HighNess

A Monte Carlo Simulation Framework for Nested Mirror Optics Approach and Applications

Workshop on Neutron Delivery Systems – NDO 2023

Richard Wagner, ILL - 11.07.2023

on behalf of the HighNESS collaboration

ILL, Grenoboble

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Outline

- ESS and HighNESS
- Nested Mirror Optics
- Simulation Framework (McStas, etc.)
- Applications
  - NNBAR
  - In-Beam UCN Source

HighNess

The ESS and the HighNESS Project

- The European Spallation Source (ESS):
  - neutron research facility currently under construction in Lund, Sweden
  - designed to be the most powerful neutron source in the world
  - An international laboratory with Sweden and Denmark as host countries and 11 European partner countries
- The HighNESS project https://highnessproject.eu/
  - Design of a second moderator system of the ESS
    - including tasks to study new concepts for neutron optics
  - Funded by the EU and consisting of an international consortium of 8 Institutes in 7 countries.

Aerial view of the ESS site February 2022 (Image from Perry Nordeng)

For detailed overview see

Development of a High Intensity Neutron Source at the European Spallation Source: The HighNESS project

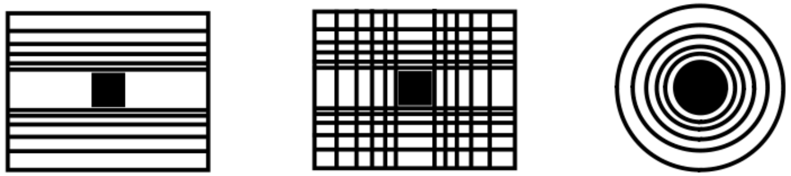
V Santoro et al, 2022, https://doi.org/10.48550/arXiv.2204.04051

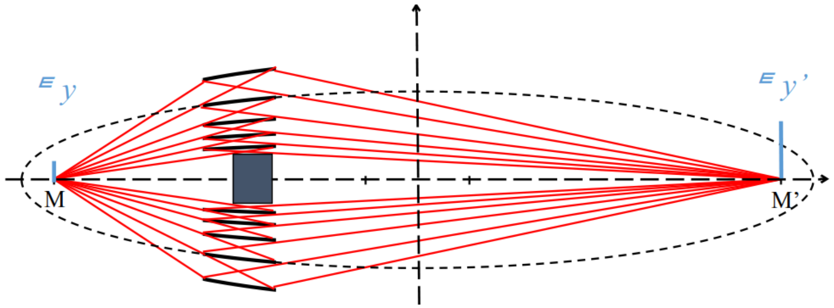
Nested Mirror Optics - NMO

- Elliptical guide: possible architecture to transport neutrons diverging from a source to a detector (sample)
- Elliptical shaped mirror - has the property to reflect a beam that emanates from one of its focal points directly to the other one
- The layers of several (shortened) guides can be nested to build up a spatial tight optical component
  → Focusing reflector in (compact) nested arrangement
- Elliptical mirrors in planar or cylindrical arrangement possible
- Goal is to verify & quantify performance of these optical systems with McStas (A neutron ray tracing simulation package)

McStas

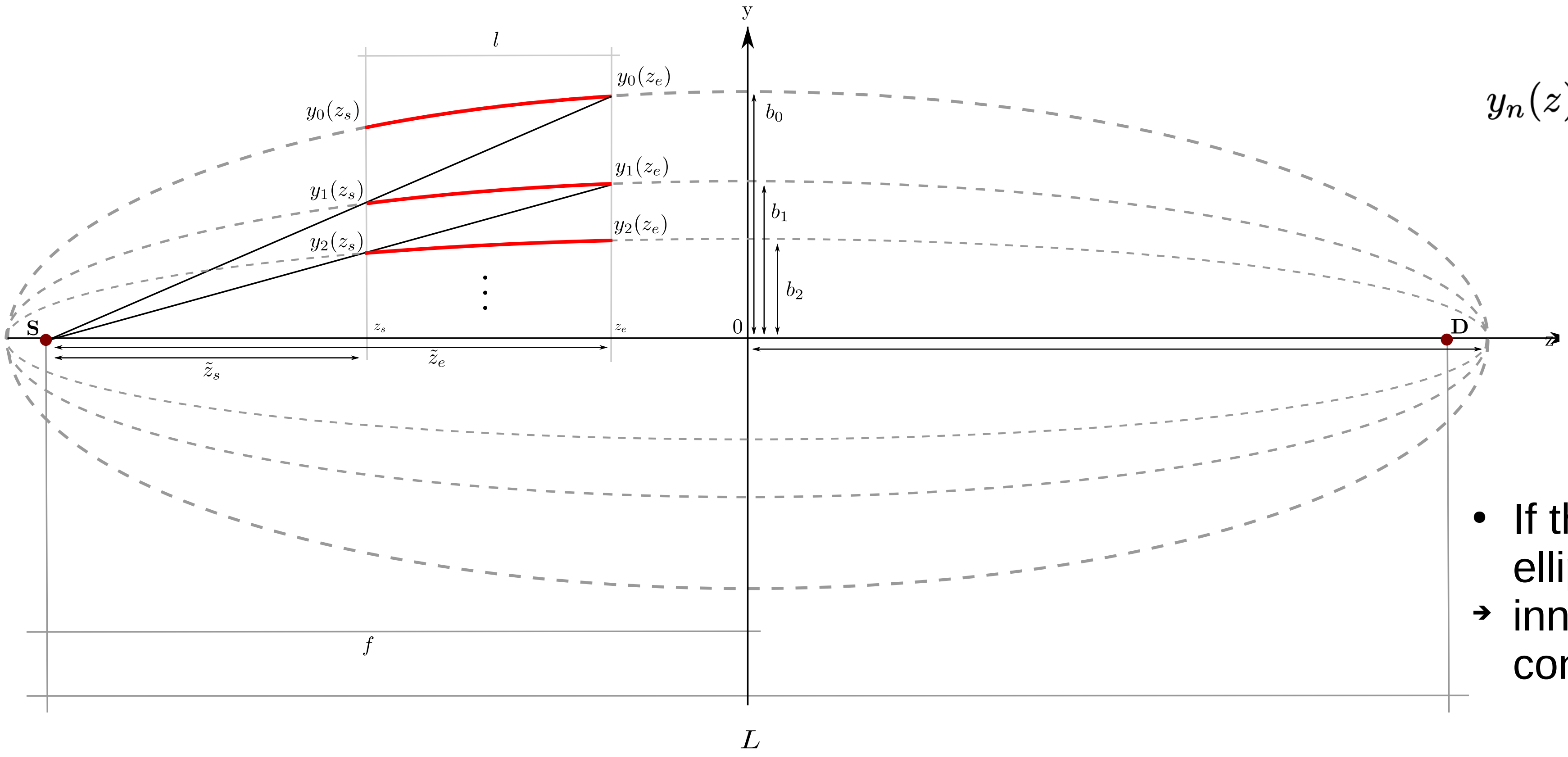
http://www.mcstas.org





O.Zimmer, arXiv:1611.07353
Journal of Neutron Research 20 (2018) 91-98

Nested optic
Construction principle



$$y_n(z) = \sqrt{\left(1 - \frac{z^2}{f^2 + b_n^2}\right) \cdot b_n^2}$$

$$y_n\left(z_s\right) = \frac{\tilde{z}_s}{\tilde{z}_e} y_{n-1}\left(z_e\right)$$

- If the outer layer of a nested elliptical guide is given
- ➔ inner layers can be constructed recursively

McStas component

- *Guide_anyshape.comp*
- Constitutes a reflecting surface of arbitrary shape defined by an OFF-File
- Reflectivity parametrized by R_0, Q_c, α, W, m

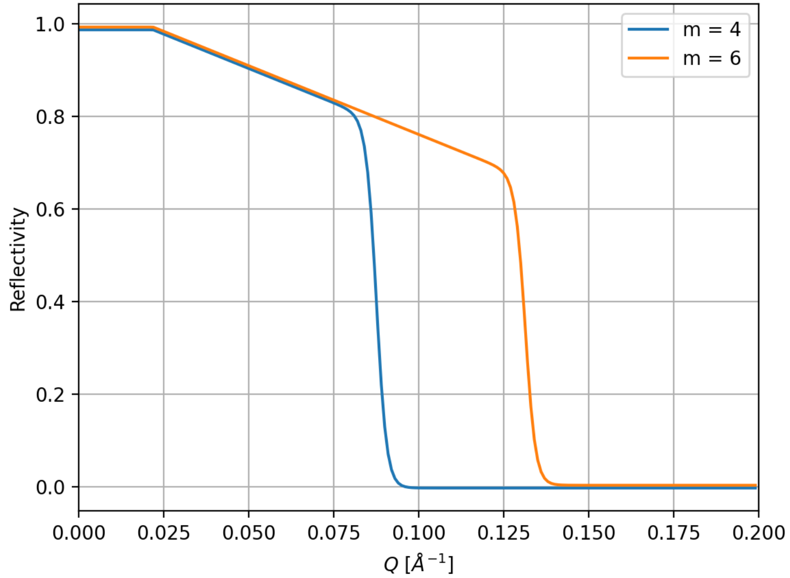


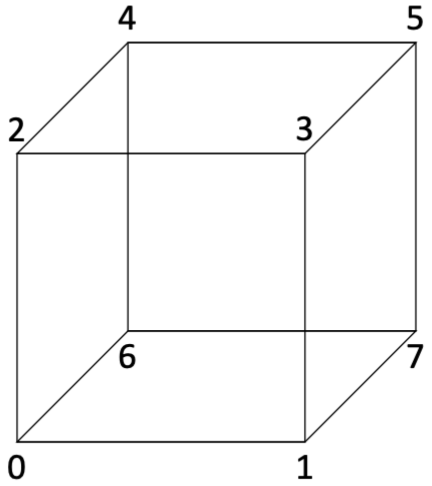
Table 1: Input parameters for the `Guide_anyshape` component

Parameter	Description
geometry	name of the OFF-file that defines the geometry of the optic
m	m-value of the optics material (zero is completely absorbing)

Gravity **fully** and **correctly** supported since McStas 3.3

OFF(object file format)-Files

```
OFF
# A cube of size 1x1x1 centred
8 6 0
-0.500000 -0.500000  0.500000
0.500000 -0.50000   0.500000
-0.500000  0.500000  0.500000
0.500000  0.500000  0.500000
-0.500000  0.500000 -0.500000
0.500000  0.50000  -0.500000
-0.500000 -0.500000 -0.500000
0.500000 -0.500000 -0.500000
4 0 1 3 2
4 2 3 5 4
4 4 5 7 6
4 6 7 1 0
4 1 7 5 3
4 6 0 2 4
```



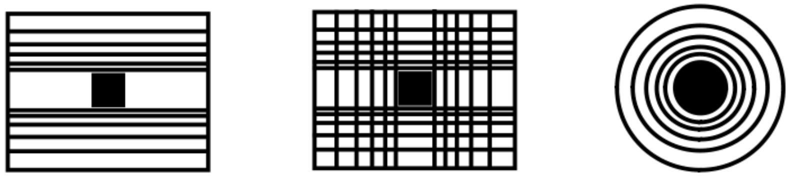
Example of an OFF-File describing a cube of side length one and its representation

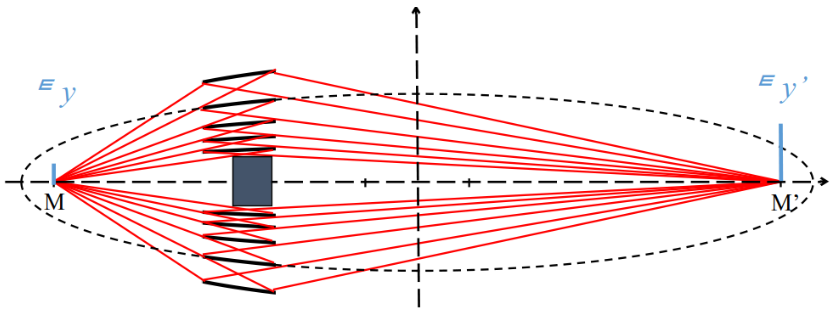
NMO - component creation library

- **Collection of Python functions for OFF File Generation of Nested Mirror Optics**
- Example

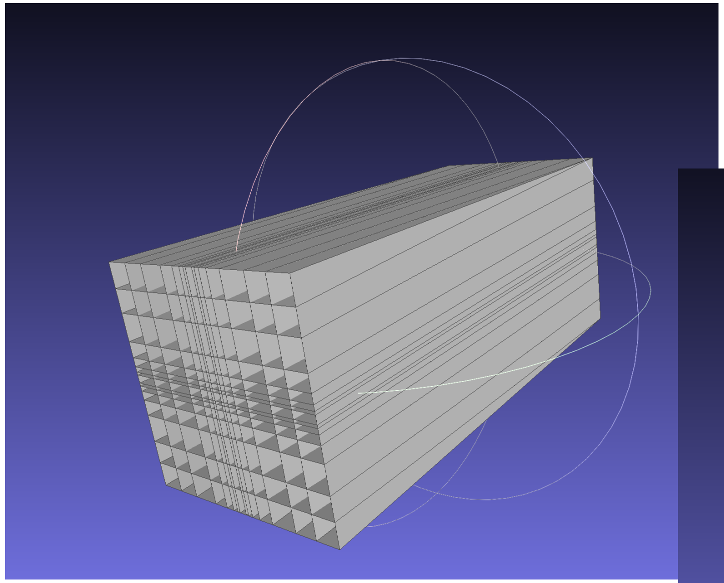
Table 5: Input parameters for the `createToroidalNestedOFFwArray()` function

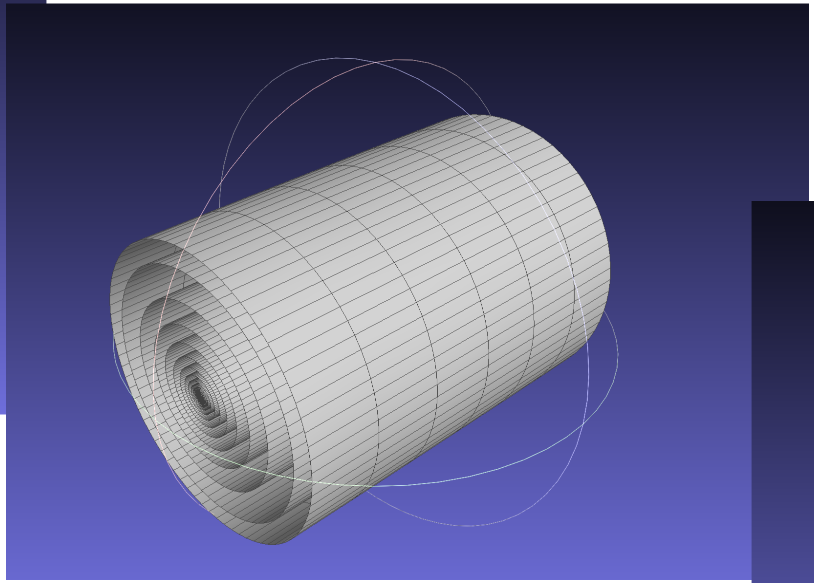
Parameter	Description
L	distance between focal points of the ellipses
b_array	array containing the minor axes of the nested ellipses
z_start	starting point of the optic, relative to the focal point
l	length of the optic
nb_segments	number of segments by which the ellipses are approximated
nb_segments_T	number of segments the circumferences of the toroidal sections are approximated with
filename	name of the generated OFF-file
opticHalfWidth	limit for extent of the optic. The area the optic can occupy is between $\pm$ `opticHalfWidth`
bBoundingBox	outer level is surrounded by a bounding box (true/false)

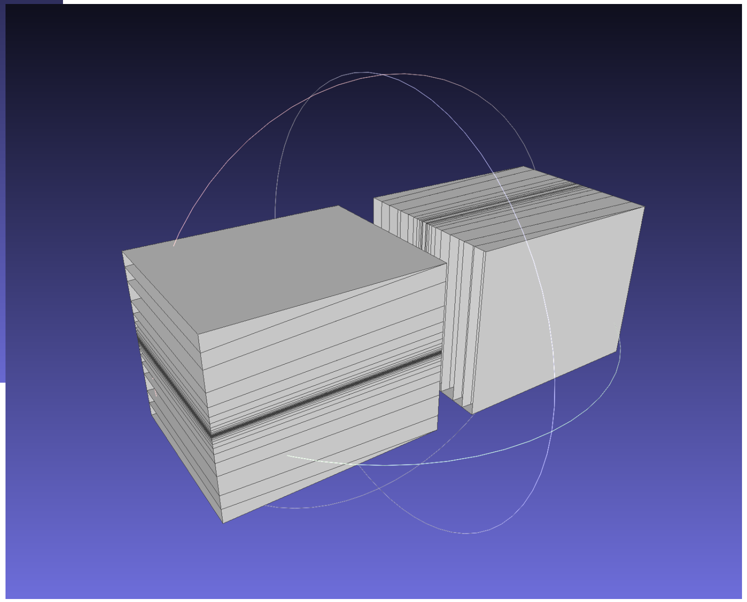




Example NMOs: Elliptical Guides







Example NMOs:
Wolter optics (type I)

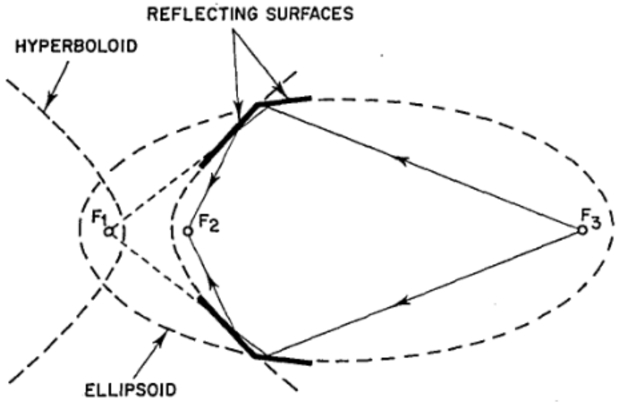
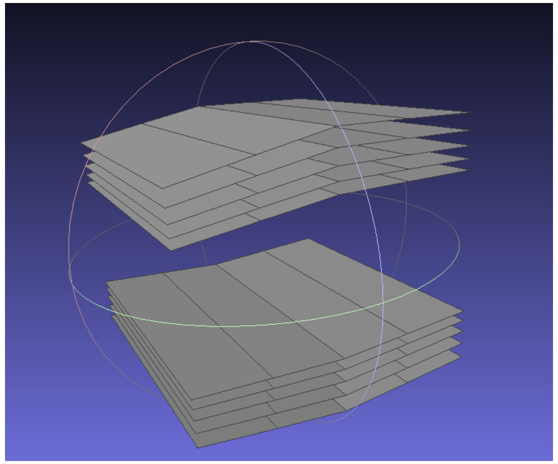
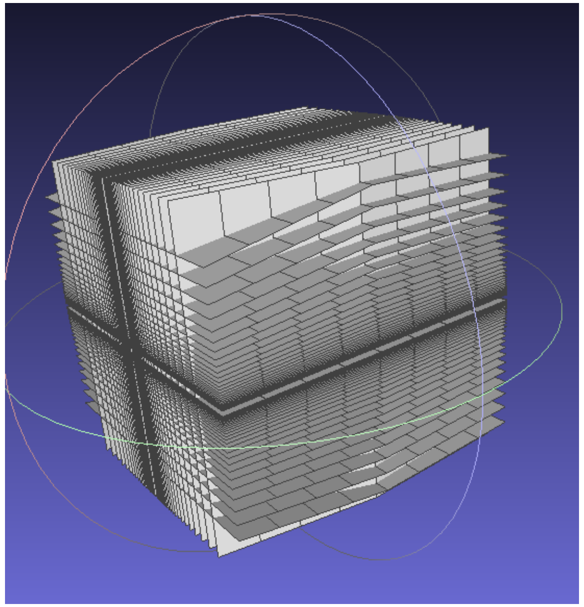
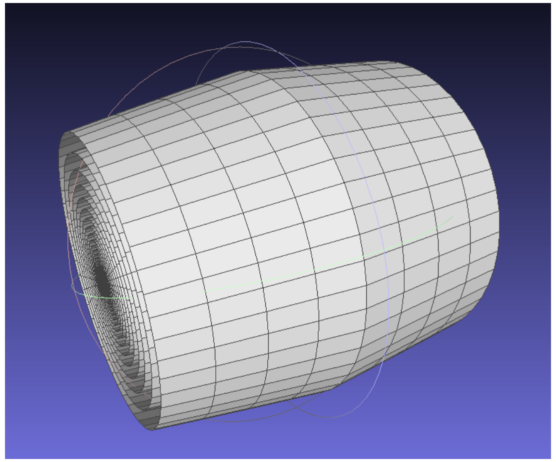


Fig. 1. Schematic representation of the ellipsoid–hyperboloid mirror. A source at one focus of the ellipsoid (F_3) is imaged at the focus of the hyperboloid (F_2) after two reflections.

From: R. C. Chase and J. K. Silk,
Appl. Opt. 14, 2096-2098 (1975)



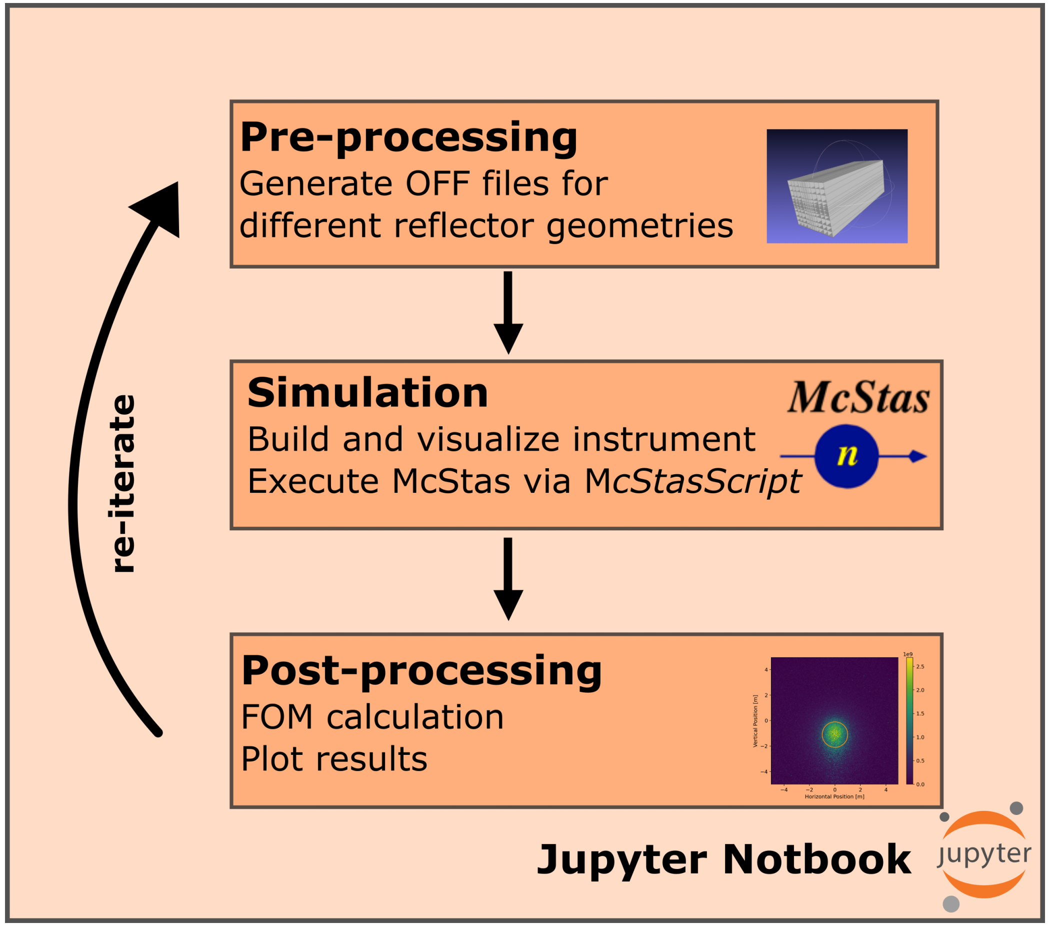




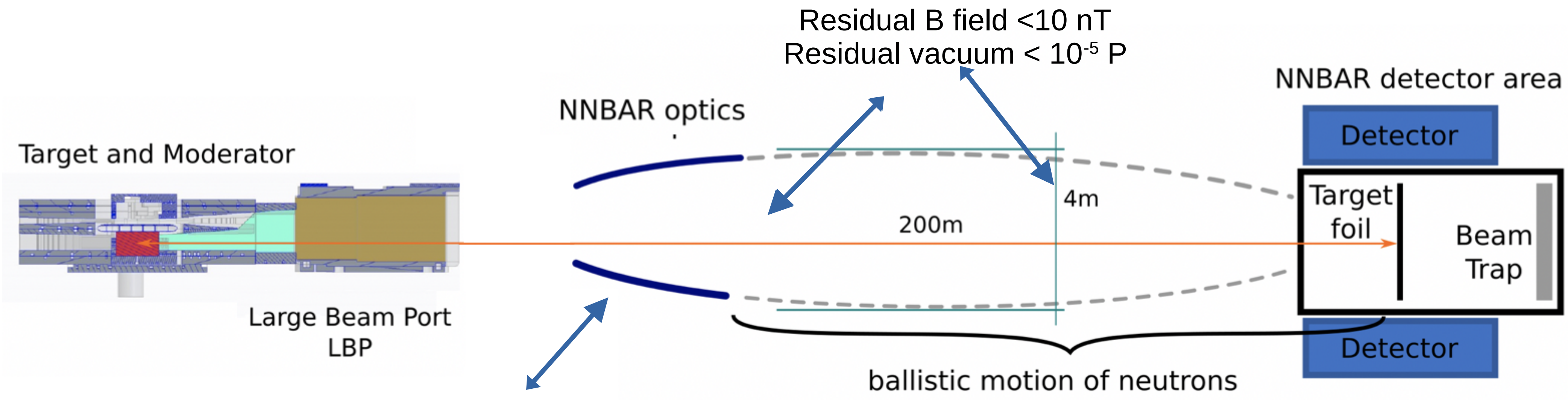
- Hyperboloid and ellipsoid segment
- Design fulfills the Abbé sine condition in good approximation
- Produce sharp and aberration free images.

- Library extended to create Wolter NMOs

Simulation process



Application Example
NNBAR Experiment at ESS



Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area (start at ~10m)

free from perturbing magnetic stray fields, interaction with walls and ambient gas particles

Transition probability
for quasi free condition

$$P_{n\bar{n}} = \left(\frac{t}{\tau}\right)^2$$

t … uninterrupted flight time
τ … free oscillation time

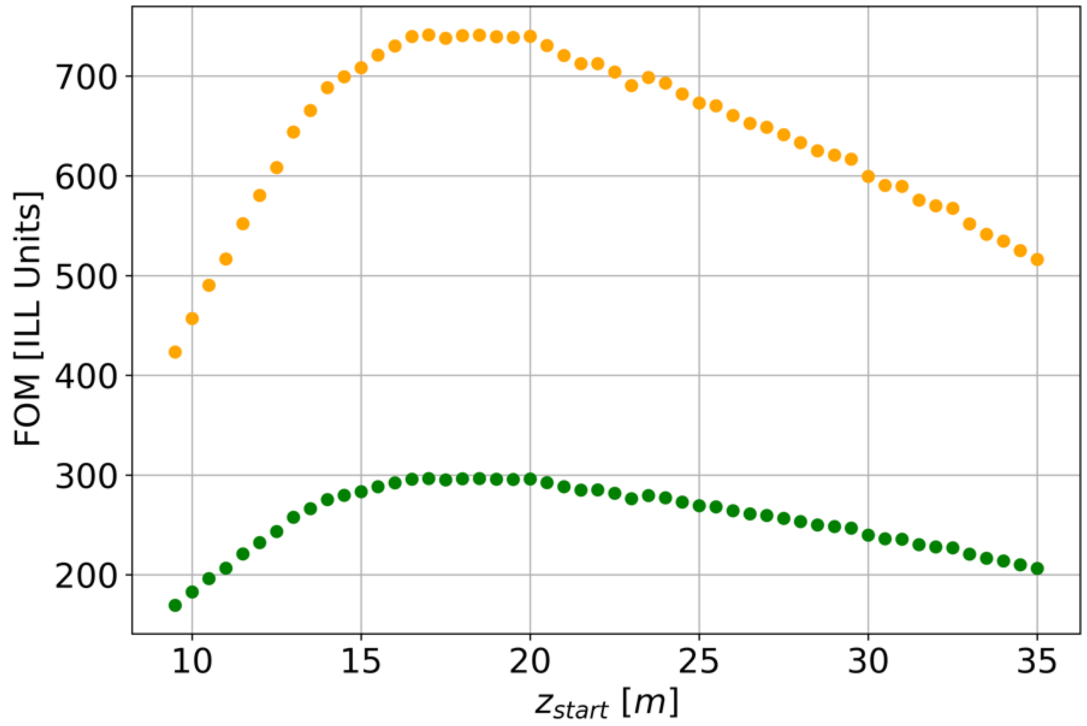
Figure of Merit - FOM

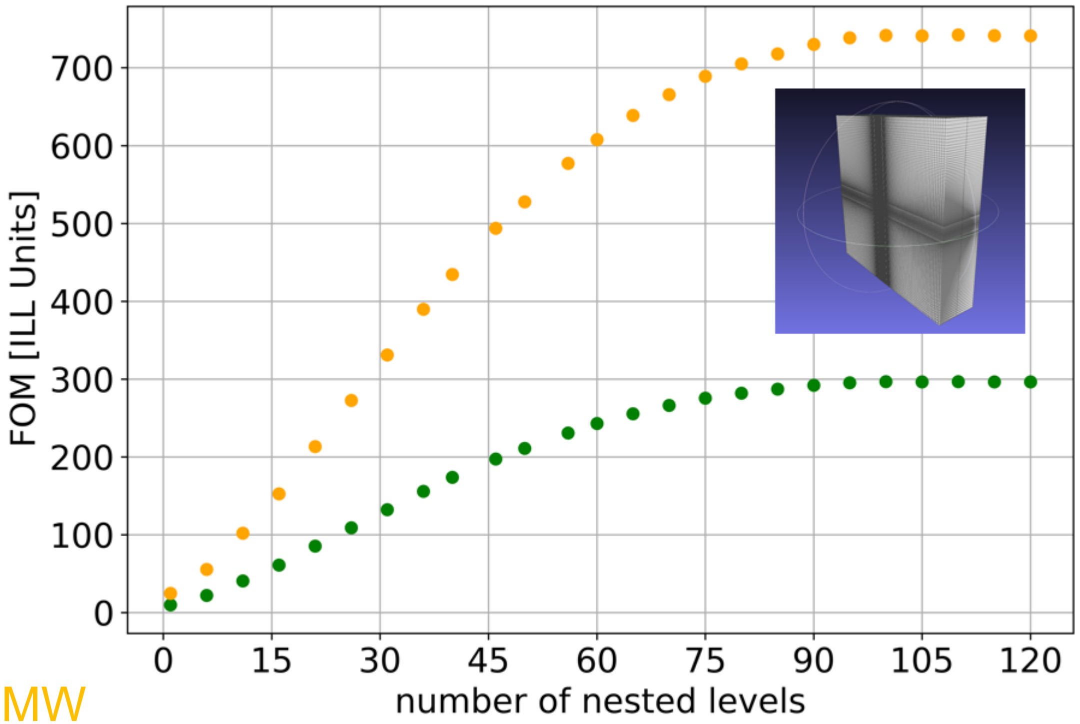
$$FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}} / \underbrace{(4 \times 10^9)}_{\text{normalization factor}}$$

Application Example
NNBAR Experiment at ESS

Find the optimum optic by varying parameters
(e.g. starting point, # of nested levels, ...)

Example: Simulations for a 1m long nested Reflector



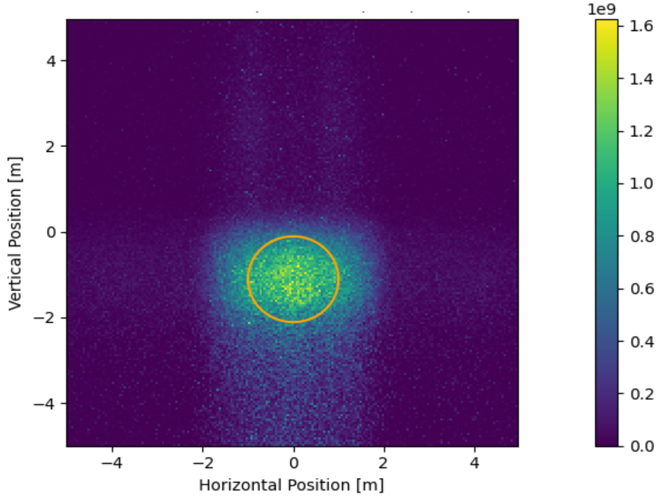


5 MW
2 MW

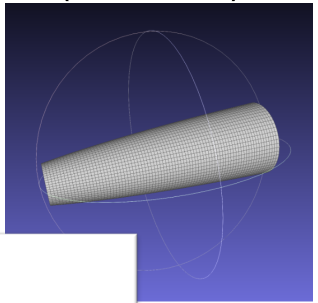
Application Example

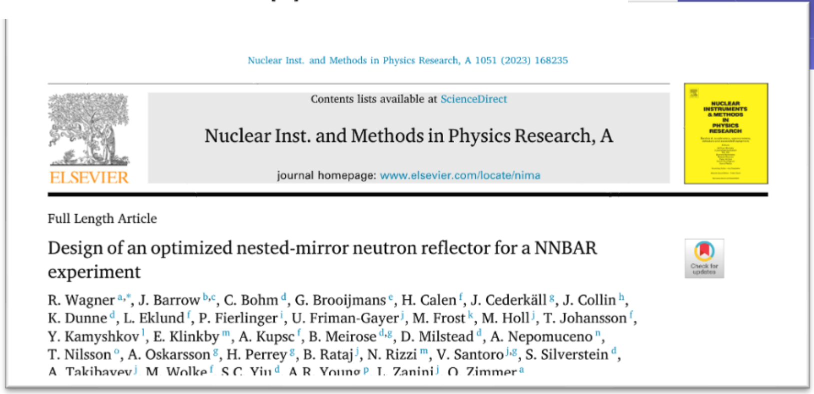
NNBAR Experiment at ESS

Example: Simulations for a 10m Nested Reflector



40m single layer (baseline)





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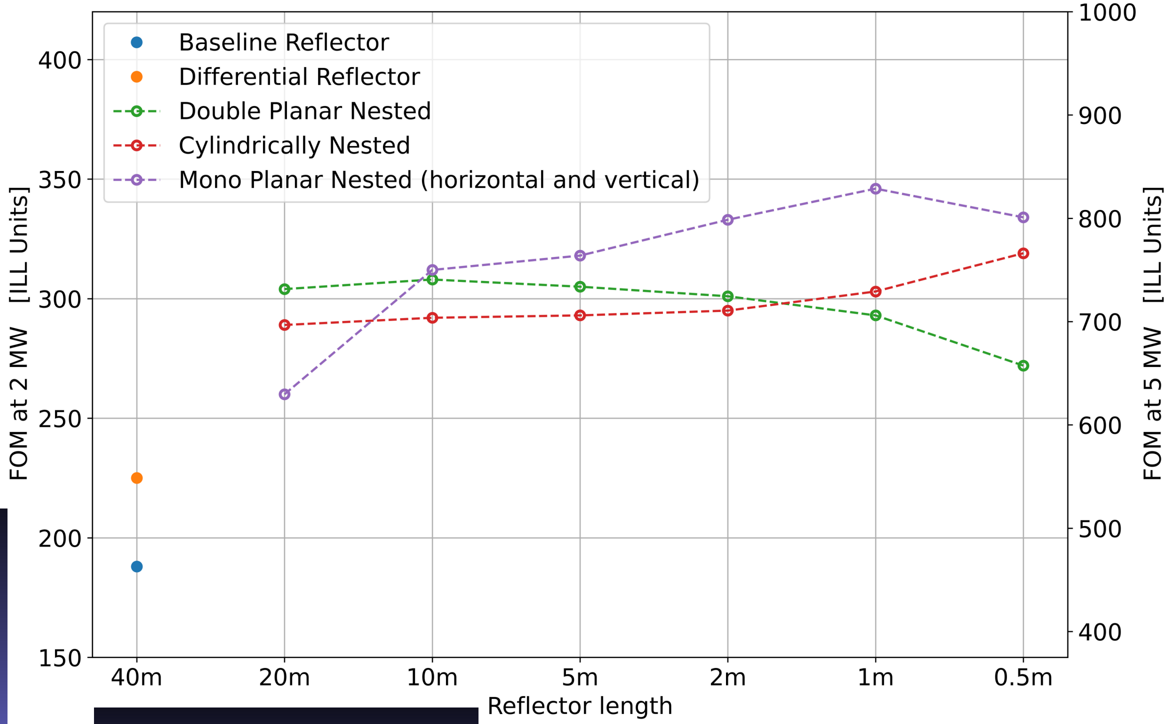
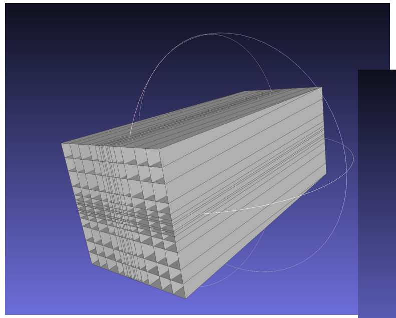
Full Length Article

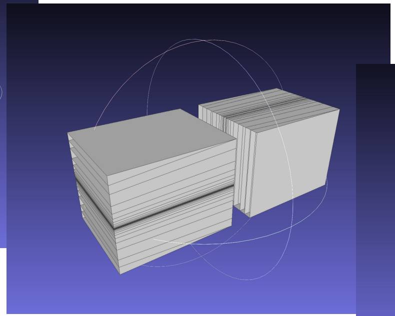
Design of an optimized nested-mirror neutron reflector for a NNBAR experiment

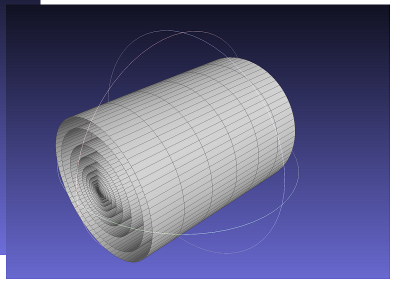
R. Wagner [a,*], J. Barrow [b,c], C. Bohm [d], G. Brooijmans [e], H. Calen [f], J. Cederkäll [g], J. Collin [h], K. Dunne [d], L. Eklund [f], P. Fierlinger [i], U. Friman-Gayer [j], M. Frost [k], M. Holl [j], T. Johansson [f], Y. Kamyshkov [l], E. Klinkby [m], A. Kupsc [f], B. Meirose [d,g], D. Milstead [d], A. Nepomuceno [n], T. Nilsson [o], A. Oskarsson [g], H. Perrey [g], B. Rataj [j], N. Rizzi [m], V. Santoro [j,g], S. Silverstein [d], A. Takibayev [j], M. Wolke [f], S.C. Yiu [d], A.R. Young [p], L. Zanini [j], O. Zimmer [a]

Collected results for different reflector systems

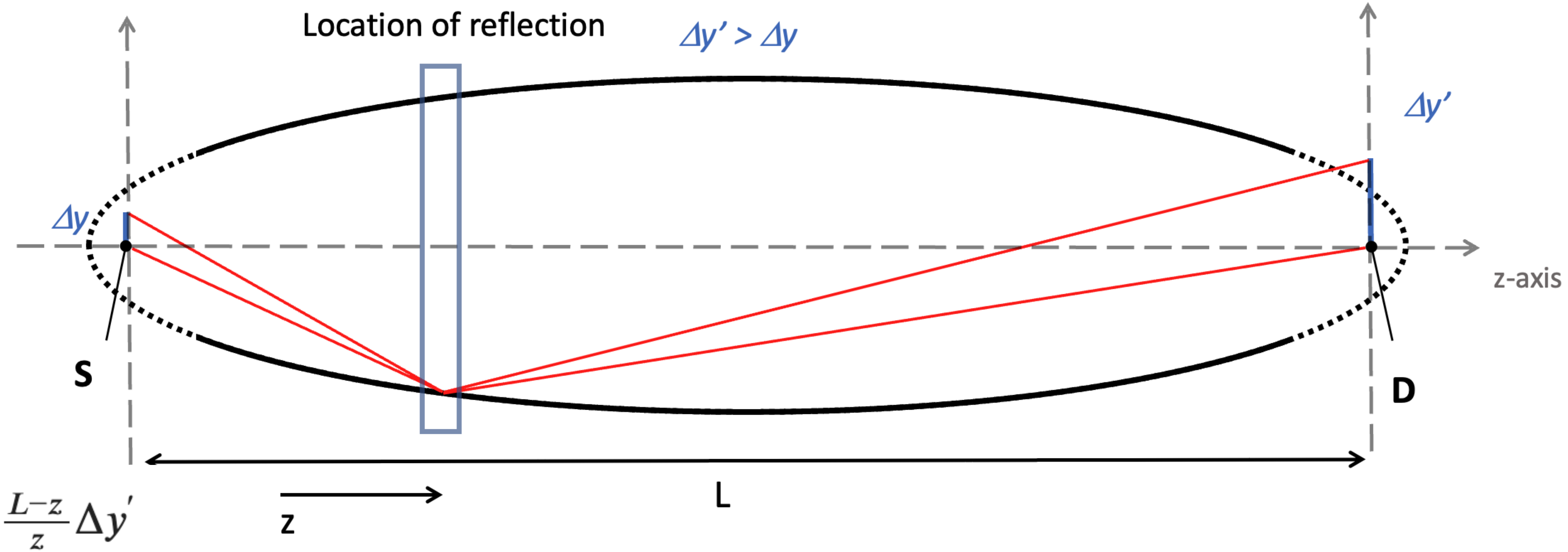








Off-Axis magnification for an elliptical reflector



$$\Delta y = \frac{L-z}{z}\Delta y'$$

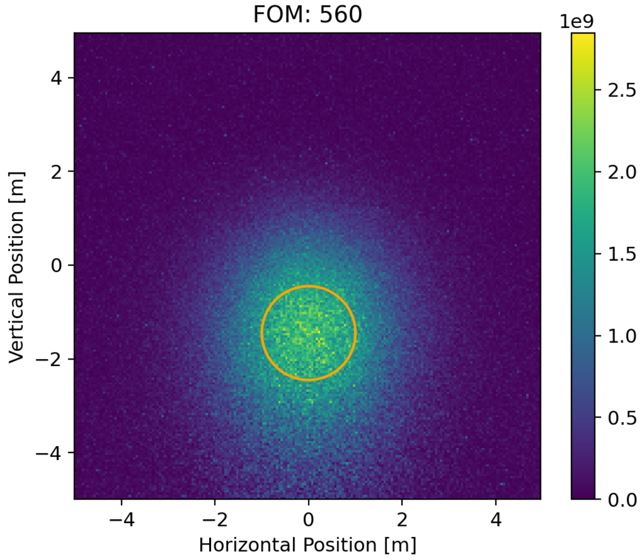
$$M = \Delta y/\Delta y' = \frac{L-z}{z}$$

Examples:

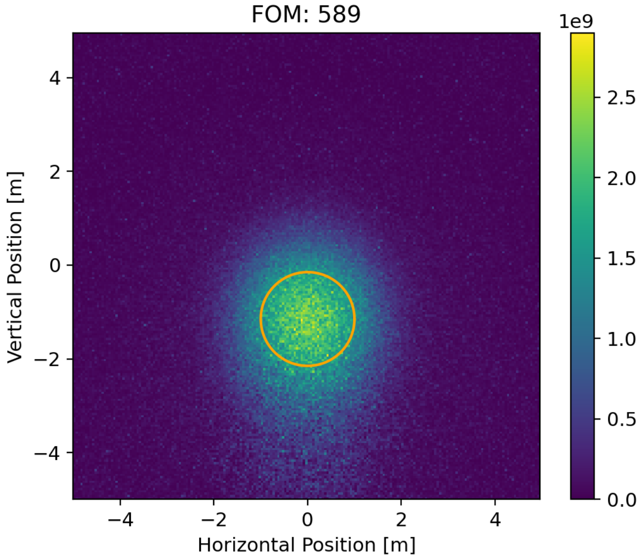
L = 200m, z = 10m -> M = 19
L = 200m, z = 20m -> M = 9
L = 200m, z = 100m -> M = 1

NNBAR: cylindrical, 10m, 4 levels (5MW)
Start of reflector: 10m, 15m, 20m

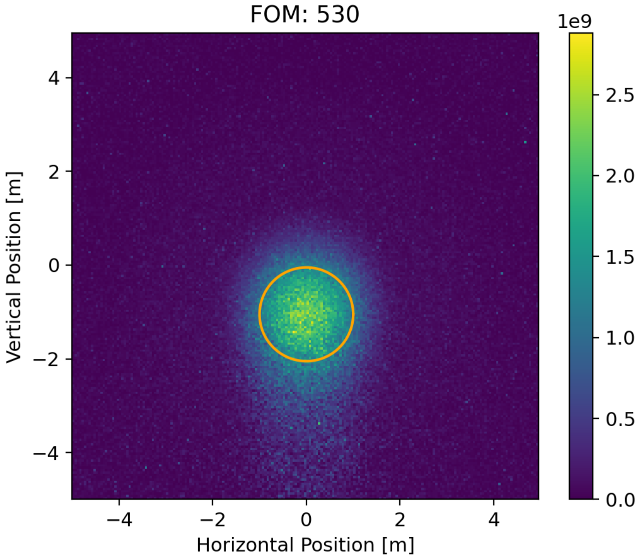
10m



15m



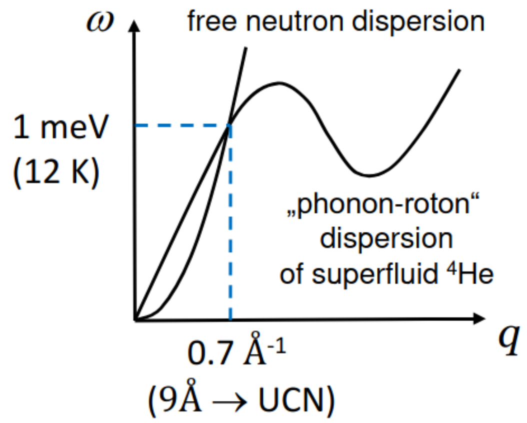
20m



Position of optic has to fulfill trade off between
focusing and covering of solid angle

Application Example
In-Beam UCN Source ESS

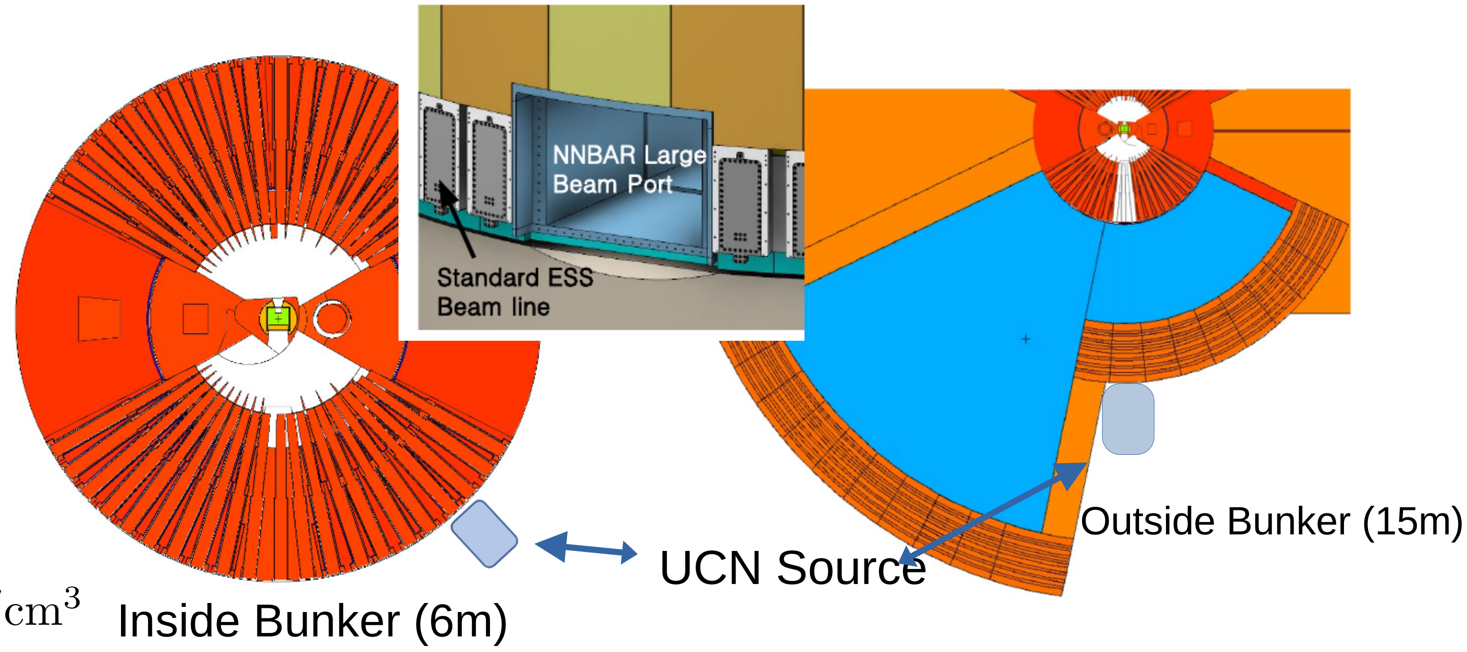
Ultra - cold neutron UCN production in superfluid Helium



<u>Production Rate:</u>

$$P\left(E_{\mathrm{UCN}}\right) = \frac{d\phi(E^*)}{dE} \cdot 1.44 \times 10^{-7} \quad \mathrm{UCN/sec/cm}^3$$

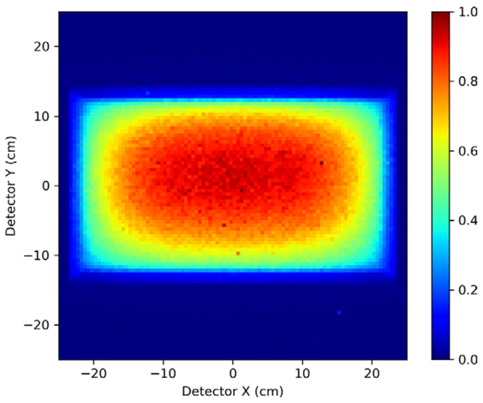
9Å flux at source will convert to UCN flux



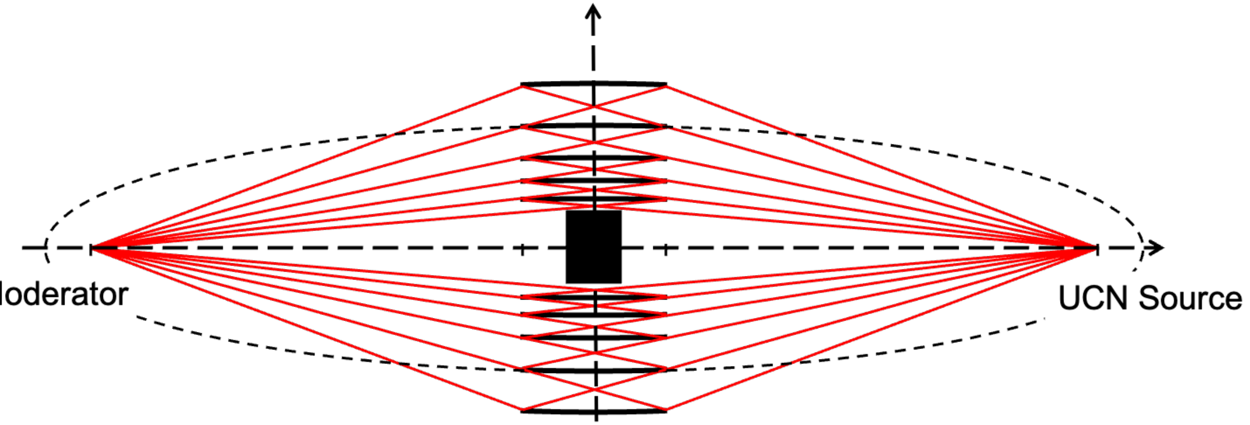
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Application Example
In-Beam UCN Source ESS

- Need a neutron delivery system with high brilliance transfer from moderator to UCN source, with largest technically possible solid angle
- Neutron imaging from the moderator to the UCN source via NMO has been identified as (one) possible solution



Intensity map (simulated) at the ESS LD2 moderator surface of neutrons with WL near 9 Å



In-beam superfluid-helium ultracold neutron source for the ESS

Oliver Zimmer[a,*], Thierry Bigault[a], Skyler Degenkolb[b], Christoph Herb[c], Thomas Neulinger[a], Nicola Rizzi[d], Valentina Santoro[d], Alan Takibayev[d], Richard Wagner[a] and Luca Zanini[d]

Journal of Neutron Research 24 (2022) 95–110 95
DOI 10.3233/JNR-220045

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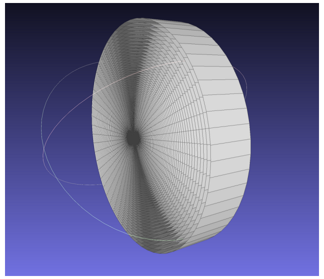
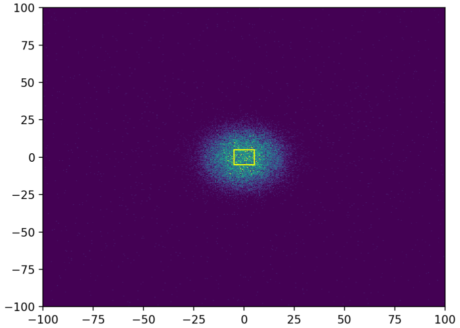
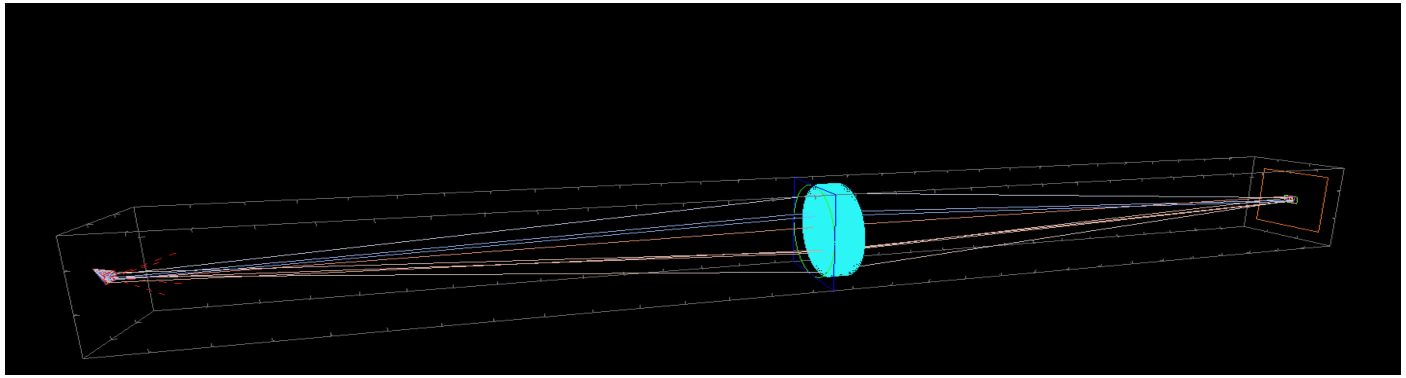
Application Example
In-Beam UCN Source ESS

NMO at 15m:
length 0.5m, 119 levels

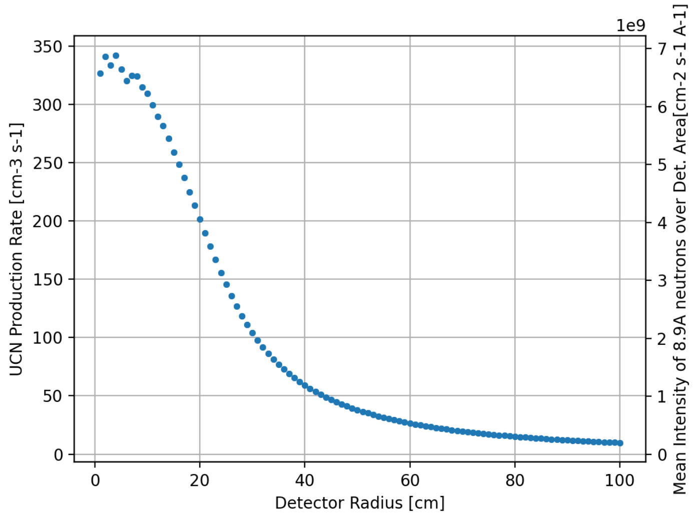
Distance Source-Detector
30m







Production Rate



"...at the top of the range of other current projects."
Zimmer et al., JNR 2022

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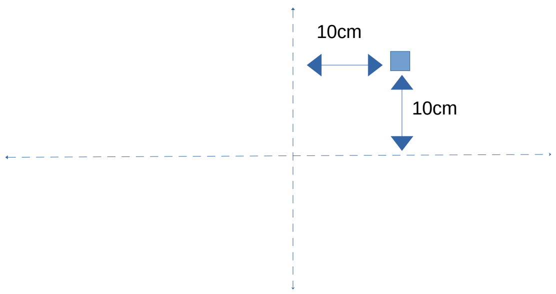
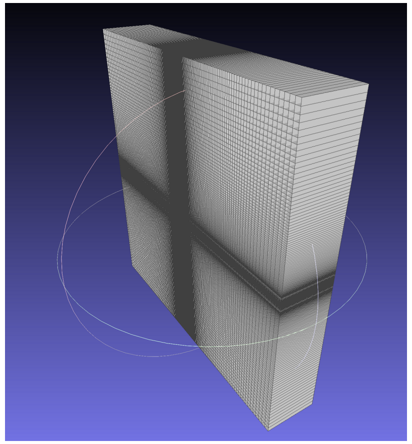
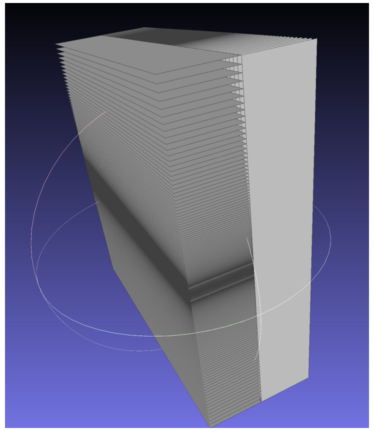
NMOs as (non)-imaging device



off-axis “point” source

1 Double- or
2 Monoplanar
elliptical NMOs
at 15m
focal length 15m





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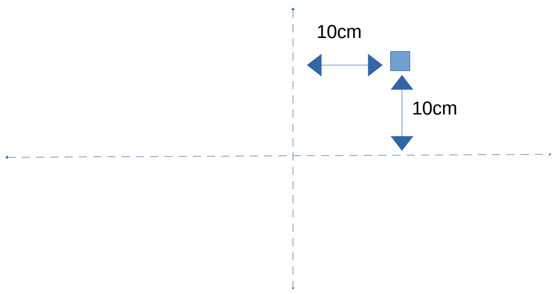

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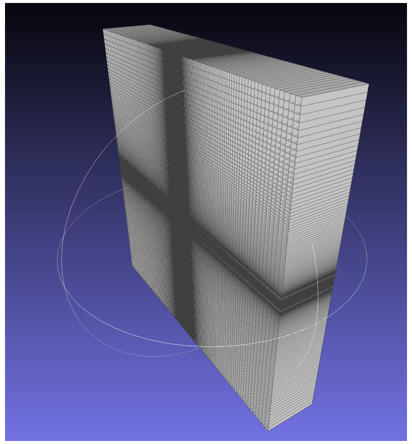
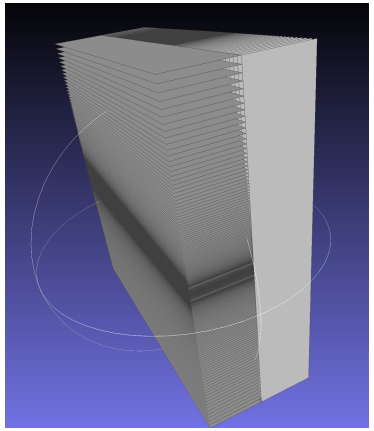
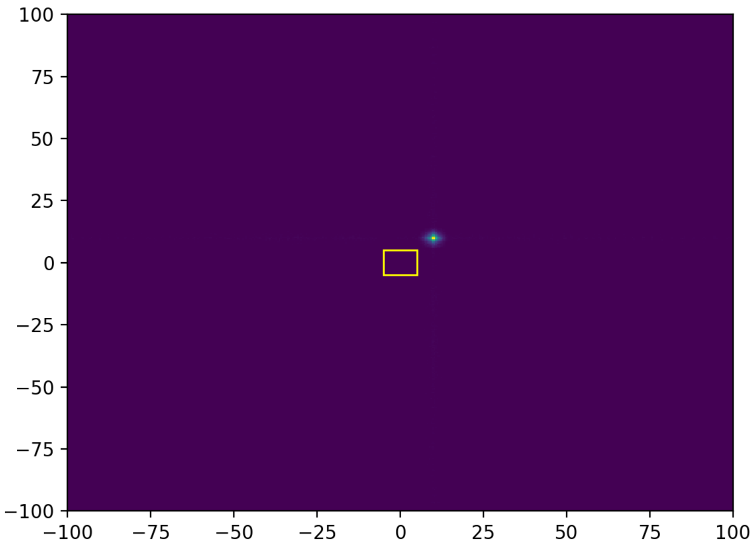




Detector at 30m



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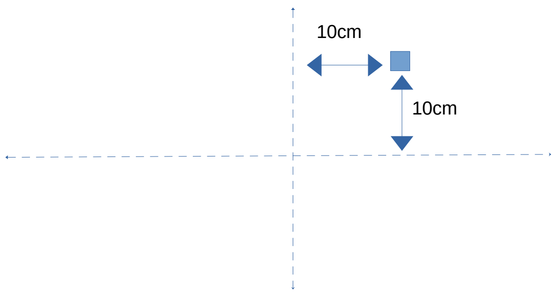
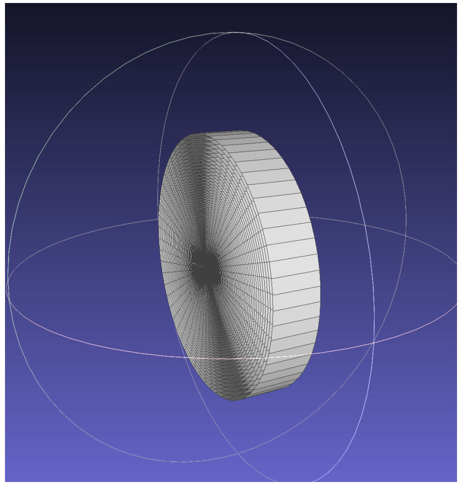
NMOs as (non)-imaging device

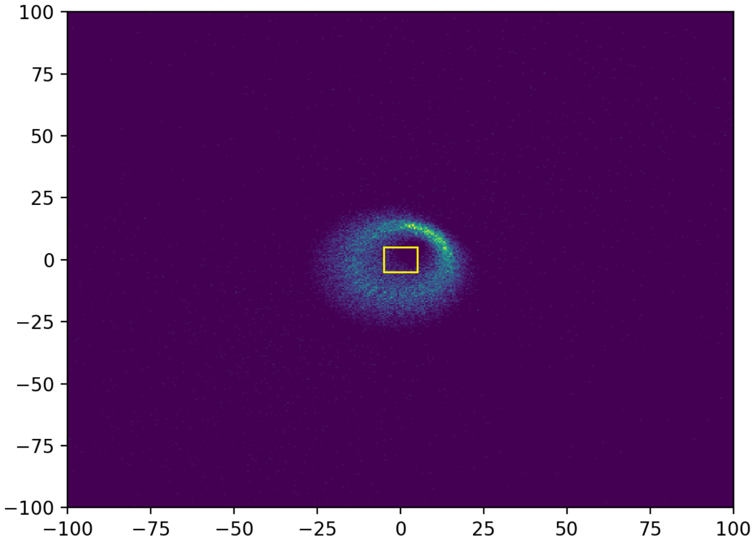
Toroidal (cylindrical)
elliptical NMO
at 15m
focal length 15m



off-axis “point” source



Detector at 30m



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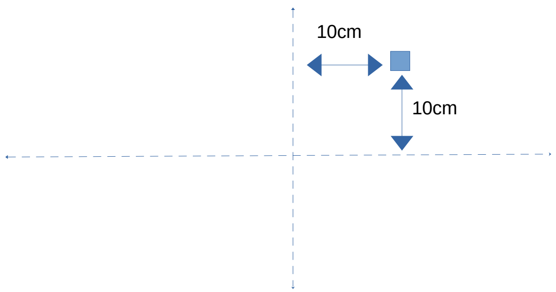
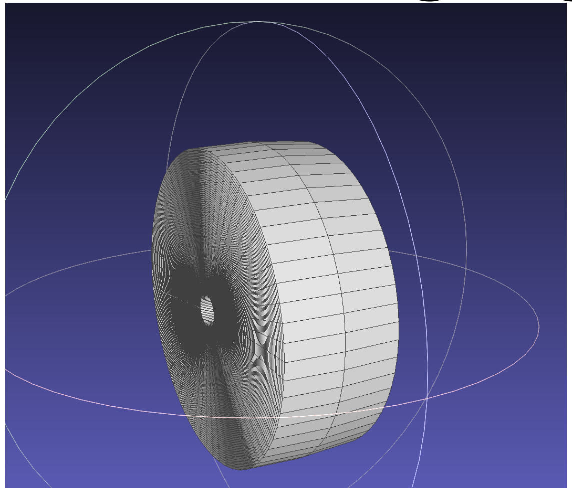
NMOs as (non)-imaging device

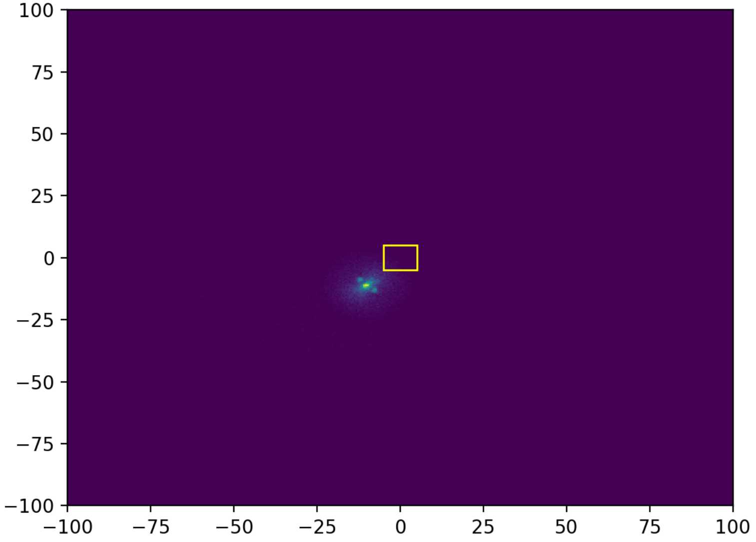


off-axis “point” source

Wolter optic NMO
at ~15m
f_s = 14.9m



Detector at 30m



HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Outlook

- Support nested layers with different m-values:

  → Guide_anyshape_r.instr

- Asymmetric NMOs: i.e. different half-axis arrays
  for upper and lower half
- Nested parabolic NMOs (stand-alone or as part of Wolter optic)
- Take into account losses:
  - Thickness of mirrors (model mirror as boxes not simple perfect planes)
  - Waviness, roughness of mirrors
  - Off-specular reflection
- Tidy up and streamlining of software for release on GitHub

https://github.com/highness-eu/NNBAR_Optics

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HighNess

Thank you for your attention!

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