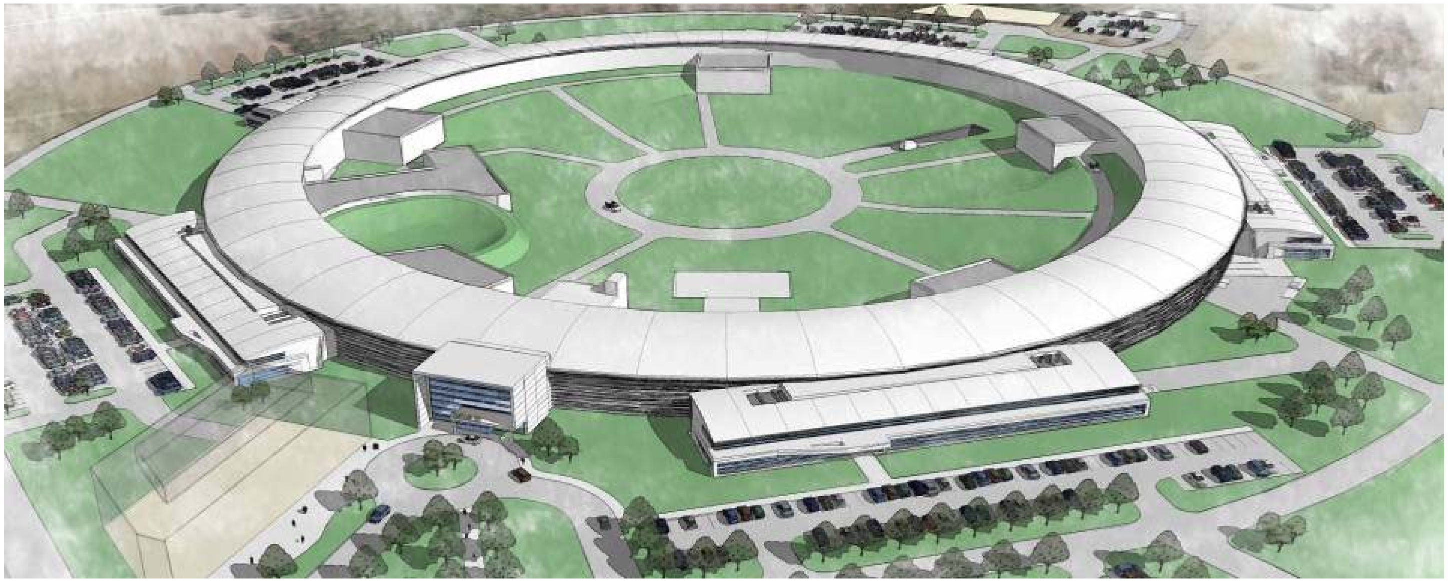
Path Towards 0.1 meV



Project R+D progress and plans

Presented by X. R. Huang (APS) and Z. Zhong (NSLS)
Thanks to Yuri Shvyd'ko (APS) and all contributors
October 4 or 5??? , 2007

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0.1 meV: Outlines

I. Principle verification and detailed dynamical theory calculations of Angular Dispersion X-ray Optics

II. Reexamine previous experiments — synchrotron topography of the thin crystals

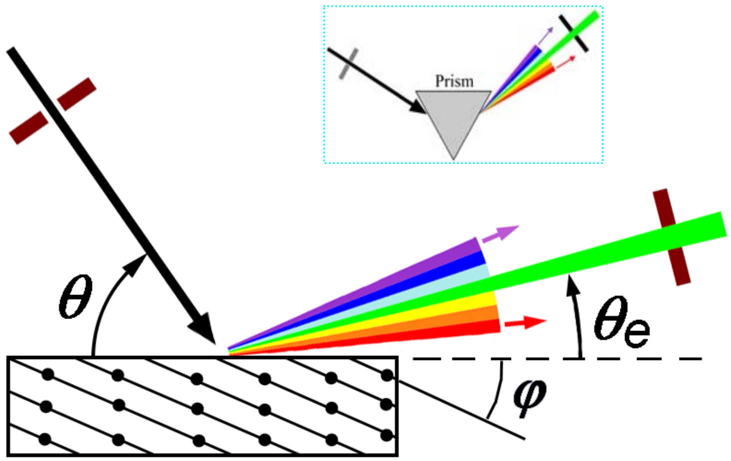
III. Semi-permanent setup at the NSLS and APS for 0.1 meV R&D, experiments ongoing

IV. Technical challenges and solutions

V. Exploring alternative approaches of 0.1 meV resolution — principles, designs, and calculations

VI. 0.1 meV R&D Schedule

I. Principles Verifications



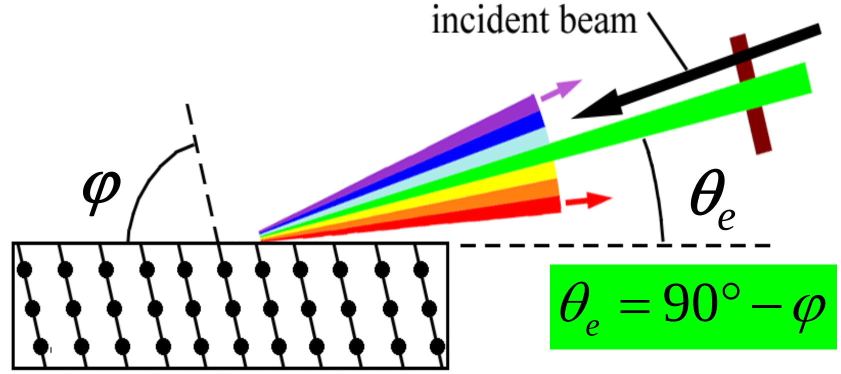
$$\cos\theta_e = \cos\theta + \frac{\sin\varphi}{d}\lambda$$

$\theta =$ const

Rigorous!

$$\frac{\Delta\theta_e}{\Delta\lambda} = -\frac{\sin\varphi}{d\sin\theta_e}$$

General Angular Dispersion
in asymmetric diffraction



$$\theta_e = 90° - \varphi$$

$$\frac{\Delta\theta_e}{\Delta\lambda} = -\frac{\sin\varphi}{d\sin(90° - \varphi)} = -\frac{\tan\varphi}{d}$$

$$\frac{\Delta E}{E_H} = \frac{\Delta\theta_e}{2\tan\varphi} \quad \text{where} \quad E_H = \frac{hc}{2d}$$

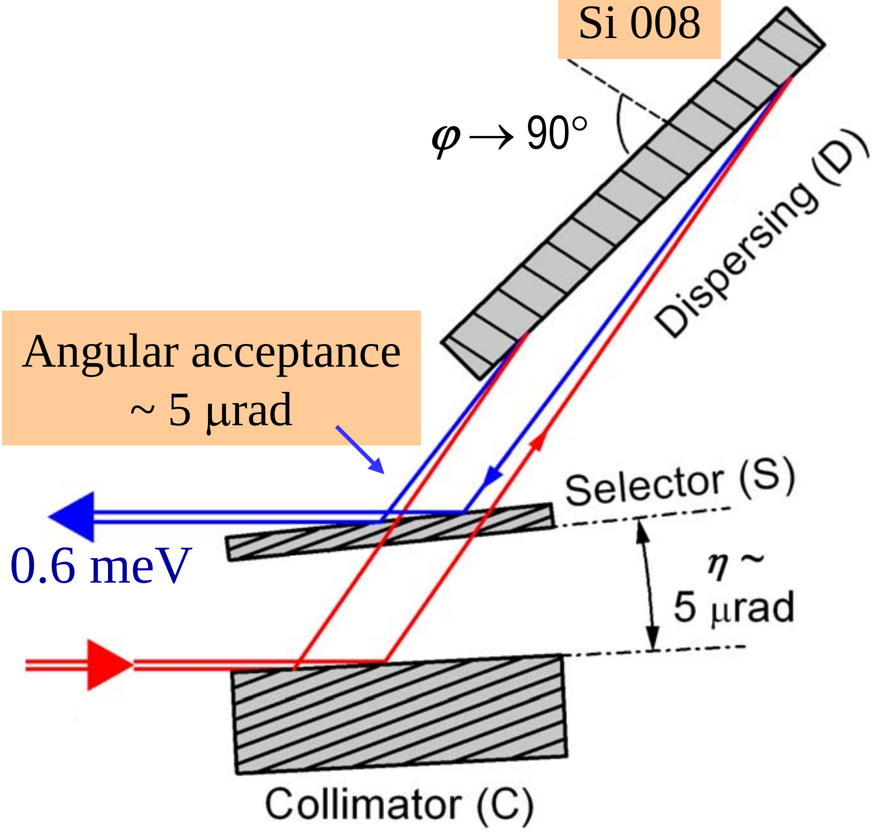
Grazing backscattering, independent of the Structure Factors and Darwin Curve Width

Resolution determined by φ and $\Delta\theta_e$

For Si (008), $E_H \approx 9.1$ KeV, $\Delta\theta_e = 3$ μrad,
$\varphi = 89.6°$ ⇒ **ΔE = 0.1 meV**

Implementation of 0.1 meV optics for *E* < 10keV

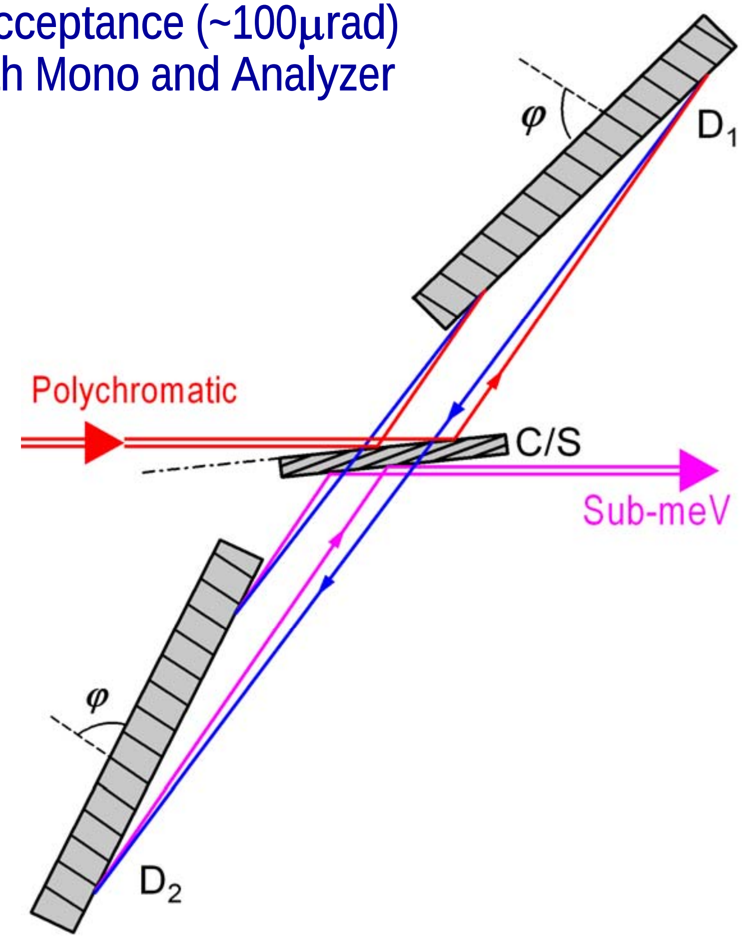
(Yuri Shvyd'ko's designs)



Si (220), $\theta_B = 20.7°$
Asymmetric factor $|b| \approx 20$

Backward CDS geometry

Wide acceptance (~100μrad)
For both Mono and Analyzer

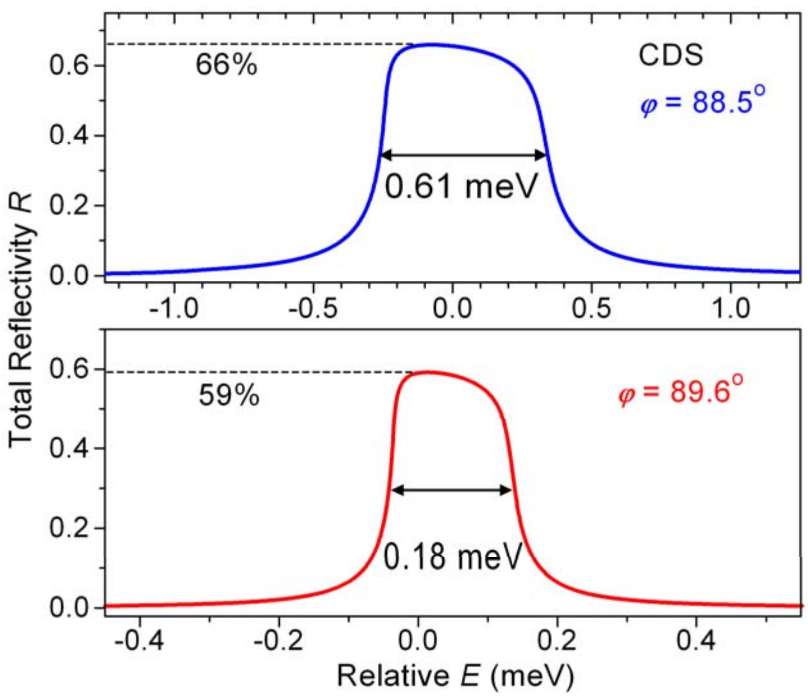


In-line (forward) CDDS geometry

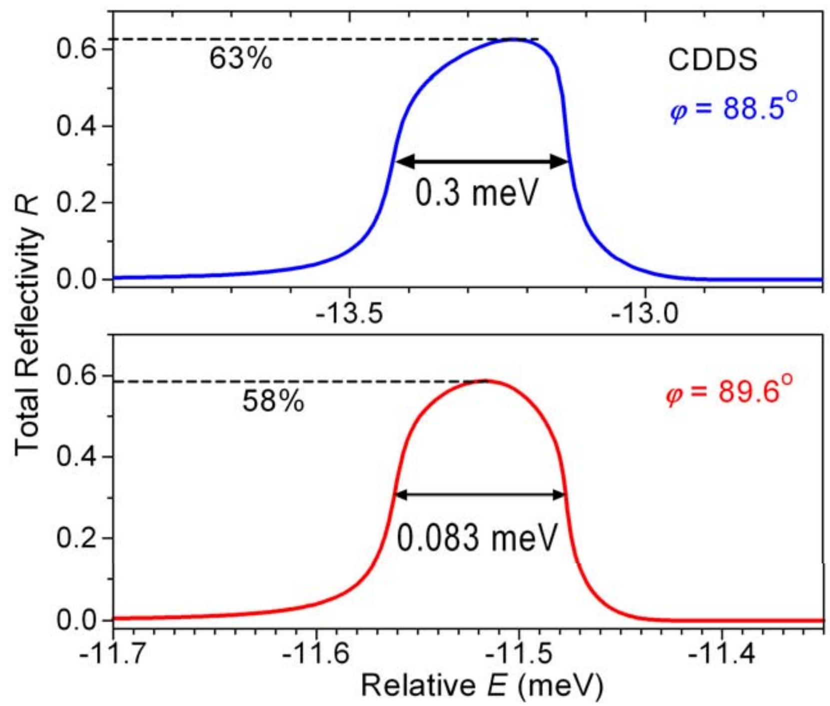
Dynamical Theory Calculations

Full computation programs based on rigorous dynamical theory have been developed

- Developed from scratch, error-proof
- Component-orientated, easy plug in (using C++ classes)
- For backscattering, extremely asymmetric diffraction, transmission, Borrmann effect, ...
- Spectrum calculation, simulating experiments (alignment, energy tuning)



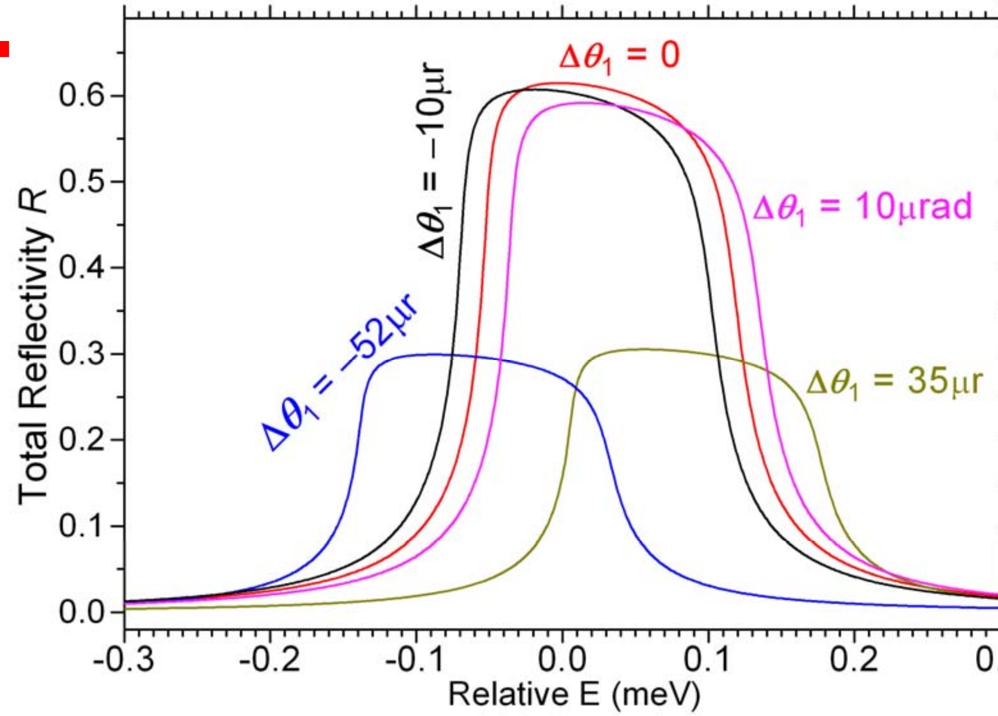
Backward CDS geometry



Forward CDDS geometry

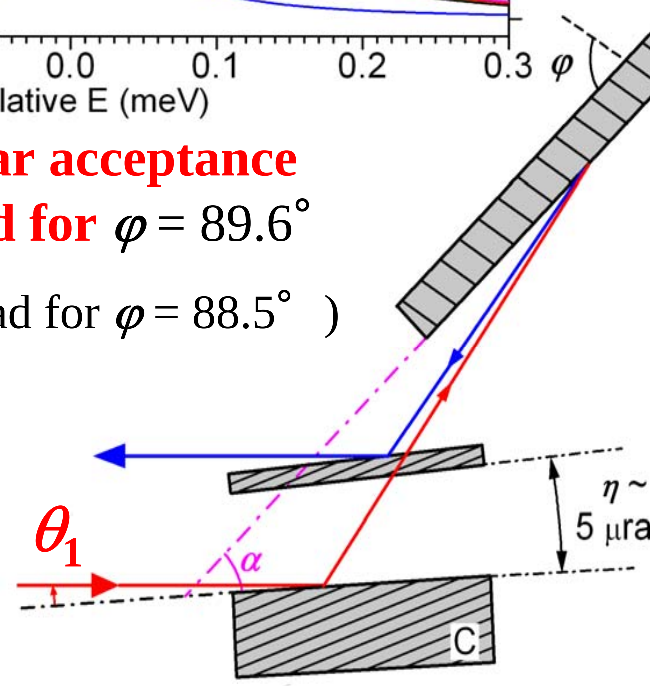
Angular acceptance and beam requirements

- No strict requirements for the incident beam, working for completely divergent beam (that's why it can be used as analyzers).
- So most optics development experiments (with limited flux) can be performed at NSLS using BM beamlines (e.g. X15A)



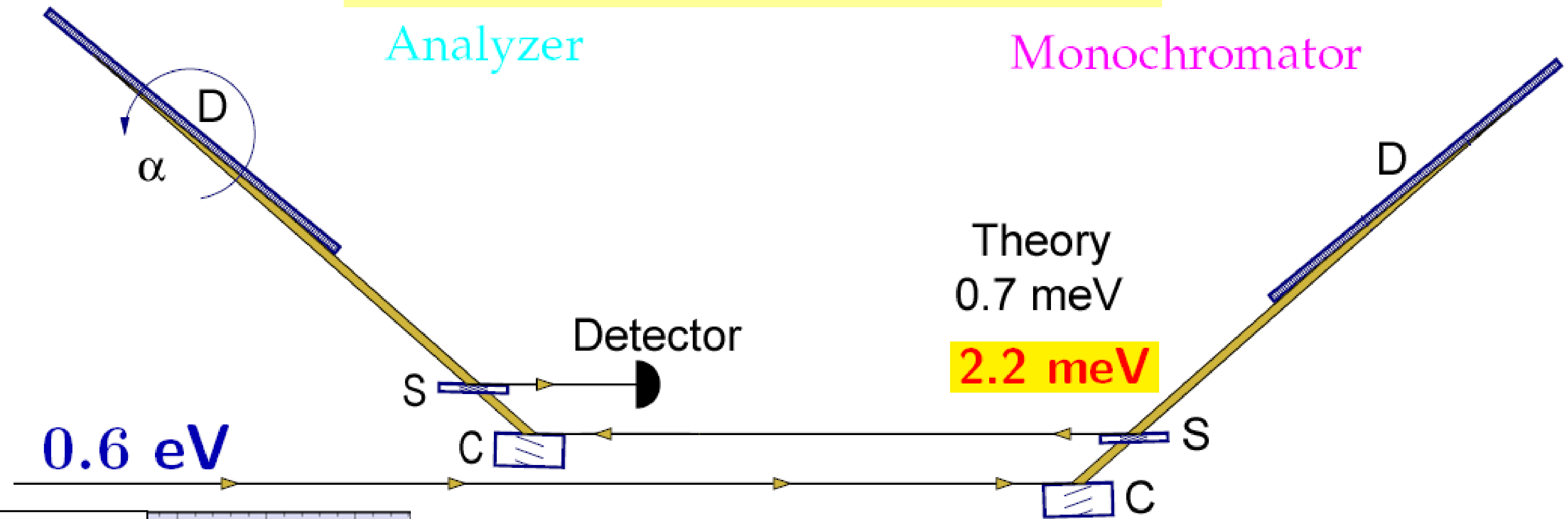
Angular acceptance
~ 87 μrad for φ = 89.6°

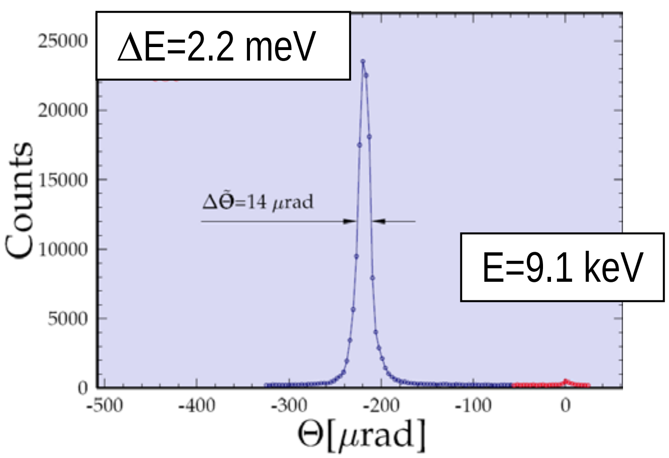
(> 100 μrad for φ = 88.5°)



II. Re-examine previous experiments

Shvyd'ko's First Experiment

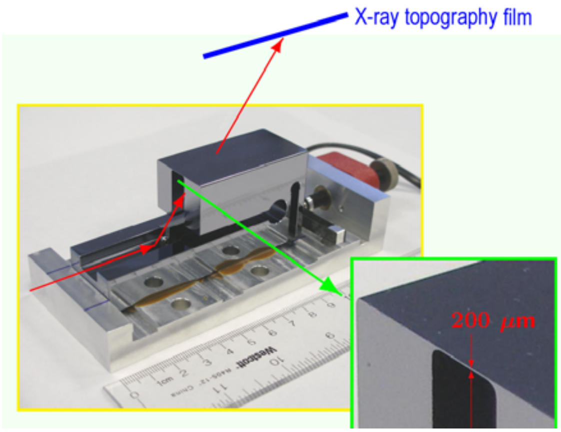




Shvyd'ko et al., *PRL* **97**, 235502 (2006)

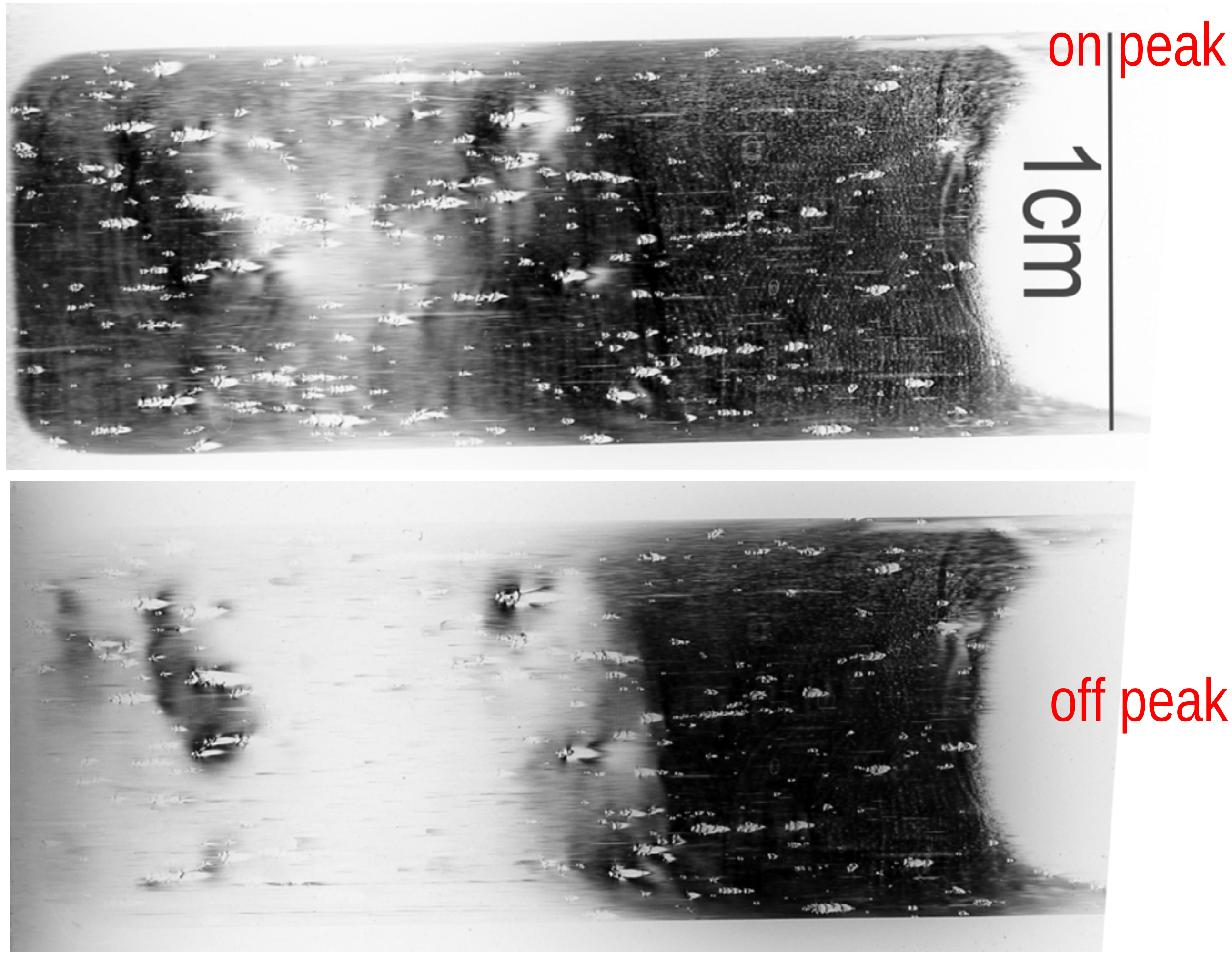
- Already successful, very promising
- Darwin curve 34 meV ⇒ narrowed to 2.2 meV
- meV resolution for *E* < 10keV never realized before
- Reasons for the discrepancy???

X-ray topography of selector (thin crystal)



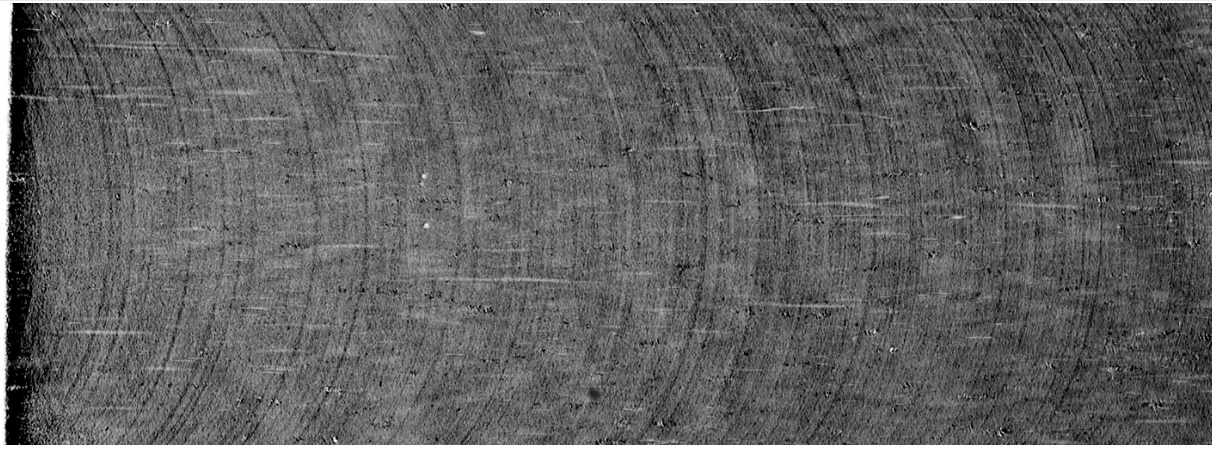
Problems:

- Damages caused by cutting and polishing
- Crystal bending (strains) caused by gravity and picomotor
- Surface roughness (next slide)

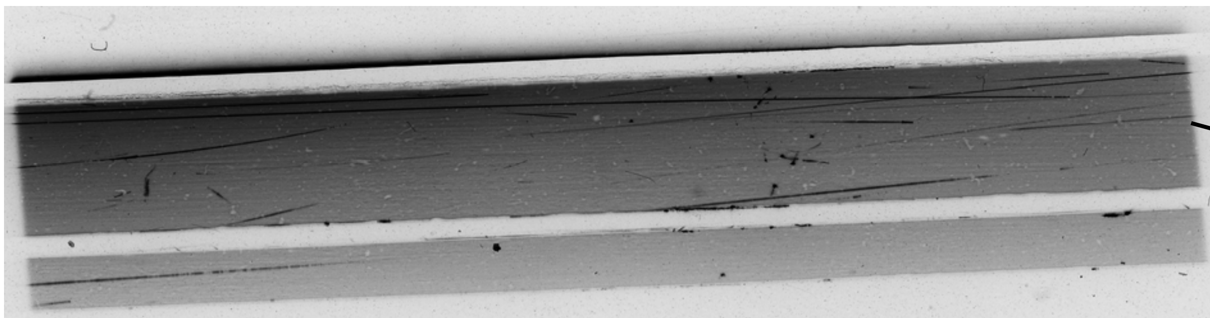


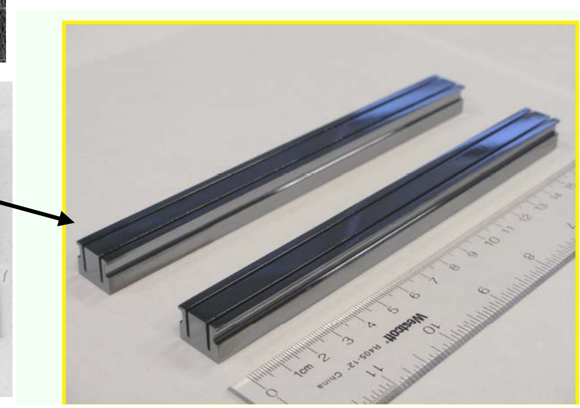
Transmission Image taken at 33 BM, APS

X-ray topography (cont.)



Reflection topograph taken from the upper surface of thin crystal showing **surface roughness**





Reflection topograph of the long crystal. Almost perfect except scratches.

Lesson learned: Discrepancy between theory and experiment is due to the bad quality of thin crystals. No mistake about principles.

Solutions: Completely re-design—detach from collimator, make it independent, see later

III. R+D ongoing

1. Semi-permanent optics development facilities at NSLS

- Readily available x-rays is a NSLS advantage, a luxury for APS, ESRF and Spring-8
- A semi-permanent setup is attractive for serious experimentalists
- Access may entice experts (such as Shvyd'ko) to come to BNL more often
- A playground may entice local experts (Siddons, Berman, Kao to name a few) to roll up their sleeves, and play
- Develops local expertise: one can only learn by doing, and making mistakes

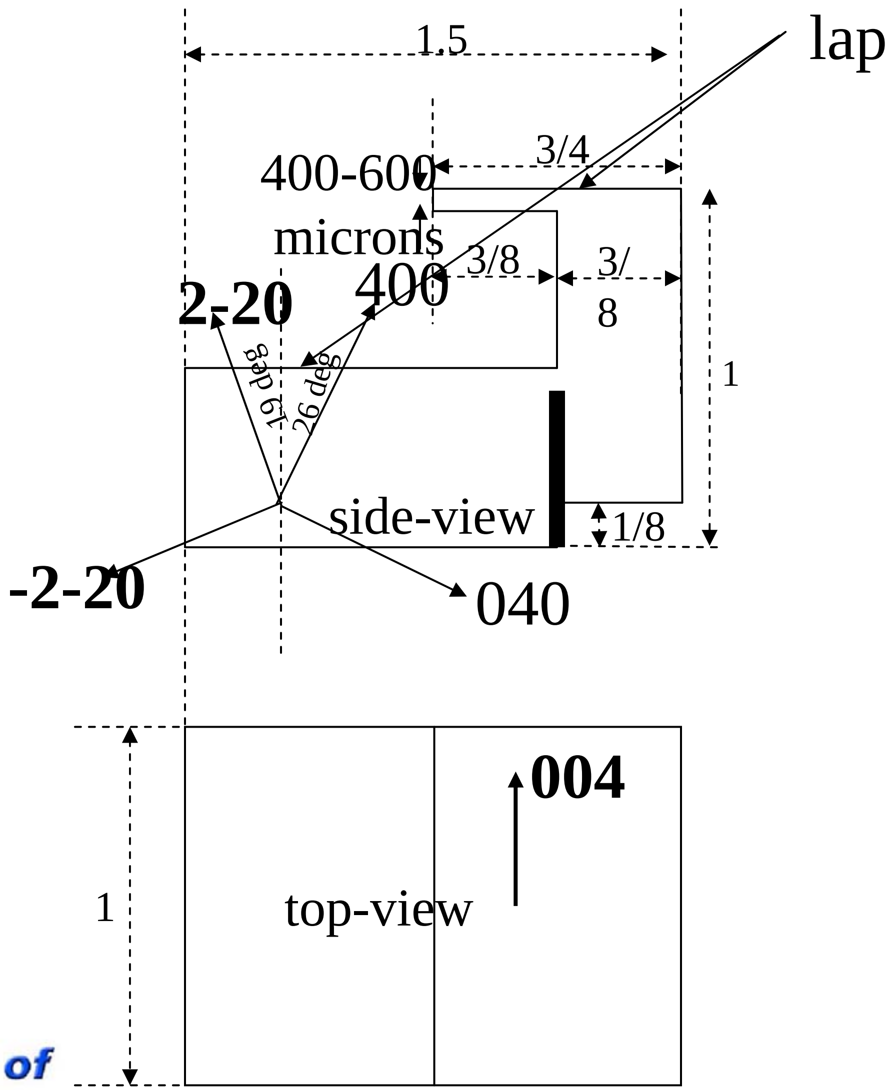
2. Repeat Shvyd'ko's experiment at NSLS

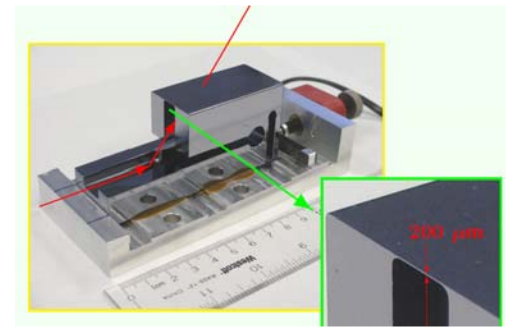
0.7 meV experiment but simplify the thin crystal

Feasibility:

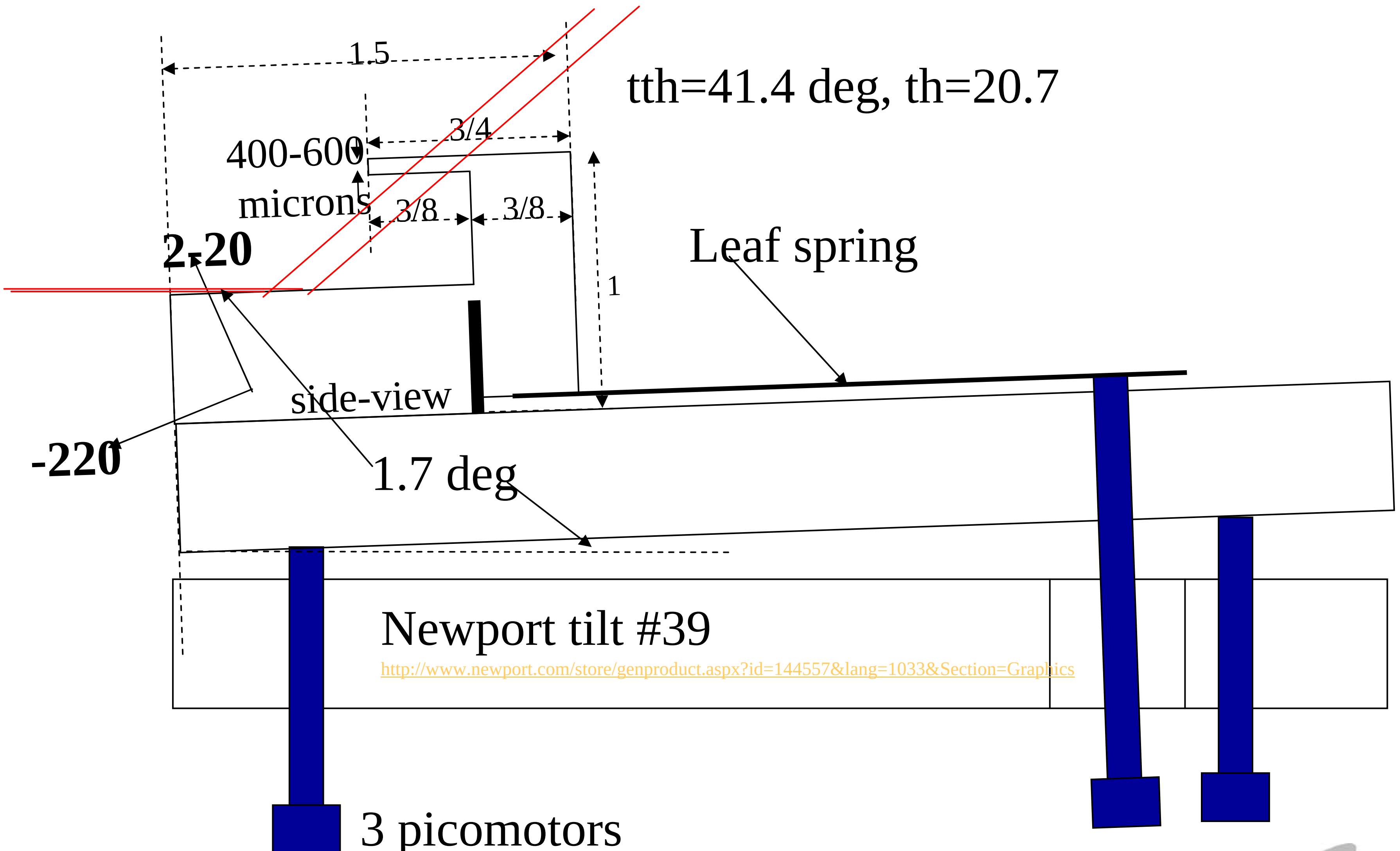
- Involves direct beam, flux should not be a problem.
- The angles involved are large (100 μrad) and should not be a problem.
- The divergence Shvyd'ko used is 15 μrad. We can do that at the NSLS with a slit of 200 μrad at 15 m.
- 200 μm in-plane beam size -> 4 mm footprint on *C*, *S* crystals (*b*=20), and 4/tan(1.5)=120 mm on *D* crystal (1.5º offcut). Thus small crystals are sufficient.
- Temperature stability is important but we may be able to get by with ambient and see what other problems we have.

Temporary Channel-Cut Design of Thin Crystal

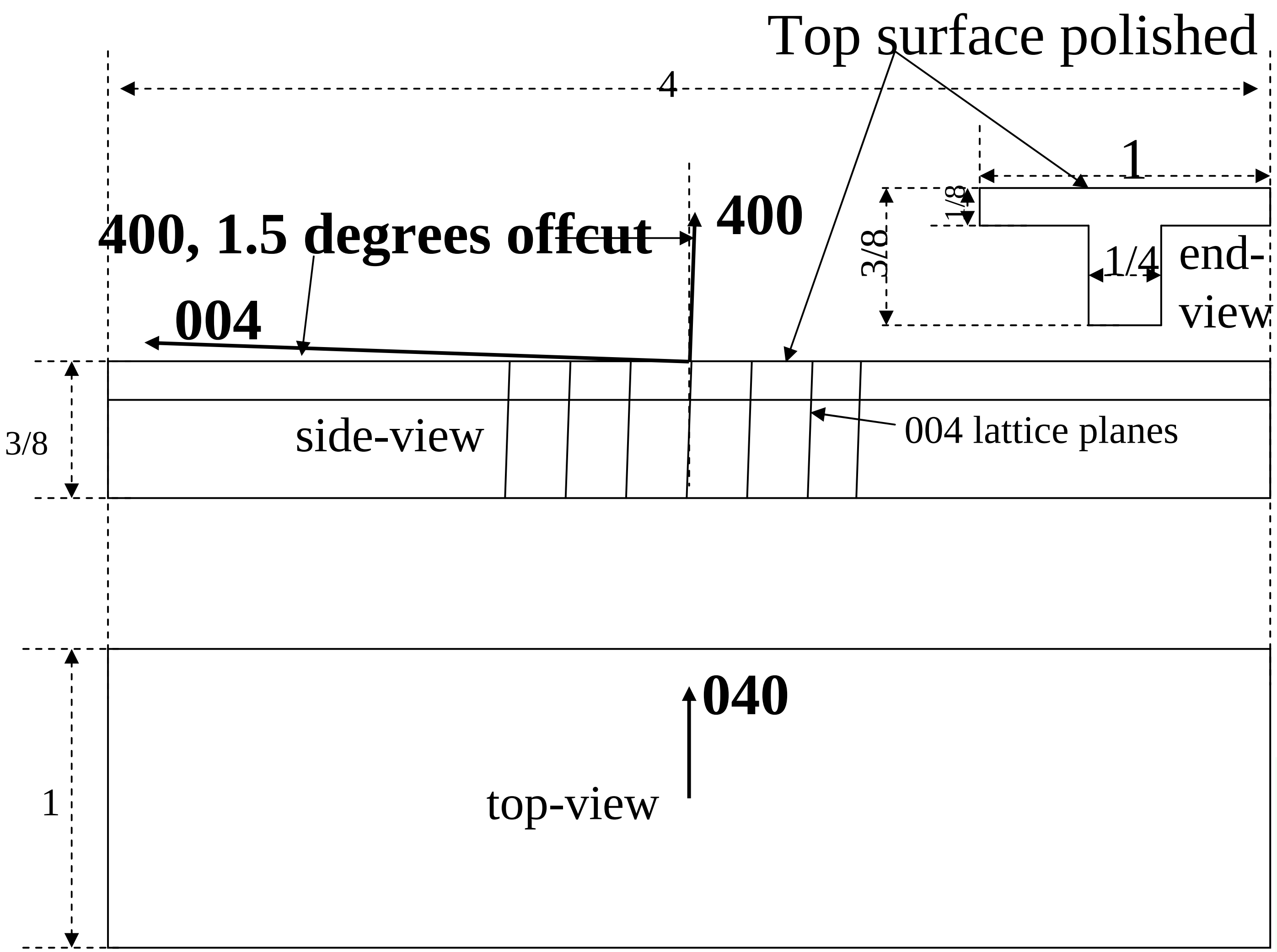


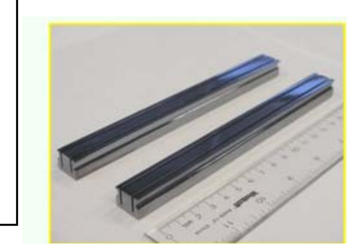


C/S Thin Crystal Mount

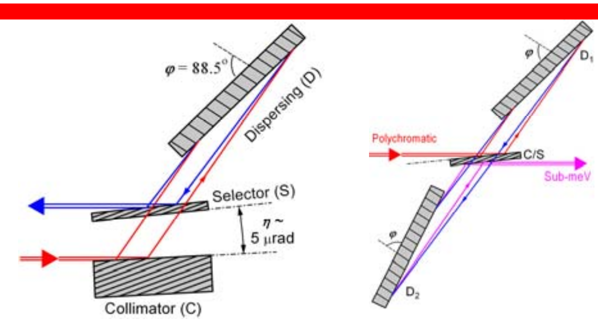


D-crystal Design

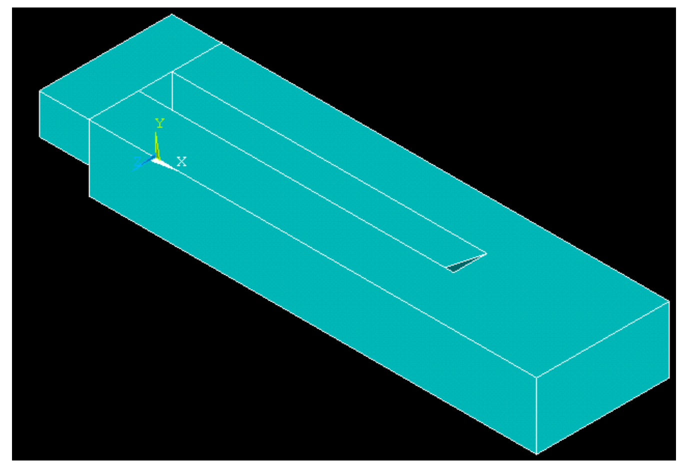


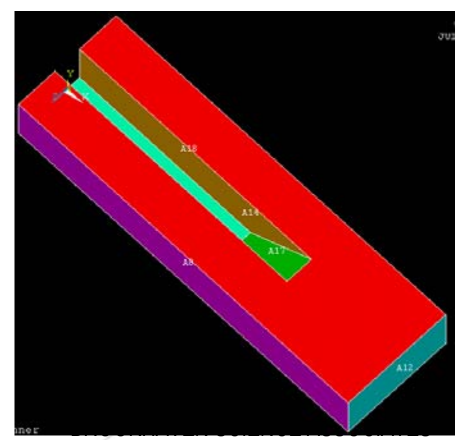


3. Redesign the thin crystals



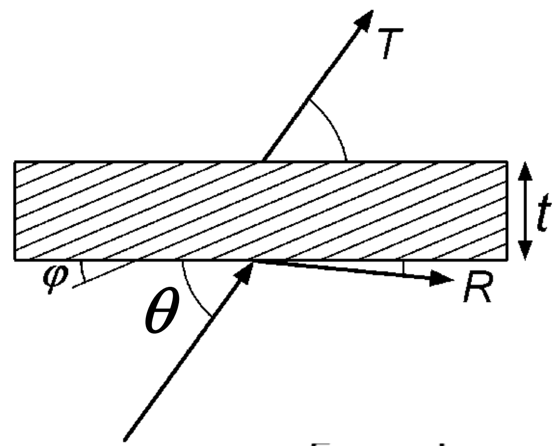
- The thin crystal used by Shvyd'ko are too complicated, venerable, troublesome
- Redesigned it to an independent component, used in both backward CDS and forward CDDS schemes. ANSYS analysis shows robustness to mounting, gravity
- To be cut and tested soon (using the previous long crystals) at BM 33, APS.
- Regular beam time has been applied for monochromatic topography and diffraction at APS.

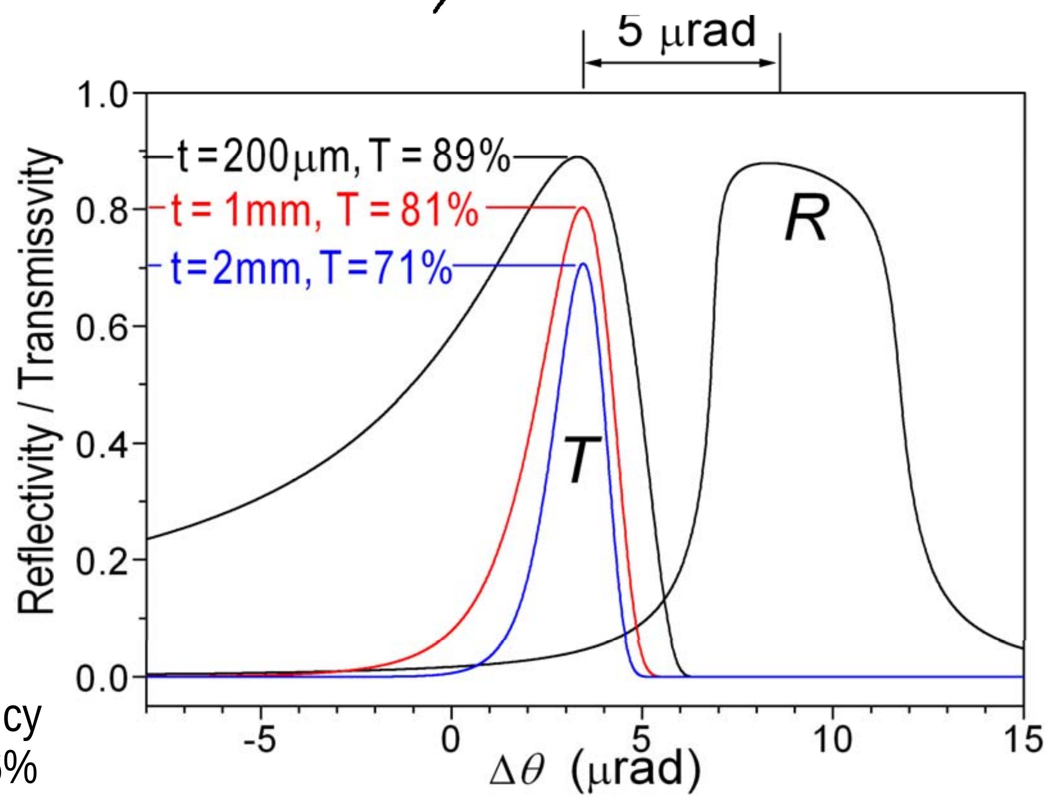




Redesign the thin crystals (Cont.)

- Transmission through thin crystal is due to the **Borrmann effect**
- Thickness from 0.2 to 1mm, *T* decreases less than 10%.
- So we can set thickness to 1~2 mm without much intensity loss
- Steeper wings
- Need to test since imperfection (low crystal quality) can destroy Borrmann effect.
- If successful, make free-standing selector crystal





Total efficiency
58%,52%,46%

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4. Crystal fabrication and characterization

- Cutting, polishing, and etching all the necessary crystal components
- Rocking curve measurements: strains, bending, surface quality
- Topographic imaging: bending, roughness, defects

  (at X19C, Mike Dudley’s topography facility, always available, beamtime abundant there)
- Metrology measurement of roughness, figure errors...
- Optimize crystal fabrication procedure

IV. Technical challenges and solutions

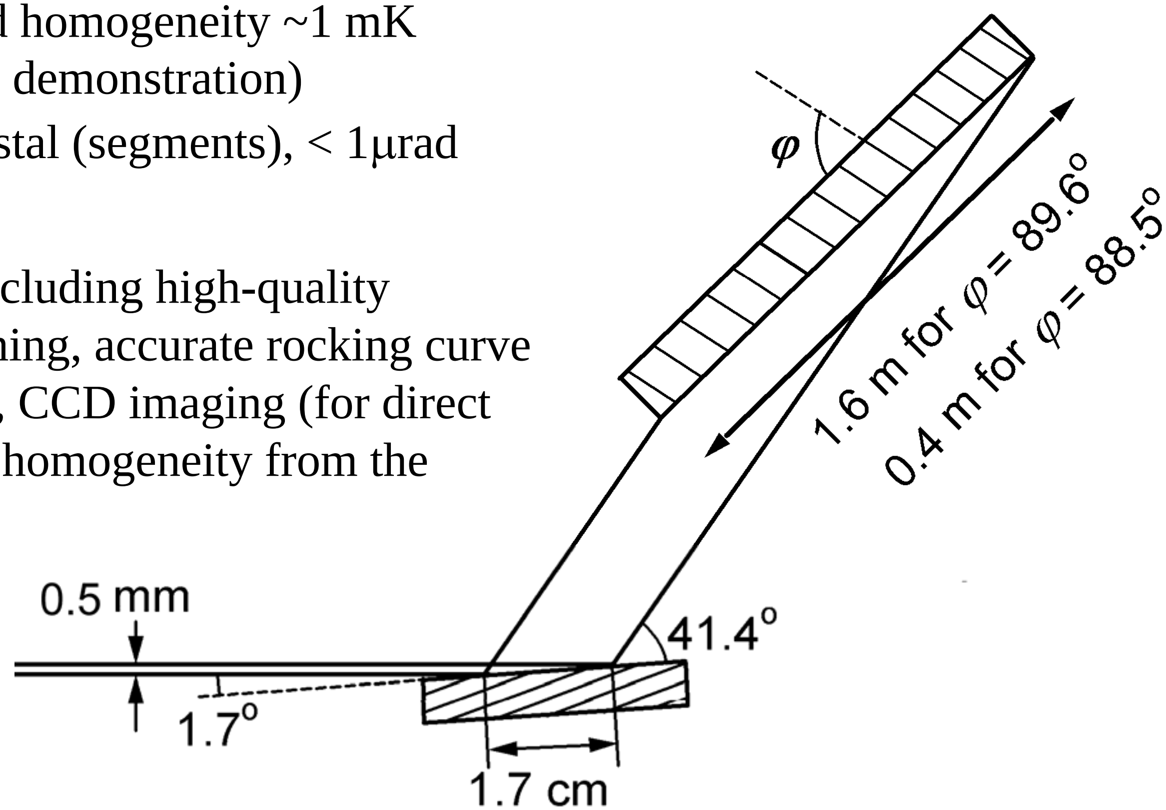
1. Thin crystals: not so challenging

2. Long (segmented) dispersing crystal

20-30 cm; In early developments < 20 cm

- 0.1 meV, $\Delta E/E \sim 10^{-8} \Rightarrow \Delta d/d \sim 10^{-8}$ Thermal coefficient of Si: $2.56\times10^{-6}\,K^{-1}$
  - $\Rightarrow$ crystal fabrication, lattice homogeneity (growth, doping)
  - $\Rightarrow$ temperature stability and homogeneity ~1 mK (achievable from Yuri's demonstration)
- No bending of the long crystal (segments), < 1μrad strain-free mounting

Needs detailed experiments, including high-quality crystals, high-precision machining, accurate rocking curve measurements and topography, CCD imaging (for direct visualization of the diffraction homogeneity from the surface).



Cont.

➤ Surface roughness and strains for grazing diffraction

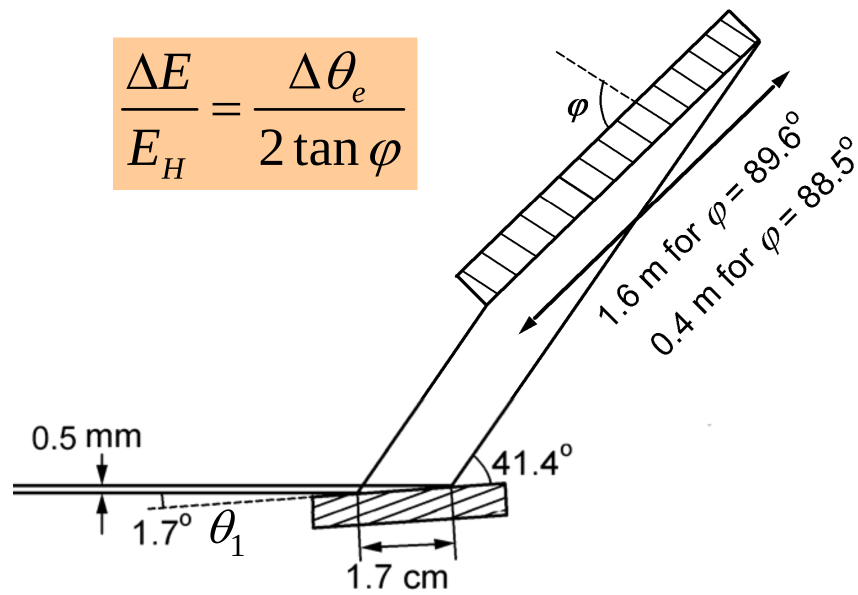
a. In non-grazing diffraction, our recent studies show for well-etched but not polished Si surfaces, RC width very close to theory. So roughness has little effect for non-grazing (but strains do!)

b. Calculations shows the thin crystal can tolerate local surface slope error $< \pm 0.05^{o}$. This is quite achievable.

c. Roughness of *D* crystal does affect the bandwith, particularly for grazing angle ~0.4^{o} ($\varphi = 89.6^{o}$).

d. Energy resolution depends on both φ and $\Delta\theta_e$. Make $\varphi = 89.2^{o}$ (well above the critical angle) and $\theta_1 = 0.7^{o}$ ($\Delta\theta_e \propto \theta_1$), resolution the same—long crystal not shortened, but extremely small grazing angles avoided, so roughness effect alleviated.

$$\frac{\Delta E}{E_H} = \frac{\Delta\theta_e}{2\tan\varphi}$$



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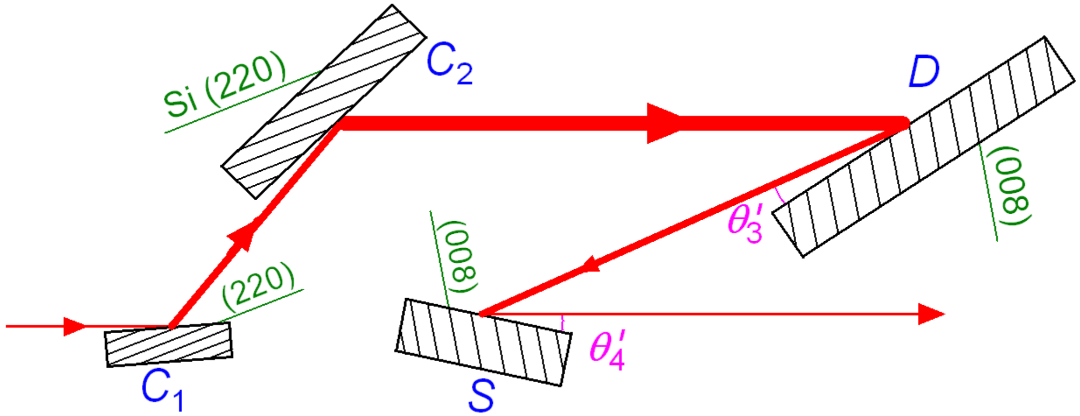
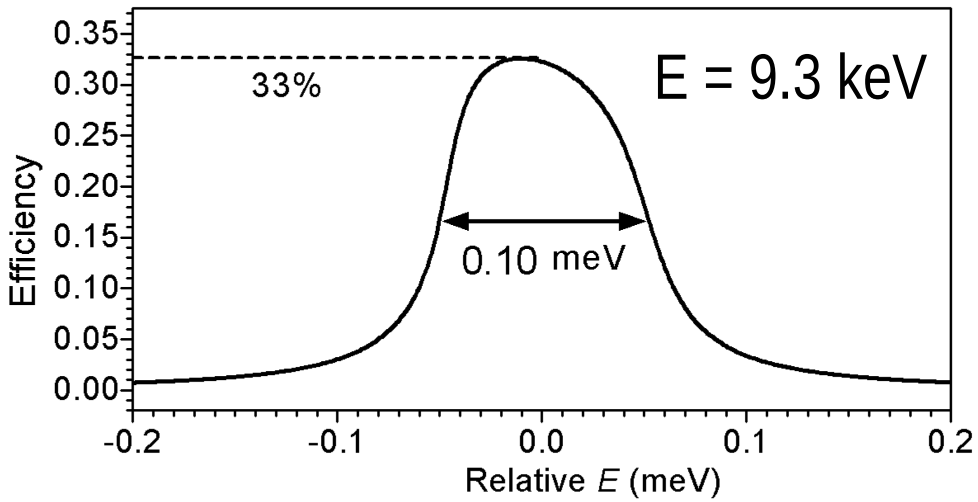
V. Alternative approaches of 0.1 meV

1. Four-bounce, for both mono and analyzer (Arbitrary energy)

$$\frac{\Delta\theta_e}{\Delta\lambda} = -\frac{\sin\varphi}{d\sin\theta_e}$$

Acceptance
> 100 μrad





More work is undergoing to optimize and to shorten the crystals

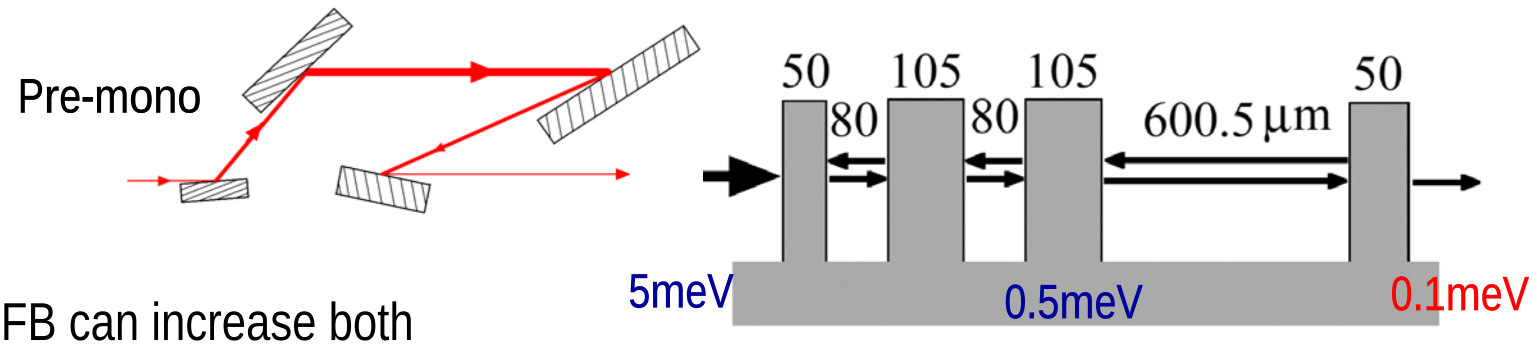
Cons:

- Long crystals not significantly shortened
- Efficiency less than CDDS.

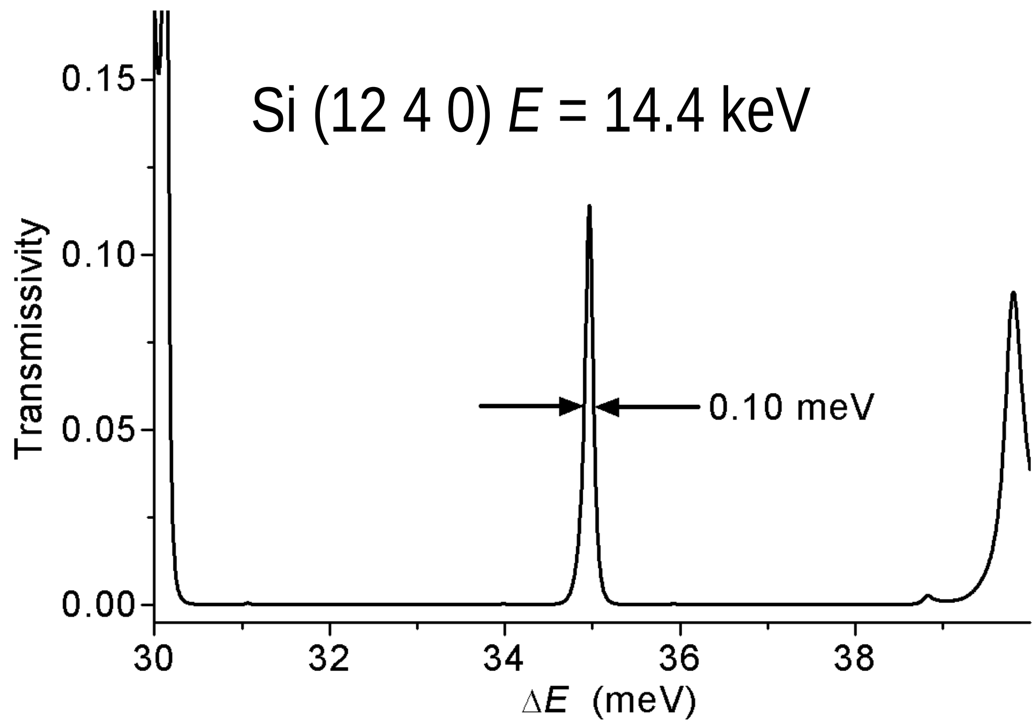
Pros:

- More flexible, many variants
- Avoid multi-beam diffraction
- **Arbitrary energy**

2. Multi-cavity Fabry-Perot Interferometer



- Multi-cavity FB can increase both Free Spectral Range and Finesse.
- Reduce bandwith from ~10 meV to sub-meV
- Pre-monochromatization not difficult.
- Ultra-component, single-component, powerful
- In principle, with no limit, → neV



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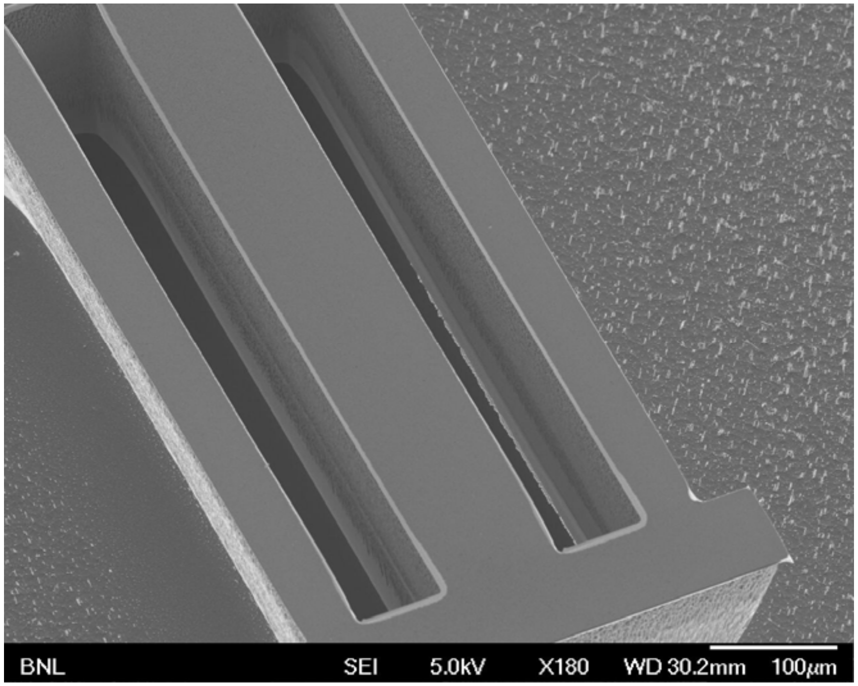
Fabrication of two-cavity FB

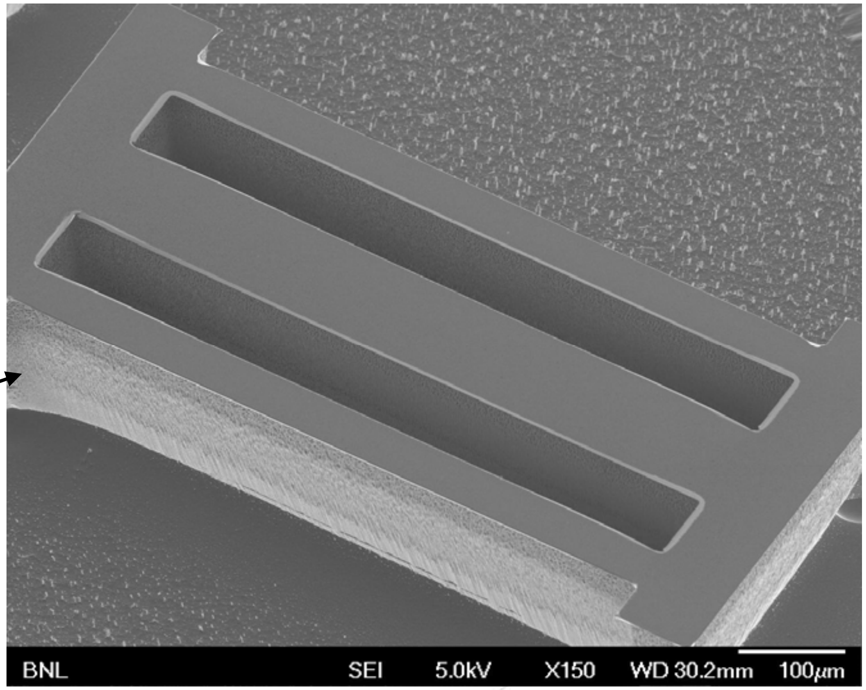
D. Peter Siddions, Ken Evans-Lutterrodt, Abdel Isakovic (NSLS).



Substantial undercut on the outside wall is largely corrected this time, without messing up the verticality of the inside wall.

Note that we etched deeper than 100 microns.

There is still some bowing near the corner of the structure, but there is a way to address that.



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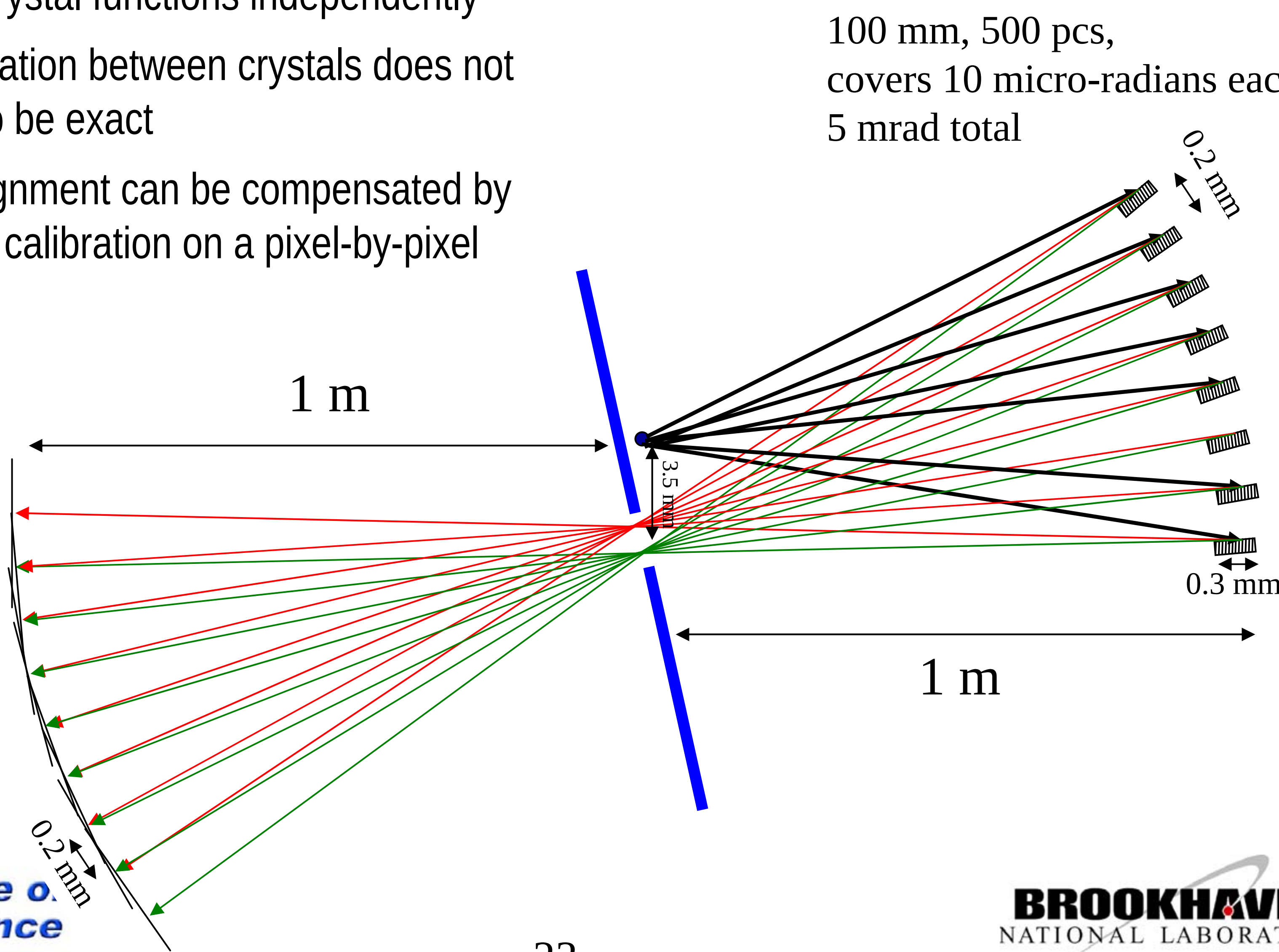
(to be tested)

3. Massive Parallel Approach

- Each crystal functions independently
- Registration between crystals does not need to be exact
- Mis-alignment can be compensated by energy calibration on a pixel-by-pixel basis



VI. 0.1 meV R+D Schedule

FY 07-08 (selected items) — achieve 0.7 meV

- Set up all the necessary facilities (monos, slits, detectors, CCD, motors etc) at X15A, NSLS
- Fabricate crystals and repeat Shvyd'ko's experiment, 0.7 meV
- Set up temperature-controlled chambers for long dispersing crystals and repeat 0.7 meV
- Test Bormman effect of and optimize redesigned thin crystals, repeat 0.7 meV
- Crystal characterization to check crystal quality and its influence
- Start testing the inline scheme to achieve 0.3 meV resolution

- Dynamical theory calculations of the design (already mature, but to help simulate experiments and optimize designs.)
- Dynamical theory calculations of alternatives (interferometer, four-bounce, multi-crystal analyzer), concentrating on applicability as analyzer

FY 09 — achieve 0.3 meV, move toward 0.1 meV prototype

- Full work on the forward inline CDDS mono to achieve 0.3 meV resolution (using the backward CDS analyzer), small-scale
- Detailed explore crystal quality (defects, impurities, inhomogeneities)
- Detailed study of fabrication issues (figure error, roughness)
- Detailed explore temperature control
- Increase asymmtric angle and elongate crystals for testing 0.1 meV resolution prototype optics (small scale with limited flux)

- Determine appropriate focusing and collimating mirrors
- Test four-bounce design (small scale with limited flux)
- Develop and test of Fabry-Perot interferometry and other alternatives undergoing parallel

FY10-FY11

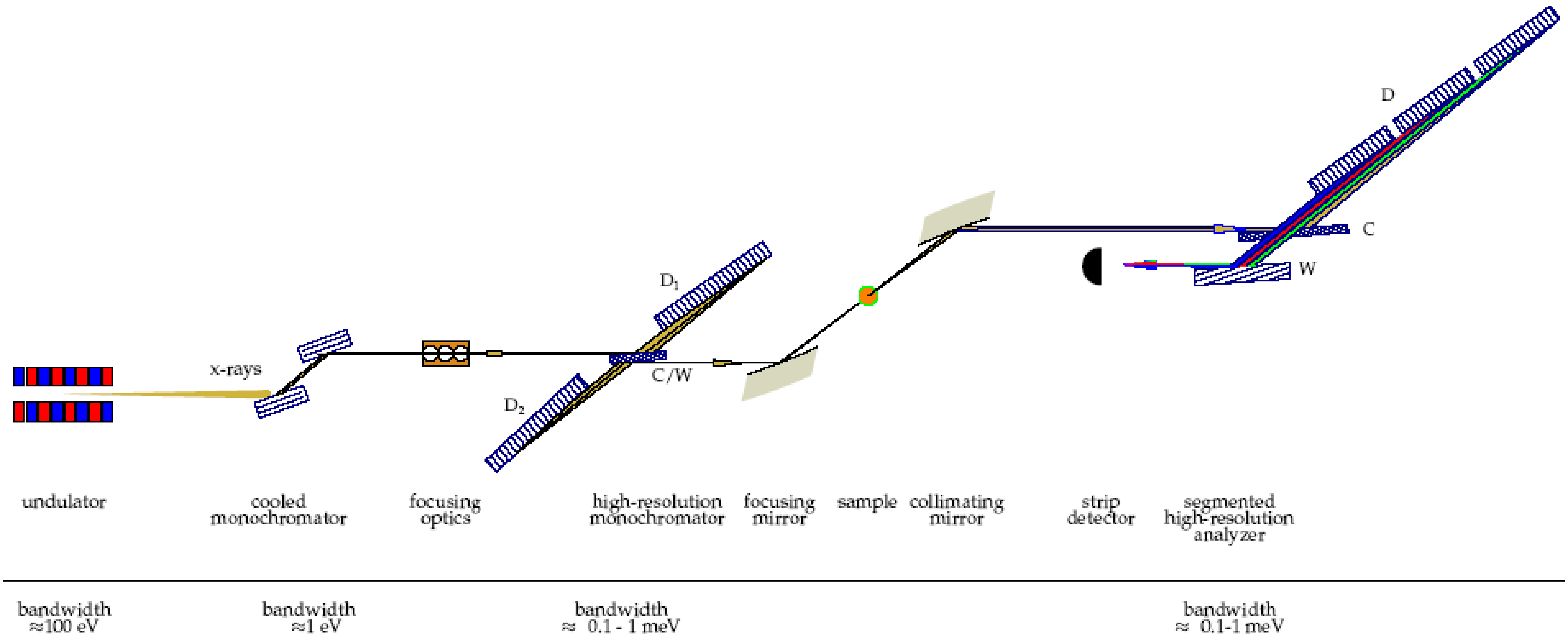
FY10

- Full test of small-scale 0.1 meV optics with limited flux
- Design and test of focusing and collimating mirrors
- Engineering design of full-scale 0.1 meV spectrometers
- Design and develop engineering solutions for adequate temperature homogeneity and control for full-scale 0.1 meV optics
- Test small-scale segmented CDS analyzer

FY11

- Fabrication of large-scale 0.1 meV spectrometer components, quality test
- Test large-scale 0.1 meV segmented analyzer (maybe at APS)
- Test of alternative full-scale multi-crystal analyzer prototypes

Full-scale 0.1 meV spectrometer



0.1 meV R&D Milestones

FY 08

Design of prototype CDS internally reviewed
Dynamical theory calculations of the design performed
Dynamical theory calculations of the alternative multi-crystal design performed
Achieve 0.7 meV prototype

FY 09

Report on fabrication issues (figure error, roughness) in limiting resolution and flux
Report on effects of crystal quality (defects, impurities, inhomogeneities)
Focusing mirror designed and reviewed
In-line monochromator optics fabricated
Achieve 0.3 meV prototype

FY10

Design for crystal environment reviewed
First test of focusing mirror performed
First test of monochromator optics performed
Achieve small-scale 0.1 meV prototype

FY11

First test of segmented CDS analyzer performed
First test of alternative multi-crystal prototype performed