Spectrograph optical design for POLLUX.

Cross-disperser design and efficiency budget

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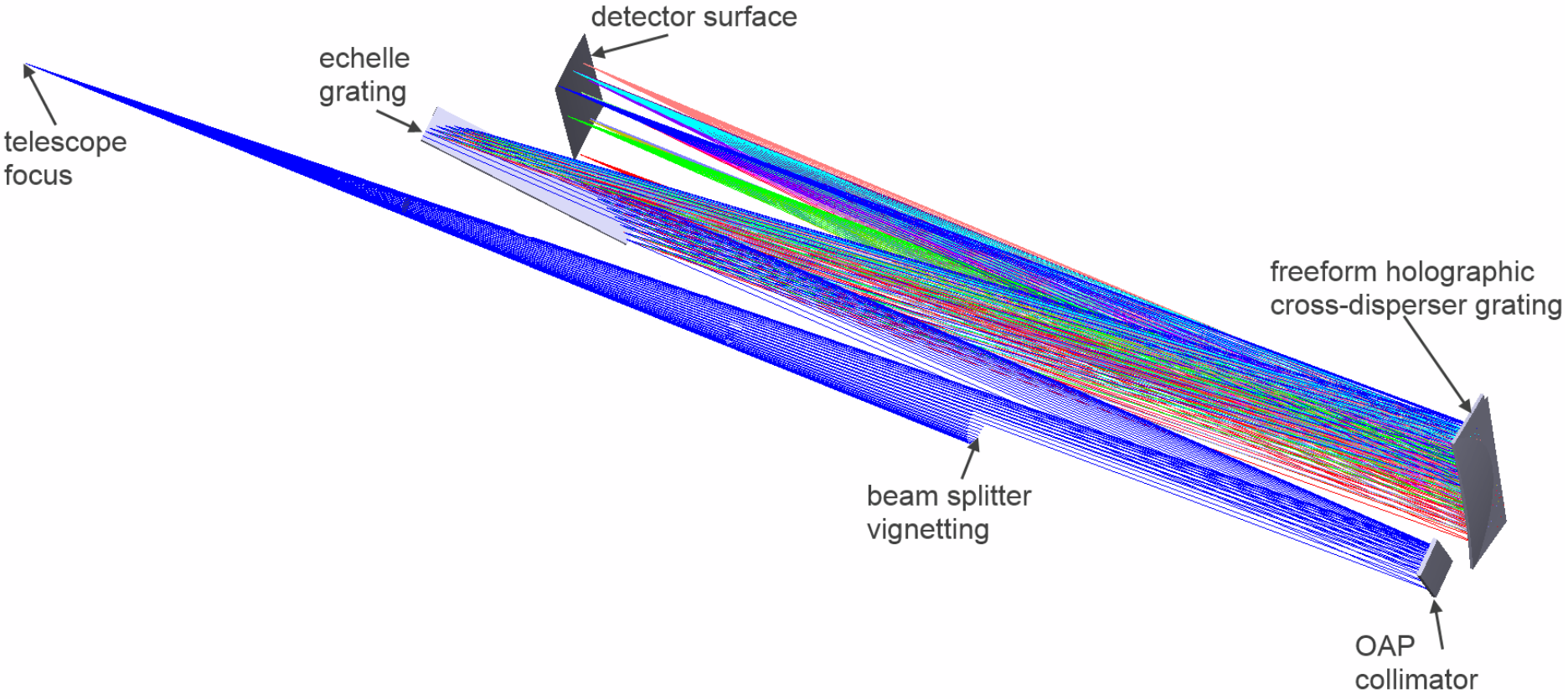
Outline

- Current optical design
- Cross-dispersers design
- Integration of 3 channels
- Diffraction efficiency estimation
- Summary
  - ✓Critical points
  - ✓Advantages and potential reserves
  - ✓Open questions

Current optical design

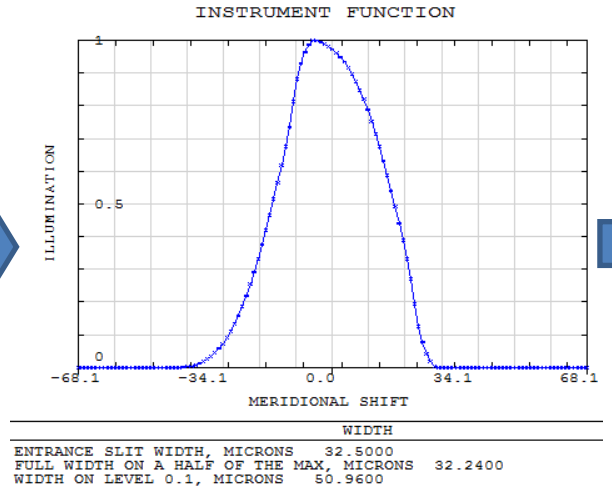


Baseline optical design concept
(on example of the MUV channel)

Optical quality & resolution

Resolution defined by the aberrations

(Line Spread Function)
⊗
(Slit rectangular function)



Instrument function

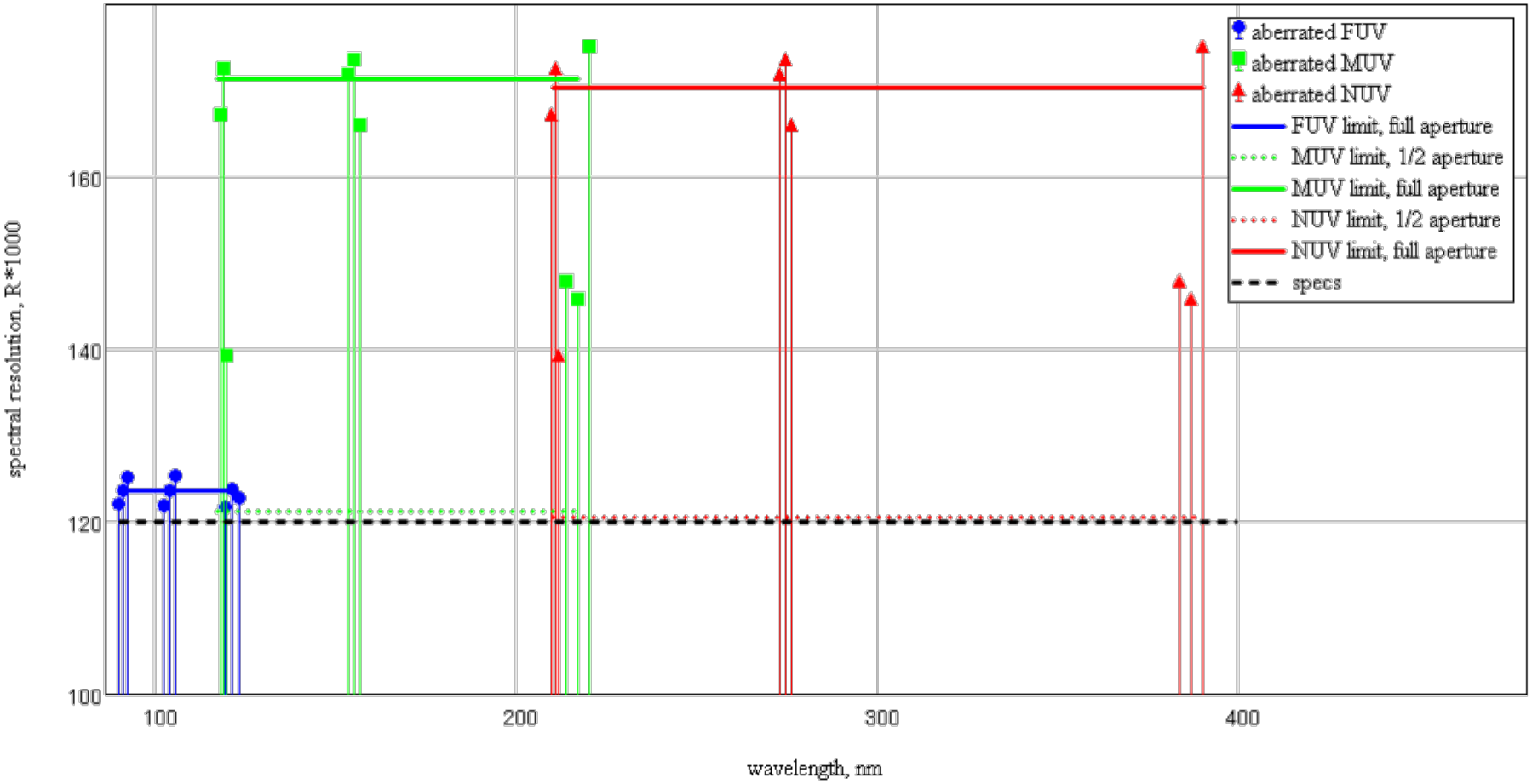
$(\mathrm{FWHM})\cdot\frac{\lambda_{order}}{L_{order}}$

$\Delta\lambda$,
$R = \lambda/\Delta\lambda$

Theoretical limit

$$R_{theor} = \frac{2 \cdot D_{collim} tg(\varphi_{blaze})}{F_{telescope} tg(\omega_{slit})} C \qquad \text{where} \quad C = \sqrt{\frac{D_{collim}}{D_{inc..beam}}} \text{ - crop-factor}$$

Image quality & resolution



Spectral resolution of the spectrographs with aberrations and aperture crop taken into account

Components summary

	FUV	MUV	NUV
Wavelengths, nm	90-123	119-220	210-390
Spectral length of orders, nm	2.3-3.9	1.86-6.1	1.9-6.3
Min theoretical spec. resolution (full/cropped aperture)	123638/n.a.	171298/121126	170377/120475
Collimator			
Focal length, mm	3898	1884,96	1812.5
Clear aperture, mm	185.0	94.6x48	91.1x47
Aperture decenter, mm (Y)	-208.5	-124	-119
Echelle			
Frequency, mm^{-1}	313.7	235	76.2
Blaze angle, deg	34.683	63.234	64.006
Orders	30-40	35-64	61-112
Clear aperture, mm (X*Y)	185.4x237.4	48x210	47x107
Ap. decenter, mm (X*Y)	0,0	-24	-23.5
Detector			
Format, mm (X*Y)	150x64.2	152x44.8	90.5x44.9
Pixel size, um	12.5	12.5	13
Sampling	3	2.5	2.5

Cross-dispersers: summary

	FUV	MUV	NUV
Type	Concave freeform surface+ 1st generation holographic grating		
Focal length, mm	3350	1350	1350
Grooves frequency , mm^{-1}	621.9	332.9	186.99
Recording wavelength, nm	532	532	532
Recording sources coordinates	(647.084, 3968.782) and (-692.588, 4016.068)	(135.299, 2347.341) and (-284.741, 2363.875)	(52.260, 1642.907) and (-111.742, 1647.737)
Clear aperture, mm (X*Y)	348x202	247x65	181x58
Aperture decenter, mm (X*Y)	2,0	2.5, -24	2, -23.5
Asphericity RMS/PTV, microns	0.8/2.4	2.5/4.0	2.1/3.2

Cross-dispersers: surface shape

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{N} A_i Z_i(\rho,\varphi)$$

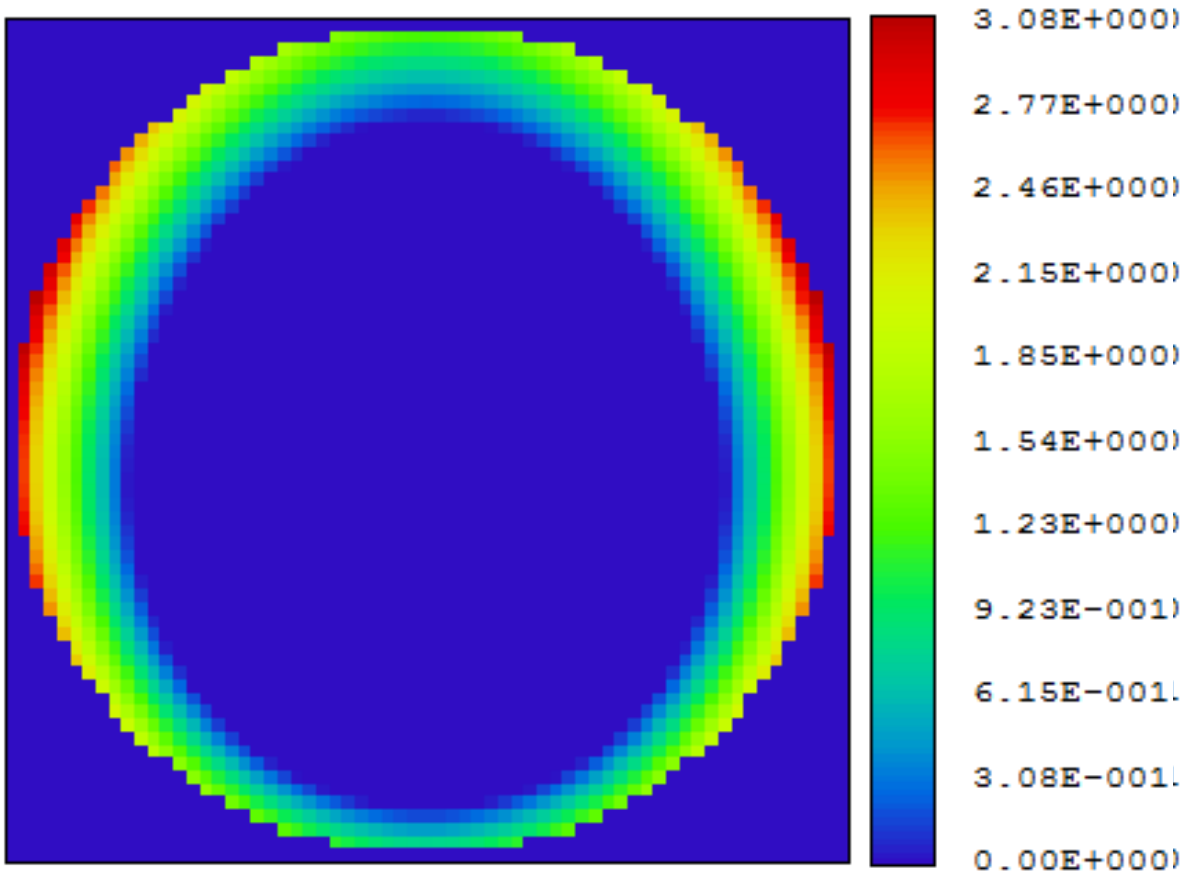
Z_5	$\sqrt{6}(\rho^2\cos 2\varphi)$	Obl. ast.
Z_6	$\sqrt{6}(\rho^2\sin 2\varphi)$	Vert. ast.
Z_7	$\sqrt{8}(3\rho^3-2\rho)\sin\varphi$	Vert. coma.
Z_9	$\sqrt{8}\rho^3\sin 3\varphi$	Vert. tref.
Z_{11}	$\sqrt{5}(6\rho^4-6\rho^2+1)$	Sph.
Z_{12}	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\varphi$	V. 2nd ast.
Z_{13}	$\sqrt{10}(4\rho^4-3\rho^2)\sin 2\varphi$	Ob. 2nd ast.
Z_{14}	$\sqrt{10}\rho^4\cos 4\varphi$	Vert. quadr.

Freeform surfaces summary

Channel	FUV	MUV	NUV
BFS radius, mm	6708.51	2711.13	2714.74
BFS center shift, µm	0.9	3.7	3.1
RMS residual, µm	0.8	2.5	2.1
PTV residual, µm	2.4	4.0	3.2
Size, mm (full surface/clear aperture)	312.07/ 348x202	184.03/ 247x65	143.84/ 181x58

Cross-dispersers: surface shape

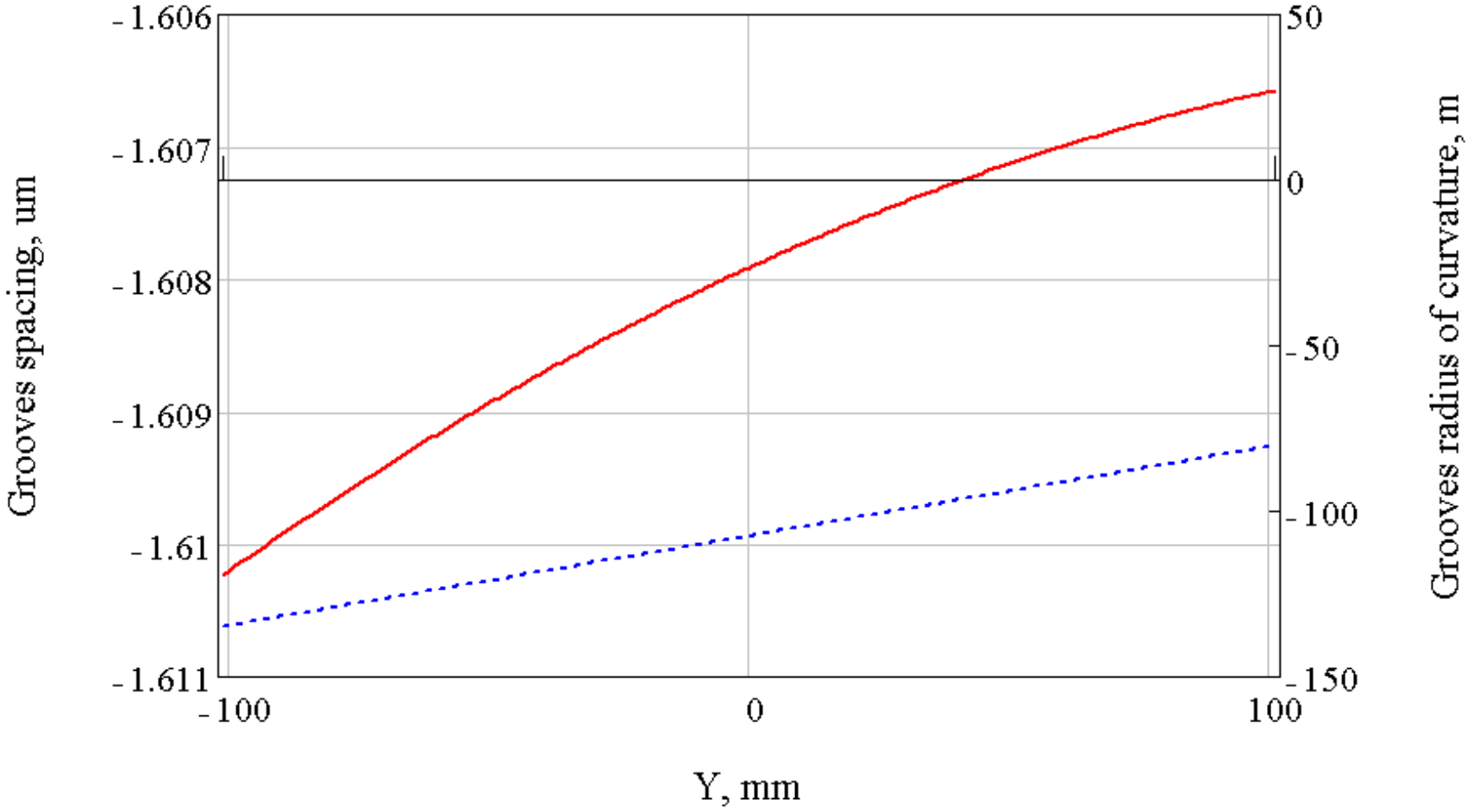
NUV



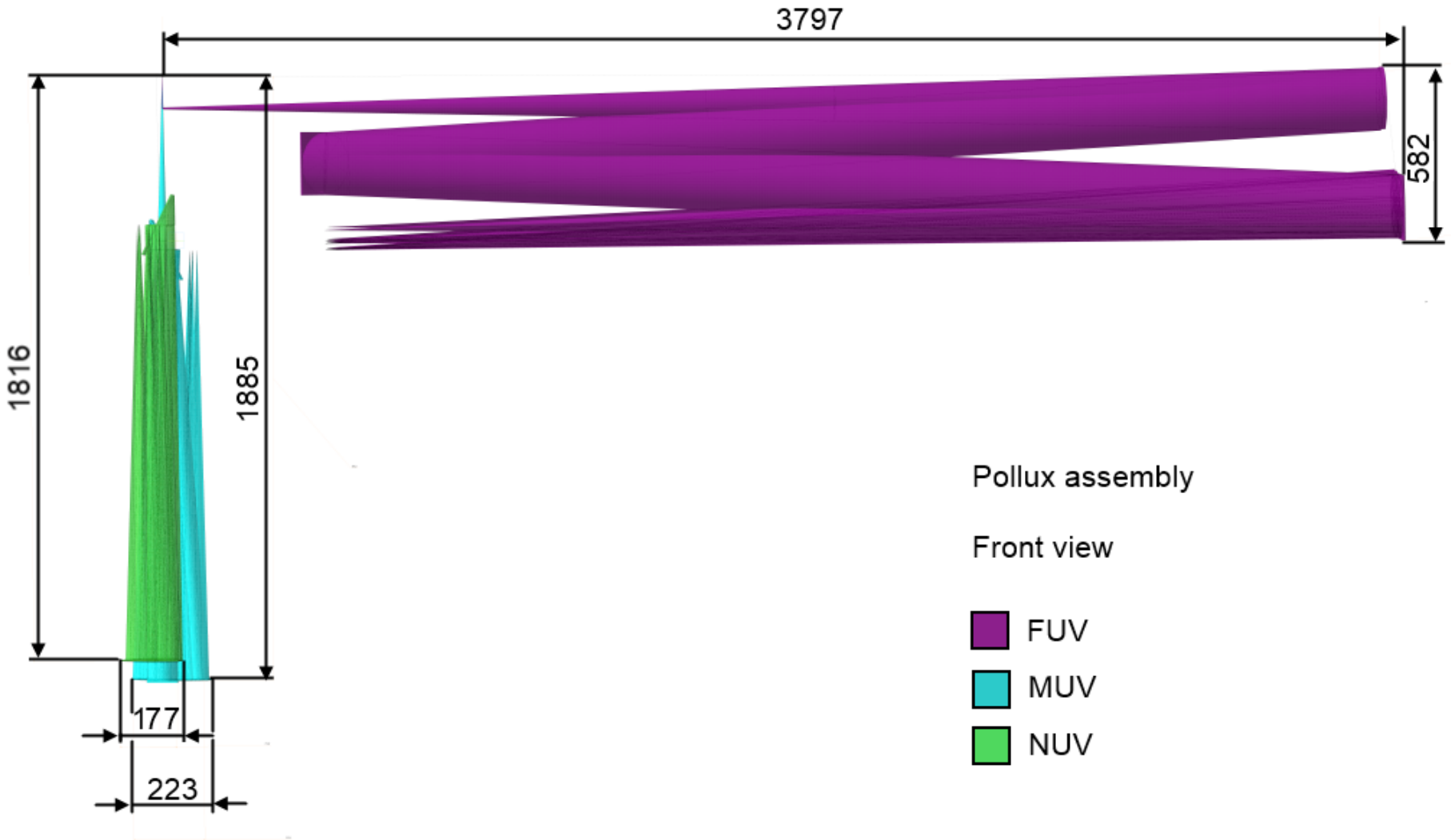
Deviation of the cross-disperser surface shape from the BFS (in microns)

Cross-dispersers: holographic gratings

FUV

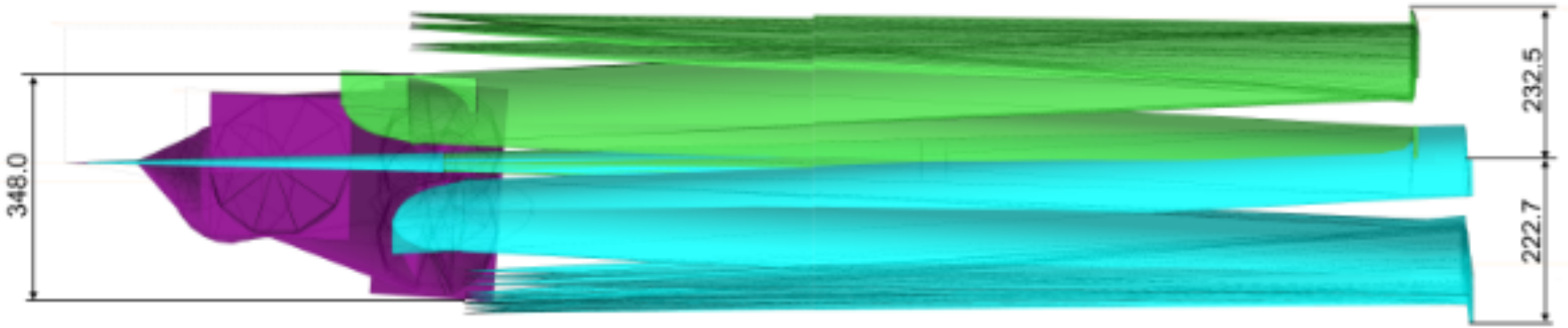


Channels integration

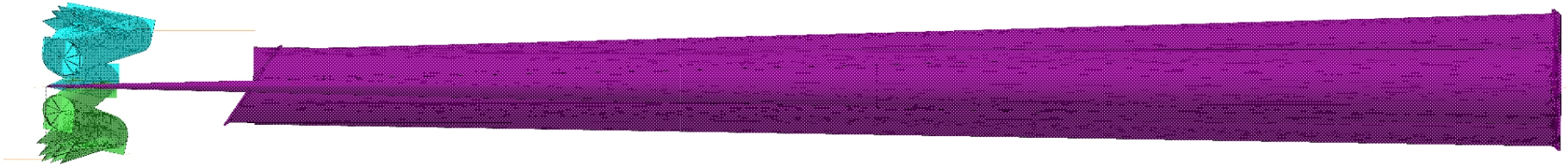


Channels integration

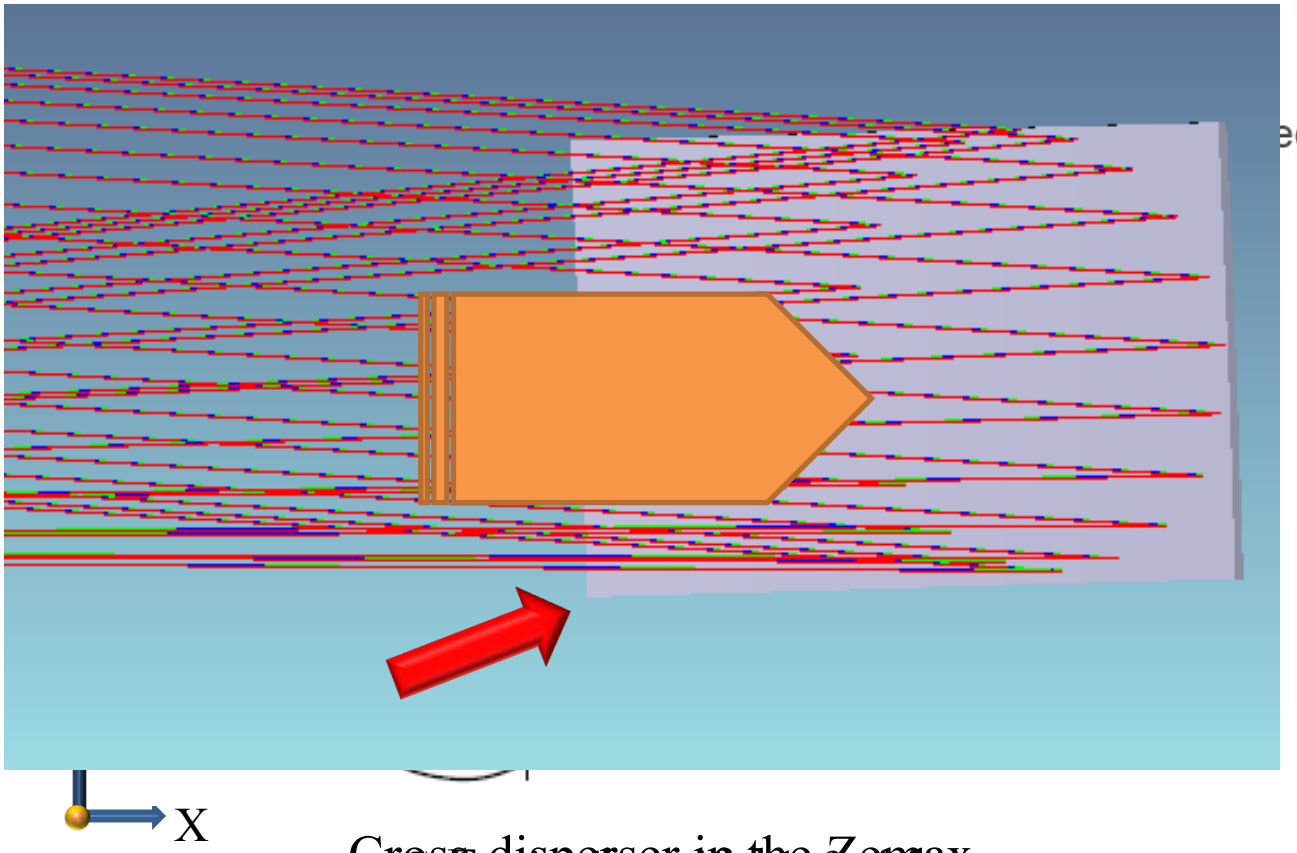
Left view
(scaled and rotated)



Top view



Data for diffraction efficiency modelling



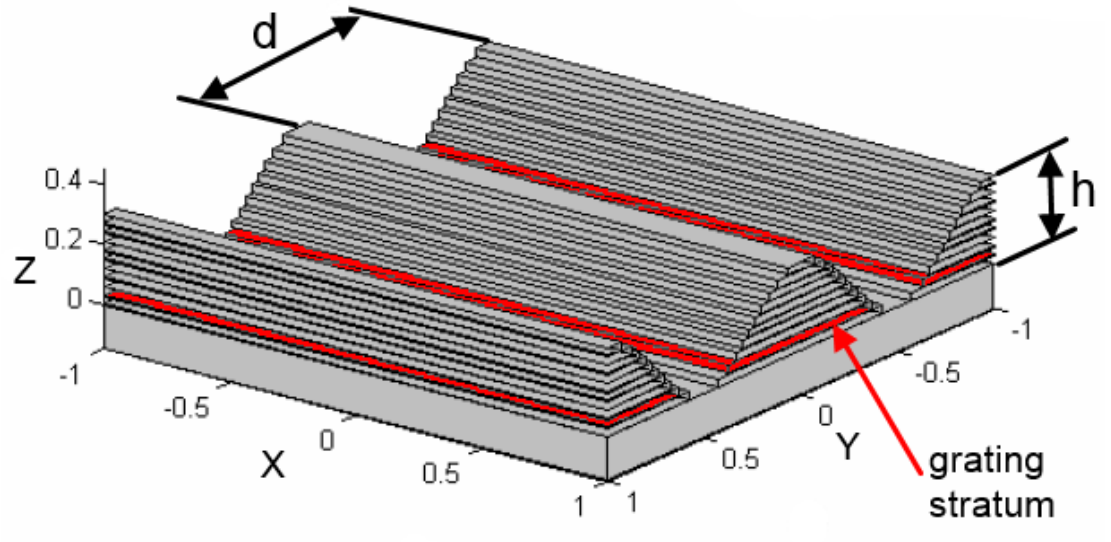
Cross-disperser in the Zemax raytracing model

Spherical angles ray data

Rigorous coupled wave analysis

RCWA simulations are implemented with GD-calc (© Kenneth C. Johnson)

Input parameters
- ✓ Layer permittivity [(1.37+7.62i)^2 for Al]
- ✓ Grating period
- ✓ Wavelength
- ✓ Grating height
- ✓ Number of grating strata (for "staircase" approximation)
- ✓ Max diffraction order index [10]
- ✓ Spherical angles (θ,φ)

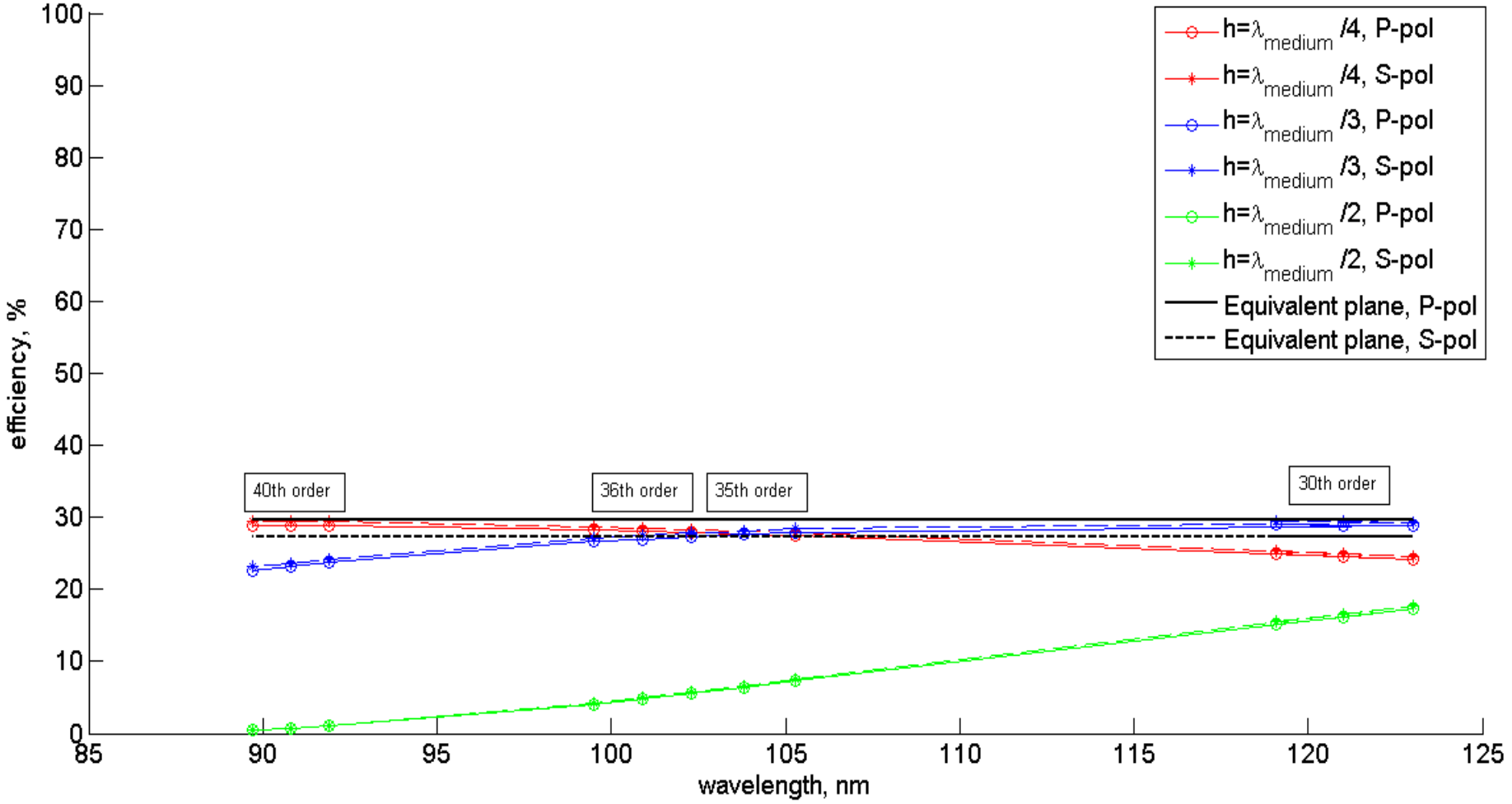


Definition of the grating profile

Assumpltions:
- \+ Sinusoidal profile
- \+ Exact shape of the surface is used
- \+ Dispersion on the echelle is accounted for
- \- Grooves spacing change neglected
- \- Grooves curvature neglected

Computation results

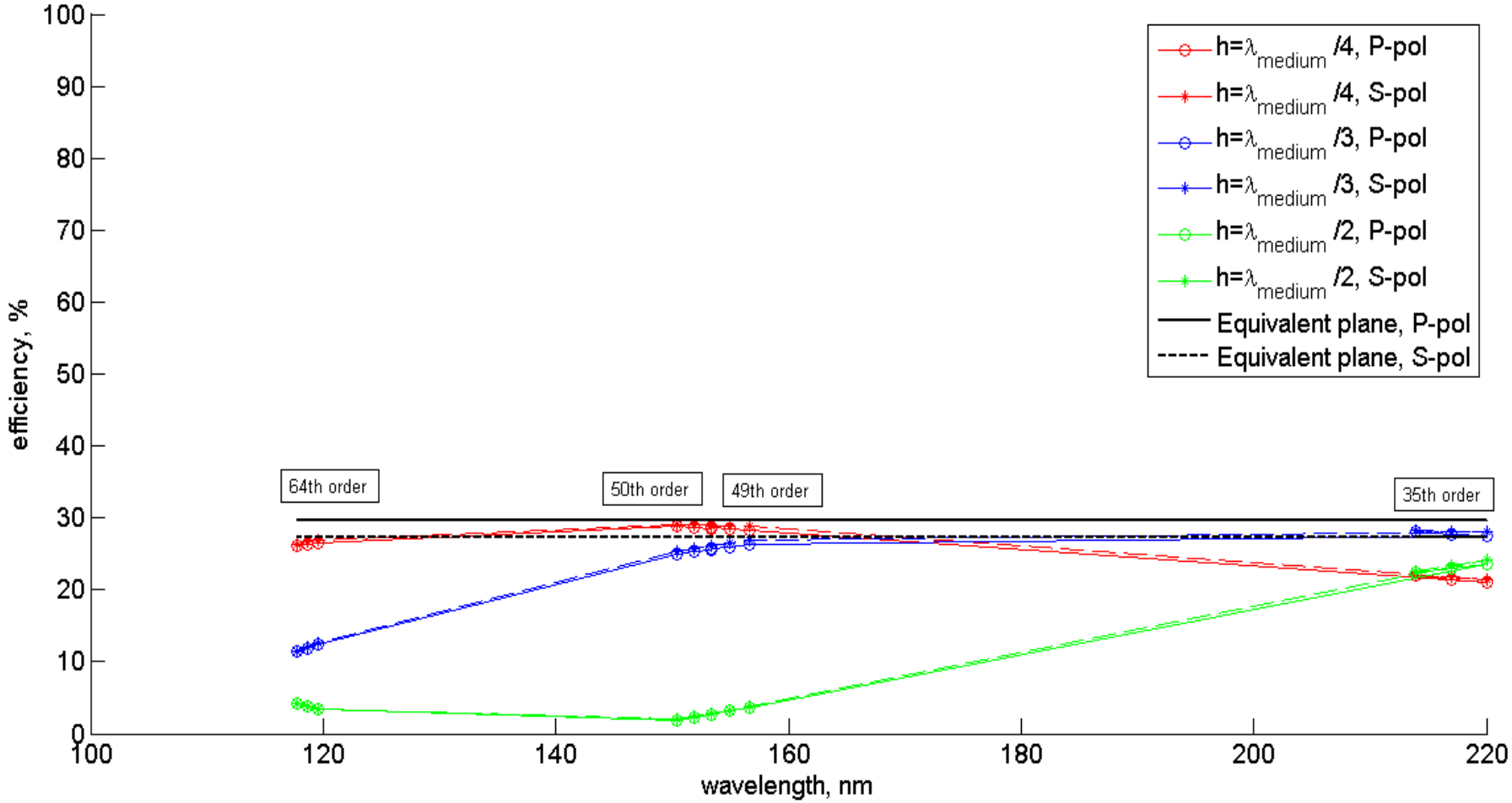
FUV



*λ_{medium}=104.4 nm

Computation results

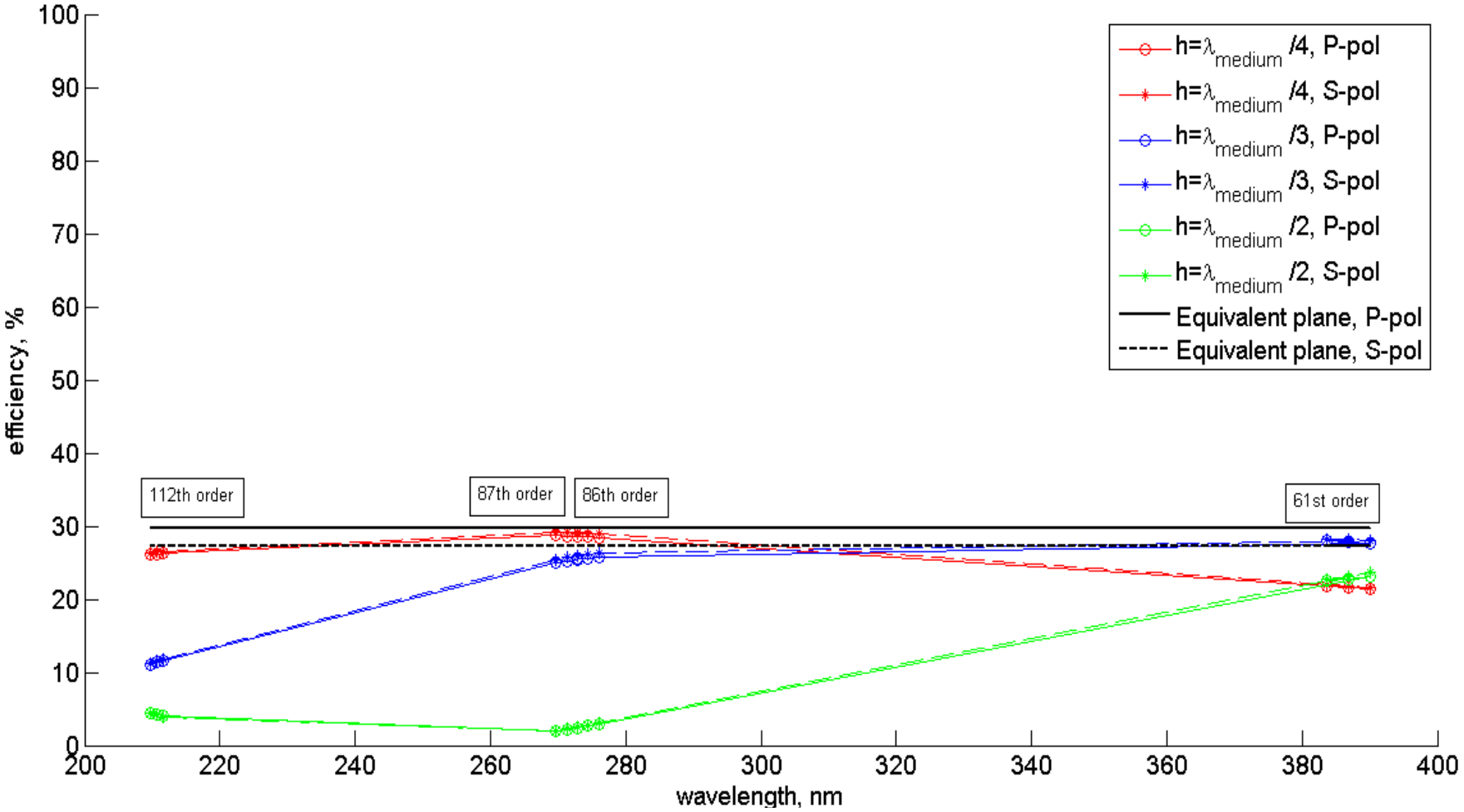
MU V



*λ_{medium}=165.8 nm

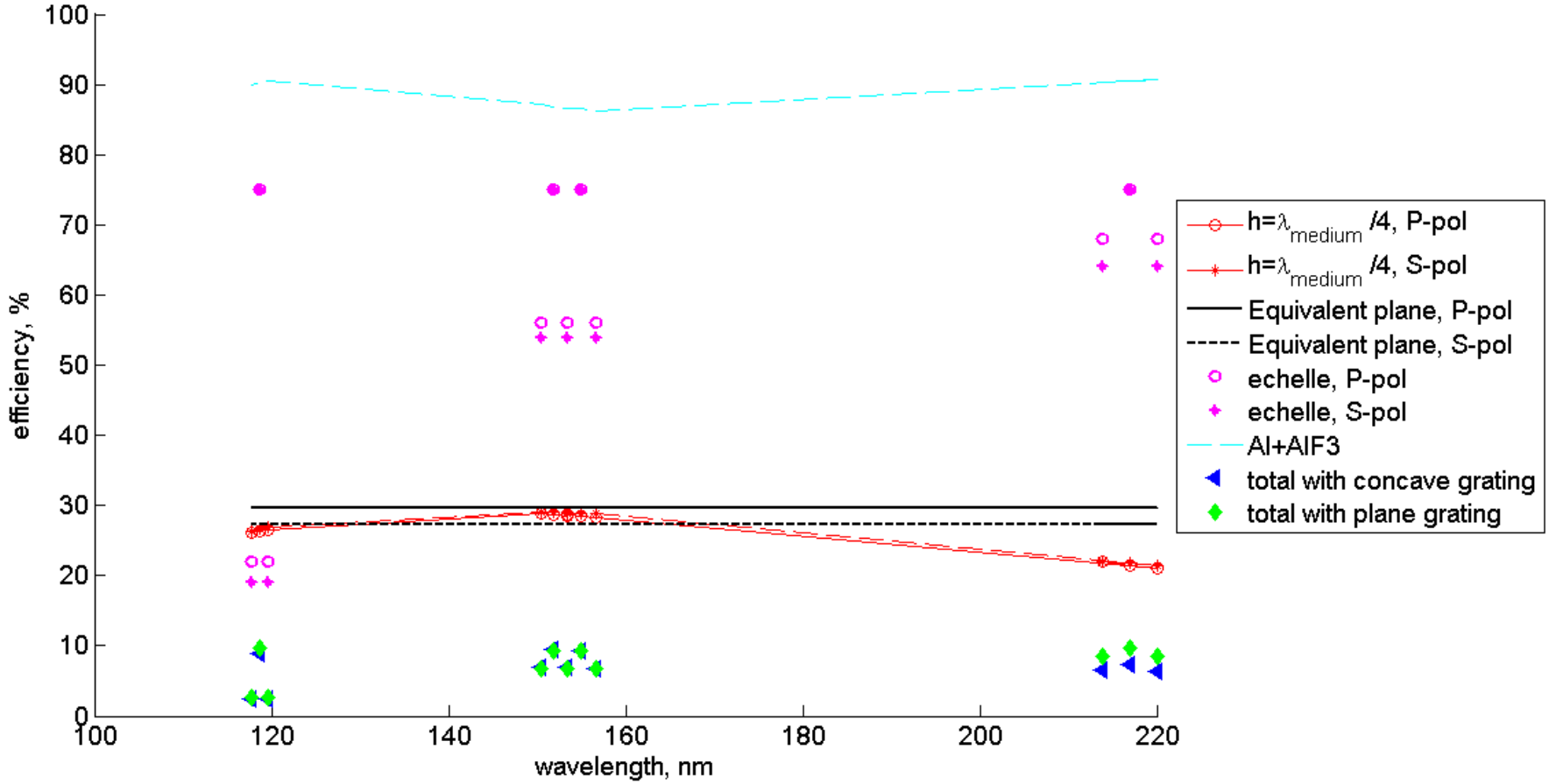
Computation results

NUV



*λ_{medium}=296.75 nm

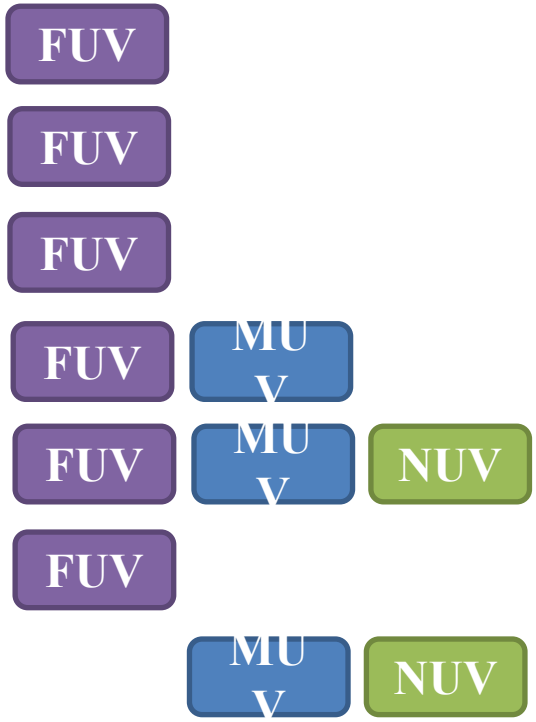
Estimation of overall efficiency



Example of overall efficiency estimation for MUV channel

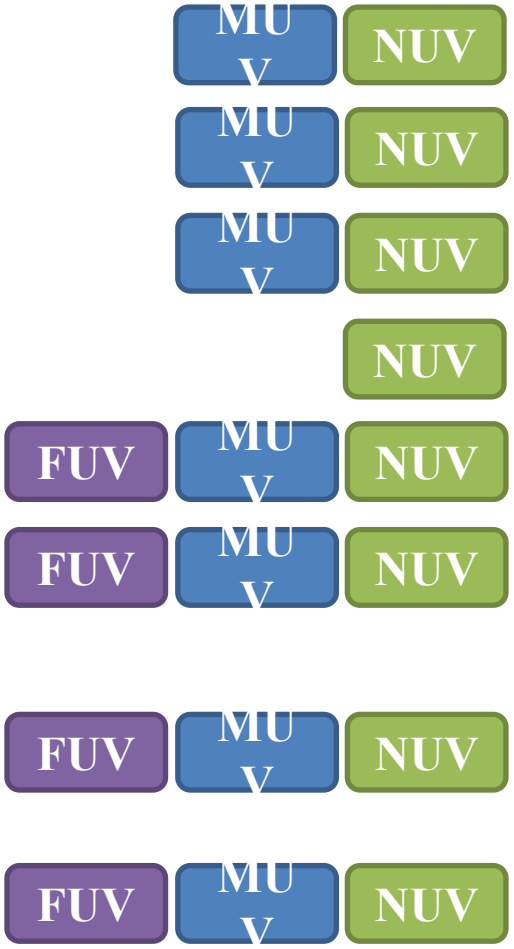
Critical points

- Order spectral length
- Dimensions
- Echelle frequency
- Echelle ruled area
- Efficiency (all the components)
- Number of components
- Cross-disperser DE uniformity



Potential reserves

- ✓Dimensions
- ✓Collimator focus and clear aperture
- ✓Resolution
- ✓Echelle parameters
- ✓Camera aberrations correction
- ✓Cross-dispersers grooves profile
- ✓Hologram recording layout and grooves pattern
- ✓Cross-disperser mosaic design



Open questions

- Currently achievable/prospective echelle parameters?
- Manufacturability of the holographic grating on freeform surface?
- Cross-disperser groove profile?
- Detector tiling?
- Unify some parameters? (e.g. MUV and NUV collimators)
- Design sensitivity?
- Simulated image and orders stitching?
- Advanced end-to-end simulations? (gratings + polarimeters + coatings etc.)

Thank you
for your attention!

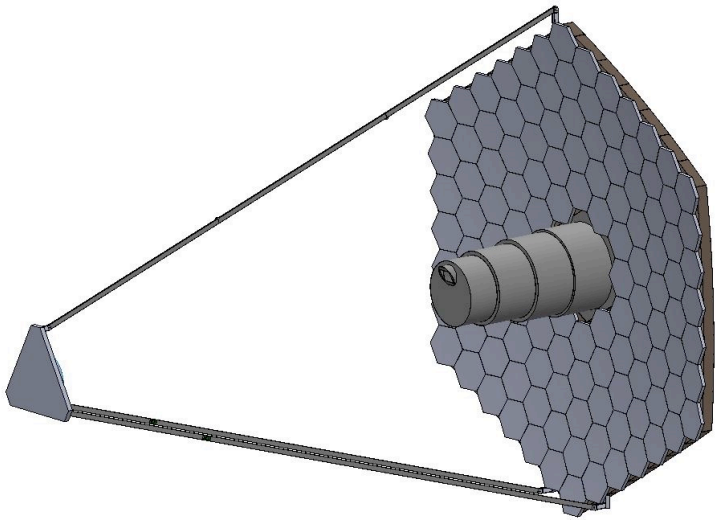
LUVOIR telescope

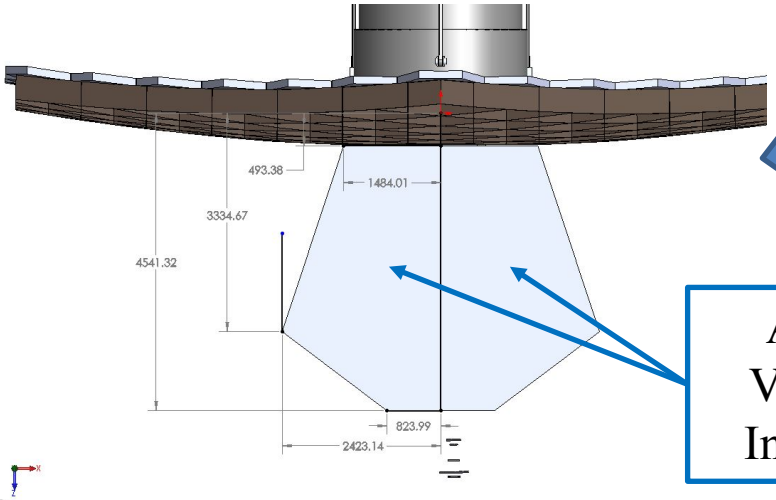
- LUVOIR (Large UV/Optical/Infrared) is one of four Decadal Survey Mission Concept Studies initiated by NASA in Jan 2016.
- The current baseline telescope design is a 15-m deployable TMA
- It will accommodate four instrument bays:
  - ✓ High Definition Imager – HDI (STScI+)
  - ✓ UV/O/IR Coronagraph (STScI+)
  - ✓ UV Multi-object Spectrograph – LUMOS (Univ. of Colorado +)
  - ✓ UV Spectropolarimeter – Pollux (CNES+)

Telescope parameters

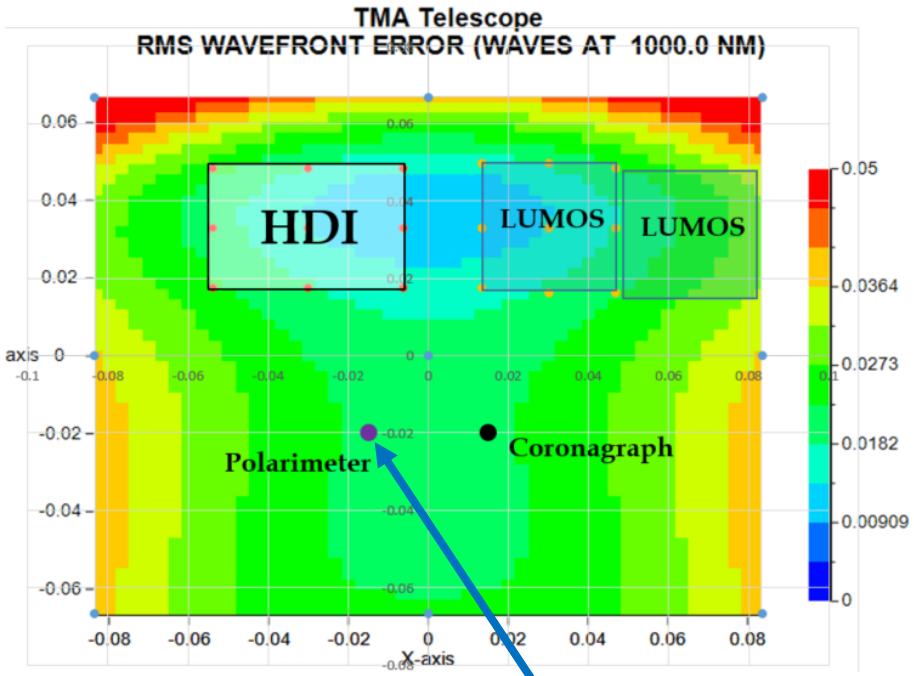
FoV	10'x8'
Eff. Focal length	~300 m
F/#	20
Primary mirror F/#	1.45
Primary diameter	15 m
Obscuration	~3m

LUVOIR payload





Telescope FoV (Coordinates in deg)

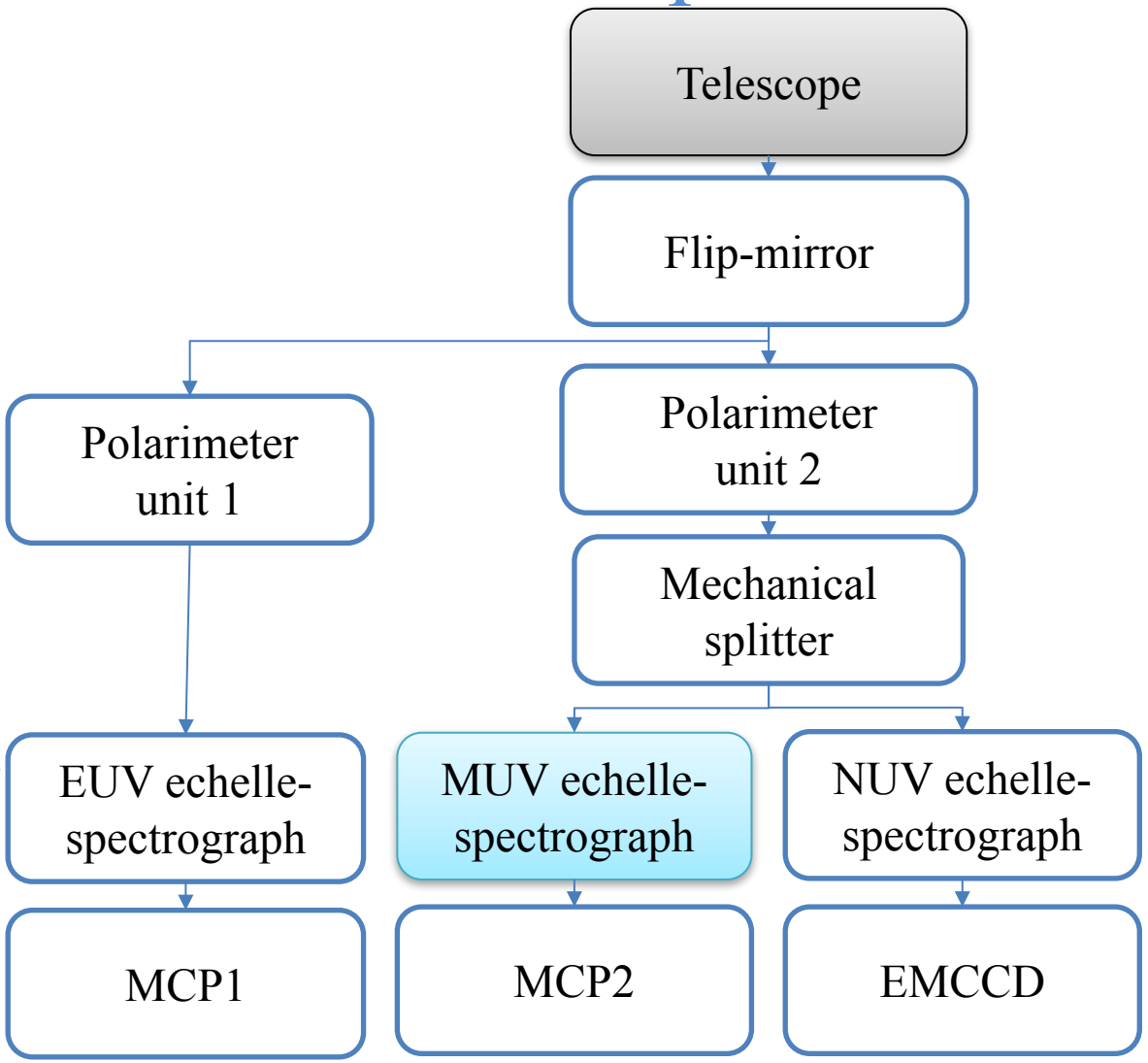


Available Volume for Instruments

Spectropolarimeter Field Bias
-0.015° X
-0.02° Y

Problem statement and assumptions

- Echelle-spectrograph
- 3 channels coupled according to the given architecture
- Polarimetric units are not considered
- As few elements as possible
- The components technological feasibility
- **Hereafter the MUV channel is considered**



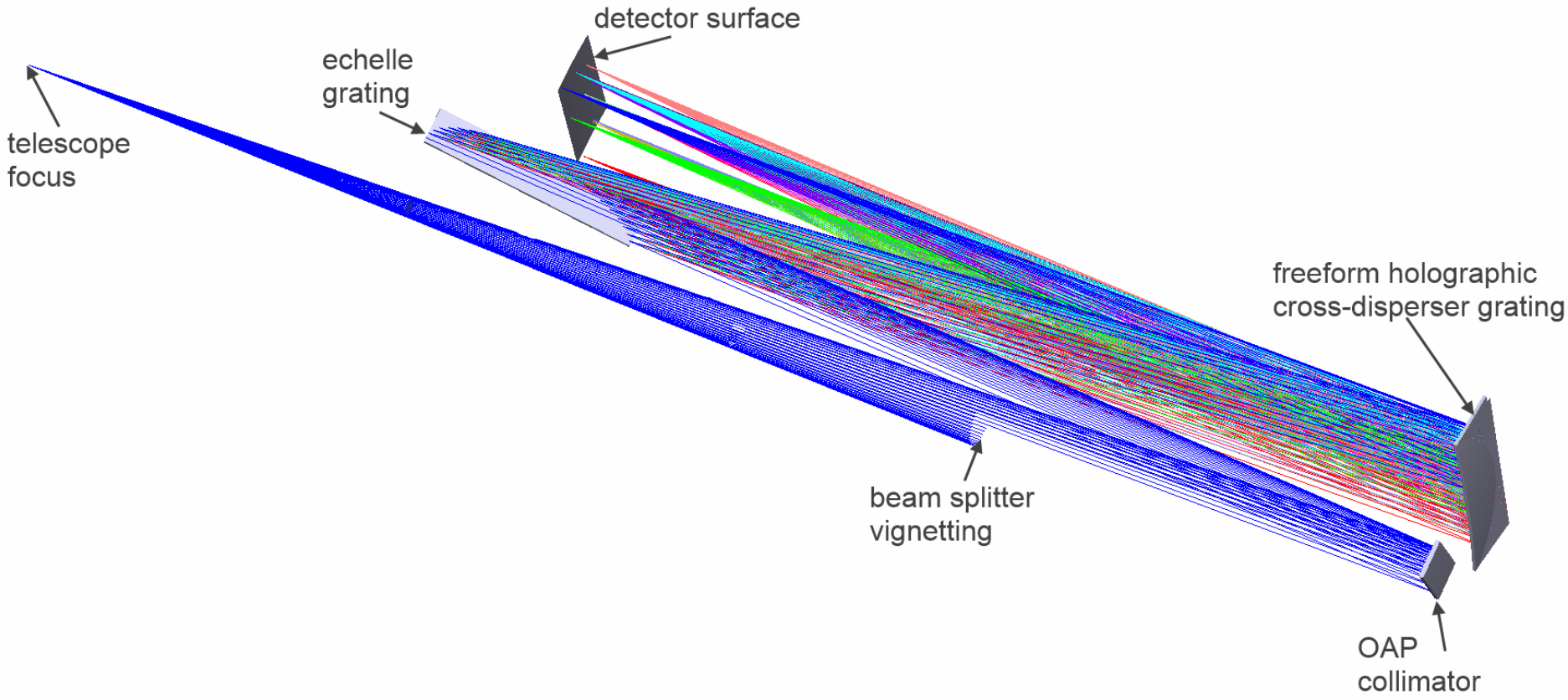
Specifications

Technical specifications of the medium UV-spectrograph*

Parameter	Target value
Spectral range	119-220 nm
Spectral resolution	>120 000 (up to 200 000)
Entrance slit angular width	0.03”
Sampling	2.5-3 pix/resolution element
Spectral length in the image line	6 nm
Total volume (for the entire instrument)	~4800x4000x2382 mm

*- the actual values can be changed

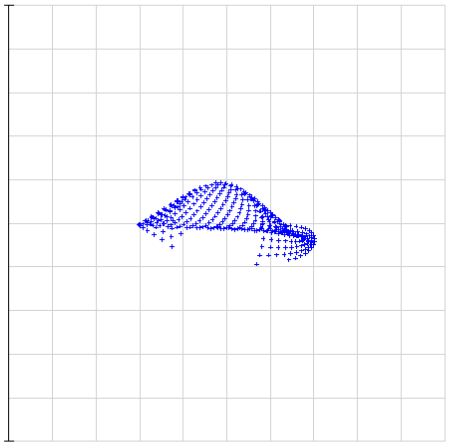
Spectrograph optical design



General view of the spectrograph optical scheme
F_{col}=1365.8 mm, F_{cam}= 900 mm

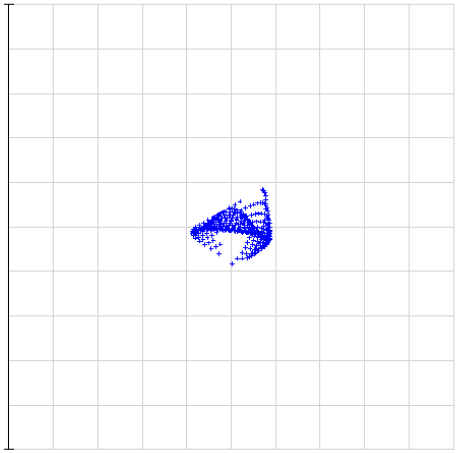
Image quality and spectral resolution

118.7 nm



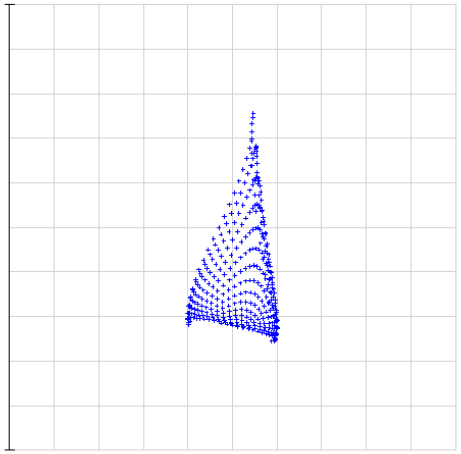
RMS radius 12.3 µm

155.0 nm



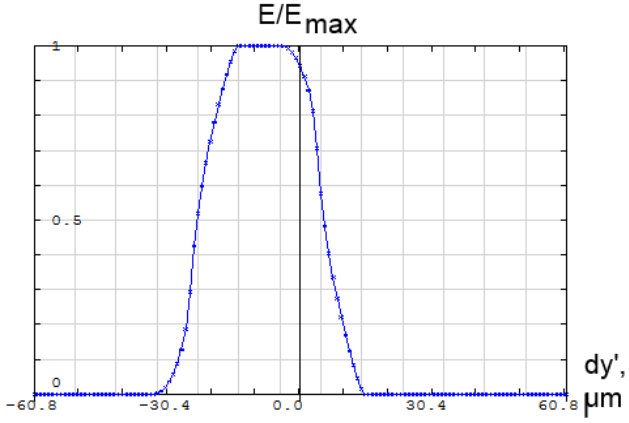
RMS radius 6.1 µm

217.0 nm

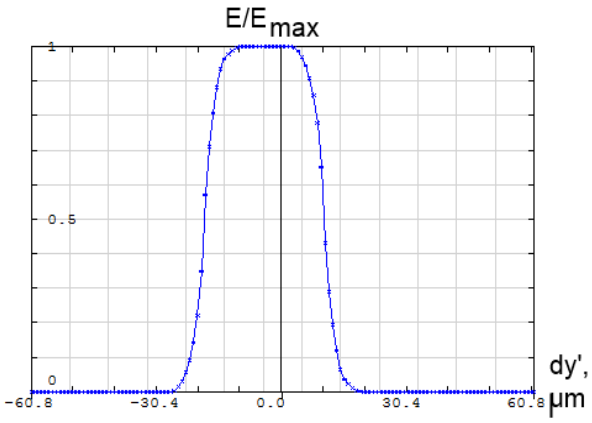


RMS radius 17.1 µm

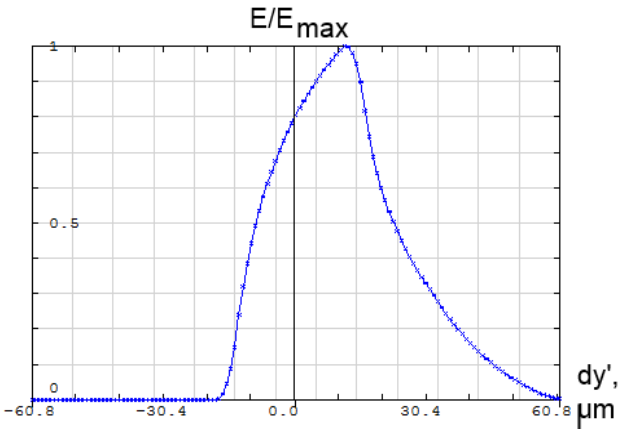
Spot diagrams



FWHM 29 µm



FWHM 29 µm

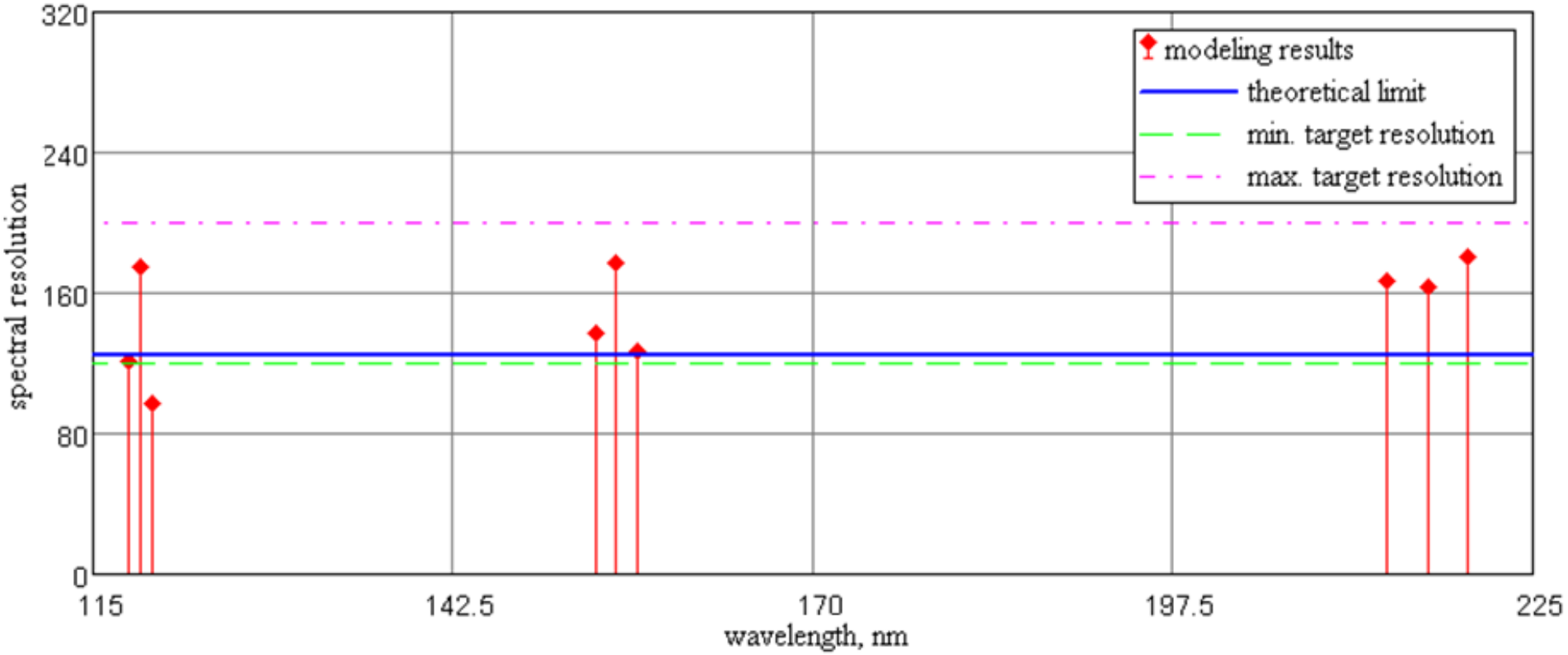


FWHM 31.6 µm

Instrument functions

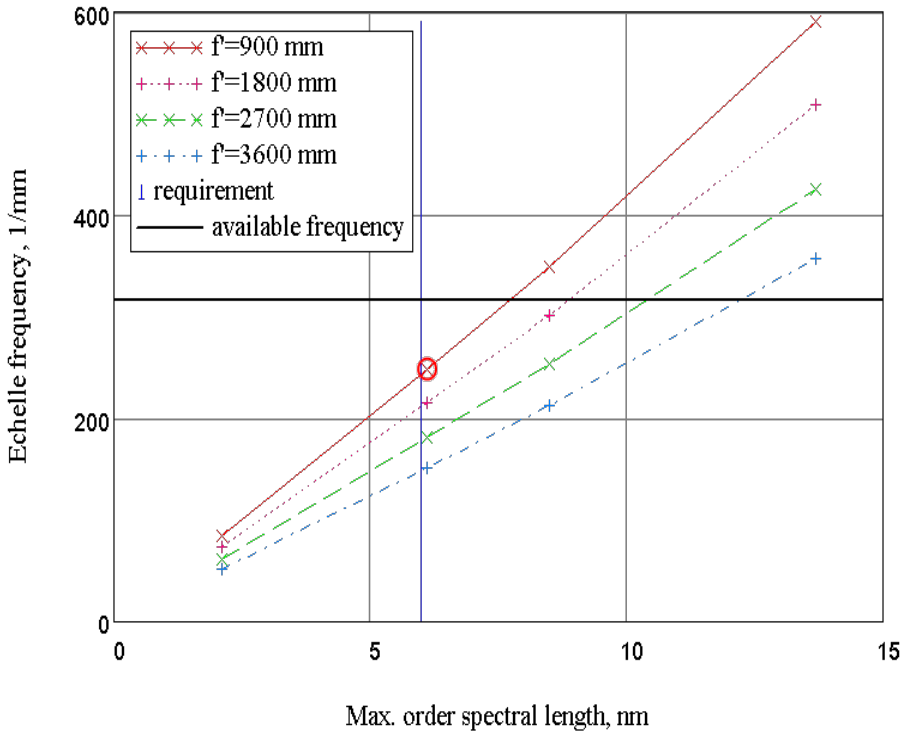
(entrance slit projection with is 29 µm)

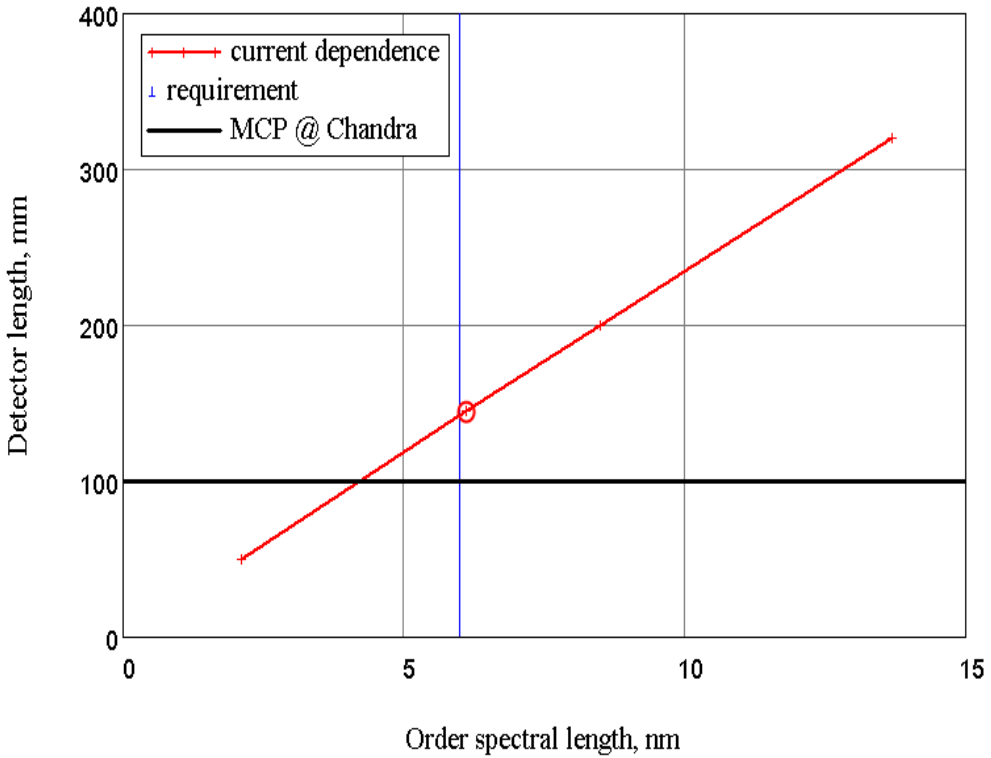
Image quality and spectral resolution



Spectral resolution defined by the aberrations
compared to the target values and theoretical limit for ½ aperture

Echelle design and challenges





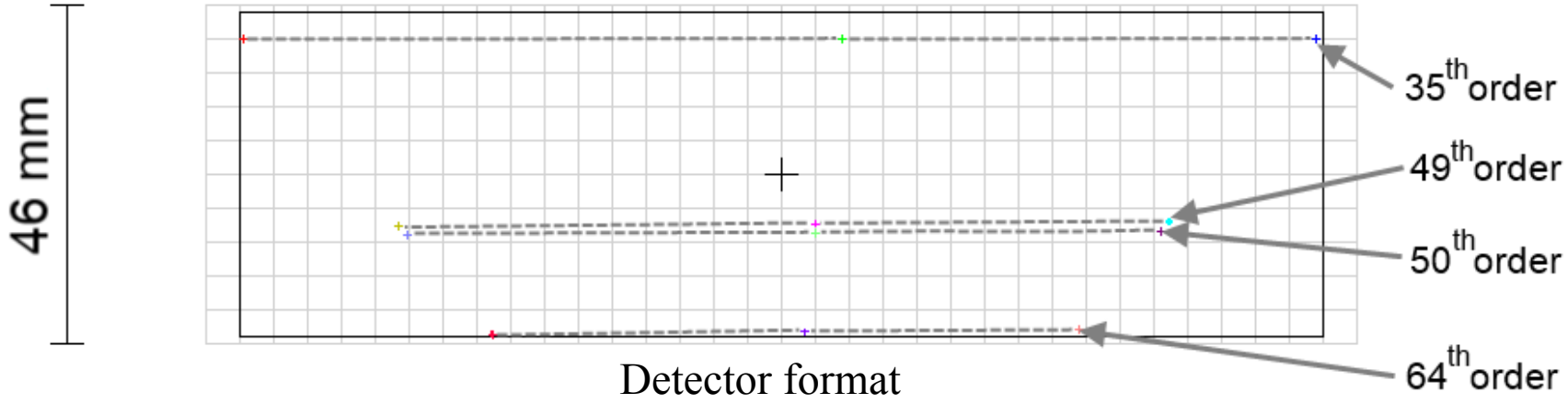
Demonstration of the key parameters trade-off:
Left – Echelle frequency vs. the order length;
Right – Detector length vs. the order length.

Current echelle parameters

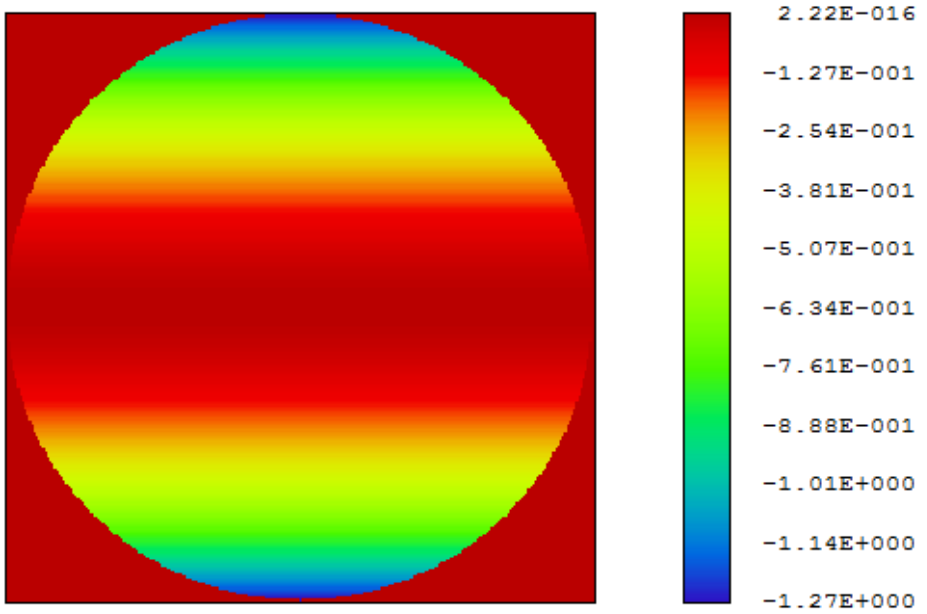
Ruled area	31.1x201.0 mm
Grooves frequency	248 mm^{-1}
Blaze angle	70.12°

*Newport's Richardson Gratings

Detector format



Detector format

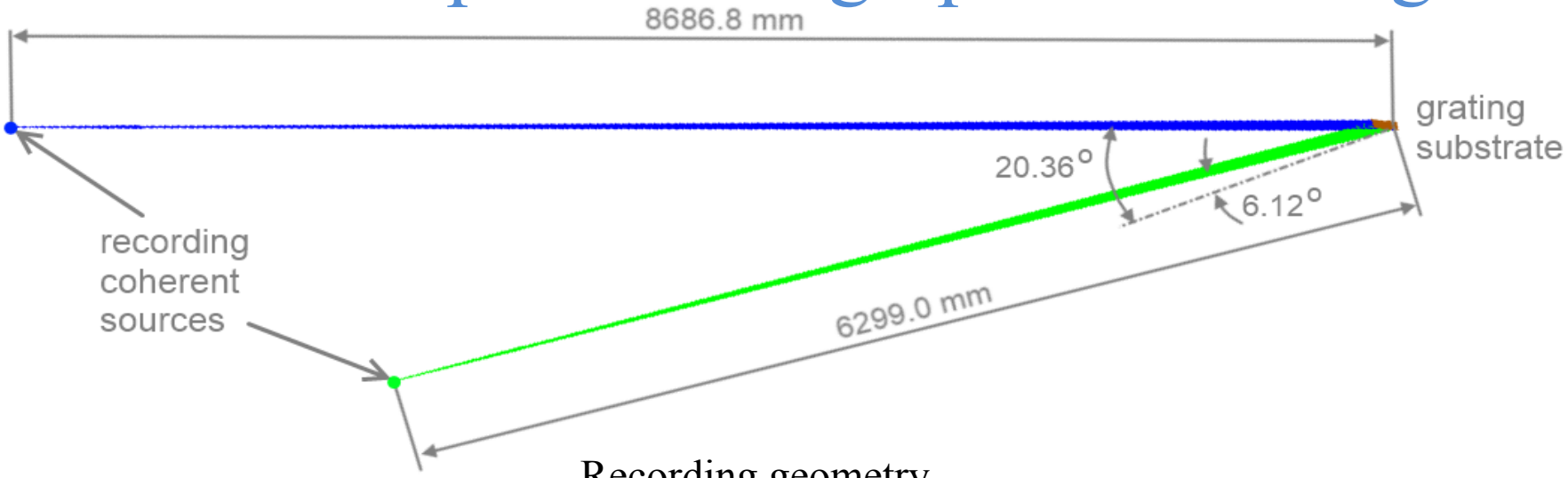


Detector sag (mm)

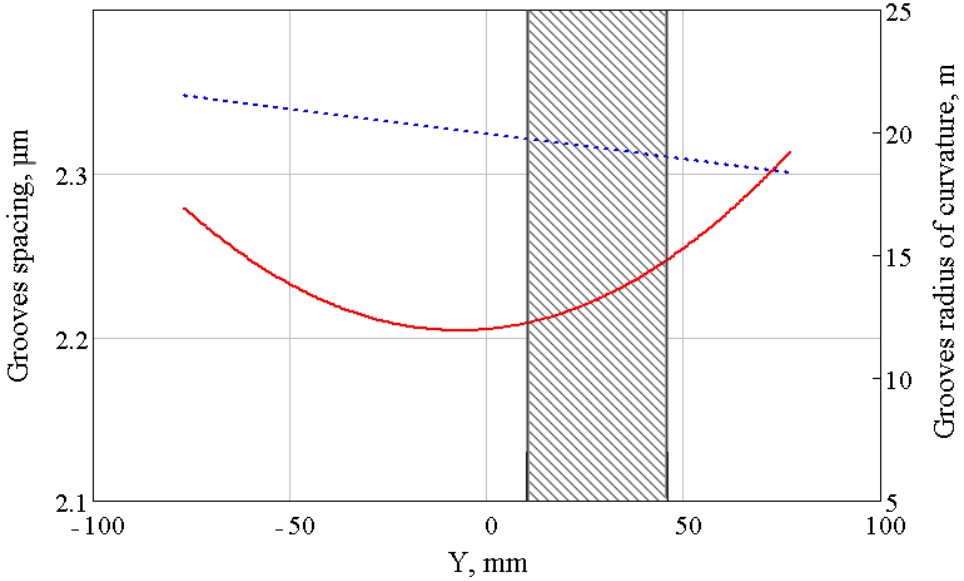
Detector parameters

Active area	145.7x40.2mm
Radius of curvature (Y)	579.54 mm
Resolution element	12.5 µm

Cross-disperser holographic recording



Recording geometry



Change of the grooves spacing and curvature

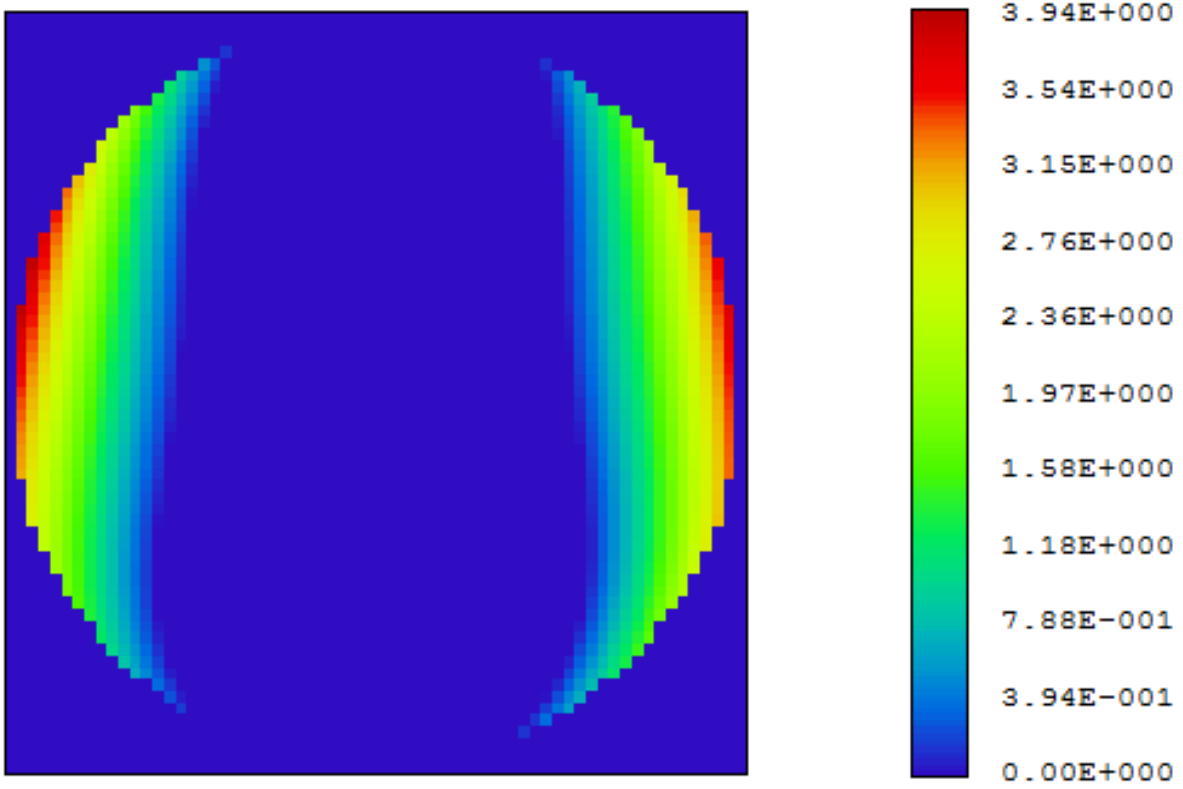
Grating parameters

Type	1st generation holographic grating
Recording wavelength	532 nm
Grooves frequency @ vertex	453.5 mm^{-1}

Surface shape

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{N} A_i Z_i(\rho,\varphi)$$

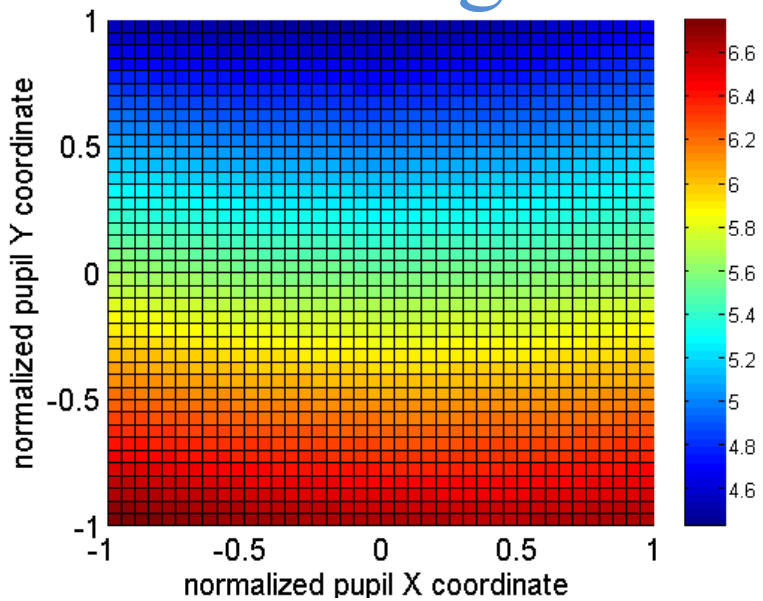
Z_5	$\sqrt{6}(\rho^2\cos 2\varphi)$	Obl. ast.
Z_6	$\sqrt{6}(\rho^2\sin 2\varphi)$	Vert. ast.
Z_7	$\sqrt{8}(3\rho^3-2\rho)\sin\varphi$	Vert. coma.
Z_9	$\sqrt{8}\rho^3\sin 3\varphi$	Vert. tref.
Z_{11}	$\sqrt{5}(6\rho^4-6\rho^2+1)$	Sph.
Z_{12}	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\varphi$	V. 2nd ast.
Z_{13}	$\sqrt{10}(4\rho^4-3\rho^2)\sin 2\varphi$	Ob. 2nd ast.
Z_{14}	$\sqrt{10}\rho^4\cos 4\varphi$	Vert. quadr.



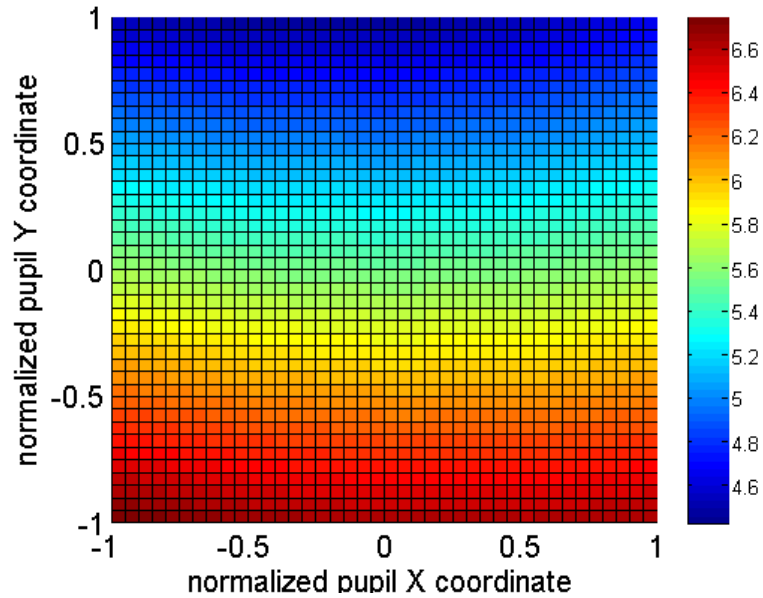
Asphericity of the cross-disperser grating surface (µm)
BFS radius 1806.48 mm, center displacement 2.8 µm
RMS residual 1.35 µm, Max. residual 3.94 µm

Angle of incidence variation

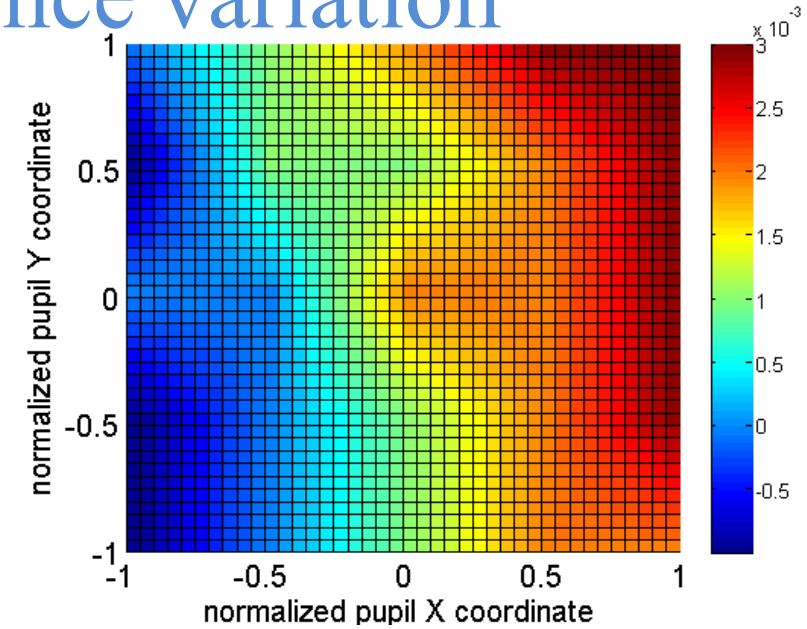
a



b



c



Variation of the AOI:

Plot	Wavelength	PTV, °	RMS, °
a	217	2.322	0.780
b	118	2.320	0.779
c	differential	0.004	0.001

The efficiency will be notably less than that of an equivalent plane grating

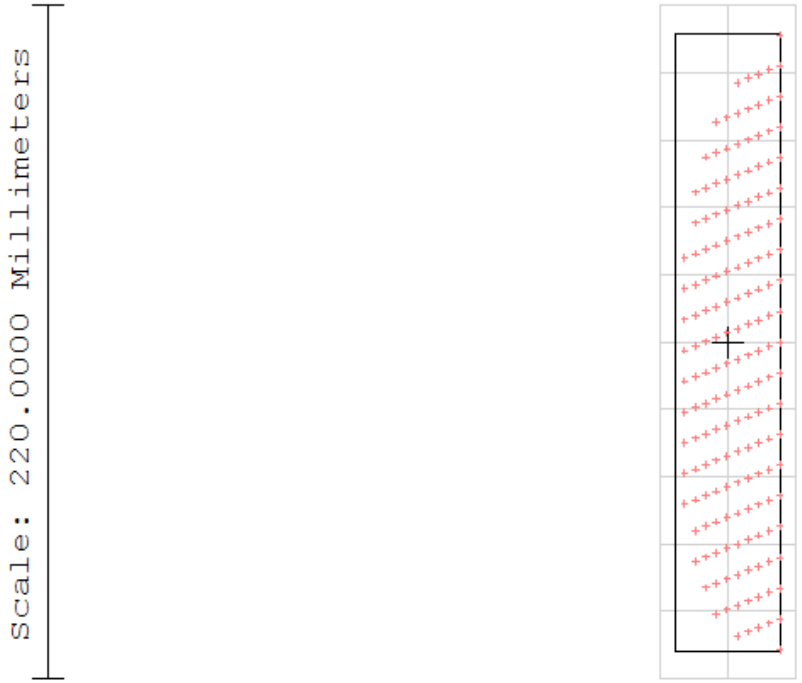
Conclusions

- The optical design allows to meet the main requirements
  - 6.1 nm coverage in a single order
  - Spectral resolution R=120200.
- The design has only three reflective surfaces and it is relatively compact.
- The design relies on an innovative free-form holographic grating.
- Technological feasibility was demonstrated for the freeform shape and holographic recording separately.

Open questions

- Currently achievable/prospective echelle parameters?
- Manufacturability of the holographic grating on freeform surface?
- Cross-disperser groove profile?
- Possible diffraction efficiency losses?

Echelle aperture



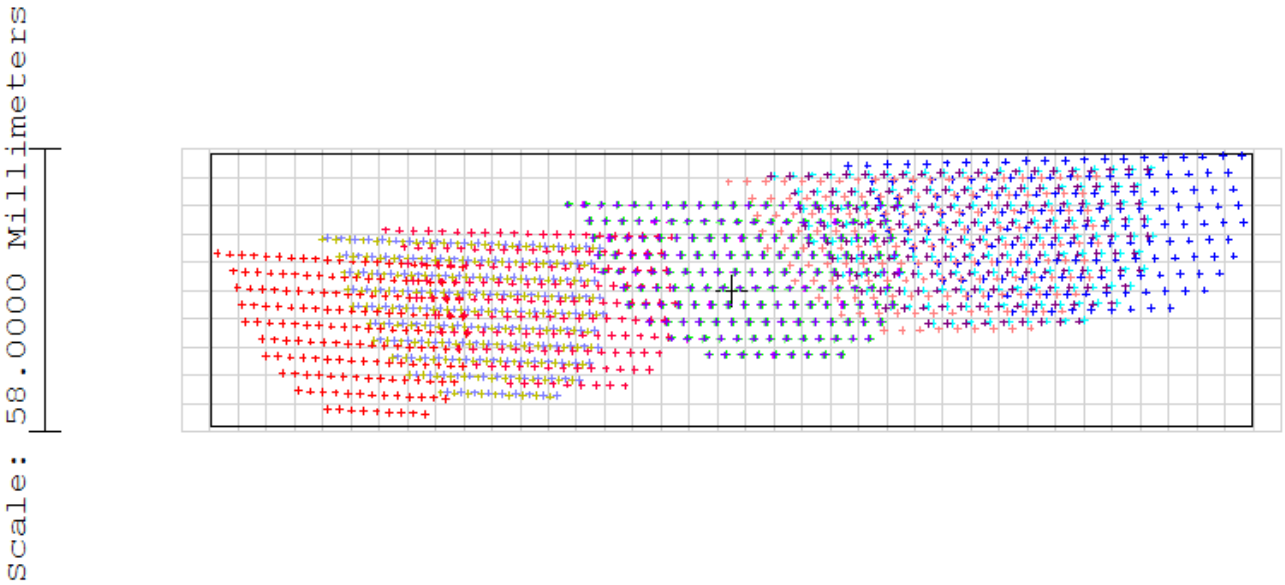
Aperture Full X Width : 34.0000
Aperture Full Y Height: 202.0000 % rays through = 53.00%

Footprint Diagram

29.08.2017
Surface 12: echelle
Ray X Min = -14.1617 Ray X Max = 16.9591
Ray Y Min = -100.5045 Ray Y Max = 100.4710
Max Radius= 101.9253 Wavelength= 0.1177

MUV EOS DO 2017.ZMX
Configuration: All 12

Cross-disperser aperture



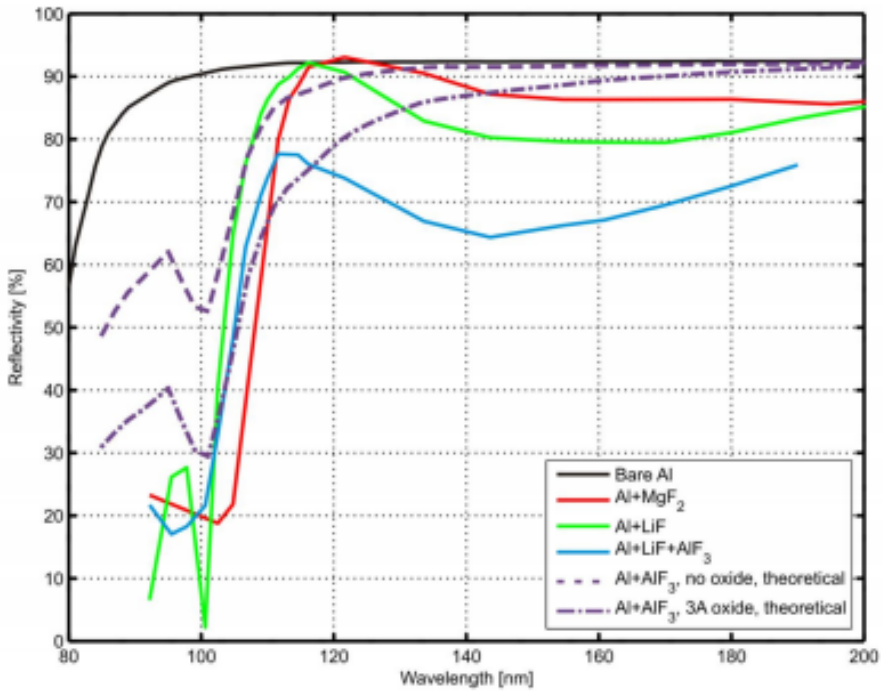
Aperture Full X Width : 214.0000
Aperture Full Y Height: 56.0000 % rays through = 53.00%

Footprint Diagram

29.08.2017
Surface 17: cross disp
Ray X Min = -105.8375 Ray X Max = 105.3089
Ray Y Min = -25.4373 Ray Y Max = 27.7752
Max Radius= 108.7179 Wavelength= 0.1177

MUV EOS DO 2017.ZMX
Configuration: All 12

Waveband



Extracted from tech. note LUVOIR; M. Bolcar

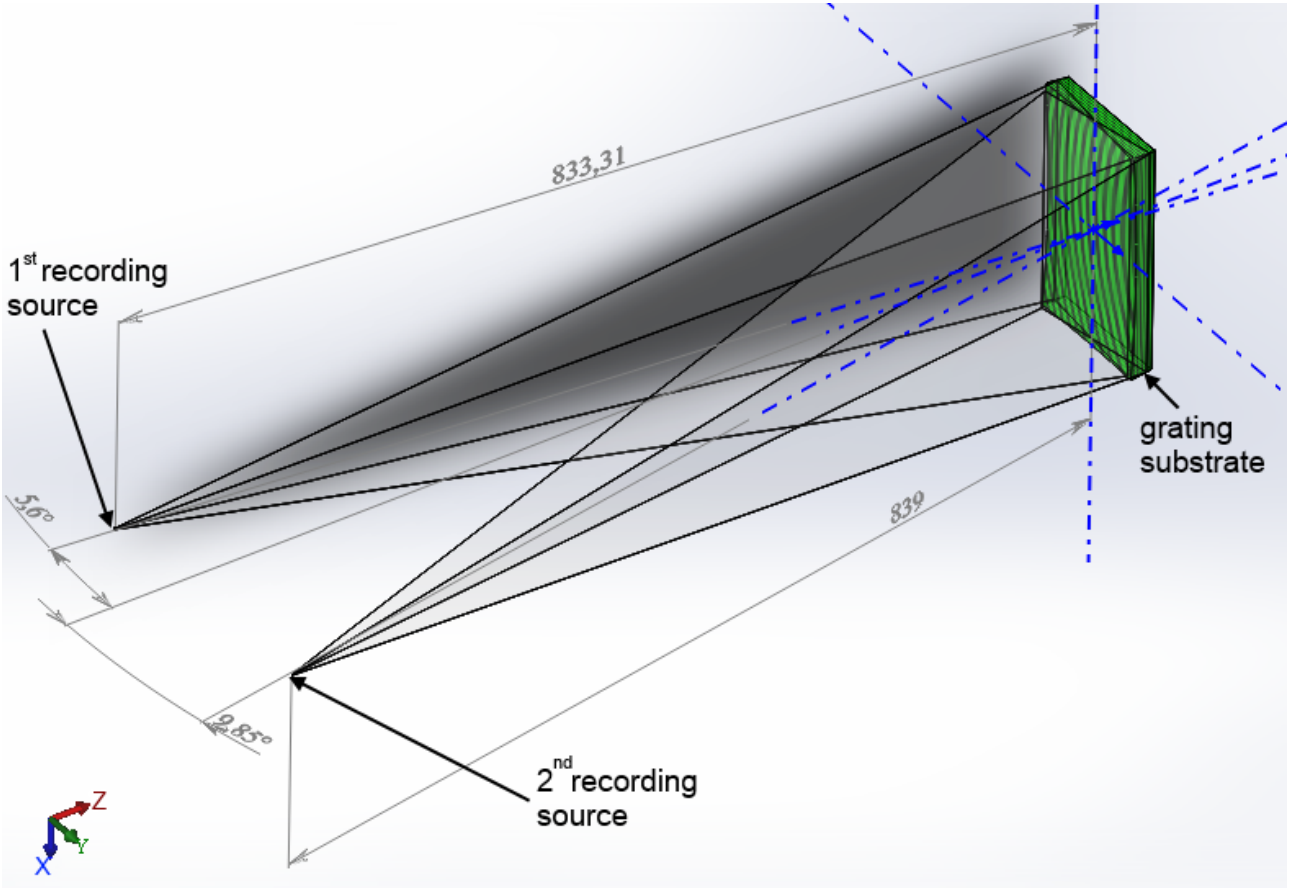
- Telescope Transmission
  - 30%^4 = 8%
- Instrument transmission
  - 50%^3 = 12.5%
- Optical efficiency: 1%
- Without polarization, without QE
- Impact on the transmission in the rest of the band

Preliminary radiometric estimate

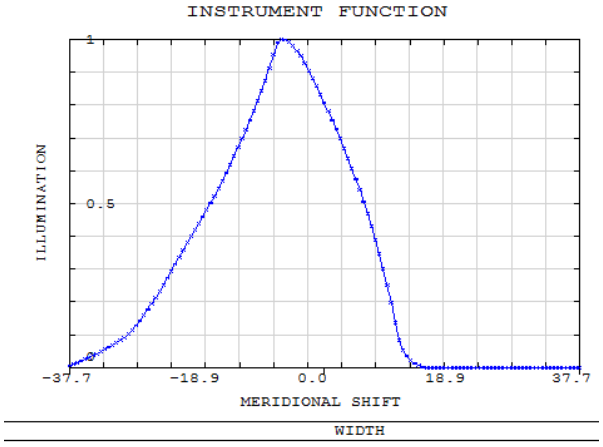
			90	98	115	120	120	150	200	250	300	350	400
			EUV				MUV			NUV			
TOTAL with polarizer			0,000%	0,000%	0,404%	1,069%	0,417%	0,984%	1,743%	1,674%	1,674%	1,674%	1,674%
Telescope (2)			1,2%	0,8%	24,0%	37,0%	37,0%	52,2%	65,6%	65,6%	65,6%	65,6%	65,6%
	Mirror (1)		33,0%	30,0%	70,0%	78,0%	78,0%	85,0%	90,0%	90,0%	90,0%	90,0%	90,0%
Instrument with pol			0,0%	0,0%	1,7%	2,9%	1,1%	1,9%	2,7%	2,6%	2,6%	2,6%	2,6%
Instrument without pol			1,1%	0,9%	4,9%	6,1%	2,4%	3,1%	3,6%	3,6%	3,6%	3,6%	3,6%
	Optics												
		Polarimeter (4,5)	3,6%	2,7%	34,3%	47,5%	47,5%	61,4%	72,9%	70,0%	70,0%	70,0%	70,0%
		Splitter(3,1)	100,0%	100,0%	100,0%	100,0%	39,0%	42,5%	45,0%	45,0%	45,0%	45,0%	45,0%
		Collimator (1)	33,0%	30,0%	70,0%	78,0%	78,0%	85,0%	90,0%	90,0%	90,0%	90,0%	90,0%
		Echelle	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%
		Cross-disp.	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%
		Folding M.(1)	33,0%	30,0%	70,0%	78,0%	78,0%	85,0%	90,0%	90,0%	90,0%	90,0%	90,0%
	Detector (8)		40,0%	40,0%	40,0%	40,0%	40,0%	40,0%	40,0%	40,0%	40,0%	40,0%	40,0%

(1): Al+AlF3+3A oxyde
(2): 4 mirrors for the telescope
(3): MUV+NUV: Al+AlF3+3A oxyde for the folding + spatial splitter
(4): Al+AlF3+3A oxyde with 3 mirrors
(5): MgF2: 70%
(6): Estimate
(7): Estimate
(8): 40% from Robert Grange email

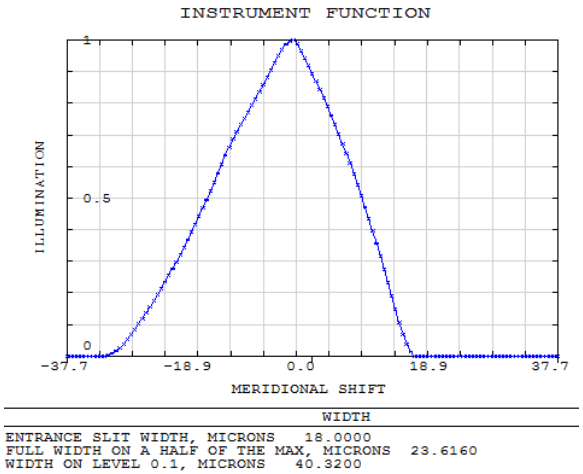
Comparison with VLS



The holographic grating recording scheme:
The two sources are points emitting @ 532 nm.



IF @ 120.3 nm with VLS grating
IF FWHM = 23 µm



IF @ 120.3 nm with hologr. grating
IF FWHM = 23.6 µm