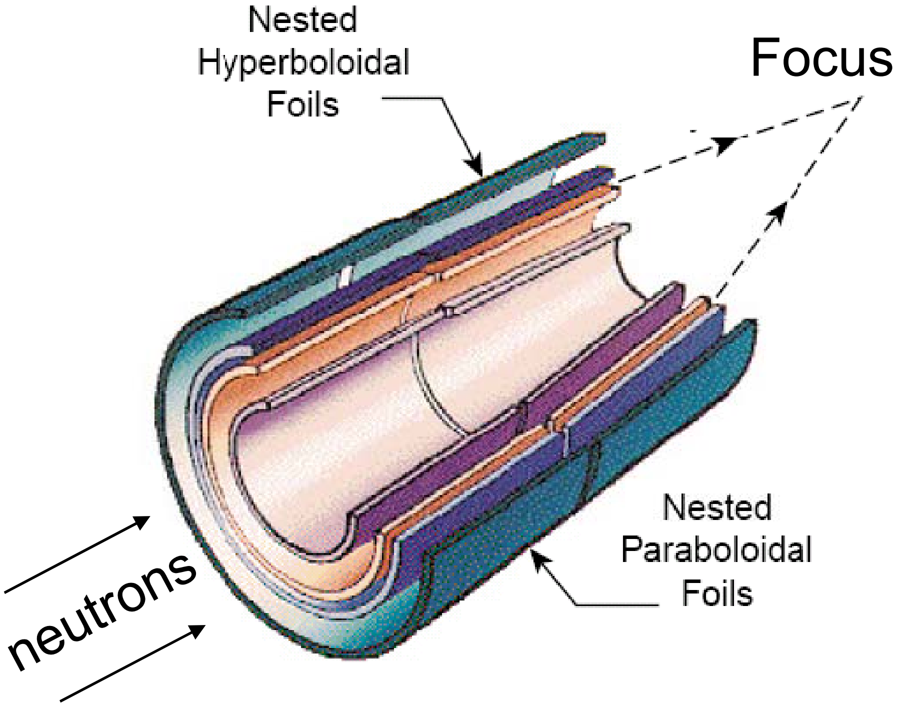
Focusing Optics for Neutrons:

From x-ray telescopes to Compact Neutron Sources



Boris Khaykovich
David Moncton
Nuclear Reactor Laboratory, MIT

Mikhail Gubarev
Marshall Space Flight Center, NASA

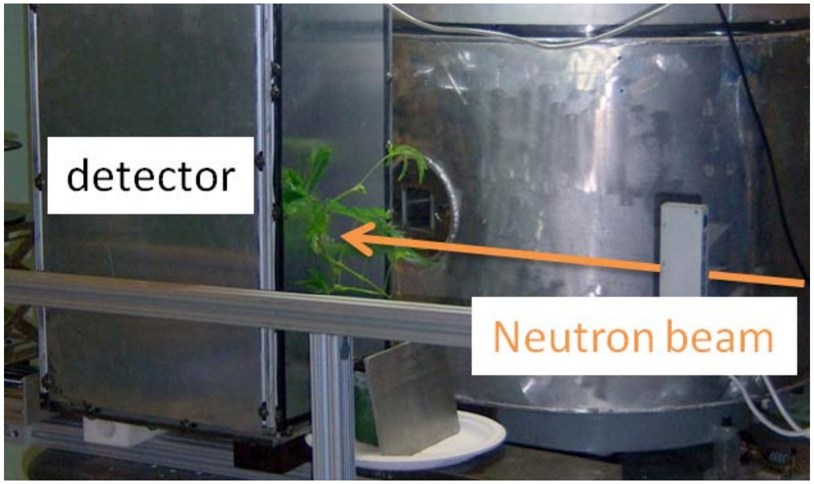
Jeffrey Gordon
Ben-Gurion University, Israel

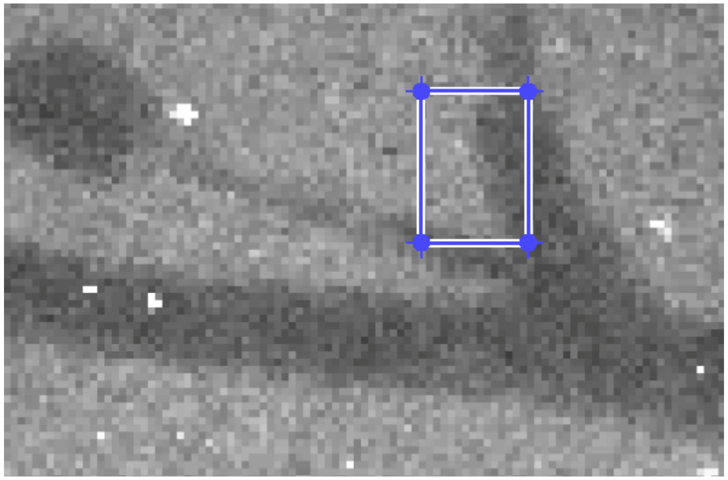
The Second Meeting of
The Union for Compact Accelerator-Driven Neutron Sources
UCANS-II

July 2011

MIT Reactor: a “compact source” at 6 MW

- Students training and preliminary experiments
- Thermal neutron diffractometer (~ 10^7 n/s @ 14.7 meV)
- Thermal neutron imaging facility





- Neutron-optics test station
- Student time-of-flight spectrometer with on-line capabilities

Motivation for focusing neutron optics

Preservation of source brilliance $(n/s\ \Delta_x\ \Delta_y\ \Theta_x\ \Theta_y\ \Delta\lambda)$

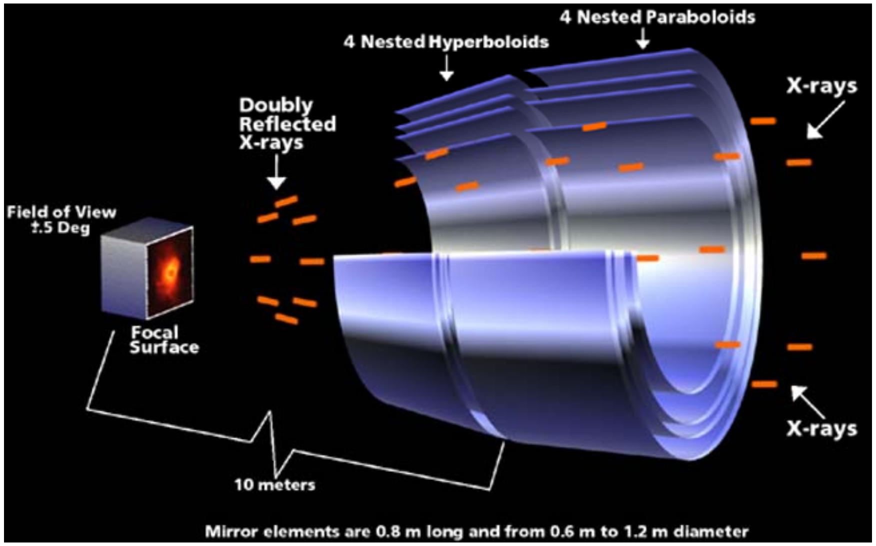
while trading-off beam size and angle

Choices for focusing optics for thermal neutrons

- **Diffractive optics:**
  - monochromatic applications only

- **Refractive optics:**
  - strong chromatic aberrations: $f \sim 1/\lambda^2$
  - very long focal length (~ 100 m for thermal neutrons)

- **Reflective optics:**
  - critical angle for thermal neutrons similar to that for hard x-rays
  - use technologies developed for x-ray telescopes



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

Current state-of-the-art: focusing guides

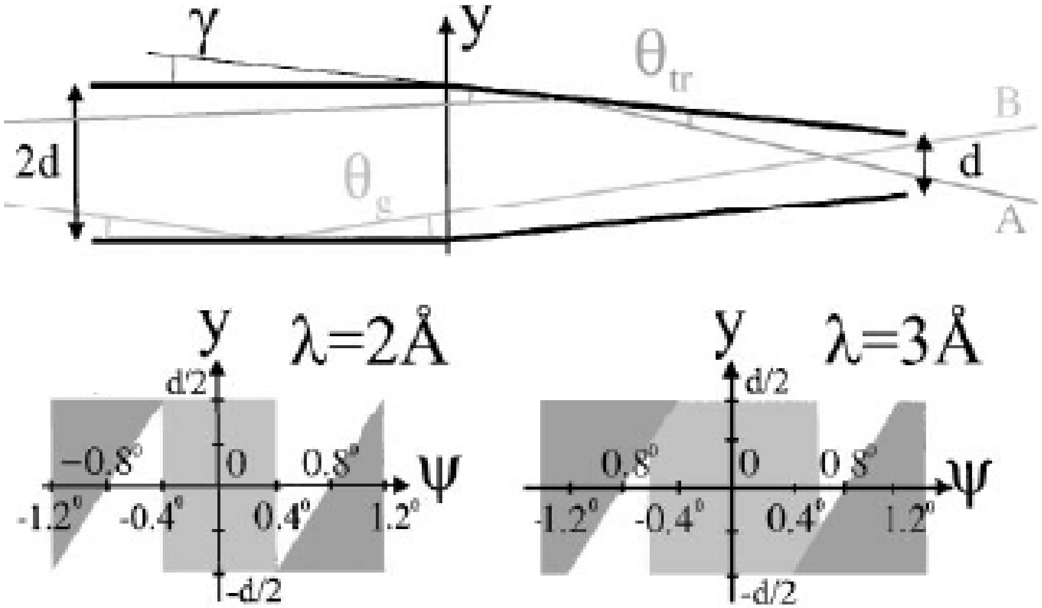
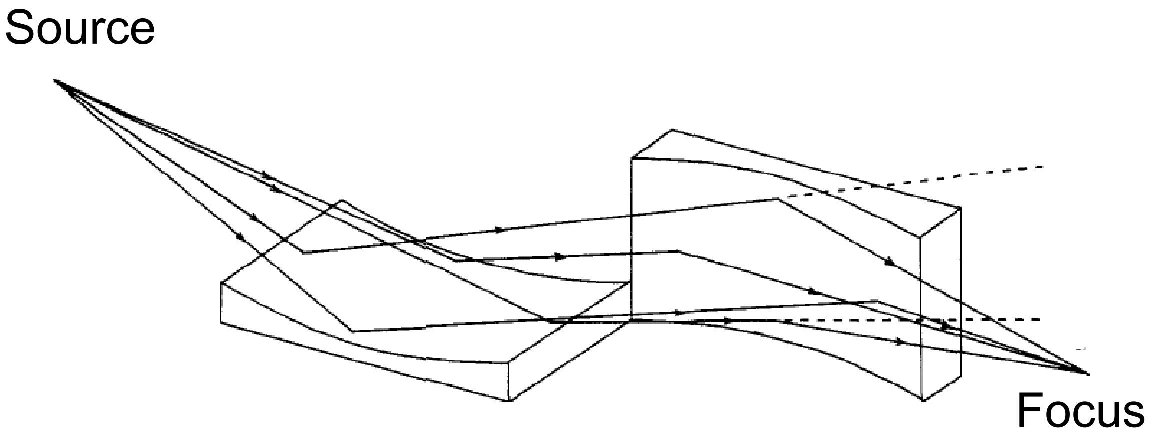


Figure from: P. Böni and collaborators

Preservation of source brilliance $(n/s\ \Delta_x\ \Delta_y\ \Theta_x\ \Theta_y\ \Delta\lambda)$
while trading-off beam size and angle

Kirkpatrick-Baez (KB) mirrors



Gene Ice and collaborators

- Relatively easy to produce
- Excellent for creating very small beams at synchrotrons

But

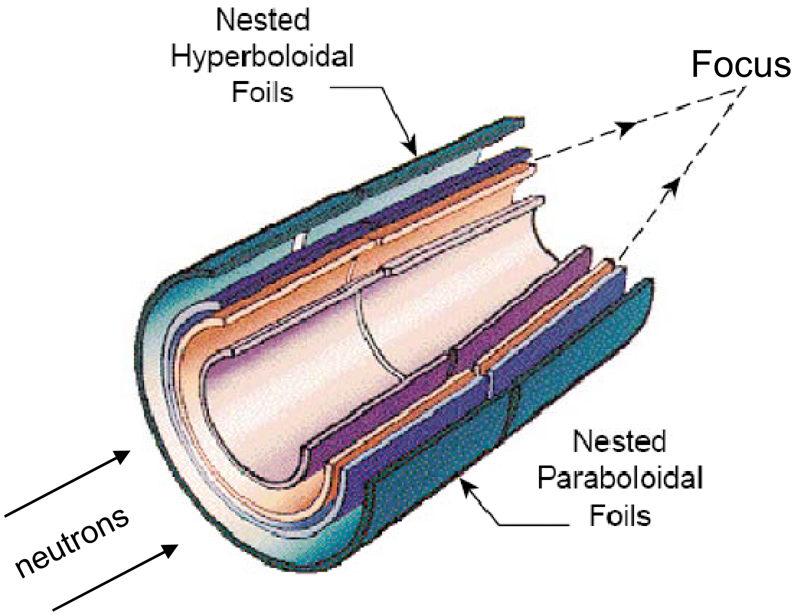
- Not very practical for neutron beam sources > 1 mm
- Only one reflection limits collection efficiency

New approach: axysimmetric Wolter optics

Advantageous for large neutron sources

Collect larger solid angle than KB and increase high-energy efficiency

Practically aberration-free: useful for some ToF methods



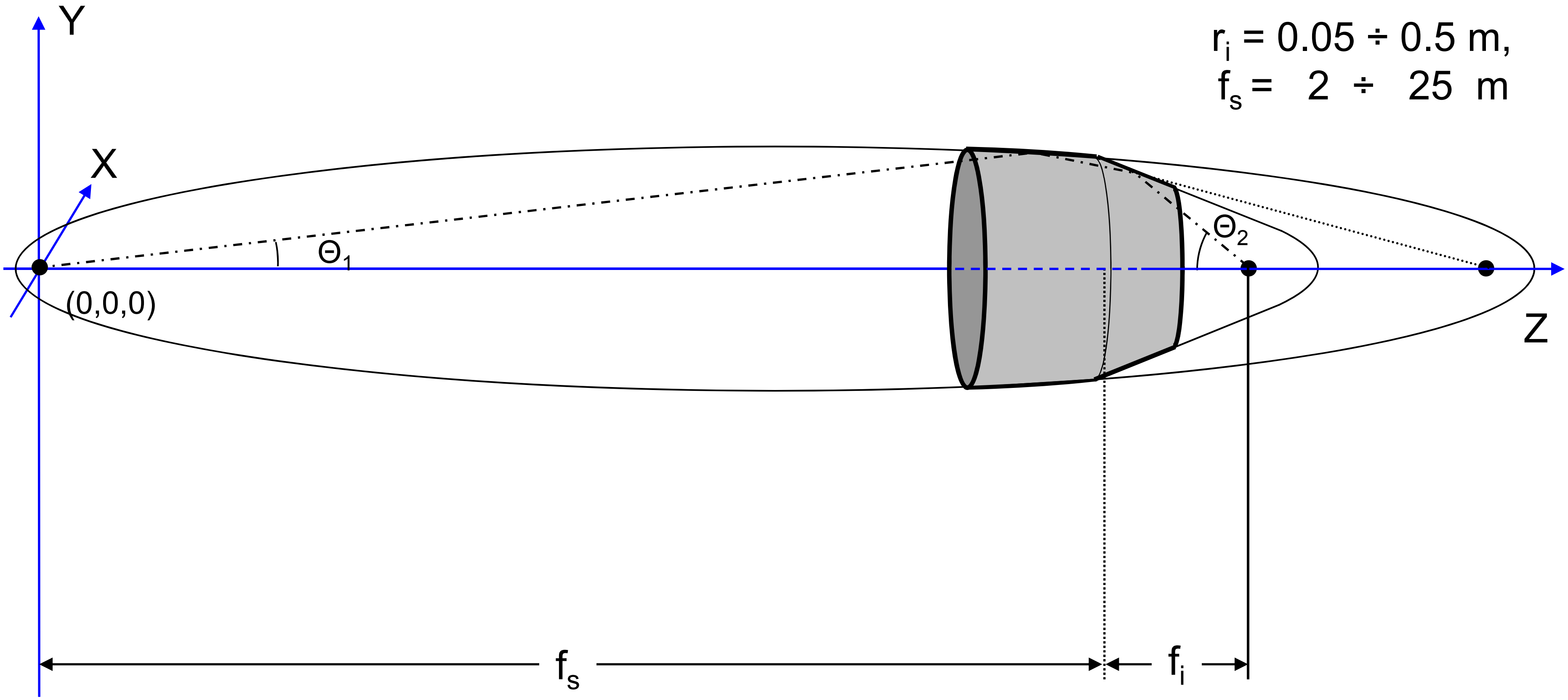
Wolter optics geometry

Magnification:

$M = f_i/f_s = \Theta_1/\Theta_2 < 1$

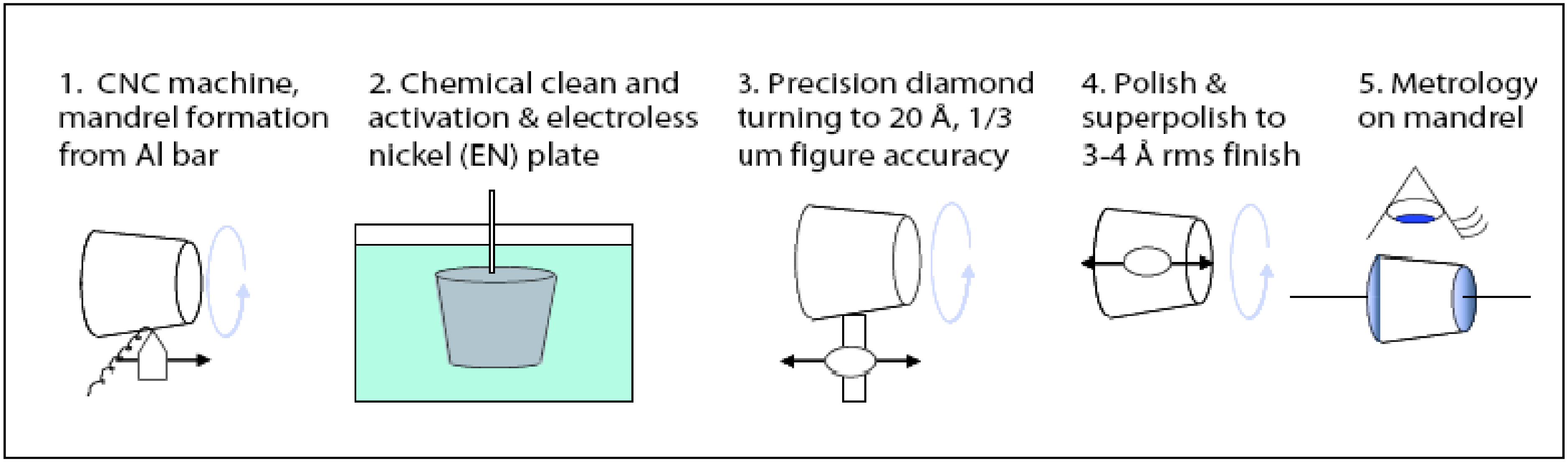
$r_i = 0.05 \div 0.5$ m,

$f_s = 2 \div 25$ m



How to implement Wolter design

Utilize state-of-the-art technology for hard x-ray optics, telescopes and medical imaging optics, developed at NASA and Harvard-Smithsonian Center for Astrophysics



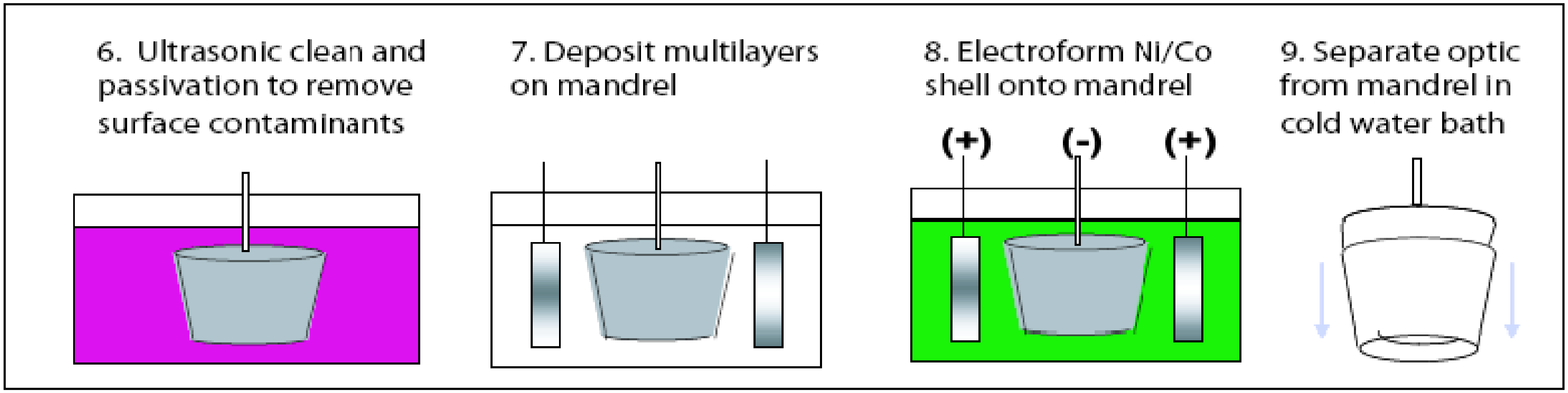
1. CNC machine, mandrel formation from Al bar

2. Chemical clean and activation & electroless nickel (EN) plate

3. Precision diamond turning to 20 Å, 1/3 um figure accuracy

4. Polish & superpolish to 3-4 Å rms finish

5. Metrology on mandrel



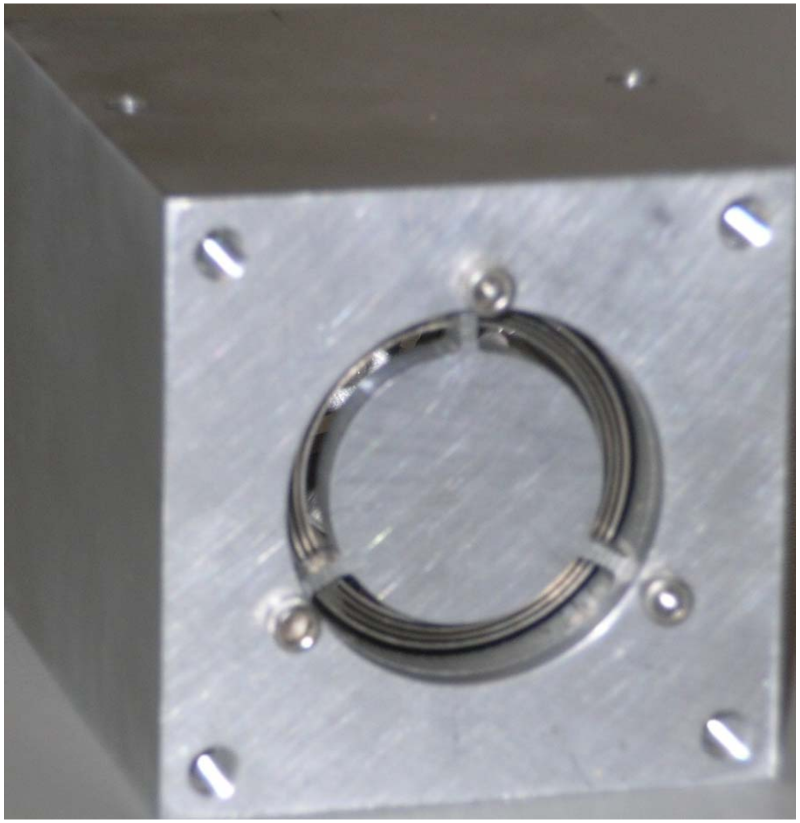
6. Ultrasonic clean and passivation to remove surface contaminants

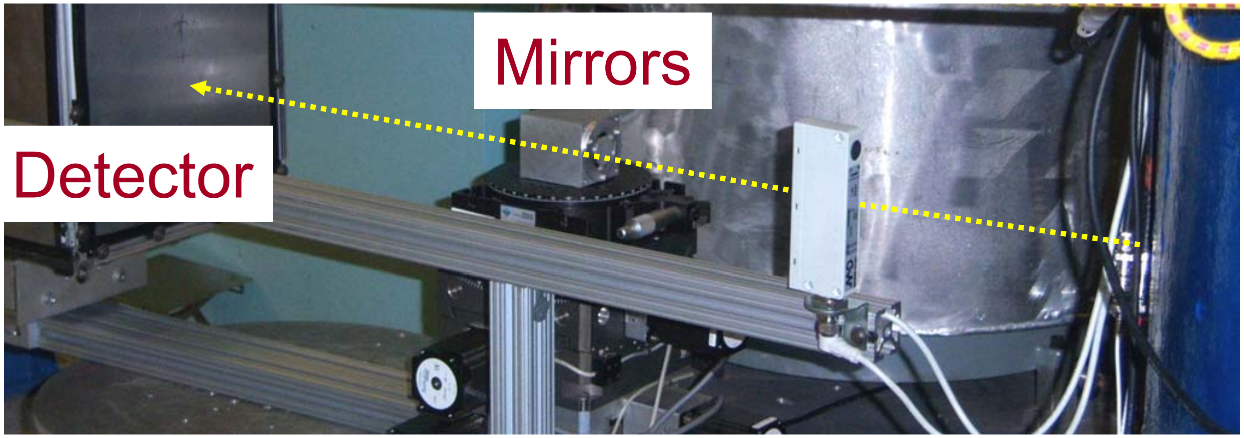
7. Deposit multilayers on mandrel

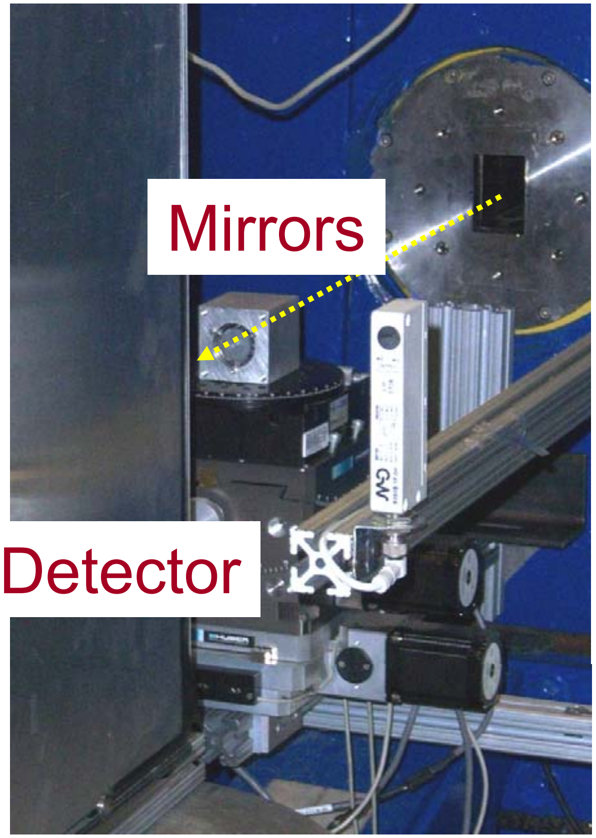
8. Electroform Ni/Co shell onto mandrel

9. Separate optic from mandrel in cold water bath

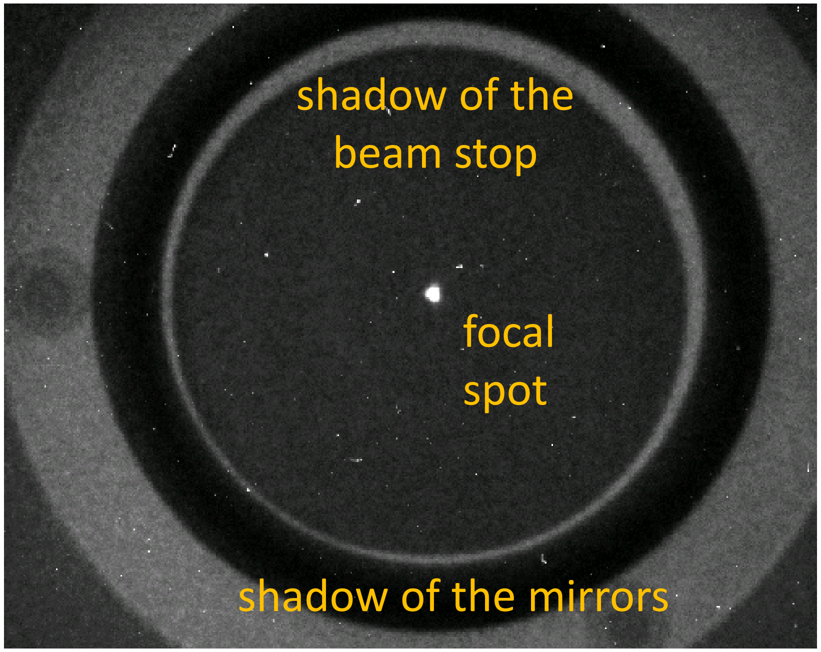
Demonstration at MIT







Focusing of a thermal neutron beam



Neutrons in the focal spot are below 5 meV: cold neutron filter

Image of a 2mm diameter aperture in the beam at the MIT Reactor, using two nested Ni shells.

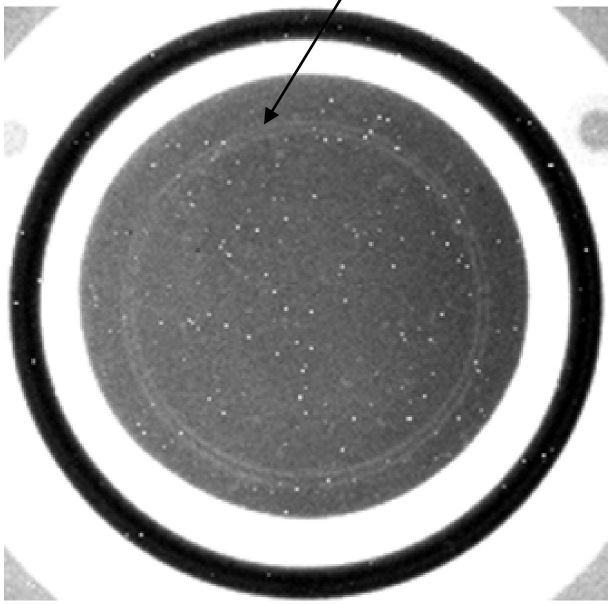
Focal distance = 3.2 m, mirrors length = 60 mm, demagnification = 4.

Both the source and detector are in focii.

Exposure = 10 sec, reactor power = 4.2 MW (maximum 6 MW).

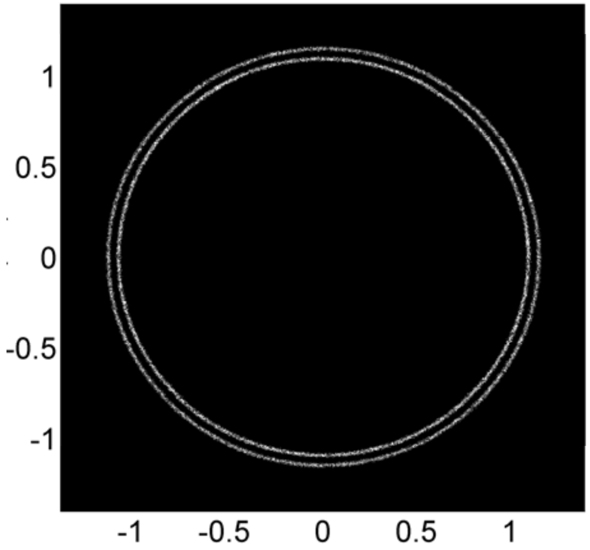
Off-focus image showing reflections from two nested concentric mirror shells

Two concentric rings formed by the neutrons reflected by the two nested mirror shells

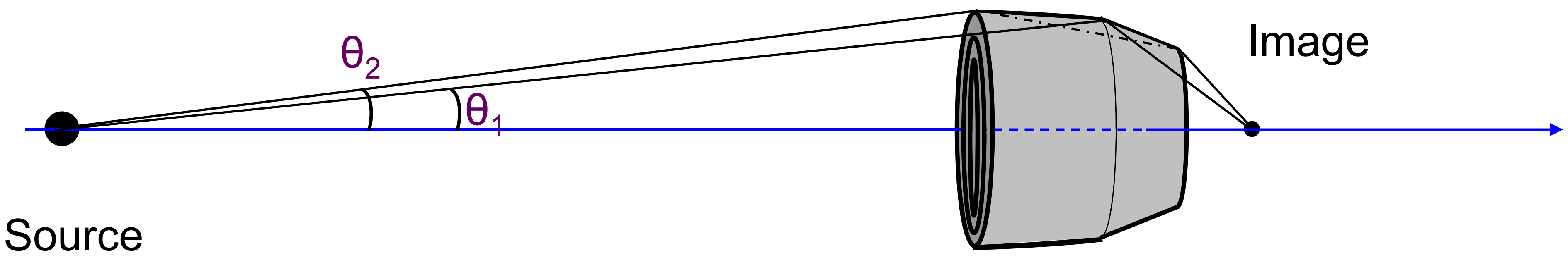


Rings of 20 mm diameter
measured 440 mm upstream from focus

Ray-tracing



Example: optimization of Wolter optics for collection by ray-tracing

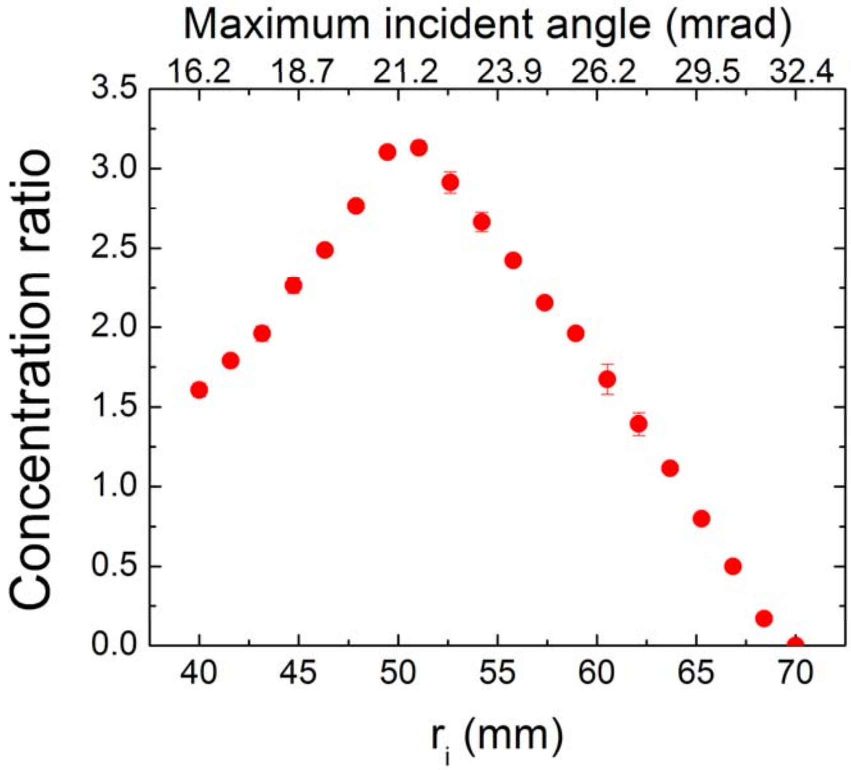


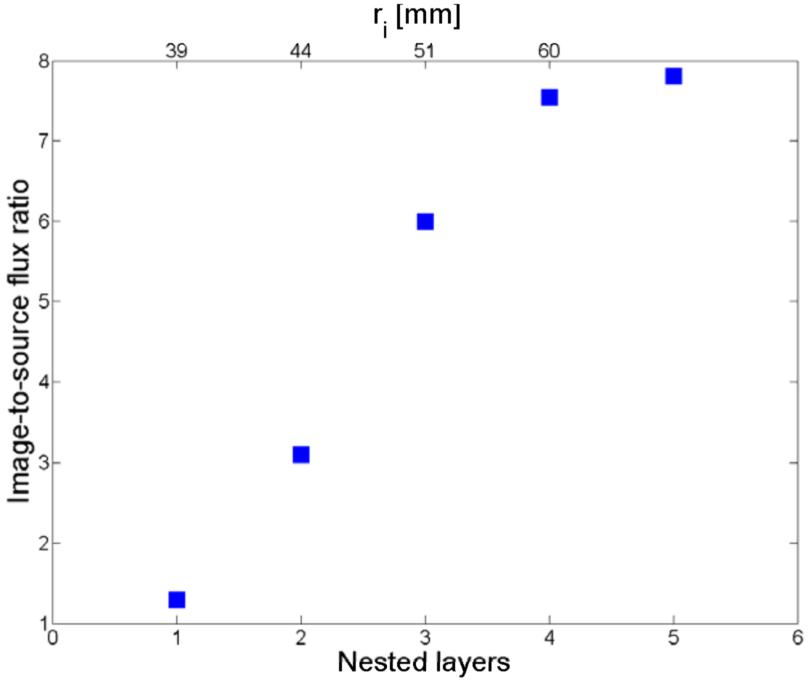
Flux collection:

- Solid-angle coverage ~ $(\sin^2(\theta_1) - \sin^2(\theta_2))$
- Nesting increases solid-angle coverage by ↘θ_1

nested mirrors
m = 3 supermirror coating
E = 5 meV
Source-to-image distance 10 m and 25
Magnification: 1 ÷ 10

Example: ray-tracing optimization of Wolter optics for flux collection



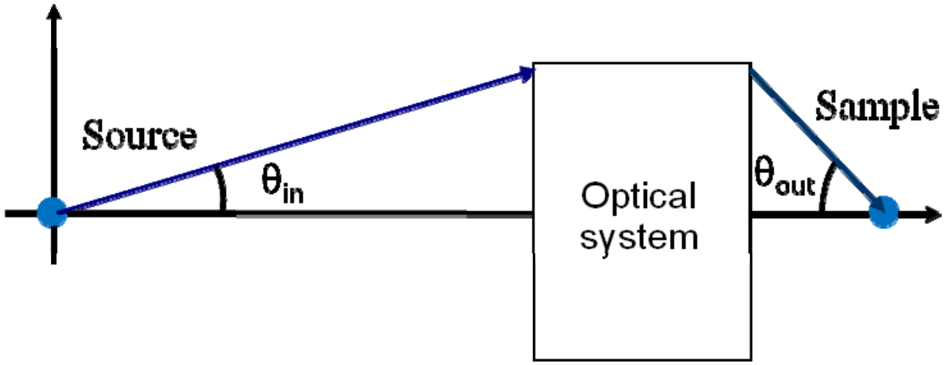


Concentration ratio = (Image flux density)/(Source flux density)

Magnification = M

Theoretical limit of concentration = M^2 = 100

Phase-space conservation dictates that the maximum flux concentration is determined by the number of reflections



$$\theta_{out,MAX} = 2N\theta_c + \theta_{in}$$

$$C_{flux} \le \left(\frac{\sin\theta_{out}}{\sin\theta_{in}}\right)^2 \le (2N+1)^2$$

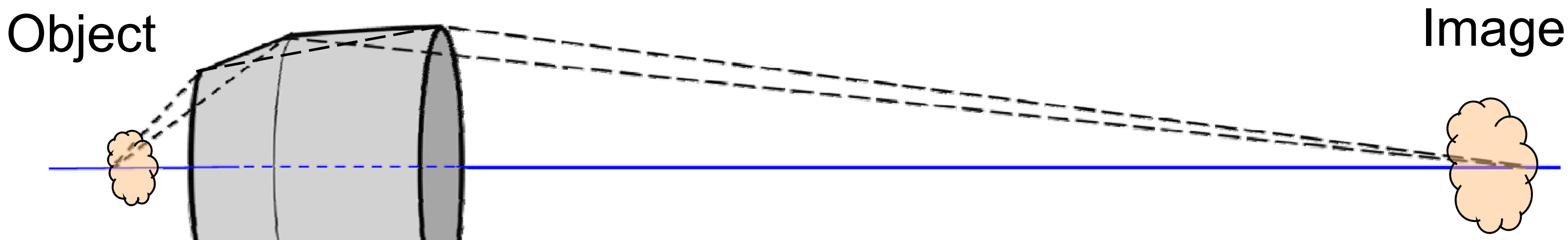
C_{flux} is the ratio of the flux densities at the sample and the source.

2 reflections work best for systems of up to 10 m

For longer systems, 3 or 4 reflections are advantageous

Application: replace guides close to moderator to reduce congestion

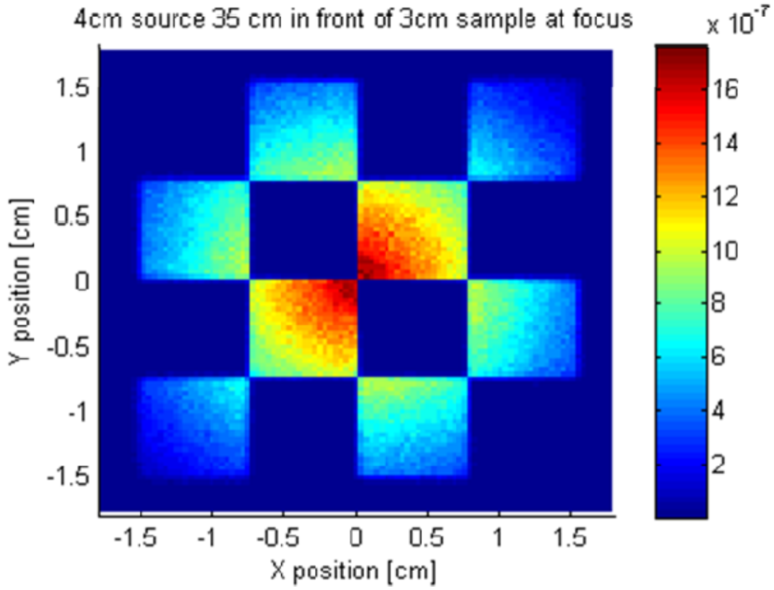
Applications: Neutron Imaging



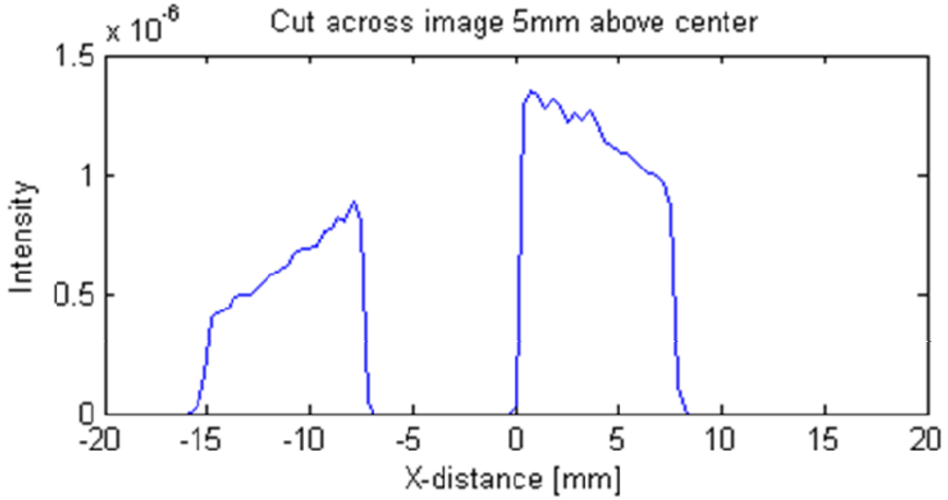
Aberration-free optics ➔

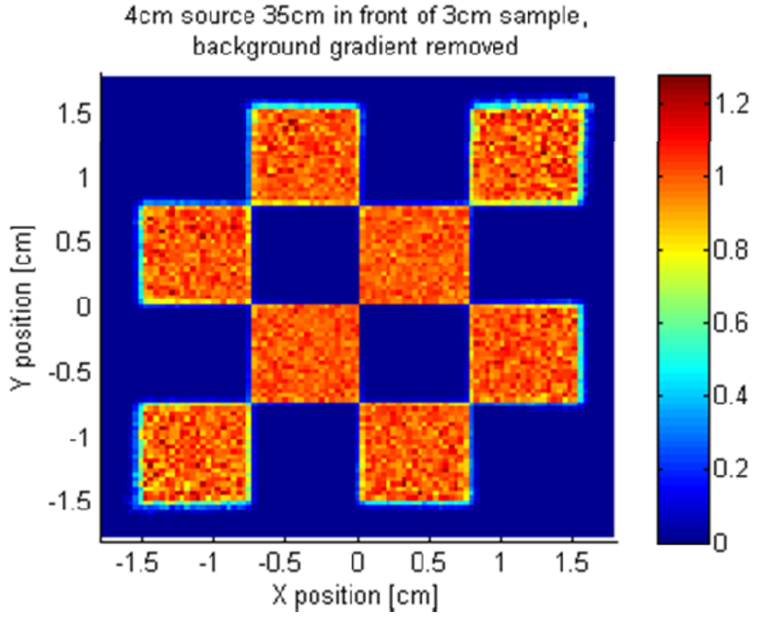
same time of flight for all neutrons object to focus

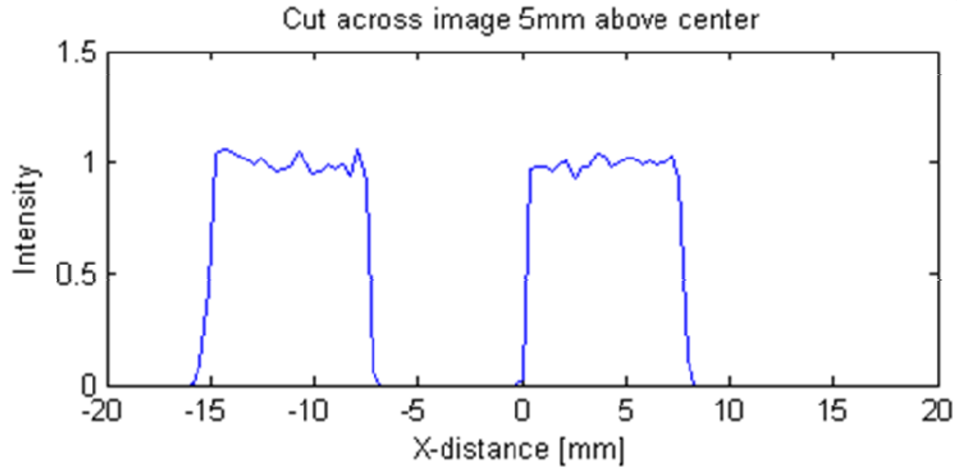
Imaging simulations


4cm source 35 cm in front of 3cm sample at focus

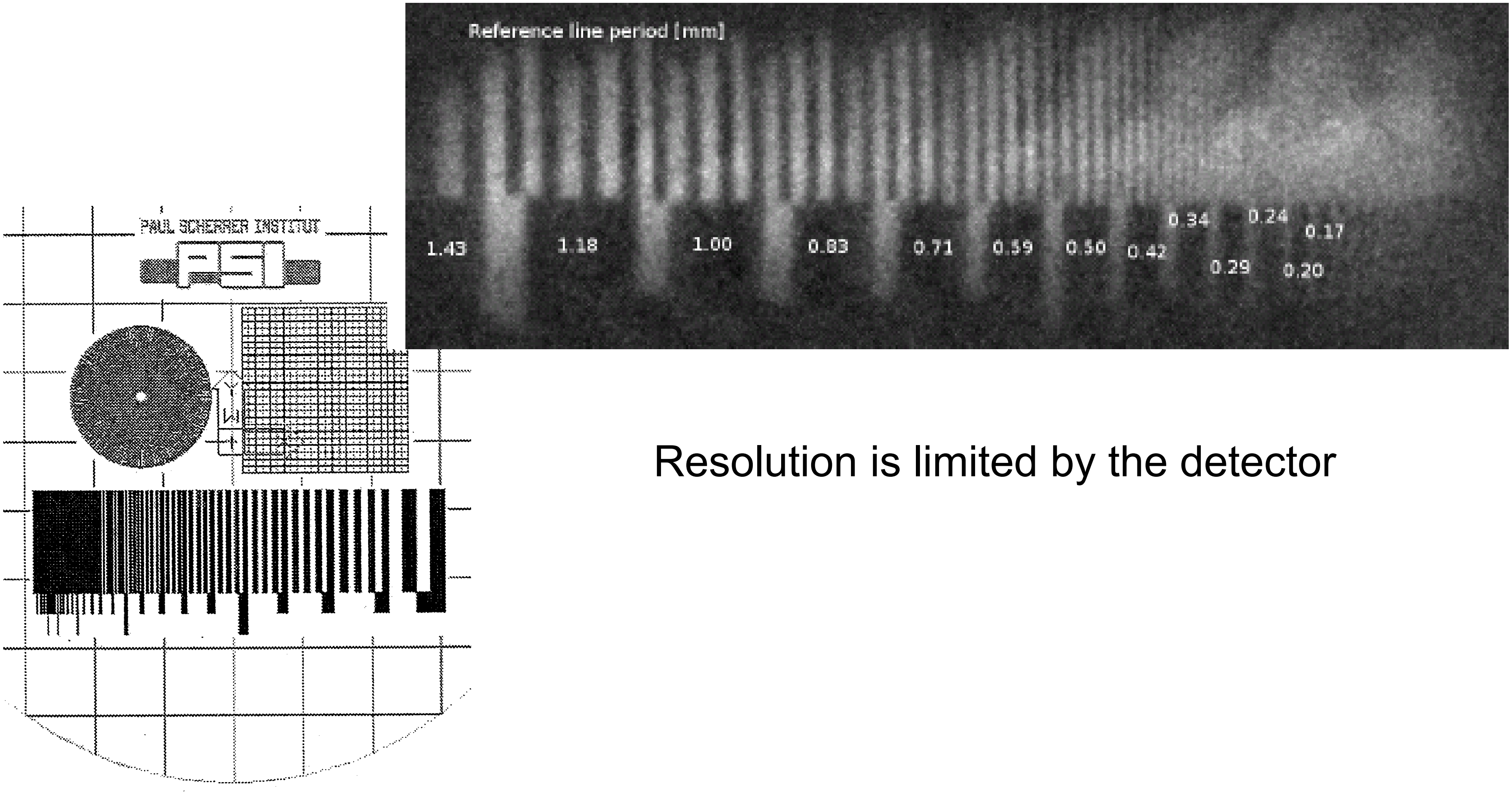
M = 1, L = 10 m, radii = 15-19 cm


Cut across image 5mm above center


4cm source 35cm in front of 3cm sample, background gradient removed


Cut across image 5mm above center

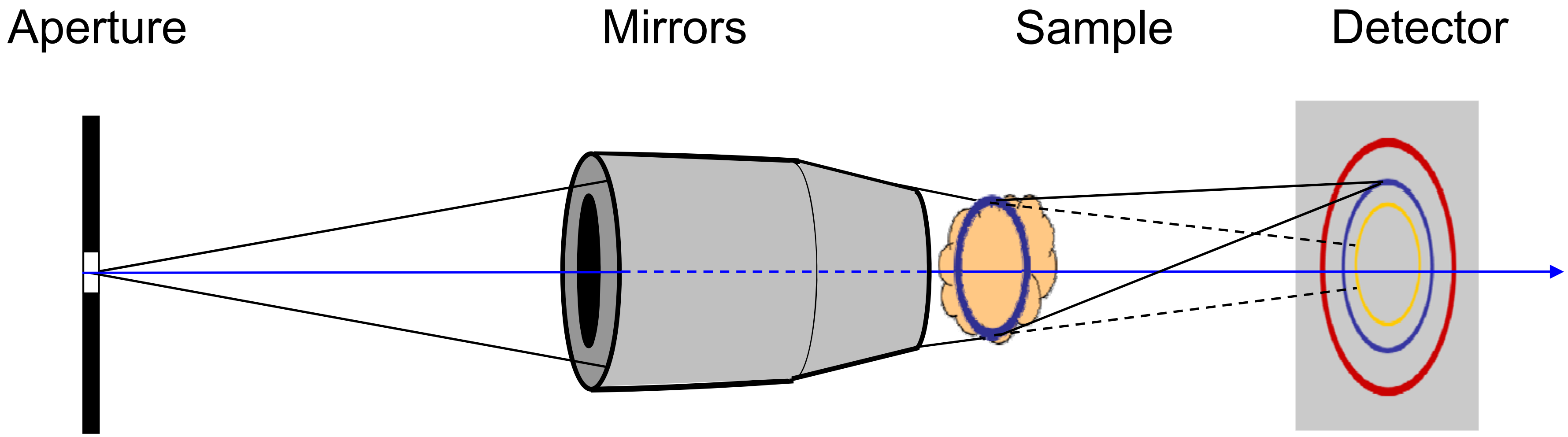
Imaging at HFIR:
same short Ni mirrors, magnification = 4



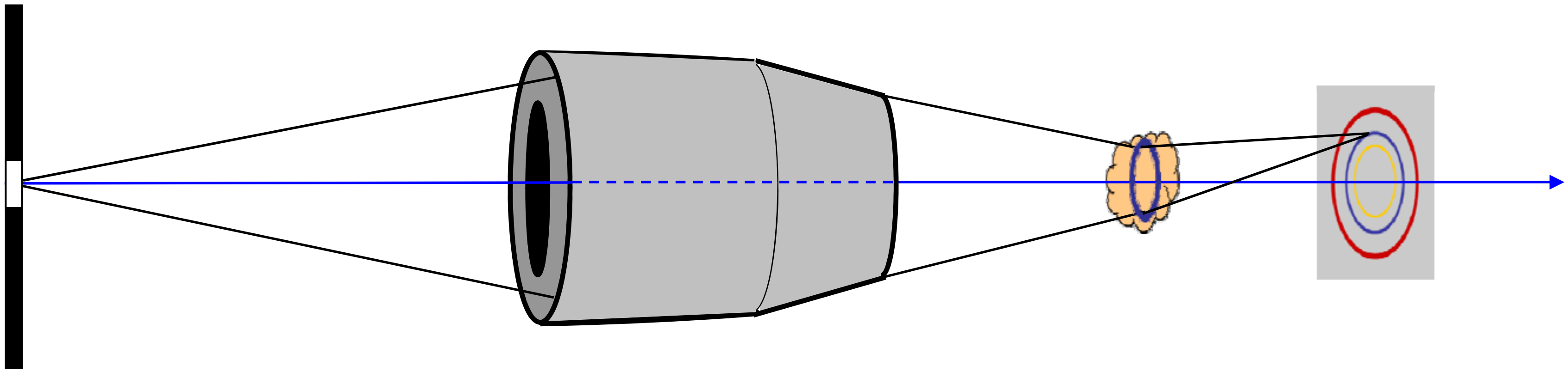
Gd test object CG

Resolution is limited by the detector

SANS with focusing mirrors: adjustable resolution

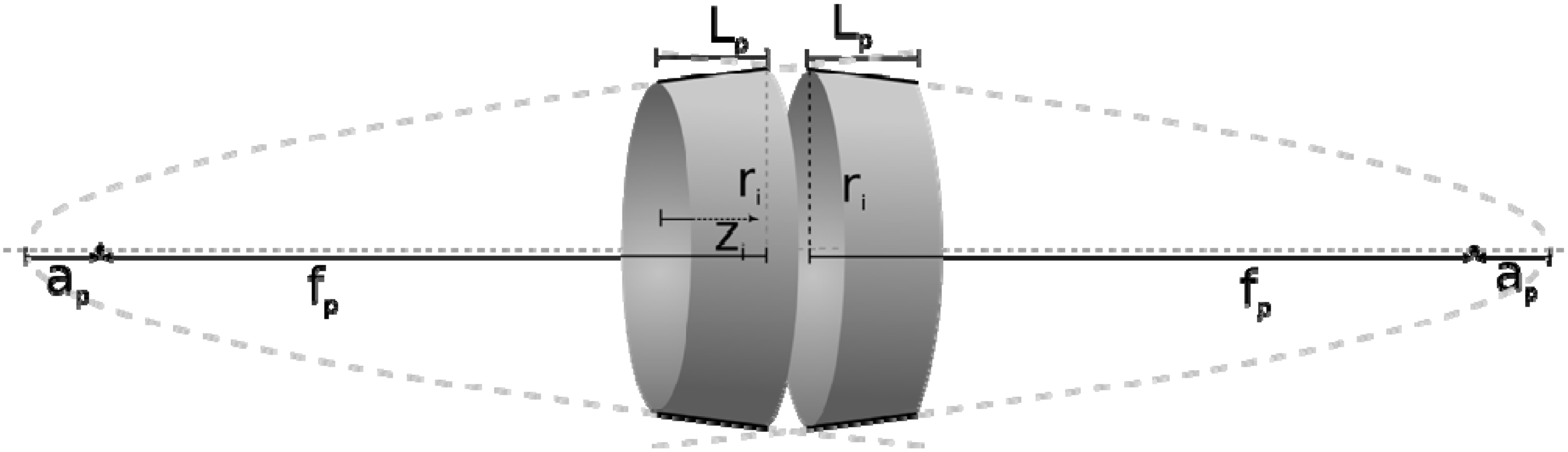


Higher resolution, lower flux density on a sample



Lower resolution, higher flux density

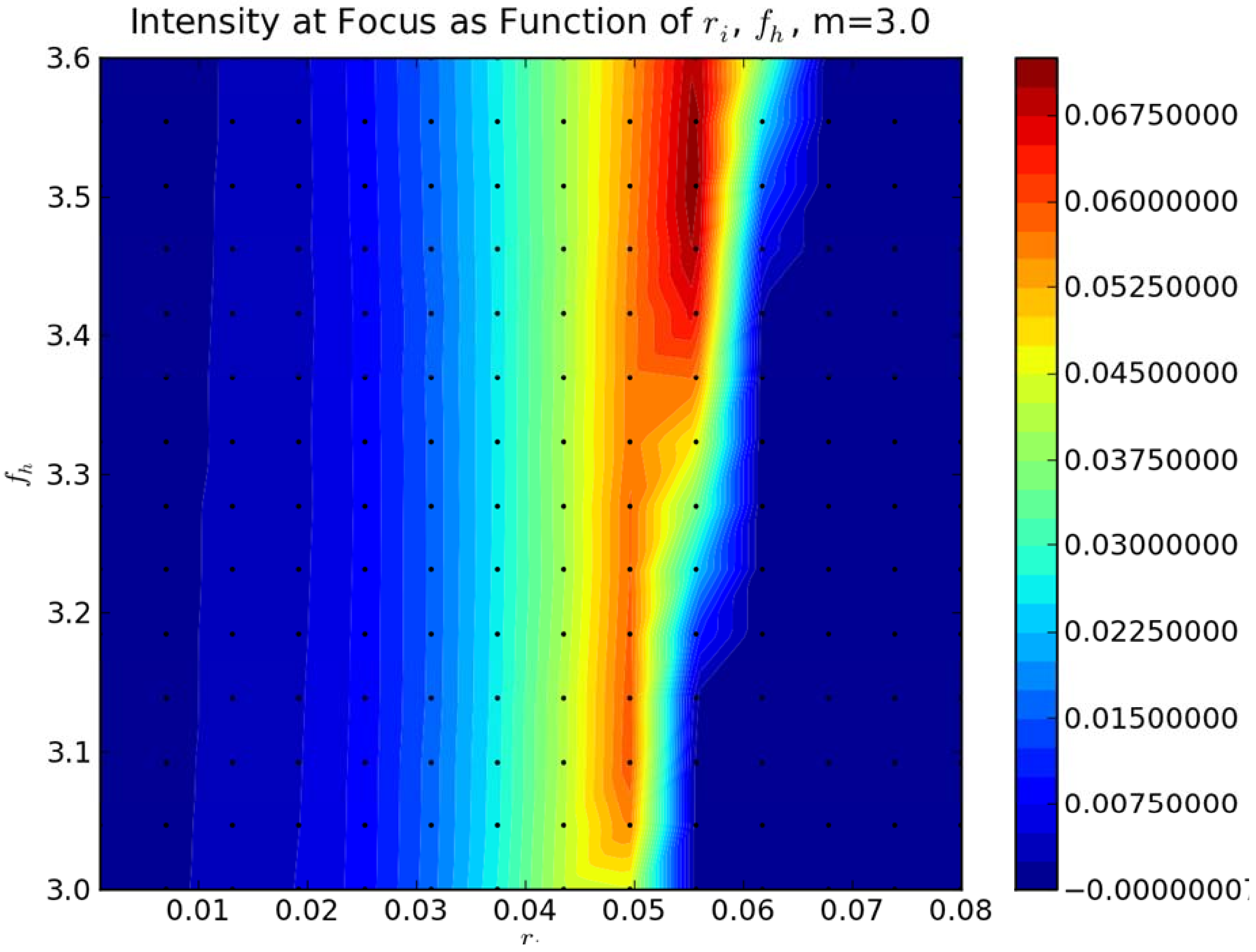
Example of optimization: Paraboloid-paraboloid optics for SANS



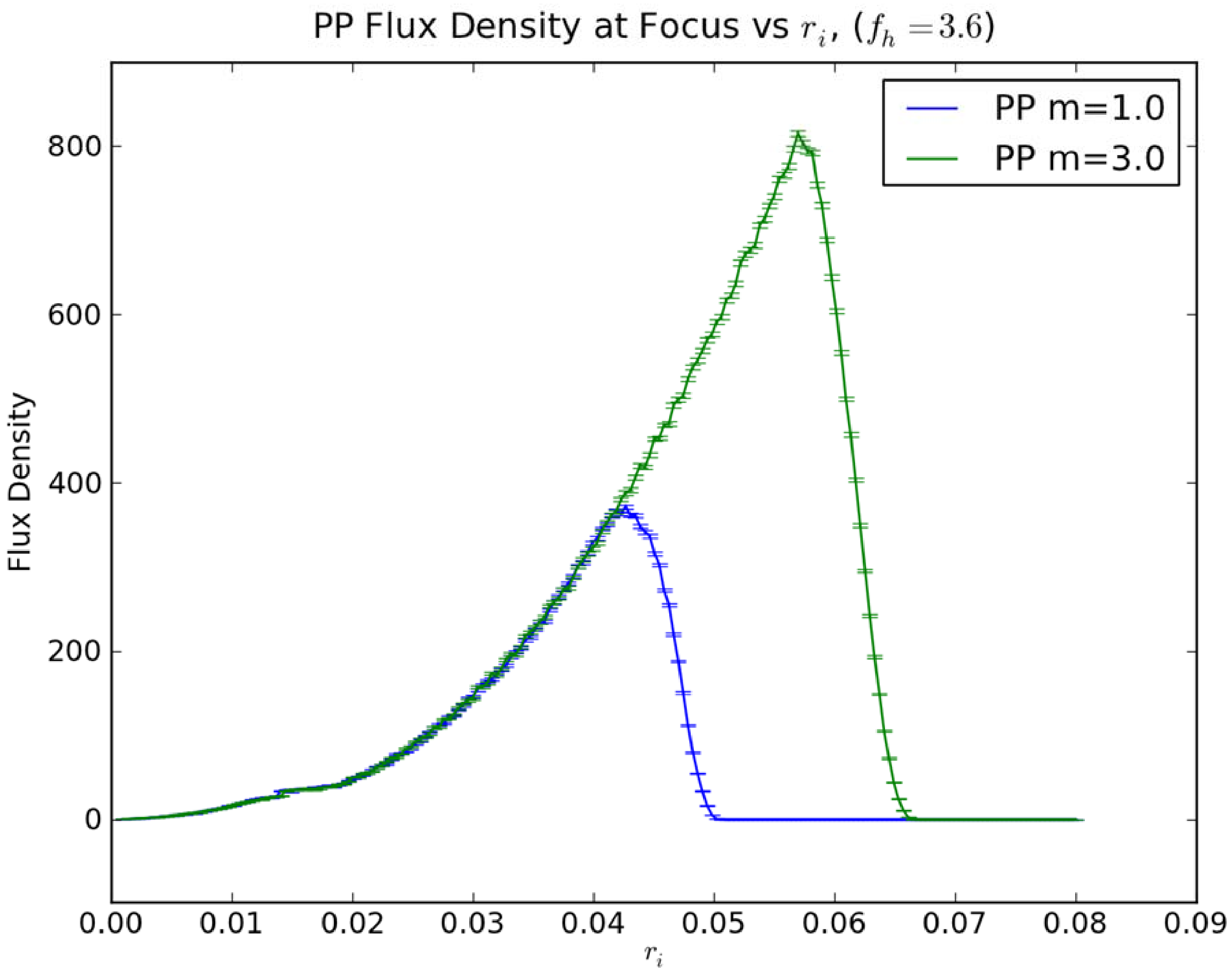
Magnification M = 1

L_p = 0.2 m

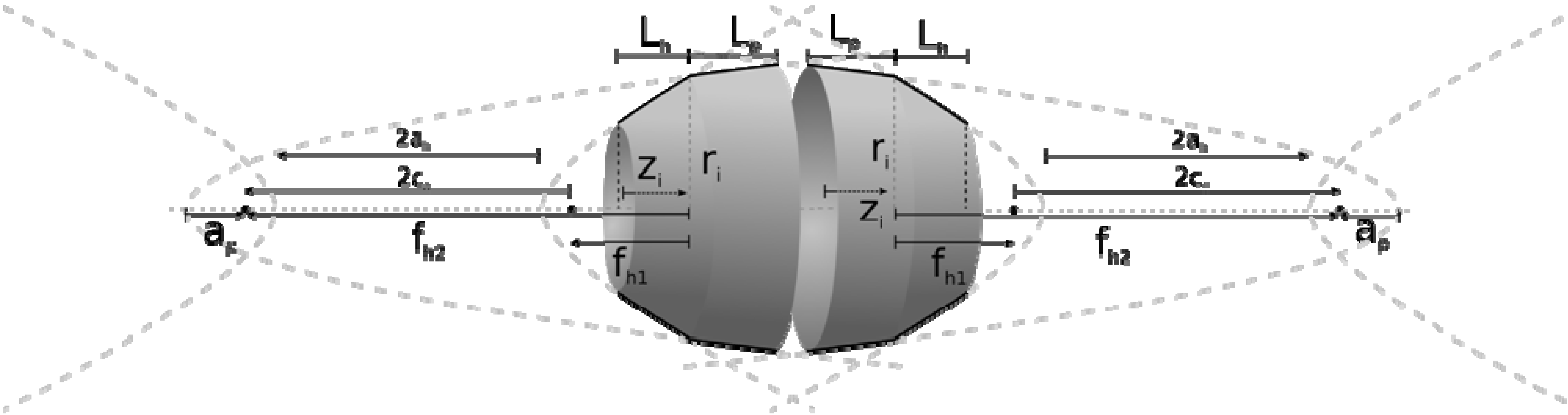
Source-detector distance L = 8 m


Intensity at Focus as Function of r_i, f_h, m=3.0
f_h
3.6
3.5
3.4
3.3
3.2
3.1
3.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.06750000
0.06000000
0.05250000
0.04500000
0.03750000
0.03000000
0.02250000
0.01500000
0.00750000
−0.000000

Flux density at the detector



Example of optimization:
Paraboloid-paraboloid optics for SANS

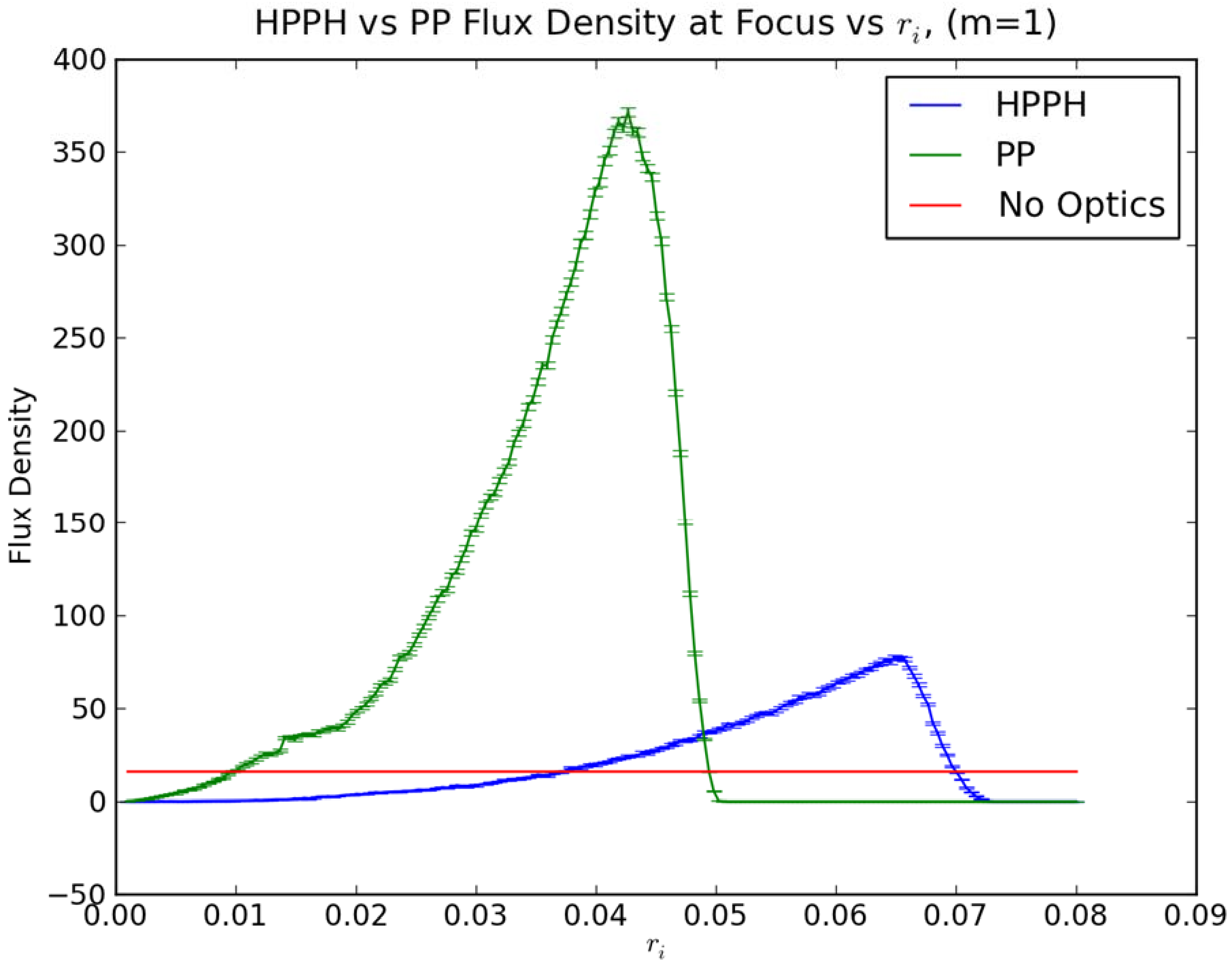


Magnification M = 1

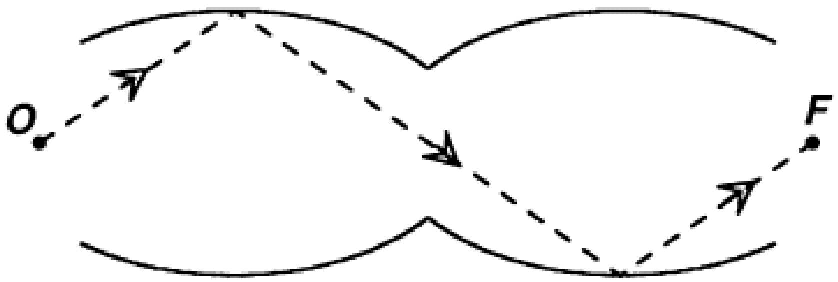
$L_p + L_h = 0.2$ m

Source-detector distance L = 8 m

Flux density at the detector



Optics for spin-echo applications



Symmetric ellipsoid-ellipsoid optics:
no aberrations ➔ time-of-flight is the same for all neutrons

If a sample is placed in between, the spin-echo can be realized

Conclusions

- Major advantages of Wolter mirrors:

  Very flexible

  Excellent collection efficiency, comparable or better to that of focusing guides and KB

  Possibility of nesting

  Same time of flight for all neutrons reflected from one mirror

- Applications: SANS, imaging, guides replacement, neutron beam collection, ToF and spin-echo methods

- We are getting ready to test neutron (and x-ray) supermirror coating

- Support: U.S. Department of Energy, BES, Award # DE-FG02-09ER46556 (Wolter optics studies) and NSF (construction of Neutron optics test station and diffractometer at MIT).