Improving Glass TGF & Glass Science/Technology

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Glass Thermal Forming (GTF) – Recent Status

- Recently at least 6 groups working on GTF for X-ray optics (NASA GSFC, SAO, Brera/Merate, Garching, Rigaku Prague, ICT Prague)
- The technologies/approaches they use are NOT identical
- Glass Science important issue

What can be improved

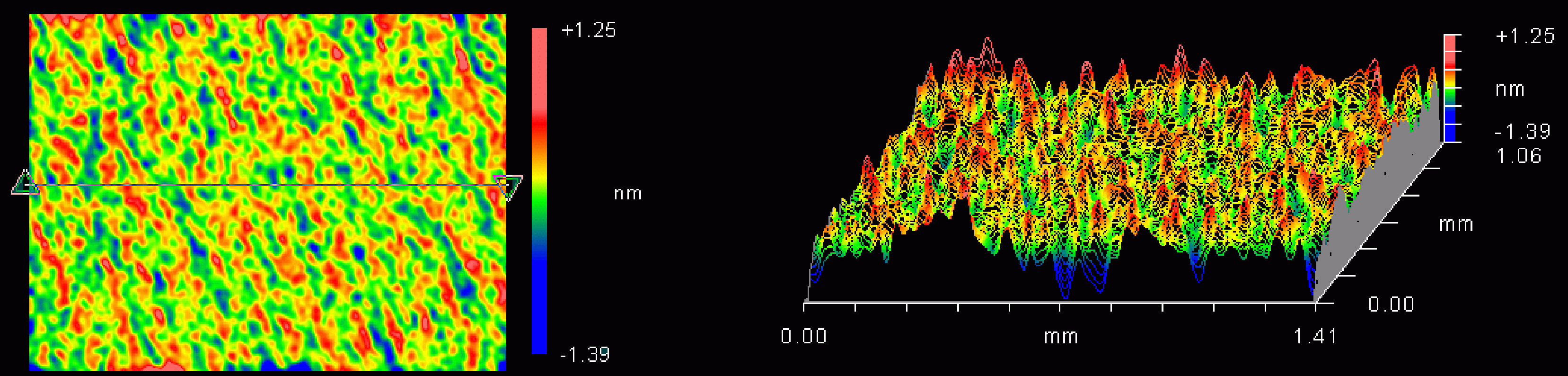
- Incoming glass quality
- Mandrels
- Technology of glass slumping

Comparing Glass and Si incoming quality

- **The incoming quality of borofloat glass is worse than those of Si wafers (but note that the superiour surface quality of Si is due to double sided lapping/polishing at the late stages of Si wafer production)**
- **Direct comparison based on manufacturers fact sheets is difficult. The Si manufacturers use precise definition parameters but this is not the case of float glass manufacturers**
- **Direct comparison possible only by measurement by identical device**

Measuring of roughness: Si wafer

Interferometer Zygo

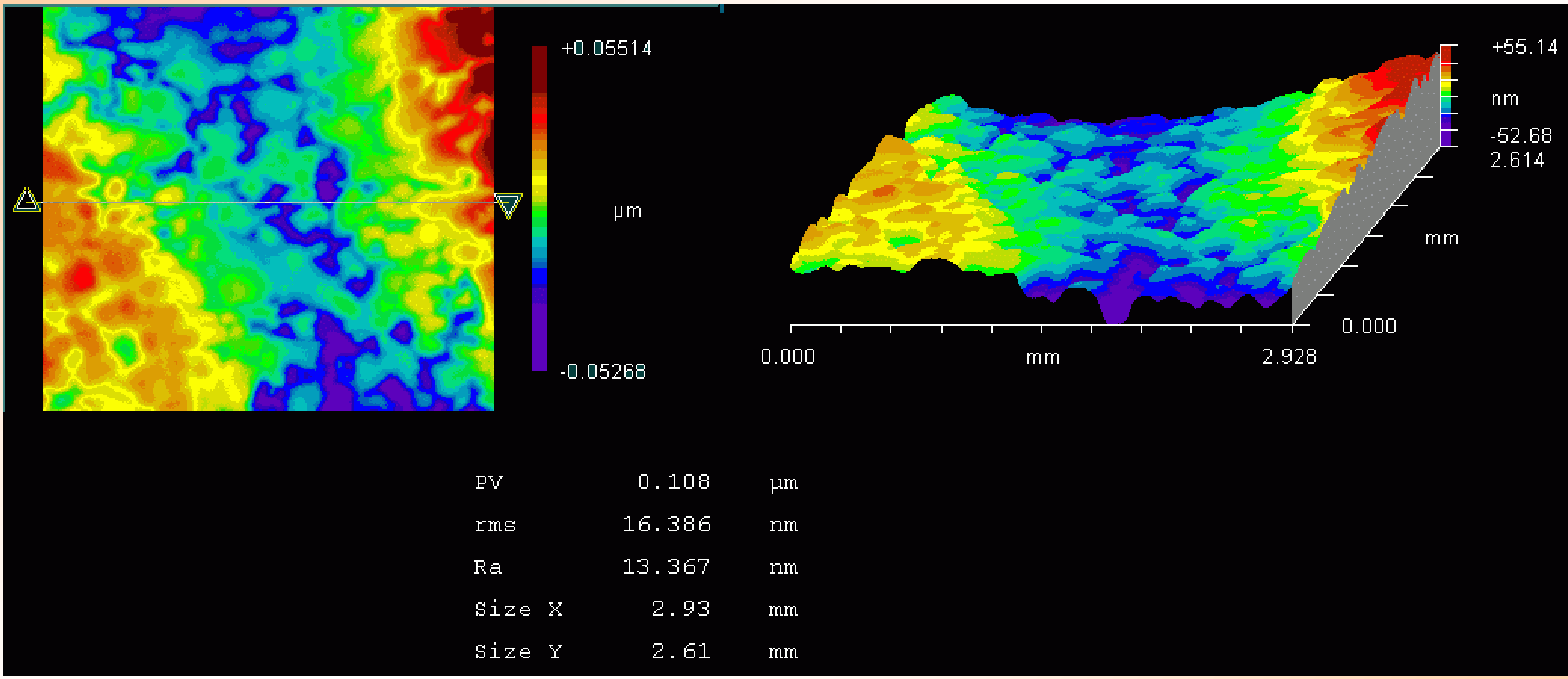


PV	2.640	nm
RMS	0.238	nm
Ra	0.186	nm
Rz	2.17	nm
R3z	2.03	nm
Rtm	1.83	nm

dopant B, D = 150 mm, t = 0.625 mm
ON Semiconductor, Czech Republic

Measuring of roughness: Glass

Interferometer Zygo

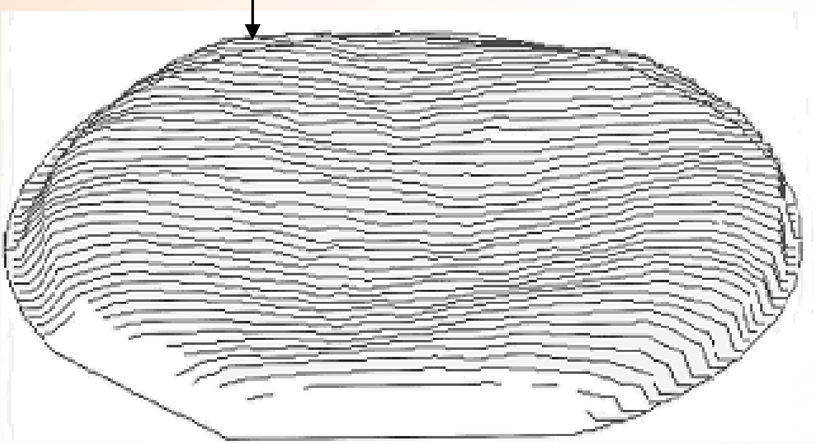


flat thin glass , 100 x 70 x 0.75 mm

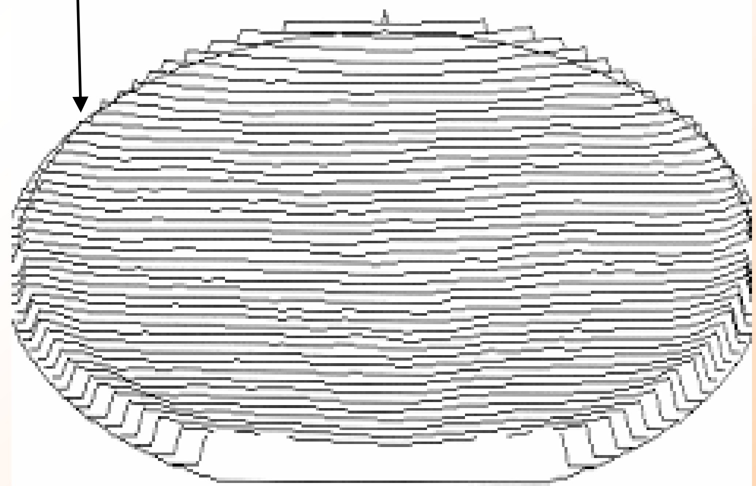
6" Silicon Polished Wafer: Flatness Evolution (TTV)

The effect of improved grinding/polishing on final quality of a Silicon wafer

TTV < 2 μm (2005) process optimization → TTV < 1 μm (2006) grinding technology → TTV < 0.5 μm (2007) new polisher



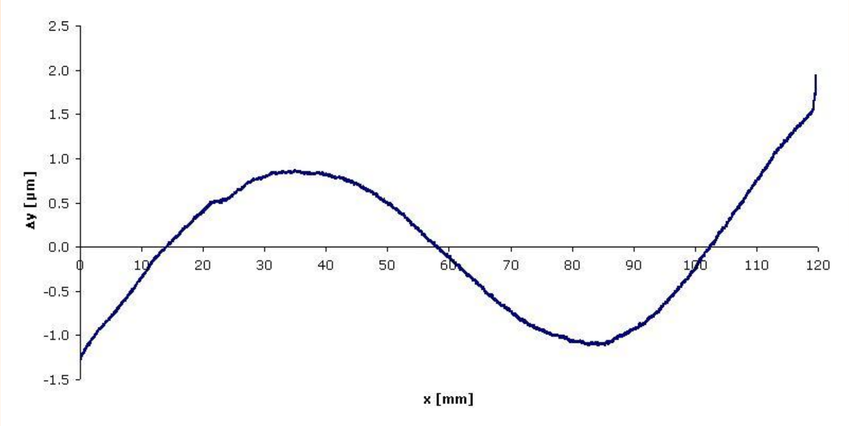
TTV = 1.68 μm

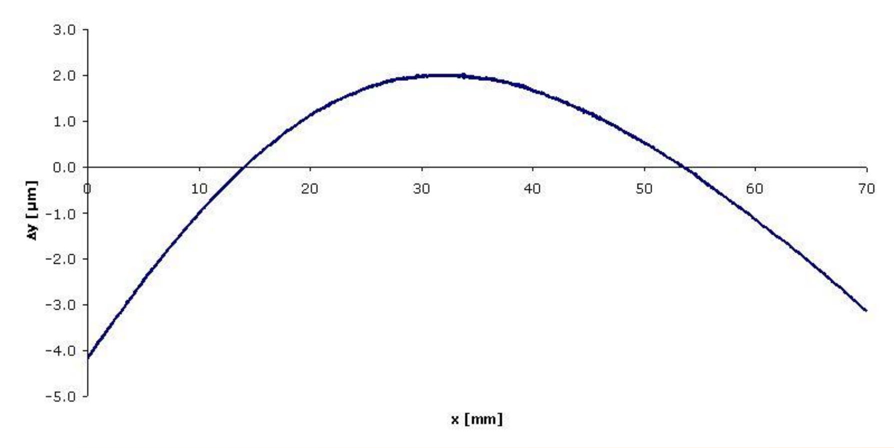


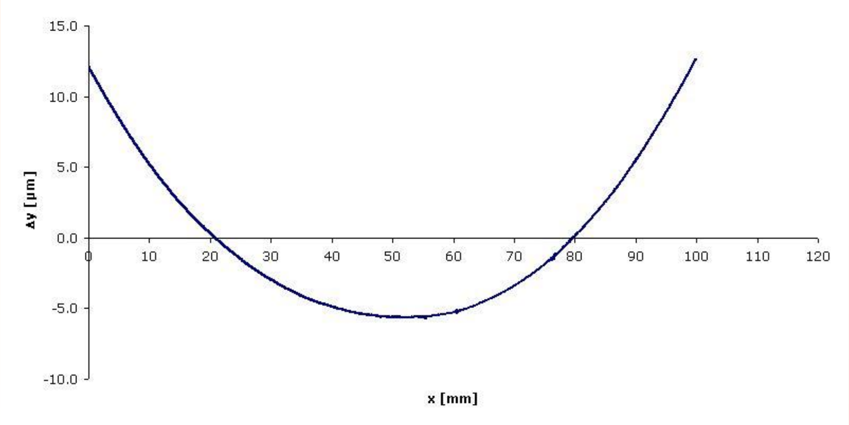
TTV = 0.76 μm

measured Total Thickness Variation

Incoming quality – surface profiles (figure errors)







Left Si wafers (standard)
Right D263 glass

Improving the process of GTF

The parameters of the GTF may be improved by:

- optimization of the glass material
- optimization of the mandrel material/design (different used!)
- optimization of the GTF process
- optimization of the GTF temperature and duration

Expectations (goals)

microroughness of float - glass not degraded

~ 0.3 nm RMS or better

deviation PV < 0.02 μm (recently ~ 0.5 micron in best case, 100 mm length)

Incoming glass quality

- The better incoming glass quality can be achieved by optimizing glass composition, as well as manufacturing process (visit to Schott)
- Additional surface improvements may be achieved after manufacturing process (such as double sided lapping used in final stage of Si wafer manufacturing)

Borosilicate Glass

- Na_2O-K_2O-Al_2O_3-B_2O_3-SiO_2
- high chemical durability at low and higher temperatures
- micro-roughness of few 0.1 nm
- amorphous – easy thermal forming
- mass production: Schott Desag D263; AF45
  Corning 1737
- stable in vacuum and during coating

Borosilicate Glass

Desag D263	
Density (20°C)	2.51 g/cm^3
Thermal expansion coeff.	$7.2 \cdot 10^{-6}$ 1/K
Young’s modulus	73 kN/mm^2

Glass Thermal Forming Study

- Effects of soaking time and temperature
- Influence on glass shape and surface micro-roughness

Properties Important for Forming

- Young's modulus E - measure of stiffness

$$\frac{F}{A} = E\,\frac{\Delta L}{L_0}$$

F / A … tensile stress

$\Delta L / L_0$ … tensile strain

- viscosity η - hinders the glass melt flow

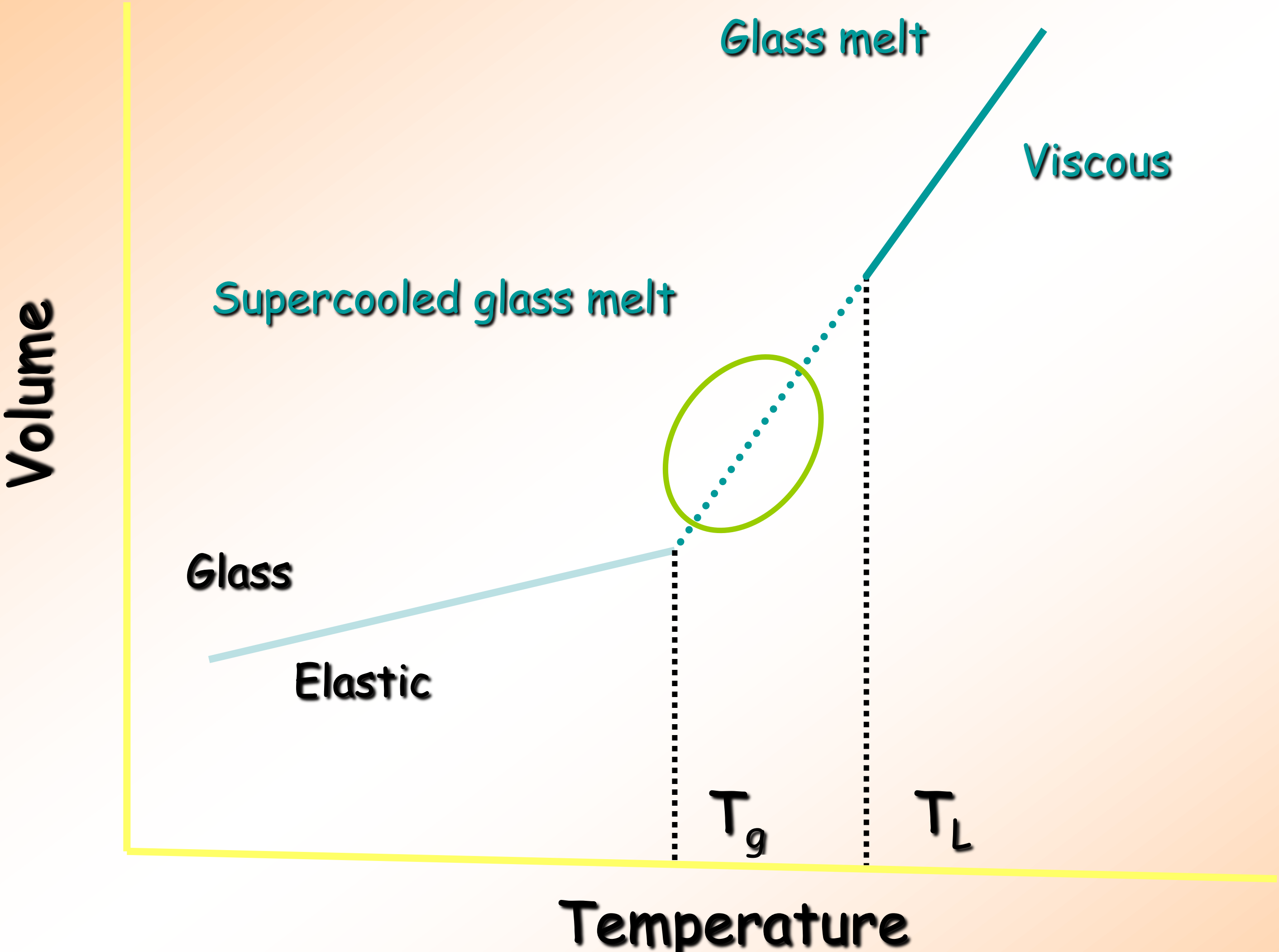
$$\frac{F_{yx}}{A} = \eta\,\frac{dv_y}{dx}$$

F_{yx} / A … shear stress

dv_y / dx … velocity gradient

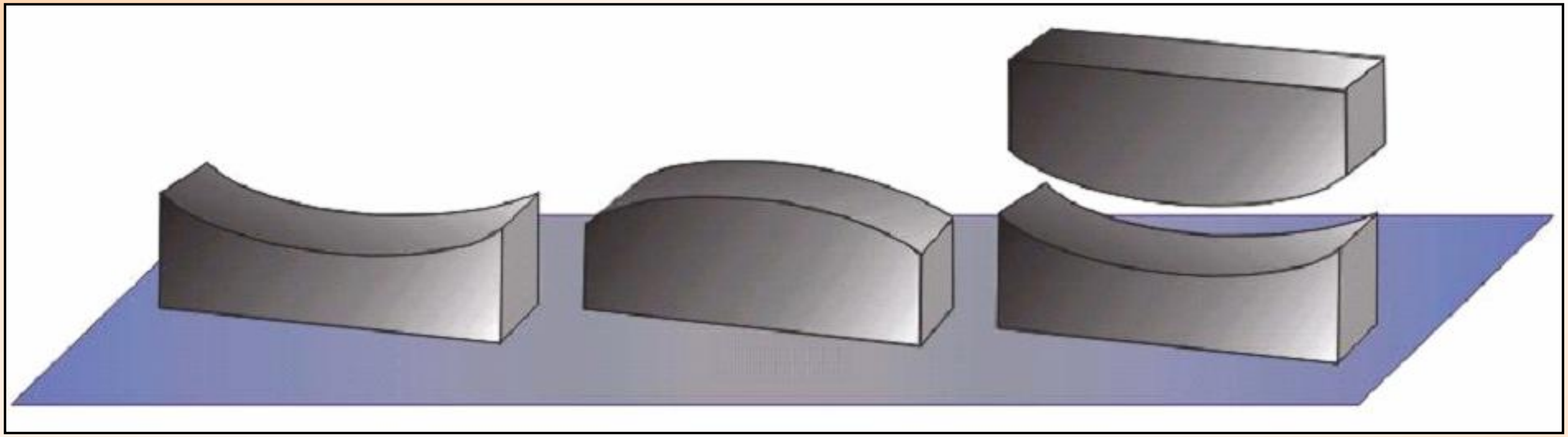
- surface tension γ - flattens the glass surface

Glass



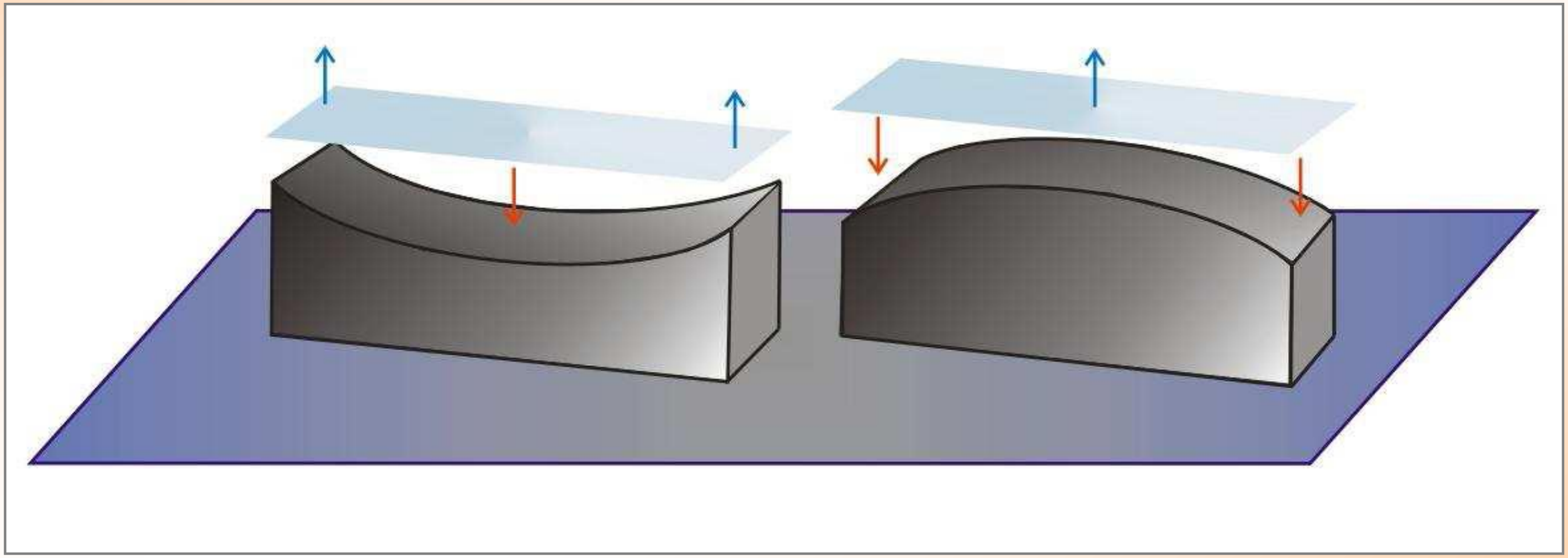
T_g ~ Annealing point

Various approaches in Glass Thermal Forming used by different groups

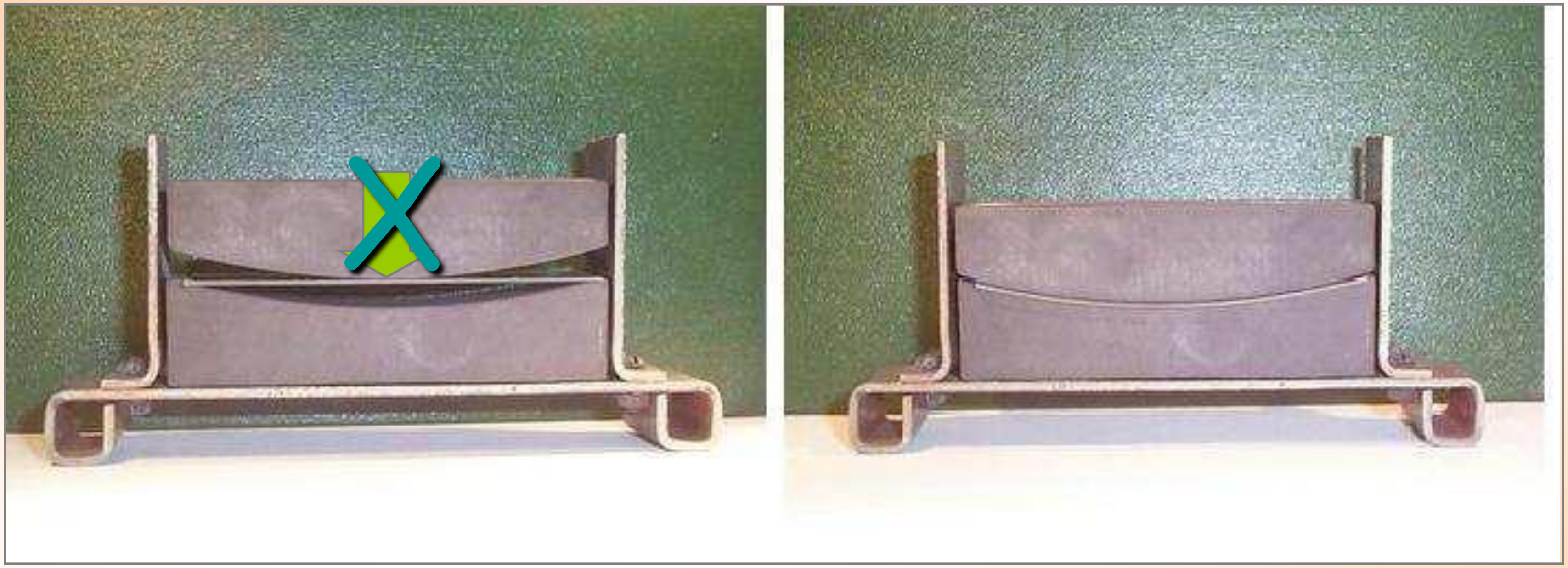


- low-cost design needed (the goal is to produce very large number of shells at a low cost)
- expensive production/material are to be avoided
- the mandrel material/design is important
- recent CZ design: proprietary technology (composite)

Forming Surface

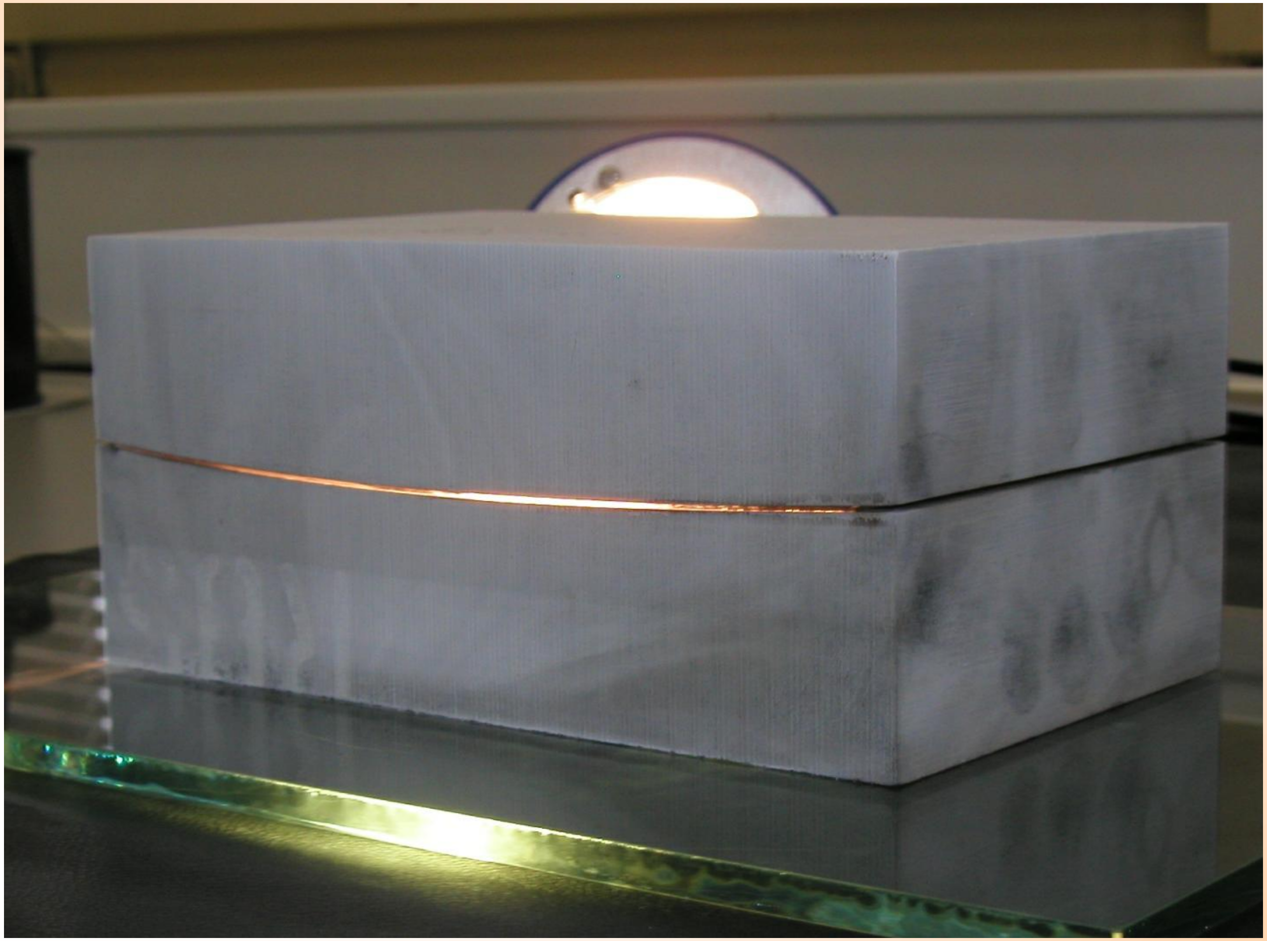


Slumping Process



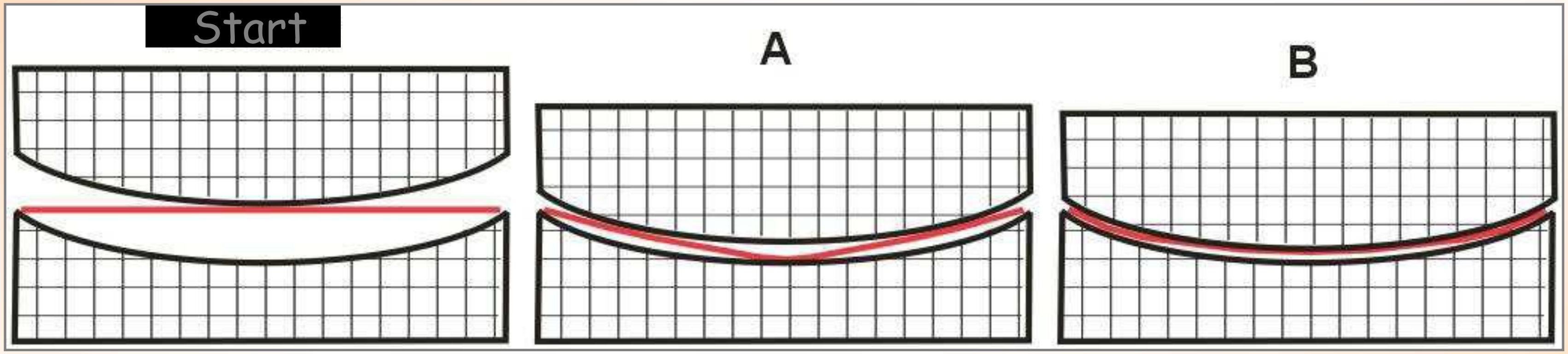
Slab size 80 x 20 x 0.75 mm

Glass Thermal Forming – one of studied approaches at Rigaku Prague



parabolic profile

Forming Stages

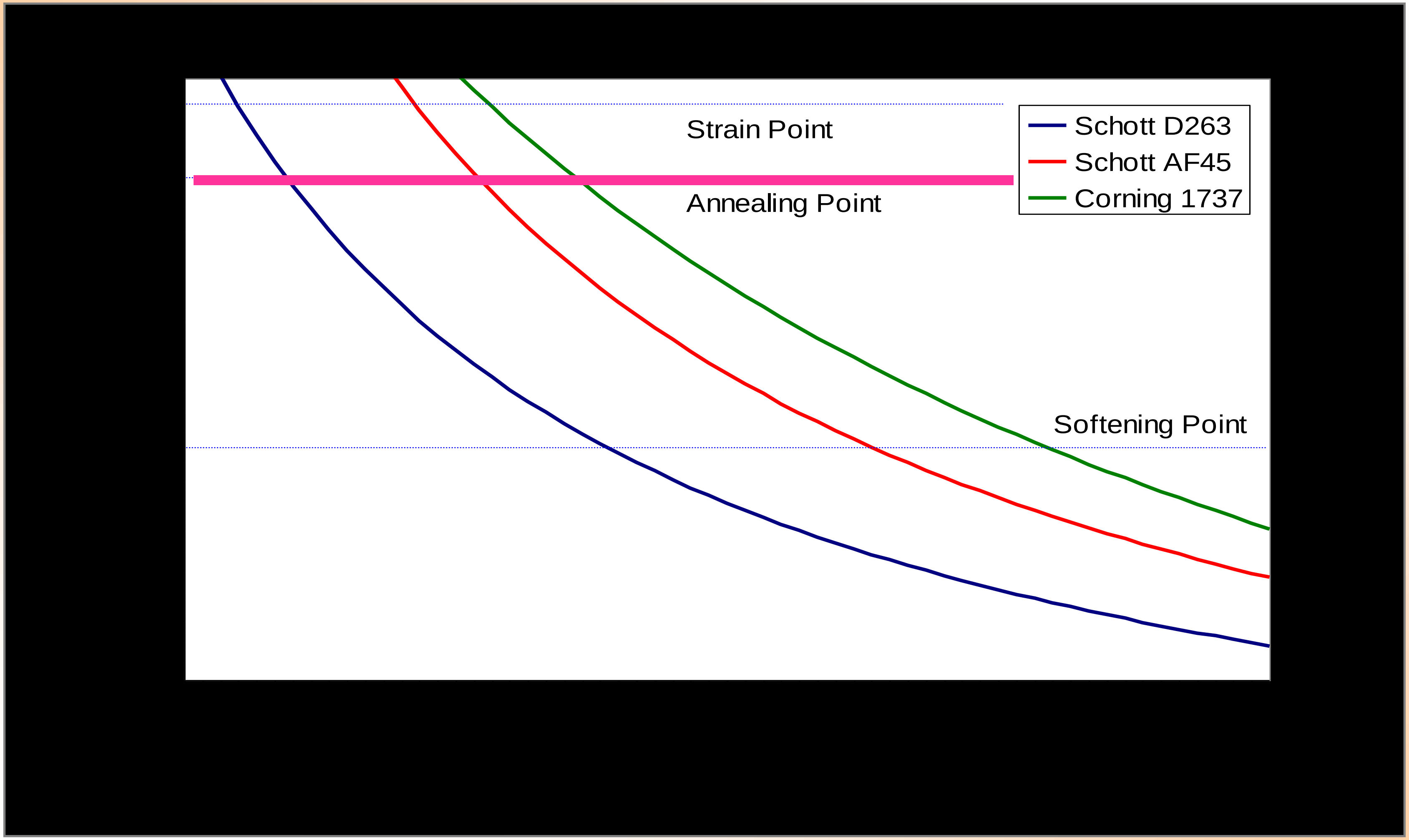


$a_M < a_G$

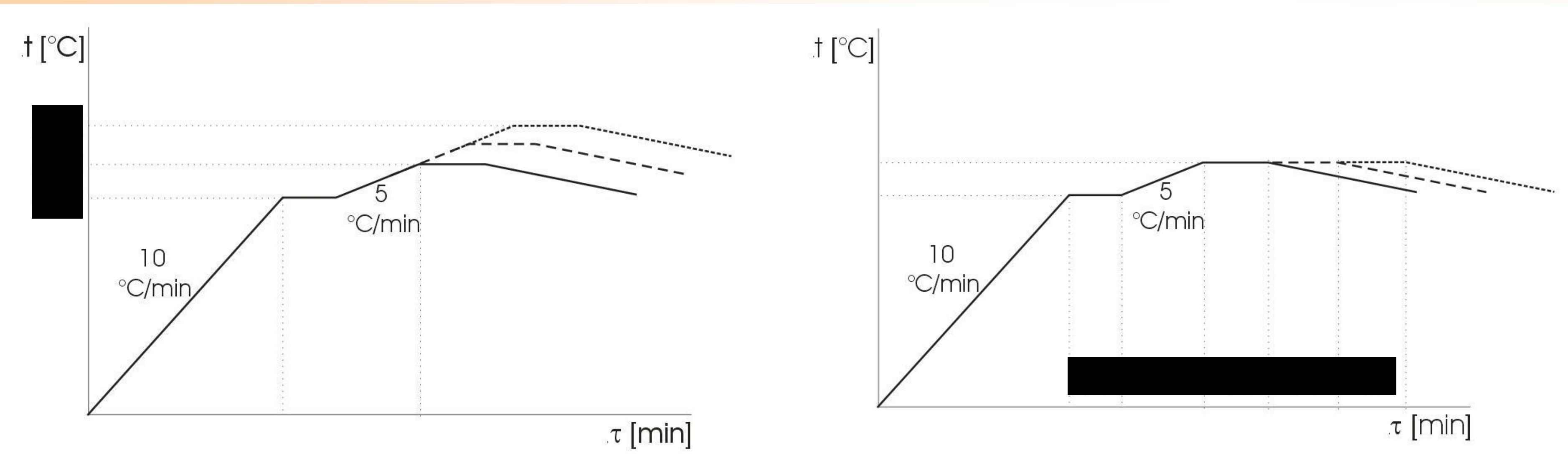
$a_M > a_G$

M – mandrel   G – glass

Viscosity Curve



Heat Treatment Program

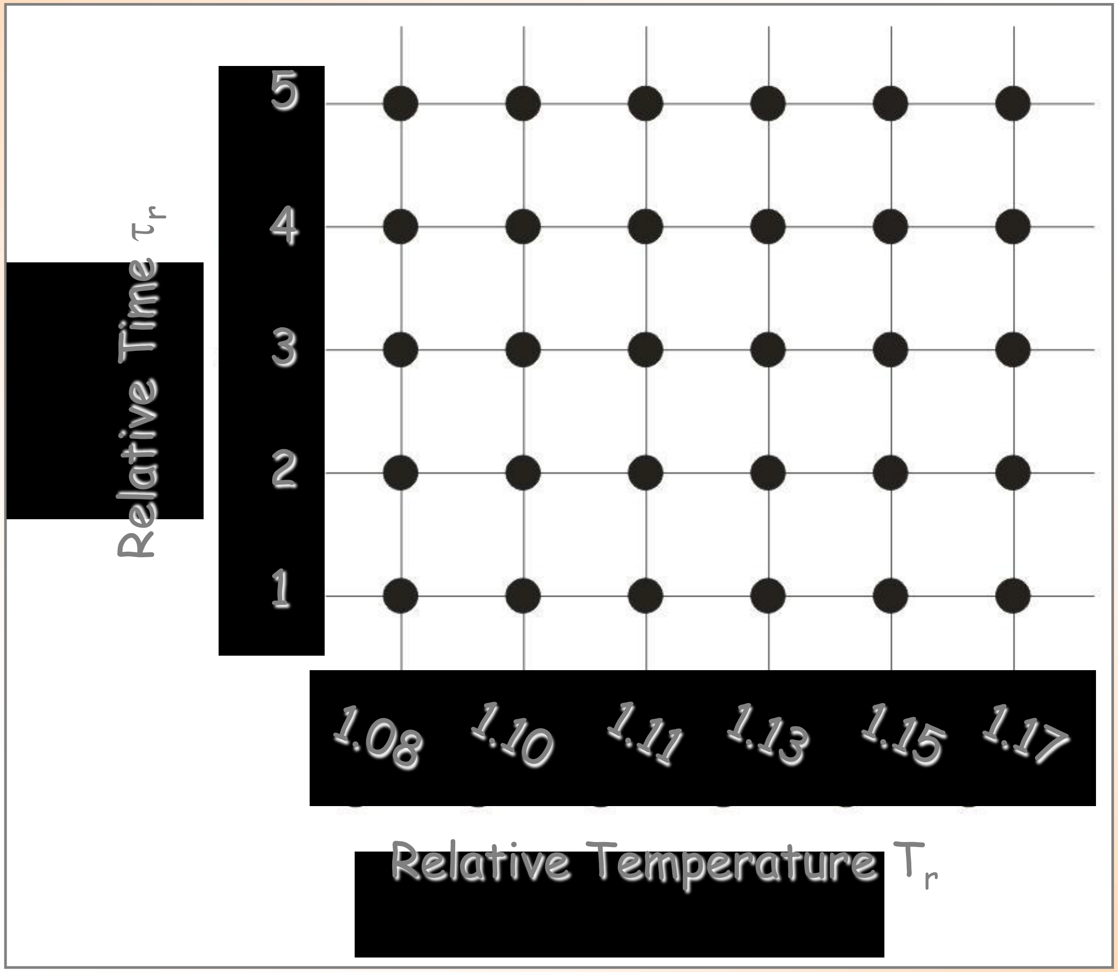


- Cooling rate 2°C/min

GTF Optimization

- The quality of GTF mirrors depends on parameters (e.g. duration, temperature) of GTF, need of optimization
- The situation is complex as (i) different surface parameters require different parameters of GTF, and (ii) the optimal parameters depend on size and thickness of formed glass sheets
- Additional improvement by precise temperature control (T distribution in mandrel/glass sheet) during GTF

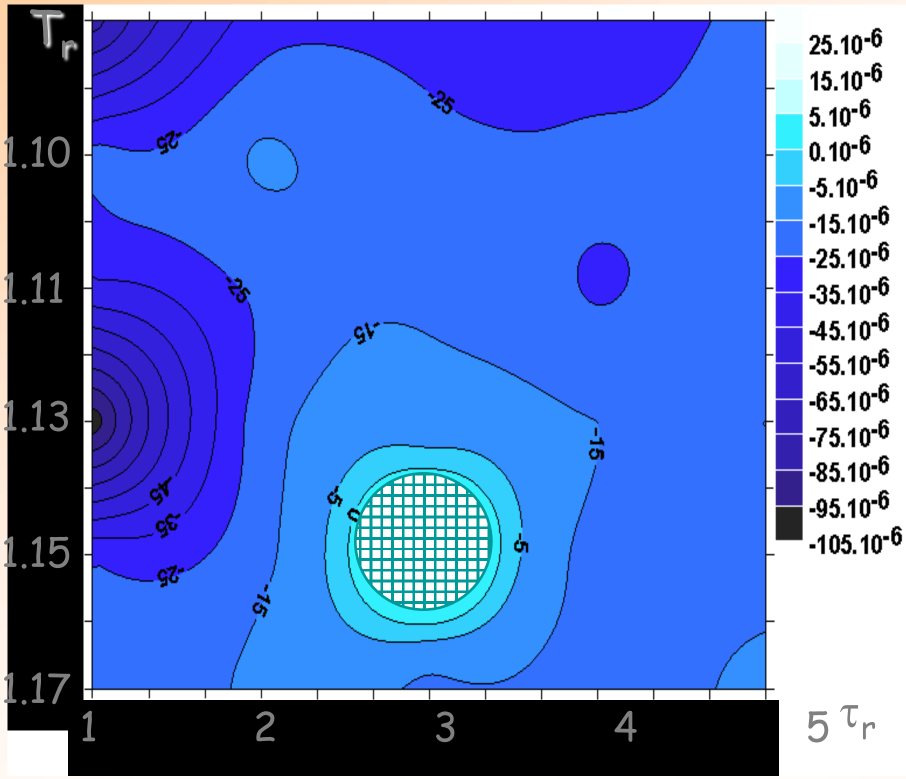
Experiment Design

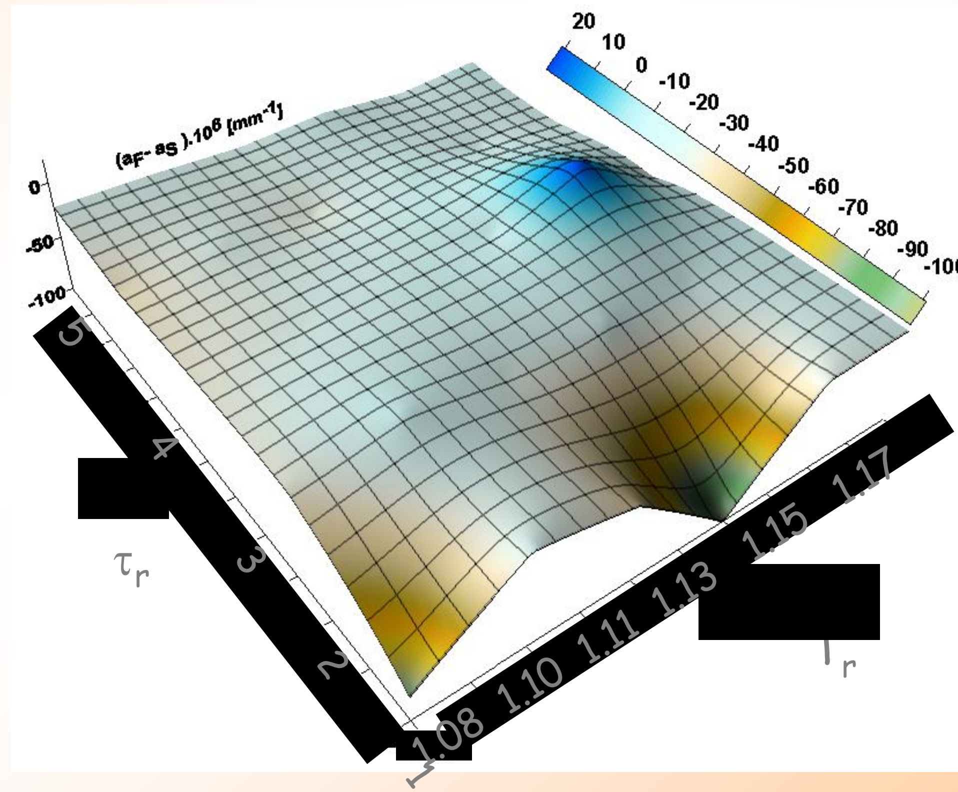


$$T_r = \frac{T}{T_g}$$

$$\tau_r = \frac{\tau}{\tau_0}$$

Shape Difference





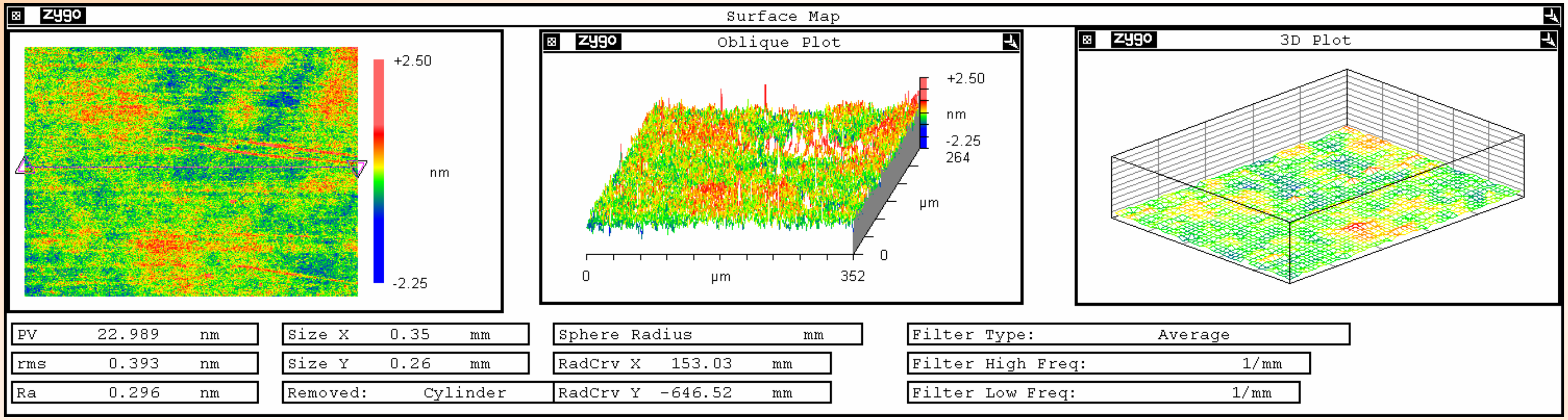
$a_M - a_G \sim -105{\cdot}10^{-6} - 25{\cdot}10^{-6}\ mm^{-1}$

M – mandrel   G – glass

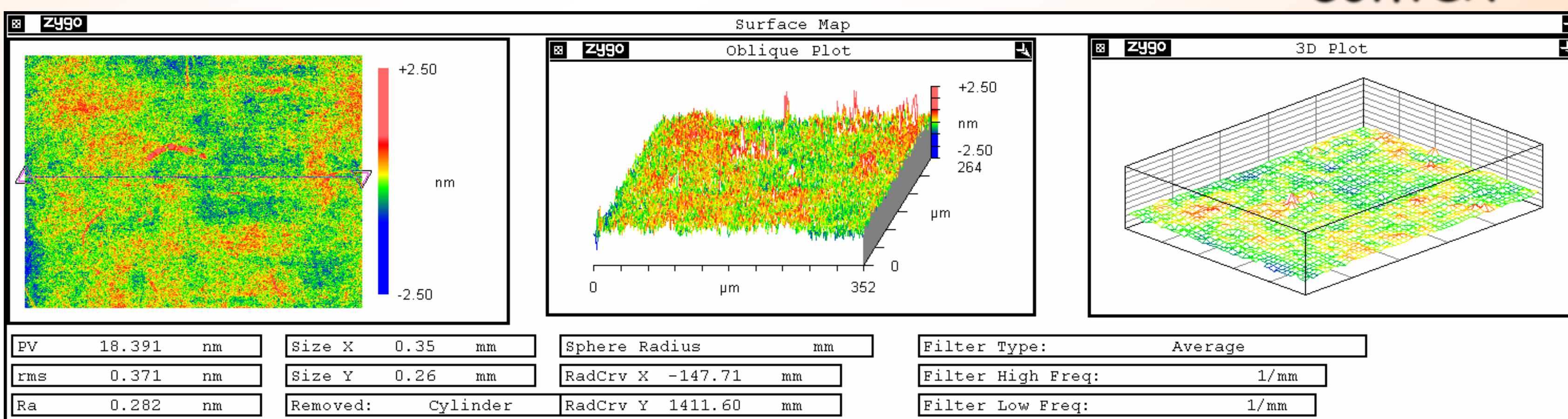
Surface Micro-Roughness Measurement

Interferometer Zygo

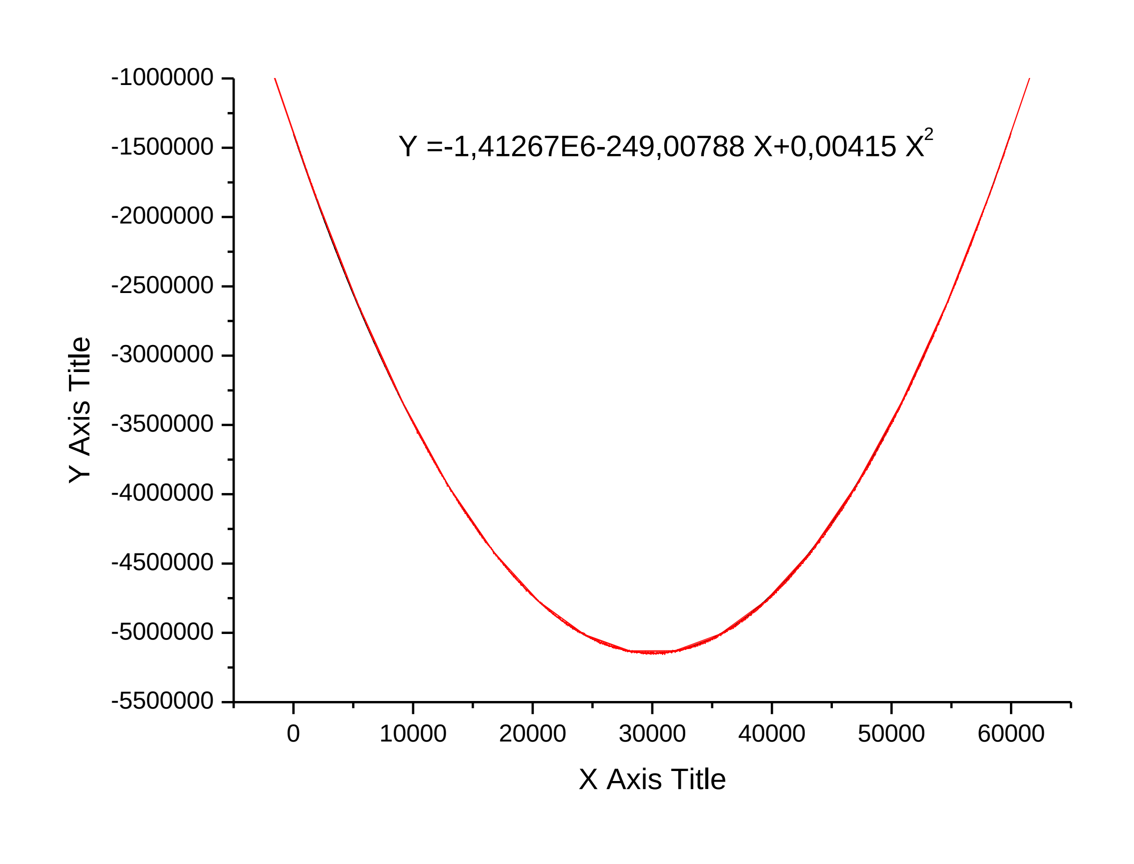
concave



convex



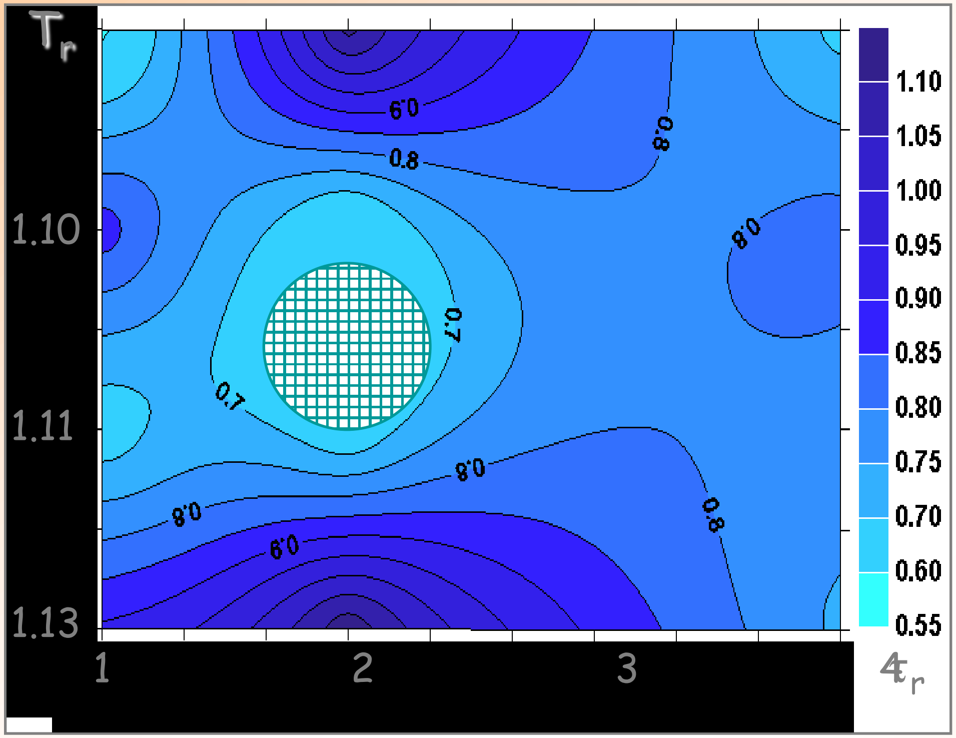
Fitting Shape

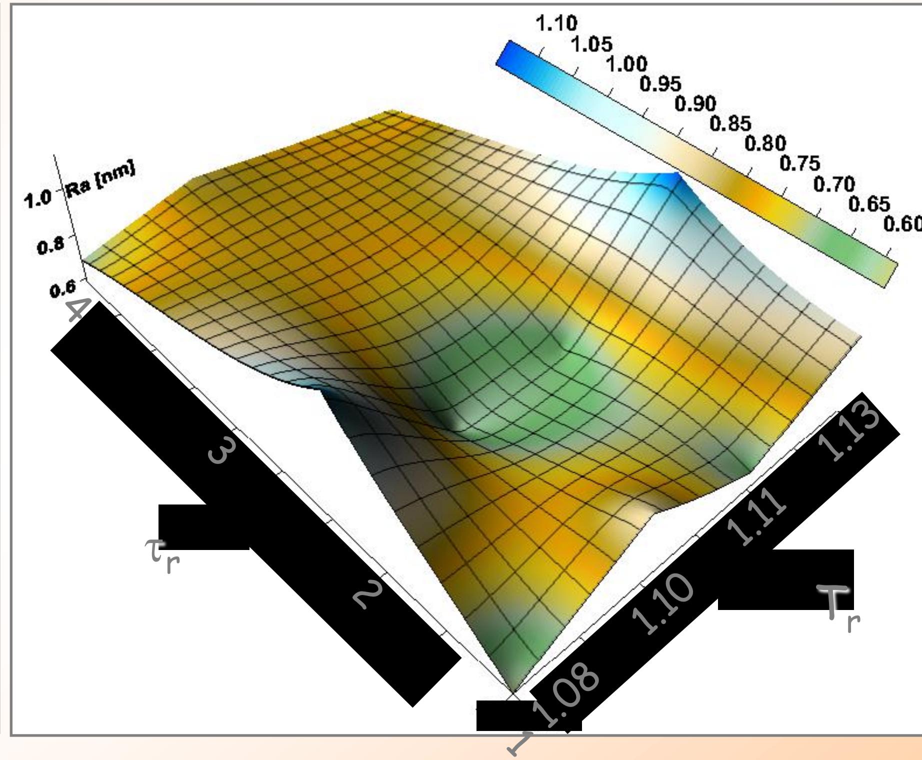


$$y = ax^2$$

$R^2 = 0.999 - 0.99999$

Micro-Roughness

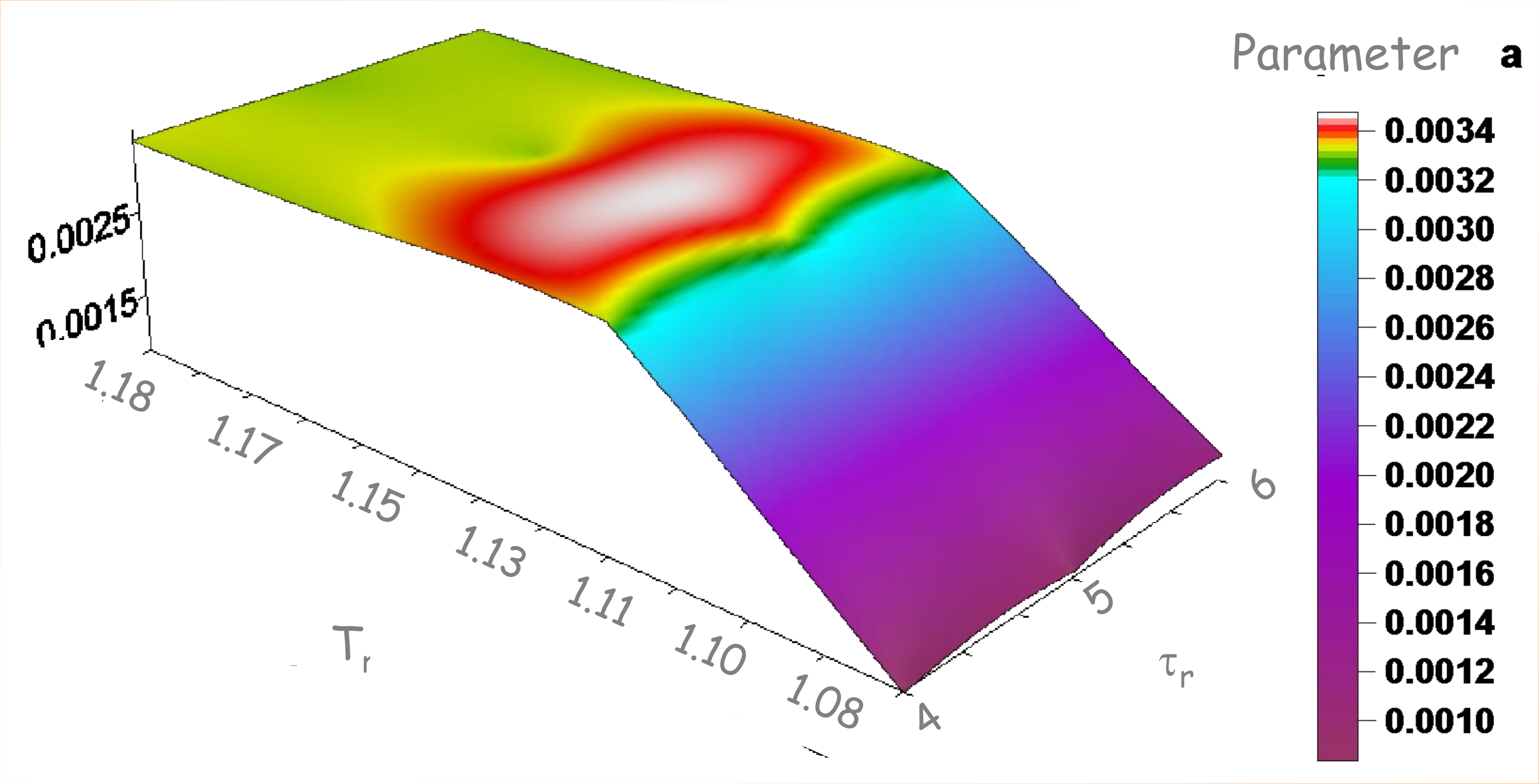




R_a ~ 0.6 – 1.1 nm

AFM R_a ~ 0.3 – 1.2 nm

Shape Variation – Without Add. Force

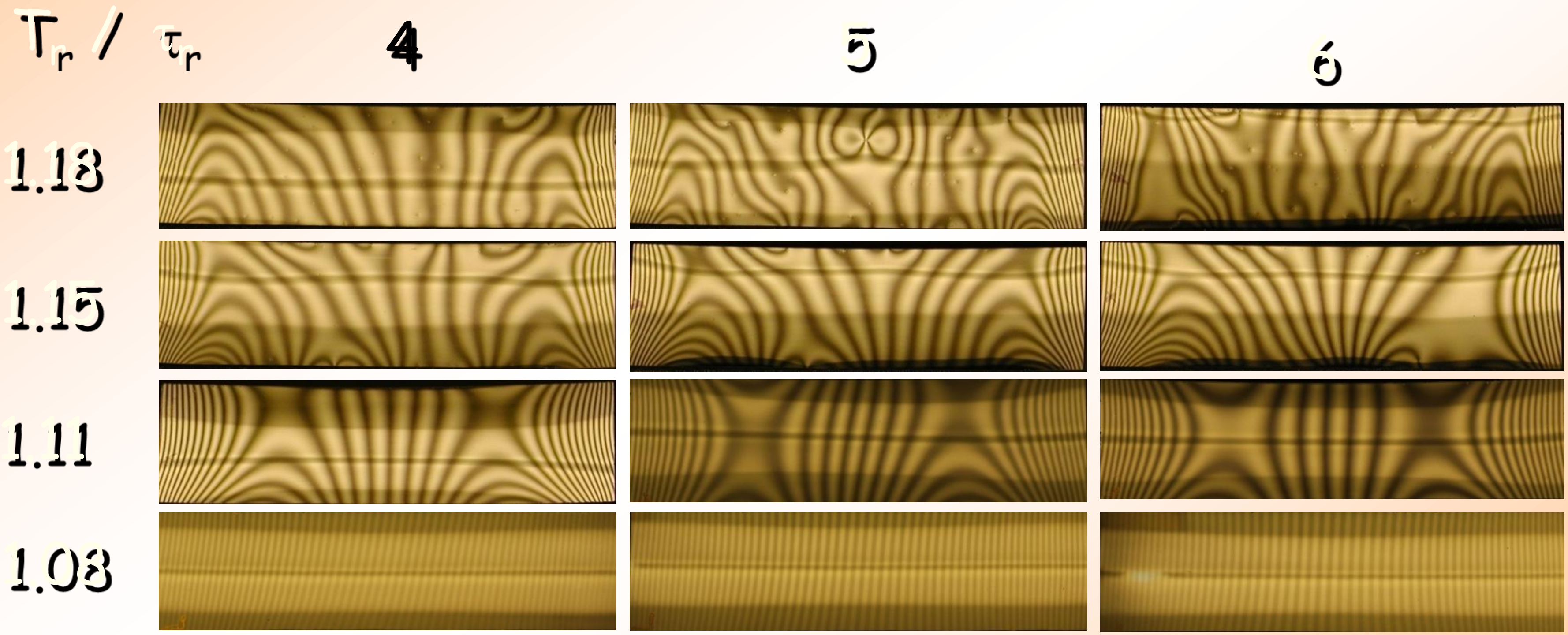


SE = 0.3%

a_G ~ $0.100 \cdot 10^{-2}$ – $0.334 \cdot 10^{-2}$ mm^{-1}

a_M = $0.330 \cdot 10^{-2}$ mm^{-1}

Ronchi Test



Additional Improvements

- The performance of mirror shells can be further (significantly) improved by methods of active X-ray optics (fine tuning of surface shape by ative elements and computer control)

Scientific background in Glass Science

- The expertise and background in glass science may be essential in achieving very high quality/fine angular resolution
- This is recently provided by the Institute of Glass and Ceramics in Prague Institute of Chemical Technology

Institute of glass and ceramics in Institute of Chemical Technology, Prague

•Long term experience in glass formulation and glass composition optimization to achieve target glass properties.

•Melting of glass.

•Glass thermal forming. Free or forced slumping. Stress measurements.

•Measurement of important physical and chemical properties of glass and glass melts. Temperature dependence of viscosity, electric conductivity, density, surface tension, crystallization properties, chemical durability, thermal expansion, optical properties (refractive index, absorption)…see below.

•Development of composition-property models for glass optimization and tailoring its properties.

•detailed knowledge of oxid glass, its structure and properties

•atomar simulations based on molecular dynamics (both classical and quantum), the atomary level view of glass

•interaction of glass with radiation

•interaction of glass with radiation: experimental metodology including interaction with electrons (with energy 1 – 50 keV), experience with 2.5 MeV electrons and MeV protons

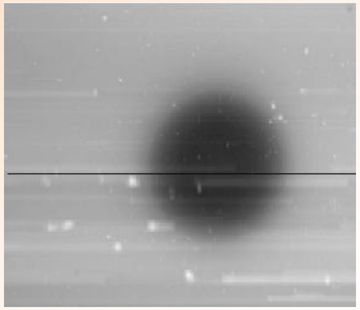
•detailed study and characterization of glass materials (FE SEM, EPMA, AFM, XPS, XRD, DTA, TG,XRF)

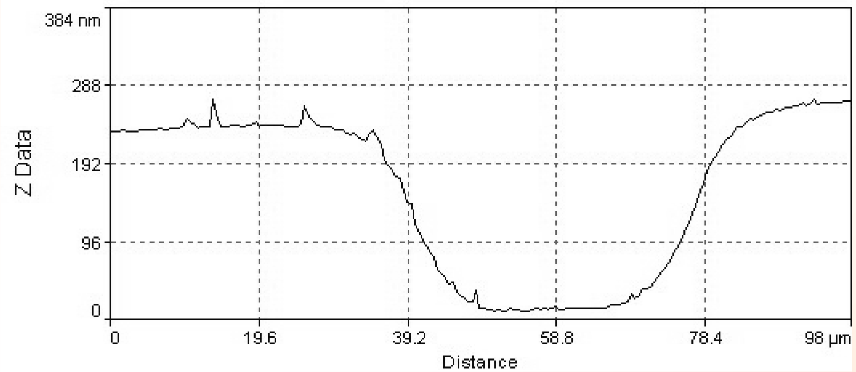
Irradiation Problem/Tests

- **The mirrors based on thin Si or glass substrates will work in space environment with influences that can damage the superior shape and surface quality.**
- **Irradiation by electrons and protons may play the main role. Depends on satellite orbit (radiation belt passages)**
- **Detailed tests on various substrates are necessary to exploit the possible damage.**

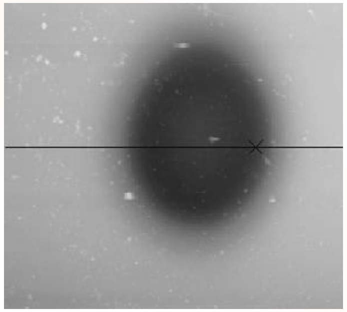
Preliminary Results: Glass Irradiation Tests

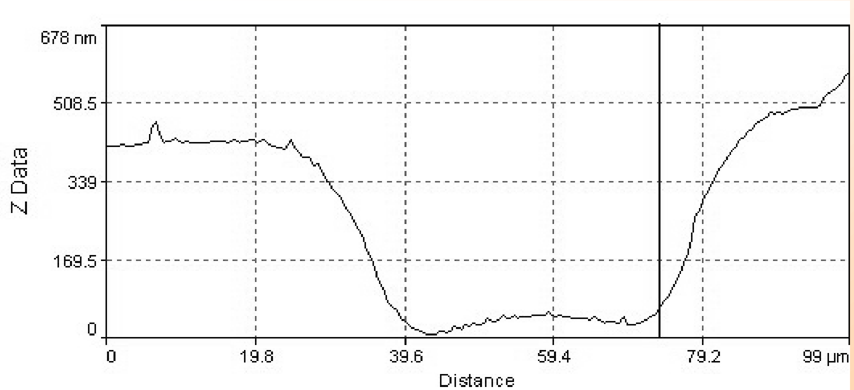
vitreous silica





borosilicate glass





Electron beam energy	50 keV
Time	10 min
Diameter of beam	60 µm
Absorbed current	50 nA

A typical AFM picture of the irradiated glass surface spot (left). The line shows the track of the following scan, results of which are on right.

Final Note

- The GTF and Si MPO are NOT the only possible technologies for X-ray telescopes like IXO, as there also alternative options exist such as Si wafers slumping, glassy carbon etc.

Conclusions

- The quality of GTF can be improved by: (1) improved glass sheets (ii) double-sided lapping/polishing (iii) optimizing mandrel material/design (iv) optimizing GTF parameters (v) precise T control (using advanced computer control) during GTF
- Additional improvement of the shape of the mirrors by active X-ray optics methods

The End

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