IAXO X-ray optics
and possible italian contributions

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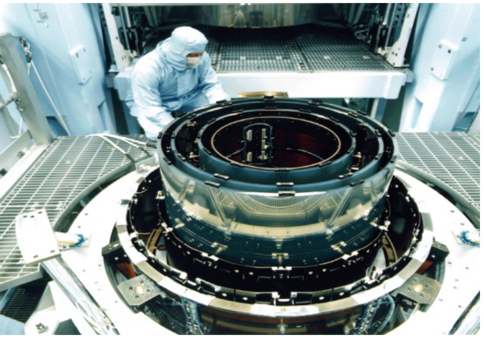
Manufacturing techniques utilized so far

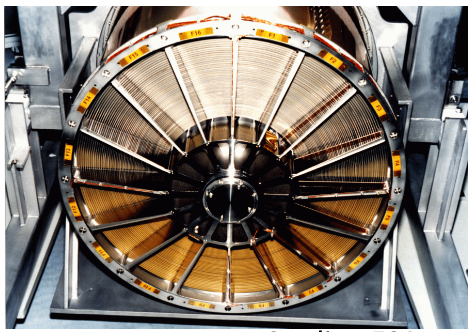

Credits: NASA

1. Classical precision optical polishing and grinding

Projects: *Einstein, Rosat, Chandra*

Advantages: *superb angular resolution*

Drawbacks: *high mirror walls ➔ ➔ small number of nested mirror shells, high mass, high cost process*

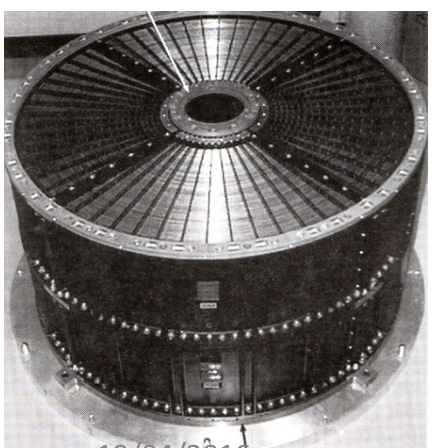

Credits: ESA

2. Replication

Projects: *EXOSAT, SAX, JET-X/Swift, XMM, ABRIXAS (➔ examples follow hereafter)*

Advantages: *good angular resolution, high mirror "nesting" the same mandrels for many modules*

Drawbacks: *relatively high cost process; high mass/geom. area ratio (if Ni is used).*


Credits: ISAS

3. "Thin foil mirrors"

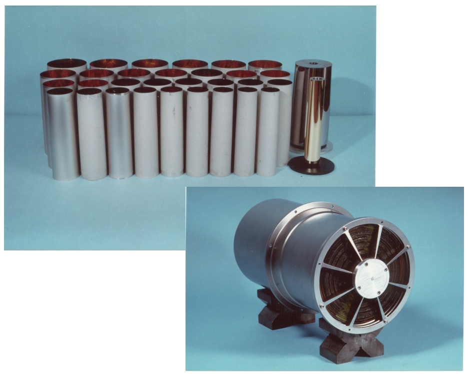
Projects: BBXRT, *ASCA, SODART, ASTRO-E*

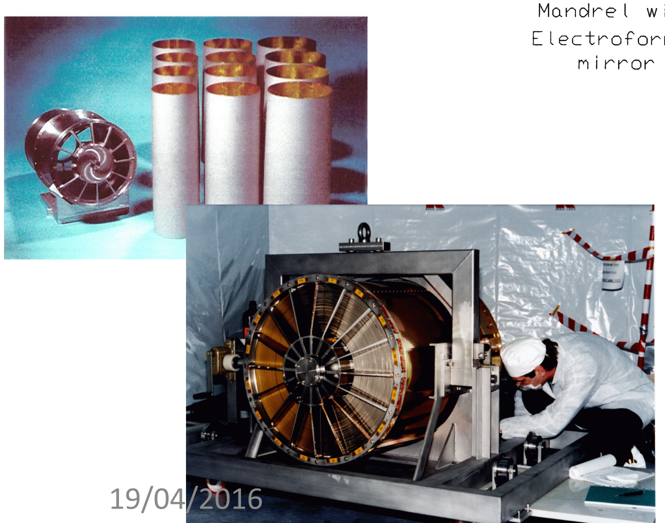
Advantages: *high mirror "nesting" possibility, low mass/geom. area ratio (the foils are made of Al), cheap process*

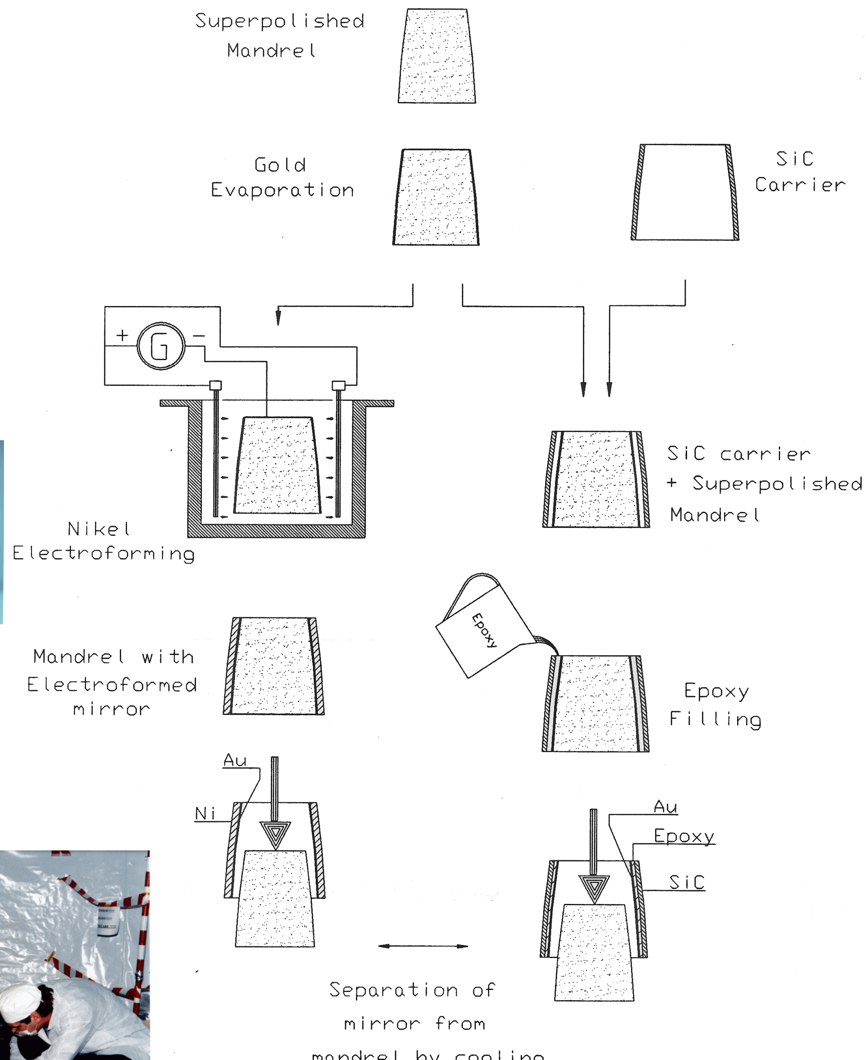
Drawbacks: *until now low imaging resolutions (1-3 arcmin)*

Replication methods

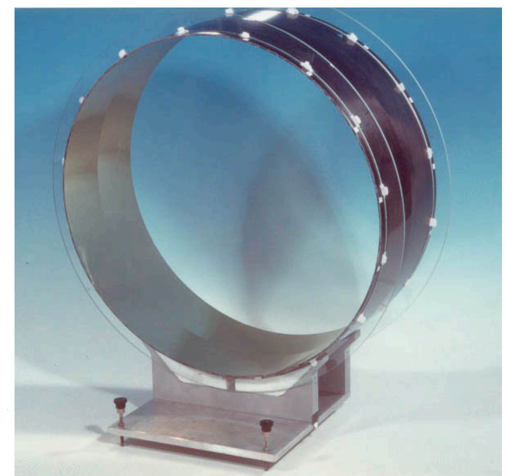
- Ni electroforming replication (SAX, JET-X/Swift, XMM, ABRIXAS, E-Rosita…)







- *epoxy replication*: EXOSAT (Be), WFXT (Alumina & SiC prototypes)



Italian“replication by electroforming” technology has enabled almost all X-ray observatory missions of the last 20 years with high-precision nickel mirrors

1993 1995 1999 2010 2013

Beppo SAX (ASI)

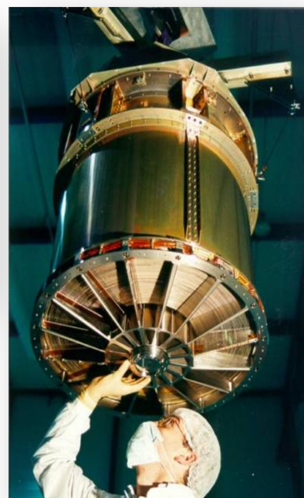
- 4 mirror modules
- 30 mirrors/module
- Thickness: 0.4-2 mm
- HEW@1,5keV: 60 “

JET-X → SWIFT (NASA-ASI)

- 1 mirror module
- 12 mirrors/module
- Thickness: 0.4-1.5 mm
- HEW@1,5keV: 15 “

XMM (ESA)

The most powerful X-ray telescope ever built

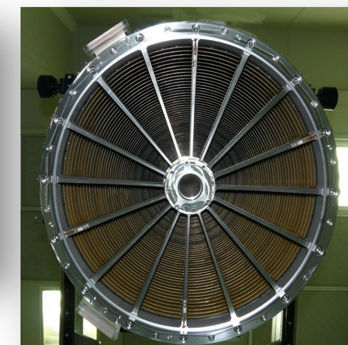


- 3 mirror modules
- 58 mirrors/module
- Thickness: 0.5-1 mm
- HEW@1,5keV: 13”

ASI-sponsored technology development for NHXM

- New mandrel manufacturing technology
- Aperiodic multilayer for hard-X ray reflection

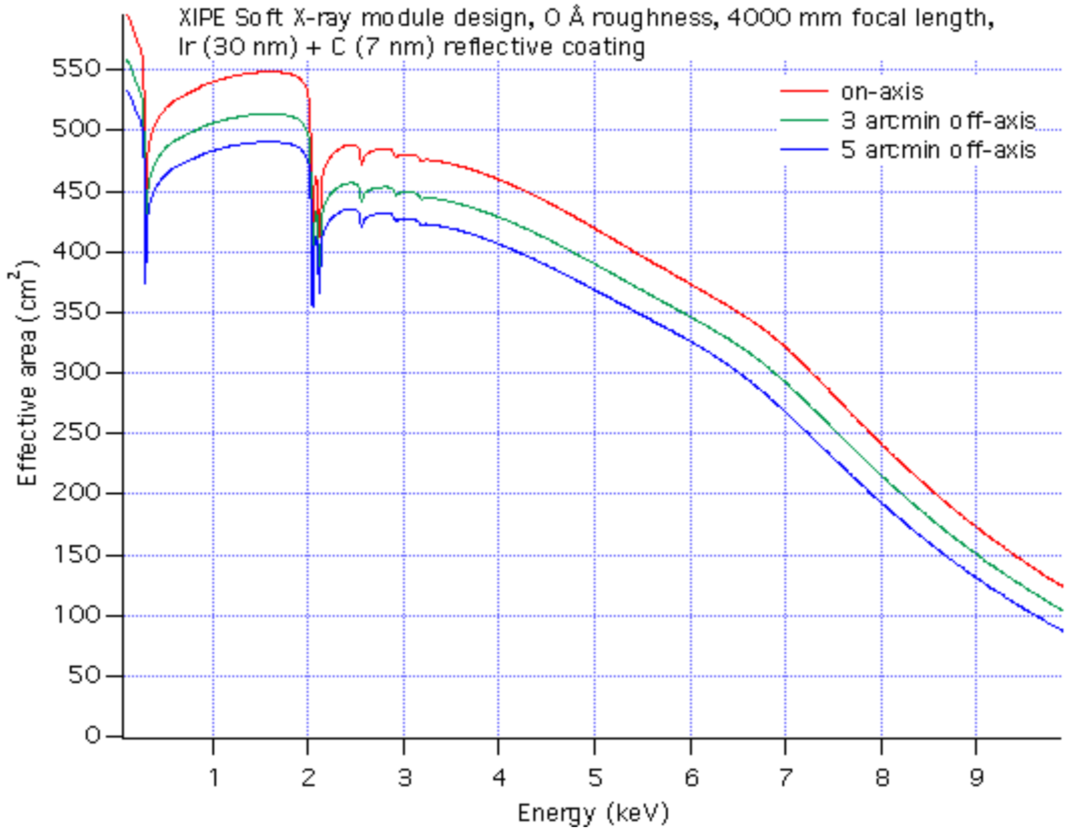
EROSITA (MPE)



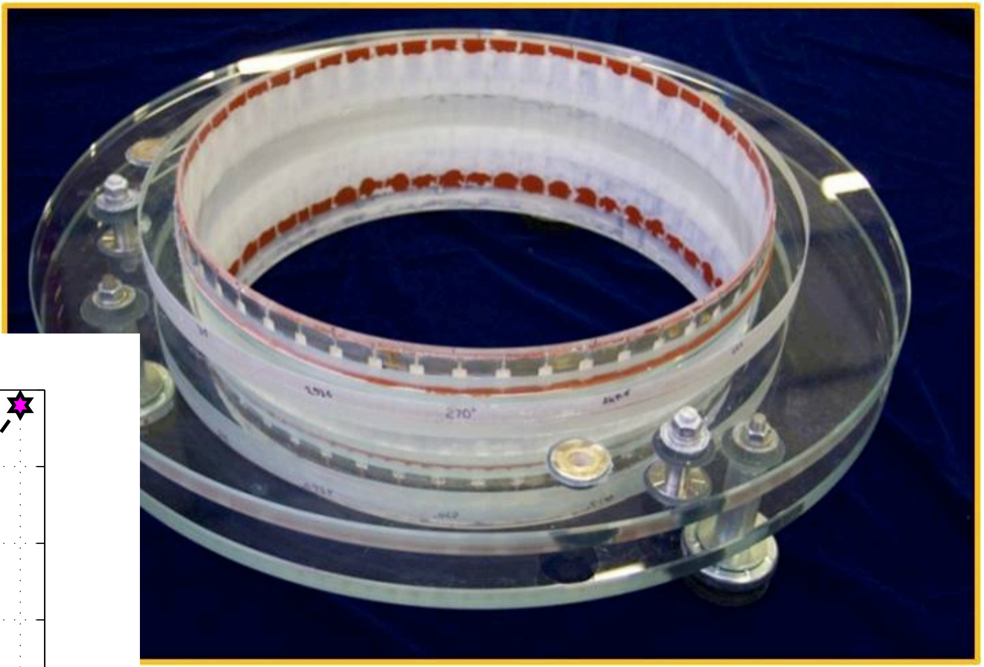
- 7 mirror modules
- 54 mirrors/module
- Thickness: 0.2-0.5 mm
- HEW@1,5keV: 14”

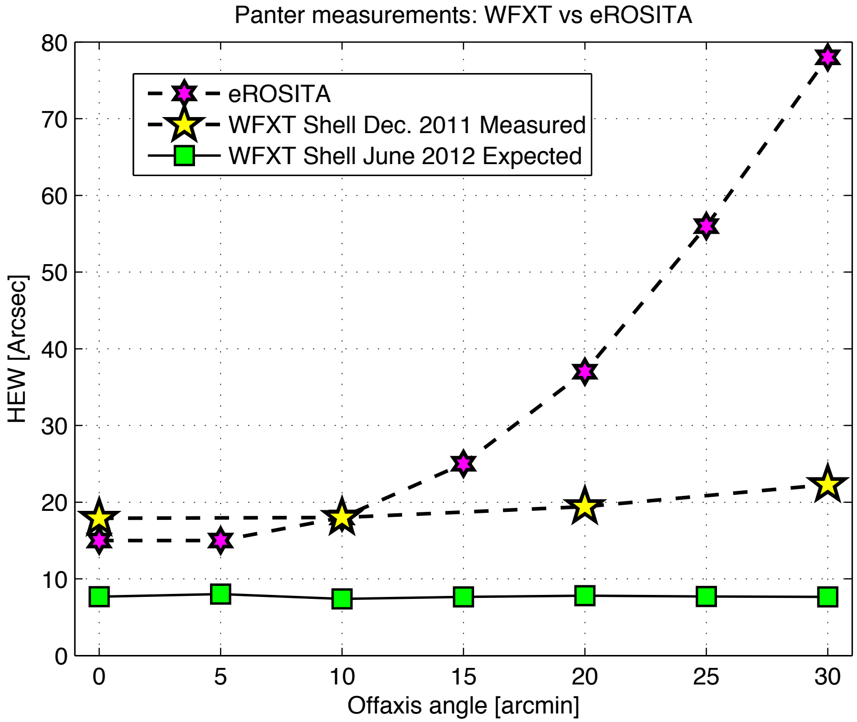
Proposed mirror design in Nickel for XIPE mirrors

- 3-mirror modules with FL=3.5 m
- 27 shells with the same thickness as for NHXM (250 microns, max) - 12 mandrels already available
- diameters min=183 mm, max=400 mm
- Electroformed in Ni (or NiCo) with Ir+C coating
- Total weight of 1 MM is ~40 kg (shells 30kg, 30% structure, total for 3MM=120 kg)
- HPD : 15 arcsec



WFXT prototype 2011: direct polishing approach



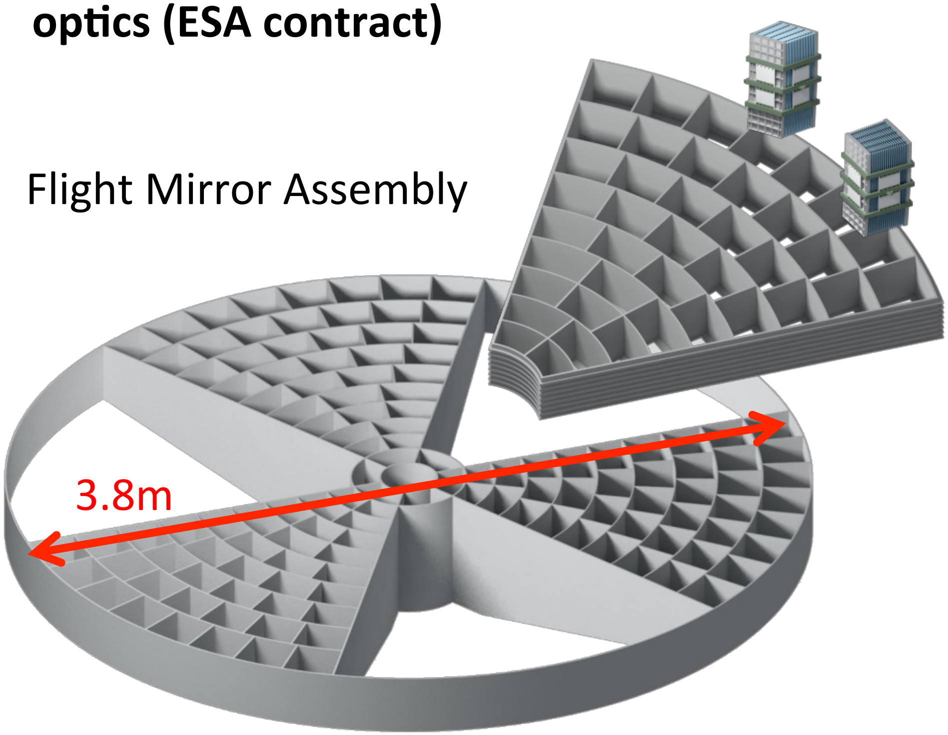


Measured values @0.93keV With TRoPIC

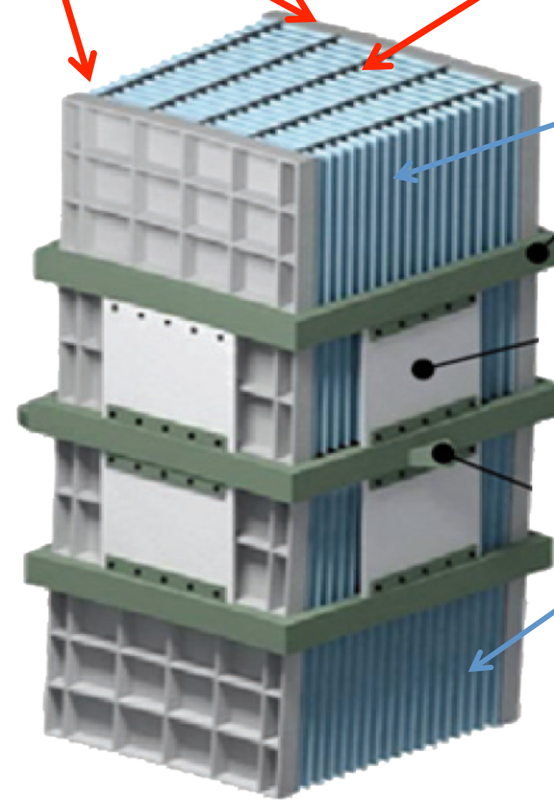
Slumped Glass Optics (SGO)

IXO backup technology optics (ESA contract)

Flight Mirror Assembly

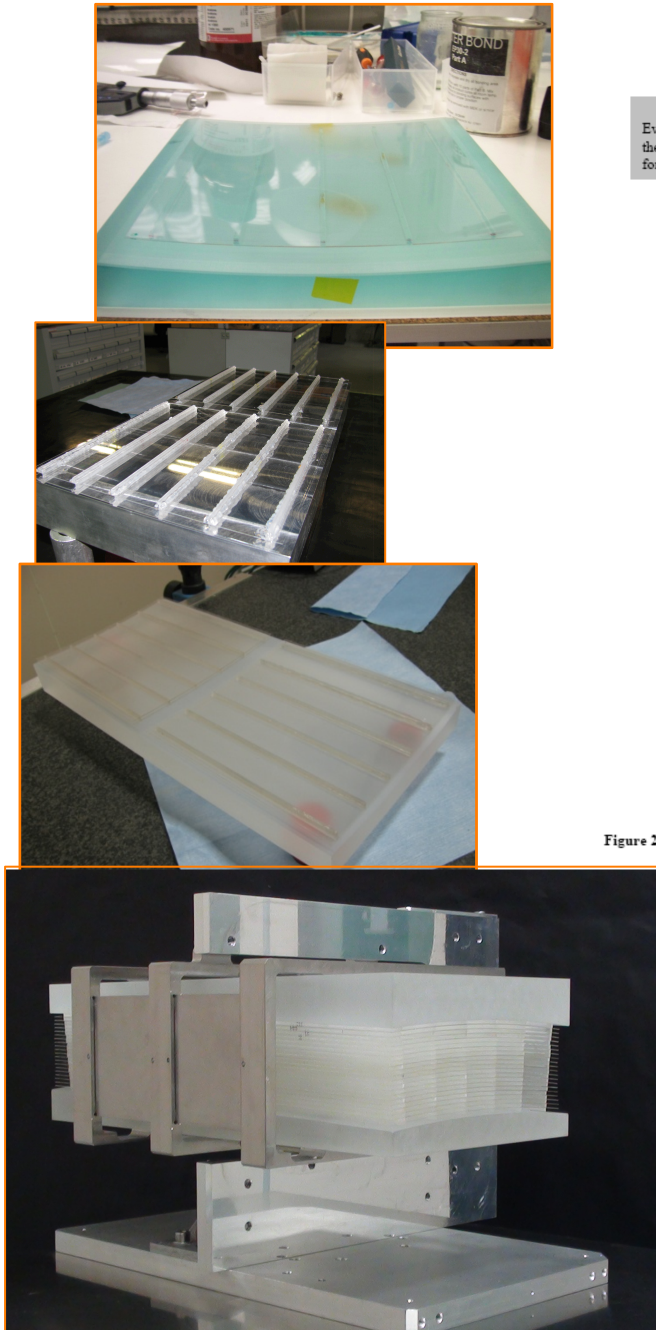


Glass D263T
200mmx200mm x0.4mm



X-Ray Optical Unit (XOU)

Sep. 2009



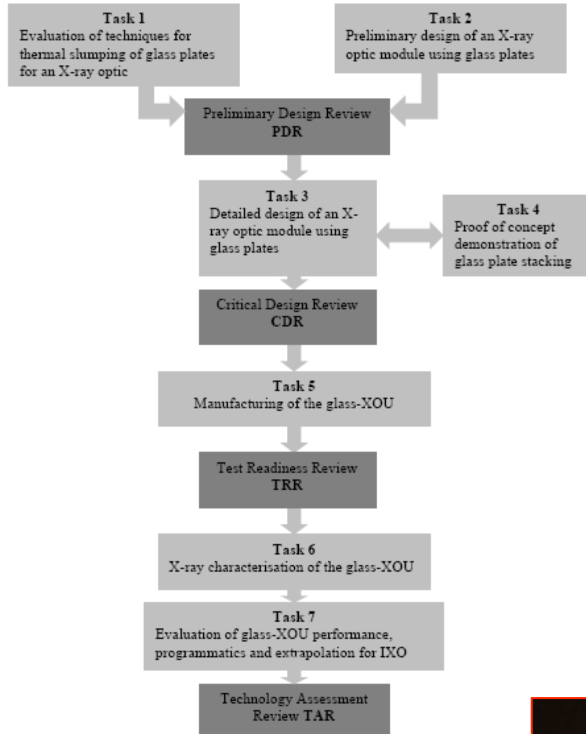
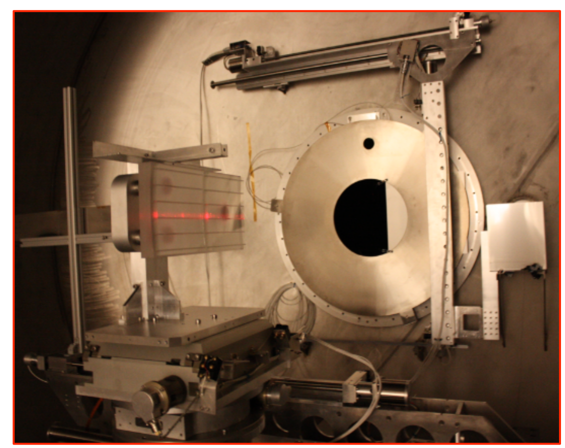


Figure 2-2: Workflow diagram

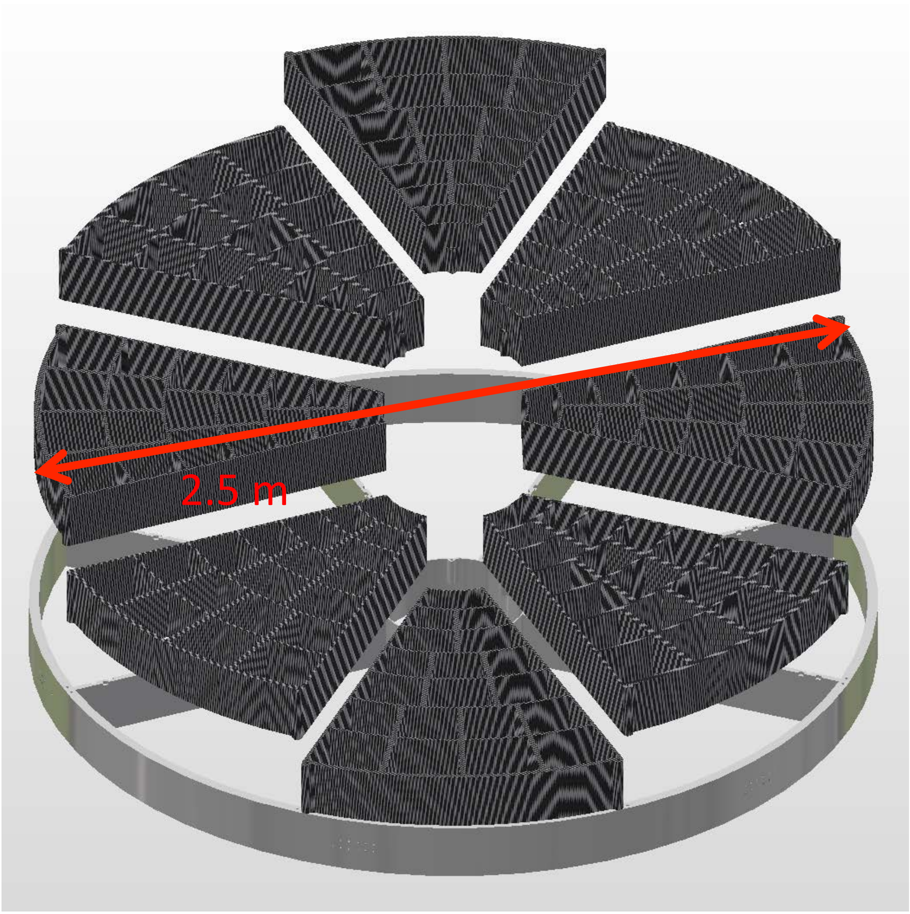
Goal of the study : To demonstrate the feasibility of large segmented X-ray optics having high angular resolution

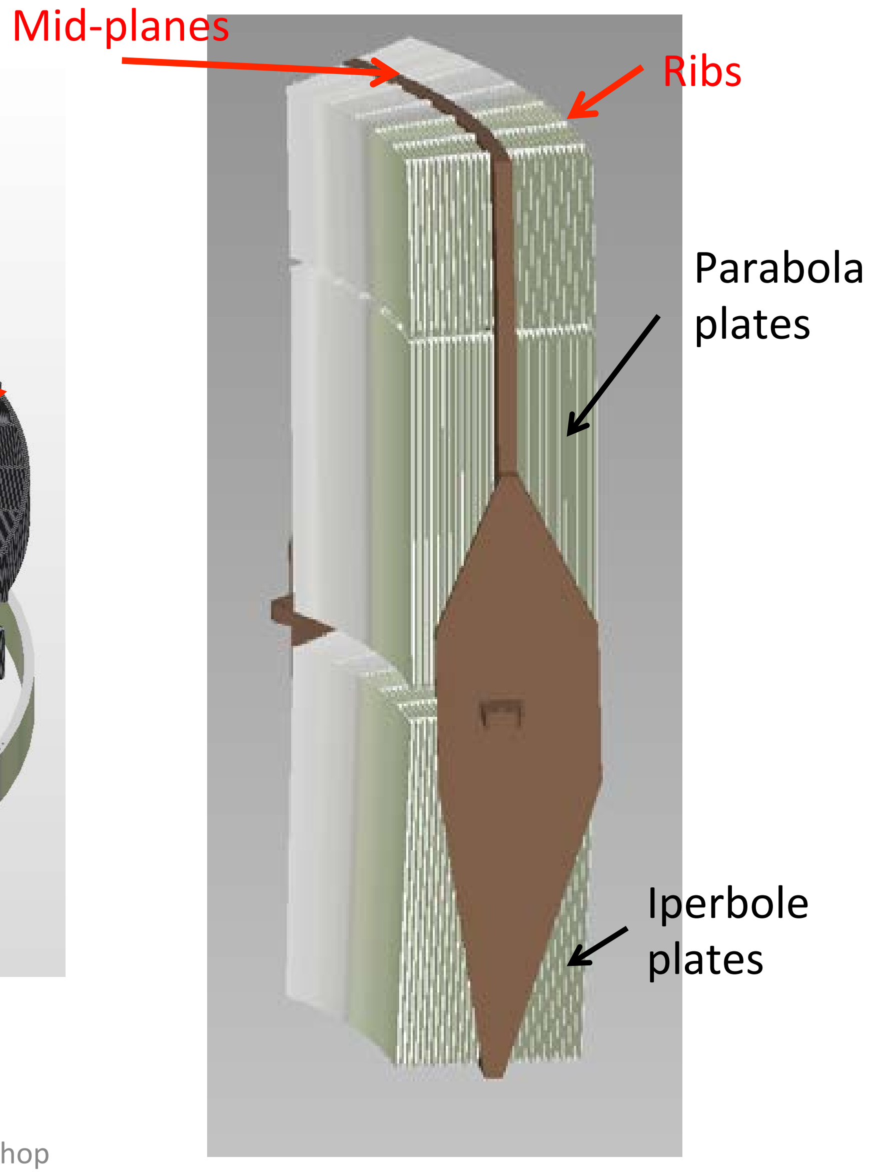
Time



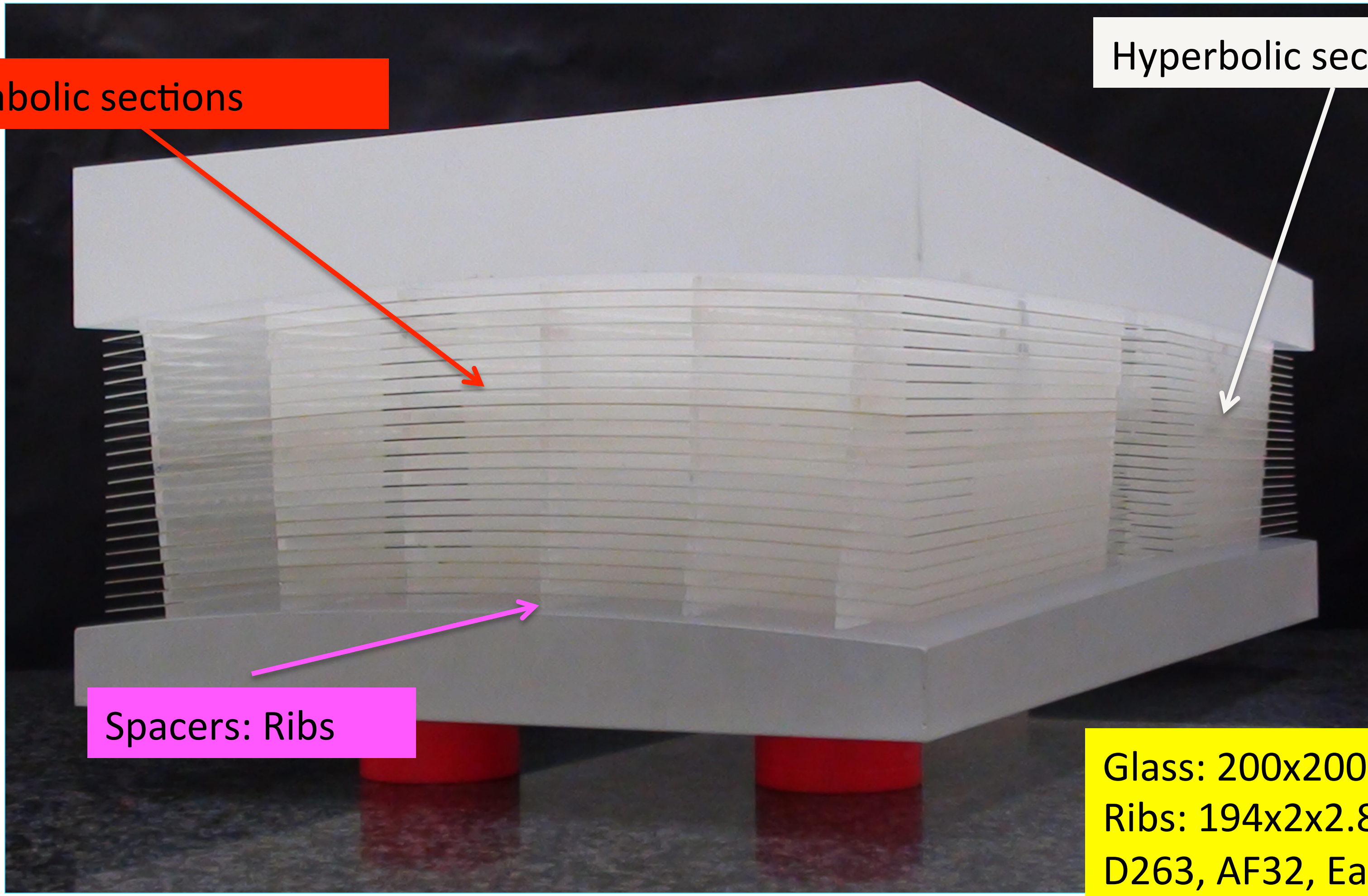
Now

Still on going… Athena like missions with glass





SGO: x-ray optical unit details

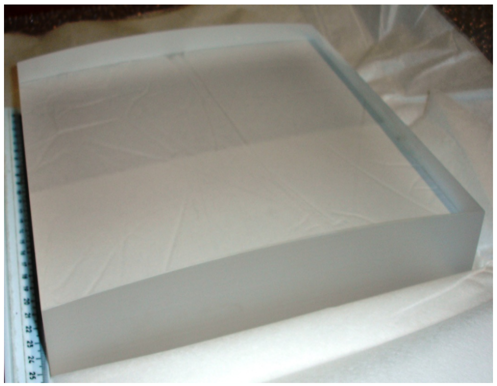


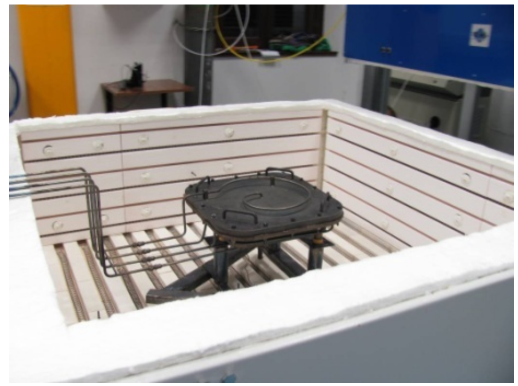
Glass: 200x200x0.4mm
Ribs: 194x2x2.8mm
D263, AF32, Eagle
BK7, Borofloat
MasterBond EP30-02

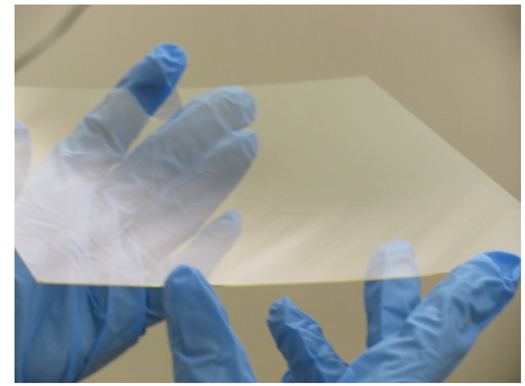
SGO: OAB present approach

Forming molds | Slumping process | Result

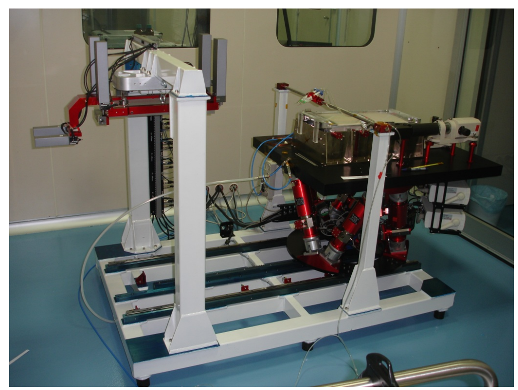
Hot slumping with active pressure to produce cylindrical glass plates

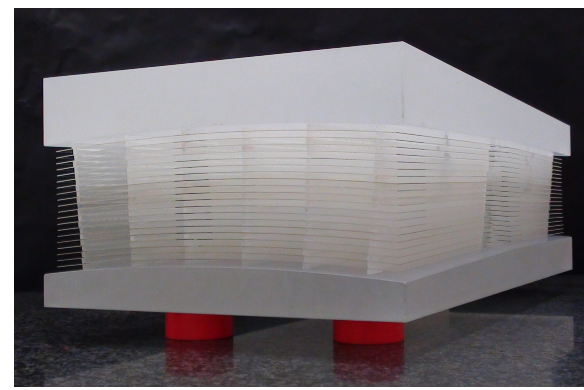




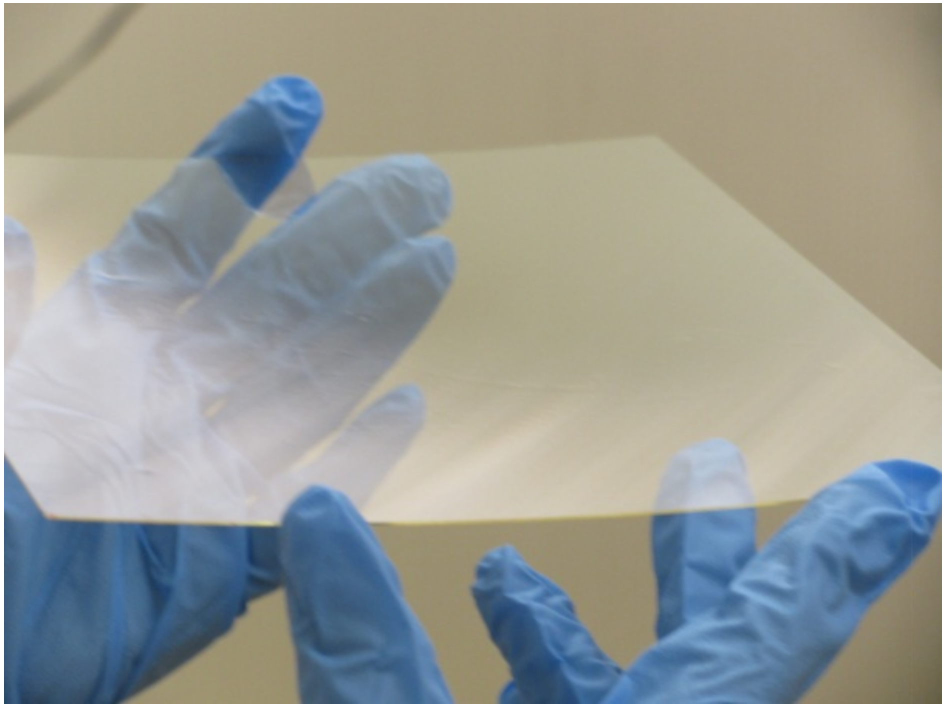


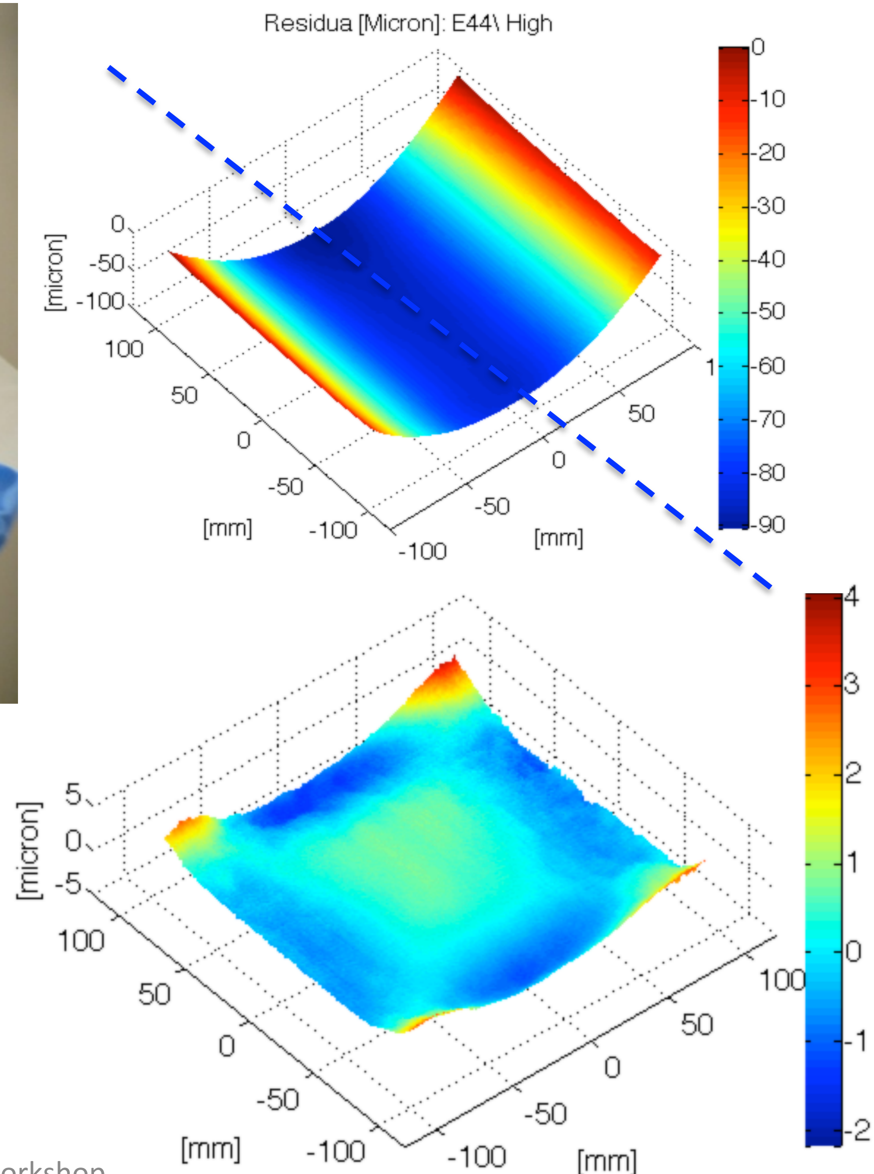
Cold slumping for plates shaping to Wolter I & alignement





SGO: Slumping results

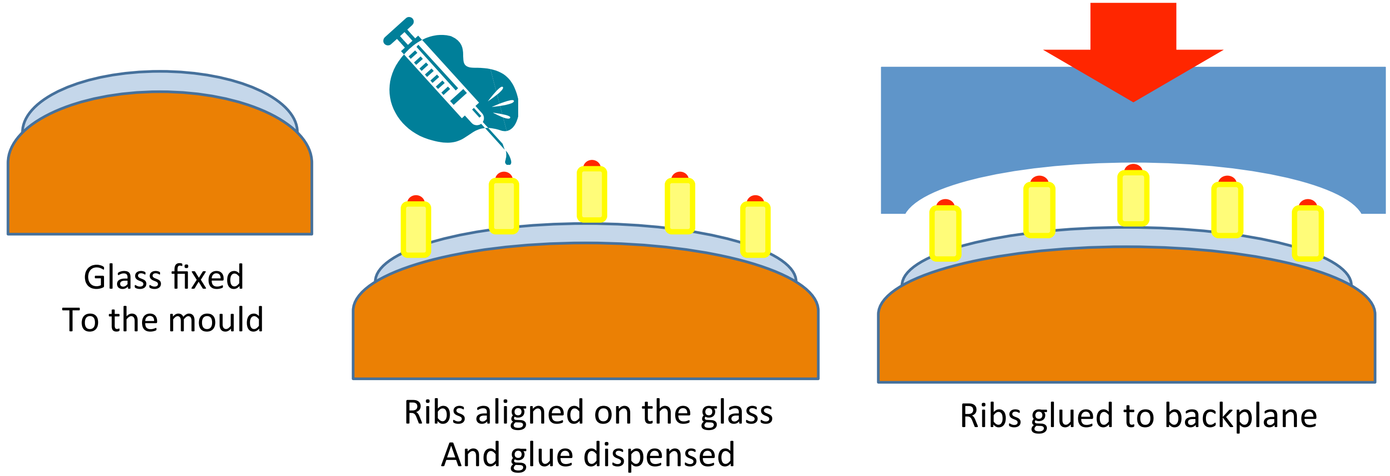


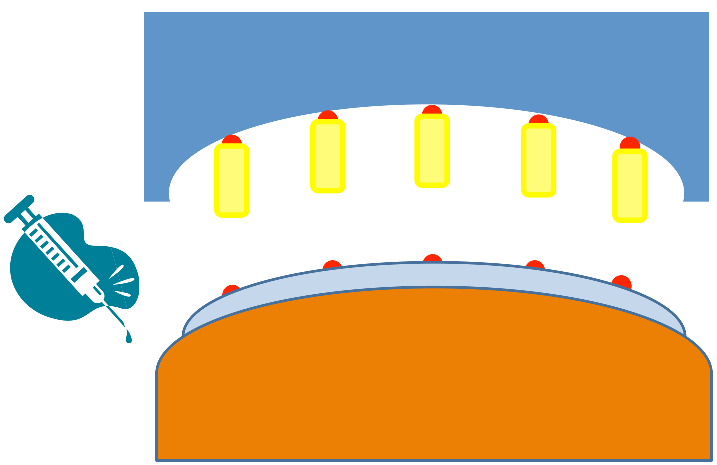


3D Typical shape of the last serie Eagle slumped glass

Cylinder 1m radius of curvature
200 mm x 200 mm x 0.4mm

SGO: Mould integration approach



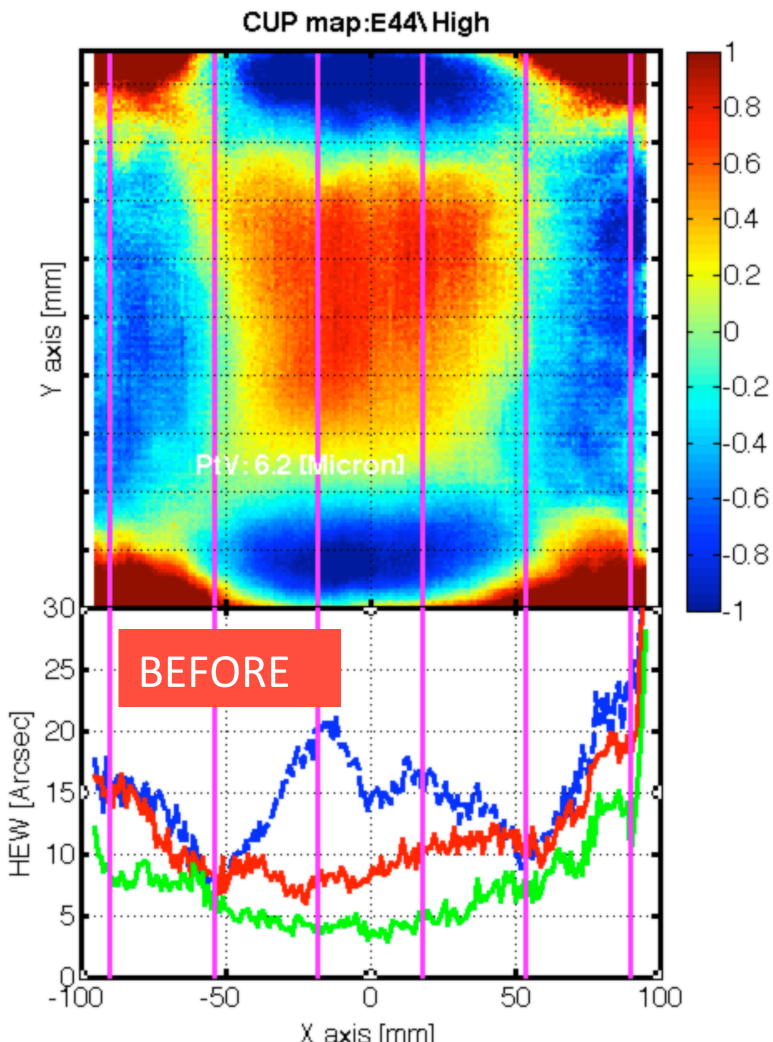


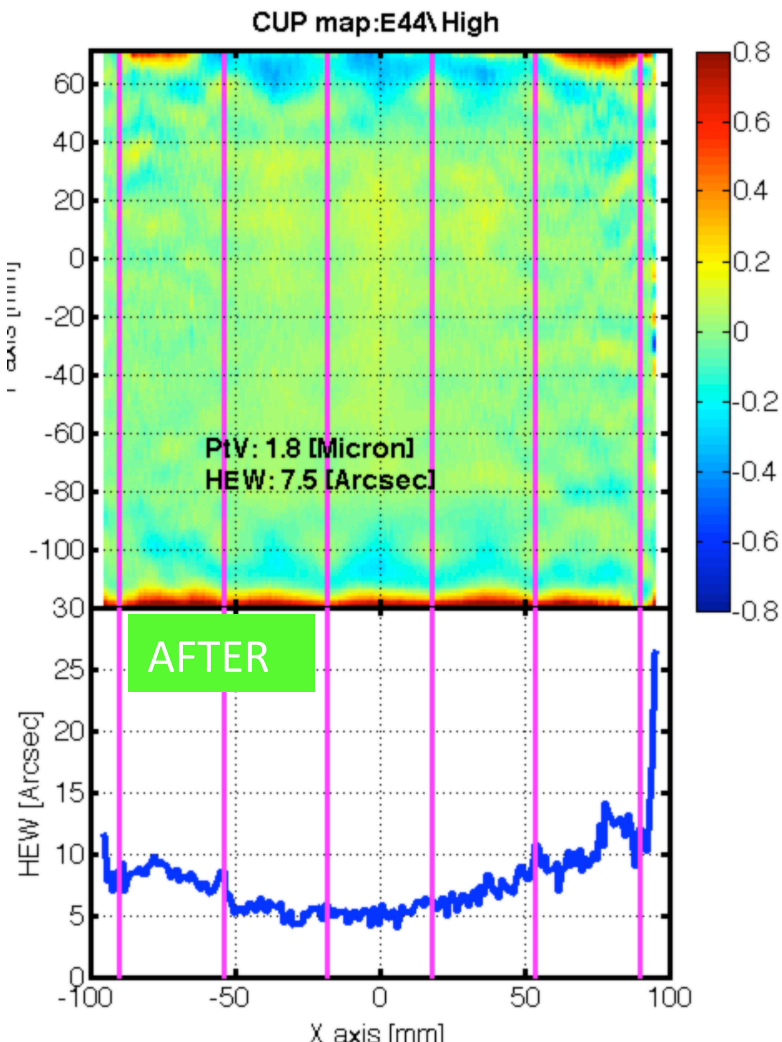
Backplane with ribs glued to glass fixed on mould

- Glass plate has the **SAME SHAPE** of the mould
- Glass plate shape is **FROZEN** with ribs
- The mould can be taken as a **REFERENCE**

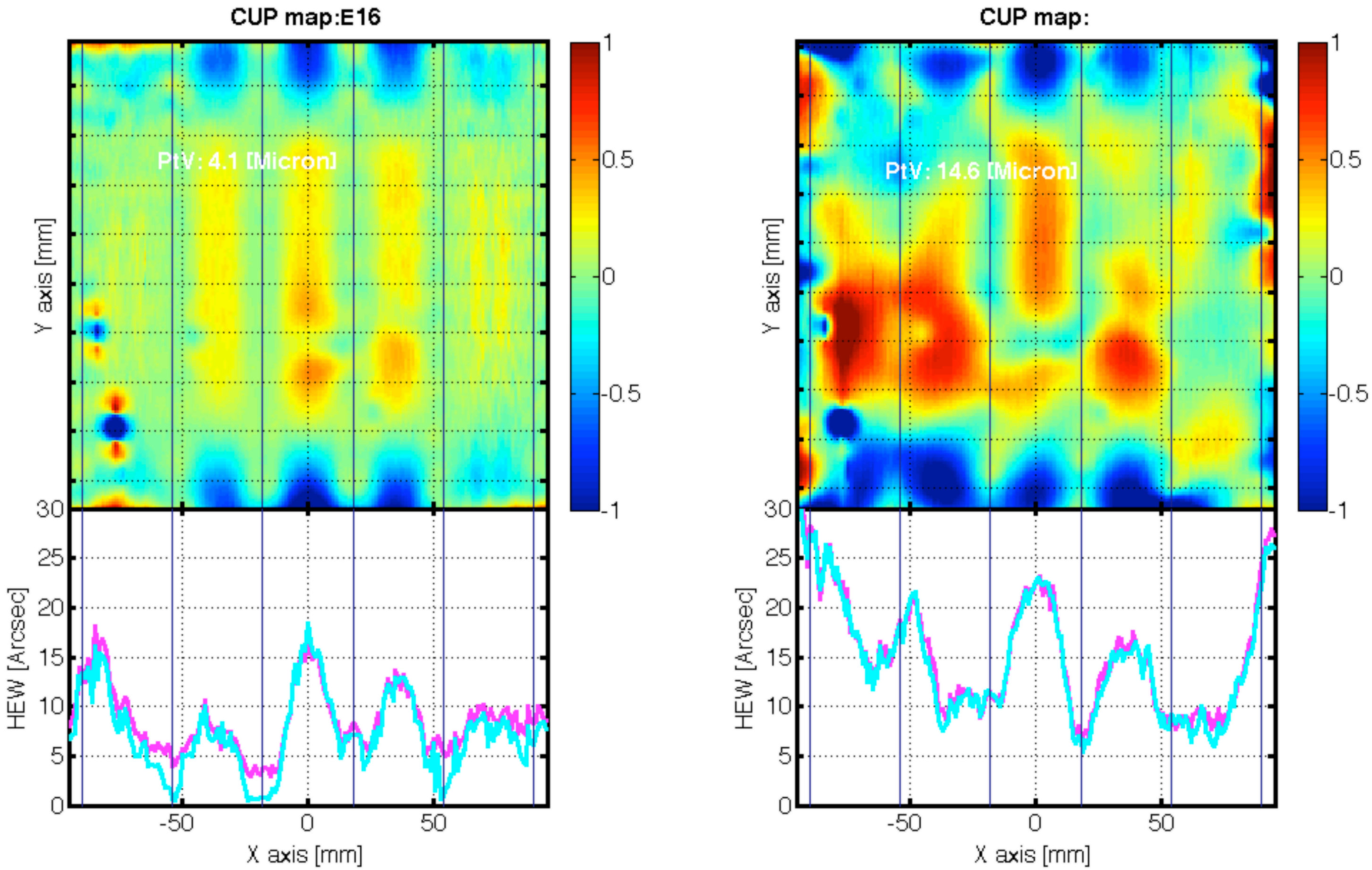
Integration corrective capabilities

SIMULATIONS: theoretical mold + perfect integration





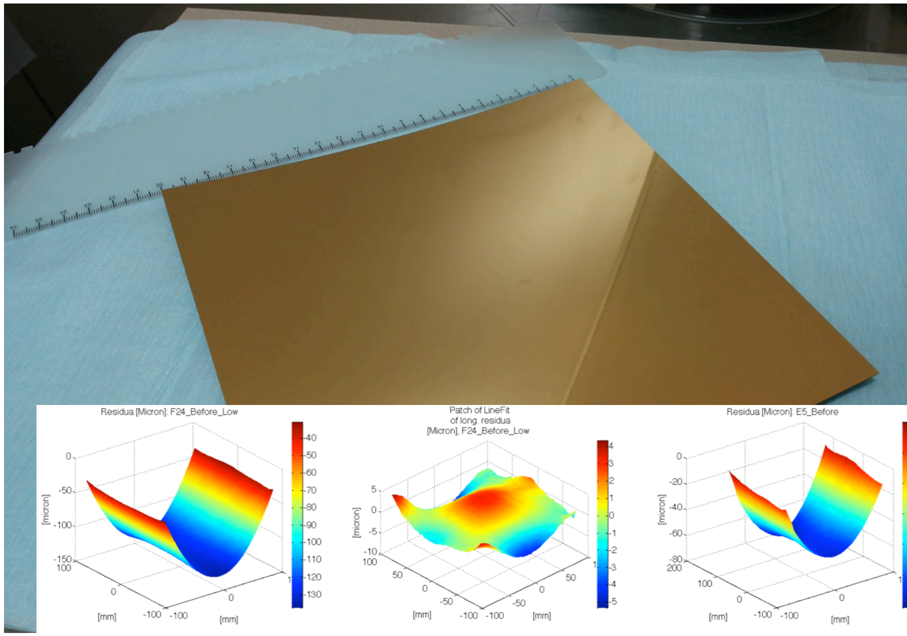
Integrated sample results

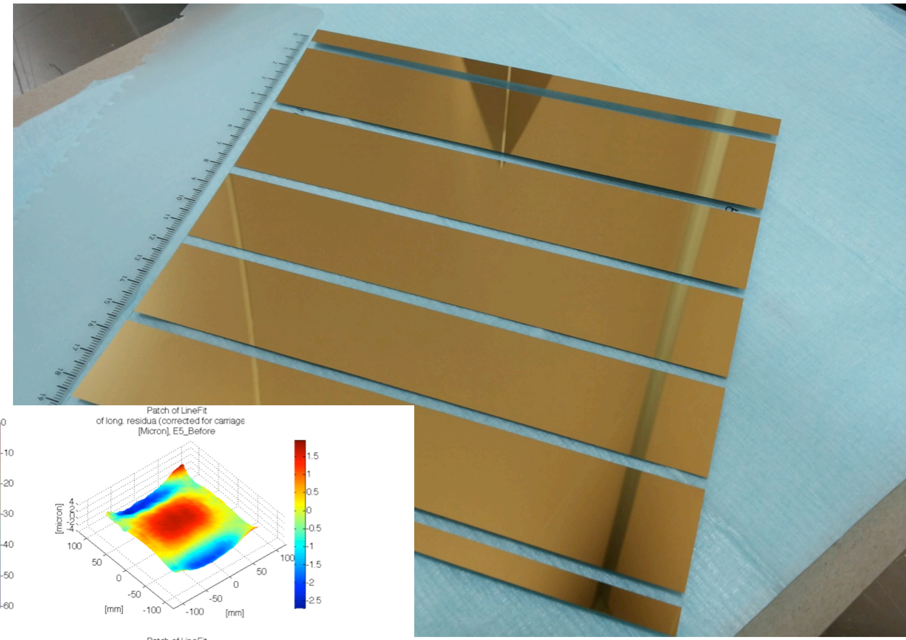


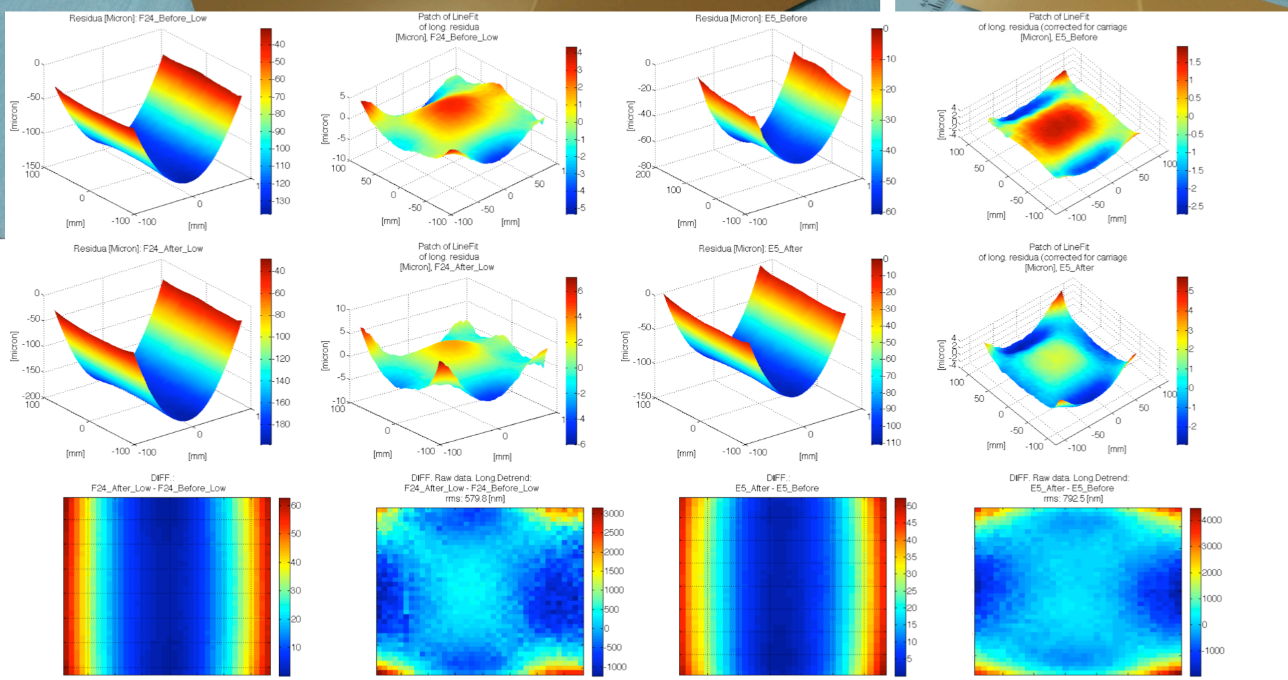
Integration error: 0''-5'' → TO BE IMPROVED:

- Slumping figure error
- Slumping set-up cleaning
- Integration set-up cleaning
- Integration mold figure error correction (@OAB with ion beam figuring) to reach 1-2'' HEW.

Coating of segments





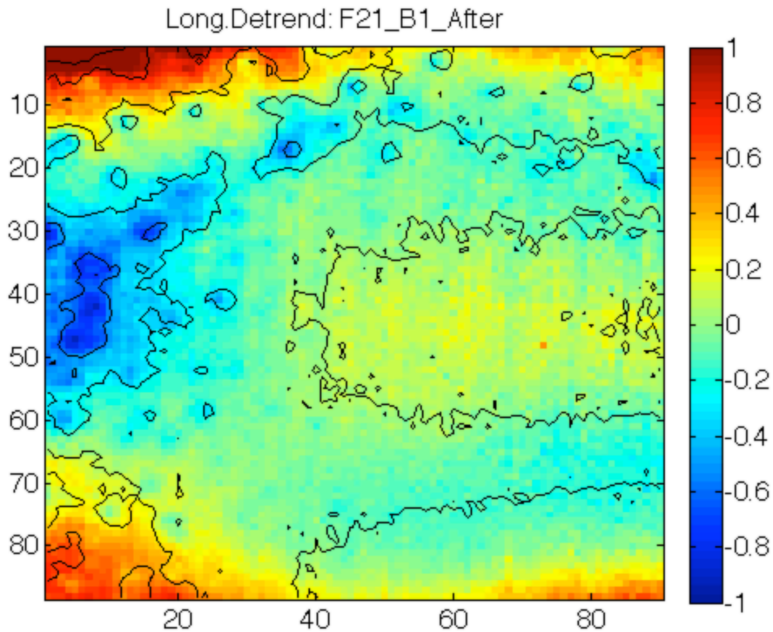


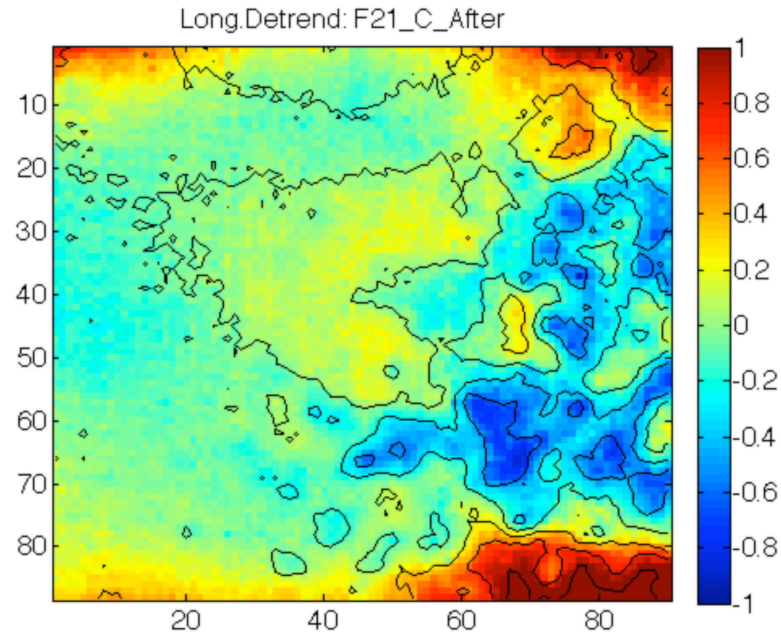
Au evaporated coating @MLT

Coating of segments & Mid.frequencies

F21_B sample: Before/After

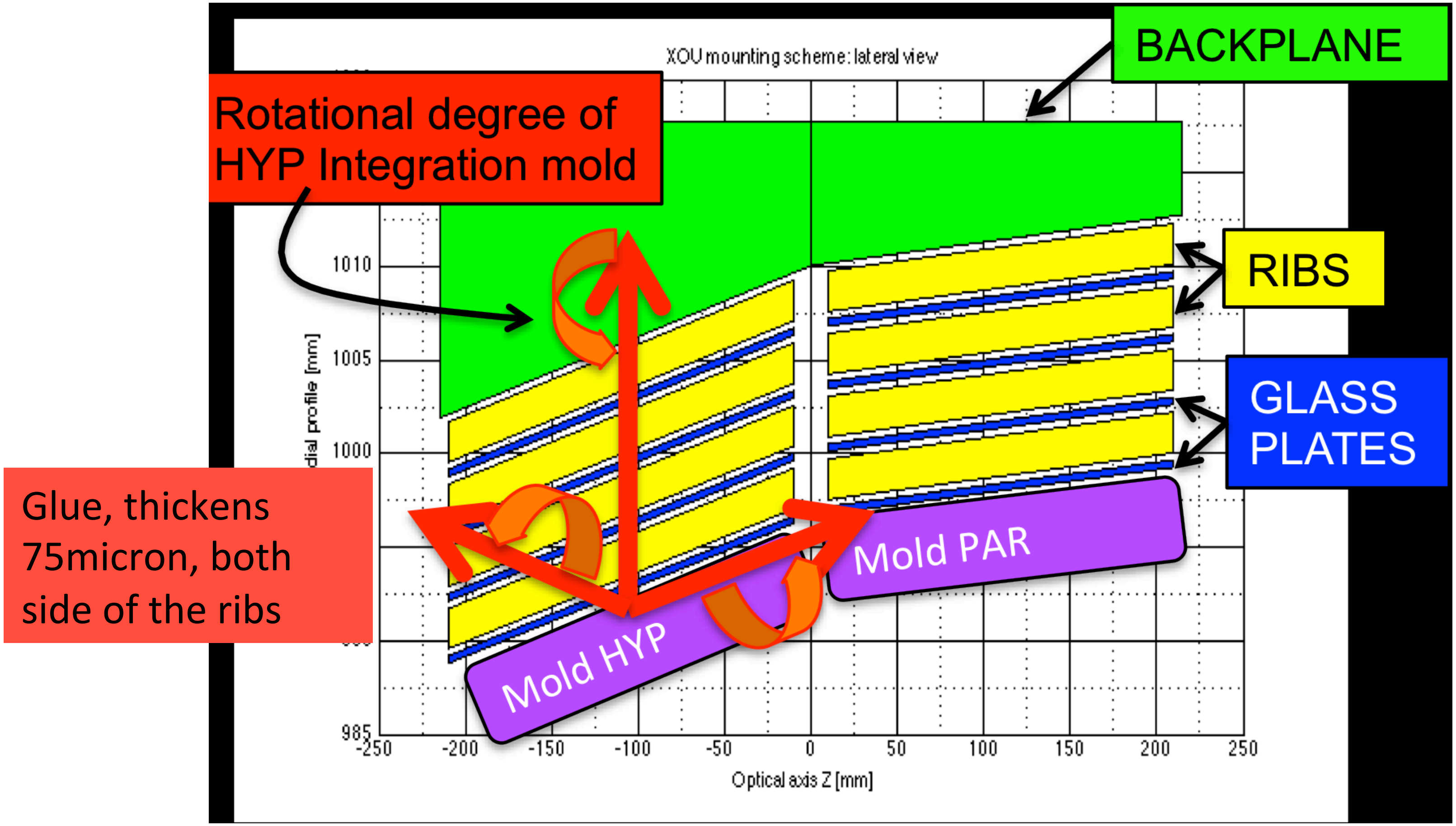
F21_C sample: Before/After



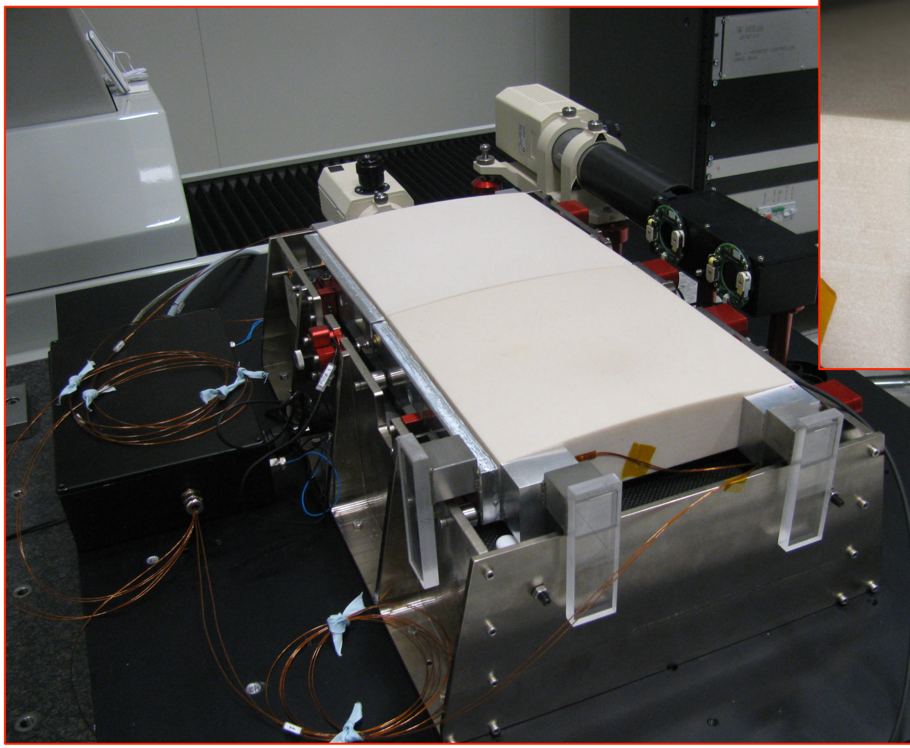


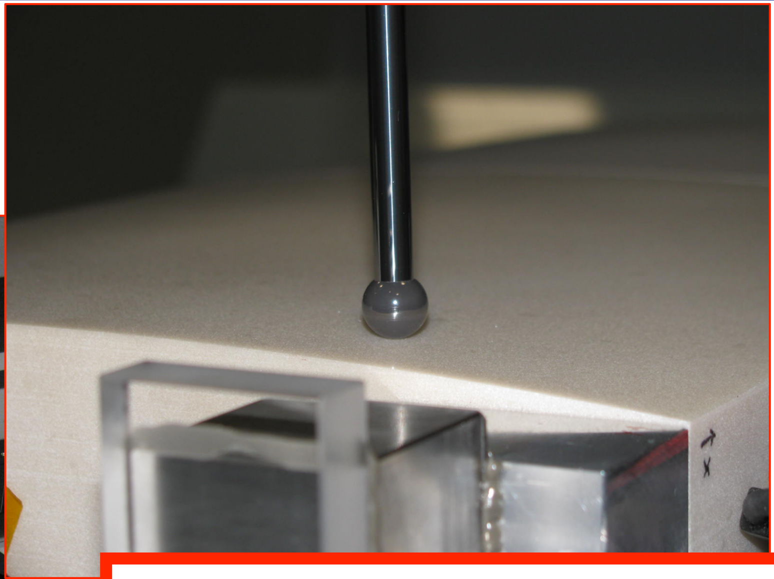
The coating changes only low frequency shape of the glass: mid-frequencies remain un-changed

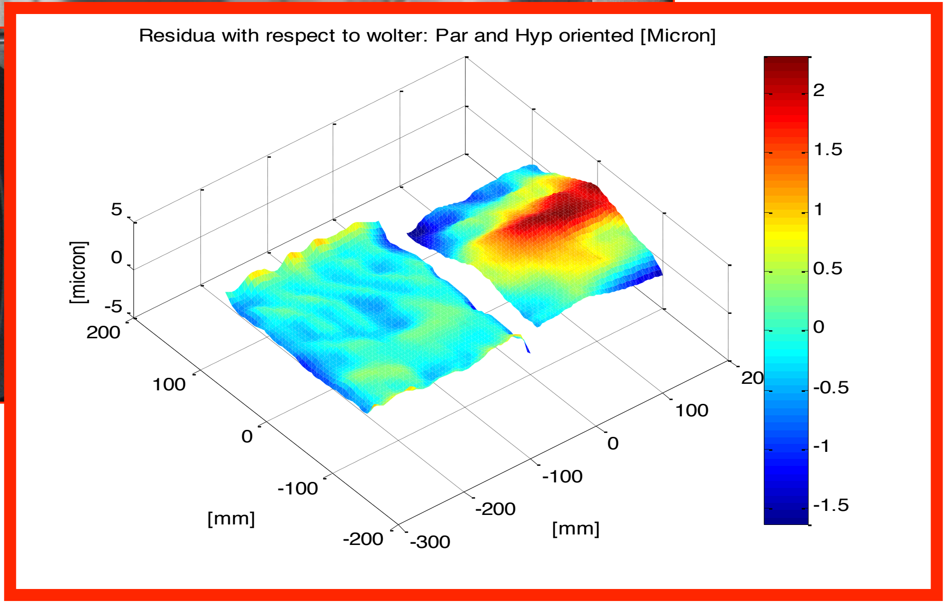
Stacking concept



Mould alignment under the UPMC

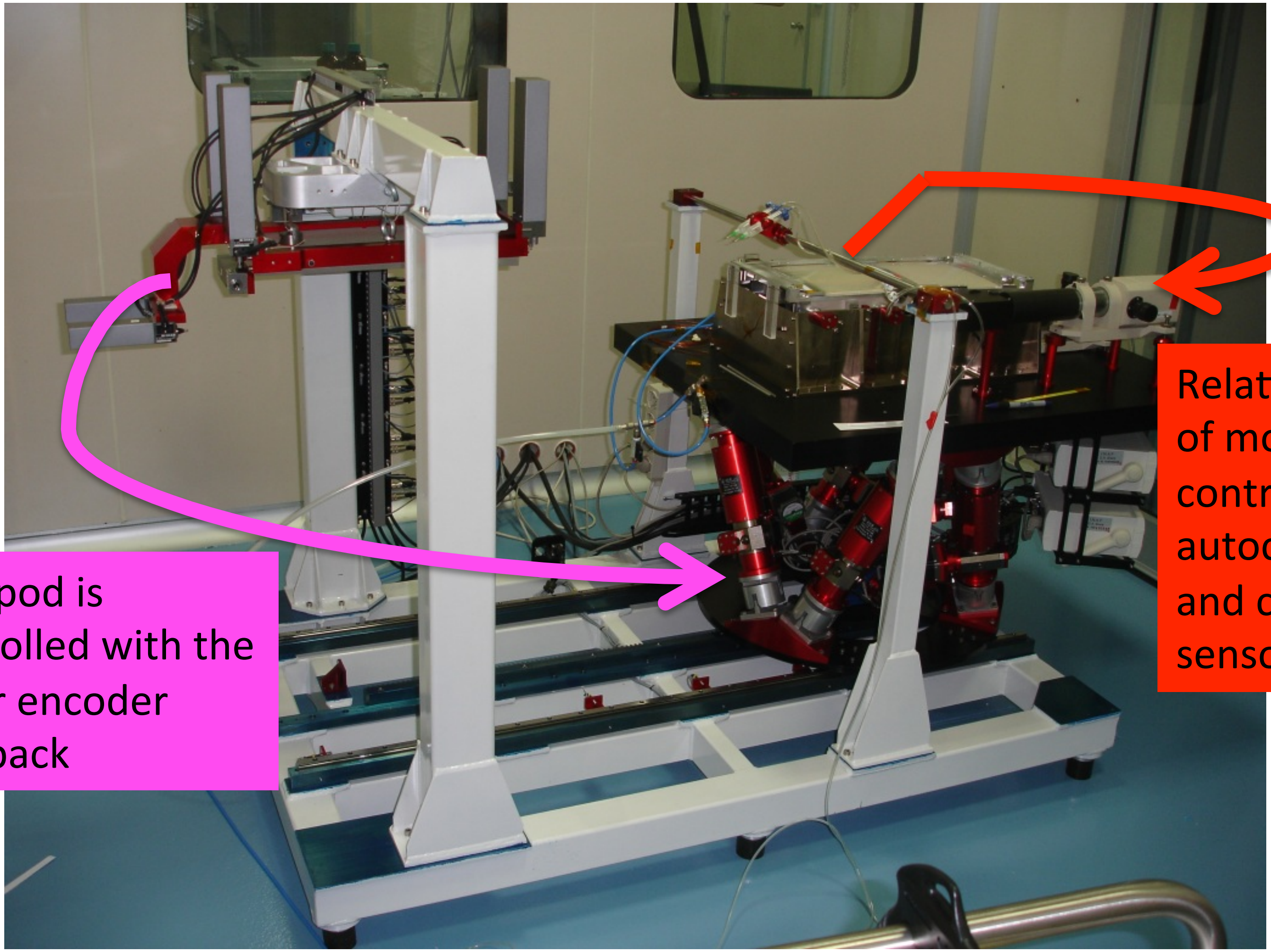






Measurement repeatability of 1’’

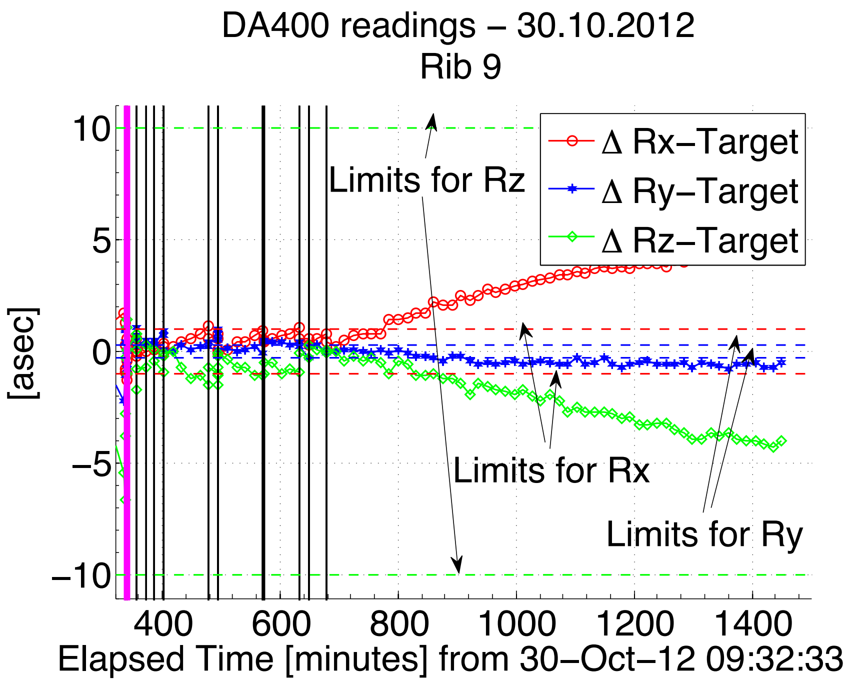
SGO: Integration MAchine (IMA)



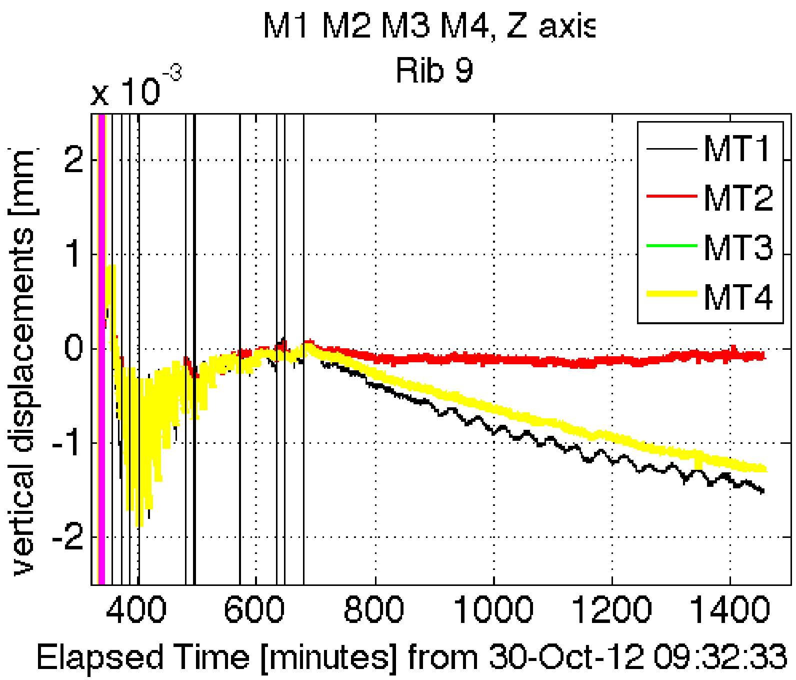
Hexapod is controlled with the linear encoder feedback

Relative attitude of molds in controlled with autocolllimators and capacitive sensors.

IMA control loops

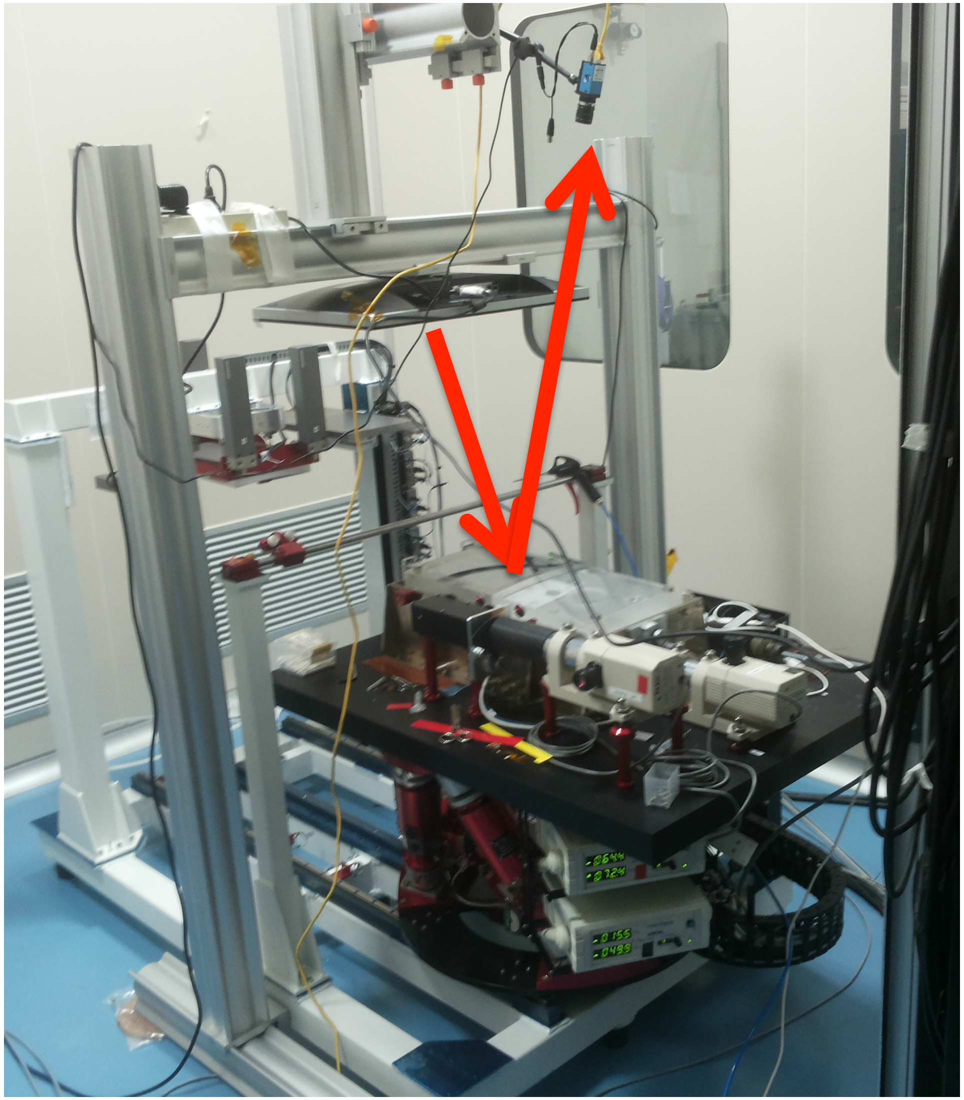


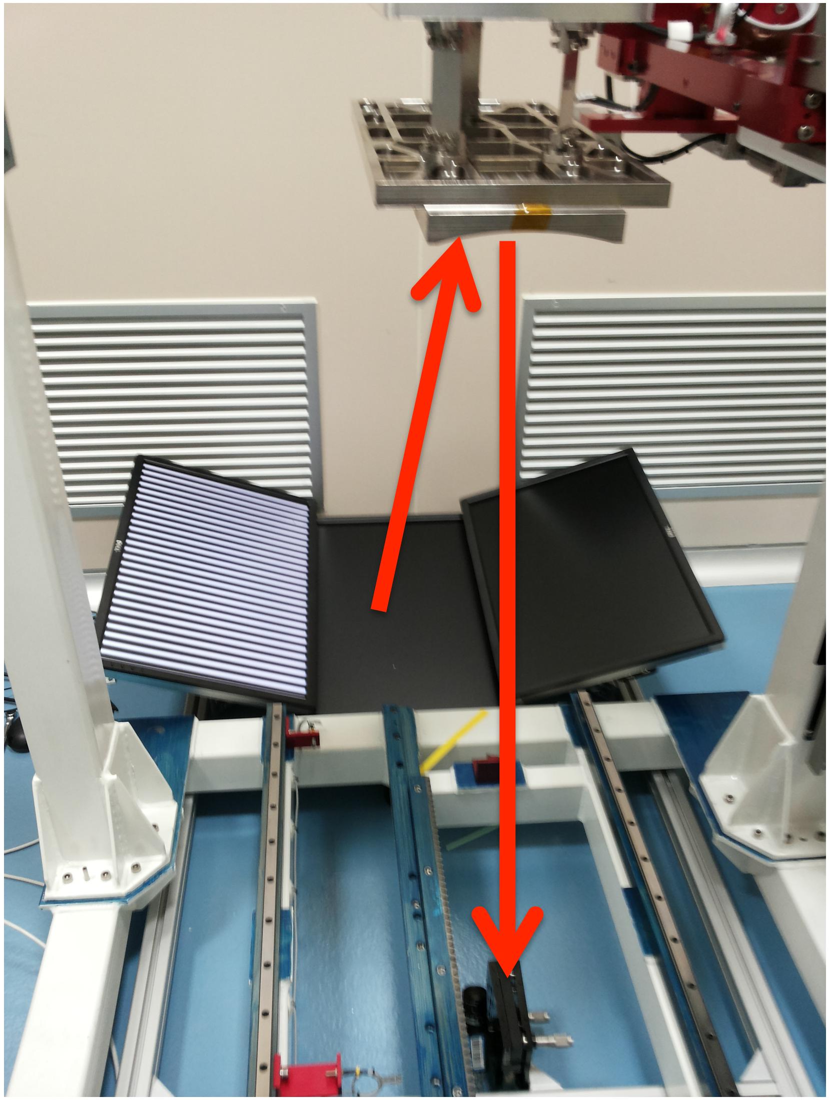
(a)



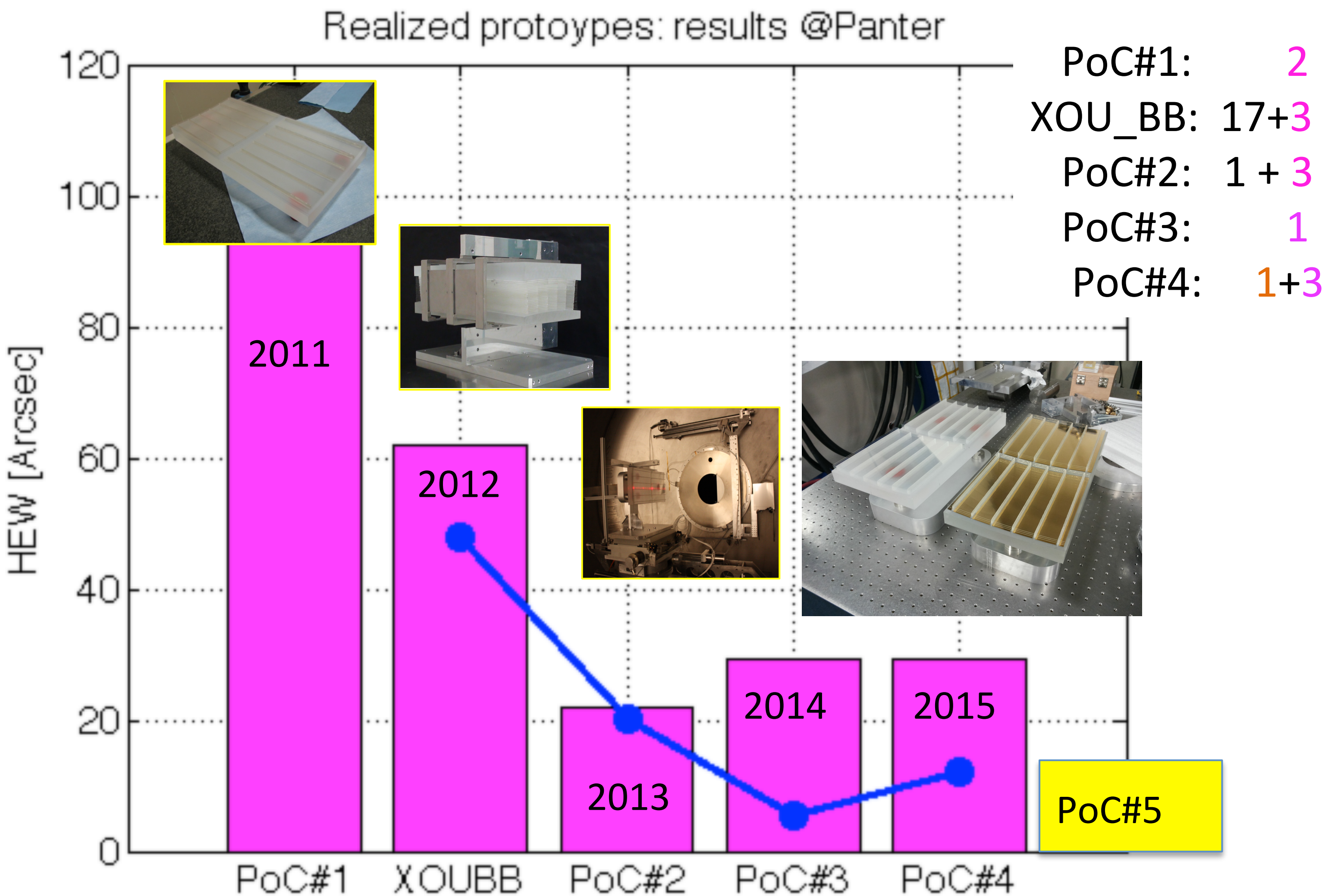
(b)

SGO: latest equipment based on deflectometry





SGO: results



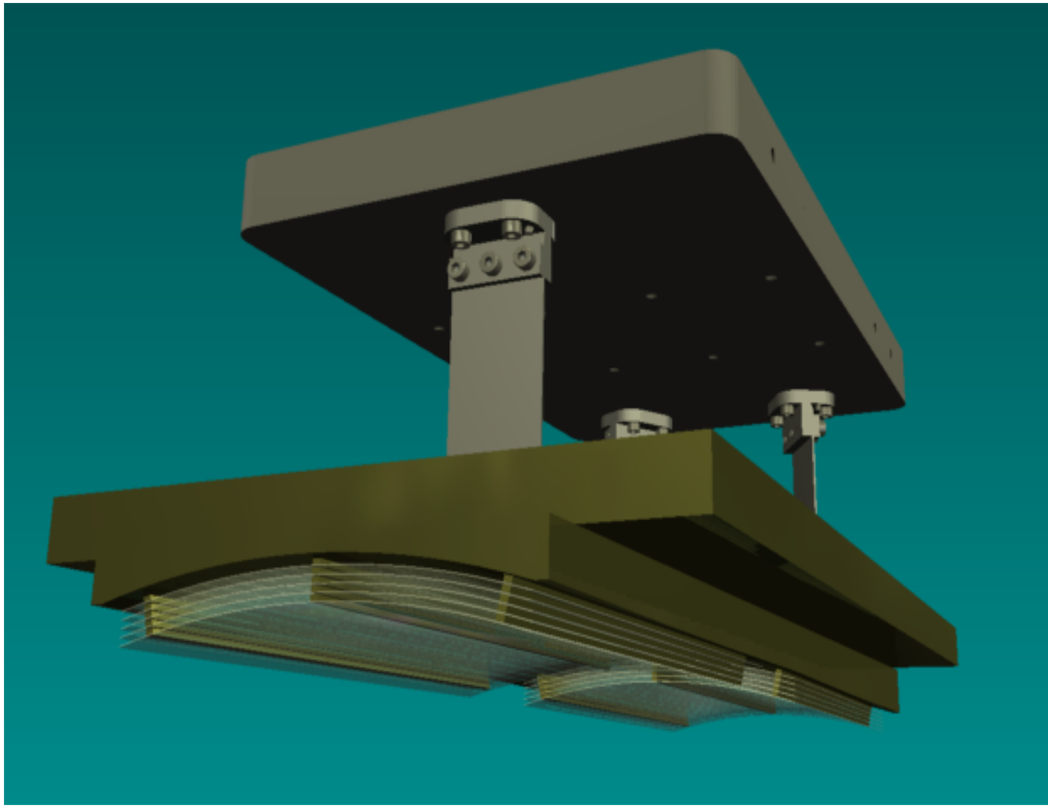
Realized protoypes: results @Panter
HEW [Arcsec]
120
100
80
60
40
20
0
2011
2012
2013
2014
2015
PoC#5
PoC#1
XOUBB
PoC#2
PoC#3
PoC#4
PoC#1: 2
XOU_BB: 17+3
PoC#2: 1 + 3
PoC#3: 1
PoC#4: 1+3

SGO: Proof Of Concept with NASA slumped glass

- One integration mold pair, in alluminium (radius @IP of 485mm and focal length of 8.4m) by LT-Ultra. Measured quality ≈ 10'' HEW

- The distance between the plates chosen for a fix rib thickness of 1.5mm (same order of the expected theoretical one for a module with this focal length and radius of curvature)

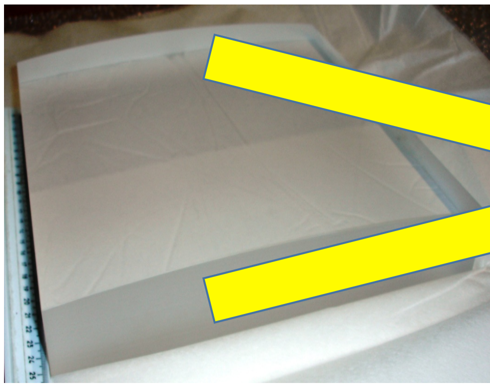
- Up to 5 different plate pairs integrated in co-aligned configuration

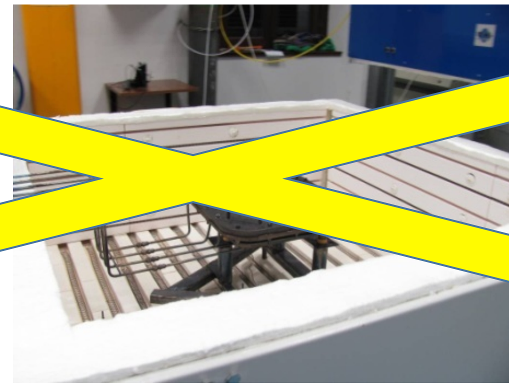


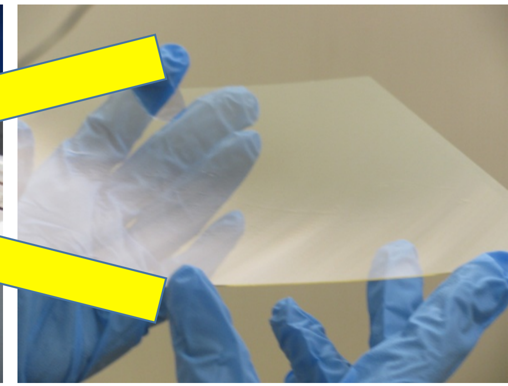
Cold Slumped Glass Optics

Forming molds | Slumping process | Result

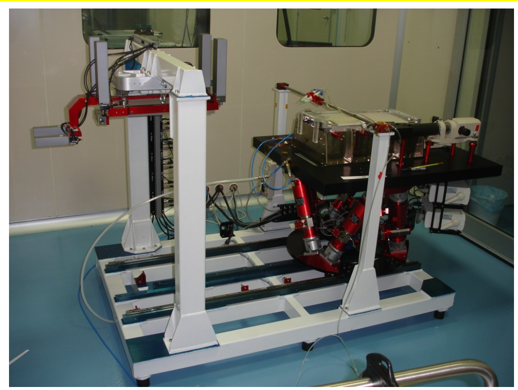
Hot slumping with active pressure to produce cylindrical glass plates

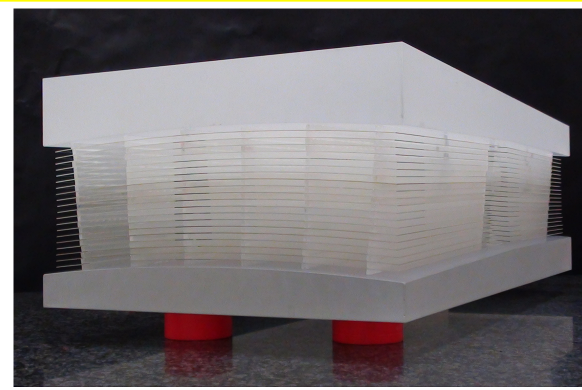






Cold slumping for plates shaping to Wolter I & alignement





Need of flexible glass: Willow as example

Ultra-slim flexible glass is a 50-200μm thick glass

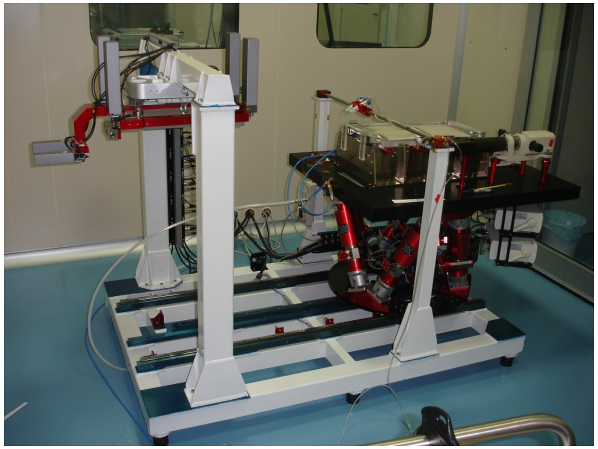
Fusion process

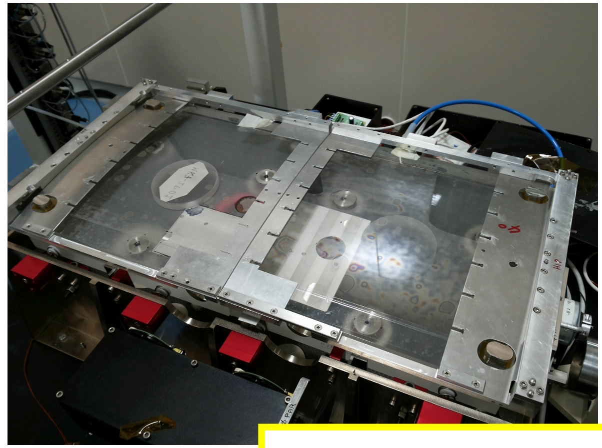
Sheets	250mm x 300mm
Rolls	10m long x 300mm wide
Quantity	Development quantities

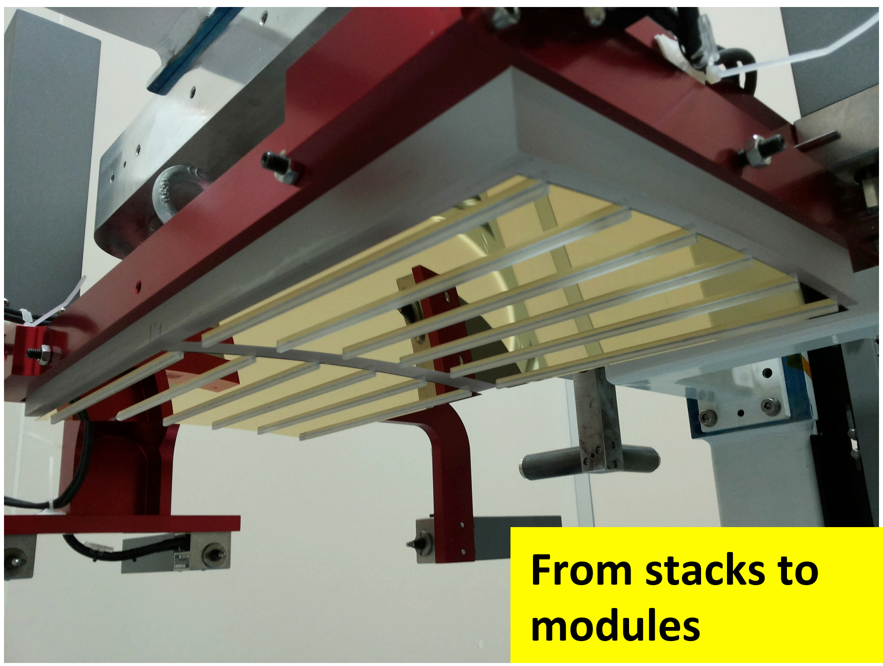
CORNING

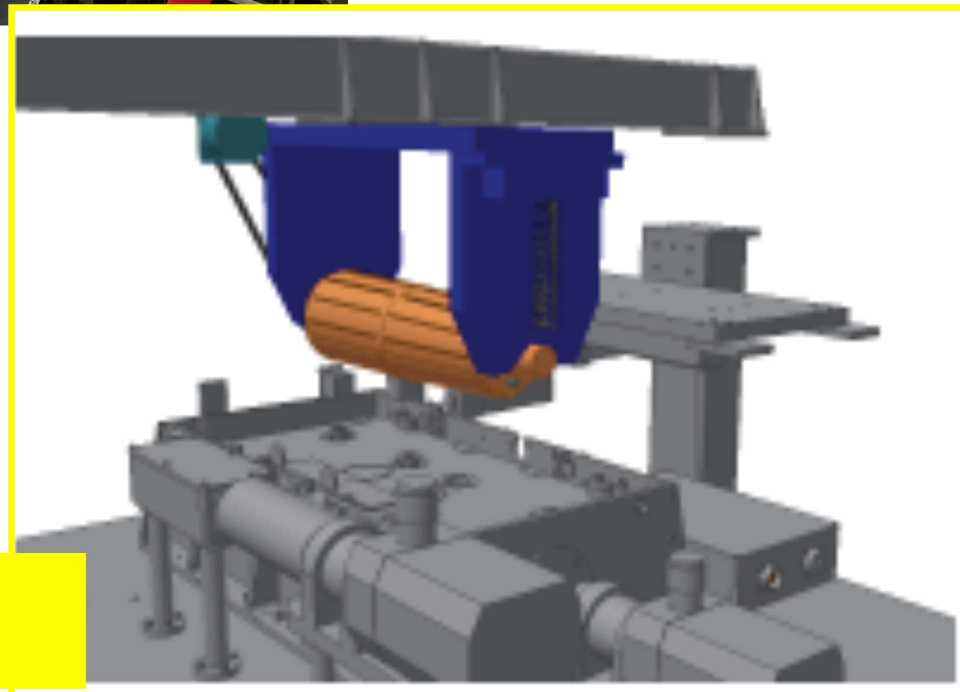
ONLY COLD INTEGRATION WITH REINFORCING RIBS

Integration Machine up-grade



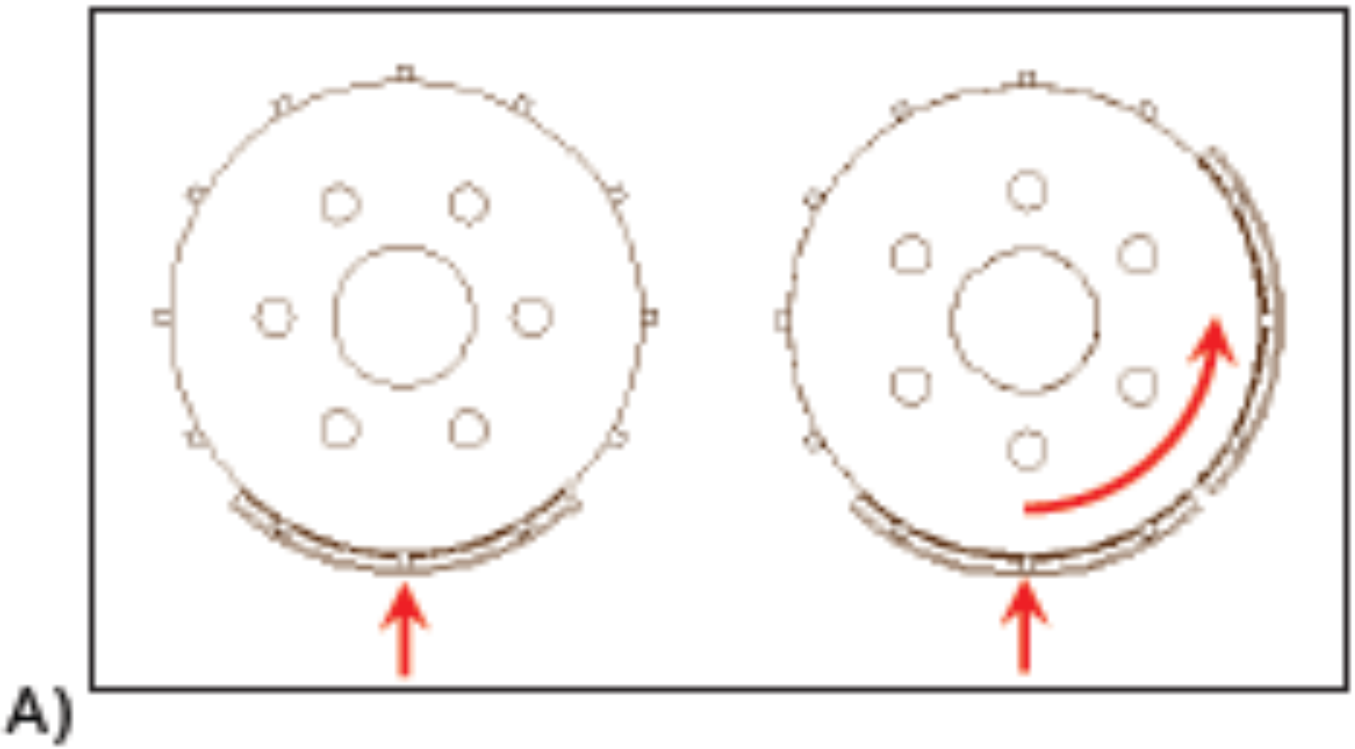






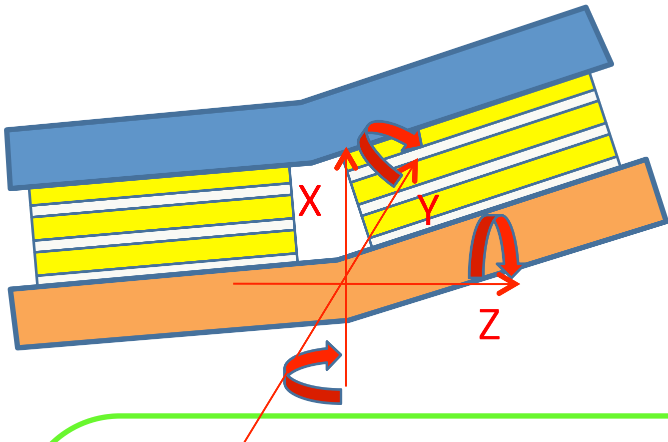
From stacks to modules

Integration procedure for not-modular optics



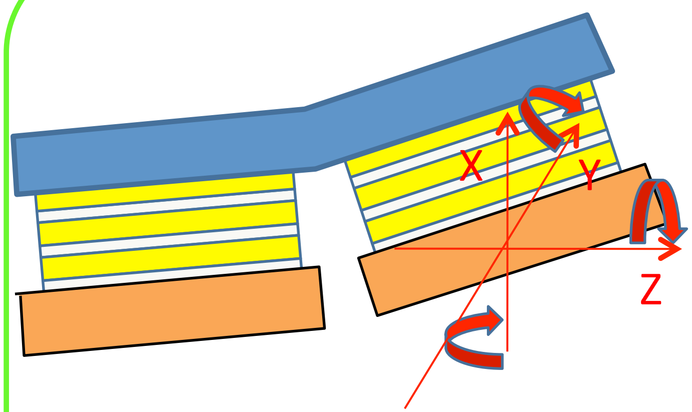
- The glass foils are integrated starting from the internal one
- The integration machine would be an updated version of our IMA used for S.G.O. (Slumped Glass Optic) prototypes

Enhance the range of opportunities



There is no need to control with high accuracy the alignment of the mould

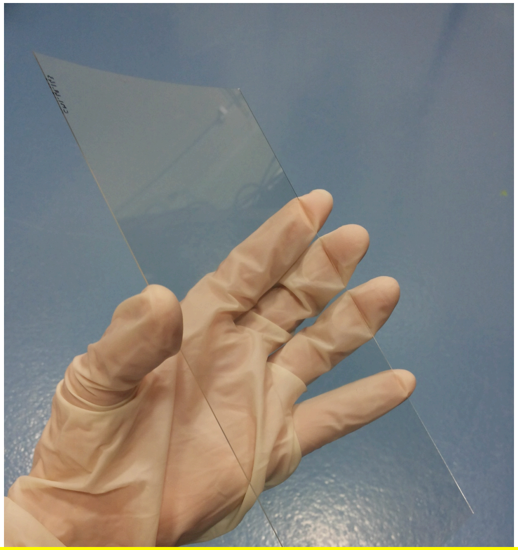
High tolerances on mould realization

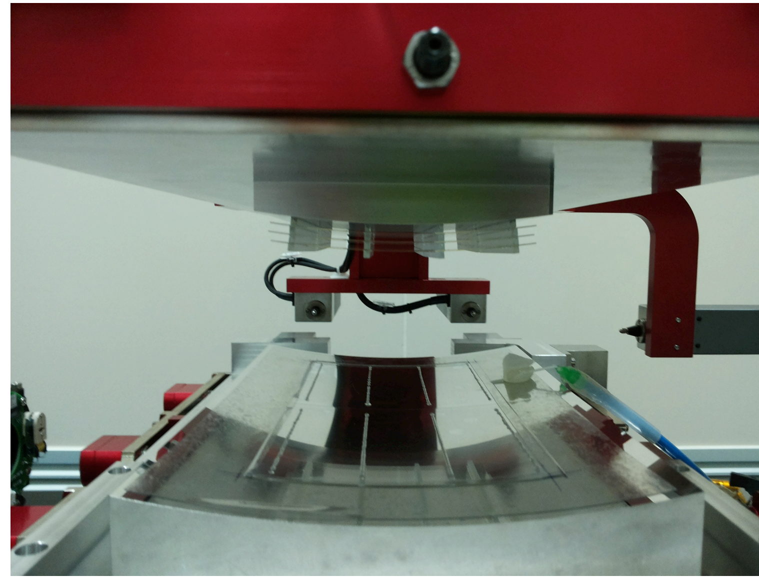


The alignment of the two plate has to be controlled with high accuracy

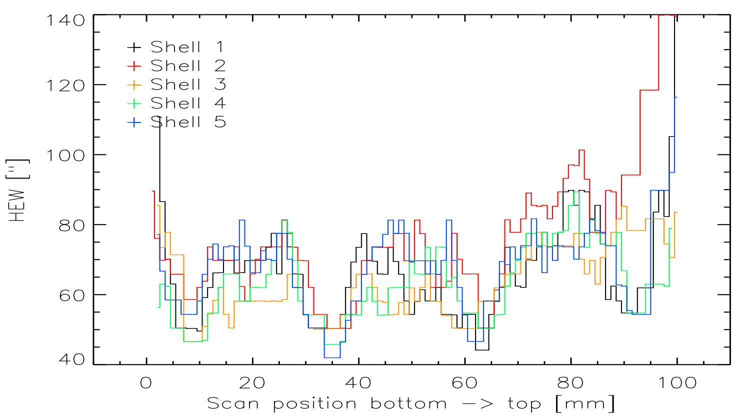
Higher flexibility in the design and mould fabrication error correction capability

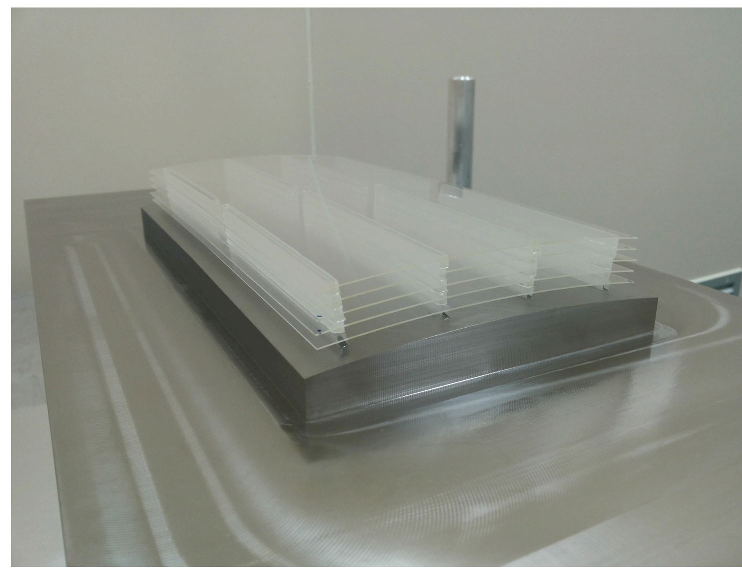
Indirect integration on IMA: JIM1 MPE SGO



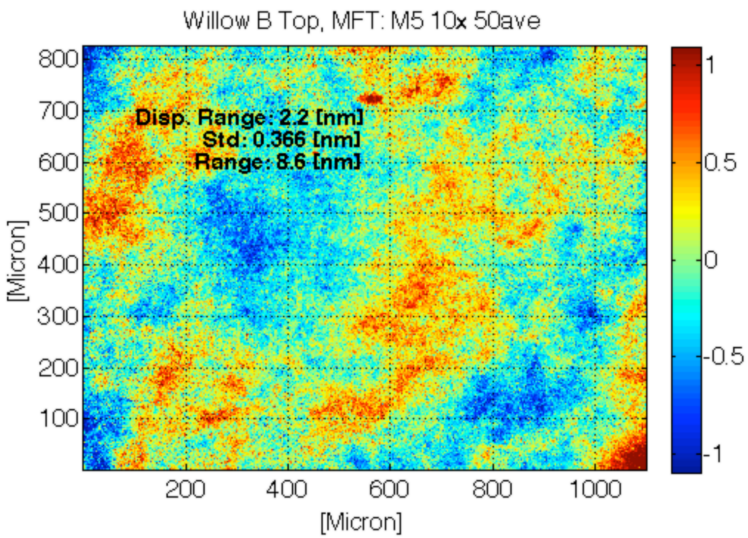


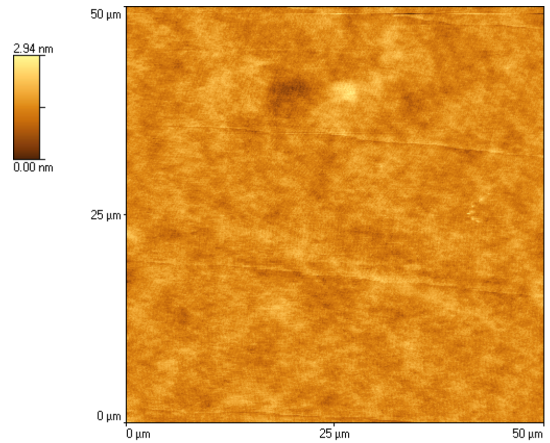
Indirect slumped glass
Monolithic indirect integration mold
Realized 02/2015

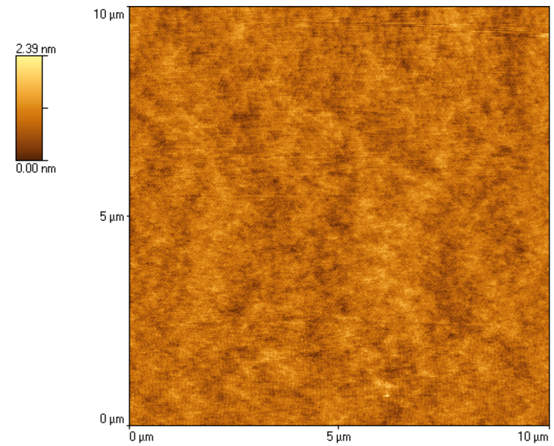




Willow Glass: MICRO-ROUGHNESS







MFT 1000 microns:
σ = 0.35nm
PtV =8.6nm

AFM 50 microns:
σ = 2.3A
PtV =2.9nm

AFM 10 microns:
σ = 2.4A
PtV 2.4nm

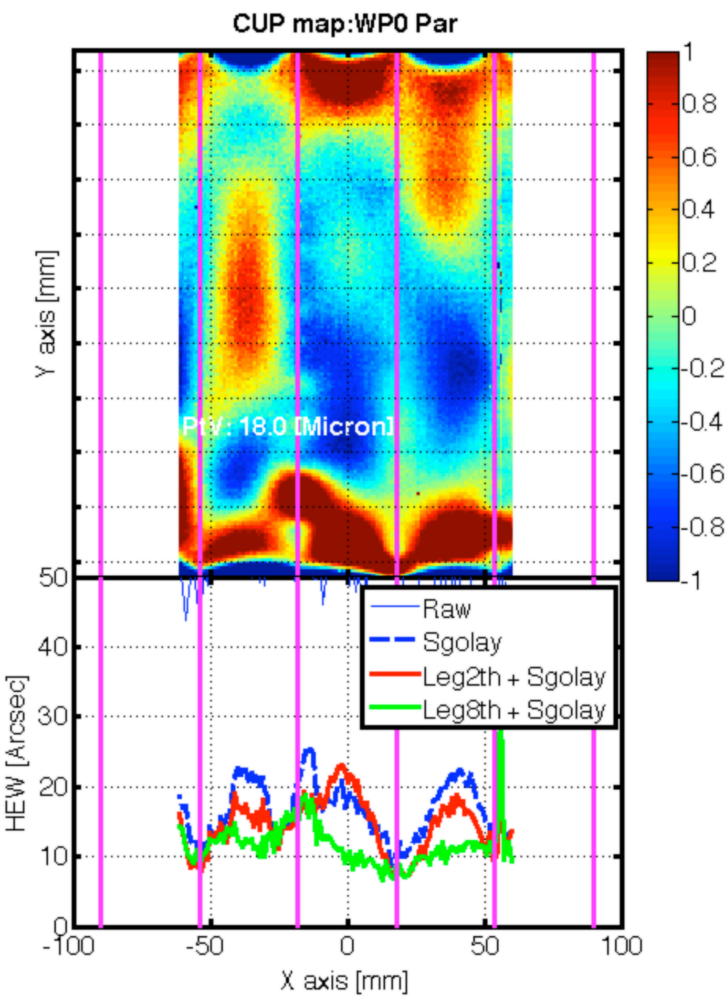
→ **Ideal substrate for coating application**

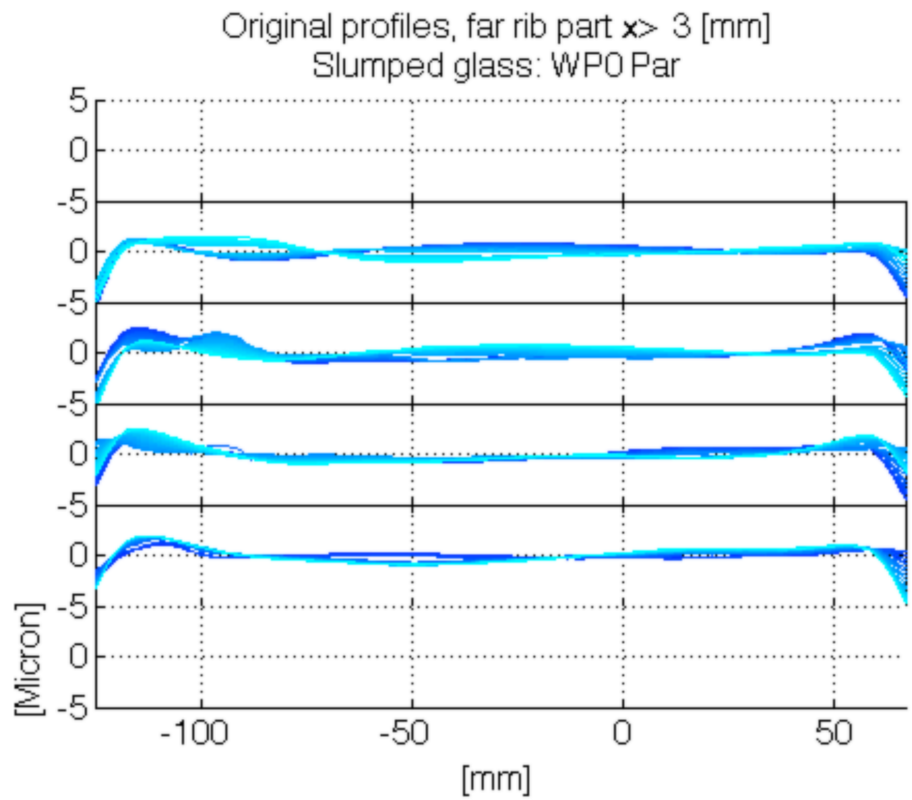
WP0 prototype: CONFIGURATION

- Glass Material: Willow from Corning
- Plate size: 200x200x0.2mm
- Ribs: Bk7
- Backplane: alluminium

- Focal lenght = 20m
- Radius of curvature = 1m.
- Integration mold: Bk7 (used also for slumped glass for PoC2,PoC3 and Poc4 modules)
- Integrated with IMA.

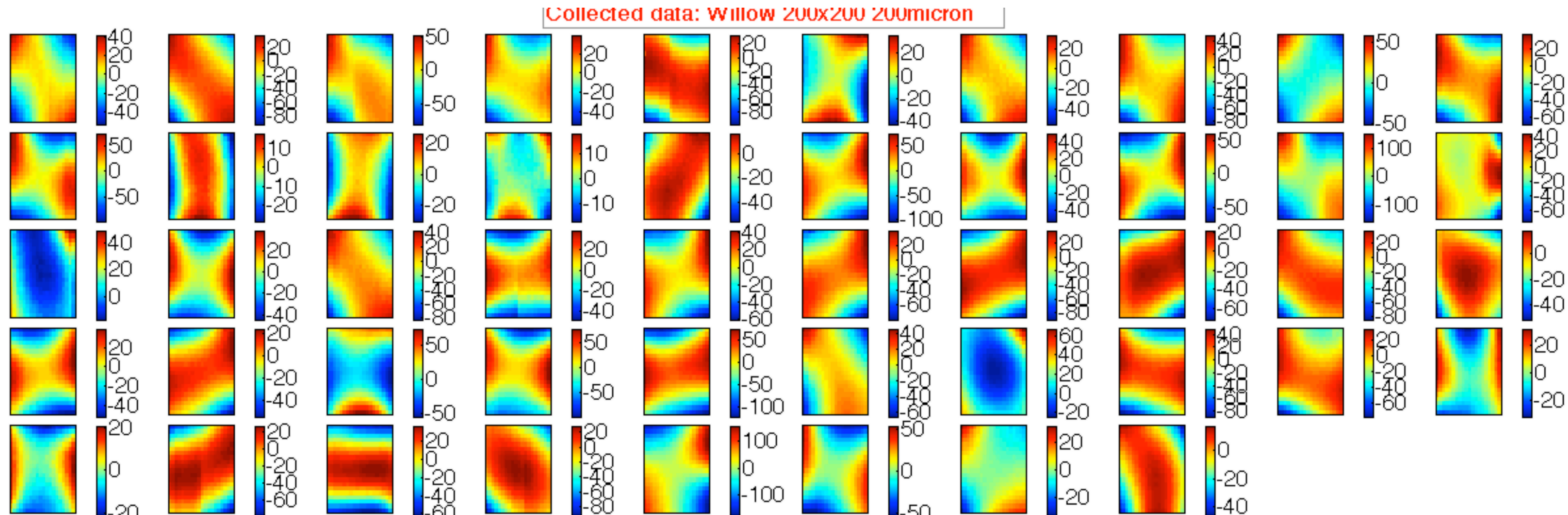
WP0 prototype: PRELIMINARY RESULTS

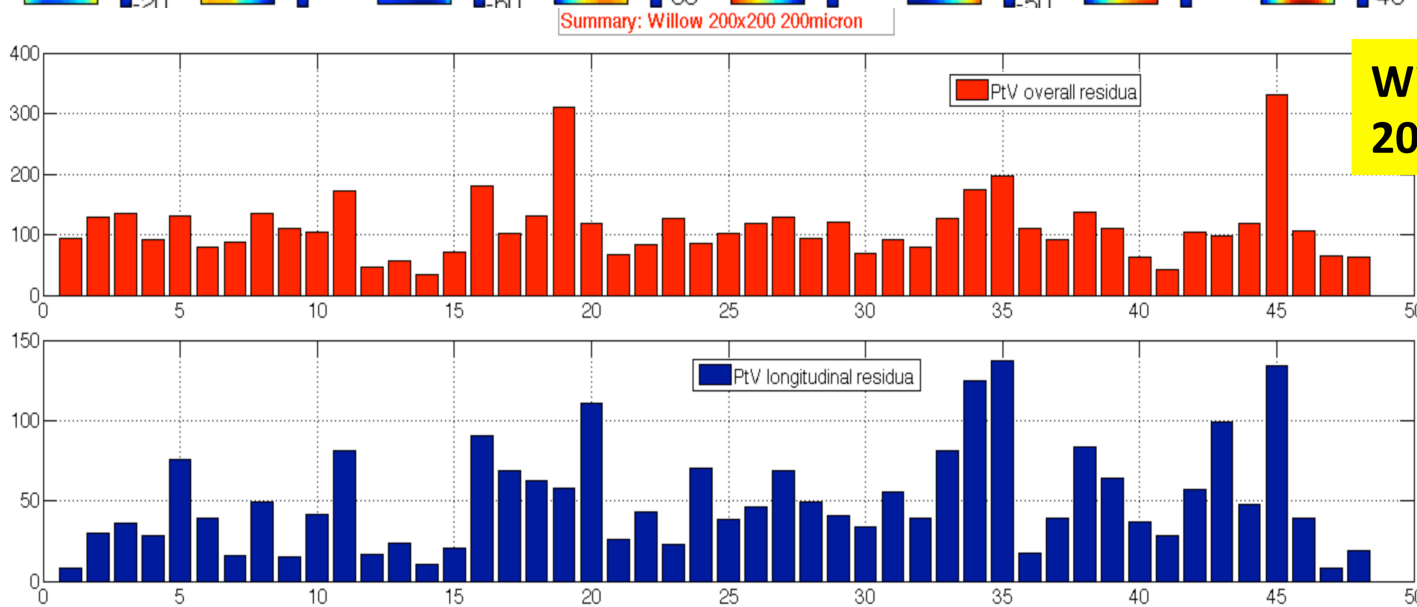




Very promising result:
→ HEW ≈ 20'' single reflection

Willow Glass: Initial residual error



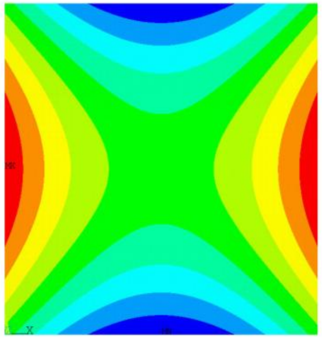


Willow glass 200x200x0.2mm

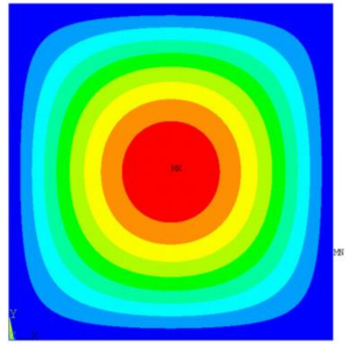
FEM simulations of expected results

BCV
simulations

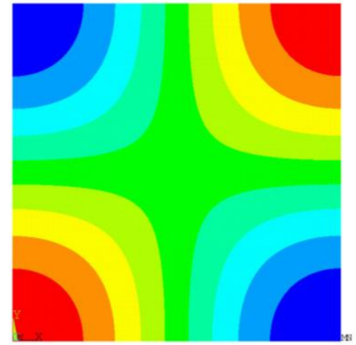
R@IP=150-400mm
F = 12m



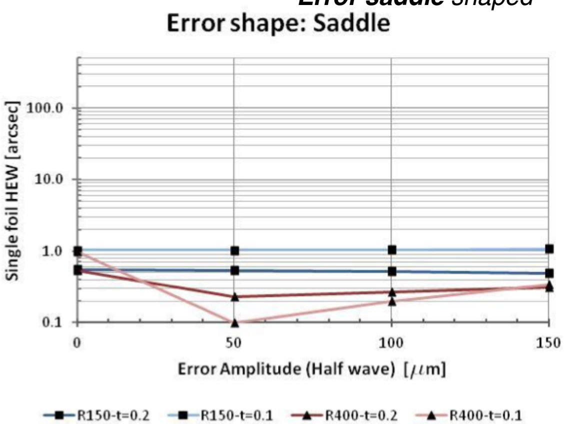
Error saddle *shaped*

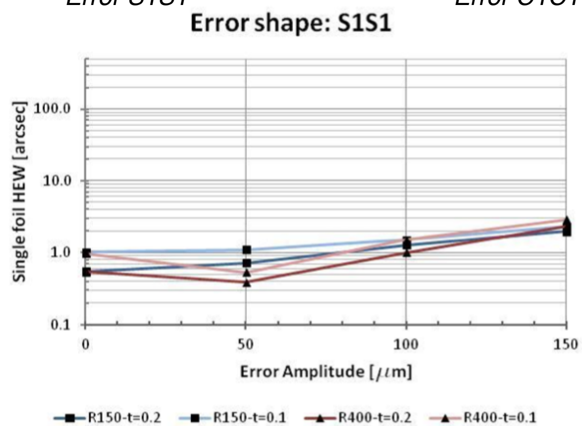


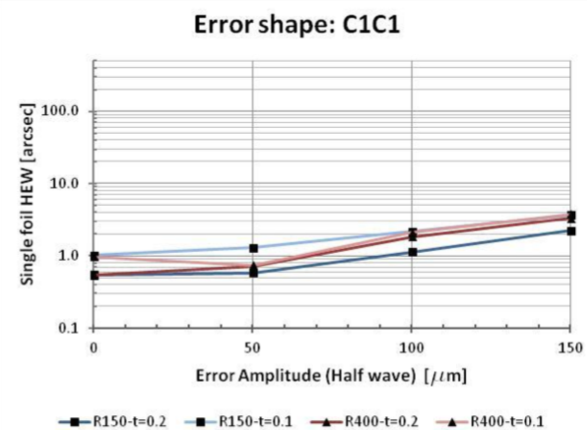
Error S1S1

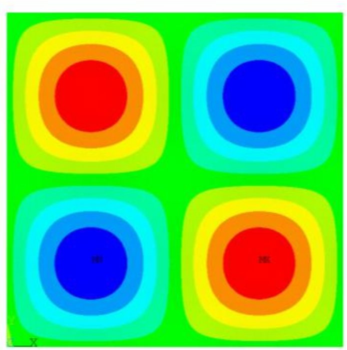


Error C1C1

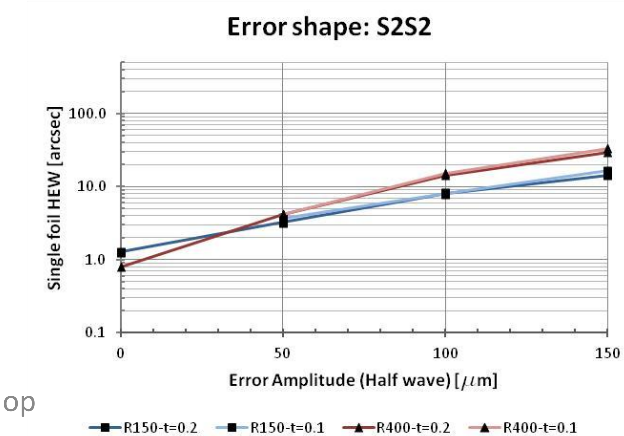






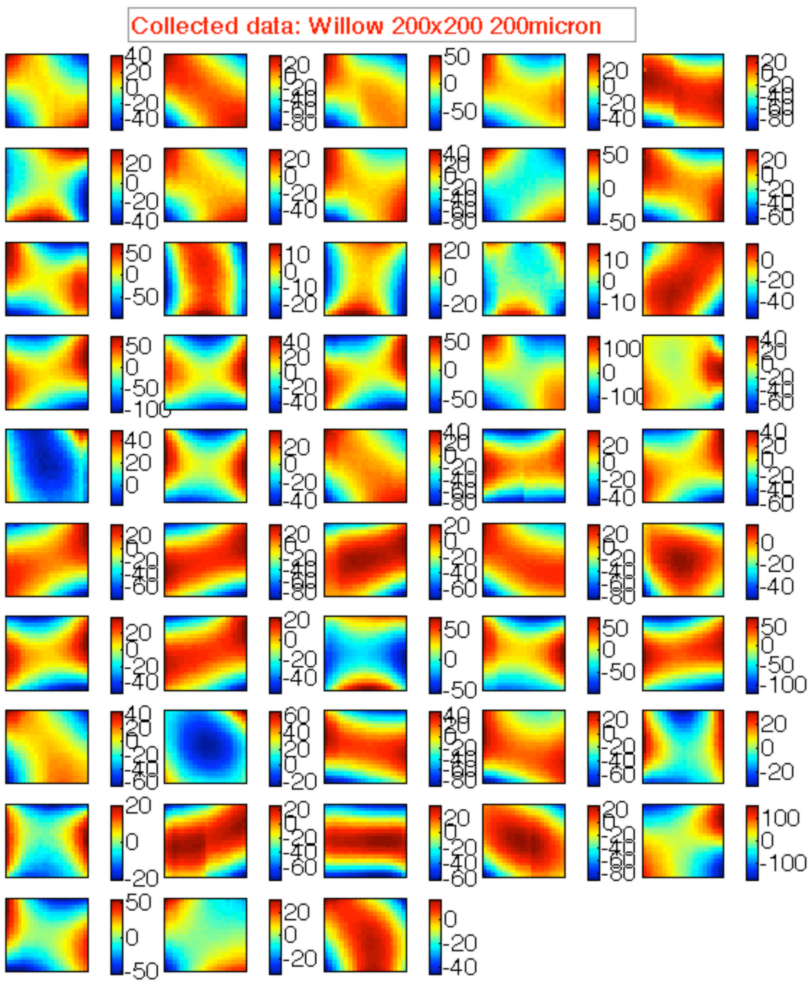


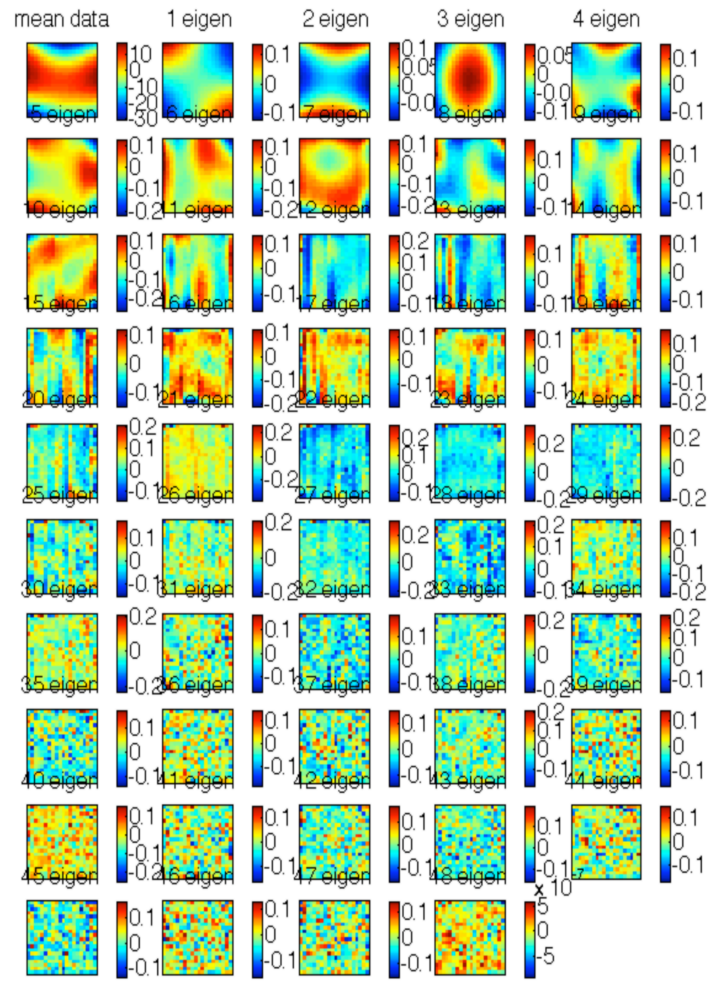
Error S2S2



Willow Glass: Principal Component Analysis

Measured figure error on latest acquired samples:
200 x 200 x 0.2mm



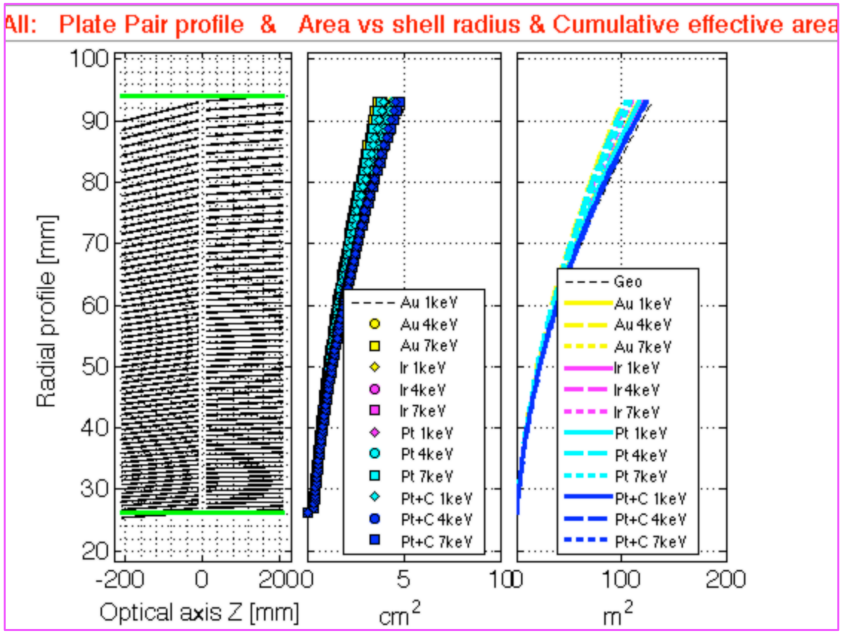


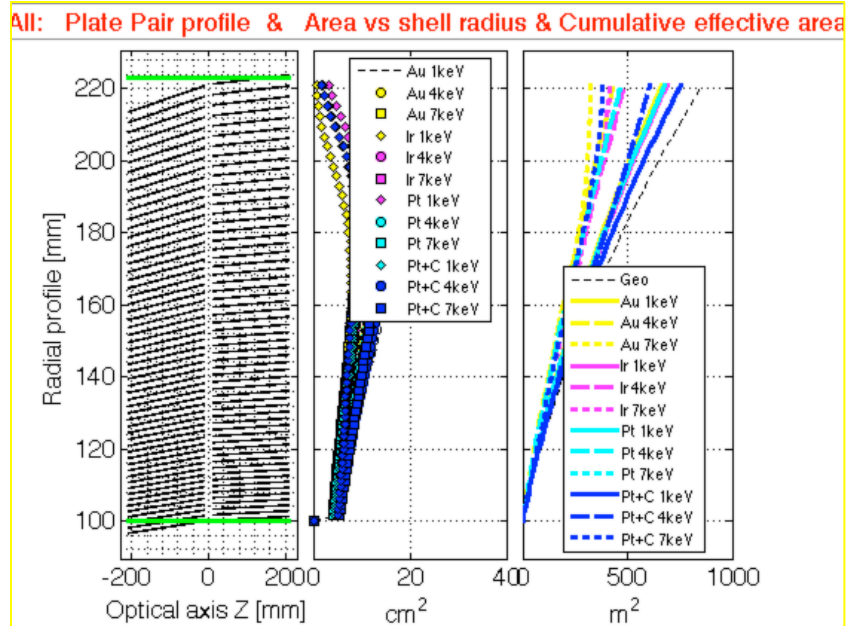
XTP: telescopes

	HFA	LFA
Number of telescopes	5	8+2
Focal Length	5.5m	4.5m
Aperture	550mm	450mm
Envelope max diam.	<=650mm	<=550mm
Energy range	>800 cm^2 @2-6keV >60cm^2 @30keV	0.5-10keV
FoV	16armin	16 arcmin (8 telescopes) 12 arcmin (2 telescopes)
Angular resolution	1 arcmin	1 arcmin (8telescopes) 15’’ (2 telescopes)
Mass	<50kg	<=40kg

→ To save weight: low density material as glass/graphite
→ To save money: cost reduction of current production process
→ To save time: process semplification

LFA Optical design: Effective area per Shell





	Inner part	Outer part
Radial limit	26.3-94mm	100-223mm
NumShell	68	57
GlassWeight	≈ 1.2kg	≈7.5 Kg
GlassThickness	0.03-0.1mm	0.1-0.2mm
RangeRibThickness	≈ 0.65-1.45mm	≈ 1.6-3mm
WeightRib	≈ 1.2Kg	≈ 5Kg

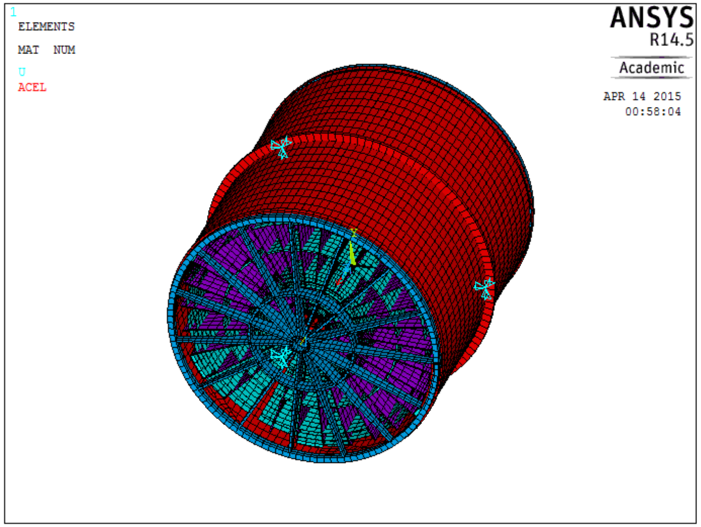
LFA: RAW cost estimation

# Oven	3
# IMA	8
# Module	8
# Shell xModule	100
# Ave shell azimutal	4,5
# Tot Glass Module	450
# Tot Glass sheet	900
# Shell integration Xday	1
# Shell slumping Xday	15
Integration Time (years)	2,25
Slumping time	0,3
TOTAL TIME per XTP years	2,25

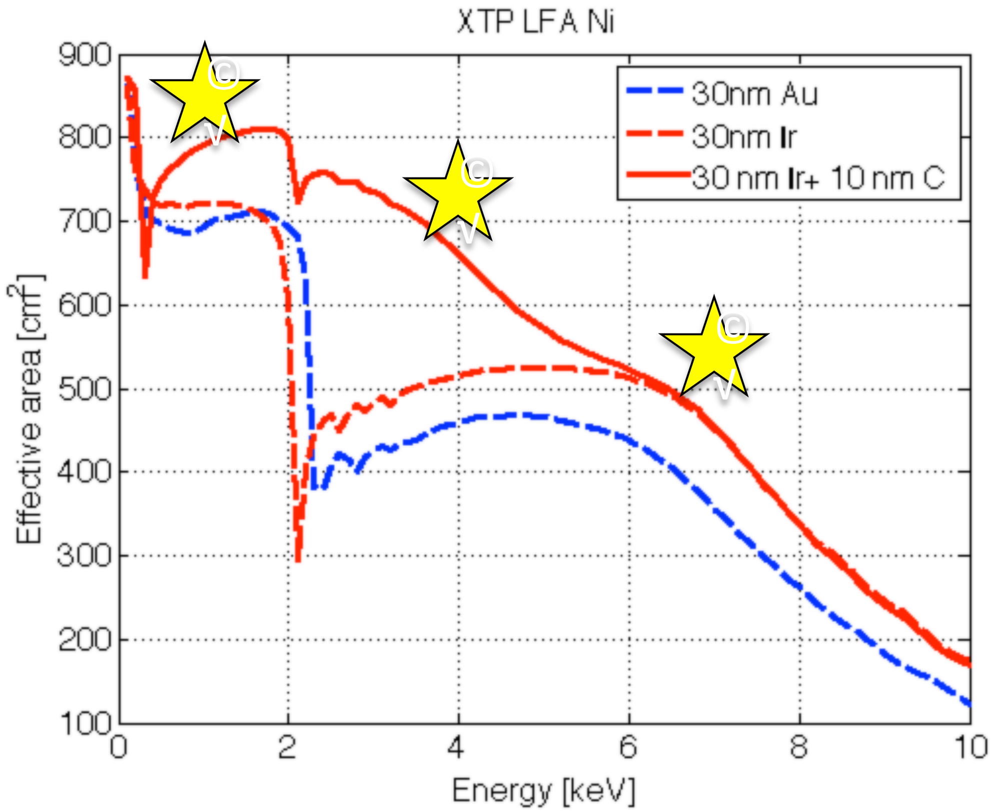
5-10 Meuro for LFA

Cost IMA				200000	1600000
autocollimator	18000	2	36000		
hexapod	40000	1	40000		
linear encoder	5000	7	35000		
other	10000	1	10000		
partial			121000		
Cost Mandrel				1000000	1000000
scale factor mandrini	4				
unitary price	5000				
# Mandrel (Par+Hyp)	50				
# mandrel for parallel usage	4				
Cost Oven				45000	45000
Oven price	15000				
# Oven	3				
Cost Ribs				54000	432000
unitary price	10				
# ave azimutal	54				
# ribs x module	5400				
Cost structure	30000			30000	240000
Cost Glass	10			2000	16000
Cost Manpower				288000	2214000
Unitary price xYear	60000				
# person x oven	1		18000		
# persone x IMA	2		270000		
Cost Trasportation				100000	800000
unitart price	100000				
TOTAL COST (MEuro)				1,719	6,347

Proposed concept for XTP LFA: Nichel Vs Glass



Parts	Material	[kg]
spiders	Titanium	5.57
Internal shaft	Invar	1.92
Ribs	Graphite	6.55
Shells	Willow	6.60
mid and back planes	Borofloat33	6.58
Blades	Invar	0.64
Case	Invar	7.98
TOT.		35.85



	Value
Radial limit IP	100-217 mm
NumShell	39
Shell Weight	≈29kg
Shell Thickness	0.1-0.2mm

Conclusions

- Trade off among different technologies for IAXO to be studied as Nikel replication still attractive

- The results obtained so far in prototypal realization based on hot/cold glass slumping process are very promising and are fully compatible with an HEW below 1arcmin.

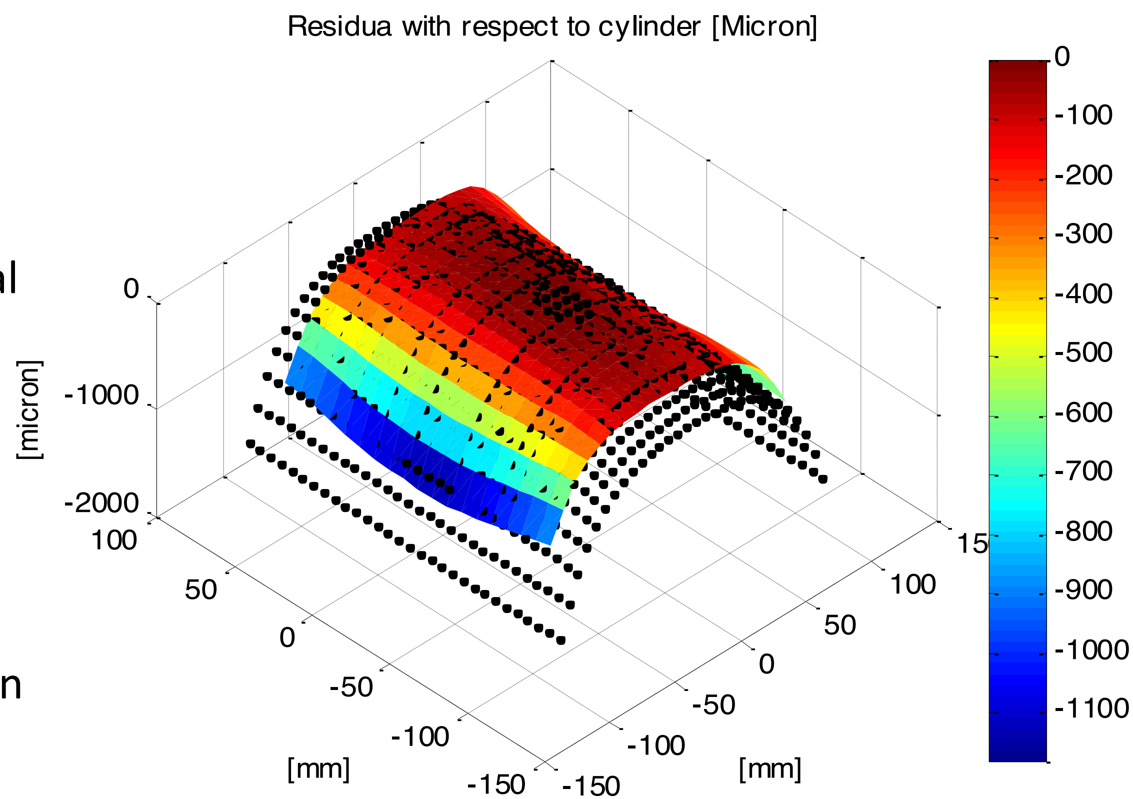
- The cold slumping approach is an effective solution for low cheap/fast production of x-ray optics.

- Ready for collaborations in different missions as XTP /IAXO

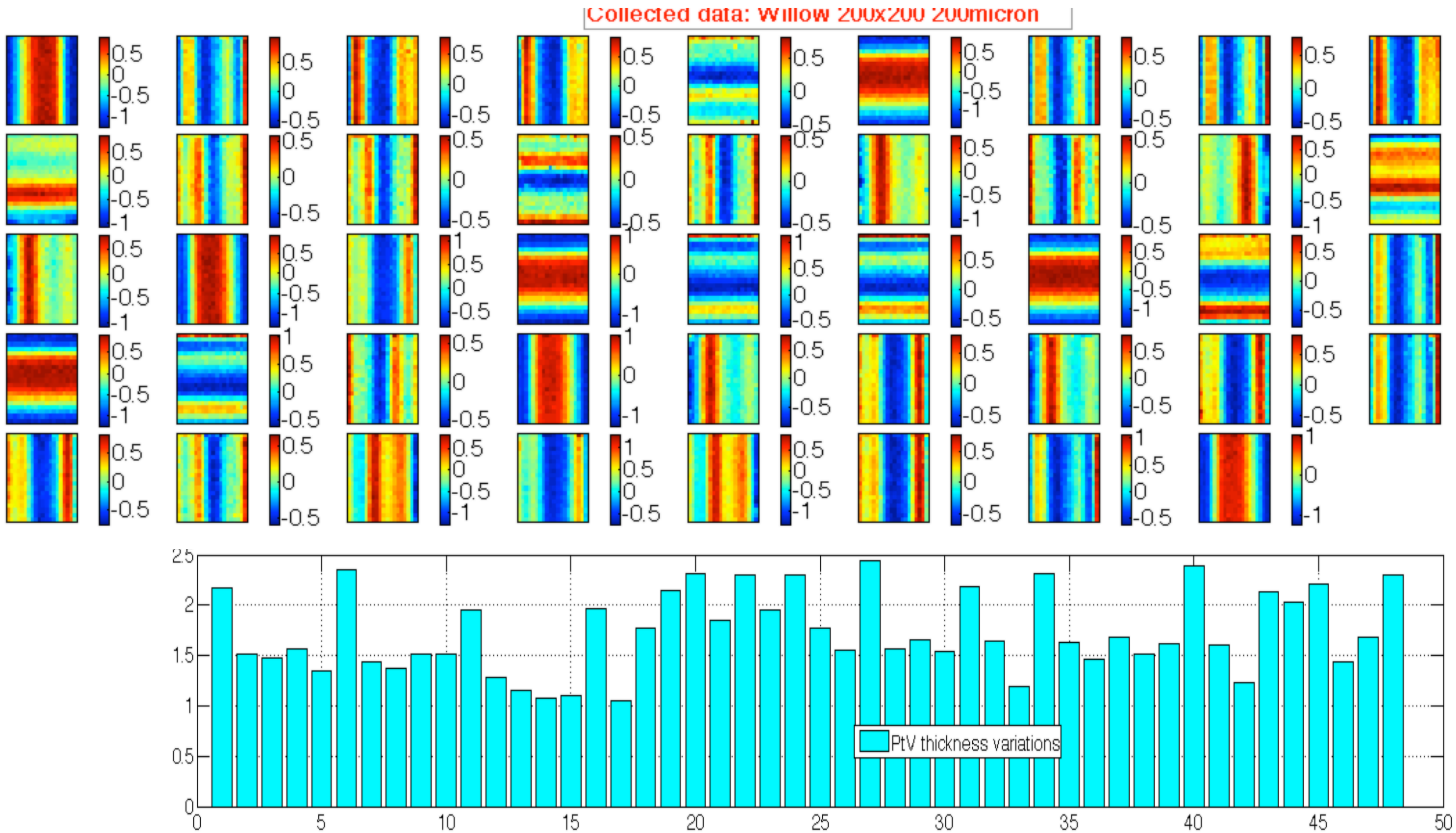
Gravity assisted slumping

Preliminary test perfomed
On glass D263,
Size:
200 mm x 200 mm x 0.4 mm:

→ Achieved Pseudo cylindrical configuration with <100Micron longitudinal error
→ Achieved radius of curvature ≈ 500mm
→ After integration expected HEW ≈ 25 ’’ single reflection



Willow Glass: THICKNESS VARIATIONS



→ Choosing the right direction the impact to the HEW is negligeble even if indirect integration techinique is applied.