Focusing of 80 keV x-rays using Si sawtooth lenses at 1-ID: first results

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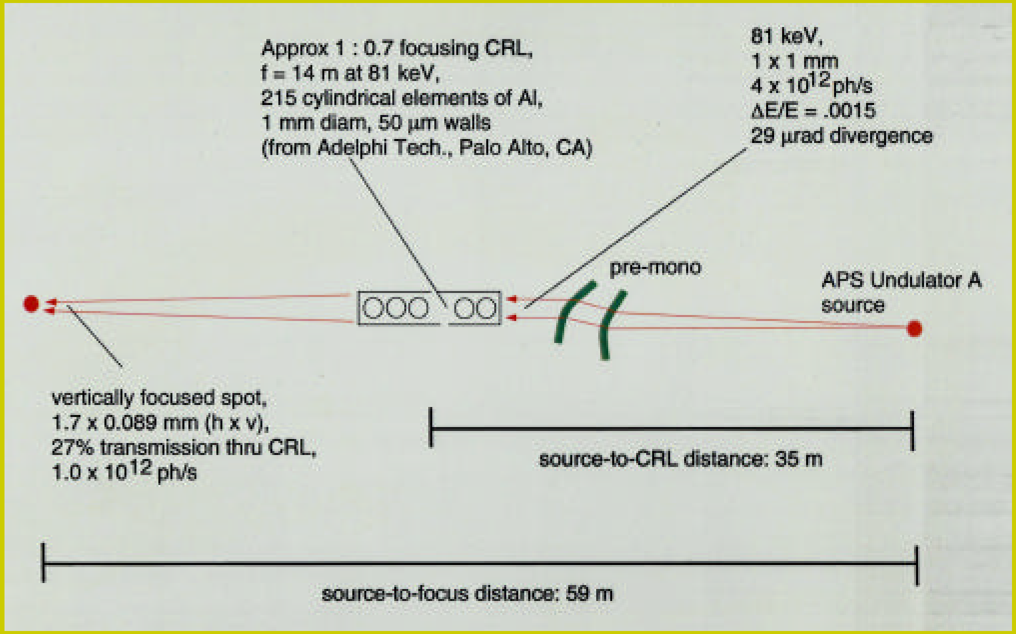
Motivation

Use CRLs for weak vertical focusing (s_o:s_i=1:0.7) of monochromatic high-energy x-rays (50<E<120 keV). Monochromator – 2 bent Si crystals, Rowland geometry – brilliance preserving

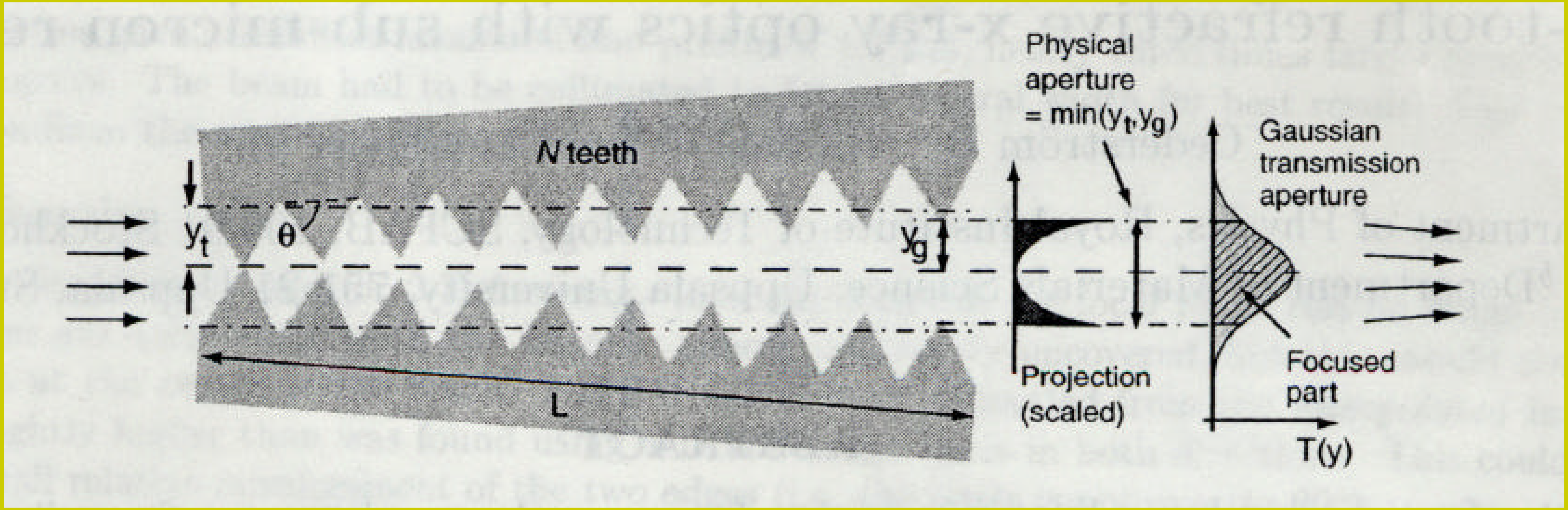
- Applications include SAXS and WAXS (including anomalous scattering with high-resolution mono after CRL)
- First CRL work at 1-ID: drilled holes in polycrystalline Al
- Gave ~4x gain in ~90um



Attempt to use sawtooth CRLs

- 'Parabolic' profile – reduced geometric aberrations
  - Single-crystal Si – reduced CRL-induced SAXS, cleaner profile
- Easy to modify focal length

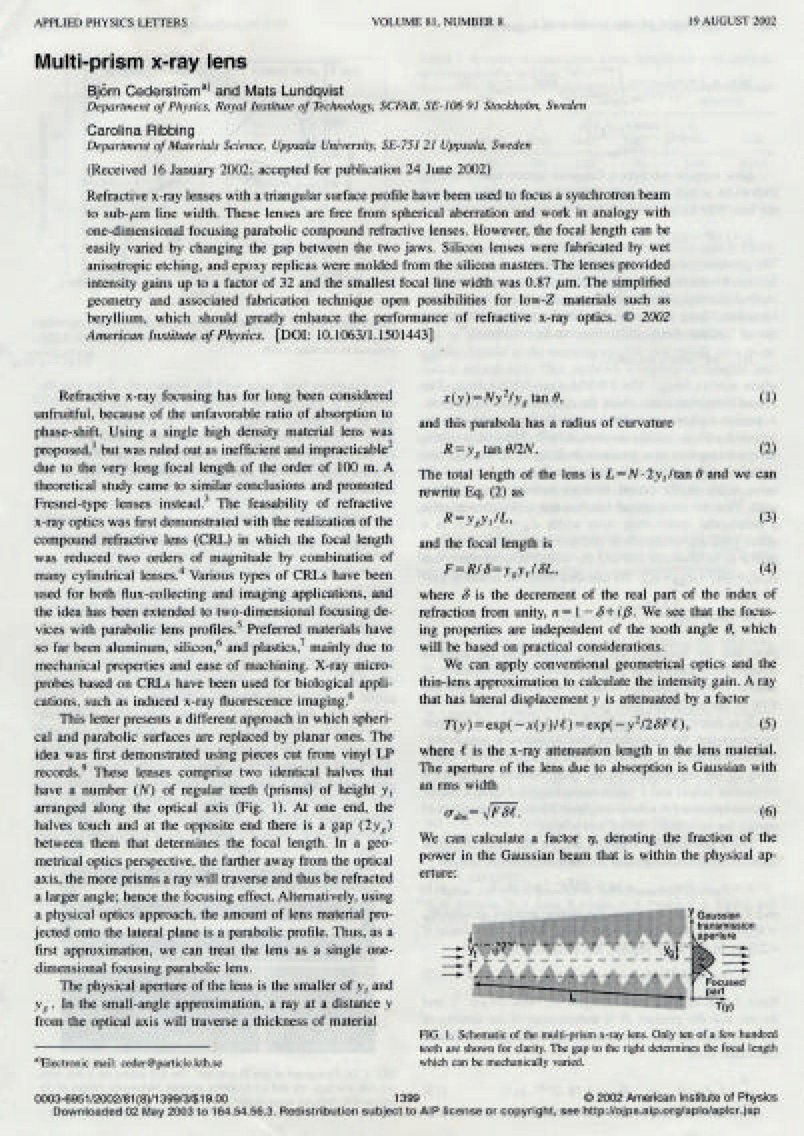
Sawtooth CRLs - principles



- Focusing principle – further away a photon is from the optical axis, the more teeth it will traverse and thus be refracted.
- Photons passing along optical axis will suffer zero absorption (in contrast to cylindrical geometry)
- The amount of lens material projected on the lateral plane is a (nearly) parabolic profile

  can treat as a single 1-d focusing parabolic lens
- Magnitude of the gap (y_g) determines the focal length

Sawtooth CRLs – background



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Multi-prism x-ray lens

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Refractive x-ray lenses with a triangular surface profile have been used to focus a synchrotron beam to sub-μm line width. These lenses are free from spherical aberration and work in analogy with one-dimensional focusing parabolic compound refractive lenses. However, the focal length can be easily varied by changing the gap between the two jaws. Silicon lenses were fabricated by wet anisotropic etching, and epoxy replicas were molded from the silicon masters. The lenses provided intensity gains up to a factor of 32 and the smallest focal line width was 0.87 μm. The simplified geometry and associated fabrication technique open possibilities for low-*Z* materials such as beryllium, which should greatly enhance the performance of refractive x-ray optics. © 2002 *American Institute of Physics.* [DOI: 10.1063/1.1501443]

Refractive x-ray focusing has for long been considered unfruitful, because of the unfavorable ratio of absorption to phase-shift. Using a single high density material lens was proposed,[1] but was ruled out as inefficient and impracticable[2] due to the very long focal length of the order of 100 m. A theoretical study came to similar conclusions and promoted Fresnel-type lenses instead.[3] The feasibility of refractive x-ray optics was first demonstrated with the realization of the compound refractive lens (CRL) in which the focal length was reduced two orders of magnitude by combination of many cylindrical lenses.[4] Various types of CRLs have been used for both flux-collecting and imaging applications, and the idea has been extended to two-dimensional focusing devices with parabolic lens profiles.[5] Preferred materials have so far been aluminum, silicon,[6] and plastics,[7] mainly due to mechanical properties and ease of machining. X-ray microprobes based on CRLs have been used for biological applications, such as induced x-ray fluorescence imaging.[8]

This letter presents a different approach in which spherical and parabolic surfaces are replaced by planar ones. The idea was first demonstrated using pieces cut from vinyl LP records.[9] These lenses comprise two identical halves that have a number (N) of regular teeth (prisms) of height y_1 arranged along the optical axis (Fig. 1). At one end, the halves touch and at the opposite end there is a gap ($2y_g$) between them that determines the focal length. In a geometrical optics perspective, the farther away from the optical axis, the more prisms a ray will traverse and thus be refracted a larger angle; hence the focusing effect. Alternatively, using a physical optics approach, the amount of lens material projected onto the lateral plane is a parabolic profile. Thus, as a first approximation, we can treat the lens as a single one-dimensional focusing parabolic lens.

The physical aperture of the lens is the smaller of y_1 and y_g. In the small-angle approximation, a ray at a distance y from the optical axis will traverse a thickness of material

$$x(y) = Ny^2/y_g \tan\theta, \qquad (1)$$

and this parabola has a radius of curvature

$$R = y_g \tan\theta/2N. \qquad (2)$$

The total length of the lens is $L = N \cdot 2y_1/\tan\theta$ and we can rewrite Eq. (2) as

$$R = y_g y_1/L, \qquad (3)$$

and the focal length is

$$F = R/\delta = y_g y_1/\delta L, \qquad (4)$$

where δ is the decrement of the real part of the index of refraction from unity, $n = 1 - \delta + i\beta$. We see that the focusing properties are independent of the tooth angle θ, which will be based on practical considerations.

We can apply conventional geometrical optics and the thin-lens approximation to calculate the intensity gain. A ray that has lateral displacement y is attenuated by a factor

$$T(y) = \exp(-x(y)/\ell) = \exp(-y^2/2\delta F\ell), \qquad (5)$$

where ℓ is the x-ray attenuation length in the lens material. The aperture of the lens due to absorption is Gaussian with an rms width

$$\sigma_{abs} = \sqrt{F\delta\ell}. \qquad (6)$$

We can calculate a factor η, denoting the fraction of the power in the Gaussian beam that is within the physical aperture:

FIG. 1. Schematic of the multi-prism x-ray lens. Only ten of a few hundred teeth are shown for clarity. The gap to the right determines the focal length which can be mechanically varied.

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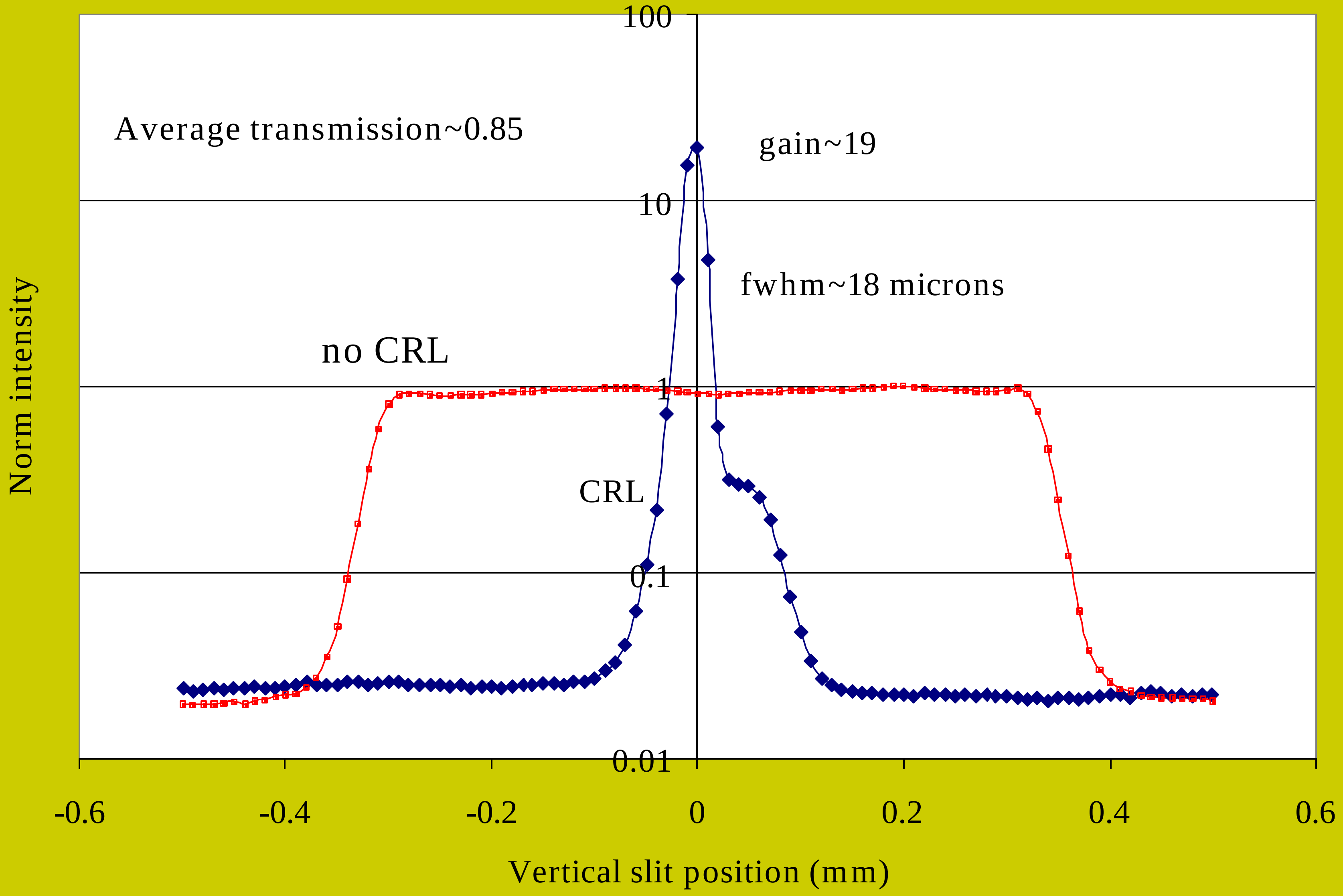
- First tests at ESRF BM5 on vinyl LPs (!), Si, Be and epoxy-based systems
- Focal lengths f~ 30 cm (s_o :s_i ~ 120:1)
- Using Si at E=30 keV, achieved 1-d vertical beamsize of 0.74 μm at gain of 40
- Also did 2-d focusing (crossed-CRLs) to 1x5.4 μm^2 for a gain of 84.

- Some activity with Li-based CRLs at APS (Dufresne)
- We got Si-based CRLs from Carolina Ribbing fall 2003…

CRL testing at 1-ID

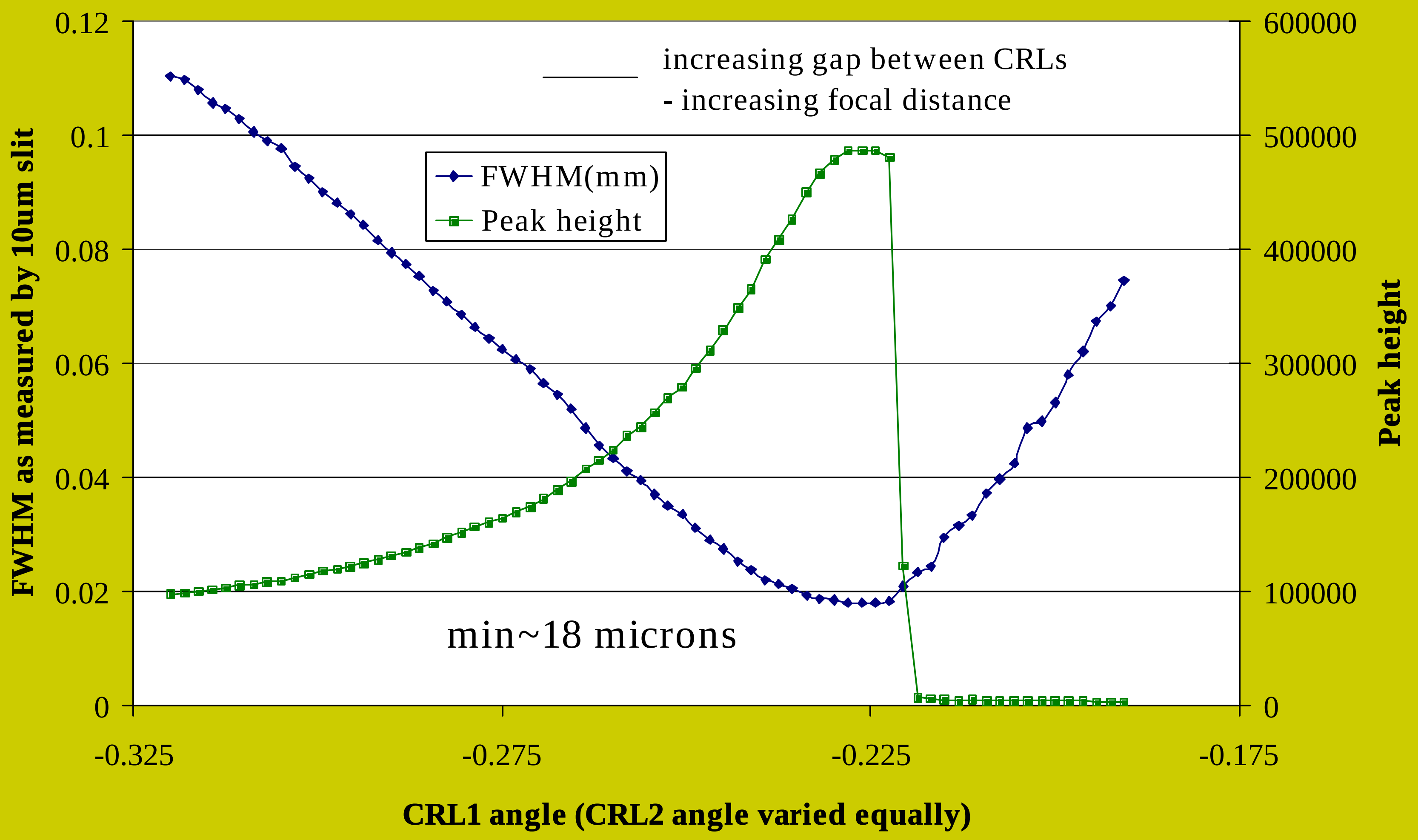
- Use 2 CRLs for vertical focusing:
  - 230 teeth per CRL
  - Tooth angle=57 degrees (anisotropic etch away from 111)
  - Tooth depth y_t=0.2 mm (maximum aperture=0.4mm)
  - Length=65mm (~1/e absorption length at 80keV)
- Experiment
  - Put CRLs in B-hutch, measure in C-hutch (s_i/s_o~24m/35m=0.7)
  - CRLs offset 1m along beam, mounted on separate stages
  - Set HE mono at 80.7 keV (Au edge)
  - Use UA at closed gap (11.5mm), in low-emittance mode – σ_y=8μm (d_o(fwhm)=19μm)
  - Theoretical minimum size $d_i=d_o(s_i/s_o)$ ~ 19*0.7 ~ 13μm
  - Theoretical gain=43

CRL results – beam profile

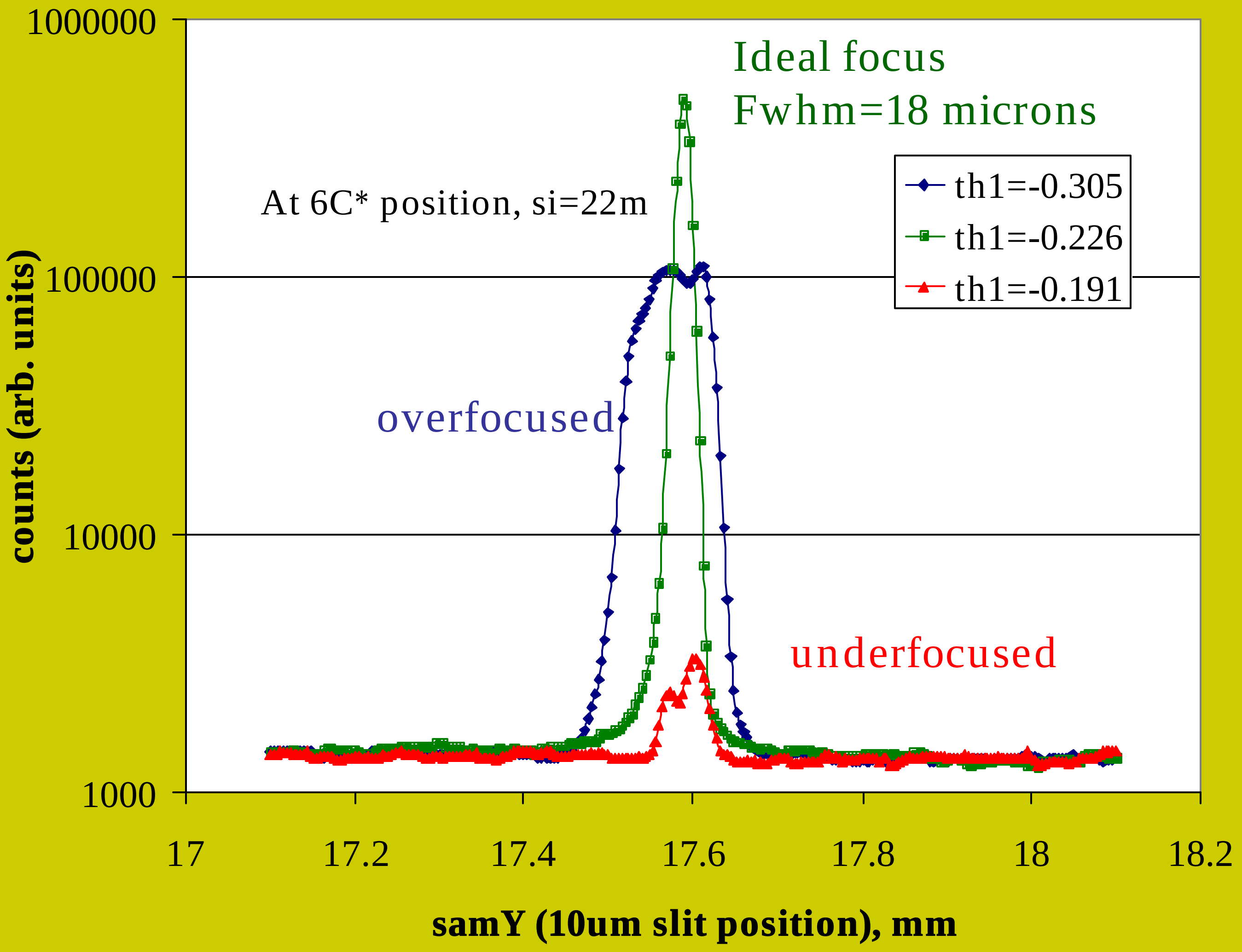


CRL results - focusing

Focusing of 80.7keV x-rays at 6C* position using Si sawtooth CRLs in B-hutch



CRL results – beam profile



Summary

- First test of Si sawtooth CRLs indicates good 'weak' focusing of high-energy x-rays
  - Focal size~18 microns (13 micron ideal)
  - Gain~19 (43 ideal)
  - Both significant improvements over Al cylindrical lenses
- Show clean tails – good for HE-SAXS
- Combine with other optical elements
  - High-resolution monochromator
  - Sagittal bending of mono (horizontal focusing)