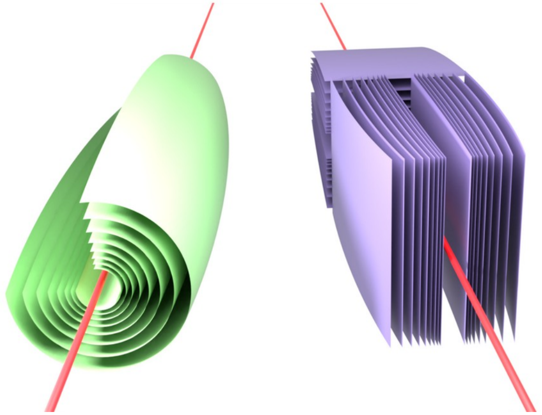
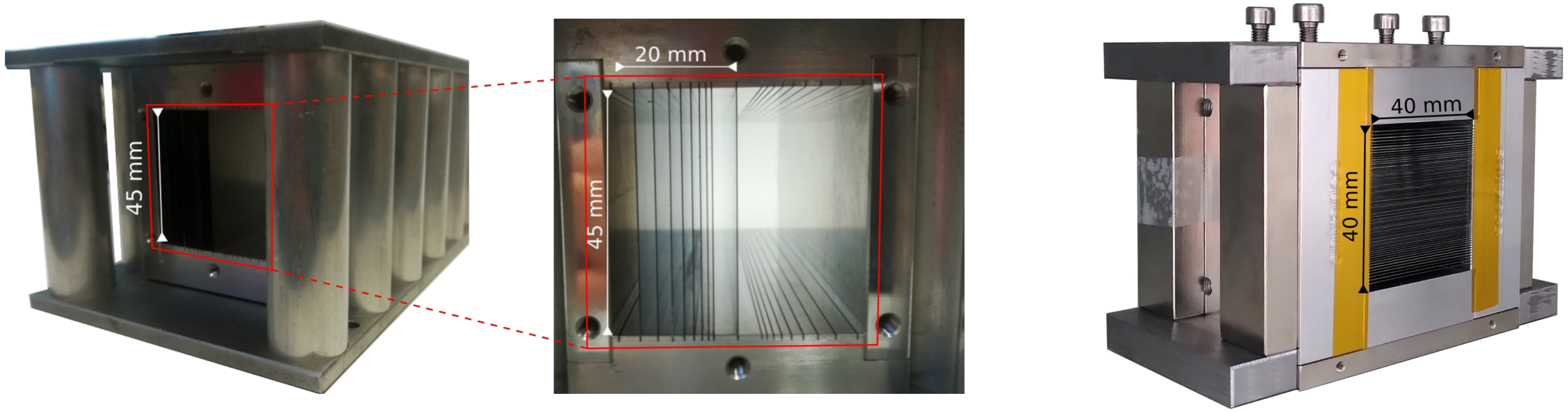
Nested Mirror Optics – Towards a New Generation of Neutron Transport Systems?

Christoph Herb[a,c], Richard Wagner[b], Oliver Zimmer[b], Robert Georgii[c], Peter Böni[a]





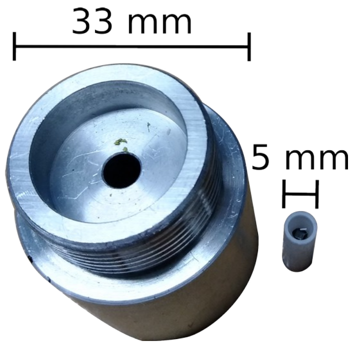
Herb, C., Zimmer, O., Georgii, R., & Böni, P. (2022). Nested Mirror Optics for Neutron Extraction, Transport, and Focusing. NIMA, 1040, 167154. doi:10.1016/j.nima.2022.167154

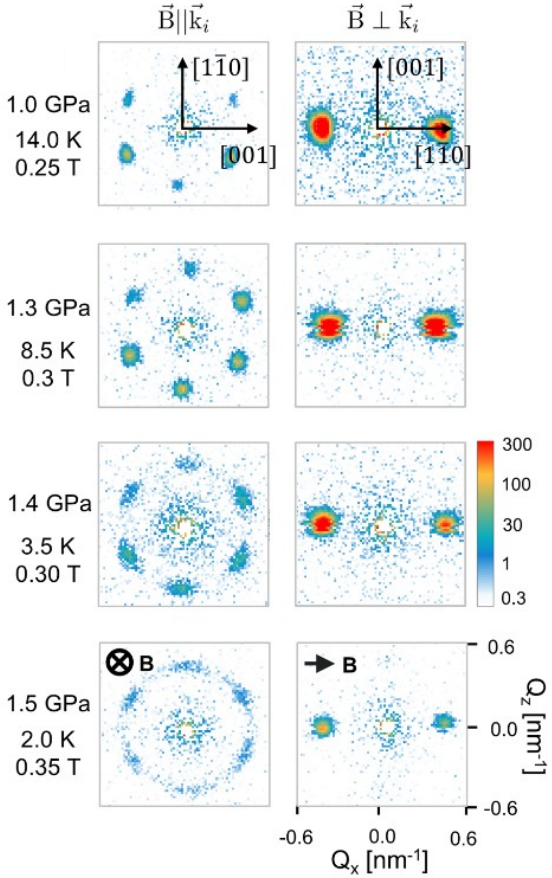
[a]Physics Department E21, Technical University of Munich, D-85748 Garching, Germany
[b]Institut Laue-Langevin, 71 avenue des Martyrs, F-38042 Grenoble, France
[c]Heinz Maier-Leibnitz Zentrum, Technical University of Munich, D-85748 Garching, Germany

MLZ is a cooperation between:

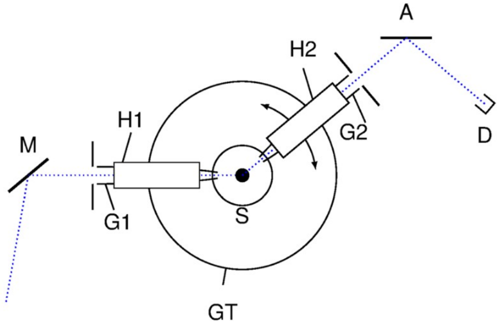
Small Samples at Extreme Conditions

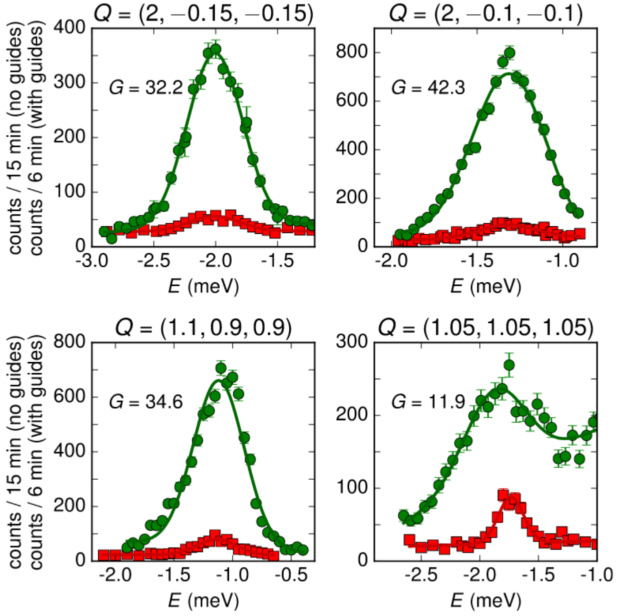
- Small samples of exotic crystals
- Investigation of novel effects requires sophisticated sample environment
    - High pressure
    - Cryogenic temperatures
    - Magnetic fields
- Neutron guides increase the signal-to-noise ratio





Bannenberg, L. et al. (2019). Skyrmions and Spirals in MnSi under Hydrostatic Pressure. Physical Review B, 100(5), 054447. doi:10.1103/PhysRevB.100.054447

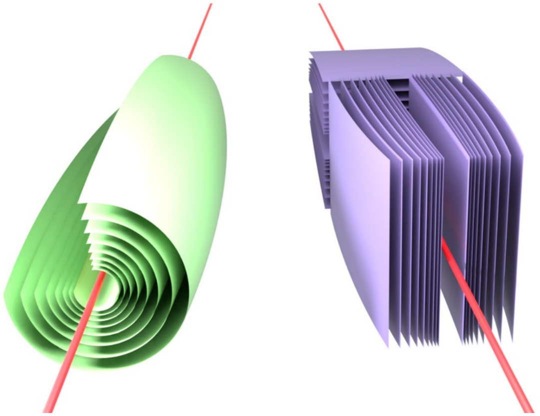


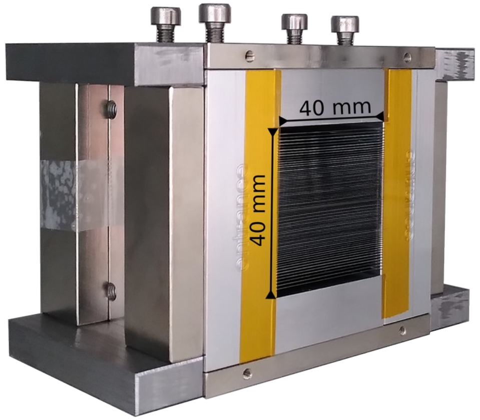


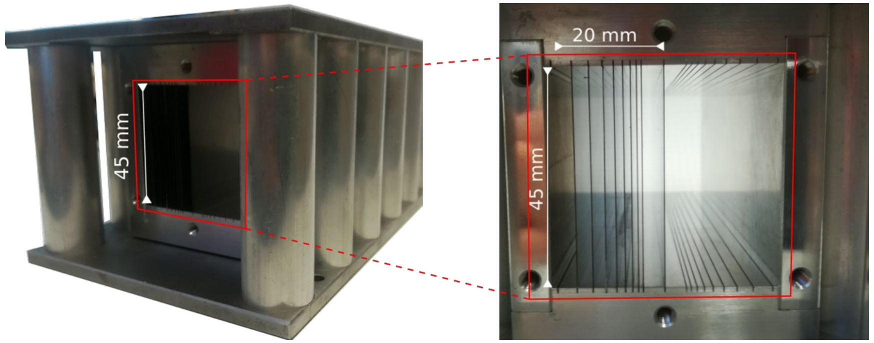
Brandl, G. et al. (2015). Compact turnkey focussing neutron guide system for inelastic scattering investigations. Applied Physics Letters, 107(25), 253505. doi:10.1063/1.4938503

Outline

- Small Samples at Extreme Conditions
- Theory of Nested Mirror Optics (NMO)
- NMO in Simulation and Experiment
  - Elliptic NMO
  - Parabolic NMO
- Applications
  - Beam Extraction
  - Beam Shaping
- Conclusions and Outlook

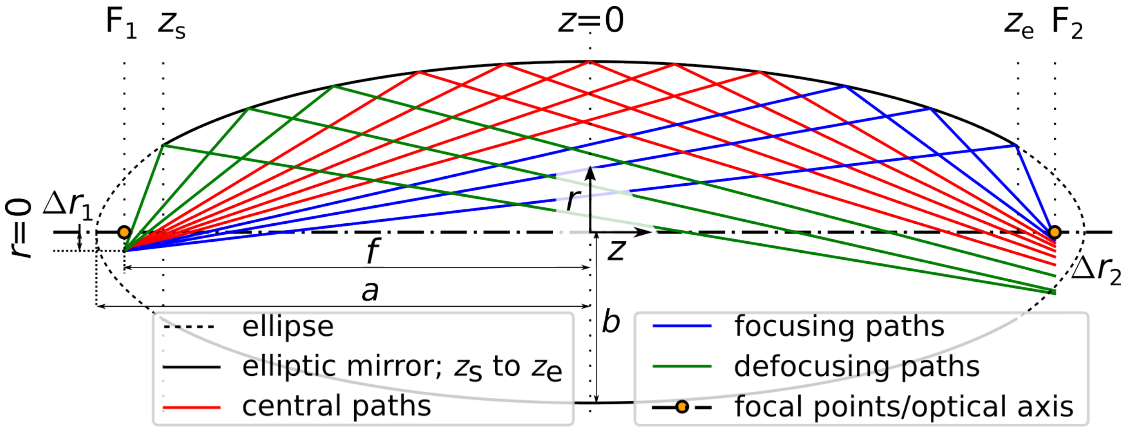






Long Elliptic Guides: Geometric Aberrations

- Elliptic guides enable point-to-point-transport of neutrons [1]
- Depending on the point of reflection, *z,* off-axis-neutrons are focused or defocused
- Deviations from optical imaging, i.e., $\Delta r_1 \neq \Delta r_2$, are only small for reflections close to the semi-minor axis, $z \approx 0$ [2]



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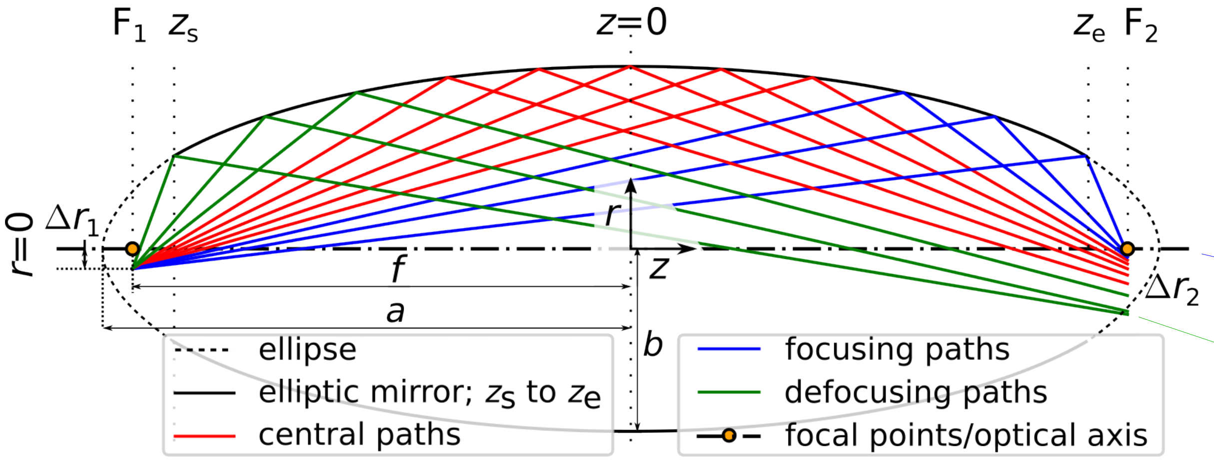
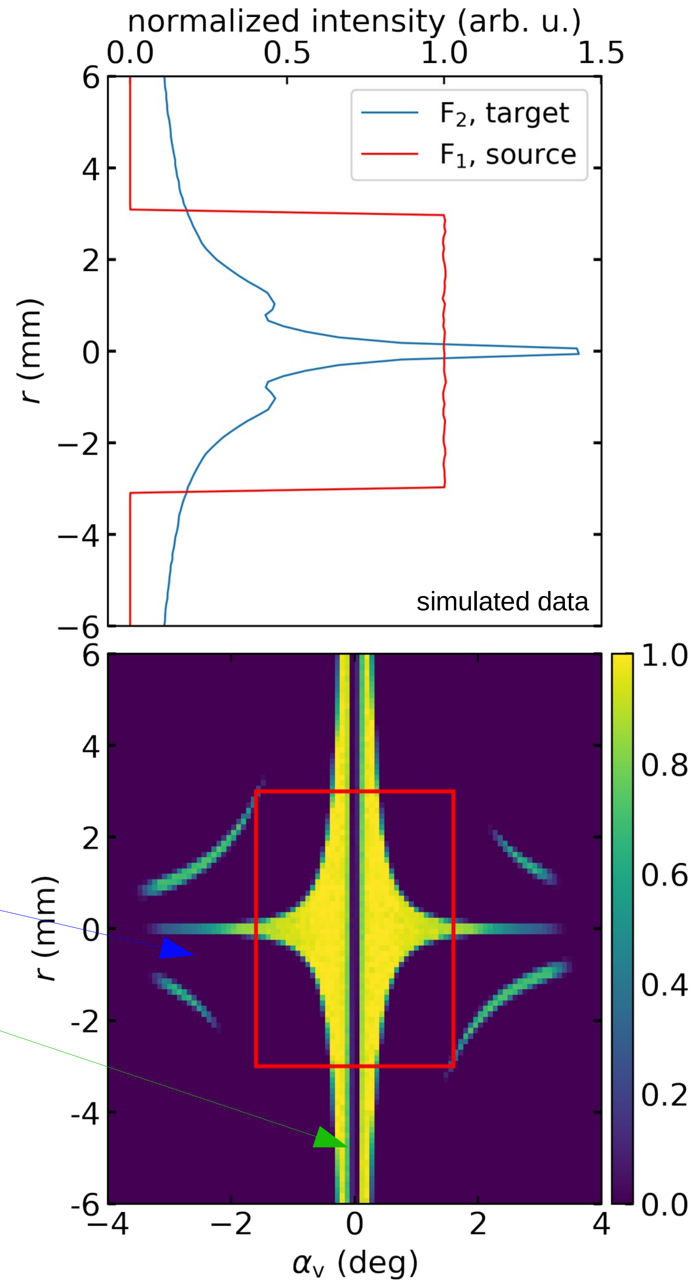
[1] Schanzer et al. (2004). Advanced geometries for ballistic neutron guides. NIMA. 529 63-68. doi:10.1016/j.nima.2004.04.178
[2] Oliver Zimmer. (2016). Multi-mirror imaging optics for low-loss transport of divergent neutron beams and tailored wavelength spectra.

Long Elliptic Guides: Distortion of Phase Space

- Inhomogeneous intensity distribution after transport
- Severe distortion of phase space
- Double reflections

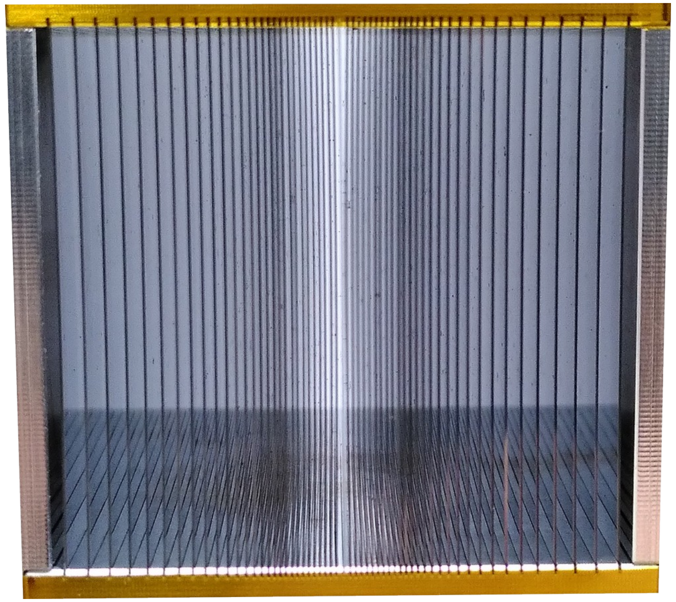


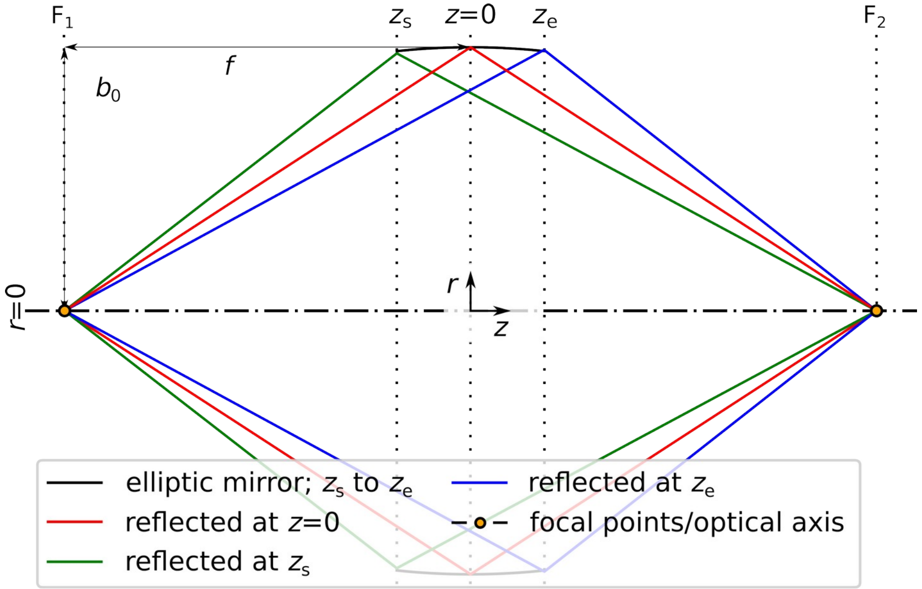


Elliptic Nested Mirror Optics (NMO)

- Restrict reflections to the ellipse center → $\Delta r_2 \approx \Delta r_1$ → preservation of neutron phase space during reflection between focal points

- Transport of required divergence by nesting short elliptic mirrors according to simple recipe





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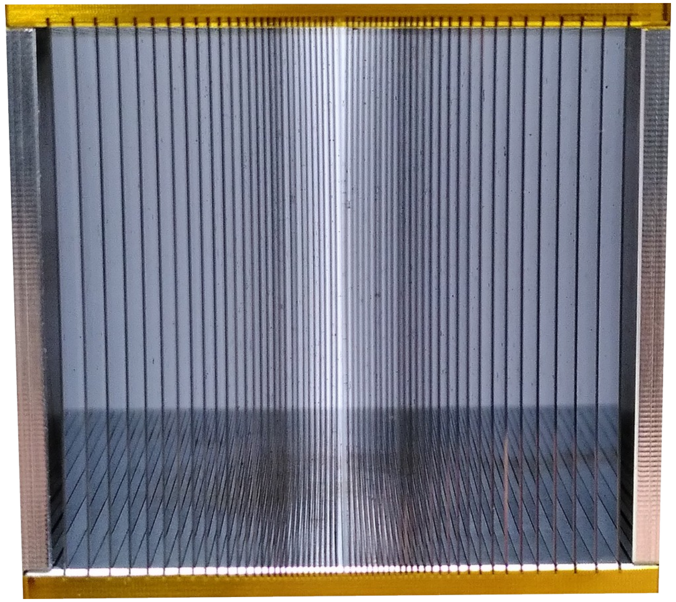
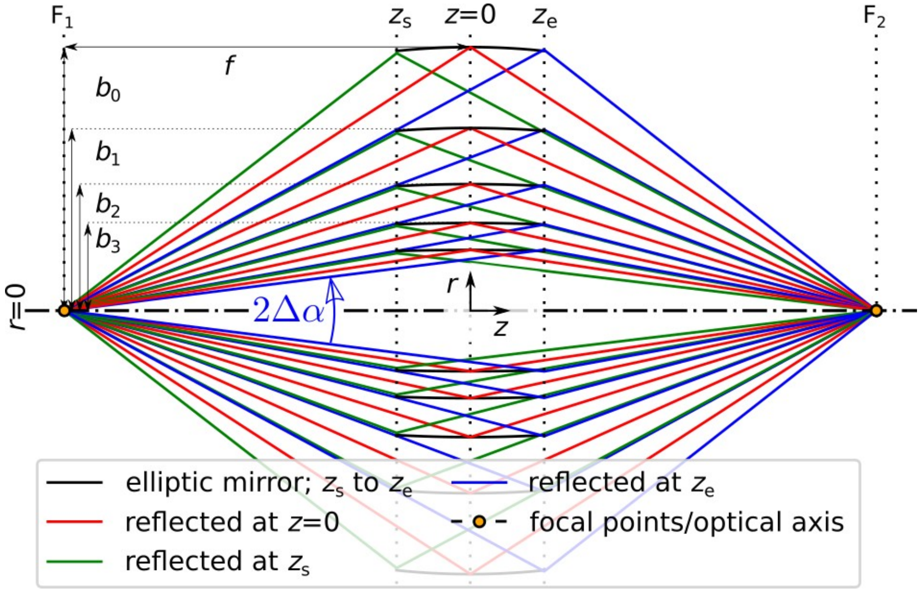
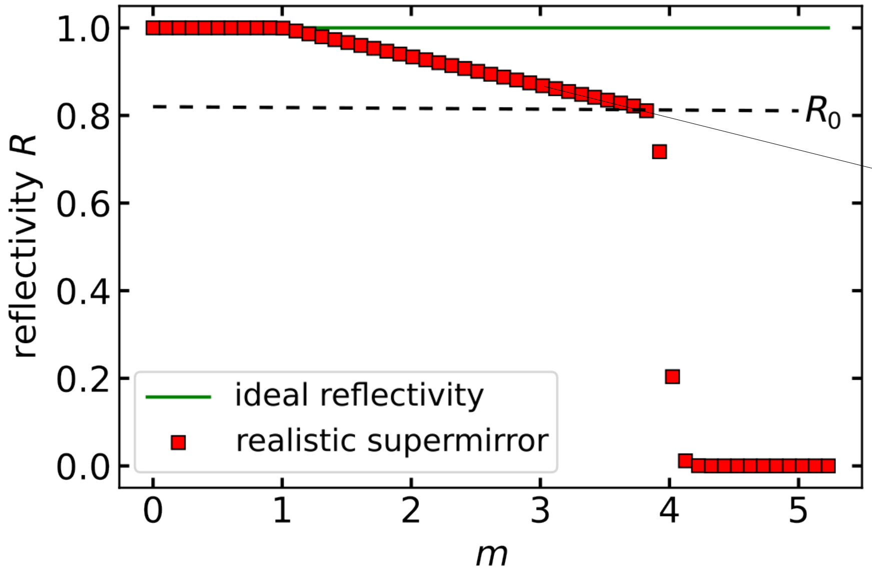
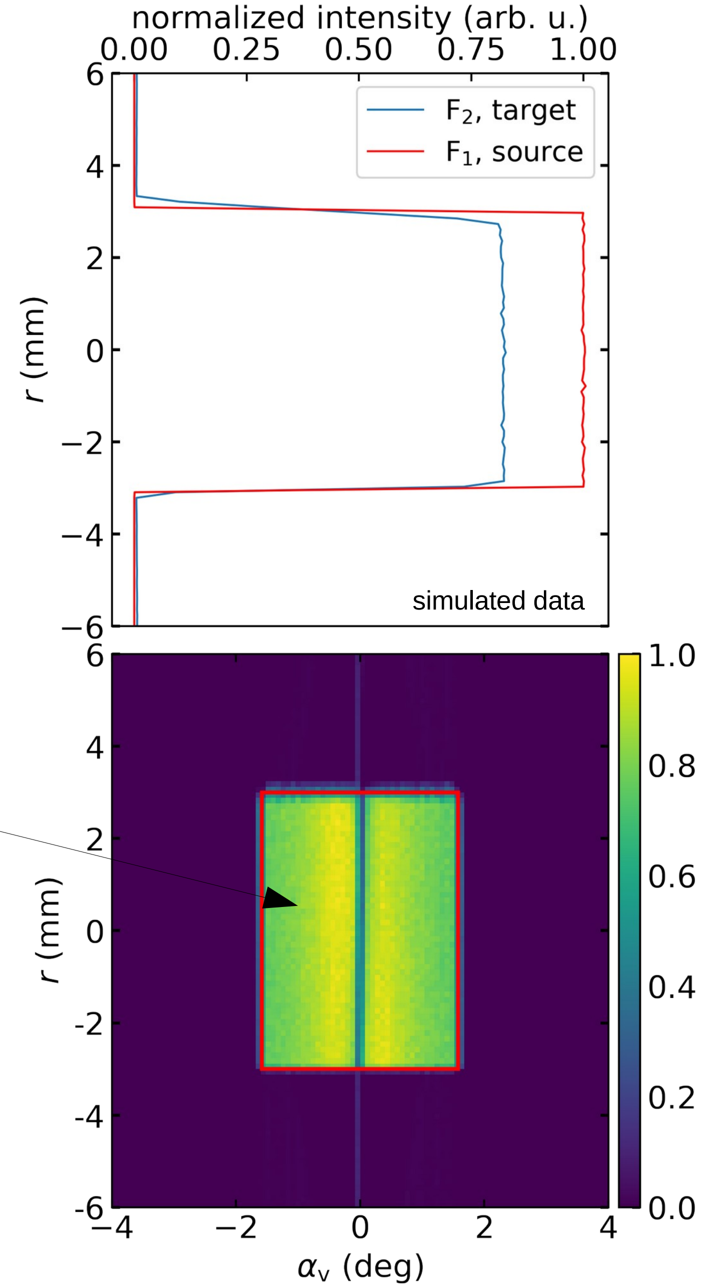




Elliptic NMO: Preservation of Phase Space

- Spatial intensity distribution is well reproduced
- Volume of phase space is preserved during reflection

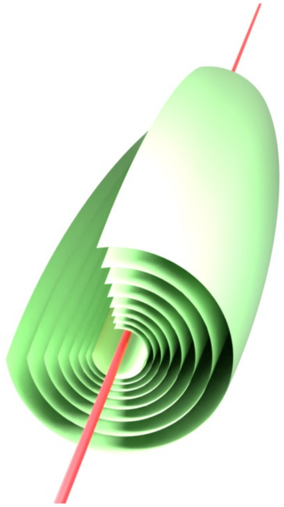


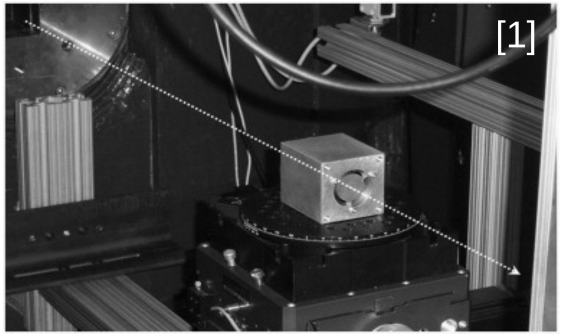


Toroidal NMO versus Double-Planar NMO

+ Single reflection for 2D-imaging

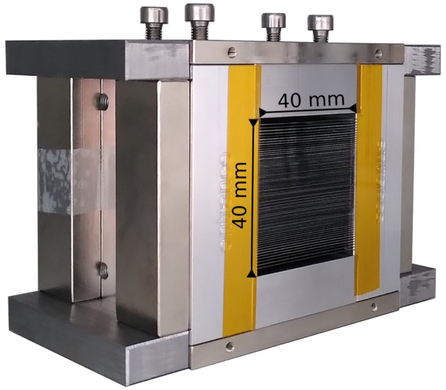
- Technically demanding

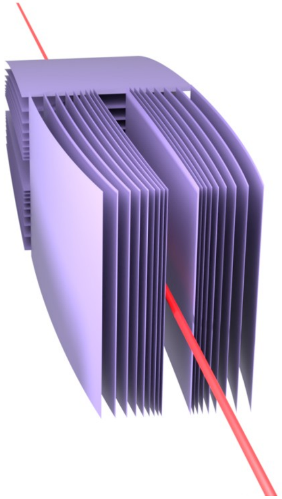




+ Technically simple
+ Transversal beam polarization
+ Compatible with rectangular guides
+ Less susceptible to gravity

- Two reflections





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[1] B. Khaykovich et al. "From x-ray telescopes to neutron scattering: Using axisymmetric mirrors to focus a neutron beam". Nuclear Instruments and Methods 2011; 631(1):98 – 104. doi:10.1016/j.nima.2010.11.110

Nested Mirror Optics: Past Work

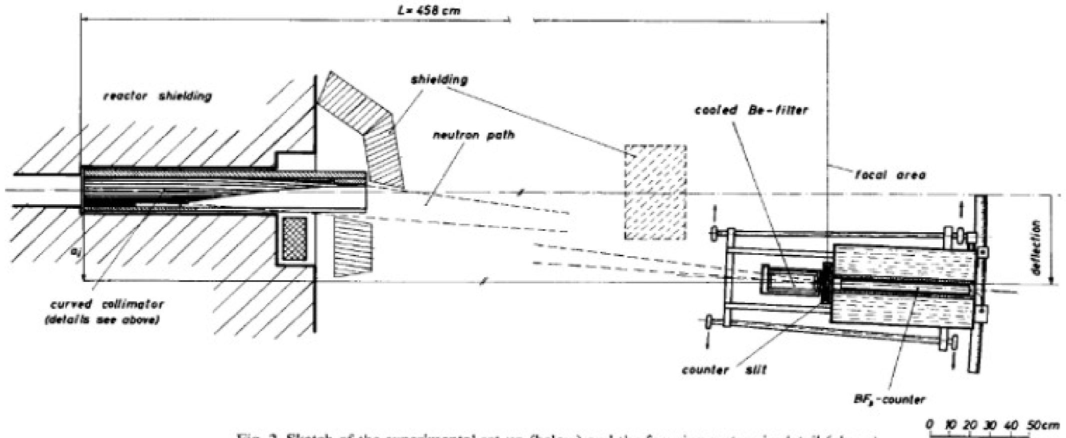
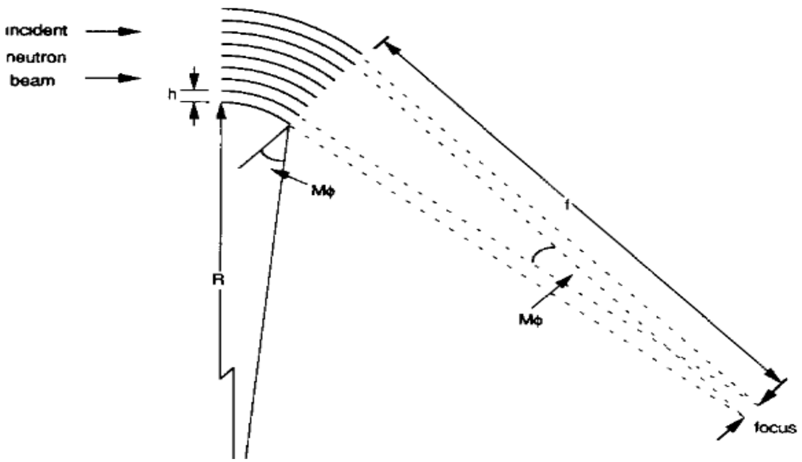


Fig. 2. Sketch of the experimental set-up (below) and the focusing system in detail (above).

M. Friedmann; H. Rauch (1970). Neutron focusing by a curved soller collimator system. NIMA, 86(1), 55–59.
doi:10.1016/0029-554X(70)90035-2



D.F.R. Mildner (1990). The neutron microguide as a probe for materials analysis. NIMA, 299(1-3), 416–419.
doi:10.1016/0168-9002(90)90816-o

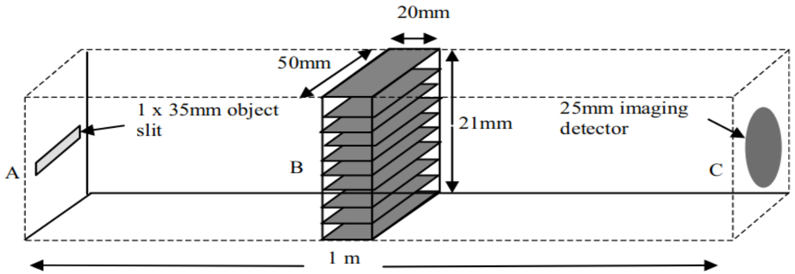


Fig. 2. Schematic of the experimental set up used to demonstrate the focussing effect of the NSL.

Mark R Daymond; Michael W Johnson (2002).
An experimental test of a neutron silicon lens. NIMA, 485(3), 606–614.
doi:10.1016/s0168-9002(01)02132-5

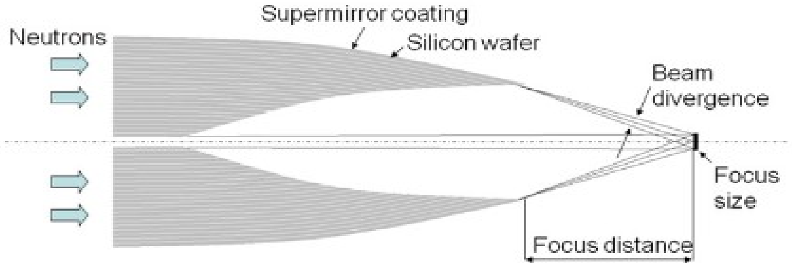
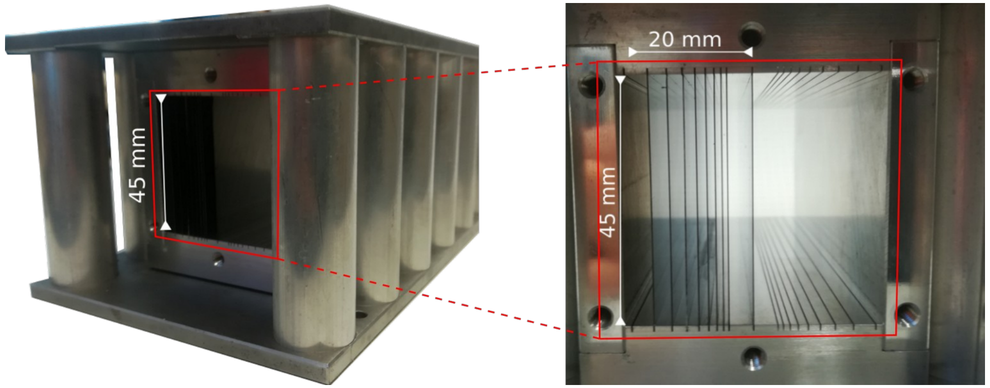
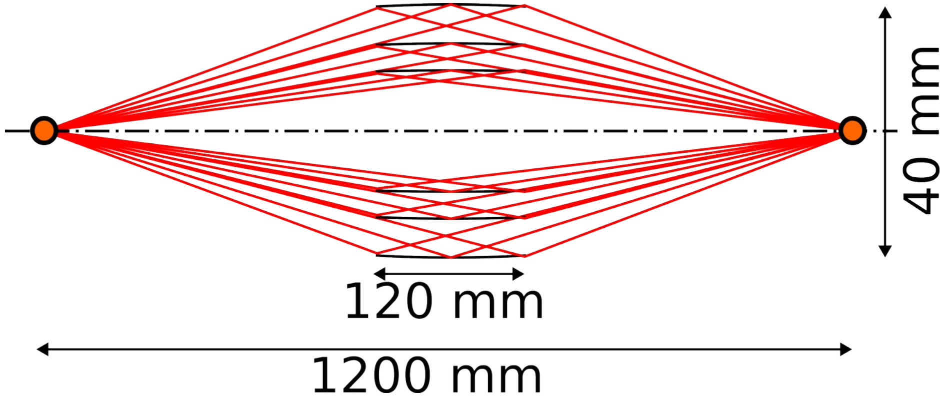


Fig. 1. Schematic of the neutron silicon lens with two stacks of bent supermirror coated silicon wafers.

Roland Bartmann; Nicolas Behr; André Hilger; Thomas Krist (2011). New solid state lens for reflective neutron focusing. NIMA, 634(1-supp-S), 0–0.
doi:10.1016/j.nima.2010.05.040

Properties of Elliptic Polarizing NMO





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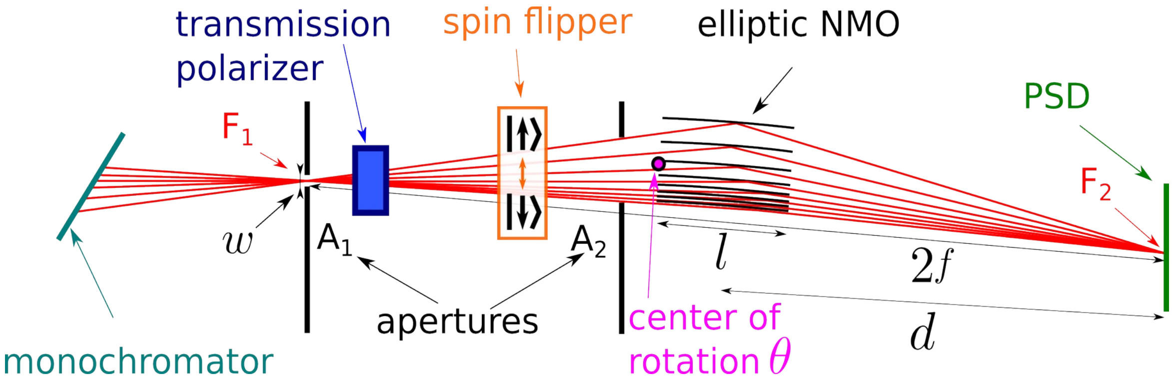
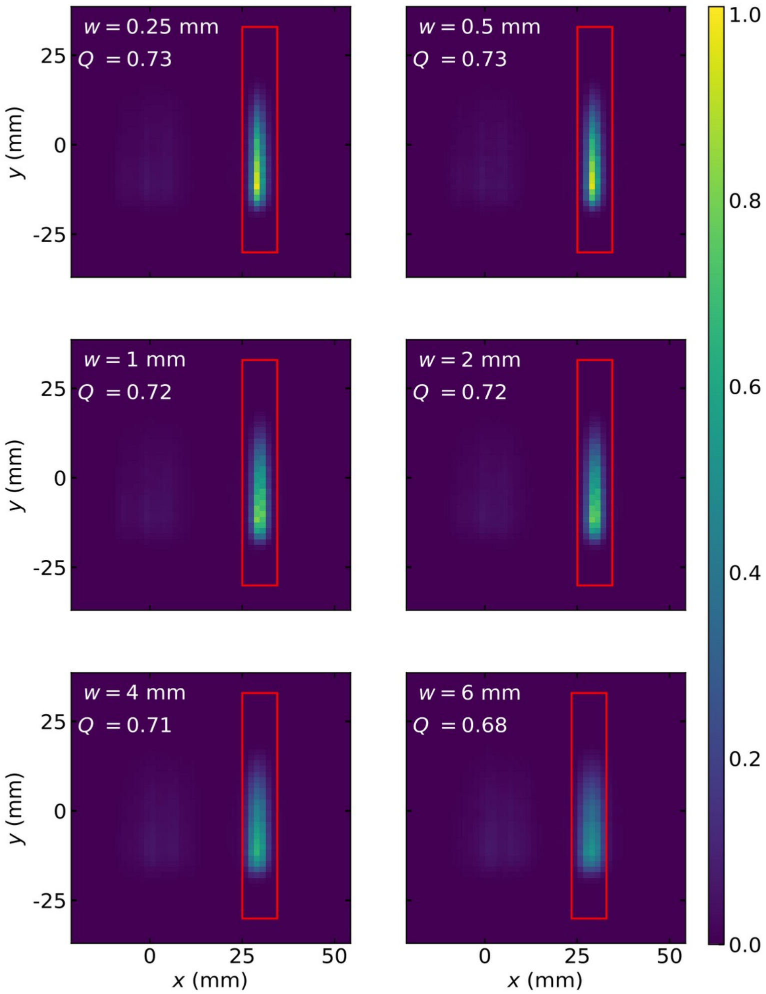
Properties of Elliptic Polarizing NMO (MIRA)

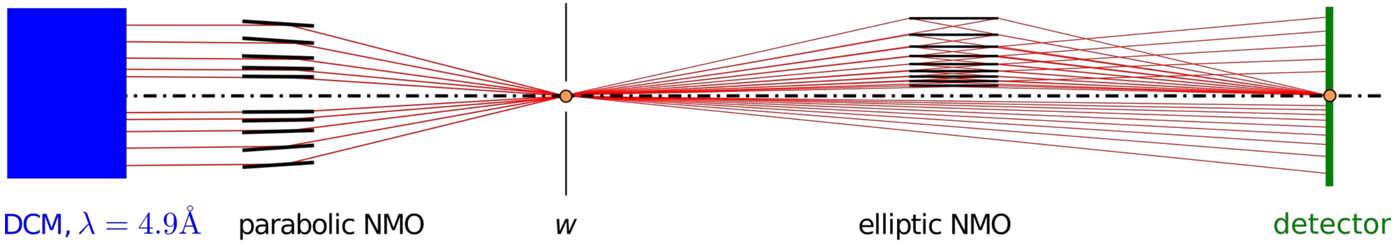
- High fraction of neutrons arriving at the target (outlined in red), Q = 72%
- Determination of beam width limited by detector resolution

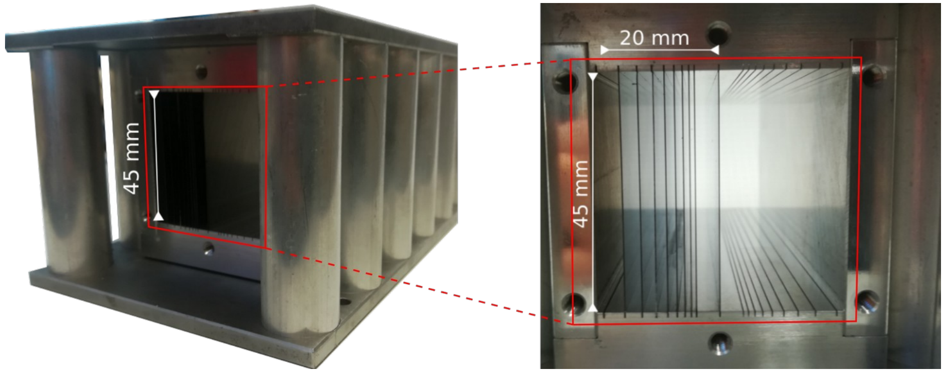


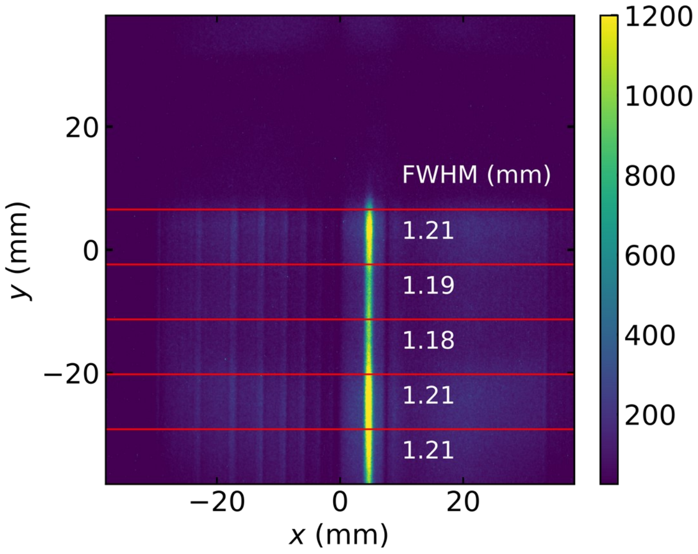


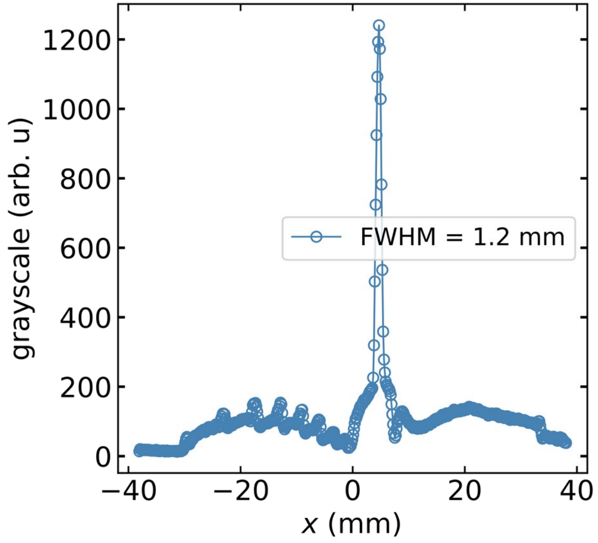
Properties of Elliptic NMO (BOA, Matteo Busi)

- Control of beam size (FWHM) at F_2 using an aperture at F_1 (*w*)
- Intensity distribution determined by using a neutron scintillator



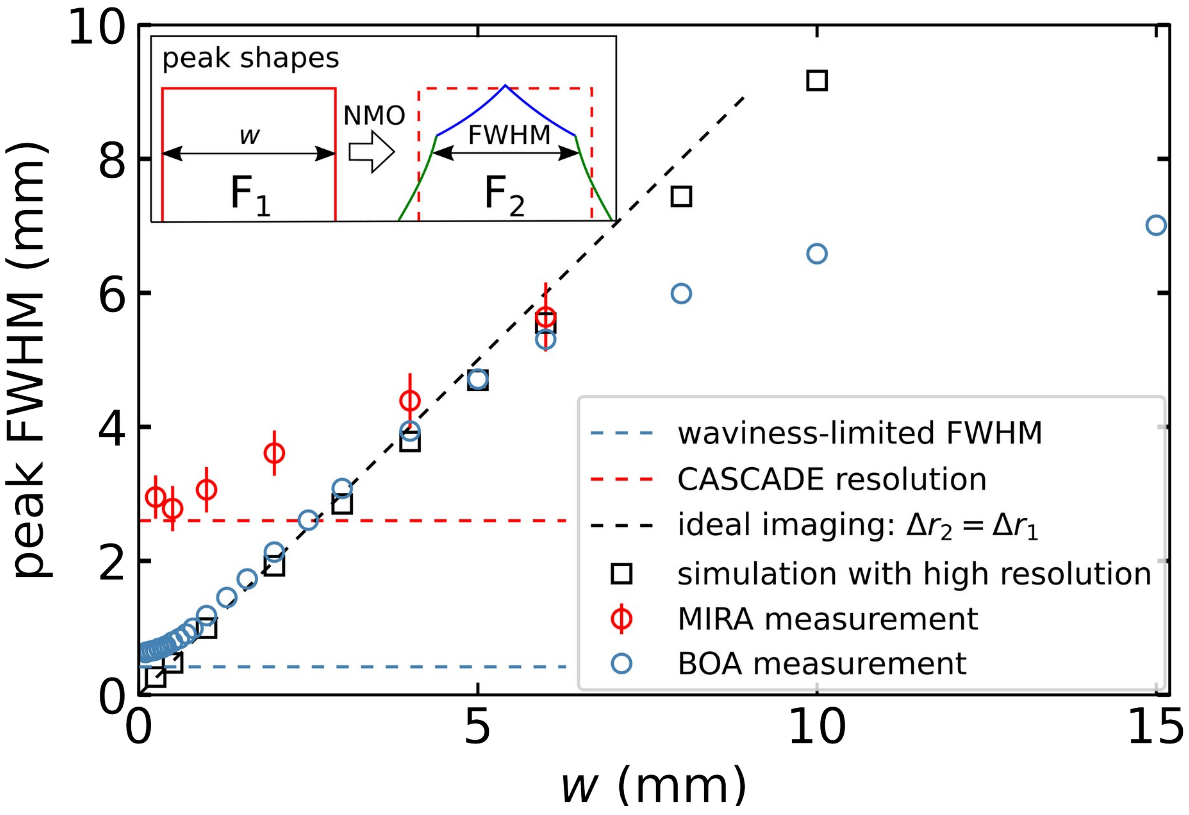




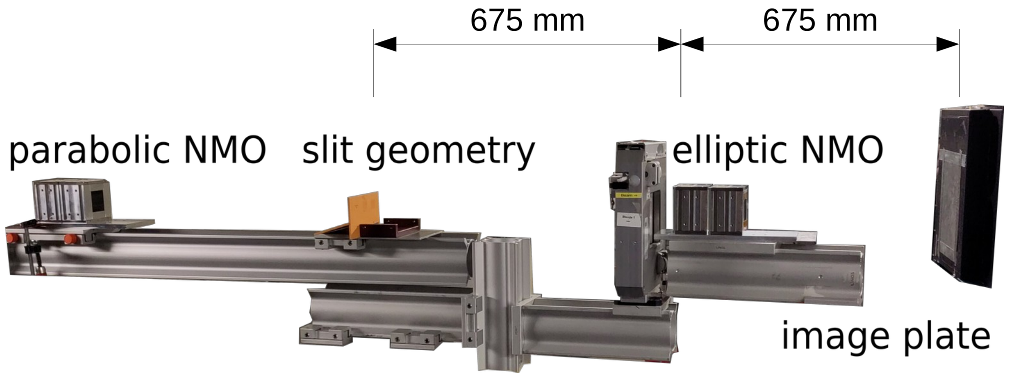


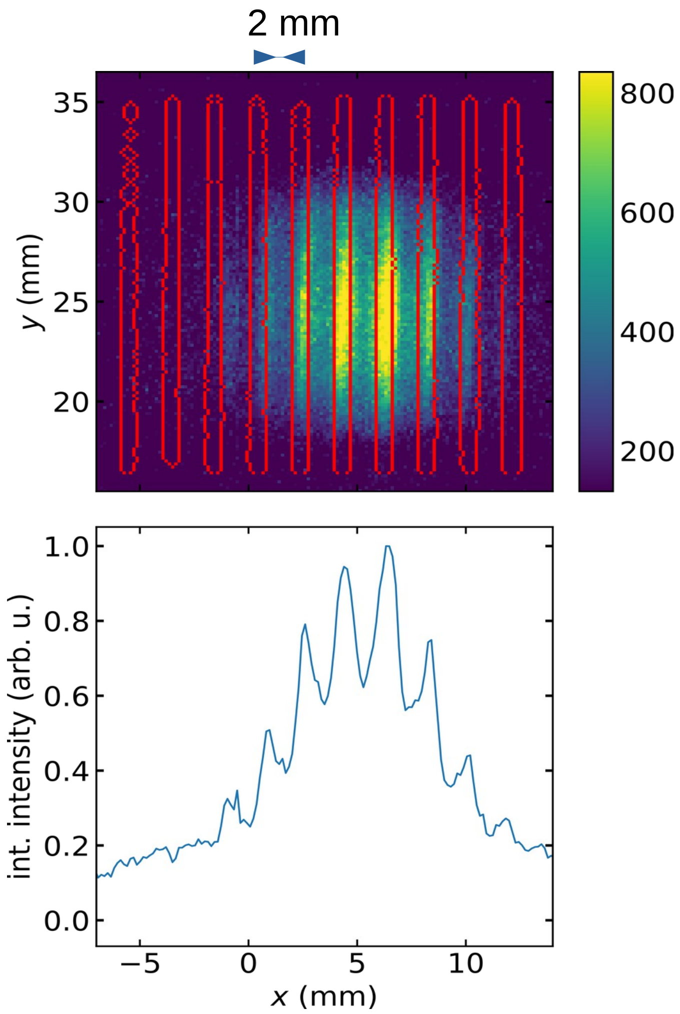
Properties of Elliptic NMO

- MIRA: High fraction of neutrons arriving at sample position, $Q = 72\%$
- BOA: Control of beam size (FWHM) at F_2 via aperture at F_1 (w)

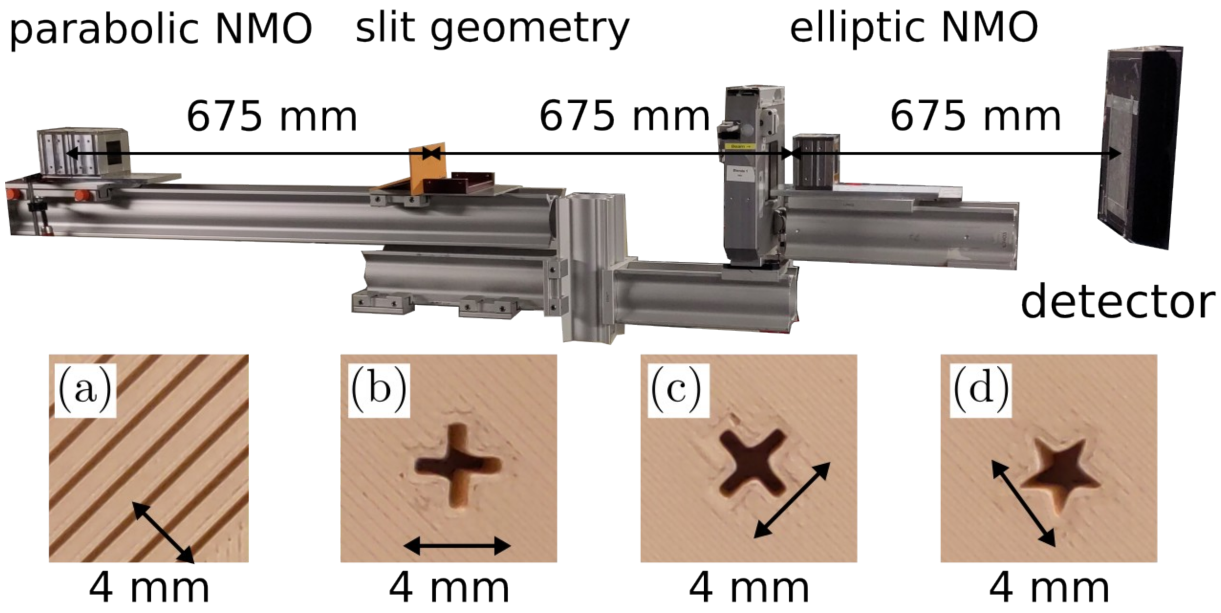


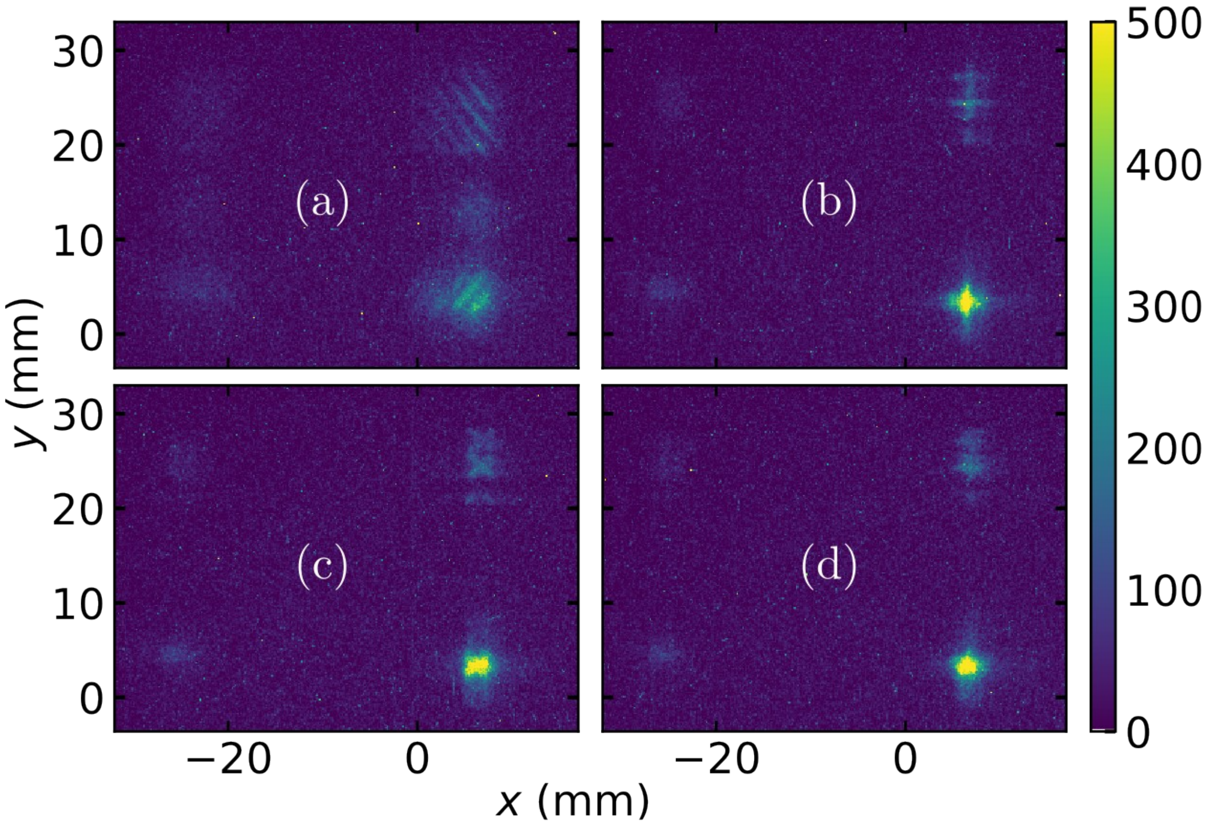
Imaging of a 1D Grid (BOA)



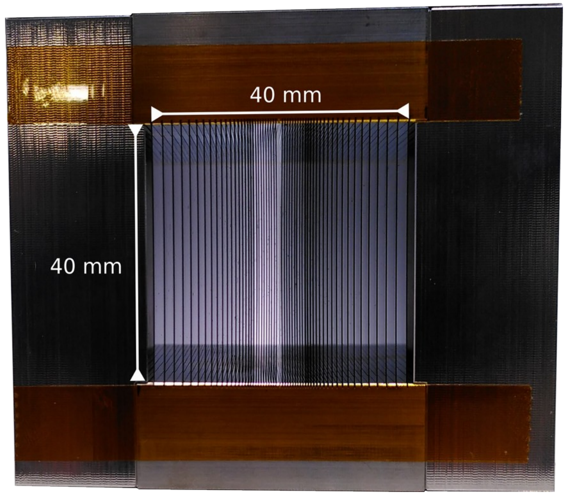


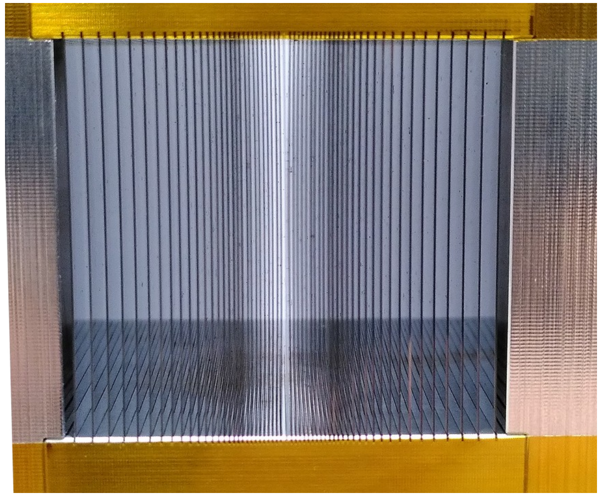
2D-Imaging of Complex Structures (BOA)

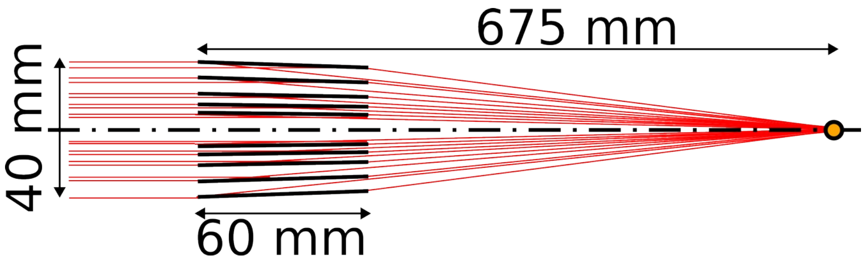




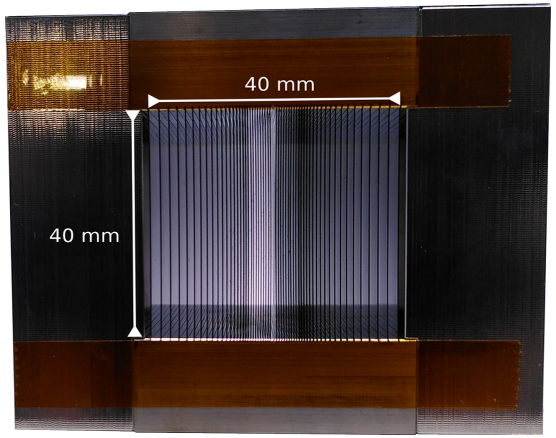
Properties of Parabolic NMO (BOA)

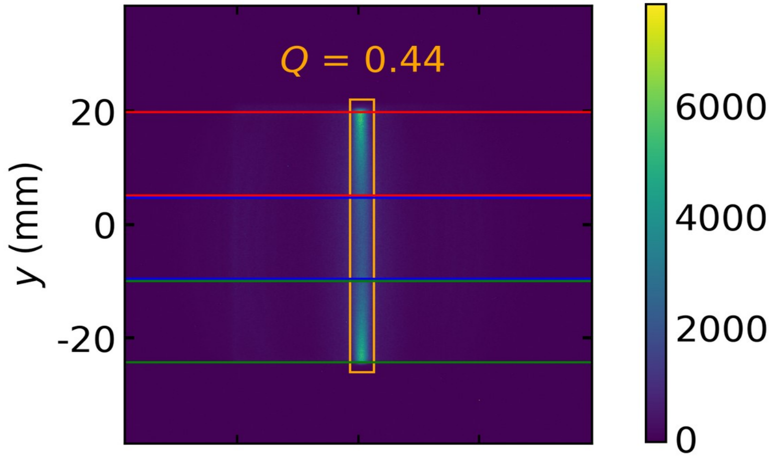


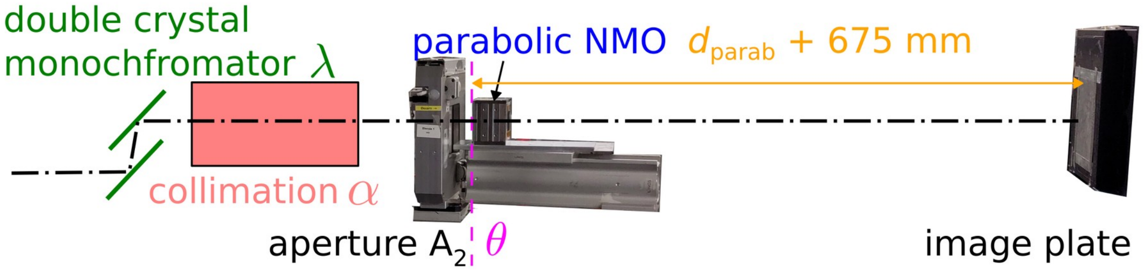


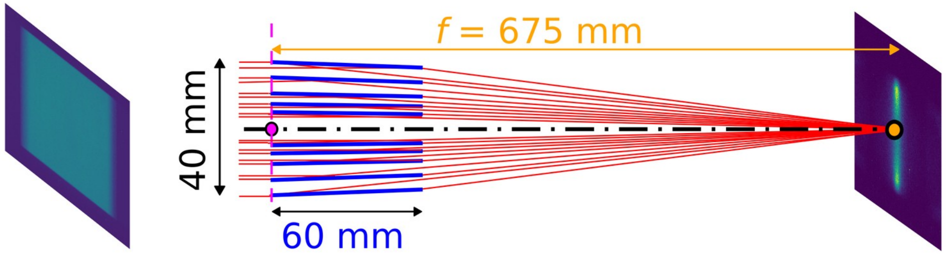


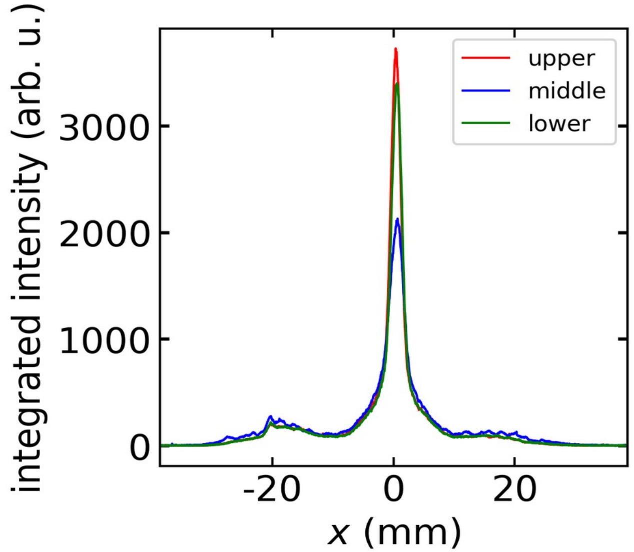
Properties of Parabolic NMO (BOA)



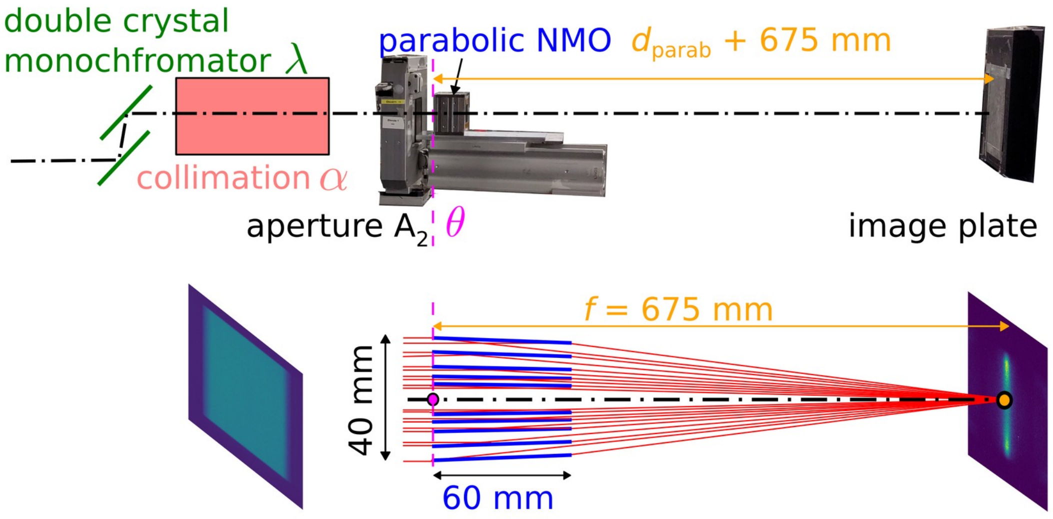




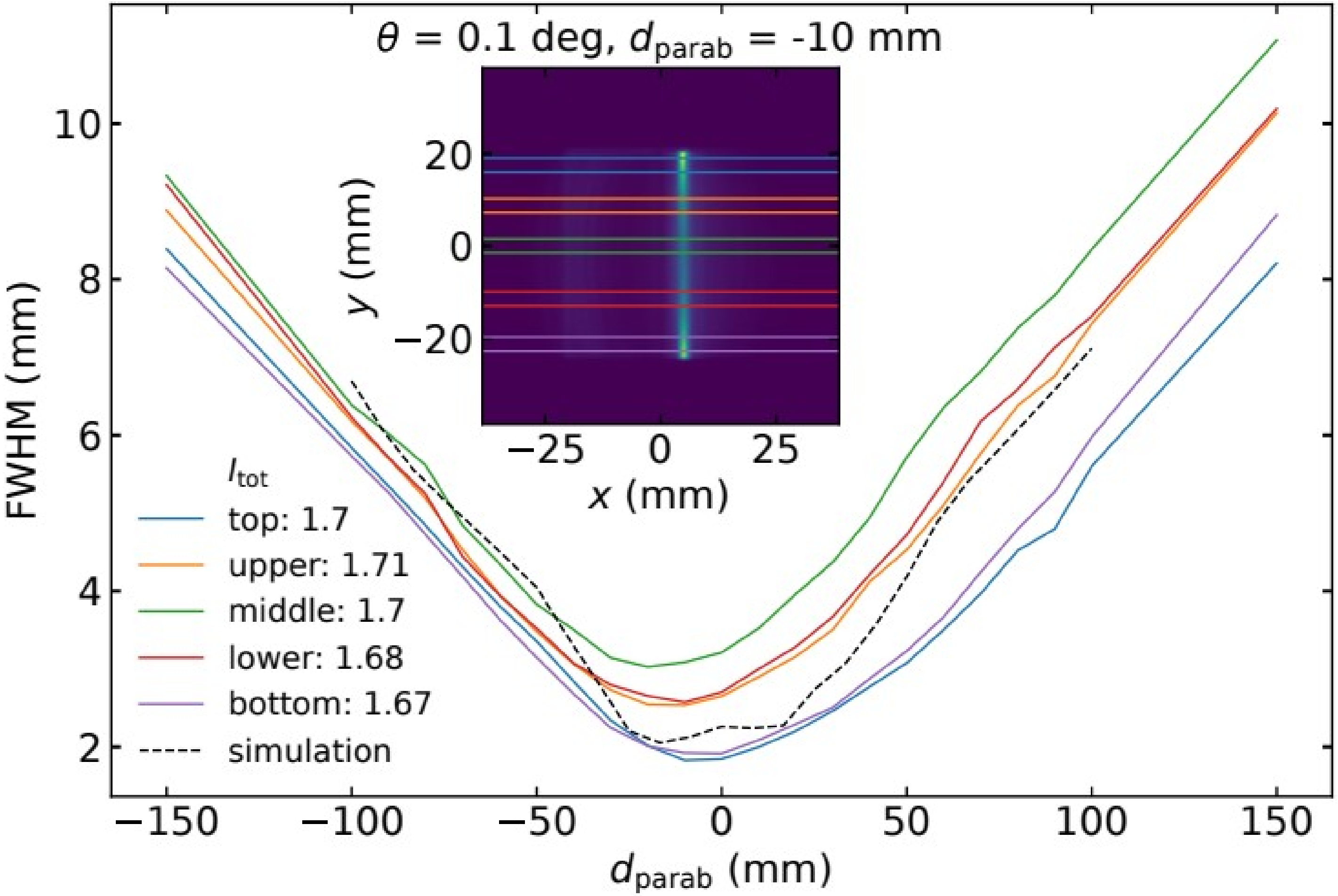




Properties of Parabolic NMO (BOA)

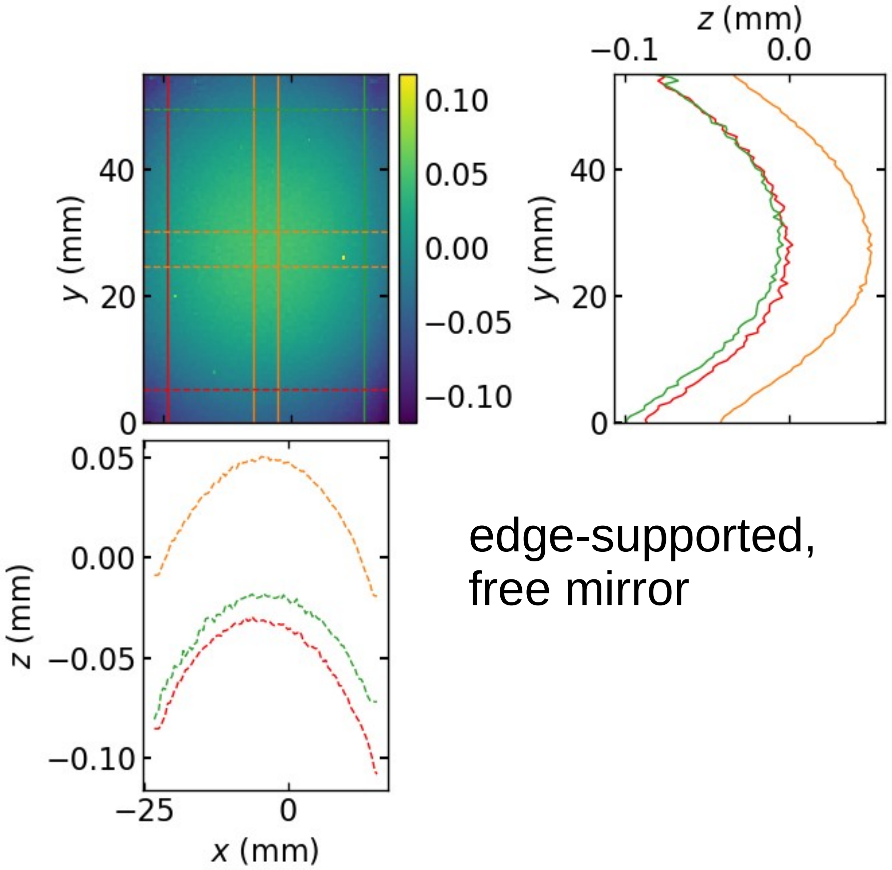


- Quality of focusing decreases with distance from shape-determining grooves
- Total intensity does not change with distance from the grooves
- Mirrors curve more strongly towards the center -> Shift of focal point closer to the NMO, smaller d_{parab}



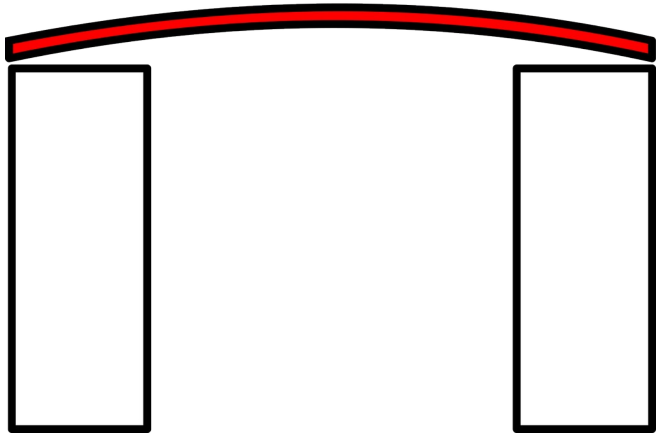
Mirror Deformation

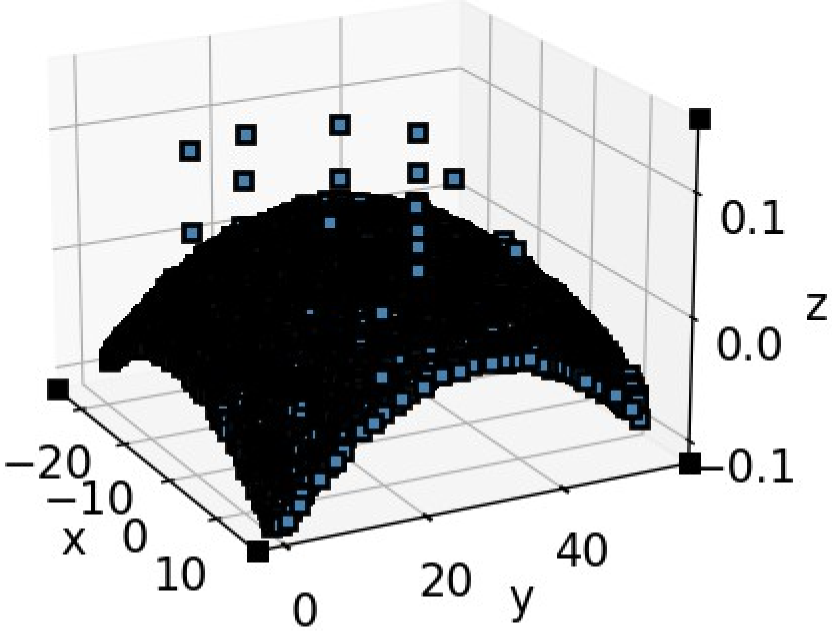
- Ongoing investigation of true mirror shape using a 3D scanner



edge-supported,
free mirror

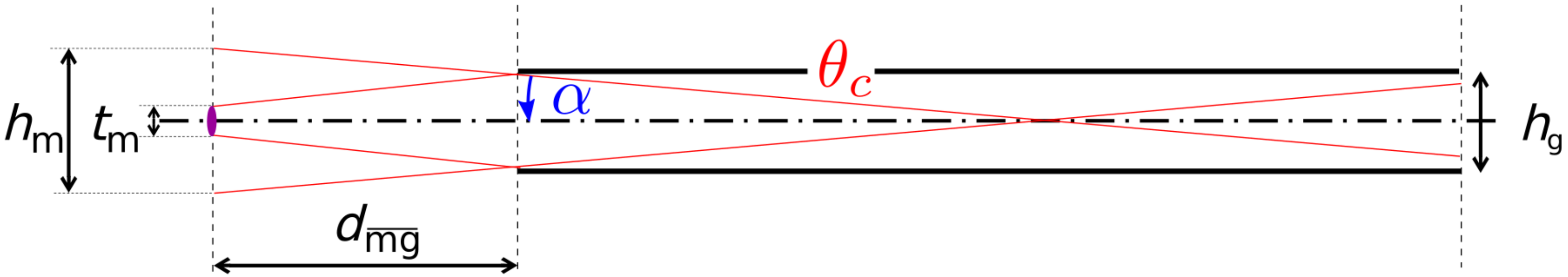
edge-supported



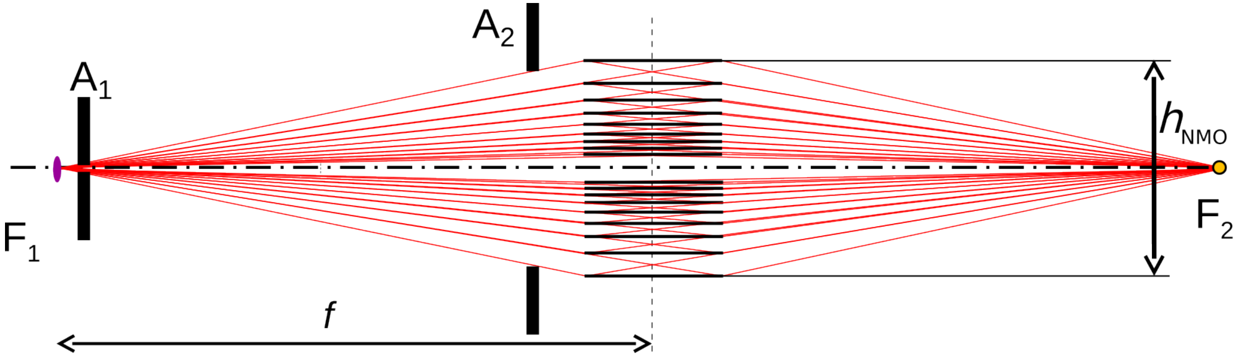


Neutron Extraction from Compact Sources

- Compact sources, large guides → dilution of phase space, “under-illumination“
- Liouville's theorem: Phase space density can only decrease

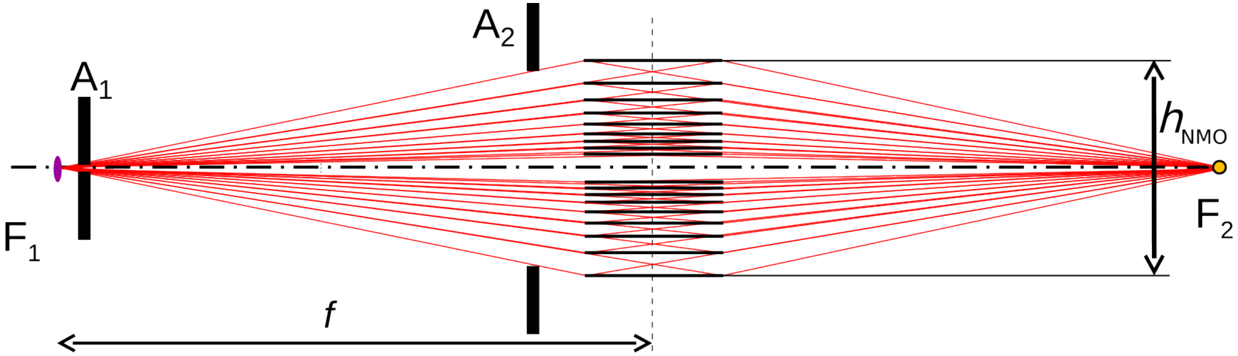


- Elliptic NMO images compact sources onto second focal point

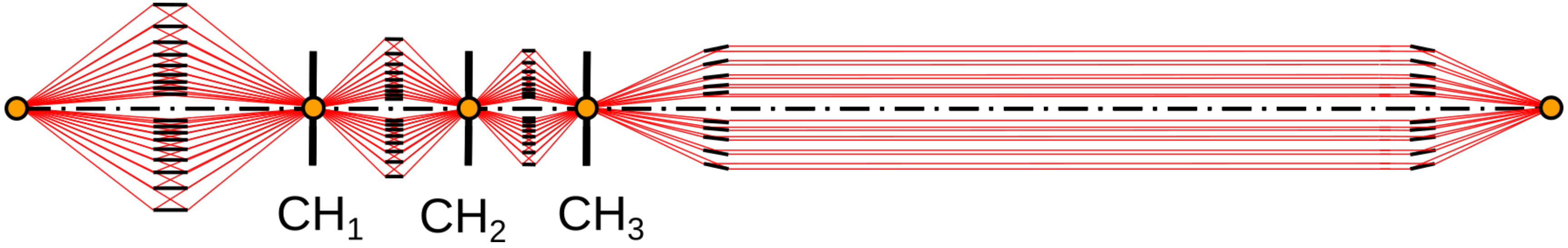


Neutron Transport

- Controlling beam size and divergence by apertures distant to the sample

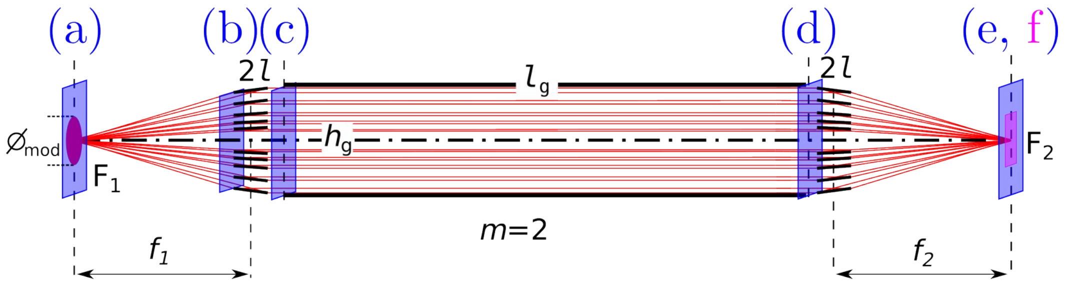


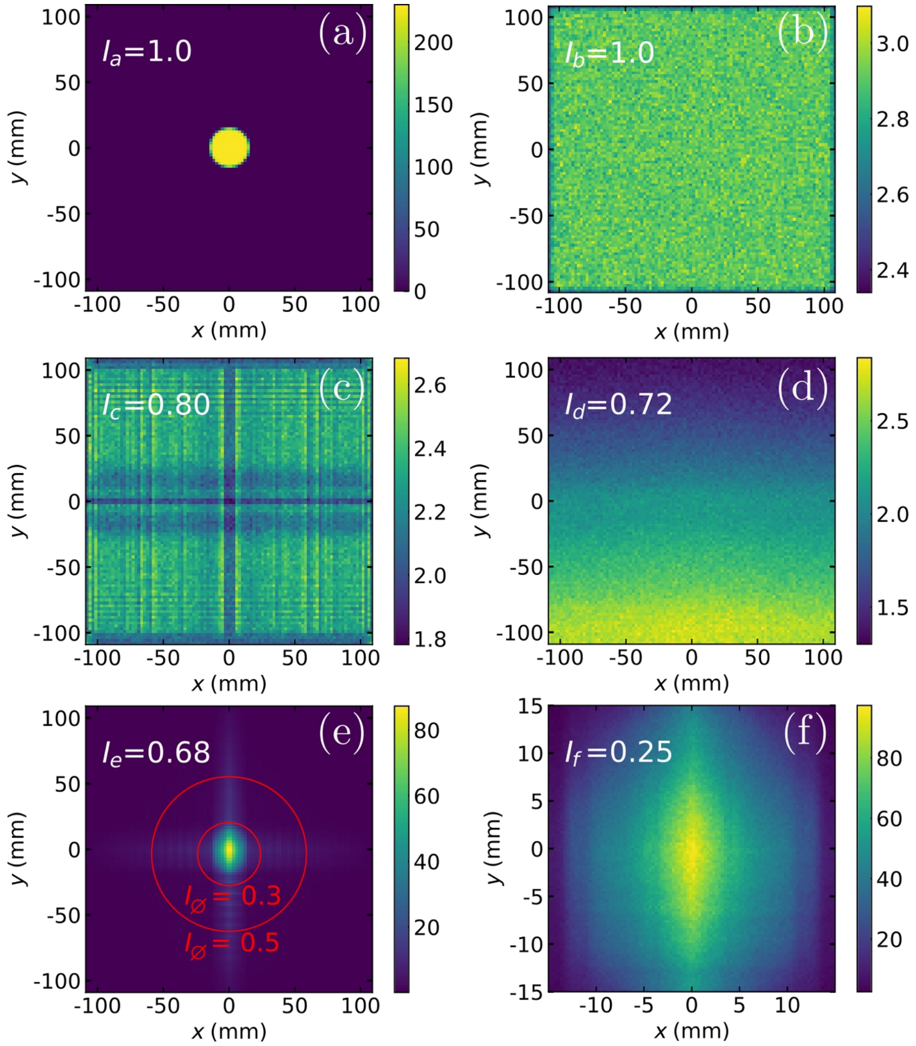
- Series of elliptic NMO might allow for efficient chopper placement and illumination



Transport of Low-Divergence Beams

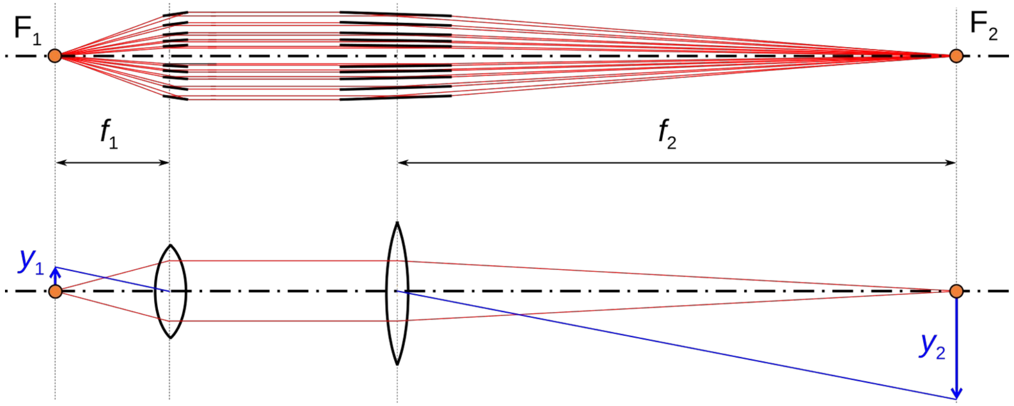
- Transform source to low-divergence beam using parabolic NMO
- Efficient transport over l_g = 160 m
- Refocusing by parabolic NMO

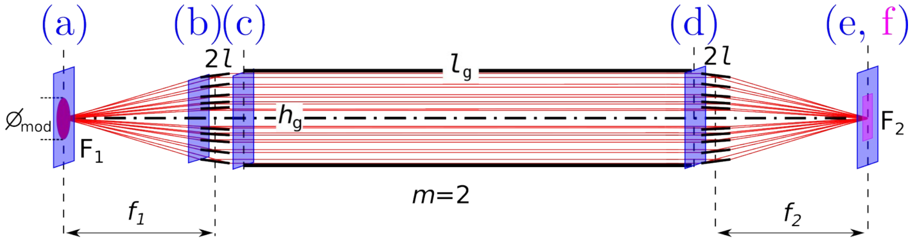


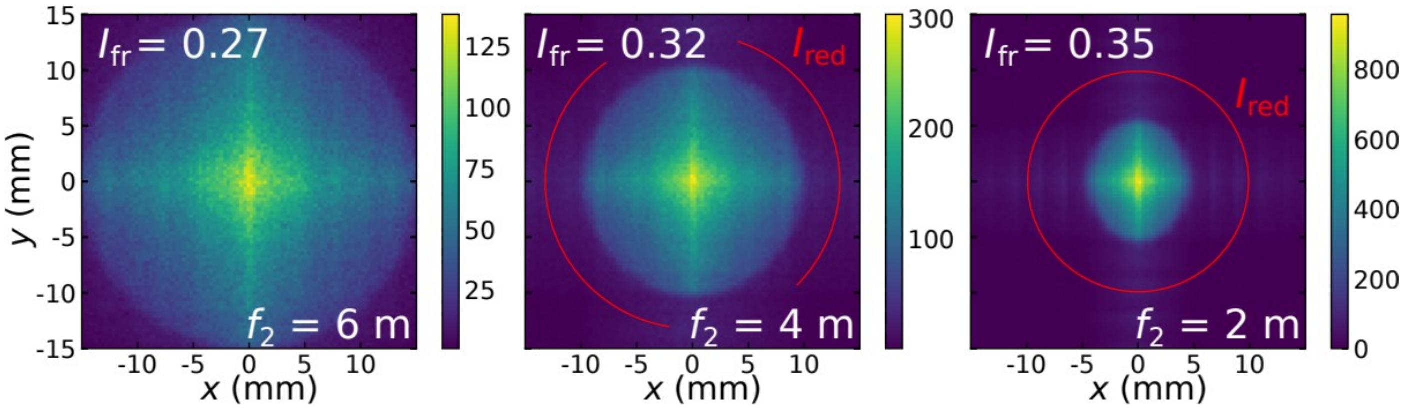


Adjustment of Beamsize

- Combinations of parabolic NMO with different focal lengths allow to adjust the size of the beam
- $\Delta r_1/f_1 = \Delta r_2/f_2$

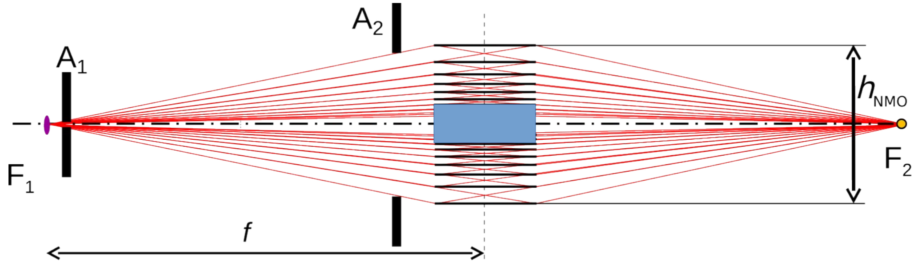


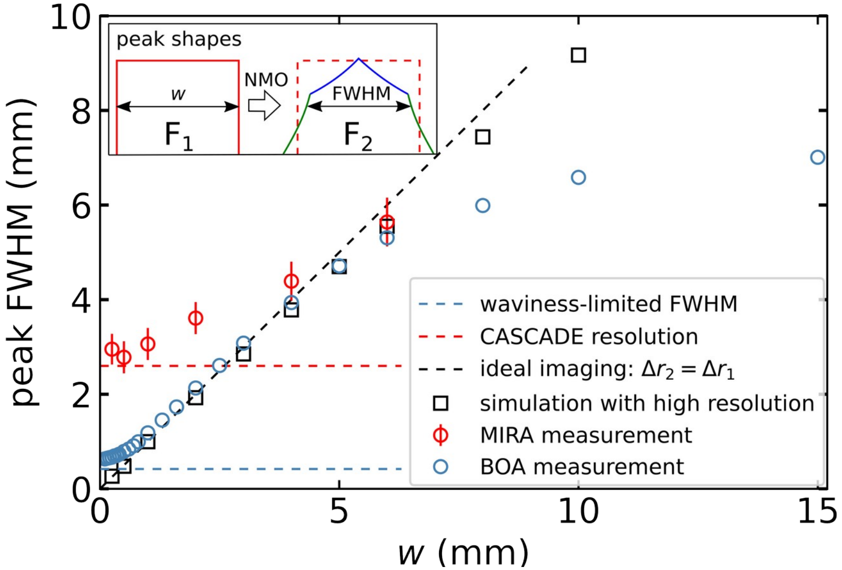


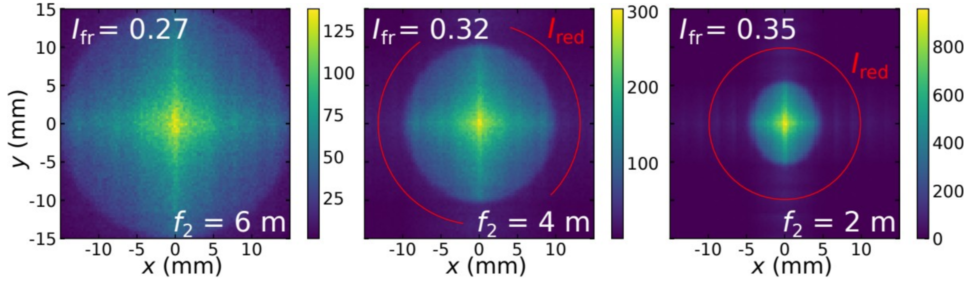


Conclusions and Outlook

- NMO as modular units for extraction and transport of neutrons
  - Beam can be tailored to experimental requirements (size, divergence)
  - Clean spatial definition of the beam (no penumbra)
  - Short-wavelength cut-off with central beam stop



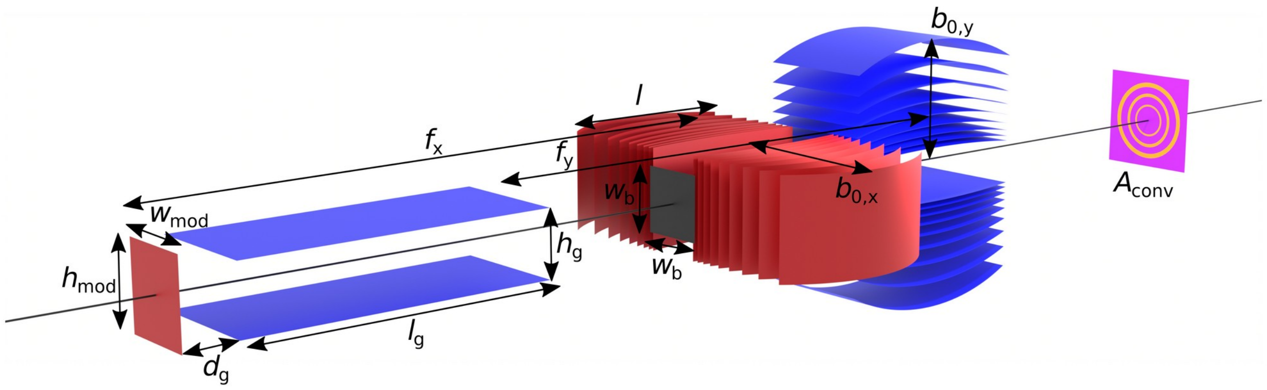




Conclusions and Outlook

- Practical advantages
  - Space for sample environment and biological shielding
  - Simple alignment
  - Simple to manufacture
  - Simple replacement/exchange

- Further applications
  - Extraction of very-cold neutrons under large angles from high-brilliance moderators [1]
  - High divergence options for existing beam lines



[1] Zimmer, O. et al. (2022). In-beam superfluid-helium ultracold neutron source for the ESS. Journal of Neutron Research, 24(2), 220045. doi:10.3233/JNR-220045

Acknowledgments

- Peter Böni (supervisor)
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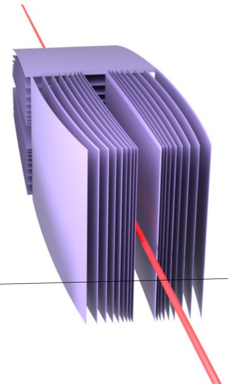
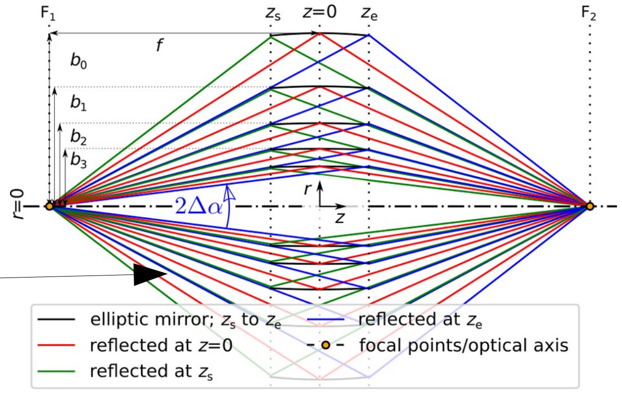
- Tobias Neuwirth & Simon Sebold (3D-printing)
- Boris Khaykovich (provided McStas code)
- The MIRA group

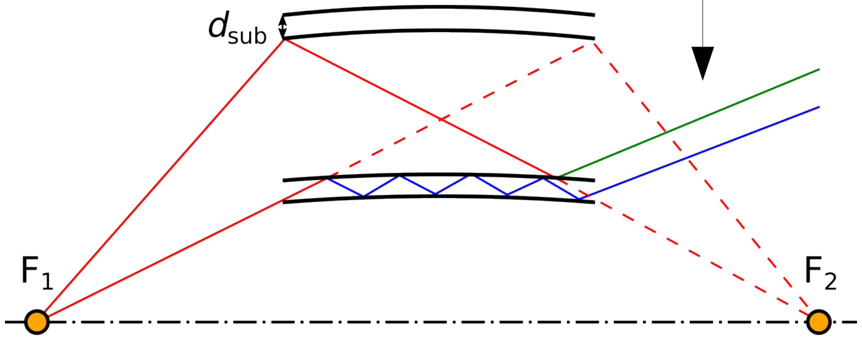
Thank you for your attention!
Questions?

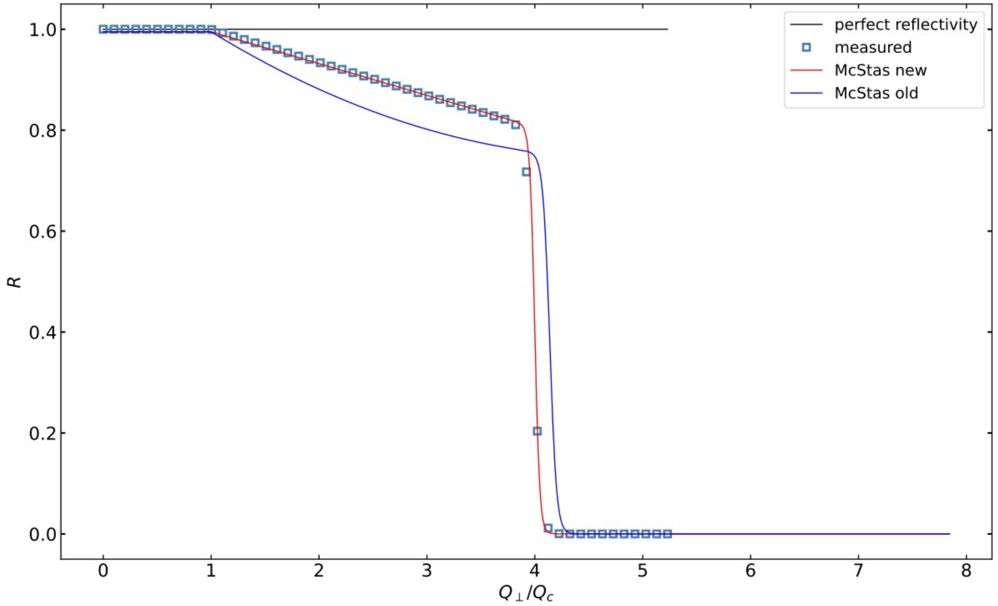
McStas Component

- Based on code by Giacomo Resta
- Added functionalities include:
  - Double-planar systems
  - Calculation of mirror dimensions from the outermost mirror
  - Realistic super mirror reflectivity
  - Silicon substrates with finite thickness including absorption and refraction
  - Double-side coated mirrors





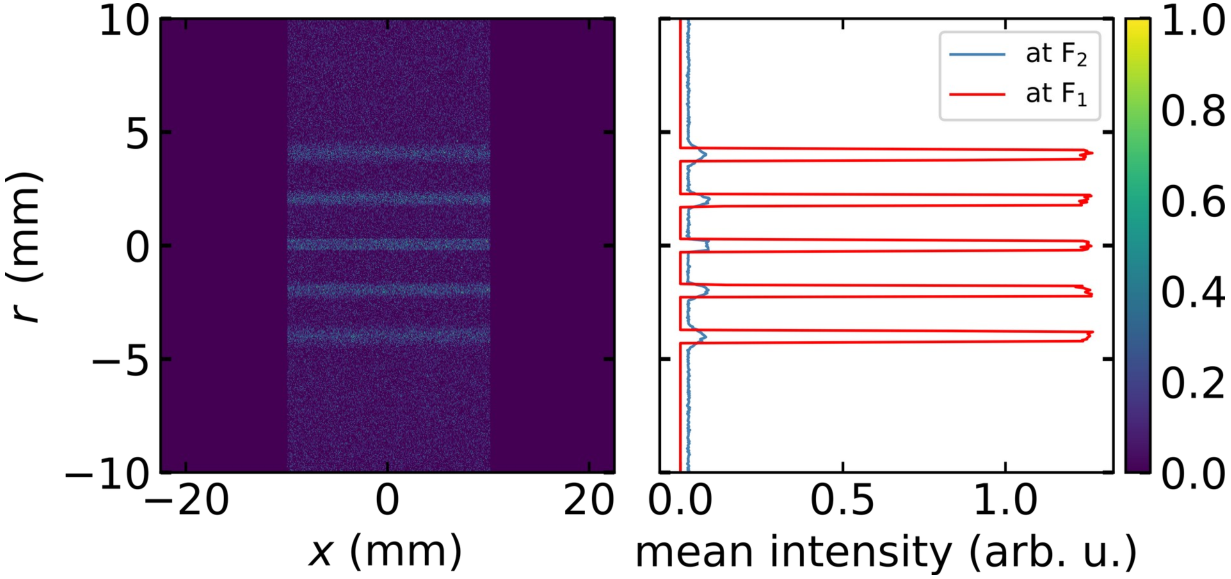


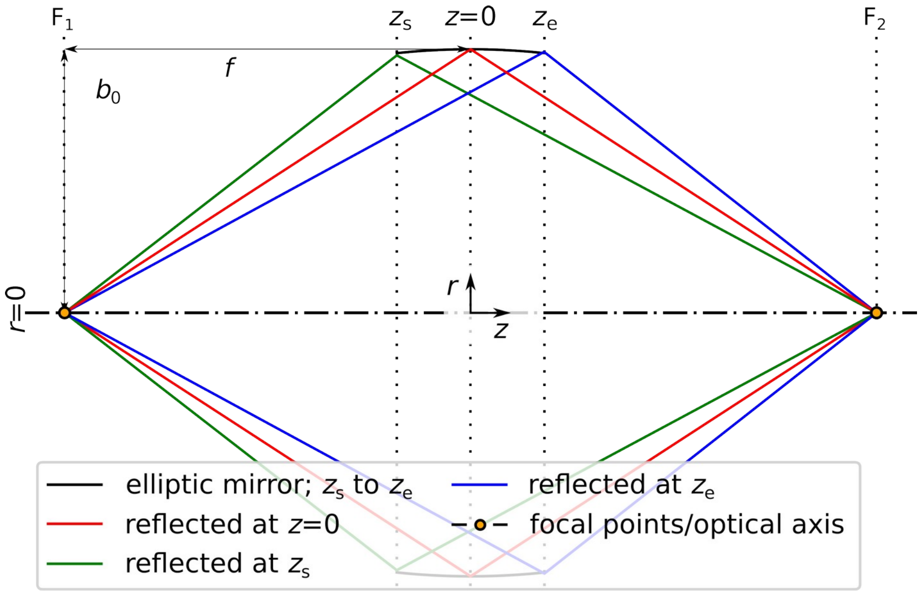


Elliptic Nested Mirror Optics (NMO)

- Restrict reflections to the ellipse center →$\Delta r_2 \approx \Delta r_1$→ preservation of neutron phase space during reflection between focal points

- Simulation of single, short mirror → good imaging, at the cost of low efficiency

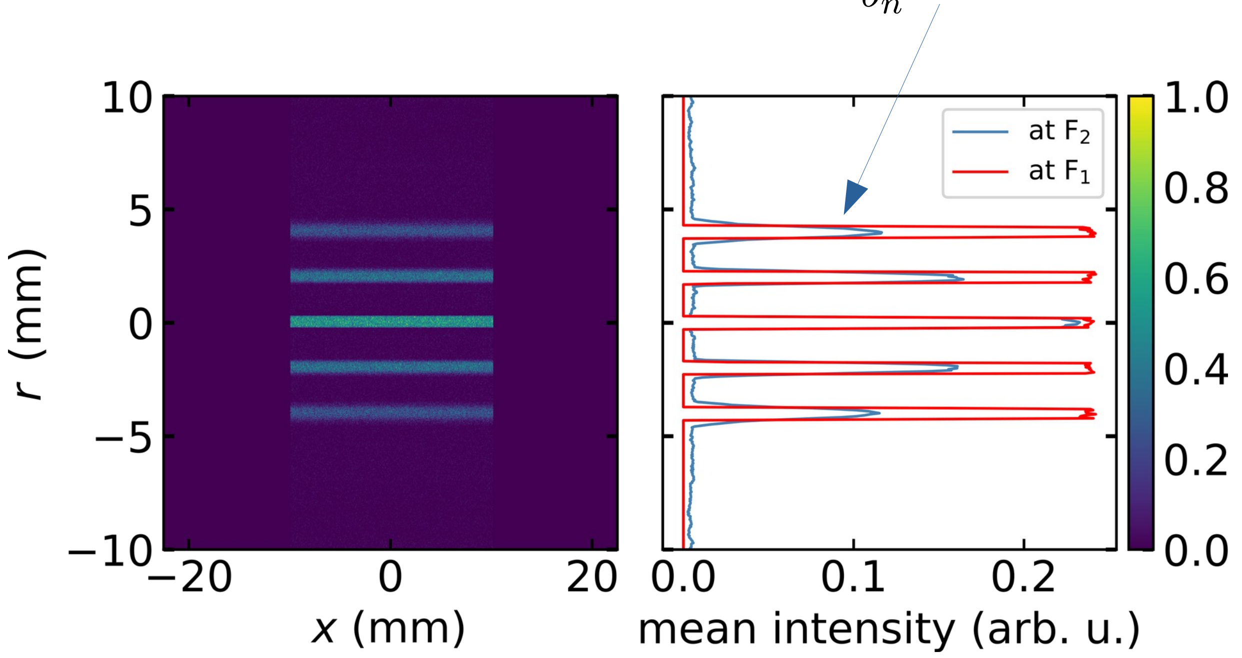


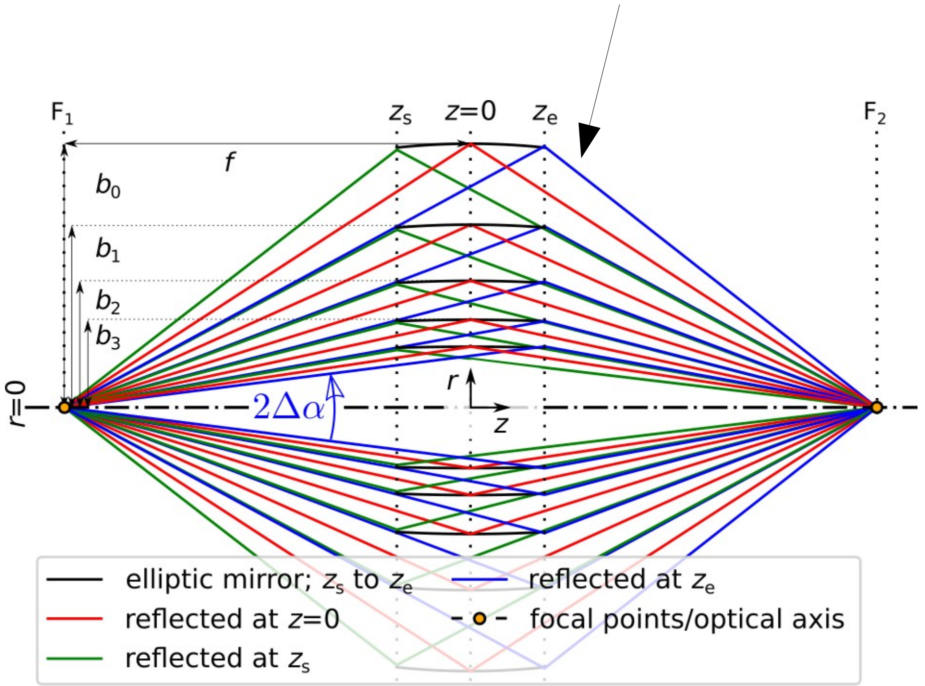


Grid Imaging (NMO)

- Restrict reflections to the ellipse center →$\Delta r_2 \approx \Delta r_1$→ preservation of neutron phase space during reflection between focal points

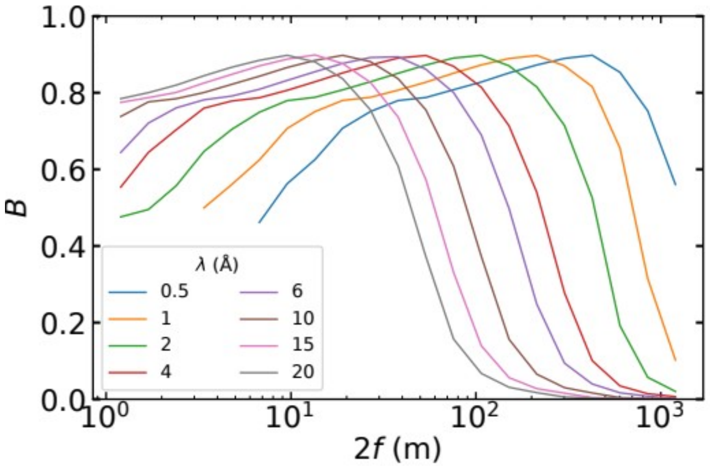
- Transport of required divergence by nesting short elliptic mirrors according to simple recipe
- Geometric losses proportional to $\frac{\Delta r_1}{b_n}$





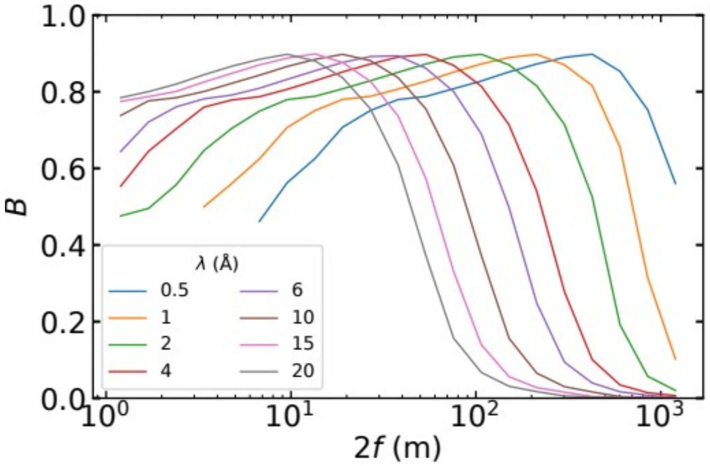
Neutron Transport

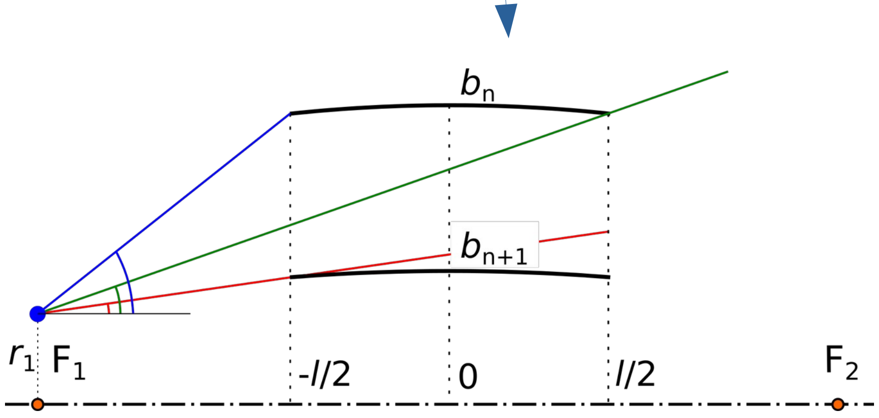
- Size related dependence of the brilliance transfer of a simple elliptic NMO



Neutron Transport

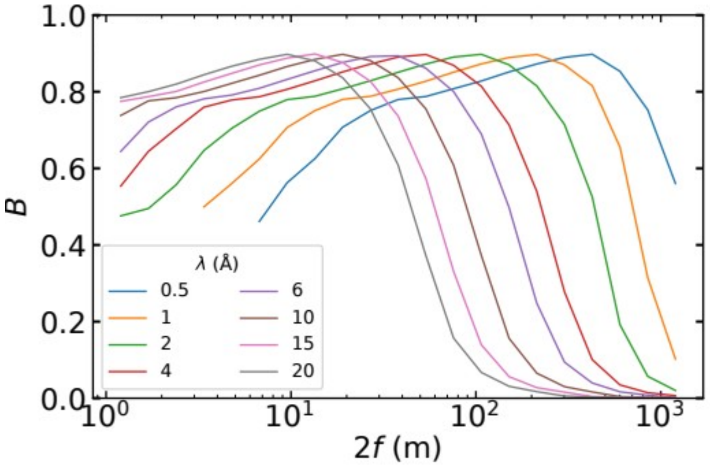
- Size related dependence of the brilliance transfer of a simple elliptic NMO
- Better transport for smaller source/target relative to NMO size
  - Geometric losses scale proportionally to the ratio of beam width to semi-minor axis $\frac{\Delta r_1}{b_n}$

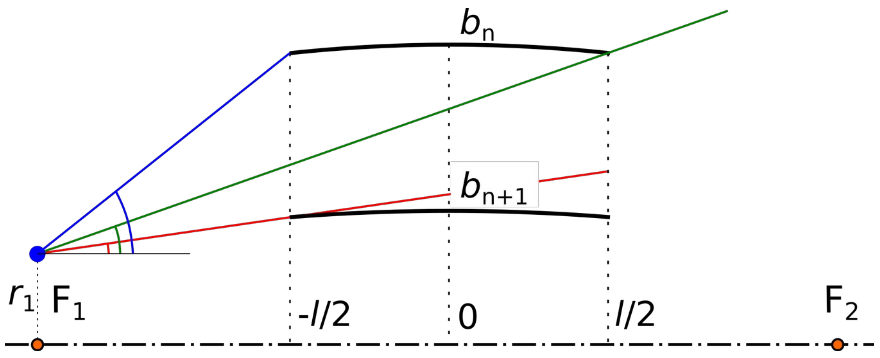


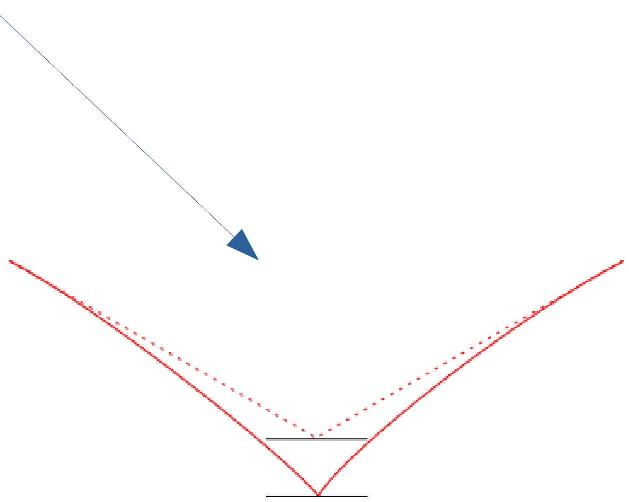


Neutron Transport

- Size related dependence of the brilliance transfer of a simple elliptic NMO
- Better transport for smaller source/target relative to NMO size
  - Geometric losses scale proportionally to the ratio of beam width to semi-minor axis
- Initially minor influence of gravity due to symmetric flight paths reflected at approximately flat mirrors

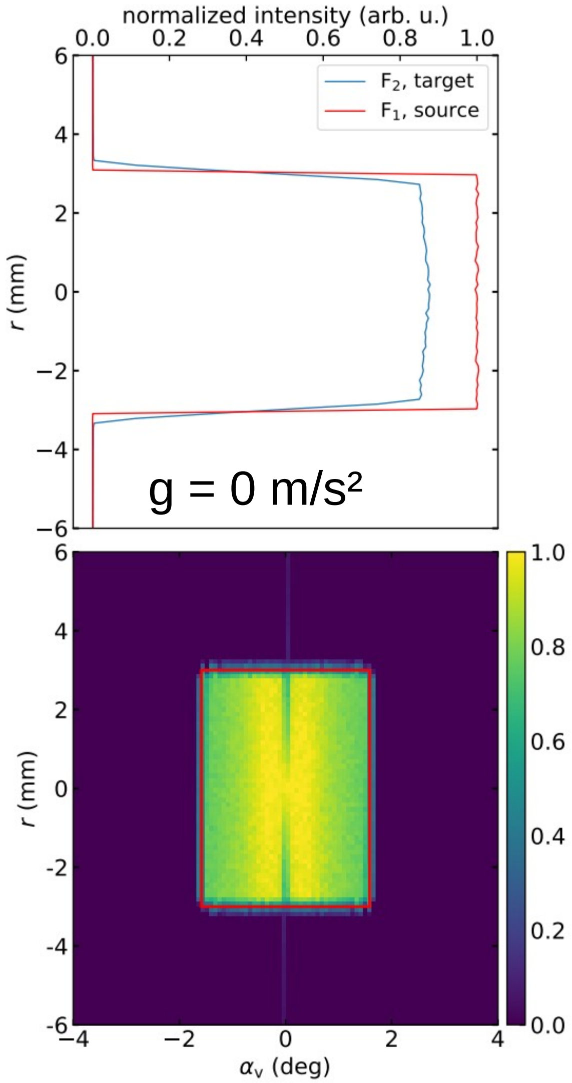


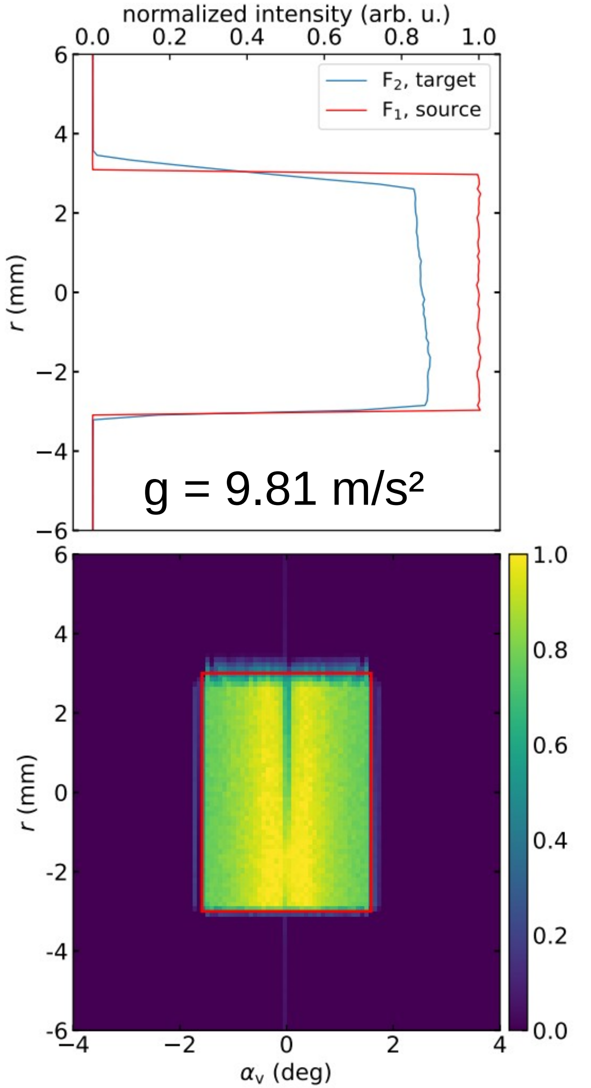




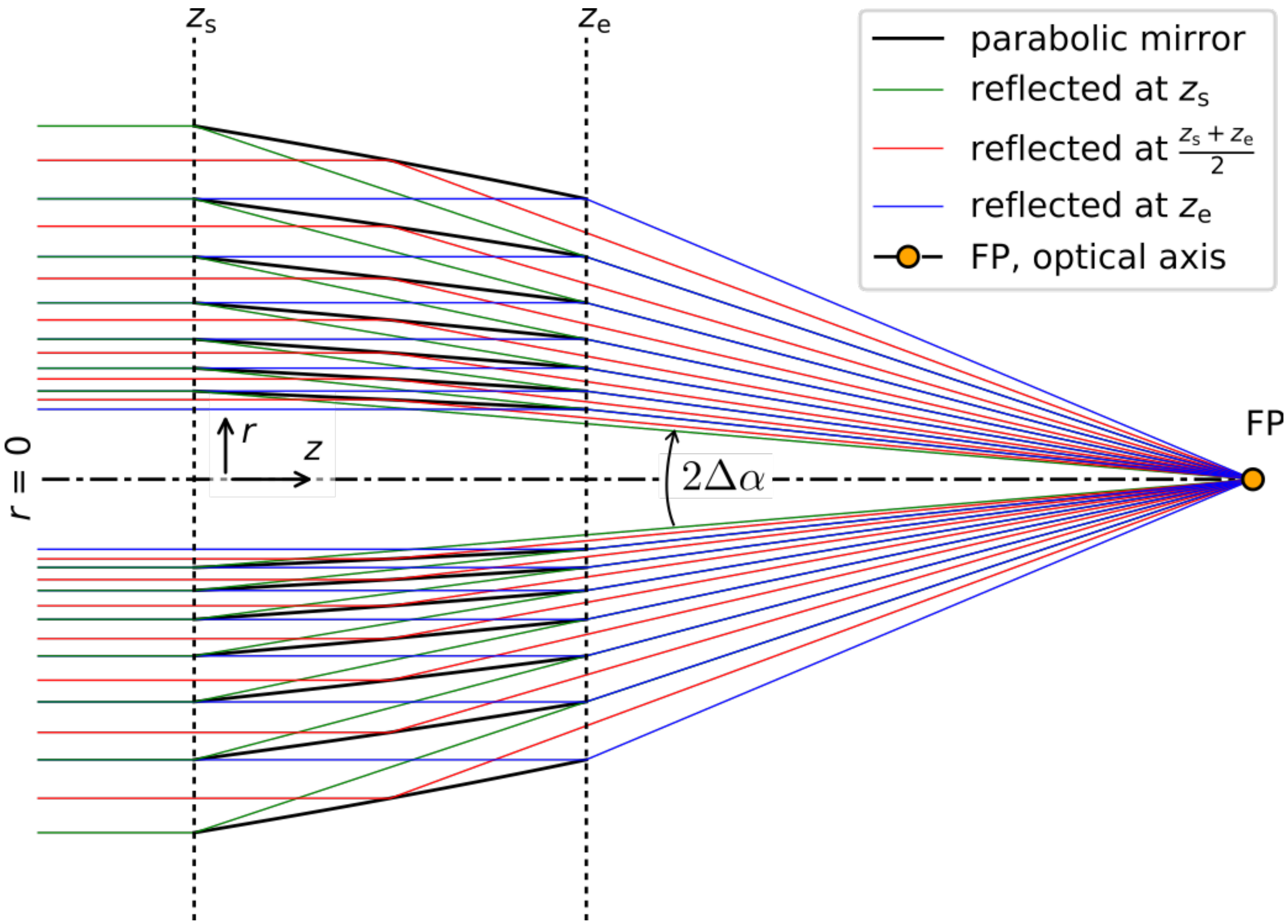
Influence of Gravity on Phase Space

- Source: lam = 4.0 A, div = 2*1.6 deg
- NMO: f = 20 m, l = 0.5 m, b0 = 0.7 m
- dy = (20/1000)^2*5 m = 2 cm
- Another mirror enables the reflection



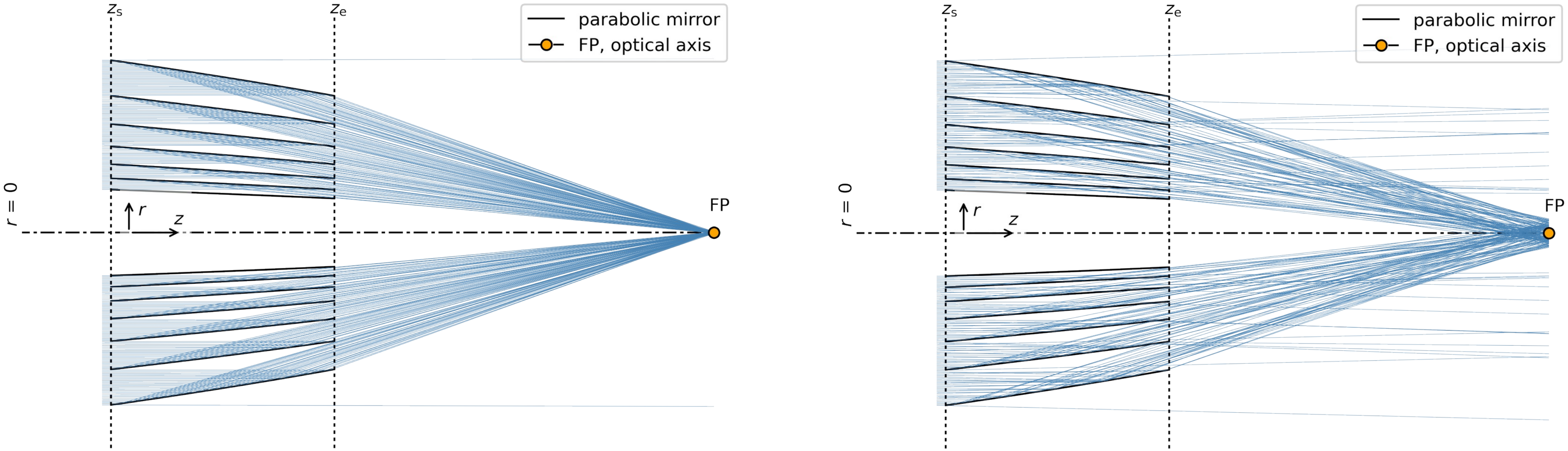


Parabolic NMO Construction



Parabolic NMO: Focusing a Parallel Beam

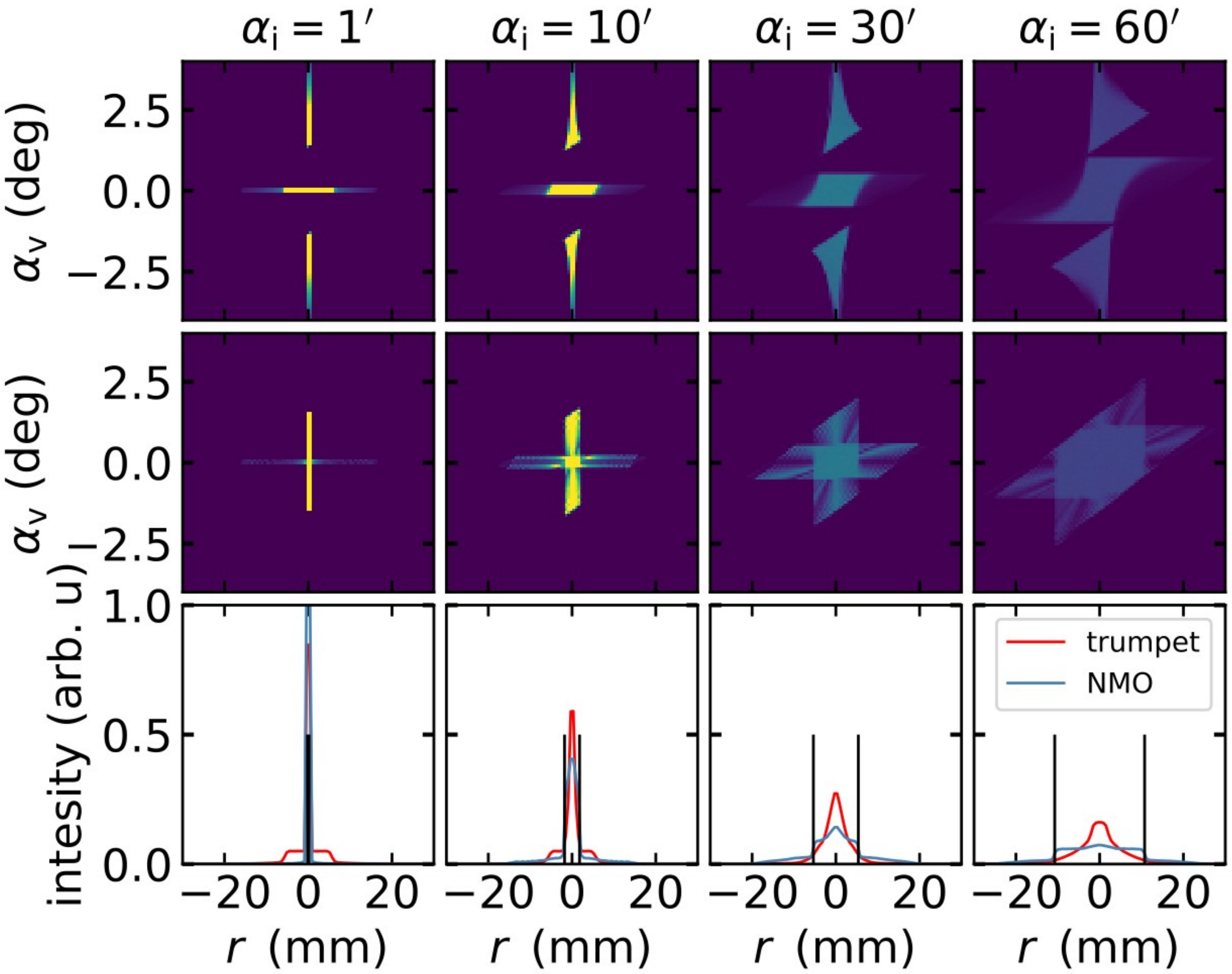
- Points of reflection are limited to a small range of distances from the focal point:
  Beam divergence before NMO → beam width at the focal point, $\Delta r \approx \alpha f$



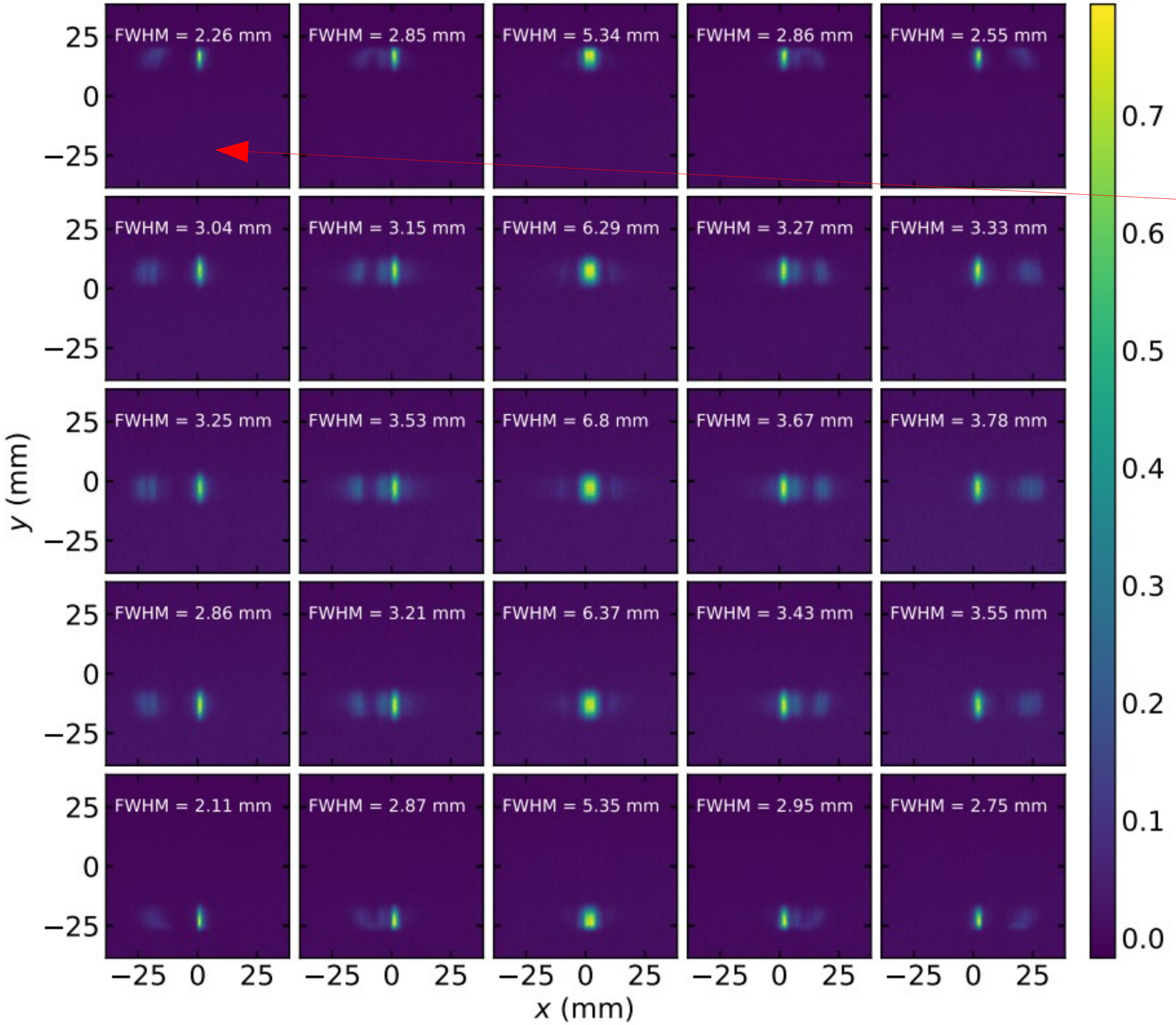
Parabolic NMO Phase Space

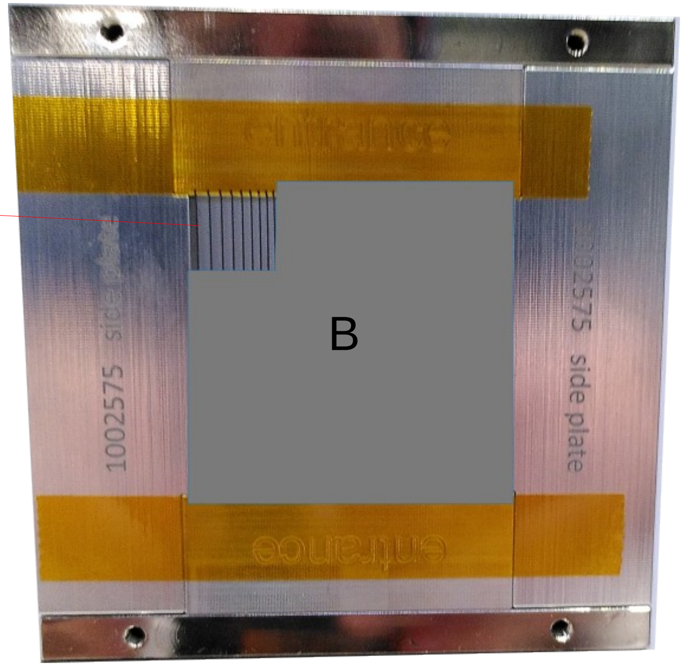
trumpet

NMO



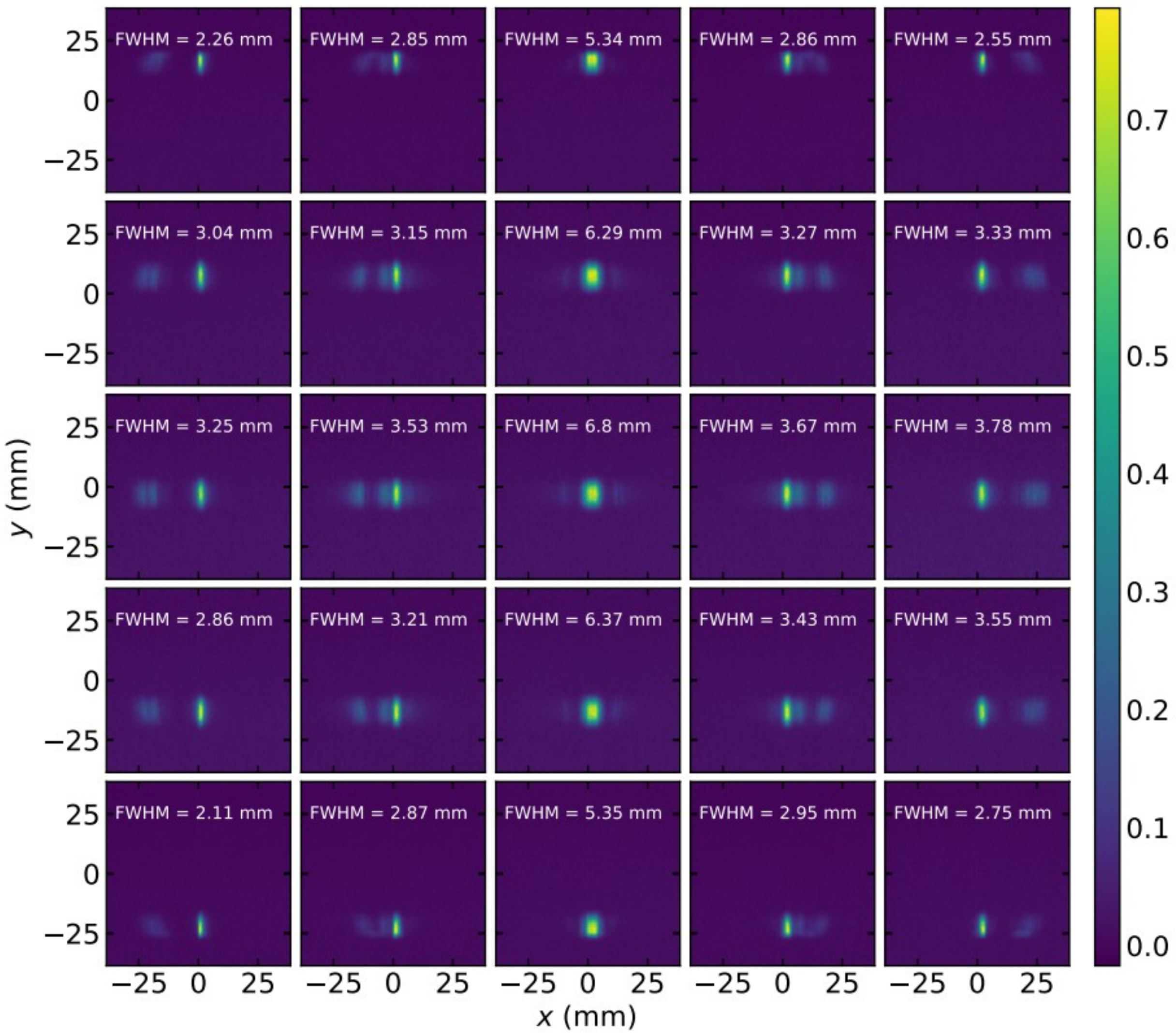
Properties of Parabolic NMO (BOA)

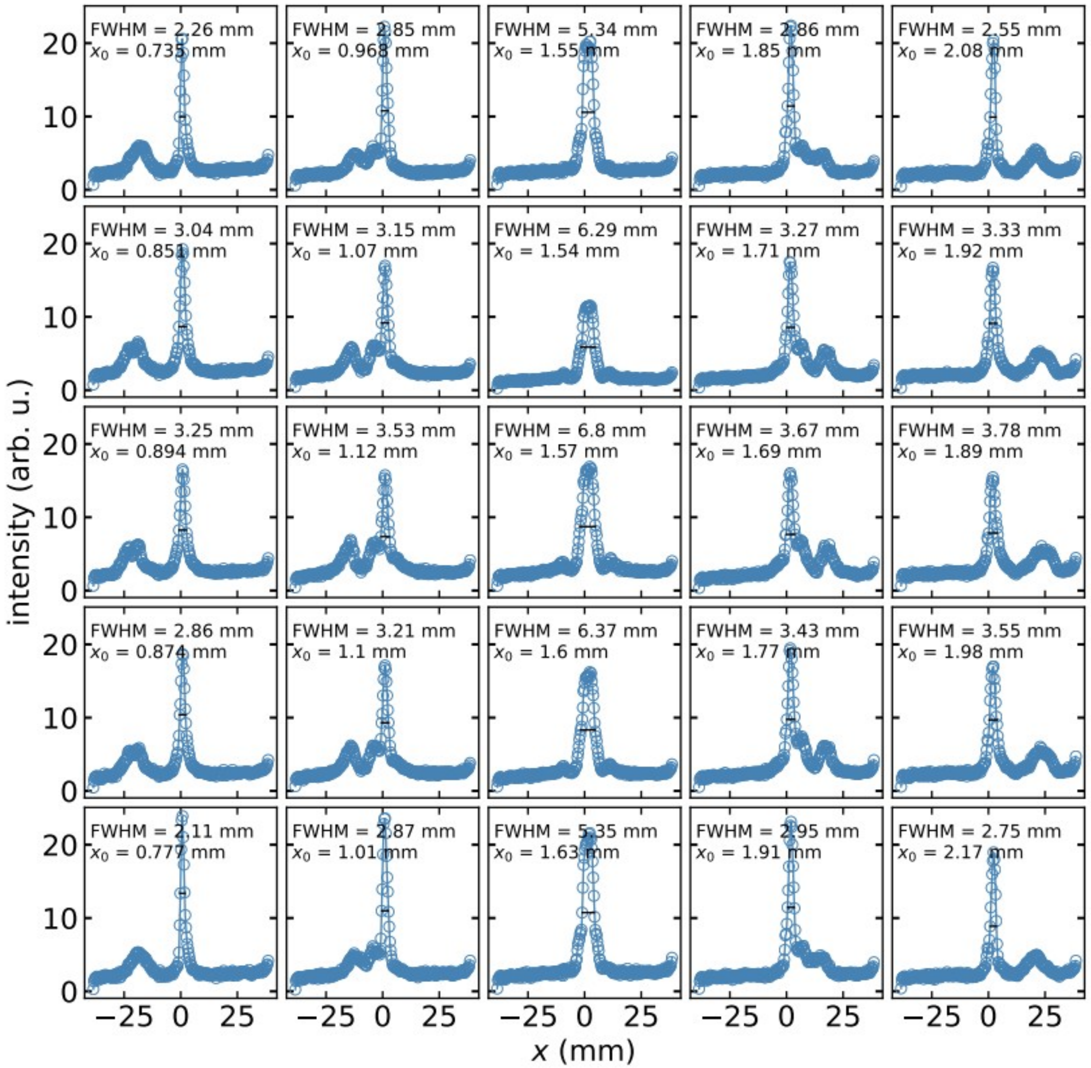




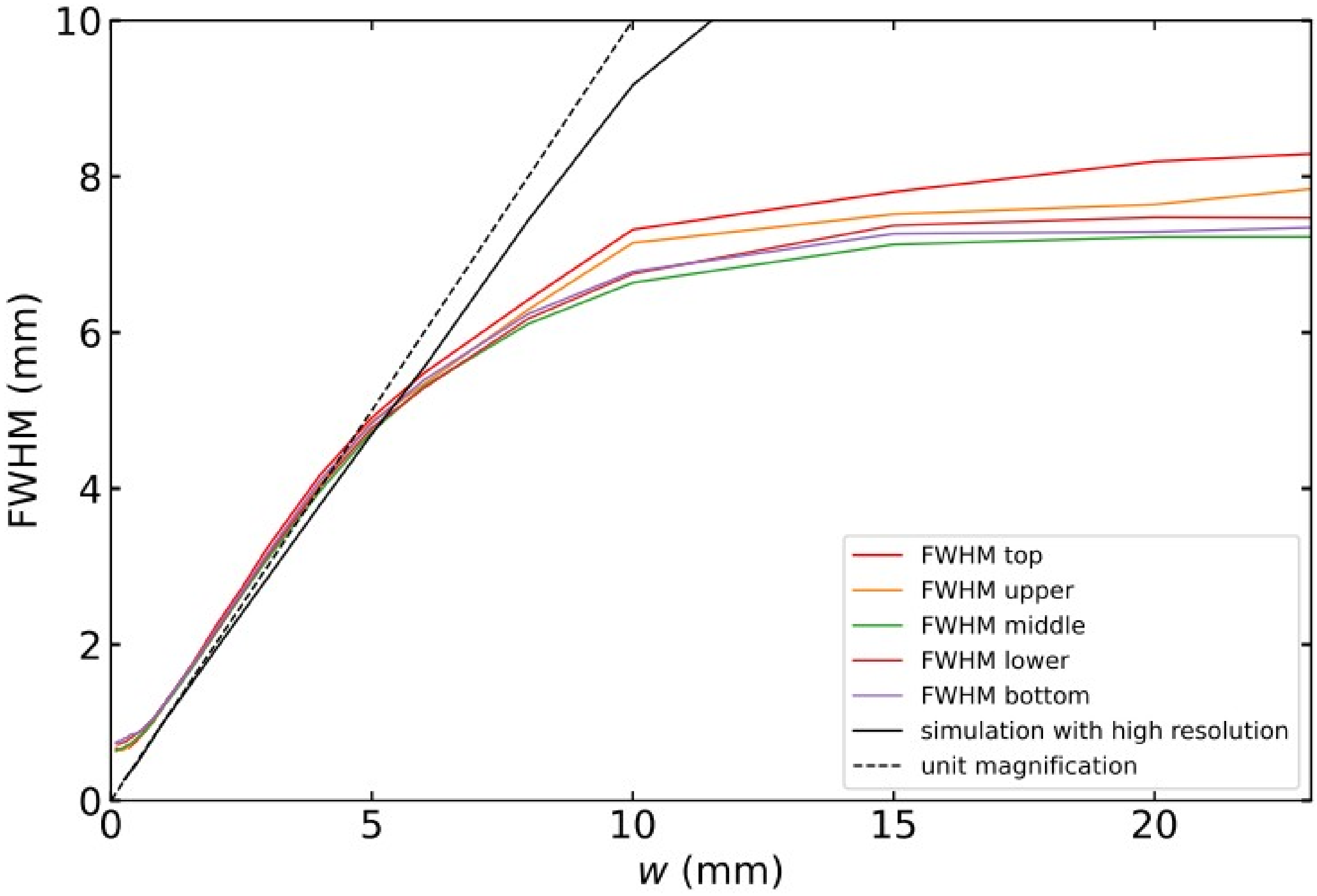
- Segmentation of NMO entrance window in 5 x 5 segments A = 8 x 8 mm²
- Relative position of panel corresponds to the illuminated segment

Properties of Parabolic NMO (BOA)



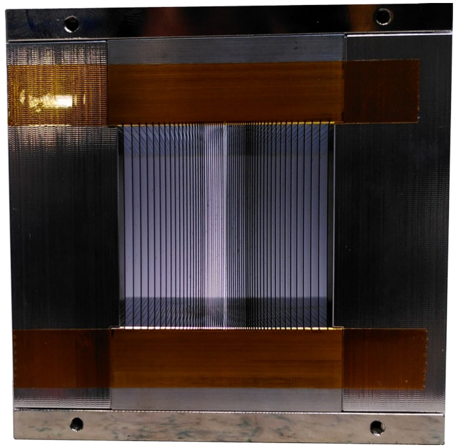


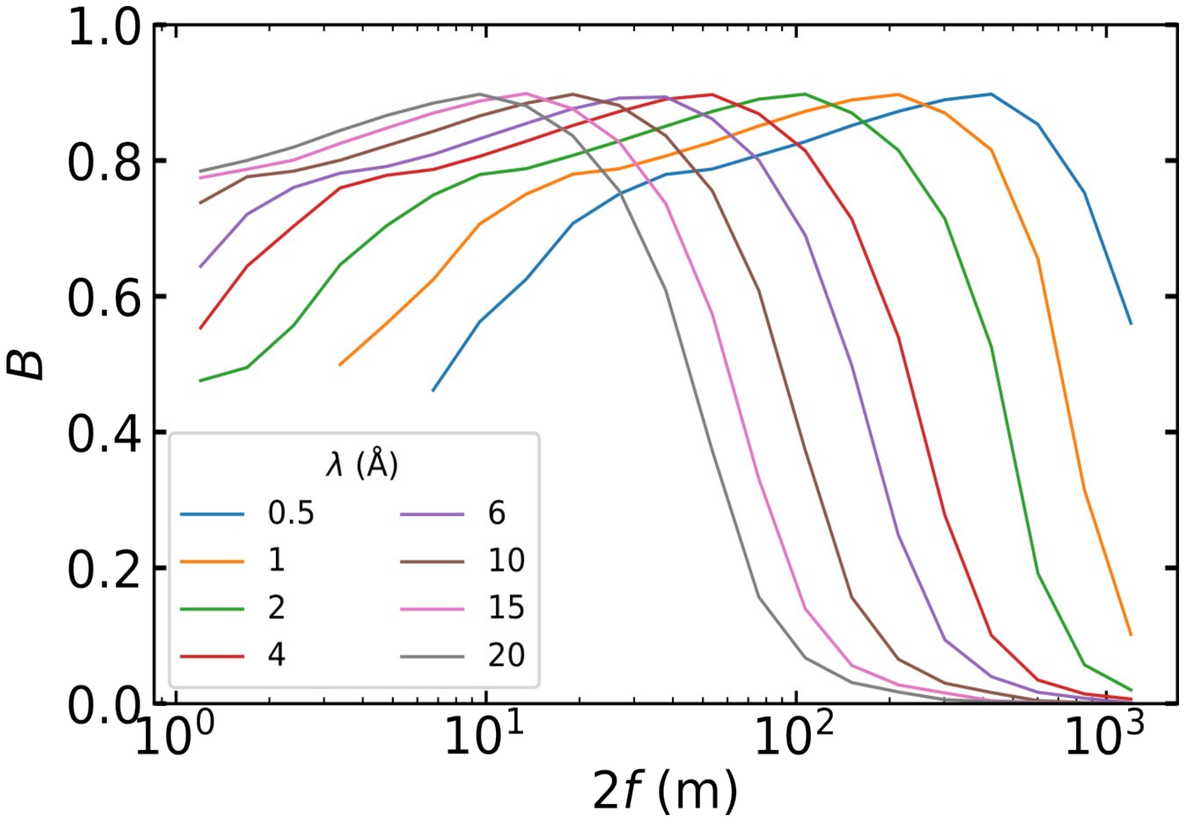
Properties of Elliptic NMO (BOA)



Neutron extraction from small sources

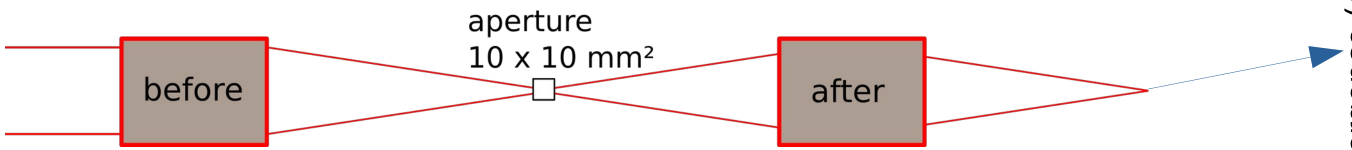
- NMO come with divergence hole
- Minimum distance of mirrors is limited by mirror thickness
- Larger NMO provide higher brilliance transfer, *B*, until gravity dominates
- Larger wavelengths allow larger angles of reflection → higher *B*

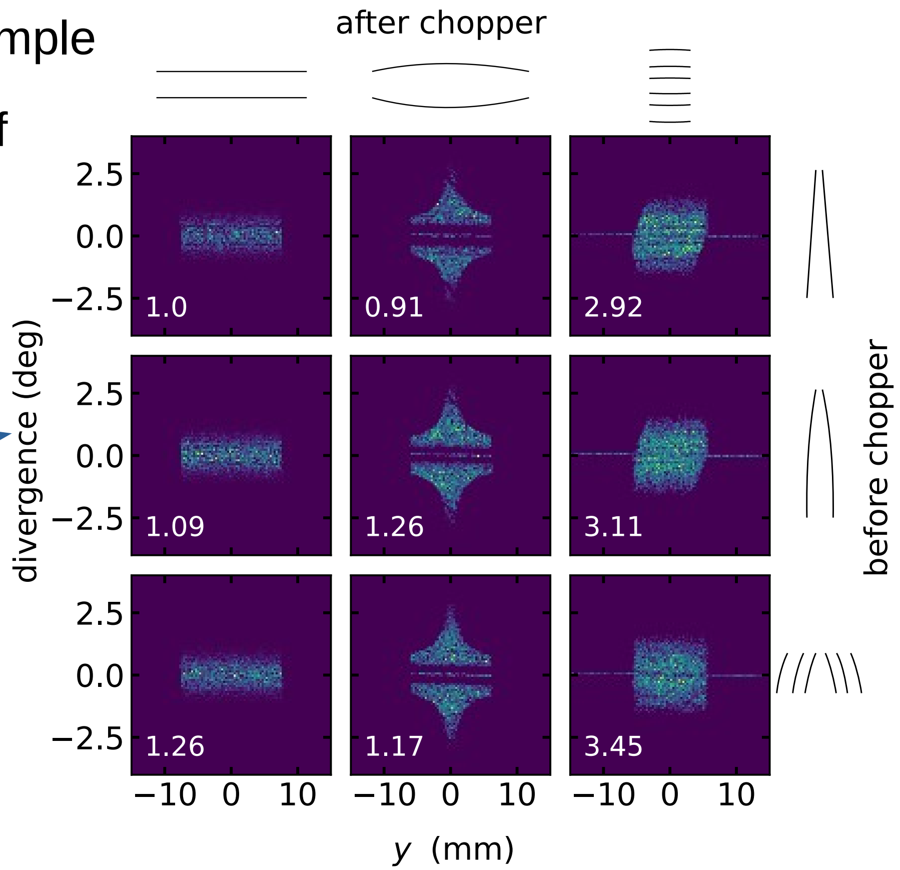




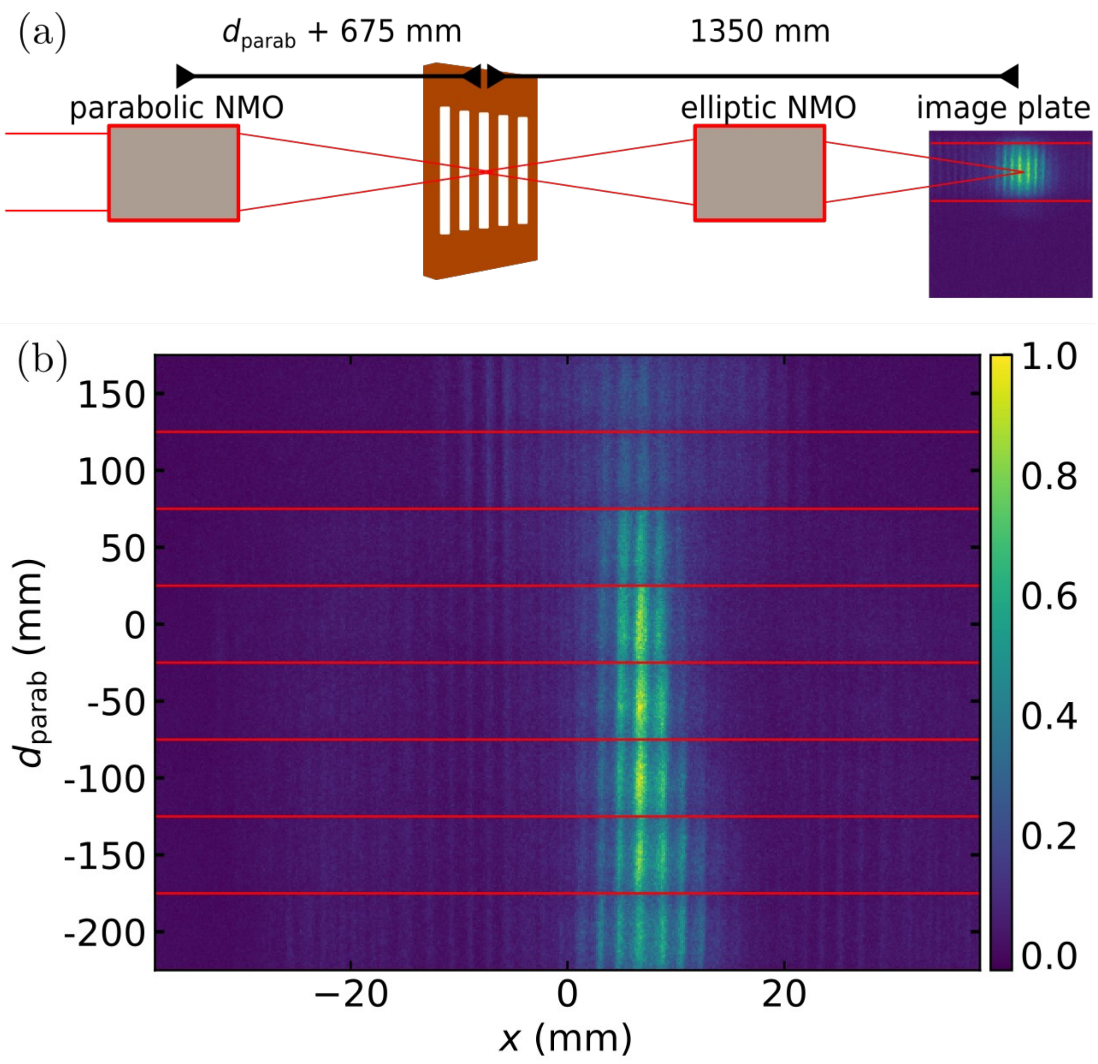
NMO for Illumination of Virtual Sources

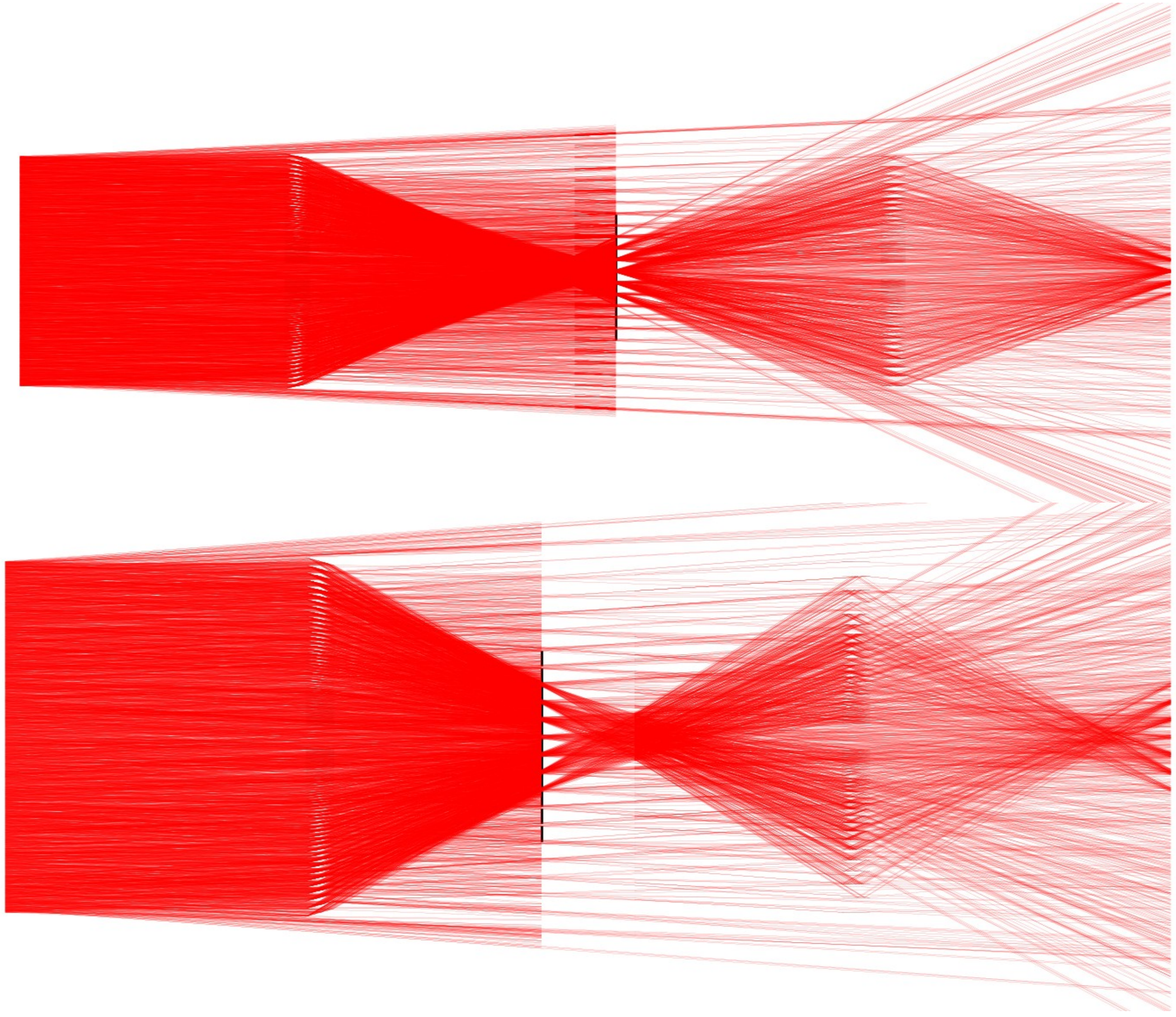
- Controlling beam size and divergence by apertures distant to the sample
- NMO yield uniform volumes of phase space with good efficiencies of transport





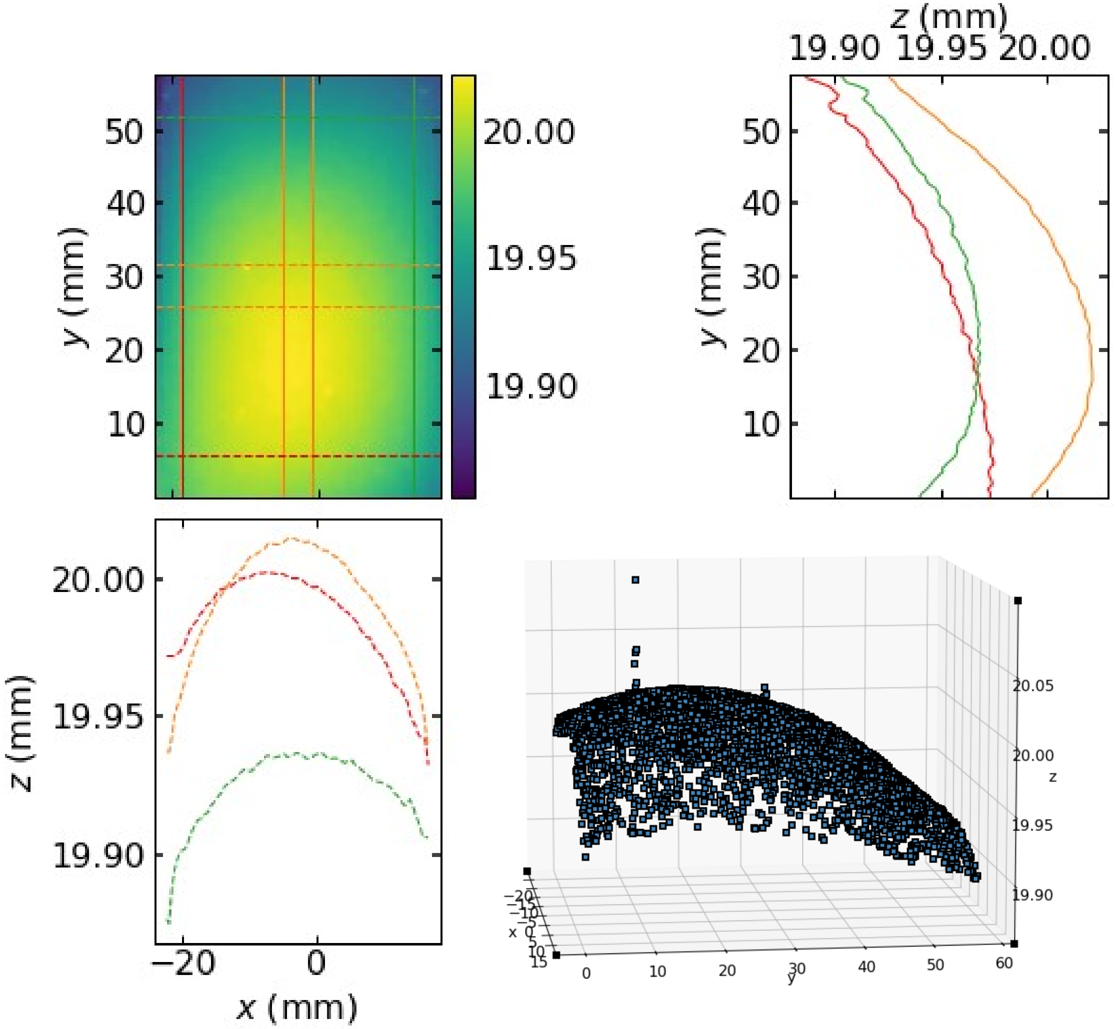
Combination of Parabolic and Elliptic NMO (BOA)



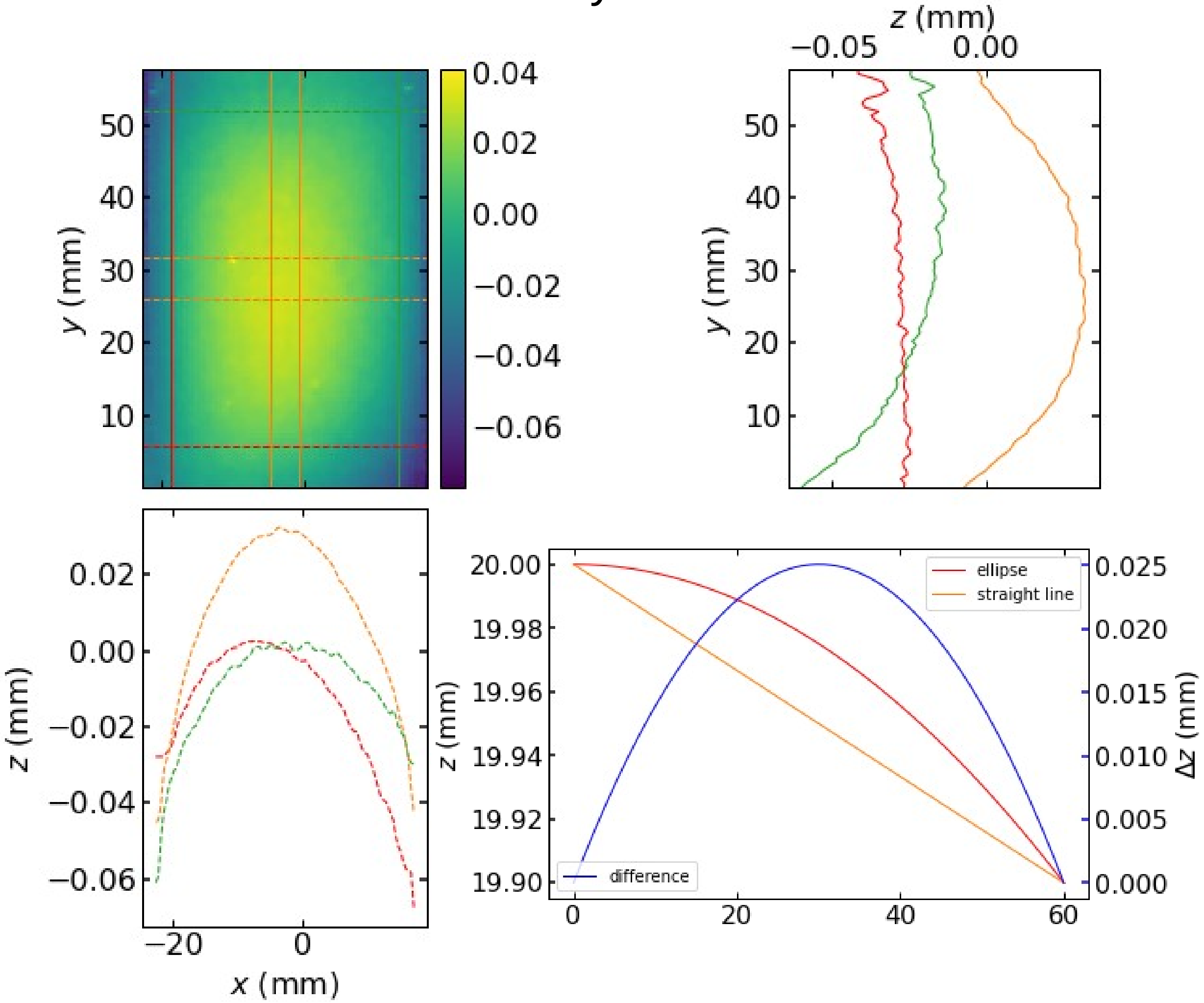


Properties of Elliptic NMO (BOA)

obtained elliptic height profile

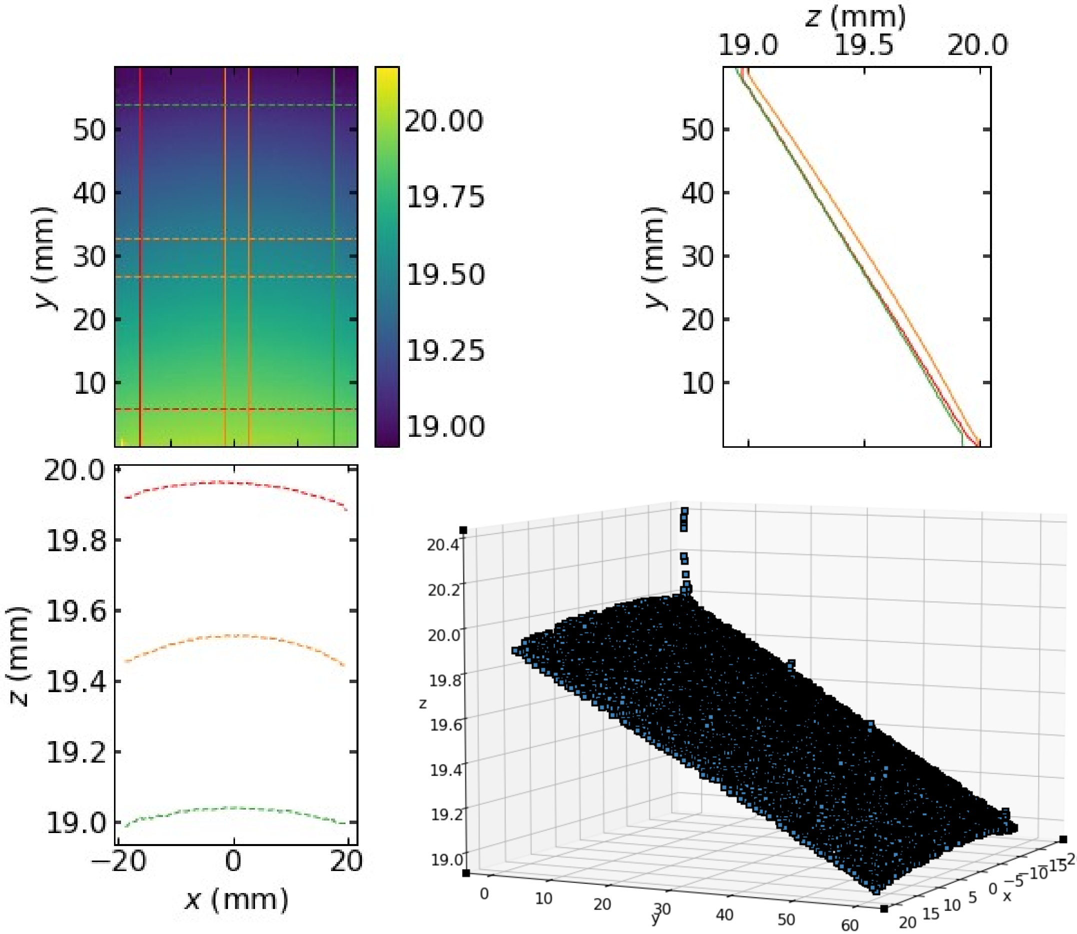


difference to theory

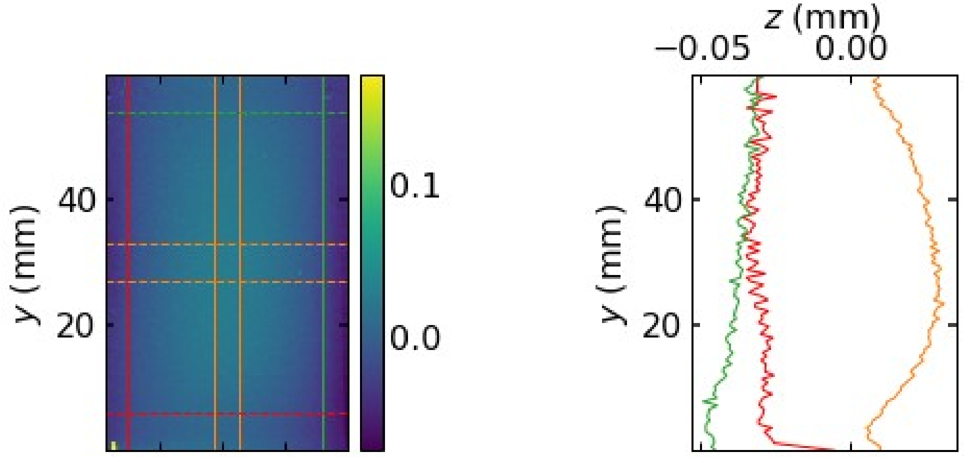


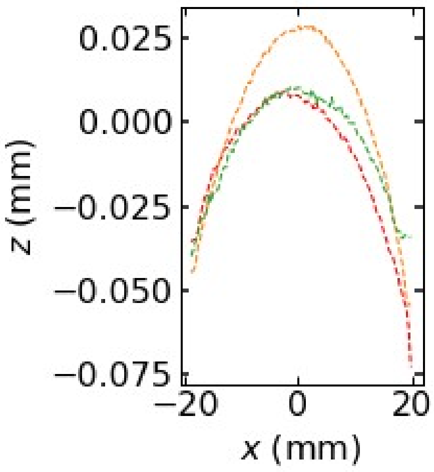
Properties of Parabolic NMO (BOA)

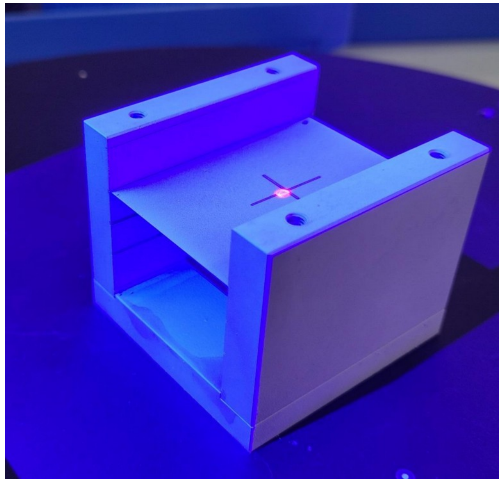
obtained parabolic height profile



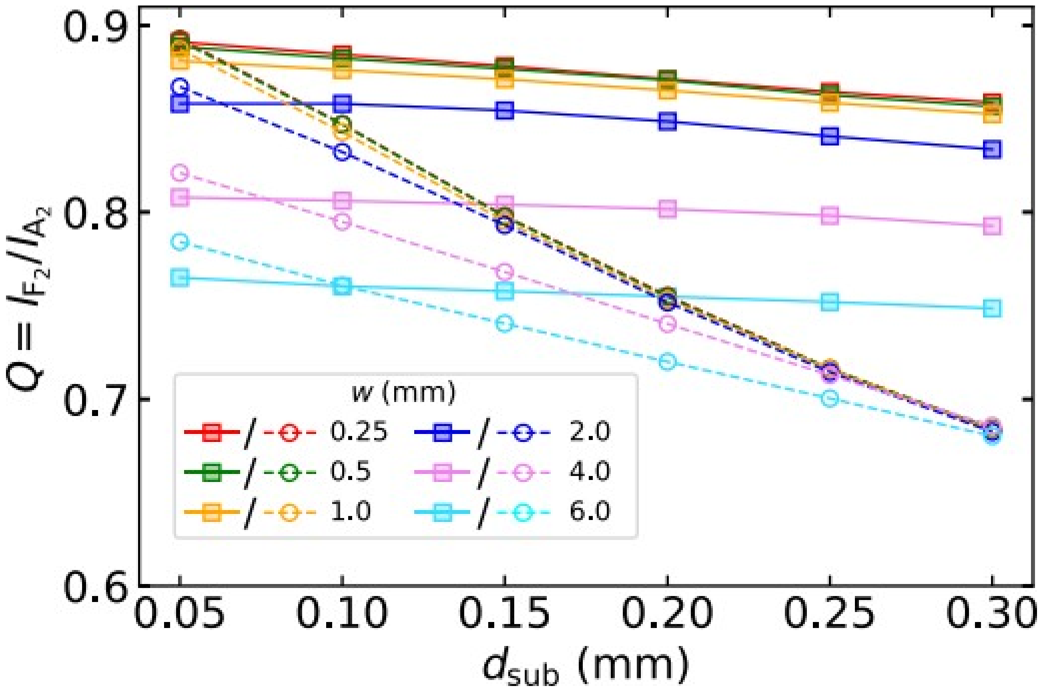
difference to theory



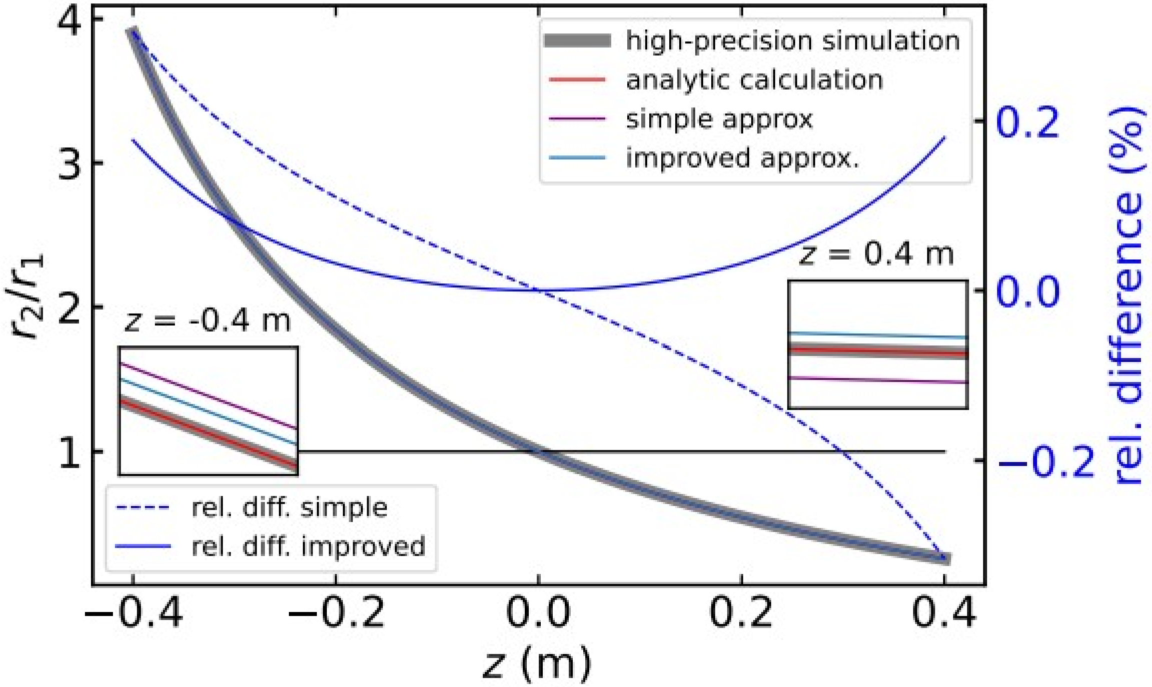




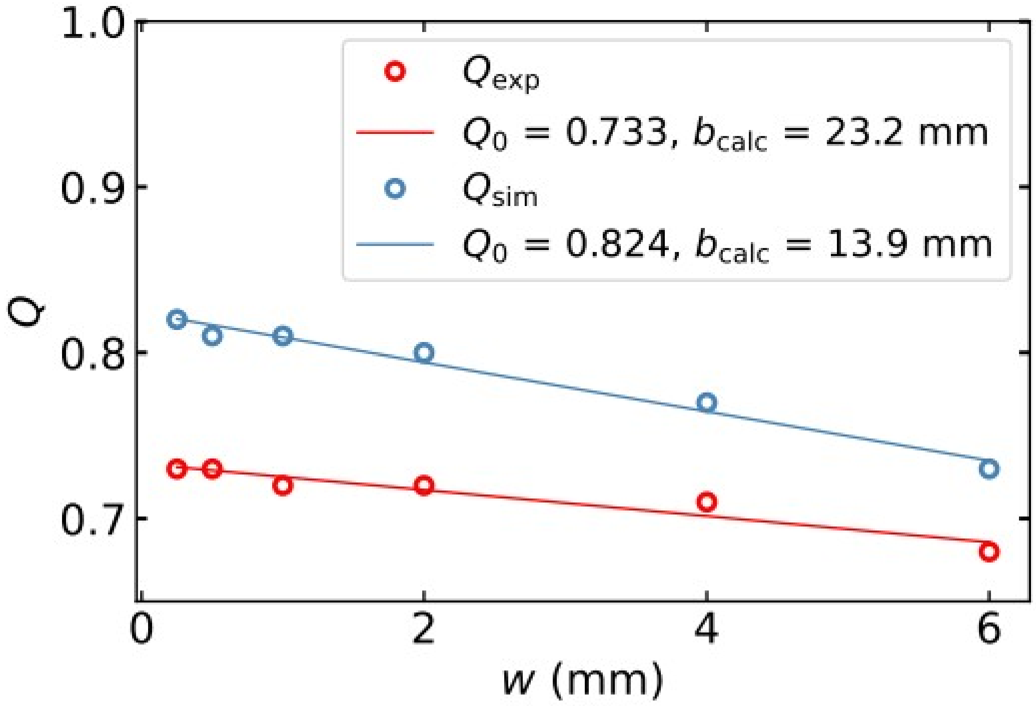
Single-Side vs. Double-Side Coating



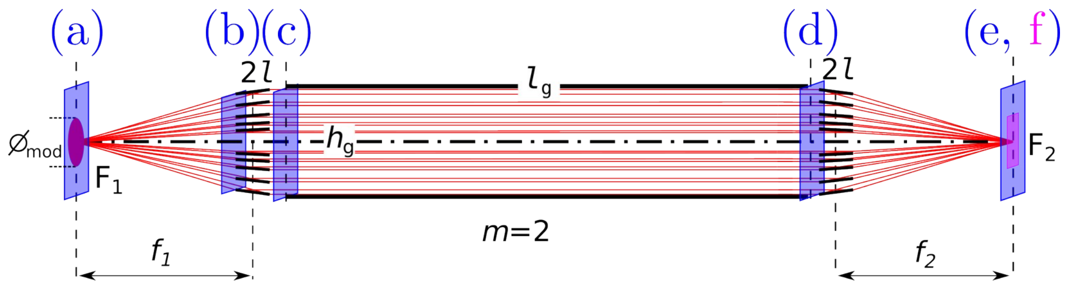
Improved Approx

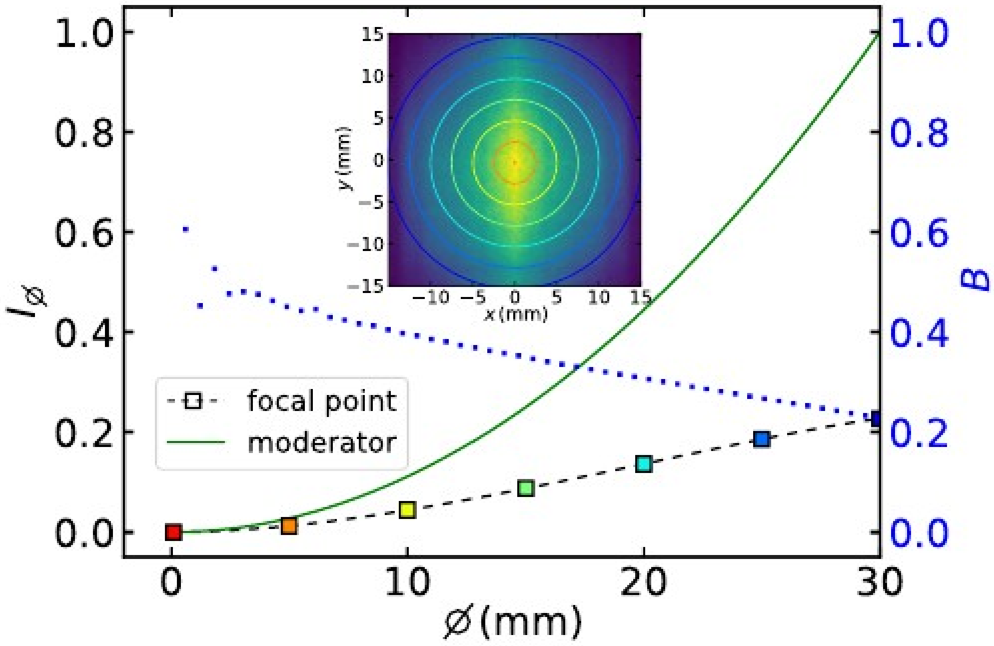


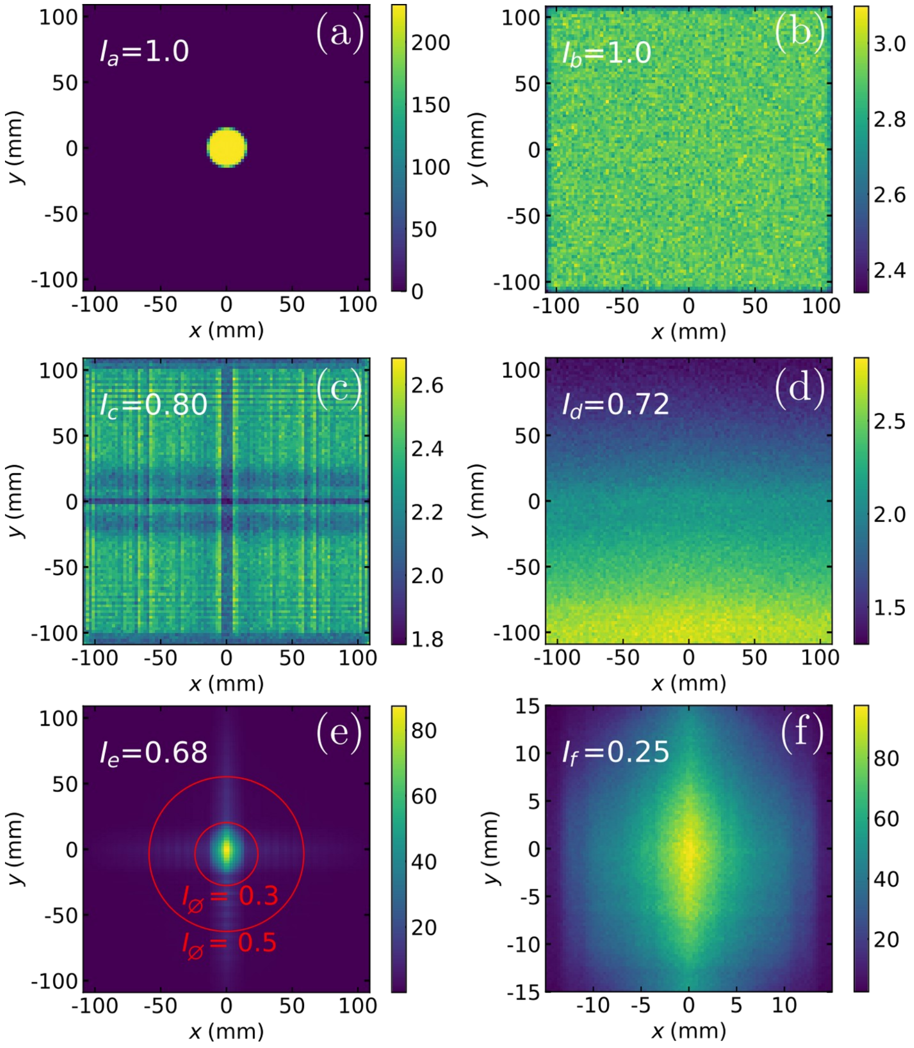
Efficiency of Transport



Addition to extraction into low div

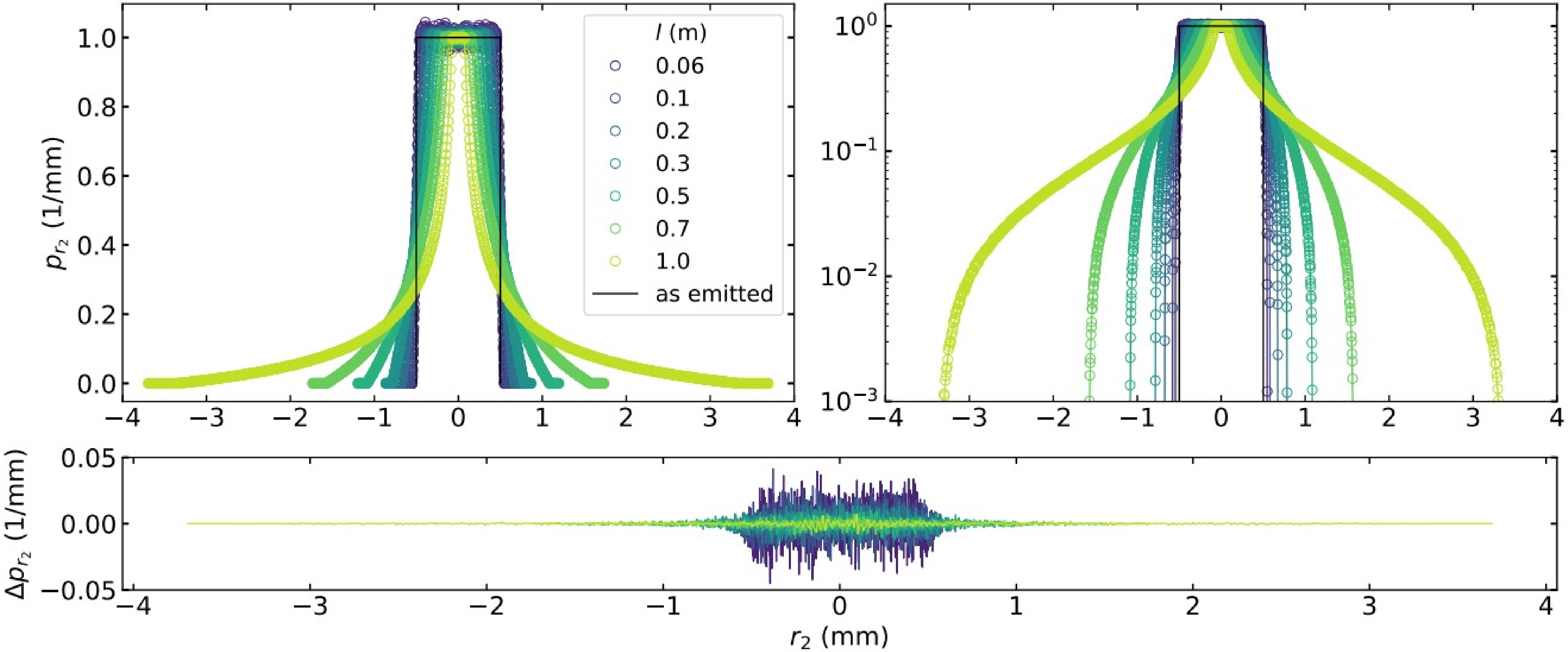






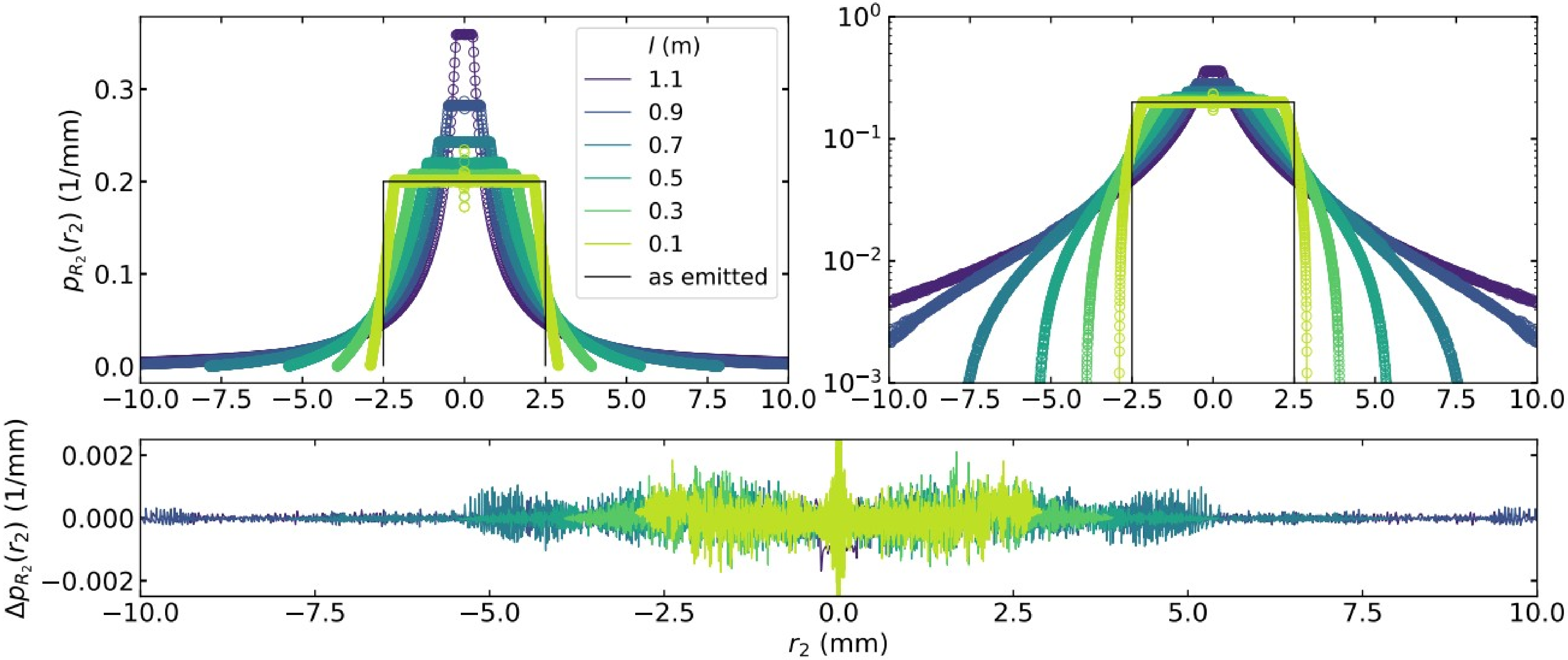
Analytic Calculations

Realistic reflection



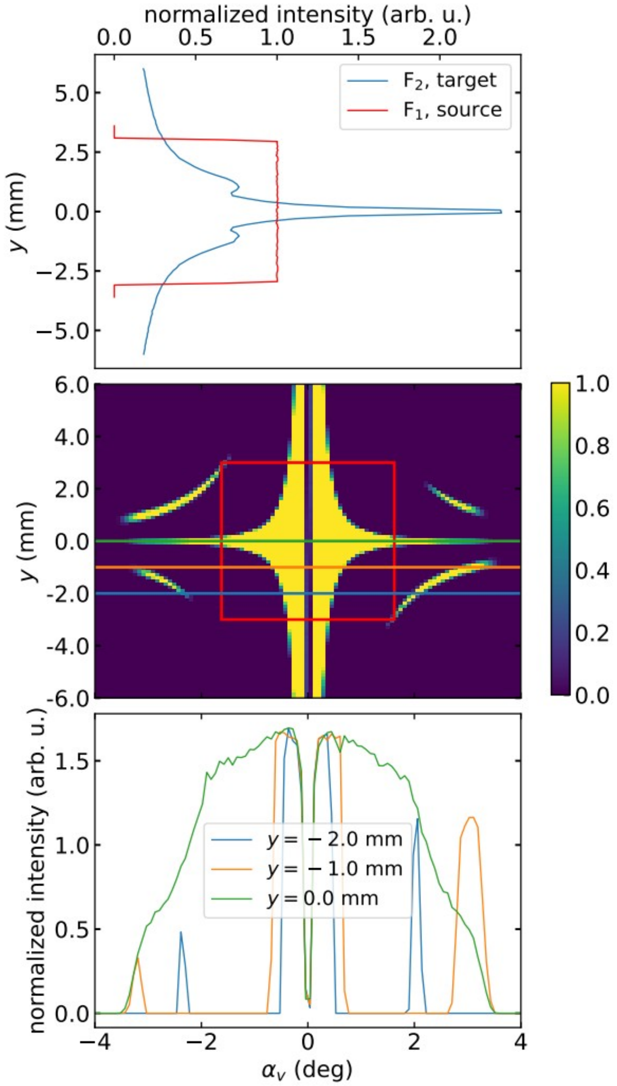
Analytic Calculations

Equidistant in z



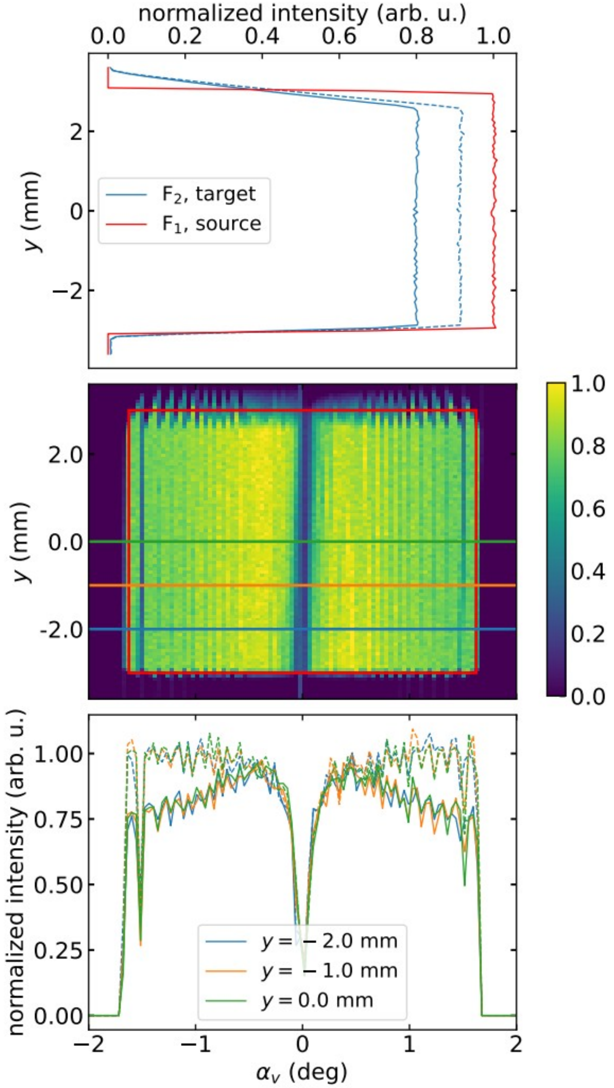
Long Guide Simulation

- f = 40 m
- l = 39.75 m
- B0 = 13 cm
- w = 6 mm
- m = 4



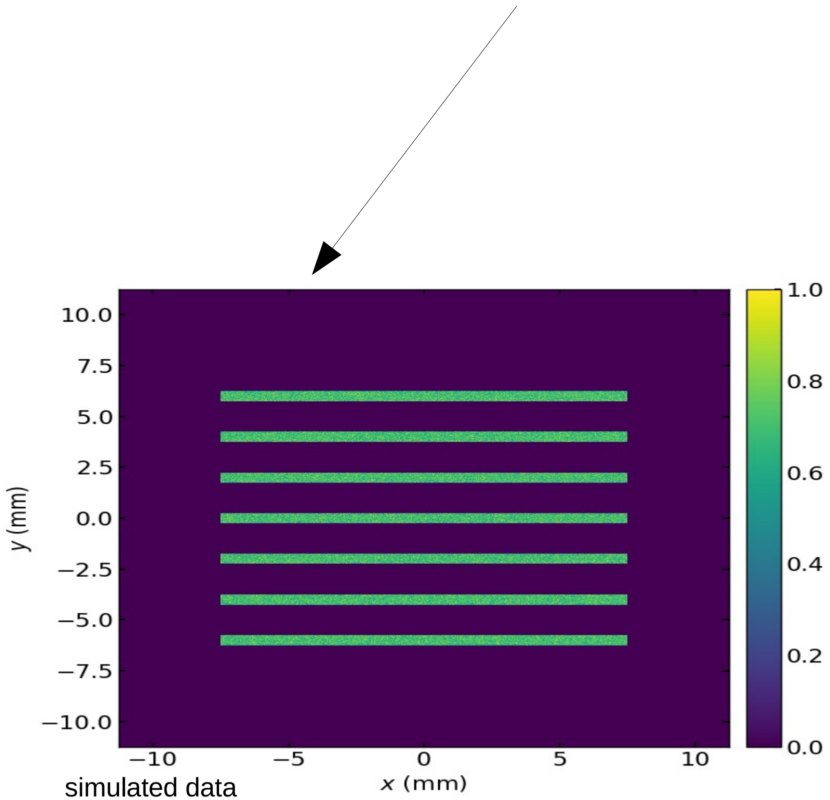
NMO Simulation

- f = 40 m
- l = 2 m
- n = 60
- b0 = 66 cm
- w = 6 mm
- m = 4
- Includes g = 9.81 m/s² and refraction
- d_{sub} = 0.15 mm



Geometric Aberrations in Long Elliptic Guides

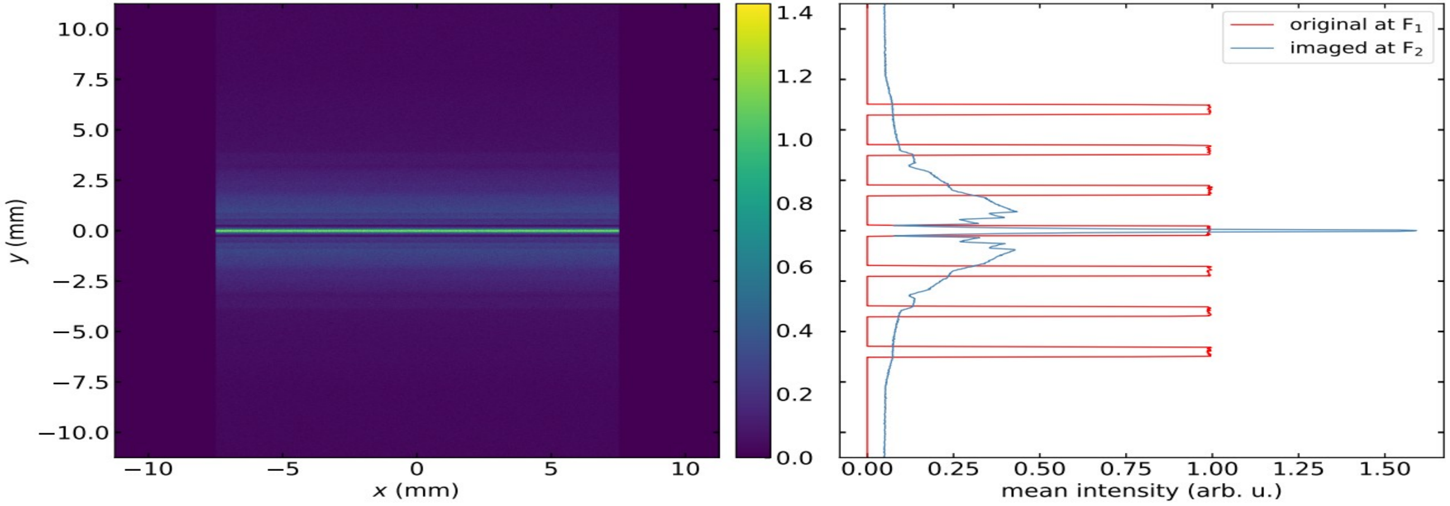
- Strong distortion of original grid-shaped intensity distribution



simulated data

2*f* = 1.35 m, 2*l* = 1 m, b_0 = 0.02 m

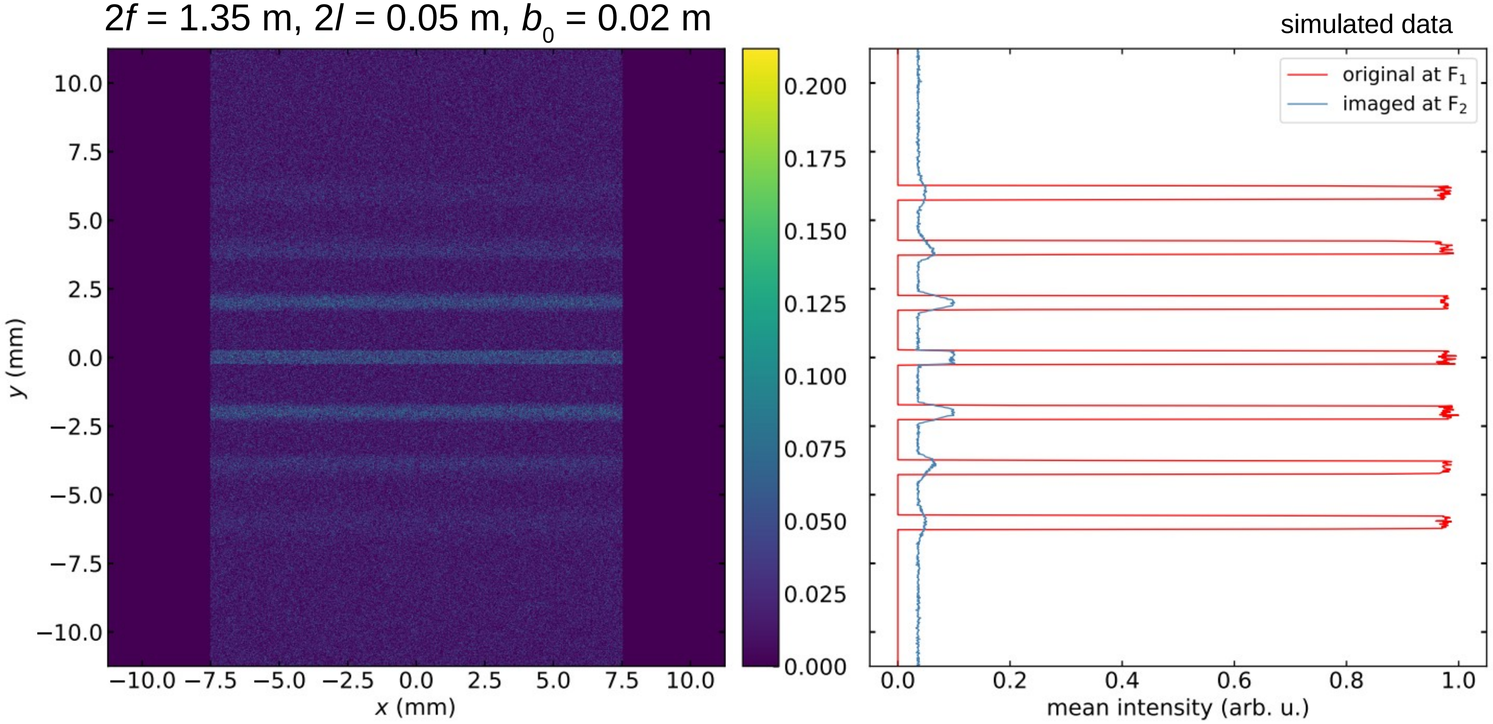
simulated data



Elliptic Nested Mirror Optics (NMO)

- Restrict reflections to the ellipse center → $\Delta r_2 \approx \Delta r_1$ → preservation of neutron phase space during reflection between focal points
- Simulation of single, short mirror → good imaging, low efficiency

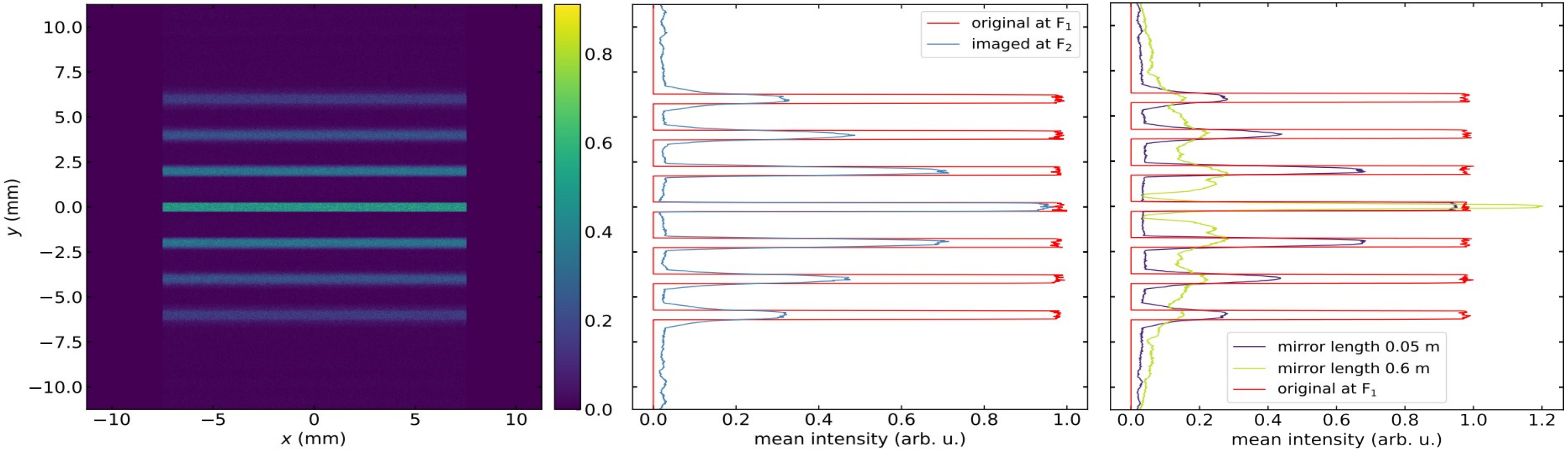
$2f$ = 1.35 m, $2l$ = 0.05 m, b_0 = 0.02 m



Elliptic Nested Mirror Optics (NMO)

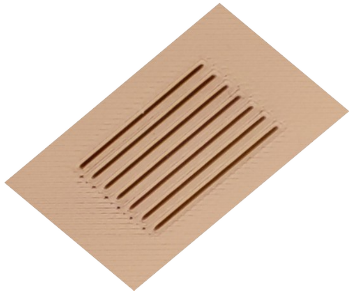
- Nested mirror system, *n* = 2 x 30 (simulation) → good imaging, high efficiency
- Shorter mirrors yield better images

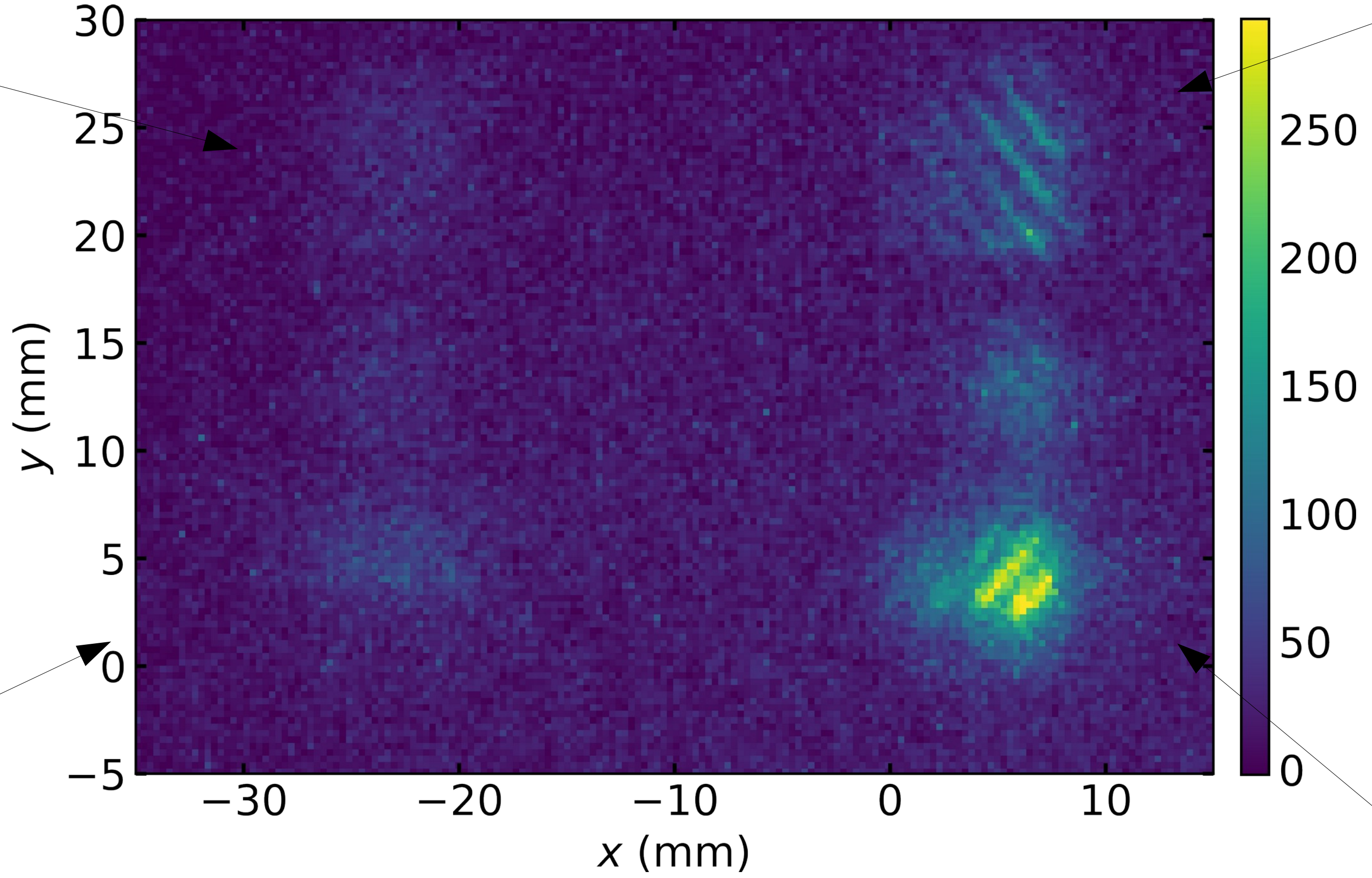
$2f = 1.35$ m, $2l = 0.05$ m, $b_0 = 0.02$ m



simulated data

2D-Imaging of a Grid (BOA)





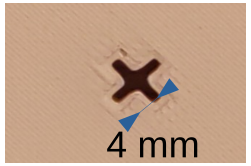
reflected horizontally

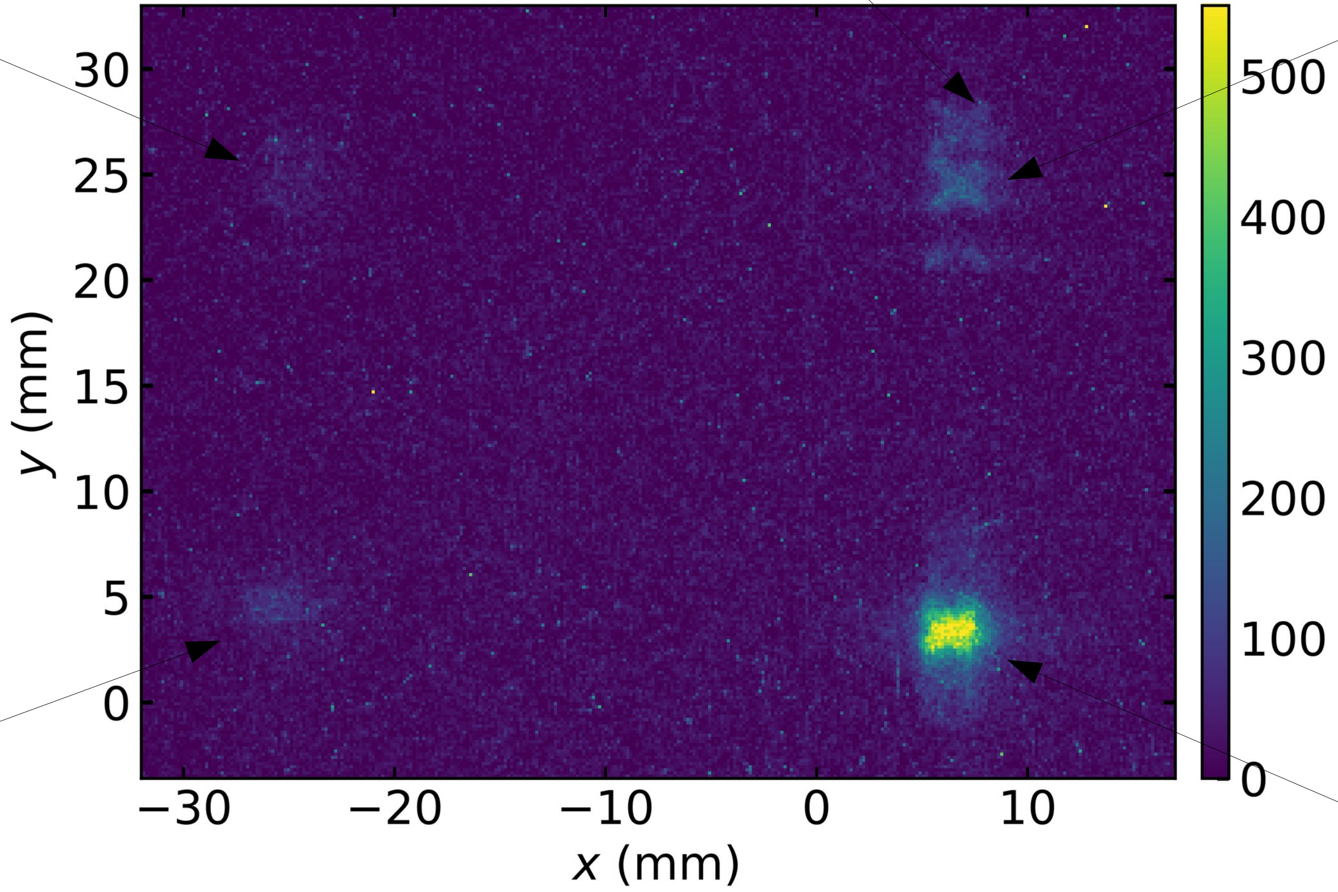
non-reflected

reflected vertically

doubly reflected

2D-Imaging of a Grid (BOA)





non-reflected

not reflected vertically

reflected horizontally

reflected vertically

doubly reflected

Combination of Parabolic and Elliptic NMO (BOA)