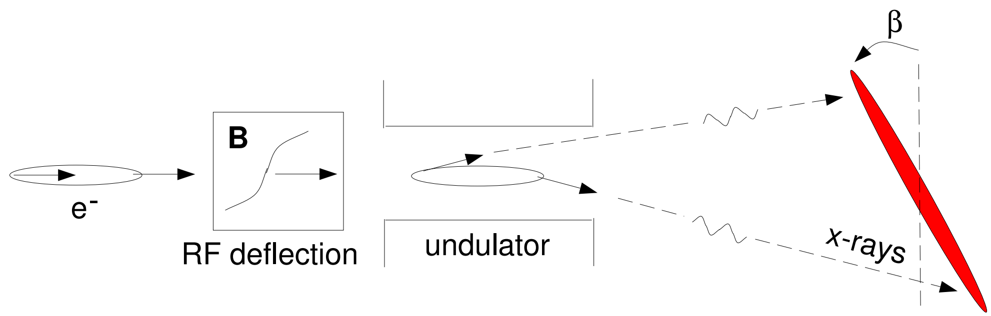
Picosecond X-Ray Pulse Compression Optics Following RF Bunch Deflection

S. D. Shastri, R. J. Dejus, L. Assoufid

APS
Argonne National Laboratory

Advanced Photon Source

RF Deflection Followed by . . .



RF voltage: 4 MV
RF freq: 8 × 352 MHz = 2.8 GHz

Gives deflection gradient ± 380 μrad / σ_t
where σ_t = 40 ps is r.m.s. bunch length

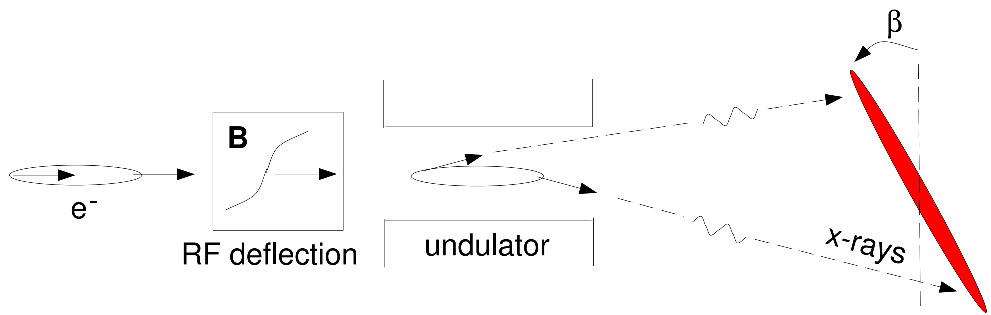
For x-rays at 30 m, β = ± 46° ,
1 σ_t vertically dispersed by 11.6 mm

Zholents, et al., NIM A**425**, 385-389 (1999)

. . . Pulse Compression Optics

- x-ray tilt-rotation by asymmetric crystals
- undulator radiation following RF bunch deflection
- ps compression concept using Bragg geometry and mirrors
- flux and tunability: optimization over 5 - 40 keV
- geometrical effects
- mirror issues
- Laue geometry and bent crystals

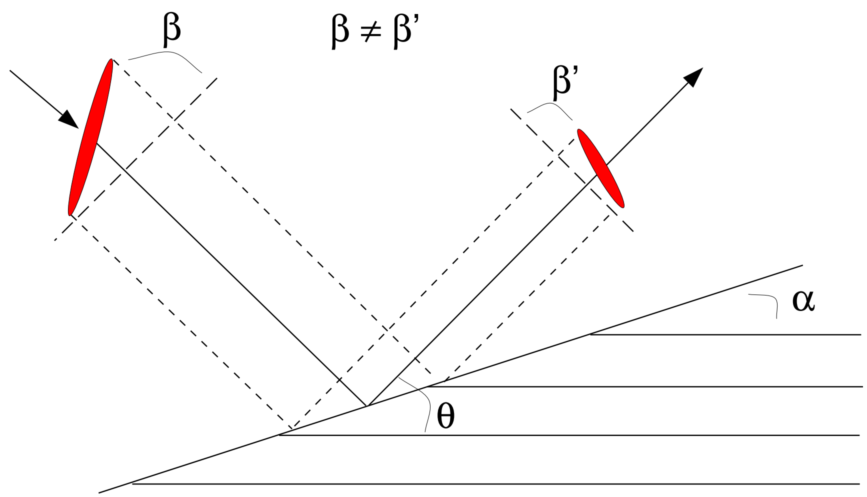
RF Deflection Followed by Tilt - Rotation by Asymmetric Crystals



RF voltage: 4 MV
RF freq: 8×352 MHz = 2.8 GHz

Gives deflection gradient $\pm$ 380 μrad / σ_t
where σ_t = 40 ps is r.m.s. bunch length

For x-rays at 30 m, $\beta = \pm 46°$,
1 σ_t vertically dispersed by 11.6 mm



Bragg geometry $-\theta < \alpha < \theta$

Laue geometry $\theta < \alpha < 180° - \theta$

Rotation

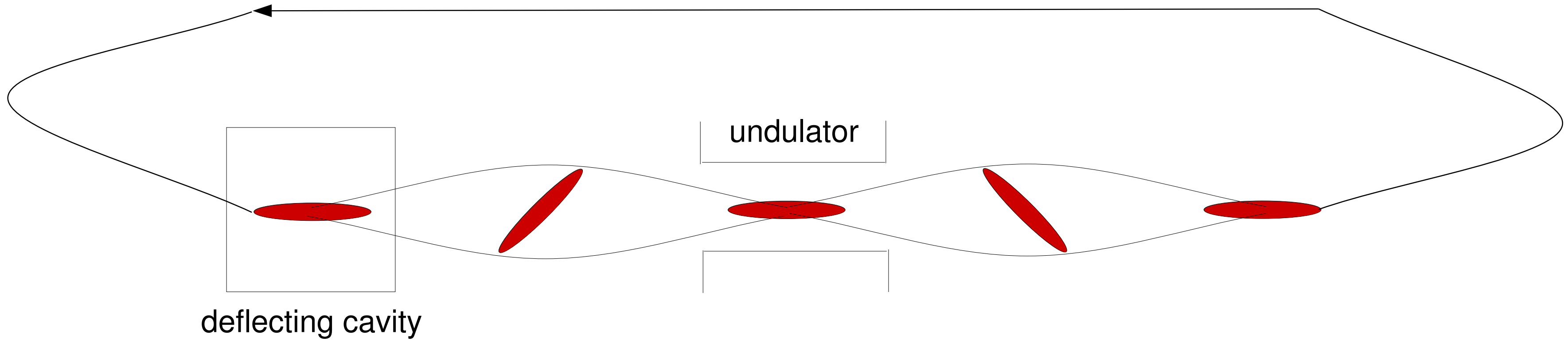
$$\tan \beta' = \frac{\tan \beta \sin(\theta + \alpha) - 2 \sin\theta \sin\alpha}{\sin(\theta - \alpha)}$$

Beam size magnification $1 / |b|$

$$b = \frac{\sin(\theta + \alpha)}{\sin(\alpha - \theta)}$$

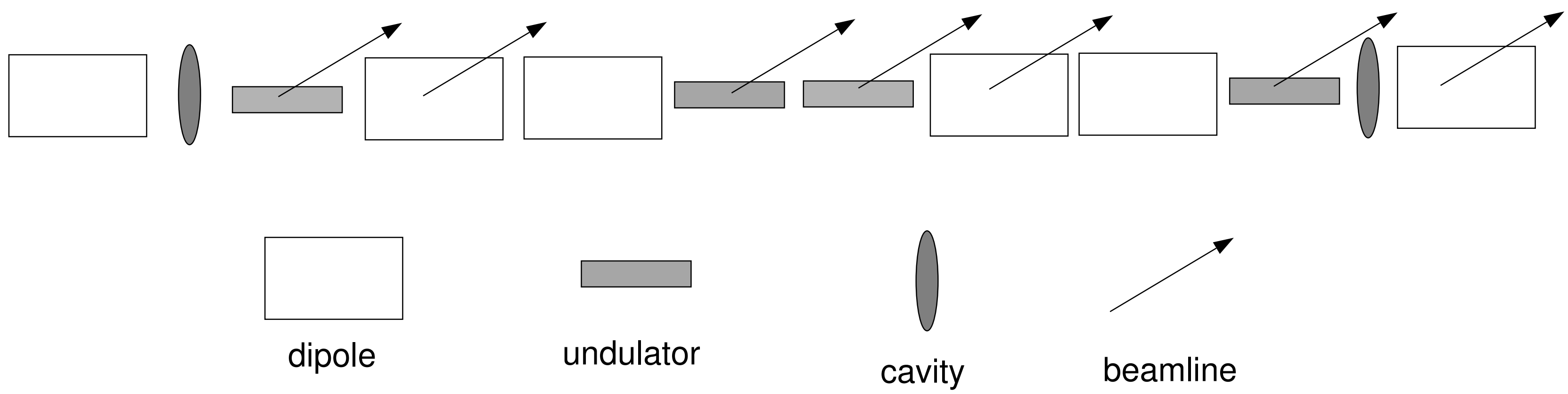
Angular divergence change $\Delta\theta \longrightarrow -b\,\Delta\theta$

Betatron Oscillations Enable ...

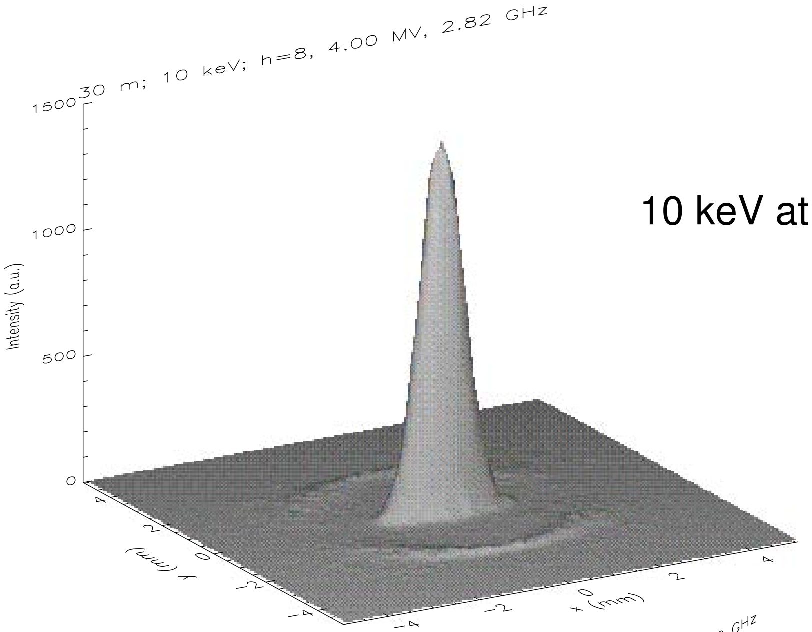


... Multiple Picosecond Beamlines Inside 2 Deflecting Cavities

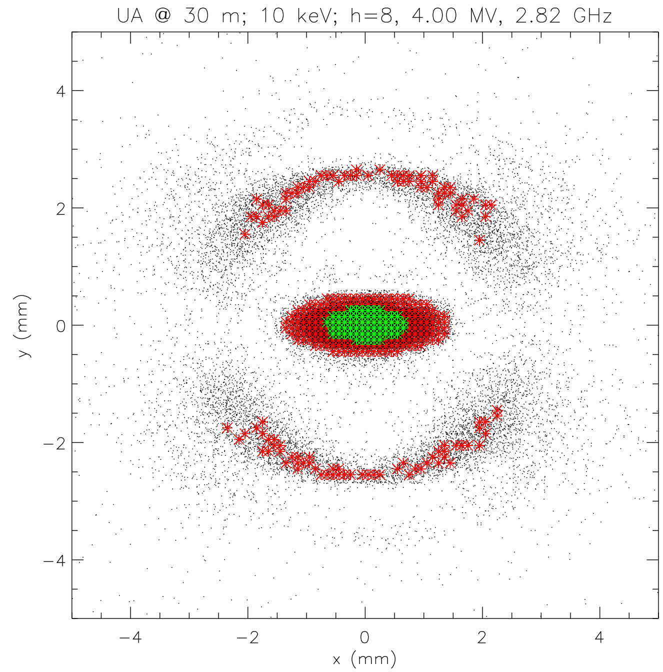
Example: 3 straight sections, 4 IDs, 2 BMs

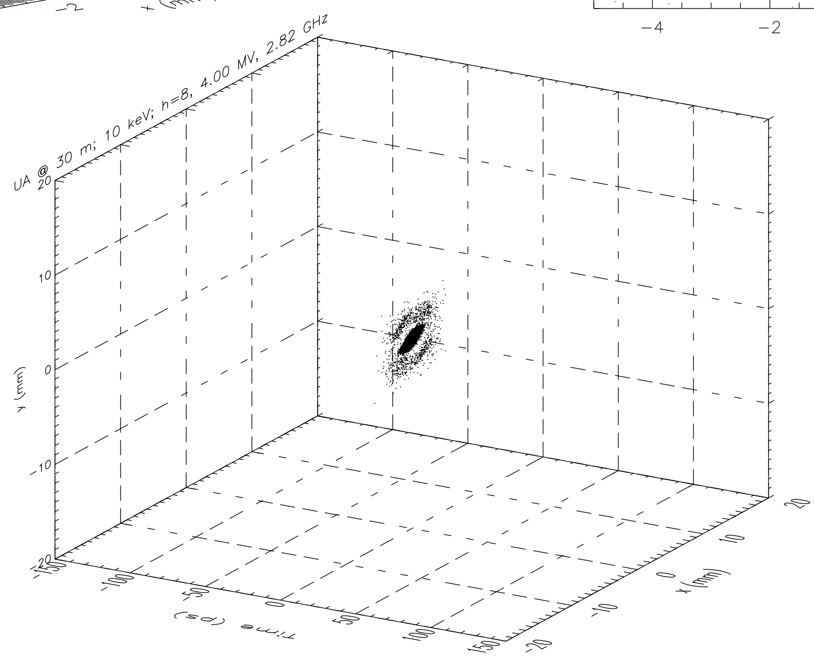


UA Central Cone - No RF Deflection (or Single Slice with Deflection)

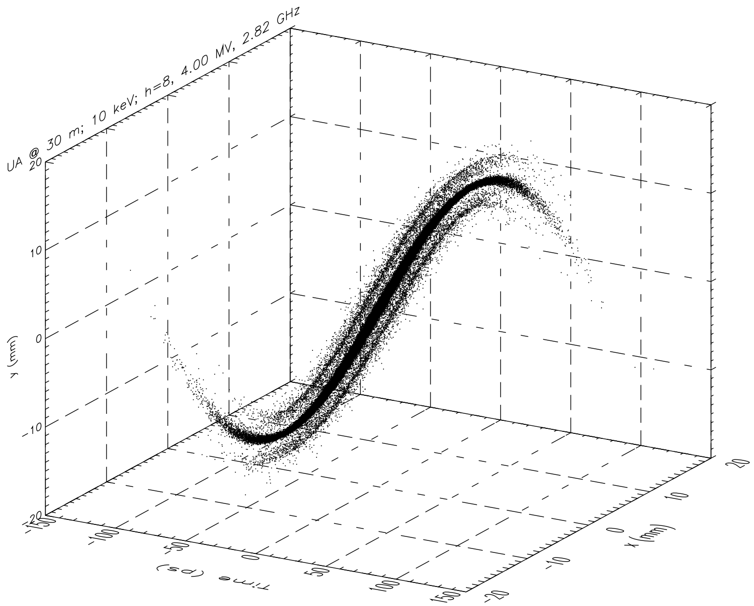


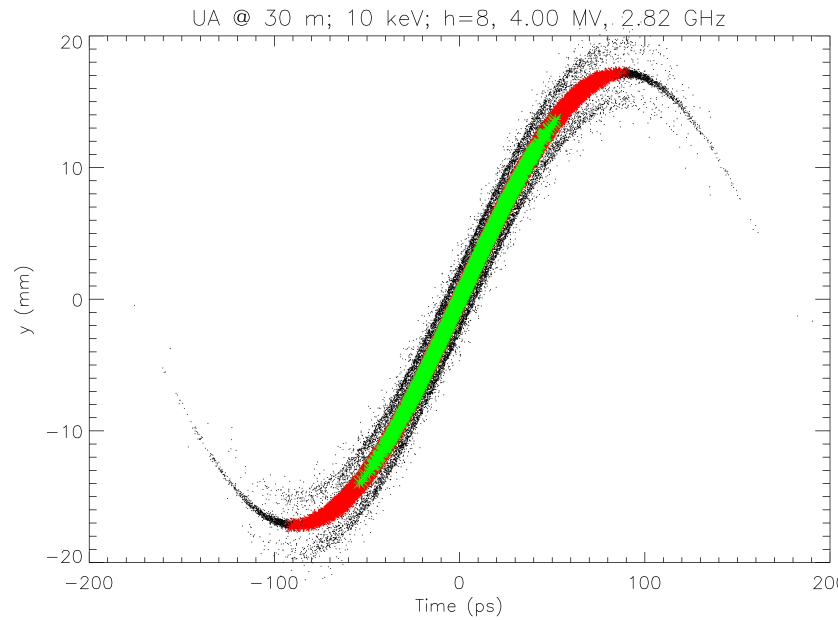
10 keV at 30 m

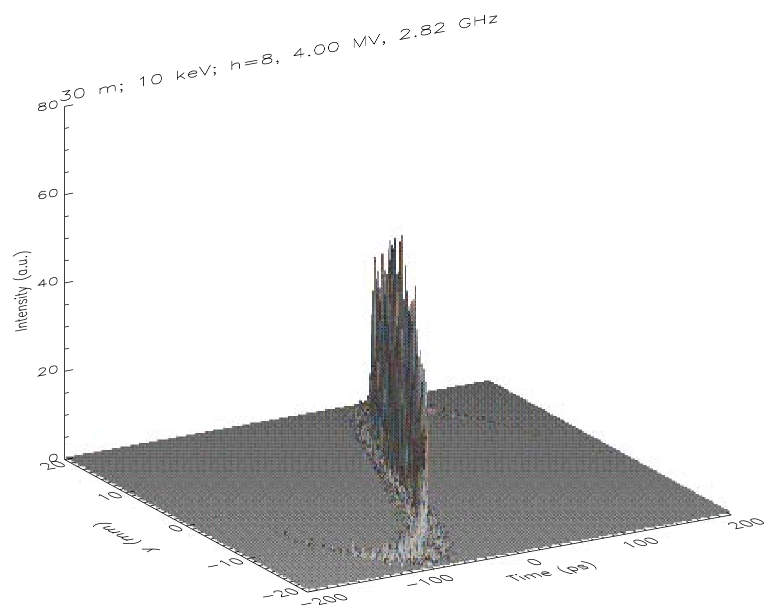




Undulator Radiation with RF Deflection - 10 keV at 30 m





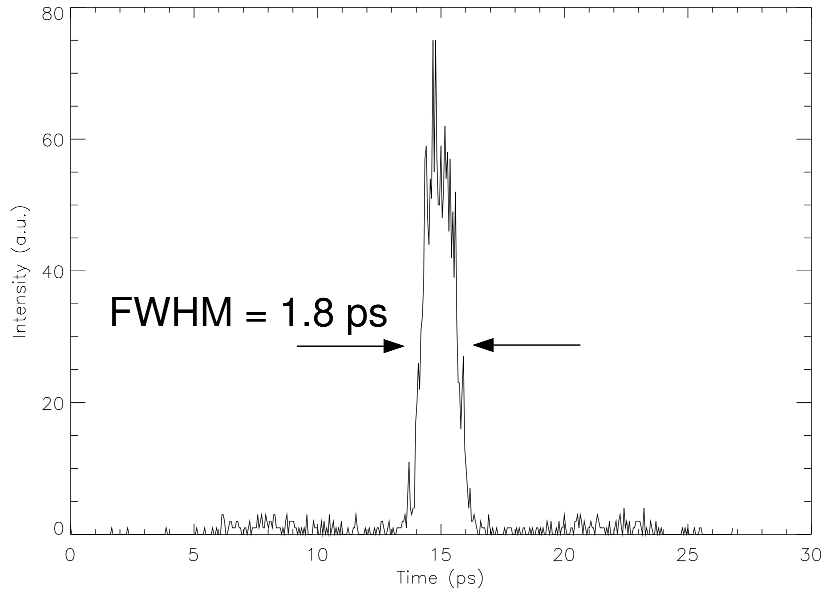


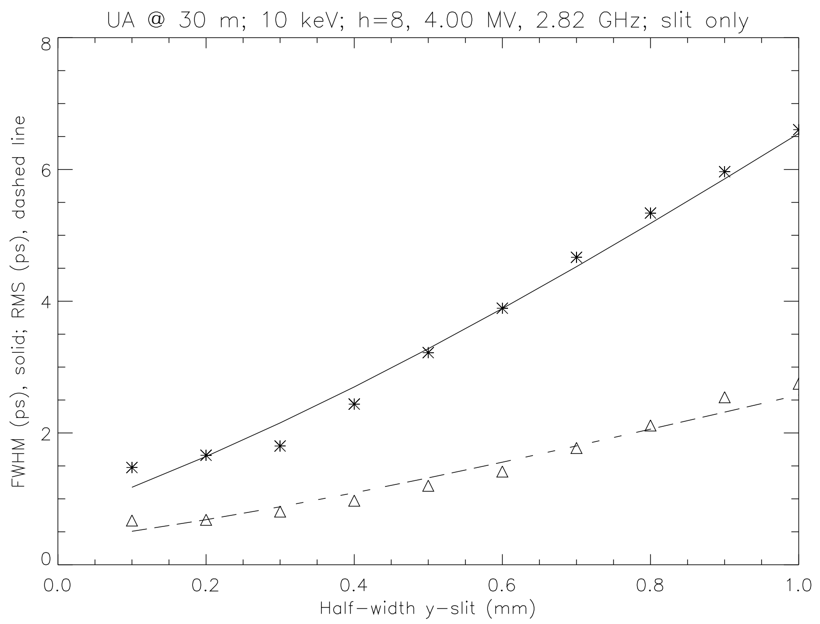
$\sigma_x = 245\ \mu m$ $\sigma_{x'} = 12.3\ \mu rad$

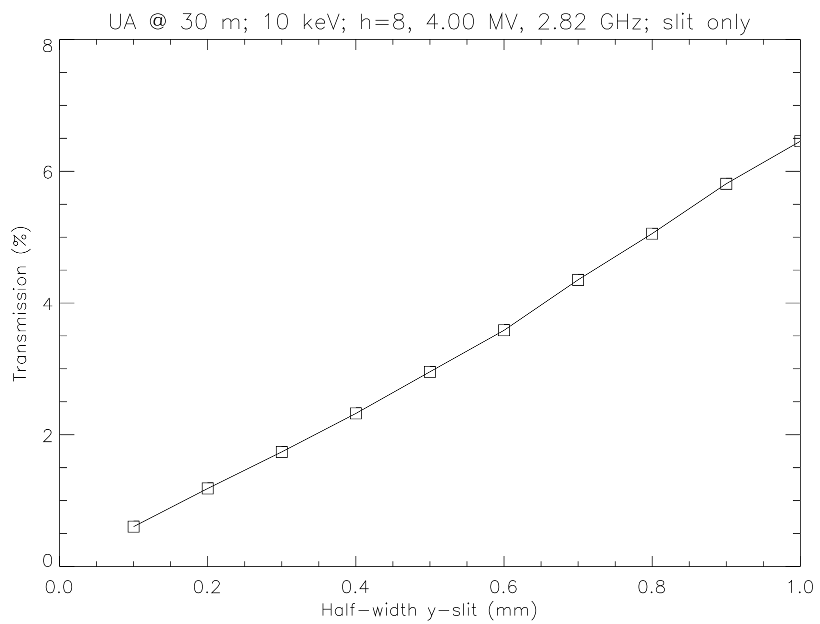
$\sigma_y = 12.3\ \mu m$ $\sigma_{y'} = 2.0\ \mu rad$

$\sigma_E / E = 0.001$

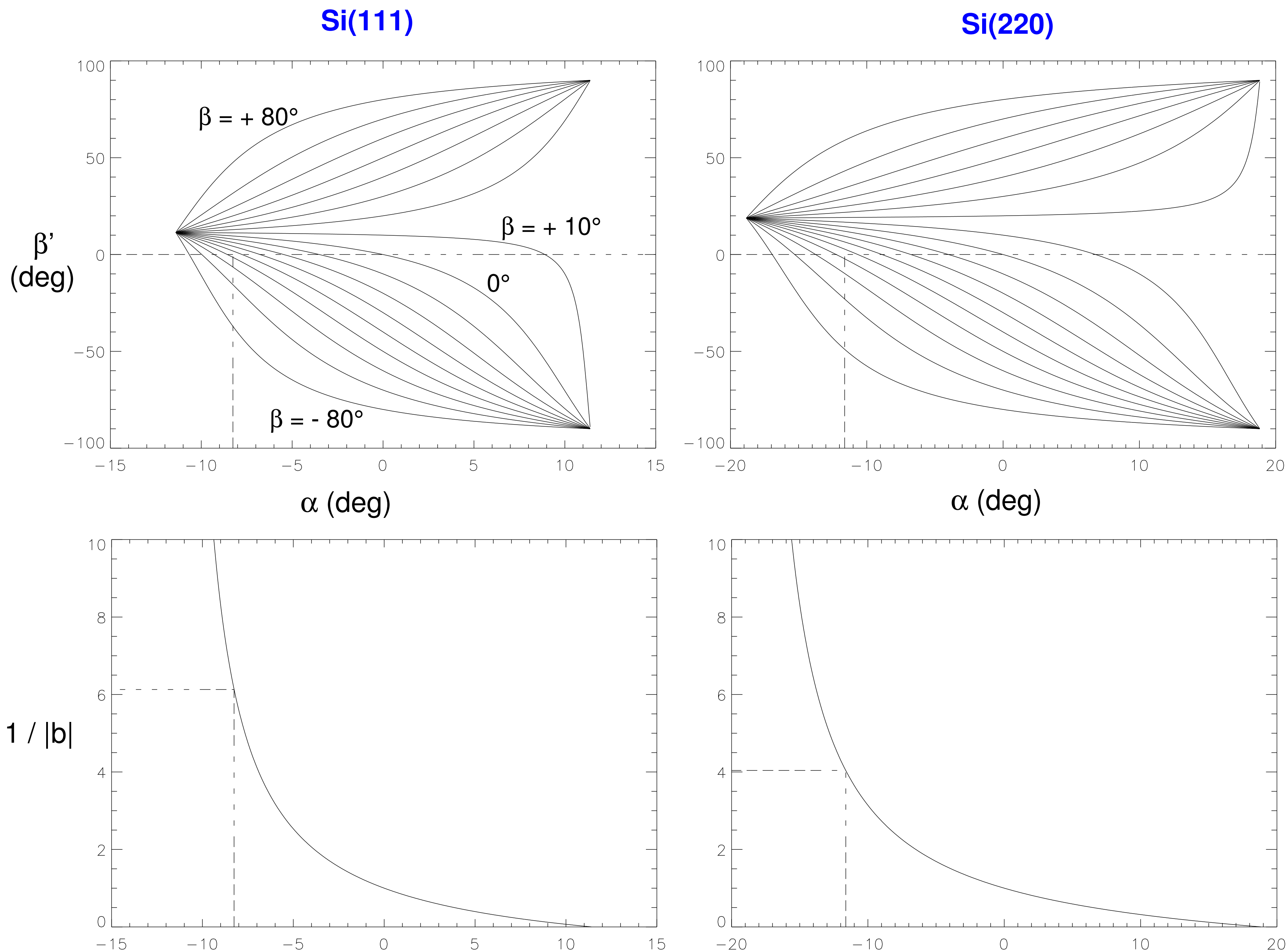
Slits Only - No Optics Compression



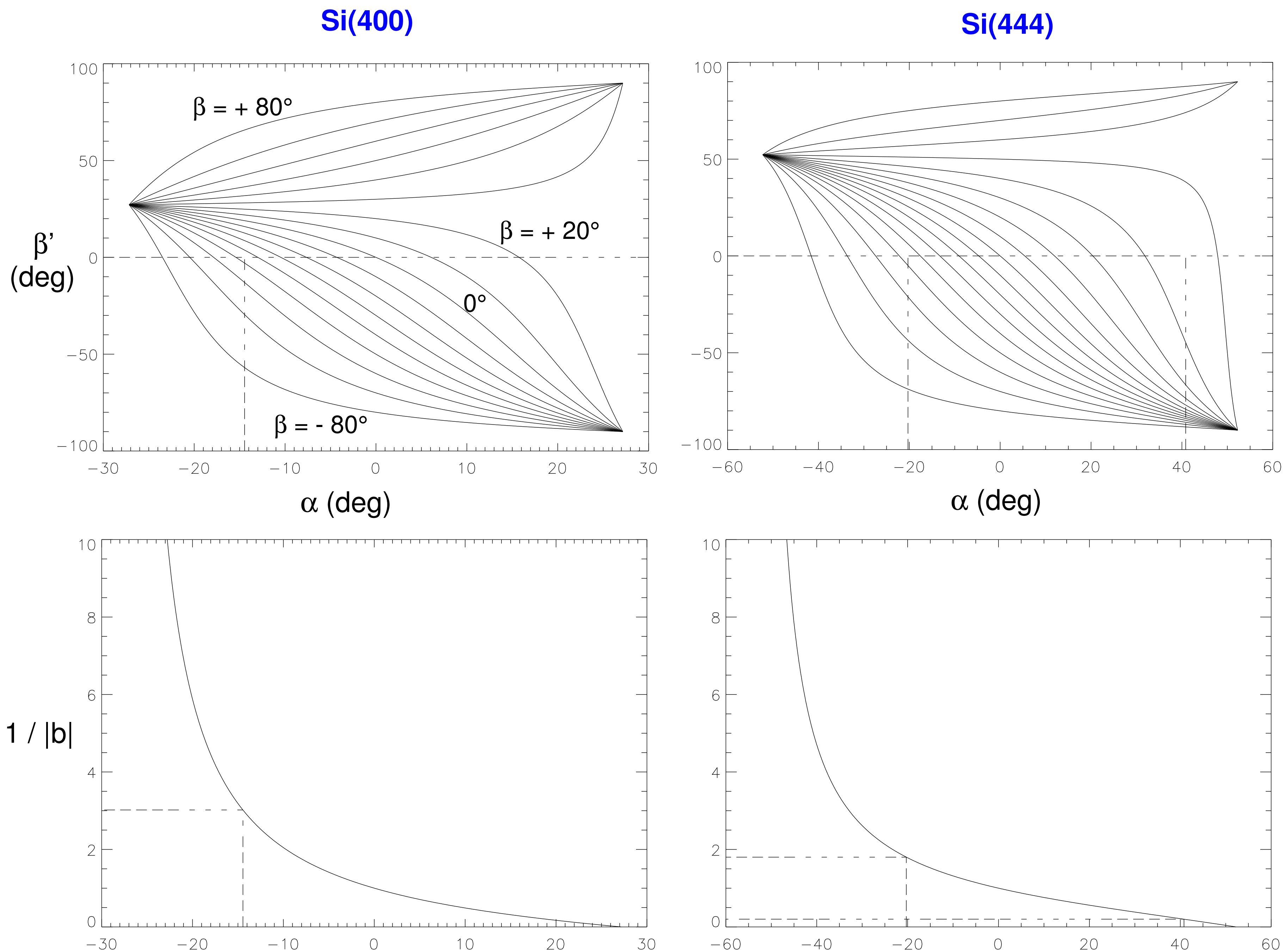




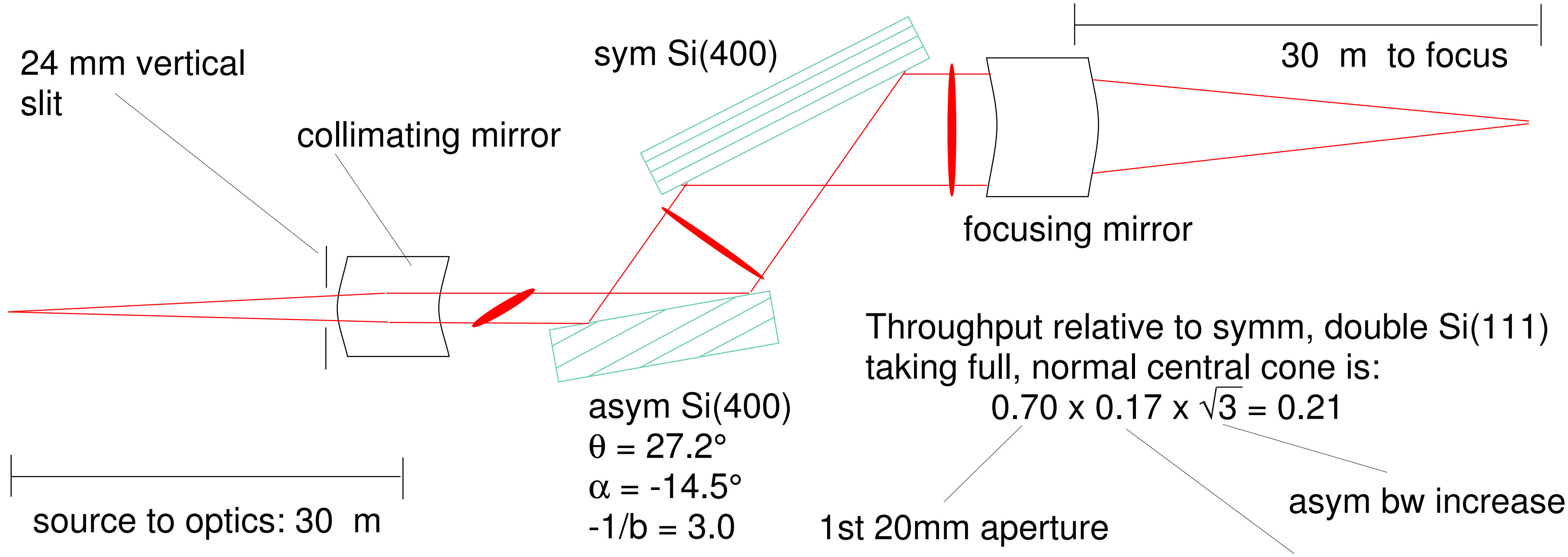
Tilt - Rotation, 10 keV, Bragg Geometry



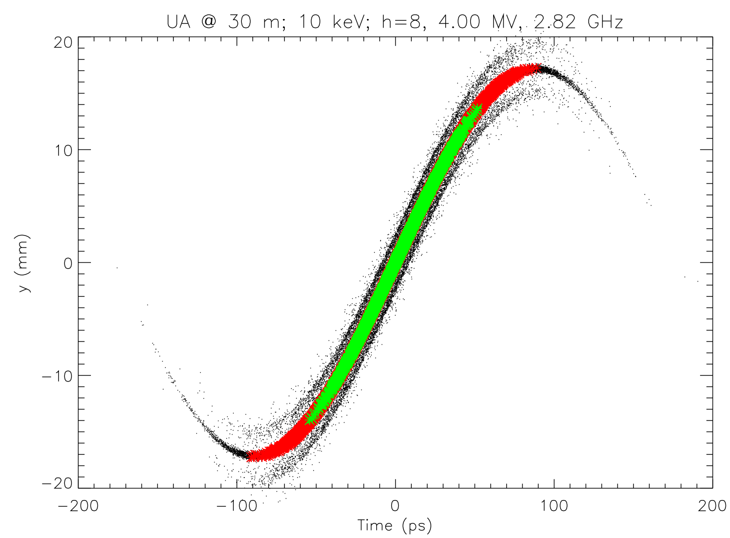
Tilt - Rotation, 10 keV, Bragg Geometry

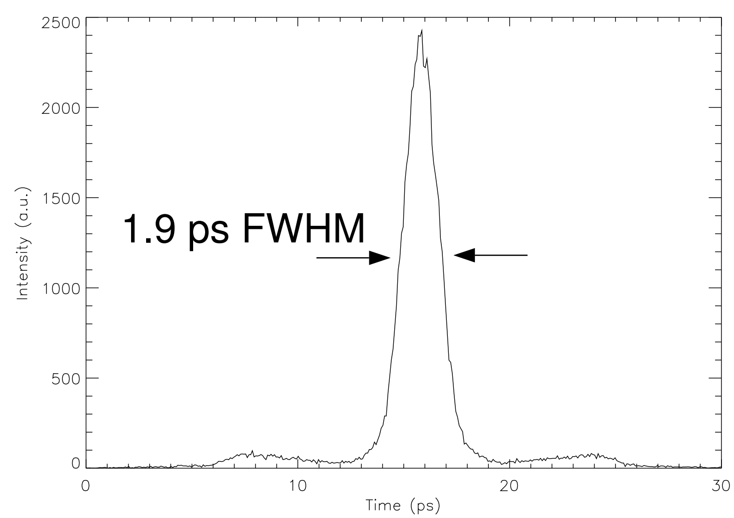


Pulse Compression Concept: 10 keV and Si(400) Example

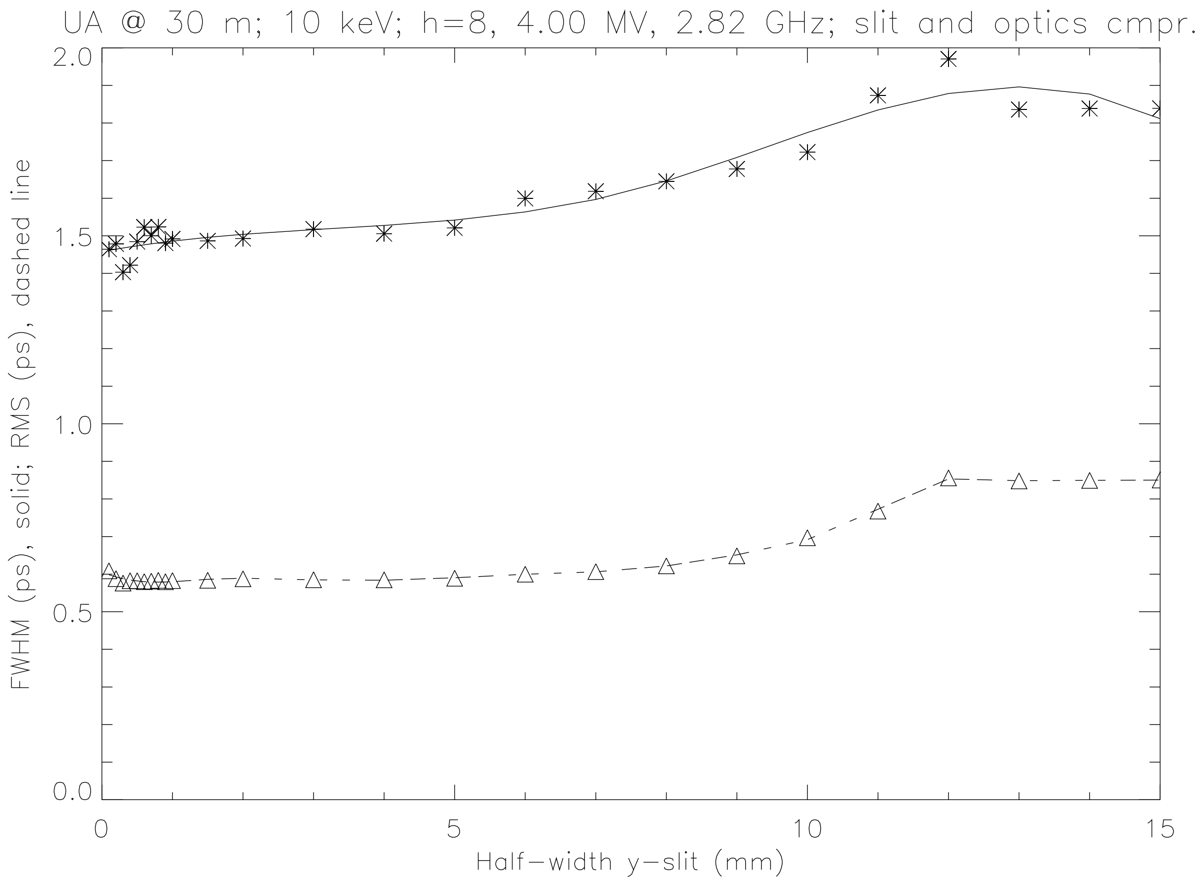


bandwidth = 0.4 eV

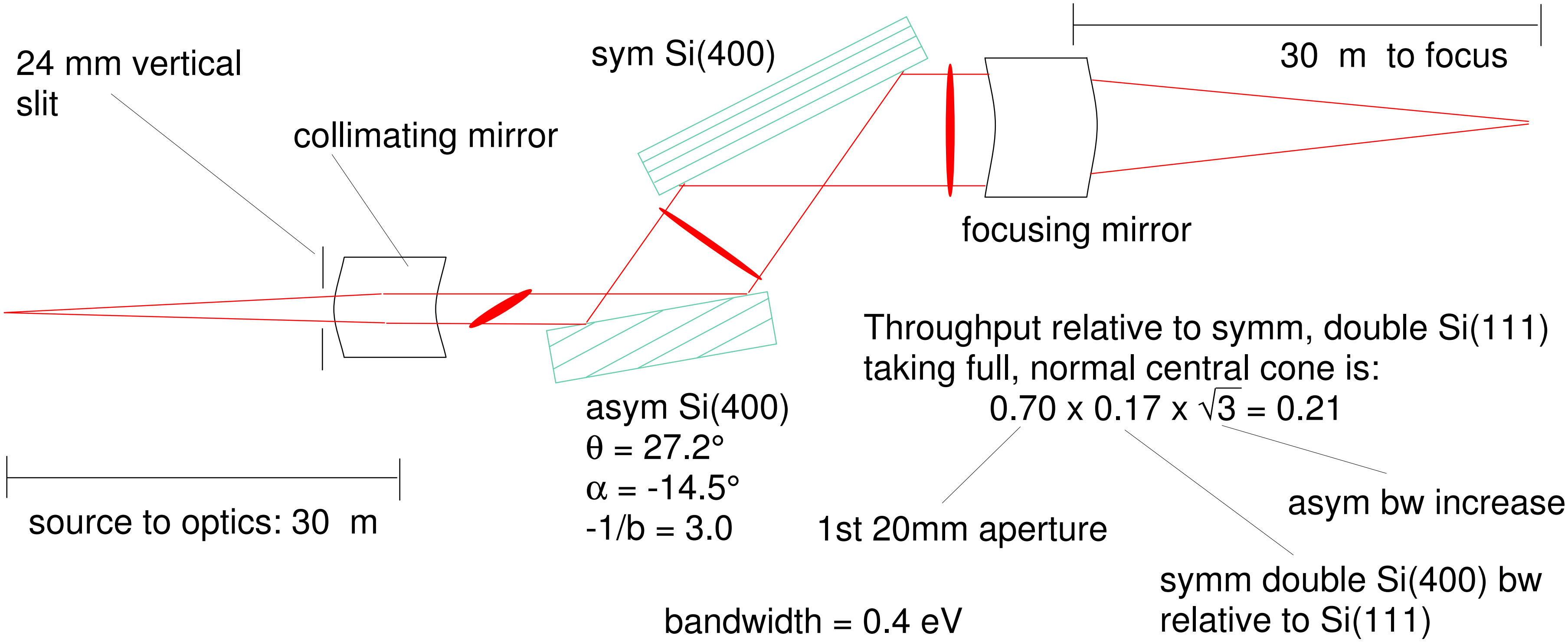




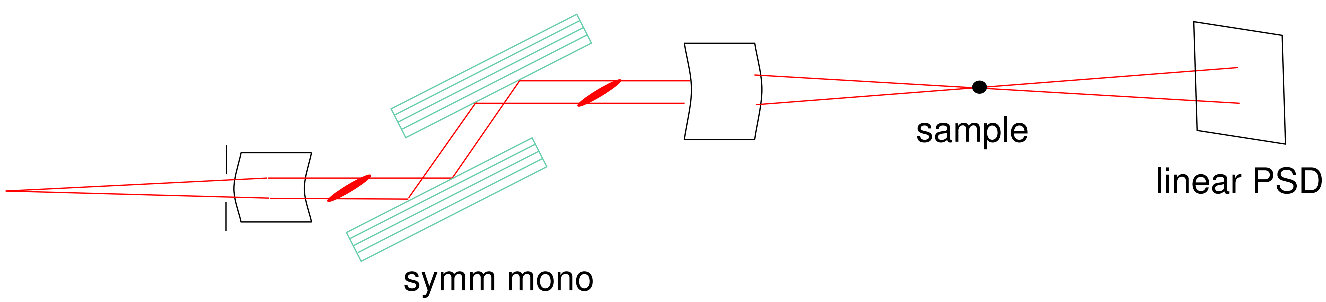
Optics Compression Pulse Widths



Pulse Compression Concept: 10 keV and Si(400) Example

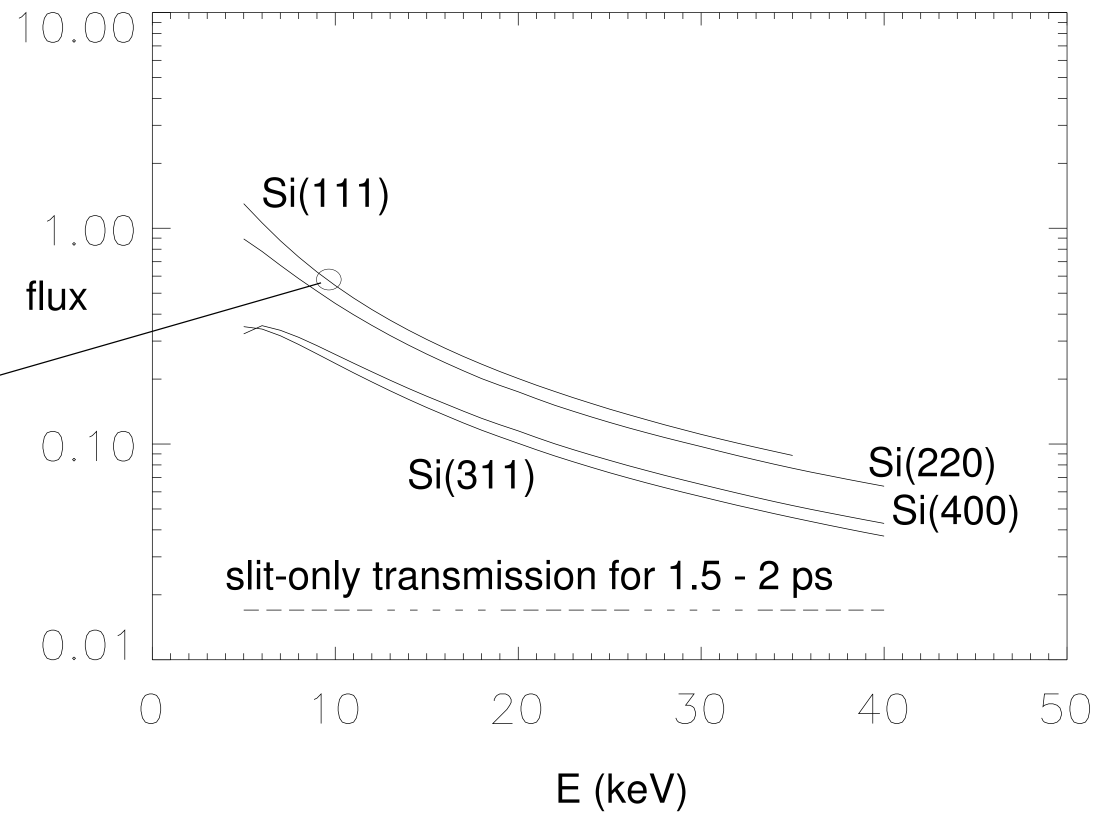


Picosecond Time-Resolution Without Picosecond Pulses



Throughput Optimization of Pulse Compression Monochromators

Optimization assuming:
- 24 mm first aperture
- 200 mm long crystals
- 100 mm aperture after crystals
  (before focusing mirror)
- 100% mirror reflectivites



Example - Analysis of Si(111) at 10 keV

$\theta = 11.403°$

$\alpha1 = -8.4°$ $\alpha2 = .3°$
$-1/b1 = 6.5$ $-1/b2 = 0.95$

crystal system's vertical aperture = 24 mm x 0.44 x 0.60 = 6.3 mm = 0.54 x (11.6 mm)

$$1/\sqrt{(2\pi)} \int_{-0.54/2}^{0.54/2} \exp(-1/2\, y^2)\, dy = 0.21$$

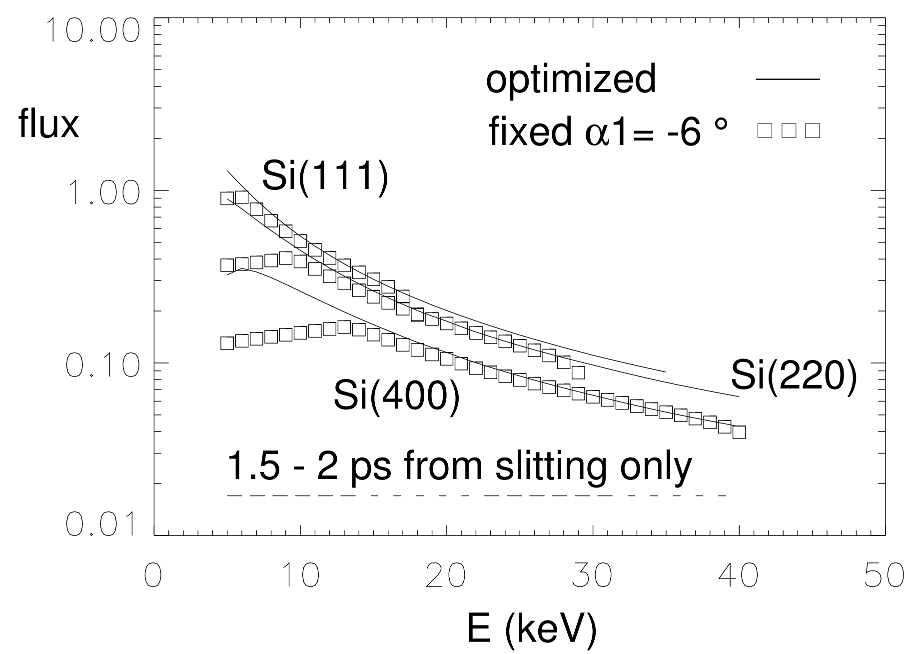
$.21 \times \sqrt{(6.5)} = 0.54$ throughput

bandwidth = 3.7 eV

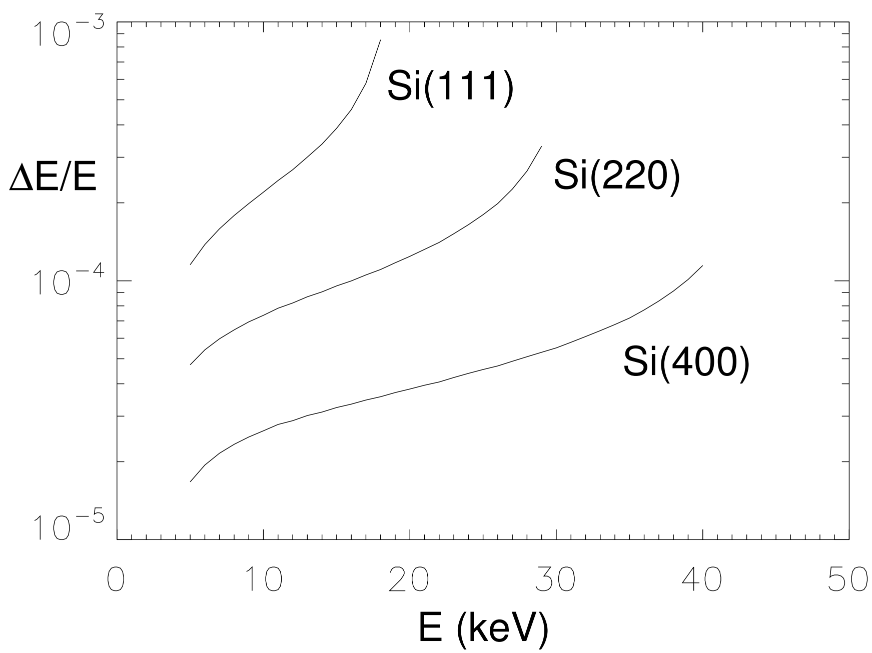
How Near-Optimized Can One Be with Fixed First-Crystal Asymmetry?

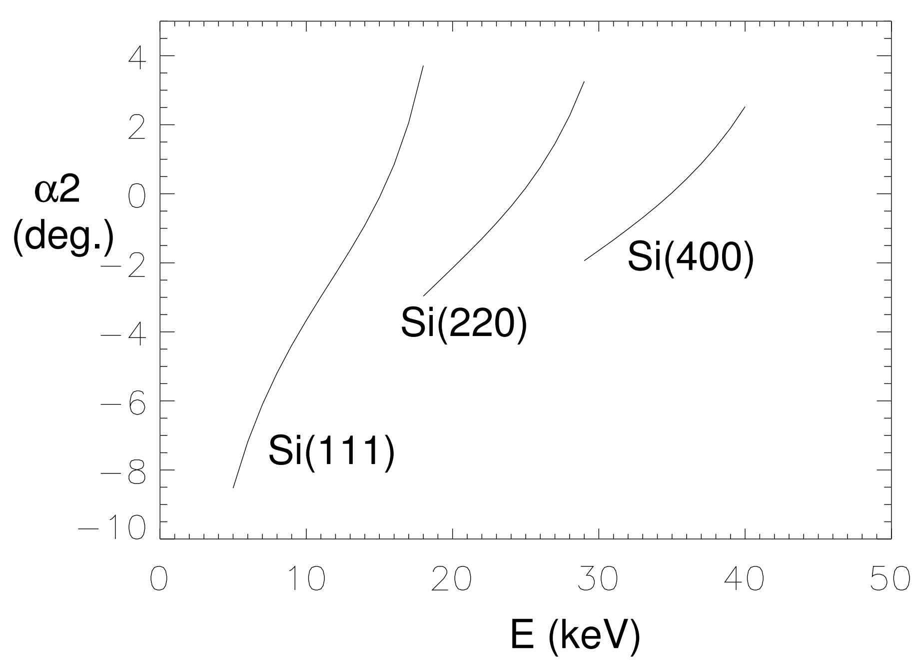
Fix 1st crystal asymmetry to

$\alpha 1$ = - 6.0 °



Second crystal asymmetry $\alpha 2$ varies to satisfy pulse compression condition



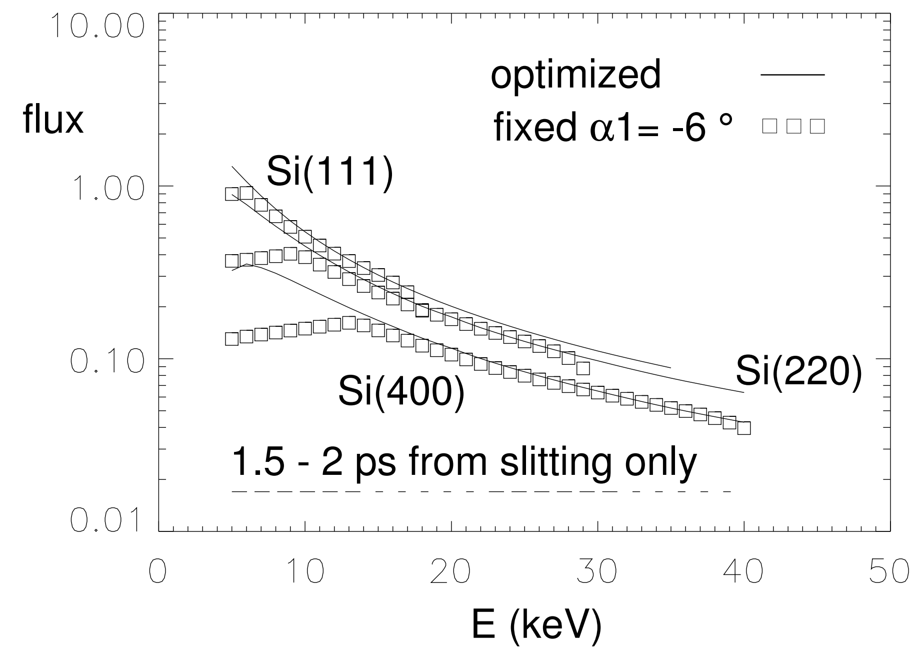


How Near-Optimized Can One Be with Fixed First-Crystal Asymmetry?

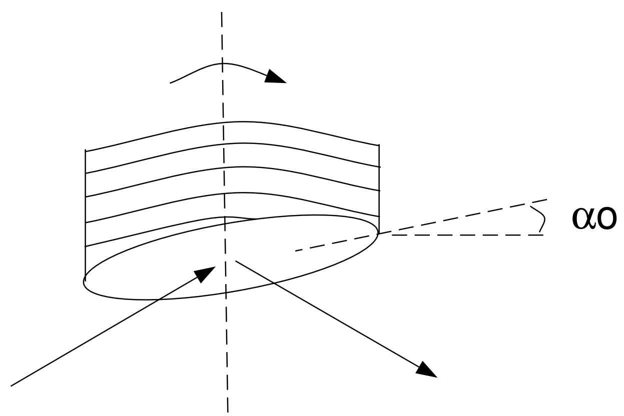
Fix 1st crystal asymmetry to

$\alpha 1 = -6.0°$

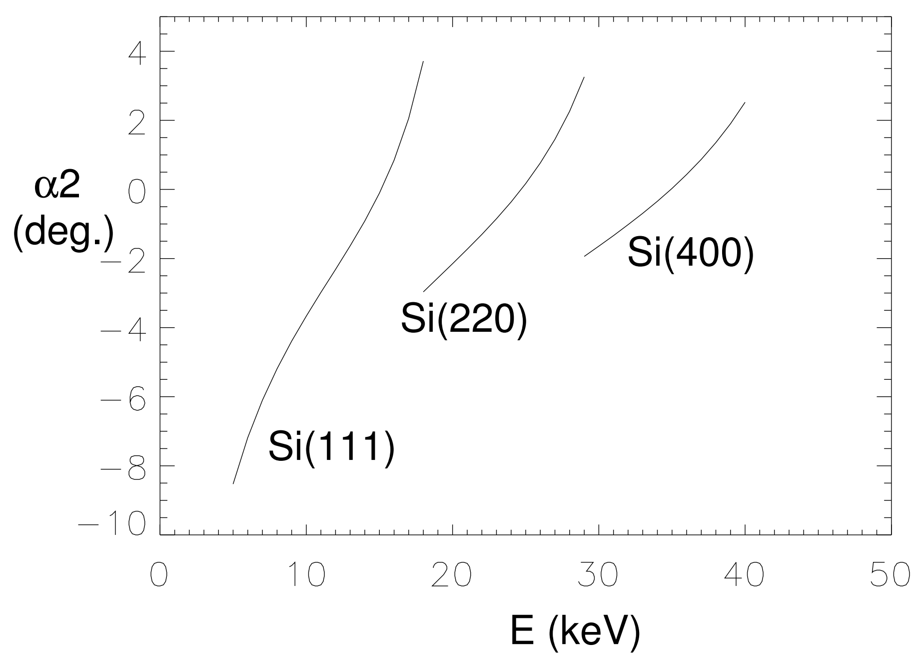
Second crystal asymmetry
$\alpha 2$ varies to satisfy pulse
compression condition



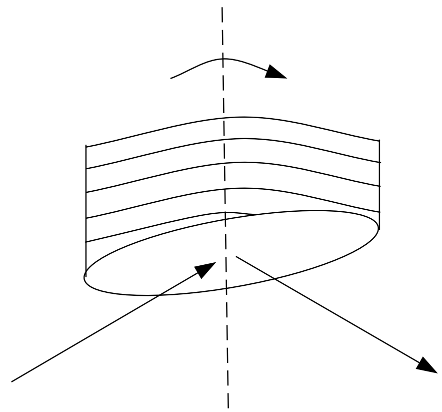
Continuously Tunable 2nd Crystal Asymmetry

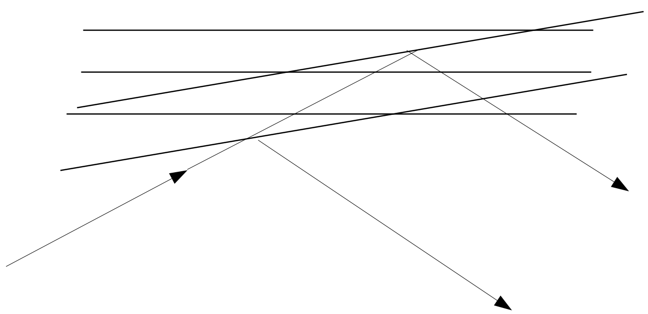


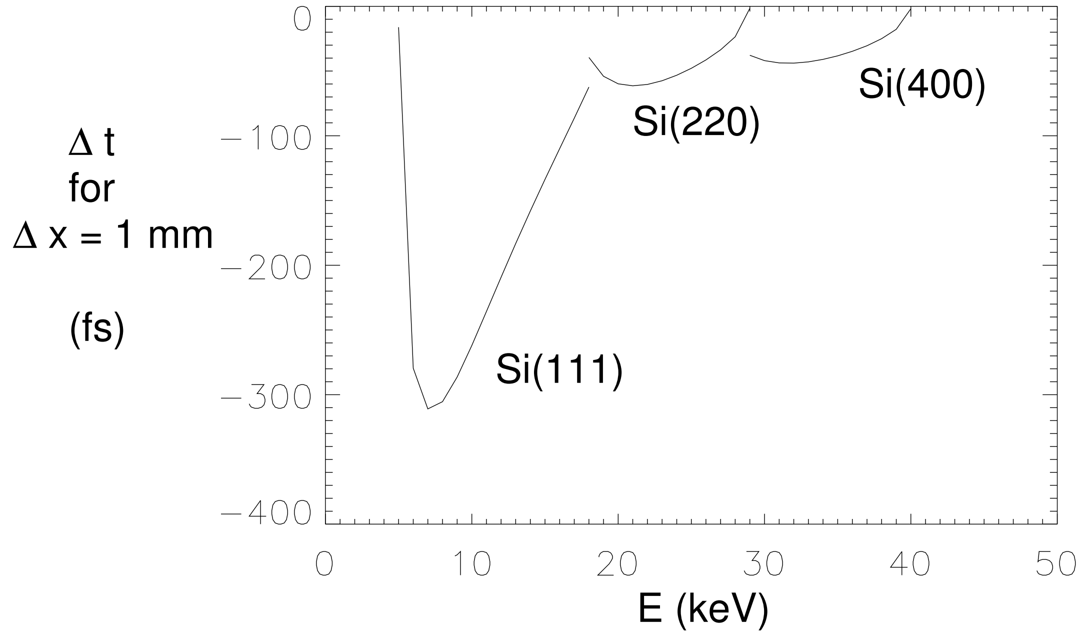
$-\alpha o < \alpha 2 < \alpha o$

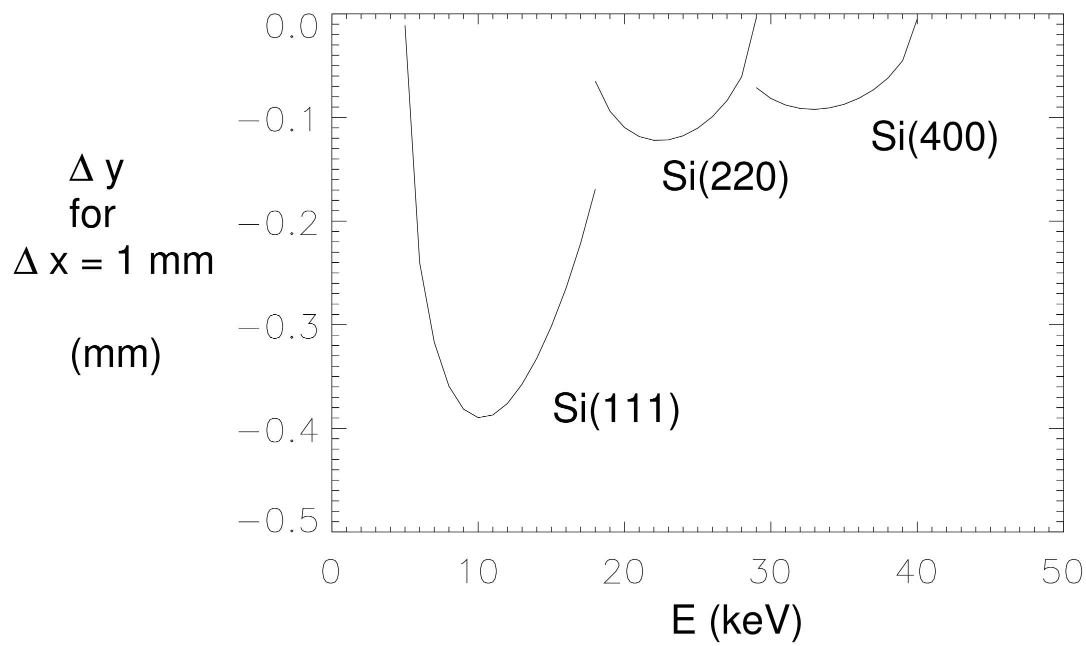


Tunable Asymmetry Effects

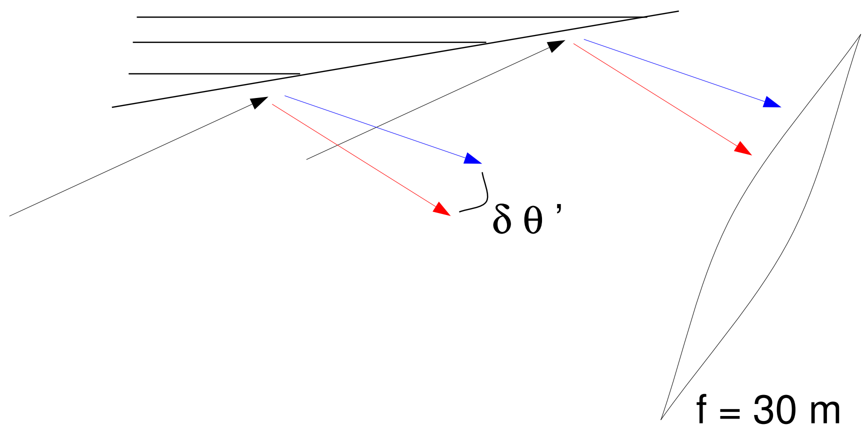


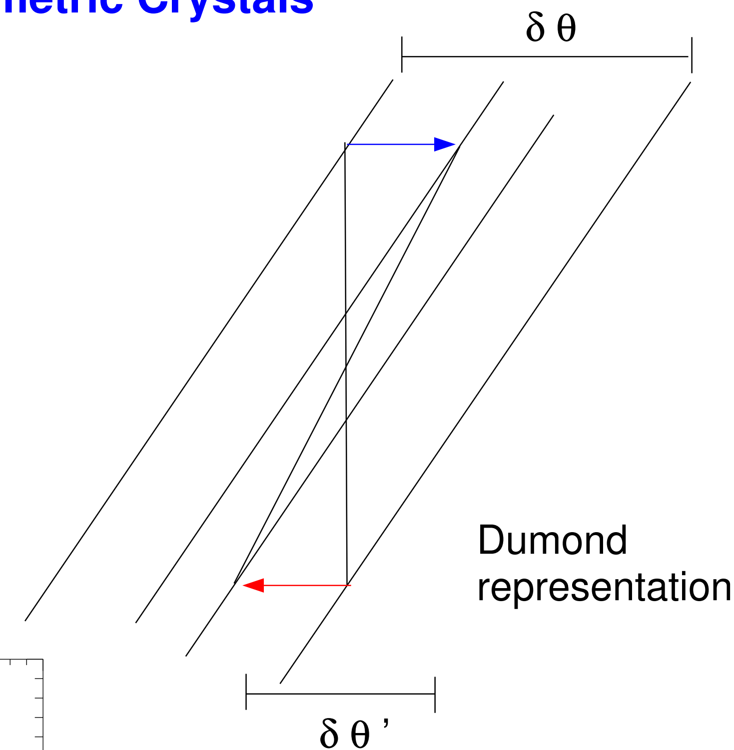


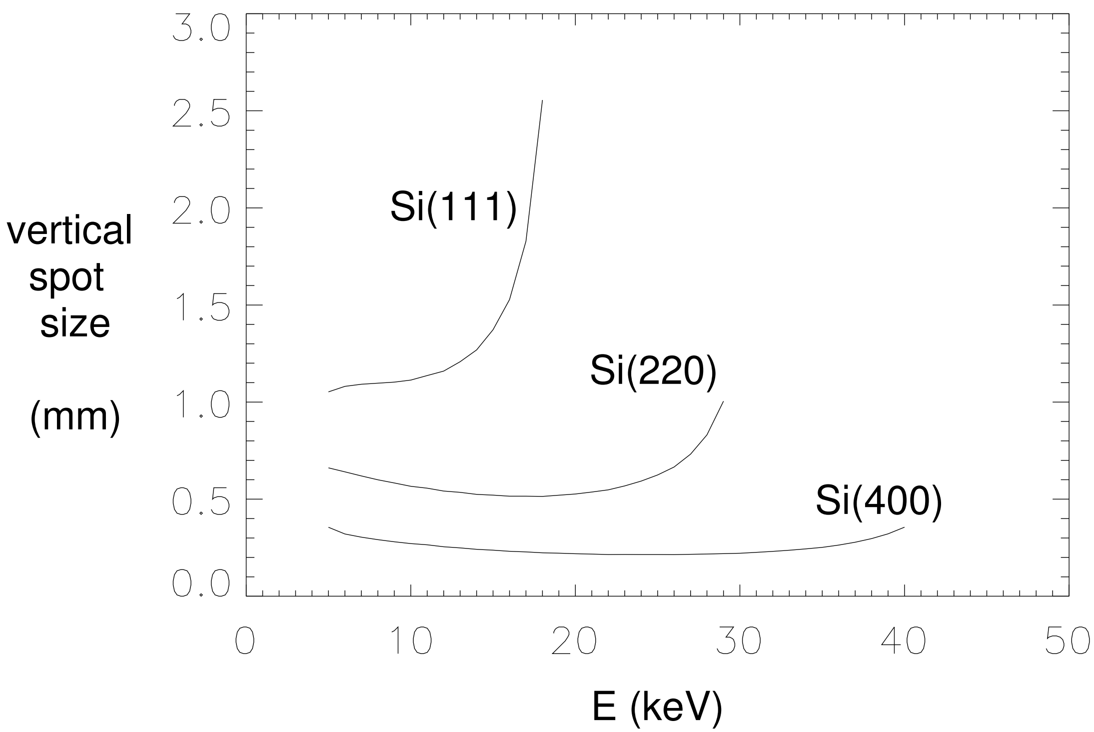




Vertical Spot Size Due to Asymmetric Crystals







Single reflection
$\delta\theta' = \delta\theta\,(1 + b)$

Double reflection
$\delta\theta' = \delta\theta\,(1 - b1\,b2)$

2nd Sagittal Mirror Length and Reflectivity / Coating

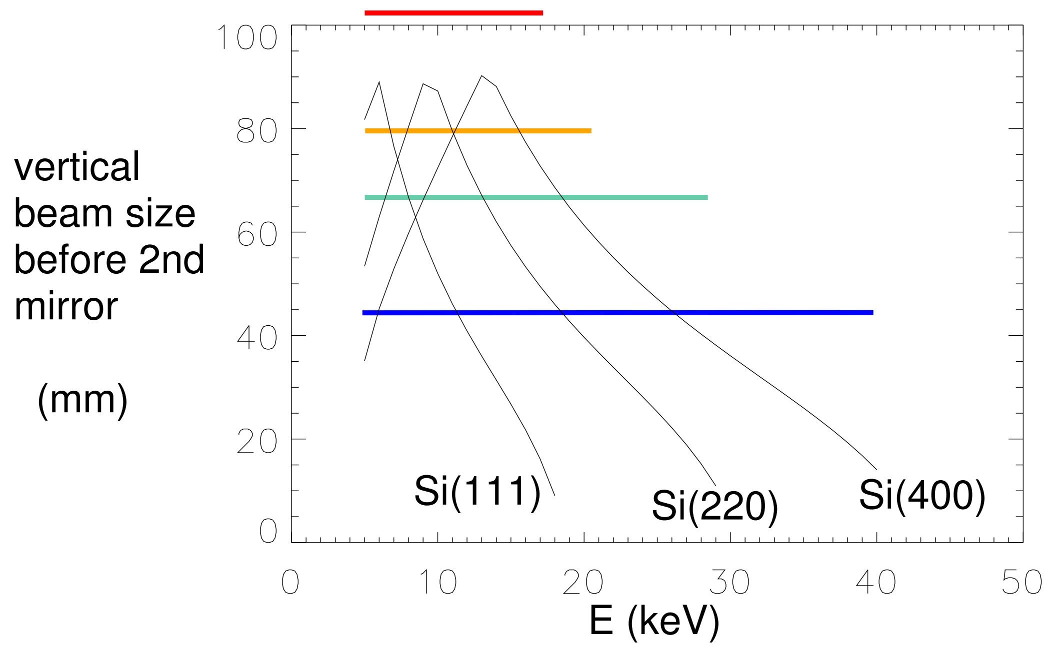
$$L = L_1 + L_2$$

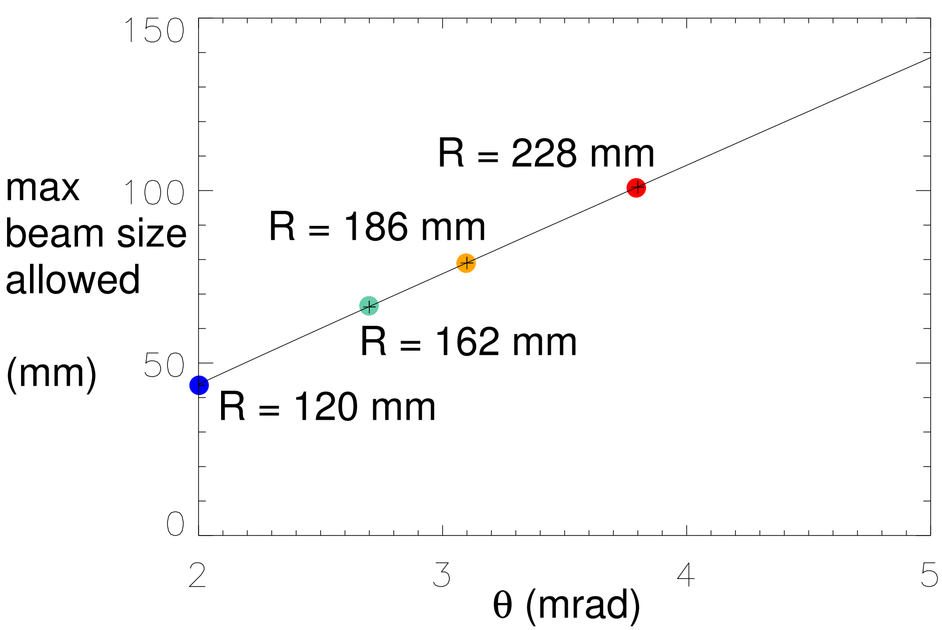
$$= \frac{h_m}{\theta} + \frac{h_s^2}{8 R \theta}$$

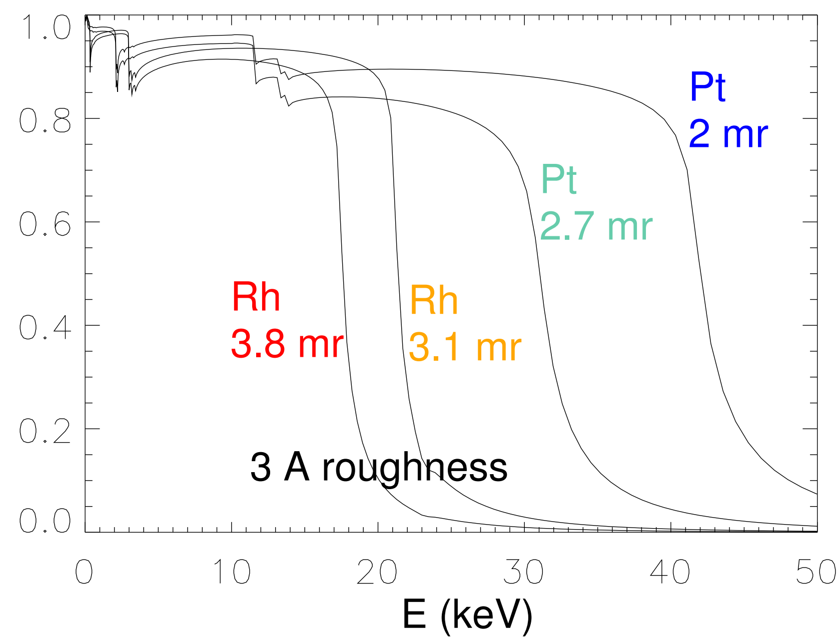
$$h_s < \sqrt{\left(L - \frac{h_m}{\theta}\right) 8 R \theta}$$

L: 2 m

h_m: 2 mm



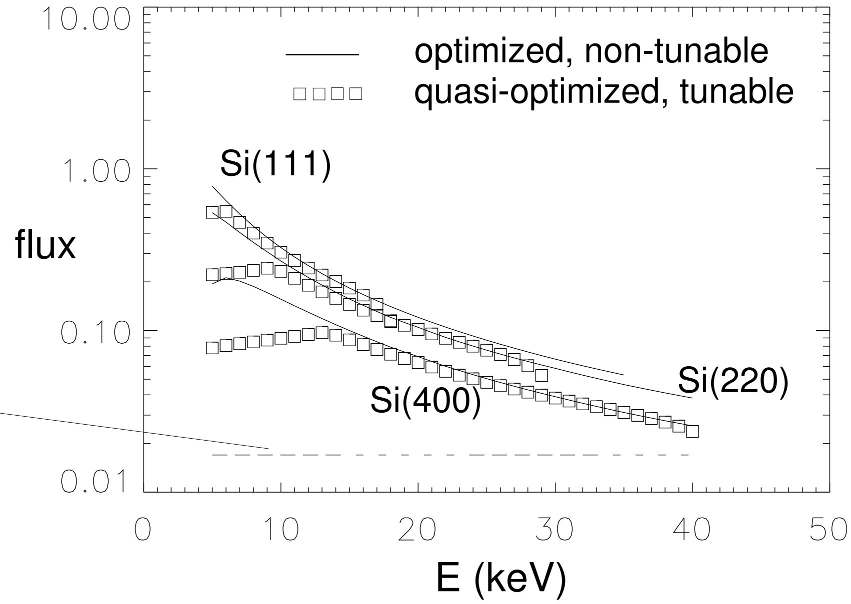




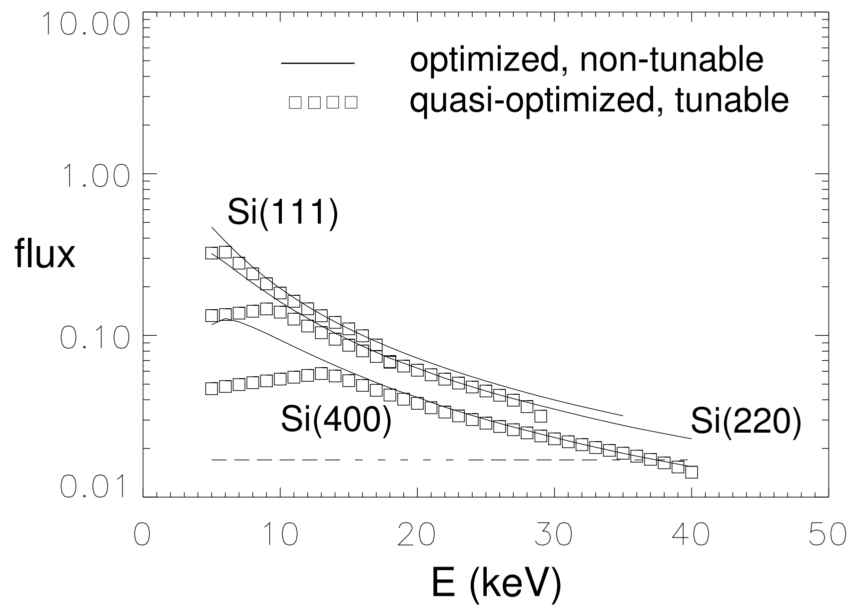
Throughput Including Mirror Reflectivities

2 m long second mirror

0.5 mm slit-only trans for 1.5 - 2 ps



1 m long second mirror

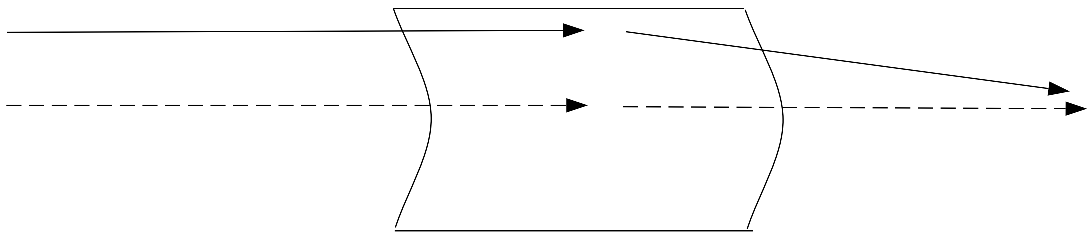


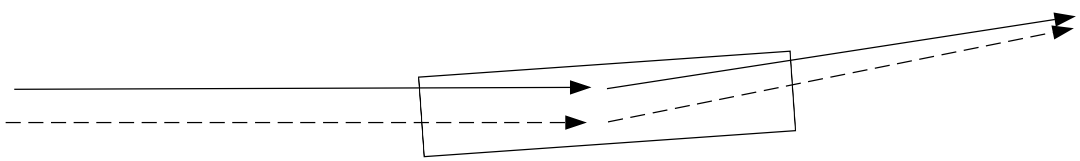
Isochronicity of Sagittal Mirrors

Paths are isochronous, from Fermat's principle of stationary (least) time for aberration-free (parabolic) profile.

For cylindrical profile we have the following:

longer by $\frac{R}{2 \sin \theta} \left(1 - \cos \left(\arcsin \frac{h_s / 2}{R / 2 \sin \theta} \right) \right)$





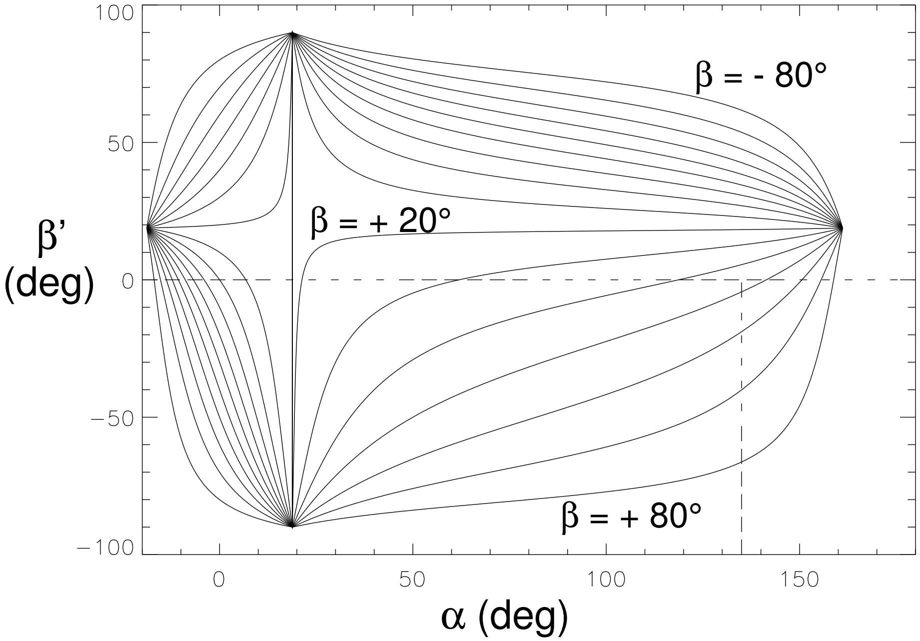
longer by $R \left(1 - \cos \left(\arcsin \frac{h_s}{2 R} \right) \right) \sin 2\theta$

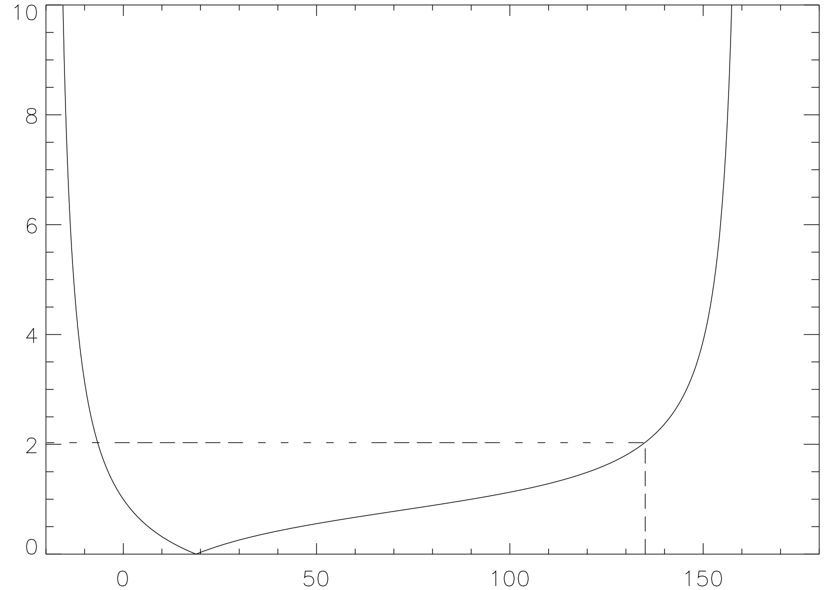
For h_s = 100 mm, θ = 2 mrad, R = 120 mm,

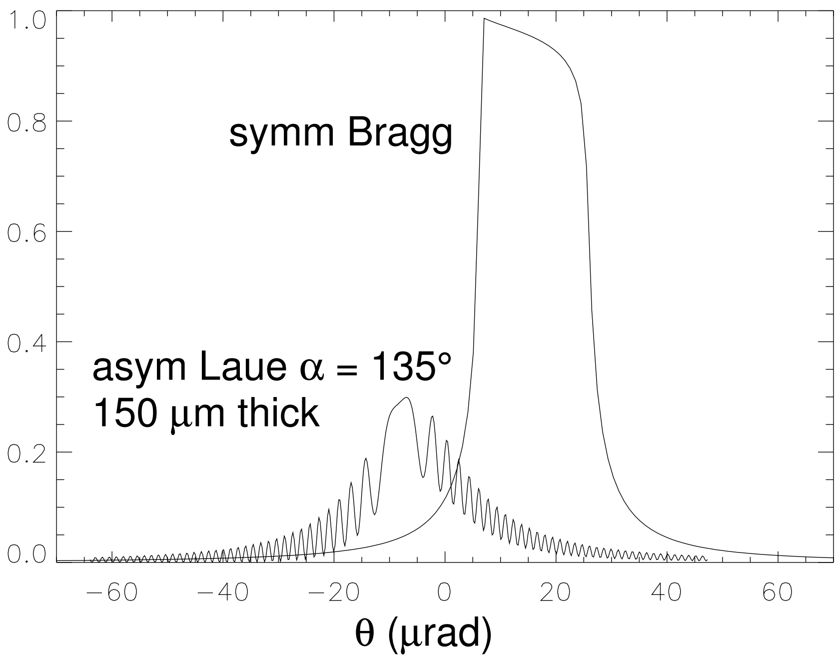
these lengths are 41.7 μm and 43.7 μm,

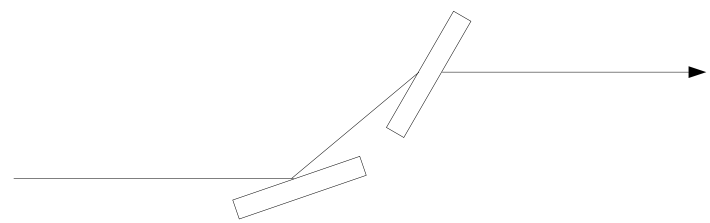
difference of 2 μm or 7 fs

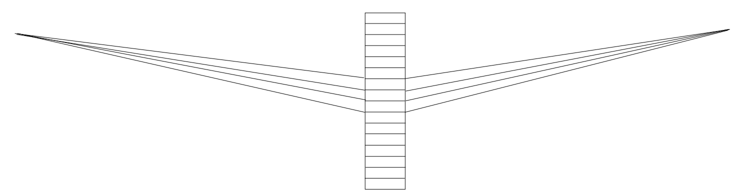
Tilt - Rotation, 10 keV, Si(220), Laue Geometry



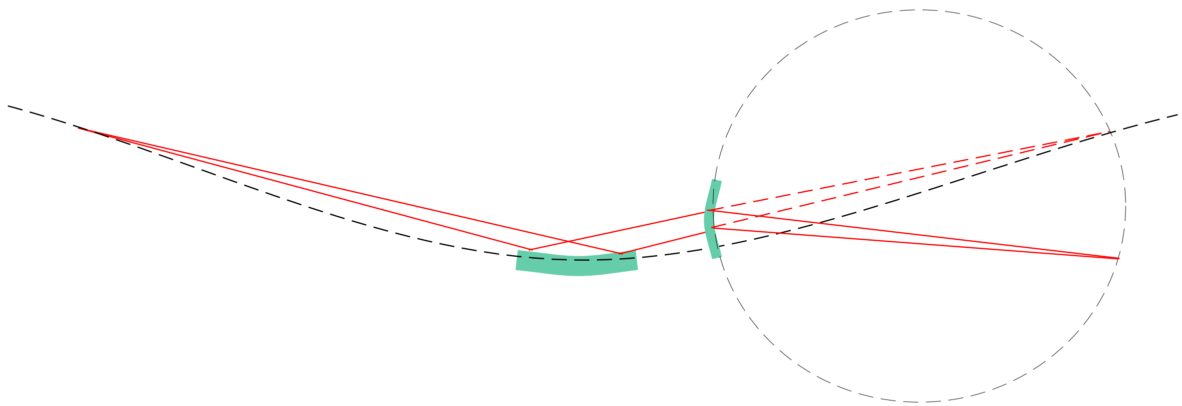




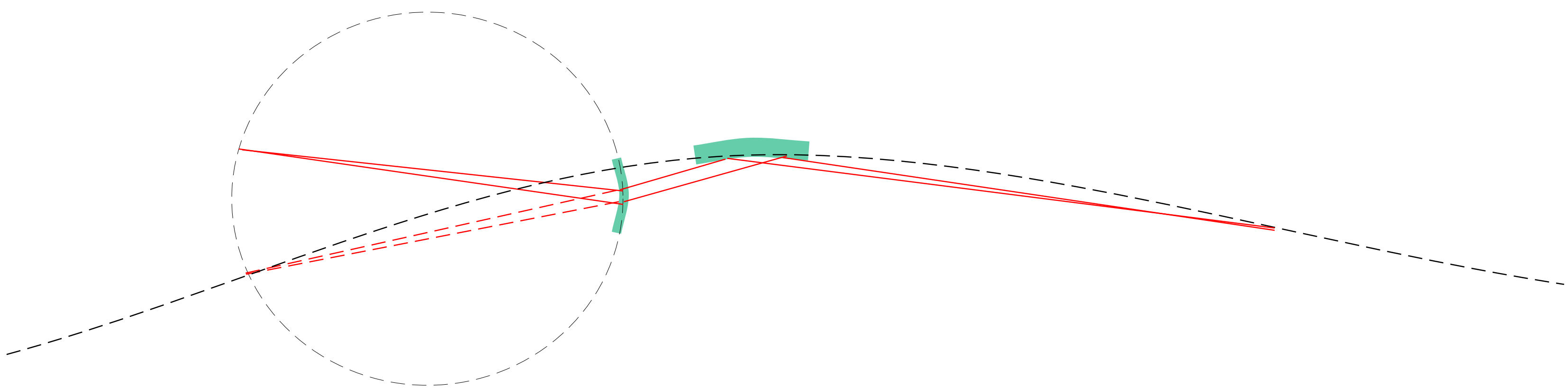




Minimizing Energy Spread and Focusing Without Mirrors



Laue-Bragg geometry with bent crystals in nested Rowland conditions



Summary

- Implementing compression optics to get < 2 ps seems possible.

- Compared to slitting alone, compression optics throughput enhancement would be 15- to 2-fold over 5 - 30 keV.

- Flux at ~10 keV would be about an order of magnitude less than "what you are used to" (i.e., flux delivered by ordinary Si(111) monochromator in central radiation cone).

- A given optics system could be tuned/scanned in energy over roughly 10 keV wide ranges.

- Main "loose end" has to do with mirrors and focusing the transversely large, time-compressed beam to a reasonable (~mm) spot size. Simulations in progress.

- Microfocusing does not seem possible with compression, but can be done with just slitting alone.

- Remember: RF-deflection destroys the source vertical brilliance, resulting in large vertical divergence. One might have to do scattering experiments in the horizontal plane.