Silicon Pore Optics for IXO

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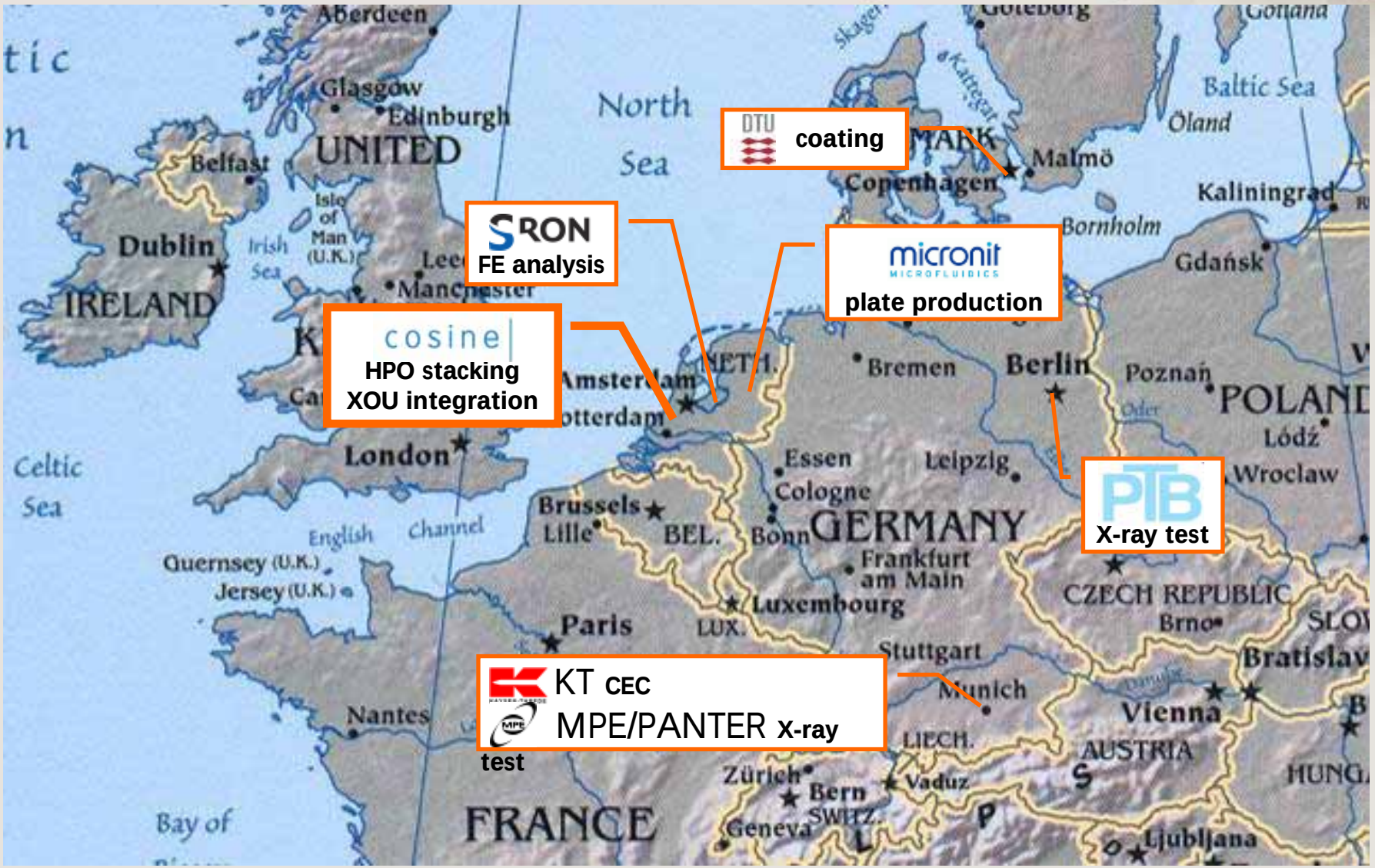
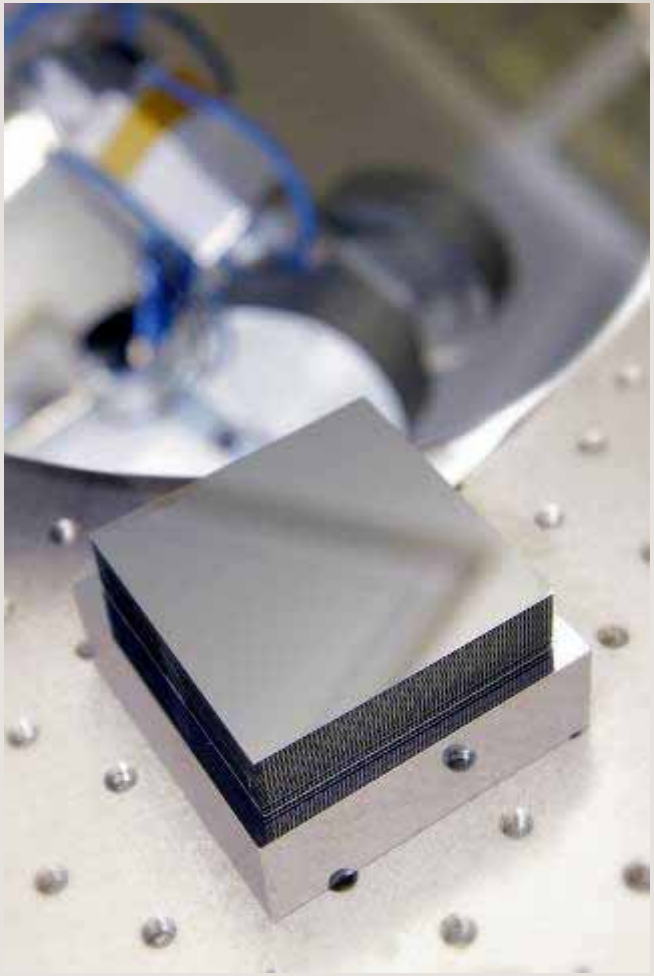


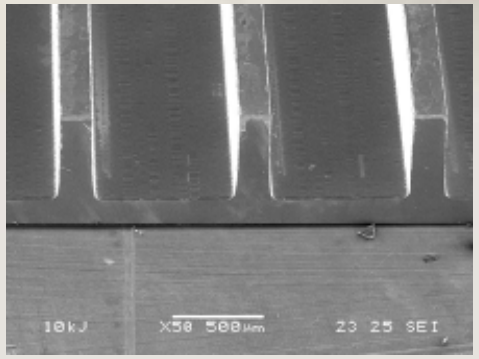
Outline

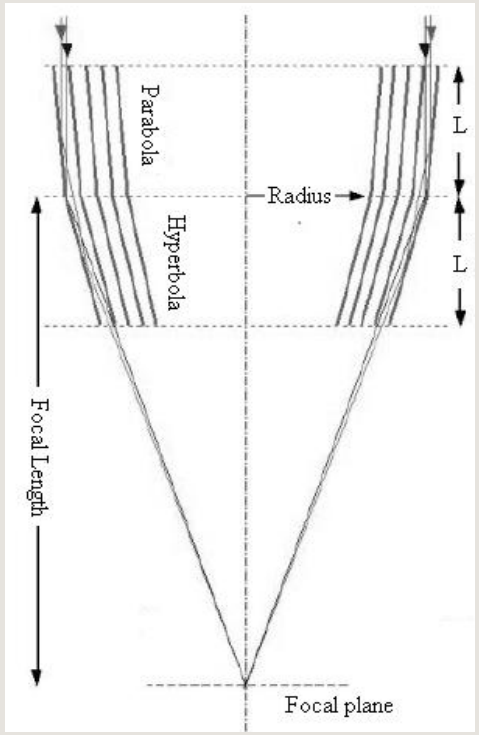
- Silicon Pore Optics
  - **Principles of stacking**
- Recent developments
- Status
  - **X-ray measurements**
- Near future



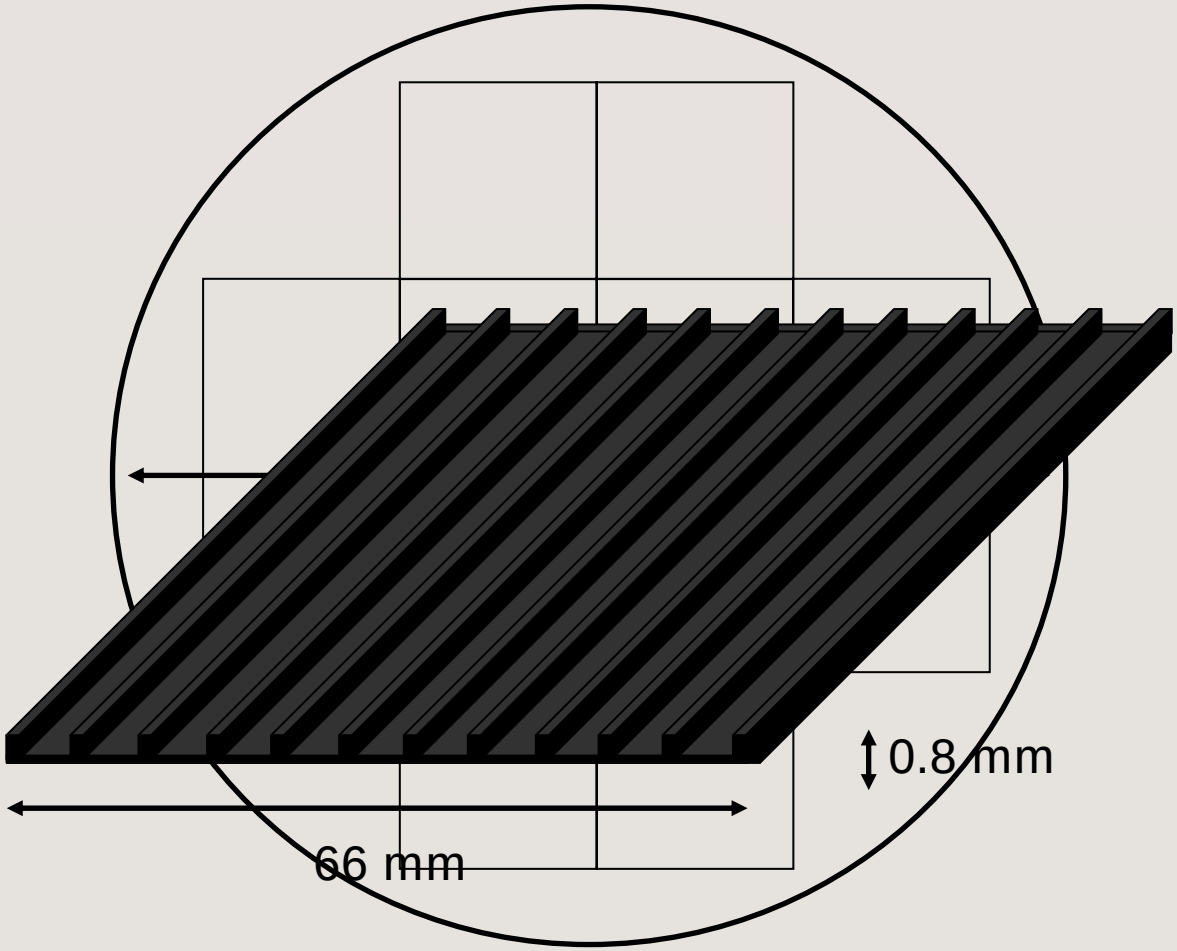
Silicon Pore Optics

- Technology for Future X-ray imagers
  - **Low mass** ***< 200 kg/m²***
  - **High resolution** ***5 arcsec (goal 2 arcsec)***
  - **Large effective area** ***5 m²***
- Principle:
  - **inherently stiff stacks of mirrors and spacers**
  - **Beijersbergen et al., SPIE 5488, p. 868 (2004)**
- Uses commercial high-quality 12” silicon wafers for DRAM production
  - **plan-parallel < 3 (0.6) μm over 300 mm**
  - **TTV < 1 μm over 300 mm**
  - **large-scale production, cheap**
- Surface finish
  - **determined during wafer production**
  - **50 × 50 μm² σ_{rms} < 0.1 nm (AFM)**
  - **not significantly influenced by dicing, ribbing and assembly process**
- Figure
  - **Determined during assembly process**





Stacking of silicon pore optics – plate production 1/2



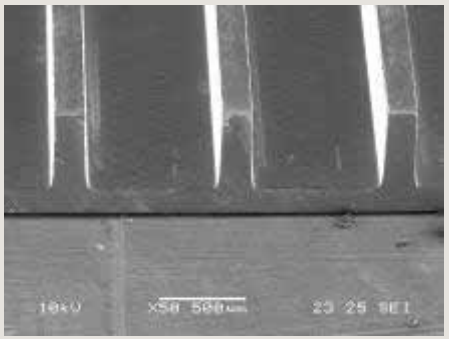
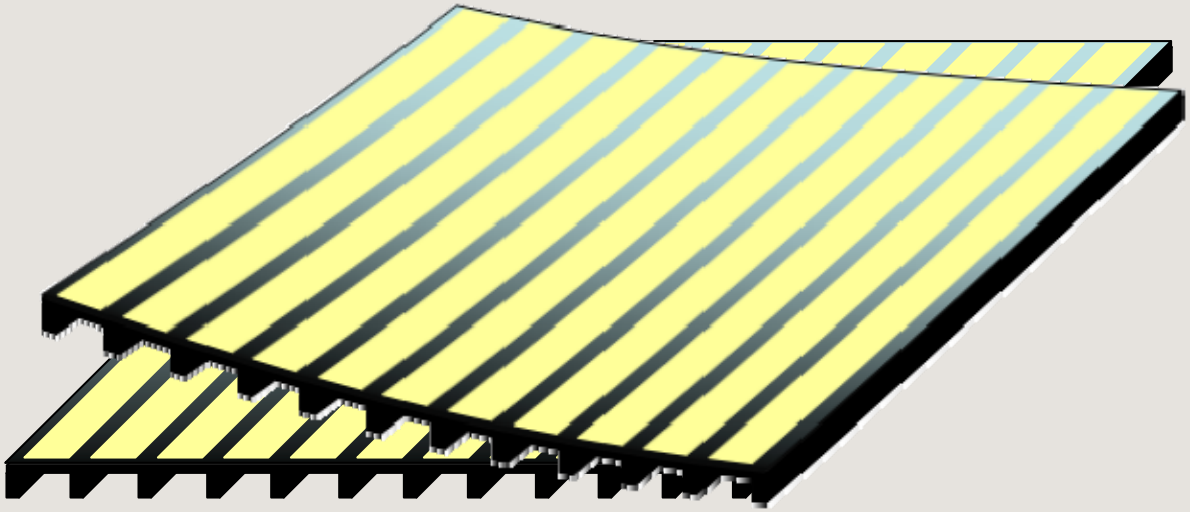


Plate dicing and ribbing

Conventional 300 mm diameter double-sided polished wafer

Stacking of silicon pore optics – plate production 2/2



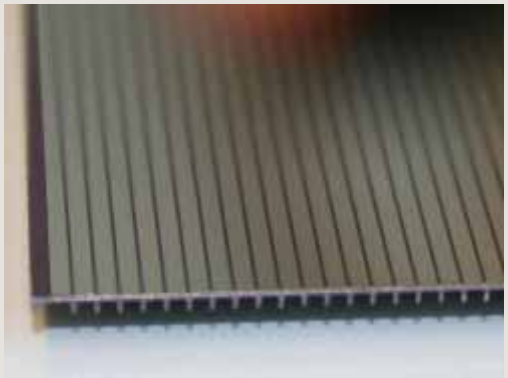
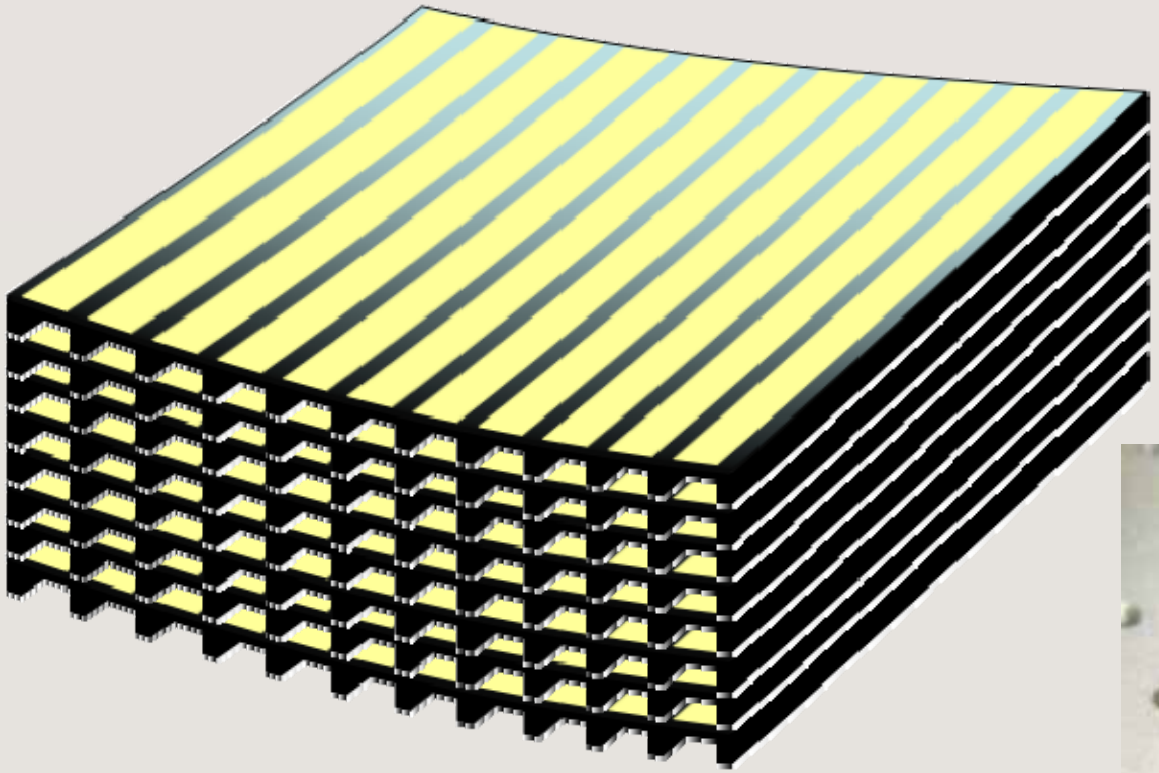


Plate wedging, coating and bending

Stacking of silicon pore optics – stack production



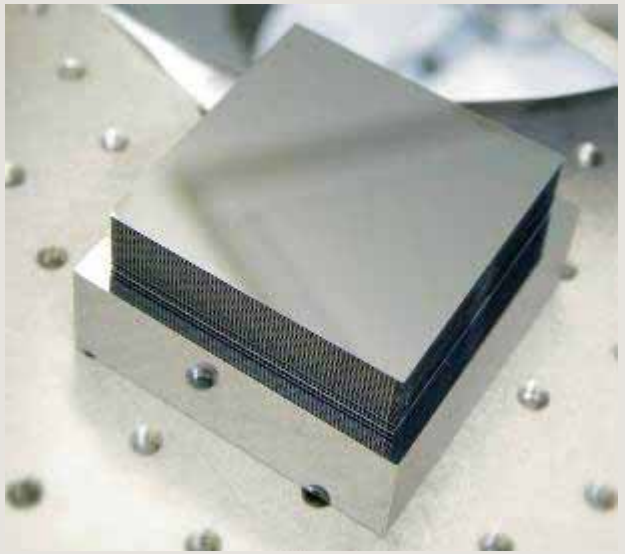
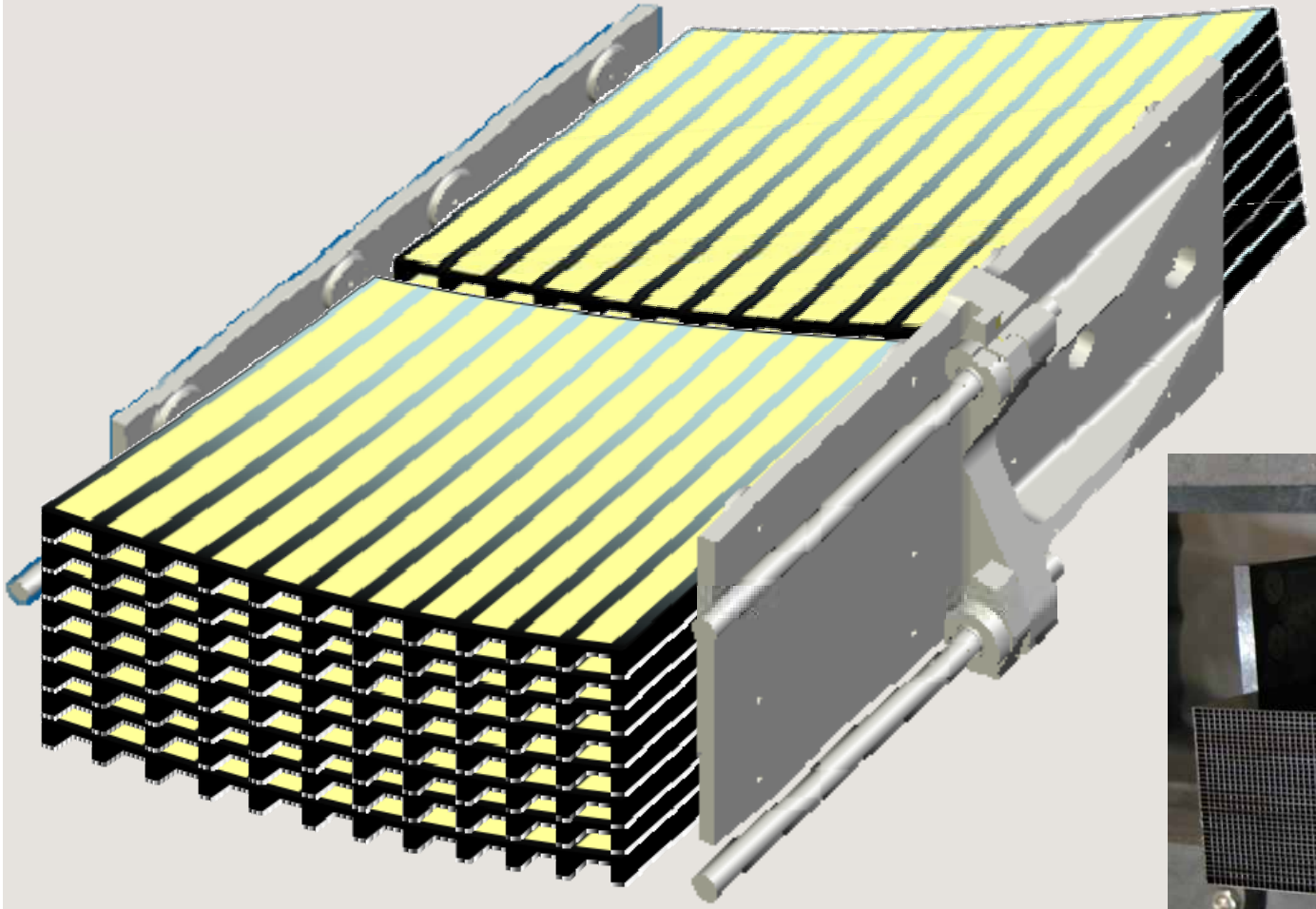
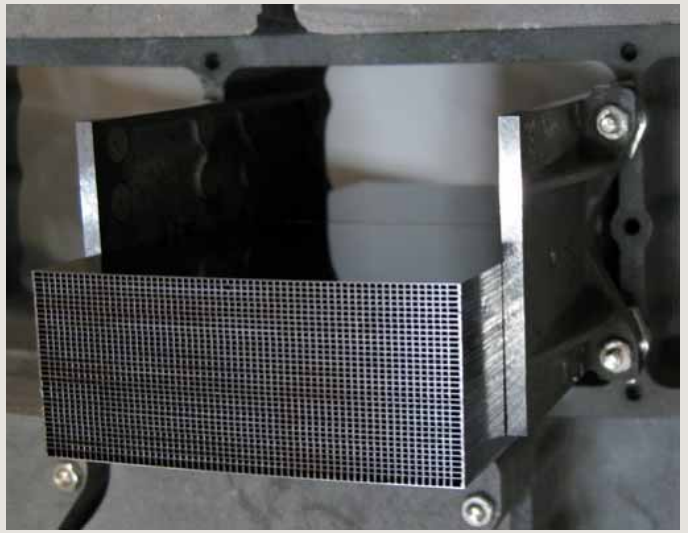


Plate stacking

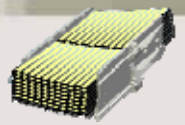
Stacking of silicon pore optics – module production



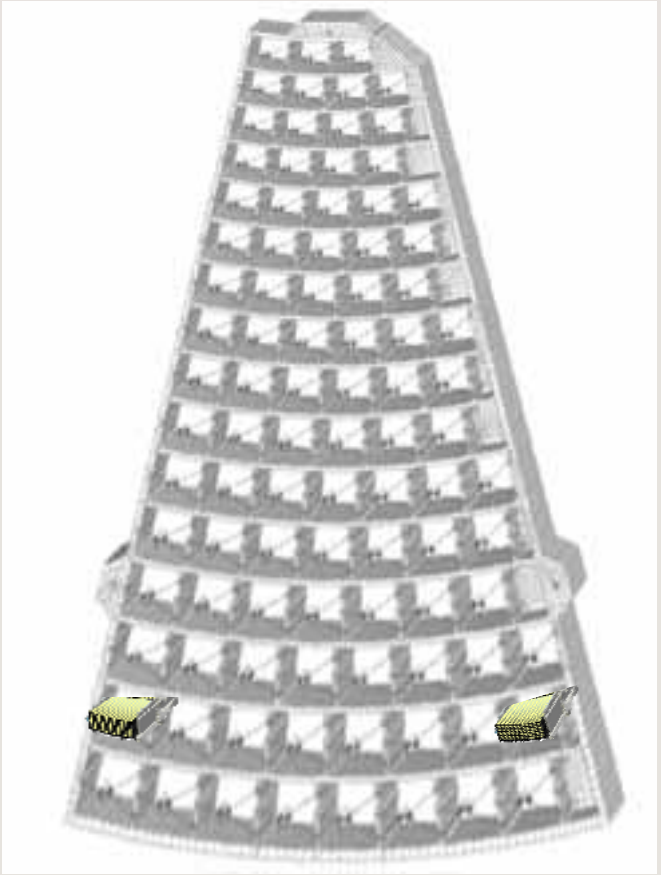


Module integration

Stacking of silicon pore optics – petal integration

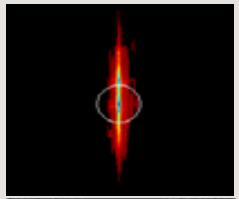
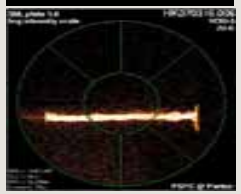


1.1 m



Module integration into petals

IXO Optics – Development & Production

Steps	Done		Next
Plate production	Industrial process	 	Reduce cost Different sizes
	Wedged, coated, non-conical		
	500 produced		
Stack production	Automated	 	Improve HEW
	Particle inspection, cleaning, bending, interferometry, stacking		
	200 produced		
Module production	Design to spec	 	Shorter focal length
	Integration method to spec		
	Mounting method		
	3 produced		
Module validation & qualification	Synchrotron & beam testing in place	 	Environmental testing Focal plane testing
	Ruggedness assessment		
Petal production	Design to spec		
	1 produced	 	
Petal validation & qualification	First X-ray testing		Environmental testing Focal plane testing

2007-2009 focus on plate production and stacks

Plate production – Industrialization

Off-the-shelf 300 mm DSP Si wafers
(starting material)

⇓

Wafer dicing
Plate ribbing
Chemical processing
Wedging
Patterned coating

⇓

Stackable Si mirror plates
(product)

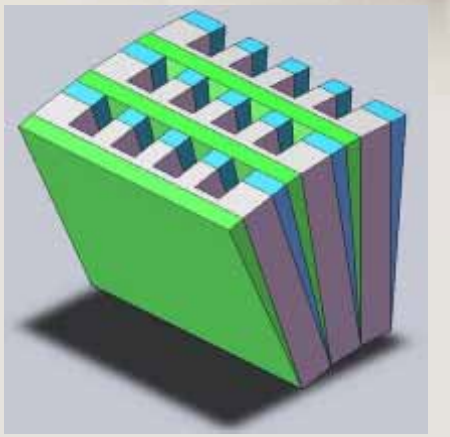
dicing

cleanroom processing

- Entire process flow based on standardized Si/MEMS technology
- Designed for scaling up to high-volume batch processing

Plate production – wedged plates

- Wedge angle for IXO per plate ~2”
  - **R_1=0.25 m Max wedge height 1.90 / 5.70 μm**
  - **R_2=1.90 m Max wedge height 0.25 / 0.75 μm**
- Linear wedging now routine
  - **Automated**
  - **Can wedge with accuracy of 0.5% (0.06”)**
- Can wedge both sides (required for IXO)



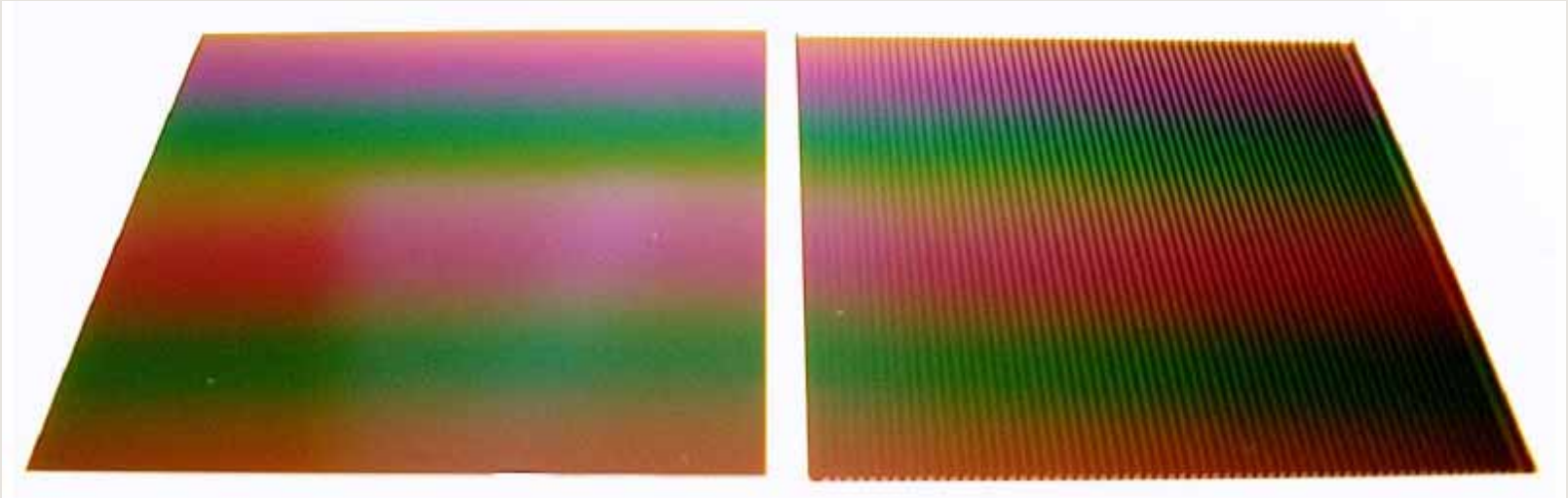


Plate production – coating

- Coating
  - **Two options: lithographic and masked**
  - **Tried both, current baseline masked, in future lithographic**
  - **Coating structured, therefore no stress propagation perpendicular to pore direction. In longitudinal direction stiffened by ribs.**
- Coated Ir+C
  - **using mask**
  - **bonding successful**
- Coated Pt
  - **using lithography**
  - **bonding requires improvement**

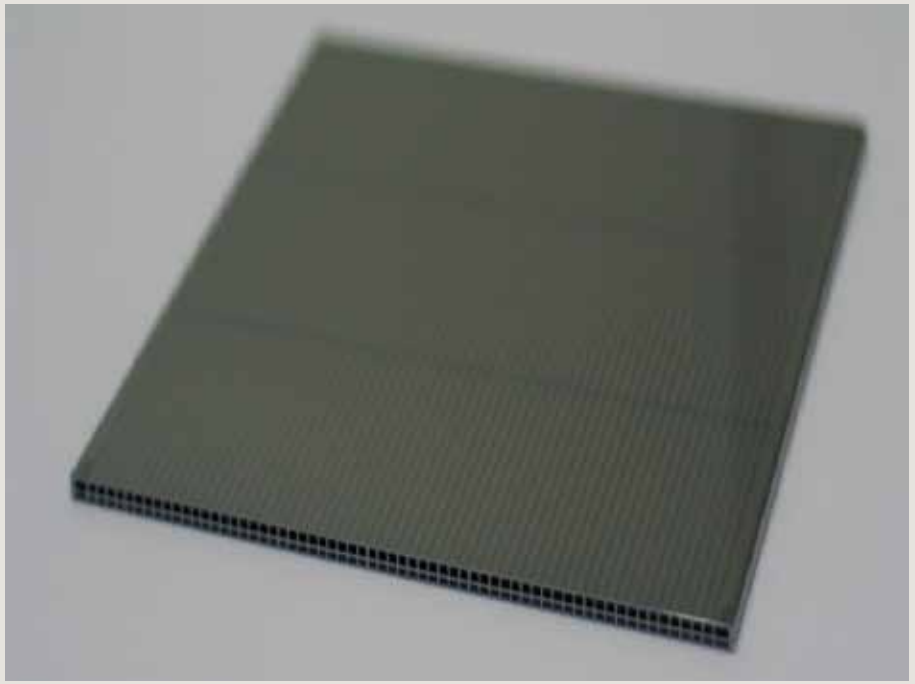
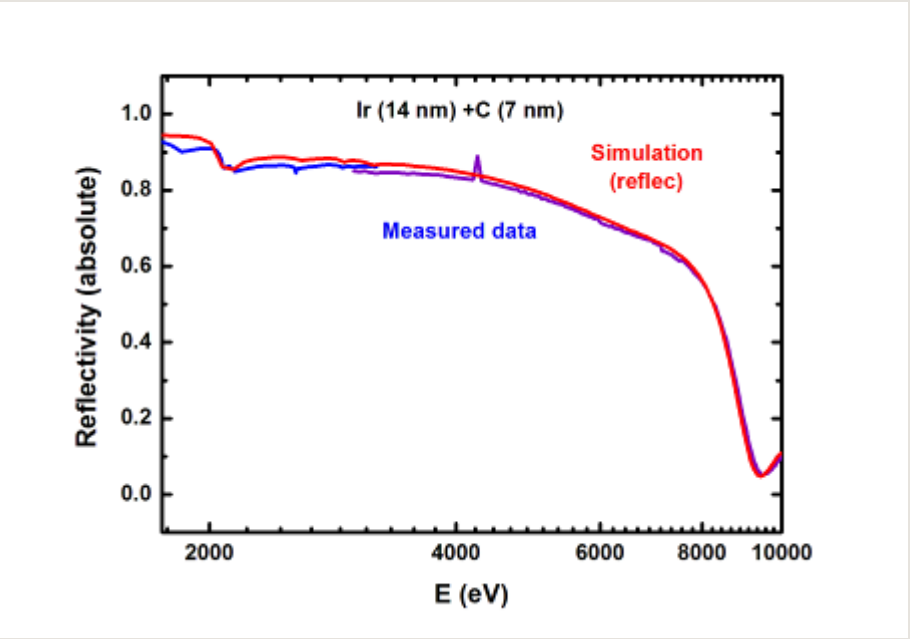
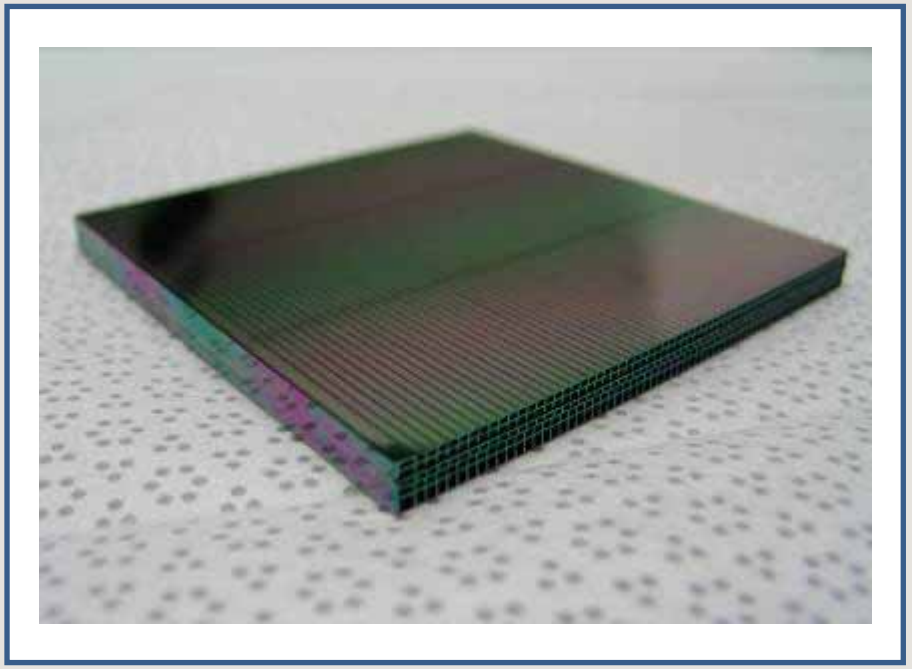


Plate production - Stacking coated plates

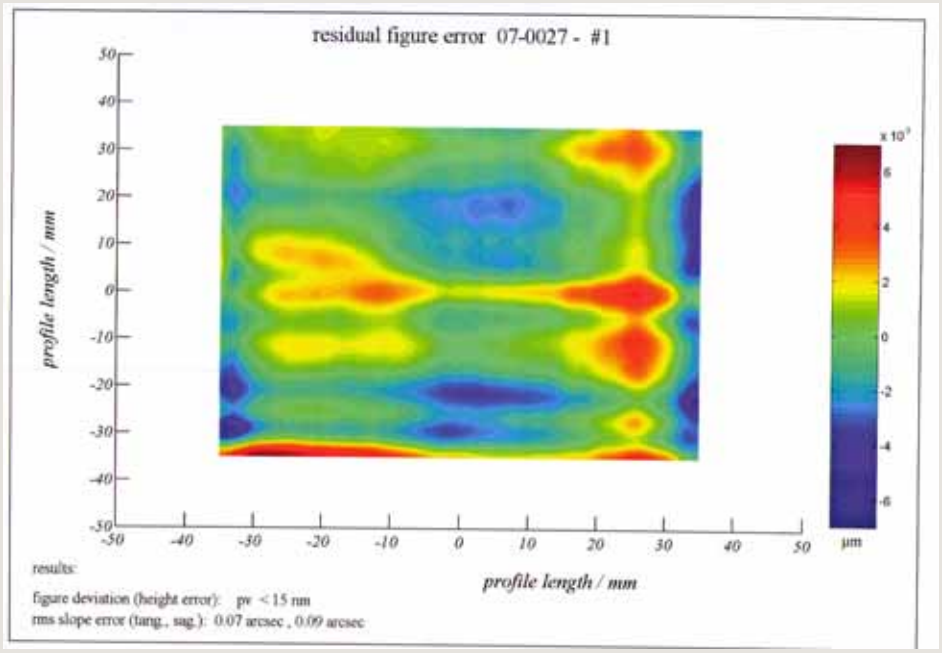
- Successfully fabricated wedged and coated stack
  - **First test: 2 coated plates, bonded flat on flat (12-2008)**
  - **Second test: HPO with 6 wedged and coated plates (10-2009)**
- Have Ir+C inside pores, as required for IXO
  - **Measured reflectivity as expected from simulations**

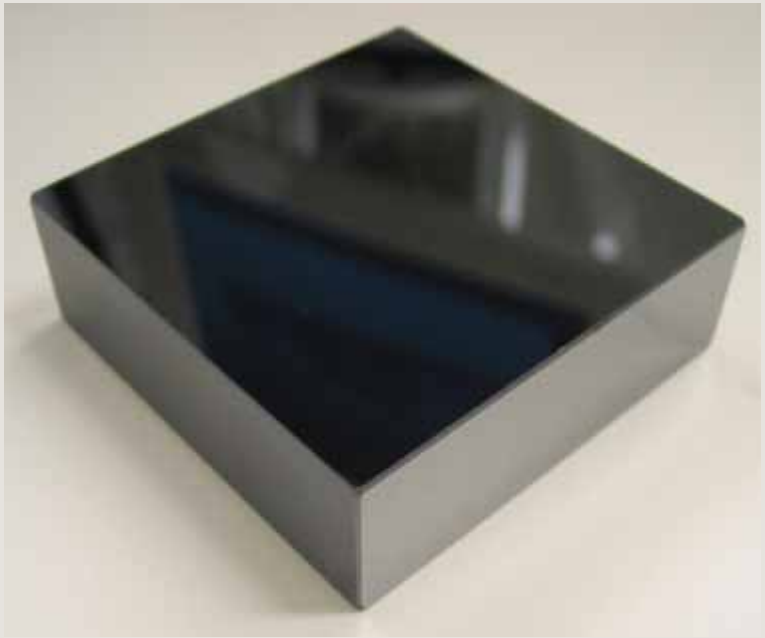




Stacking – mandrels

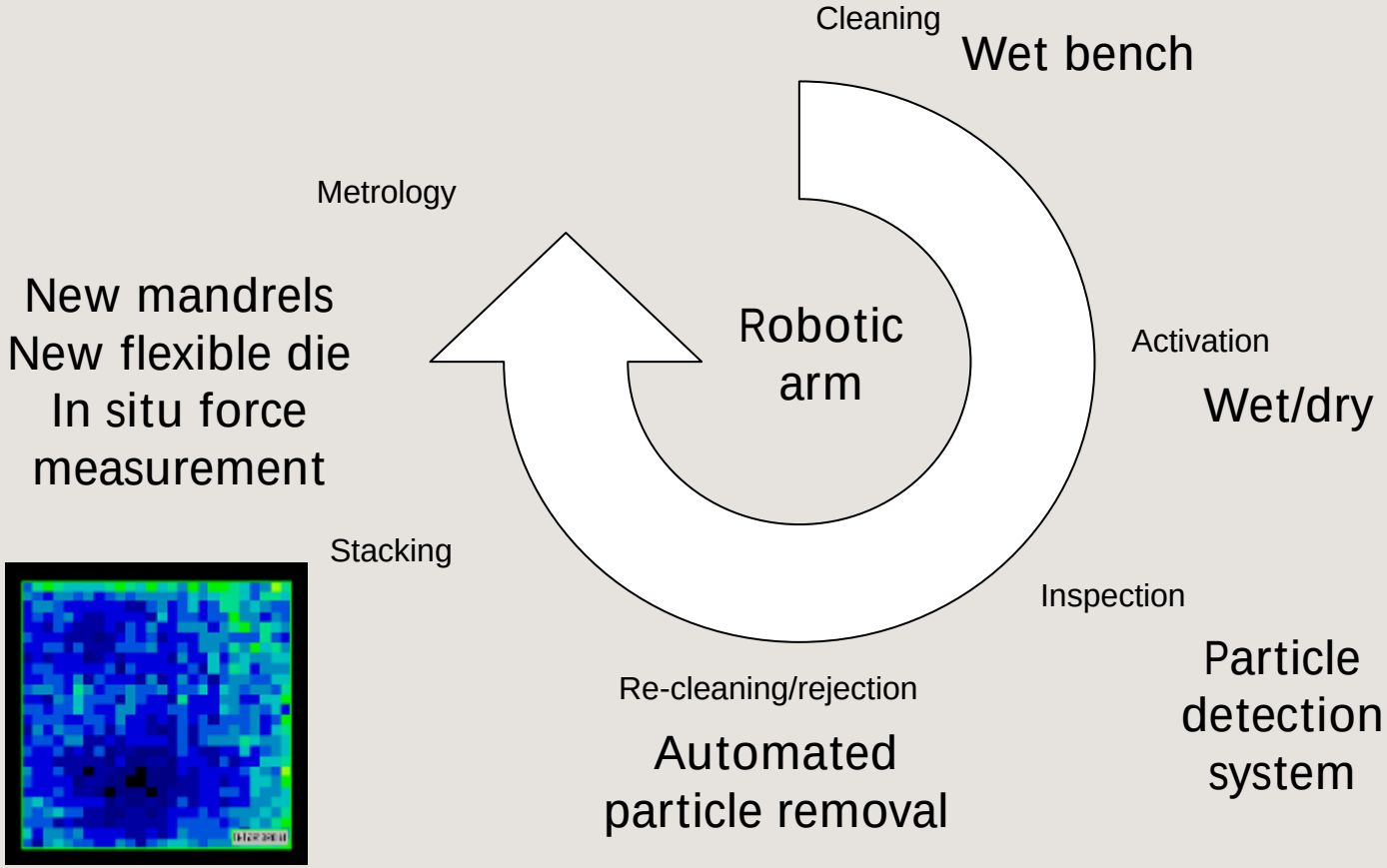
- Cylindrical mandrels from Zeiss
  - **0.1” rms residual error**
  - **Only figure (not roughness) important**
  - **need only 2 mandrels per ring (64 for IXO, not expensive, small)**





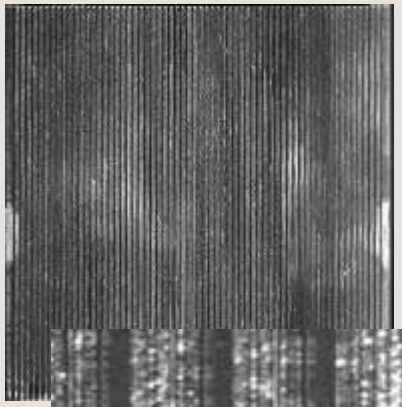
Stacking – 3rd generation stacking robot

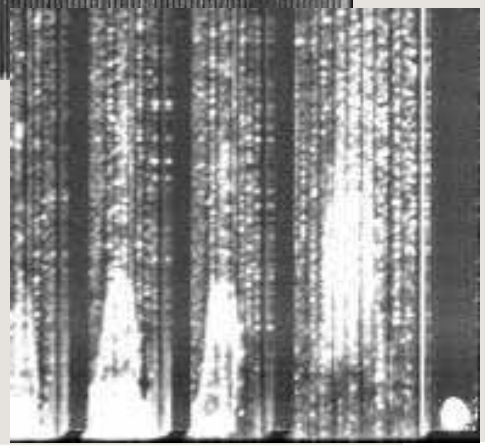
- Developed new stacking robot XOAT-3
  - **modular approach, fully automated**
  - **Combination of standard semicon tools**

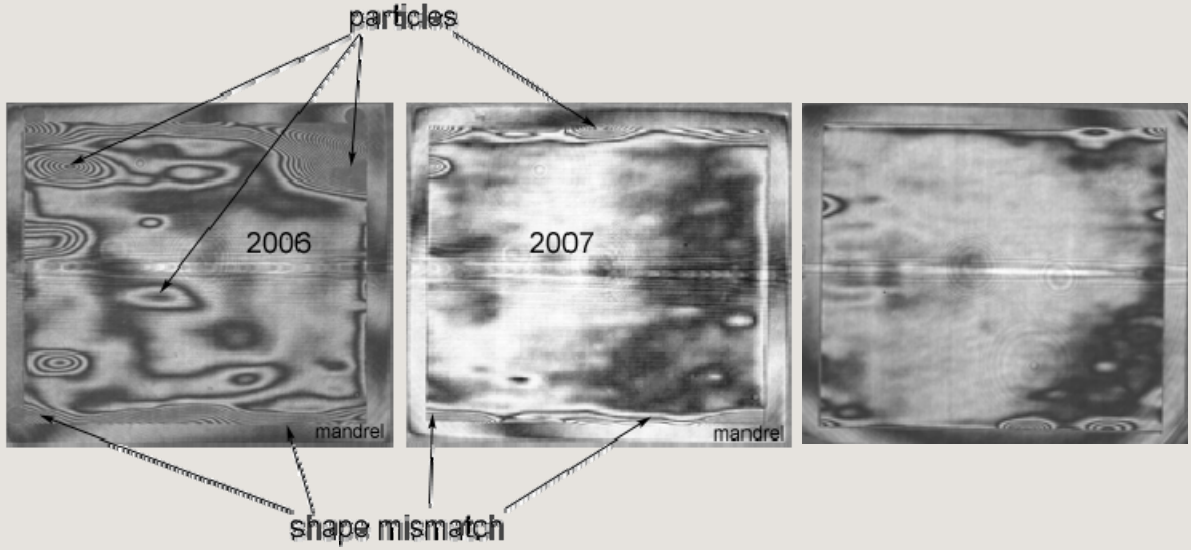


Stacking – Developed particle detection

- Particle detection with custom system based on scattering
  - **Difficult is detection on ribbed side**
  - **Current requirement (particles < 1 µm)**
  - **Final goal < 100 nm (elastic deformation of silicon)**

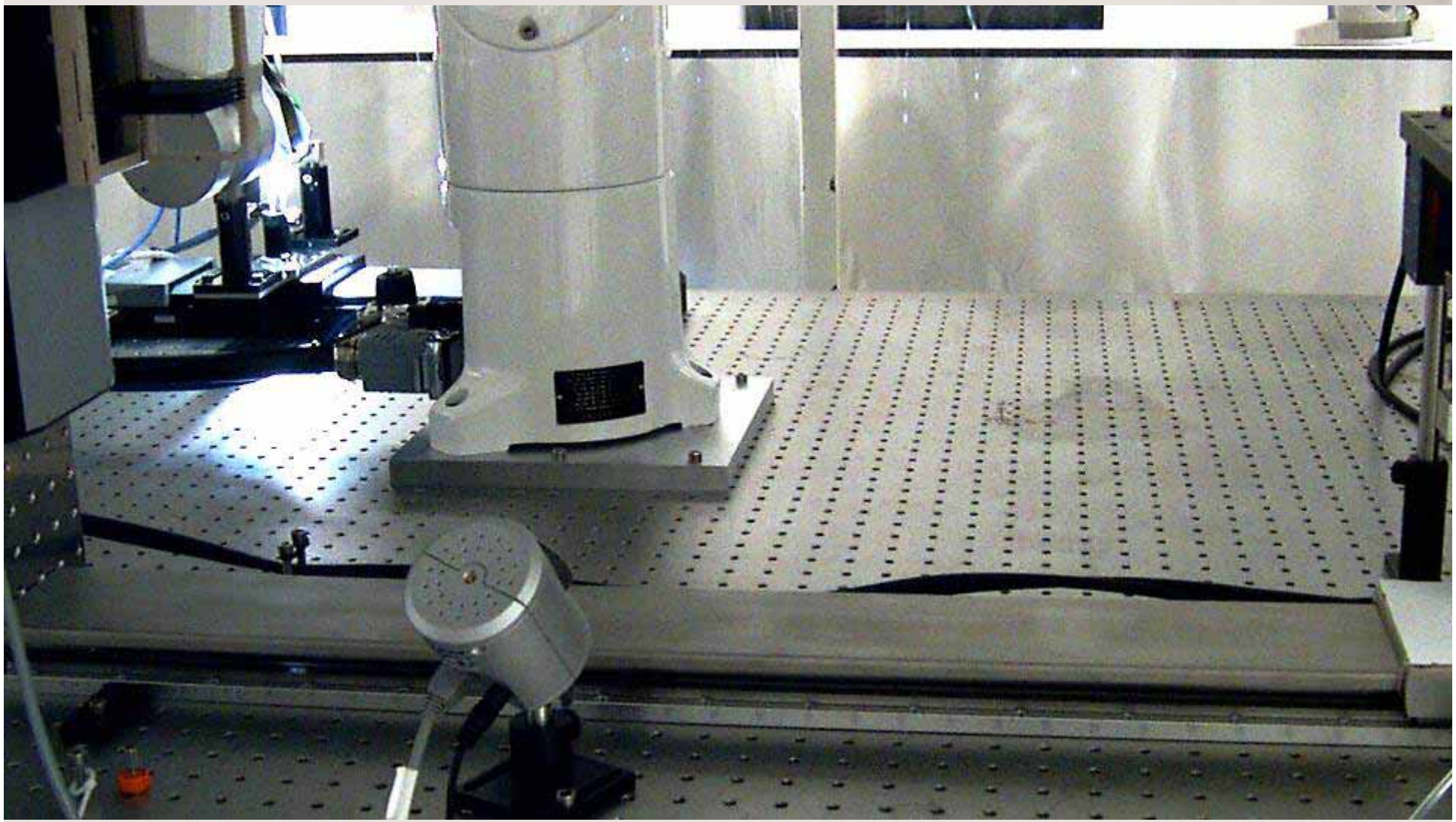






year 2006 **year 2007** **year 2009**

Stacking – Stacking robot at cosine



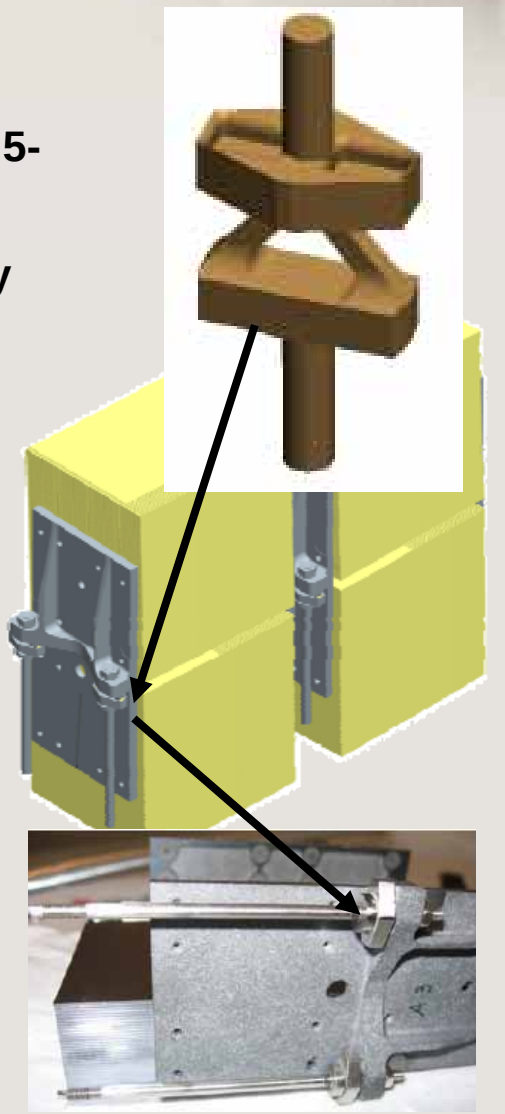
Stacking – Metrology in place

- Stacking metrology in place
  - **Metrology loop to X-ray data closed**
- Particle measurement
  - **custom particle detection system**
  - **calibration ongoing, special contaminated wafers will be ordered**
- Plate-Plate alignment
  - **microscopic / image analysis (< 5 μm accuracy)**
  - **force sensors (15 sensors / cm², 1 mN resolution)**
  - **front / back radii adjustable from 1900 to 2025 mm with 0.03 μm accuracy)**
  - **Tip/tilt 0.3 μrad resolution**
- Figure
  - **Twyman Green interferometer with CGH cylindrical nulling lens (FoV 100 mm)**

Stacking – Module production

- Initial design loads **(80g lateral/100g axial acting separately)**
- Design loads from XEUS system studies **(5-35g lateral & 5-130g axial combined, depending on XOU location)**
- All M.o.S. > 0, **using HB CeSiC as bracket material and Safety Factor of 3 for brittle materials**
- Stiffness requirement >200 Hz is being met easily **(assuming a rigid quasi iso-static dowel pin design)**

	plate size	# plates	first Res. freq. f_0
Generic design	66 x 66 mm	70	1100 Hz
R 2019 mm P-plate H-plate	 93 x 45 mm 93 x 42 mm	70	1500 Hz
R 689 mm P-plate H-plate	 72 x 139 mm 72 x 120 mm	70	500 Hz

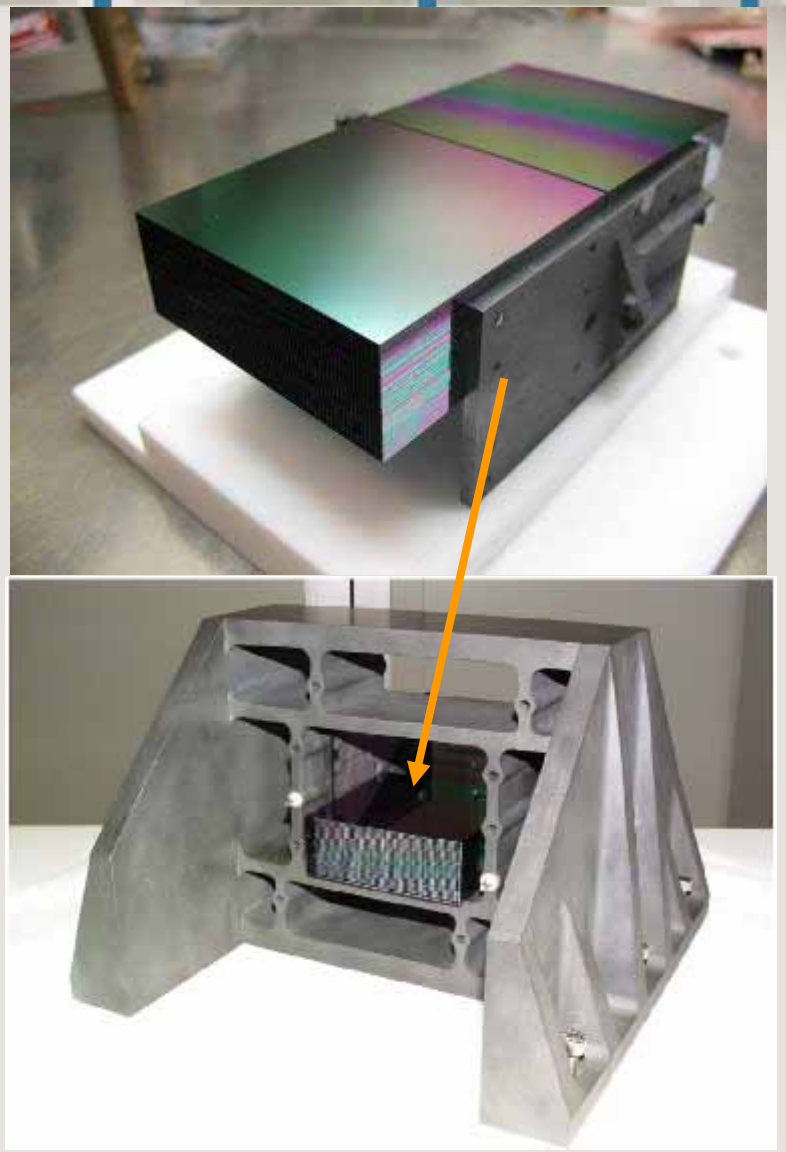


Vibration and X-ray testing in flight configuration

- X-ray testing mounted optics in flight representative configuration
- Build sub-set of petal to allow identical mounting at BESSY and PANTER
- Adapter also used for vibration testing

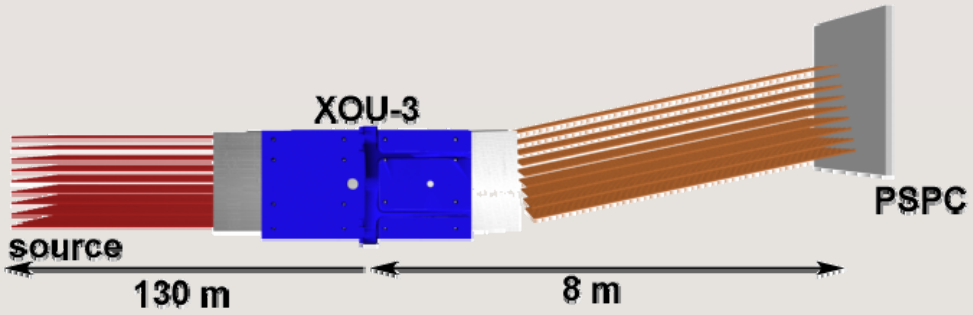
Test adapter properties

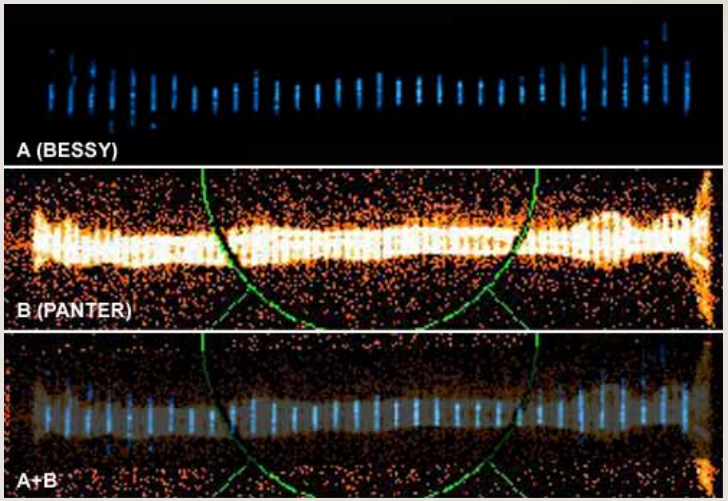
- Design Loads
  - **80 g lateral**
  - **100 g axial**
- Ops. Temperature Range
  - **238 K to 293 K**
- Material
  - **HB-Cesic©**
- Mass
  - **2.7 kg**
- High Precision Interface
  - **Reference Surfaces < 3 µm**



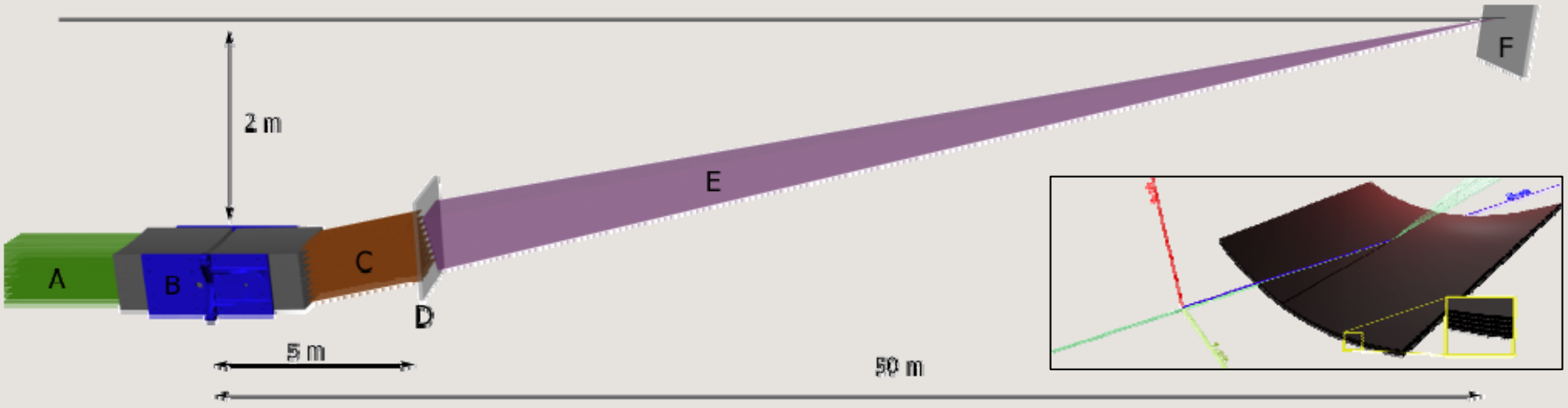
Mirror module testing

- PANTER full beam (divergent)

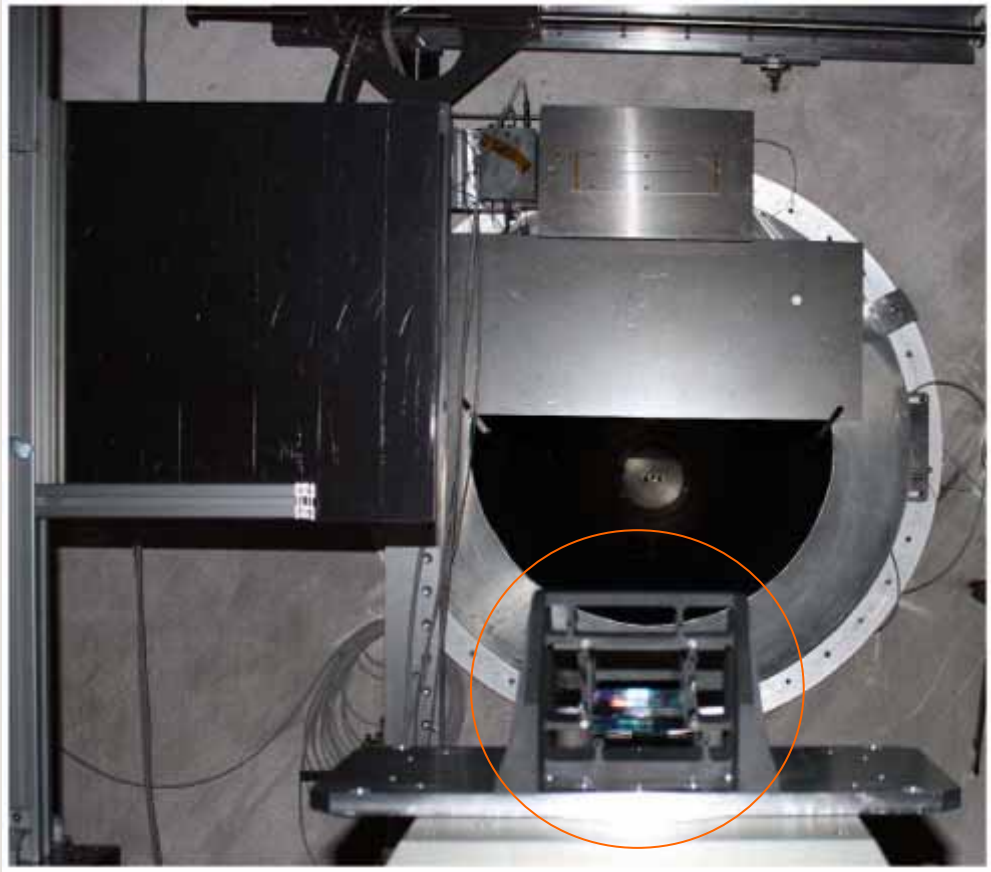




- BESSY pencil (50μm) beam



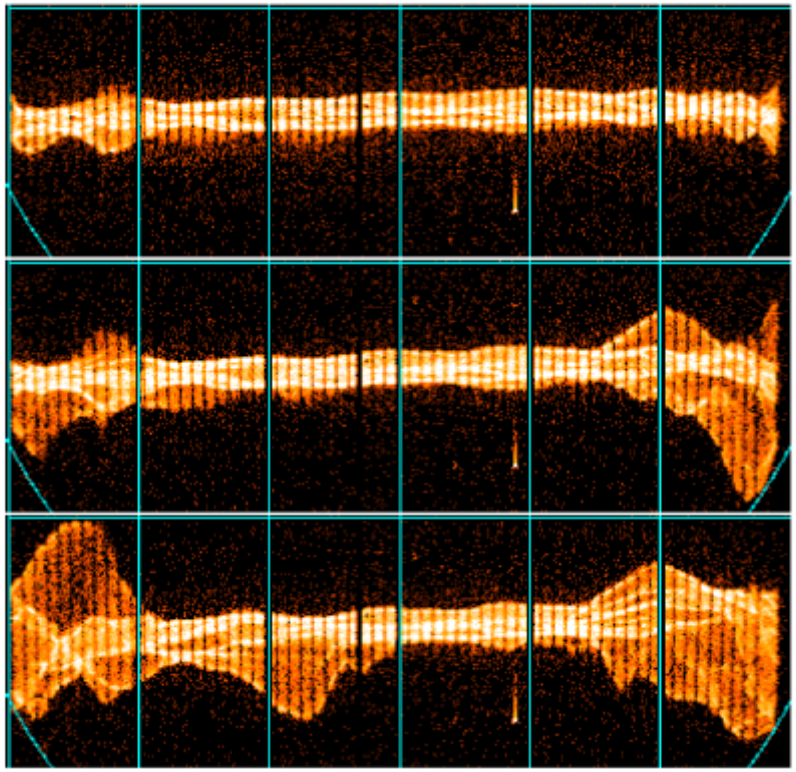
MPE (PANTER) X-RAY TEST RESULTS of XOUs



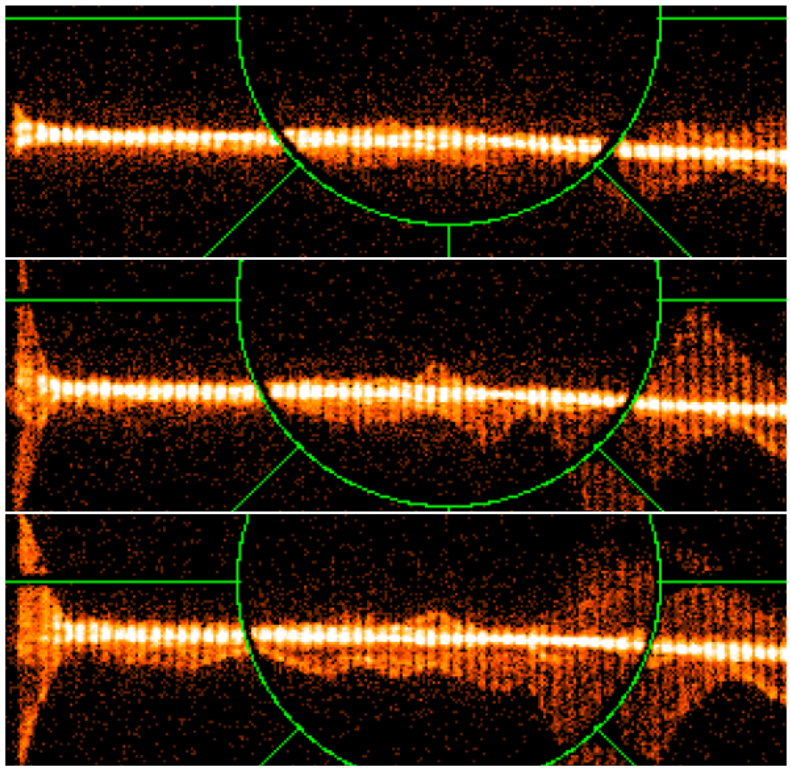
Mirror module testing – PANTER results

- Comparison plates 1, 4, 8

XOU-3: for comparison: plates 1, 4, 8 (EPIC-pn)



XOU-5: improvement: plates 1, 4, 8 (PSPC)



2007 **2009**

Mirror module testing – PANTER effective area

Wedged XOU 2009

Energy	eV	280	1490	2980	4510
Reflectivity SiO @ 0.5 nm (rms)		0.923	0.918	0.439	0.021
Expected effective area	mm^2	540	534	122	0.27
Measured effective area	mm^2	528	485	107	1
Measured / expected		**0.98**	**0.91**	**0.88**	

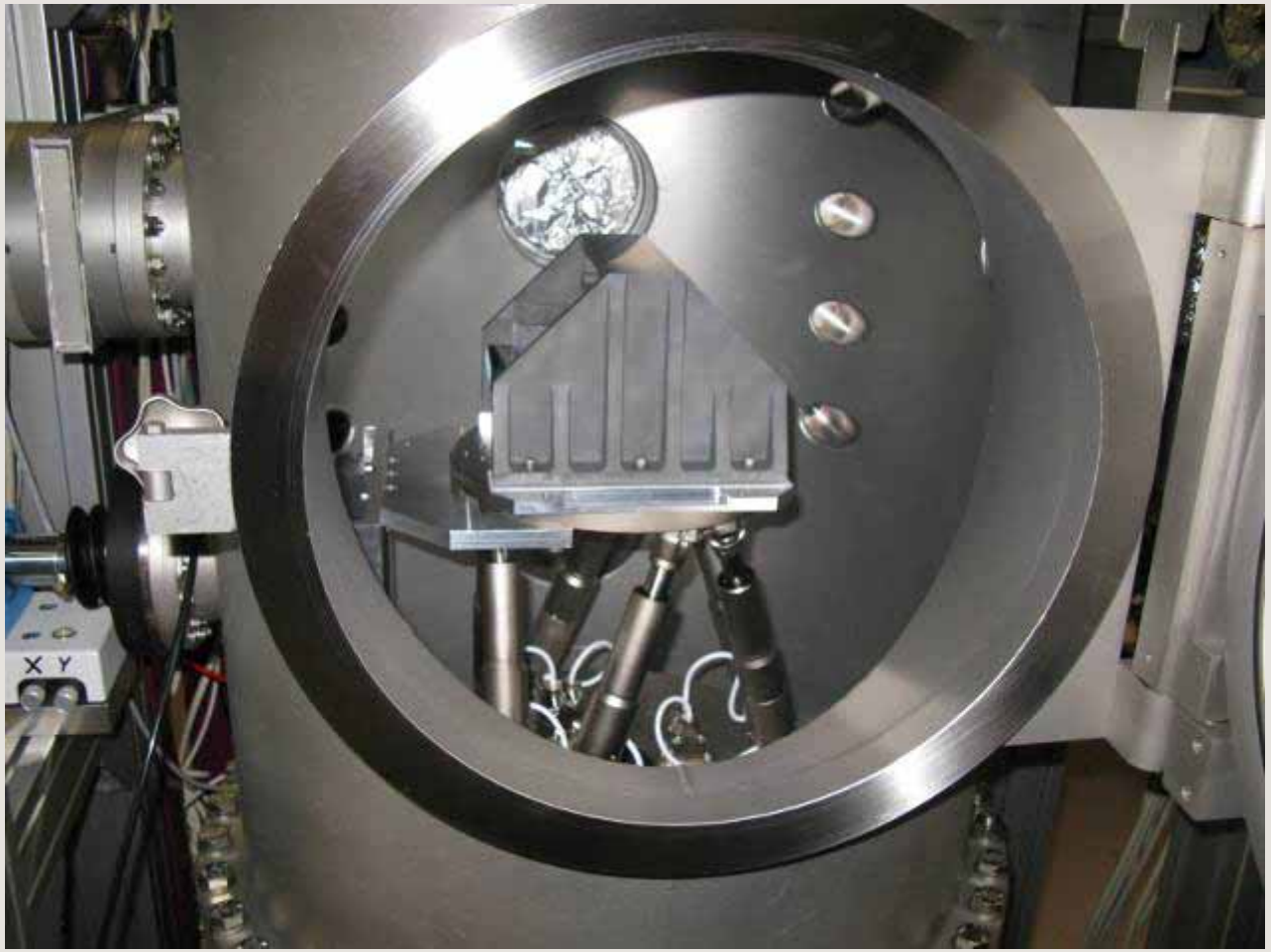
Unwedged XOU 2007

Energy	eV	280	1490	2980	4510
Reflectivity SiO @ 0.5 nm (rms)		0.923	0.918	0.439	0.021
Expected effective area	mm^2	883	874	200	0.44
Measured effective area	mm^2	828	815	140	8
Measured / expected		**0.94**	**0.93**	**0.70**	

- Remaining losses
  - **Increased roughness due to re-used plates**
  - **Small alignment errors HPO-p / HPO-h**
  - **Particulate contamination**
    - **pores partially blocked**
    - **local change in incidence angle**
  - **Underlying model to calculate expected reflectivity**

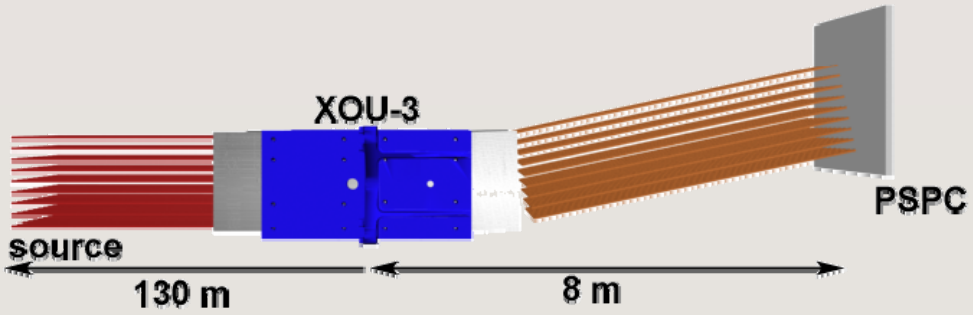
Mirror module testing – BESSY

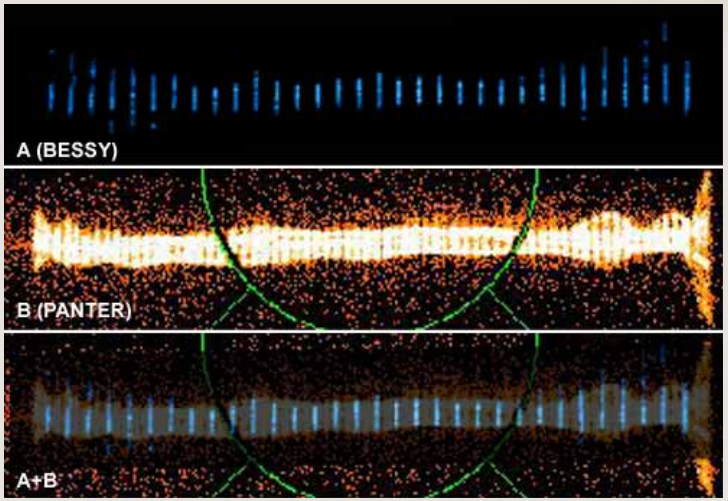
PTB (BESSY) X-RAY TEST RESULTS of XOUs



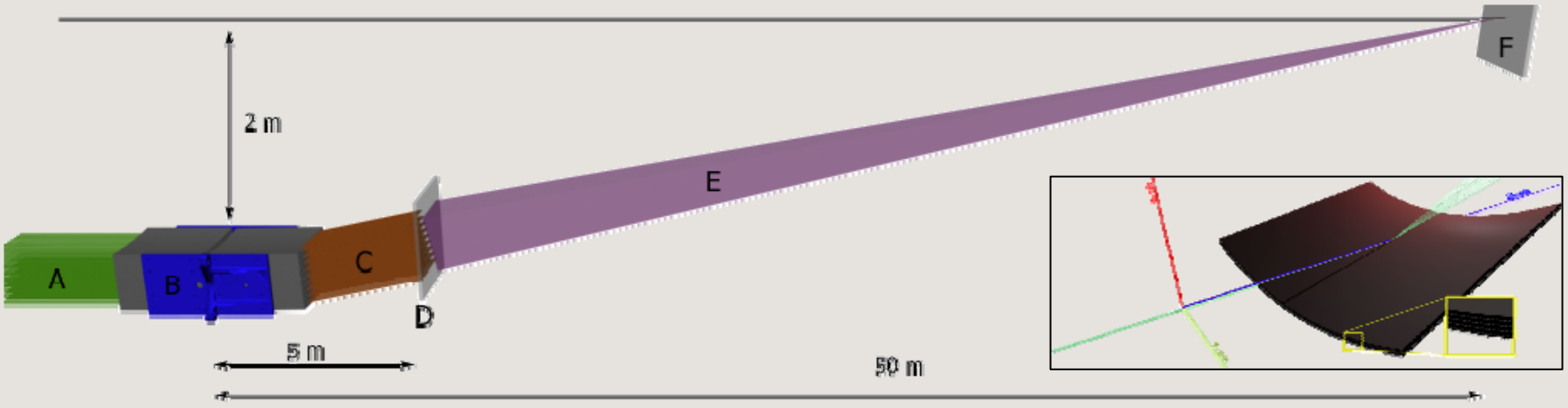
Mirror module testing – BESSY

- PANTER full beam (divergent)

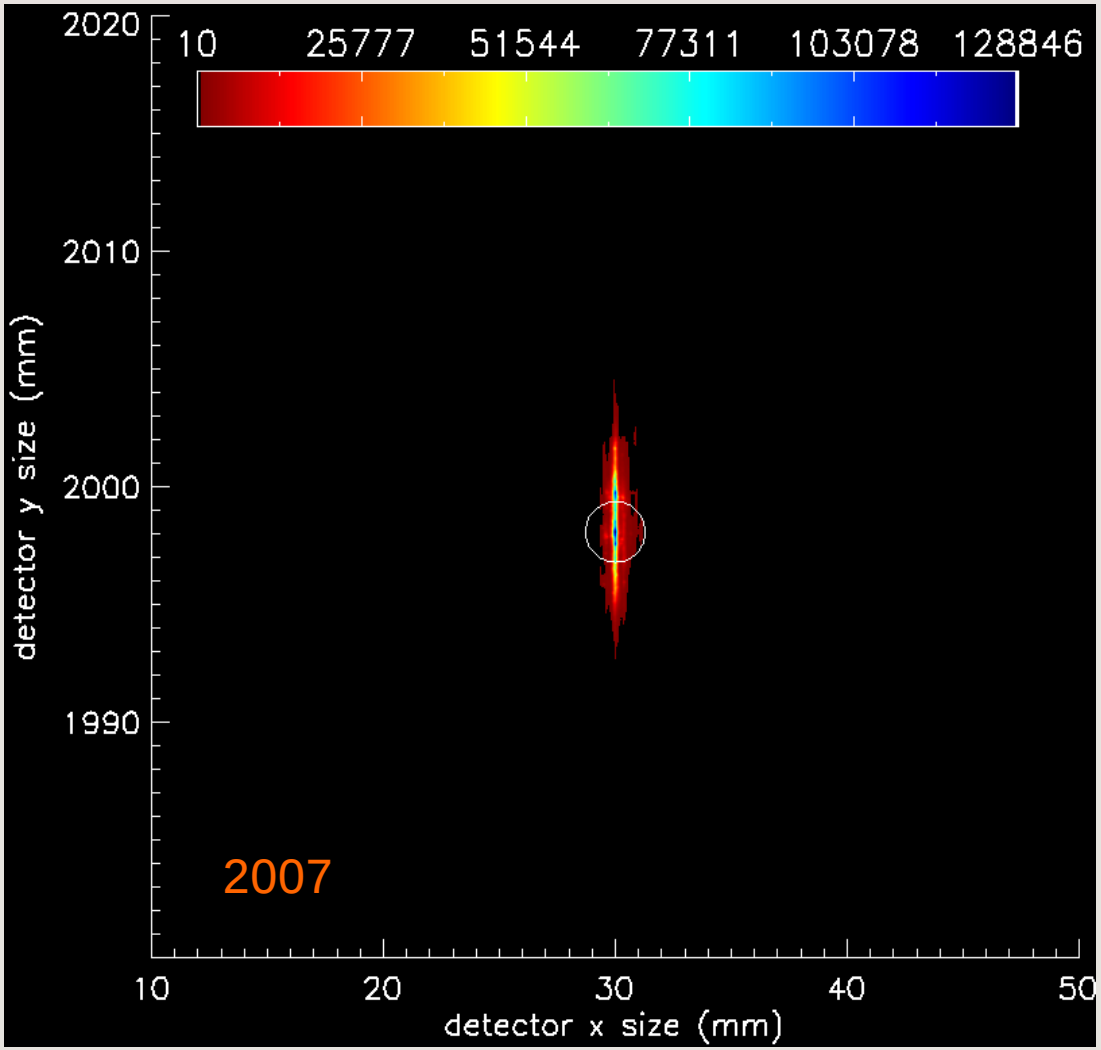


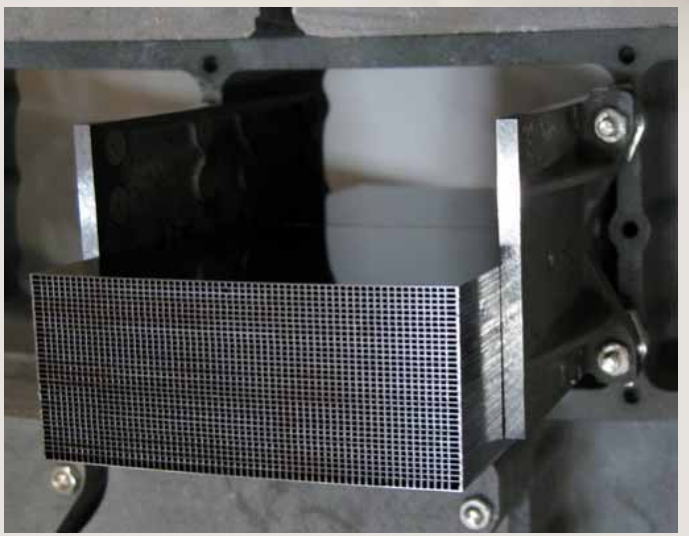


- BESSY pencil (50μm) beam



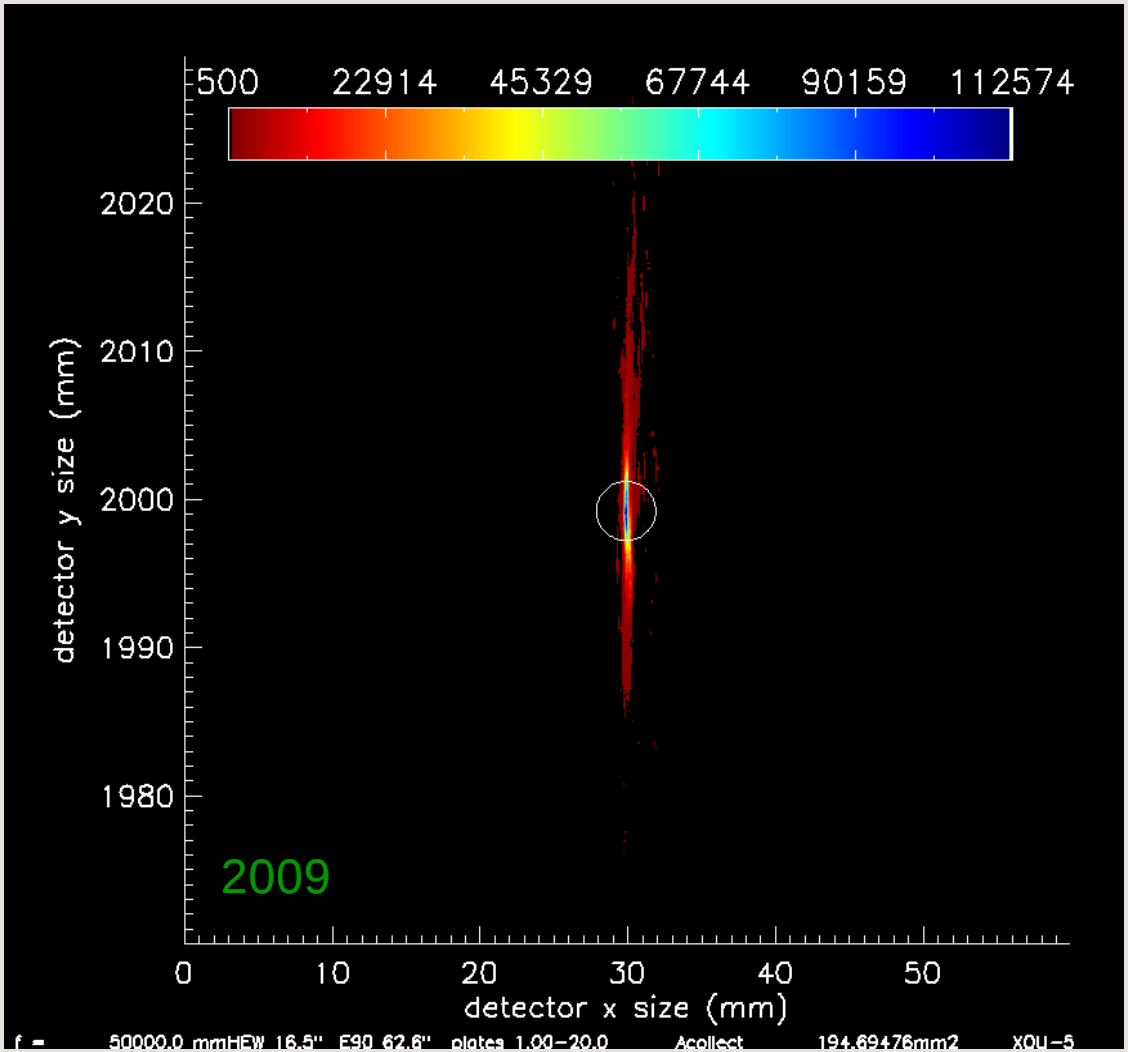
Mirror module testing – previous results

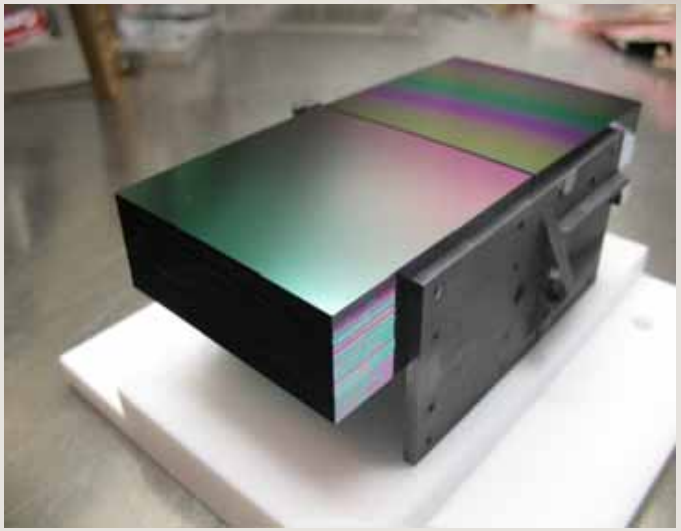




- HEW 17” @ 50 m
  - **double reflection**
  - **mounted optics**
  - **absolute**
  - **no subtraction**
- Plates 1-4
  - **full width**
  - **A_{col} = 1.25 cm²**

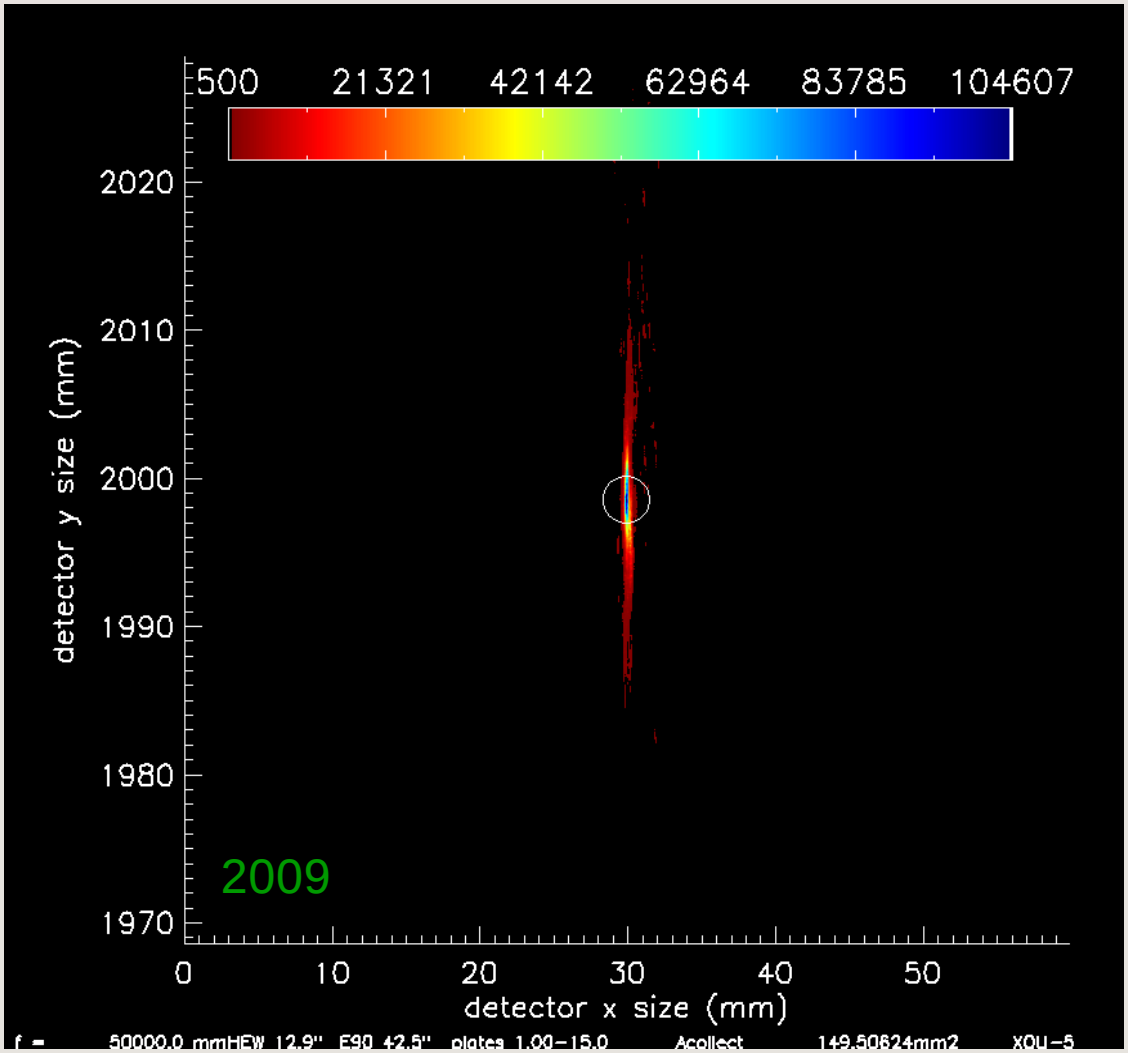
Mirror module testing – new results

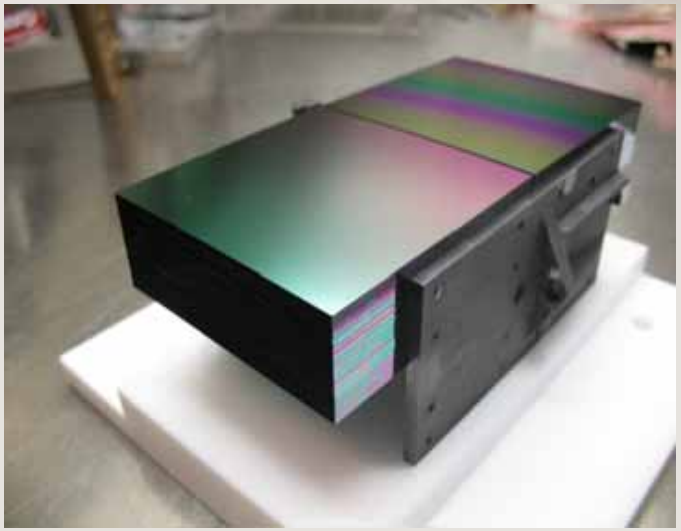




- HEW 16” @ 50 m
  - **double reflection**
  - **mounted optics**
  - **absolute**
  - **no subtraction**
- Plates 1-20
  - **full width**
  - **A_{col} = 6.3 cm²**

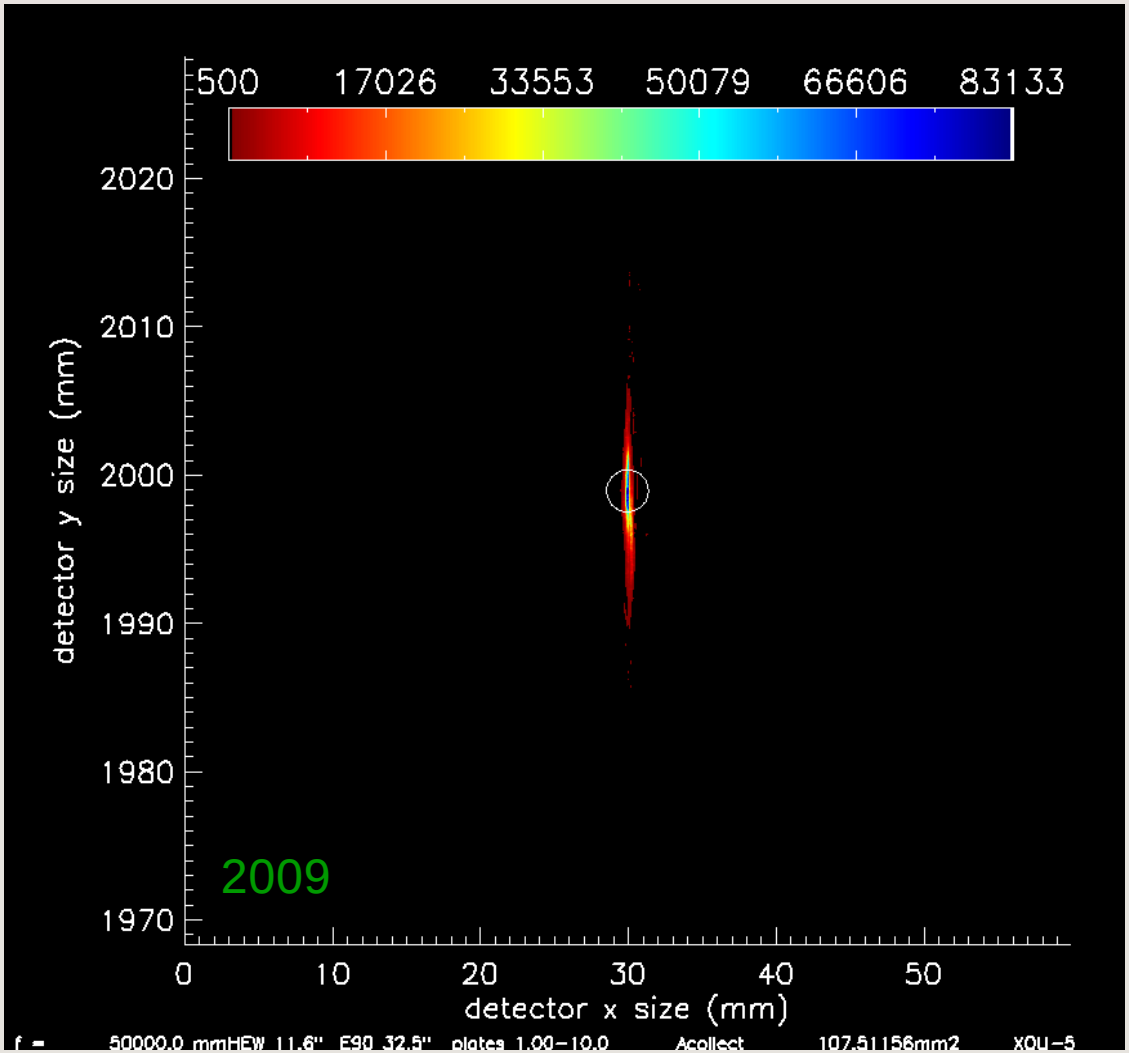
Mirror module testing – new results

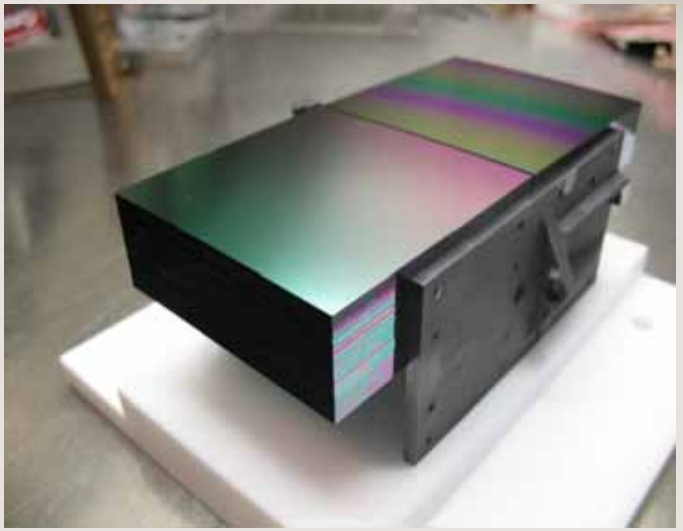




- HEW 12” @ 50 m
  - **double reflection**
  - **mounted optics**
  - **absolute**
  - **no subtraction**
- Plates 1-15
  - **full width**
  - **A_{col} = 4.7 cm²**

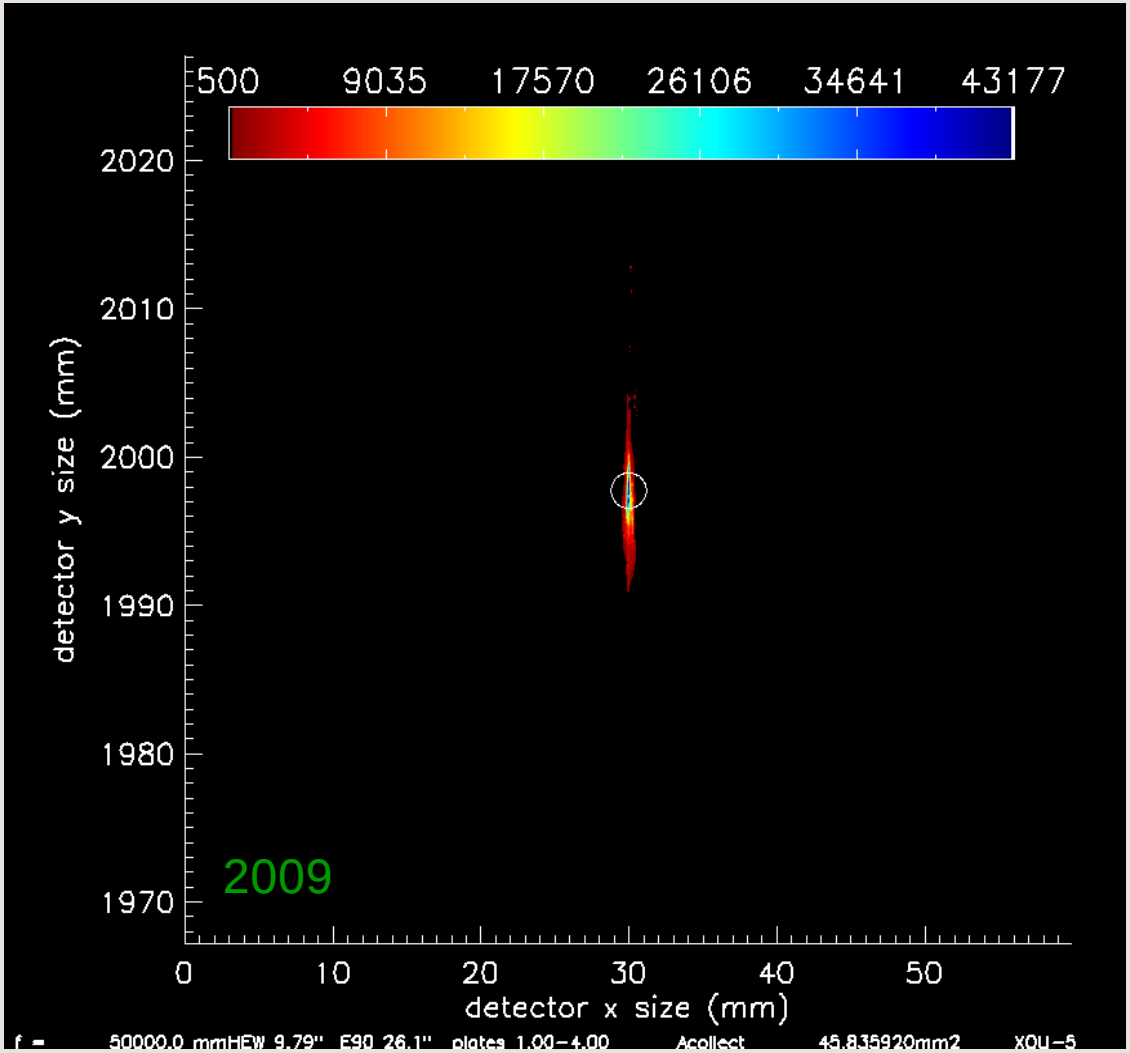
Mirror module testing – new results

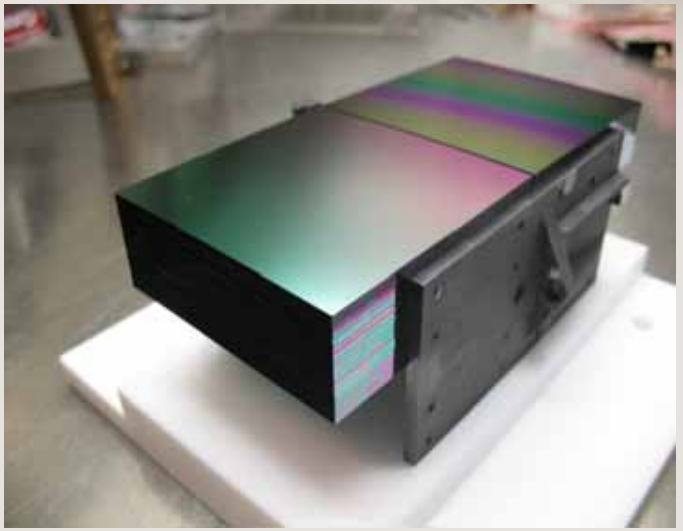




- HEW 11” @ 50 m
  - **double reflection**
  - **mounted optics**
  - **absolute**
  - **no subtraction**
- Plates 1-10
  - **full width**
  - **A_{col} = 3.13 cm²**

Mirror module testing – new results

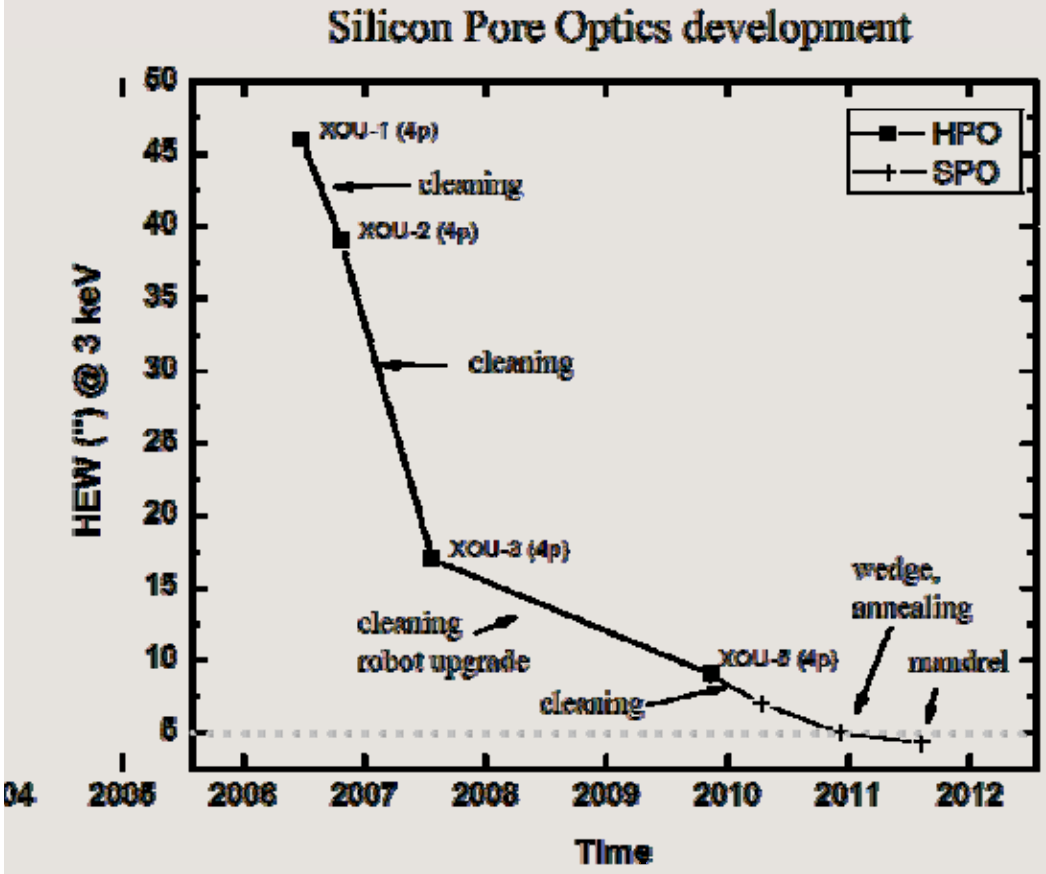




- HEW 9” @ 50 m
  - **double reflection**
  - **mounted optics**
  - **absolute**
  - **no subtraction**
- Plates 1-4
  - **full width**
  - **A_{col} = 1.25 cm²**

Development status

- Silicon pore optics development, phase A



1. Further industrialisation
   - **2nd robot for 20 m focal length**
   - **Metrology upgrade**
   - **Plate manufacture**
   - **Plate cleaning process**
2. Beam line upgrade
   - **BESSY 20 m May 2010**
   - **PANTER 20 m Dec 2010**

   …
3. Environmental testing
   - **Vibration testing 2010**

Development status

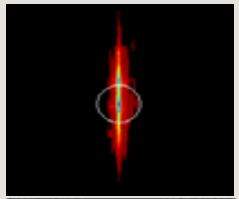
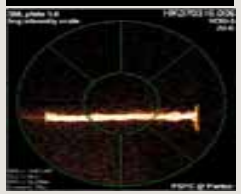
- Mass manufacturing of wedged plates
- Demonstrated Ir+C coating inside pores
- New, fully automatic stacking robot operational
- Built and tested best XOU ever, fully focusing
  - **wedged plates, mounted optics, double reflection**
  - **X-ray testing results (HEW at 50 m, 3 keV)**
    - **4 plates @ 9”**
    - **10 plates @ 11”**
    - **15 plates @ 12”**
    - **20 plates @ 16”**

For comparison: XOU-3 in 2007 4 plates @ 17”, artificial wedge

Overall conclusions

- Silicon Pore optics have TRL 3-4
  - **Plates are mass produced by industry**
  - **Have mirror modules and a mounting method**
  - **Coating inside pores (Ir+C)**
  - **We are testing mounted optics in flight configuration**
- Mass production of modules ramping up
  - **industrial consortia are forming**
  - **co-locate plate production, coating and stacking in semicon fab**
    - **industrial stacking robot fits onto one optical table**
    - **production of one coated stack (45 plates) every 2 hours possible**
- ESA technology roadmap includes for 2009-2010
  - **ruggedization**
  - **figure improvement**
  - **industrialisation**

IXO Optics – Development & Production

Steps	Done		Next
Plate production	Industrial process	 	Reduce cost Different sizes
	Wedged, coated, non-conical		
	500 produced		
Stack production	Automated	 	Improve HEW
	Particle inspection, cleaning, bending, interferometry, stacking		
	200 produced		
Module production	Design to spec	 	Shorter focal length
	Integration method to spec		
	Mounting method		
	3 produced		
Module validation & qualification	Synchrotron & beam testing in place	 	Environmental testing Focal plane testing
	Ruggedness assessment		
Petal production	Design to spec		
	1 produced	 	
Petal validation & qualification	First X-ray testing		Environmental testing Focal plane testing

Silicon Pore Optics