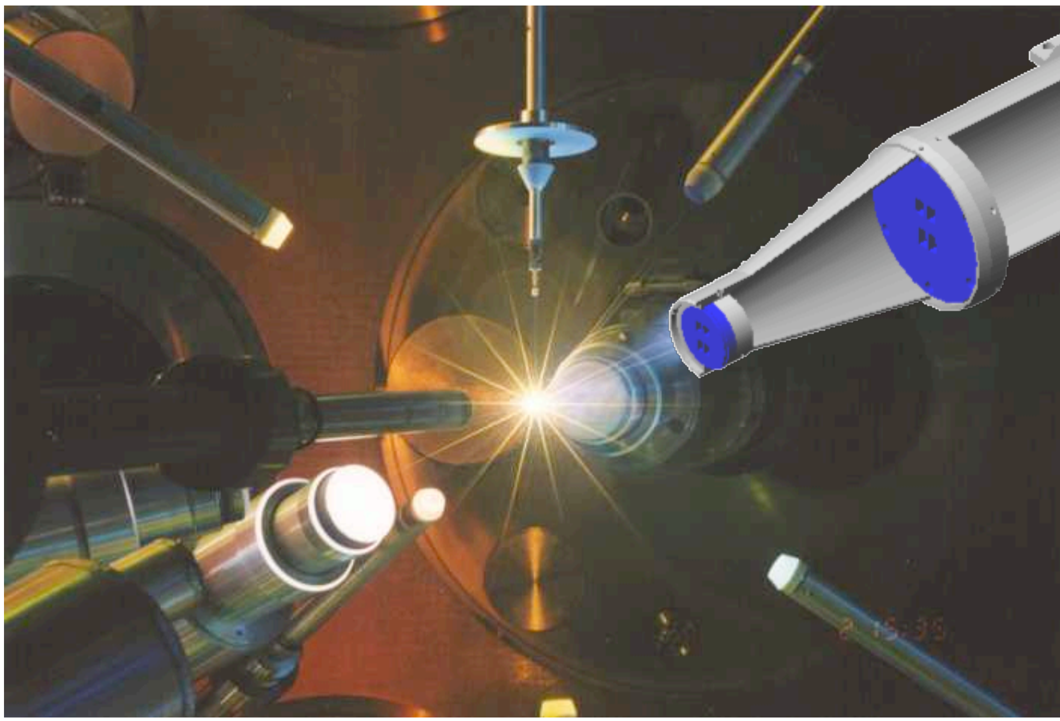
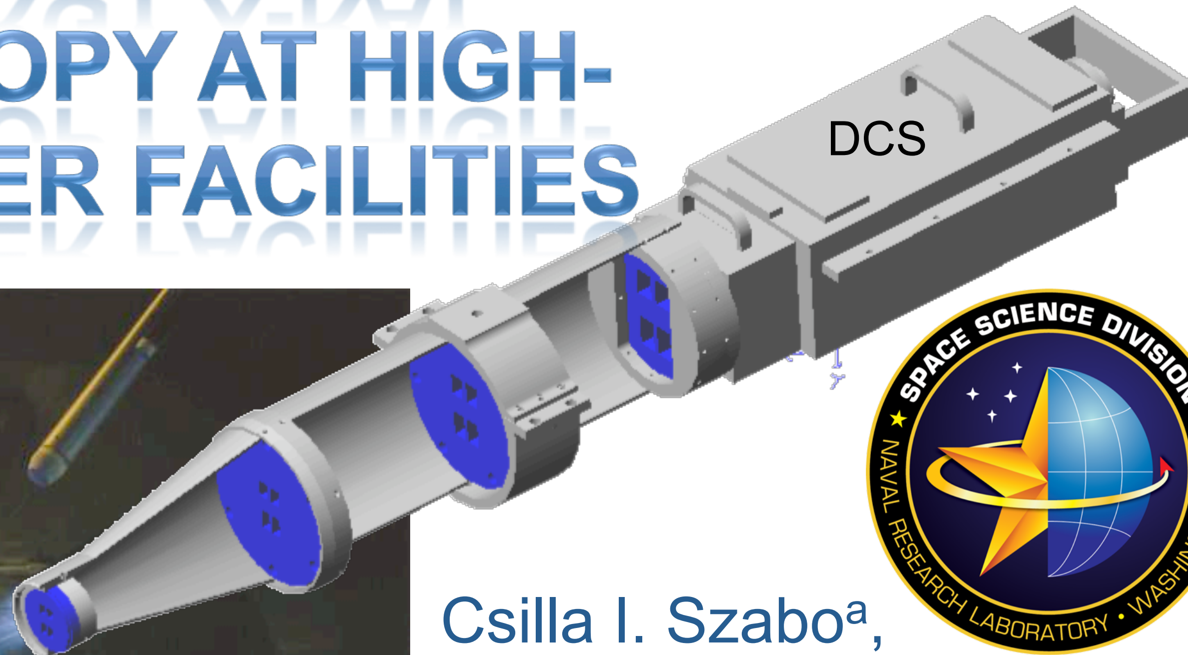
X rays as a tool for probing Extreme States of Matter
EMMI workshop, GSI, Darmstadt, Germany, June 7-9, 2010

HIGH ENERGY X-RAY SPECTROSCOPY AT HIGH-ENERGY LASER FACILITIES





Csilla I. Szabo[a],

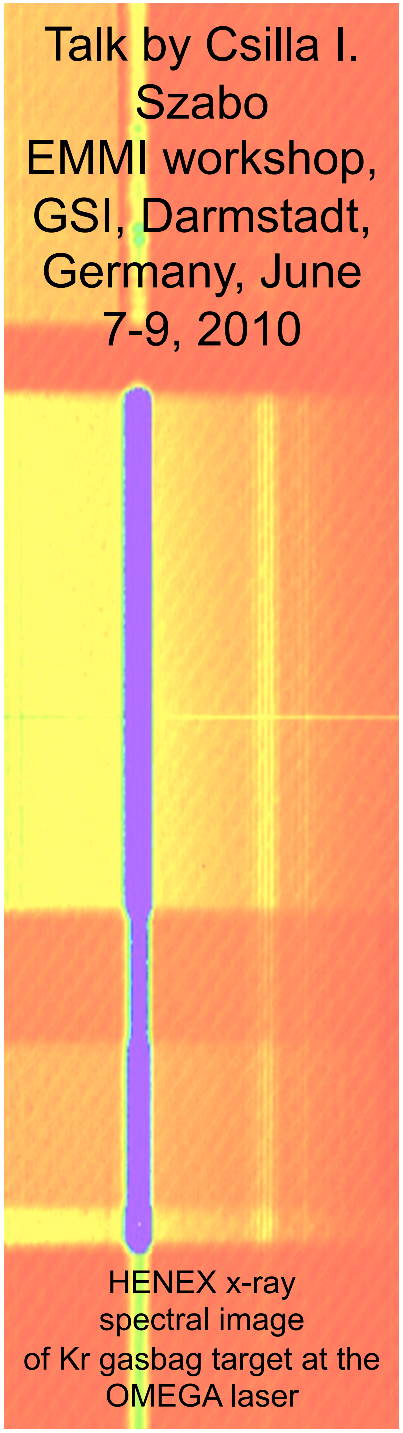
J.F. Seely[b], U. Feldman[a], L.T. Hudson[c], A. Henins[c]

[a]*Artep Inc., 2922 Excelsior Spring Circle, Ellicott City, MD 21042 USA*

[b]*Space Science Division, Naval Research Laboratory, Washington DC 20375 USA*

[c]*National Institute of Standards and Technology, Gaithersburg, MD 20899 USA*

Collaboration: LLNL, LANL, LLE, LULI, CELIA



HENEX x-ray spectral image of Kr gasbag target at the OMEGA laser

HIGH ENERGY X-RAY SPECTROSCOPY AT HIGH-ENERGY LASER FACILITIES

- Outline -

① Introduction

- High Energy Density Physics and Inertial Confinement Fusion (ICF) research
- X-ray spectroscopic needs at high energy density facilities
- How to detect a high energy x-ray spectrum in a few nano seconds?

② Cauchois type x-ray spectrometer for laser facilities

③ Enhancement of resolving power and source size measurement with the Cauchois type spectrometer

- a few examples of the diagnostics built by the NRL-NIST team
- Newest spectrometers

Motivations of ICF Research

Energy research:
IC fusion ignition
and energy gain

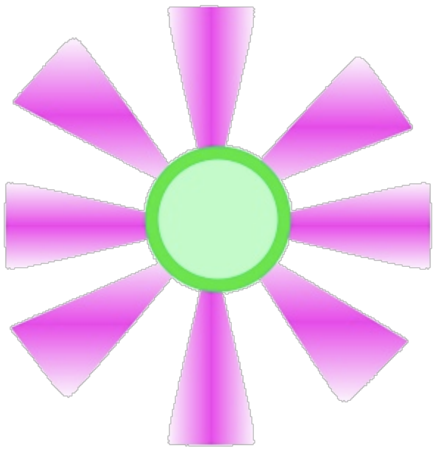
National security -
Nuclear weapons
effects & testing

- Basic science:
  - -- plasma physics, (99% of the visible universe)
  - -- radiative properties and radiation transport
  - -- material properties (under extreme conditions)
  - -- hydrodynamics
  - -- atmospheric and astrophysical phenomena
  - -- atomic physics of highly-charged ions, etc., etc.

Inertial Confinement Fusion (ICF) research

ICF uses implosion of a spherical shell to compress solid DT up to 4000x with 2 kinds of implosion drive

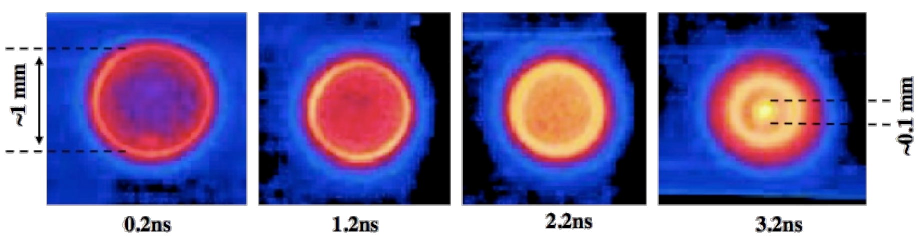
Direct Drive



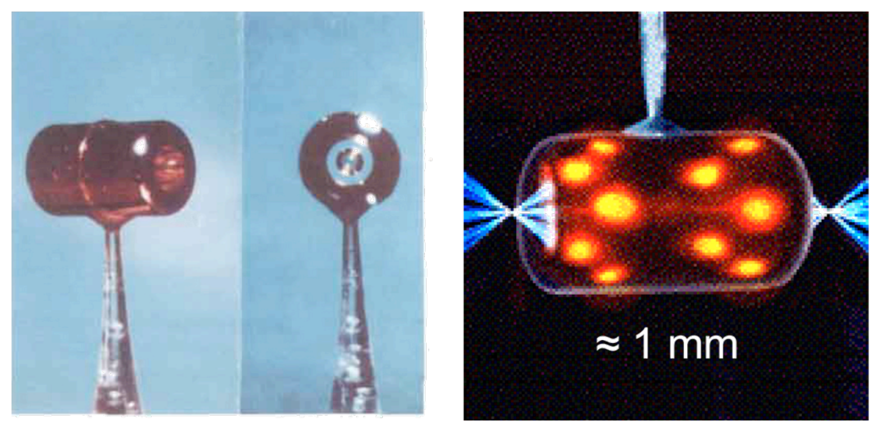
Laser ablation

Indirect Drive

Thermal x-ray ablation



capsule implosion at OMEGA (plastic ablator + heavy H ice)

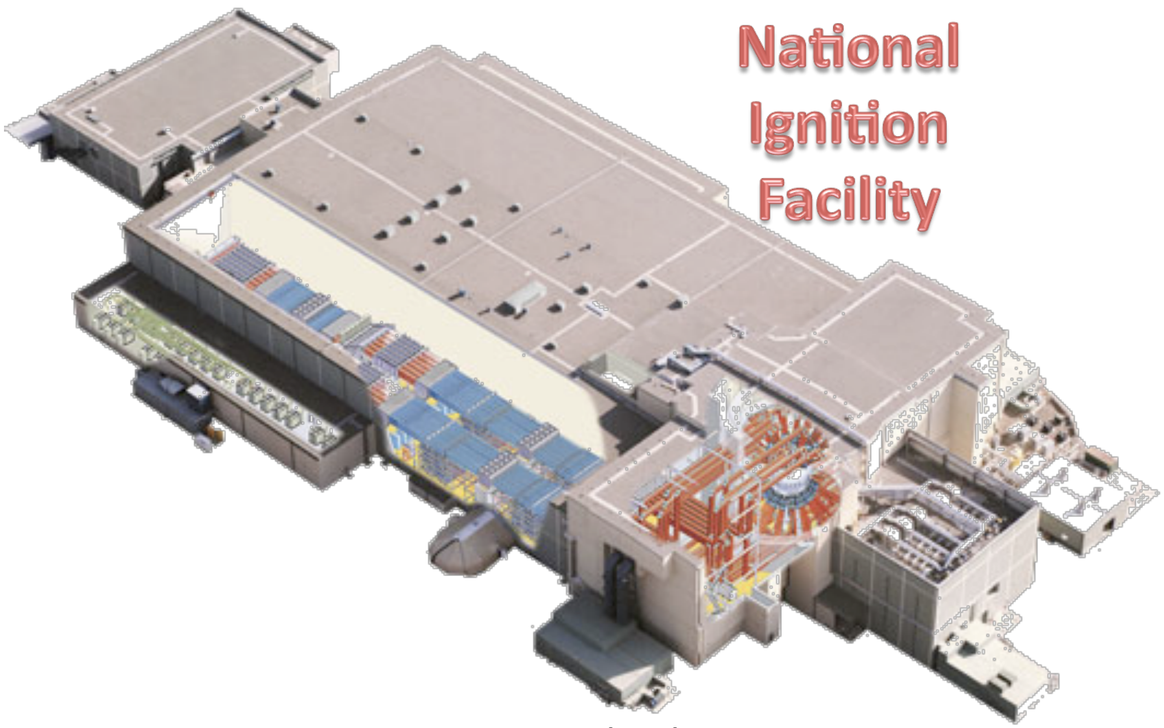


Gold hohlraum used at NOVA (LLNL). Thermalized x-ray hotspots (Mega-Kelvin) are seen radiating through the walls.

Inertial Confinement Fusion research

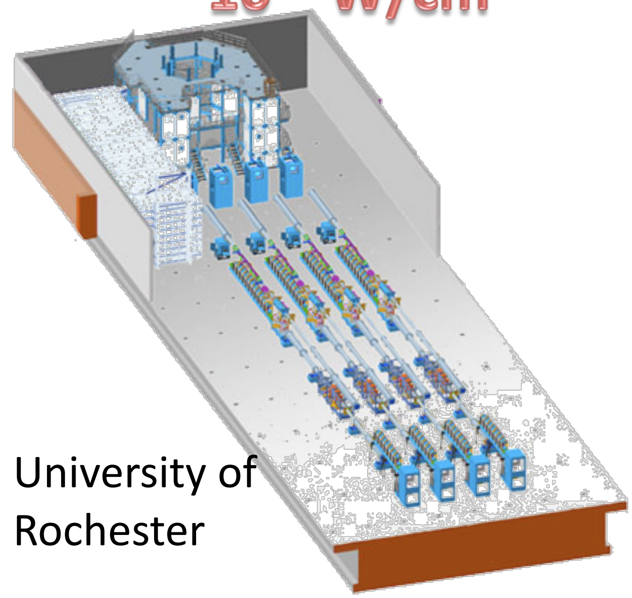
40 kJ OMEGA laser facility

2 MJ National Ignition Facility



Lawrence Livermore National Laboratory

OMEGA-EP 10^{20} W/cm^2

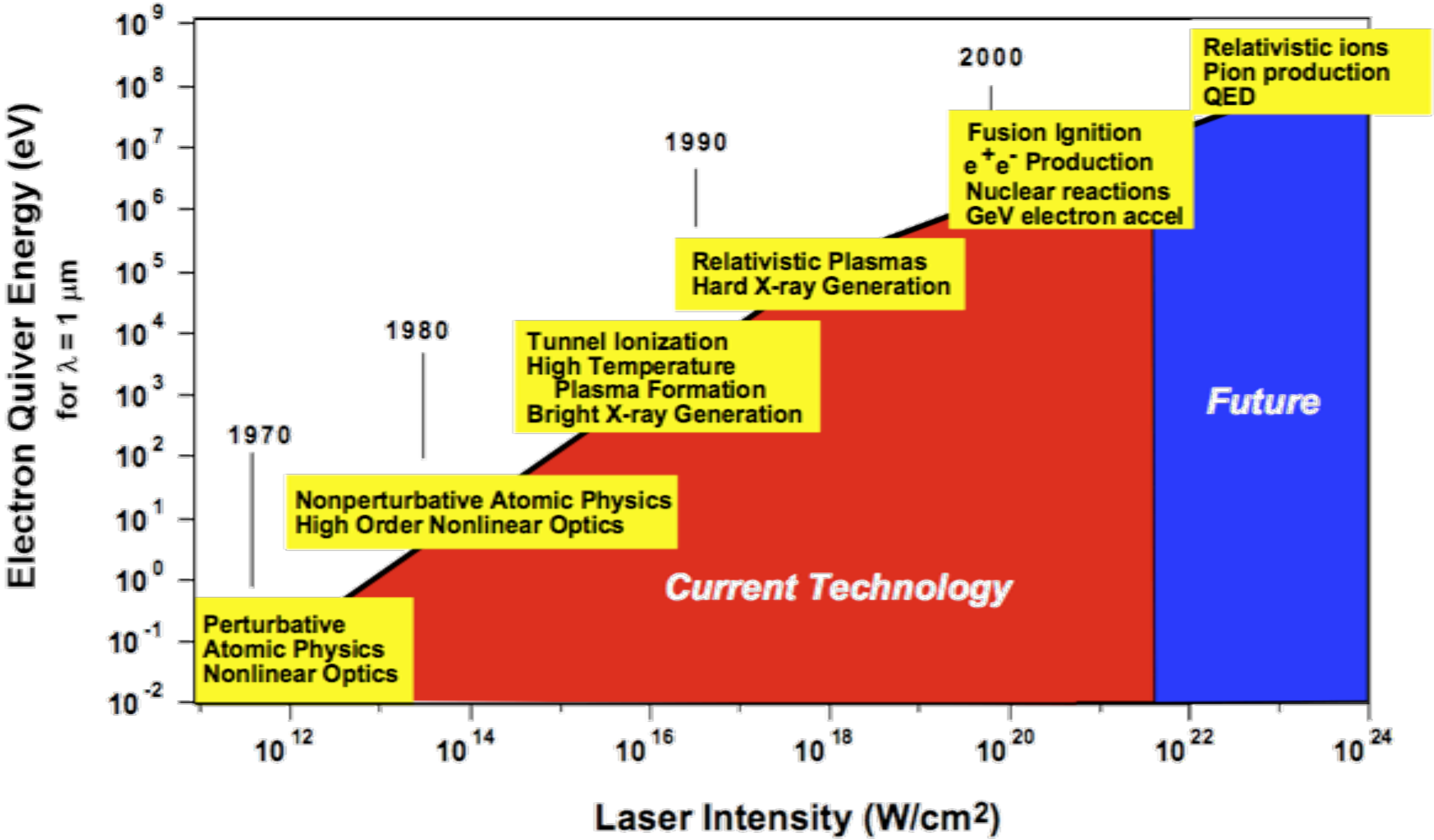


University of Rochester

Laboratory for Laser Energetics

Emission of high energy x-rays

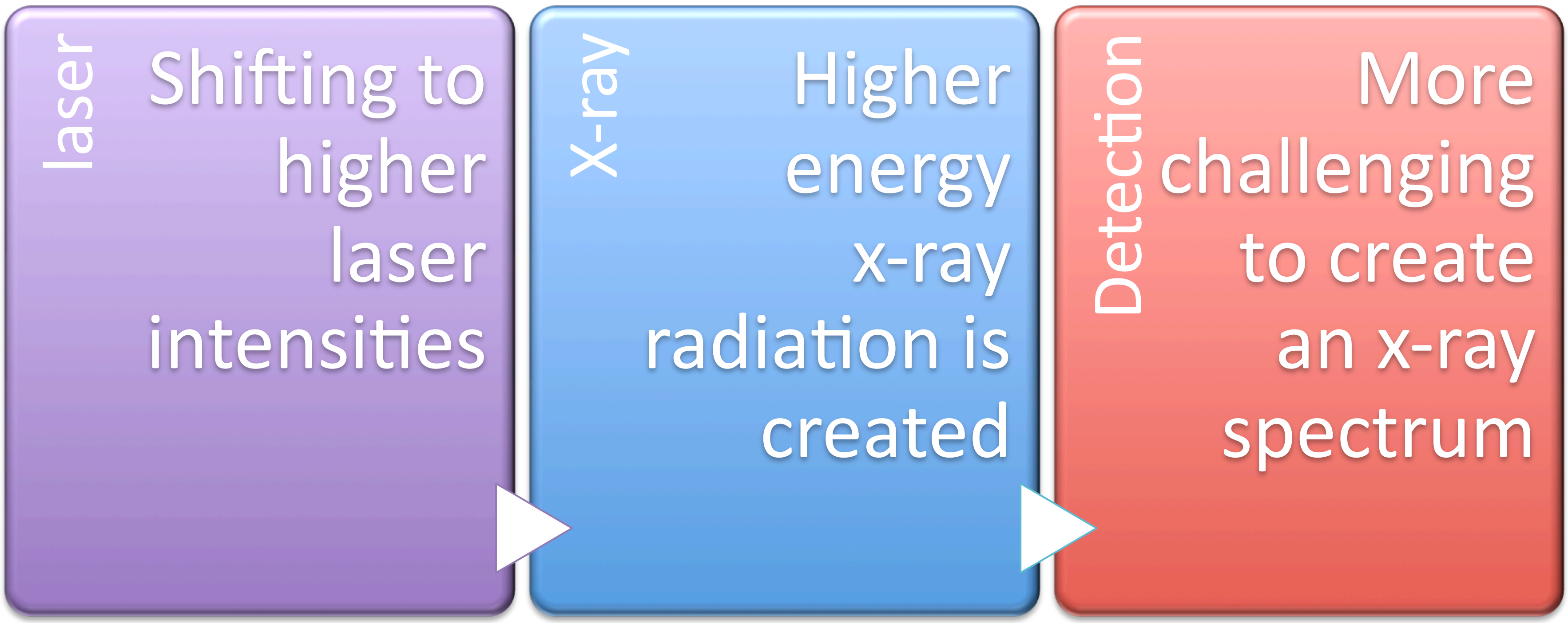
New and exotic physical regimes can be accessed with ultra-high intensity Lasers



X-ray spectroscopic diagnostic needs at HEDP facilities

- **Identification of x-ray sources by bound-bound line transitions**
  - Detection of presence of highly-ionized low to high-Z elements (Z=13-79)
  - Needed to confirm composition and ionization state(s) of backlight sources
- **Spectroscopic line ratios**
  - Needed for non-perturbative measure of electron temperature or density in hohlraum plasmas
- **Continuum emission**
  - Verification of bound-free opacities
- **Line widths and shapes**
  - Needed for density sensitive measurements - capsule implosions
- **Time-integrated absolute intensities**
  - Needed for conversion efficiency measurements
- **Relative intensities**
  - Needed for opacity in absorption or emission

High Energy X-ray observation at high intensity laser facilities



- Characterization of the high energy x-ray spectrum is essential for high energy x-ray radiography studies.
- Track High energy electrons through their Bremsstrahlung and characteristic radiation.
- New area: Gamma ray detection, e.g. 511 keV positron anihilation photon detection – spectral observation

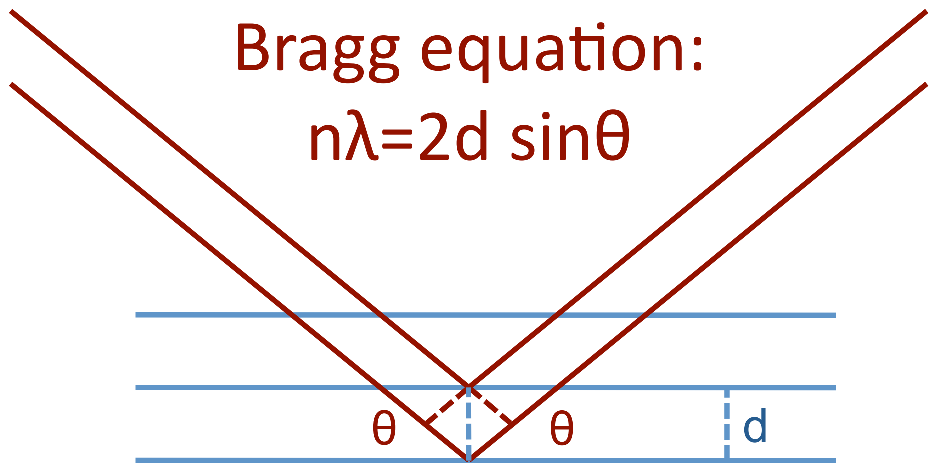
High energy x-ray spectrum in nano seconds !!!

- Energy dispersive methods do not work well due to the short time scales.

- Wavelength dispersive method: Crystal diffraction – good choice with appropriate detection (fast)

Bragg equation:

$n\lambda = 2d \sin\theta$



Advantage: high resolution

Trade offs: the higher resolution the less sensitivity

Challenge: the higher energy the smaller Bragg angles.

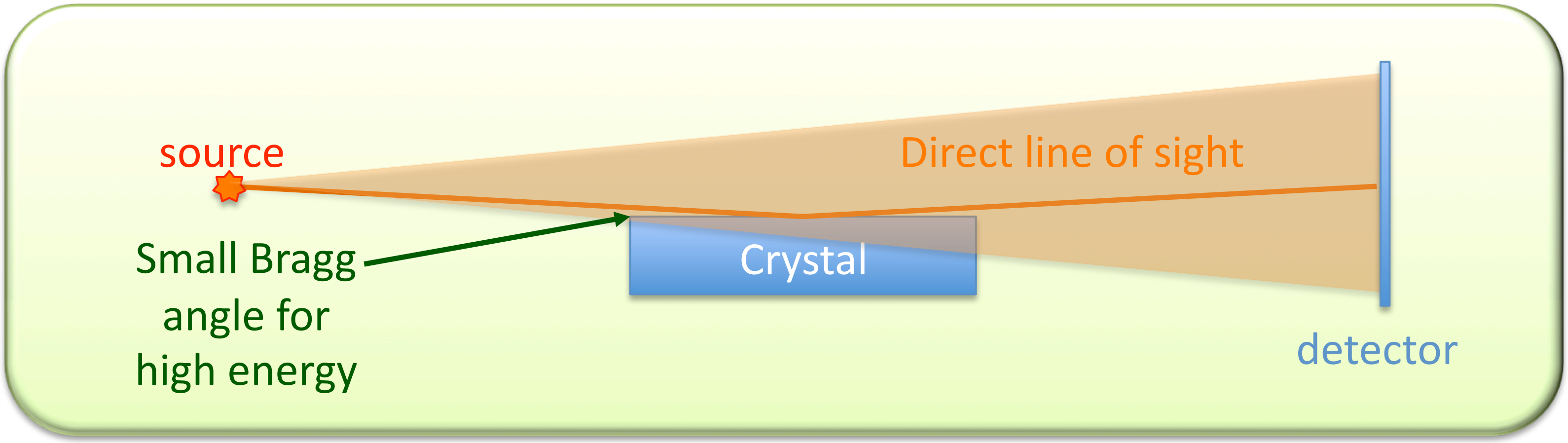
Enhancements for crystal spectrometers

Bent crystal geometries

Convex curved crystal: larger energy range	Concave curved crystal for higher intensities. Focusing geometries. (e. g. Von Hamos, Johann…)
difficult geometry for plate function limitations at high x-ray energies valid	limitations at high x-ray energies valid

Bragg geometry

Limitations for high energy x rays



Higher x-ray energy

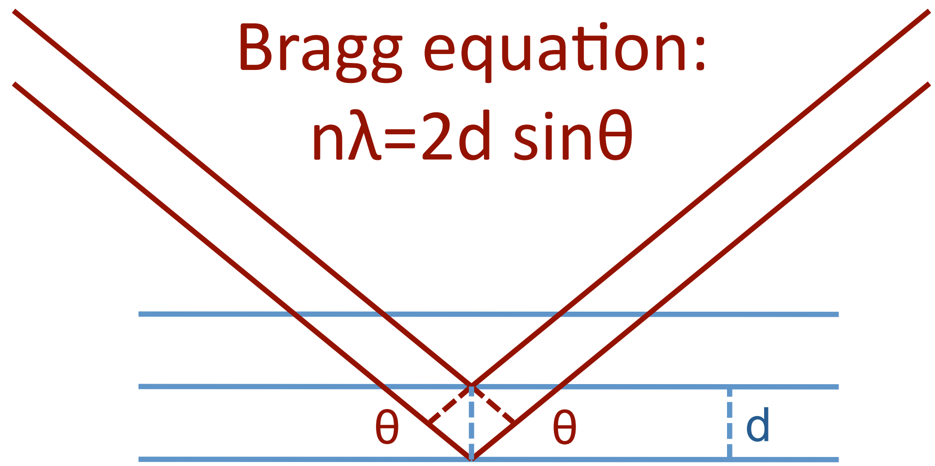
Bragg geometry becomes unfeasible due to direct light to detector.

smaller Bragg angle

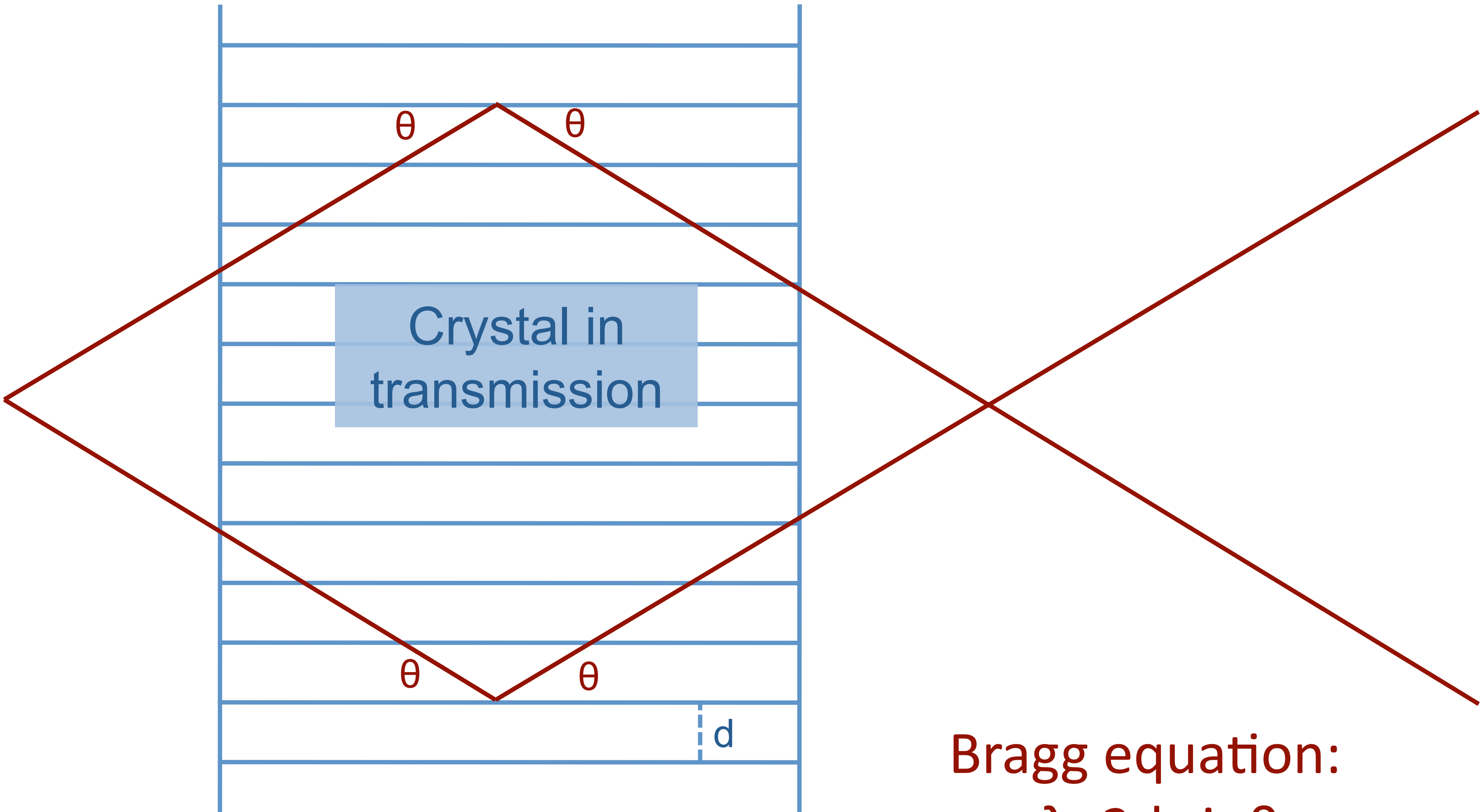
Bragg Reflection Geometry

Bragg equation:

$n\lambda = 2d \sin\theta$



Laue Transmission Geometry

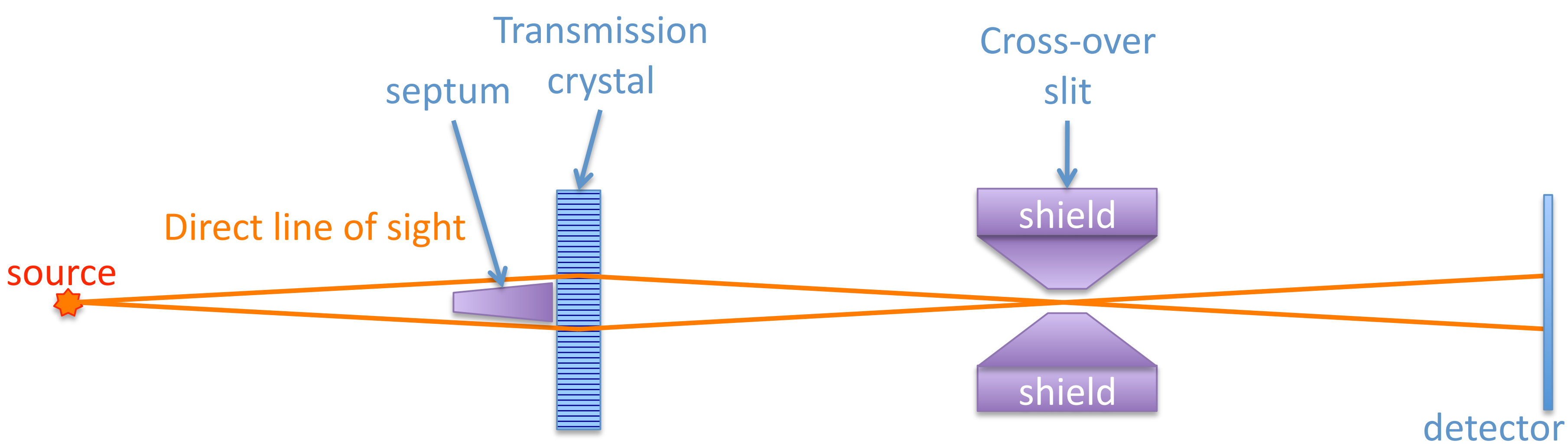


Bragg equation:

$n\lambda = 2d \sin\theta$

For high x-ray energies the answer is transmission

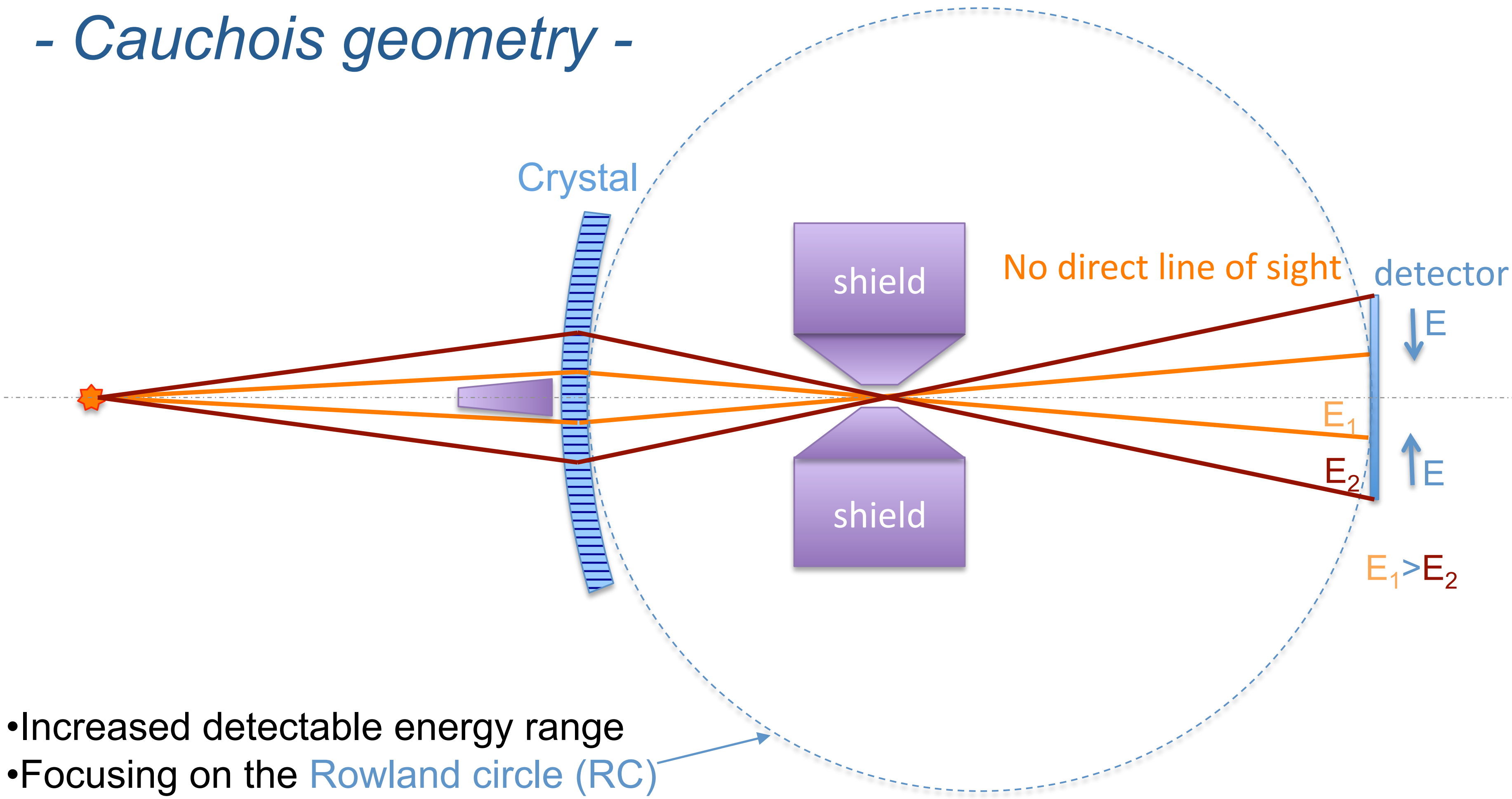
Laue Transmission Geometry



- Shielding is easier, septum and cross over slit can be used in a symmetric "double sided" geometry
- Higher energies can be reached.
- Optimization for x-ray energy, lattice spacing and crystal thickness needed

Cylindrically bent transmission crystal geometry

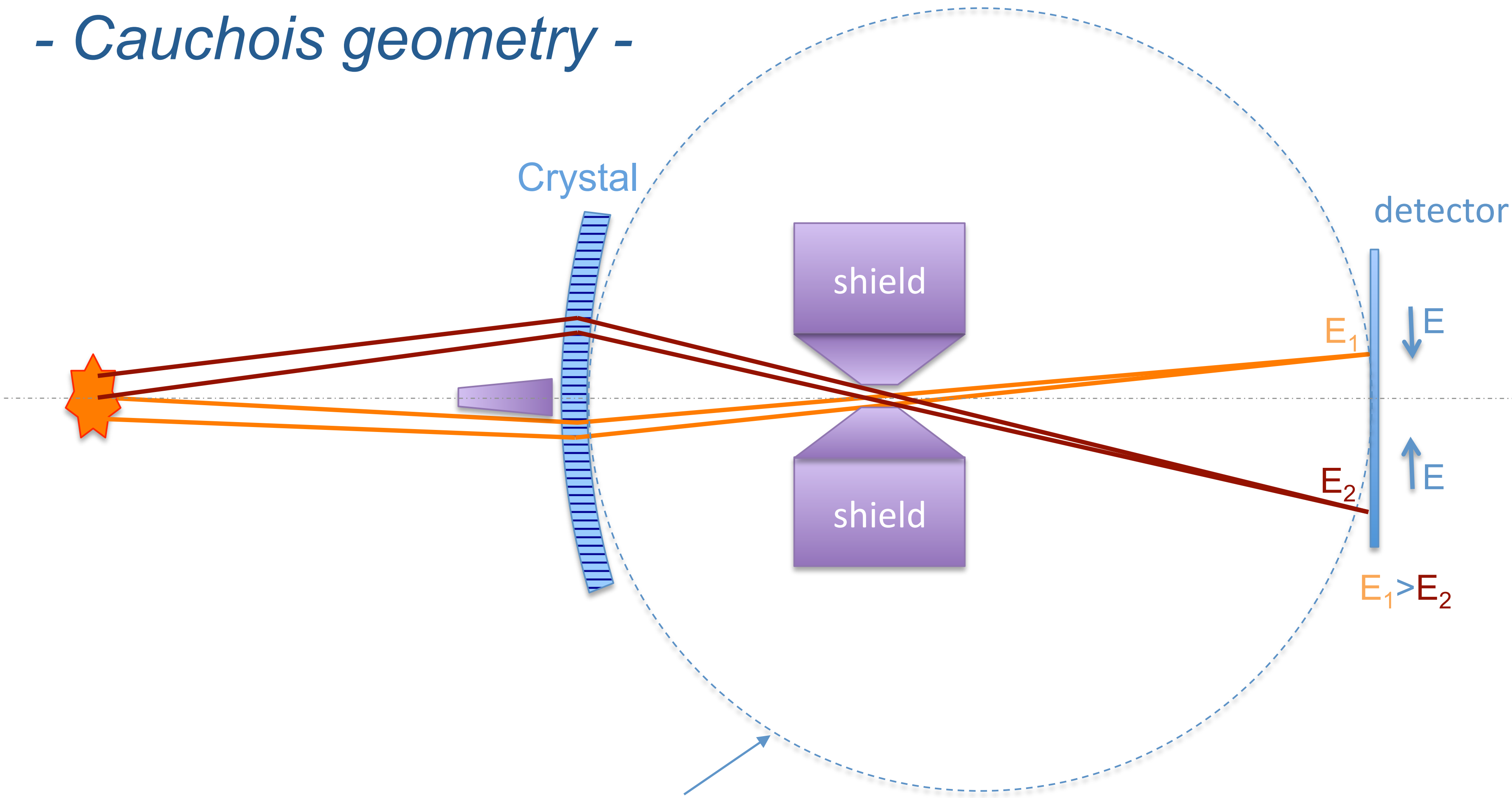
- Cauchois geometry -



- Increased detectable energy range
- Focusing on the Rowland circle (RC)
- No direct line of sight from source to detector
- Source size measurement option in off RC geometry

Focusing on the Rowland circle in case of a large source

- Cauchois geometry -



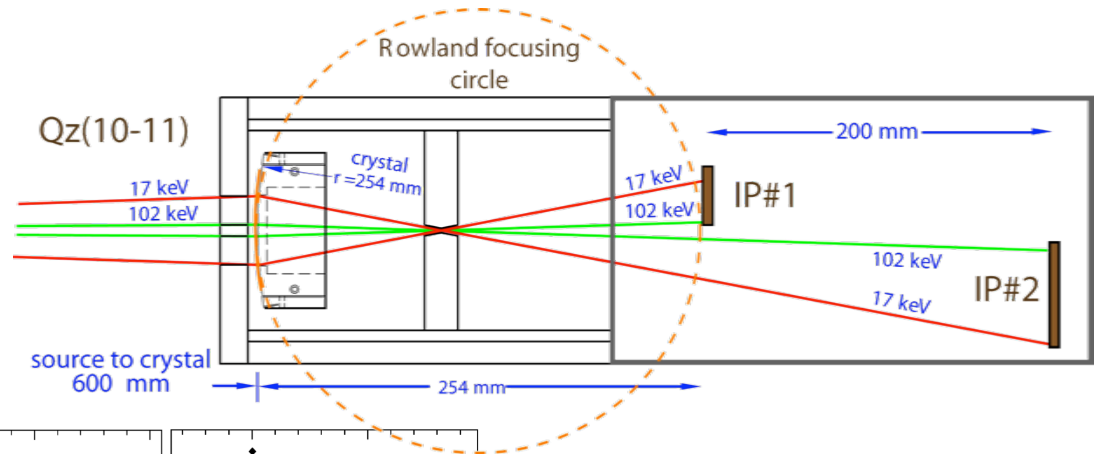
•Each wavelength is focused on the Rowland circle

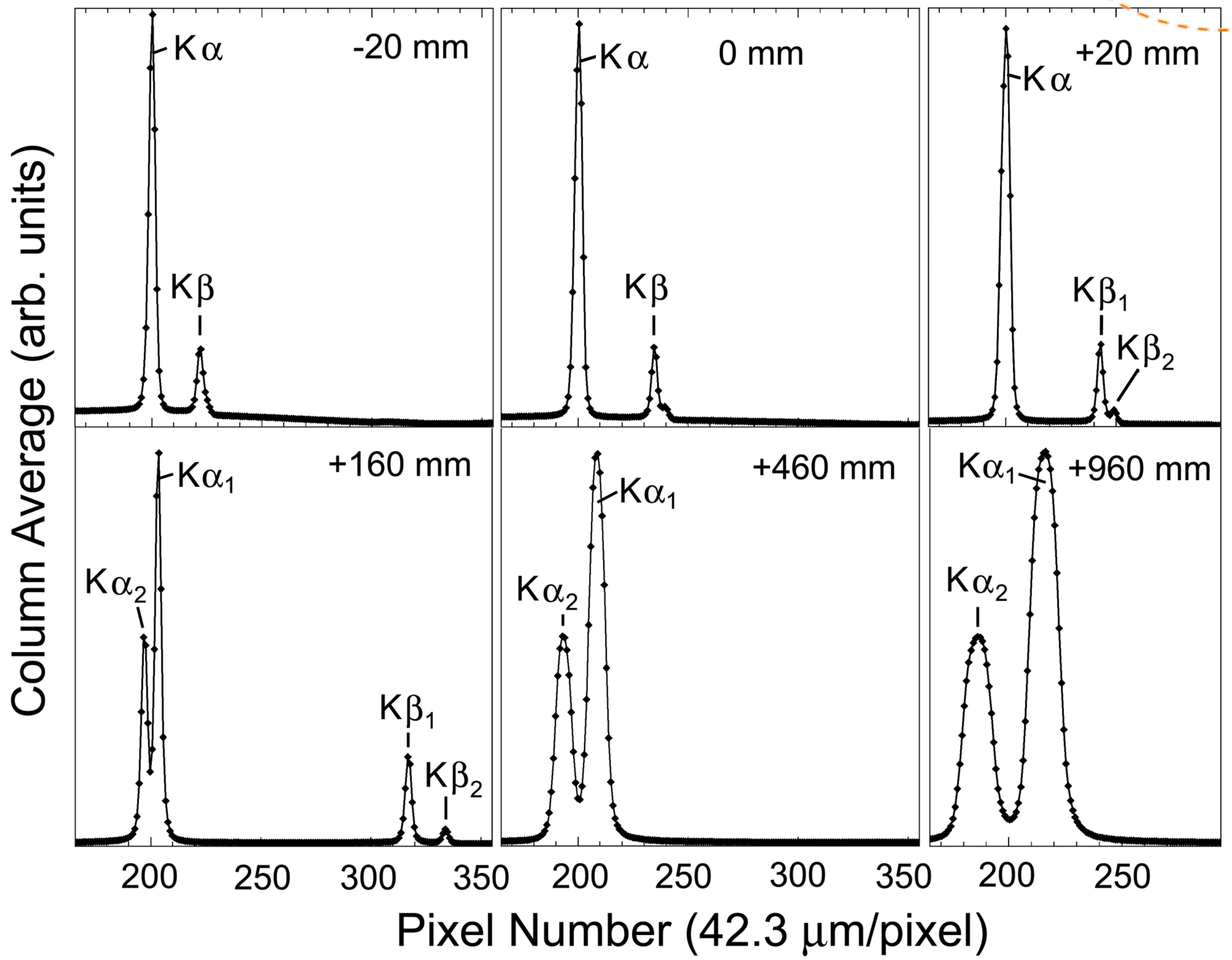
Challenges and trade-offs

- High Energy – more penetration (shielding more challenging)
- Secondary fluorescence, diffuse background, scattering
- Smaller wavelength (higher x-ray energy) challenges resolving power

Could resolving power be improved?

What happens if we move the detector off the Rowland circle?



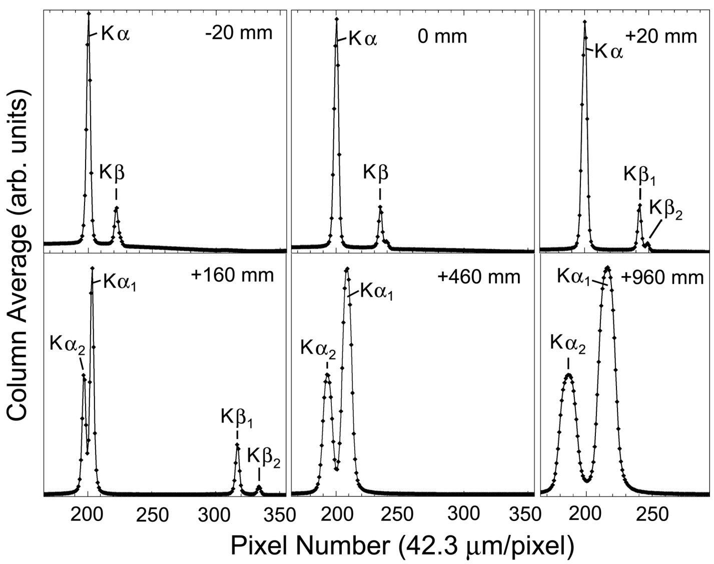


K-shell spectra from a **Mo microfocus** source with changing crystal to detector distance

Source Broadening of the Spectral lines

- Spectral lines recorded by a detector on the RC are primarily broadened by the detector resolution.
- Spectral lines recorded far behind the RC are primarily source broadened.
- For increasing distance behind the RC, the dispersion increases faster than the source broadening, and the spectral resolution increases if the source is sufficiently small.

K-shell spectra from a Mo microfocus source:



Line widths:

1 – Total

2 – Detector

3 – Source

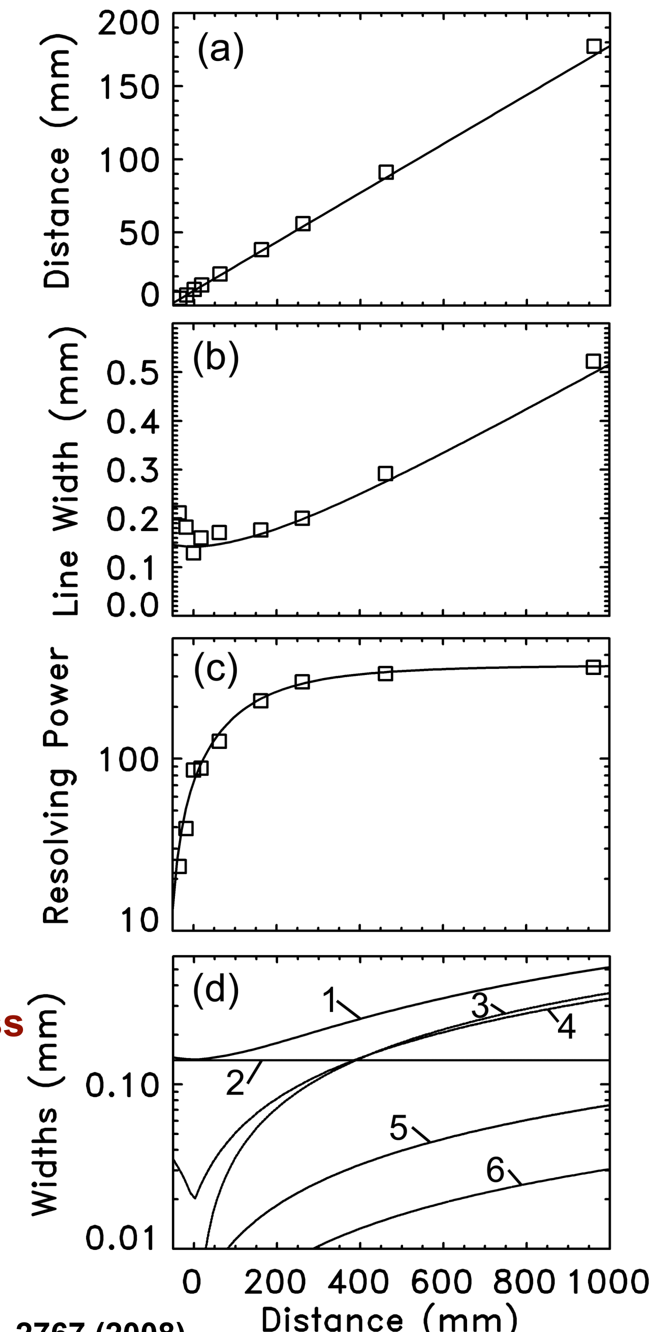
4 – Crystal thickness

5 – Natural width

6 – Crystal rocking curve

7 – Aberrations (very small)

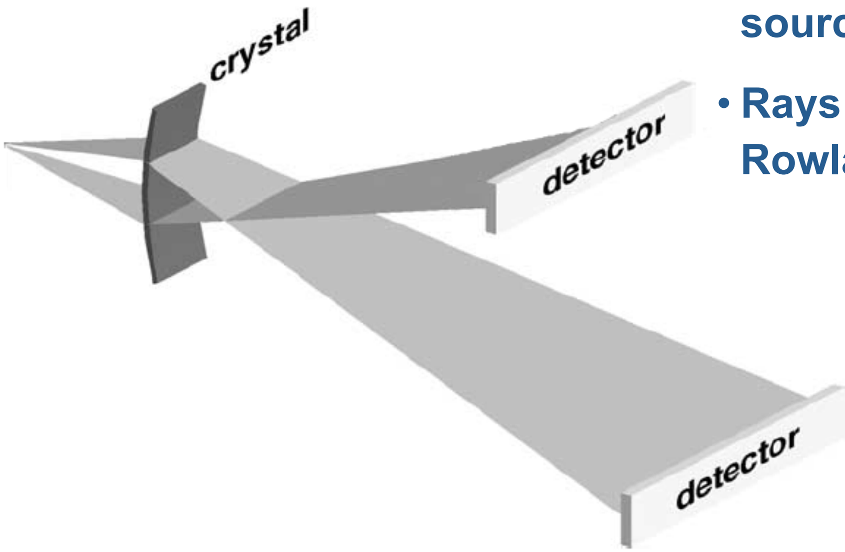
Mo $K\beta_1$ data & spectrometer model:



Seely *et al.* Appl. Opt. 47, 2767 (2008)

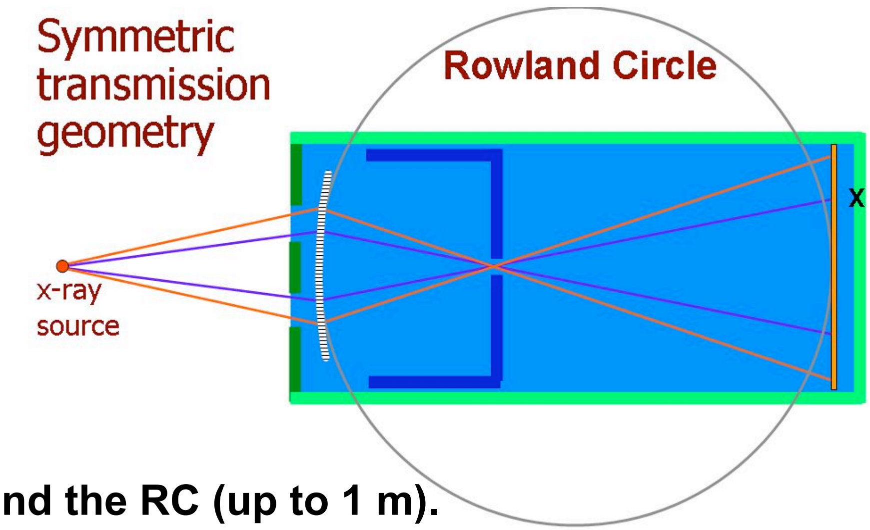
Transmission Crystal Spectrometer

Transmission crystal (Laue geometry) accommodates small diffraction angles compared to Bragg reflection crystals and covers harder x-rays/gammas.



Cauchois type transmission crystal spectrometer

- **All rays with the same energy and from an extended source are focused on the Rowland circle.**
- **Rays with different energies are dispersed on the Rowland circle.**



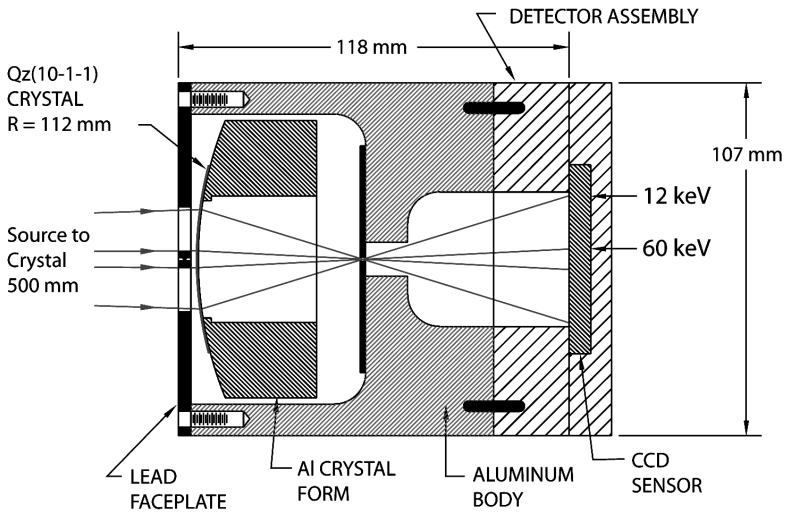
Unique features of NRL/NIST spectrometers

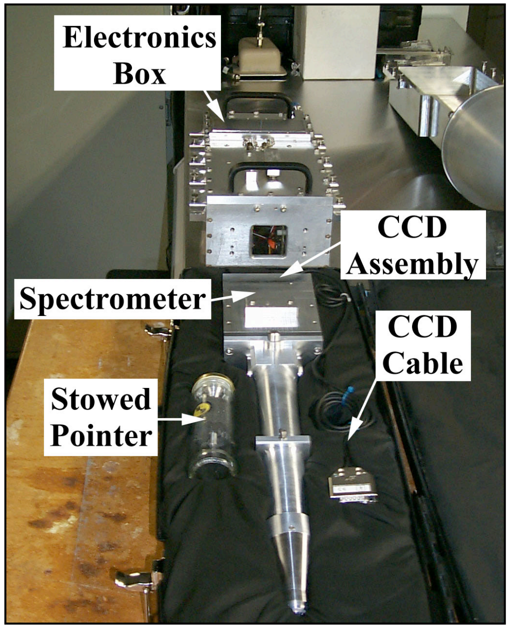
- **Detectors are placed at varying distances beyond the RC (up to 1 m).**
- **For sufficiently narrow sources (such as LPP) the spectral resolution increases dramatically with distance beyond the RC.**
- **Source broadening dominates & can be used to measure source size as small as 20 µm.**

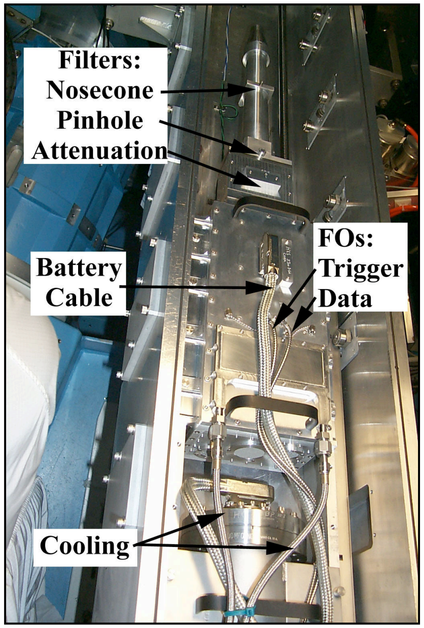
Seen on the door to a light-wave lab:

"Do not look into laser with remaining good eye."

HXS (High-Energy X-Ray Spectrometer)

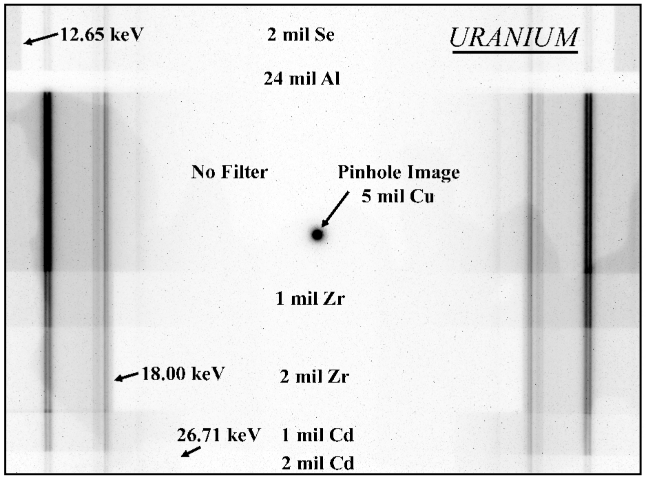


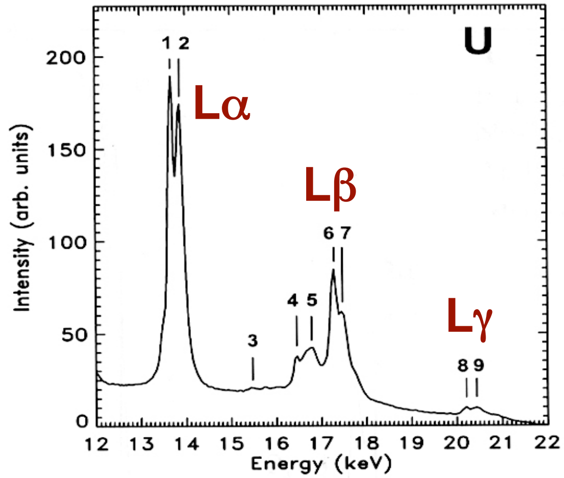


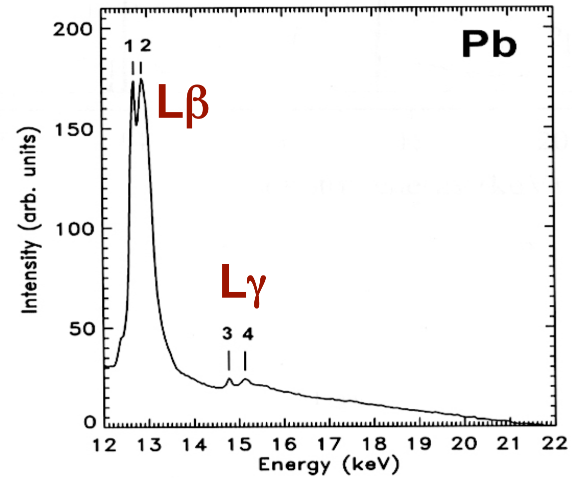


- Fielded at OMEGA in 2000 and 2001.
- Survey spectrometer covering 12-60 keV with moderate resolution (≈100).
- Detector (dental x-ray CCD) on the Rowland circle, on-board electronics and battery power, and fiber optic communications to lab computer (EMI isolation).
- Two spectra are symmetrical on either side of an axial pinhole image – good *in situ* knowledge of the instrument pointing.
- Attenuation filters at the crossover slit provide *in situ* energy scale calibration.
- Convenient linear geometry is compatible with TIM/DIM instrument insertion modules and with streak/framing cameras.
- There is no direct path from the x-ray source to the detector (except through the pinhole), and massive detector shielding is possible.

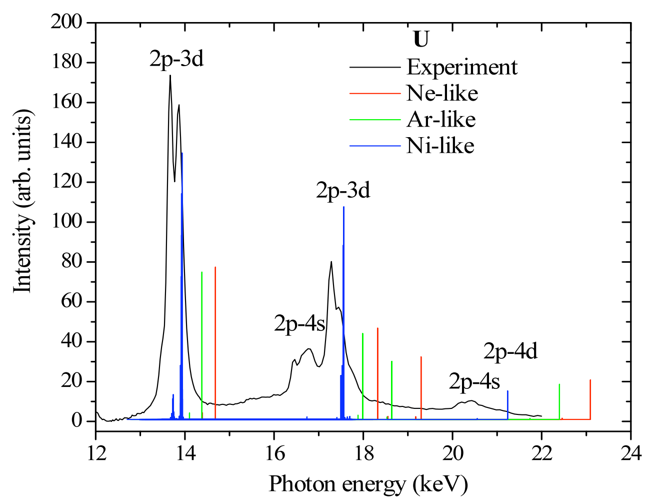
HXS Spectra and Results



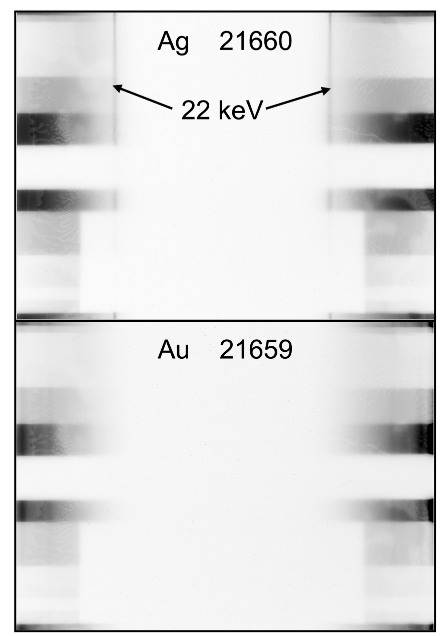




- **HULLAC calculations indicate inner-shell transitions in U ions in the vicinity of Ni-like ions.**
- **STA and other calculations indicate <Z>=58, T_e=900 eV, and n_e=7x10^{23} cm^{-3}, and large opacity.**
- **L-shell vacancies are created by energetic electrons.**

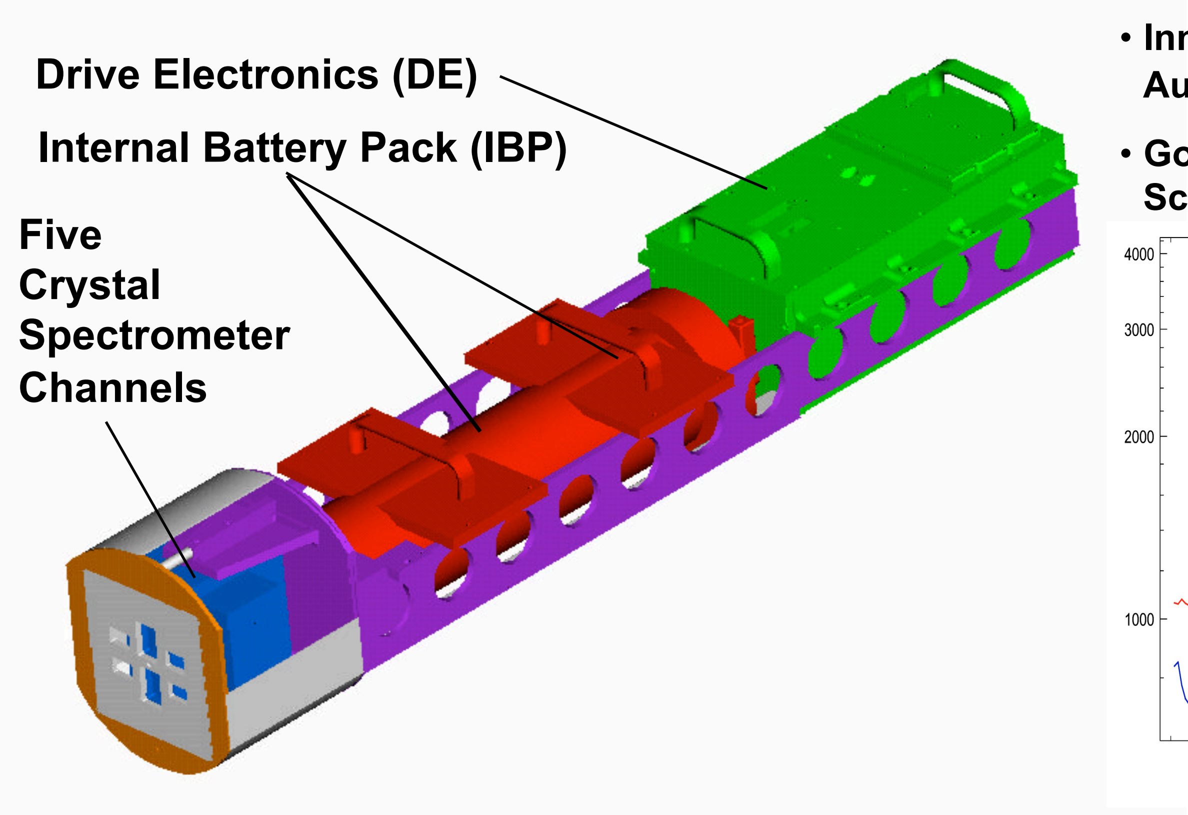


Observed K-shell lines up to Ag:

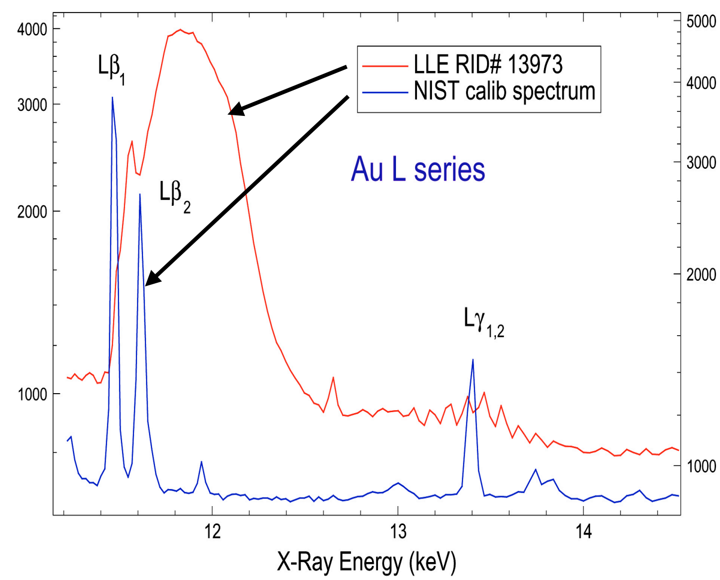


Seely_JQSRT 81 p. 421 (2003)

HENEX (High-Energy Electronic X-Ray)

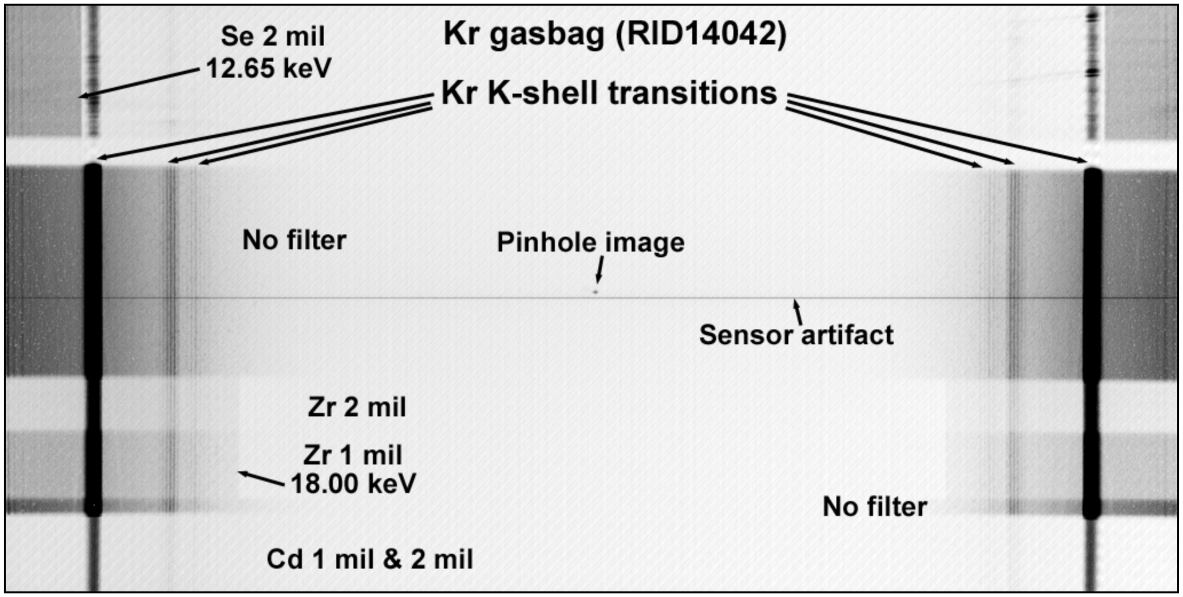


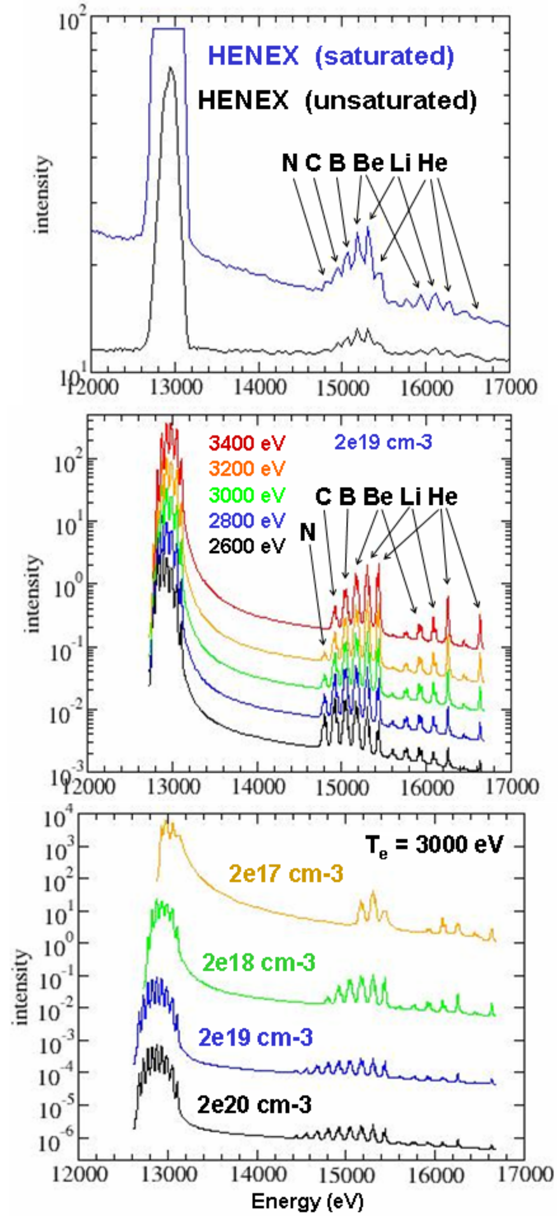
- Inner-shell L transitions from ionized Au (modeled by Mark May).
- Gold half hohlraum (Marilyn Schneider), OMEGA 23 beams, 11 kJ.



- Four reflection crystals cover 1-20 keV and one transmission crystal covers 11-40 keV with high resolution (>300).
- Spectral images are recorded on 5 CMOS sensors with optimized phosphor screens, on-board electronics and battery, FO communications to lab computer.
- Deployed in Omega TIM with 0.5 m target-crystal distance (2003-present).

HENEX Spectra and Results





100% Kr-filled gasbag (0.5-0.8 atm) with Zn backlighter, 49 OMEGA beams, 22 kJ (Duston Froula).

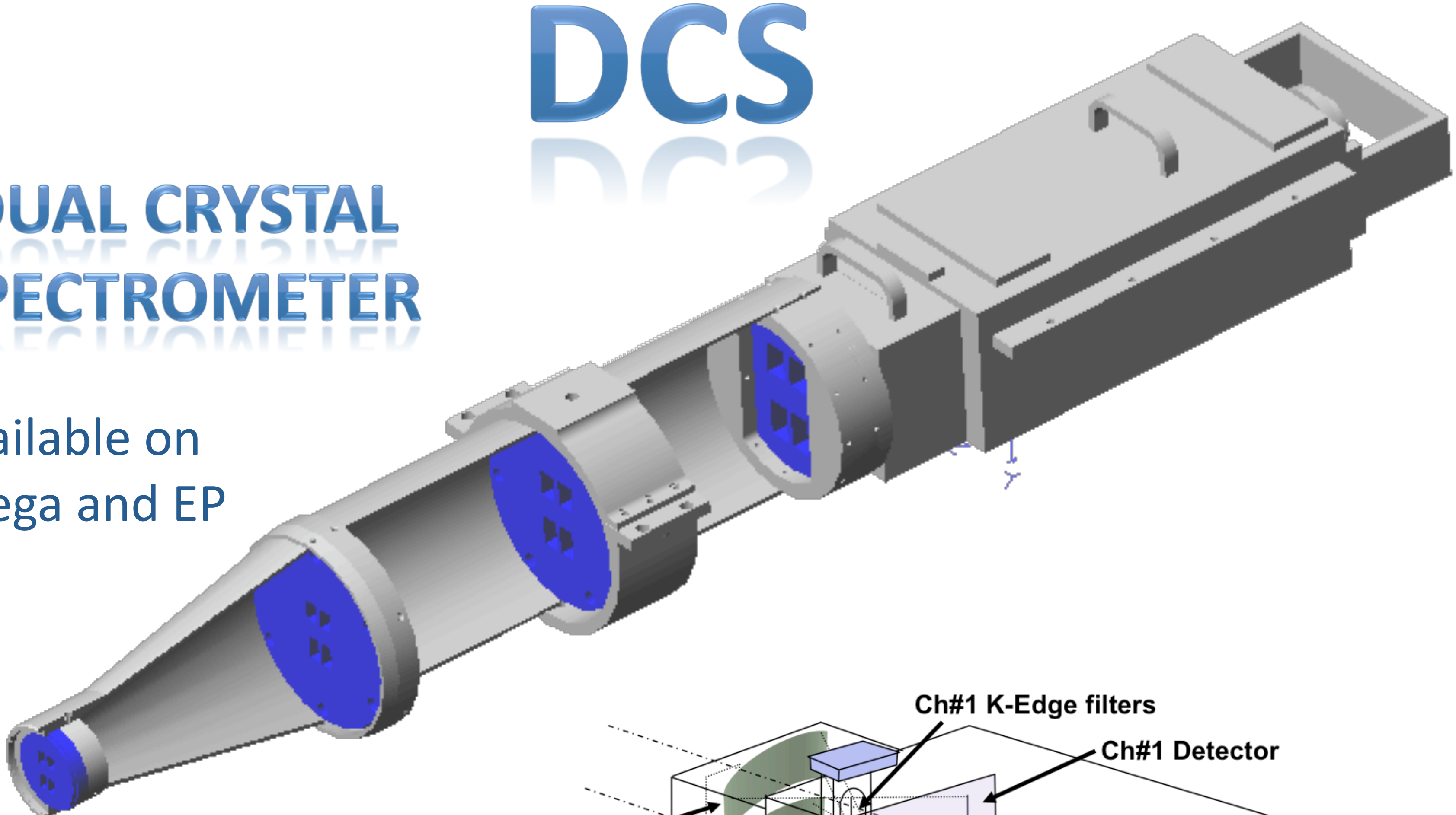
Comparison of experimental and calculated spectra (FLYCHK, Lee and Chung) indicate T_e=3000 eV and N_e=2×10^{18} cm^{-3} (RPHDM2004).

Seely JQSRT 99 p572 (2006)

DCS

DUAL CRYSTAL SPECTROMETER

Available on
Omega and EP



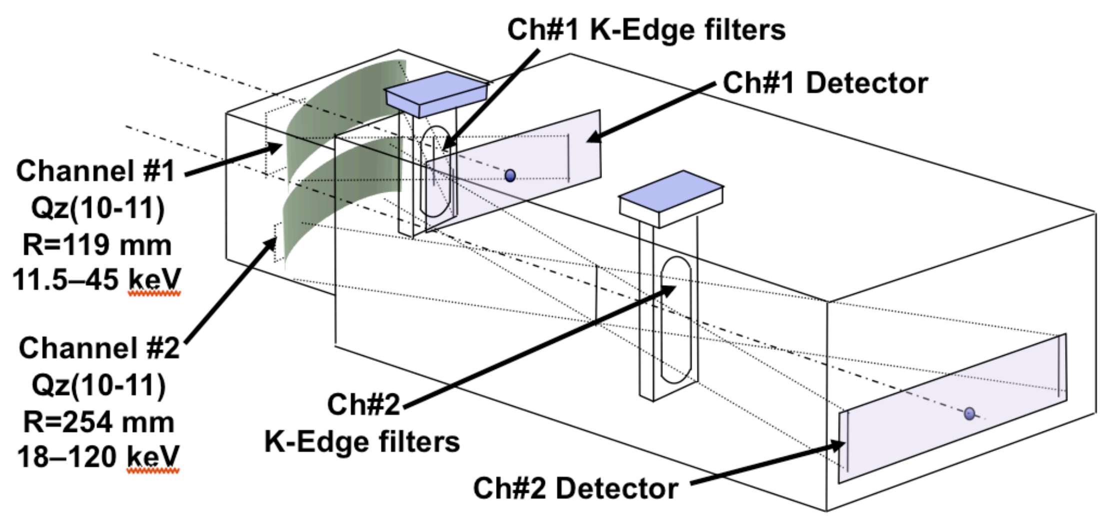
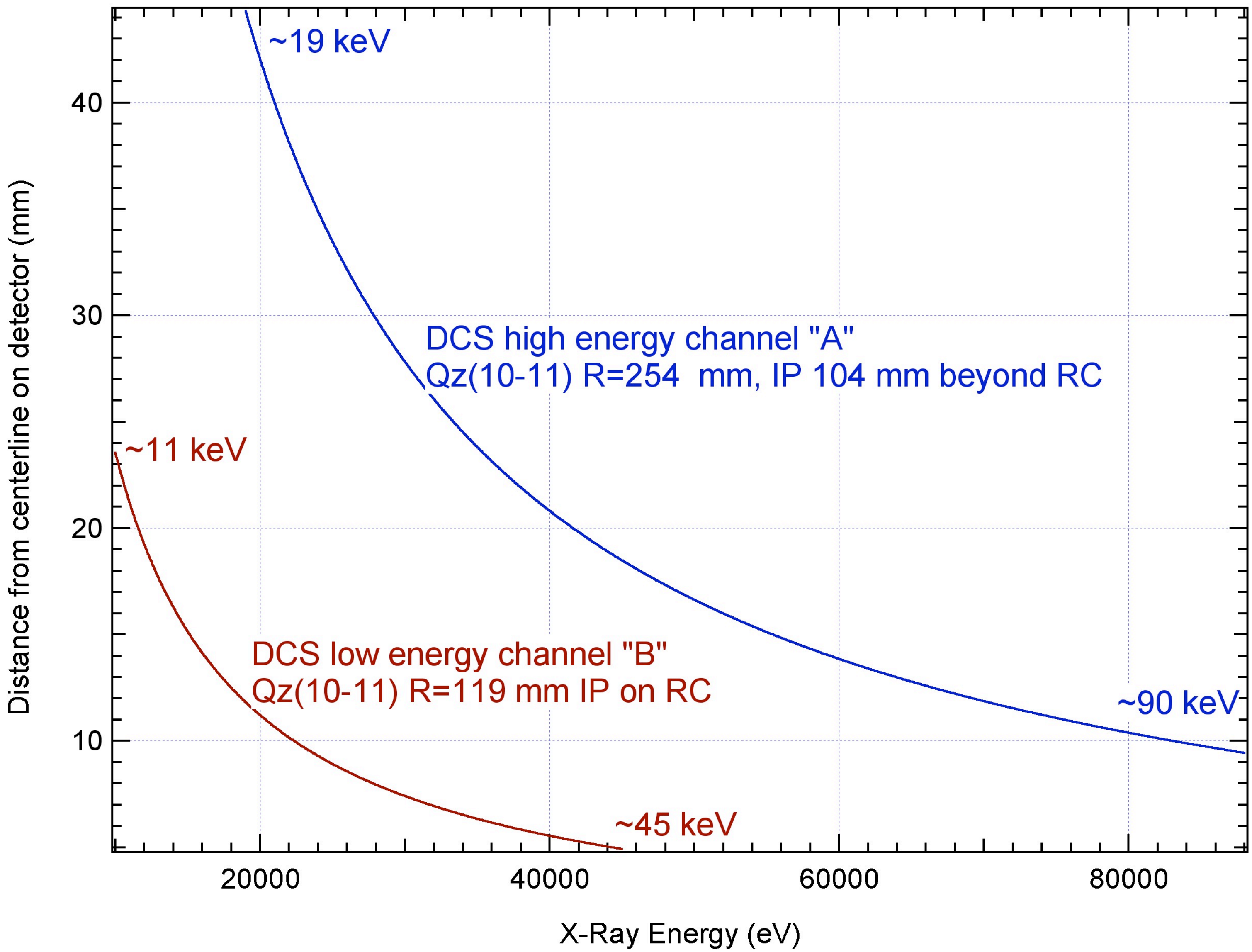
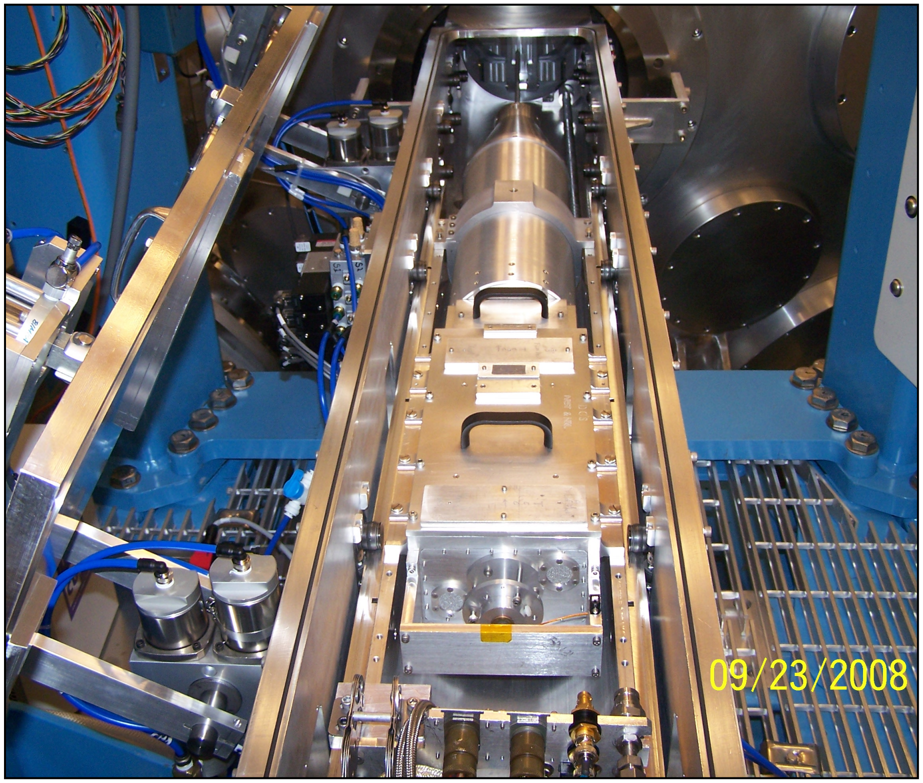


PLATE FUNCTIONS OF THE TWO DETECTOR CHANNELS OF DCS



DCS IS NOW QUALIFIED FOR EP AND OMEGA TIMS

Nosecone and pointer for 1.2 m source to crystal standoff

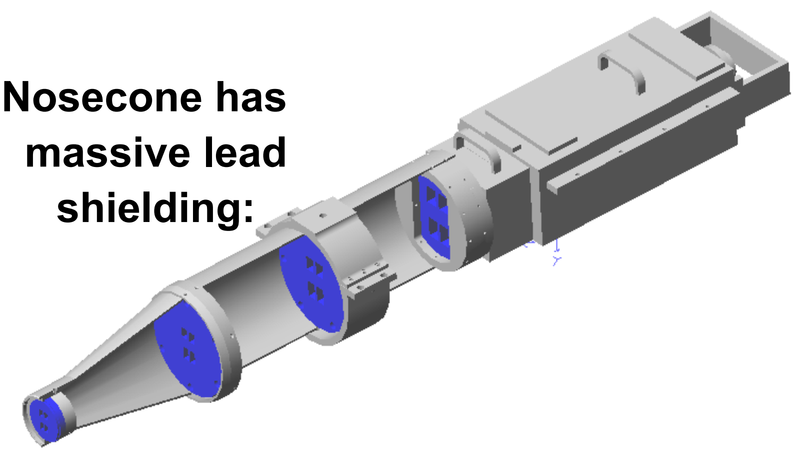


Used at shots on EP:

Tom Boehley / Hye-Sook Park;	January 27-29.
Jonathan Workman, LANL;	March 24, 2009
Hui Chen, LLNL;	April 16, 2009
Uri Feldman, Artep Inc.	Aug. 26-27, 2009
etc.	

Parameter	Channel "A" high energy channel	Channel "B" low energy channel
Crystal	Qz(10-11)	Qz(10-11)
Radius of curvature	254 mm	119 mm
Source to Crystal distance	1.2 m	1.2 m
Crystal to detector distance	358 mm	119 mm on RC
Energy range	11 to 45 keV	19 to 90 keV

Nosecone has massive lead shielding:

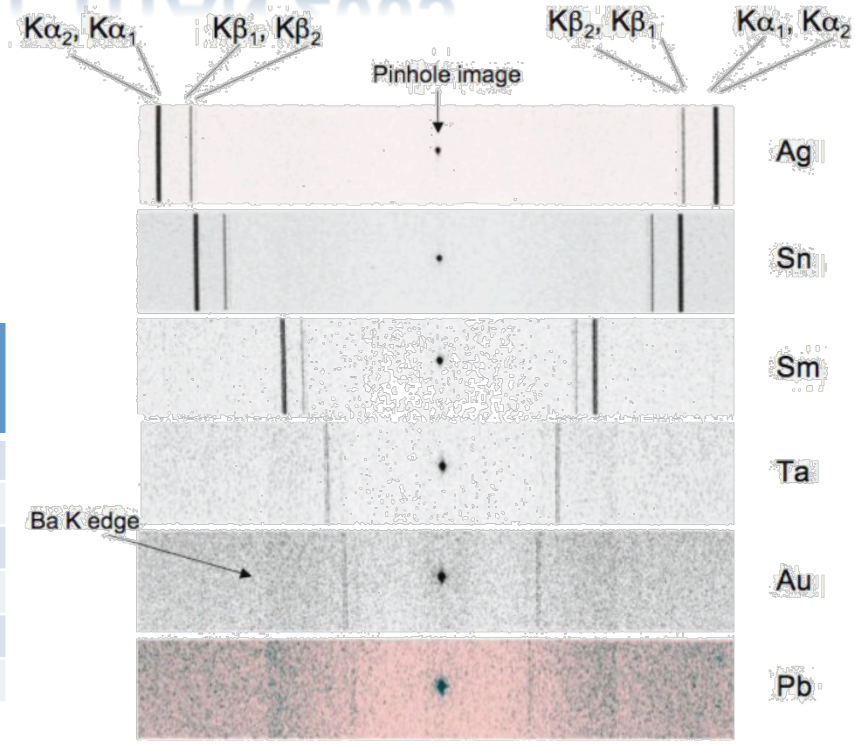


HISTORY - DCS AT TITAN 2005

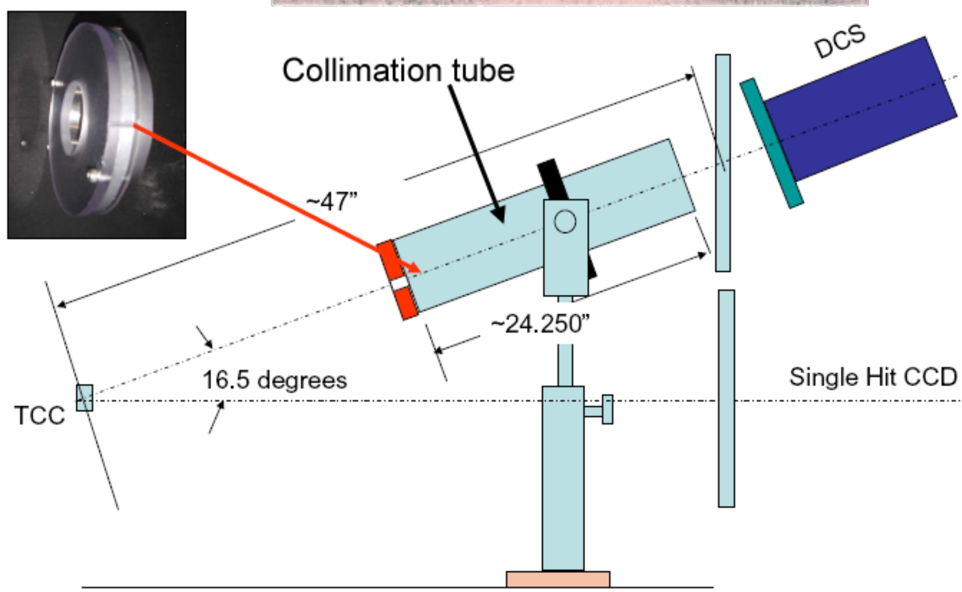
DCS spectra characterize the TITAN hard x-ray source (Riccardo Tommassini, Hye-Sook Park and Prav Patel).

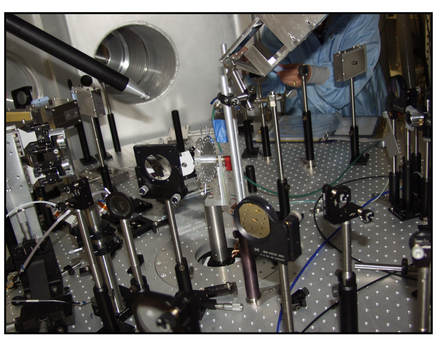
K-shell transitions result from inner-shell ionization by the hot electron distribution.

Element (Z)	$K\alpha_1$ Energy (keV)	$K\beta_1$ Energy (keV)	1s Electron Binding Energy (keV)
Ag(47)	22.162	24.942	25.514
Sn(50)	25.270	28.483	29.200
Sm(62)	40.124	45.400	46.834
Ta(73)	57.523	65.209	67.416
Au(79)	68.778	77.968	80.724
Pb(82)	74.970	84.939	88.006



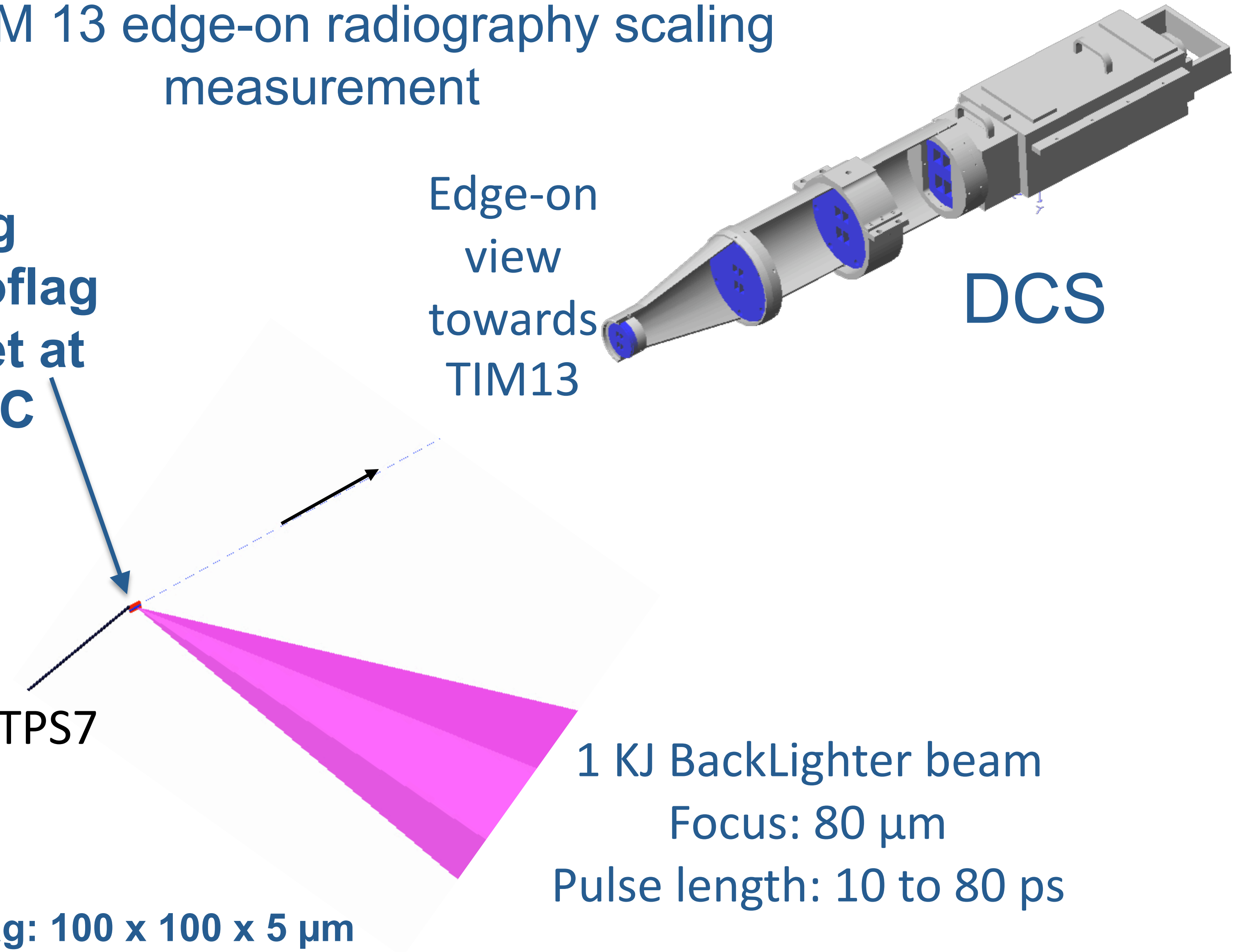
Numerous objects near the target fluoresce hard x-rays and were occulted by a collimation tube with a thick lead/plastic front aperture.





EXPERIMENTAL SETUP AT EP

BL/TIM 13 edge-on radiography scaling measurement



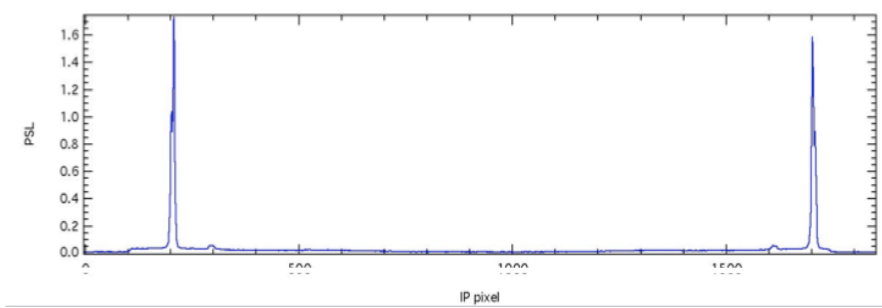
Microflag: 100 x 100 x 5 µm

SAMPLE RAW SPECTRA WITH DCS AT EP

Silver K lines on the high energy channel

DCS Channel A: high energy

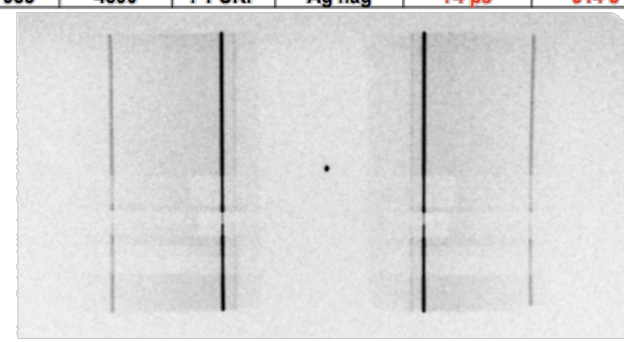
Date	RID	Shot#	Target	Target descritption	Tmeas	Emeas	Time
03/24/09	27938	4890	7-PURP	Ag flag	74 ps	914 J	19:24

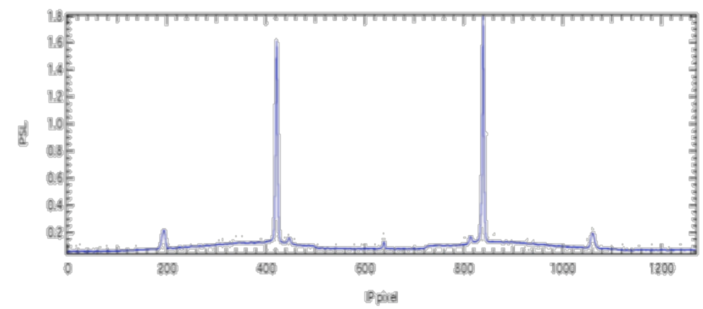


Silver K lines on the low energy channel

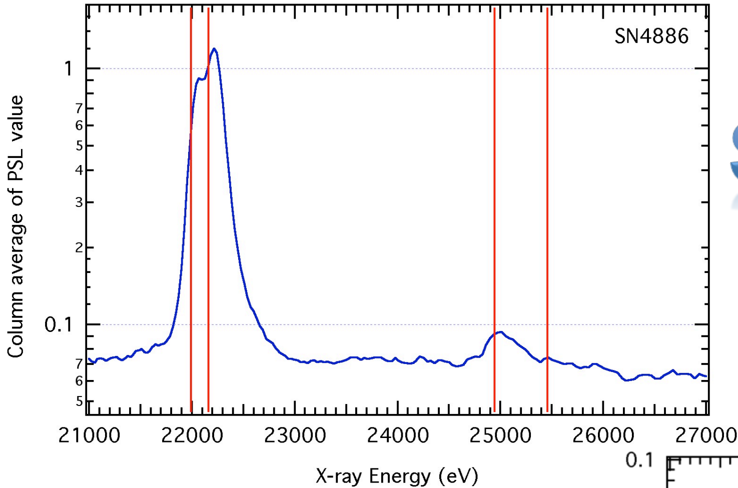
DCS Channel A: high energy

Date	RID	Shot#	Target	Target descritption	Tmeas	Emeas	Time
03/24/09	27938	4890	7-PURP	Ag flag	74 ps	914 J	19:24

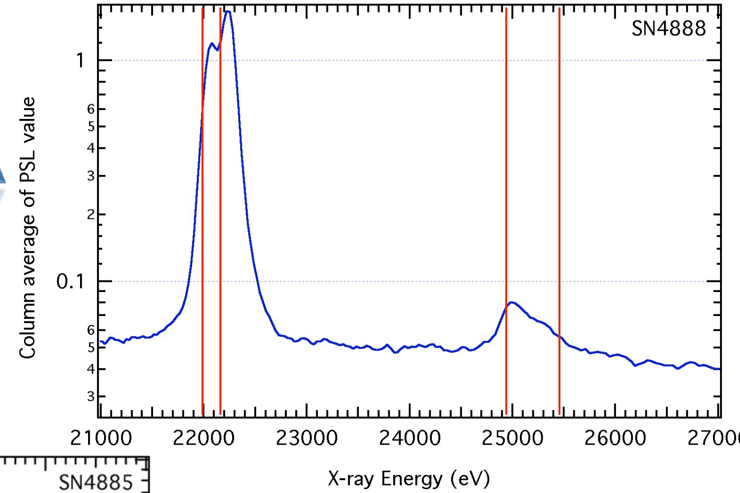




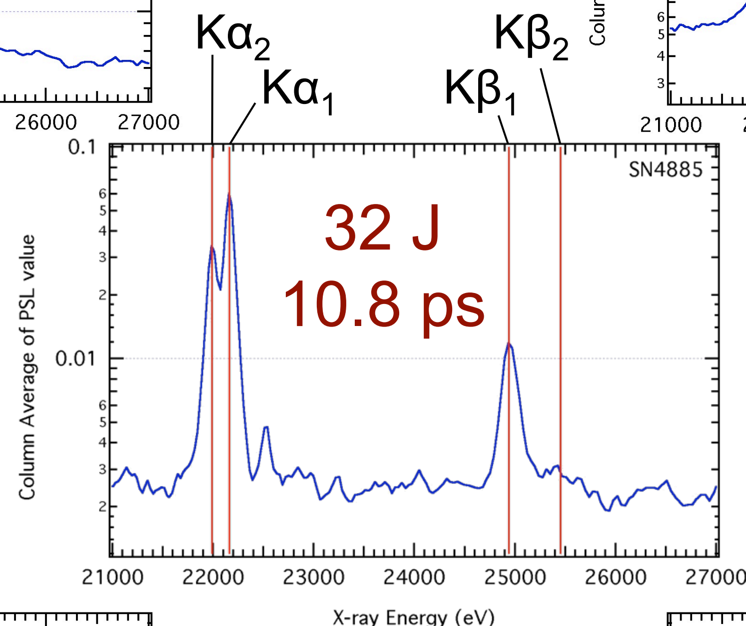
DCS SPECTRA



960 J, 10.8 ps



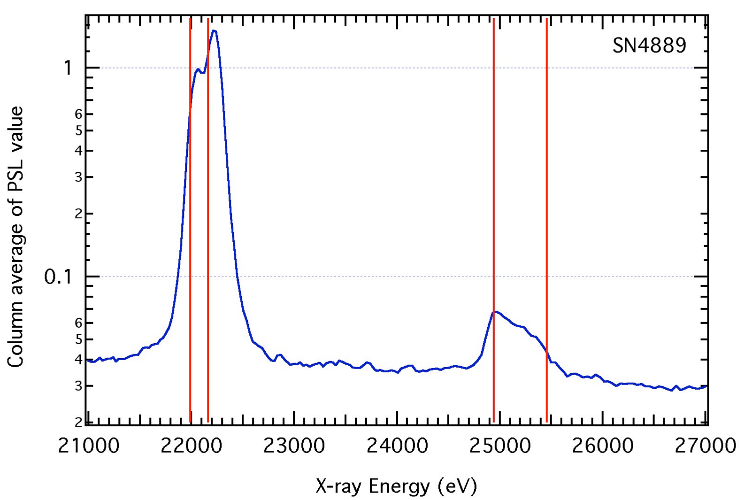
956 J, 39 ps



32 J
10.8 ps

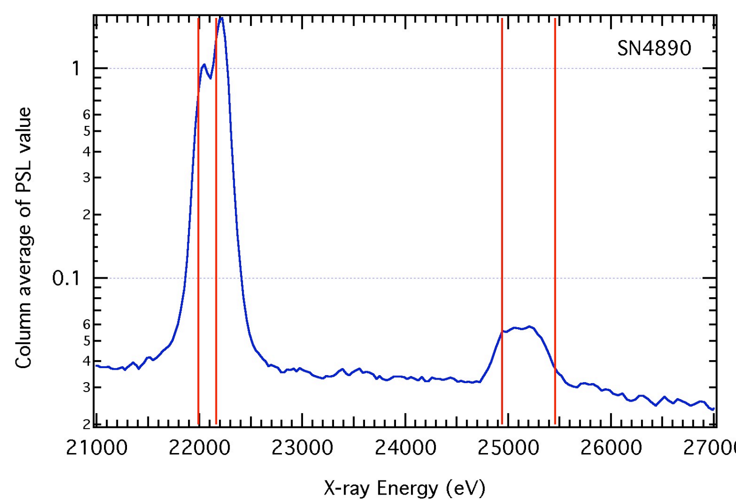
946 J, 21 ps

914 J, 74 ps



Los Alamos NATIONAL LABORATORY EST. 1943

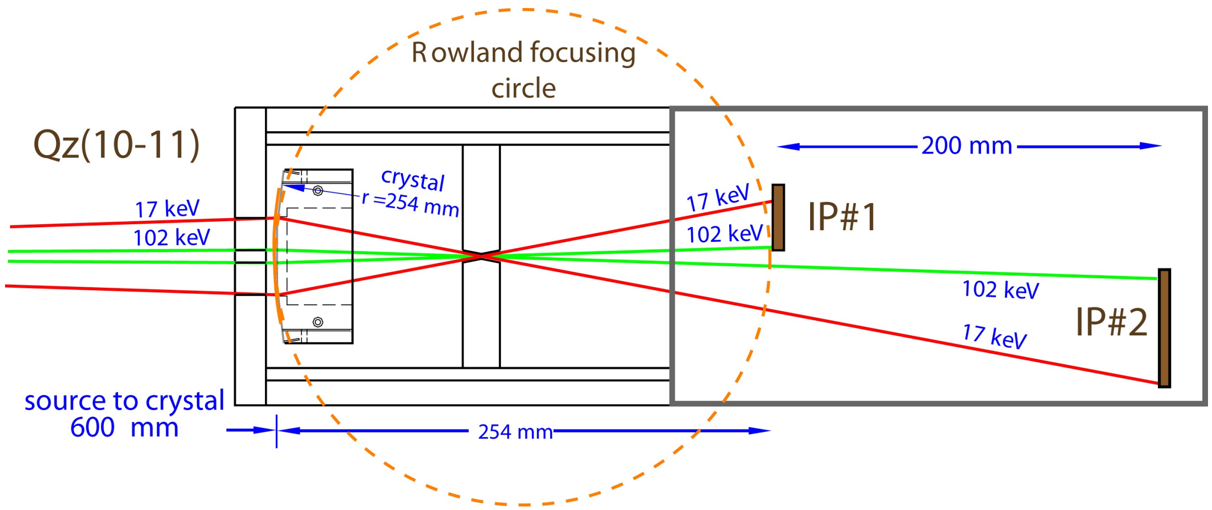
PI:J. Workman
LANL,
March 24, 2009



LULI Crystal Spectrometer (LCS)

First spectrometer optimized for source size measurement: small standoff, large RC, large IP distance.

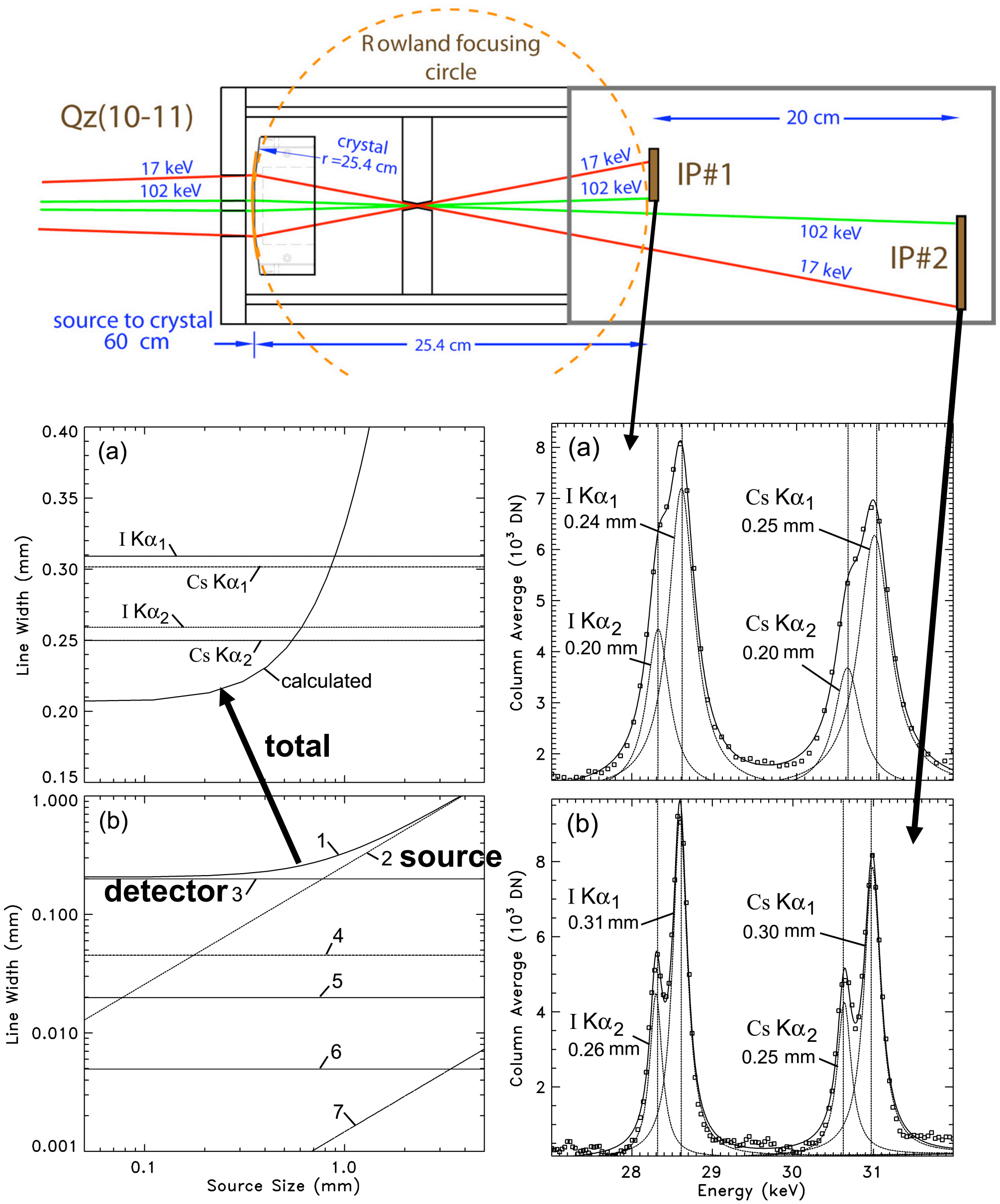
- **Crystal has 0.6 m standoff distance and covers 17-102 keV.**
- **Multiple image plates can be placed:**
  - **On the RC for high sensitivity, where detector resolution dominates.**
  - **Beyond the RC for high spectral resolution and source size measurement.**



- **Fielded inside LULI chamber 2007-2008.**
- **Qualified for EP and OMEGA with new name: Transmission Crystal Spectrometer (TCS).**

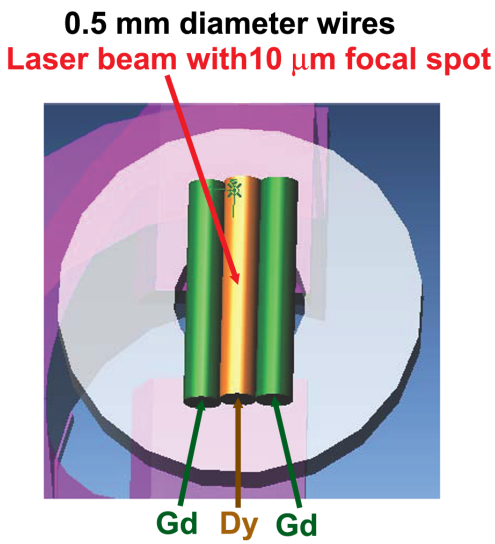
LULI X-Ray Source Size

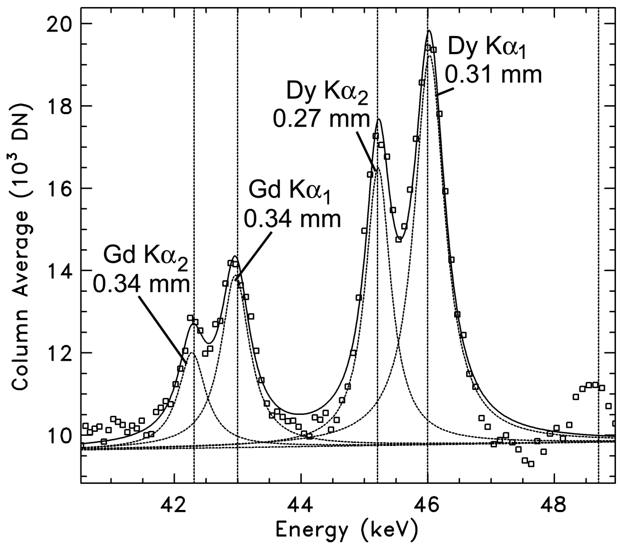
- **LULI PICO2000 laser: 100 J, 1 ps, 10 μm focal spot, 10^{20} W/cm^2 focused intensity, incident 34° from normal.**
- **Spectra were recorded by placing two MS image plates on the RC (detector broadening) and 20 cm behind the RC (source broadening).**
- **Comparisons with our geometrical model of the spectrometer indicate x-ray source size up to 1 mm.**
- **Energetic electrons generated in the focal spot propagate into the cold solid material beyond the focal spot and produce characteristic K-shell lines.**



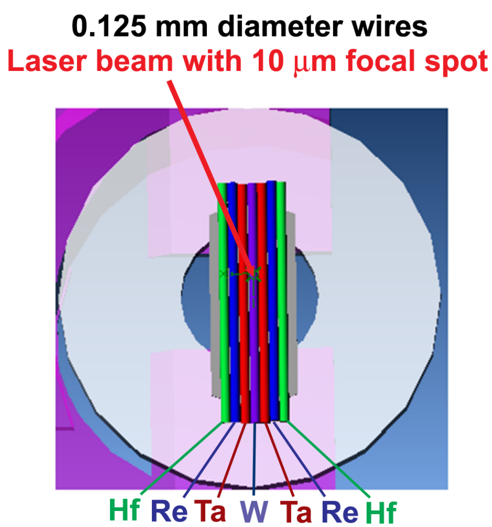
Energetic Electron Propagation Range

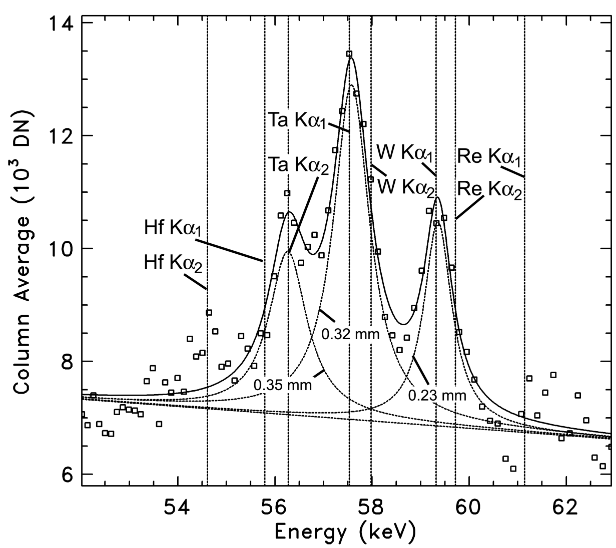
Indicated by spectral line intensities and line widths from targets composed of fine metal wires.





- **Lines from the two adjacent Gd wires are half as intense and are broader than the Dy lines.**
- **Indicates 0.38 mm lateral range (0.53 g/cm^2) and 0.80 MeV electron energy.**



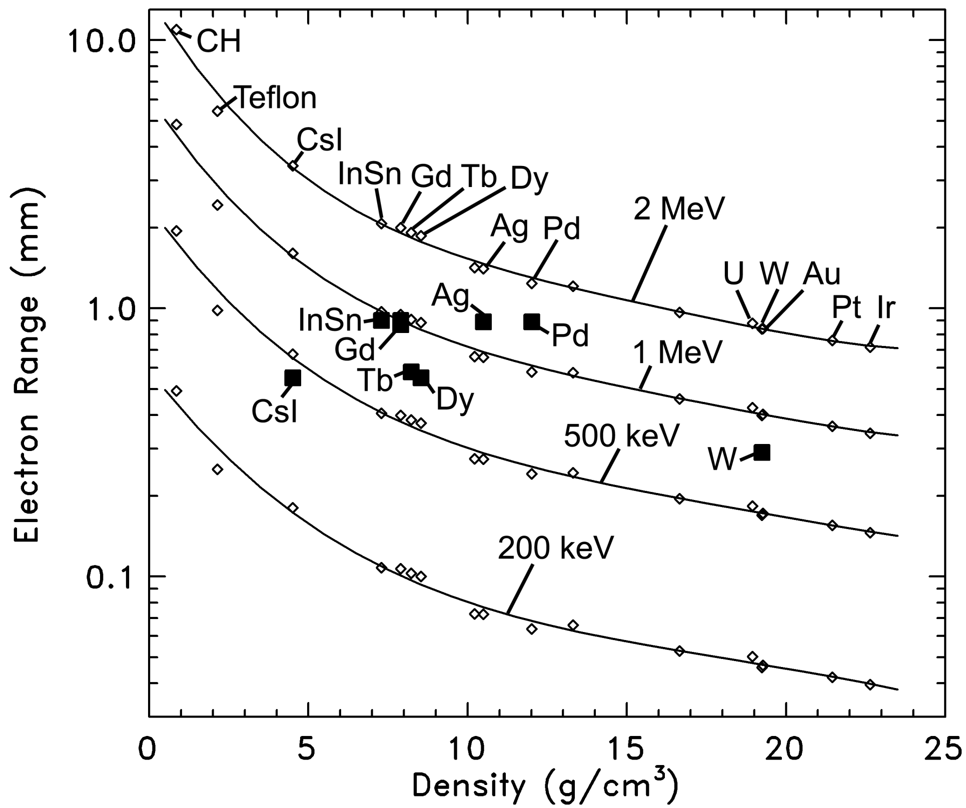


- **Lines from the two adjacent Ta wires are twice as intense and are broader than the W lines.**
- **Indicates 0.19 mm lateral range (0.64 g/cm^2) and 0.85 MeV electron energy.**

Electron Ranges in Various Elements

Planar and wire targets composed of numerous elements with a wide range of material properties were irradiated.

- **The range in electrically resistive CsI is relatively smaller than in highly conducting Ag and Pd.**
- **This suggests that energetic electron propagation in the resistive material is inhibited by a smaller electron return current.**



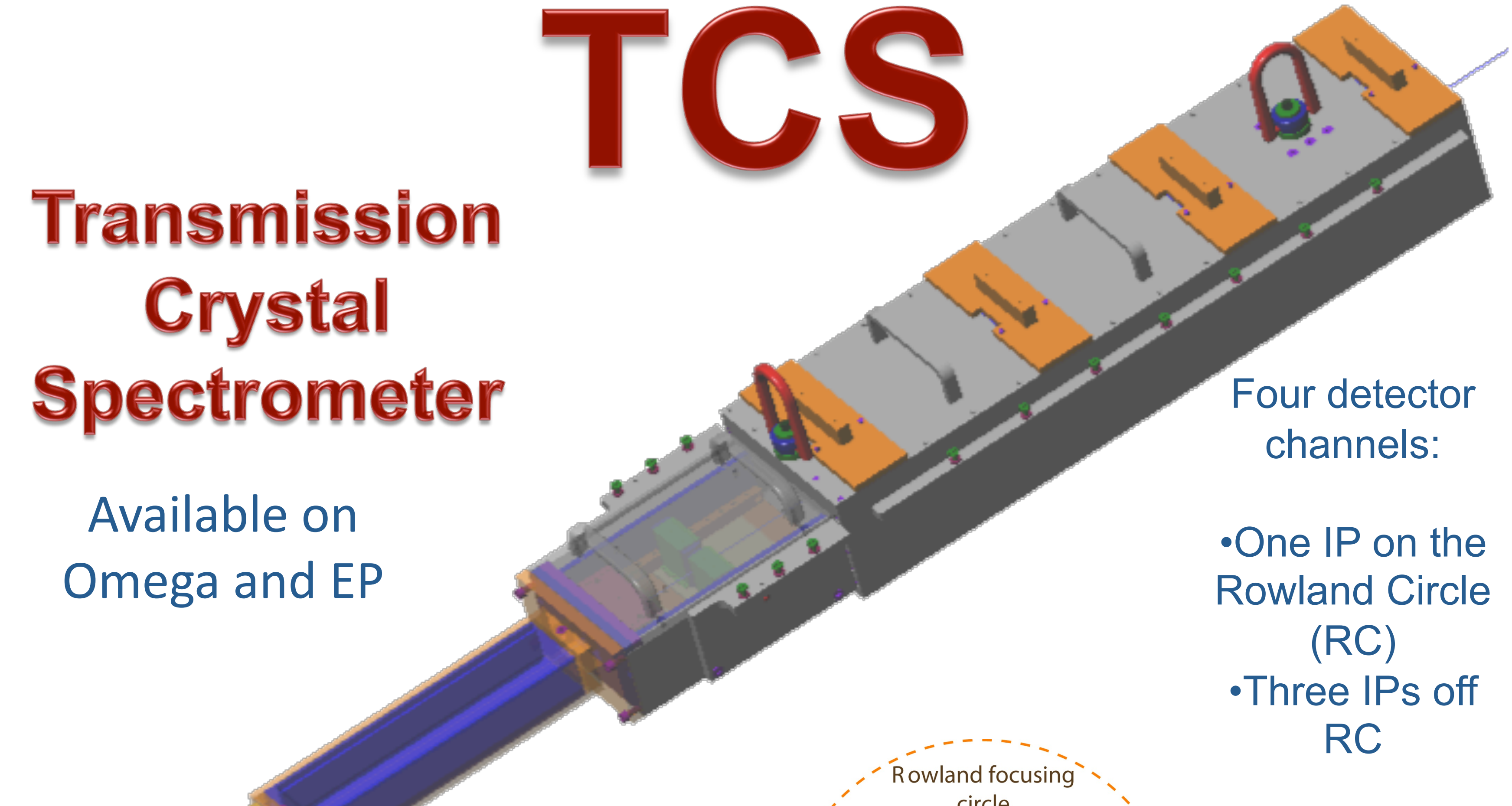
Range curves are calculated and

■ = data

TCS

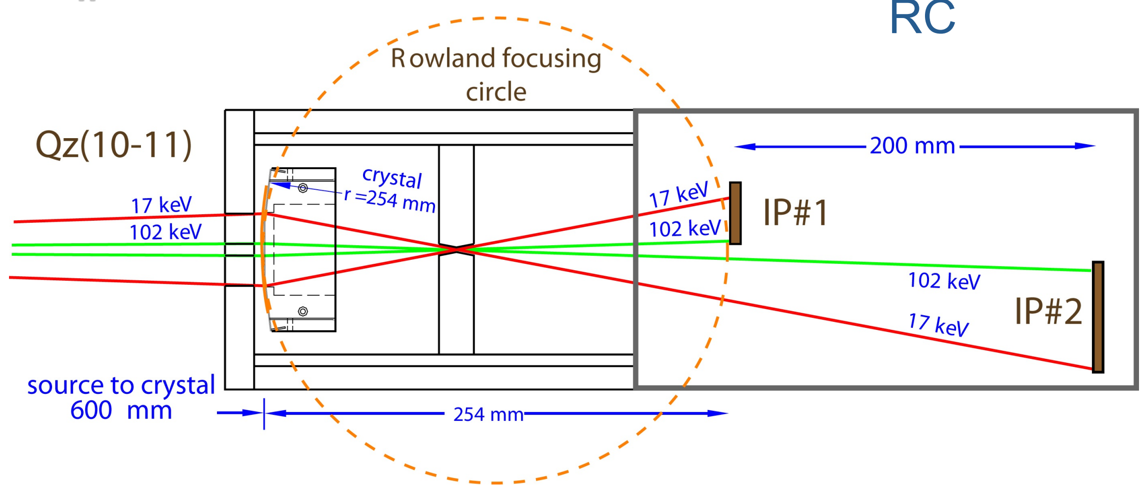
Transmission Crystal Spectrometer

Available on Omega and EP



Four detector channels:

- One IP on the Rowland Circle (RC)
- Three IPs off RC



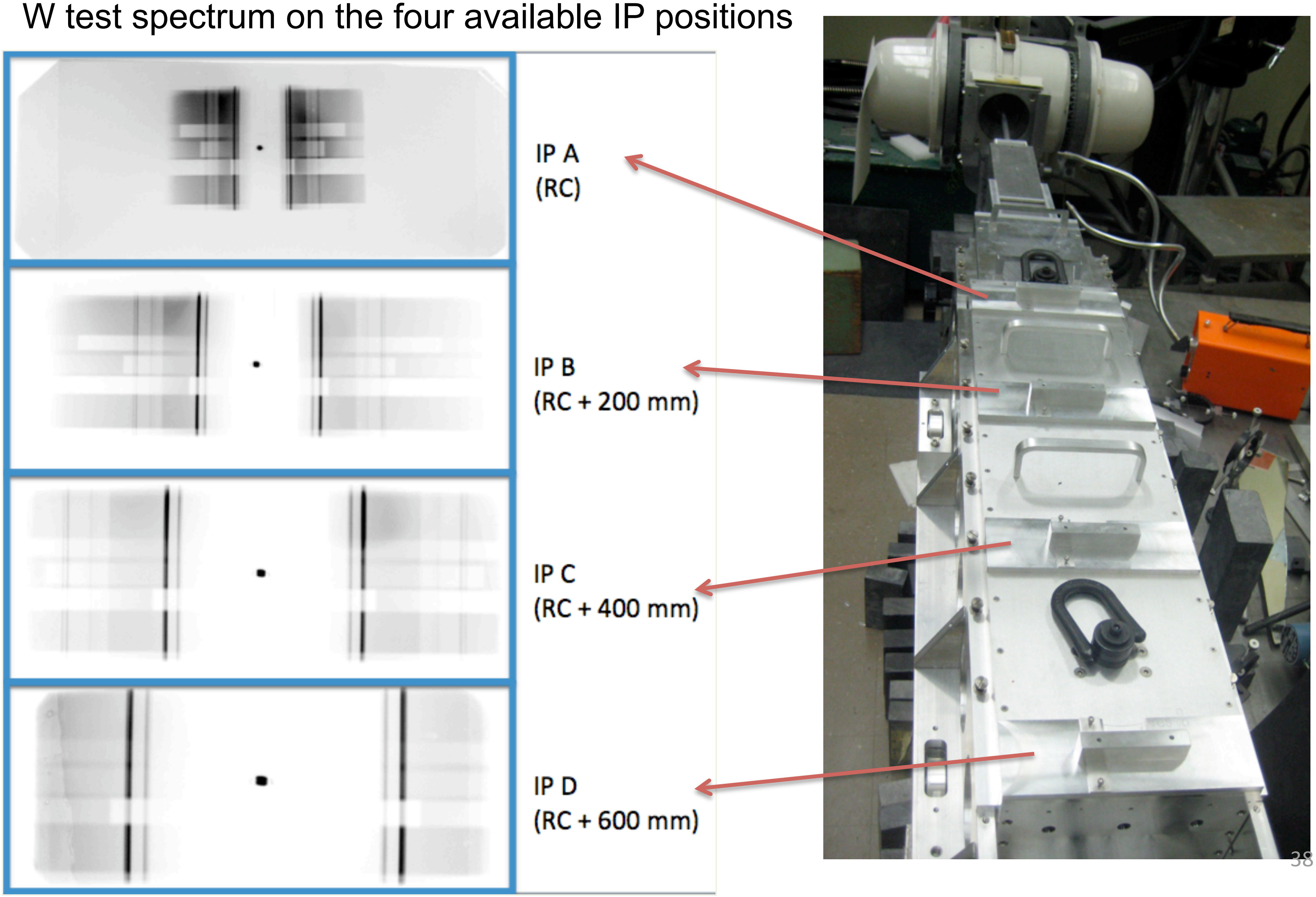
TCS

NRL NIST

Instrument on long term loan from LULI, France

Transmission Crystal Spectrometer (TCS)
- available at OMEGA and EP -

W test spectrum on the four available IP positions

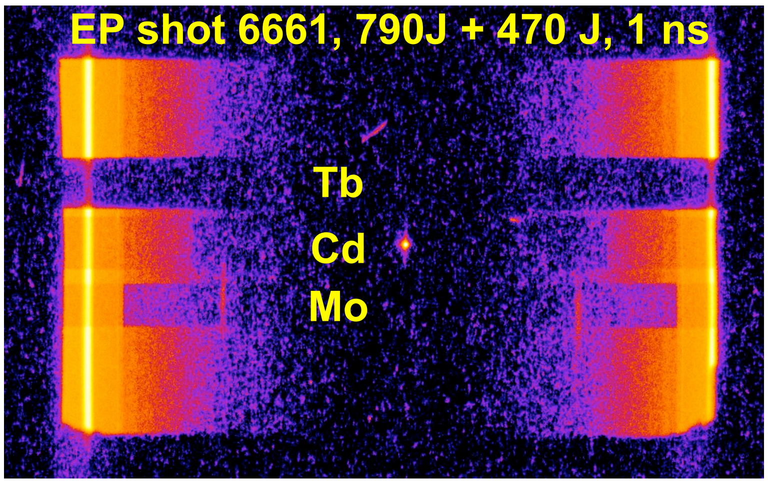


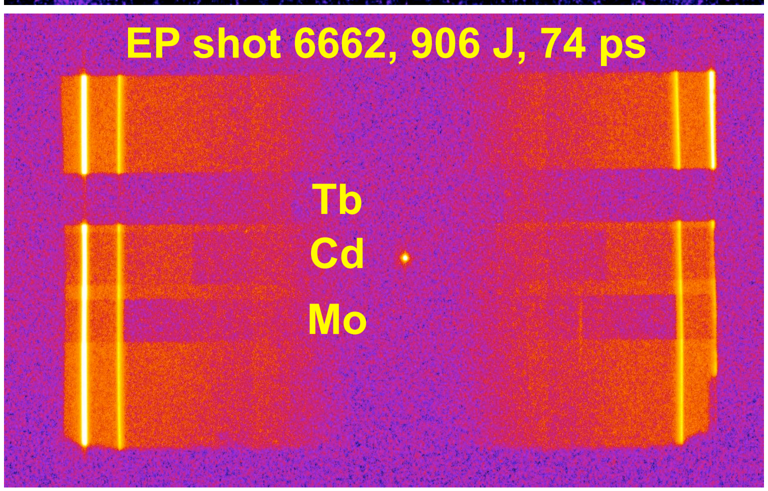
TCS results at EP with Mo backlighter

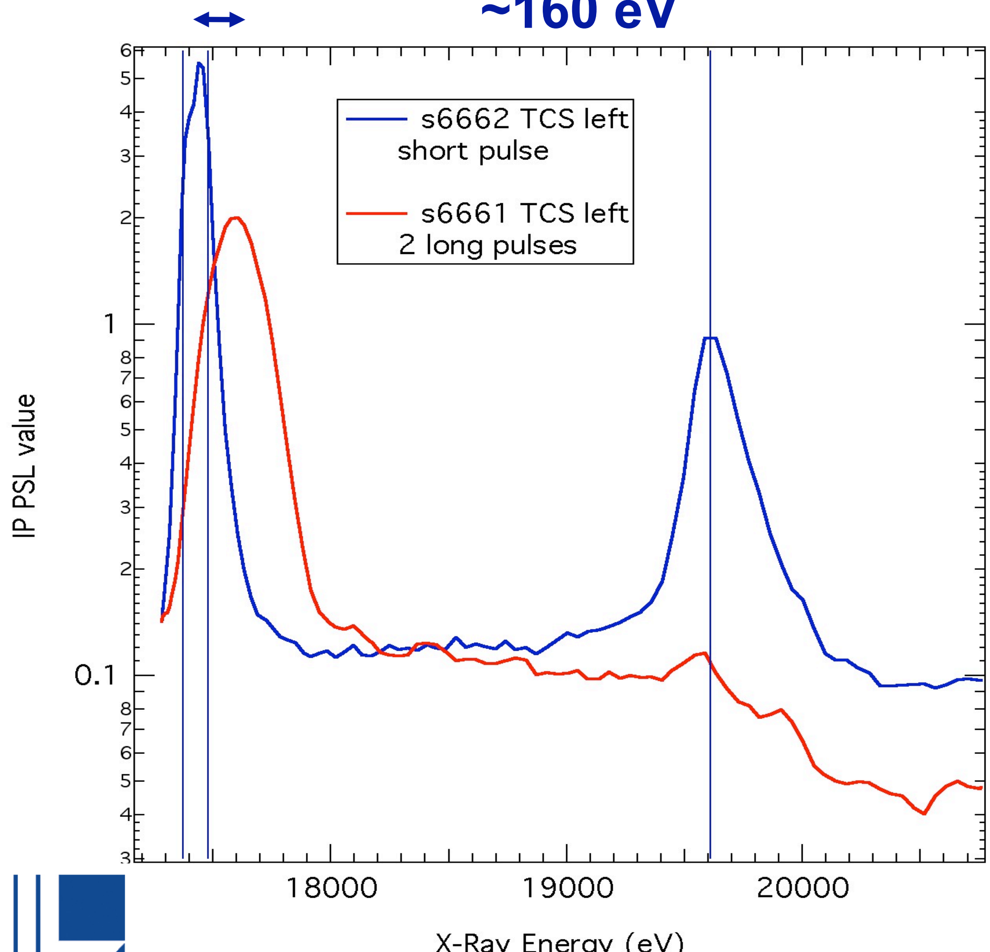
Metal	Thicknes (mm)	K-edge (kev)
Tb	0.127	51.995
Cd	0.025	26.711
Mo	0.025	19.99

Energy scale based on absorption edges and K lines in short pulse shot

Mo Kα peak shift in case of long pulse shot ~160 eV





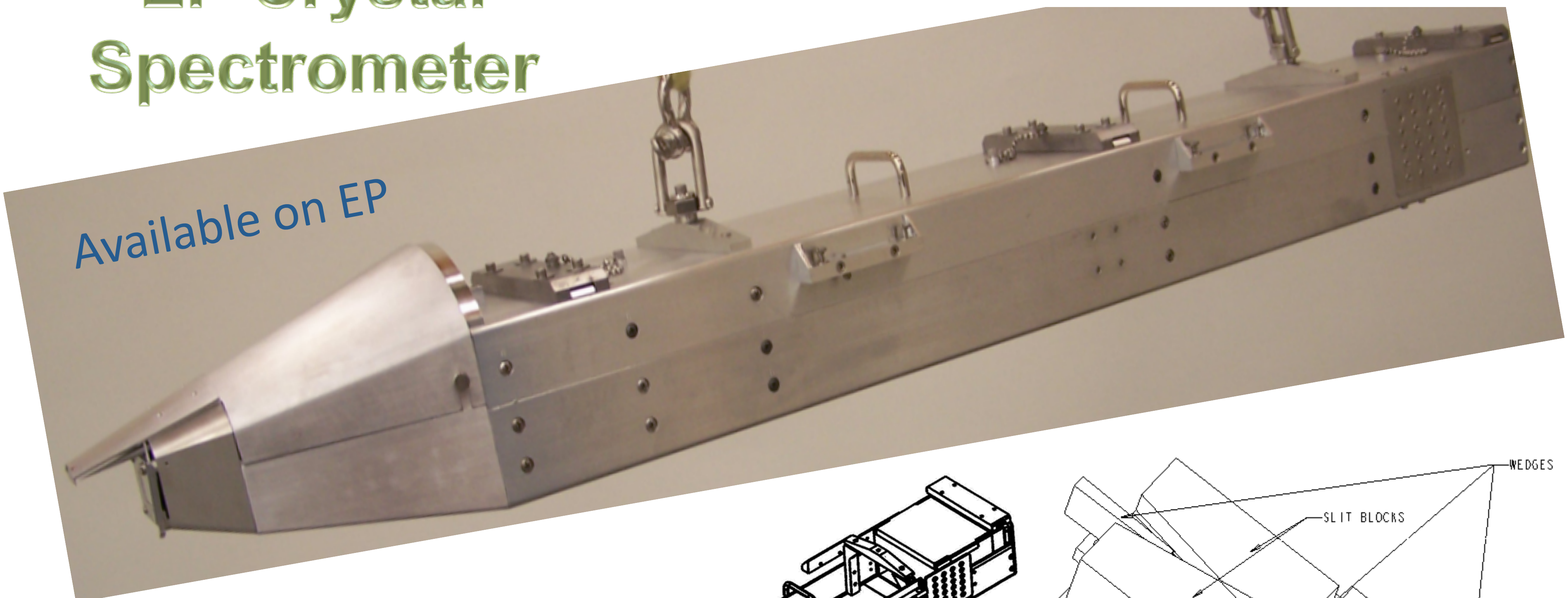


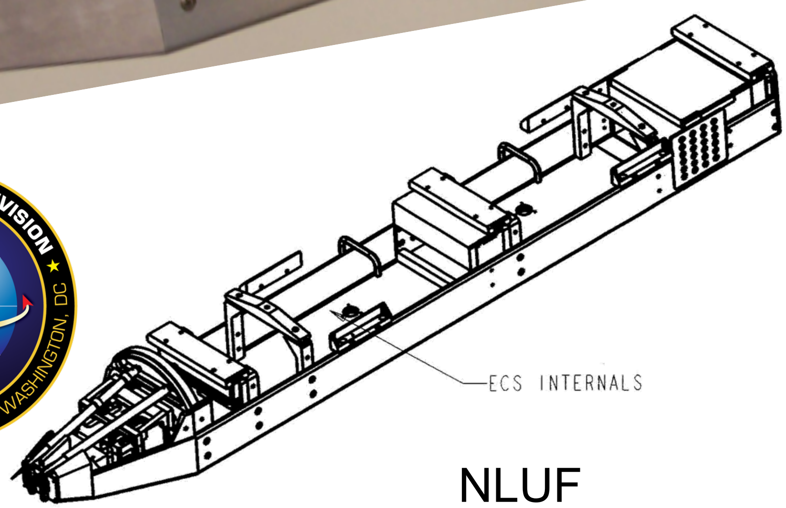
EP; Hye-Sook Park (LLNL) 12-10-2009

ECS

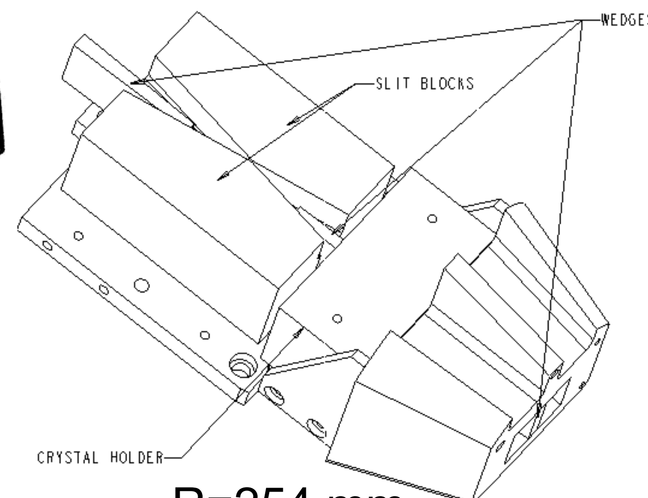
EP Crystal Spectrometer

Three detector channels:
- One IP on RC
- Two IPs off RC





NLUF

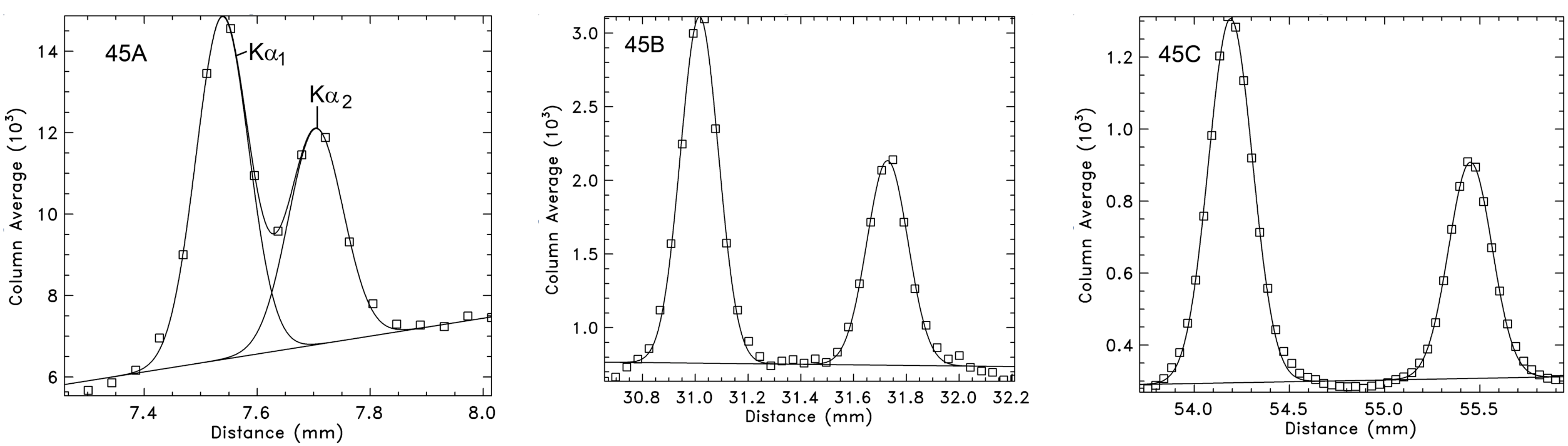


R=254 mm

Laboratory spectra

With a microfocus x-ray source at the Space Science Division of NRL

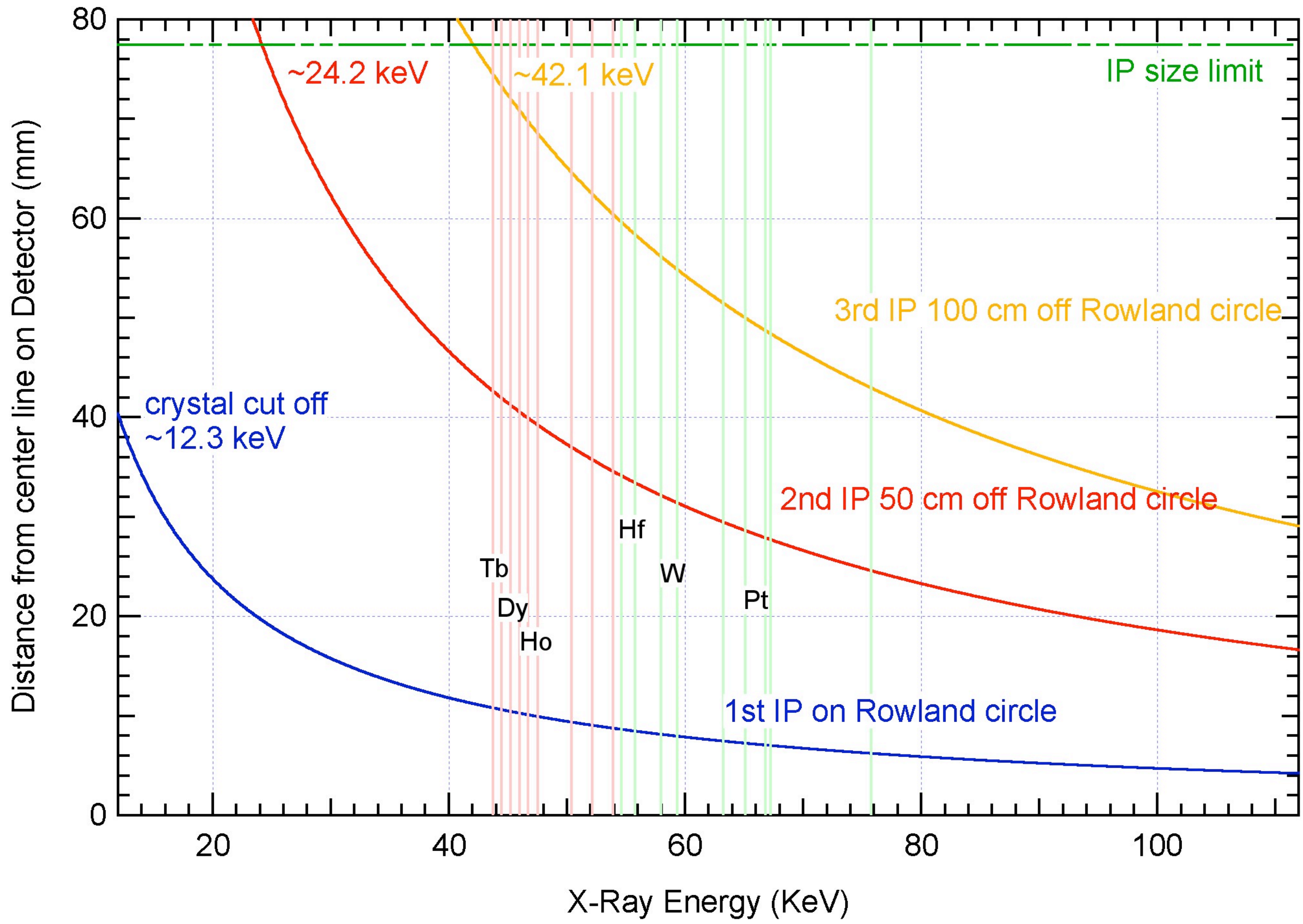
The ECS spectrometer was designed to have x1 magnification of the source width in IP position B and x2 in position C. Given the expected resolution (118 μm) of the SR IP, ECS should be capable of detecting approximately 70 μm source size in position C.



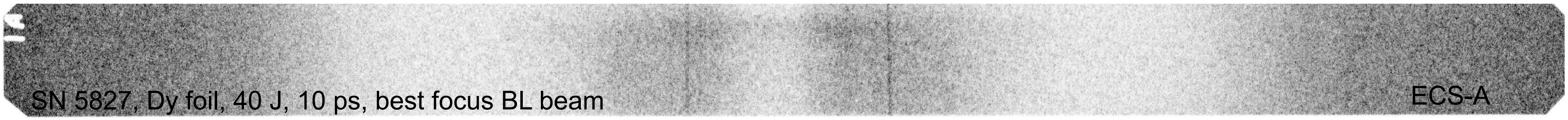
The left side spectra recorded using the larger source size (exposure 45) fitted to Gaussians. The IP positions are (A) on the RC, (B) 500 mm behind the RC, and (C) 1000 mm behind the RC.

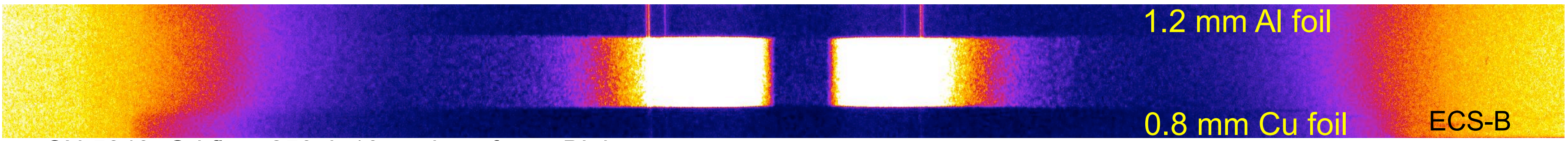
105-120 μm for the smaller spot setting on the Trufocus power supply and 130-145 μm for the larger spot setting, same as pinhole measurement

Plate Function of ECS at the three detector positions

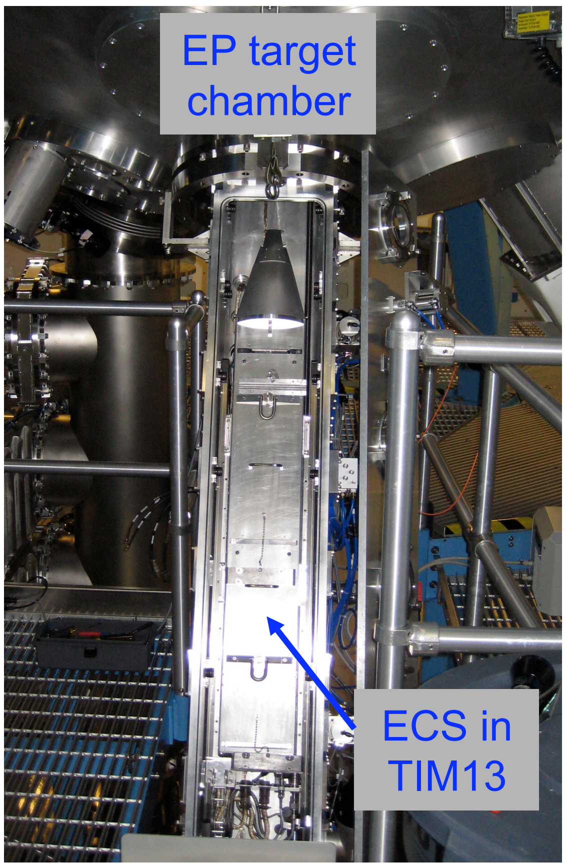


ECS at Omega-EP – August 26-27, 2009





SN 5843, Gd flag, 250 J, 10 ps, best focus BL beam

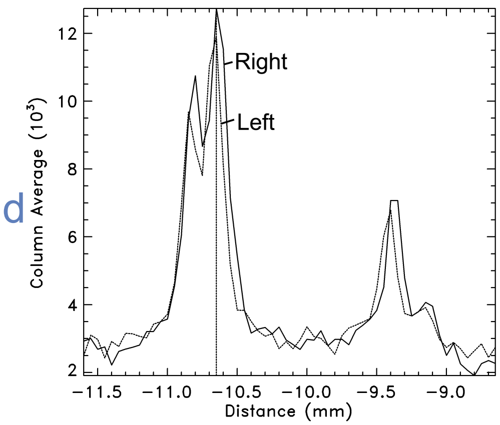


Spectral lines on ECS at first shot on EP

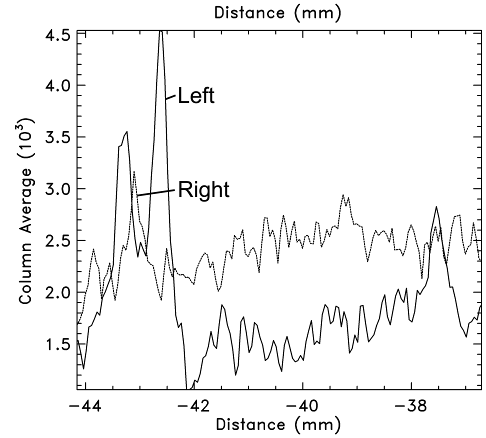
X-ray source size measurement on Gd Flag

inferred lateral source width: 360 μm

ECS-A SR image plates On Rowland Circle



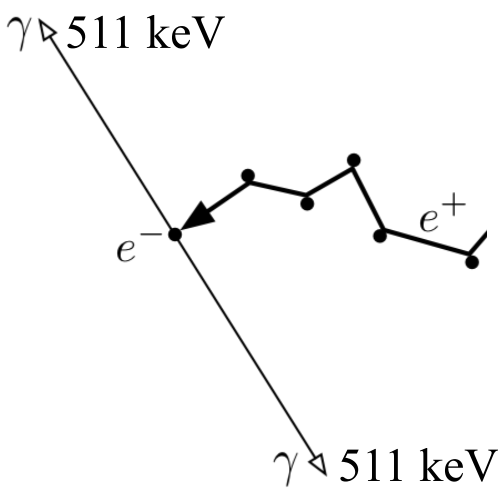
ECS-B SR image plates 500 mm off Rowland Circle



EP shots by Uri Feldman (Artep Inc) 8-27-2009

Gamma-Ray Spectrometer (GCS) project

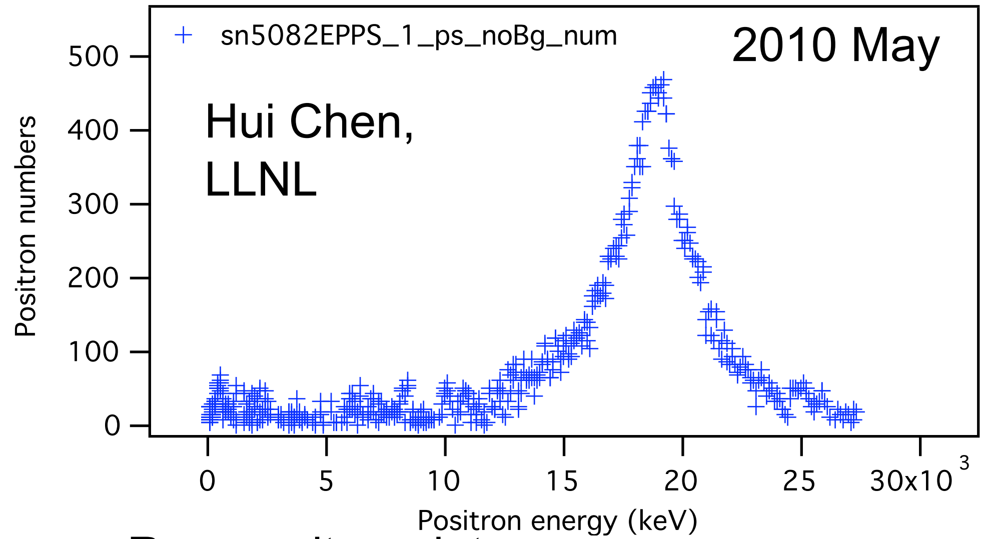
Electron-Positron Annihilation



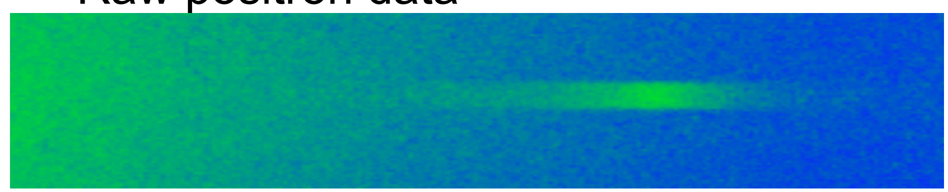
Spectrometer needed to see peak shifts due to non zero initial positron velocity

Direct detection

Preliminary positron spectrum from EP



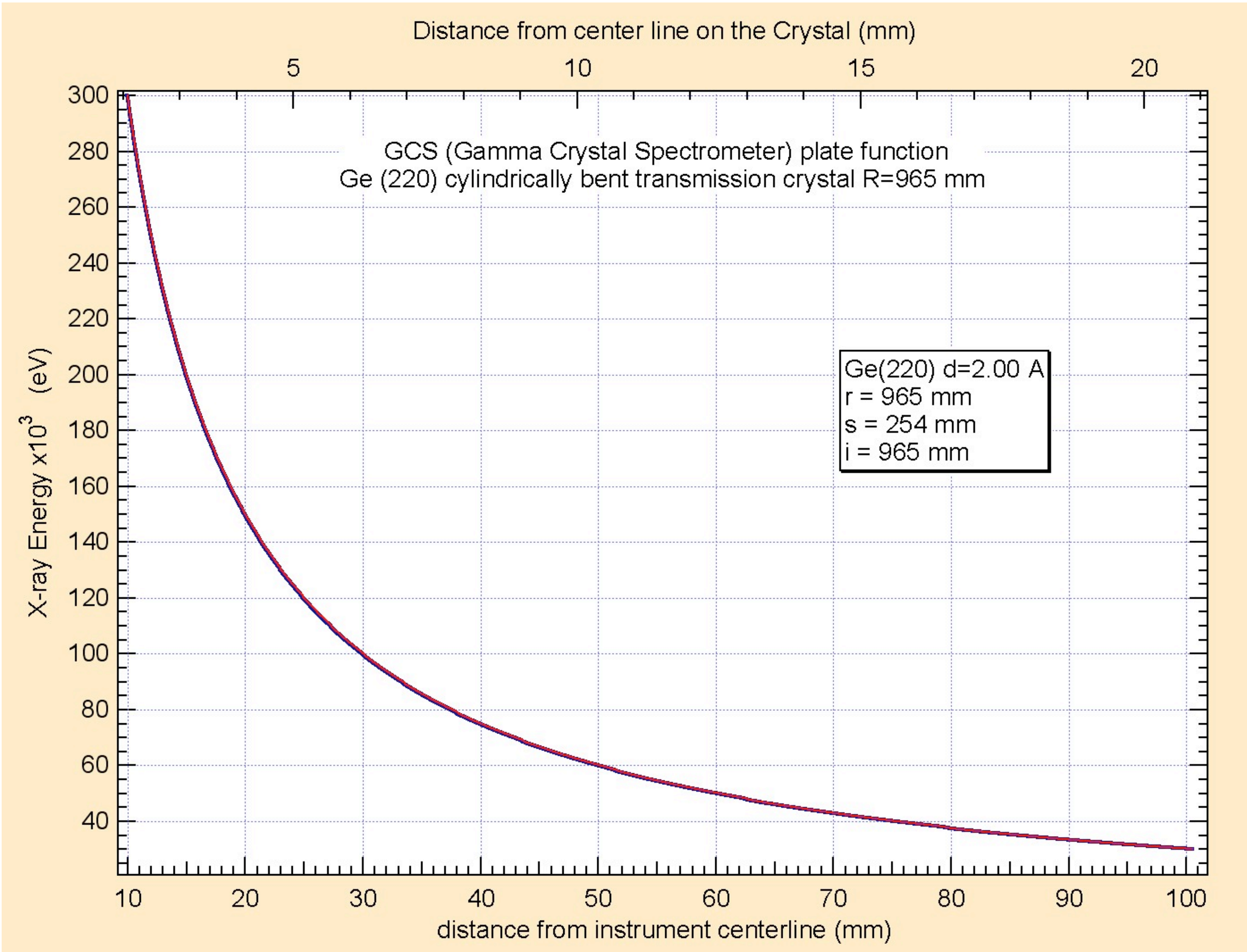
Raw positron data

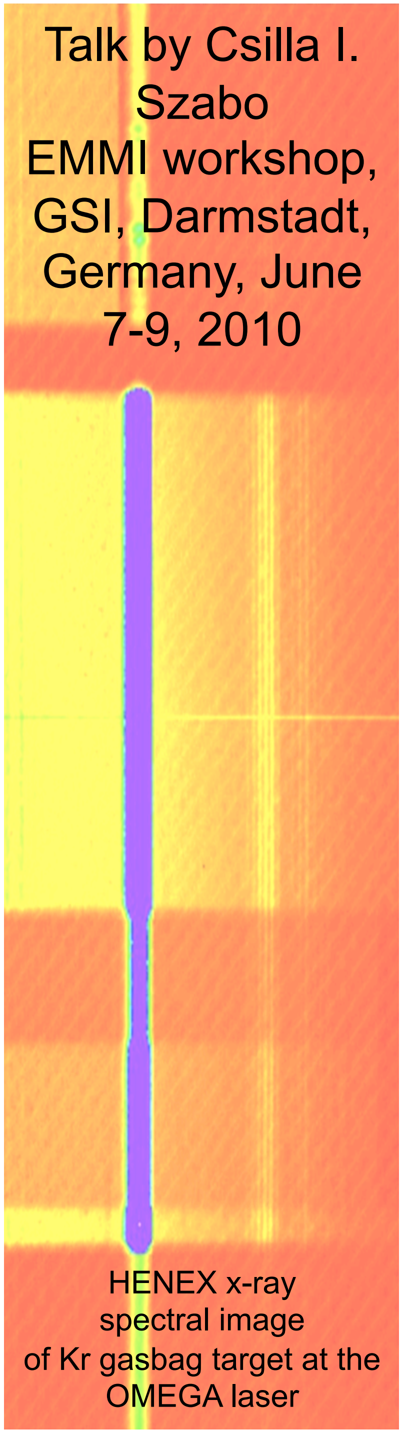


<u>Rough Estimate:</u>
Positron number:
3.5 million in detector
45.6 billion per sr.
~0.12% laser-positron energy conv.

GCS plate function in first order, Ge(220)

The 511 keV gamma rays will be detected in second order or by using the Ge (440)





HENEX x-ray spectral image of Kr gasbag target at the OMEGA laser

HIGH ENERGY X-RAY SPECTROSCOPY AT HIGH-ENERGY LASER FACILITIES

- Summary-

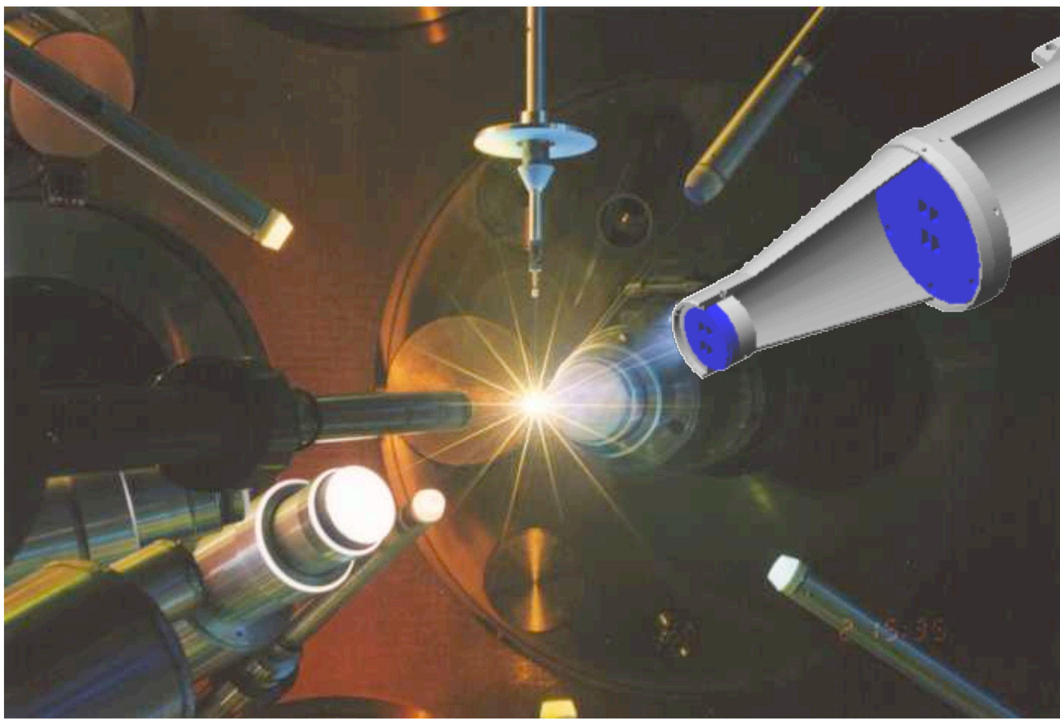
① Introduction
- High Energy Density Physics and Inertial Confinement Fusion (ICF) research
- X-ray spectroscopic needs at high energy density facilities
- How to detect a high energy x-ray spectrum in a few nano seconds?

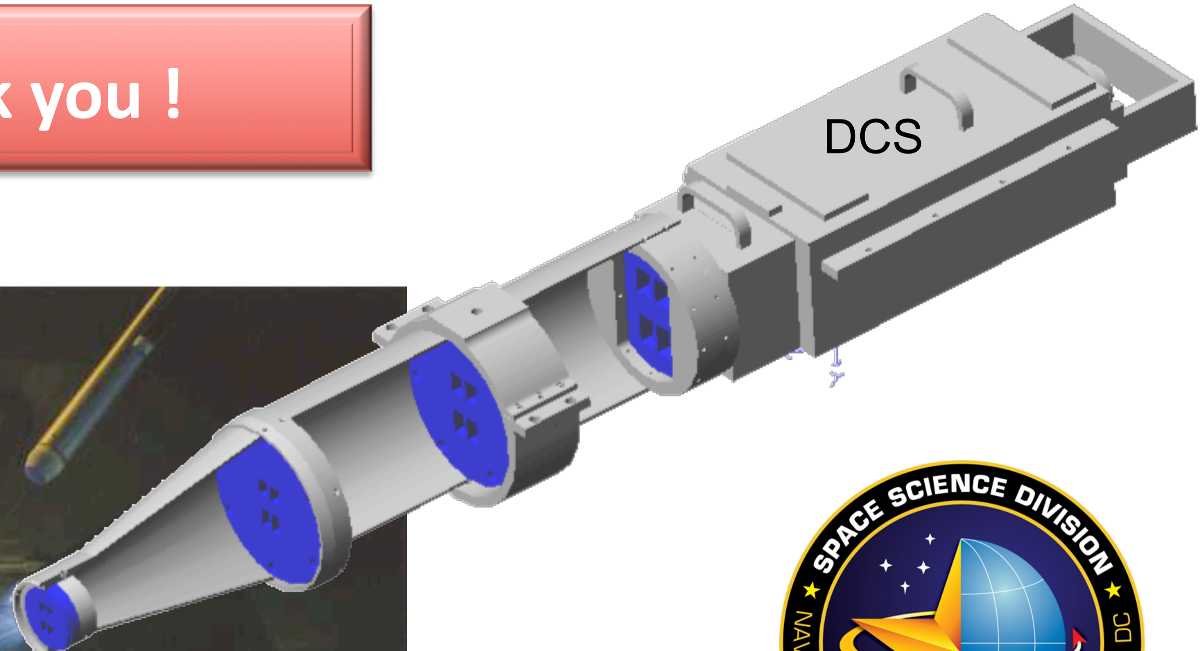
② Cauchois type x-ray spectrometer for laser facilities

③ Enhancement of resolving power and source size measurement with the Cauchois type spectrometer
- a few examples of the diagnostics built by the NRL-NIST team
- Newest spectrometers

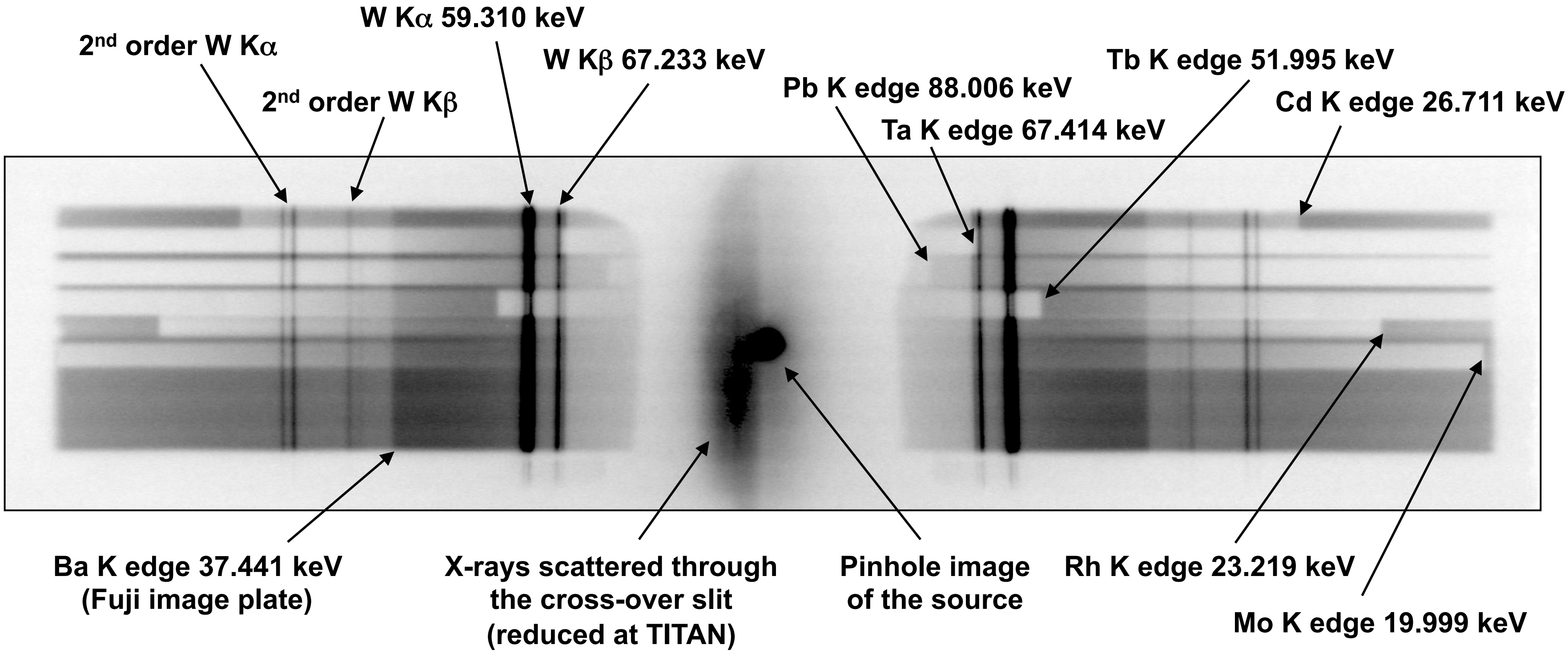
X ray as a tool for probing Extreme States of Matter
EMMI workshop, GSI, Darmstadt, Germany, June 7-9, 2010

Thank you !



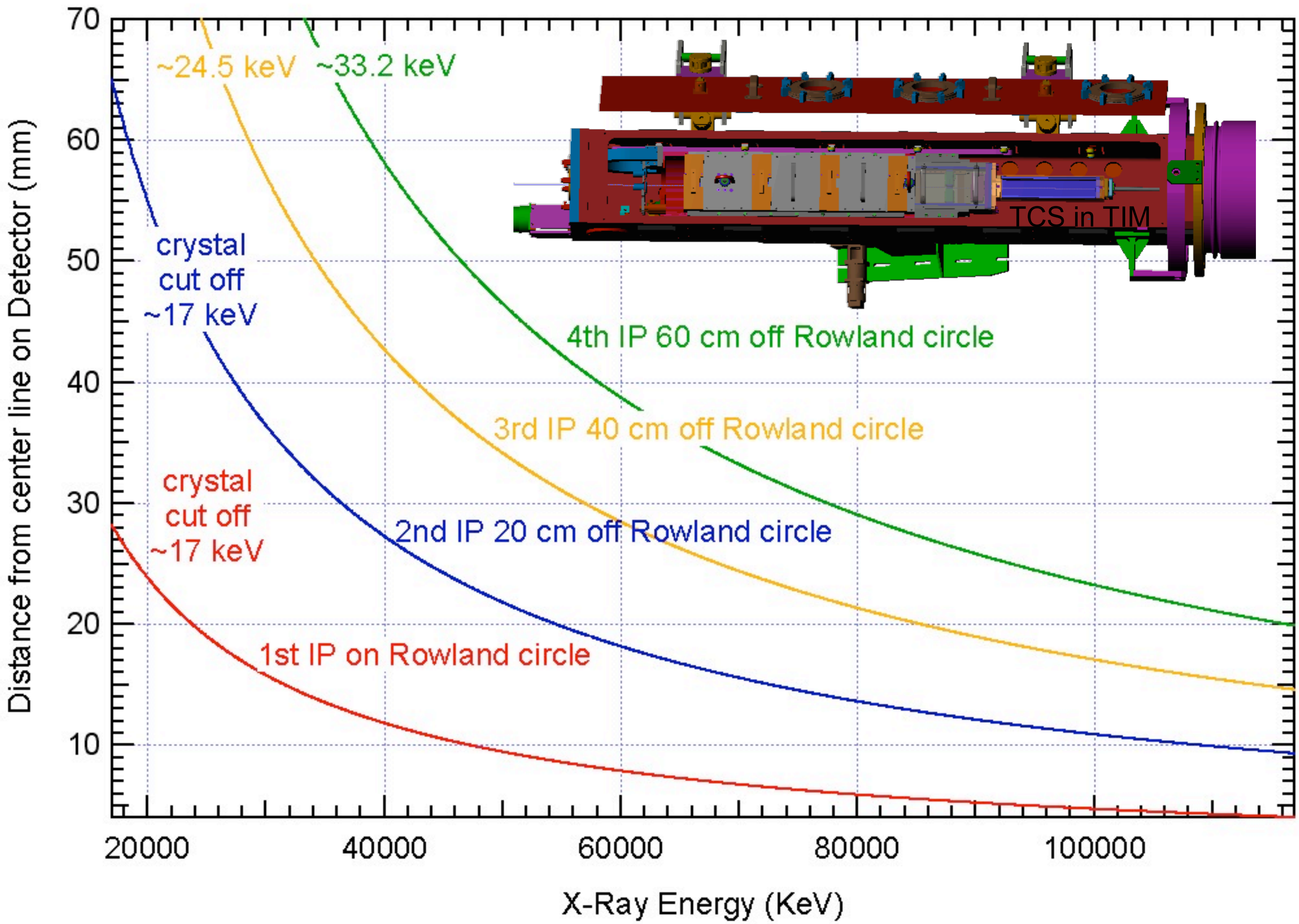


DCS LABORATORY TESTING

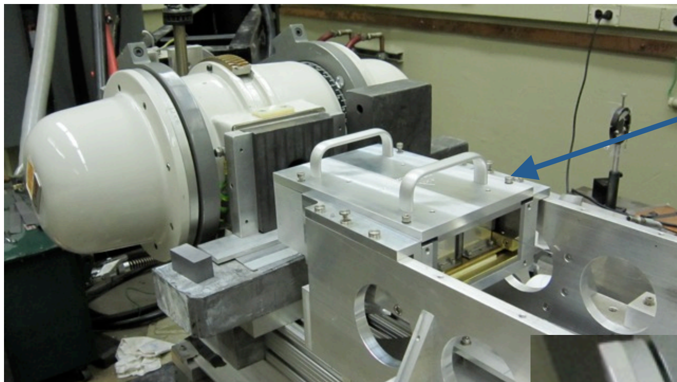


- 1.2 m standoff from the W anode laboratory source.
- W Kα and Kβ lines were observed in 1st and 2nd orders and were well resolved.
- Filter K edges and Ba edge (from IP) establish an accurate energy scale.
- Instrument issues, such as scattered x-rays, were studied and corrected.
- Detector sensitivity and resolution were studied and optimized (Fuji image plates and BIOMAX film with and without various x-ray conversion screens).
- W anode, 250 kVp, 4 mA, 40 sec (typical) exposure on a Fuji image plate.

TCS is now qualified for EP and Omega TIMs

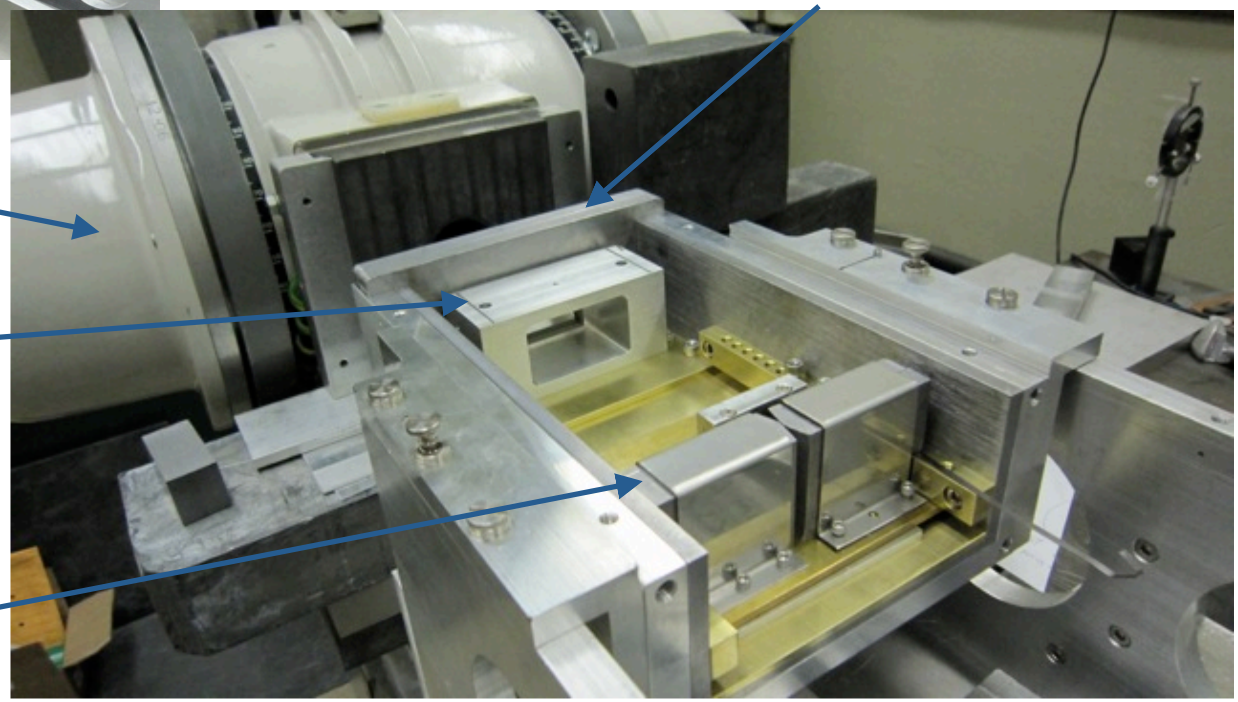


Testing at NIST



Spectrometer box in front of the 420 kV Tungsten industrial x-ray source at NIST

Front shielding allowing symmetric mirror spectra

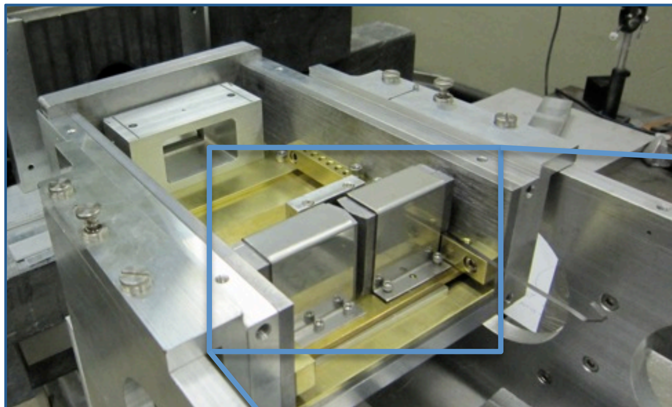


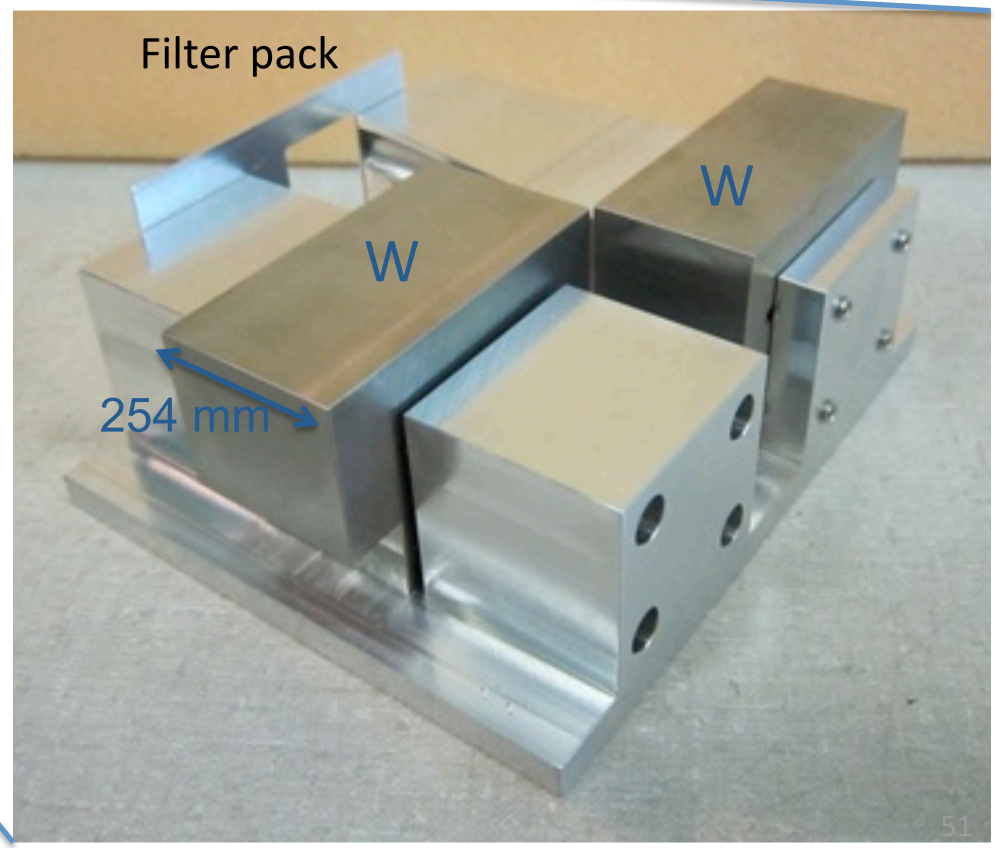
X-ray tube

0.4 mm thick cylindrically bent Ge(220) crystal, R=965 mm

Cross over slit allowing symmetric mirror spectra

Final Slit assembly to replace test slit



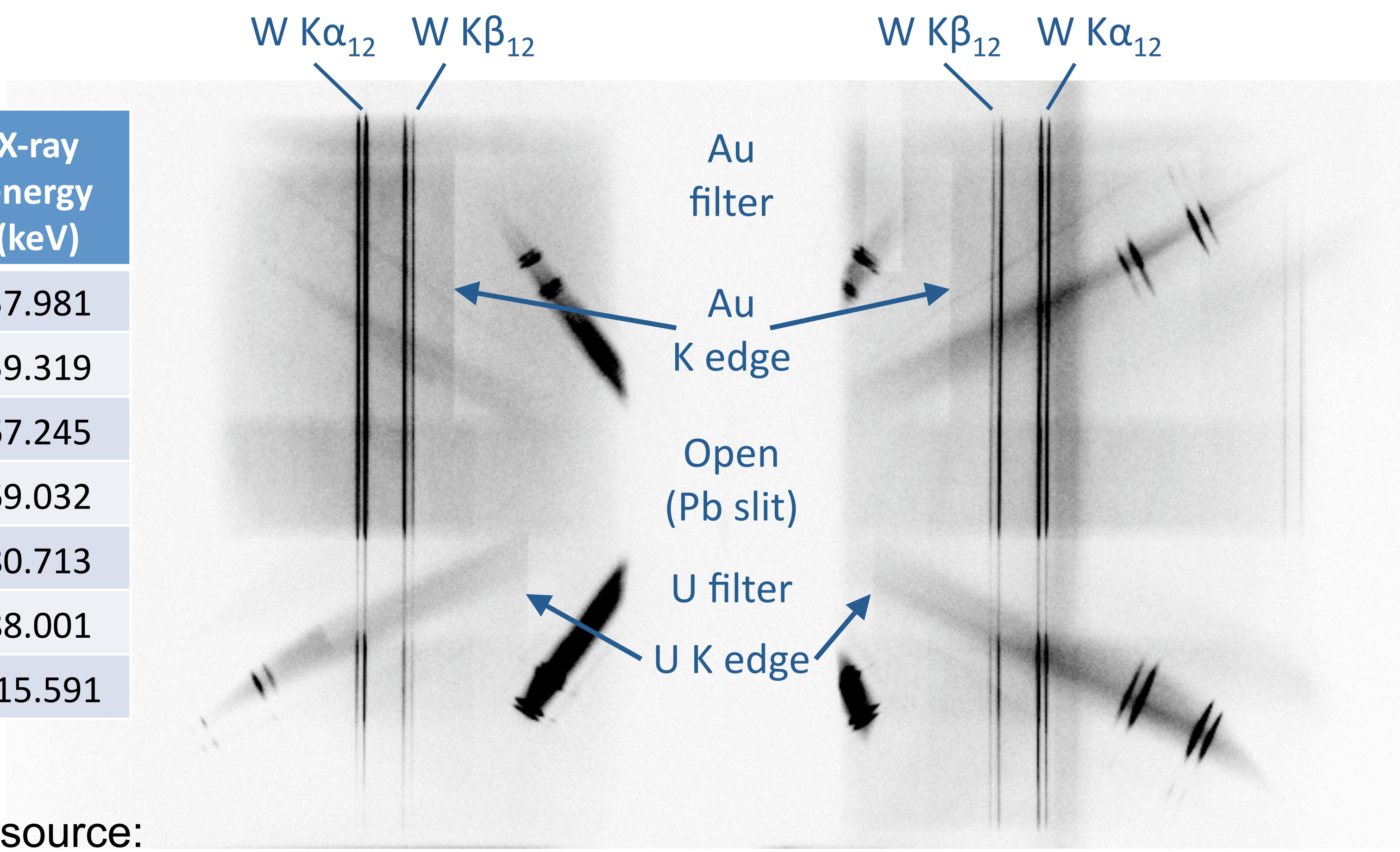


Test Spectrum

- Mirror spectra with Pb front aperture and cross over slit -

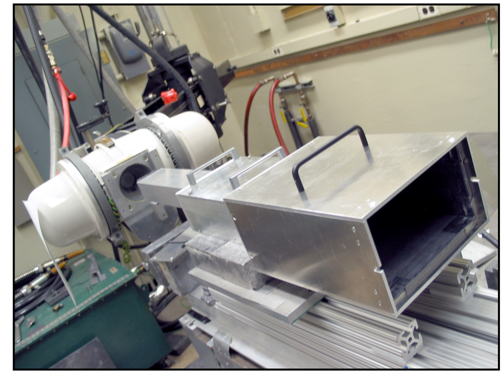
The first test of the new thick (0.4 mm) Ge(220) crystal was successful!

Line or edge	X-ray energy (keV)
W Kα_2	57.981
W Kα_1	59.319
W Kβ_1	67.245
W Kβ_2	69.032
Au K edge	80.713
Pb K edge	88.001
U K edge	115.591

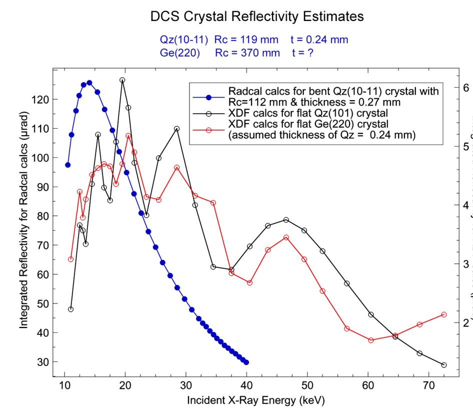


W x-ray source:
Exposure time: 0.8 min = 48s, peak voltage: 256 kV, Target current: 4 mA

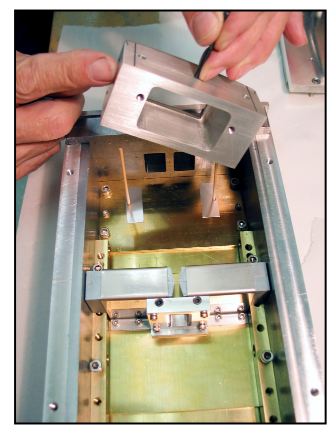
Absolute Sensitivity Calibrations



Bent-crystal spectrometers must be calibrated under the same geometrical conditions as they are used for experiments (e.g. point source provided by a laboratory microfocus source).



Crystal efficiency codes are useful as guides but are not sufficiently accurate, particularly for bent crystals.

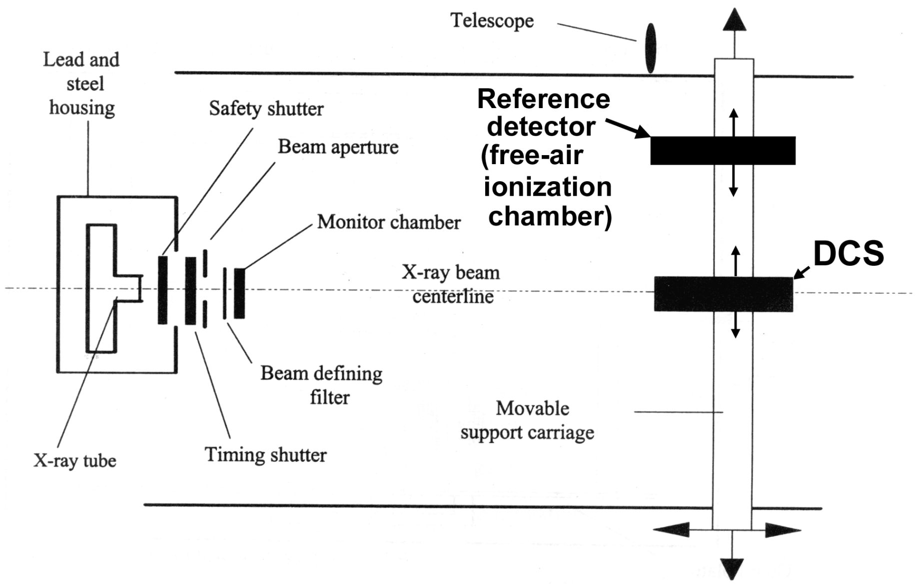


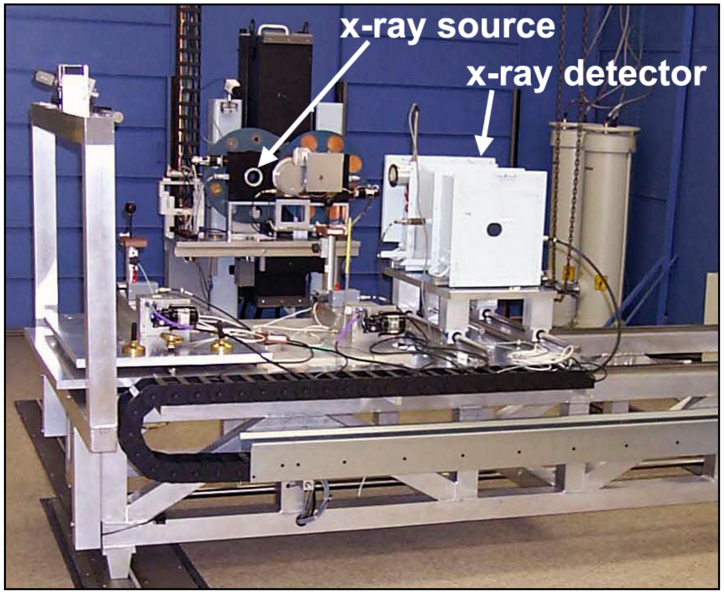
Spectrometer components (crystals, detectors/scanners) should be calibrated separately and in an interchangeable manner and then compared to the end-to-end spectrometer calibration.

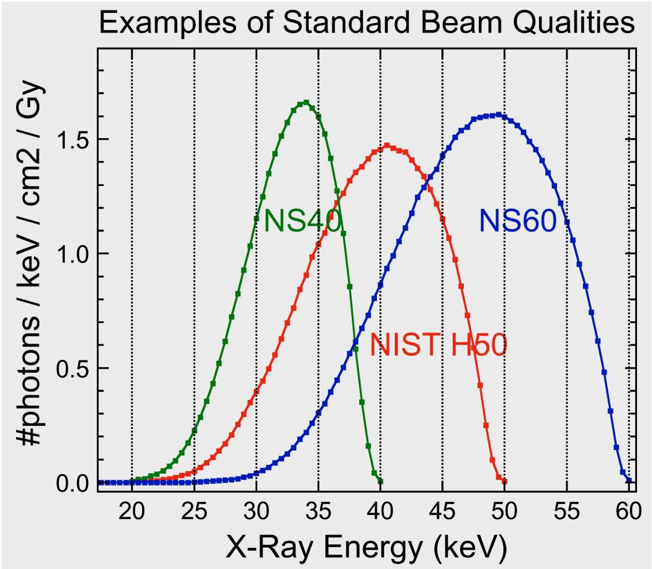
Different calibration techniques provide redundancy:

- **NRL: W & Mo microfocus sources and calibrated detectors.**
- **NIST: calibrated medical and other radiography sources.**

NIST Calibration Facility







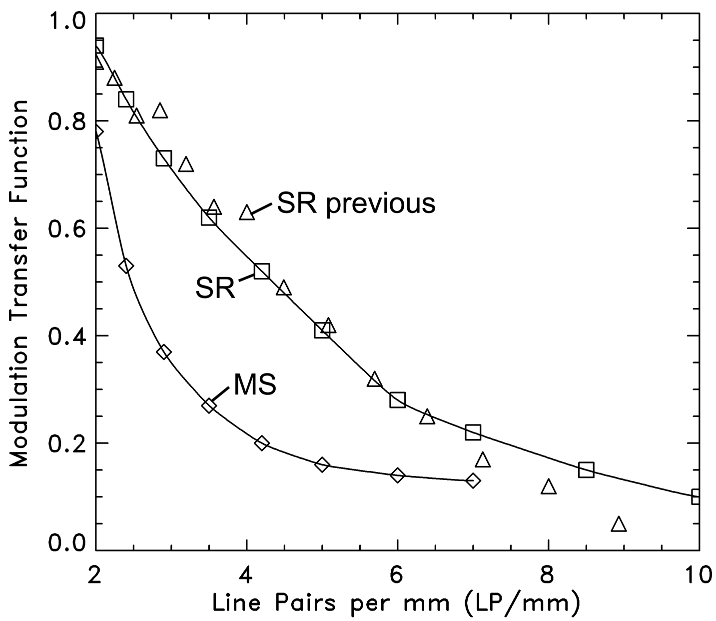
Source-based calibration:

- **A known x-ray fluence from the NIST source is provided by using standard filtration, voltage, current, and exposure time.**
- **Relate the detector data (IP counts or CCD exposure) to the known fluence.**

Image Plate Resolution

Measurement of the image plate spatial resolution enables deconvolution of the detector resolution and accurate measurement of source size.

- **The modulation transfer functions (MTF) and point spread functions (PSF) of Fuji SR and MS image plates were determined from:**
  - **The contrast produced by a bar pattern with up to 10 LP/mm.**
  - **Line shapes produced by narrow spectral lines recorded on the RC.**
  - **Edge spread function produced by the Pb bars of the test pattern.**
- **(a) SR PSF is Gaussian with 0.13 mm FWHM.**
- **(b) MS PSF is Lorentian with 0.19 mm FWHM.**



Seely *et al.* Appl. Opt. 47, 5753 (2008)