High Energy X-ray Spectroscopy for Radiography and Atomic Physics Investigations in Laser Produced Plasmas

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Outline:

- Spectrometer optical design and capabilities.
- Spectrometers deployed at laser facilities (Omega, Titan, LULI) and example results.
- Presently building spectrometer for EP.

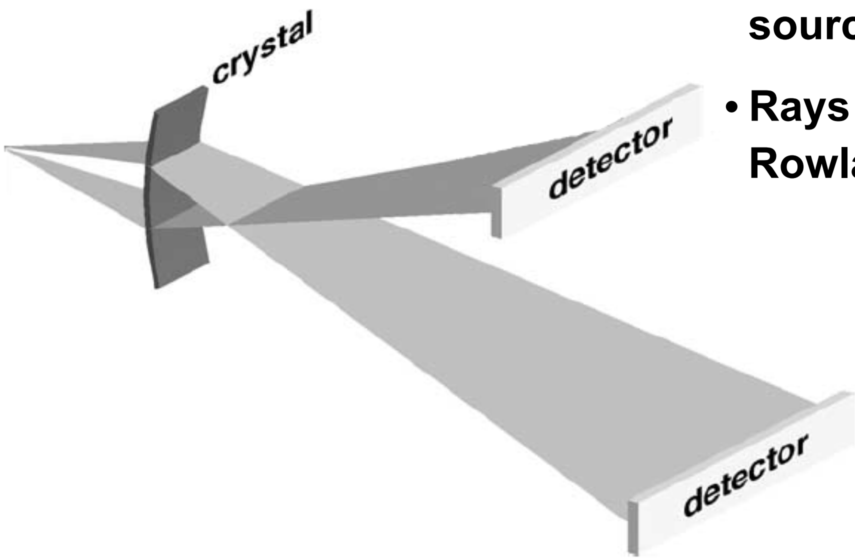
Science Motivation:

- Atomic physics of inner-shell transitions in high atomic number atoms and ions (up to U).
- High-energy spectroscopic diagnostics: temperature, density, ionization balance, opacity.
- Conversion efficiency to hard x rays: flash radiography of dense objects.
- Energetic electron distribution, hard x-ray backlighter optimization, small source size.
- MeV electron propagation through conductive and resistive materials (return current, etc).

LLE, 28 April 2009

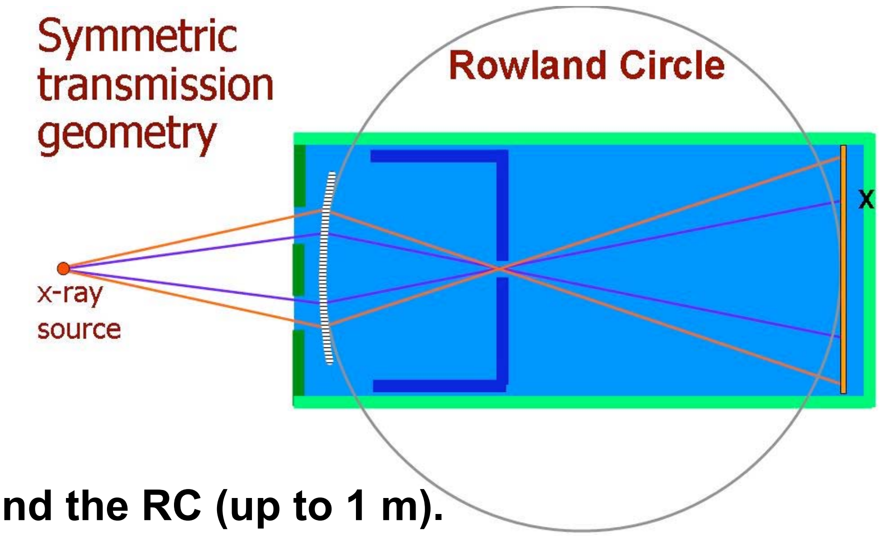
Transmission Crystal Spectrometer

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



<u>Cauchois type transmission crystal spectrometer</u>

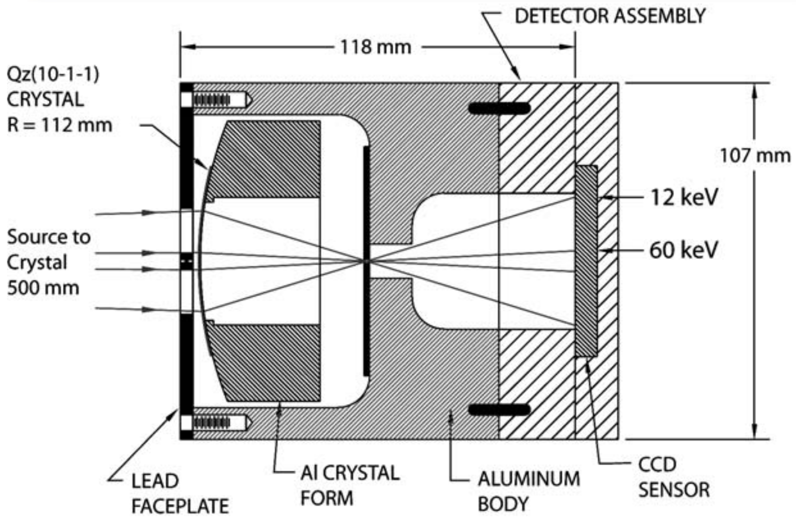
- **All rays with the same energy and from an extended source are focused on the Rowland circle.**
- **Rays with different energies are dispersed on the Rowland circle.**

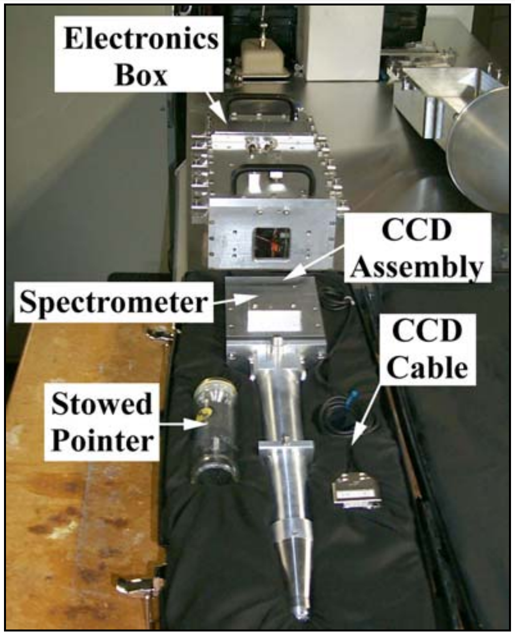


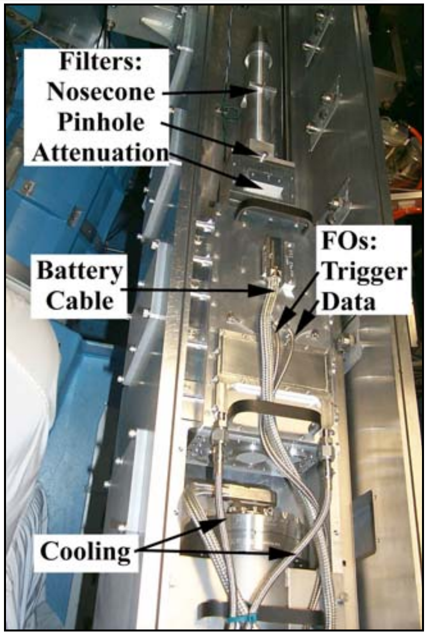
<u>Unique features of NRL/NIST spectrometers</u>

- **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 10 μm.**

HXS (High-Energy X-Ray Spectrometer)

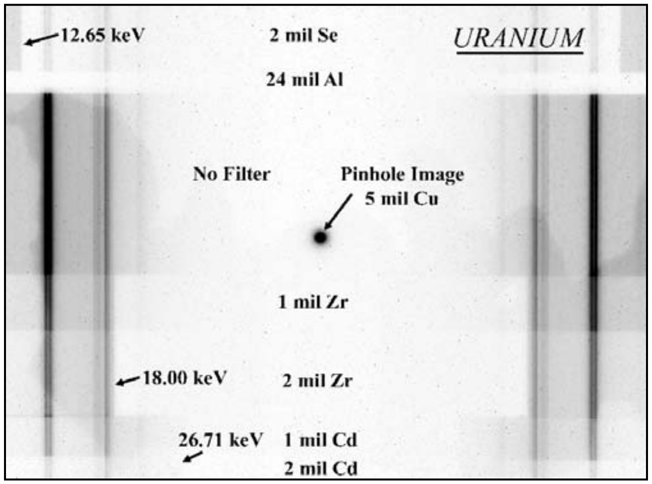


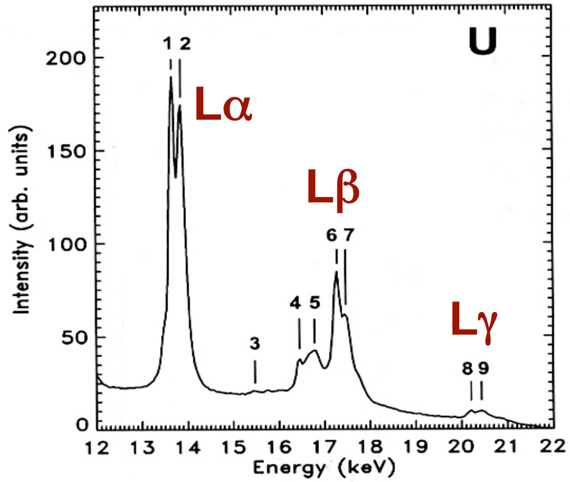


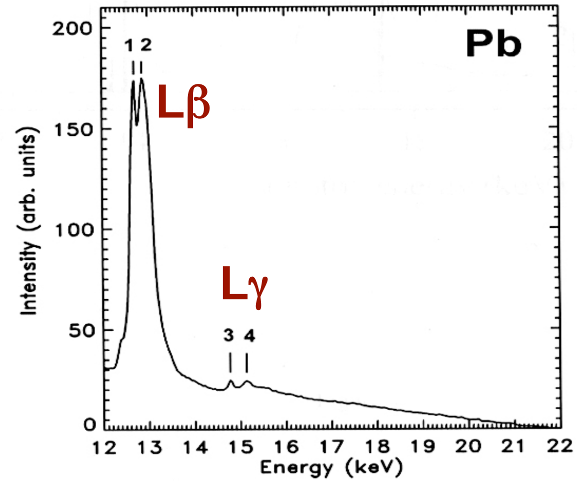


- **Fielded at OMEGA in 2000 and 2001.**
- **Survey spectrometer covering 12-60 keV with moderate resolution (≈100).**
- **Detector (dental x-ray CCD) on the Rowland circle, on-board electronics and battery power, and fiber optic communications to lab computer (EMI isolation).**
- **Two spectra are symmetrical 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.**

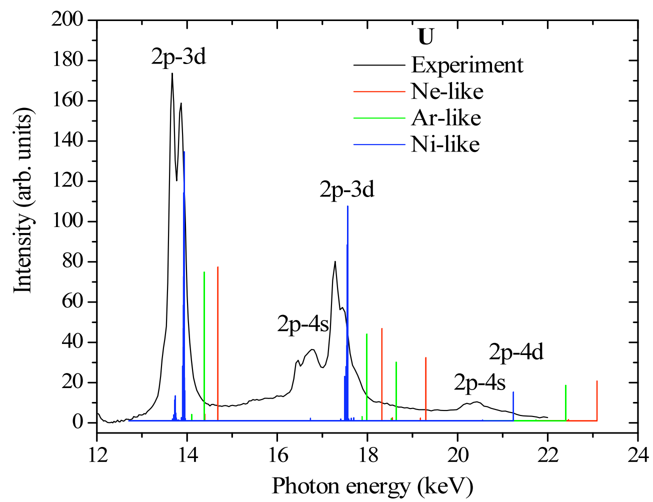
HXS Spectra and Results



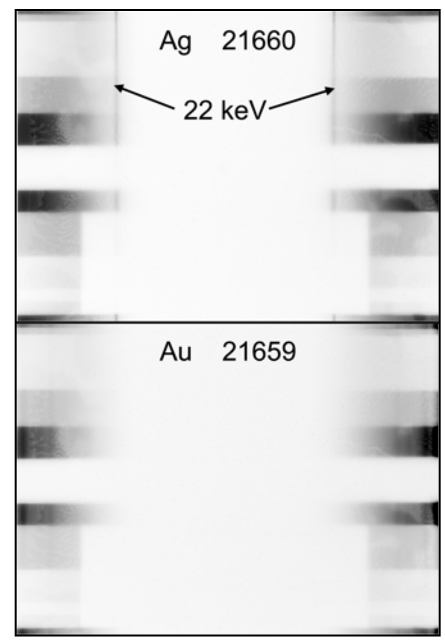




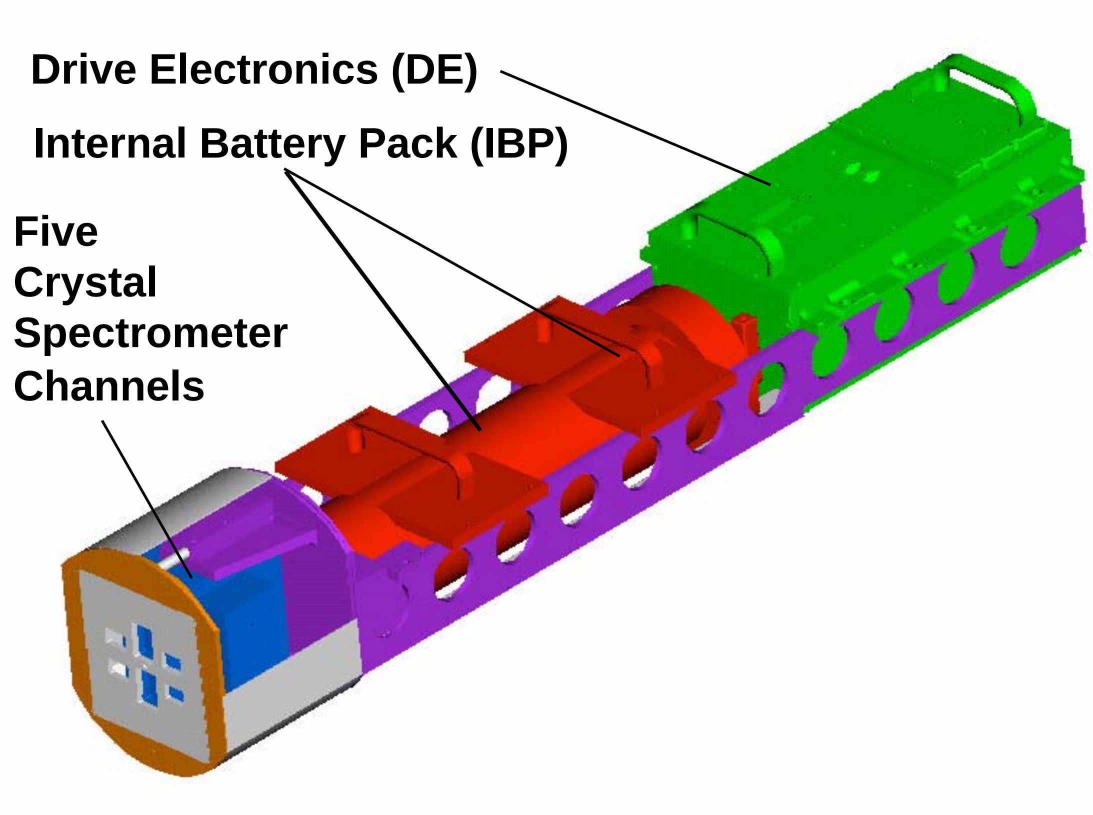
- HULLAC calculations indicate inner-shell transitions in U ions in the vicinity of Ni-like ions.
- STA and other calculations indicate <Z>=58, T_e=900 eV, and $n_e=7\times10^{23}$ cm^{-3}, and large opacity.
- L-shell vacancies are created by energetic electrons.



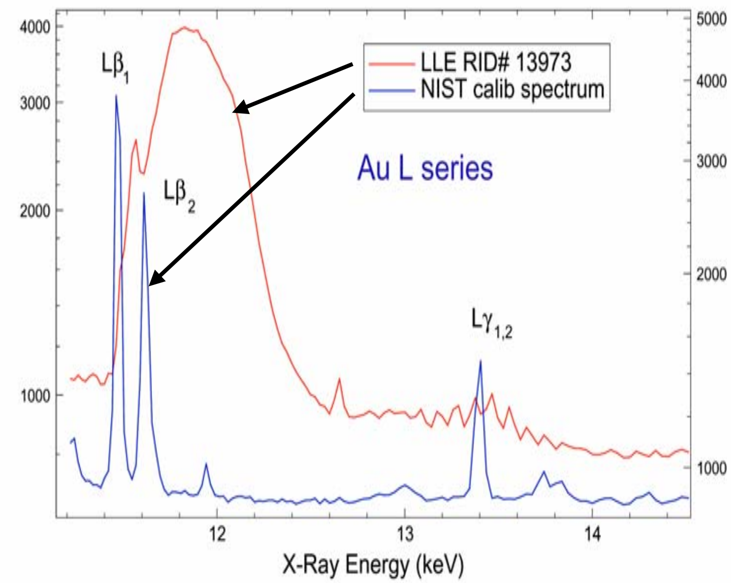
Observed K-shell lines up to Ag:



HENEX (High-Energy Electronic X-Ray)

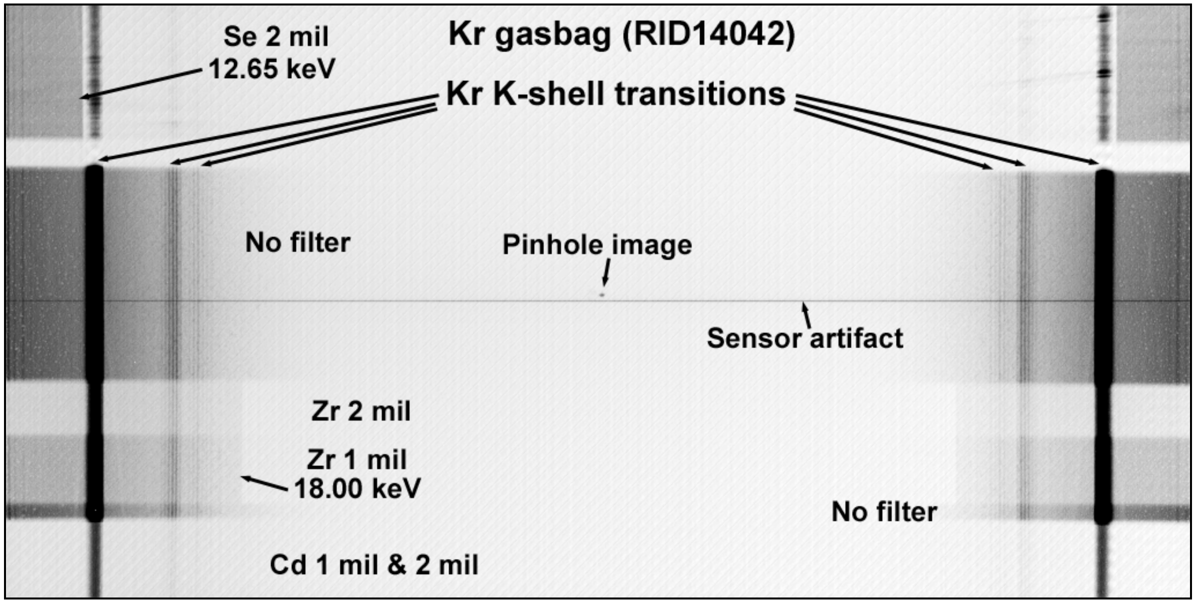


- Inner-shell L transitions from ionized Au (modeled by Mark May).
- Gold half hohlraum (Marilyn Schneider), OMEGA 23 beams, 11 kJ.

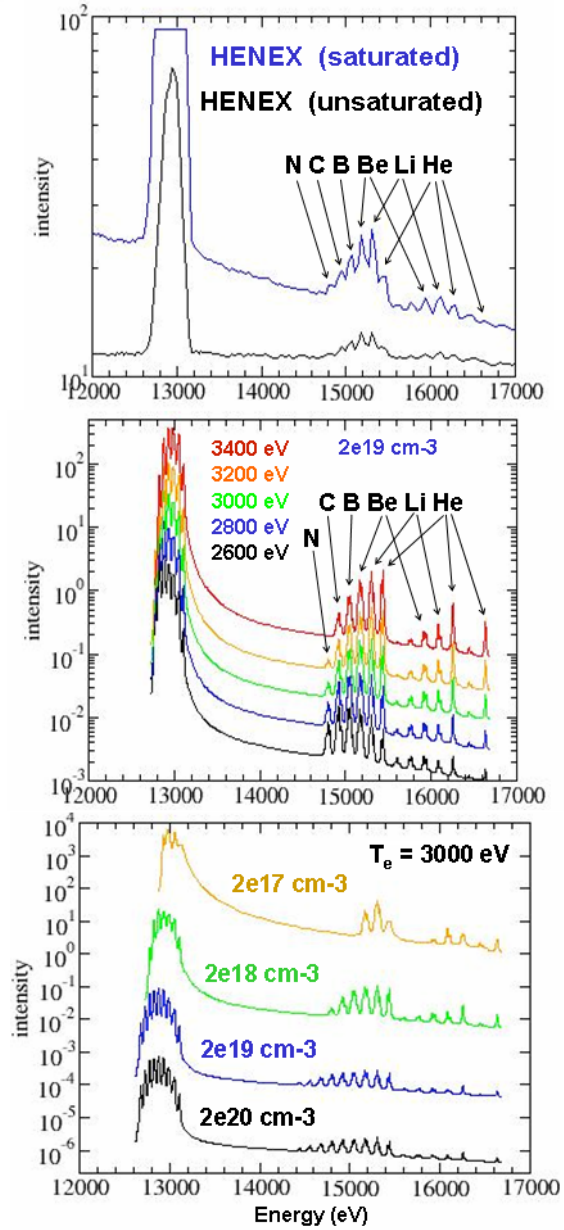


- Four reflection crystals cover 1-20 keV and one transmission crystal covers 11-40 keV with high resolution (>300).
- Spectral images are recorded on 5 CMOS sensors with optimized phosphor screens, on-board electronics and battery, FO communications to lab computer.
- Deployed in Omega TIM with 0.5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

HENEX Spectra and Results



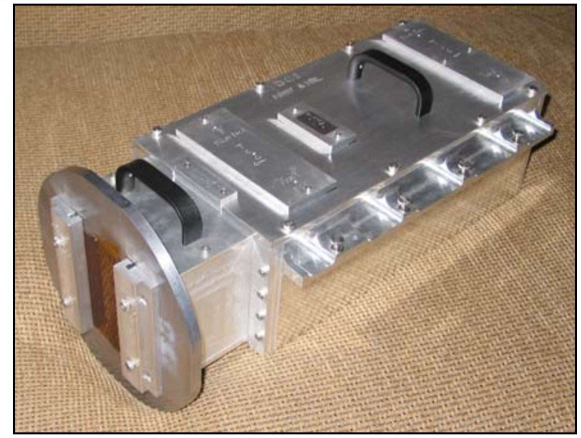
100% Kr-filled gasbag (0.5-0.8 atm) with Zn backlighter, 49 OMEGA beams, 22 kJ (Duston Froula).

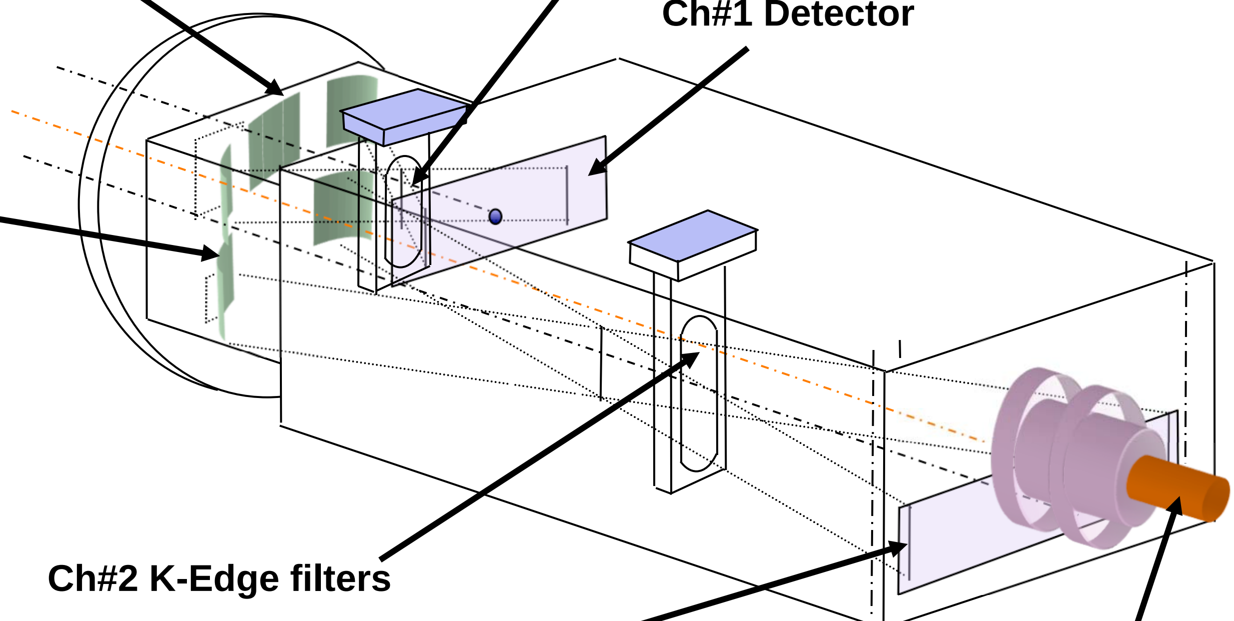


Comparison of experimental and calculated spectra (FLYCHK, Lee and Chung) indicate T_e=3000 eV and N_e=2x10^{18} cm^{-3} (RPHDM2004).

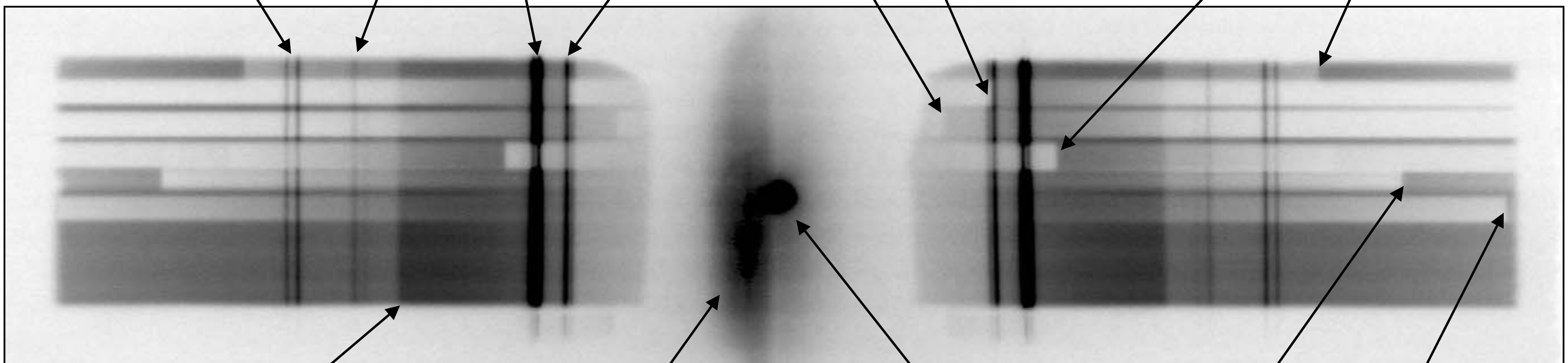
DCS (Dual Crystal Spectrometer)

- Two crystals cover 11.5-45 keV and 18-120 keV.
- Spectra are recorded on two image plates near the RCs.
- Fielded at Omega (2005), TITAN (2006), and now qualified for EP.





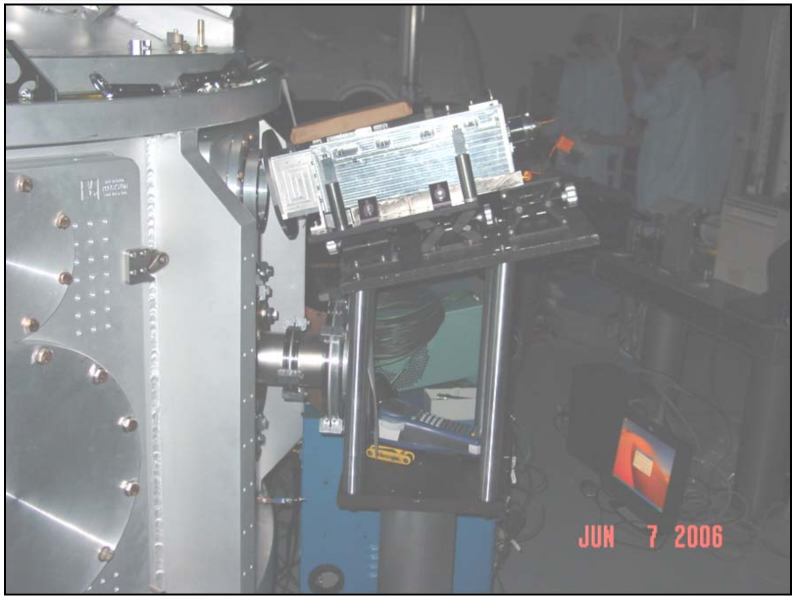
DCS Laboratory Testing



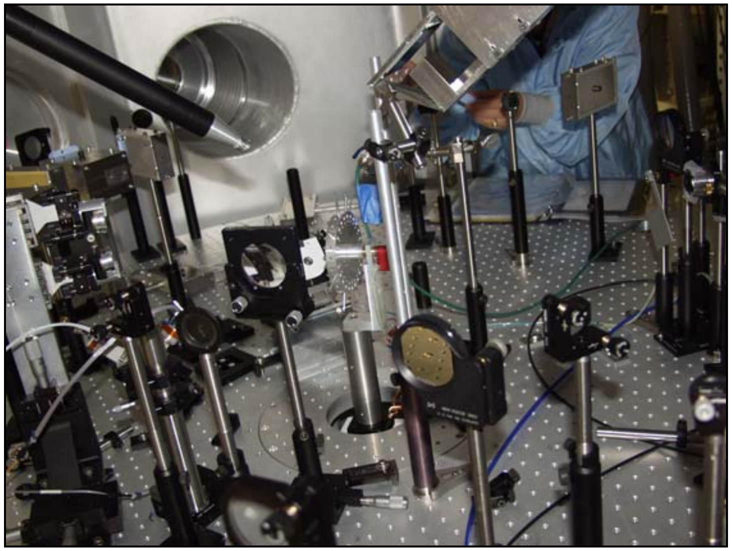
- 1.2 m standoff from the W anode laboratory source.
- W Kα and Kβ lines were observed in 1st and 2nd orders and were well resolved.
- Filter K edges and Ba edge (from IP) establish an accurate energy scale.
- Instrument issues, such as scattered x-rays, were studied and corrected.
- Detector sensitivity 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.

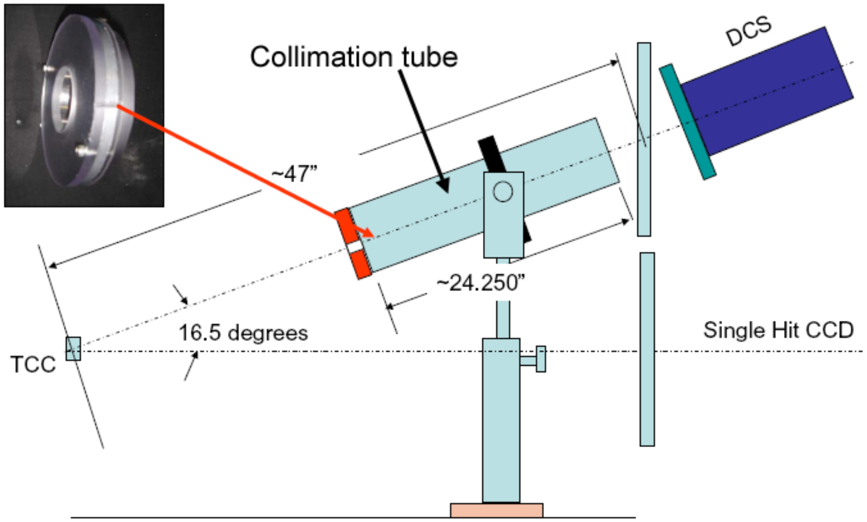
DCS Deployed at TITAN

DCS viewed the target through a Lexan vacuum window, and the crystals were 1.2 m from the target.

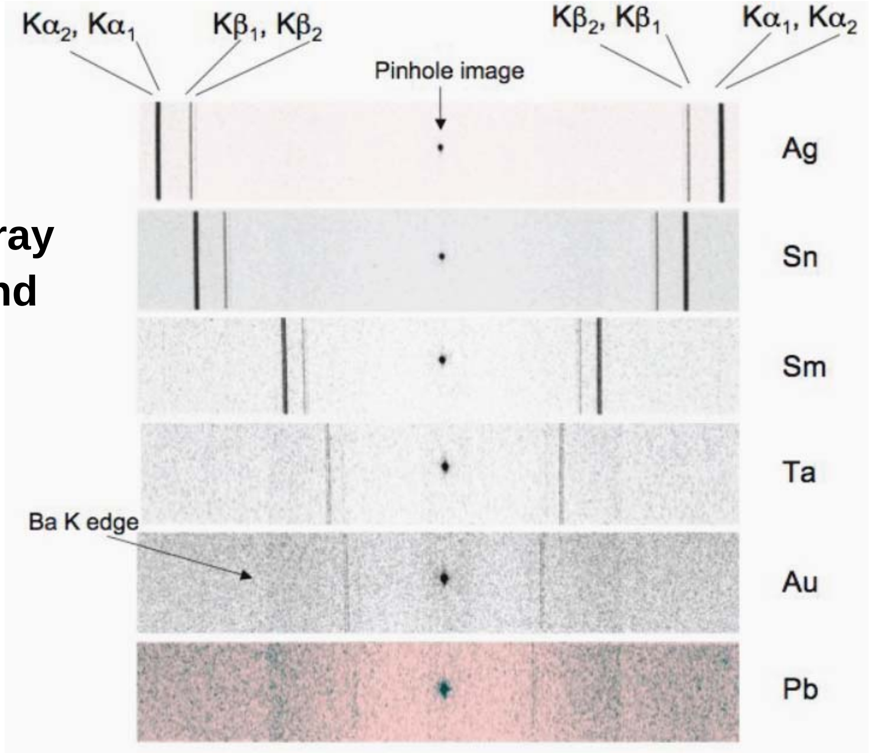


Numerous objects near the target fluoresce hard x-rays and were occulted by a collimation tube with a thick lead/plastic front aperture.





TITAN Spectra



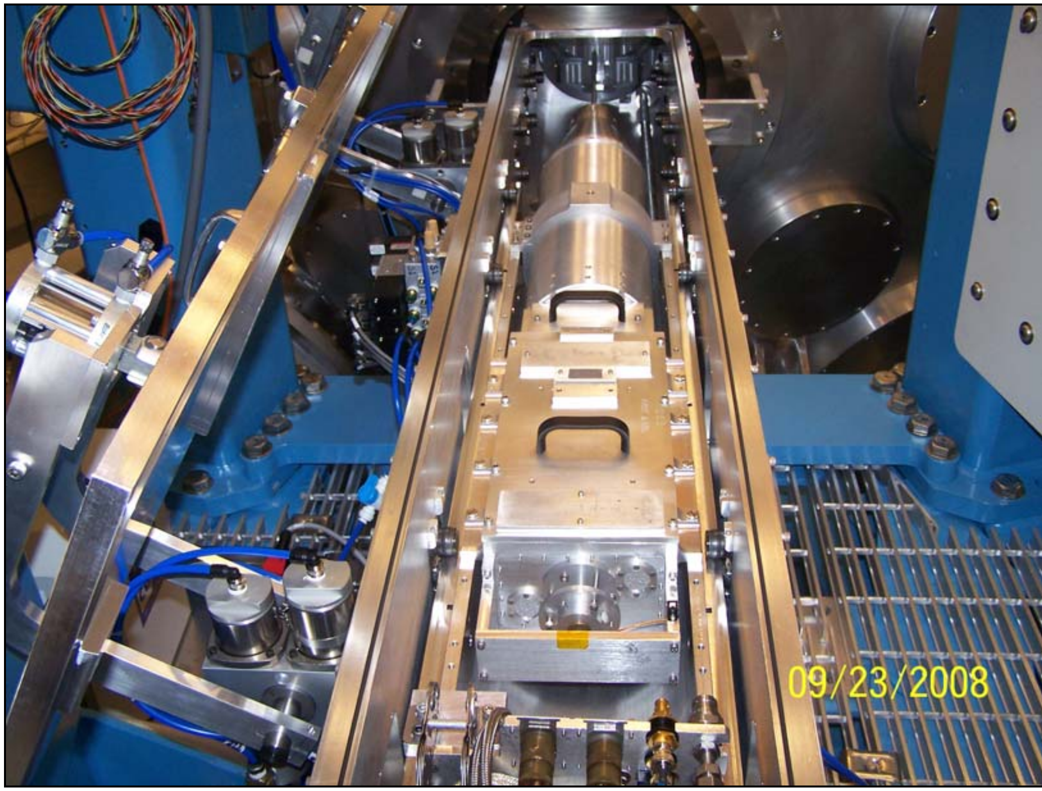
DCS spectra characterize the TITAN hard x-ray source (Riccardo Tommassini, Hye-Sook, and Prav Patel).

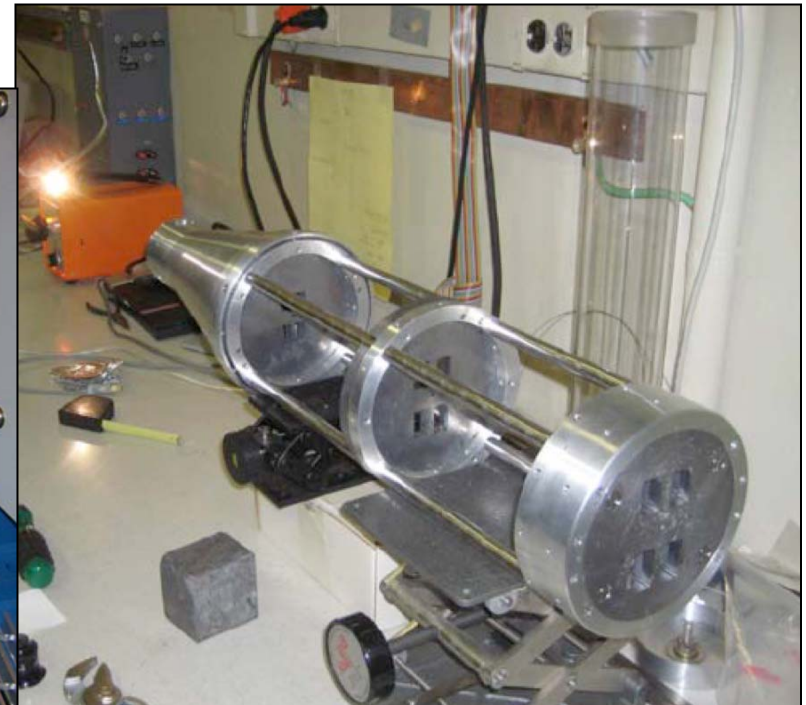
K-shell transitions result from inner-shell ionization by the hot electron distribution.

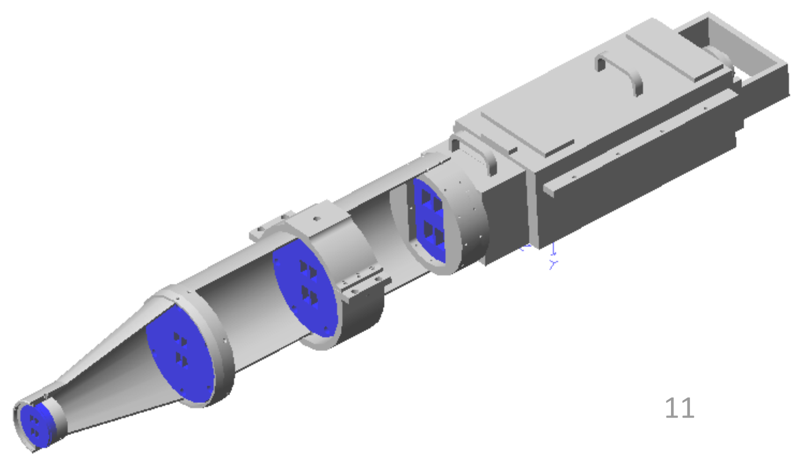
Element (Z)	$K\alpha_1$ Energy (keV)	$K\beta_1$ Energy (keV)	1s Electron Binding Energy (keV, neutral atom)
Ag(47)	22.162	24.942	25.514
Sn(50)	25.270	28.483	29.200
Sm(62)	40.124	45.400	46.834
Ta(73)	57.523	65.209	67.416
Au(79)	68.778	77.968	80.724
Pb(82)	74.970	84.939	88.006

DCS is Now Qualified for EP TIM

New nosecone has massive lead shielding:







Used at shots on EP:

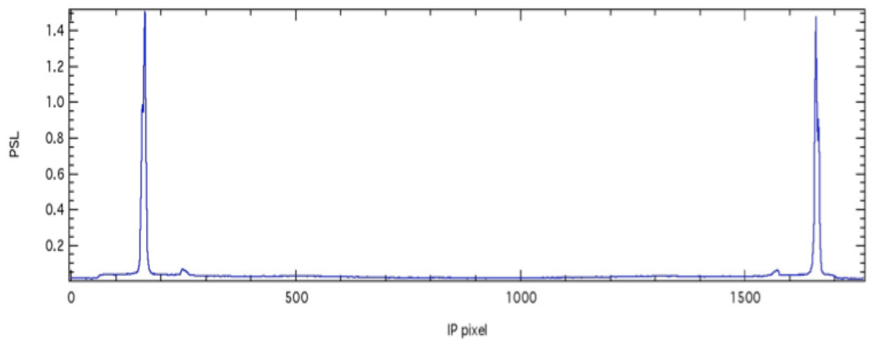
Tom Boehley / Hye-Sook Park; January 27-29.
Jonathan Workman, LANL; March 24, 2009
Hui Chen, LLNL; April 16, 2009

High energy x rays observed by DCS at EP

Silver K lines

DCS Channel A: high energy

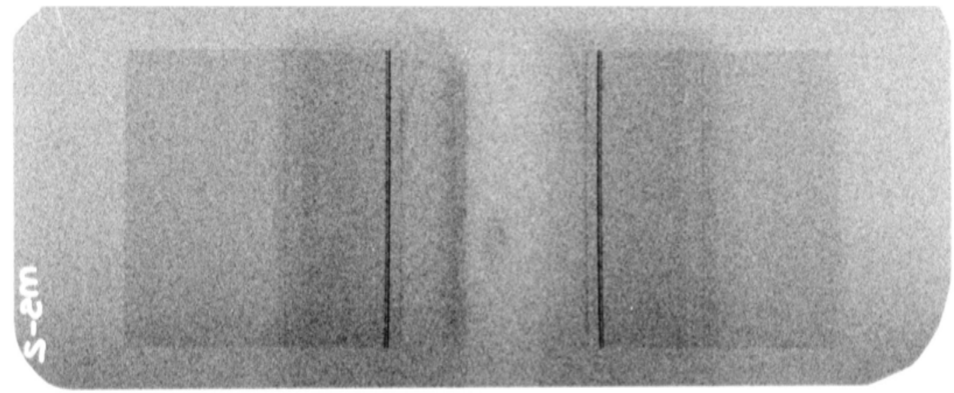
Date	RID	Shot#	Target	Target descritption	Tmeas	Emeas	Time
03/24/09	28024	4889	6-PURP	Ag flag	39 ps	956 J	17:53

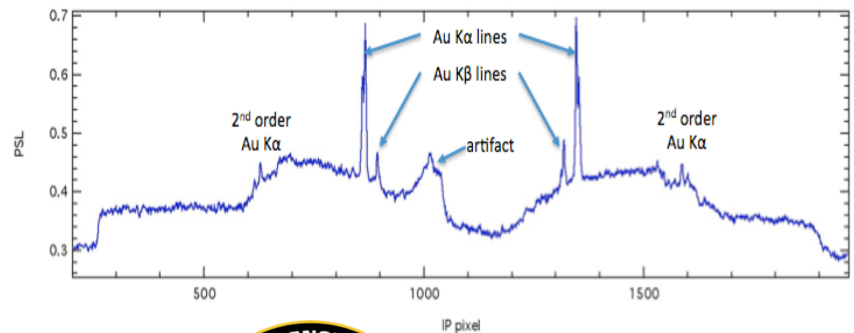


Gold K lines

DCS Channel A: high energy

Date	RID	Shot#	Long pulse	Target descritption	Tmeas	Emeas	Laser Irradiance
04/16/09	?	5081	yes	thick Au	~10 ps	~820 J	? W/cm²

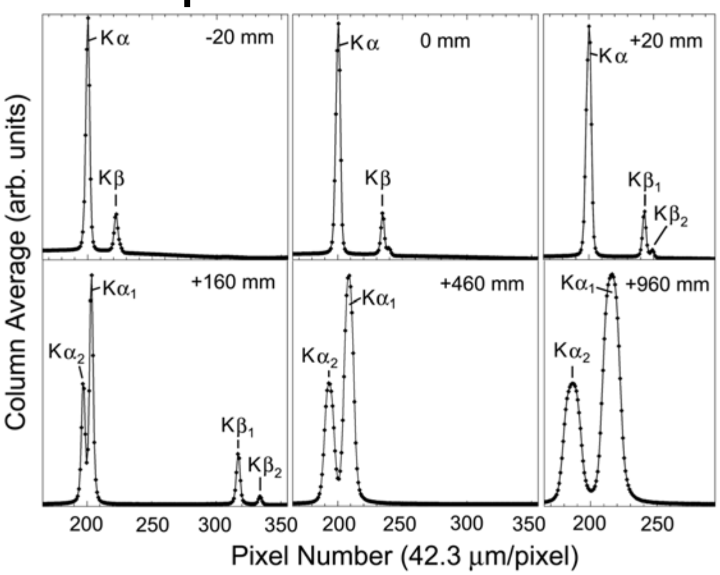




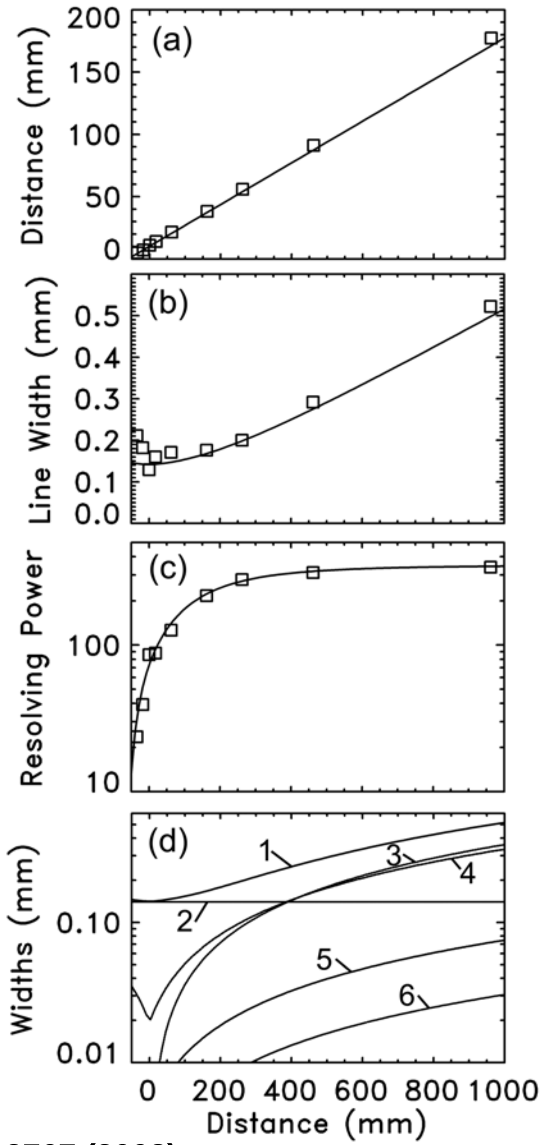
Source Broadening of the Spectral lines

- **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 an Mo microfocus source:



Mo $K\beta_1$ data & spectrometer model:



Line widths:

1 – Total

2 – Detector

3 – Source

4 – Crystal thickness

5 – Natural width

6 – Crystal rocking curve

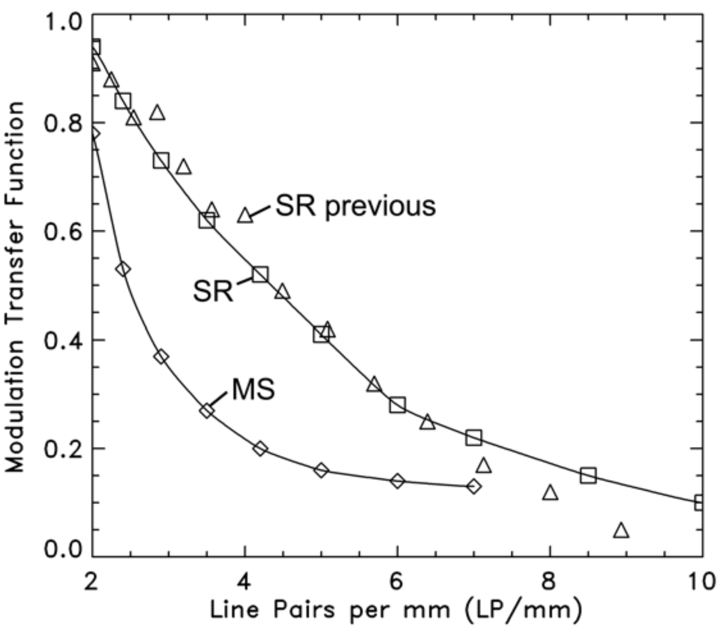
7 – Aberrations (very small)

Seely *et al.* Appl. Opt. <u>47</u>, 2767 (2008)

Image Plate Resolution

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

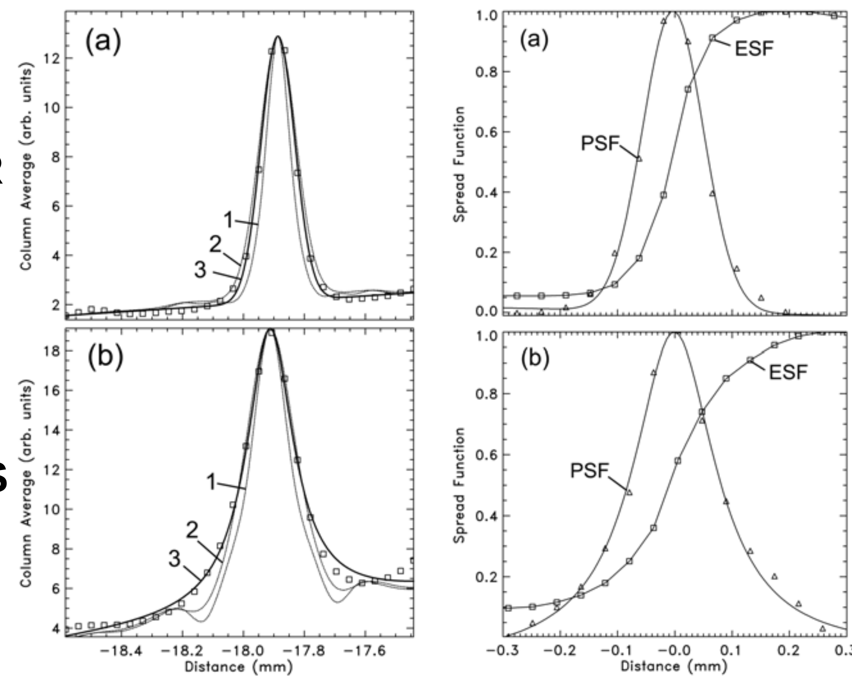
- **The modulation transfer functions (MTF) and point spread functions (PSF) of Fuji SR and MS image plates were determined from:**
  - **The contrast produced by a bar pattern with up to 10 LP/mm.**
  - **Line shapes produced by narrow spectral lines recorded on the RC.**
  - **Edge spread function 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. <u>47</u>, 5753 (2008)

SR

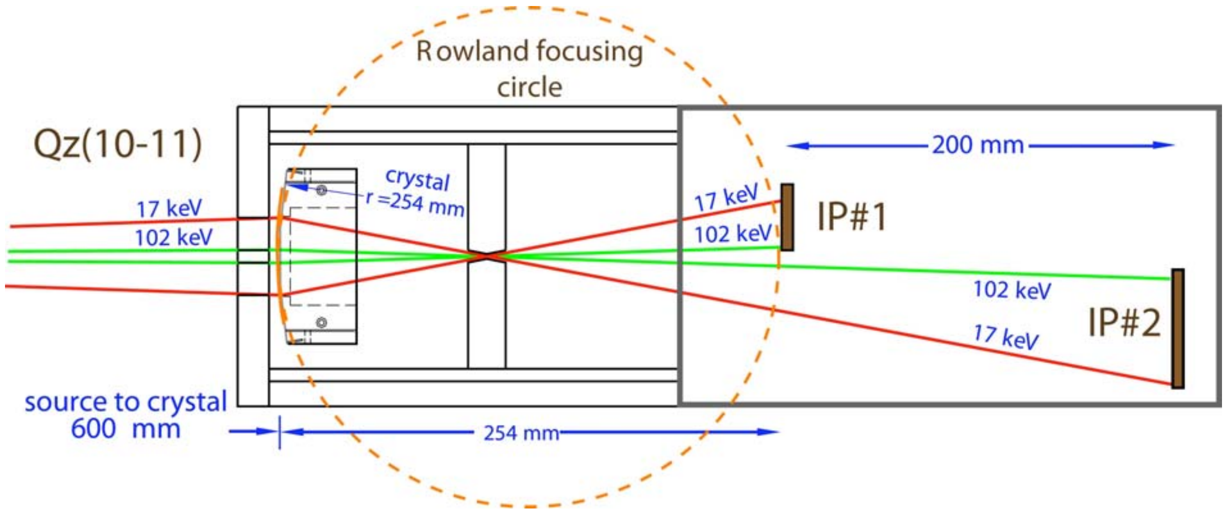
MS



LULI Crystal Spectrometer (LCS, Patrick Audebert)

Optimized for source size measurement: small standoff, large RC, large IP distance.

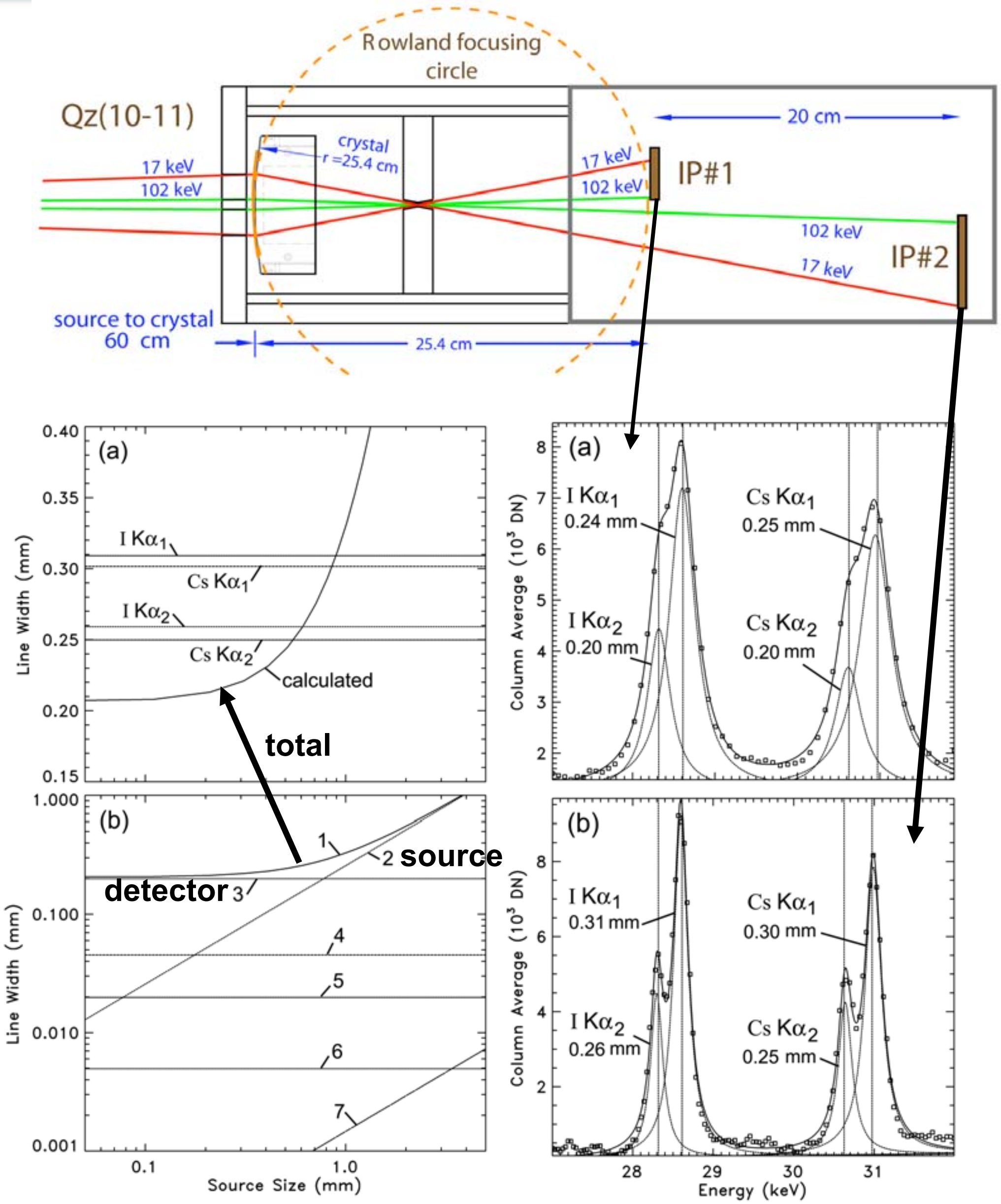
- **Crystal has 0.6 m standoff distance and covers 17-102 keV.**
- **Multiple image plates can be placed:**
  - **On the RC for high sensitivity, where detector resolution dominates.**
  - **Beyond the RC for high spectral resolution and source size measurement.**



- **Fielded inside LULI chamber 2007-2008.**
- **Is in the review process for EP qualification with new name: Transmission Crystal Spectrometer (TCS).**

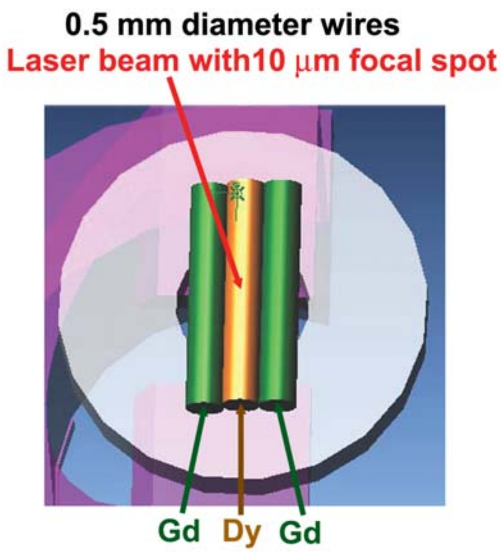
LULI X-Ray Source Size

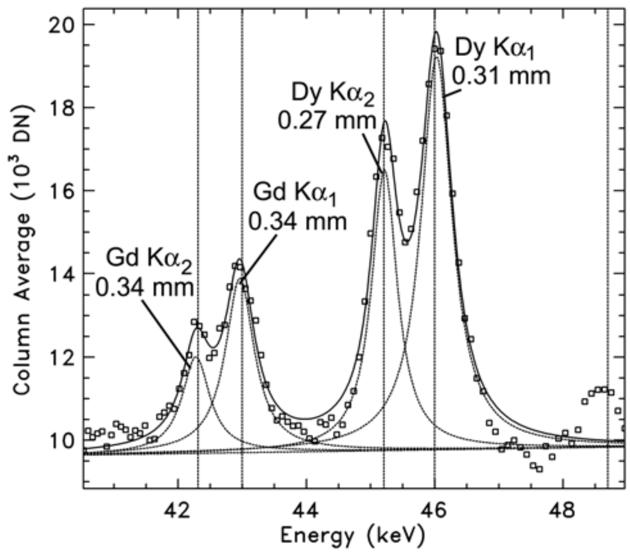
- LULI PICO2000 laser: 100 J, 1 ps, 10 μm focal spot, 10^{20} W/cm^2 focused intensity, incident 34^o from normal.
- Spectra were recorded by placing two MS image plates on the RC (detector broadening) and 20 cm behind the RC (source broadening).
- Comparisons with our geometrical model of the spectrometer 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.



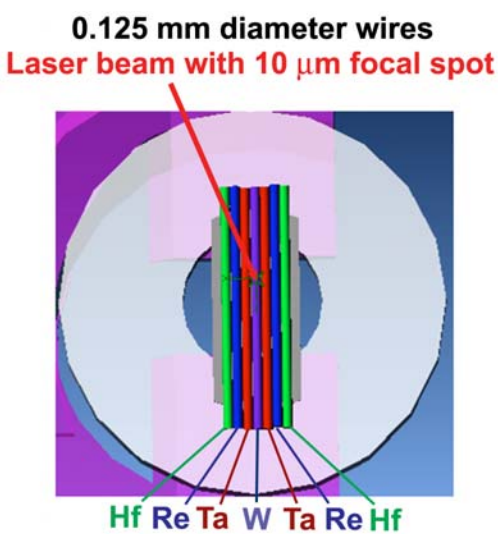
Energetic Electron Propagation Range

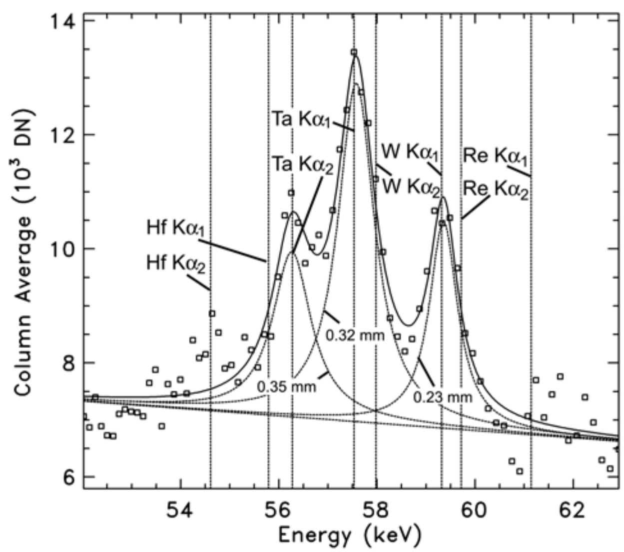
Indicated by spectral line intensities and line widths from targets composed of fine metal wires.





- **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.**



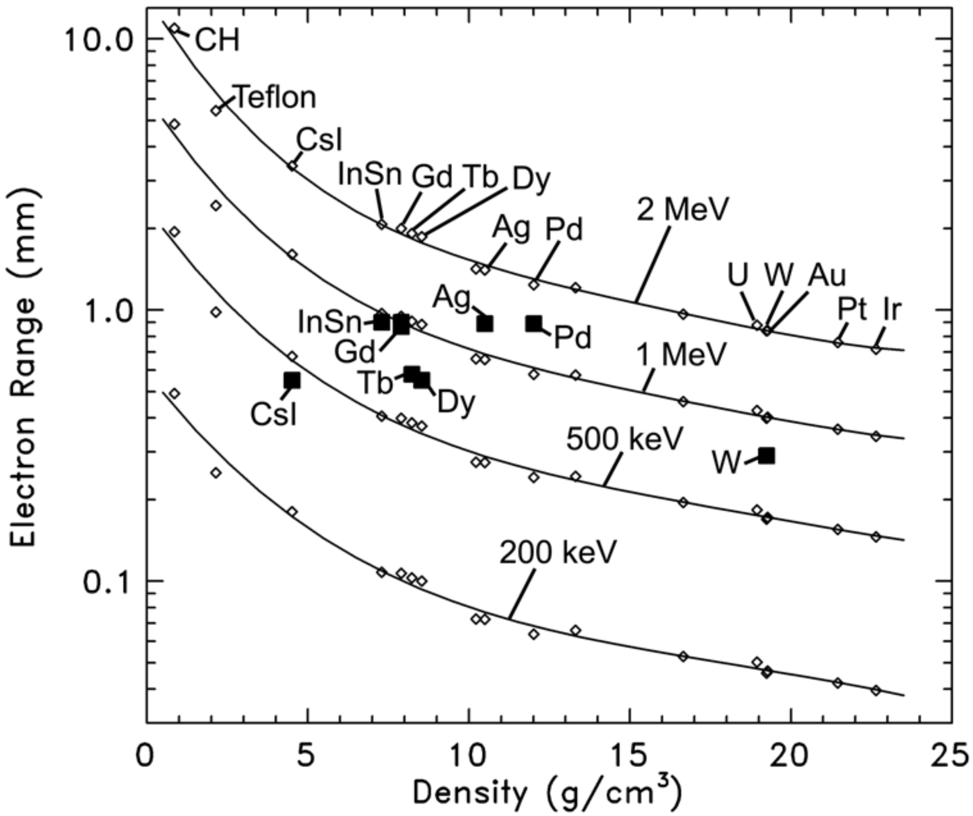


- **Lines from the two adjacent Ta wires are twice as intense and are broader than the W lines.**
- **Indicates 0.19 mm lateral range (0.64 g/cm^2) and 0.85 MeV electron energy.**

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.**

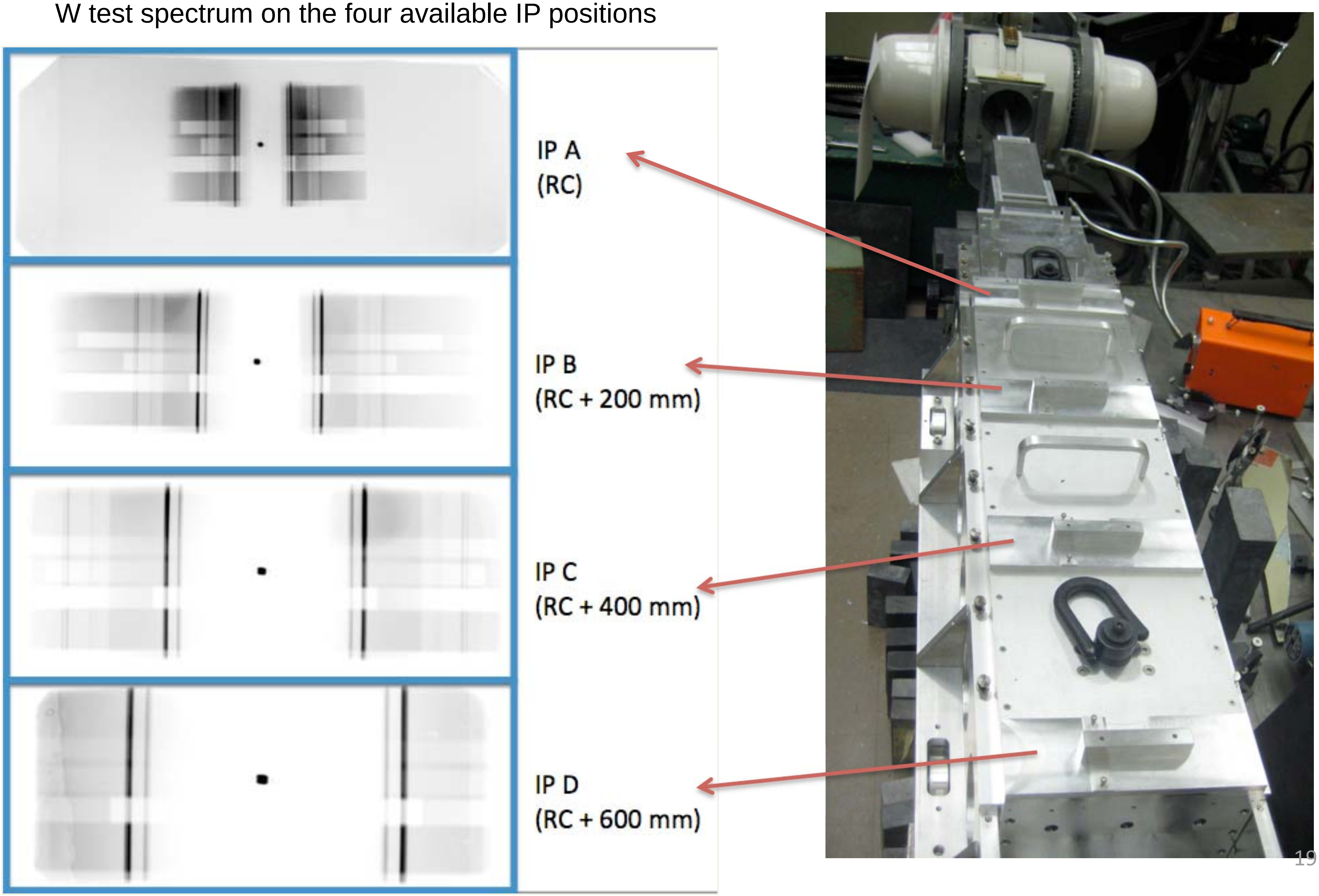


Range curves are calculated and

■ = data

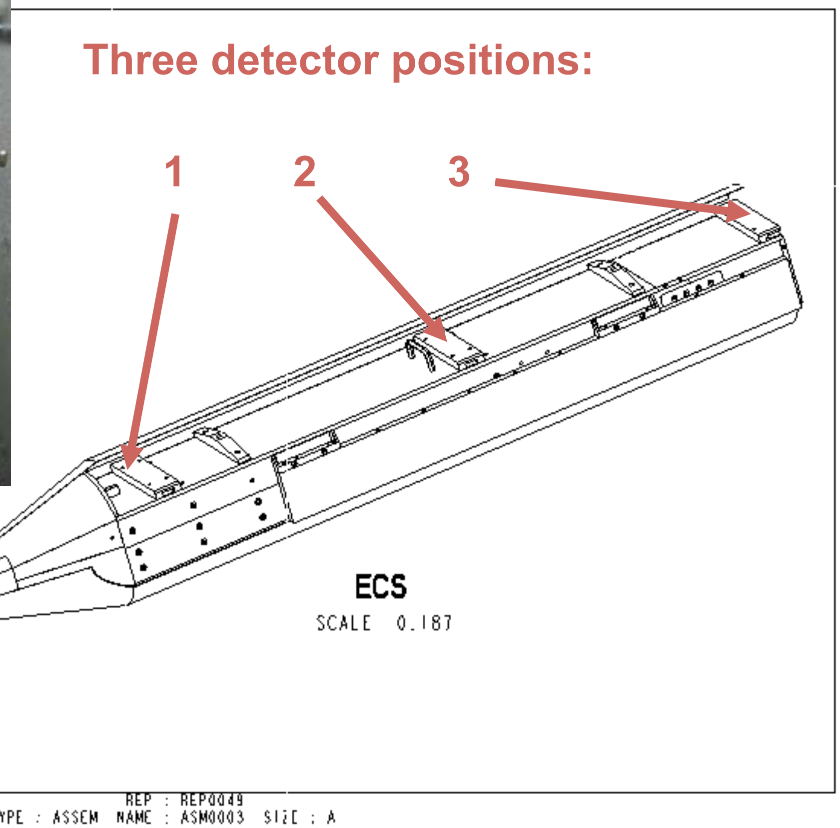
Transmission Crystal Spectrometer (TCS)

W test spectrum on the four available IP positions

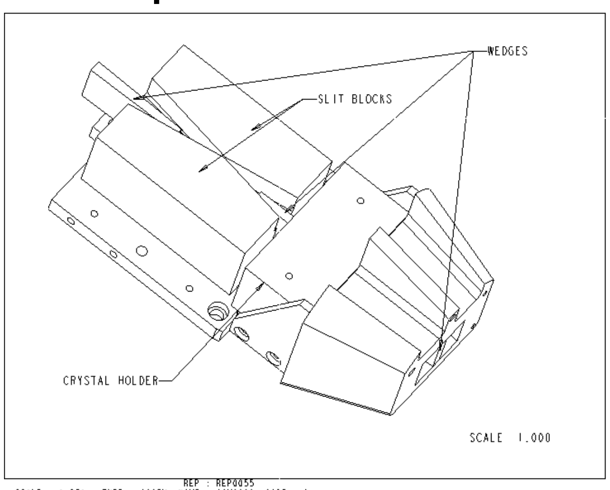


EP Crystal Spectrometer (ECS)

- ECS is designed for high energy resolution and source size resolution (10-20 µm).
- Achieved by small standoff (0.25 m) and large detector distance behind the RC (1 m).
- IP detectors (1,2,3) and electronic detectors behind 3.
- Operational summer 2009 (Uri Feldman, Artep Inc.).

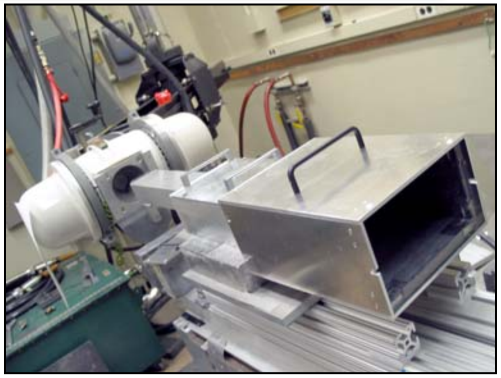


Massive W internal shielding as optimized during the ARL 2-6 MeV linac experiments:

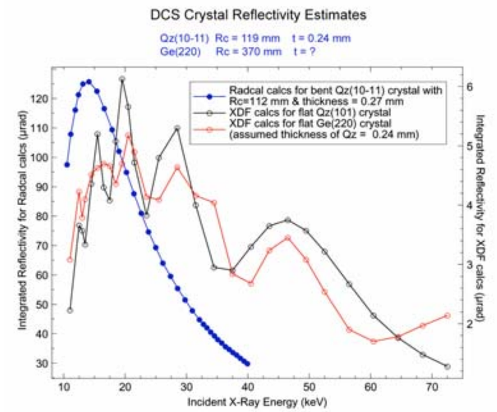


Position	Distance	Energy Coverage	Resolving Power
1	0 mm	12 to 115 keV	60 to 1800
2	500 mm	23 to 115 keV	240 to 1800
3	1000 mm	40 to 115 keV	420 to 1800

Absolute Sensitivity Calibrations

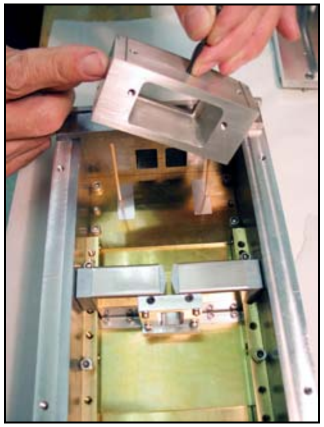


Bent-crystal spectrometers must be calibrated under the same geometrical conditions as they are used for experiments (e.g. point source provided by a laboratory microfocus source).



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

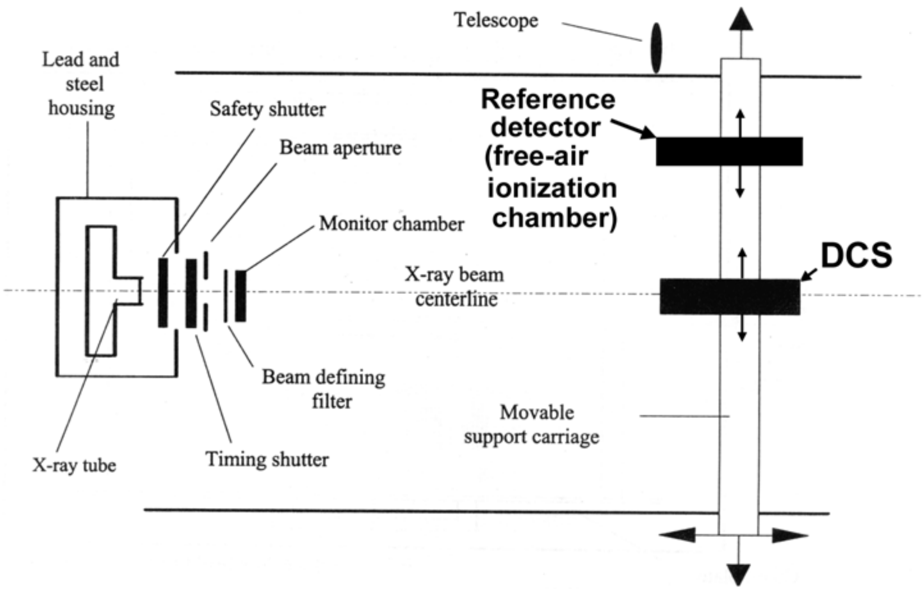
Spectrometer components (crystals, detectors/scanners) should be calibrated separately and in an interchangeable manner and then compared to the end-to-end spectrometer calibration.

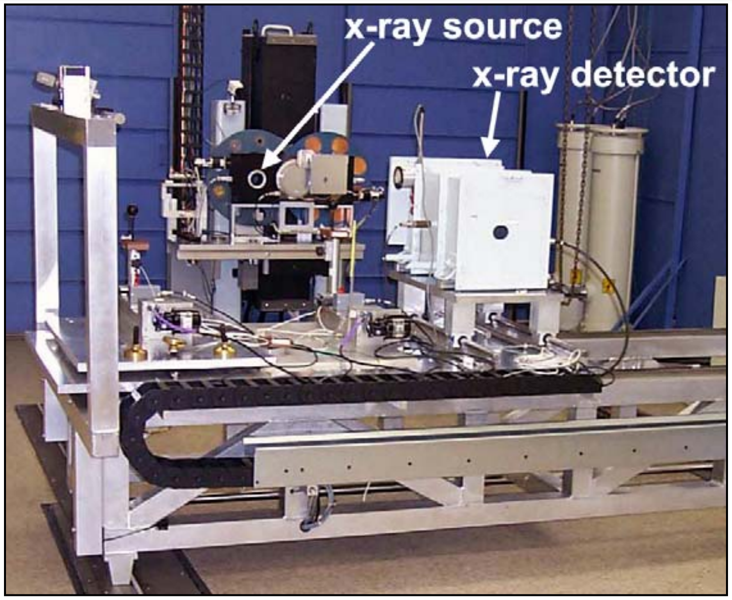


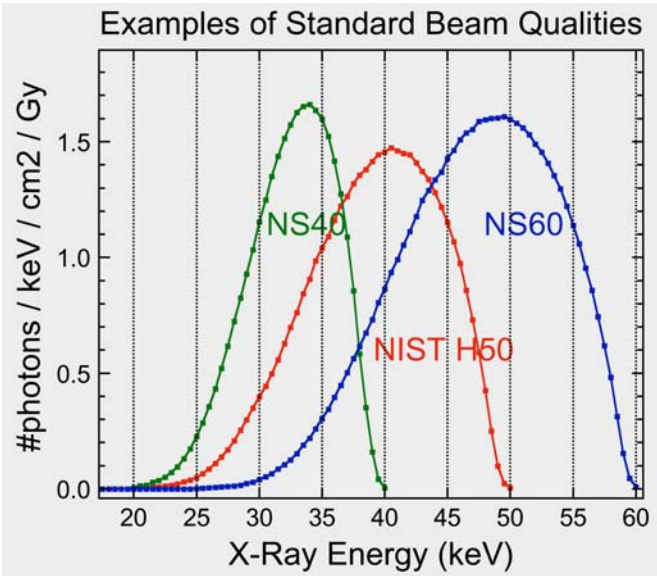
Different calibration techniques provide redundancy:

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

NIST Calibration Facility







<u>**Source-based calibration:**</u>

- **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.**

Thank you !

artep

NIST

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