Wolter Optics in 2 parts

1. McStas Wolter optics from the X-ray telescope community
2. McStas Wolter optics from neutron scatterers at MIT

Astronomical Wolter Telescopes

Simulation capabilities AstroX/McXtrace and McStas

Astro-Wolter Optic Variants

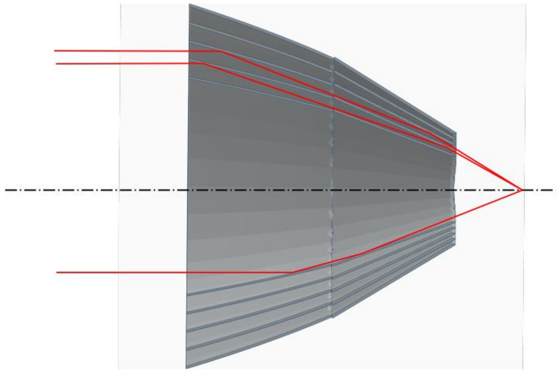
True Wolter-I:
Parabolic+Hyperbolic

Conical approximation:
Linear Conic x 2

Wide field optics:
Hyperboloid-Hyperboloid:

Imaging:
Elliptic Hyperboloid:

Etc...



Wolter type I

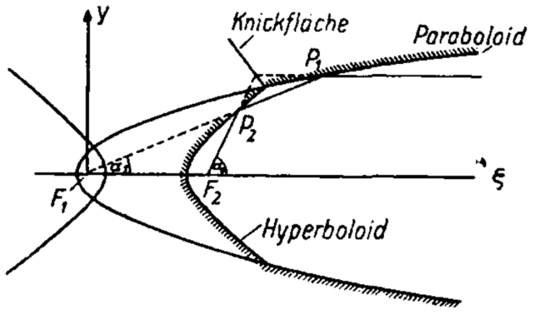


Abb. 6. Paraboloid und Hyperboloid in konfokaler Lage als Spiegelsystem für streifenden Einfall

Wolter type II

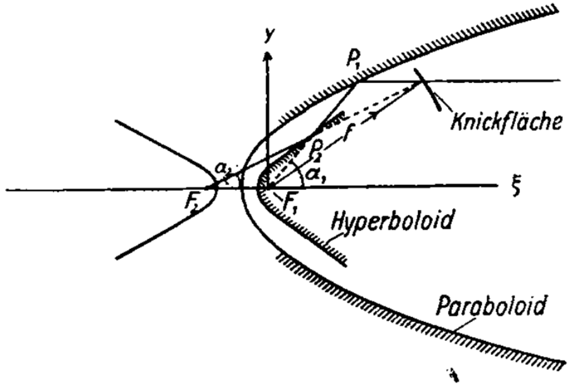


Abb. 15. Spiegelsystem 2. Art

Wolter type III

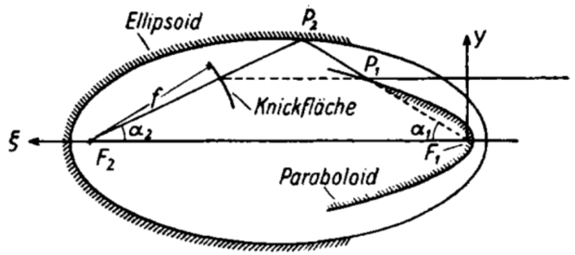


Abb. 16. Spiegelsystem 3. Art

AstroX – addon toolbox for McXtrace

Set of components concept orignally based on Silicon Pore Optics (SPOs). A tech for creating lightweight but stiff large area Wolter Optics.

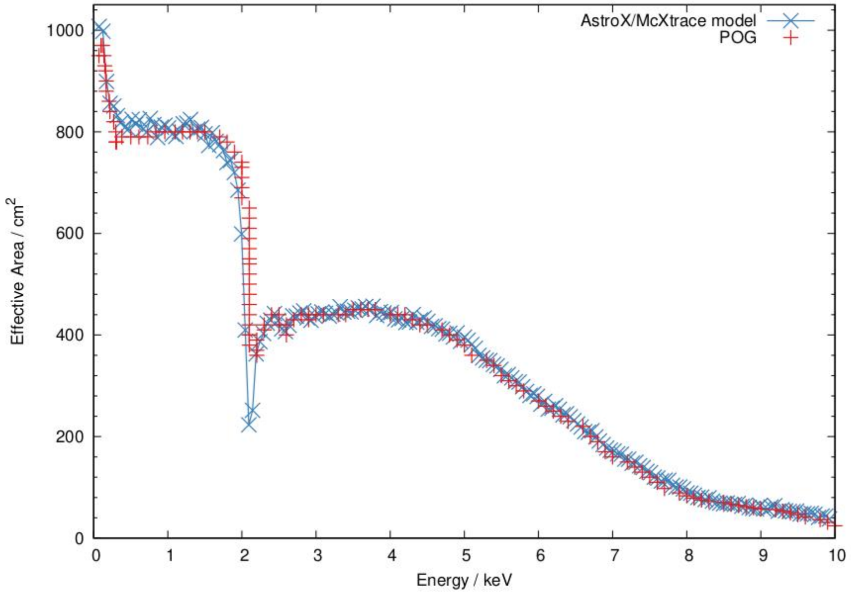
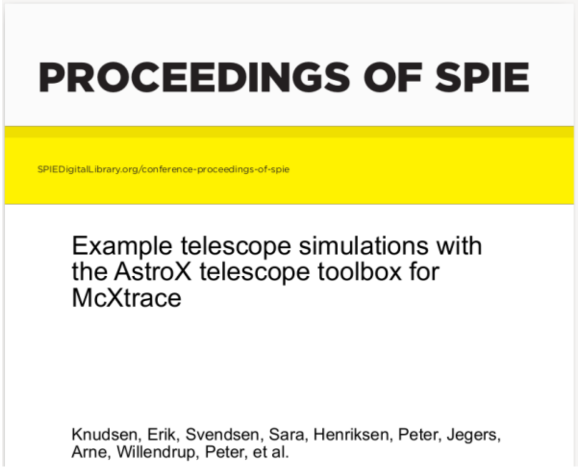


Figure 6. Effective area as a function of energy for an ideal model of the Chandra X-ray Observatory. Blue is the AstroX/McXtrace model, Red is the effective area extracted from the Proposers' Observatory Guide (POG).[24]

Erik B. Knudsen, Sara Svendsen, Peter L. Henriksen, Arne S. Jegers, Peter K. Willendrup, Desirée D. M. Ferreira, "Example telescope simulations with the AstroX telescope toolbox for McXtrace," Proc. SPIE 11444, Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 114443Q (13 December 2020); https://doi.org/10.1117/12.2561372



PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Example telescope simulations with the AstroX telescope toolbox for McXtrace

Knudsen, Erik, Svendsen, Sara, Henriksen, Peter, Jegers, Arne, Willendrup, Peter, et al.

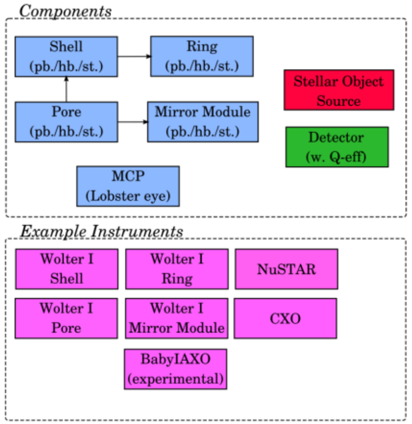


Figure 3. Contents of the AstroX/McXtrace library. Optical devices in the broad sense are known as "Components" whereas an arrangements of components constitute "Instruments". Note that, in addition, all component within McXtrace are also automatically available to AstroX-users.

Silicon Pore Optics/Mirror Modules

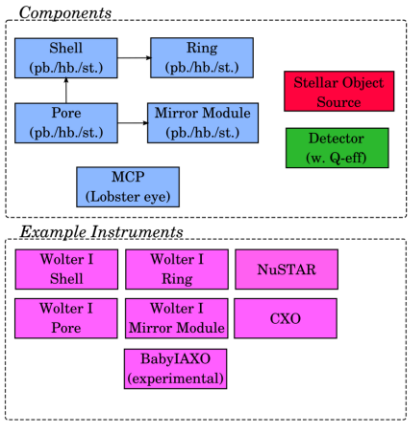
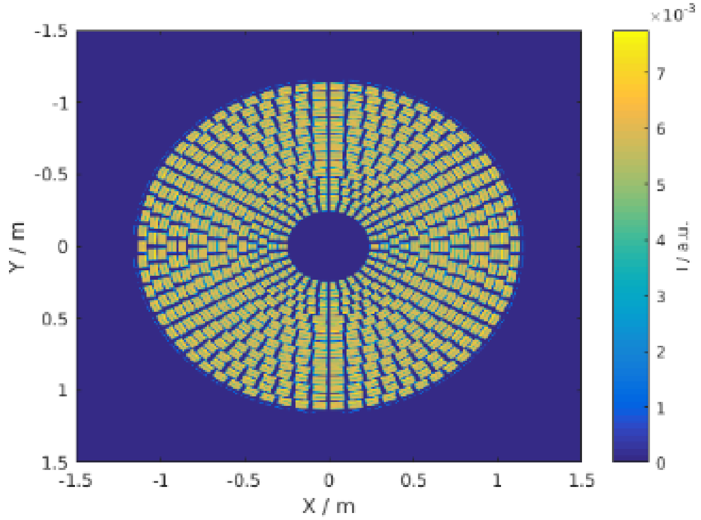
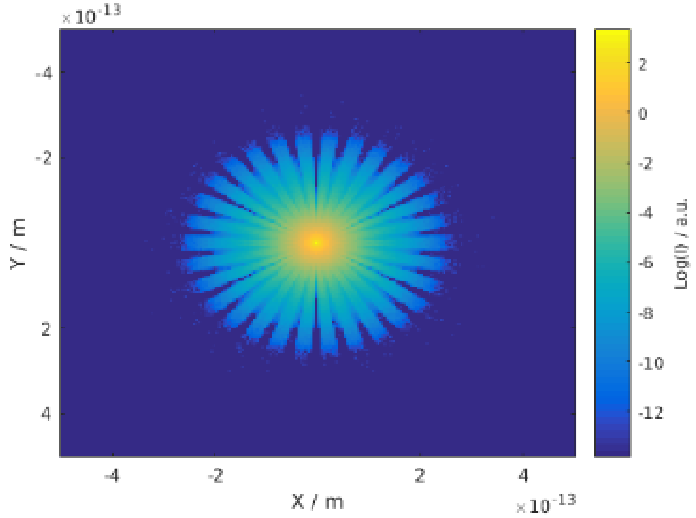
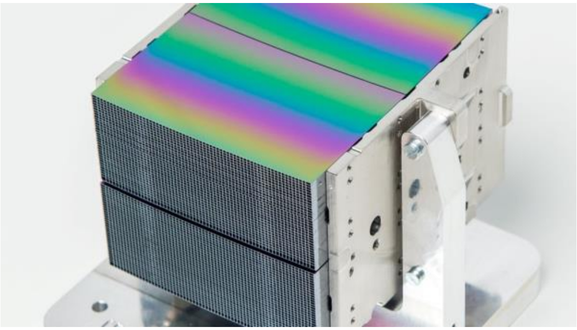


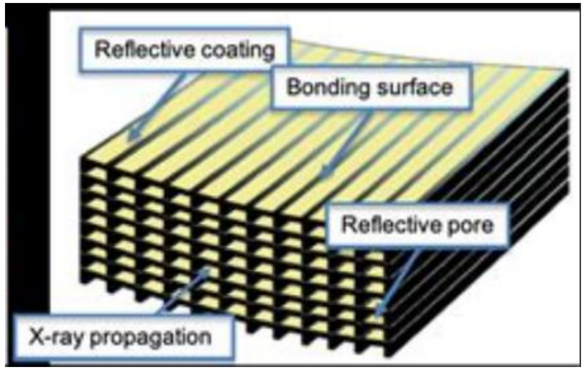
Figure 3. Contents of the AstroX/McXtrace library. Optical devices in the broad sense are known as "Components" whereas an arrangements of components constitute "Instruments". Note that, in addition, all component within McXtrace are also automatically available to AstroX-users.

ATHENA simulation

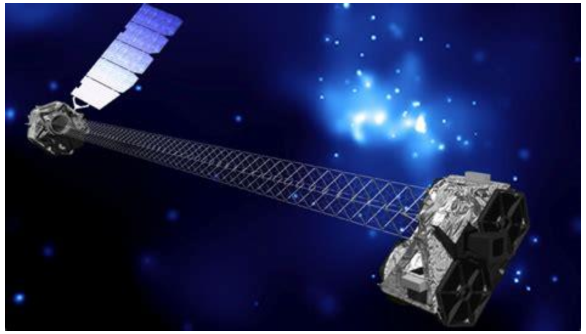








Conical Approximation /NuSTAR



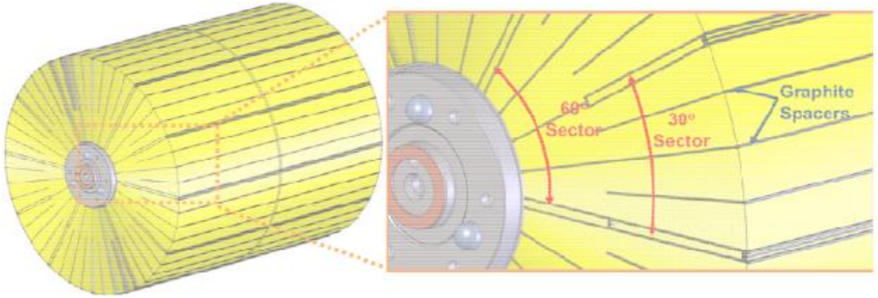


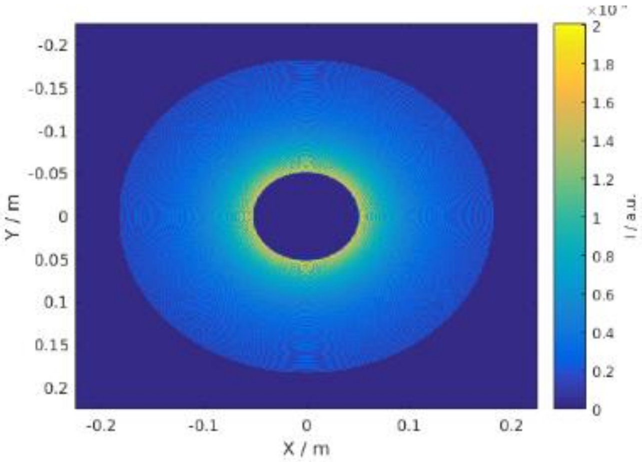
Figure 3: The NuSTAR optics are composed of 133 concentric layers of conic-approximation Wolter I mirrors aligned and held together by epoxy and precisely machined graphite spacers that run along the optic axis. The inner 65 layers are comprised of 6 × ~60° sectors (sextants) and the outer 65 layers are comprised of 12 × ~30° sectors (twelvetant), each aligned with five axial spacers. The transition from sextant to twelvetant mirrors is made with three intermediate sextant layers using nine spacers per sector with wide outside spacers that are shared by adjacent mirrors to provide azimuthal connectivity between adjacent layers.

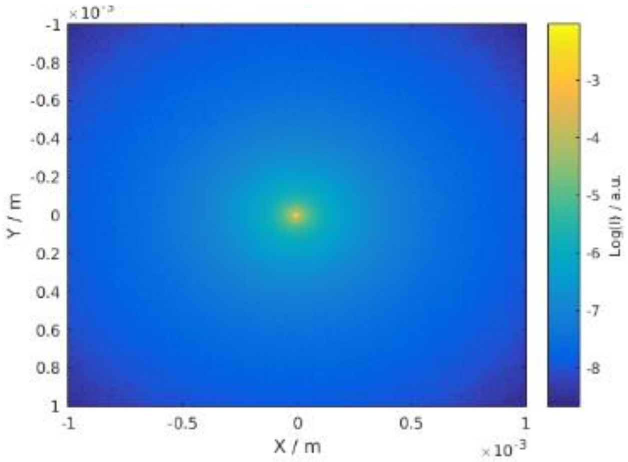
Jason E. Koglin, HongJun An, Kenneth L. Blaedel, Nicolai F. Brejnholt, Finn E. Christensen, William W. Craig, Todd A. Decker, Charles J. Hailey, Layton C. Hale, Fiona A. Harrison, Carsten P. Jensen, Kristin K. Madsen, Kaya Mori, Michael J. Pivovaroff, Gordon Tajiri, William W. Zhang, "NuSTAR hard x-ray optics design and performance," Proc. SPIE 7437, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IV, 74370C (31 August 2009); doi: 10.1117/12.826724

SPIE.

Event: SPIE Optical Engineering + Applications, 2009, San Diego, California, United States

NuSTAR conic approximation





Parabolic Shell

The `Shell_p` Component

Single parabolic shell as part of a Wolter optic.

Identification

- **Site:**
- **Author:** Erik B Knudsen and Desiree D. M. Ferreira
- **Origin:** DTU Physics, DTU Space
- **Date:** Feb. 2016

Description

```
A single shell is simulated. The top and bottom are curved cylindrically
azimuthally. The sagital profile is defined by a parabola, which passes through the radii raidus_m
at z=0, and radius_p at zentry (<0).

To intersect the Wolter I plates we take advatage of the azimuthal symmetry and only consider the radial component
of the photon's wavevector.

Imperfect mirrors may be modelled using one of 4 models. In all cases the surface normal of the mirror
at the ideal mirror intersection point is perturbed before the exit vector is computed.
1. Longitudinal 1D. A perturbation angle is chosen from a uniform distribution with width waviness.
2. Isotropic 2D. The surface normal is perturbed by choosing an angle on a disc with radius waviness
3. Externally measured/computed data. We interpolate in a data-file consisting of blocks of dtheta/theta
with 1 block per energy. dtheta is a sampled angle offset from the nominal Fresnel grazing angle
theta.
4. Double gaussian. dtheta is chosen from one of two gaussian distributions. Either specular or off-specular, where the
widths (sigmas) are given by the tables in the file "wave_file". If the off-specular case the behaviour is similar
to 2D uniform case.
```

Input parameters

Parameters in **boldface** are required; the others are optional.

Name	Unit	Description	Default
radius_p			
radius_m			
Z0			
yheight			
chamferwidth			0
gap			0
zdepth			0
mirror_reflec			""
bottom_reflec			""
wave_file			""
R_d			1
wave_model			0
waviness	rad	Waviness of the pore reflecting surface. The slope error is assumed to be uniformly distributed in the interval "[-waviness:waviness]".	0
verbose		If !=0 output extra info during simulation.	0

The `Shell_h` Component

Single Pore as part of the Silicon Pore Optics (SPO) as envisioned for the ATHENA+ space telescope.

Identification

- **Site:**
- **Author:** Erik B Knudsen and Desiree D. M. Ferreira
- **Origin:** DTU Physics, DTU Space
- **Date:** Feb. 2016

Description

```
A single shell is simulated. The top and bottom are curved cylindrically
azimuthally, and according to the Wolter I optic lengthwise (sagitally). This is the hyperbolic part.
The azimuthal curvature is defined by the radius parameters.

To intersect the Wolter I plates we take advantage of the azimuthal symmetry and only consider the radial component
of the photon's wavevector.

Imperfect mirrors may be modelled using one of 4 models. In all cases the surface normal of the mirror
at the ideal mirror intersection point is perturbed before the exit vector is computed.
1. Longitudinal 1D. A perturbation angle is chosen from a uniform distribution with width waviness.
2. Isotropic 2D. The surface normal is perturbed by choosing an angle on a disc with radius waviness
3. Externally measured/computed data. We interpolate in a data-file consisting of blocks of dtheta/theta
with 1 block per energy. dtheta is a sampled angle offset from the nominal Fresnel grazing angle
theta.
4. Double gaussian. dtheta is chosen from one of two gaussian distributions. Either specular or off-specular, where the
widths (sigmas) are given by the tables in the file "wave_file". If the off-specular case the behaviour is similar
to 2D uniform case.
```

Input parameters

Parameters in **boldface** are required; the others are optional.

Name	Unit	Description	Default
radius_m			
radius_h			
Z0			
yheight			
chamferwidth			0
gap			0
zdepth			0
mirror_reflec			""
bottom_reflec			""
wave_file			""
R_d			1
wave_model			0
waviness	rad	Waviness of the pore reflecting surface. The slope error is assumed to be uniformly distributed in the interval [-waviness:waviness].	0

Hyperbolic Shell

Code Structure

- Self-contained "regular" McStas/McXtrace component. Similar to guide.
- Mirrors may have side walls and/or bottom surface. Both may be reflective.
- Intended for use in a GROUP
- Need a pair of components to form an optic.
- In the case of ATHENA: 2 x 678 components. =>
  Mirror by Mirror = 16000
- Models for waviness/mirror imperfections included.

Port to McStas for neutron use? CXO

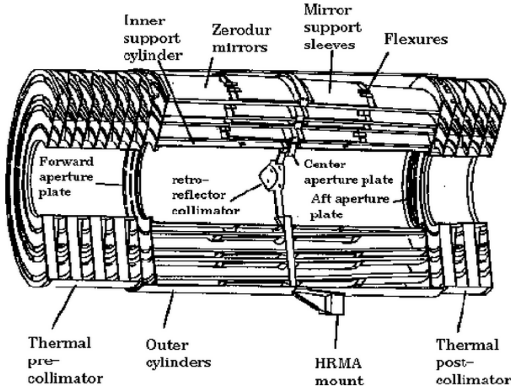
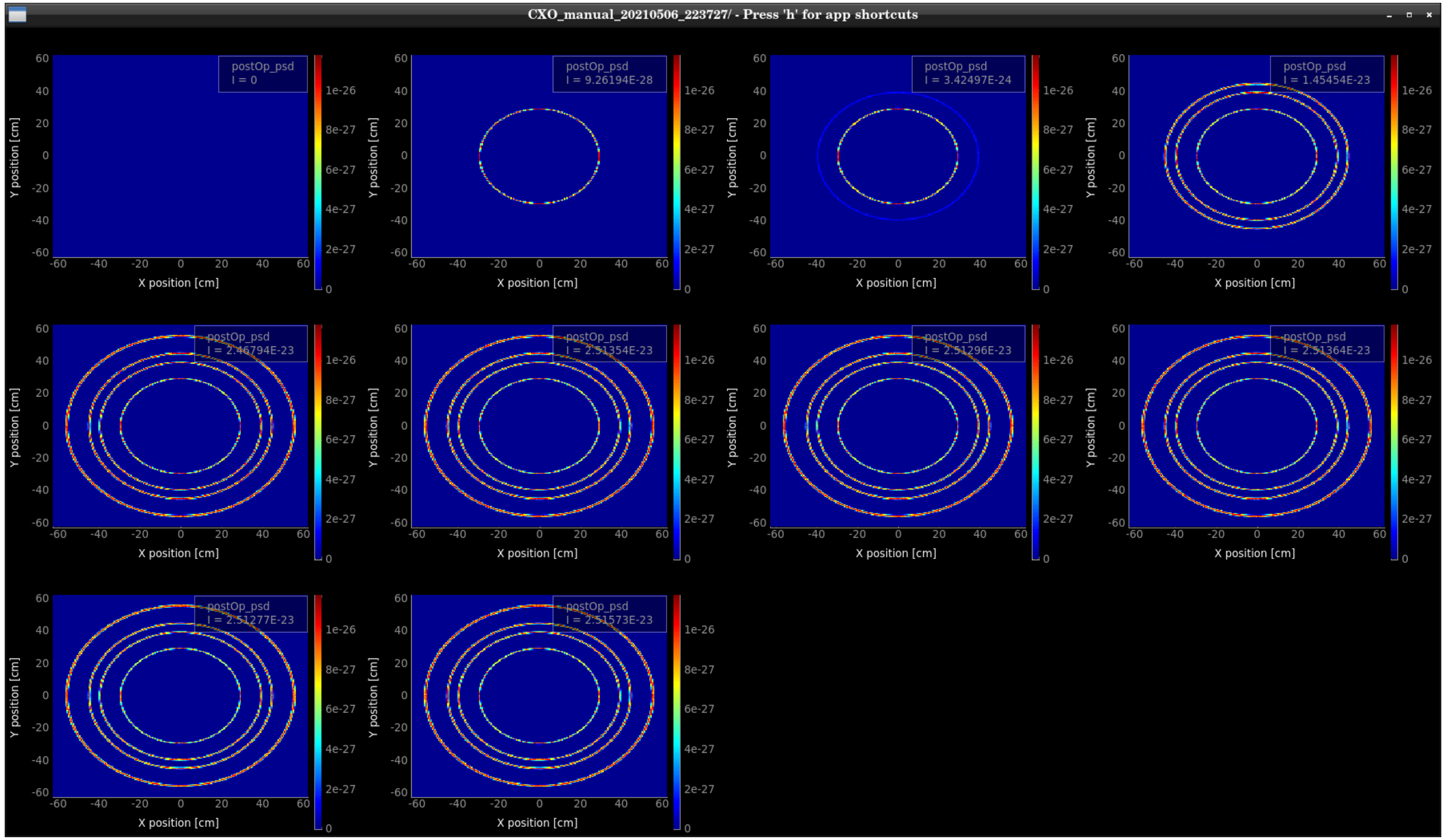


Figure 4.1: The four nested HRMA mirror pairs and associated structures.

Table 4.1: *Chandra* HRMA Characteristics

Optics	Wolter Type-I
Mirror coating	Iridium (330 Å, nominal)
Mirror outer diameters (1, 3, 4, 6)	1.23, 0.99, 0.87, 0.65 m
Mirror lengths (P_n or H_n)	84 cm
Total length (pre- to post-collimator)	276 cm
Unobscured clear aperture	1145 cm^2
Mass	1484 kg
Focal length	10.070 ±0.003 m
Plate scale	48.82 ±0.02 μm $arcsec^{-1}$
Exit cone angles from each hyperboloid:	
θ_c (1, 3, 4, 6)	3.42°, 2.75°, 2.42°, 1.80°
θ_d (1, 3, 4, 6)	3.50°, 2.82°, 2.49°, 1.90°
f-ratios (1, 3, 4, 6)	8.4, 10.4, 11.8, 15.7
PSF FWHM (with detector)	< 0.5 arcsec
Effective area:	@ 0.25 keV 800 cm^2 @ 5.0 keV 400 cm^2 @ 8.0 keV 100 cm^2
Ghost-free field of view	30 arcmin diameter

Scan for m=1, lambda=1-10Å scan,
standard neutron guide reflectivity function



The Code

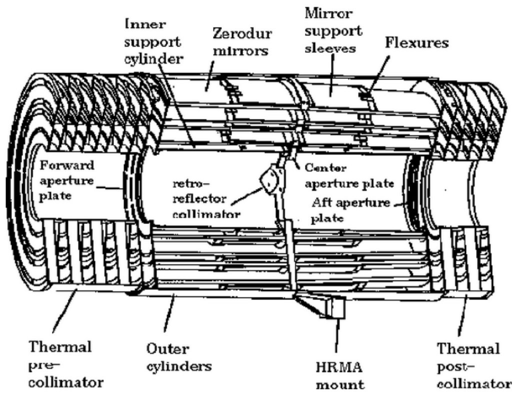


Figure 4.1: The four nested HRMA mirror pairs and associated structures.

CXO_manual.instr (~/Repositories/Wolter-optics/AstroX_comps) - GVIM

File Edit Tools Syntax Buffers Window Help

```
*****************************************************************************/
DEFINE INSTRUMENT CXO(E0=1, dE=0.001, verbose=1, string mcoat="Ir_CXO.dat", OA_angle=0)

DECLARE
%{
   double Rp[4]={1.23/2.0, 0.99/2.0, 0.87/2.0, 0.65/2.0};
   double Rm[4];
   double Rh[4];
   const double FL=10.070;
   const double PL=0.84;
   const double th_c_deg[4]={3.42, 2.75, 2.42, 1.80};
   double th_c[4];

%}

INITIALIZE
%{
   /*compute the midpoint and hyperbolic radii*/
  double alpha,thetap,thetah,P,d,e,C0;
  int i;
  for(i=0;i<4;i++){
    th_c[i]=th_c_deg[i]*DEG2RAD;
    Rm[i]=atan(th_c[i])*FL;
    alpha=th_c[i]/4.0;
    thetap=alpha;
    thetah=alpha*3;
    P=FL*tan(4*alpha)*tan(thetap);
    d=FL*tan(4*alpha)*tan(4*alpha-thetah);
    e=cos(4*alpha)*(1+tan(4*alpha)*tan(thetah));
    C0=4*e*e*P*d/(e*e-1);

    /*RP and RH is assumed given by the length along the axis=0.84*/
    Rp[i]=sqrt( P*P + 2*P*(PL+FL) + C0);
    Rh[i]=sqrt( e*e *(d+FL-PL)*(d+FL-PL) - (FL-PL)*(FL-PL));
%}

TRACE

COMPONENT origin = Progress_bar()
AT (0, 0, 0) RELATIVE ABSOLUTE

COMPONENT optics_centre = Arm()
AT(0,0,OD) RELATIVE origin

COMPONENT src_div = Source_div(xwidth=1.23,yheight=1.23, focus_aw=2*DEG2RAD, focus_ah=1e-9, E0=E0, dE=dE)
AT(0,0,-OD+PL) RELATIVE off_axis

/*primary optics*/
COMPONENT sh1_p = Shell_p(
    radius_p=Rp[0], radius_m=Rm[0], mirror_reflec=mcoat, yheight=Rp[0]-Rp[1], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP primary
COMPONENT sh3_p = Shell_p(
    radius_p=Rp[1], radius_m=Rm[1], mirror_reflec=mcoat, yheight=Rp[1]-Rp[2], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP primary
COMPONENT sh4_p = Shell_p(
    radius_p=Rp[2], radius_m=Rm[2], mirror_reflec=mcoat, yheight=Rp[2]-Rp[3], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP primary
COMPONENT sh6_p = Shell_p(
    radius_p=Rp[3], radius_m=Rm[3], mirror_reflec=mcoat, yheight=0.2, Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP primary

/*secondary optics*/
COMPONENT sh1_h = Shell_h(
    radius_h=Rh[0], radius_m=Rm[0], mirror_reflec=mcoat, yheight=Rm[0]-Rm[1], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP secondary
COMPONENT sh3_h = Shell_h(
    radius_h=Rh[1], radius_m=Rm[1], mirror_reflec=mcoat, yheight=Rm[1]-Rm[2], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP secondary
COMPONENT sh4_h = Shell_h(
    radius_h=Rh[2], radius_m=Rm[2], mirror_reflec=mcoat, yheight=Rm[2]-Rm[3], Z0=FL, bottom_reflec="mirror_coating_zero.txt")
AT(0,0,0) RELATIVE optics_centre
GROUP secondary
COMPONENT sh6_h = Shell_h(
```

ConicTracer from MIT

Erik B. Knudsen and Peter Willendrup
- with input from Boris Khaykovic, MIT

Historical stuff

- Code was never officially part of McStas, only “distributed” on a per-request basis
  (Boris never asked us to include it officially, solely out of concerns wrt. ease of use etc.)

- Developed by Boris with helped of a series of MIT students

- In ~2010 Peter helped port the code from McStas 1.x to 2.x

- The code in the ”standard” zip-file included no chosen geometry, i.e. not easy to get started for a new geometry

Communication with Boris K 2021 (this week!)

A bit of email-ping-pong resulted in access to a more digestible set of files with a relevant geometry.

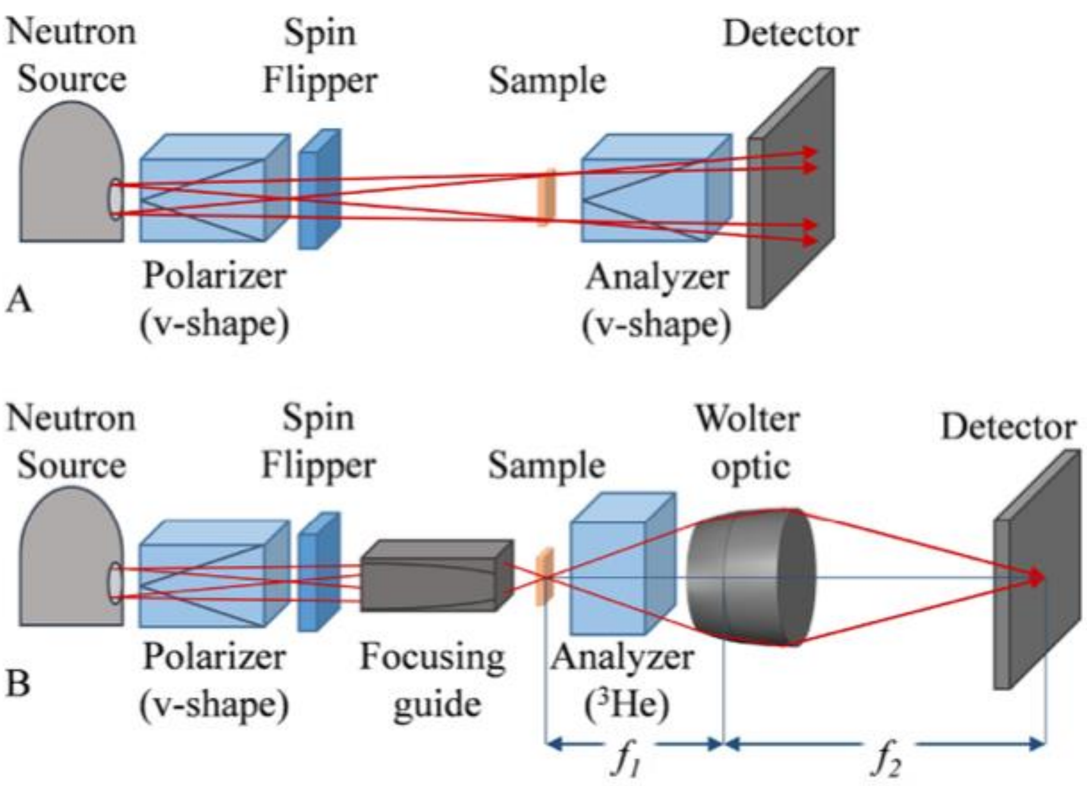


Fig. 1. Schematic of the neutron imaging techniques used in this study. (A) Standard neutron depolarization imaging. Red arrows illustrate neutron flight paths highlighting the geometrical unsharpeness due to the separation of sample and detector. (B) Polarized neutron microscope. A focusing guide increases the divergence of the neutron beam while a Wolter optic with focal lengths f_1 and f_2 behind the sample acts as a magnifying lens. A ^{3}He analyzer is placed between the sample and the optic without effecting the spatial resolution.

Journal of Magnetism and Magnetic Materials 475 (2019) 176–183

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ELSEVIER

Research articles

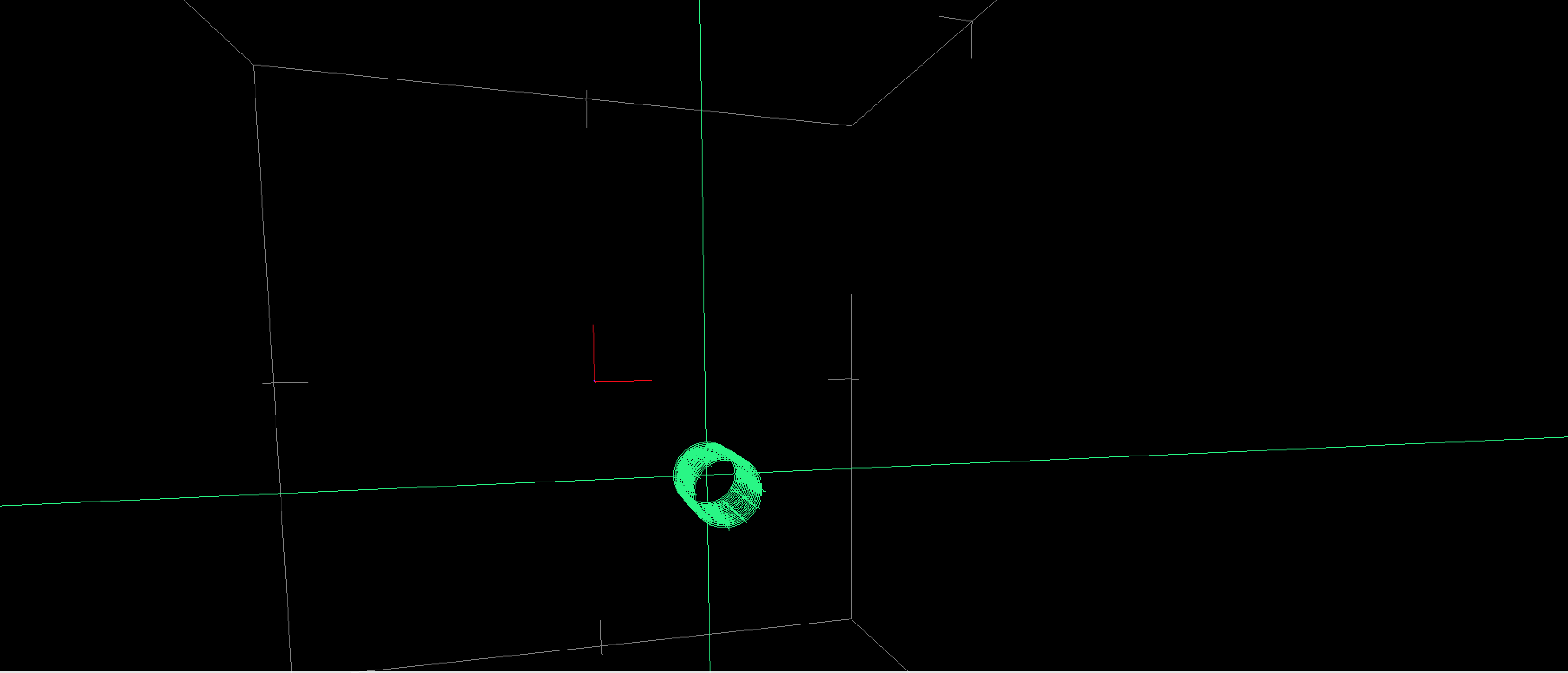
High-resolution neutron depolarization microscopy of the ferromagnetic transitions in Ni_3Al and $HgCr_2Se_4$ under pressure

Pau Jorba[a], Michael Schulz[b,*], Daniel S. Hussey[c], Muhammad Abir[d], Marc Seifert[a,b], Vladimir Tsurkan[e,f], Alois Loidl[e], Christian Pfleiderer[a], Boris Khaykovich[d]

[a] Physik-Department, Technische Universität München, D-85748 Garching, Germany
[b] Heinz-Maier-Leibnitz Zentrum (MLZ), Technische Universität München, D-85748 Garching, Germany
[c] Physical Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, MS 8461, Gaithersburg, MD 20899-8461, USA
[d] Nuclear Reactor Laboratory, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA, USA
[e] Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg, D-86159 Augsburg, Germany
[f] Institute of Applied Physics, Chisinau, Republic of Moldova

"The code implements our NIH mirrors (it needs the conic tracer library), a combination of Ellipsoid and Hyperboloid, 3.2 m focus-to-focus distance, magnification 4.

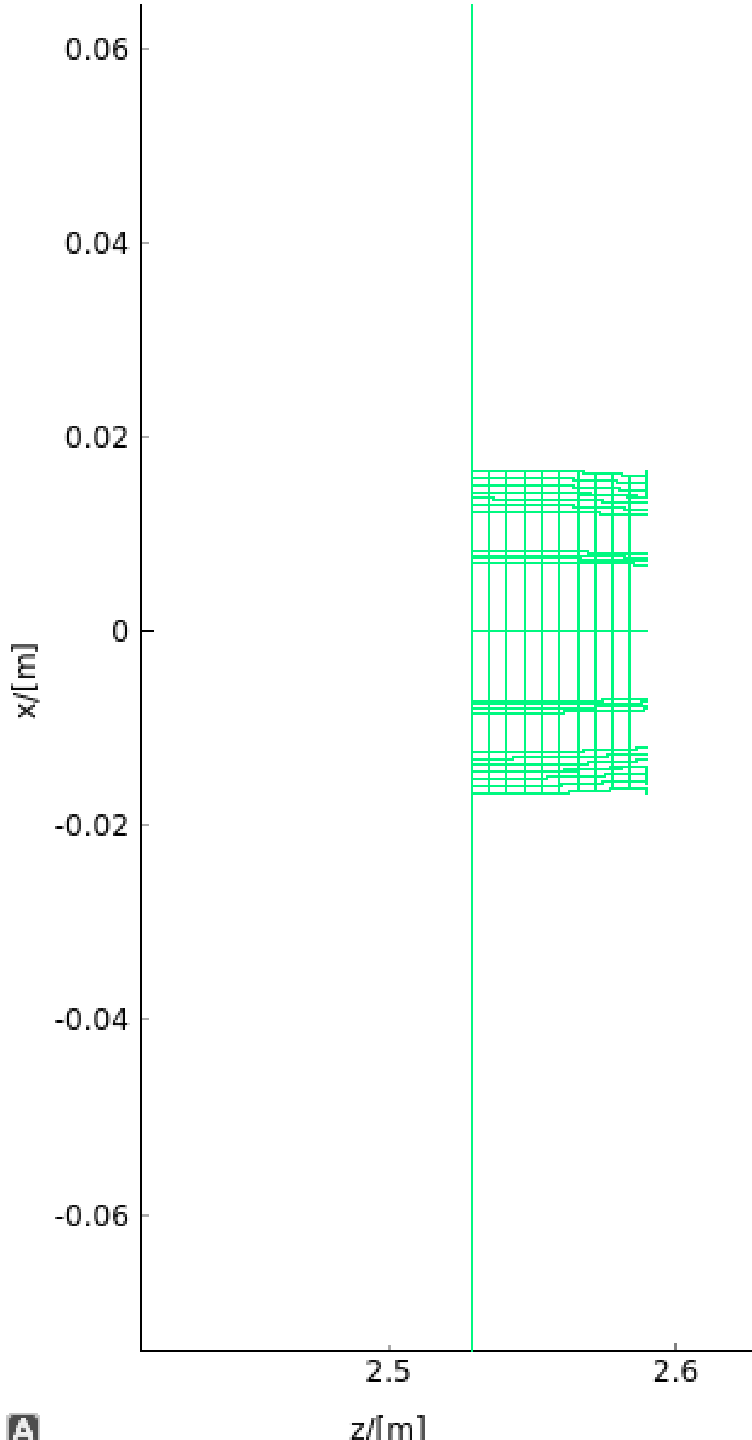
I attached the paper where polarized imaging was demonstrated. Figs 1 and 2 are particularly relevant for this discussion."



NIH mirror model from Boris Khaykovic

Structure of the W1 instrument

- Component origin AT (0,0,0) 0 m from origin
- Component source AT (0,0,-0.101) 0.101 m from origin
- Component source_slit AT (0,0,-0.1) 0.102 m from origin
- Component FocalSource AT (0,0,0) 0.202 m from origin
- Component source_dir_monitor AT (0,0,0) 0.202 m from origin
- Component conics AT (0,0,0.5) 0.702 m from origin
- Component f1_monitor AT (0,0,3.2) 3.402 m from origin
- Component PSD_FocalSpot AT (0,0,3.2) 3.402 m from origin



Structure of the code

- Instrument file: w1.instr
- Adapted source: Source_div_round.comp
- Conics component: Conics.comp, defines geometry, calls
  - w1_conics.h – with specific functions for EH and HE mirror variants, relies on
  - conic.h – with the underlying mathematical framework
    - (Includes a main() from an older stand-alone code, significant “duplication” of vector- and particle-code which can already be found elsewhere in McStas)

- To redefine geometry one should edit the Conics.comp code, not a very McStas-oriented solution :-)

The `W1` Instrument

Identification

- **Site: MITR**
- **Author:** Giacomo Resta (gresta@mit.edu)
- **Origin:** MIT NRL
- **Date:** July 2011
- **Version:** 0.01a

Description

```
McStas instrument for testing the design of Nested Wolter type
one optics consisting of paraboloid and hyperboloid segments
```

Input parameters

Parameters in **boldface** are required; the others are optional.

Name	Unit	Description	Default
r_shutter			.001
instr_len	m	Length from source to focus of instrument	3.2
m	1	Critical angle of mirrors as multiples of Ni	1
M	m	Magnification of instrument: need to determine the size of the detectors	0.25
mirr_thick	m	Thickness of mirror shell surfaces	0.0005
div_radian			0.025
lambda_l			1.0
lambda_h			8.0
imaging	-	The flag: imaging = 1 when in imaging (magnifying) configuration; =0 when in focusing configuration	0

The `Conics` Component

Identification

- **Author:** Giacomo Resta (gresta@mit.edu)
- **Origin:** MIT NRL
- **Date:** July 2011
- **Version:** 0.01a

Description

```
Dummy component to use McStas with conics.h
```

Input parameters

Parameters in **boldface** are required; the others are optional.

Name	Unit	Description	Default
reflect			"supermirror_m3.rfl"
instr_len	m	Length from source to focus of instrument	
c_m			
mirr_thick	m	Thickness of mirror shell surfaces	
imaging			

- Instrument and comp have ~ fixed geometry
- Component only serves as coupling to the conic.h functions

Hard-coded mirror-geometry in Conics.comp

```
//Make new scene
s = makeScene();

//Set Scene to use custom trace function for conic
//s.traceNeutronConic = traceNeutronConicWithTables;

//Add geometry to scene
double ro[4] = {0.014298, 0.015021, 0.015781, 0.016579};
double Ae[4] = {2.1333819, 2.1333928, 2.1334040, 2.1334153};
double Be[4] = {0.014592664, 0.015330969, 0.016106622, 0.016921513};
double Ah[4] = {0.53328210, 0.53328266, 0.53328237, 0.53328112};
double Bh[4] = {0.0072963186, 0.0076654392, 0.0080532169, 0.0084605928};
int i = 0;

EH e[4];
for (i = 0; i < 4; i++) {
    if (imaging) {
            e[i] = addHEShellM(0.0, 3.2, ro[i], 2.56012, 0.031097, 0.030, c_m, mirr_thick, Ae[i], Be[i], Ah[i], Bh[i], &s);
    }
    else {
            e[i] = addEHShellM(0.0, 3.2, ro[i], 2.56012, 0.031097, 0.030, c_m, mirr_thick,
                     Ae[i], Be[i], Ah[i], Bh[i], &s);
    }

}
if (imaging) {
    addDisk(e[0].h->zs, 0.0, rConic(e[0].h->ze, *e[0].h)*e[0].h->zs/e[0].h->ze, &s);
    //addDisk(e[3].h->zs, rConic(e[3].h->zs, *e[3].sh), 100000, &s);
            addDisk(e[0].h->zs, rConic(e[0].h->zs, *e[0].h), 100000, &s);
}
else {
    addDisk(e[0].e->zs, 0.0, rConic(e[0].e->ze, *e[0].e)*e[0].e->zs/e[0].h->ze, &s);
    addDisk(e[3].e->zs, rConic(e[3].h->zs, *e[3].h), 100000, &s);
}
```

Analogous for CXO w. conic tracer

Scan for m=1, lambda=1-10Å scan,
standard neutron guide reflectivity function – no waviness but transmission through mirrors

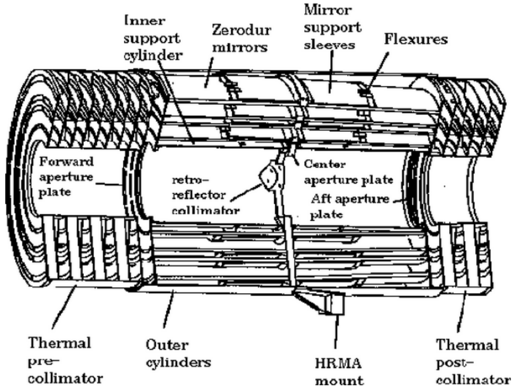
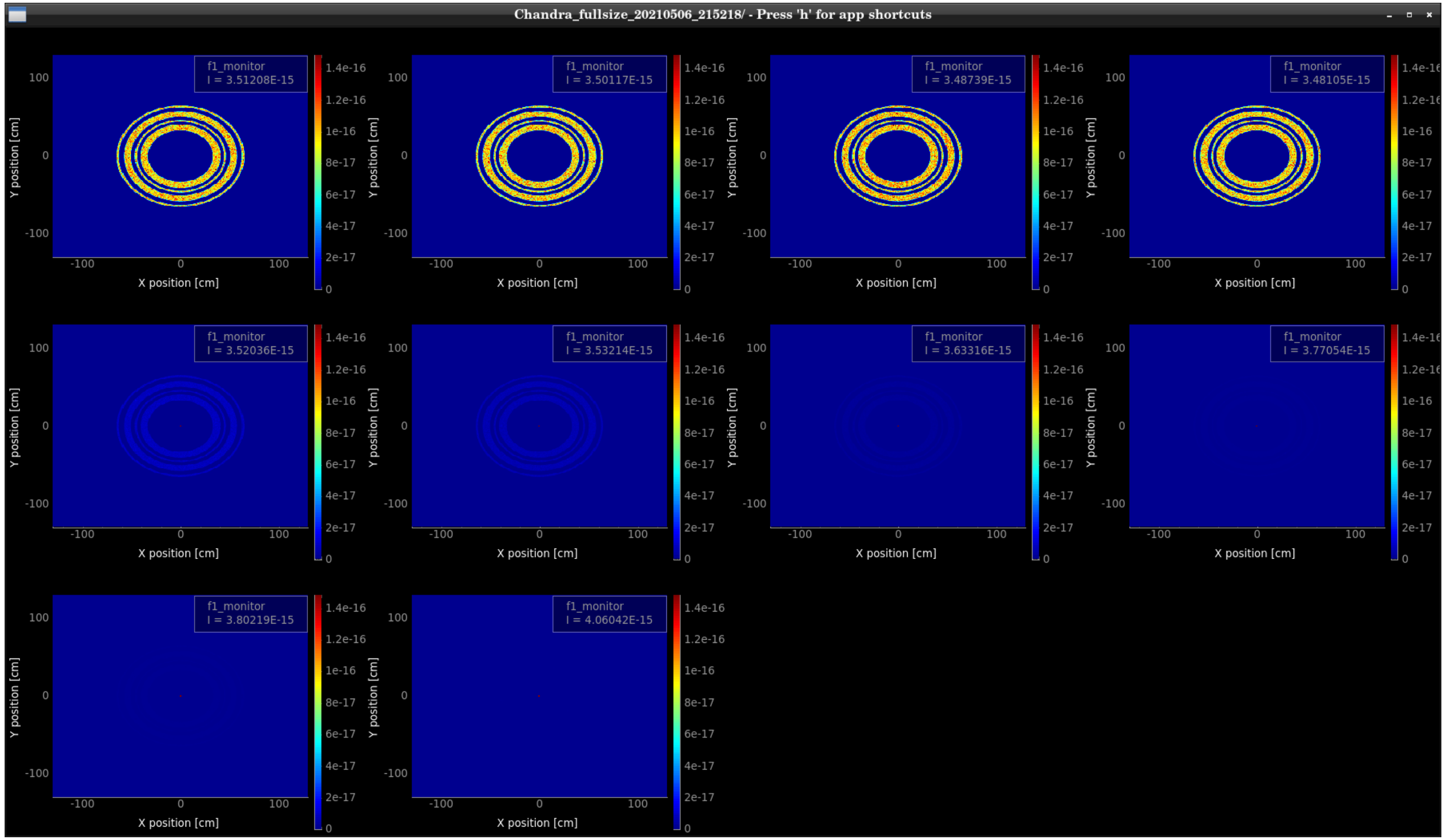


Figure 4.1: The four nested HRMA mirror pairs and associated structures.

Table 4.1: *Chandra* HRMA Characteristics

Optics	Wolter Type-I
Mirror coating	Iridium (330 Å, nominal)
Mirror outer diameters (1, 3, 4, 6)	1.23, 0.99, 0.87, 0.65 m
Mirror lengths (P_n or H_n)	84 cm
Total length (pre- to post-collimator)	276 cm
Unobscured clear aperture	1145 cm^2
Mass	1484 kg
Focal length	10.070 ±0.003 m
Plate scale	48.82 ±0.02 μm $arcsec^{-1}$
Exit cone angles from each hyperboloid:	
θ_c (1, 3, 4, 6)	3.42°, 2.75°, 2.42°, 1.80°
θ_d (1, 3, 4, 6)	3.50°, 2.82°, 2.49°, 1.90°
f-ratios (1, 3, 4, 6)	8.4, 10.4, 11.8, 15.7
PSF FWHM (with detector)	< 0.5 arcsec
Effective area:	@ 0.25 keV 800 cm^2 @ 5.0 keV 400 cm^2 @ 8.0 keV 100 cm^2
Ghost-free field of view	30 arcmin diameter



What next?

- Clean out ”dead” and duplicated code
- Try to use as much as possible from McStas 2.x runtime
  - Will serve as ”benchmark” code
- Work together on this basis with Boris and new student coming in

- Include a few versions of Conics.comp named with EH HE etc. geometry -> all using standard lib of Wolter geometries
- Do lots of comparisons with McXtrace-derived soltion

- Migrate to use of McStas 3 _particle struct -> further simplification