INAF ISTITUTO NAZIONALE DI ASTROFISICA OSSERVATORIO ASTRONOMICO DI BRERA

Specchi attivi per telescopi a raggi X: come, perché, quando?

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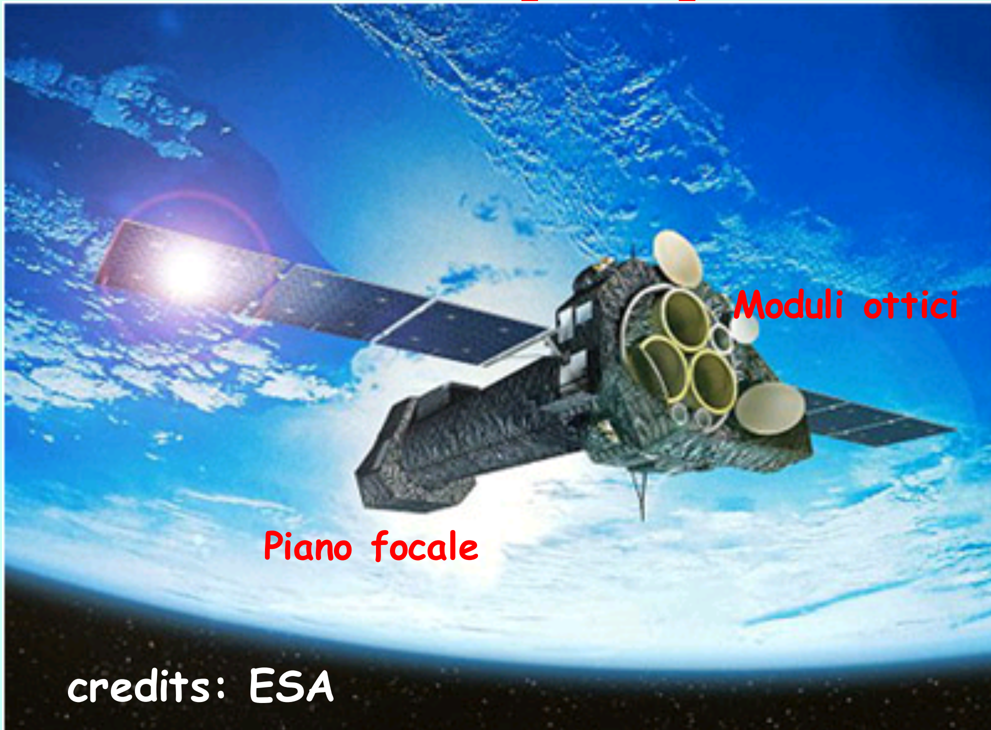
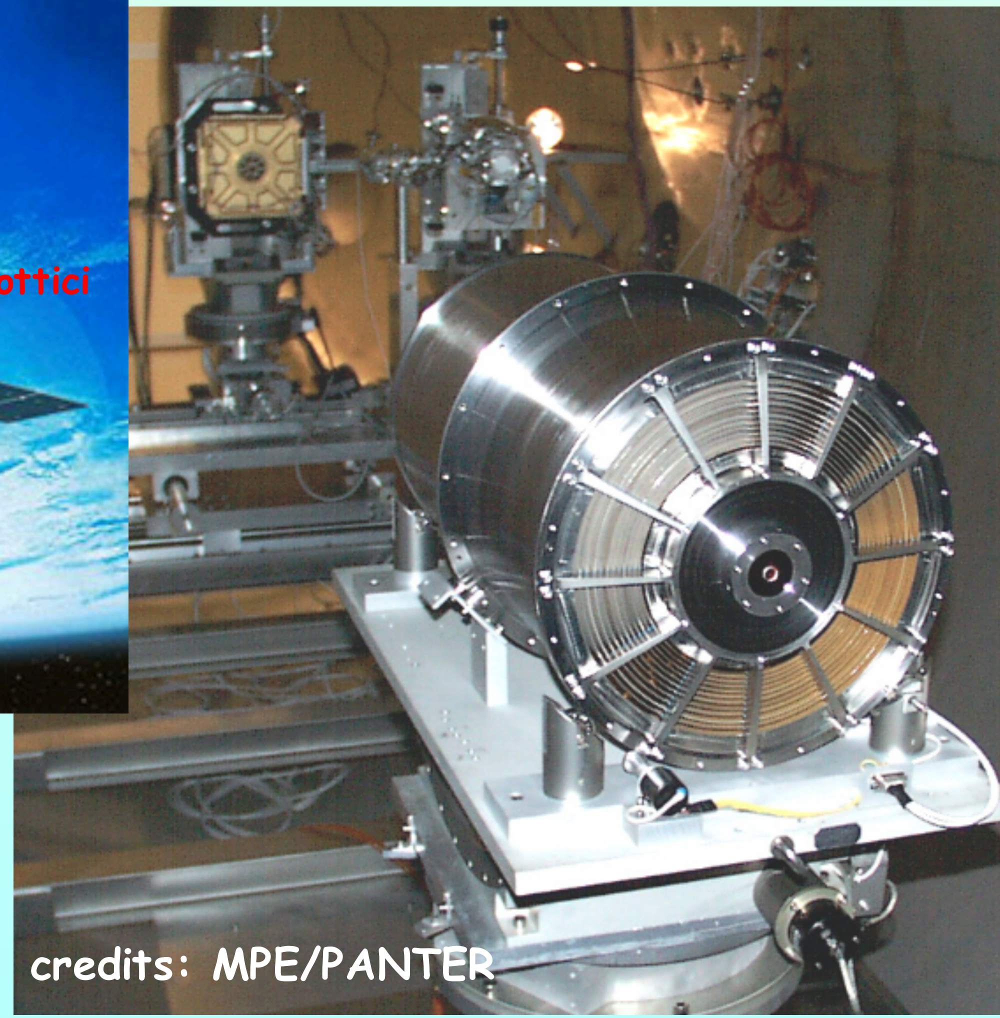
ADONI workshop, Firenze, 12 aprile 2016

I telescopi X operano solo nello spazio, quindi...

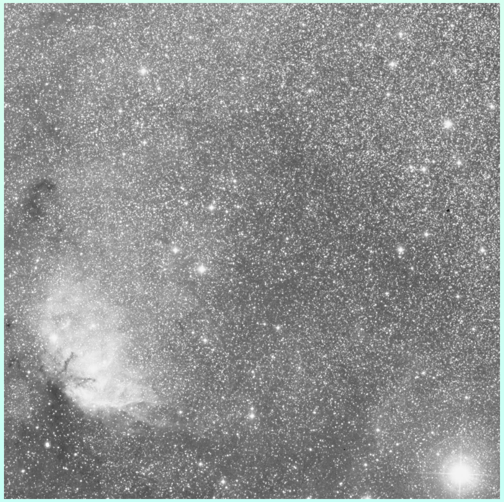




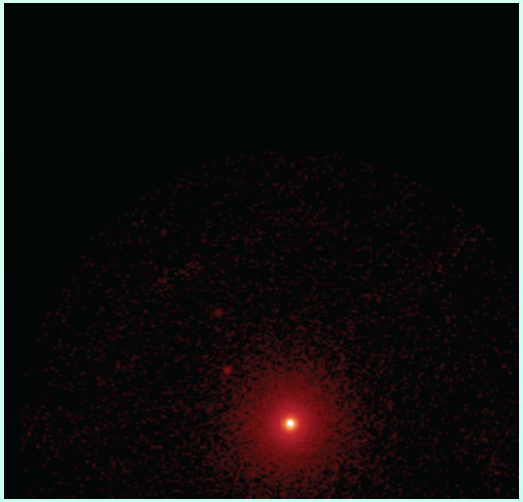
- Nessun disturbo dell'atmosfera
- Operano in microgravità

- Le ottiche devono essere leggere
- Non si appoggiano da nessuna parte
- Vanno calibrate a terra, poi lanciate
- Lo spazio è un posto pericoloso...

Astronomia nei raggi X

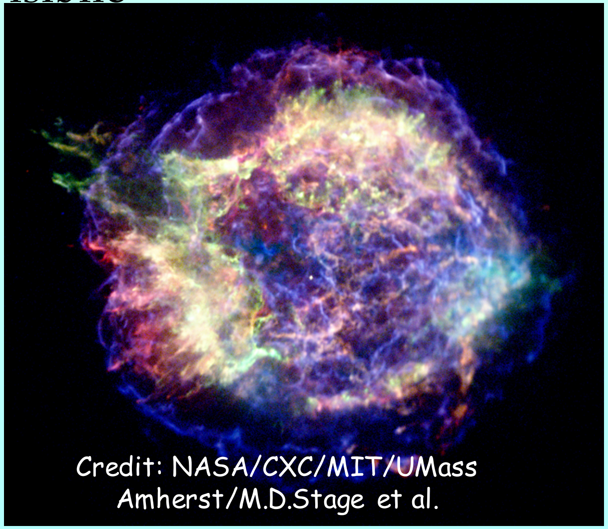


La costellazione del Cigno nel visibile

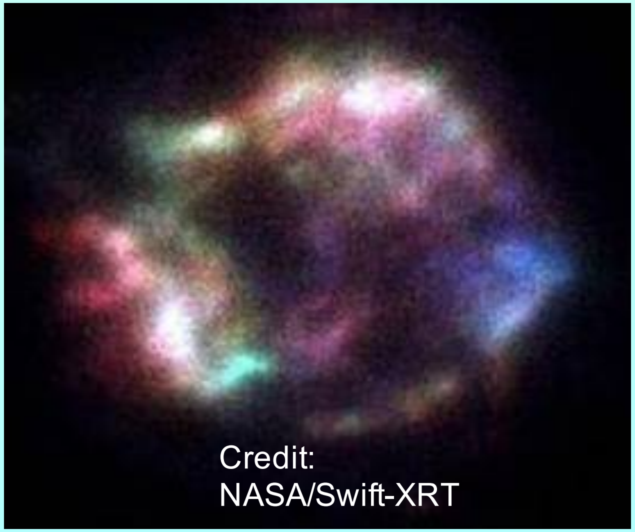


La stessa regione nei raggi X

Trova il buco nero!!!



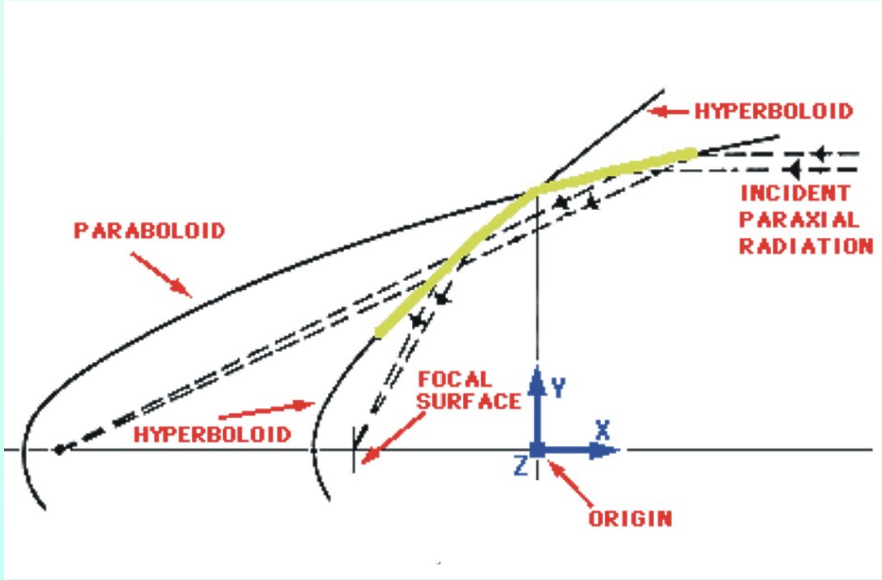
Cas-A visto da Chandra (0.5 arcsec)

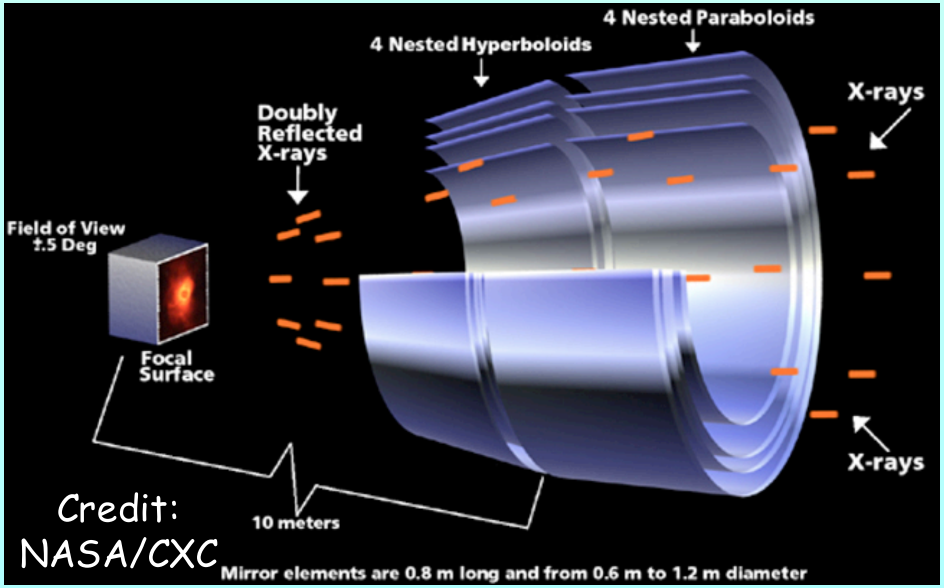


Cas-A visto da Swift-XRT

La risoluzione angolare raggiungibile è nel range di 0.5 arcsec (Chandra) - 50 arcsec (NuSTAR) HEW

Il guaio grosso: riflessione SOLO radente





I raggi X possono solo essere riflessi ad incidenza di pochi gradi dalla superficie!

Quindi, l'area di raccolta di un singolo specchio è demoltiplicata di un fattore 100 rispetto a uno specchio ottico.

Occorre quindi innestare molti specchi con diametri decrescenti.

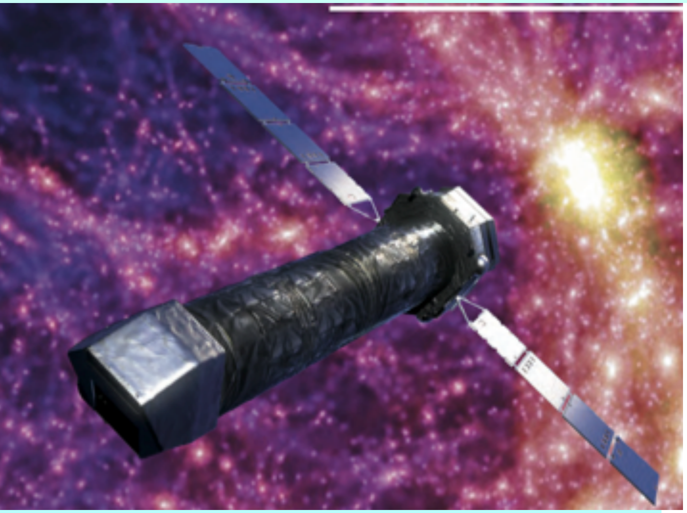
Quindi gli specchi devono essere sottili e leggeri (es. in vetro).

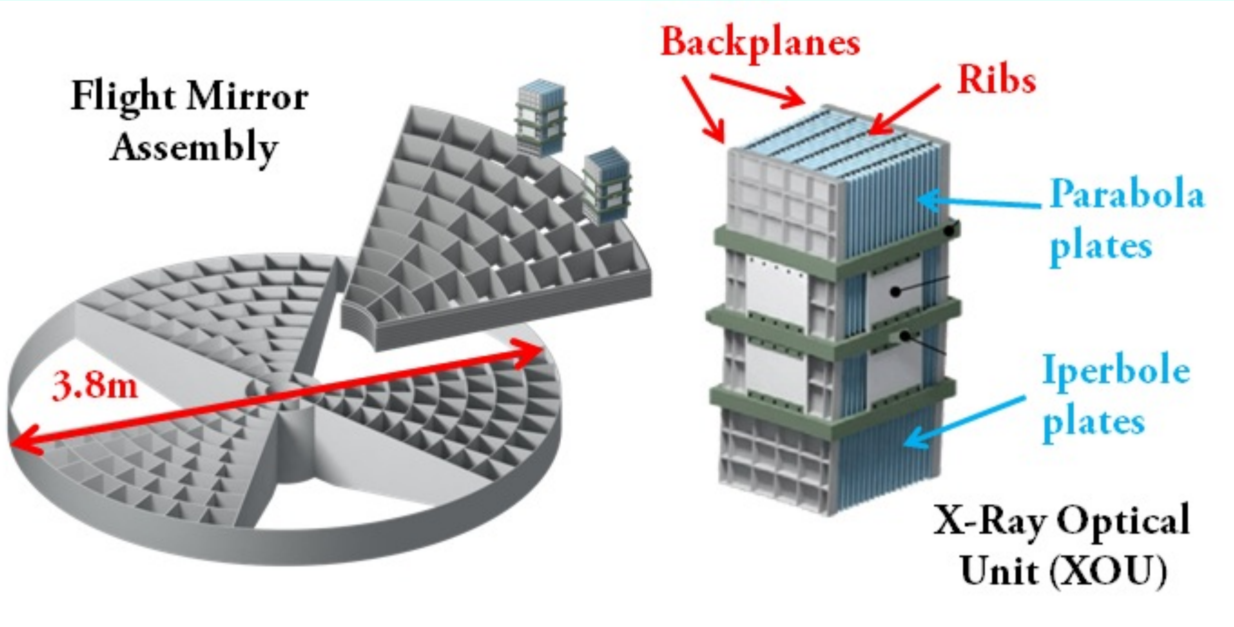
Specchi sottili si deformano facilmente, degradando la risoluzione angolare.

E' possibile correggerli **post-facto**?

Motivations for active X-ray optics

- Most X-ray sources are faint! Future X-ray optics (like ATHENA, approved by ESA, L2 call) will require a 2 m^2 effective area and a very high angular resolution (HEW < 5 arcsec).
- Keeping the mass to within acceptable limits requires lightweight materials like Silicon,or glass or plastic thin foils.
- Wide-aperture optical modules need to be based on the assembly of modular elements obtained stacking thin mirrors of high figure accuracy and surface finishing.
- INAF/OAB has been developing Slumped Glass Optics under ESA/ESTEC contract for IXO/ATHENA in 2009-2013.

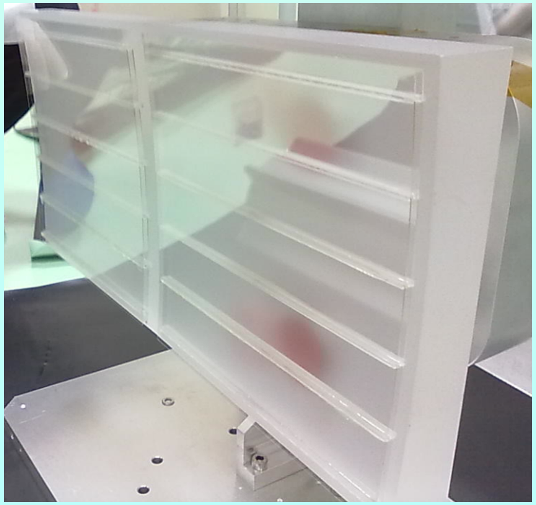




M. Civitani et al., Opt. Eng. 2013

Mirror fabrication based on slumped glasses

Item	date	tested	single shell result	method
PoC#1	Dec 2011	intrafocus	HEW ≈ 80 arcsec	from surface mapping
XOU-BB	Aug 2012	in focus	HEW = 60 arcsec	measured
PoC#2	2013 - 2014	intra/infocus	HEW ≈ 20 arcsec	reconstruct./ measured

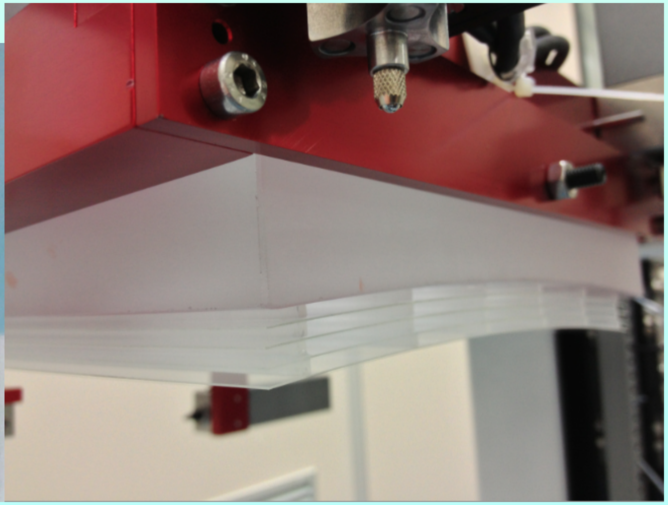


Proof of Concept (PoC) #1

2 stacked, **parallel** Wolter-I shells

X-ray Optical Unit – Bread Board (XOU-BB)

20 stacked, **parallel** Wolter-I shells



Proof of Concept #2 (PoC#2)

4 stacked, **co-focal** Wolter-I shells

M. Civitani et al., SPIE 2015

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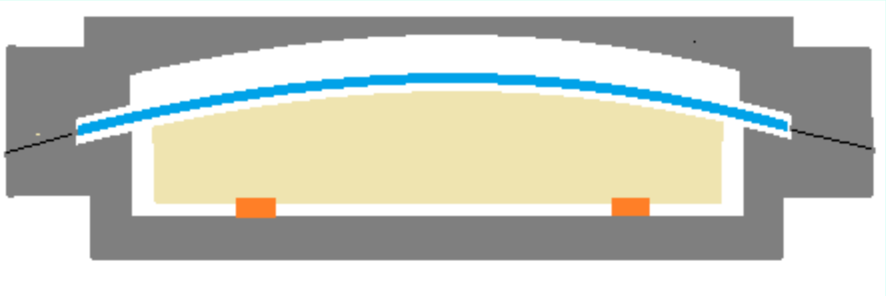
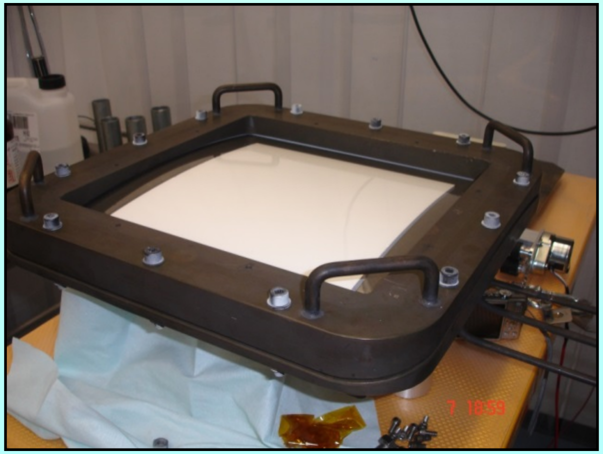
Current manufacturing process of slumped glass XOUs

- The hot slumping forming technique for thin glass foils – already succesfully implemented for the NuSTAR hard X-ray telescope - adopted at INAF/OAB is assisted by pressure using the foil itself for a better replication of the slumping mould (INAF patent).

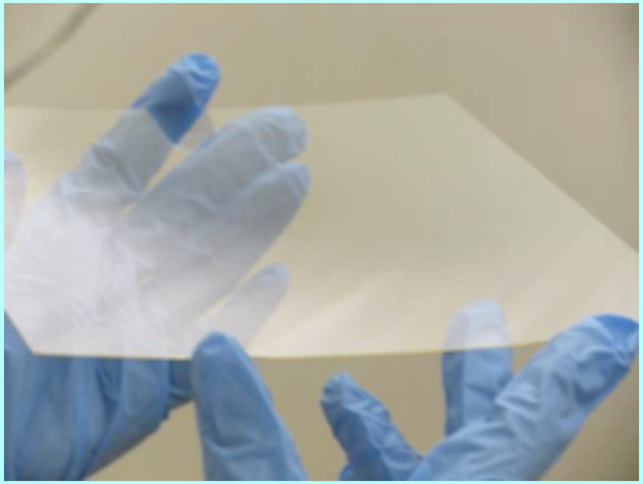


oven=>



<= muffle

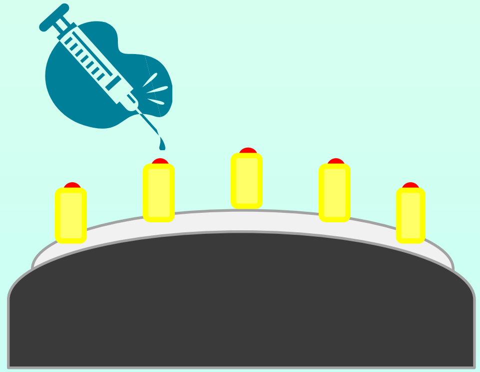
B. Salmaso et al., SPIE 2015



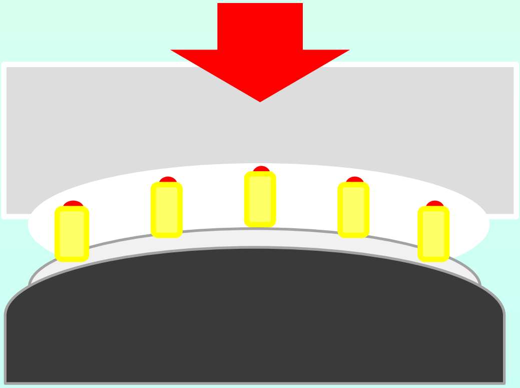
the foils are formed in cylindrical shape and => integrated onto a parabolic/hyperbolic counterform

Glass integration over a parabolic/hyperbolic mould

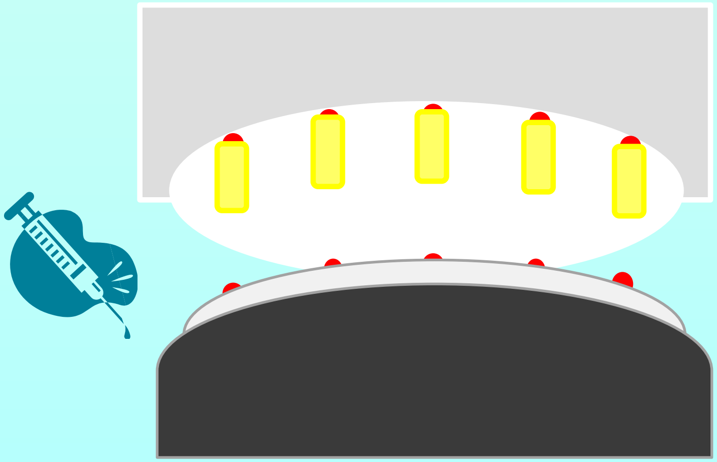
Glass fixed
To the mould



Ribs aligned on the glass
And glue dispensed



Ribs glued to backplane



Backplane with ribs glued to glass fixed on mould

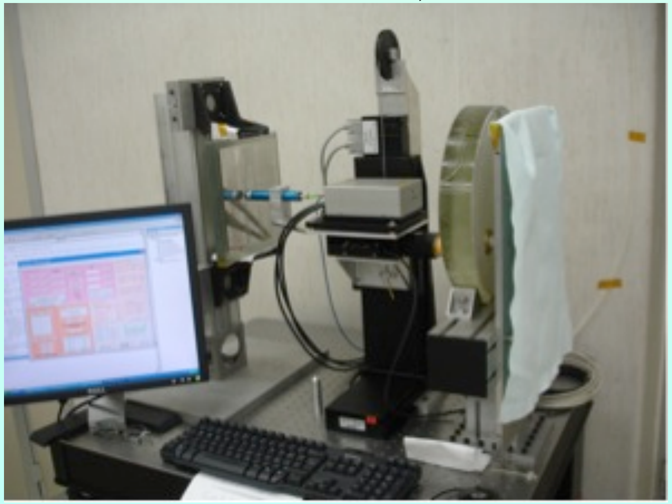
- Glass plate has the SAME SHAPE of the mould
- Glass plate shape is FROZEN with ribs
- The mould can be taken as a REFERENCE

M. Civitani et al., SPIE 2015

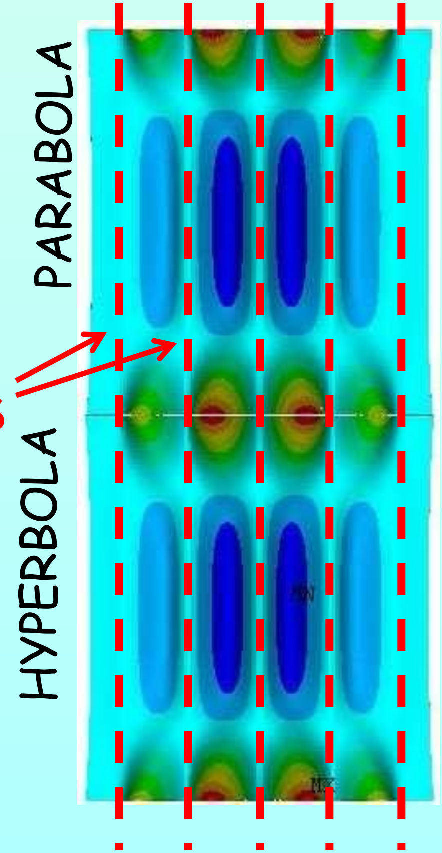
Critical points degrading the angular resolution

- After integration, the shape of the integrated glass foils can be measured using a mapping tool (CUP – Characterization Universal Profilometer)

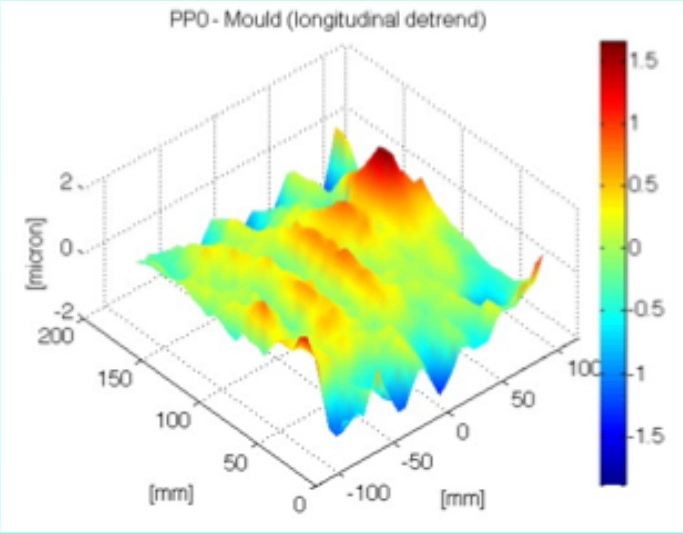
M. Civitani et al., SPIE Proc. 2013



- Measurement and FEM analysis shows that the slumping errors are corrected to an amount variable with the distance from the ribs.



- improvements below 20 arcsec HEW would require a more accurate slumping figure…
- … or *active correction* of the figure at the locations where the error is bigger…
- Finally, the surface smoothness has to be preserved!

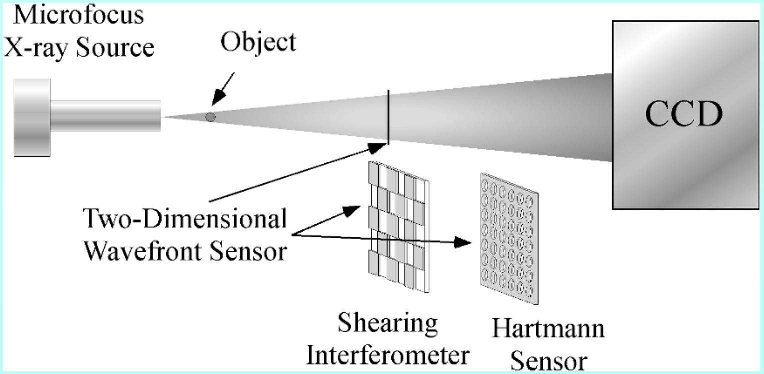


Cosa serve per fare un'ottica attiva X?

- Specchio deformabile
- Attuatori piezoelettrici
- Wavefront sensor

Problemi:

1) Dove metto i piezo, visto che non ho un piano d'appoggio?
2) Quanti piezo servono, visto che lo specchio è visto praticamente di profilo?
3) Come ci diamo tensione, visto che i raggi passano tra uno specchio e l'altro?
4) Come dargli un feedback, visto che non si misurano dopo che sono stati montati?
5) Come fare un WS senza un WS visto che un WS nei raggi X costa circa 10^5 euro?

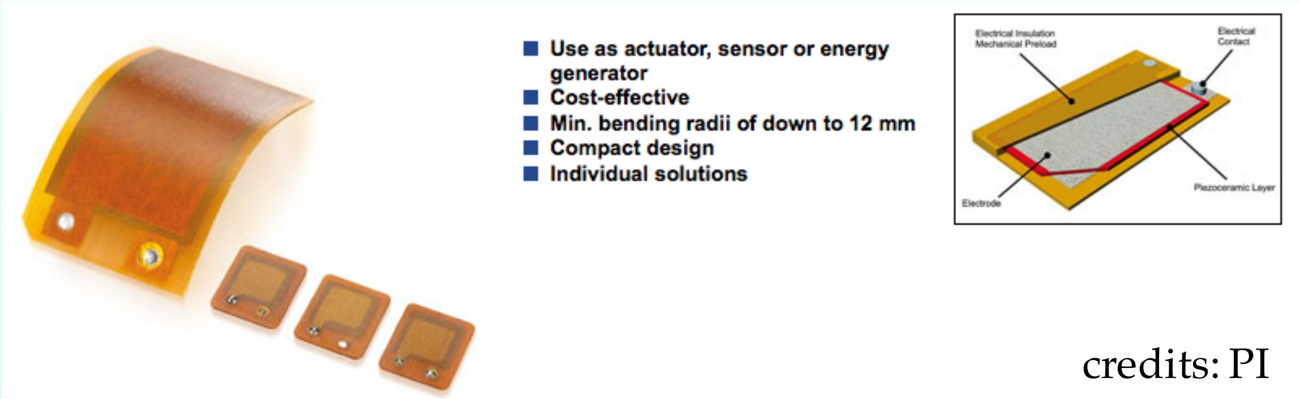


Altri gruppi al lavoro sullo stesso campo: P. Reid, D. Schwartz, R. Allured, V. Cotroneo et al. (CfA, Boston), usando anche vetri pre-formati a caldo a INAF-OAB.

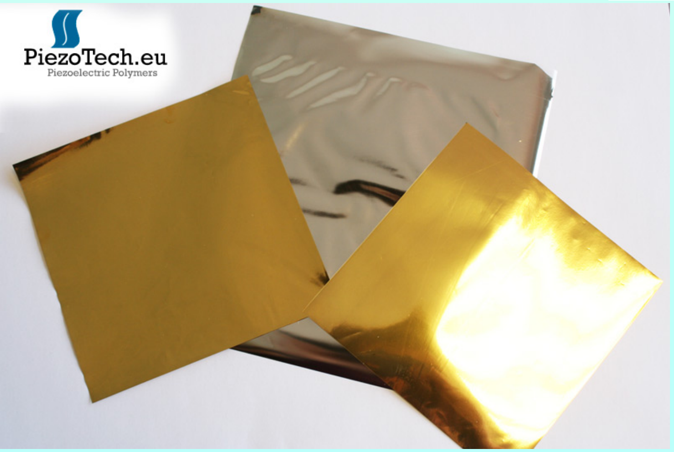
"Development status of adjustable grazing incidence optics for 0.5 arcsecond x-ray imaging," Proc. SPIE 9208, 920807 (2014)

Possible piezoelectric components

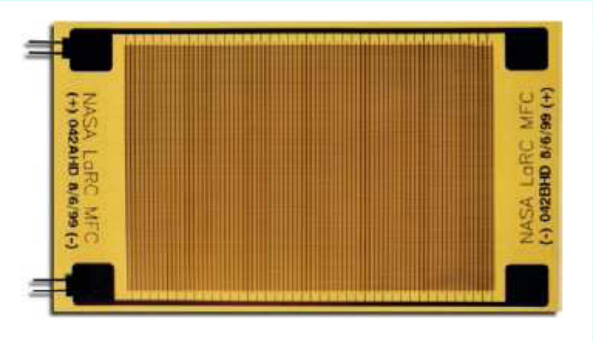
1) PIEZOCERAMICS: cheap, ready-to-use in different sizes, thickness < 100 μm, high strength, but non space-qualified (?).



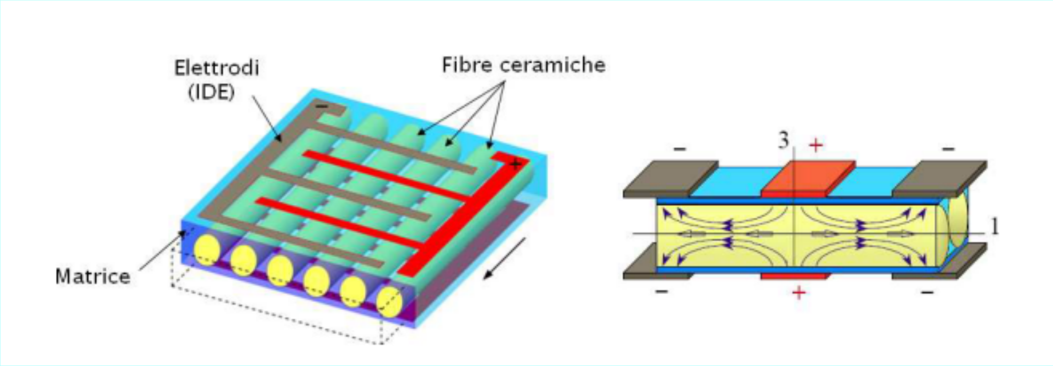
credits: PI



2) PIEZOPOLYMERS (PVDF): flexible, lightweight, can be trimmed to any size, space qualified, but expensive an bending strength 15 times lower than ceramics.

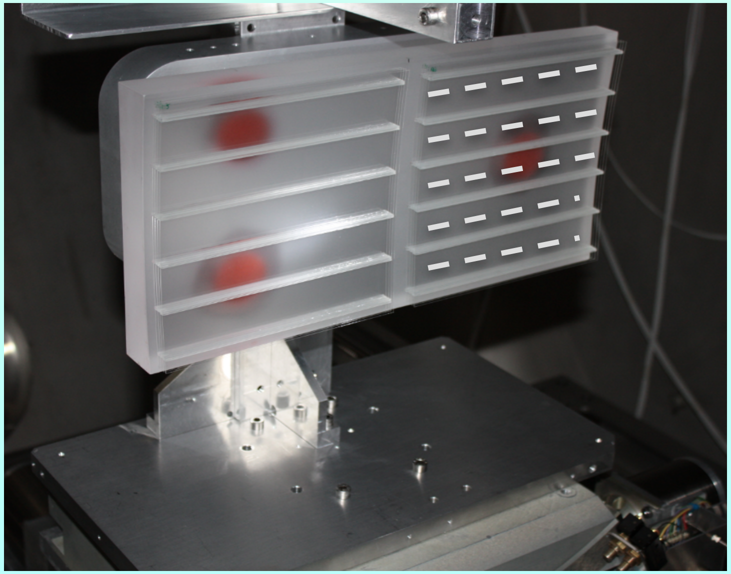


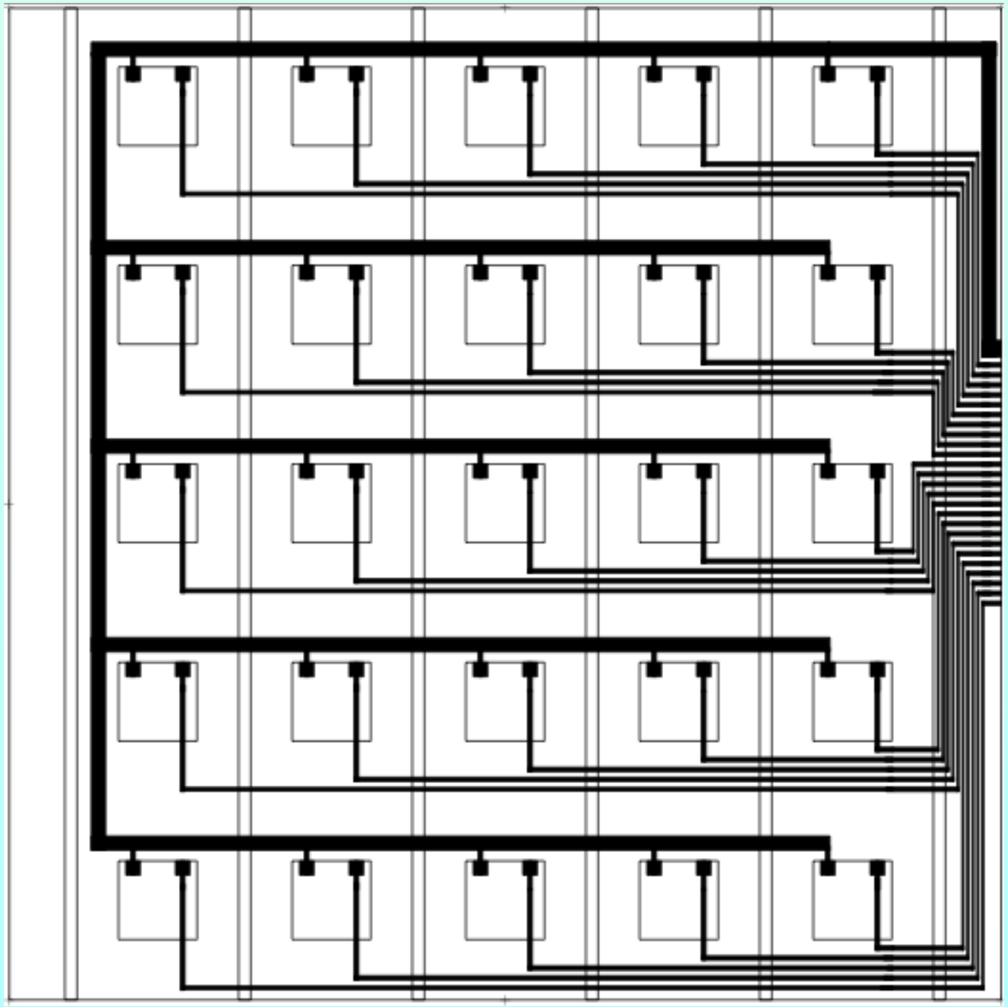
3) Microfiber Composites (MFC), strongly anisotropic, high bending strength, quite expensive.



Mirror shape correction via tangential piezo actuation

The AXYOM project (**Adjustable X-raY optics for astrOnoMy**) financed by a PRIN-TECNO INAF grant, aims at improving aims at improving via piezo actuation the existing technologies for lightweigth optics in glass or plastic foils.





For slumped glasses, small piezo actuators are applied at the anti-ribs, where the profile error is maximum.

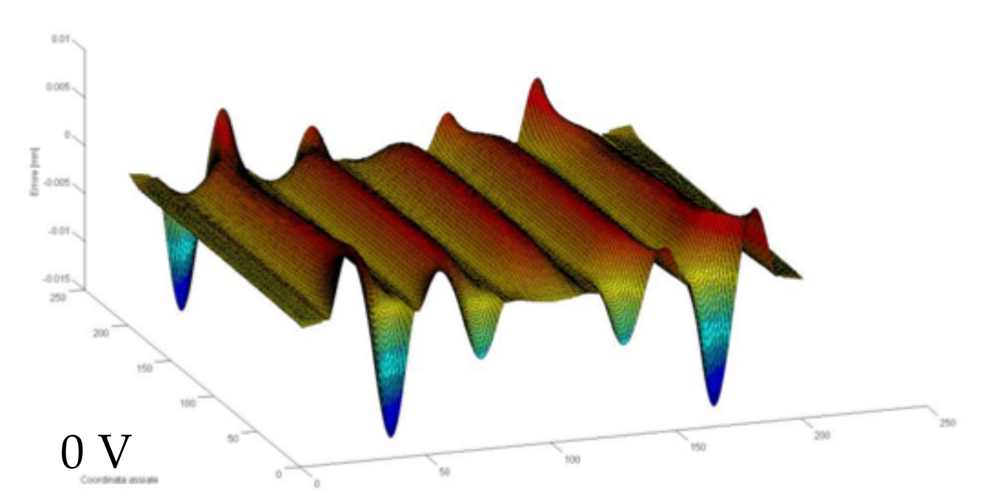
Thin electrical contacts are deposited on the rear side of the glass.

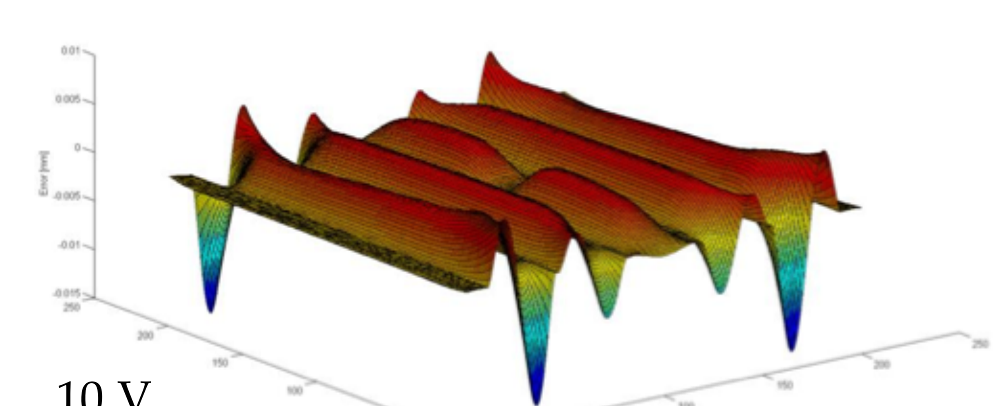
Preliminary selection of actuators for slumped glasses

The relatively high stiffness of the glass needs actuators of high strength. Piezoceramics provided by PI (16 x 13 x 0.4 mm) seem to have the characteristics required.

Configuration	Influence function [μm/V]	
1) PVDF	$1{,}3 \cdot 10^{-4}$	
2) PIC 255 A	$2 \cdot 10^{-2}$	(200 μm)
3) PIC 255 B	$3 \cdot 10^{-2}$	(500 μm)
4) PIC 255 C	$7 \cdot 10^{-2}$	(200 μm)

Propertiy	PVDF	PIC 255
E1 [MPa]	$2.5 \cdot 10^{3}$	$16.1 \cdot 10^{6}$
E2[MPa]	$2.1 \cdot 10^{3}$	$16.1 \cdot 10^{6}$
E3[MPa]	$0.9 \cdot 10^{3}$	$20.7 \cdot 10^{6}$
ν1	0.31	0.34
ν2	0.289	0.34
ν3	0.327	0.34
G12 [MPa]	$3 \cdot 10^{3}$	$6 \cdot 10^{6}$
G13 [MPa]	$1.2 \cdot 10^{3}$	$7.7 \cdot 10^{6}$
G23 [MPa]	1800	$7.7 \cdot 10^{6}$
d31 [C/N]	$14 \cdot 10^{-12}$	$-180 \cdot 10^{-12}$
d21 [C/N]	$14 \cdot 10^{-12}$	$-180 \cdot 10^{-12}$
d32 [C/N]	$-34 \cdot 10^{-12}$	$400 \cdot 10^{-12}$
d15 [C/N]	-	$550 \cdot 10^{-12}$
d24 [C/N]	-	$550 \cdot 10^{-12}$
K1 ($\varepsilon/\varepsilon_0$)	7.6	1650
K2 ($\varepsilon/\varepsilon_0$)	7.6	1650
K3 ($\varepsilon/\varepsilon_0$)	7.6	1650
ρ [g/cm3]	1.47	7.8

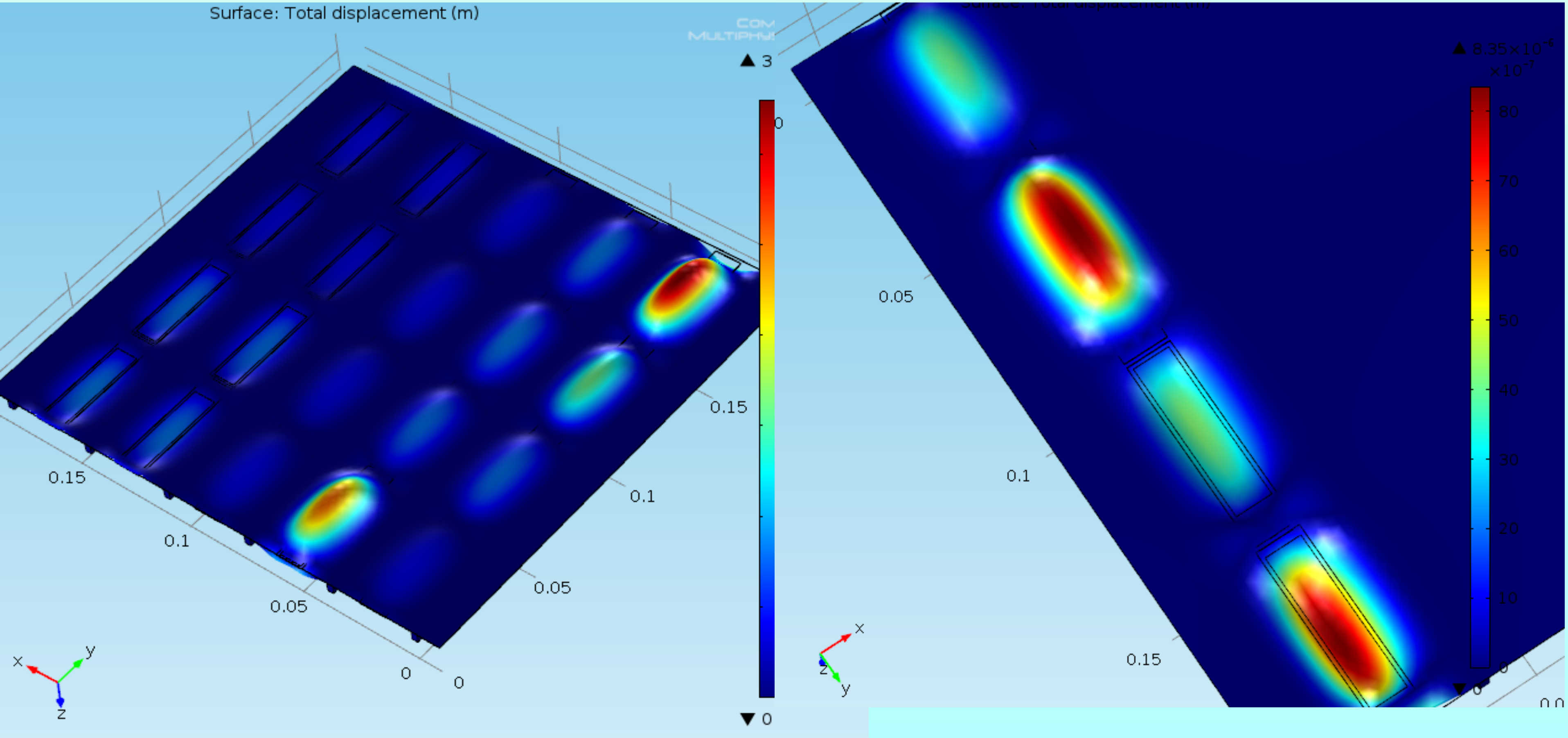




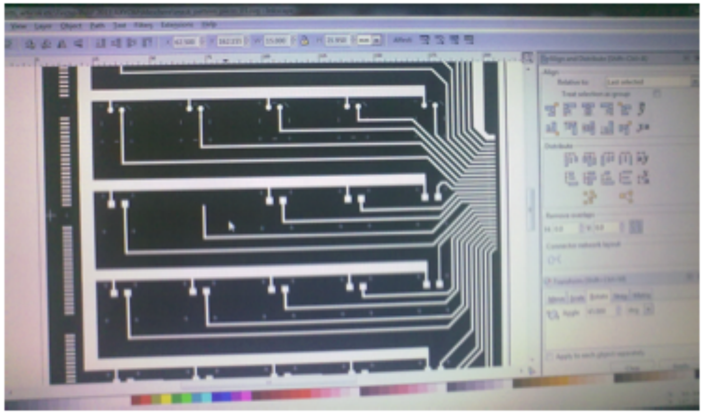
Dell'Agostino et al., SPIE Proc. 2014

More FEM simulations

The relatively high stiffness of the glass needs actuators of high strength. Piezoceramics provided by PI (16 x 13 x 0.4 mm) seem to have the characteristics required.



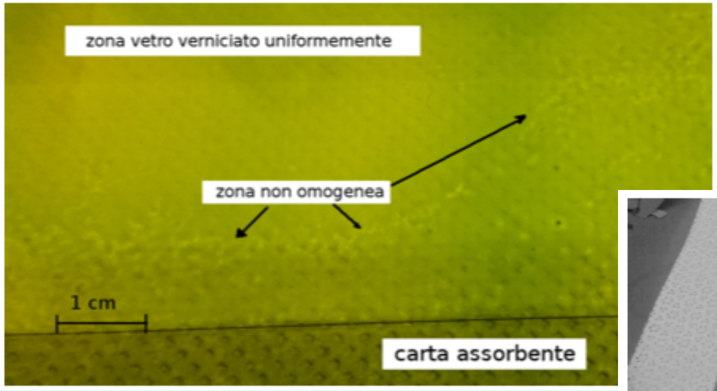
Deposing electrical contacts on the backside



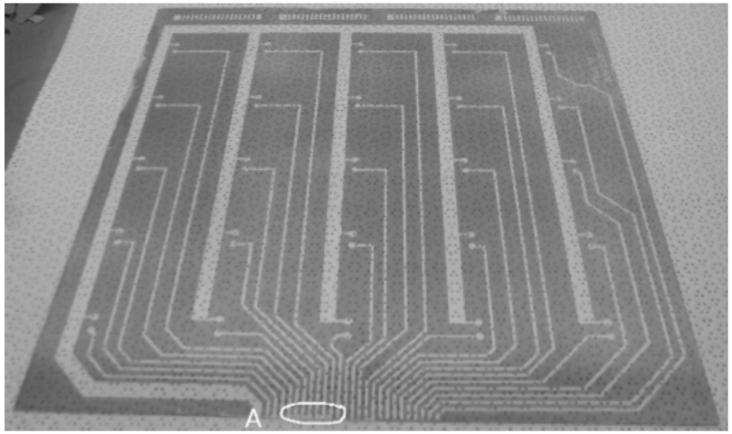
mask printing

photoresist masking and UV exposure

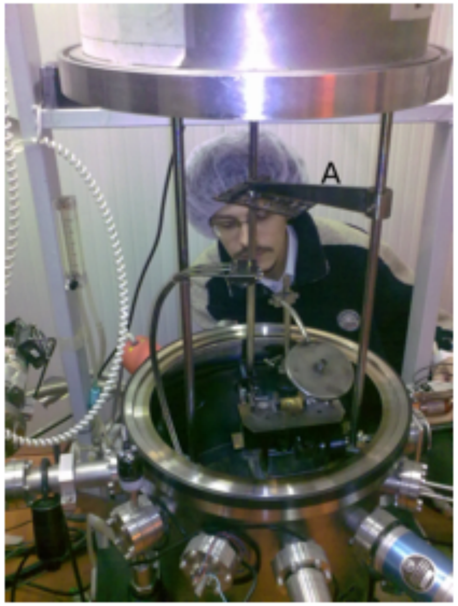
metal liftoff with Acetone



Photoresist spraying on glass backside



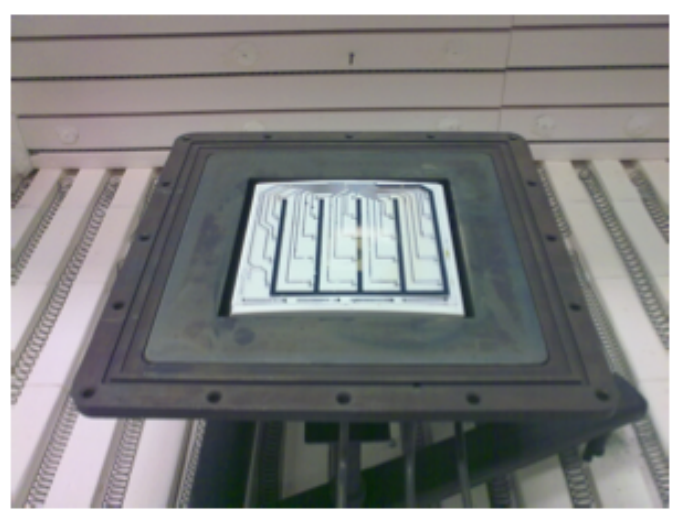
photoresist removal

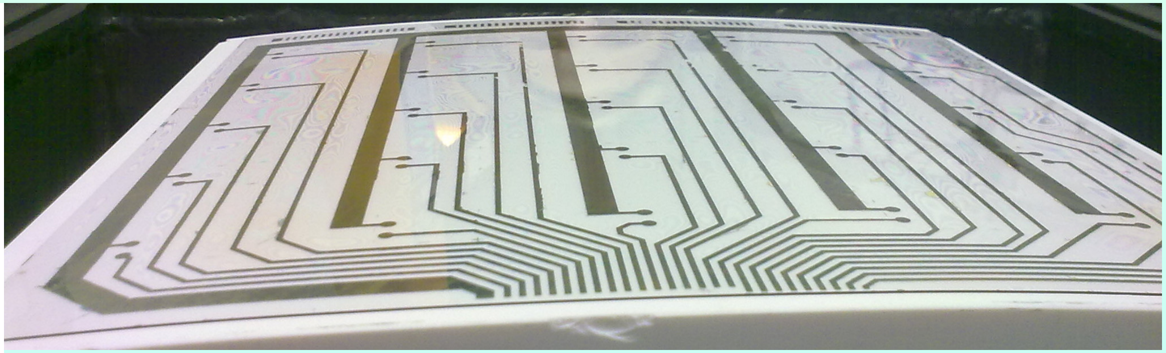


Ti+Au evaporation

Slumping glasses with electrical pattern

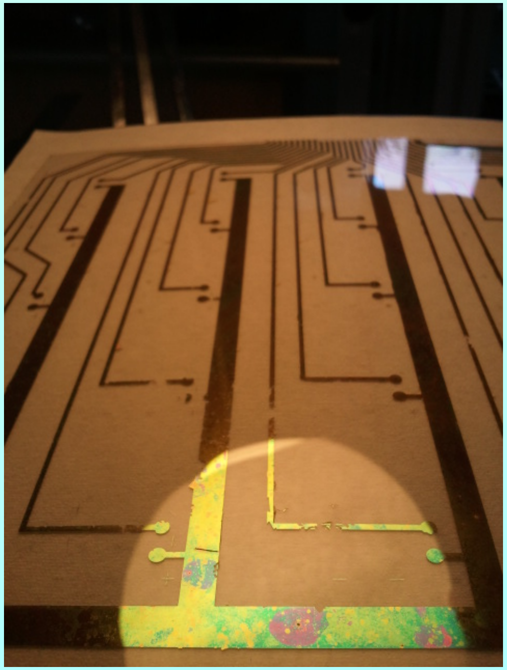
1) contact deposition BEFORE hot slumping





pattern AFTER hot slumping (notice the curvature!)

pattern BEFORE hot slumping (in over, upon the cylindrical mould)

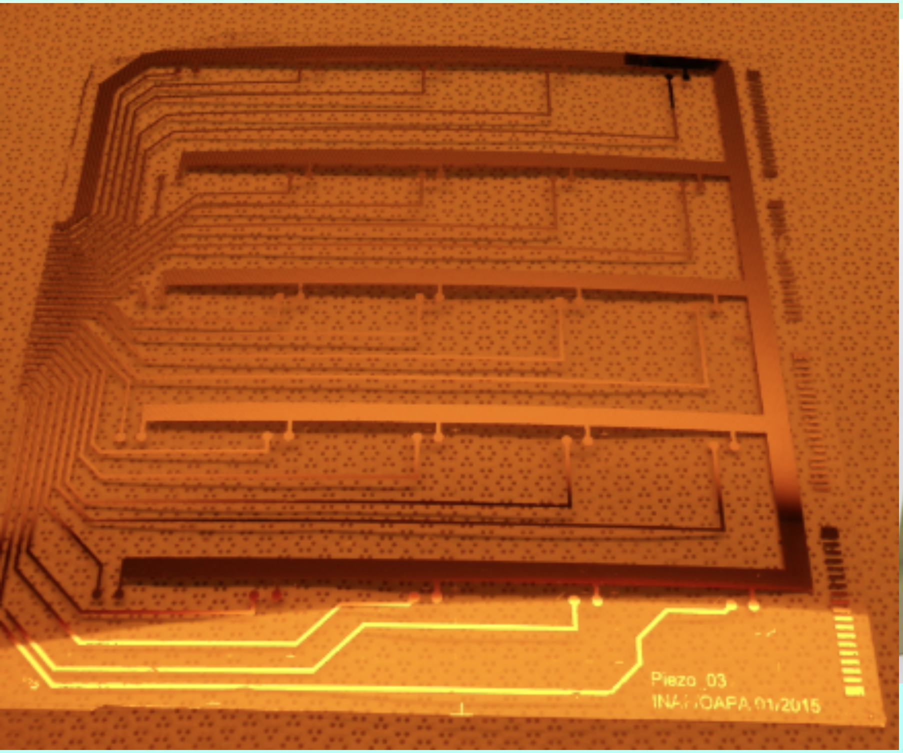


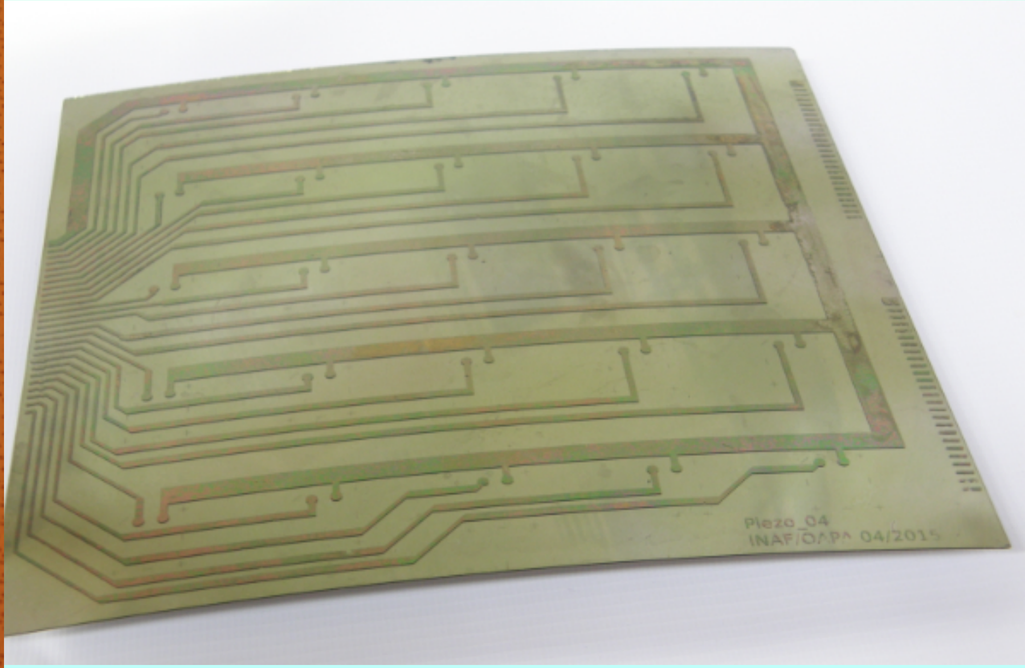
The pattern appears not to be damaged by the high temperatures (~700 ° C). Some intermixing of Ti+Au seems to be triggered.

However, the tracks conductivity is still of only 10-20 Ω (Vs.> 10 GΩ of the piezo)

Depositing electrical contacts on the backside

2) contact deposition AFTER hot slumping





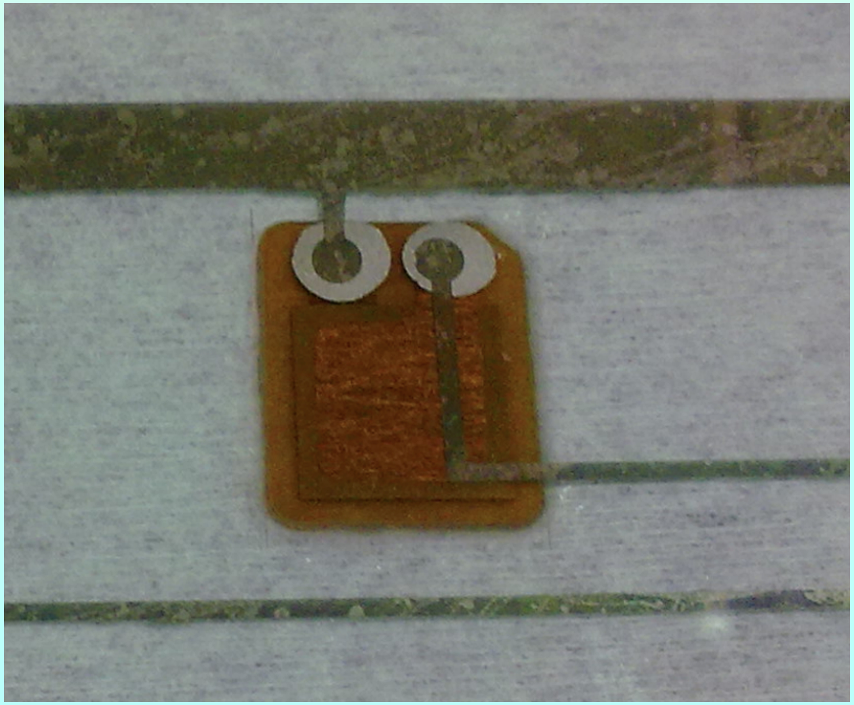
Even simpler. Metallic tracks are not exposed to high temperatures. Higher risk of glass breakage during the lithography process, and possible deformation induced by tracks.

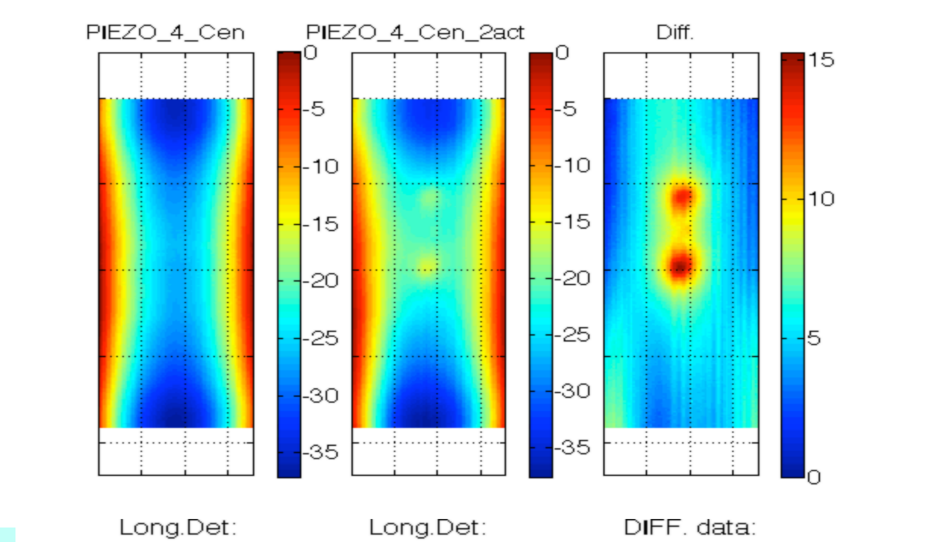
A 80 nm Titanium layer on the front side is used to allow us to measure the mirror shape with optical sensors without being affected by the track reflection.

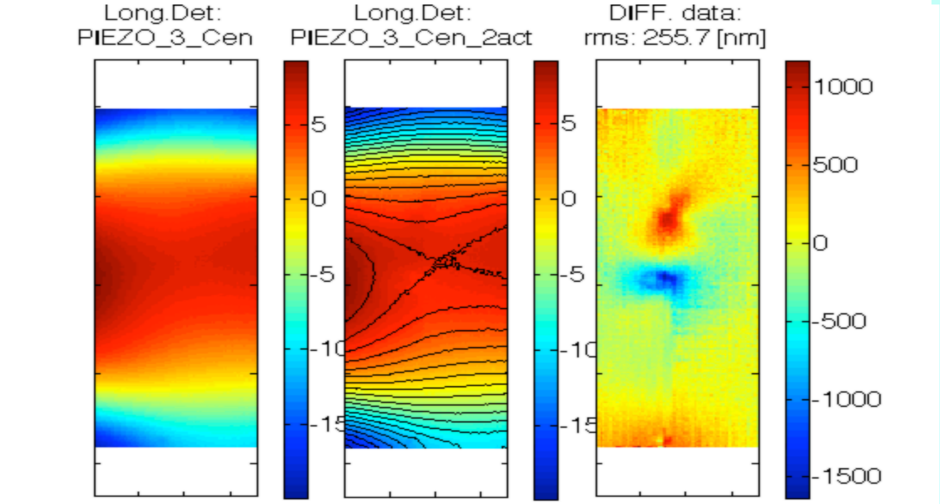
Gluing experiments

Epoxy glue + conductive glue to ensure electrical contacts. The imprints of piezos are clearly seen, but are reduced to $< 1\mu m$ if gluing is performed in contact with the mould.

D. Spiga et al., J. Sinchr. Rad.. 2016





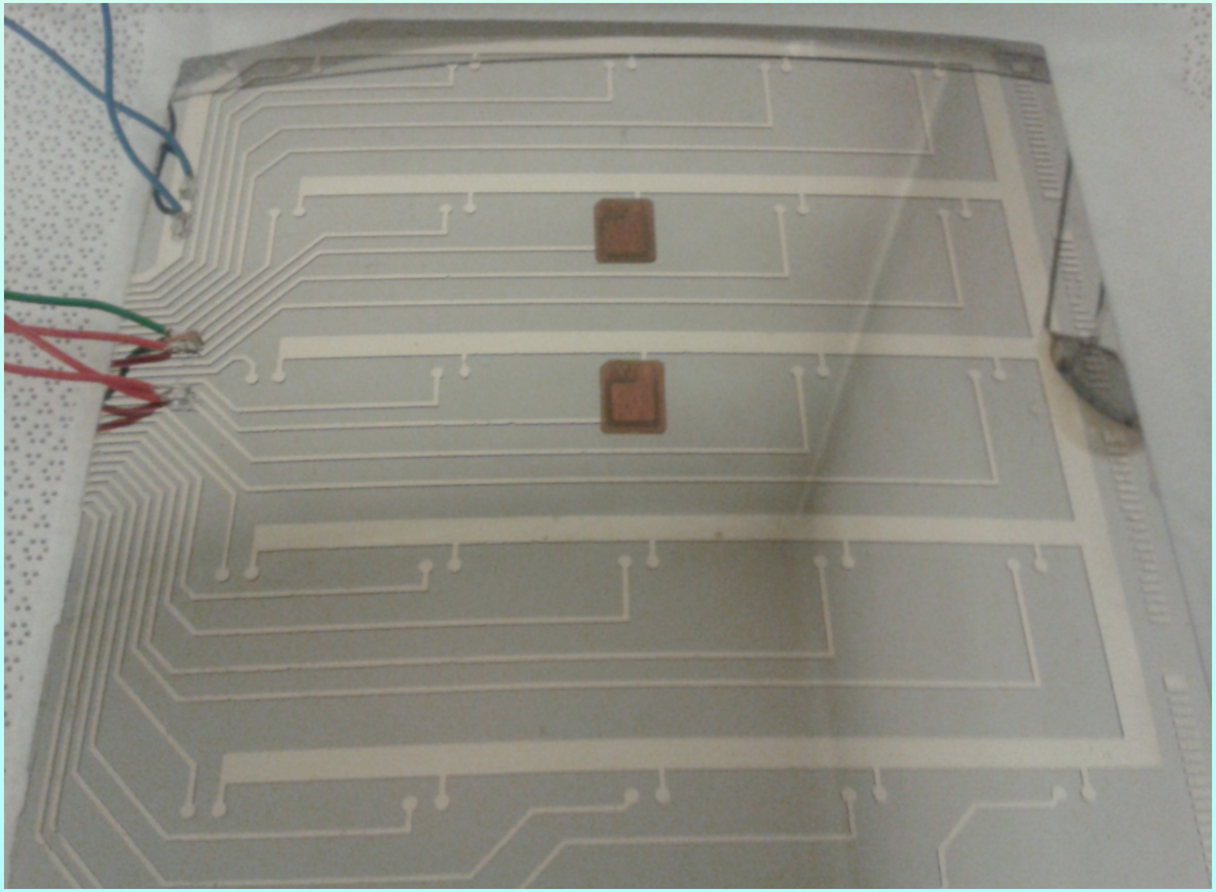


The shrinkage of the glue is not negligible.
How to control the thickness of the glue?

The very first active glass

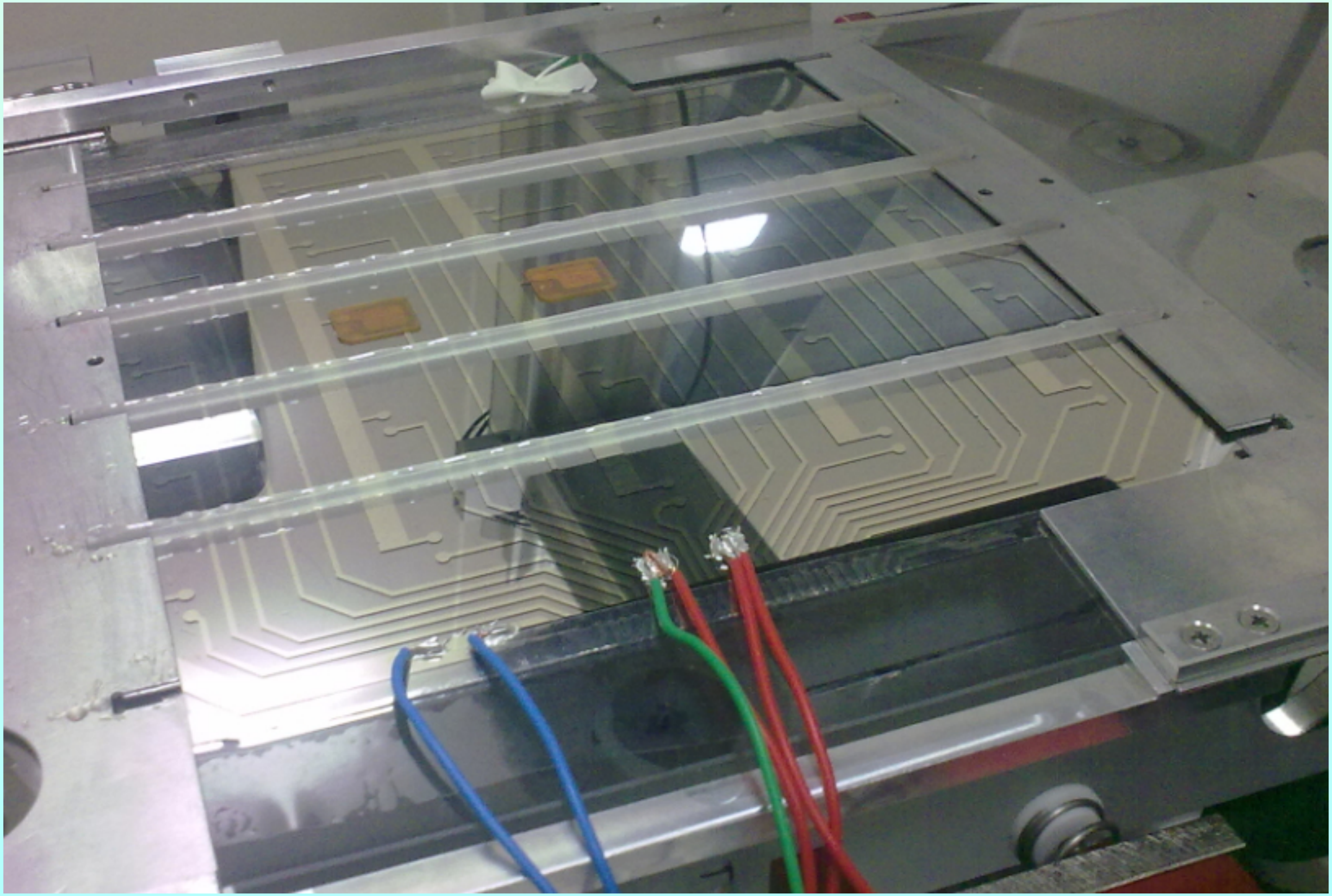
Even if the initial quality of this glass was not so good, and the piezos were not glued on a reference surface, we decided to test the effects with this simple pro-prototype.

Feeding cables will be near one of the outer ribs and the deformation will affect one of the lateral wings



D. Spiga et al., SPIE Proc. 2015

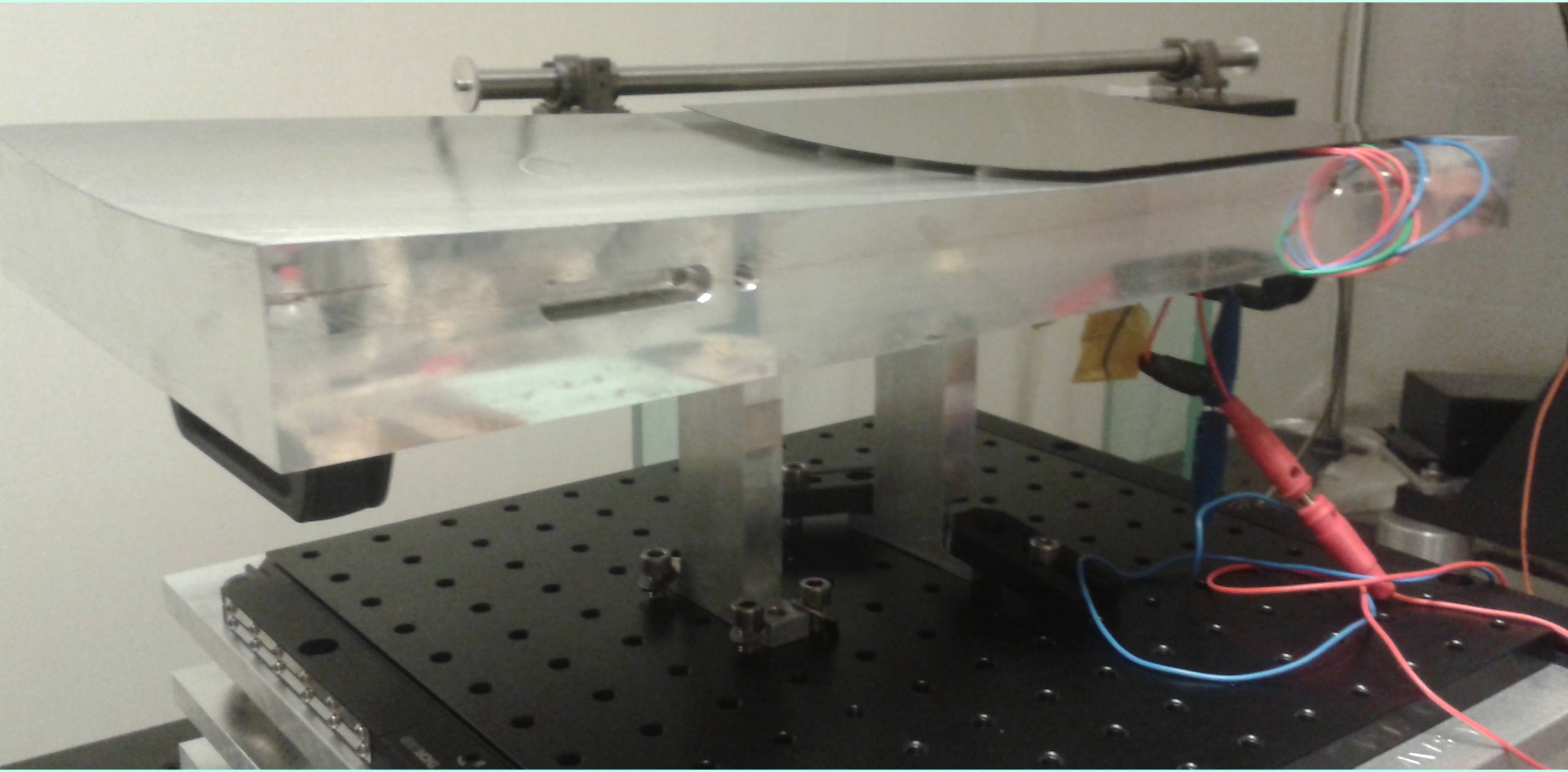
Mirror integration



D. Spiga et al., J. Sinchr. Rad.. 2016

Profile measurement with LTP

Only a single piezo could be tested at a a time (and the power supply could reach only +25 V).



D. Spiga et al., J. Sinchr. Rad.. 2016

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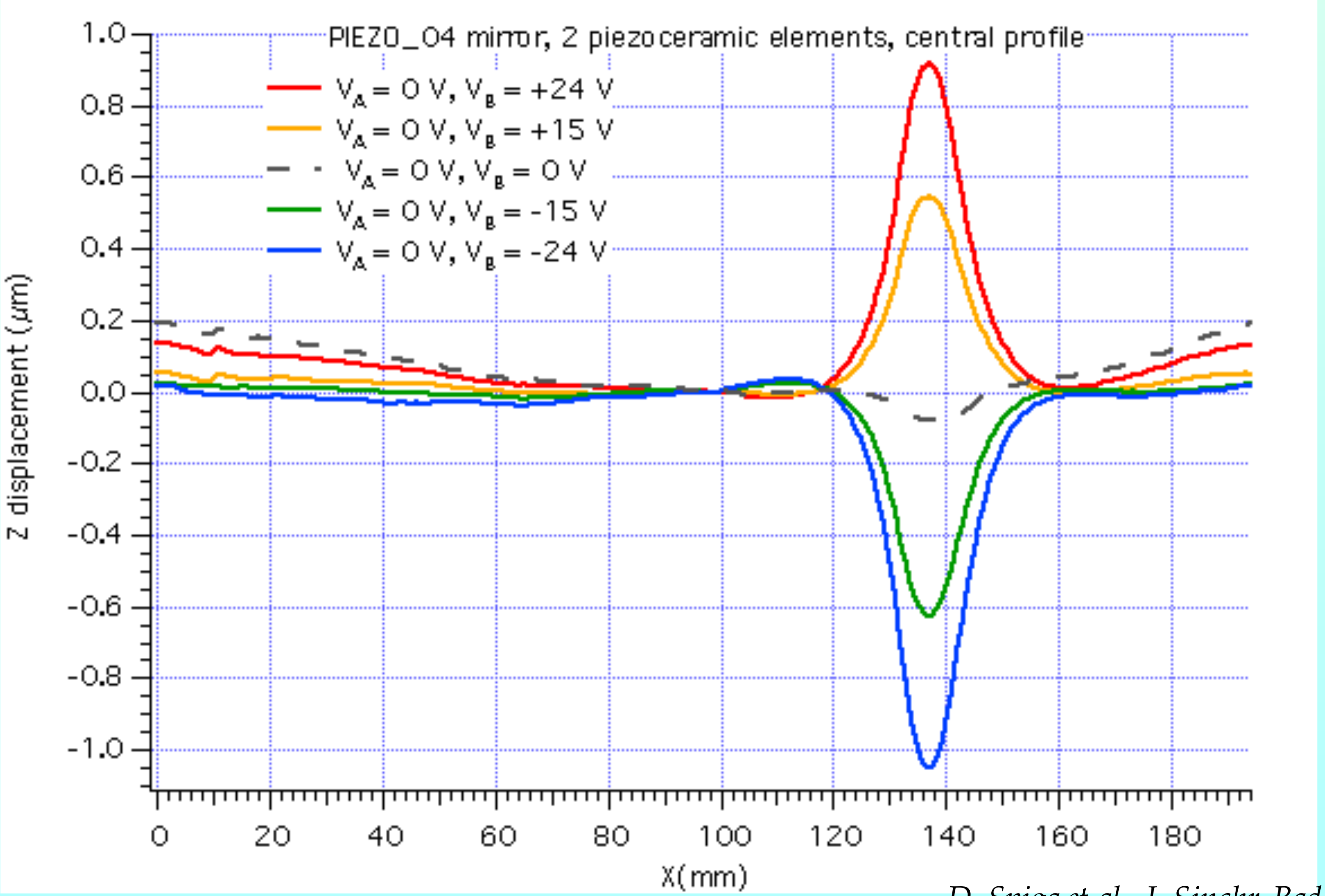
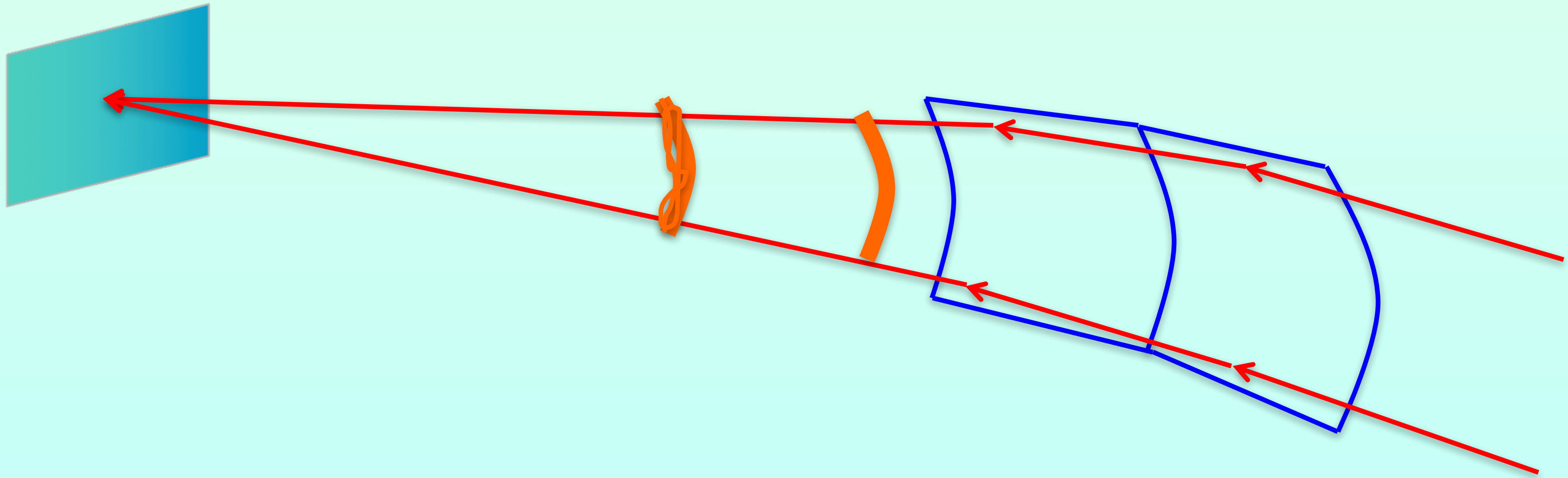


D. Spiga et al., J. Sinchr. Rad.. 2016

The feedback problem: our "wavefront sensor"

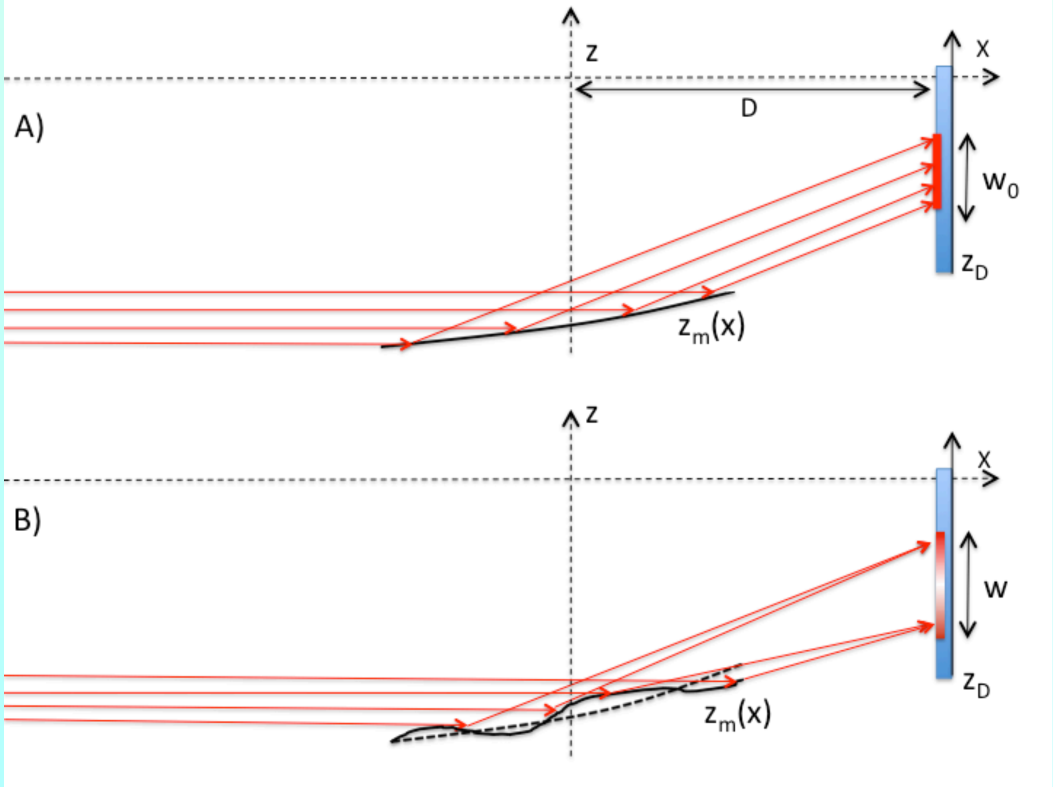


- When viewed in intra-focus position, the (either 1-refl or 2-refl.) focused beam appears like an arc (to be recorded by a large area detector, possibly scanned by a small detector).
- A *perfect mirror* would return a *regular, uniform* trace.
- In *a real mirror*, the trace has a variable *width and intensity*, related to the mirror shape.
- The closer to the mirror, *the less pronounced, but less confused* are the intensity modulations.

How to reconstruct the shape from the intrafocal image?

- Hartmann test (requires a dedicated device)
- test in UV light (uncertain aperture diffraction subtraction)
- test in pencil beam (needs a synchrotron and a dithering system)

or…directly reconstruct the mirror profile!

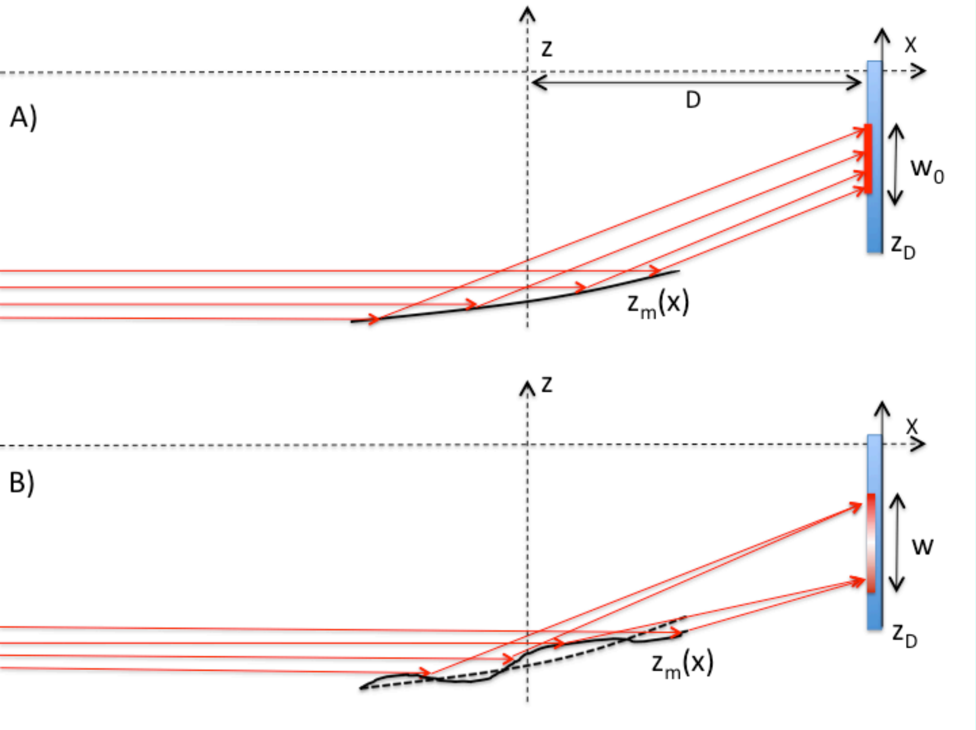


A *perfect mirror* would return in intra-focus distance a uniform trace.

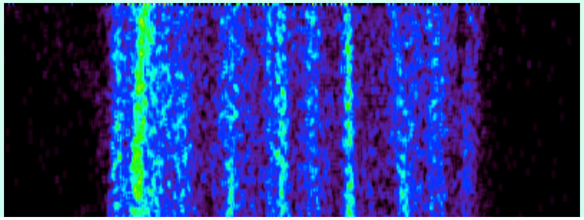
In *a real mirror*, the trace has a variable *width and intensity*. The intensity profile **can be related to the mirror profile** in the longitudinal direction.

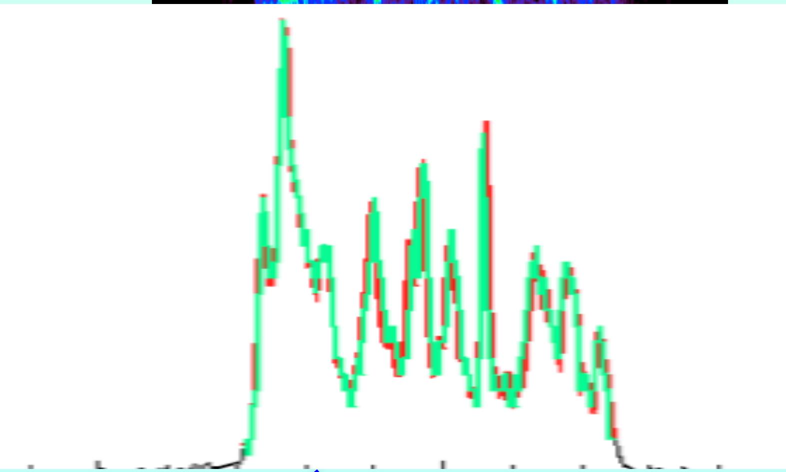
This kind of profile reconstruction was used as wavefront sensor in optical astronomy since the 80's:
F. Roddier, et al., ***Appl. Opt.*** *Vol. 27, (1988)*

Profile reconstruction in single reflection, near-field imaging



$z_D = z_D(x)$?





Unknown quantities:

Mirror profile: $z_m = z_m(x)$

Detector mapping: $z_D = z_m(x) + 2z'_m(x)\,(D-x)$

Measured quantity:

$I(z_D)$

Boundary condition:

$$\int_{-L/2}^{+L/2} z'_m(x)\,dx = L \sin\alpha$$

D. Spiga et al., ***SPIE Proc.*** *Vol. 8861 (2013)*

ADONI workshop, Firenze, 12 aprile 2016

Profile reconstruction in single reflection, near-field imaging

measured intensity, $I(z_D)$

First guess (ideal mirror)

$$x = -\frac{L}{w} z_D$$

$$z'_m(0) = \sin\alpha$$

Curvature equation (simplified)

$$z''_m(x) = \frac{z'_m(0)}{2D}\left(1 - \frac{I_0}{I(z_D)}\right)$$

Resample $I(z_D)$ over $z_D(x)$

$$z_m = z_m(x)$$

Refined mirror profile

$$z_D(x) = z_m(x) + 2\, z'_m(x)\,(D-x)$$

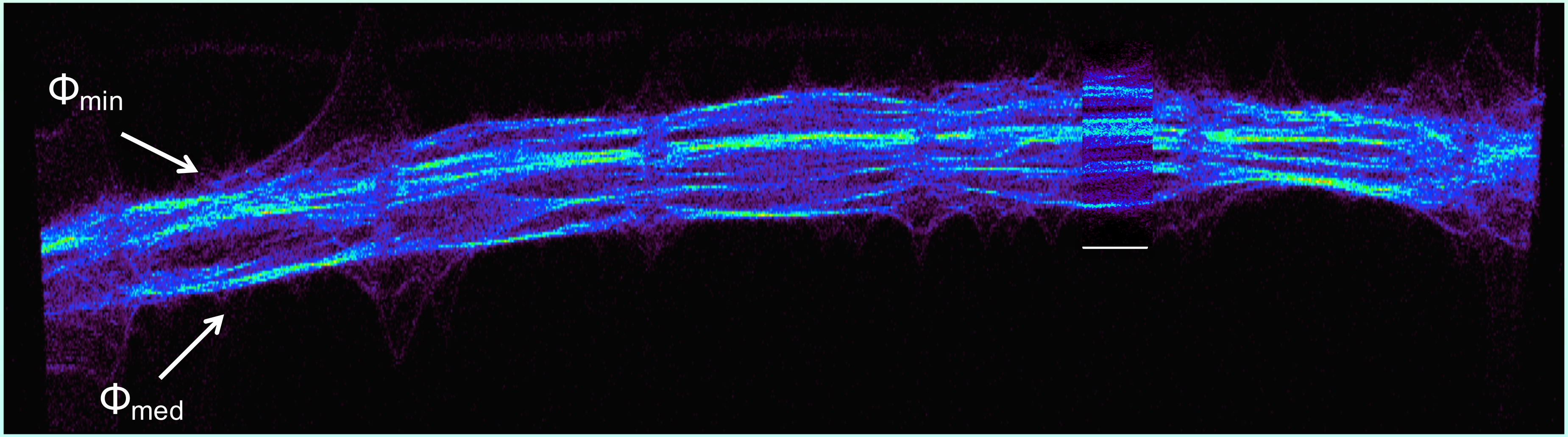
Refined detector mapping*

D. *Spiga et al.*, ***SPIE Proc.*** *Vol. 8861 (2013)*

$$I_0 = \frac{w}{L z'_m(0)} \left\langle \frac{1}{I(z_D)} \right\rangle^{-1}$$

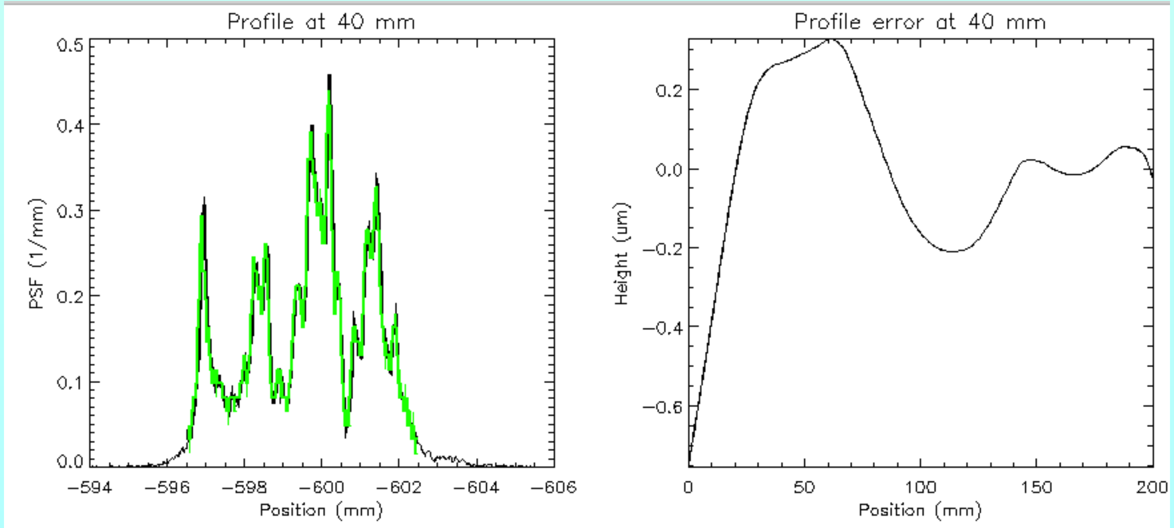
*: *D* small enough to return a monotonic $z_D(x)$ function ("near field"), i.e., non-intersecting rays!!

X-ray tests at PANTER (MPE) on the PoC2 (IXO project)

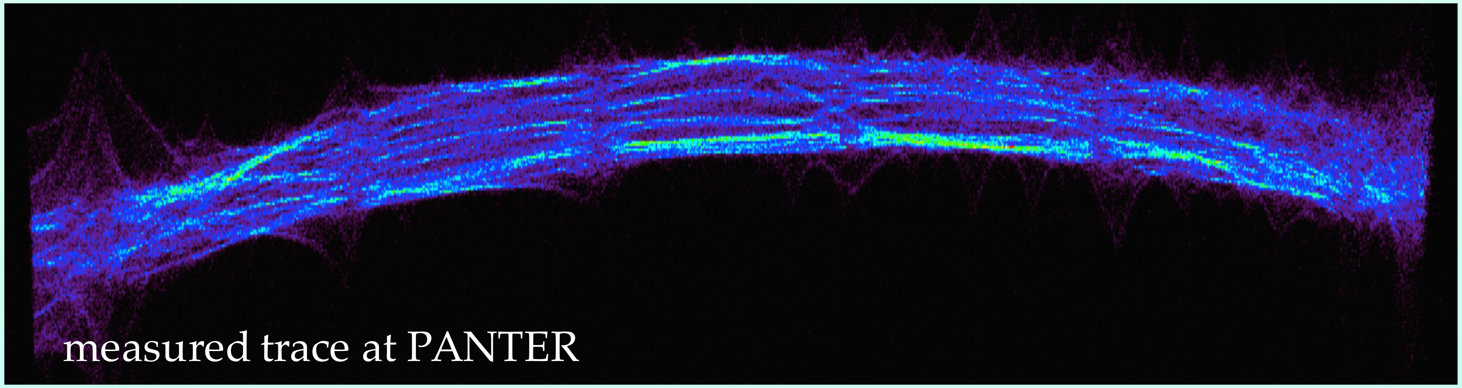


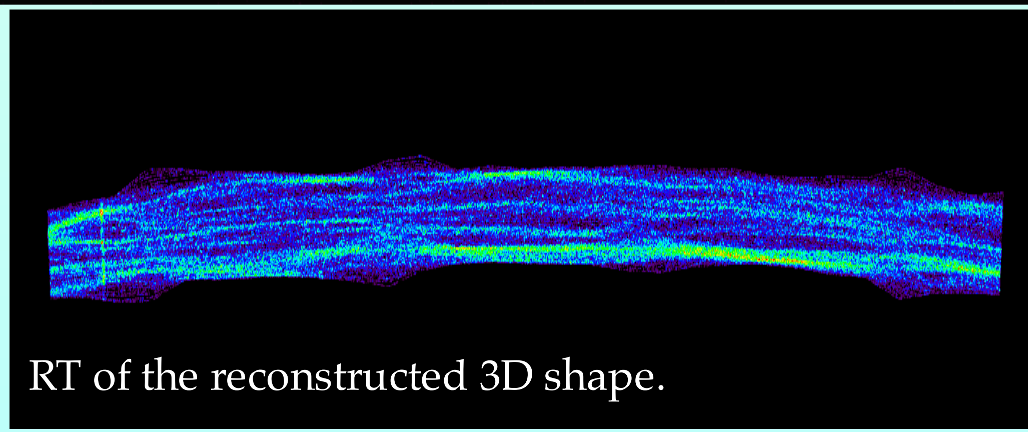
- The longitudinal profiles at -70 mm < y < 70 mm could be derived.
- Extracting a single profile requires 10-15 iterations, a few seconds computation.

*D. Spiga et al., **SPIE Proc.** Vol. 8861 (2013)*



PP0 parabola, 3D reconstruction





Simulated from Ray-Tracing on the reconstructed 3D image. Only the central part of mirror shape could be retrieved from X-ray data because the two ends of the X-ray data are too confused (mirror too rough).

The reconstruction is – to date – possible only in single reflection setup. This can be obtained also for the inner layers of a sufficiently spaced stack.

D. Spiga et al., ***SPIE Proc.*** *Vol. 8861 (2013)*

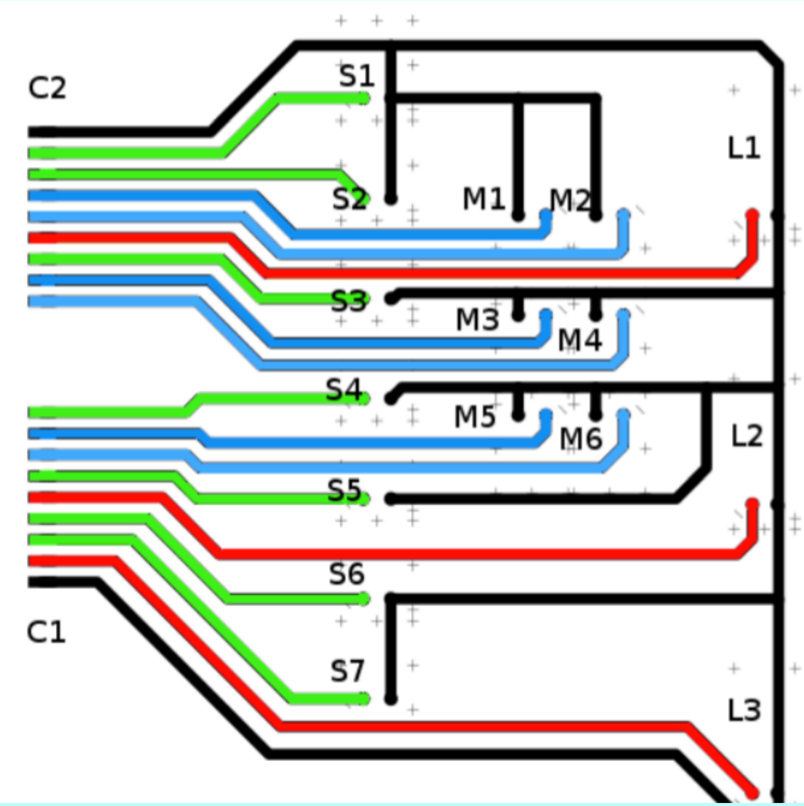
The XACT facility in INAF/OAPA

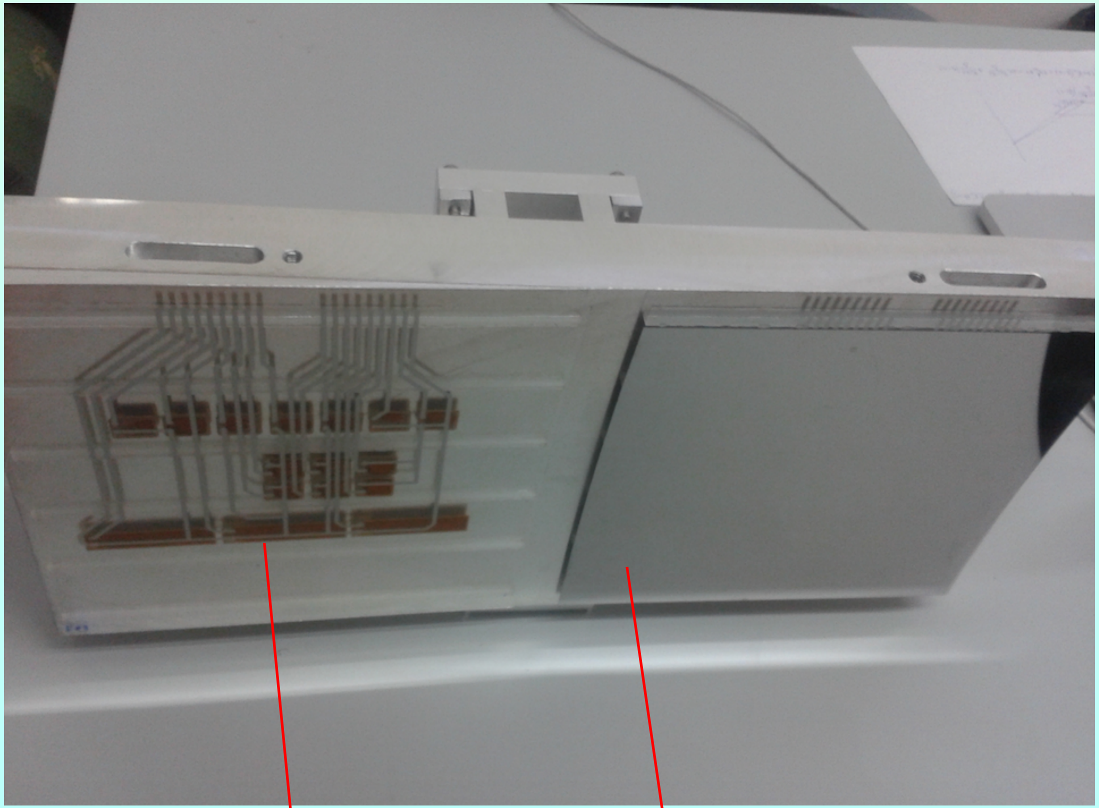
- X-ray tests in intra-focus setup can be performed using the XACT 35 m long X-ray facility in INAF/Osservatorio Astronomico di Palermo. The facility includes:

- Electron impact X-ray sources covering the range 0.1-20 keV
- X-ray monochromators
- 35 m high vacuum pipe including 3 test chambers
- Vacuum Micropositioning systems
- X-ray detectors (4 cm diam. Microchannel Plate)
- Vacuum Altazimuth mount

The intrafocal pattern will be used to reconstruct the 3D map of the active mirror under X-rays. We consequently know which actuators should be fed with an appropriate voltage using a dedicated electronic control device (developed at UNIPA).

AXYOM, test n. 2



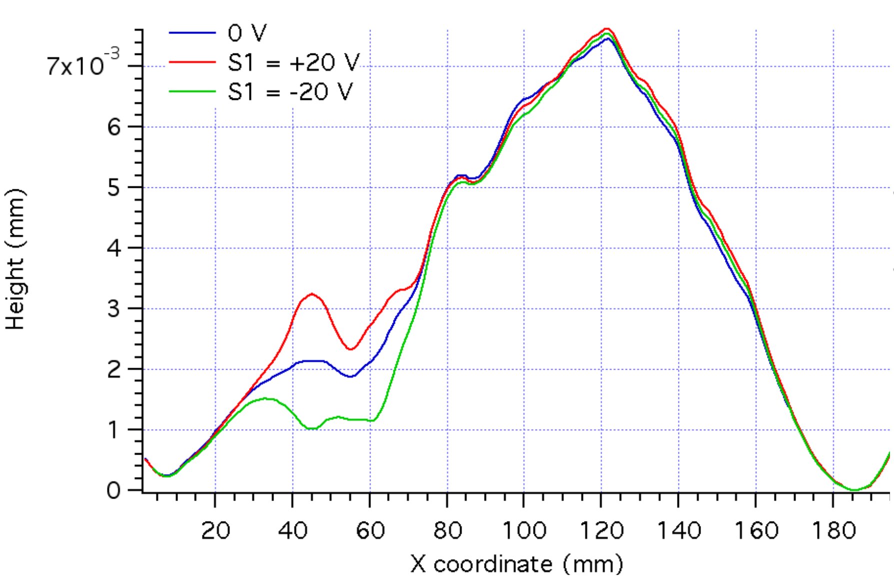


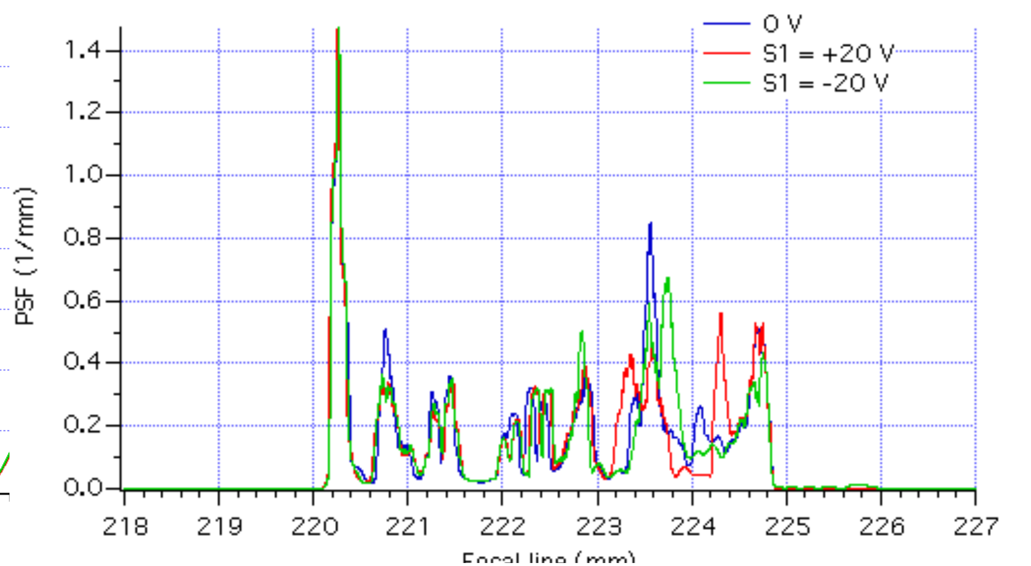
- Tre diverse disposizioni di piezo in 3 diversi settori di parabola e iperbole
- L: 3 piezo lunghi
- M: 3x2 matrice centrale di piezo corti
- S: 7 piezo corti in fila

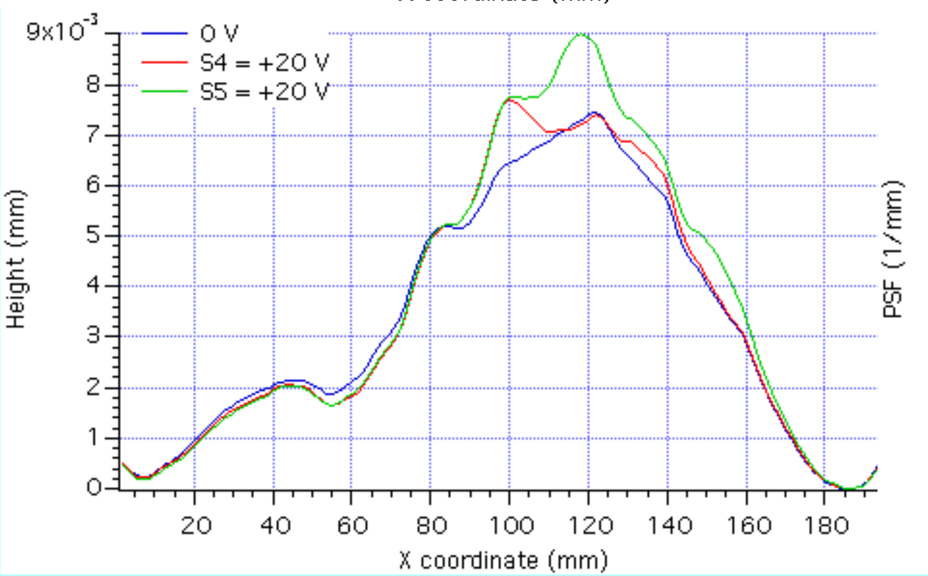
"Iperbole", no coating

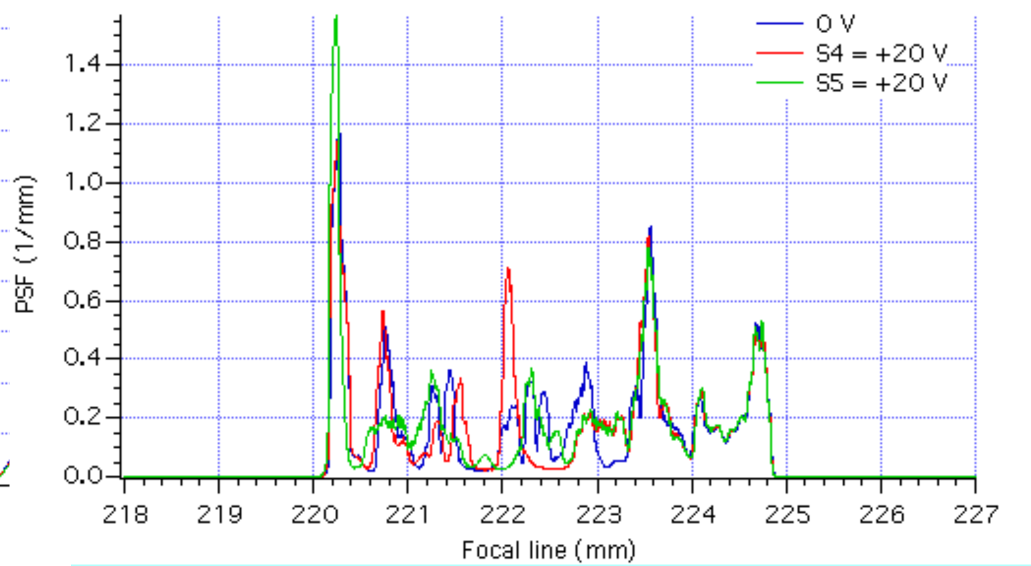
"Parabola", con coating

Profili misurati a LTP





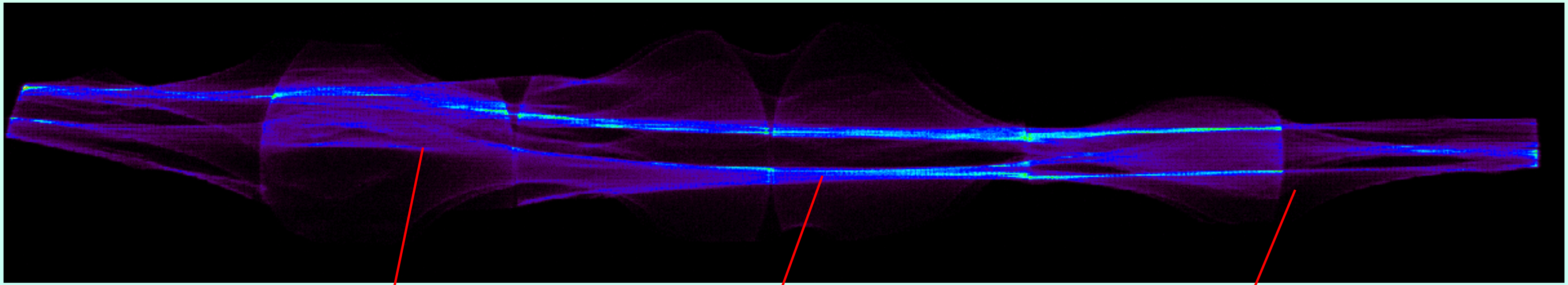




- Parabola, settore S.

Misure intrafocali: parabola e iperbole

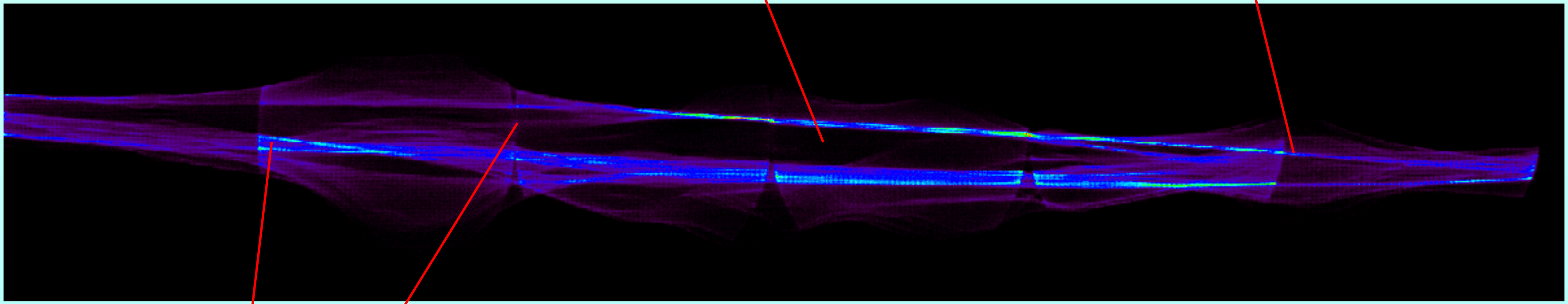
- Immagini ottenute assemblando singole immagini MCP (4 cm diam., risol. 0.1 mm). La zona centrale mostra un grosso “minimo” dovuta al massimo picco-valle.



Zona piezo L

Zona piezo M

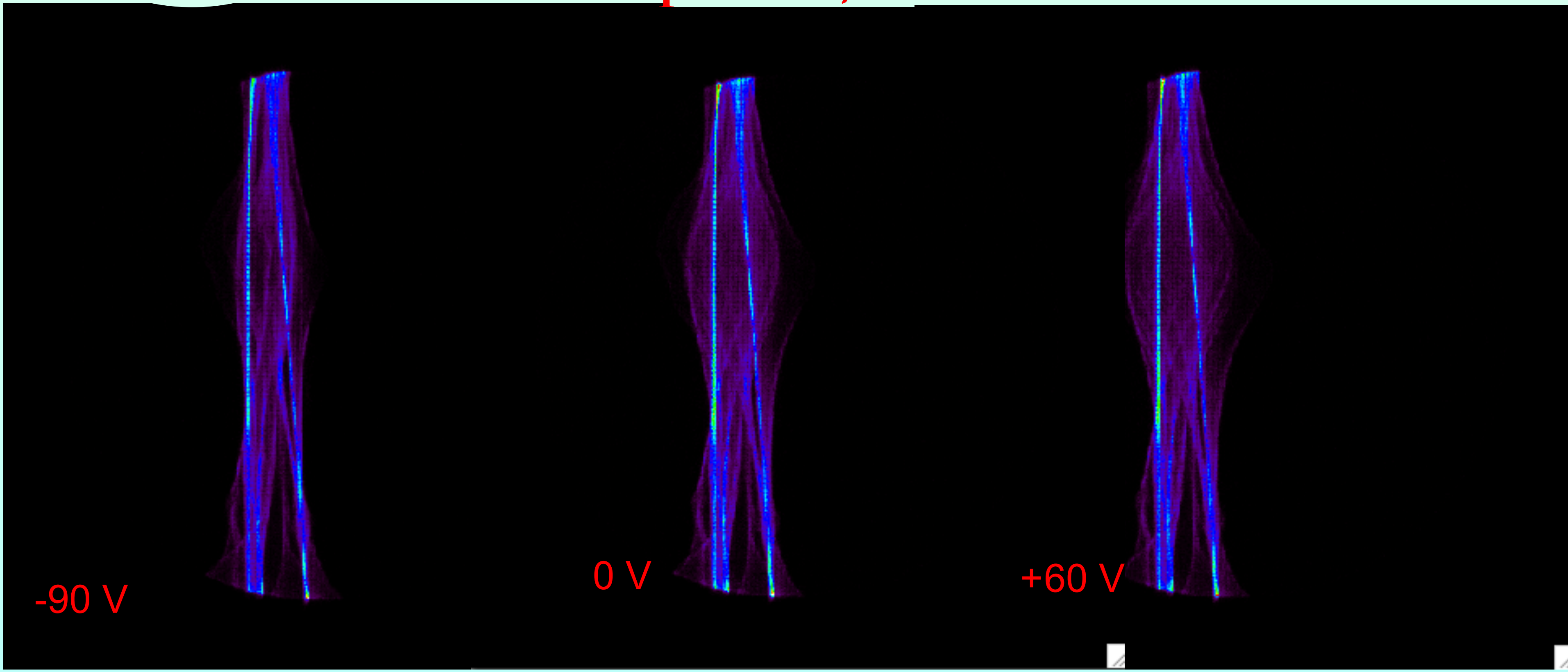
Zona piezo S



Rib staccate?

- Fasce brillanti dovute a concavità dei profili sui bordi. Non si vedono altre linee evidenti.

Iperbole, settore S



- Forte deformazione della colle in corrispondenza ai piezo,… ma ...
- Correzione nella direzione corretta per tensioni negative!
- Correzione visibile per tensioni intorno ai -50 V
- Alcune rib si sono scollate per effetto dei connettori …

Cose da fare (fra l'altro)

- Ridisegnare le piste per due file di piezo S (8x2)
- Ripensare processo di incollaggio per evitare scivolamenti
- Evitare incollaggio parziale piezo
- Ridurre deformazione riducendo spessore della colla (aumentando la pressione sui piezo)
- Evitare distacco delle rib
- Modificare connettori per allentare la presa (riduzione rischio rotture e scollamenti)
- Possibile prossima integrazione: metà aprile.
- Terzo e ultimo test: fine aprile.