, suppresses second harmonic MLM reflection**
- **Instrument on the Z machine combines MLM-reflected and standard pinhole cameras (PHC)**

MLM PHC is currently fielded on the Z accelerator



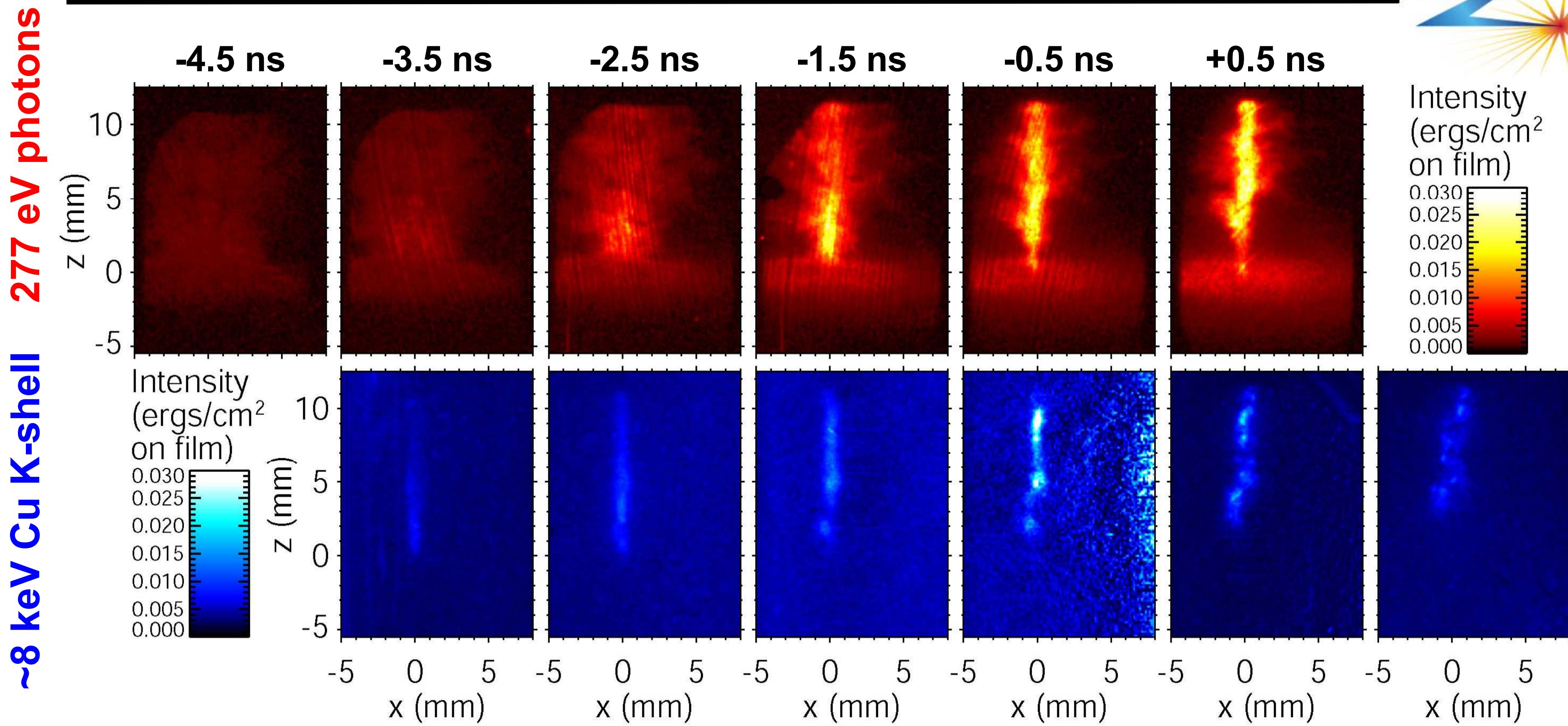


View of load region from 12° Line-of-sight

- Instrument mounts on 12° side-on LOS
- 3 PHCs can be fielded (two shown)
- Ball gimble pivots to align with source
- Alignment under vacuum corrects for pipe sag and movement in Z load region
- Instrument is differentially pumped behind gate valve

B. Jones, C. Deeney, A. Pirela, C. Meyer, D. Petmecky, P. Gard, R. Clark, and J. Davis, Rev. Sci. Instrum. 75, 4029 (2004).

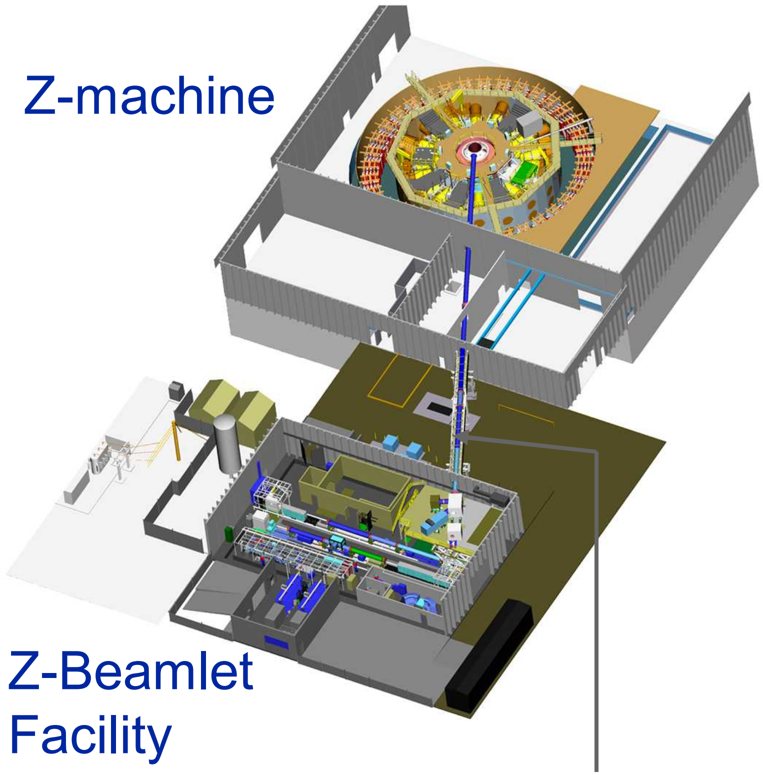
MLM PHC has excellent signal-to-noise during final implosion



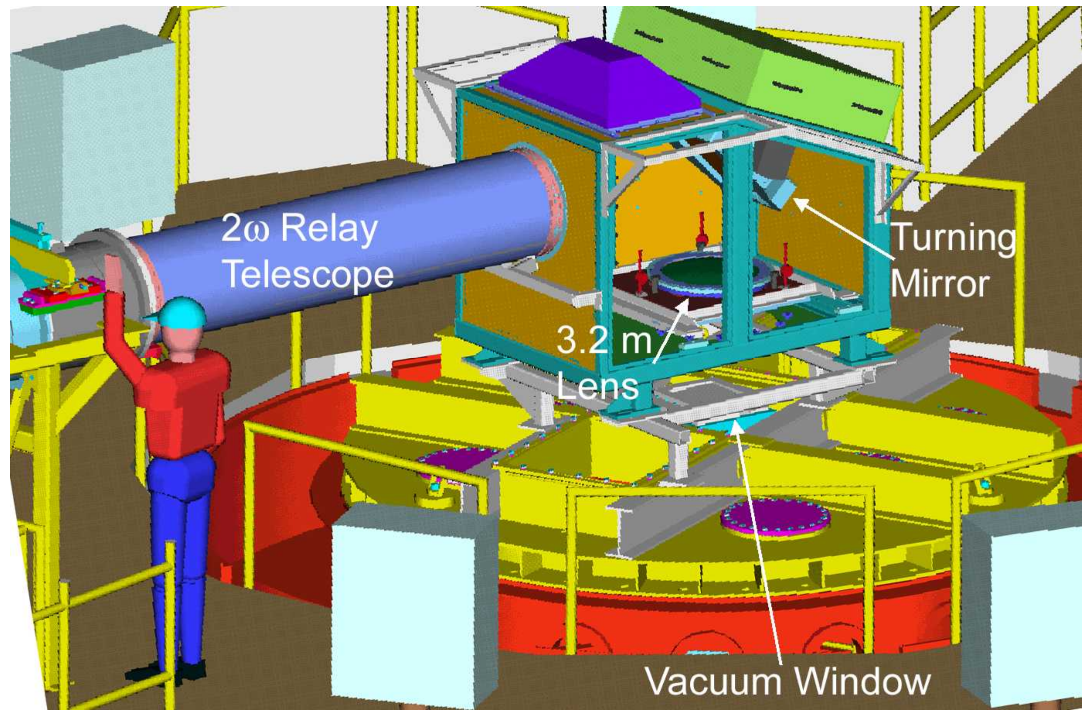
- No hard x-ray background on MLM-reflected images
- Gradual accretion of mass on axis during ~5 ns x-ray pulse rise
- 3D structure: zipper at stagnation, trailing mass at large radius
- Imaging at 2-3 energies can determine n,T profiles

Z1436 Š Coverdale Š Nested Cu Wire Array

The Z-Beamlet laser is integrated into the Z-machine using on-axis final optics

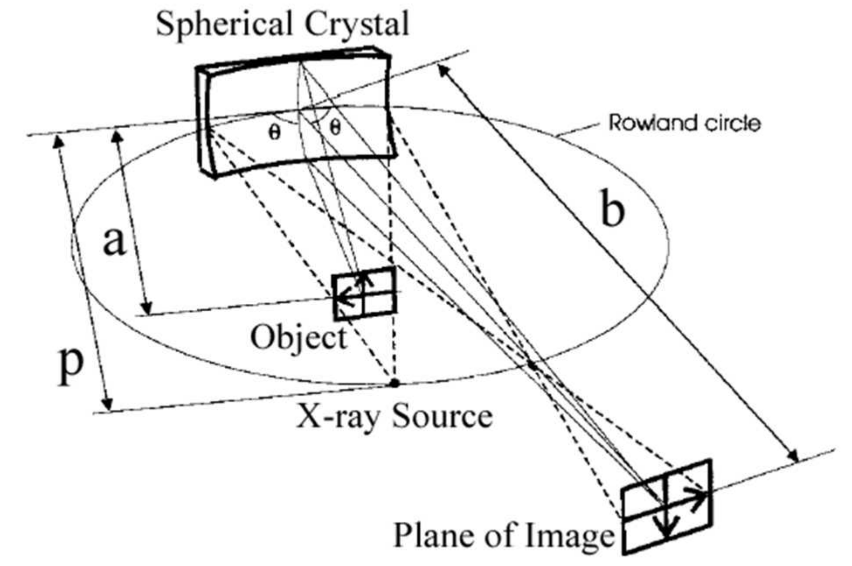


A ~ 75-m-length relay telescope brings the beam to the top of the Z chamber



At the Z-machine a turning mirror and lens are used to make 50-150 μm diameter x-ray spots 100-200 mm from the axis ($>10^{15}$ W/cm^2 on target → 0.1-1 J x rays)

Curved-crystal imaging offers an elegant solution for backlighting in hostile environments

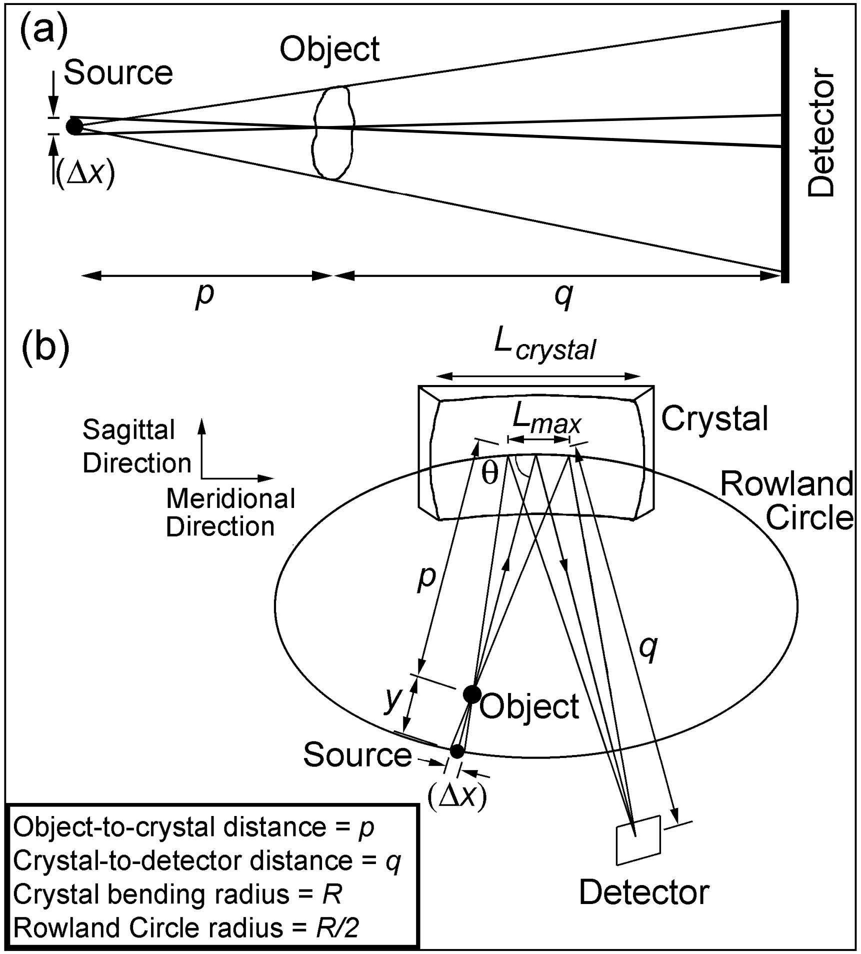


Bent-crystal Imaging

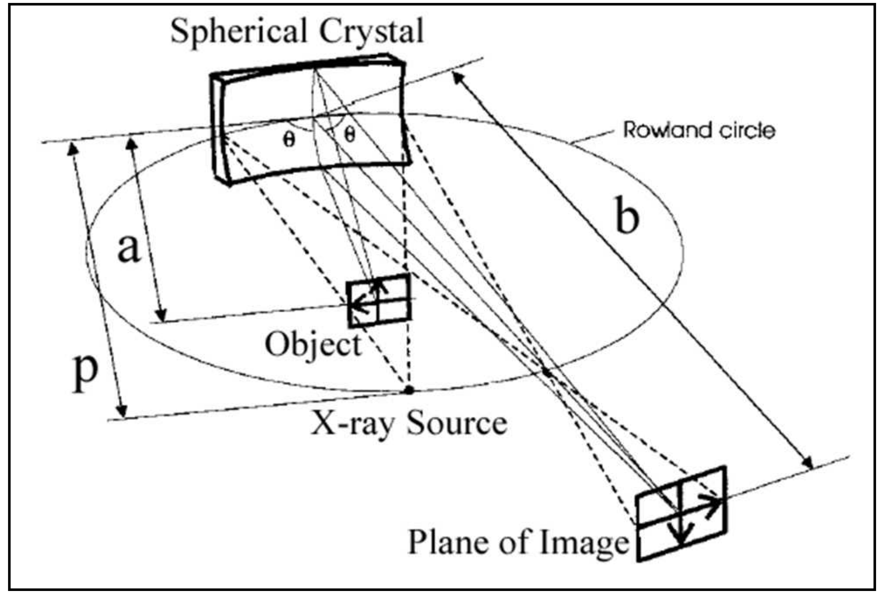
- **Monochromatic (~0.5 eV bandpass)**
- **10 micron resolution**
- **Large field of view (e.g. 20 mm x 4 mm)**
- **Debris mitigation**

- **S.A. Pikuz *et al.* proposed the concept in mid-1990s.**
  - S.A. Pikuz *et al.,* Rev. Sci. Instrum. **68**, 740 (1997).
- **Y. Aglitskiy *et al.* implemented a 1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al*., Rev. Sci. Instrum. **70**, 530 (1999).
- **J.A. Koch *et al.* proposed crystal imaging techniques for microscopy/backlighting on NIF**
  - J.A. Koch *et al*., Rev. Sci. Instrum. **70**, 525 (1999).

Monochromatic backlighting and point-projection backlighting comparison



Backlighting Geometries



Bent-crystal Imaging

- Monochromatic (~0.5 eV bandpass)
- 10 micron resolution
- Large field of view (e.g. 20 mm x 4 mm)
- Debris mitigation
- Source 0.1-1 J; Object ~1 MJ

Two versions are in use on Z: 1.865 keV or 6.151 keV radiography diagnostics*

1.865 keV Radiography

- X-ray source: He-like Si 2*p* $^1P_1$ line at 1.865 keV
- Crystal: R=250 mm Quartz 10-11 (2d=6.685)
- Bragg Angle: 83.9°
- Magnification: 6.0
- Field of view: 4 mm tall by 20 mm wide
- Spectral bandpass: <0.5 eV
- Spatial resolution: 9-10 microns
- Detector: Kodak RAR 2497 film

This diagnostic based on previous work by Y. Aglitskiy *et al.*, Rev. Sci. Instrum. 70 (1999)

6.151 keV Radiography

- X-ray source: He-like Mn 2*p* $^3P_1$ line at 6.151 keV
- Crystal: R=250 mm Quartz 22-43 (2d=2.030)
- Bragg Angle: 83.15°
- Magnification: 6.0
- Field of view: 4 mm tall by 20 mm wide
- Spectral bandpass: <0.5 eV
- Spatial resolution: 10-11 microns
- Detector: Kodak DEF film

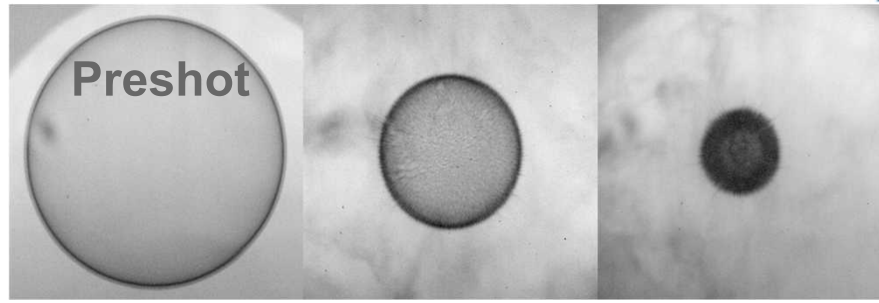
This diagnostic based on proposal in J. A. Koch *et al.*, Rev. Sci. Instrum. 70 (1999)

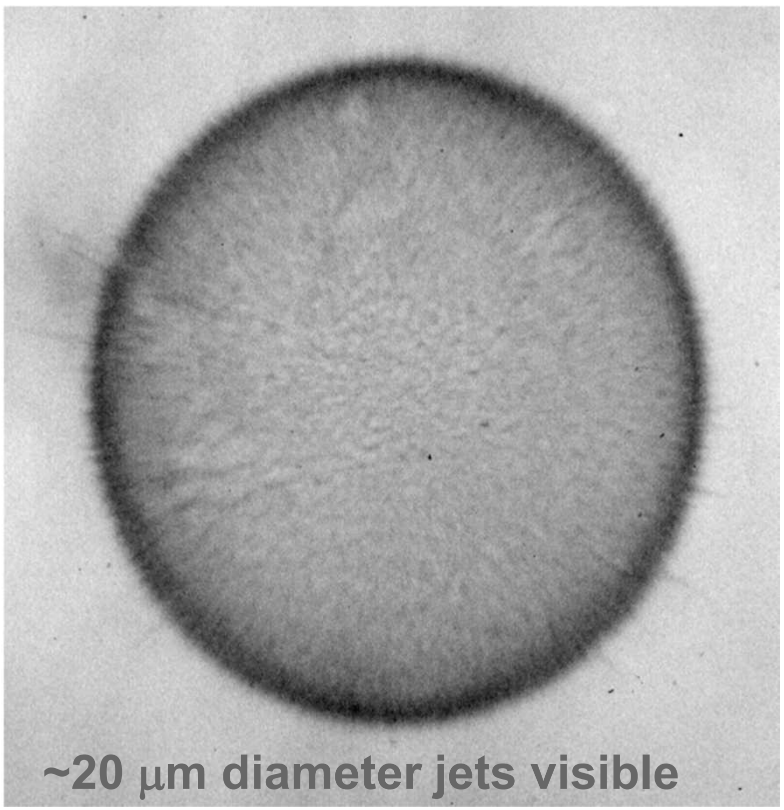
* Z radiography diagnostics described in D.B. Sinars *et al.*, Rev. Sci. Instrum. 75, 3672 (2004)

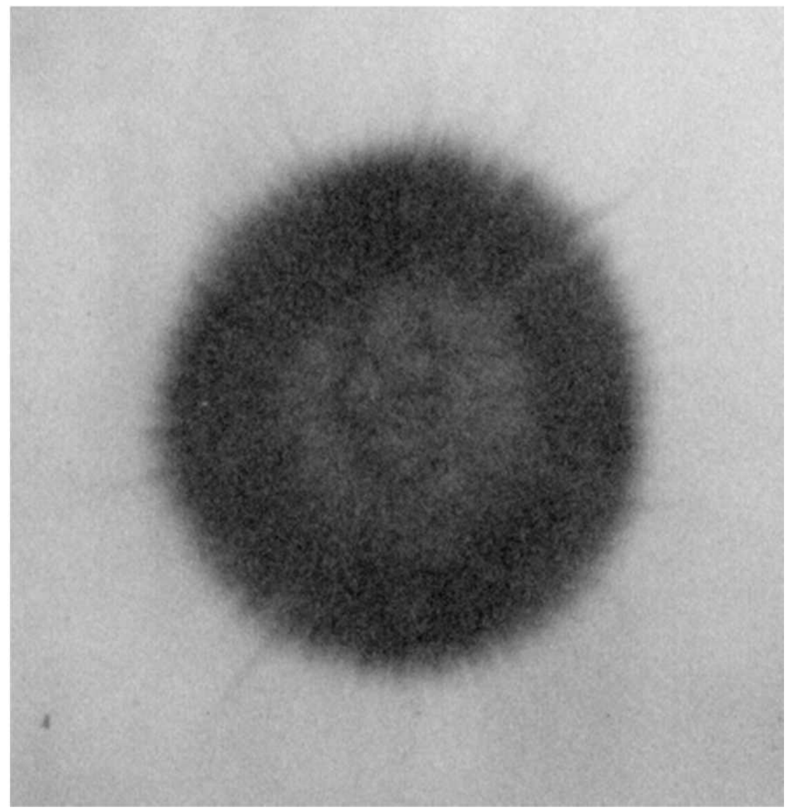
The power of the curved-crystal imaging technique in suppressing Z's hard x-ray bremmsstrahlung background and debris is clearly shown in these radiographs*

3.4-mm diameter plastic ICF capsule

Capsules had 100s of known defects on surface that apparently produced a myriad of small jets



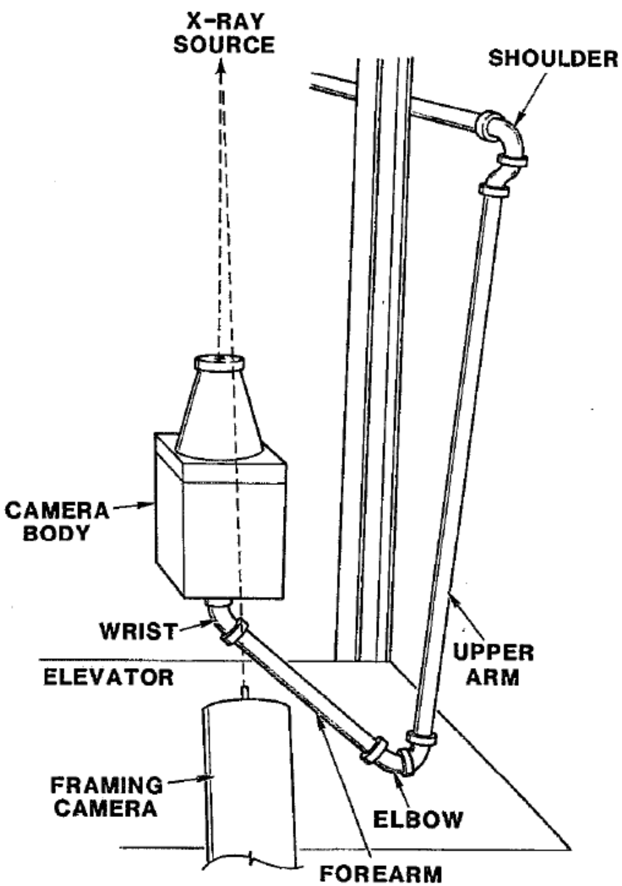




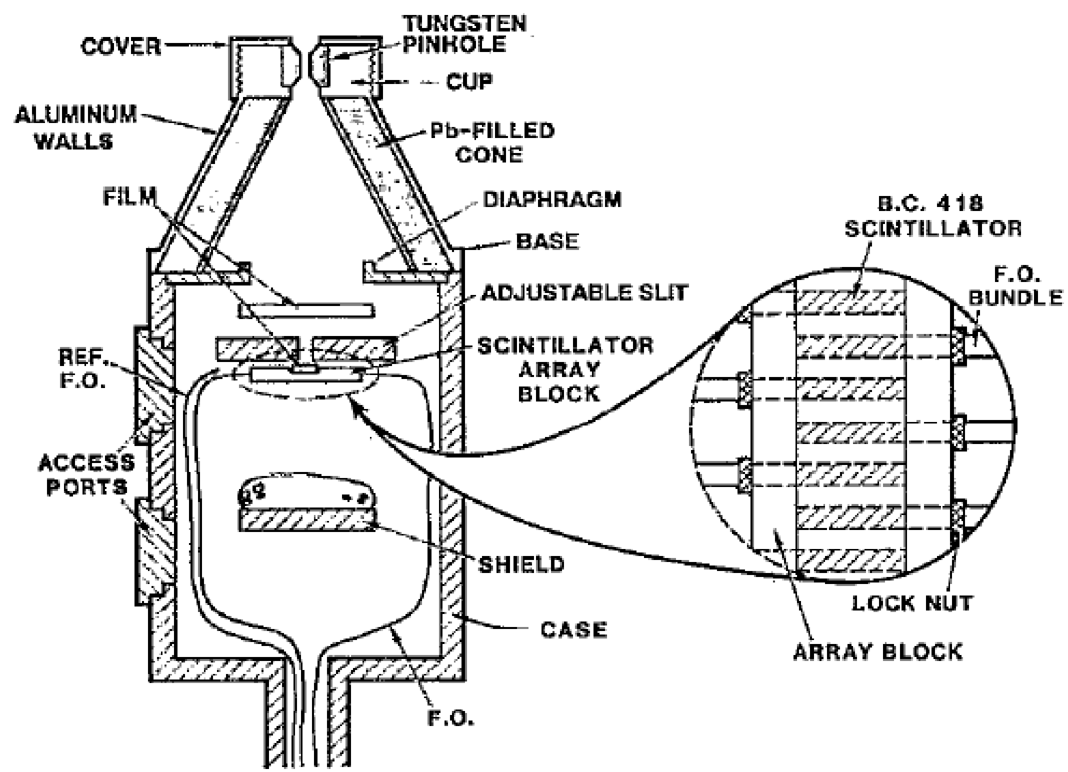
* M.E. Cuneo, G.R. Bennett

A time-resolved hard x-ray pinhole camera with scintillator/fiber optic image plane was successfully fielded on Sandia's Saturn facility

Schematic of Overall Arrangement



Schematic of Pinhole Camera Body



D. L. Fehl, R. J. Leeper, J. R. Lee, M. A. Hedemann, W. A. Stygar, B. R. Sujka, D. E. Hebron, And S. J. Robischon, Rev. Sci. Instrum. 65, 1935 (1994).

This time-resolved pinhole camera was hardened to enable operation in intense x-ray bremsstrahlung backgrounds with end-point energies of ~ 2 MeV

- The detector in this camera is a 20-channel linear array of plastic scintillators that were each 3.2 mm in diameter and 2.54 cm long
- Optical signals from the scintillators are conducted by fiber-optic bundles to a remote bank of photomultiplier tubes
- Each fiber-optic bundle contained 16 high purity stepped-index SiO_2 fibers, 200 μm in diameter and 50 m in length
- These fiber-optic bundles were shielded with steel pipe with 4-cm-thick walls
- An additional fiber-optic bundle is mounted near the scintillator array, not attached to a scintillator, samples the background signal from Cherenkov interactions in the glass fibers
- Nominally, the absolute sensitivity of the channels is ~ 18 nC/R at 1.1 MeV
- The Cherenkov background signal was ~ 2 % of the signal produced by a scintillator of equal length when the fiber bundle was oriented 90 degrees to a beam of ^{60}Co gamma-rays

A suite of neutron diagnostics have been developed for capsule experiments

DIAGNOSTIC	QUANTITY OBSERVED	USED TO OBTAIN
Neutron TOF Detector	2.45 MeV or 14.1 MeV Neutrons	Neutron Yield and Ion Temperature
Pb Activation Detector	2.45 MeV or 14.1 MeV Neutrons	Total Neutron Yield
Indium or Beryllium Activation Detector	2.45 MeV Neutrons	Total Neutron Yield
Copper Activation Detector	14.1 MeV Neutrons	Total Neutron Yield

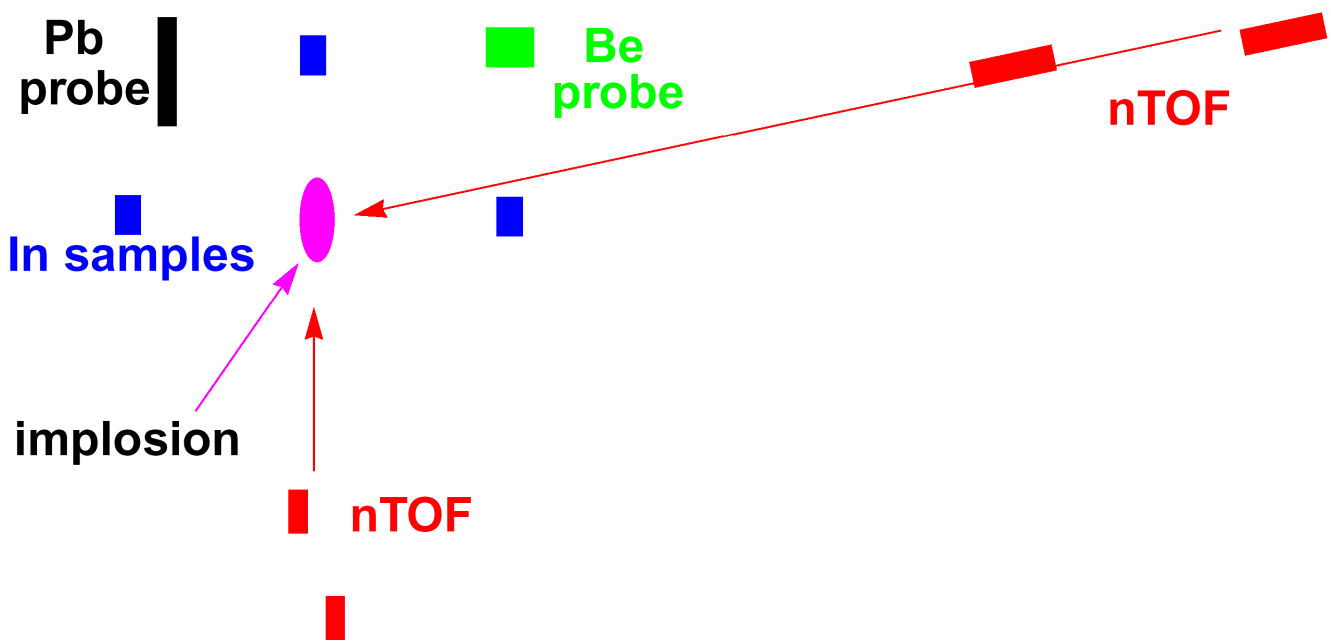
Neutron diagnostics typically fielded in high energy density experiments include neutron activation and neutron time-of-flight detectors

- **Passive (activation) detectors:**
  - **Indium -- ^{115}In (n , n′)^{115m}In (336.0 keV, $\tau_{1/2}$ = 4.49 hr.)**
  - **Copper -- ^{63}Cu(n , 2n)^{62}Cu ($\beta+$, $\tau_{1/2}$ = 9.74 min.)**
  - **Lead probe -- ^{207}Pb(n , n′)^{207m}Pb (1064 keV, $\tau_{1/2}$ = .8 sec.)**

- **Active (neutron-time-flight) detectors:**
  - **Conventional scintillator/photomultipler detector**
  - **Scintillator/microchannel plate detector**

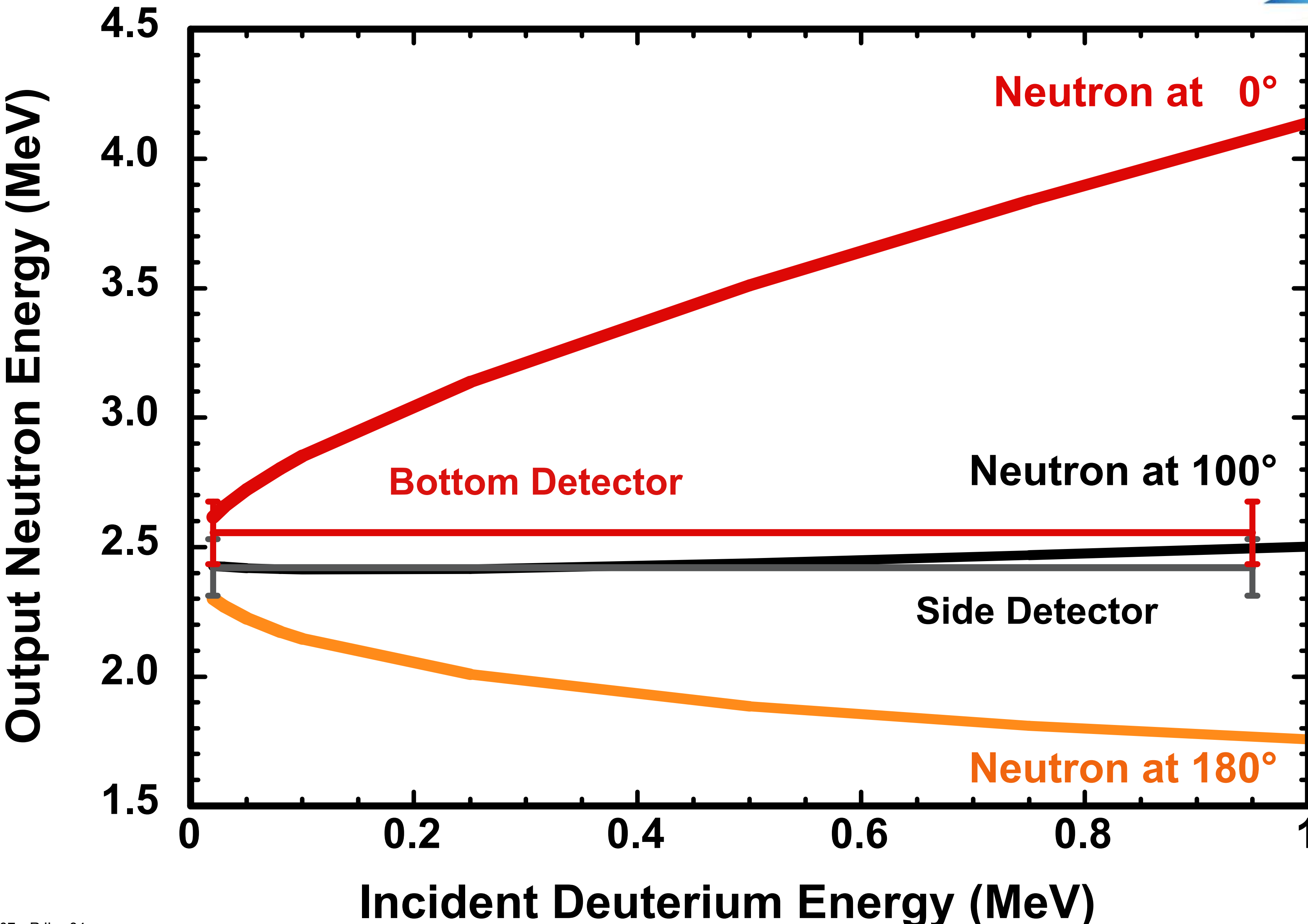
- **The ^{115}In (n , n′)^{115m}In and ^{207}Pb(n , n′)^{207m}Pb reactions may also be activated by a large flux of hard x-rays via the reactions ^{115}In (γ , γ′)^{115m}In and ^{207}Pb(γ , γ′)^{207m}Pb and so these hard x-ray backgrounds must be characterized to determine their contribution to the activation signals**

Schematic of a typical neutron diagnostic arrangement used in high energy density experiments

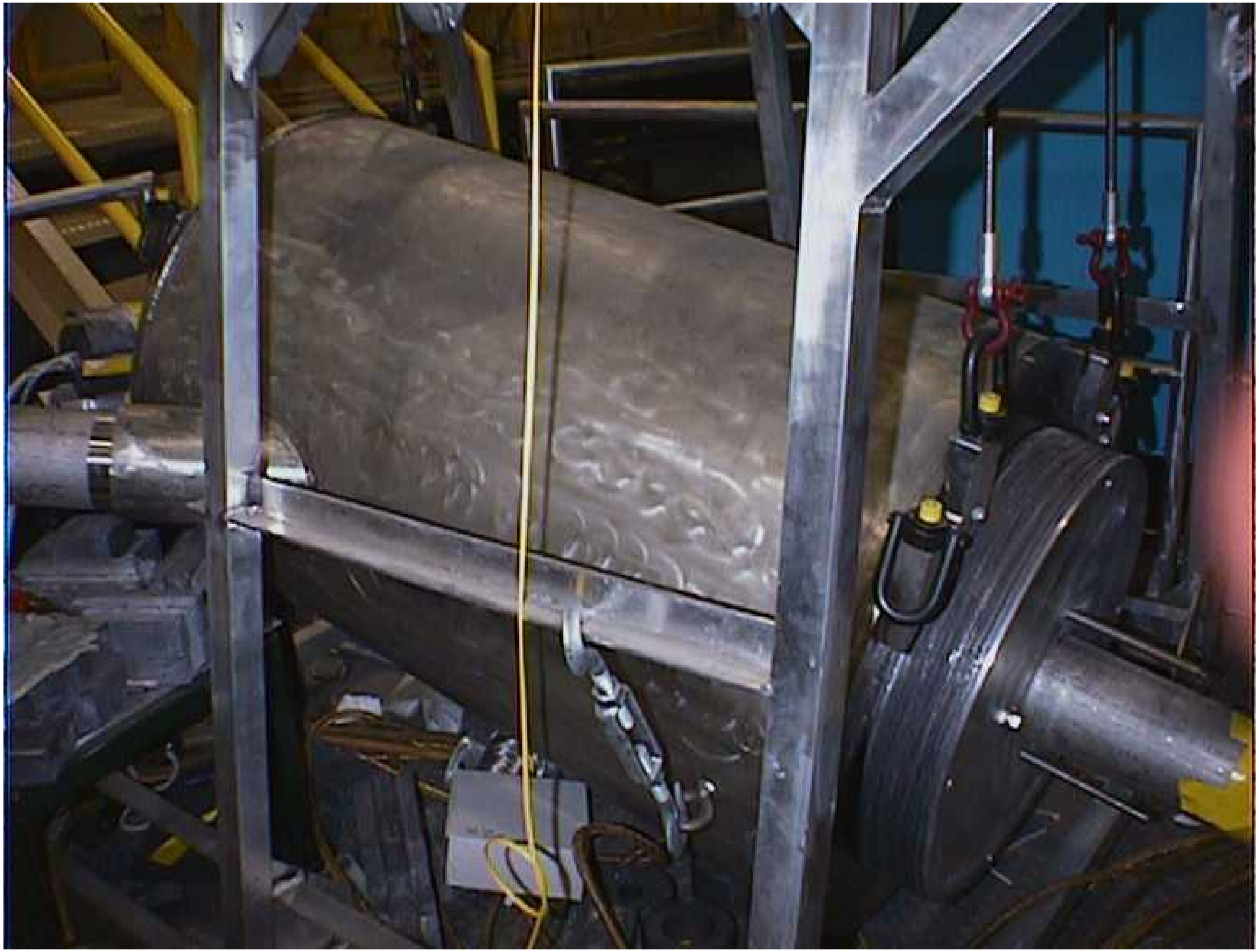


C. L. Ruiz, G. W. Cooper, S. A. Slutz, J. E. Bailey, G. A. Chandler, T. J. Nash, T. A. Mehlhorn, R. J. Leeper, D. Fehl, A. J. Nelson, J. Franklin, and L. Ziegler, Phys. Rev. Lett. 93, 015001 (2004).

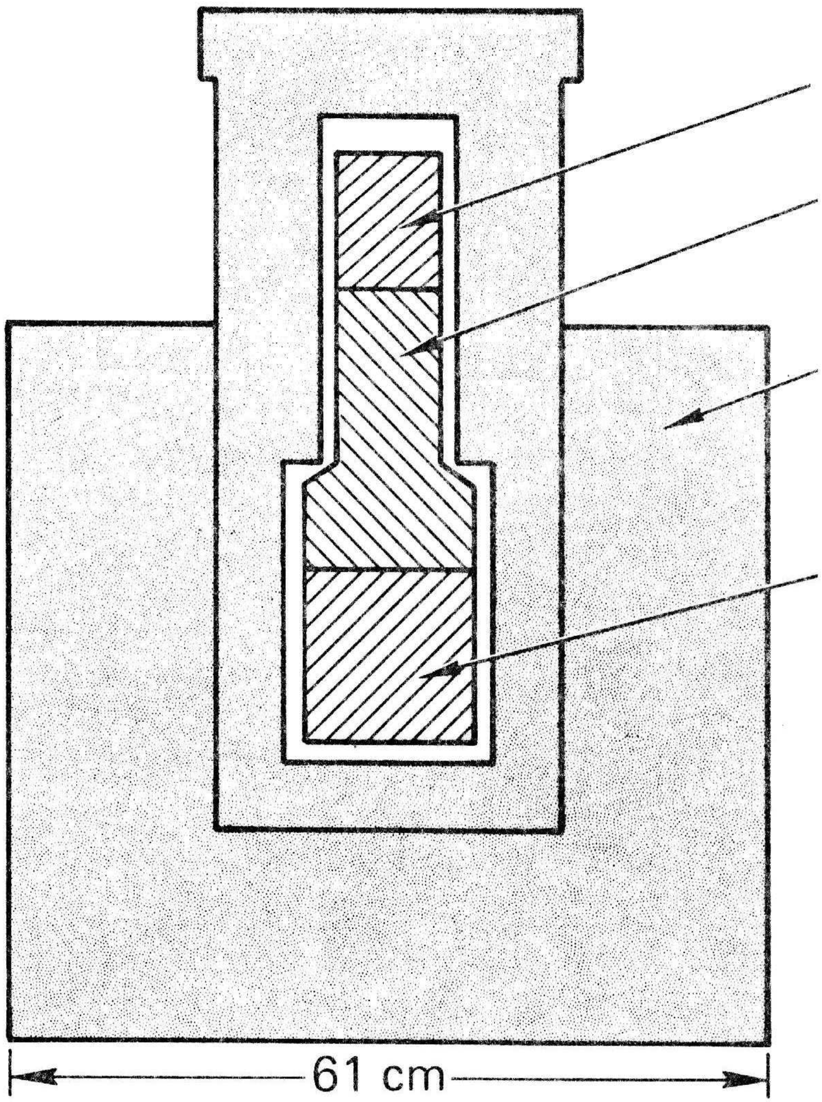
The measured side and on-axis neutron energies restricts the possibility of a beam induced neutron mechanism



A heavy Pb shield (9000 lbs.) and collimator is required for neutron time-of-flight measurements on Z



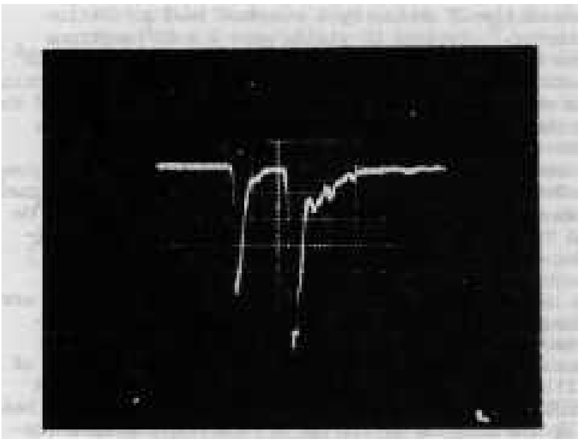
Scintillator photomultiplier combination (PMT) plus lead shielding



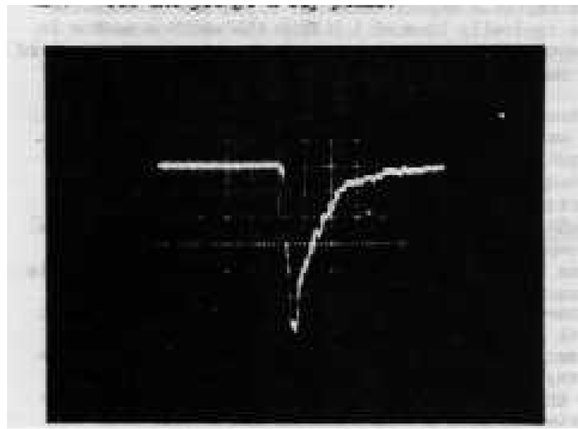
- Typical hard x-ray bremsstrahlung backgrounds in Z class pulsed power system are of order 10^9-10^{10} Rad/s
- Scintillator photomultiplier sensitivity in experiments designed to detect 10^{10} neutrons/4π is of order 0.1 amp/(Rad/s)
- Typical PMT linearity is 0.5-1.0 amps
- To prevent PMT saturation, detector shielding must provide attenuation factor of order 10^8 to 10^9

The thermonuclear neutron signature through heavily shielded scintillator photomultipliers was measured using a specially developed 3 ns neutron source (DD or DT)

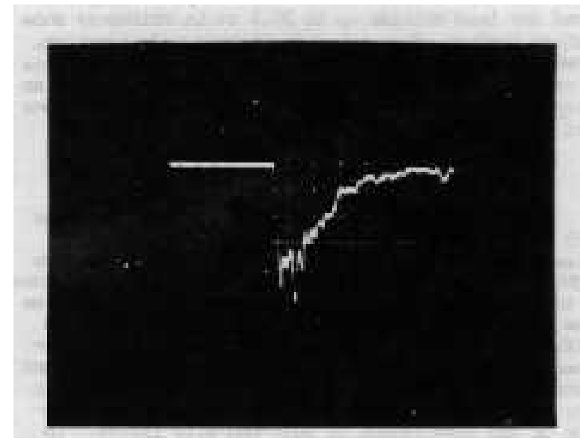
DD neutron pulse
1.9 cm Pb



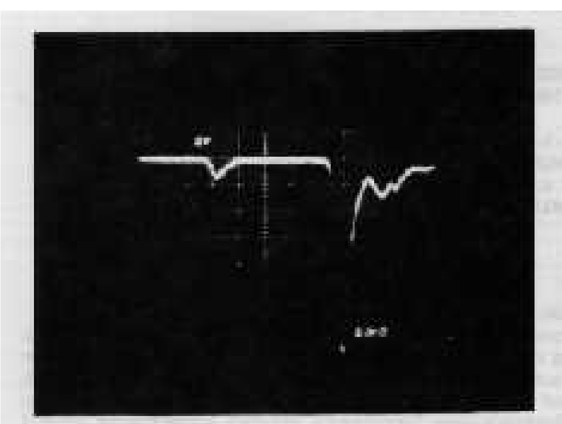
DD neutron pulse
10.2 cm Pb



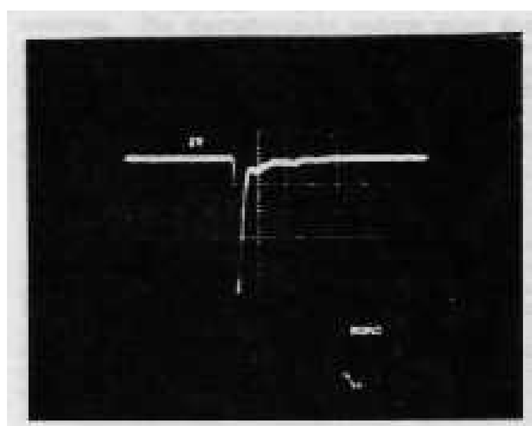
DD neutron pulse
20.3 cm Pb



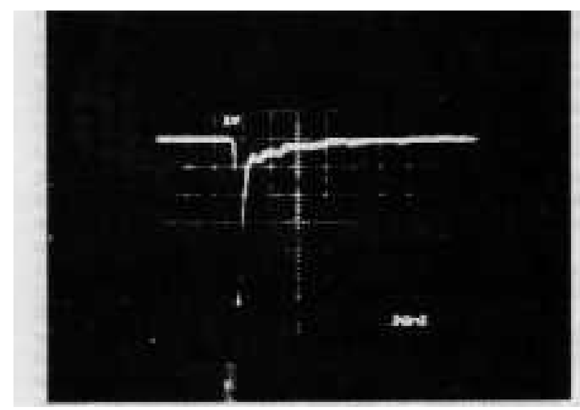
DT neutron pulse
1.9 cm Pb



DT neutron pulse
10.2 cm Pb

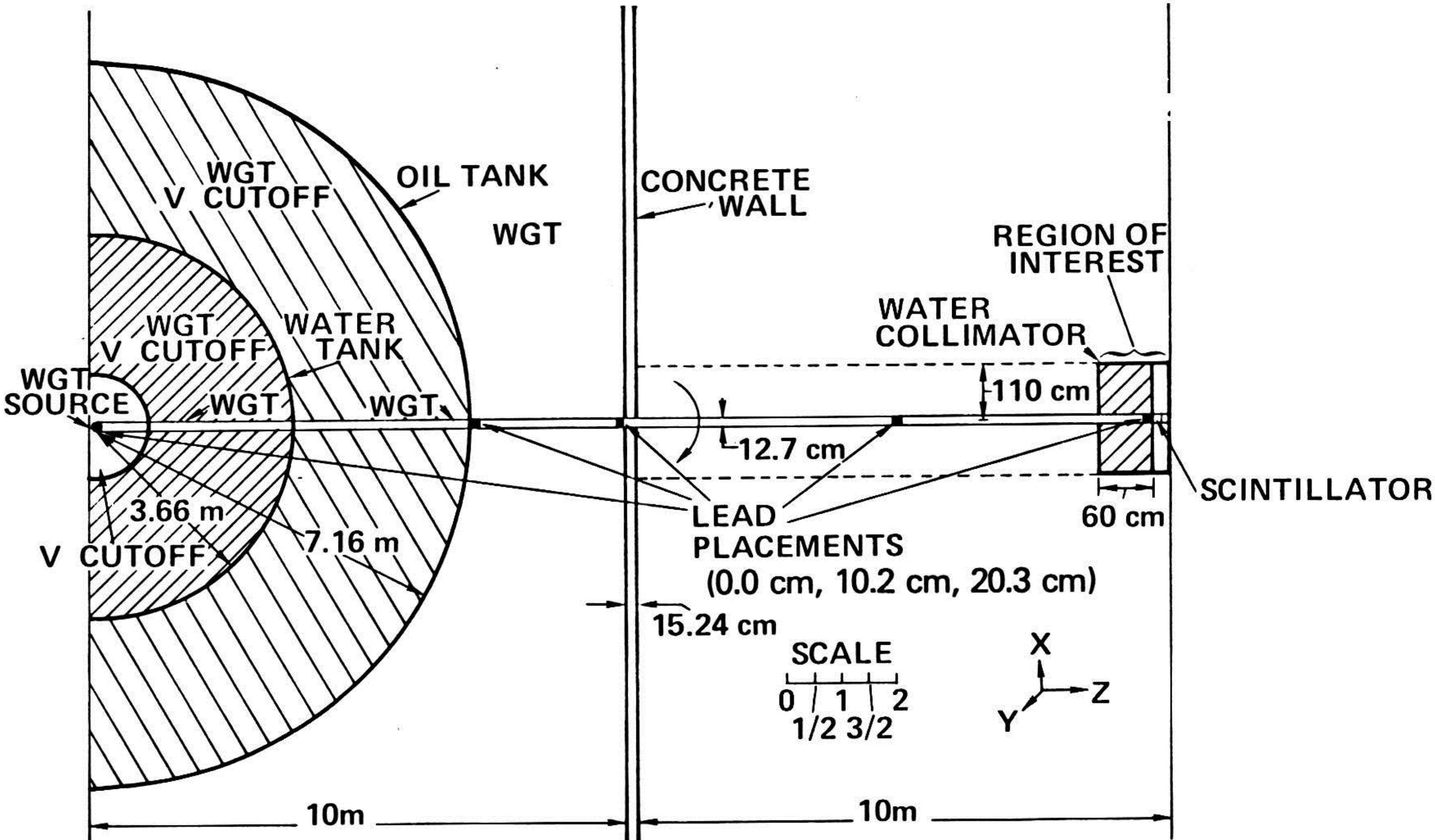


DT neutron pulse
20.3 cm Pb

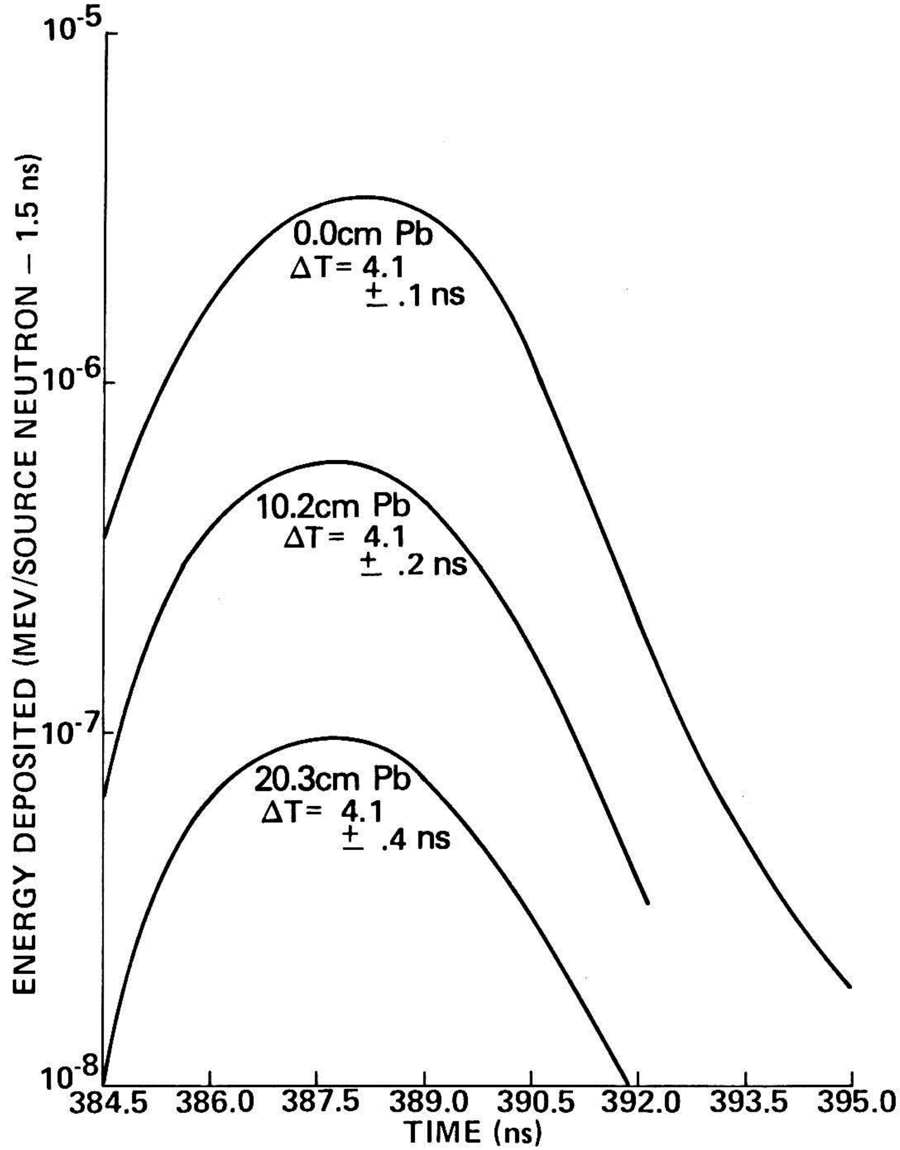


R. J. Leeper and J. Chang, IEEE Trans. Nucl. Sci. NS-29, 798 (1982).

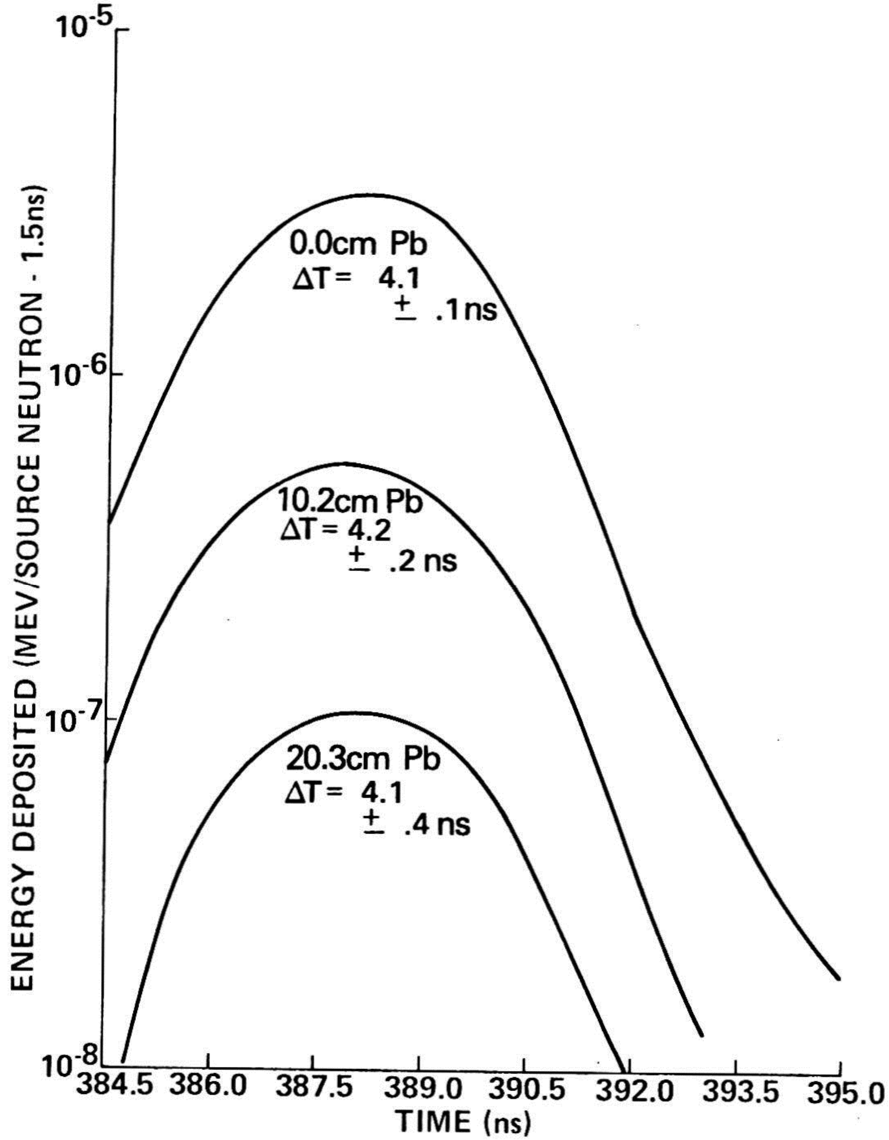
Model diagram used in Monte Carlo calculations of a 20 m line-of-sight with varying placements of Pb



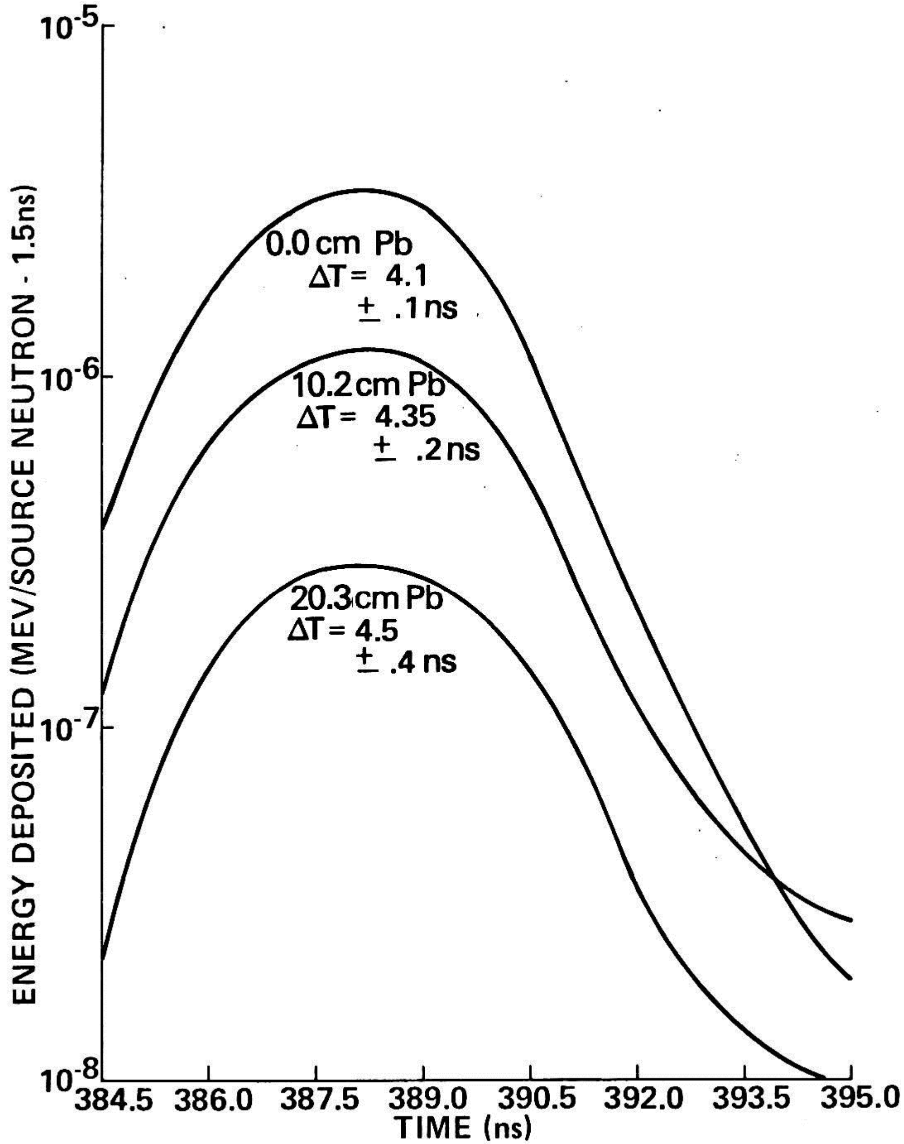
Scintillator energy deposition with lead filter 730 cm from source



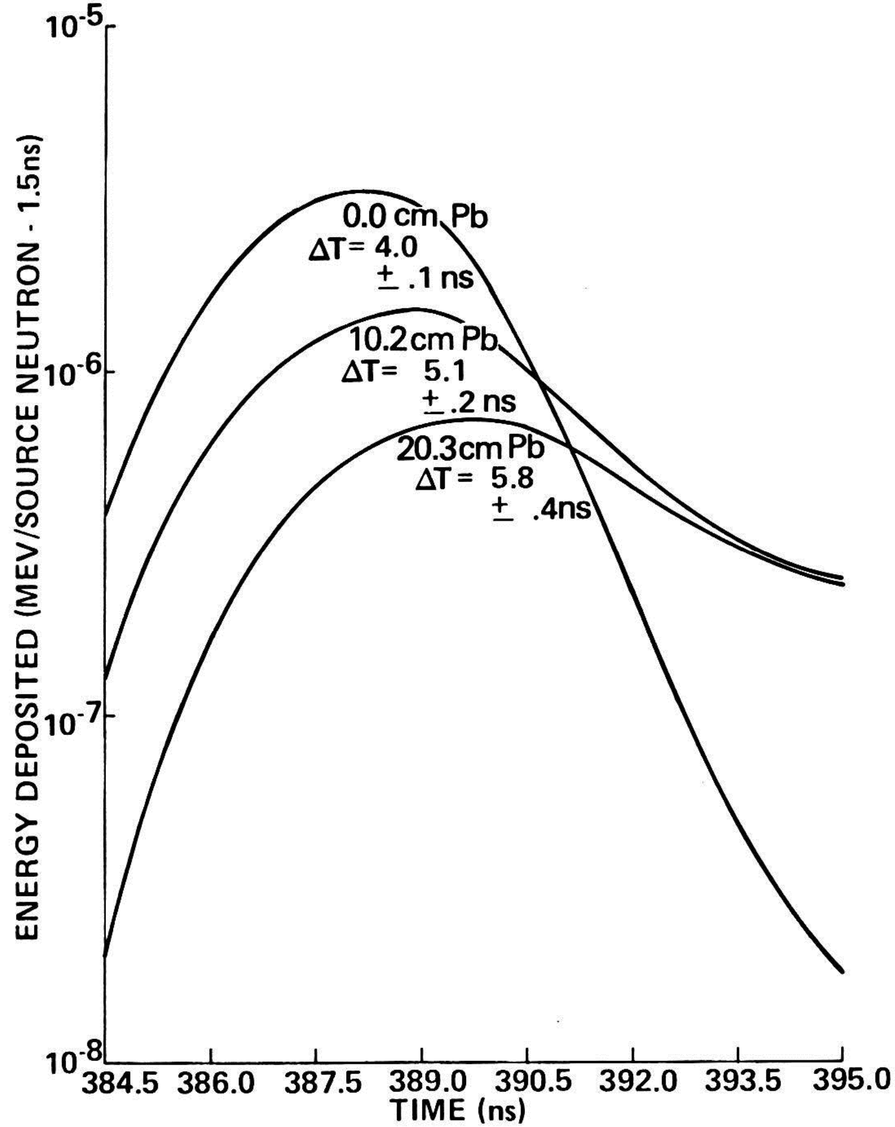
Scintillator energy deposition with lead filter 980 cm from source



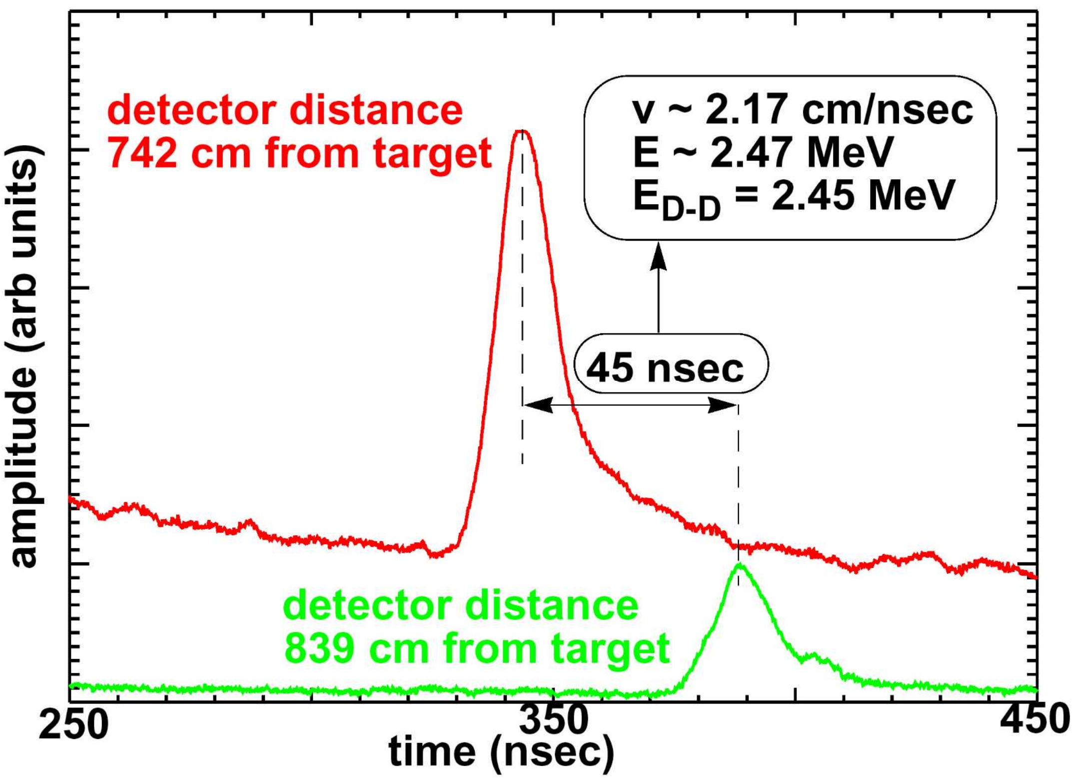
Scintillator energy deposition with lead filter 1980 cm from source



Scintillator energy deposition with extra lead shielding surrounding detector with no water collimator present



The neutron energy and yield are consistent with thermonuclear production

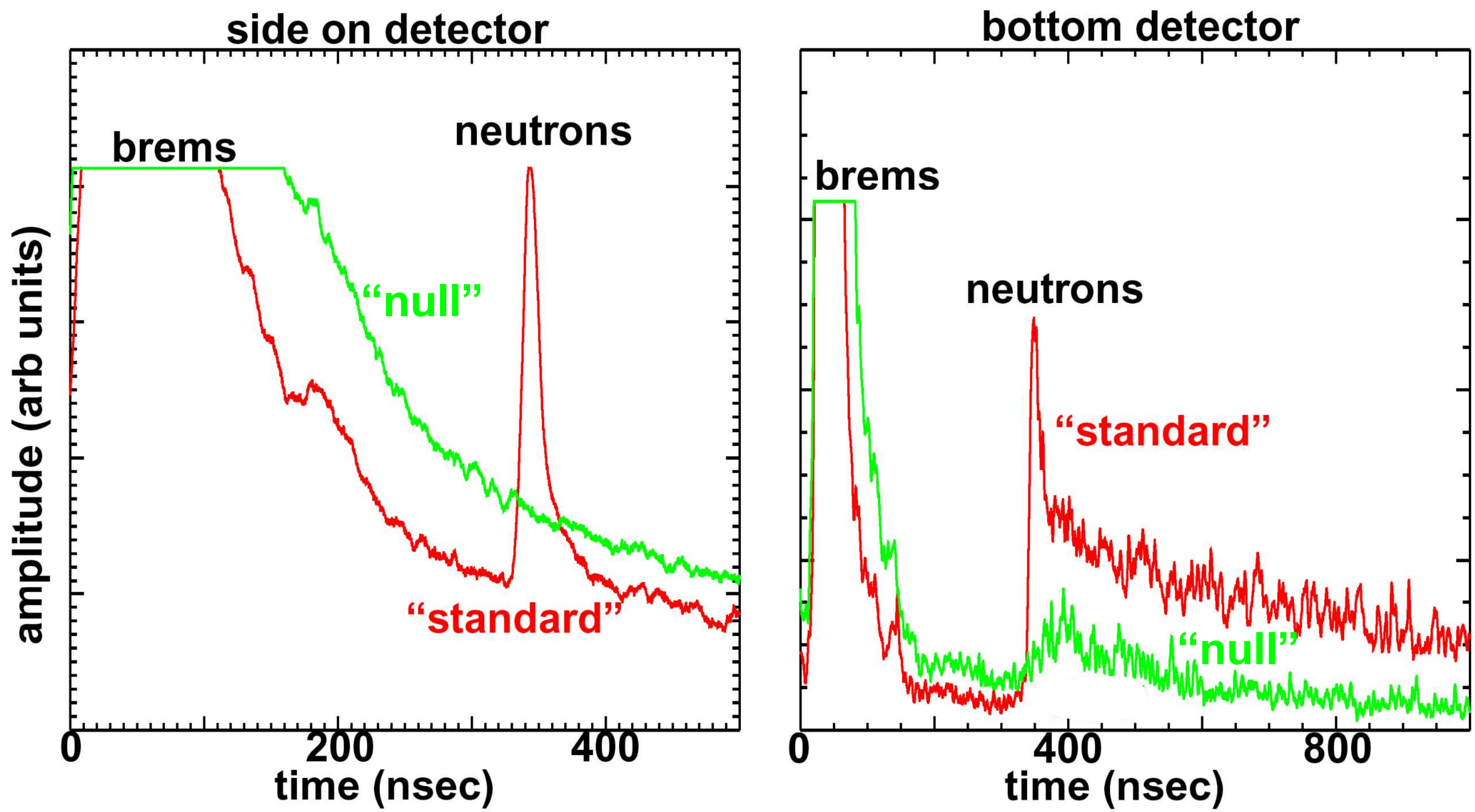


data is from z1031
50 μm CH wall,
2 mm diameter
24 atm D2 + 0.085 atm Ar

side-on detectors

- Measured neutron energy from two side-on detectors for z1031 was 2.47 ± 0.12 MeV
- Measured neutron energy from two bottom detectors for z1031 was 2.56 ± 0.13 MeV
- Neutron yield (Shot z1031) of (2.6 ± 1.3) x10^{10} measured with In activation is consistent with calculated mass averaged T_i yield of ~2x10^{10}; 1-D predicted clean yield was ~ 2x10^{11}

Neutron time-of-flight signal dramatically decreases when Xe fill gas is added to “null” the production of thermonuclear neutrons



z1031“standard” fill(24 atm D2 + 0.085 atm Ar)
z1032“standard” fill + 0.6 atm Xe

- On Ņnull shots,Oneutron yield measured by Be activation decreased by more than an order of magnitude

A comprehensive suite of diagnostics have been made operational in the harsh envirnoment of the Z-facility at Sandia National Laboratories

- **This system of diagnostics must operate in an intense multi-MeV hard x-ray background of some 10^9-10^{10} rad/s, soft x-ray (100 eV to 3 keV) environment of 1.6 MJ at power levels of 200 TW, and EMP background of ~ 1 MV/m**
- **Additionally, the diagnostics are subjected to intense debris that is mitigated by line-of-sight fast closure valves and baffle arrangements**
- **Special care is taken to minimize noise on the cable runs by installing an outer steel braid to the Heliax cable runs and securing one end to the "N" connector at the diagnostic and attaching the opposite end to the screen box feedthrough**
- **X-ray pinhole camera that employ multi-layer mirrors have been used to reduce bremmsstrahlung backgrounds in framing camera images**
- **Curved-crystal imaging offers an elegant solution for backlighting in hostile environments by offering a dramatic reduction in x-ray bremsstrahlung background noise due the inherent narrow bandwidth of the technique and its low acceptance of debris**
- **Neutron diagnostics have been developed that are robust to the hard x-ray bremsstrahlung and thermonuclear neutrons have been detected in capsule experiments with total yields as low as 1×10^{10}**
- **Neutron shielding arrangements in "good geometries" have been studied that should offer improved neutron diagnostics on Sandia's ZR facility**