Workshop: X-Ray Echo Spectroscopy – Opportunities and Feasibility
September 8-10, 2016, APS, Argonne National Laboratory.

The Ultrahigh Resolution IXS Beamline at NSLS-II: Current Status and Performance

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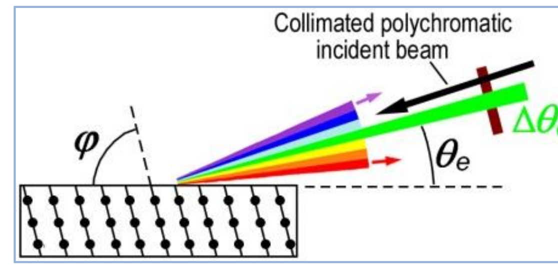
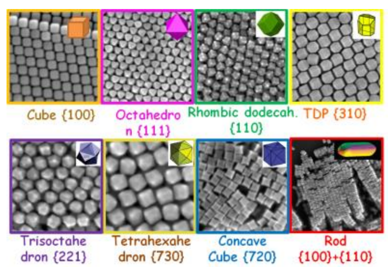
Outline

- A Brief Overview
- Advances in Crystal Optics & Beamline Development
- Performance, Recent Results & Early Experience
- Outlook

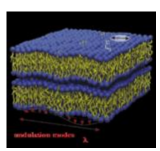
The Ultrahigh Resolution IXS Beamline at NSLS-II

- Designed to Achieve Best-in-Class Performance for vibrational dynamics by IXS :
  - Angular dispersive crystal optics for cutting-edge resolution (0.1 ~ 1 meV) with sharper tails in resolution function and high Q resolution (0.1 nm^{-1}).
  - Medium operation energy (9.1 keV) capitalizing on NSLS-II's strengths in flux and brightness
- Scientific Applications
  - Mesoscopic dynamics in liquids, soft matter, and biological systems
  - Phonons in single crystals, surfaces, interfaces and systems under extreme conditions





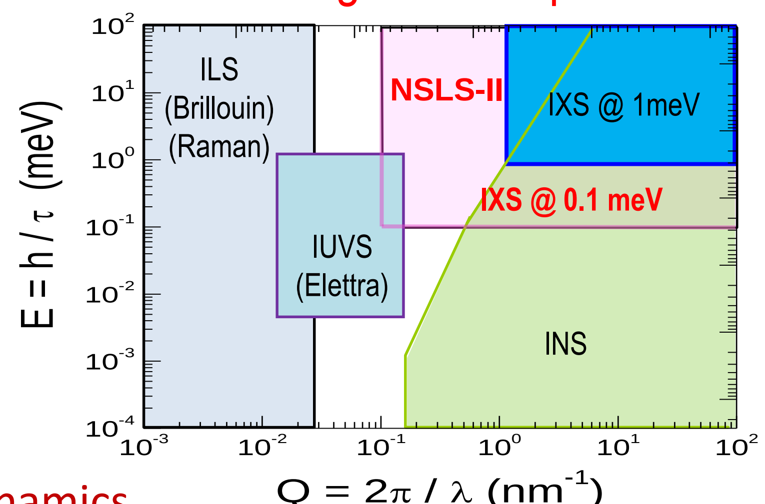
Programmable Nanoparticle Assemblies



Lipid membrane

High pressure materials

"Filling in the Gap"

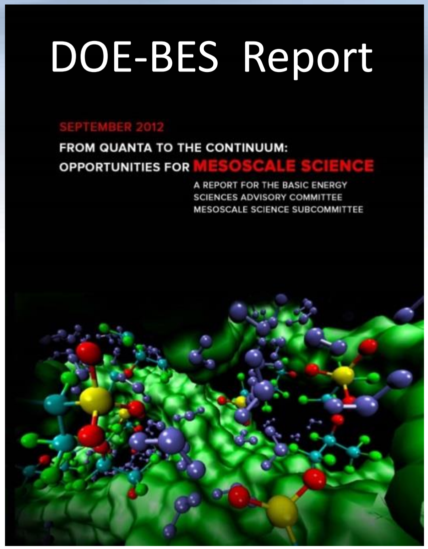


Ultimate Goal:

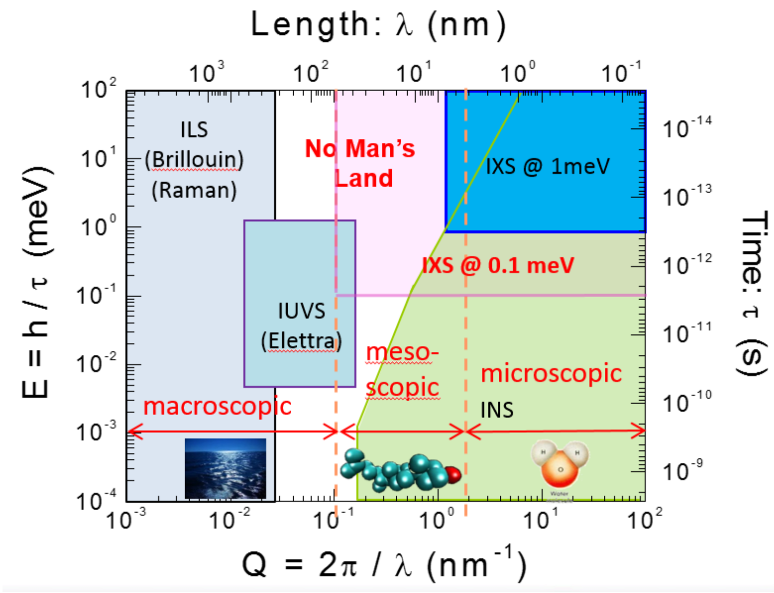
World-leading 0.1 meV energy resolution for studying dynamics

Science at the Mesoscales

- Addressing scientific challenges at the mesoscopic length scale (5 ~ 50 nm, part of “no-man’s land”)
  - Phononics in functional nanoparticle assemblies - optimizing transport and response properties by design and control of mesoscale structure
  - Fast dynamics of bio-molecular systems and their biological functions - bio-inspired mesoscale inorganic materials.
  - Intermediate regime in disordered systems.



- Recent examples: Tomorrow’s talks
  - **Giulio Monaco**:
    “High-frequency dynamics in liquids and glasses at the mesoscopic scale”
  - **Alessandro Cunsolo**:
    “High resolution inelastic x-ray measurements on soft matter systems: current results and future perspectives”
  - **Mikhail Zhernenkov**:
    “Application of inelastic scattering to study biomembranes: latest results and challenges”



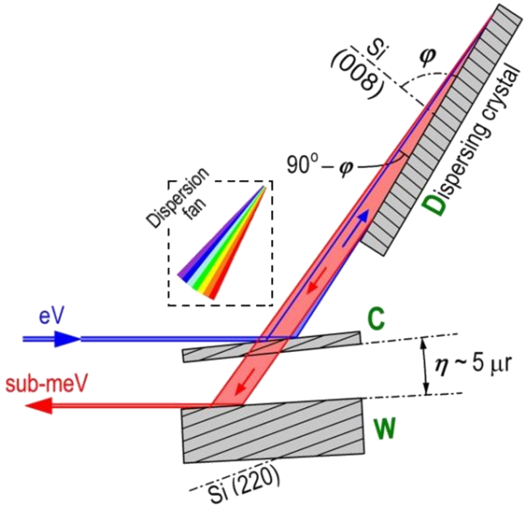
Our Approach: Angular Dispersive Optics

- Inline 4B mono for ease and range in energy scanning
- Analyzer optics based on CDW scheme proposed by Shvyd'ko (2004, PRL 2006)

CDW - Analyzer

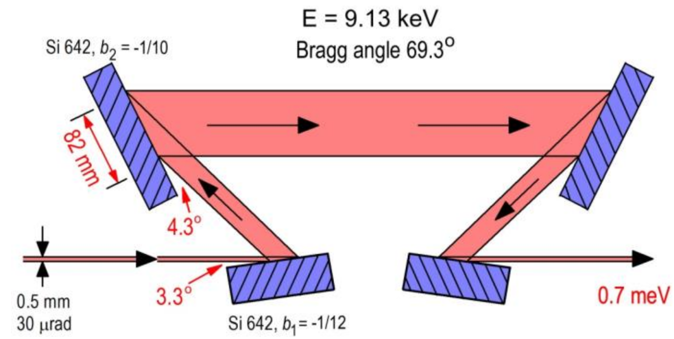
$$\frac{\Delta E}{E} \approx \frac{\Delta\theta_e}{2\tan\varphi} \approx \frac{\theta_e \Delta\theta_e}{2}$$

→ Angular acceptance ~100 μrad
→ High peak reflectivity ~38%
→ Sharp tails (multiple reflections and anomalous transmission)
→ Sub-meV resolution at ~10 keV



4B - Mono

Huang, JSR (2011)

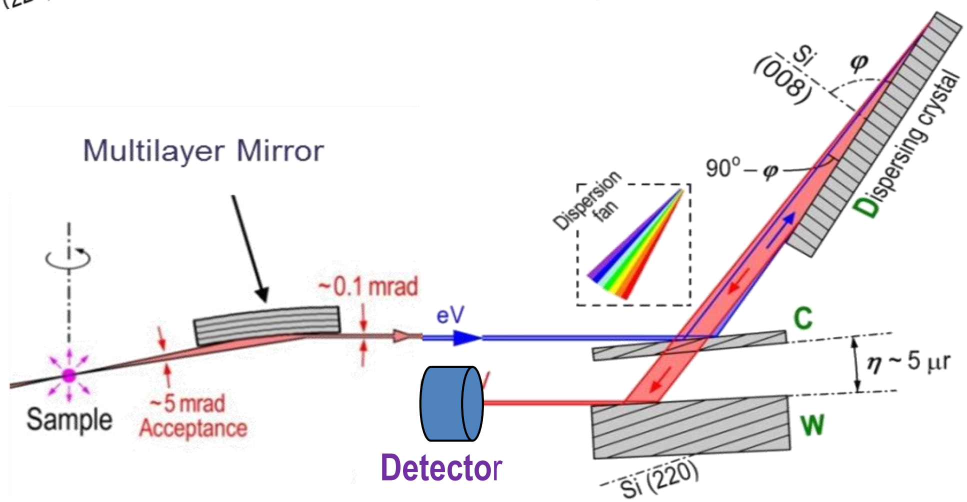


- Major technical challenges

→ Lattice homogeneity: Δd/d = ΔE/E ~ 10^{-8}
→ Mirror-like strain-free surface quality (SE: < 10 μrad)
→ Precision and stable motion control

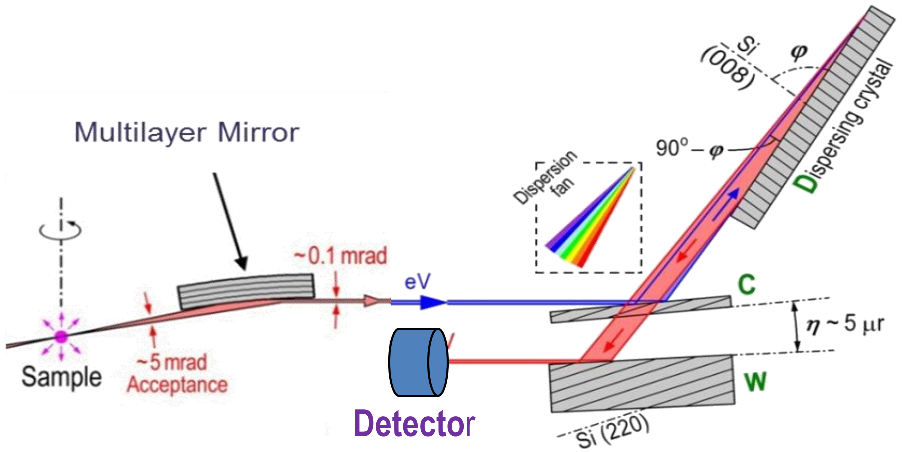
- Collimating optics (50-100:1) for large (5-10 mrad) acceptance

→ Long dispersive crystal!!!

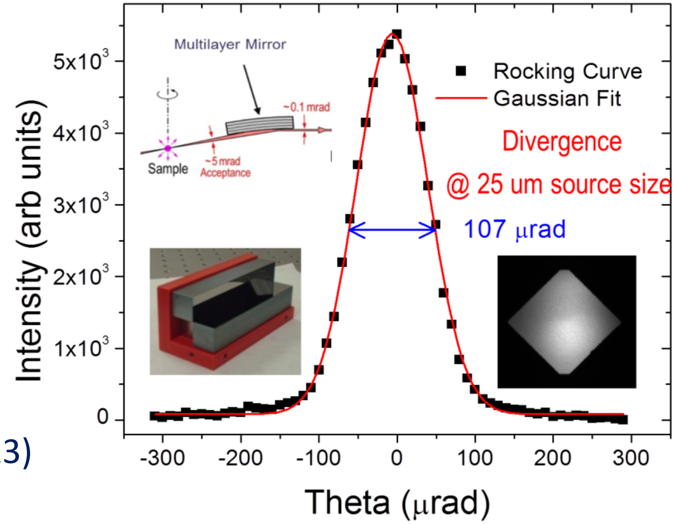


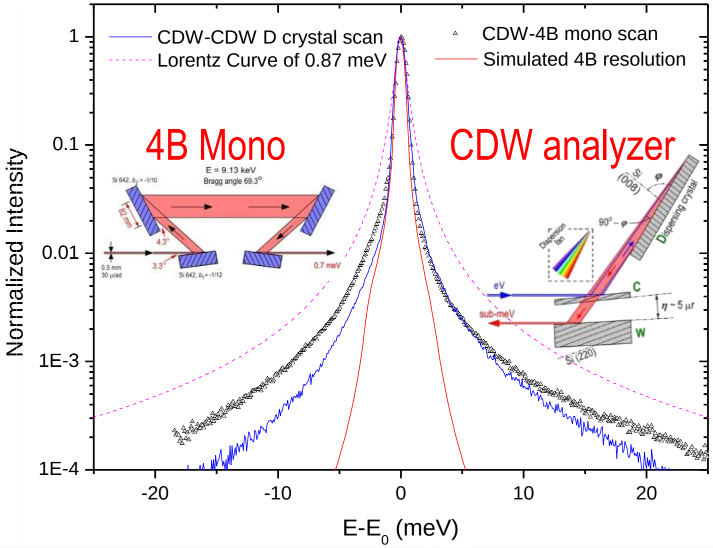
High-Resolution Optics for IXS

- Demonstrated the initial goal of sub 1 meV resolution:
  - CDW analyzer (de-convoluted) resolution: ΔE = 0.7 meV,
  - CDW analyzer efficiency ~ 20% (theory: ~ 38 %)
  - 4B mono and CDW analyzer combined resolution ΔE = 0.8 meV,
  - 4B-HRM efficiency ~ 30% (theory: ~ 35%)
  - Sharp Gaussian-like tails



- Montel collimating mirror performance verified.
  - Angular acceptance : > 10 mrad
  - Volume acceptance: ~ 20 μm, divergence < 100 μrad;
  - Efficiency measured: ~ 47% (theory: 49%)

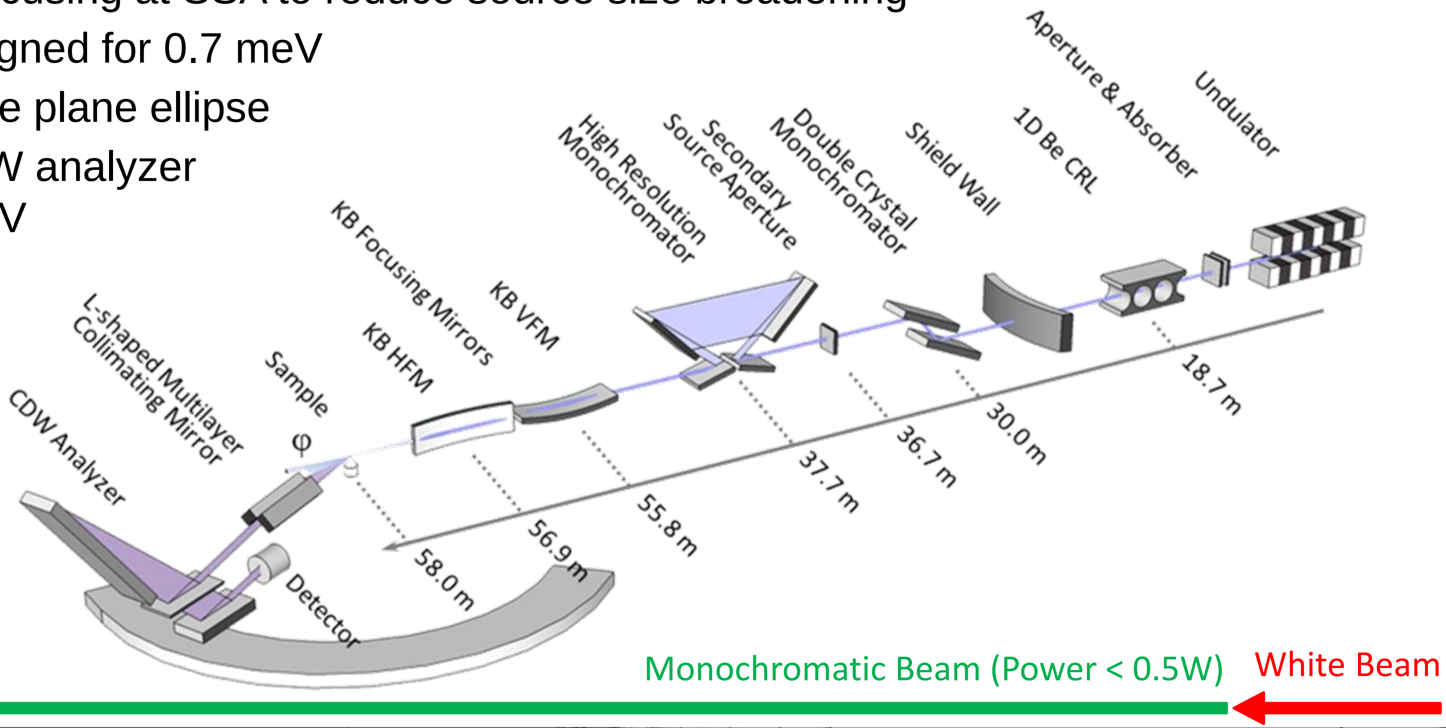


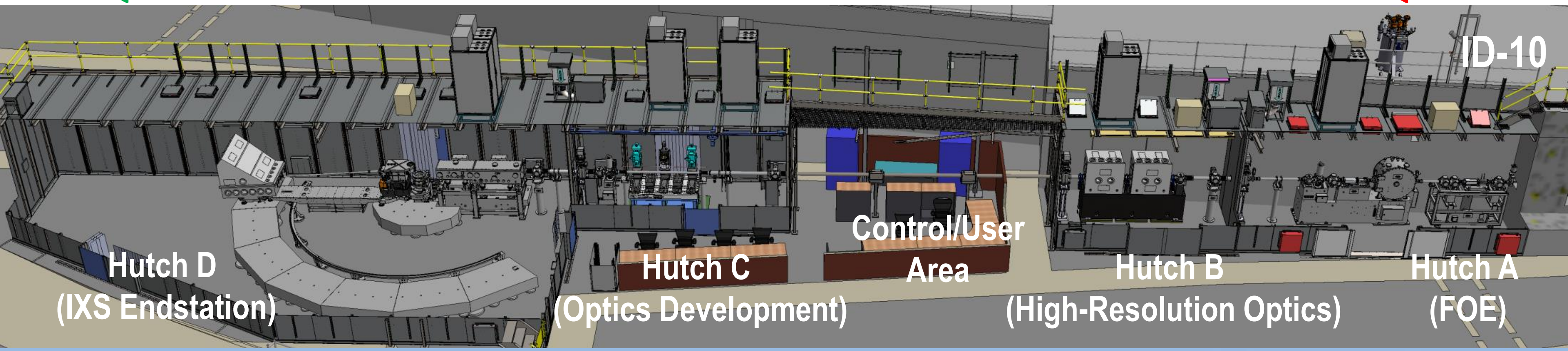


(Cai et al, J. Phys.: Conf. Ser. 2013)
(Suvorov et al, JSR, 2014)

IXS Optics Layout & Beamline Design

- Insertion device: IVU22-3m, optimized for 9.1 keV (max flux: 8×10^{14} phs/sec/0.1%bw@500mA).
- Be-CRLs for ~1:1 focusing at SSA to reduce source size broadening
- HRM: inline 4B designed for 0.7 meV
- KB Mirrors: bendable plane ellipse
- Montel mirror + CDW analyzer designed for 0.7 meV

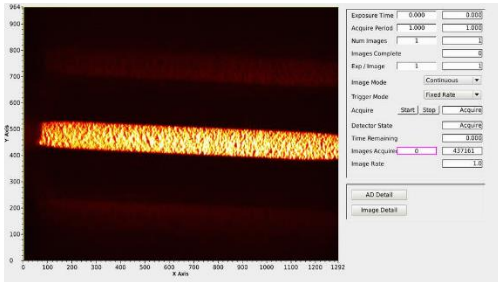




IXS Commissioning Timeline & Milestones

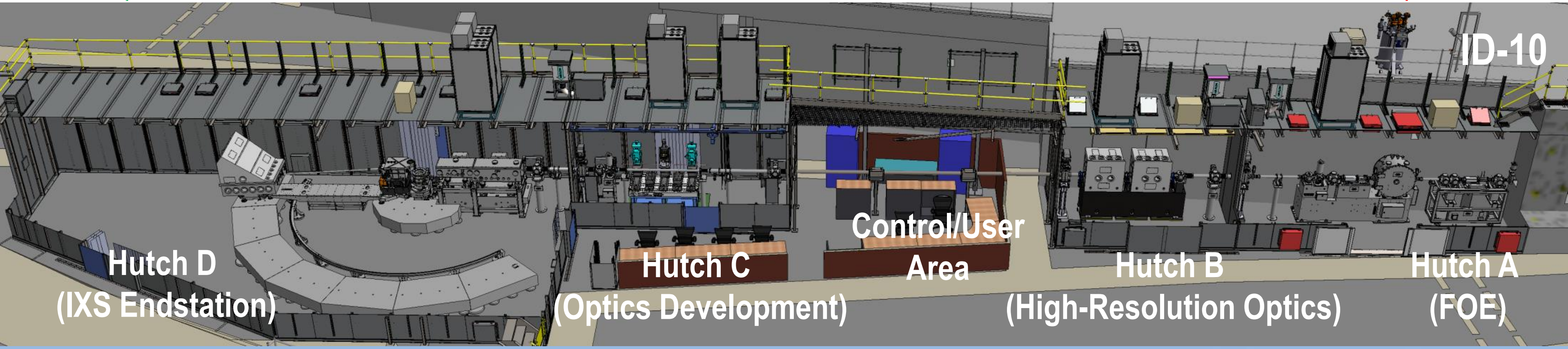
- **Nov 24, 2014**: First light – Beam delivered to white beam stop in FOE
- **Feb 7, 2015**: Beam delivered to Hutch D; all slits, SSA and BPMs commissioned.
- **March 22, 2015**: KB Mirrors aligned. Beam focus measured optimized.
- **April 25, 2015**: HRM aligned, initial performance characterized.
- **May 2015 shutdown**: Be-CRL assembly installed.
- **June 2015:** Entire beamline optics system aligned, initial performance characterized.
- **July 1, 2015**: Beamline operation at 150 mA begins
- **Oct 4, 2015**: DCM Beam Stability Feedback Control Established.
- **Oct 30, 2015**: Montel mirror & CDW analyzer optics aligned.
- **Feb 10, 2016**: Tagma detector installed.
- **Feb 11, 2016**: First User Experiment (HP H2 – Dave Mao).
- **Apr 14, 2016**: Beamline operation at 250 mA begins
- **July 12, 2016**: Beamline begins general user operation

Nov 24, 2014: First Light



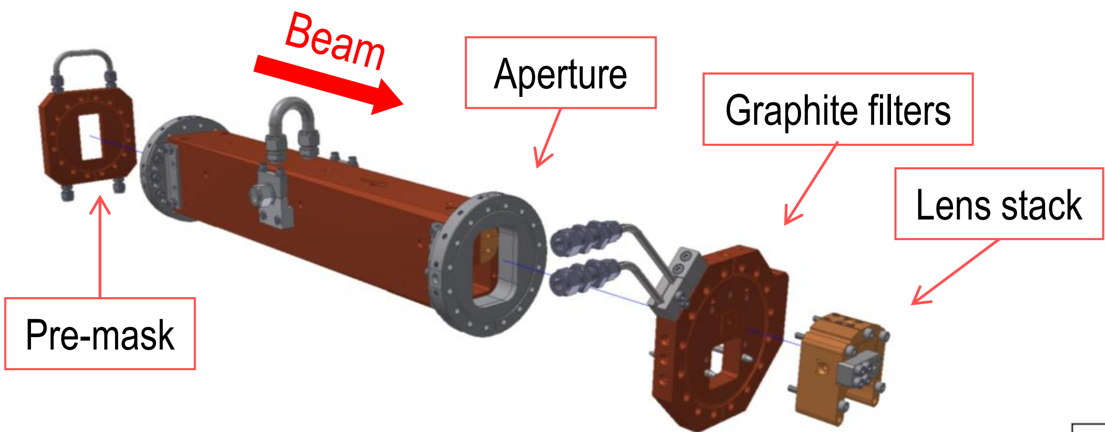
Monochromatic Beam (Power < 0.5W)

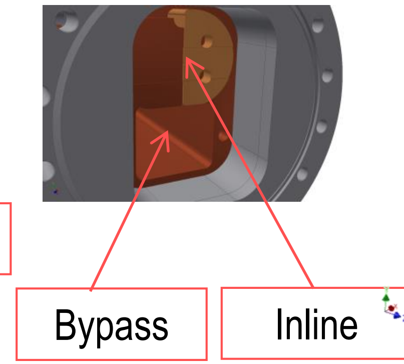
White Beam

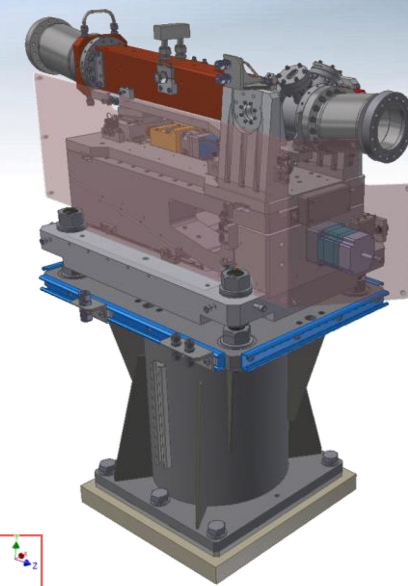


Be-CRL Assembly Performance

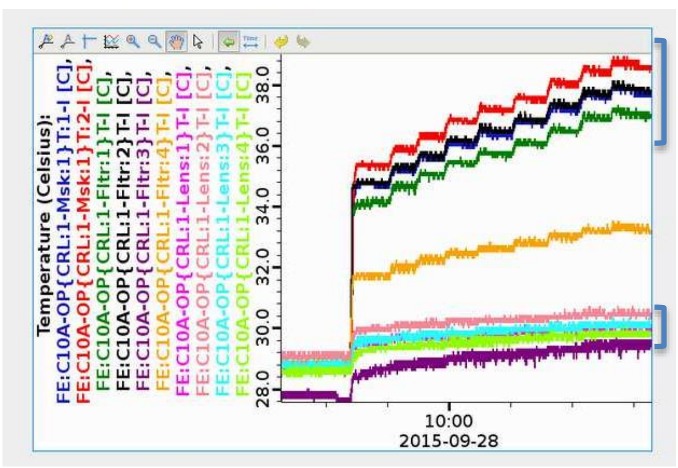
- Very first component in the front end
- Integrated fixed mask; dual mode (inline & bypass) operation
- Lens assembly with integrated graphite filters



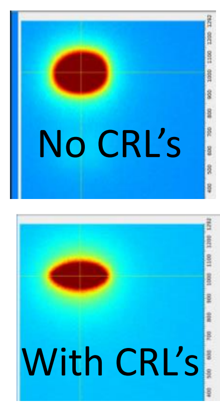




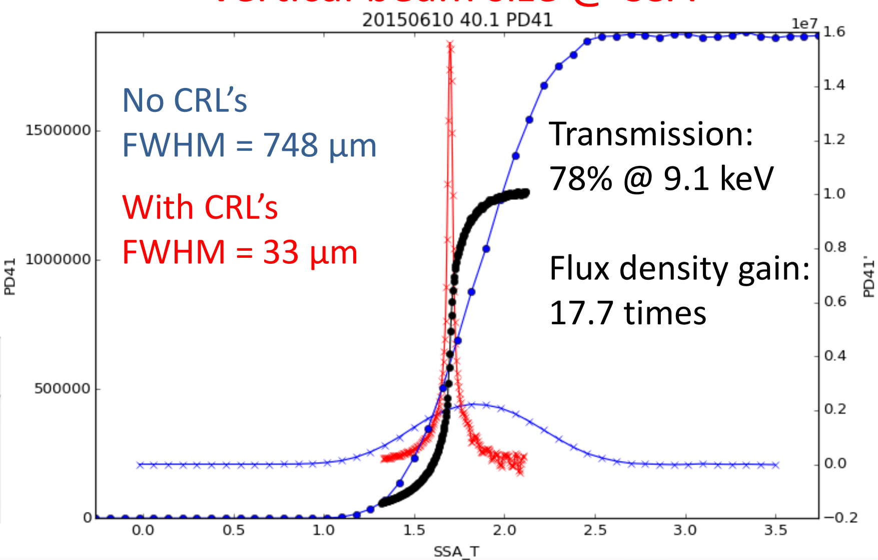
RC: 150mA …. …. 225 mA



@ BPM1

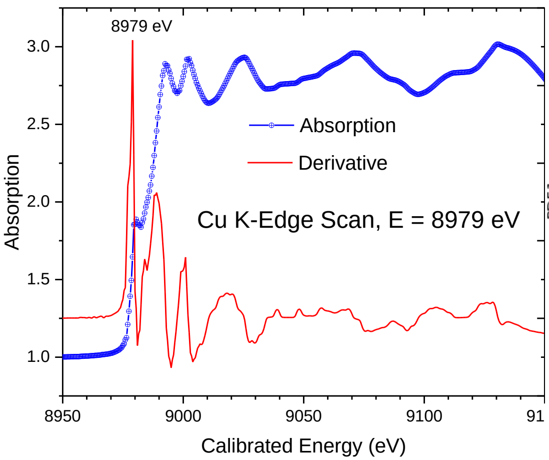


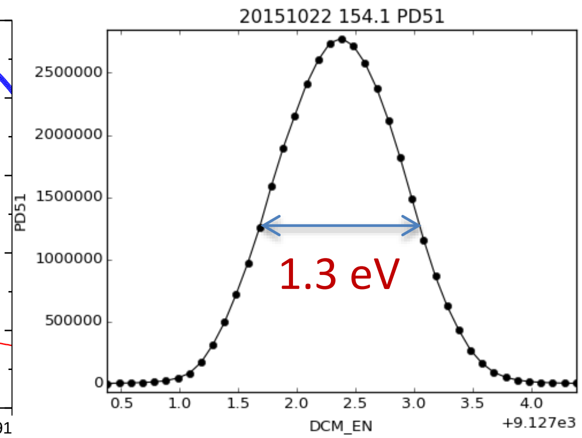
Vertical beam size @ SSA

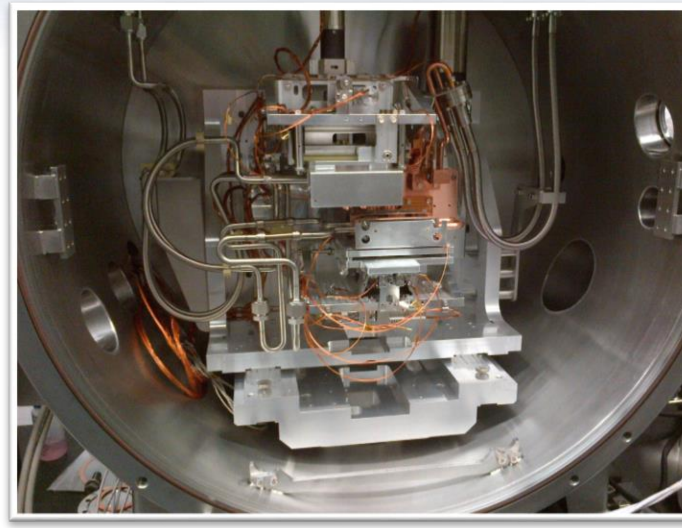


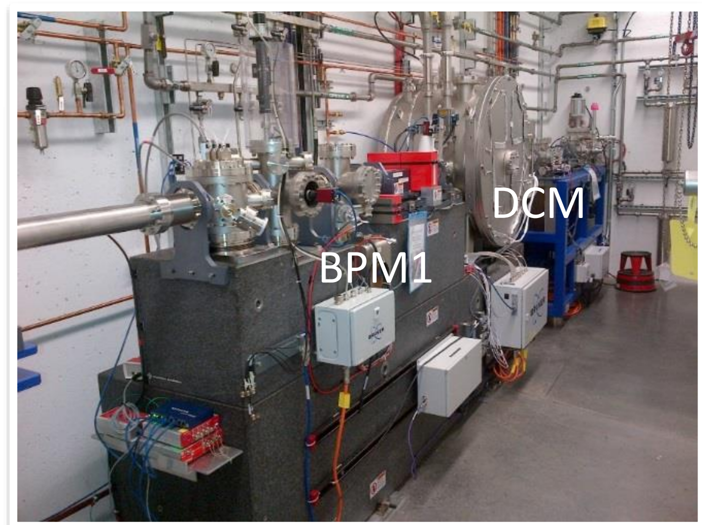
Double Crystal Monochromator Performance

- Bruker DCM with LN2 cooled Si(111) or Si(220)
- Gravity-fed water jacket to maintain temperature stability
- Fixed exit or pseudo channel-cut mode
- Energy (lattice constant) calibrated for energy scan

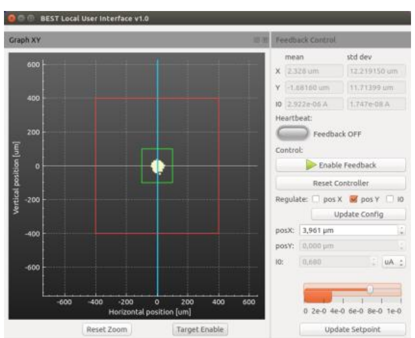






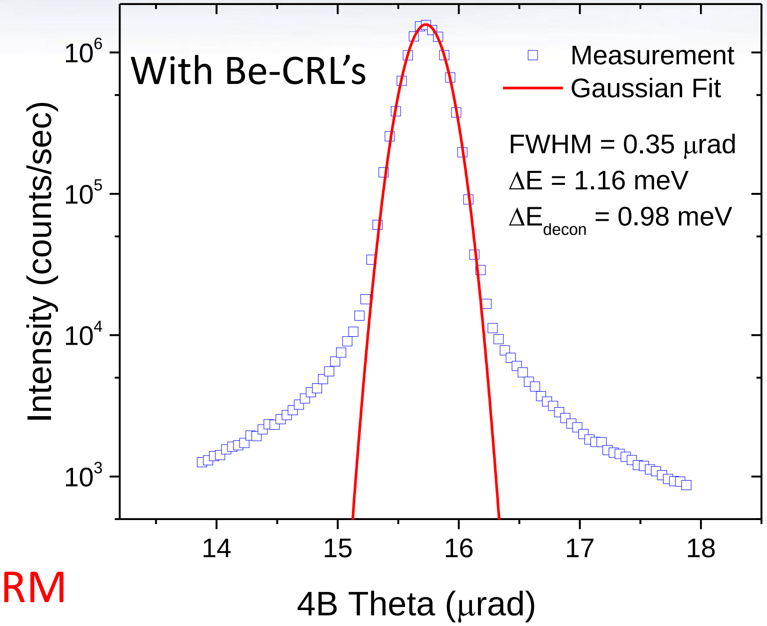


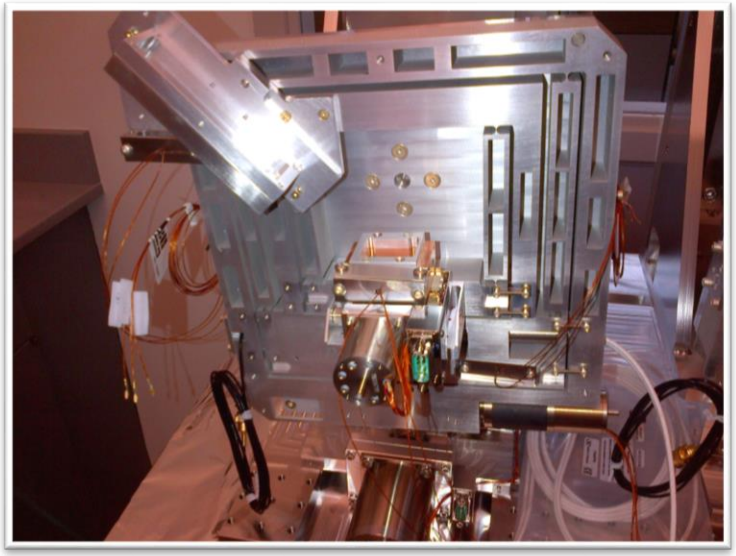
- CAENels BEST system for monitoring and feedback control



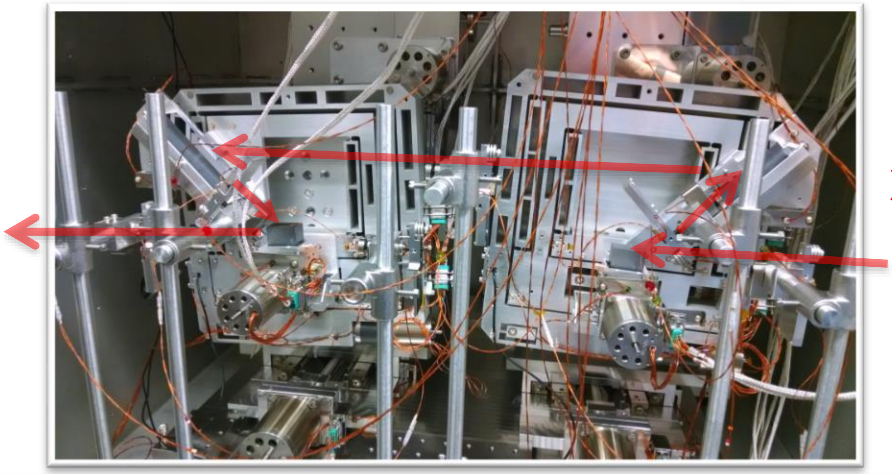
High Resolution Mono Performance

- Mechanical design based on in-house developed trapezoid flexure with 10 nrad angular resolution
- Energy resolution results
  - Measured energy resolution: ΔE ~ 1 meV
  - Characterized using the same CDW setup in R&D with a known ΔE ~ 0.65 meV
  - Sharp tails down to 2 orders of magnitude





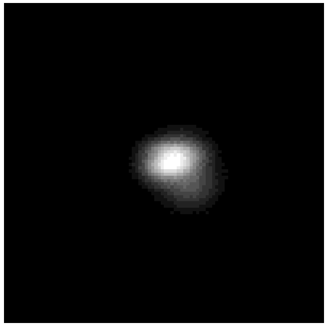
4B - HRM

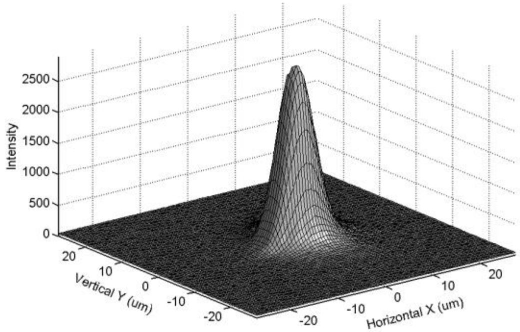


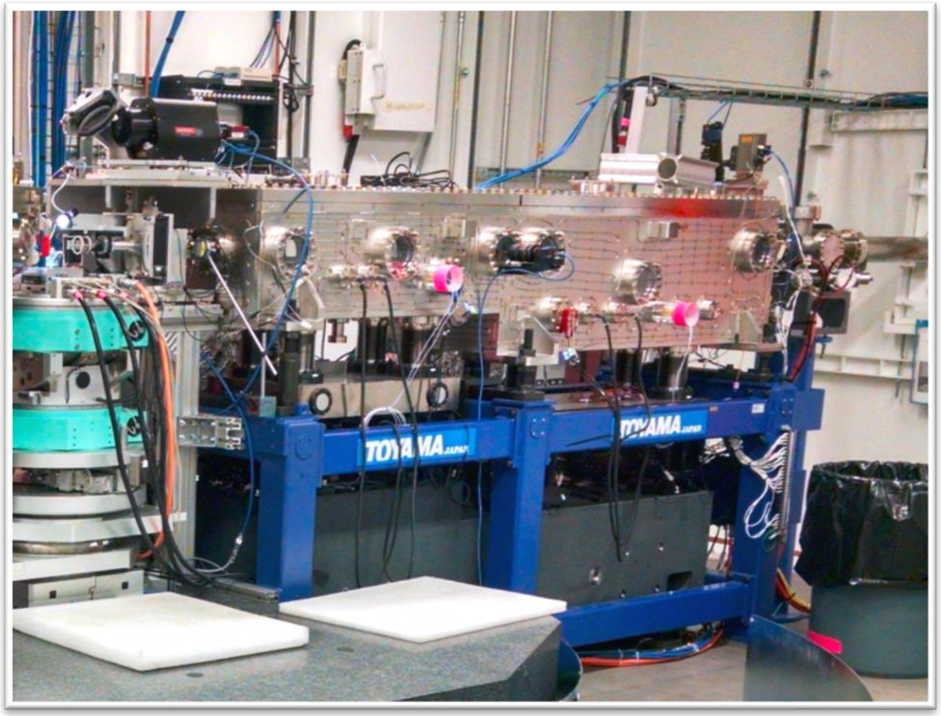
X-ray

KB Mirror Performance

- VFM: 1200 (L) x 55 (W) x 47 (H) mm^3, slope error 0.29 µrad
- HFM: 900 (L) x 50 (W) x 37 (H) mm^3, slope error 0.71 µrad.
- Measured focal size at sample compare well with designed value of 5 (V) x 7 (H) μm^2



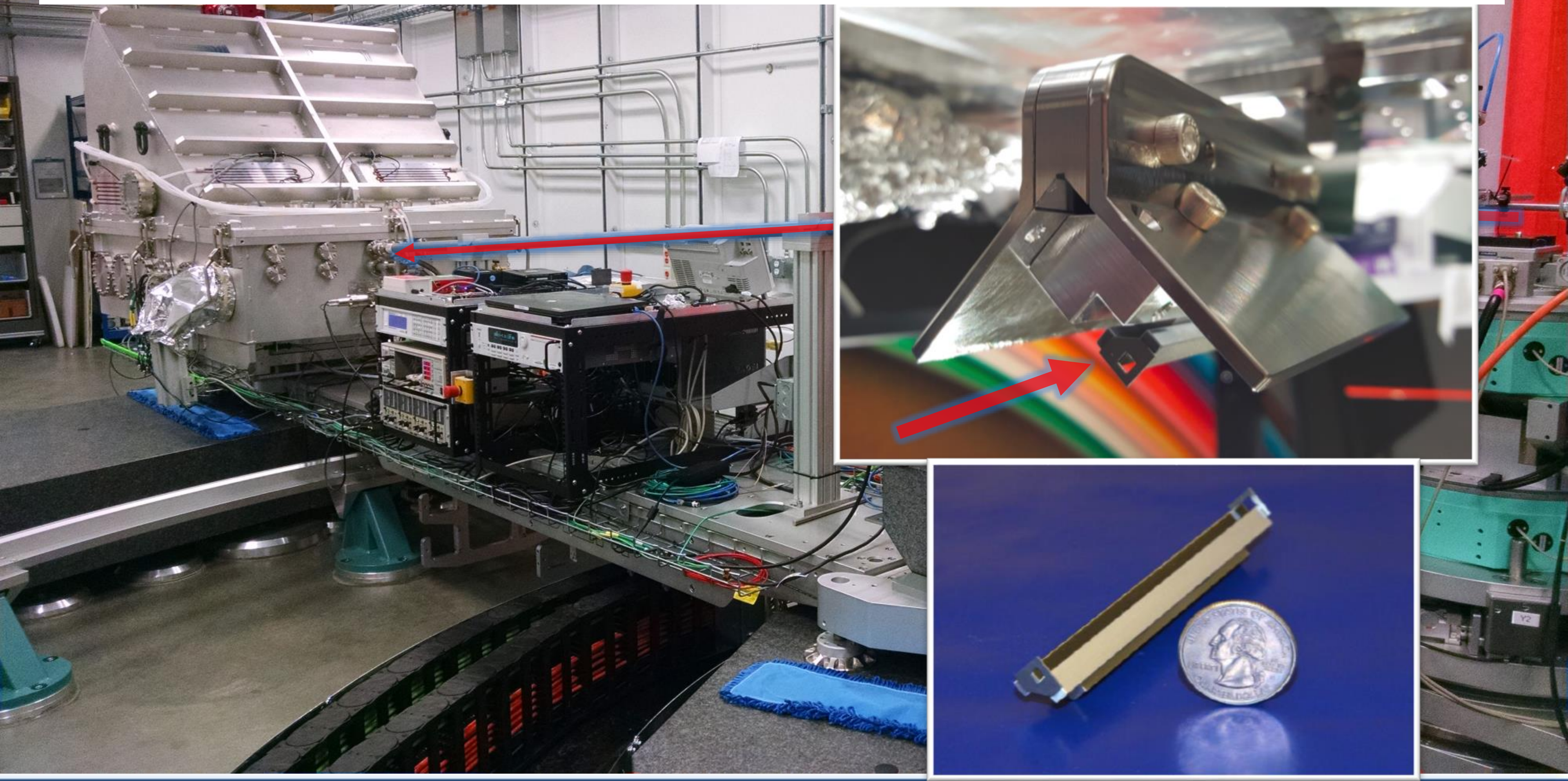




Without CRL's: FWHM = 5.9 (V) x 7.8 (H) μm^2
With CRL's, beam focus slightly broadened to ~10 x 10 um^2

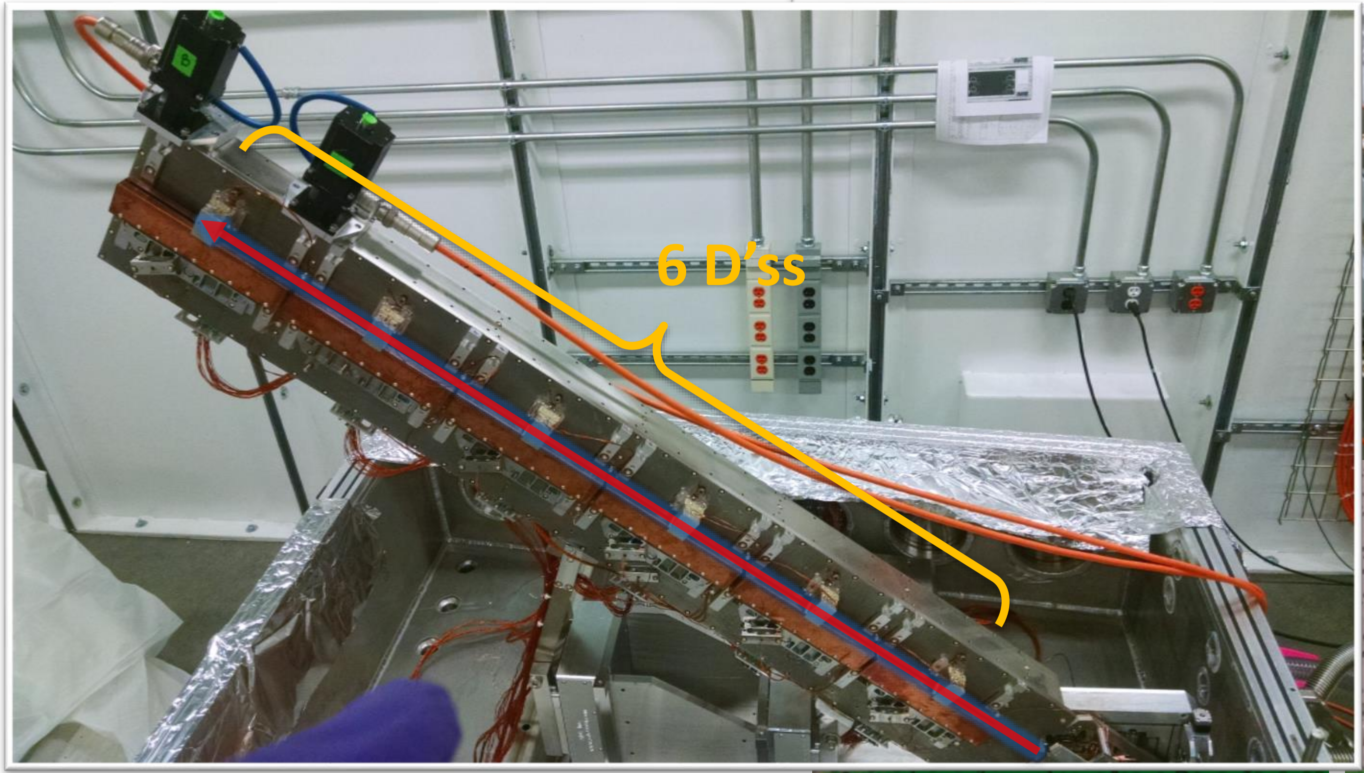
IXS Spectrometer System

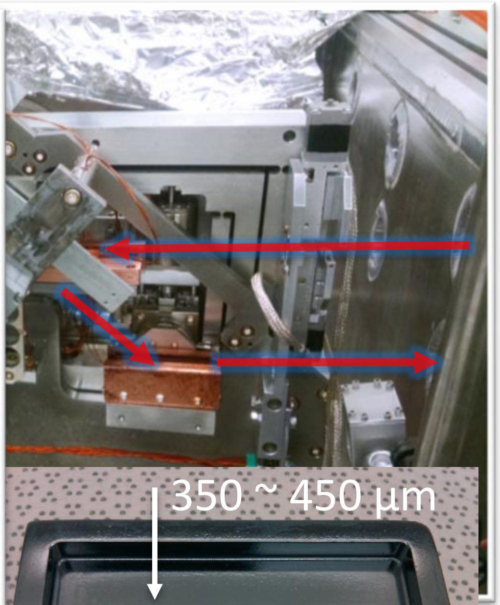
- Montel mirror to provide comparable angular acceptance to spherical diced analyzers @ full illumination: ≥ 10x10 mrad^2

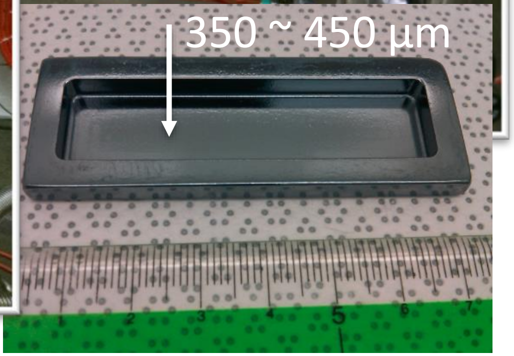


CDW Analyzer

- 6 D crystals, each 200mm long with full position control based on trapezoid flexure, make up a total length of 1.2 m to match the angular acceptance of the Montel mirror.



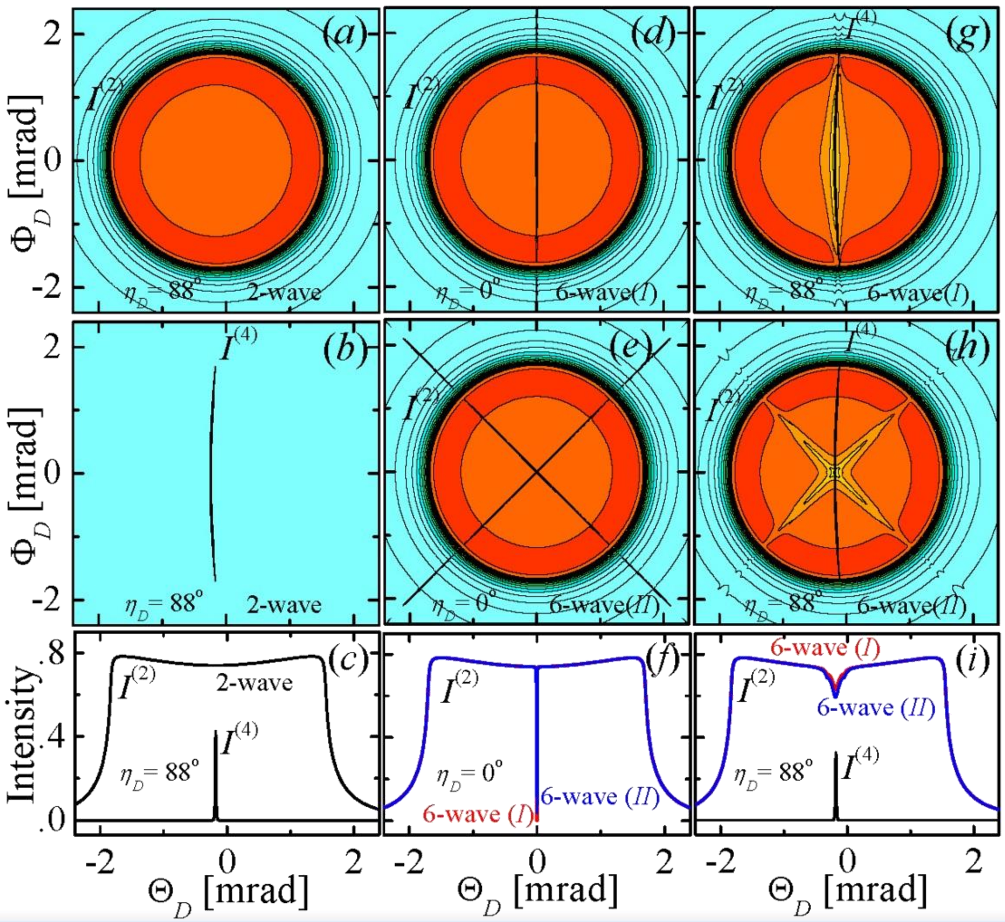


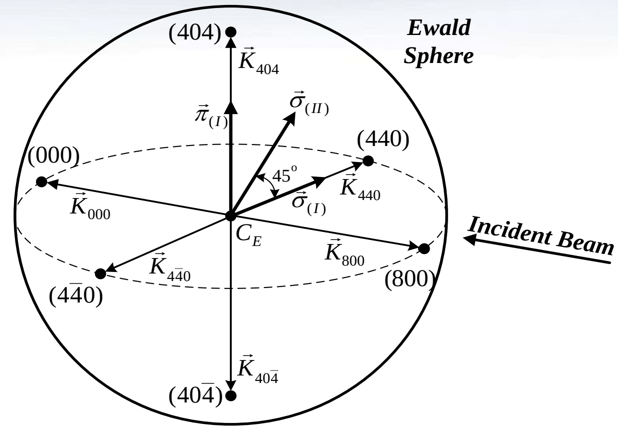


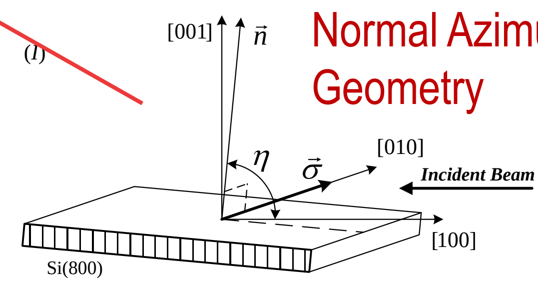
Multiple Beam Diffraction Effect

Stetsko *et al*, PRL (2011)

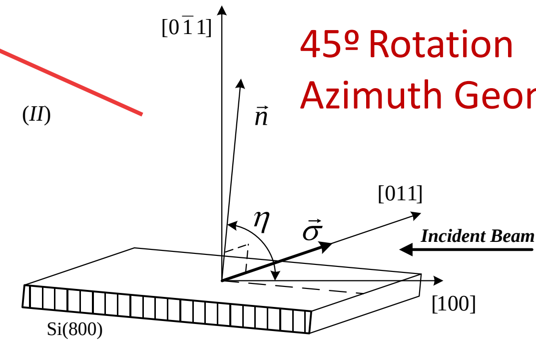
- MBD in CDW/CDDW causes 10-30% loss of spectral efficiency, but can be removed by introducing Φ angle offset with the 45º rotation azimuth geometry







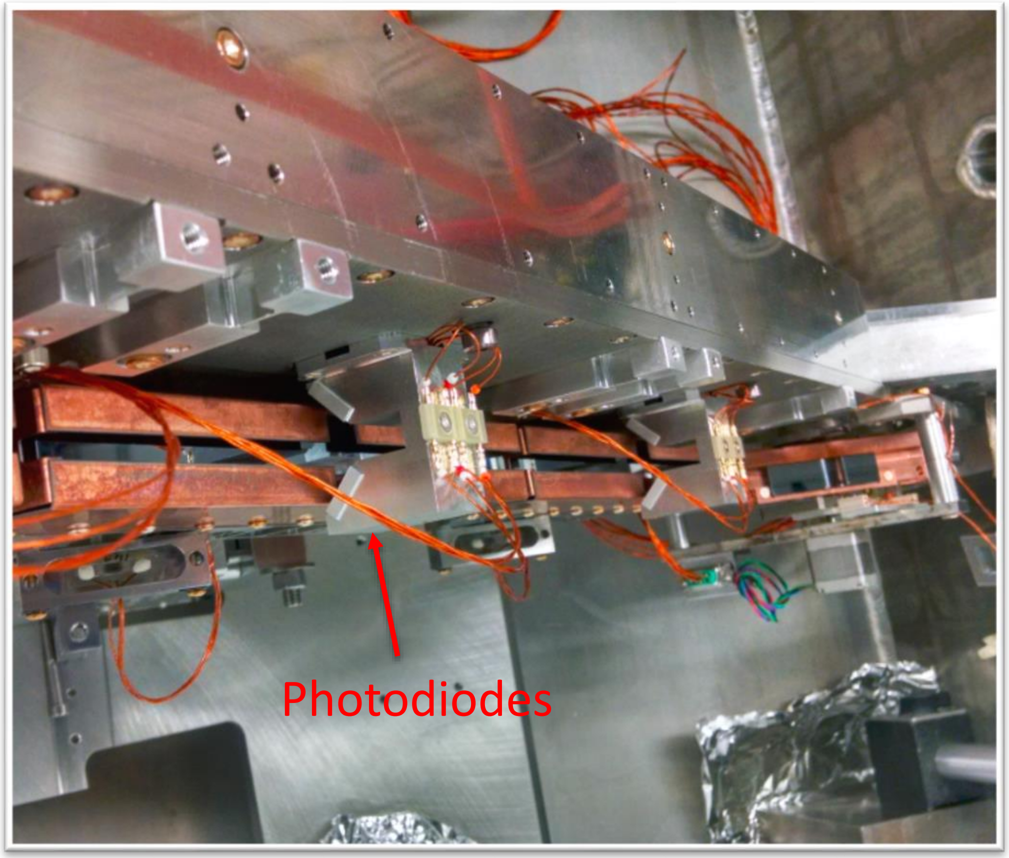
Normal Azimuth Geometry

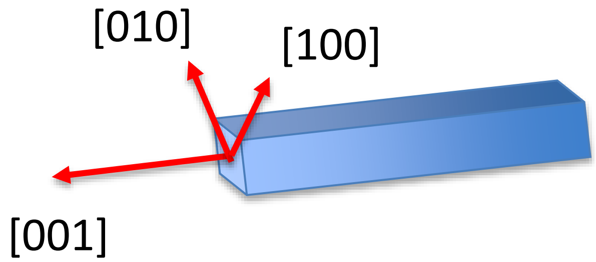


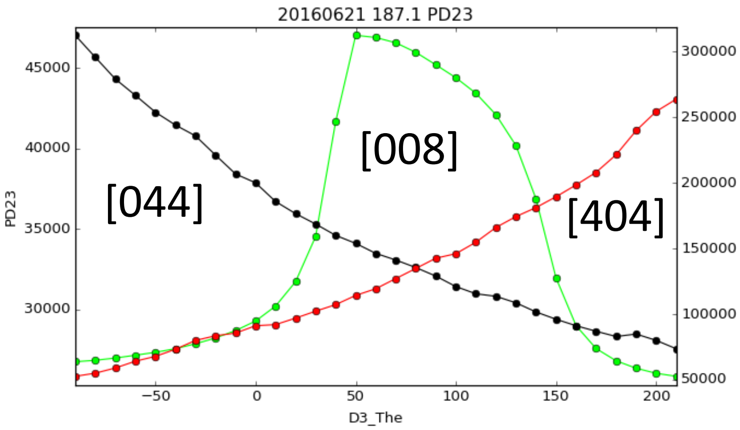
45º Rotation Azimuth Geometry

D Crystal Orientation and De-tuning

- MBD provides the most convenient diagnostic for D crystal alignment.
- Azimuthal de-tuning removes MBD and recovers ~20% of intensity.

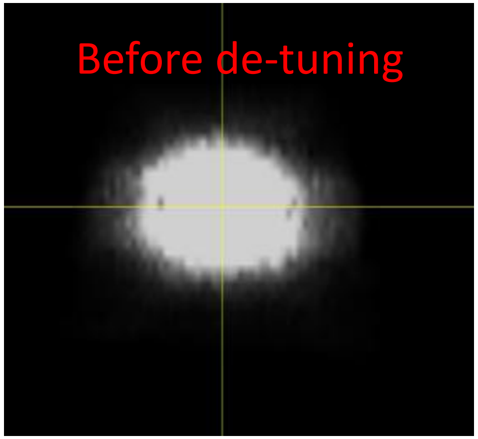


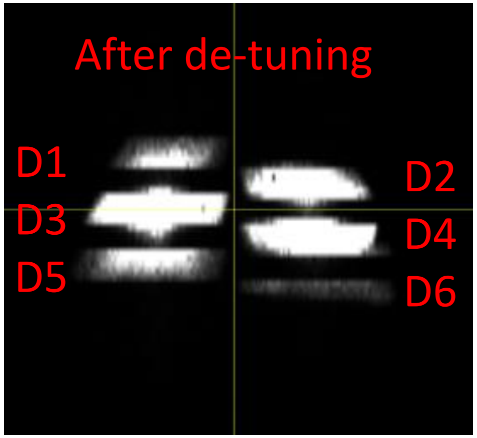


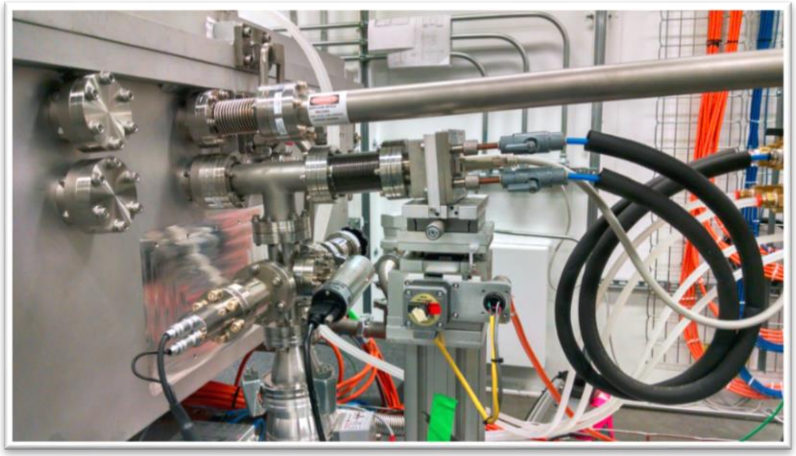


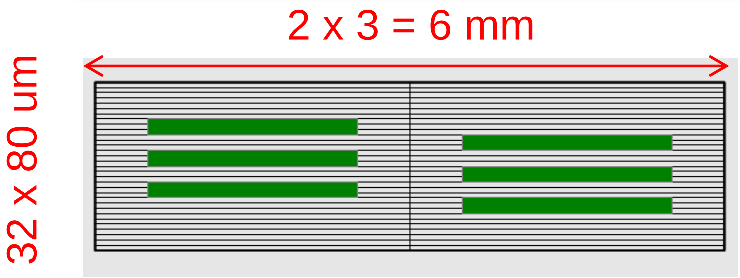
Azimuthal De-tuning and Tagma Detector

- D crystal azimuthal de-tuning allows separation of individual D reflections.

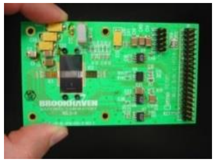


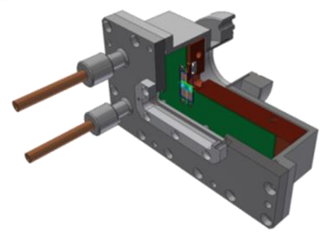






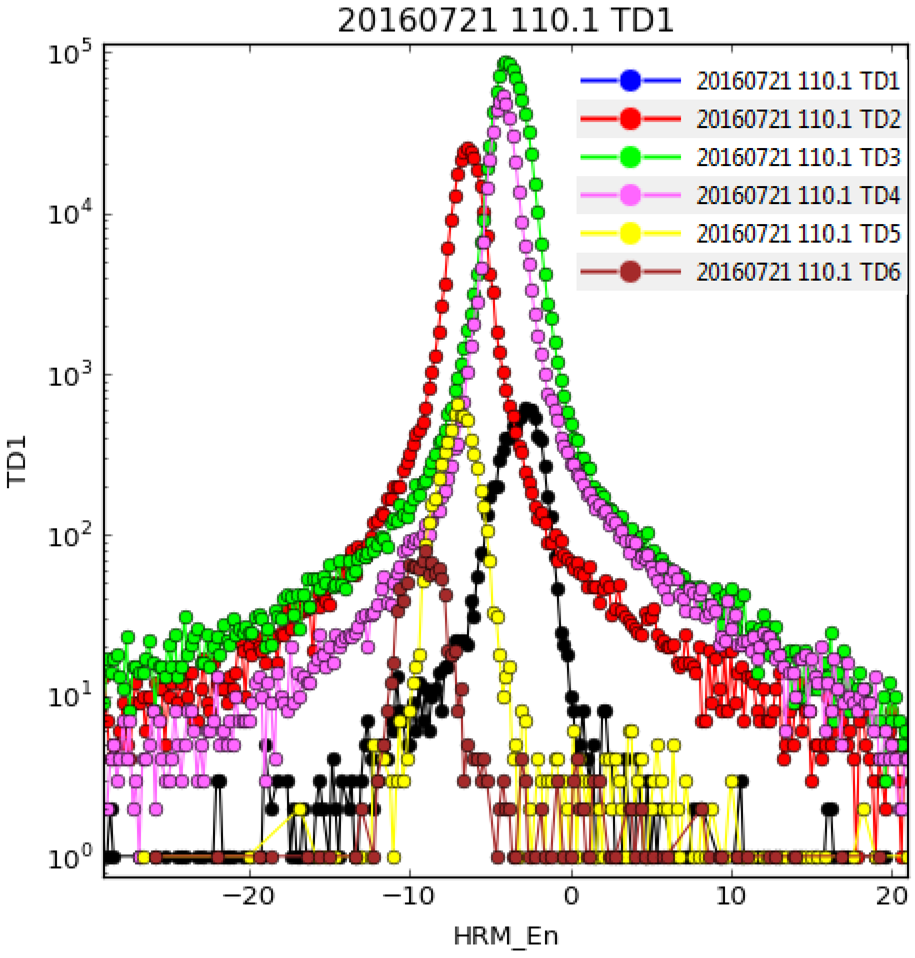
Sensor Board

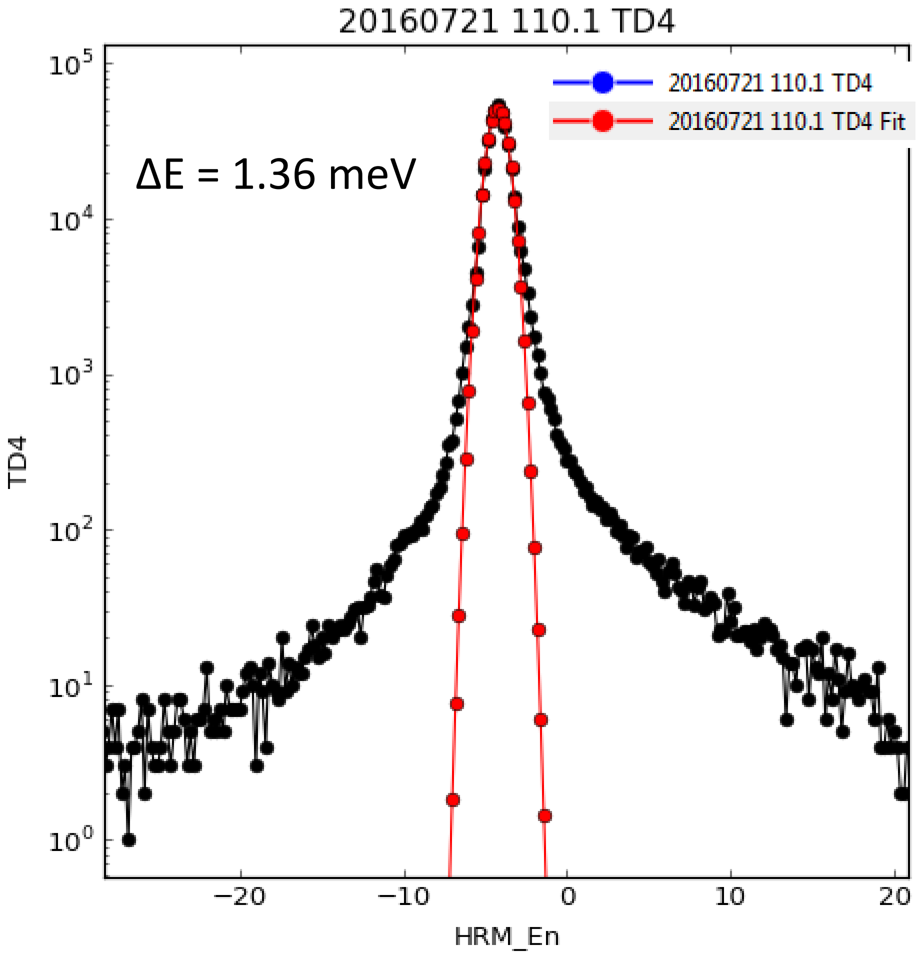




(Keister, et al, J. Phys.: Conf Ser. 2014)

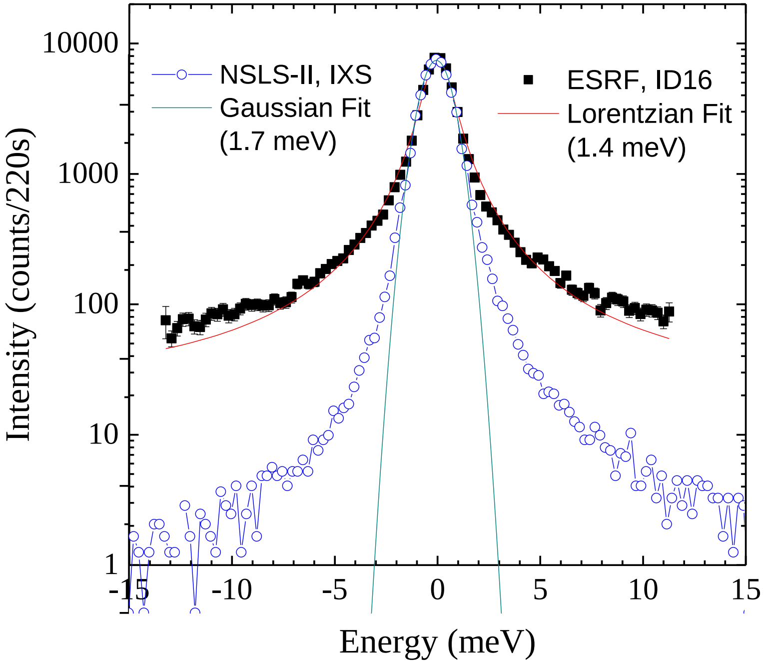
Resolution Function

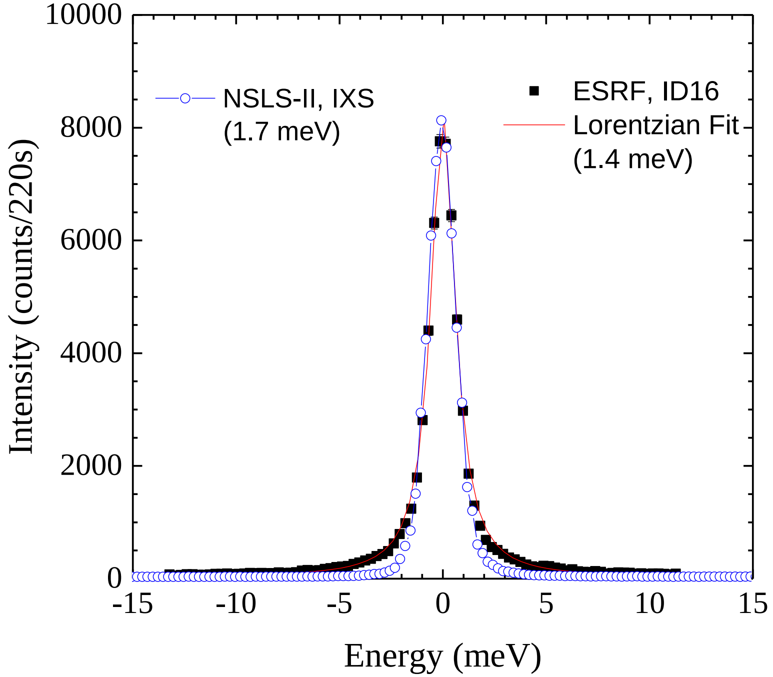




Resolution Function

- Resolution functions compared to ESRF show significantly sharper tails of the new spectrometer.



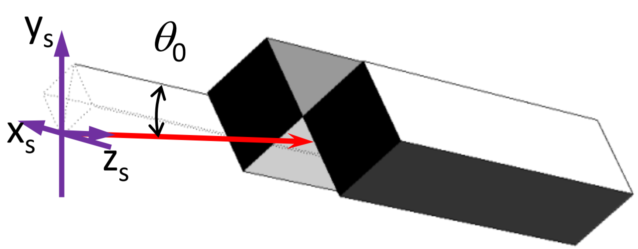


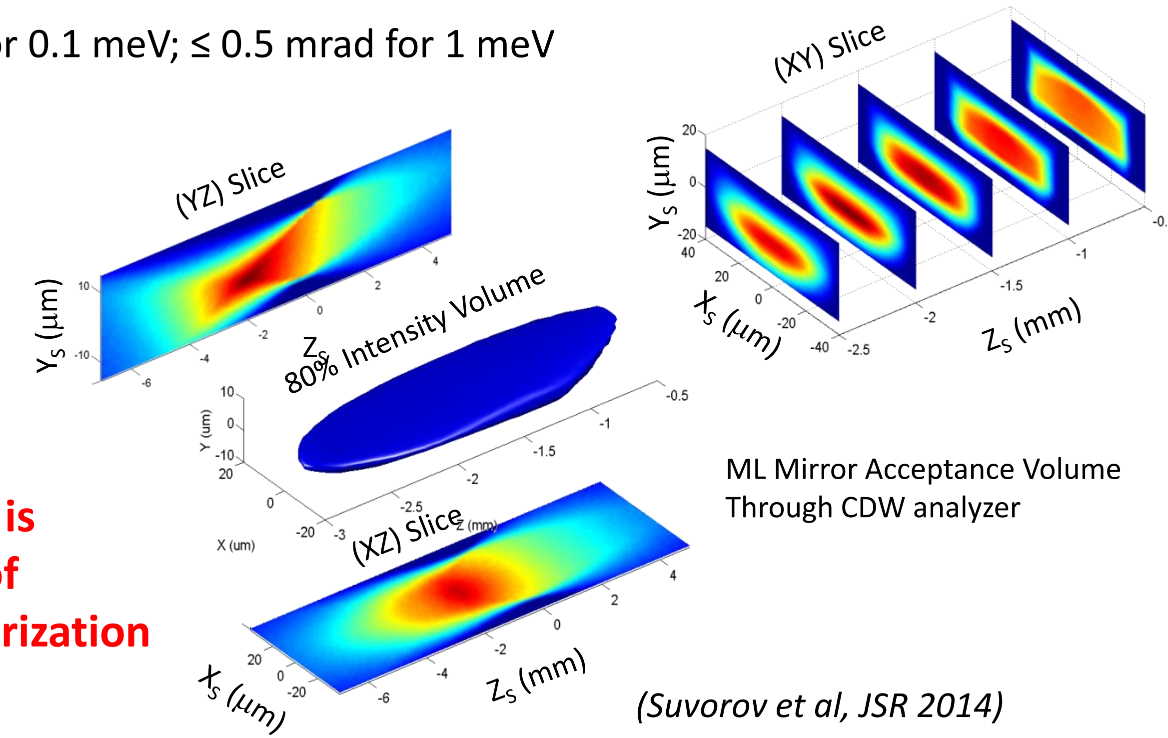
Slides on Science Commissioning Experiments were removed

Analyzer Optics: Montel Mirror

- Design (to achieve comparable acceptance to spherical diced analyzers)
  - Angular acceptance @ full illumination: ≥ 10x10 $mrad^2$
  - Collimation: ≤ 0.1x0.1 $mrad^2$
- Acceptance volume in forward scattering: ~20µm (X) x 20µm (Y) x 2mm (Z)
- Vertical divergence of collimating beam: No effect on energy resolution
- Horizontal divergence of collimating beam contributes to energy resolution

$$\left(\frac{\Delta E}{E}\right)_H = \frac{\phi^2}{2}$$: $\Phi \leq 0.15$ mrad for 0.1 meV; ≤ 0.5 mrad for 1 meV





ML Mirror Acceptance Volume Through CDW analyzer

(Suvorov et al, JSR 2014)

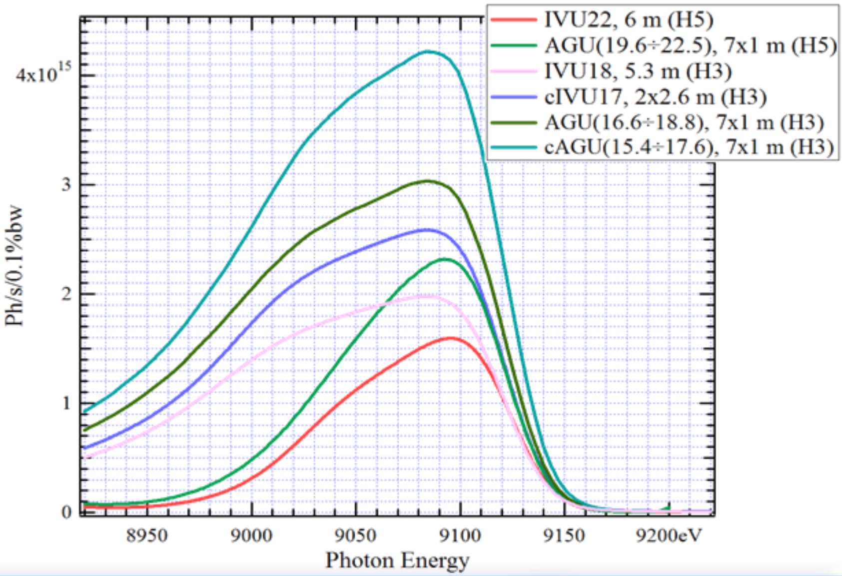
- **Projection of the scatter volume is expected to lead to faster drop of scattered intensity than the polarization factor.**

Performance Comparisons (current & outlook)

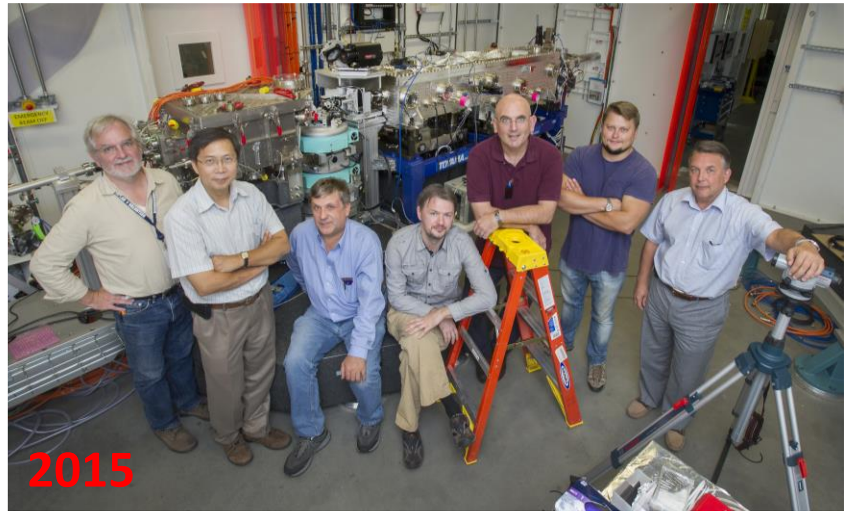
Facility (Beamline)	ΔE / E (meV) / (keV)	ΔQ** (nm^{-1})	Flux@sample (photons/sec)	Beam Size (V×H μm^2)	F.Density@sample ($photons/sec/\mu m^2$)	Analyzer Setup array/MaxSA[$mrad^2$]	Sharp Res. Tails
ESRF (ID28)	1.5 / 21.7	0.5	3.6×10^9	13×6	4.6×10^7	9x1 array / [Φ14] ea.	--
APS (30-ID-C)	1.5 / 23.7	0.6	5×10^9	20×35	7.1×10^6	9x1 array / [Φ11] ea.	--
SPring-8 (43LXU)	1.3 / 21.7	0.5	2.0×10^{10}	50×12	3.3×10^7	11x4 – 2 array / [9.4 x 8.9] ea.	--
NSLS-II (IXS)	1.7 / 9.1	0.2	4×10^9 *	5×7	3.4×10^7	Single / [15 x 15]	yes

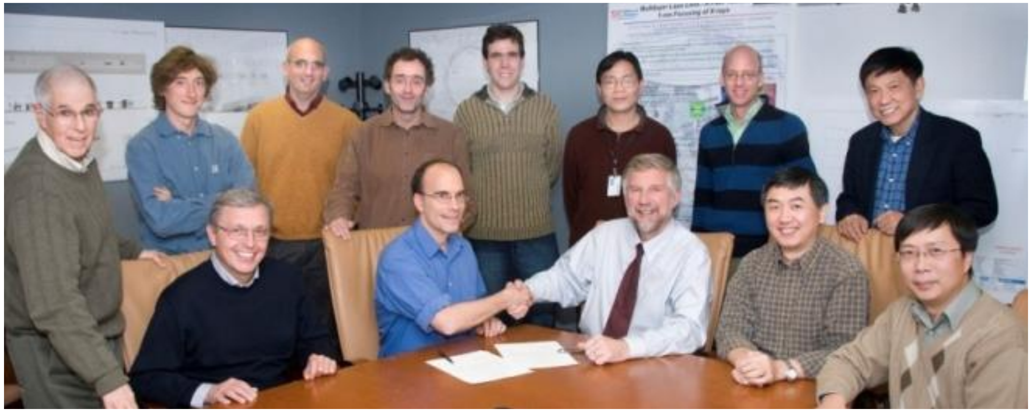
*projected flux @ 500mA, 1.2×10^9 measured @ 150mA; ** Q resolution @ 5 mrad angular acceptance.

- **Undulator upgrade can achieve a potential flux gain by more than 5 times** (using cAGU-7x1m), providing a total flux @ 9.1 keV of > 2×10^{10} photons/sec/meV. **Comparable to SPring-8 43LXU**
- **Factor of ~2 improvement with better crystals**
  - Montel mirror measured reflectivity: 42%
  - Current CDW analyzer efficiency: ~20%
- **More Analyzers**



Thank You for your attention!





BAT MOU, Dec 8, 2008

EFAC members (2007)