Optimizing the Generation of High-Energy X-Rays at the APS

(50 - 120 keV)

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- our present source (APS undulator A)
- our current optics
- optics under development
- towards optimized high-energy insertion devices

Advanced Photon Source

Present Source - APS Undulator A
(wiggler-like at high energies)

Orbit parameters:

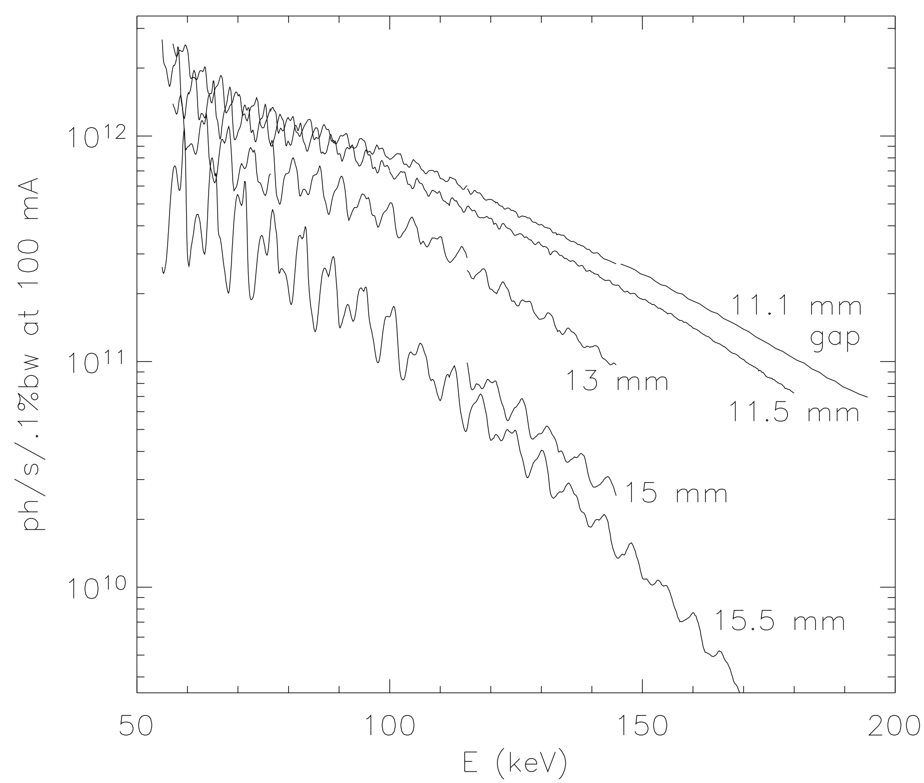
ε_x = 3 nm rad $\quad\quad$ $\varepsilon_y / \varepsilon_x$ = 1 %

σ_x = 270 µm $\quad\quad$ $\sigma_{x'}$ = 11 µrad

σ_y = 9 µm $\quad\quad$ $\sigma_{y'}$ = 3 µrad

σ_E / E = .001

Measured flux through 1x1 mm^2 aperture at 60 m



X-ray divergence:

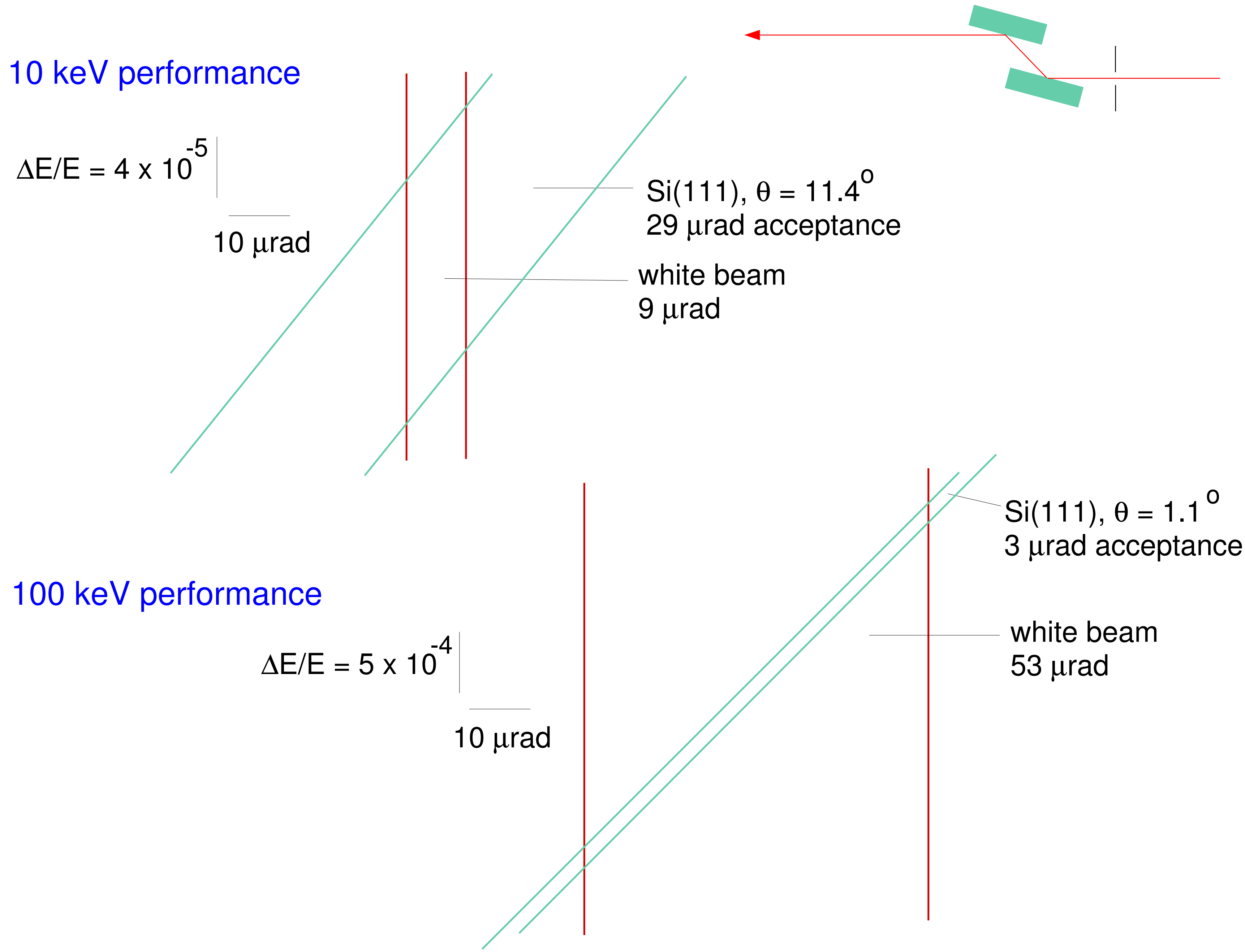
wiggler-like means $\Delta\theta \sim K/\gamma$, $1/\gamma$
and not $2.35\,\sigma_{x'}$, $2.35\,\sigma_{y'}$

At 80 keV, $\Delta\theta$ = 230 µrad , 55 µrad

For the "brilliance-obsessed":

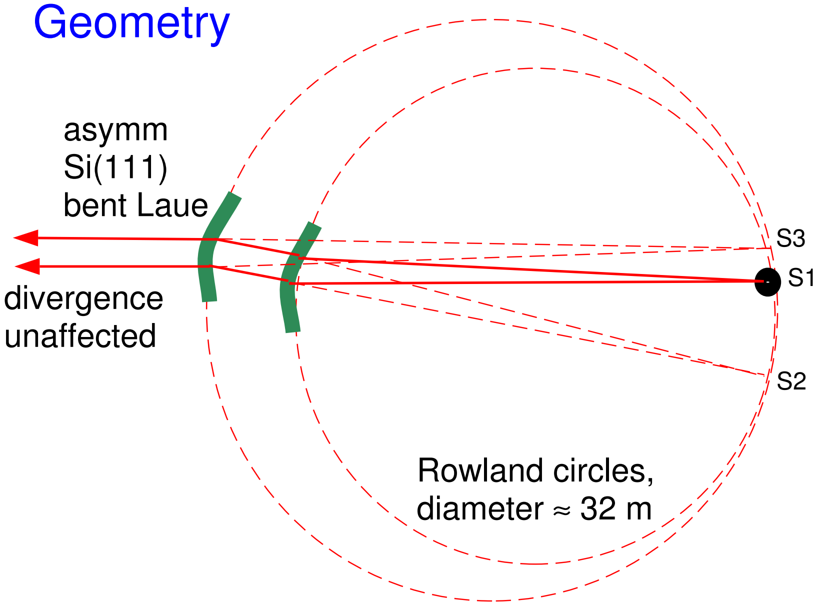
$$\underset{(1/\text{mm}^2\ 1/\text{mrad}^2)}{\text{on-axis brilliance}} = (2.7 \times 10^5) \times \underset{(1/\text{mm}^2)}{\text{on-axis intensity at 60 m}}$$

Flat, Perfect Si(111) Monochromator in APS Undulator A Beam



Bent Double-Laue Monochromator for High Energies

Geometry



Properties:

- cryo-cooling, no filtration-induced flux sacrifice at closed ID gap
- high flux, e.g., $>10^{12}$ ph/s in 1x1mm aperture at 60 m at 80 keV
- brilliance preserving (unlike mosaic monochromators)
- fully tunable (unlike single-reflection schemes)
- in-line, fixed exit (unlike single-reflection schemes)
- over 10 times more flux than flat crystals, but **without increased energy spread** ($\Delta E/E=10^{-3}$)

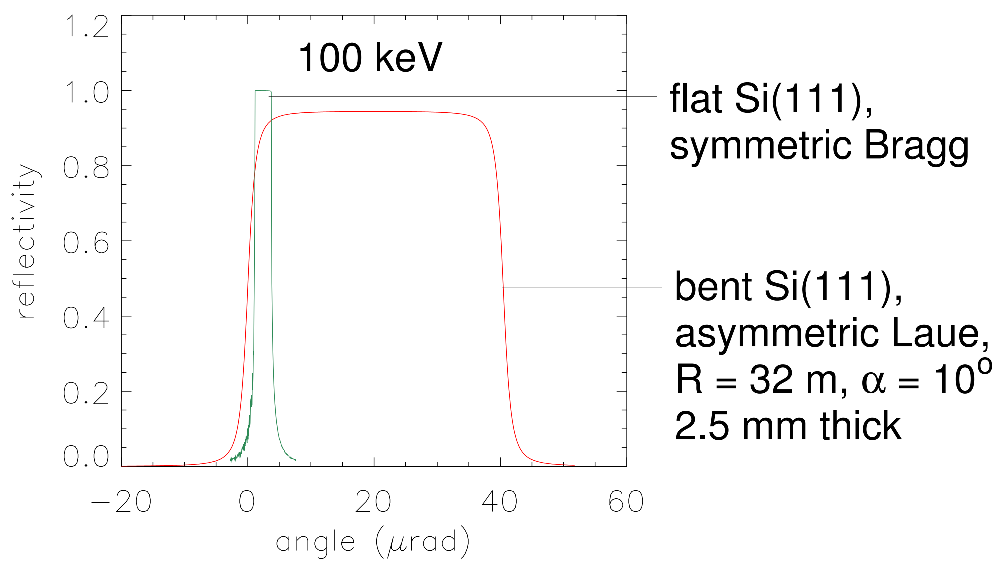
Over 10 Times Flux, but Energy Width Unchanged

$$\Delta E/E = \cot\theta \sqrt{\Delta\Theta inc^2 + \Delta\Theta acc^2}$$

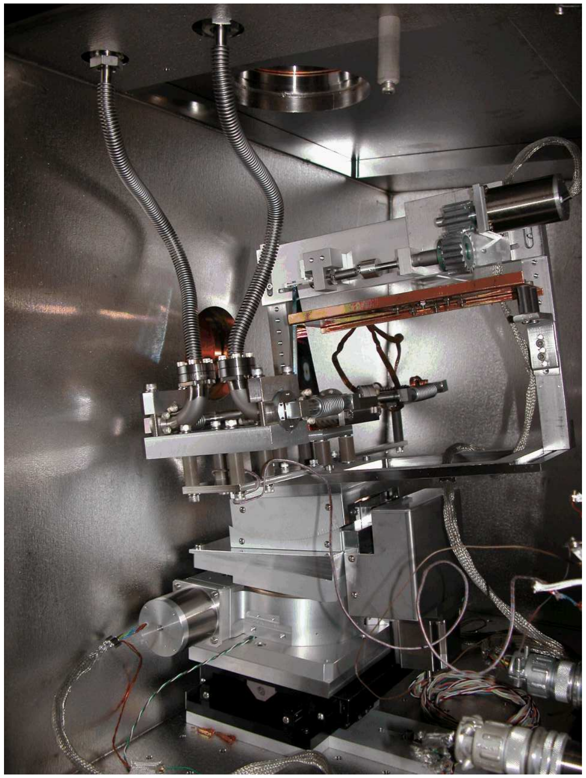
2.8 μrad → 40 μrad

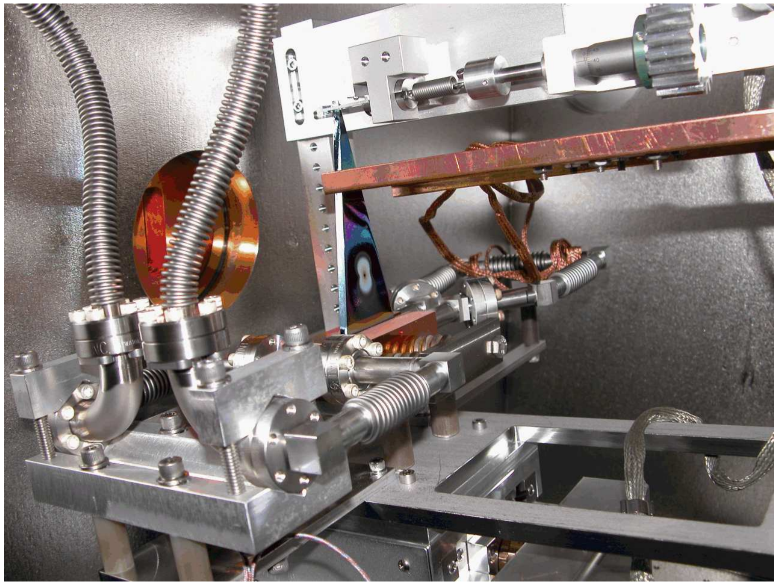
53 μrad → 1.6 μrad

2.5×10^{-3} → 2.0×10^{-3}



First Laue Crystal (cryo-cooled, in-vacuum)



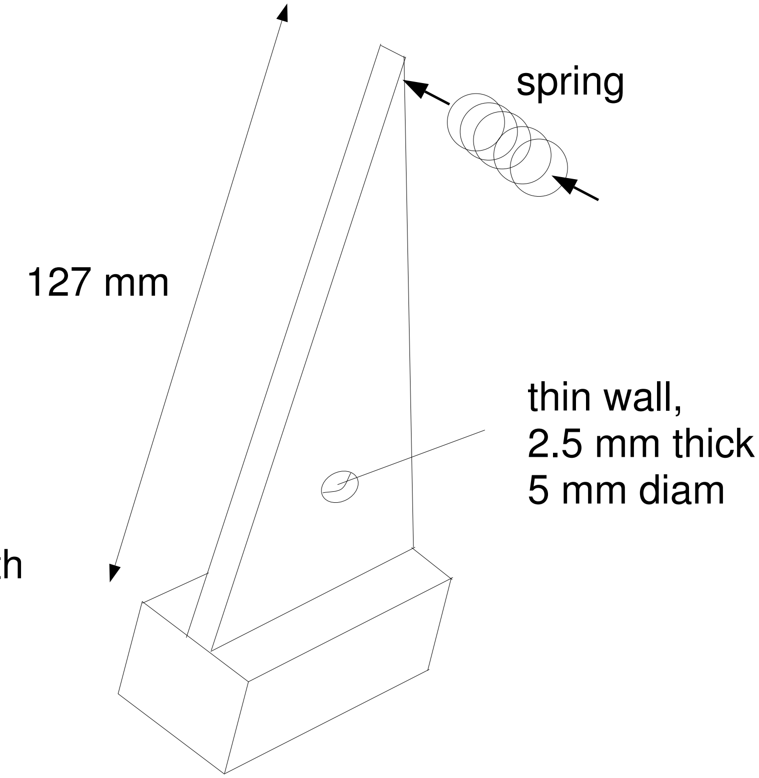


- Both crystal benders employ nearly-constant force (as opposed to displacement) for achieving ultra-stable bend radius (months - years)

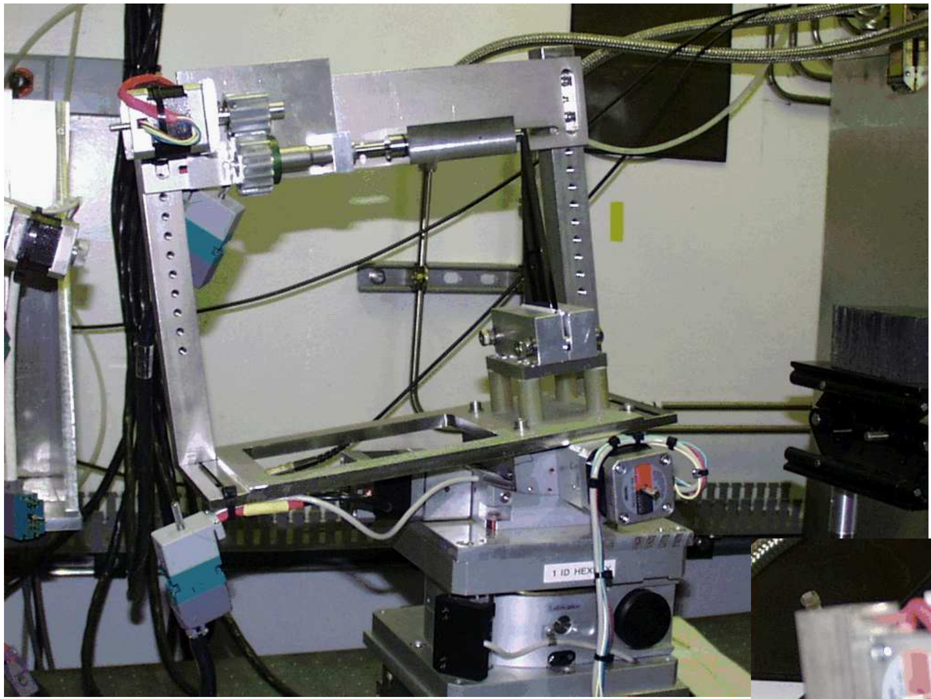
- μrad stability (~ few eV at 80 keV) plumbing design at 4 - 5 L/min LN2 flow

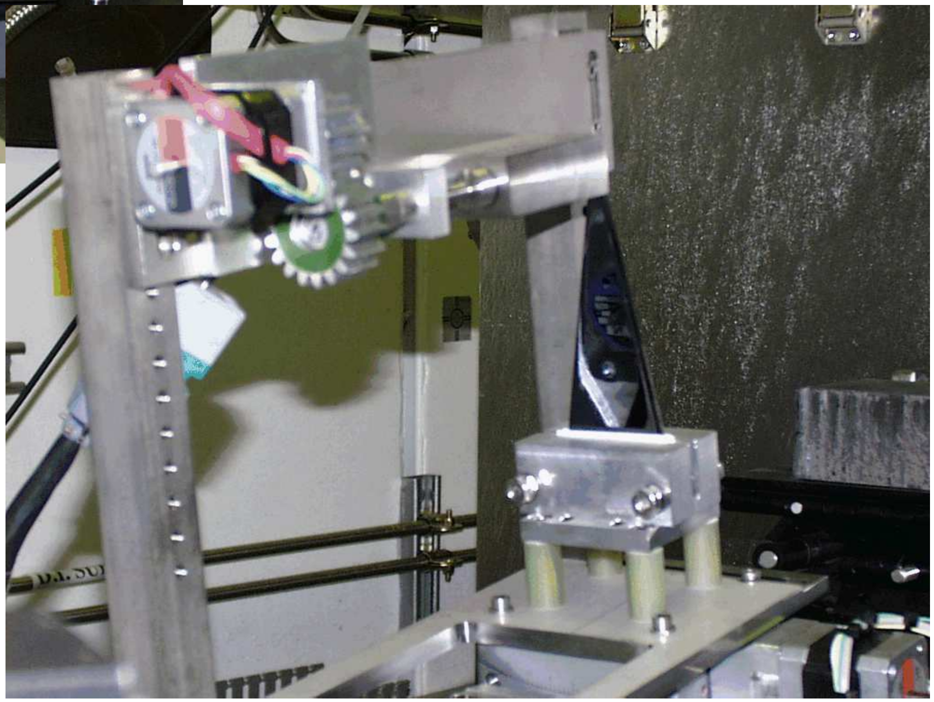
- Diffraction through thin wall (this leaves crystal stiff, with good thermal properties, and avoids spring change)

- Twist-free bending



Second Laue Crystal (in air)

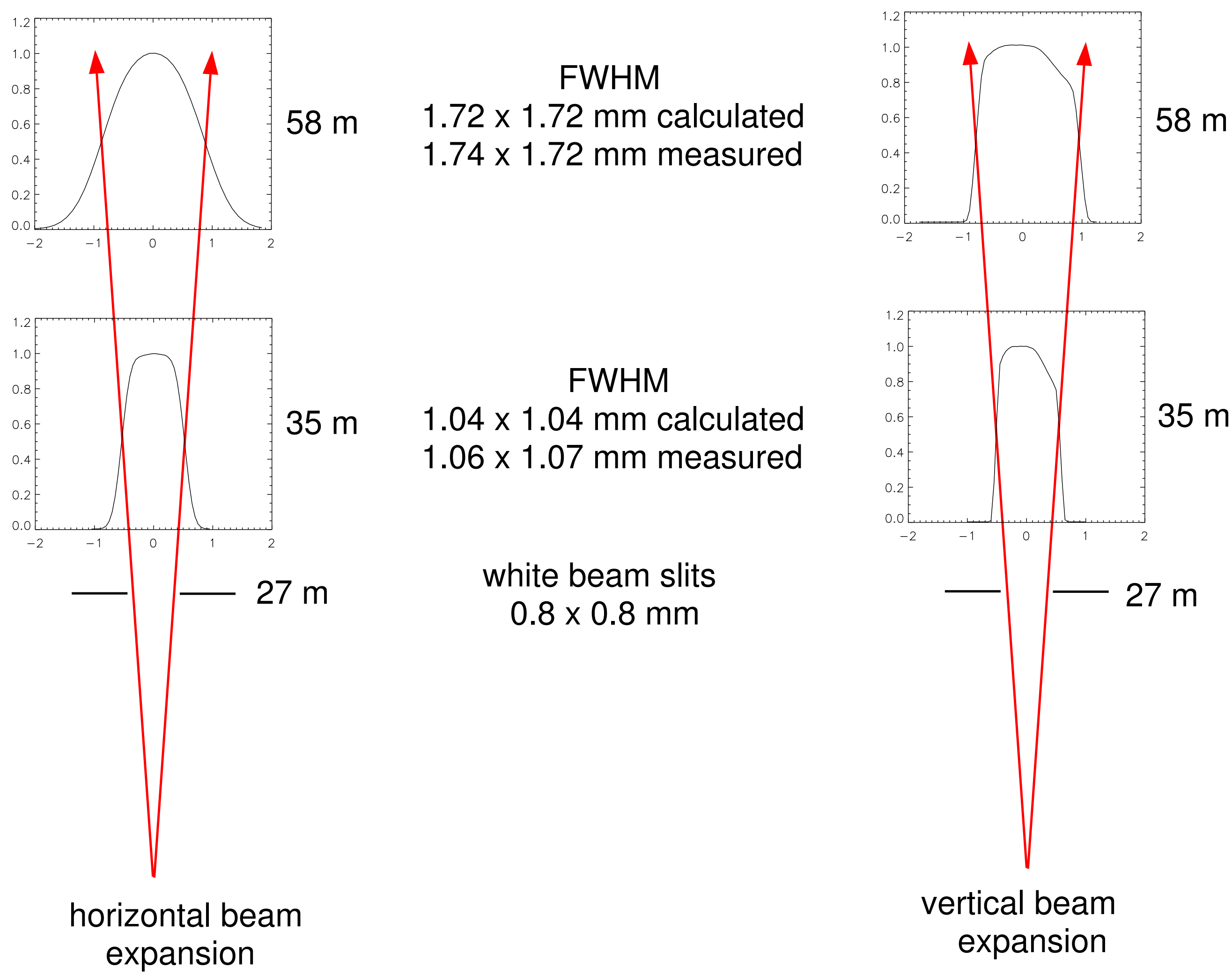




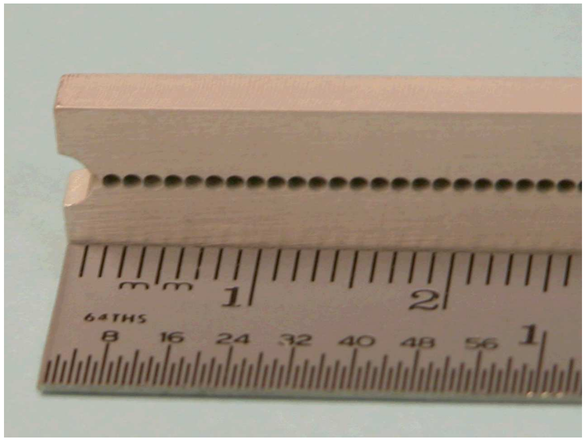
Brilliance-Preservation of (Pre-)Monochromator

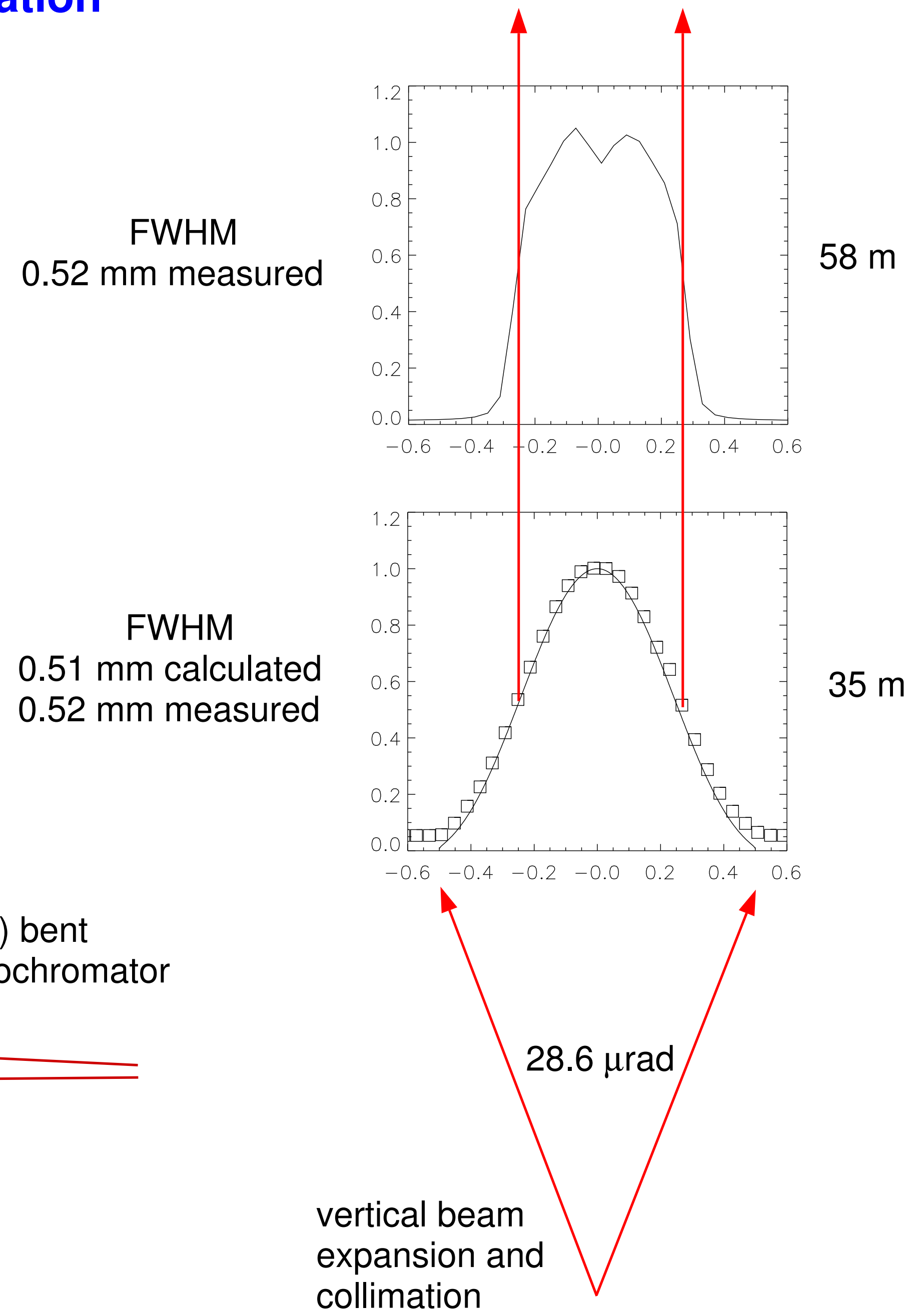
Successful post-manipulation of beam with additional optics requires that the bent double-Laue premonochromator is brilliance-reserving. Study of beam expansion/propagation with distance indicates divergence-preservation at the few (1-2) μrad level.

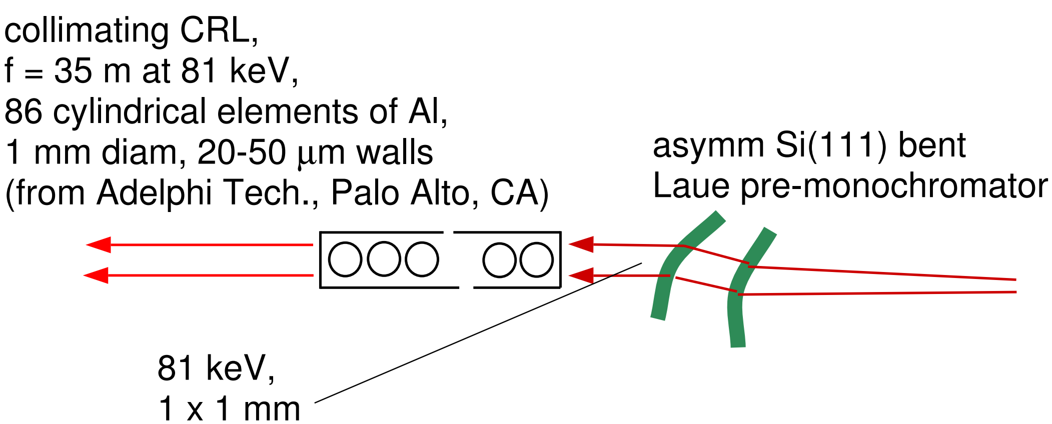
Mono set to 81 keV (location 32 m from source)



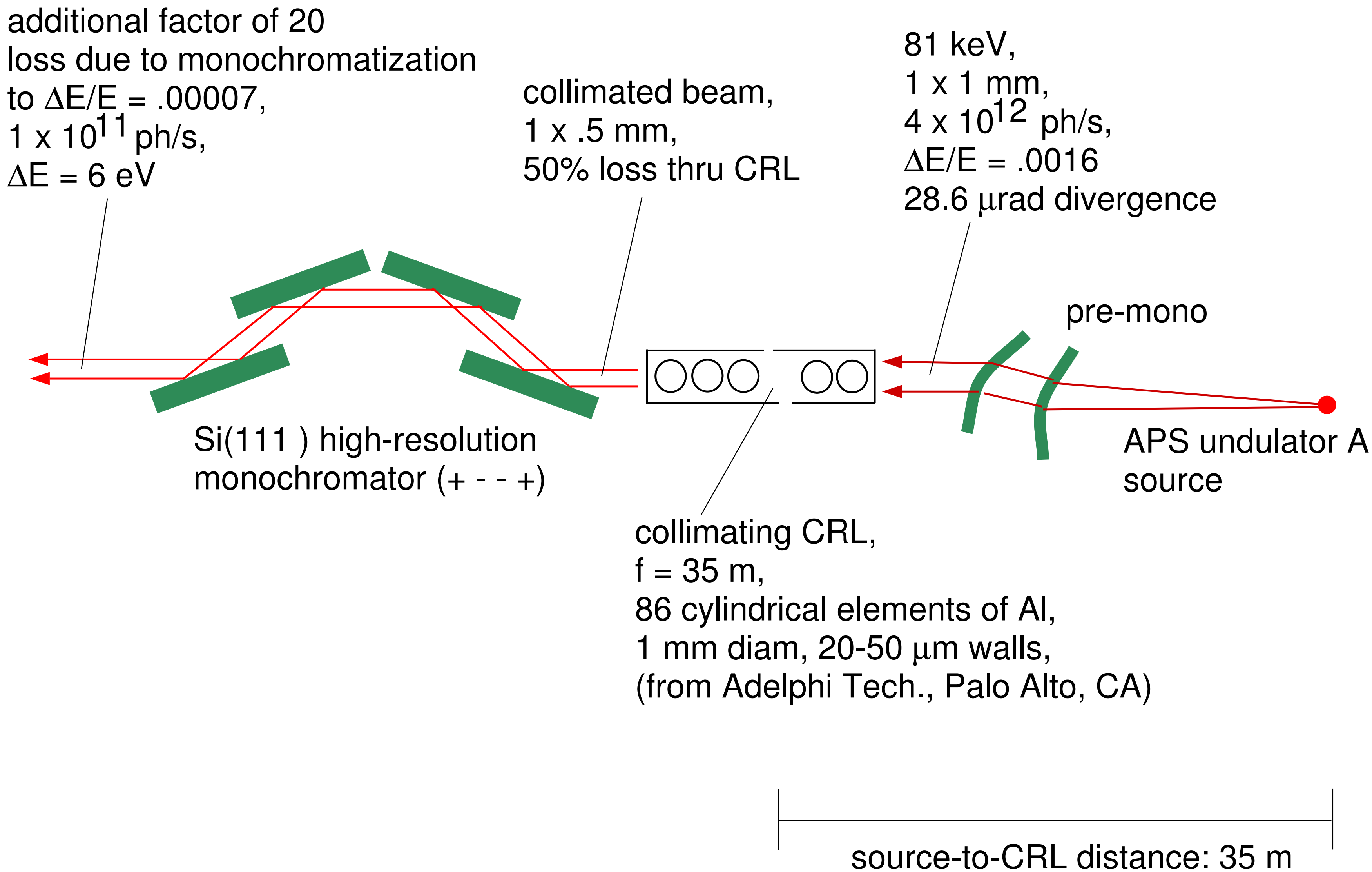
CRL Collimation



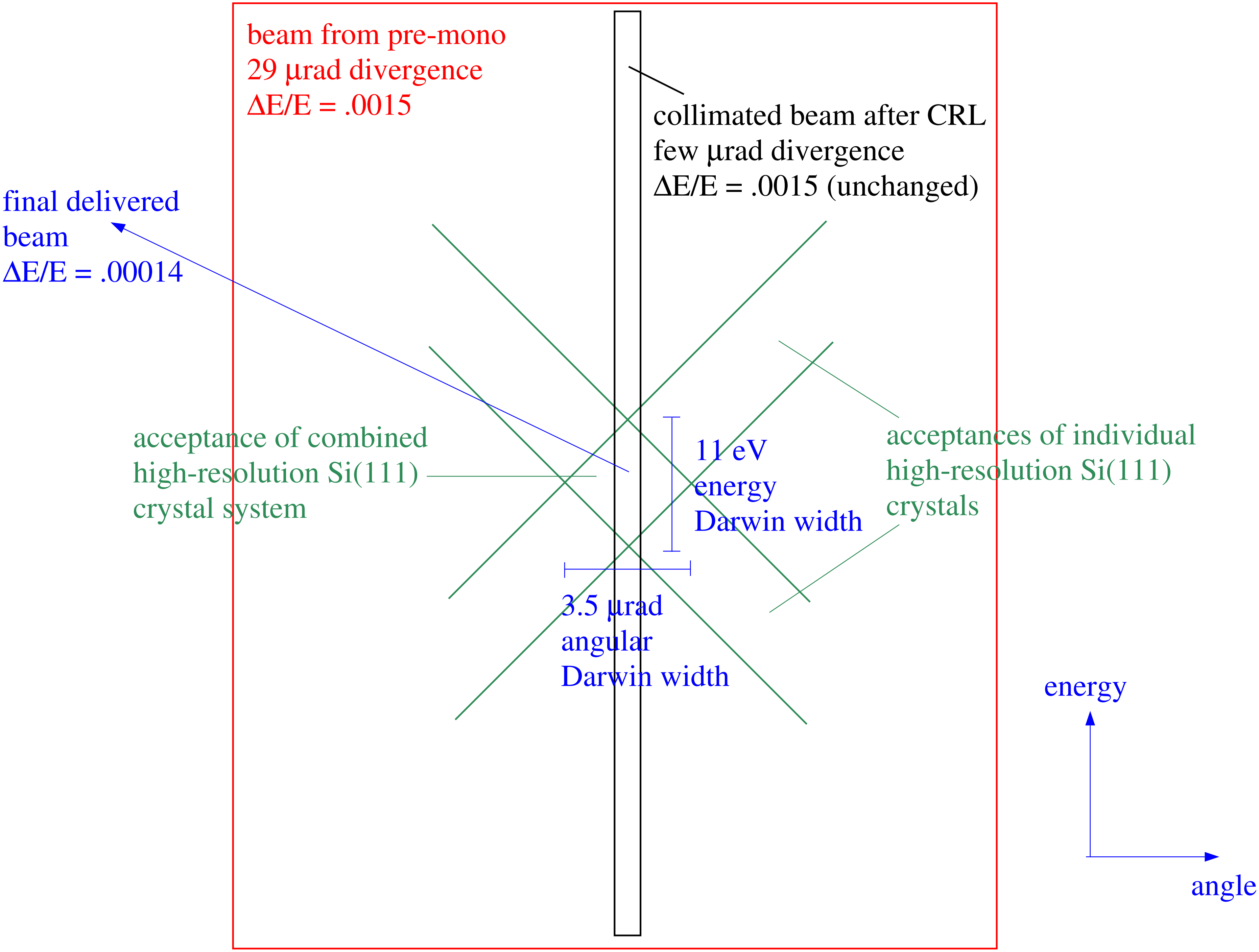




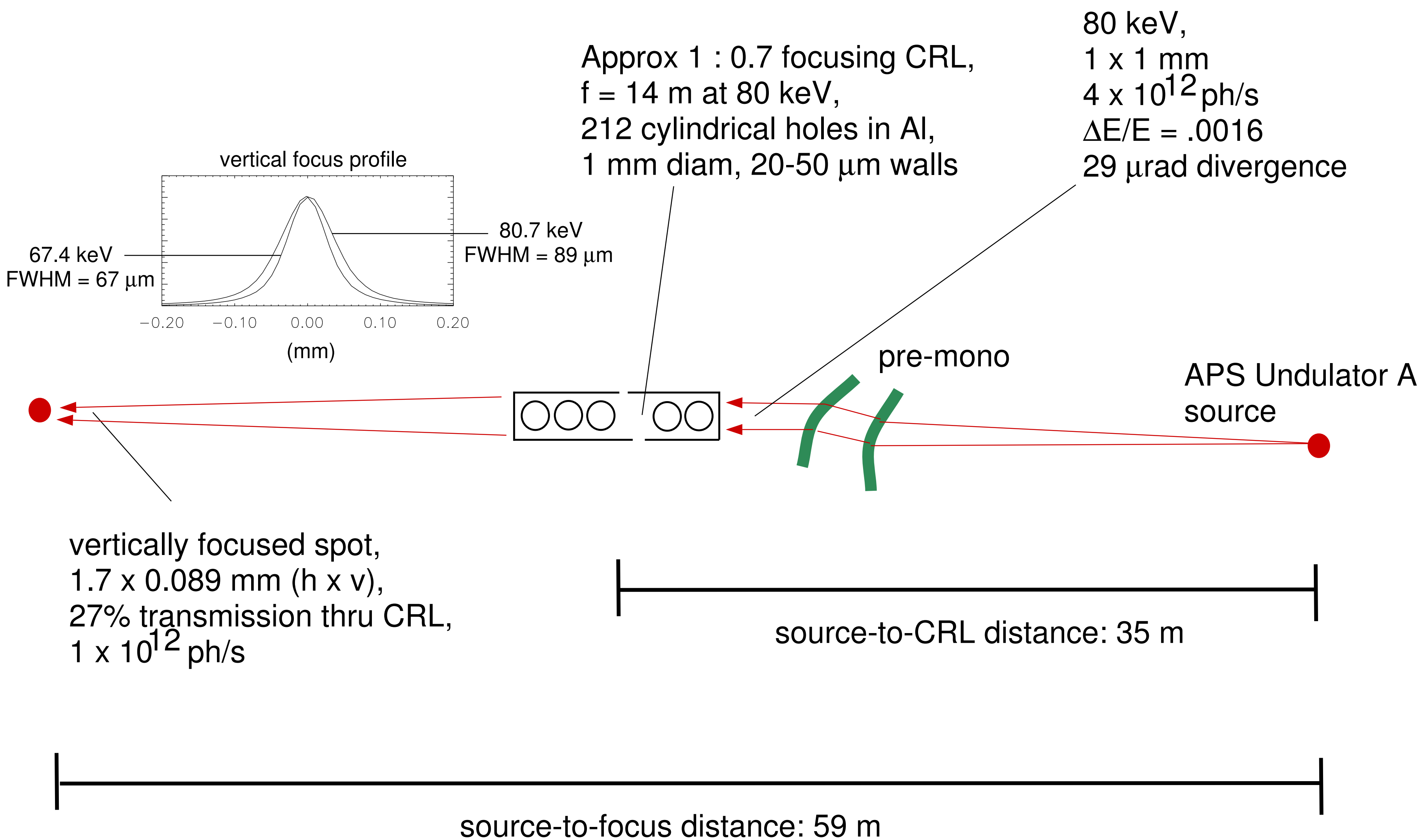
Higher Energy Resolution (80 keV)



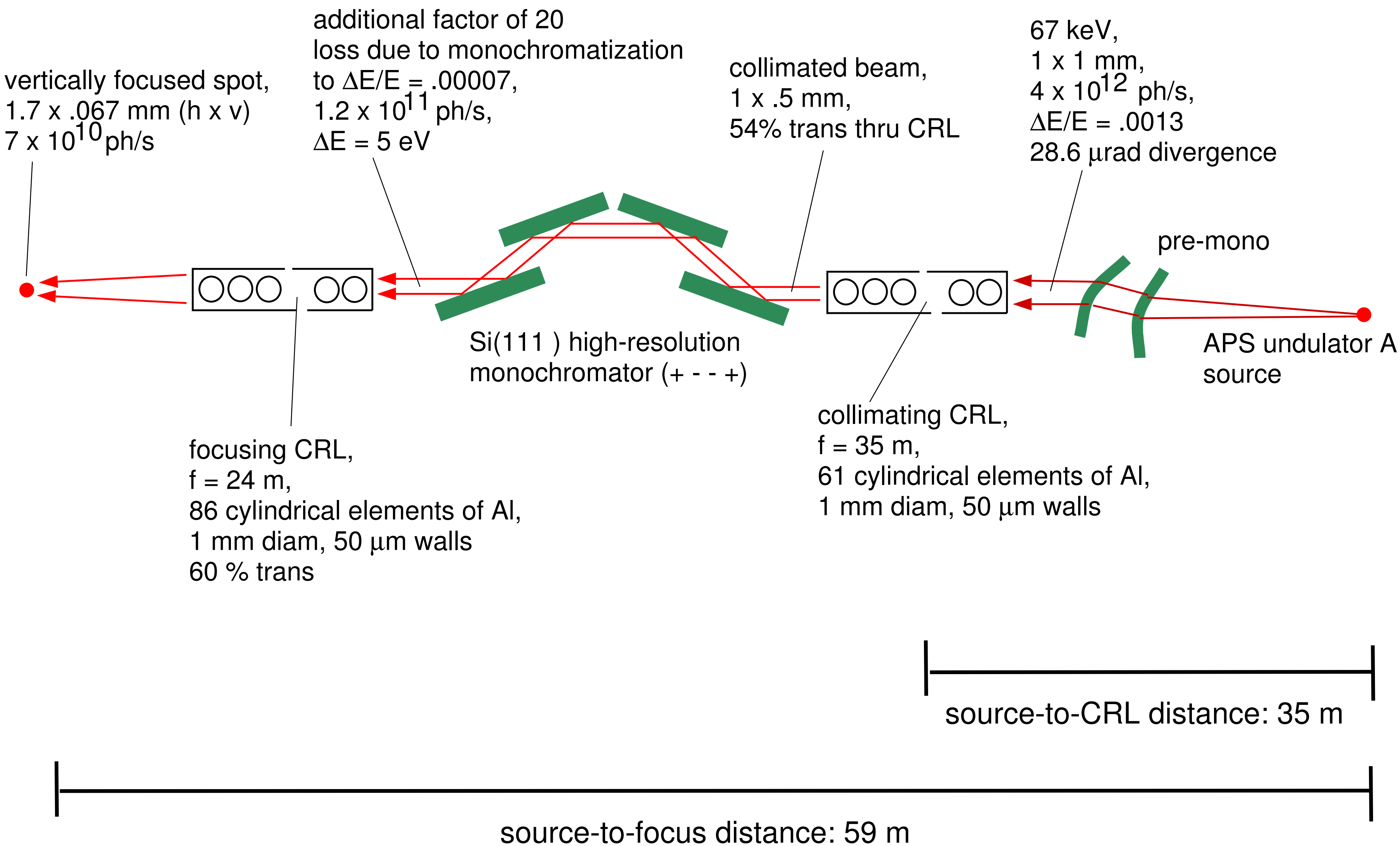
DuMond Representation of Optics (to scale)



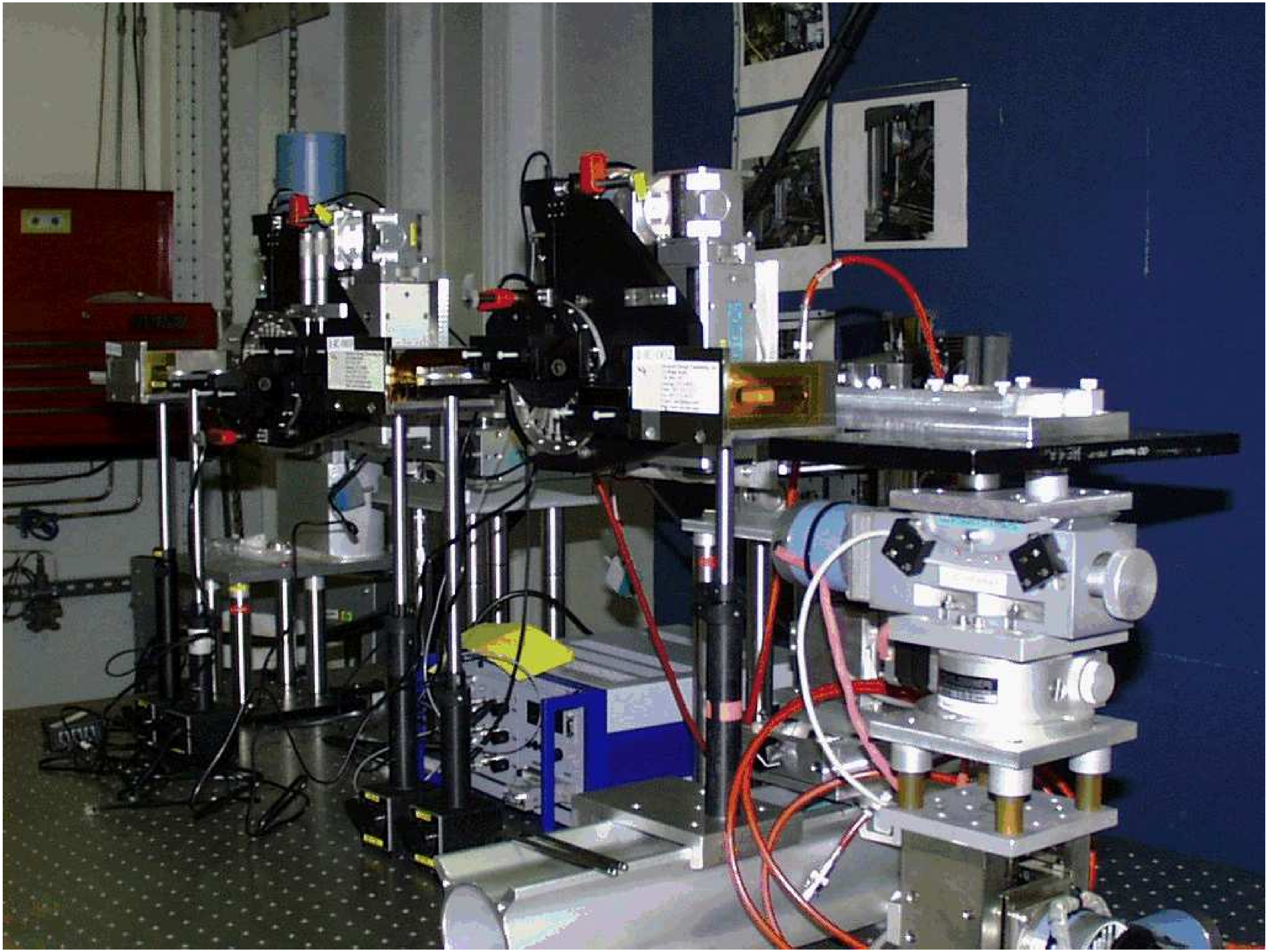
Approximately 1:1 Focusing with a CRL (60 - 80 keV)



Combining All: Collimation, High Energy Resolution, Focusing (67.4 keV)



High-Resolution Setup (looking downstream)

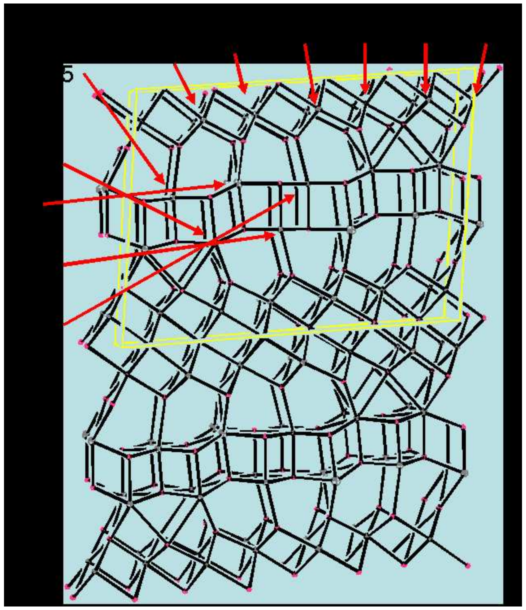


Resonant X-Ray Scattering and Pb and Bi K-edges (88 - 91 keV)

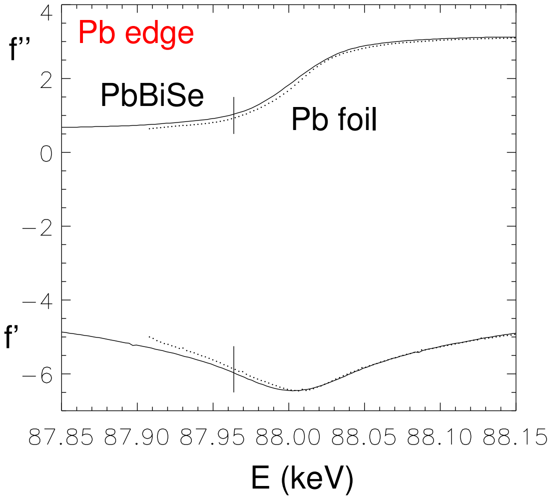
Example: Determine Pb/Bi distributions in chalcogenide thermoelectrics,
- A. Wilkinson (Georgia Inst. of Tech.), P. Lee, Y. Zhang (APS)
- $Pb_5Bi_6Se_{14}$, $CsPbBi_3Te_6$, a-$CsPbBi_2Se_6$

Resonant (i.e., "anomalous") scattering is a good approach, but L-edges are difficult for Pb and Bi due to preferred orientation and poor sampling statistics when high absorption is present.

Determination of 11 Sites



Kramers-Kronig transformation results:



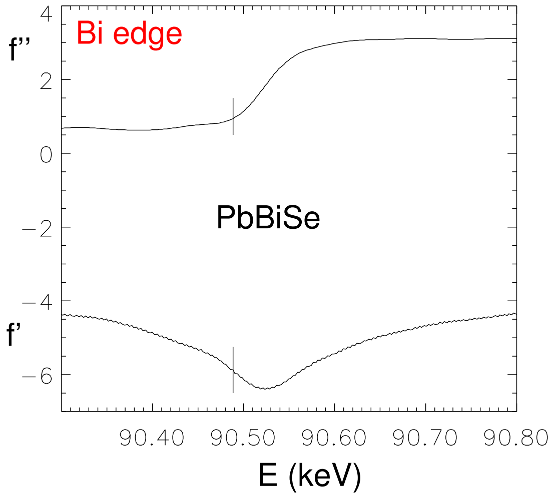
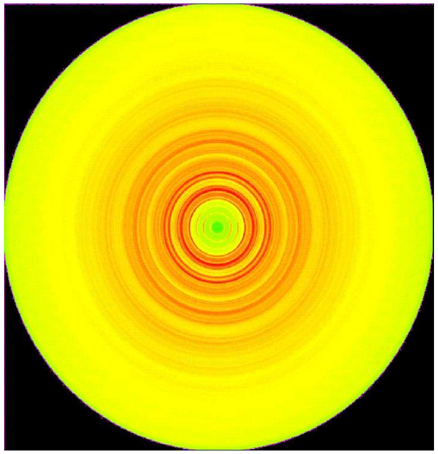
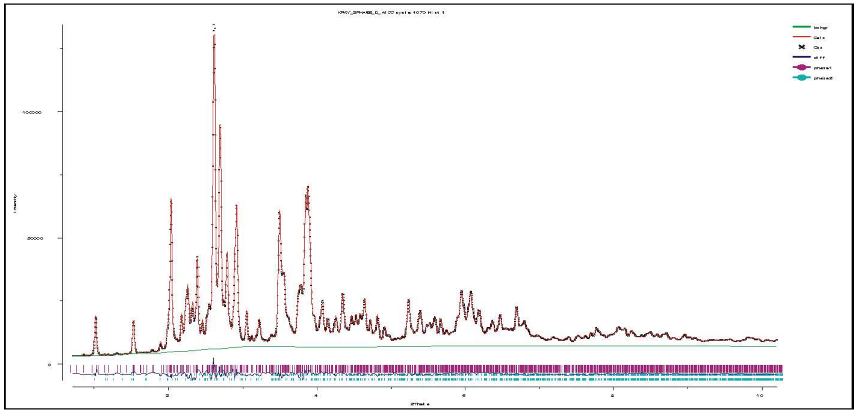
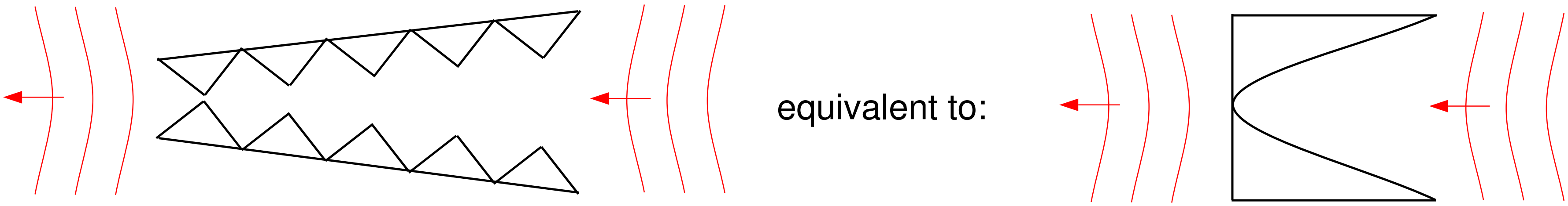


Image Plate ~ 10 s





Canted Sawtooth Lenses

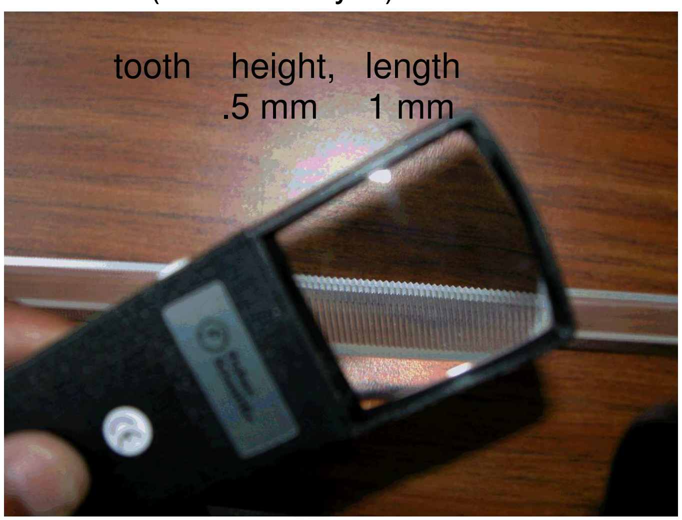


Essentially a "half-element" refractive lens that is:

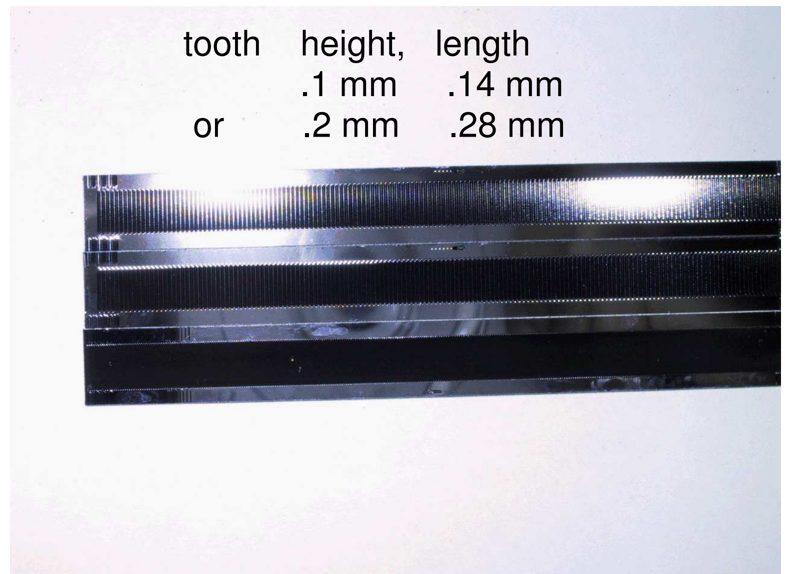
- parabolic
- tunable (by adjusting canting angle)
- unity on-axis transmission (no walls)
- no small-angle scattering halo (from single crystal Si)

Cannot ask for much more.

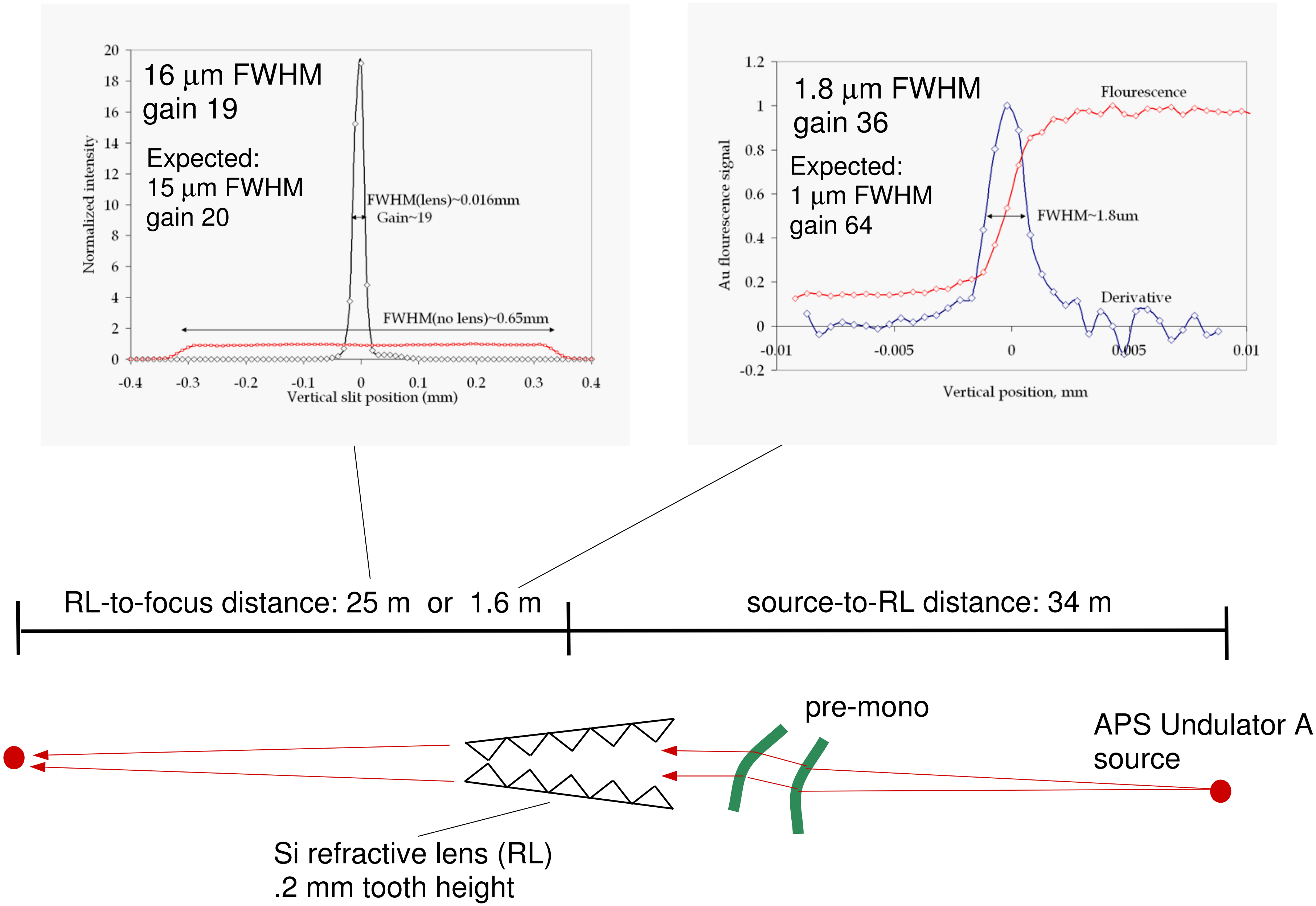
Plastic (molded acrylic) sawtooth lenses



Si (single crystal) sawtooth lenses from
C. Ribbing, B. Cederstrom (Sweden)

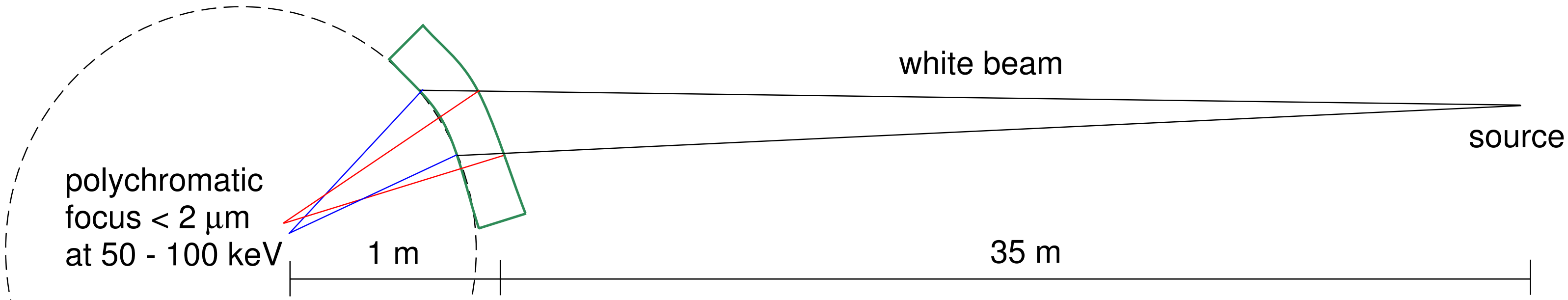


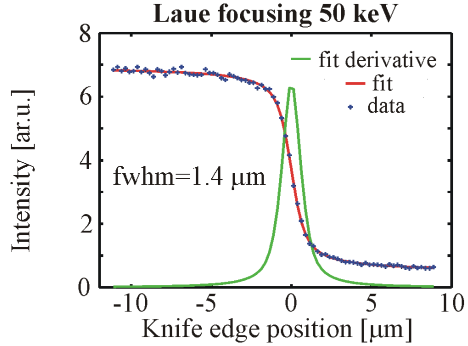
Focusing Results - Si Sawtooth Lenses (w/ J. Almer)



More High-Energy Micro-Focusing (U. Lienert)

Single Bent Laue Crystal

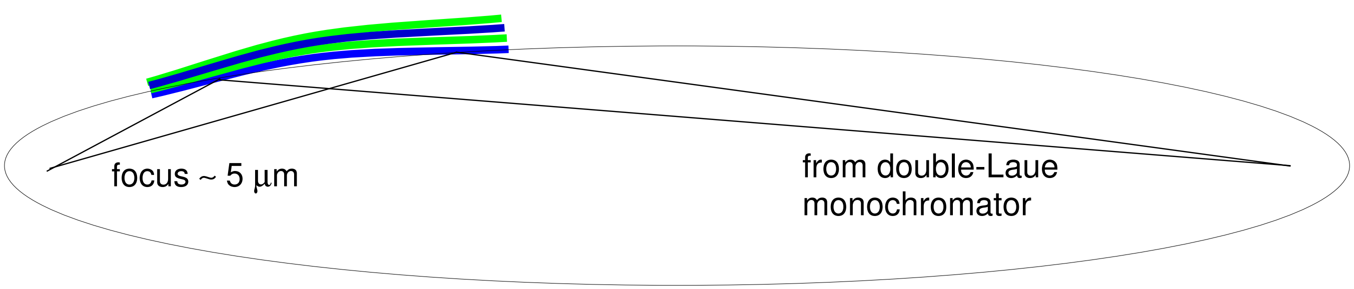




Normally, different crystal lamellae do not focus to the same spot (Laue aberrations). However, correct choice of asymmetry can make all lamellar foci coincide, achieving aberration-free focus.

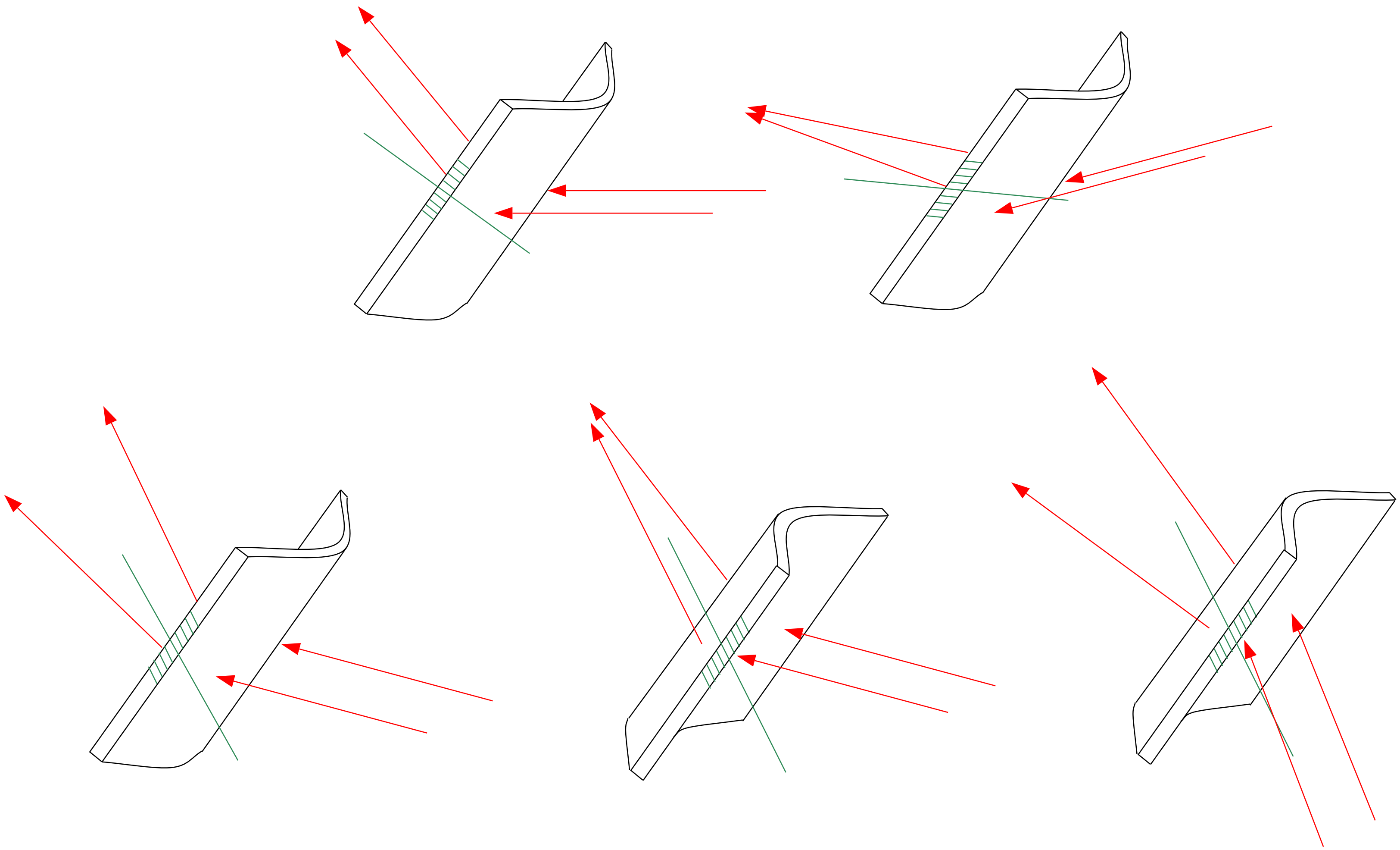
Bent Multilayers, Super-mirrors

K-B pair possible:
300 mm long, 24 A d-spacing
elliptically bent and meridionally graded in d-spacing
also, **super-mirrors** - depth graded in d-spacing (fixed exit)



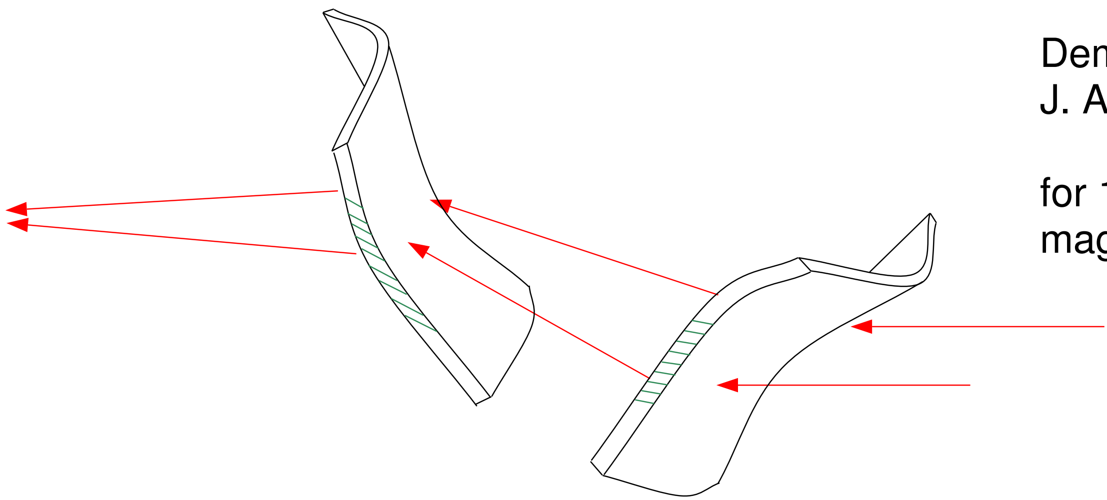
Sagittal Laue Focusing of ~ K / γ Horizontal Fan

Focusing with sagitally bent Laue crystals requires asymmetrical cut.



Reversal of asymmetry sense flips focusing to defocusing. So does reversal of bending sense.
And so does changing beam incidence from "above" to "below".

Use Anticlastic Effect for the Simultaneous Meridional (Rowland) Bending?



Demonstrated by Zhong at al.,
J. Appl. Cryst. **34**, 504-509 (2001)

for 15 - 50 keV at NSLS bending magnet beamline

Problems with implementing the above in our case:

- cryogenic cooling and heat-load on 1st Laue crystal
- opposite asymmetries of two crystals does not preserve brilliance
  (Laue thickness aberrations are not double-reflection-compensated)

So have 2nd crystal do all the horizontal (sagittal) focusing. But challenge here is:

- very small sagittal radius (even at high asymmetry), exacerbated even more by "real" high energies (50 - 110 keV).

  Rsag ≈ .4 m   whereas   Rmer ≈ 50 m
- Rmer / Rsag ≈ 100 puts us out of the range of typical anticlastic bending ratios in Si.

- hence, need to actively/independently control both radii.
- elasticity and bent-crysal dynamical diffraction simulations in progress.

Beam Sizes: APS UA vs a True High-Energy Undulator

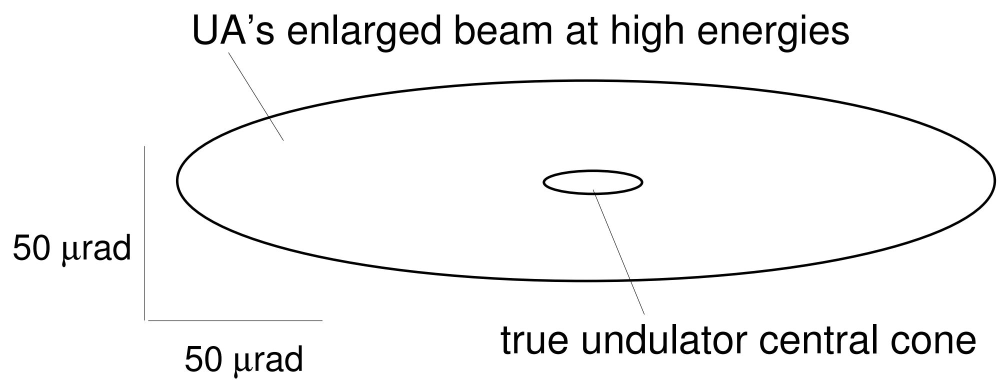
Orbit parameters:

ε_x = 3 nm rad $\quad$ $\varepsilon_y / \varepsilon_x$ = 1 %

σ_x = 270 μm $\quad$ $\sigma_{x'}$ = 11 μrad

σ_y = 9 μm $\quad$ $\sigma_{y'}$ = 3 μrad

σ_E / E = .001



Undulator A's wiggler-like divergence:

Wiggler-like means $\Delta\theta \sim K/\gamma$, $1/\gamma$
and not $2.35\,\sigma_{x'}$, $2.35\,\sigma_{y'}$

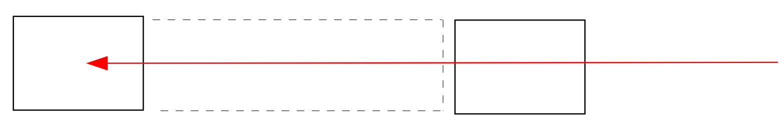
At 80 keV, $\Delta\theta$ = 230 μrad , 55 μrad

$$\text{size ratio} = \frac{(230)\,(55)}{(2.35 \times 11)\,(2.35 \times 3)} = 69$$

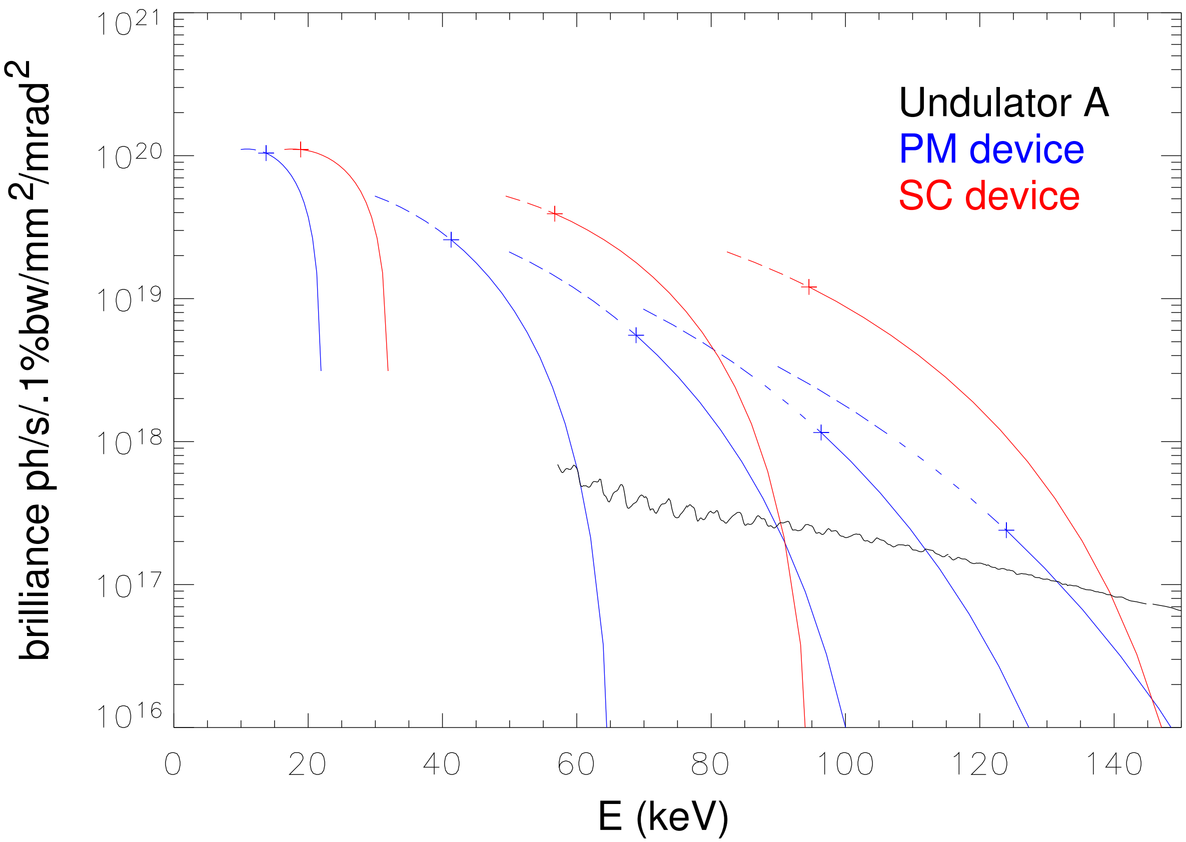
Impact of true undulator over UA

If focusing ~1/6 of the UA beam is feasible (1/2 x 1/3), then flux-driven experiments using modest-sized beams (i.e., > 200 x 50 μm) on sample will not benefit from a true undulator unless it has 10 times or greater on-axis brilliance ***at above emittances****.*

However, when spot sizes < 20 x 20 μm are required, the true undulator wins by the on-axis brilliance ratio.

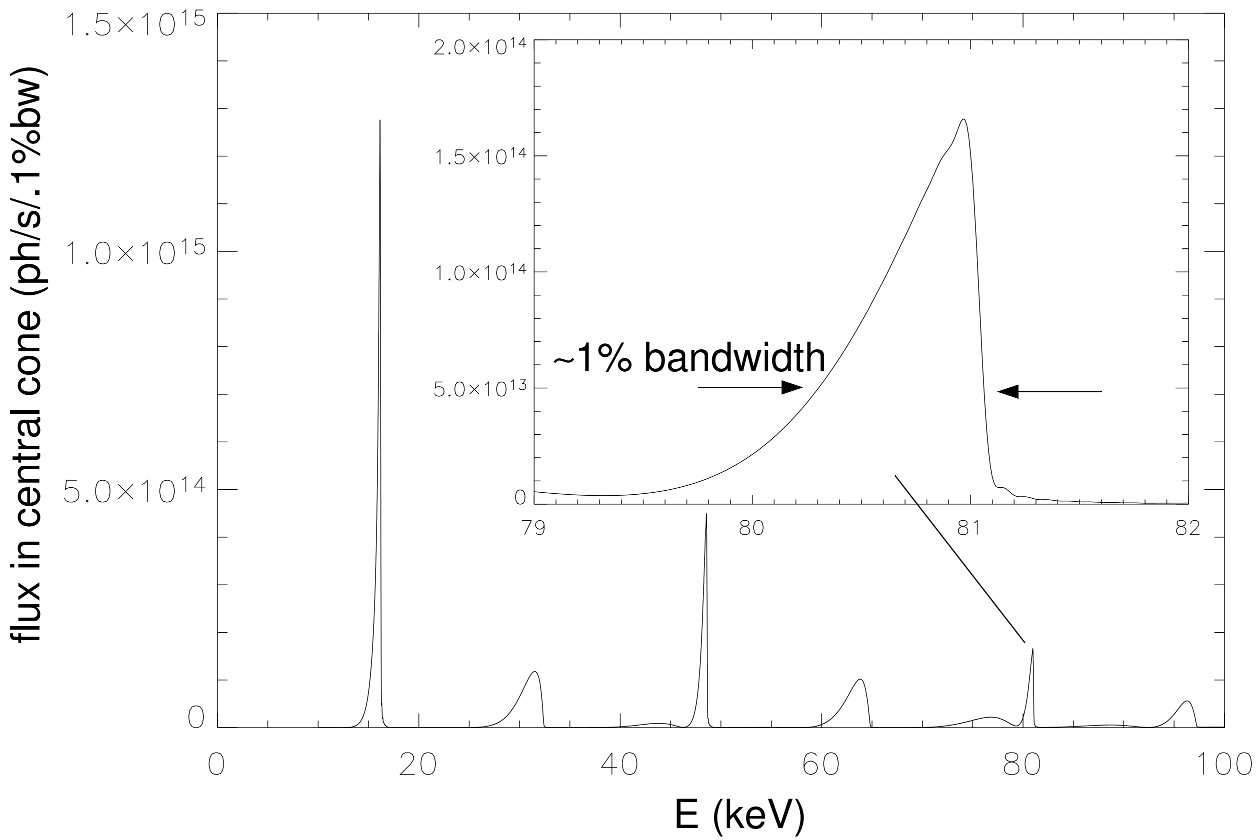


Comparison of Undulators - APS UA vs More Optimized High-Energy Devices



	maximum K	at pole-gap (mm)	period (cm)	# periods (in 2.4 m)
UA	2.6	11	3.3	70
PM	1.1 (1.5)	8.5 (7)	2.1	114
SC	1.2 (1.4)	8 (7)	1.45	165

Superconducting Undulator Harmonics and Multilayer Monochromator



- Well matched to bandwidth of a double-multilayer monochromator (also ~1%) with ~80% reflectivity.

- High flux for experiments that can handle the bandwidth (e.g., fluorescence, small angle scattering).

- Subsequent focusing optics can still be used (just like after the bent double-Laue optics)

Summary

- Optimized optics and specialized source (undulator) on dedicated beamlines are essential for satisfactory exploitation of high-energy x-rays.
- Monochromator optics should be fully tunable, in-line, and brilliance-preserving (e.g., bent double-Laue, multilayers) to enable successful post-manipulation of beam (lenses, high-resolution crystals).
- Undulator source (SC) with at least 10 times the UA brilliance over (50 - 100 keV) should be pursued at the APS.

Modest-sized beams (> 200 x 50 μm) and micro-beams

- currently, ~ 10^{12} ph/s/mm^2 and ~ 10^9 ph/s/μm^2 in .1% bw
- improvements in optics (sagittal-Laue) gives x 10 for modest-sized beams
- along with an specialized (SC) undulator gives x 50-100 total
- multilayer monochromator (for 1% bw) gives additional x 5-10
- longer straight section additional x 2

Higher energy resolution

- efficiently delivering ~ 1 eV at 50 - 120 keV is straightforward.
- resolution of ~100 meV will probably require cryogenic stabilization of high-resolution optics
- but what's the science?

Acknowledgements

Sec 1 - X-Ray Physics Group

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Undulator discussion

Roger Dejus

Lenses

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Björn Cederström (Royal Inst. of Tech.)