Lithium metal in refractive x-ray optics for synchrotrons

N. R. Pereira, Ecopulse, Inc
E. M. Dufresne, D. A. Arms, R. Clarke,
University of Michigan and MHATT-CAT

(NRP supported by SBIR from MDA)

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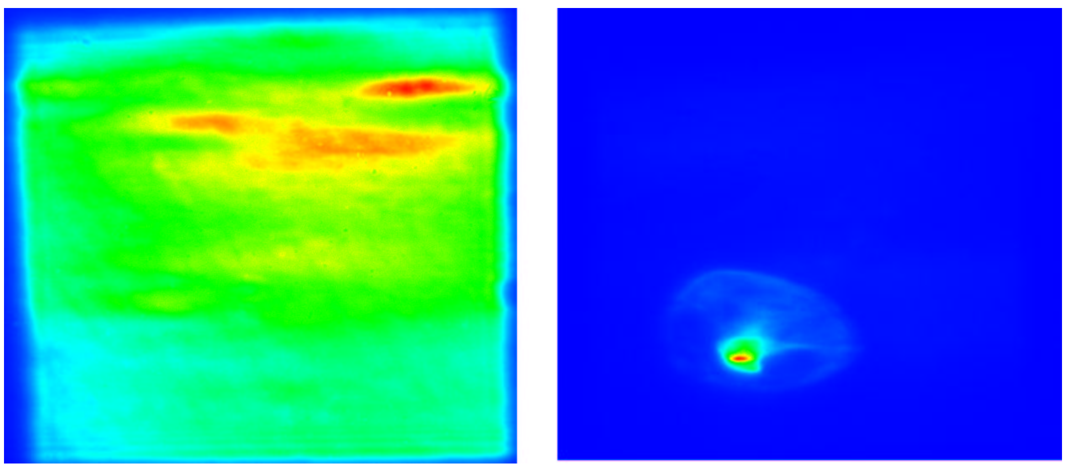
Intensity 40x w/ 50 % of hν

- 0.5 mm square, 10 keV x-ray beam into 0.03x0.02 mm
  - Intensity good for ultrafast
  - Collimation helps with nano...



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Refraction vs alternatives

- Microstructured (zone plate, Fresnel lens)
- (sub)-nanostructured (crystals, Bragg reflection)
  - curved cylindrical, spherical, ...
  - Reflection and transmission, large angles
- Uniform medium: reflection ($n < 1$) & refraction
  - K-B mirrors, capillaries, ...; need supersmooth surface
  - Refraction (small phase shifts, transmission)
    - Macrostructures, 'optical' surface, low cost

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X-ray refraction history

- Known since 1920s, understood 1930s.
    - Too small for useful lenses (on traditional sources)
        - Correction to Bragg diffraction angles
        - Glancing incidence mirrors (Kirkpatrick-Baez, 1948)
- 1991: Weak lens matches synchrotrons
        - remembered by Suehiro et al., rejected by Michette, Yang, ...
- 1996: Compound Refractive Lens (CLR)
    - 30 holes in aluminum (Snigirev et al., 1996)

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X-ray refraction basics

- Refractive index: $n = 1 - \delta - i\beta$
  - δ phase shift $((\omega_p/\omega)^2$ & $n_e)$, β absorption (nuclei)
  - Propagation: $\exp(-ik\delta x)\ \exp(-k\beta x)$
  - δ small (10^{-4}-10^{-6},like hot/cold air for visible light)
- δ/β: phase shift/attenuation length
  - Large δ/β good (δ/β almost infinite in optical)
  - δ/β = 2500 for Li (Be, 600, plastics, 200)

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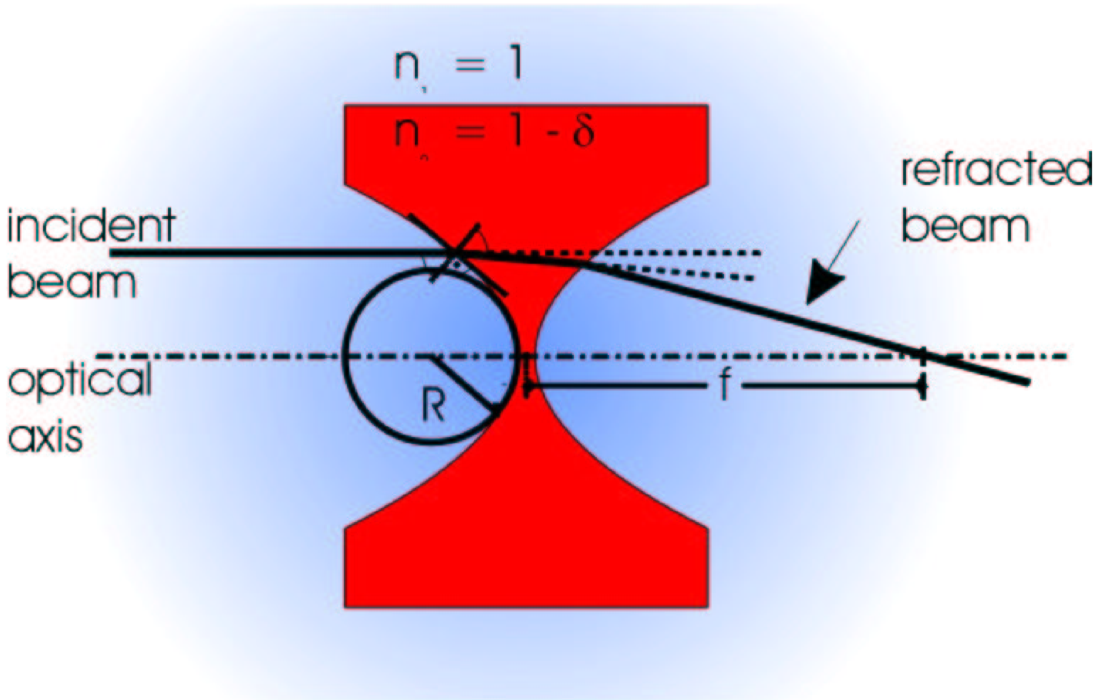
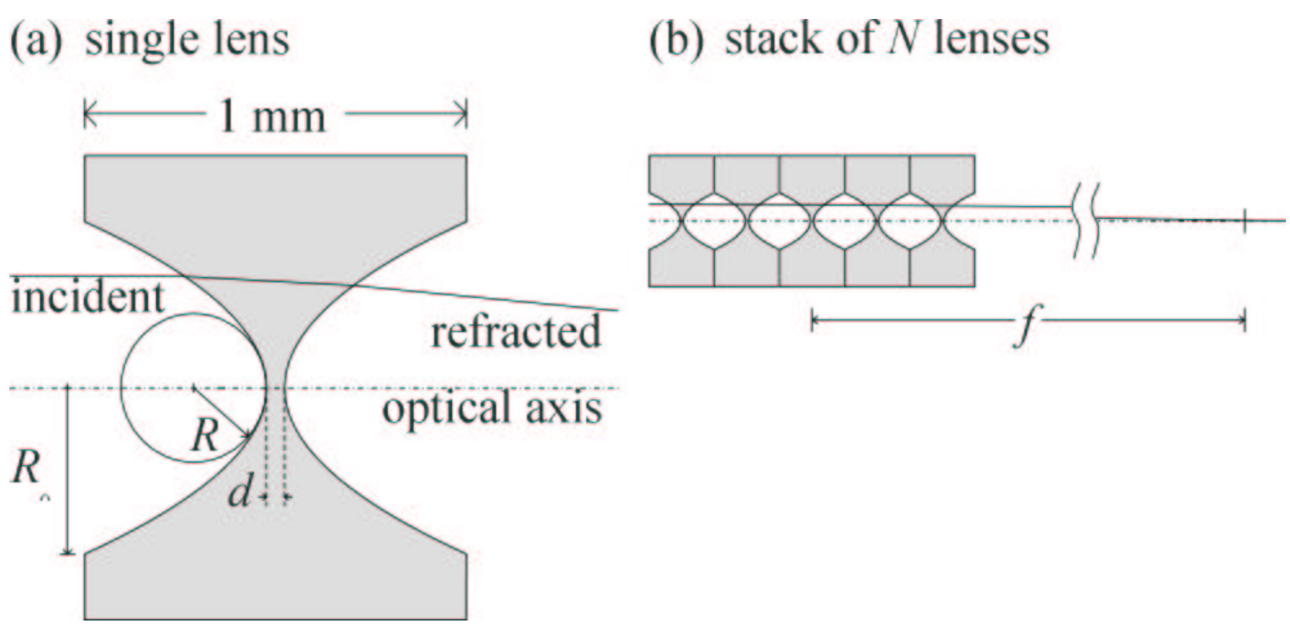
Small δ, small deflection

- Single parabolic lens (Aachen): f=R/2(n-1)= R/2δ
  - 100 m for Li (R = 0.2 mm, 10 keV, $\delta = 10^{-6}$), 20 m for Al.



Stack lenses, add deflections

- N lenses: f = R/2Nδ (Snigirev, 1996)



X-ray lenses today

- Collimators on synchrotrons (esp. ESRF)
    - Fixed focus (spherical, parabolic)
    - Variable focus (Cederstrom's multiprism)
- Imaging (Aachen, Lengeler):
    - Microbeam, microscopy, etc: research ongoing
- Materials: Al, plastics, Be
    - Fabrication favors Al, plastics (but, radialysis)
    - Ecopulse champions Li

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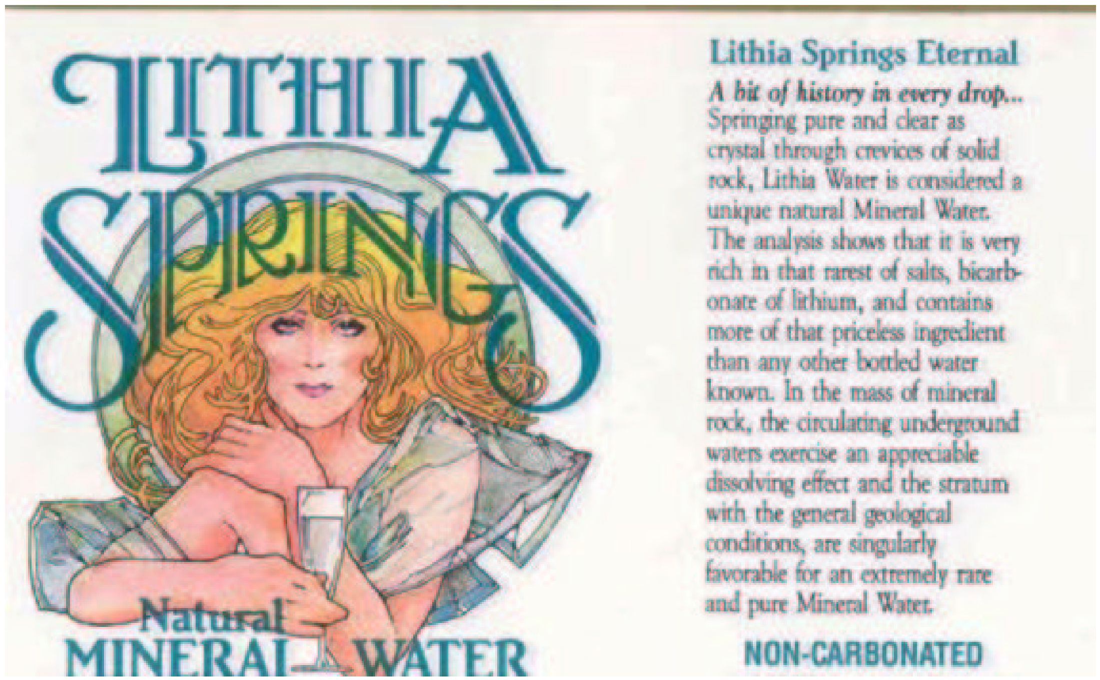
Lithium: good for you!



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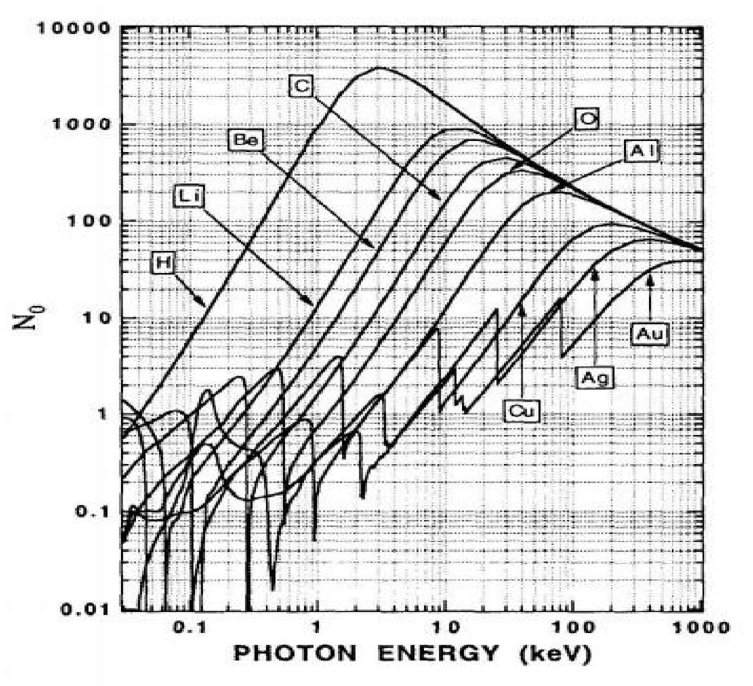
Li most promising

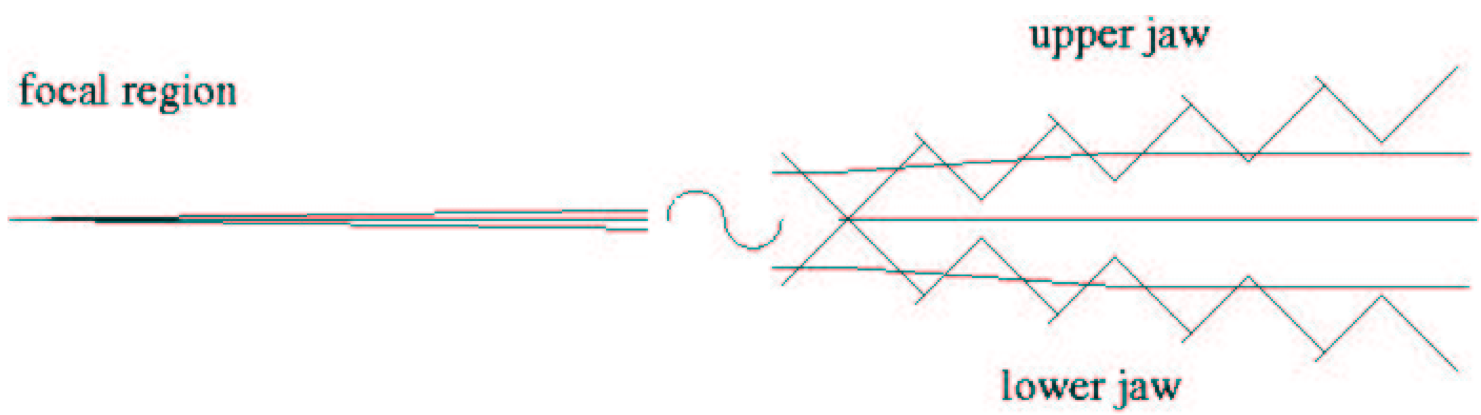
– Highest δ/β (= Yang's 1993 $N_0 = \delta/2\pi\beta$)

  • Li's density low (0.5 g/cm^3), long x-ray path



Multiprism = lens for x-rays

- Each prism deflects little (microradians)
- Many prisms approximate parabola (at shallow angle)
- Cederstrom, 2000



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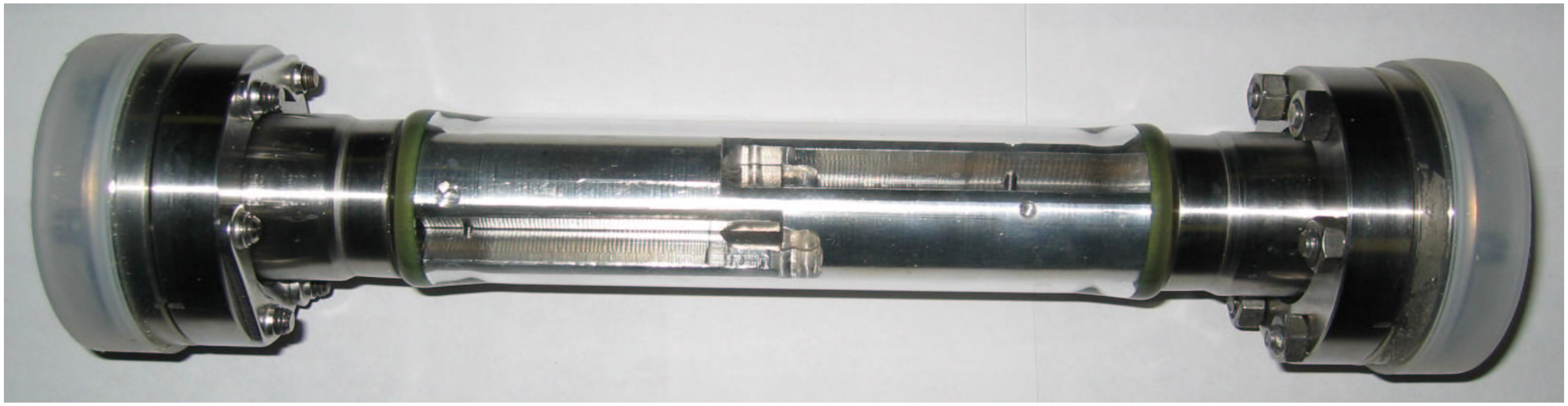
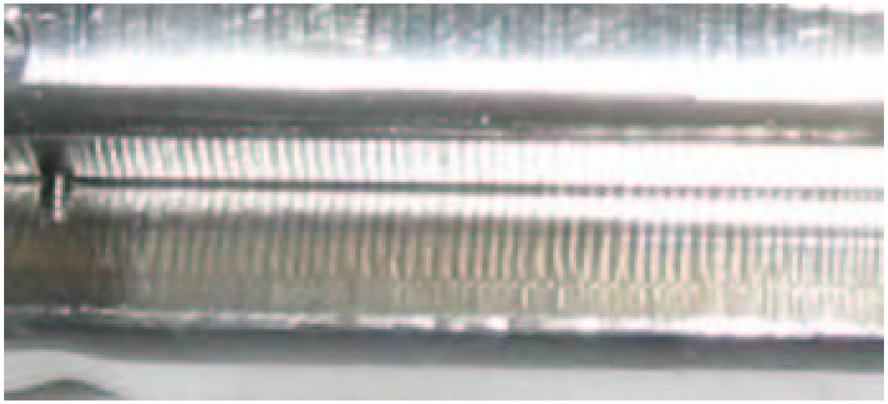
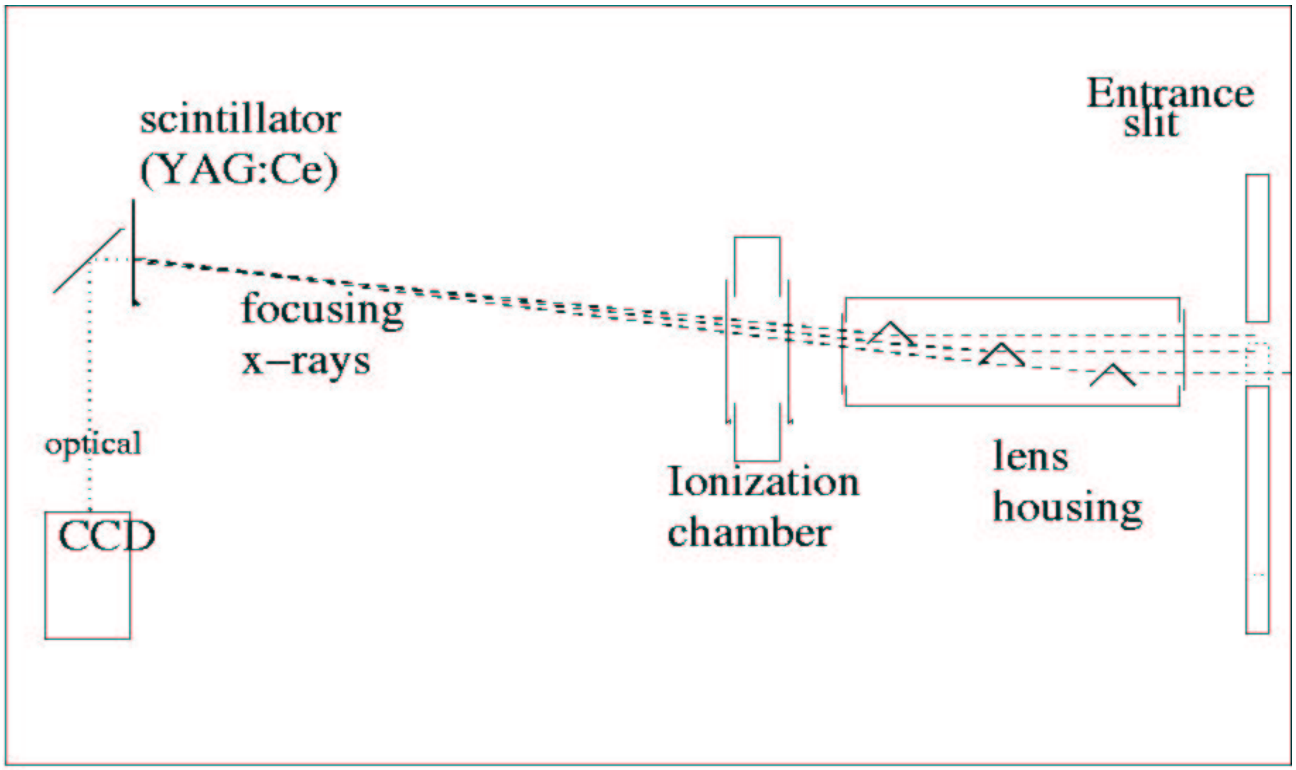
2D Li multiprism

- 2x110 prisms, 300 mm long (2 ¾ inch conflat)





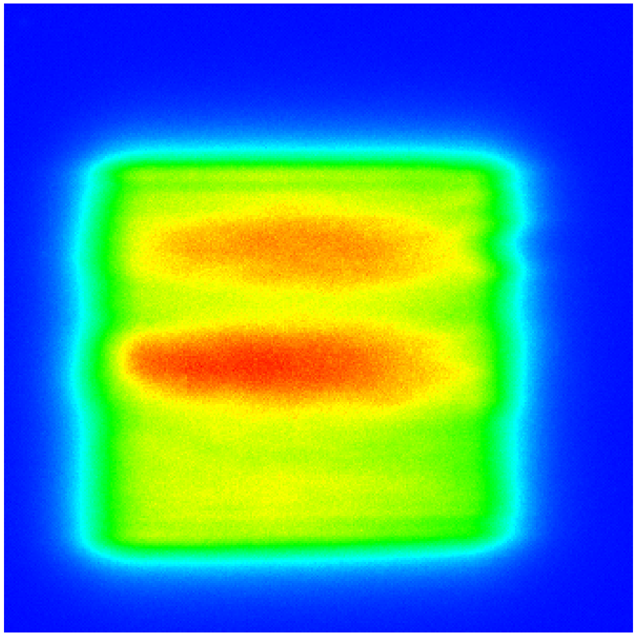
Geometry

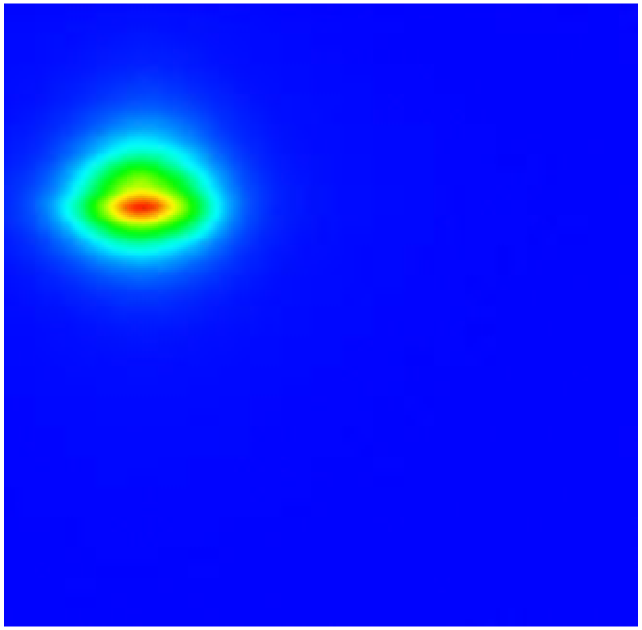


Experimental setup: the actual lens has 80 teeth, which deflect only 0.1 degree

Multiprism collimation

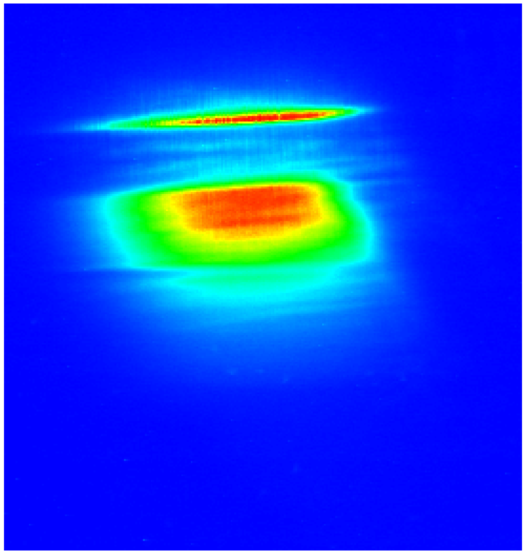
- Gain 18x: OK, not great





Multiprism is versatile

- Can focus off-axis, cleans beam
  - Image at 5x nominal focal length: filtered x-rays
  - Top is 10 keV, bottom 30, 50 keV harmonics



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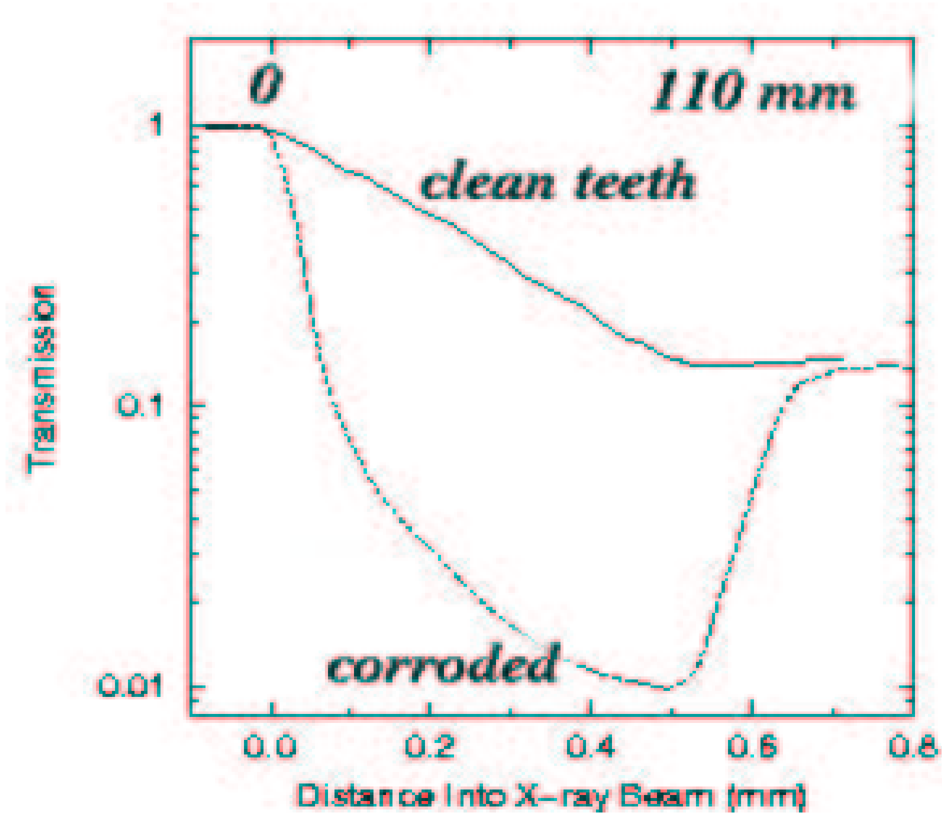
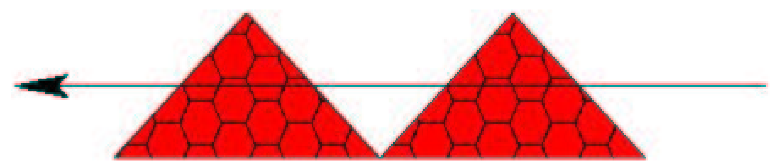
Issues with Li

- Flammable solid, corrodes in moist air
  - Permission from safety people essential
  - Inert (dry, He (Ar), vacuum) environment
  - Special shipping: Ecopulse has US approval to ship
- Fabrication: little experience & lore
  - Extrudes, molds easily
  - Sticks to metals (use polypropylene, delrin for molds)
  - Esoteric metallurgy

Corrosion easy to see





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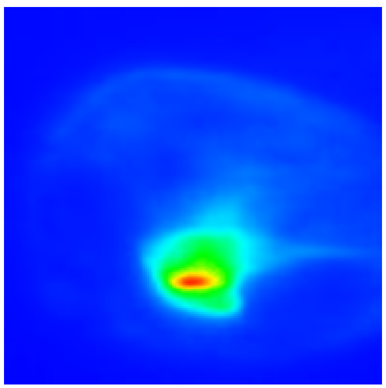
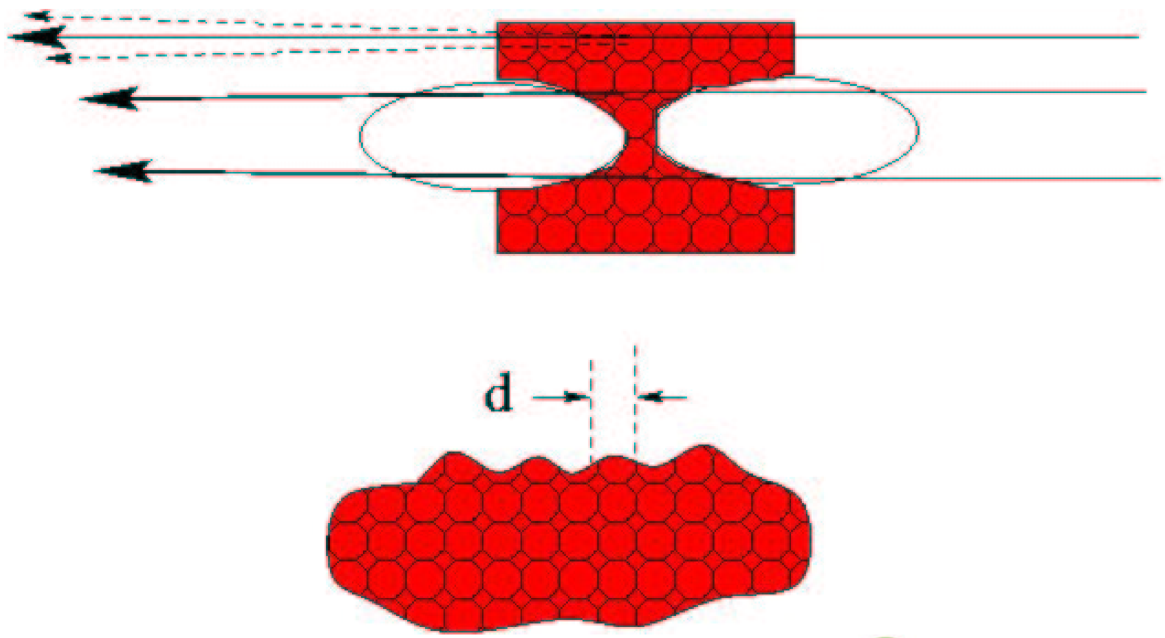
Problem: SAXS

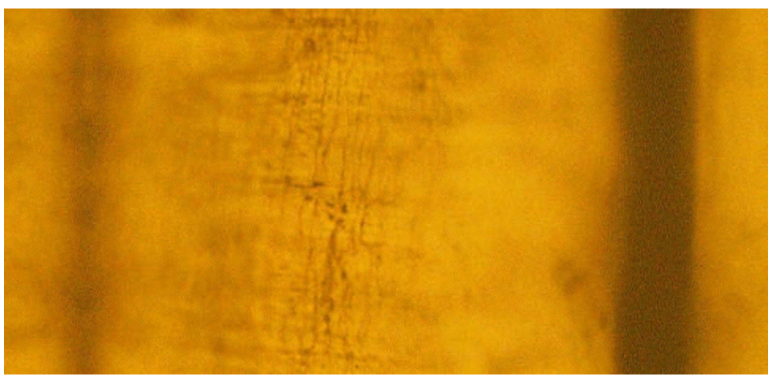
- Demagnified source 2 micron, actual 20 micron.
  - (SAXS: small-angle x-ray scattering: $\alpha = \lambda/d$)

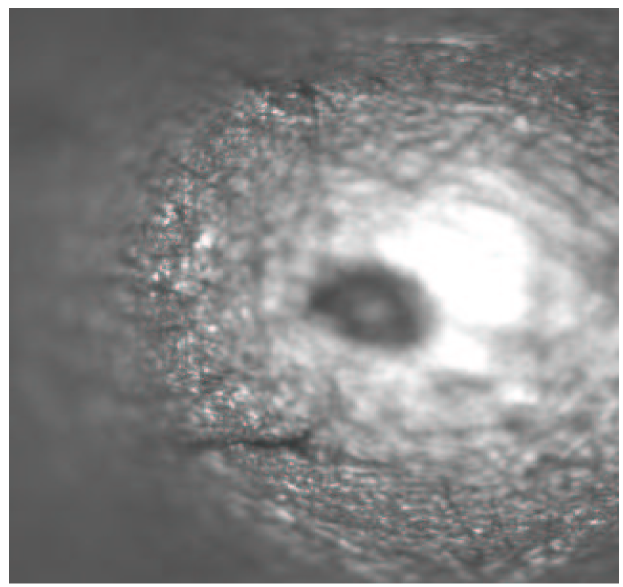




Surface scattering?

- Embossing gives modest surface quality
  - Oxide layer? (original extrusion in dry air)
  - 0.5 mm prism & 0.2 mm parabola (0.02 mm up)





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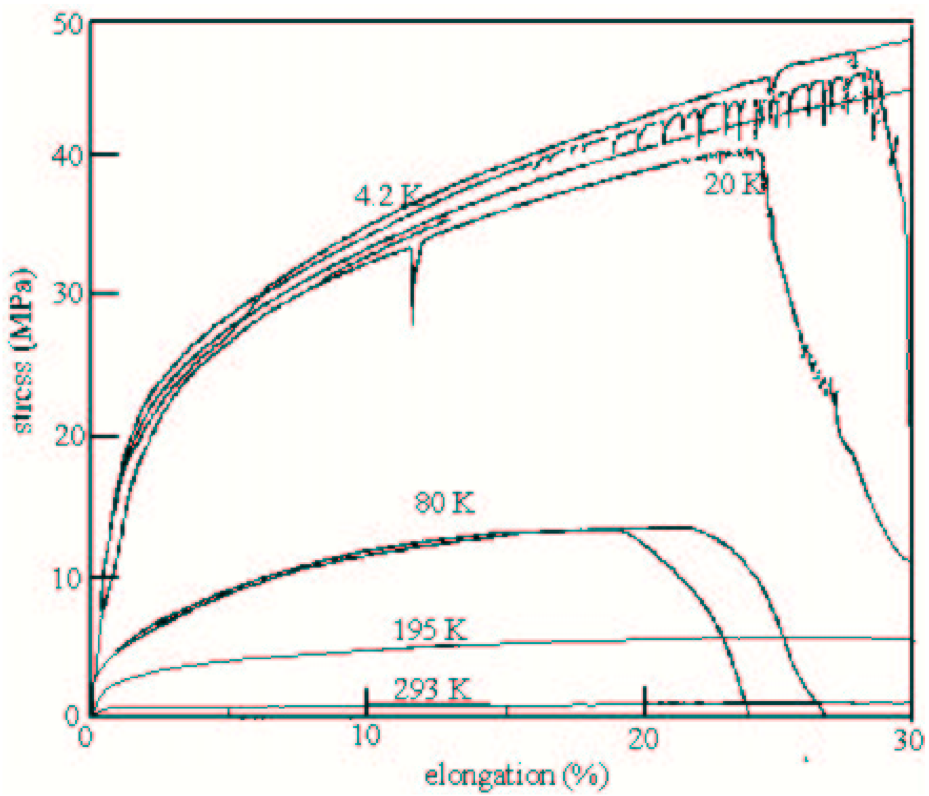
Li metallurgy (1)

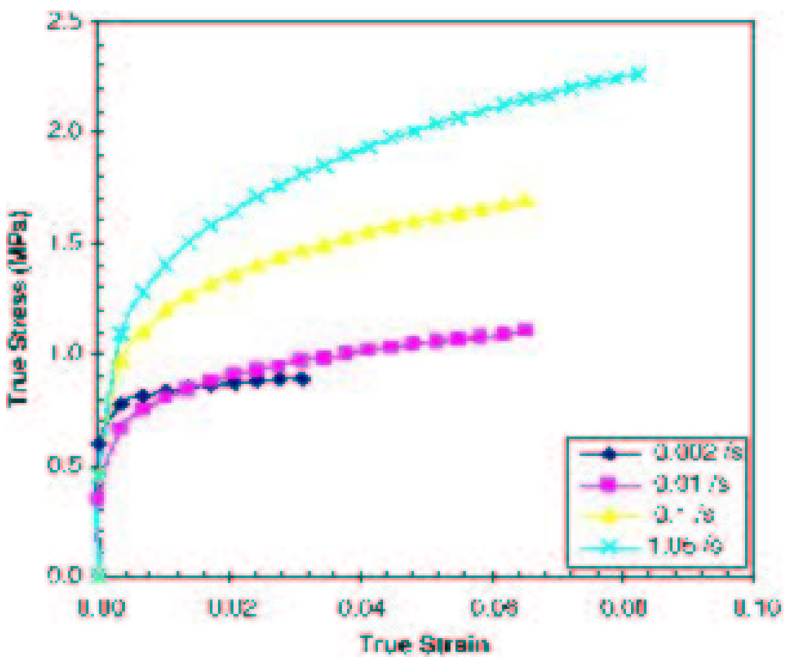
- Temperature affects strength (Hill & Rosenberg, 1959)
- Li is bcc metals, like Mo, W: cool Li mimics hot W



Li metallurgy (2)

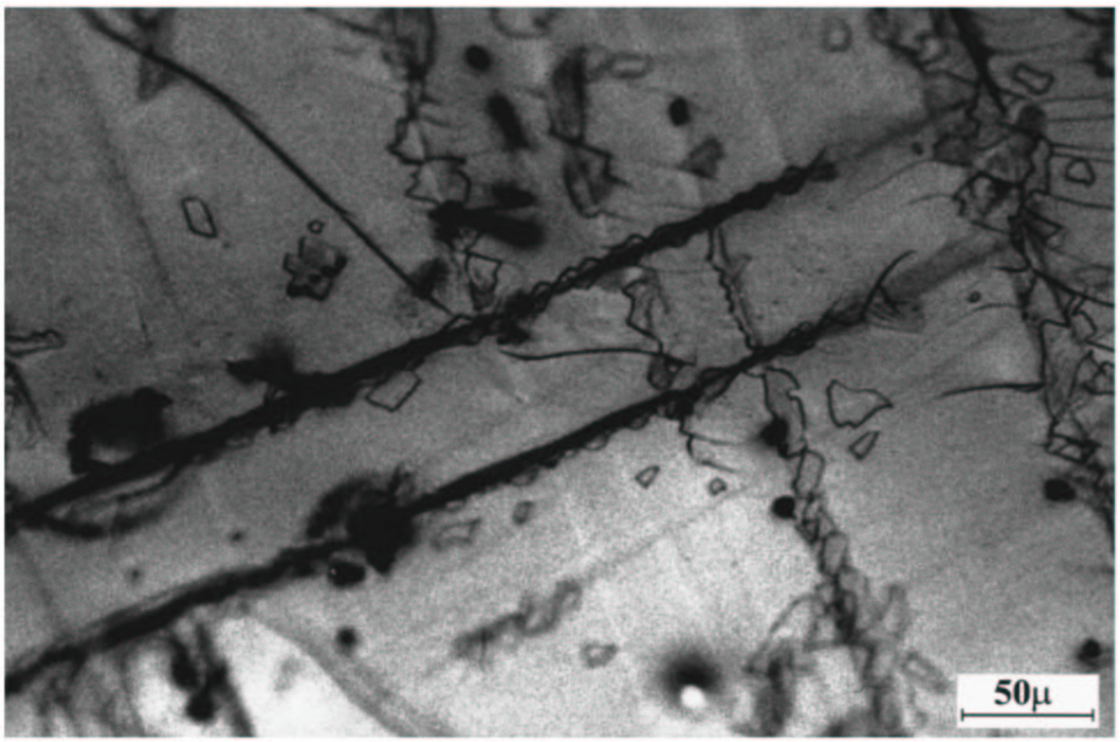
- Measured for Li proton lens (Tariq, FNAL, 2003)
- Follows Perzyna model

$$\sigma = \sigma_0[1 + (\frac{\dot{\epsilon}}{\gamma^*})^{1/\delta}]$$



Li metallurgy (3)

- Fundamental work in Vienna (Herke, Pichl, et al., 1975+)
- Flow stress in single crystals, boundaries, etc
- e.g., crystal boundaries after fcc to hcp transition at 78 K



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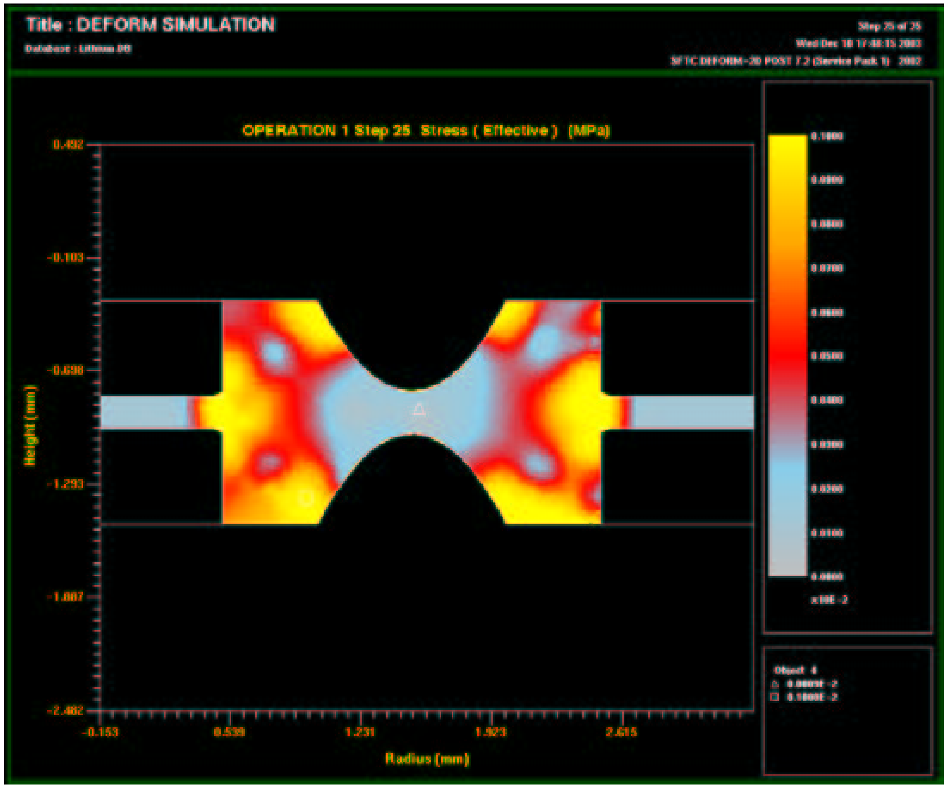
Embossing affects SAXS?

- (micro)crystallites created by embossing? Surface?
- Modeling by UW-Madison (Turng, Winardi)



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X-ray diffraction (Qadri, NRL)

- Extruded & deformed Li:
    - Sharp reflections (= large crystals)
    - Broad structure w/ 4 different (1-3 %) crystal parameters?
    - Local density variation 10 % (?)
- Li drop (slowly cooled)
    - Sharp reflections
    - Narrow structure, some reflections missing (?)

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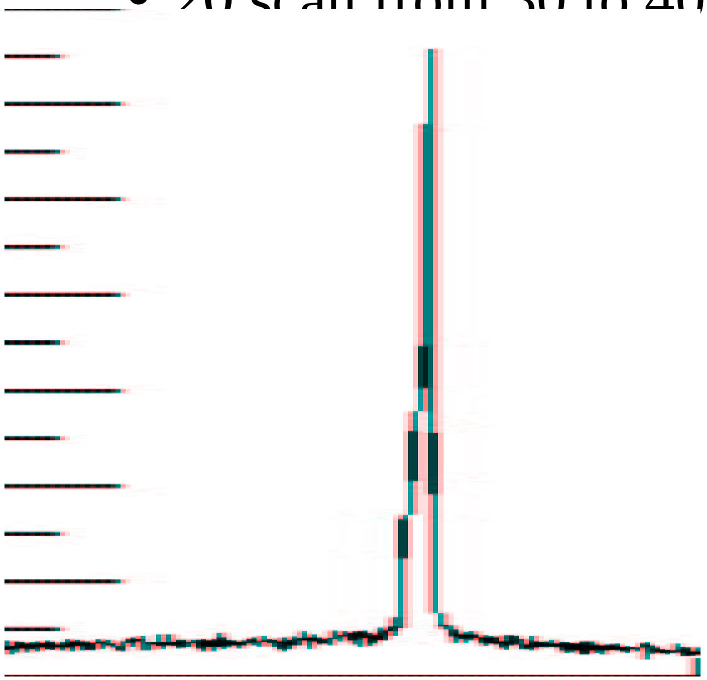
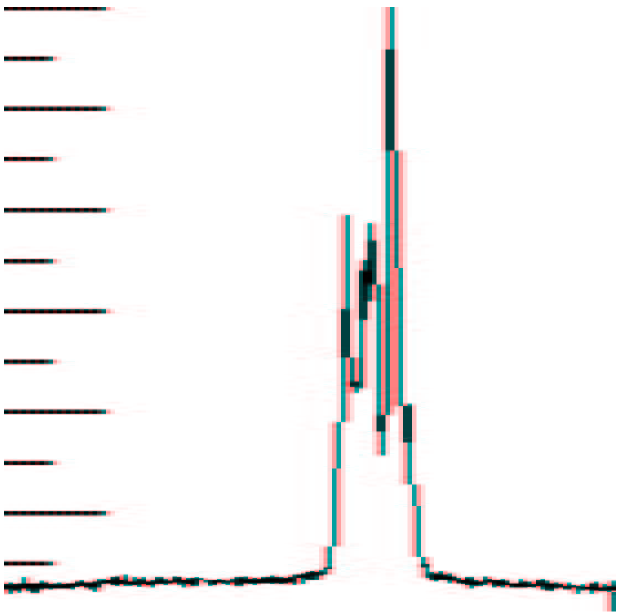
X-ray diffraction (Qadri, NRL)

- Gradually cooled (left) vs. extruded (right)
  - 2θ scan from 30 to 40 degrees: 110 reflection off bcc Li





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Fabrication alternatives:

- (electro)chemical machining of single crystal
  - For multiprism: must grow long, thin single crystal
- Liquid medium
  - Uniform density
  - shape with capillary force (0.4 N/m: water 0.07 N/m)
  - Liquid Li must wet substrate (i.e., w/o oxide layer)
- SAXS effects TBD, March 2004
  - Initial data from x-ray diffraction (Qadri, NRL)

Li ideal for intense x-rays

- $\Delta T = (\mu/\rho\, C_p)\, F$
  - (μ/ρ) lowest (7.5 & 0.5 cm^2/g at 3 & 8 keV)
  - C_p highest (25 J/gmol = 3.5 J/g at RT)
- Initial application: high fluence x-ray window
  - Survives easily at 3.1 keV & many J/cm^2
  - temperature increase 1/7 $K/(J/cm^2)$ at 8 keV
- Good for LCLS (8 keV, 0.1 J/cm^2/pulse,)

Status

- First use of Li for x-rays
  - windows
  - Collimation (on synchrotrons)
  - Microfocusing, imaging TBD
  - Interesting option for LCLS
- Issues: metallurgy, fabrication, ...
- Li x-ray lenses available now