Athena Mirror Optimization and Calibration

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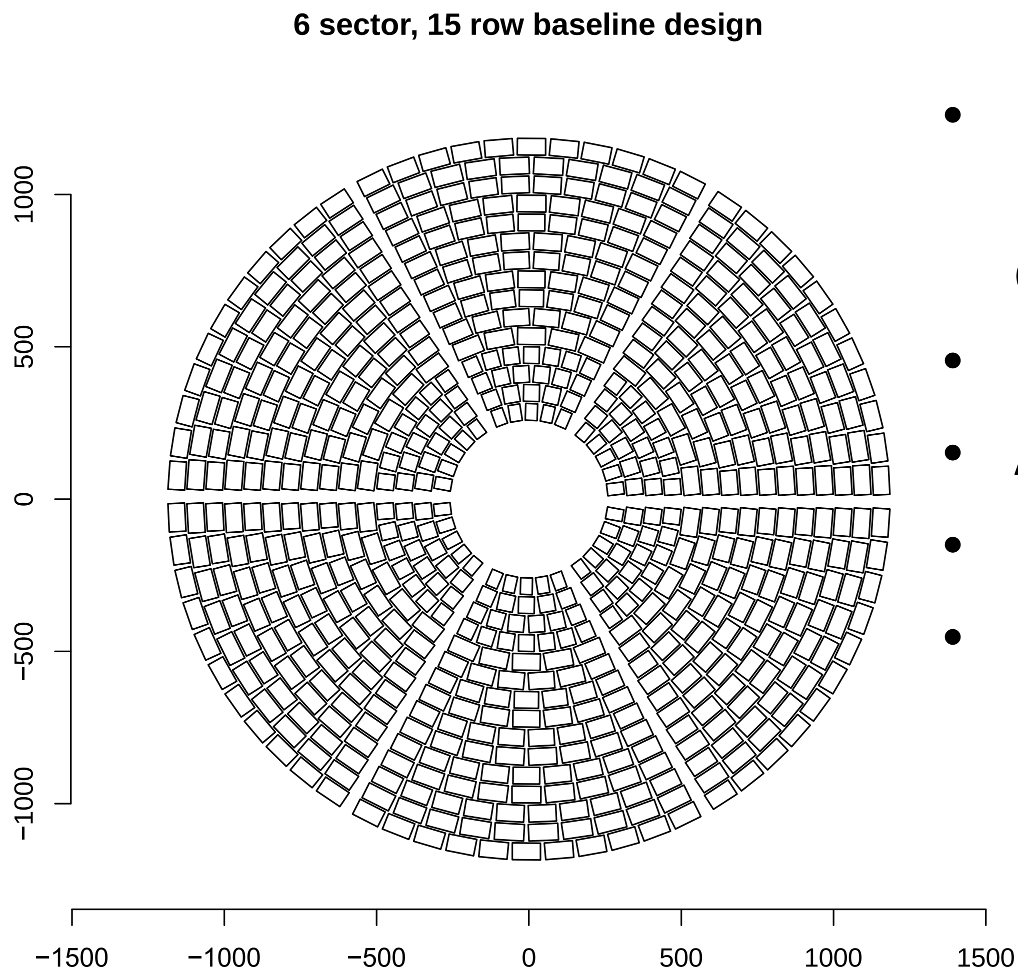


- Designed by Tim Oosterbroek ESTEC to fit in aperture diameter 2.4 m
- 15 rows, 678 SPO modules
- Active radius 259 – 1183 mm
- Rib spacing in modules 1.0 mm
- Ir coating with B_4C overcoat

Optimization

- We require:
  - Largest possible area at ~ 1 keV – ~1.4 m^2
  - Angular resolution on-axis – ~5 arcseconds
  - Flat field of view – low vignetting and little degradation of angular resolution off-axis – WFI FOV 40x40 $arcmins^2$
- Constraints:
  - Cost
  - Time (for manufacture and calibration)
  - Mass
  - Aperture – diameter < ~ 2.6 m
  - Number of SPO modules - ~700
  - Technology – SPO dimensions, rib spacing, overcoat

The SPO Module Aperture

Axial
edge

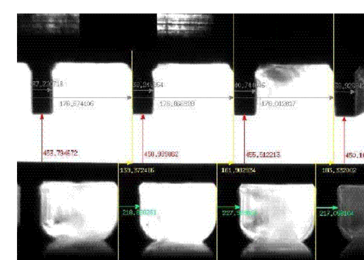
Radial height

Axial
edge

Azimuthal width

Rib
Spacing

Membrane thickness



Rib Spacing

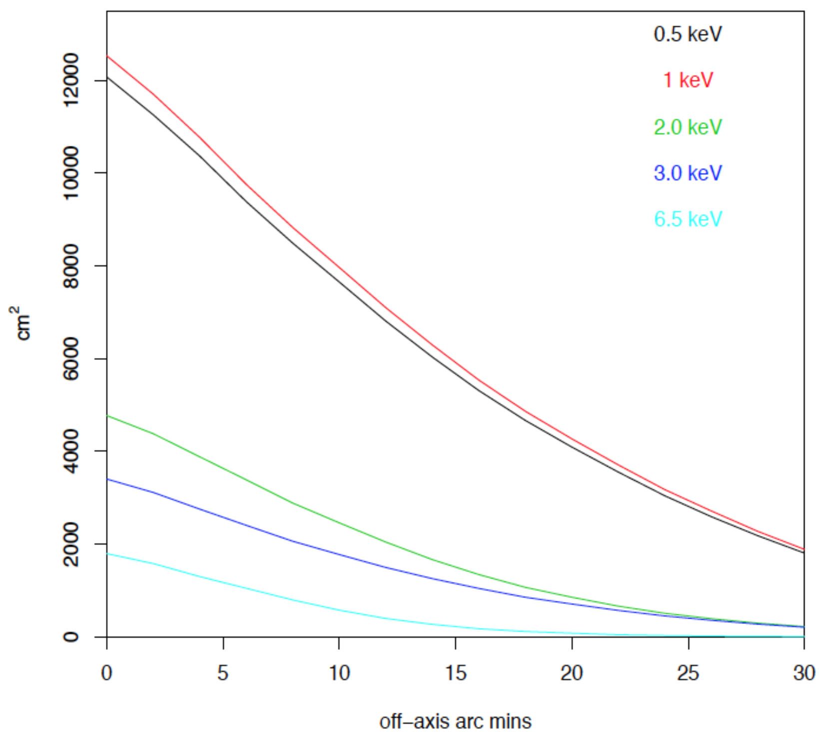
- Baseline configuration with 15 rows, 678 modules – rib spacing 1 mm
- Rib spacing of 2.3 mm used in the Athena Proposal
- The increase in area as the rib spacing is increased is independent of the coating
- Increasing the rib spacing increases the on-axis area and reduces the vignetting off-axis
- Below are the fractional changes in area from the baseline

rib spacing mm	1 keV on-axis	1 keV 20' off-axis	6.5 keV 20' off-axis
1.0	1.0	1.0	1.0
1.5	1.07	1.33	2.71
2.0	1.11	1.49	3.65
2.3	1.12	1.55	4.27

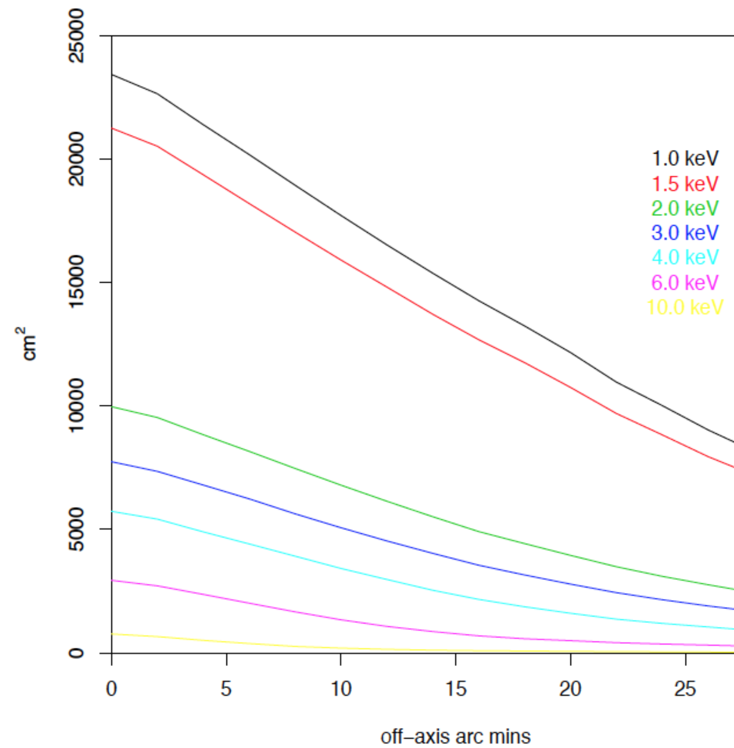
But a large rib spacing may compromise the mechanical integrity of the module!

Area + Vignetting 15 row mirror

15 row 1.0 mm rib spacing

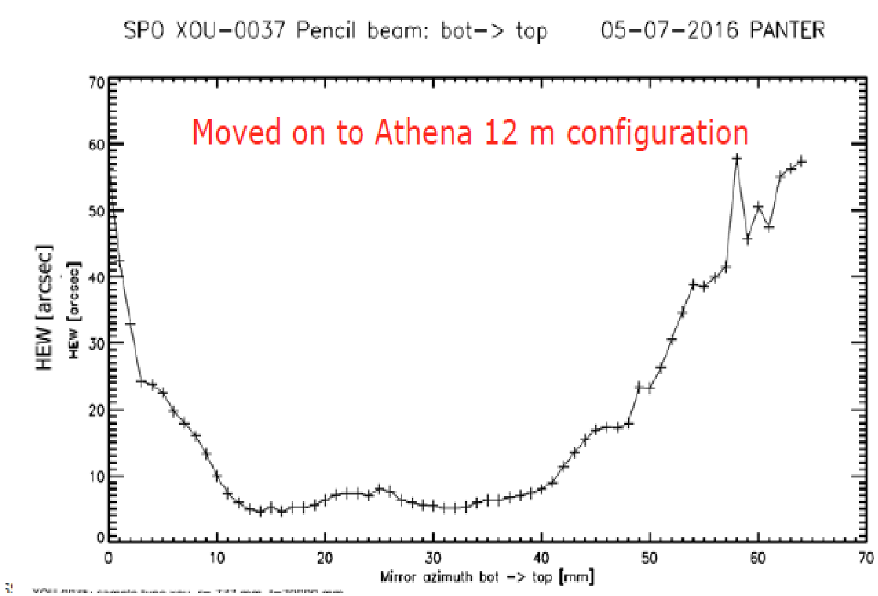


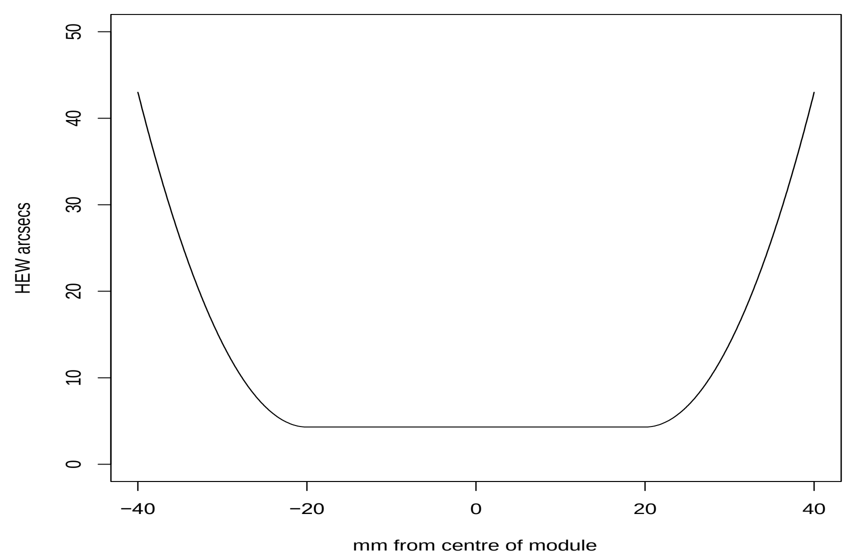
20 row 2.3 mm rib spacing



SPO Module HEW across azimuth

- The measured HEW of columns of pores varies as a function of azimuth – degrades dramatically along the axial edges of the Si plates.
- The central region is reasonably uniform, degrades ~quadratically towards edge
- Assume a simple model for every module in the aperture – 3 parameters, width of central region, HEW across central region, factor of increase at edge
- E.g. central region width module width-40 mm, central HEW 4.3 arcsecs, factor 10x increase in 20 mm towards the axial edges (see plot below)

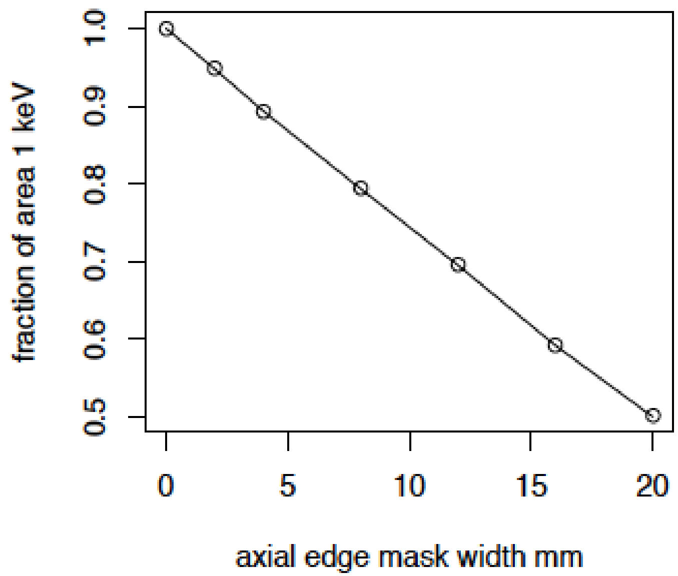


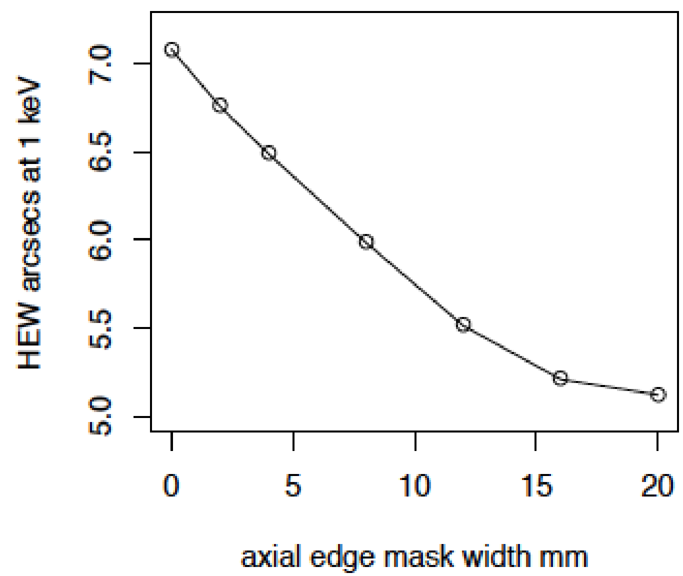


Area-HEW Tradeoff

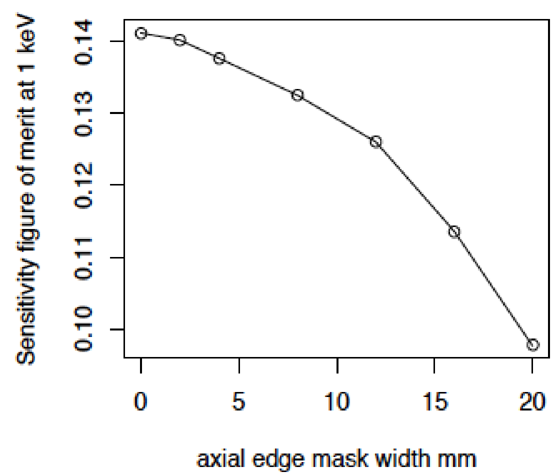
- Mask the axial edges of the modules
  - Reduction in aperture area (lower sensitivity)
  - Reduction in HEW (higher sensitivity)
- Initially number of modules per ring constant
- Increase the radii of the rings of modules to cover available aperture
  - Maximum radius 1281 mm (ring 17 in 20 row design)
- In so doing can:
  - Keep radial height of modules constant – increase the azimuthal width of modules
  - Increase both radial height of modules (more active plates) and width of modules
- If radius of a ring increases then 2 competing effects
  - Grazing angles are larger – decreases the reflection efficiency (lower sensitivity)
  - Azimuthal width of modules can be larger – increases the aperture area (higher sensitivity)
- Can also consider increasing the number of plates per stack hence increasing the radial height of each module
  - The radial gap between the modules must be kept constant so the radius of each ring must be increased
- Module layout re-packing – vary number of sectors and change criteria for defining the azimuthal width of modules

Masking 15 row baseline





- Sensitivity figure of merit ~Area/HEW
- Source confusion ~HEW^2
- Improved performance for modest mask width ~5 mm
- HEW reduced by ~0.5 arcsec using mask width ~5 mm along each axial edge



Axial Edge Mask Baseline

mask width mm	area 1 keV cm^2	HEW 1 keV arcsecs	area 6.5 keV cm^2	HEW 6.5 keV arcsecs
0.0	12532	7.08	1821	8.05
2.0	11875	6.76	1678	7.71
4.0	11196	6.49	1566	7.37
8.0	9944	5.99	1284	6.83
12.0	8712	5.52	1023	6.12
16.0	7420	5.21	777	5.59
20.0	6270	5.13	513	5.71

- Using the baseline configuration
  - 15 rings, 678 modules
  - 1 mm rib spacing
  - SiC overcoat on outer rings 9-15
- Masking axial edges reduces the HEW but also reduces the collecting area
- We would like to increase the size/efficiency of the 678 modules so we can mask axial edges without reducing the baseline area

Mirror Coating

- The Si mirror surfaces within the SPOs are coated with high-Z material to enhance the X-ray reflectivity
- Fix configuration as baseline mirror with 15 rows, 678 modules and rib spacing of 1 mm
- Compare the following coating options
  - No coating – bare Si mirror surfaces
  - Ir coating (thick ~100 nm) on all surfaces, rings 1-15
  - Ir with overcoat B_4C 10 nm rings 1-15
  - Ir coating on selected rings (remaining rings bare Si)
  - Ir with overcoat of SiC 8 nm selected rings
  - Ir with overcoat of Si 8 nm selected rings
- For each case estimate collecting area cm^2 at 0.5, 1.0, 2.0, 3.0, 6.5 keV

Coating modules in all rings – 1-15

Coating	0.5 keV	1.0 keV	2.0 keV	3.0 keV	6.5 keV
Si 1-15	12257	12523	1373	947	2.3
Ir 1-15	10841	10849	6843	4458	1827
Ir+B_4C 1-15	12636	13289	9559	5735	1828

- Bare Si no useful response > 2 keV – K absorption edge of Si 1.84 keV and density of Si is low 2.33 gm/cm^3 (hence electron density is low)
- Ir gives largest area > 6 keV – density of Ir is high 22.65 gm/cm^3 (hence electron density is high)
- Drop in area 2-4 keV is caused by M absorption edges of Iridium
- 10 nm B_4C overcoat enhances area < 6 keV - the B_4C behaves like this because the K absorption edges of both C and B are below 1 keV (C 0.282 keV , B 0.188 keV) and overcoat behaves as an interference film
- B_4C overcoat doesn't change area > 6 keV – at high energies the B_4C overcoat becomes transparent

Ir coating selected modules

Coating	0.5 keV	1.0 keV	2.0 keV	3.0 keV	6.5 keV
Ir 1-11 Si 12-15	11503	11494	5086	3633	1826
Ir 1-10 Si 11-15	11638	11660	4558	3334	1825
Ir 1-9 Si 10-15	11762	11813	4024	3003	1824
Ir 1-8 Si 9-15	11864	11953	3493	3334	1819
Ir 1-7 Si 8-15	11956	12083	2979	2285	1807
Ir 1-6 Si 7-15	12033	12198	2545	1933	1753

- Coating inner rings 1-8 with Ir gives the high response > 6 keV because grazing angles in these rings are less than the critical angle for grazing incidence reflection
- Absorption from Si reduces the area in range 2-4 keV

Ir with Si overcoat on selected rings

Coating	0.5 keV	1.0 keV	2.0 keV	3.0 keV	6.5 keV
Ir 1-10 Ir+Si 11-15	11683	11943	5142	3843	1826
Ir 1-9 Ir+Si 10-15	11810	12105	4830	3693	1825
Ir 1-8 Ir+Si 9-15	11915	12249	4546	3571	1824
Ir 1-7 Ir+Si 8-15	12008	12381	4291	3485	1823
Ir 1-6 Ir+Si 7-15	12087	12494	4078	3437	1823
Ir 1-5 Ir+Si 6-15	12153	12587	3890	3415	1799
Ir+Si all rows 1-15	12311	12808	3439	3486	1606

- Tradeoff between enhanced response at 1 keV, high area > 6 keV and suppression of area 2-4 keV caused by absorption by Si
- Overcoat of outer rings 9-15 reasonable compromise (rings 1-8 simple Ir coating)

Coating summary

- The best coating is Ir + B_4C overcoat on all rings - 13300 cm^2 at 1 keV, 1820 cm^2 at 6 keV
- If use Ir without an overcoat on all rings then significant degradation < 2 keV
- Use Ir without an overcoat on inner rings 1-8 then retain the area ~1820 cm^2 at 6.5 keV
- If use overcoat of SiC or Si on the outer rings 9-15 then get 12200-12500 cm^2 at 1 keV
- If leave the outer rings 9-15 as bare Si uncoated then get 11800 cm^2 at 1 keV compared with 10800 cm^2 using an Ir coating
- Table below summarises performance of coatings in order of preference

Coating	0.5 keV	1.0 keV	2.0 keV	3.0 keV	6.5 keV
Ir+B_4C 1-15	12636	13289	9559	5735	1828
Ir 1-8 Ir+*SiC* 9-15	12022	12535	4797	3446	1818
Ir 1-8 Ir+Si 9-15	11915	12249	4546	3571	1824
Ir 1-8 Si 9-15	11864	11953	3493	3334	1819
Ir 1-15	10841	10849	6843	4458	1827

Summary of 678 module options

- Number of rings 15, number of modules 678
- All options attempting to increase the aperture size of the modules
  - Options 1 and 2 increase azimuthal width of modules
  - Options 3 and 4 also increase the radial height of modules
- All options use the same azimuthal spacing, 16.8 mm, and 6 sectors

option	plate pairs per module	radial gap mm	comment
0	68	7	regular radial spacing
1	68	7	large gap rings 10 to 11
2	68	15.9	regular radial spacing
3	74	7	regular radial spacing
4	74	11.2	regular radial spacing

- The fractional changes in area are shown in the table to the right
- Options 2 and 4 give reduced area at 6.5 keV because the grazing angles have increased for the inner rings
- Option 3 increases the area over the full energy band

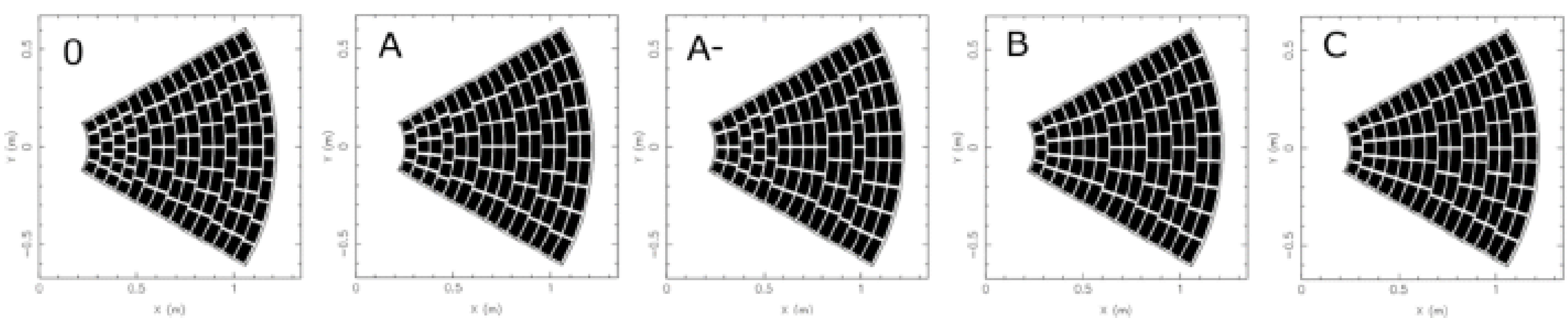
option	1 keV	3 keV	6.5 keV
1	1.04	0.88	1.00
2	1.05	0.91	0.88
3	1.11	1.05	1.05
4	1.14	1.01	0.97

Module re-packing options

Tim Oosterbroek, ESA-ATHENA-ESTEC-PL-DD-0001 16/02/2018
6 azimuthal sectors selected as optimum

	# MM	A_{eff} @ 1 keV	A_{eff} @ 6 keV
Design 0	654	1.386	0.221
Design A-	582	1.417	0.228
Design A	576	1.420	0.226
Design B	570	1.422	0.228
Design C	564	1.425	0.229

Table 6: Summary of design case #MMs, and A_{eff} at 1 and 6 keV



Conclusions

- The rib spacing has the greatest influence on both the on-axis area and vignetting – every effort should be made to increase the rib spacing to 2 mm or greater
- An overcoat can increase the area < 2 keV by factors of 10-20%
- Should avoid an overcoat configuration that reduces the area at >6 keV
- The B_4C overcoat is optimum and every effort should be made to implement this – but the signs are not good!
- If the B_4C overcoat is not possible then a SiC overcoat on rings 9-15 is the next best option
- Might achieve a modest improvement in science performance by masking 5-10 mm along the axial edges of the modules
- Increasing the radii of rings gives a ~5% increase in area below 1.5 keV but get decrease in area ~10% >2 keV – not acceptable
- Increasing the number of plates per stack so that active plate pairs per module 74 gives an increase in area of ~11% at 1 keV and ~5% at 6.5 keV
- Module re-packing – increase in area of up to ~2.8% at 1 keV ~3.6% at 6 keV