Finite Element analysis in X-ray optical systems

L Zhang (zhang@esrf.fr)
ESRF

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Introduction

X-ray optics

- Monochromator crystal
- First mirror (HHL)
- Bent focusing mirror (KB, …)
- Compound refractive lens (CRL)
- Sagittal focusing mirror
- Piezo bimorph mirror
- Bending devices
- …

Boundary conditions (P, hcv, Tf, F, D, V,…)

FEA

Analyses

- Cooling and geometry optimization
- Thermal deformation
- Performance *vs* heat load
- Thermal stress analysis
- Surface shape and profile optimization
- Mechanical stress analysis
- Performance *vs* energy tuning (bending forces)
- Bent shape
- Multi-electrodes application (gap, voltage distribution)
- …

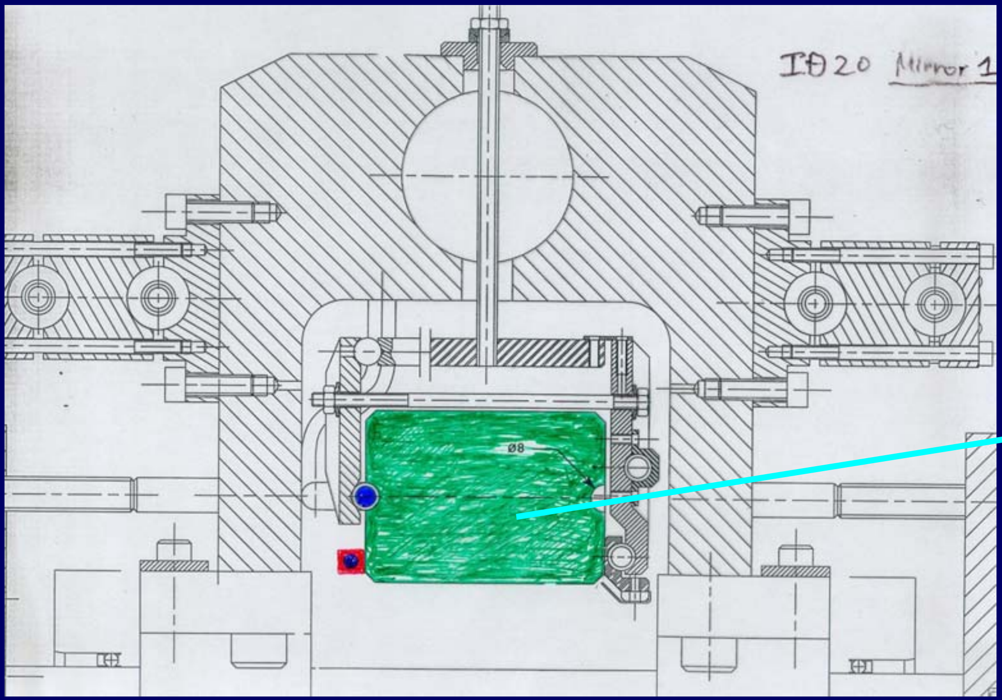
Guidelines, data for

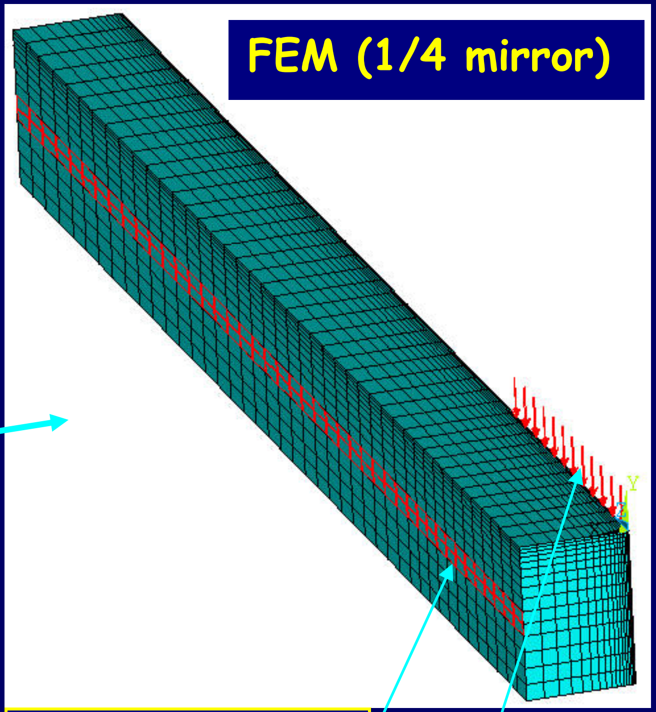
- Design, Manufacturing, Mounting, Operation

Data for

- Ray-tracing
- Dynamic diffraction simulation

Mirror – *FE model (ID20 mirror)*





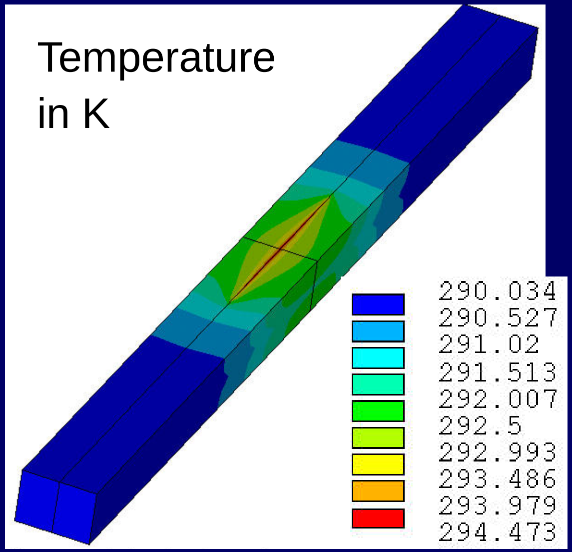
cooling		
side middle 8 mm		

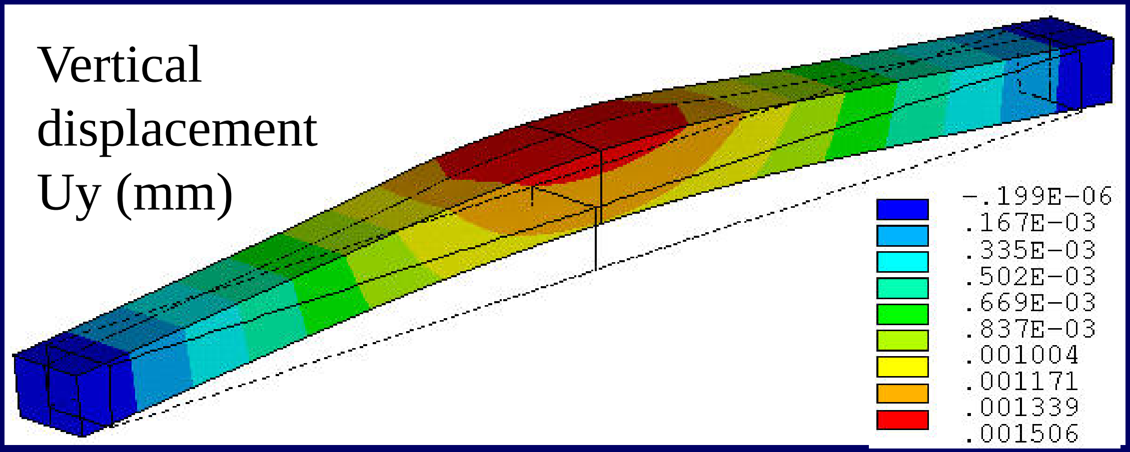
Geometry of the mirror LxWxT	1000x70x50	mm^3
Absorbed power	50	W
Primary slits HxV	1.5x0.8	mm^2
Grazing angle	3.5	mrad
Side cooling by water at 290 K		

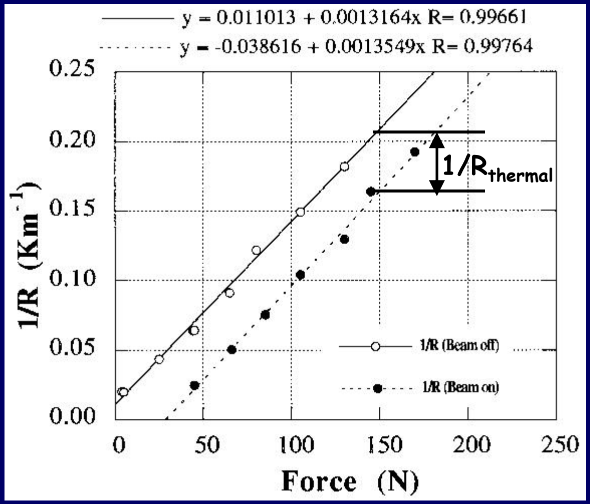
footprint	
0.8 mm	as defined

1998

Mirror – *FEA results (ID20 mirror)*







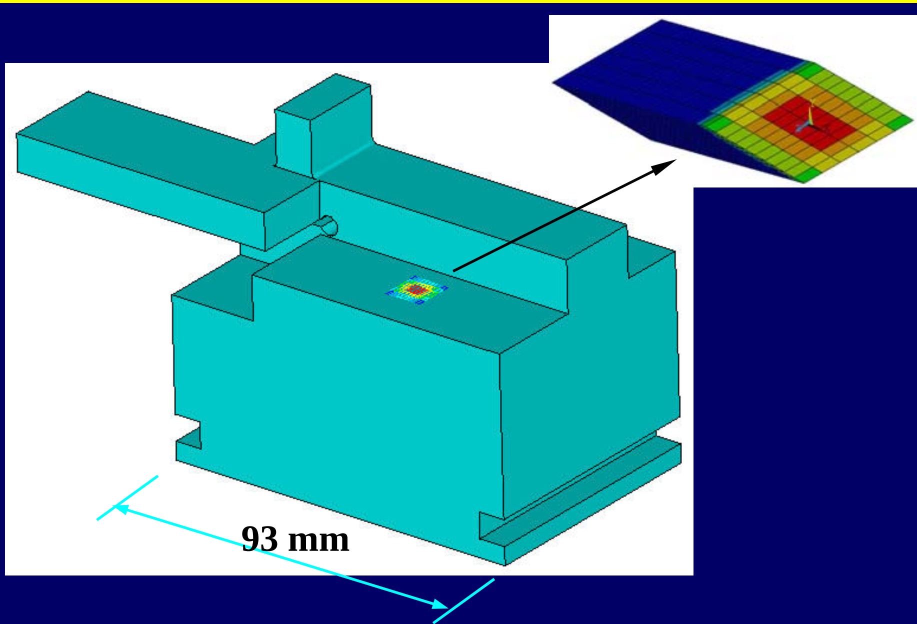
$$\frac{1}{R_{thermal}} = \frac{1}{R_{beamOFF}} - \frac{1}{R_{beamON}}$$

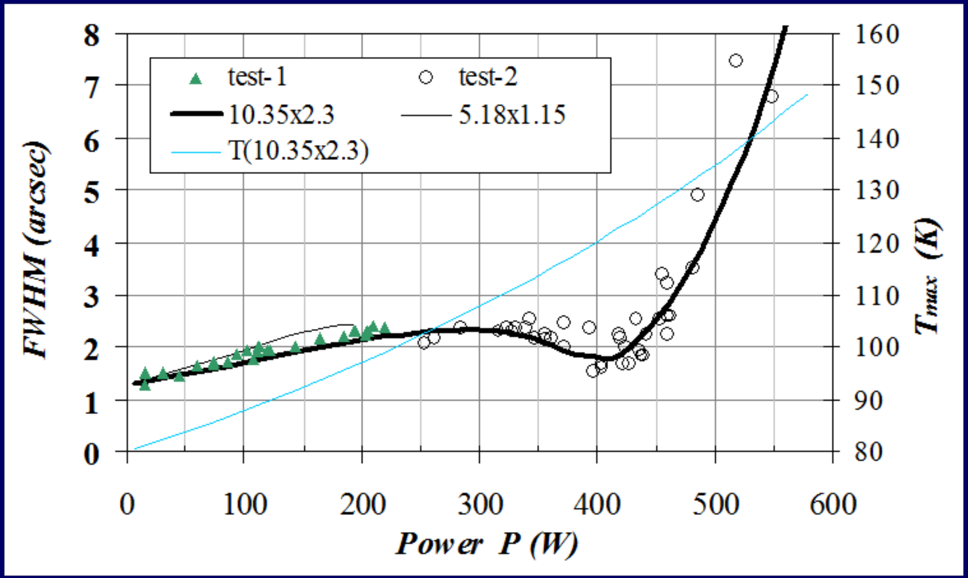
bending force F	45	80	150	N	
$R_{thermal}$ =	**23.2**	**21.2**	**25.6**	km	from **measurements** #
$R_{thermal\&FEA}$=	**22**		**30**	km	calculated by **FEA**
hcv (FEA)	**500**		**5000**	W/m2/K	

measurement # : "ID20-Test of mirror1 curvature", 1/04/98, by Ch. Vettier

Monochromator crystal – *FEA vs Test results*

- **Channel-cut Si crystal monochromator**
- **Liquid nitrogen cooling from 2 sides**
- **Beam size 10.35 mm (H) x 2.3 mm (V)**
- **Bragg angle 14°**
- **Heat load from undulators U46 + U17:** *Gaussian distribution, volume absorption*





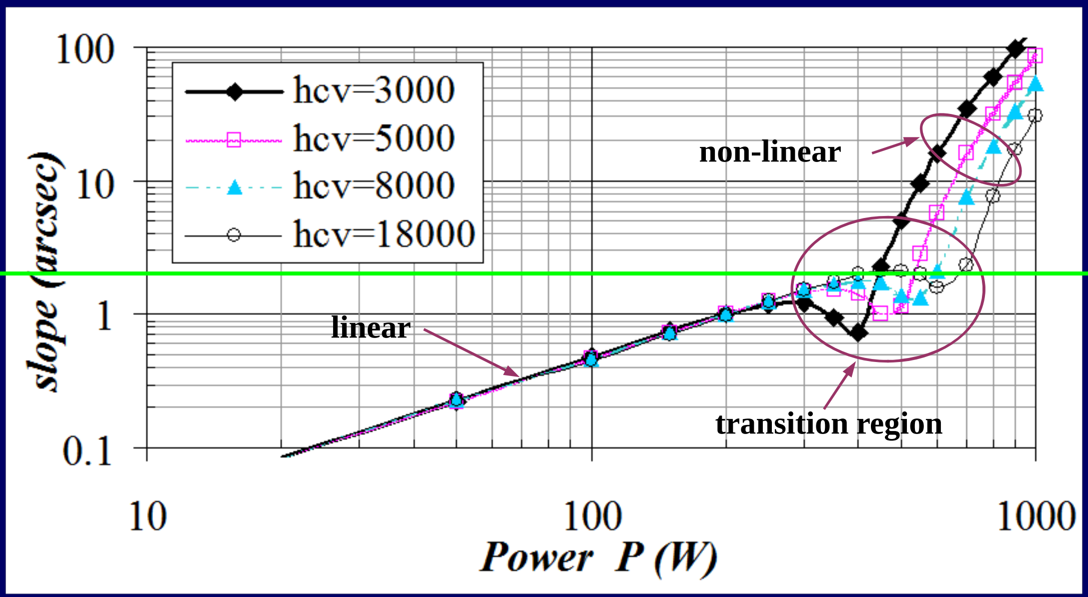
$$FWHM_c = \sqrt{(\theta_{th} + \theta_0)^2 + FWHM_{intr}^2}$$

- **Good agreement between the calculation and experimental results**
- **Local minimum in thermal slope error**

Zhang L. et al., *JSR* (2003). **10**, 313-319

Monochromator crystal – *FEA results*

Thermal slope error versus absorbed power in 4 different cooling coefficients (W/m²/°C)

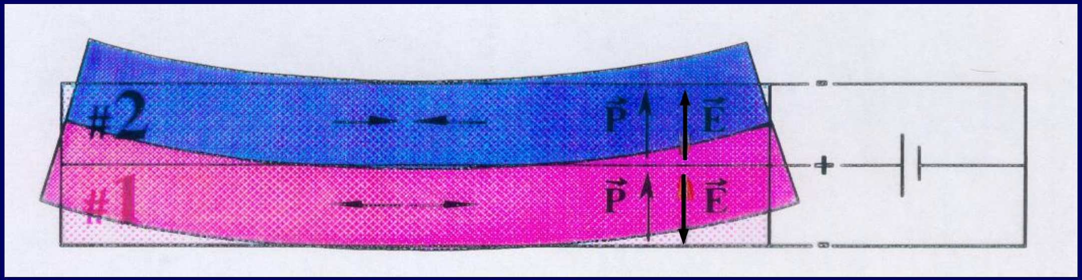


- Slope error **independent** of the cooling coefficient in the linear region → direct cooling (high *h*) is not always necessary
- Slope error varies significantly with the cooling coefficient in the non-linear region

Slope ~ P **curve can be divided into 3 regions:**

- Linear region : ***slope ~ P***
- Transition region : a local minimum
- Non-linear region : ***slope ~*** $P^{4.6}$

Piezoelectric active mirror

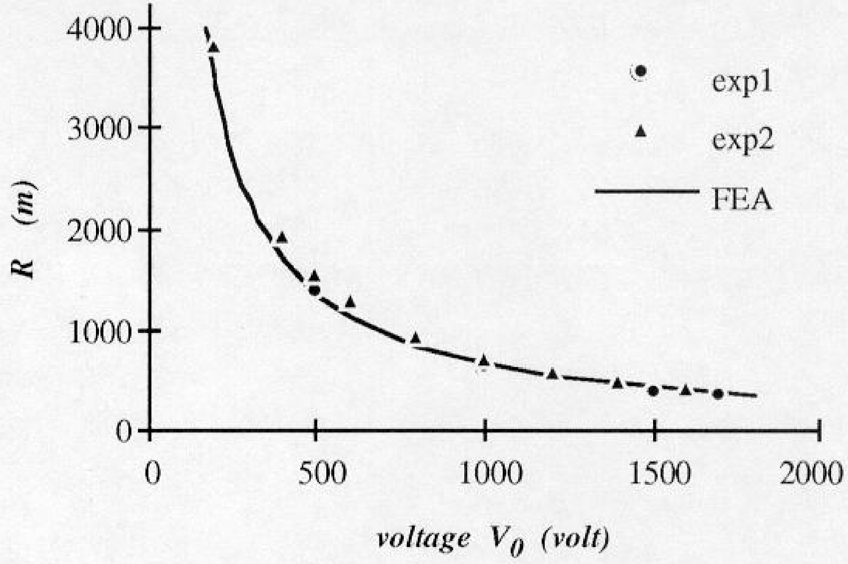


Zhang L., Labergerie D. and Susini J., Proceedings ***STRUCOME*** (1994), 371-379

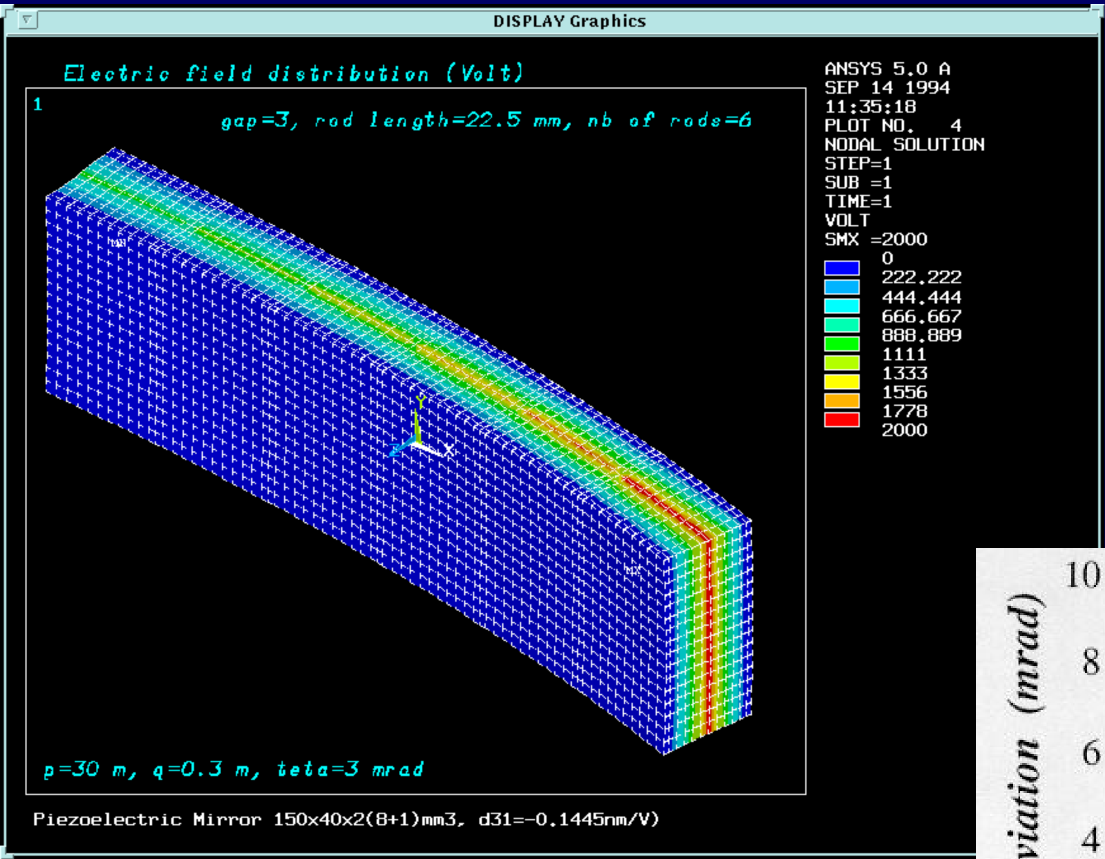
Susini J., Labergerie D. and Zhang L., ***RSI*** (1995), **66**, 2229-2231

- **Piezoelectric bimorph: spherical shape**
- **Active mirror**
  - Spherical shape (mono-electrode)
  - Toroidal shape (multi-electrodes)
  - **Active: variation of the radius of curvature by changing electric voltage**
- **FEA key points**
  - electrode distribution, gap effects for a required shape
  - Piezoelectric matrix, elastic coefficient matrix

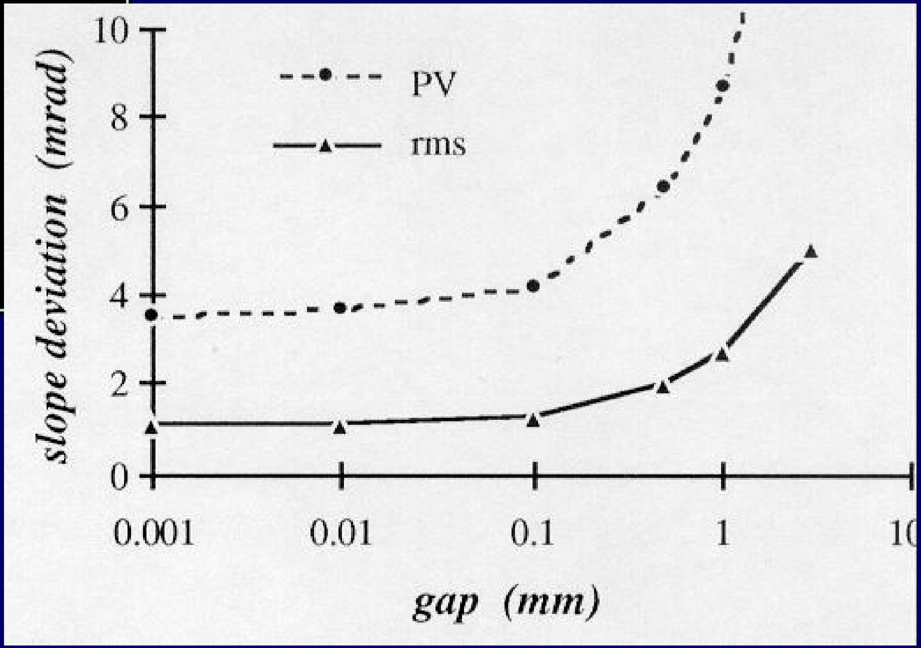
Comparison with experiments



Piezoelectric active mirror *(2)*

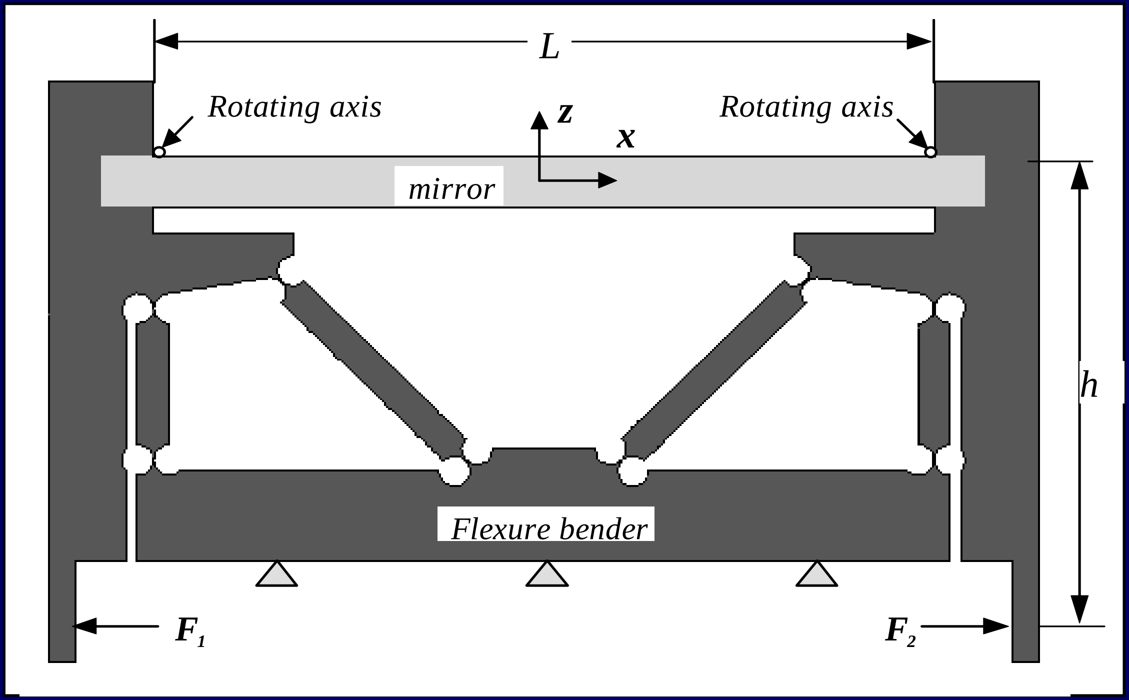


- Multi-electrodes
  → elliptical shape
- Gap between electrodes, gap induced residual slope error



Slope deviation = $slope_{FEA} - slope_{ref}$

Bending devices – *Flexor bender*

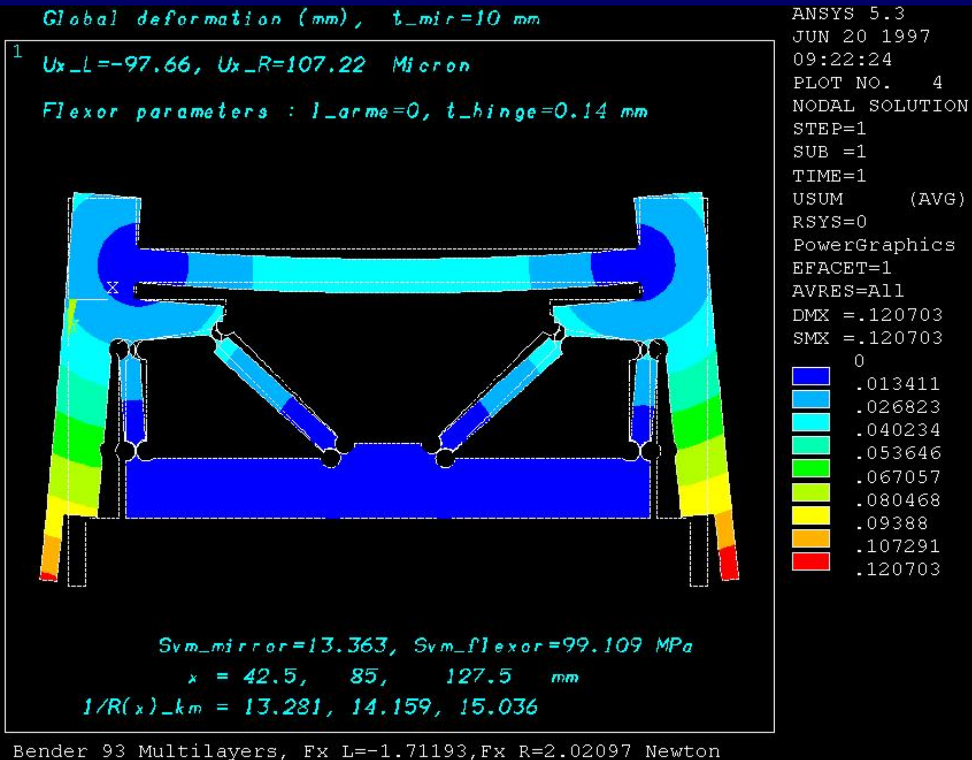


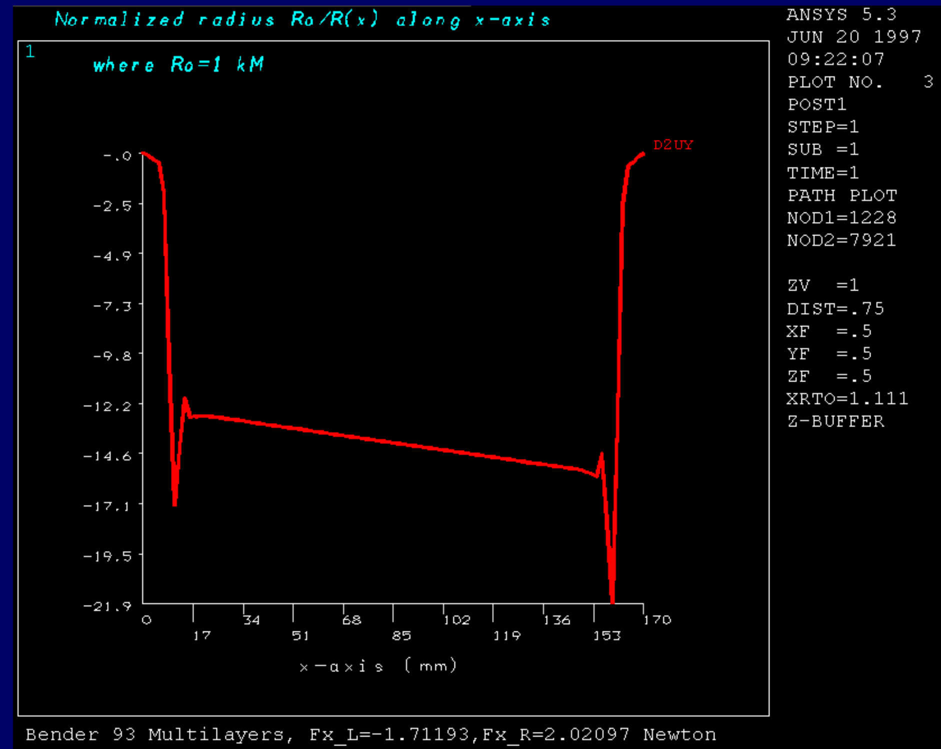
$$\frac{d^2z}{dx^2} = \frac{h}{EI}\left(\frac{(F_1+F_2)}{2}(1-\delta)+(F_2-F_1)\frac{x}{L}(1-\delta_x)\right)$$

- Flexor bender widely used in KB micro-focusing mirror device
- FEA used to
  - — *optimize the position and the size of mirror*
  - — *evaluate bending forces*
  - — *Simulate the performance*

Zhang L. et al., ***JSR*** (1998). **5**, 804-807

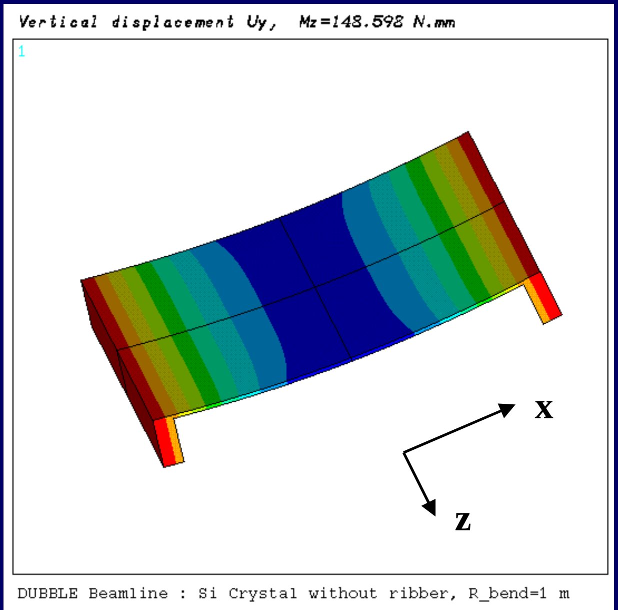
Bending devices – *Flexor bender (2)*

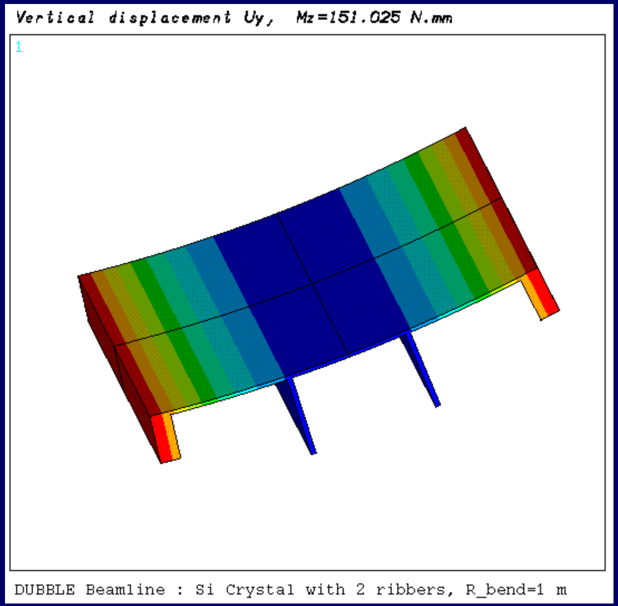


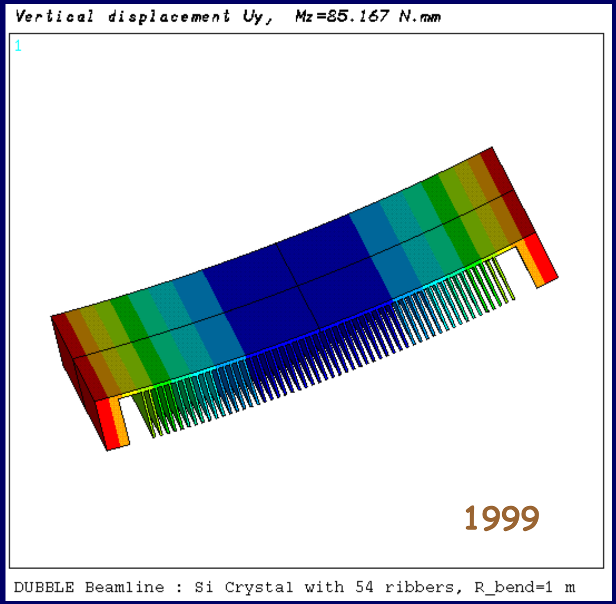


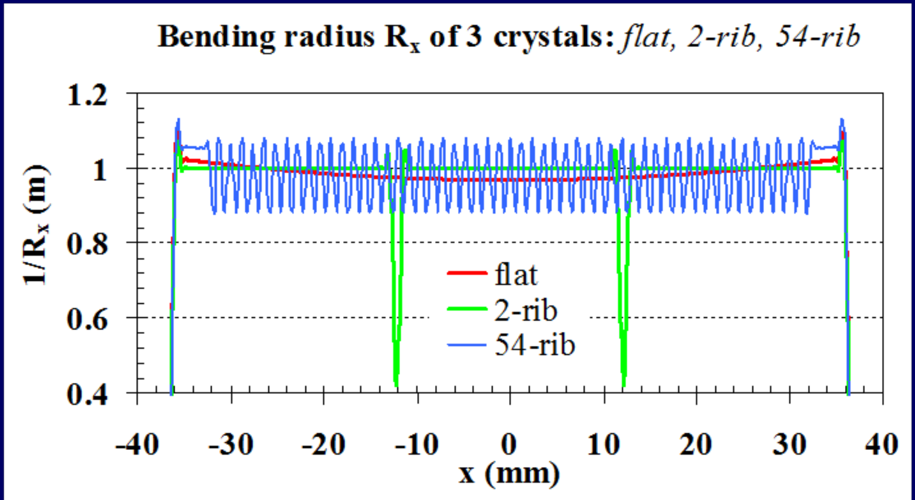
- **2 different bending moments / rectangular mirror**
  → 1/R(x) ~ P1(x) linear function of x
- **Rotation axis should be on the neutral plane of the mirror – to avoid bending capability loss**

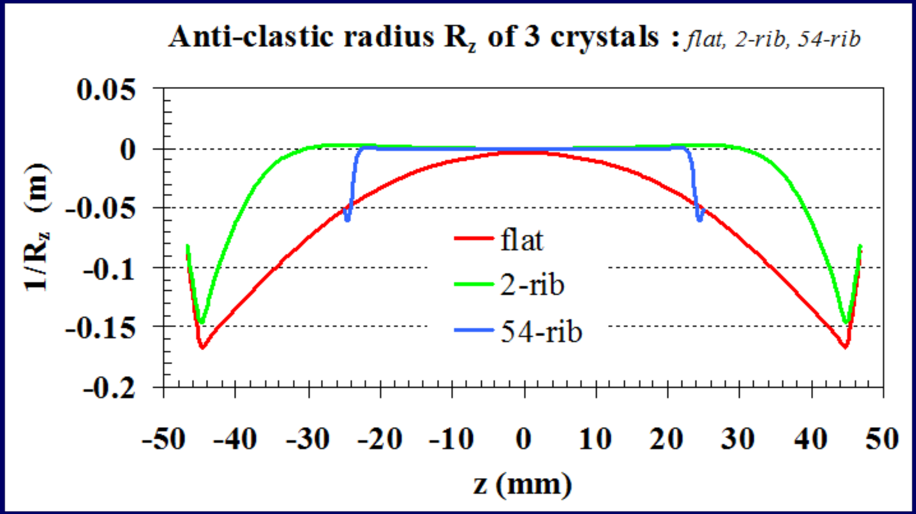
Sagittal focusing crystal *– anticlastic deformation ~ ribs*







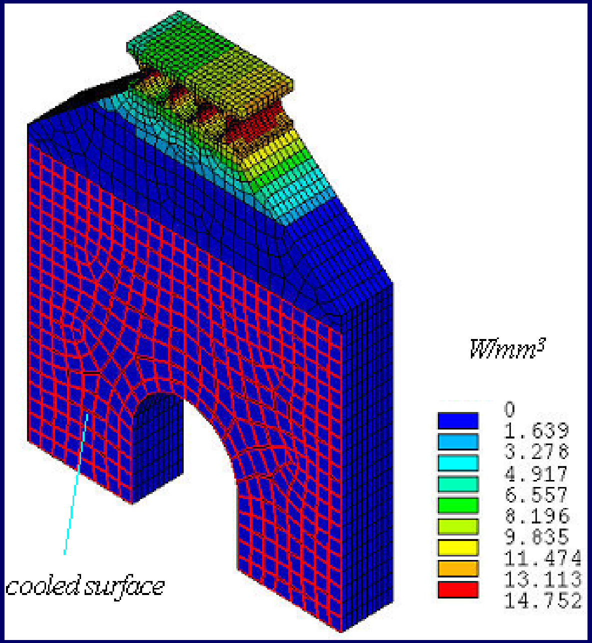




Compound Refractive Lens – *failure analysis*

- Beryllium CRLs installed in 1997 in FE
- → CRL with 4 holes of 1mm in diameter to focus 8 keV X-ray beam
- bonded to a water cooled copper block
- Failure observed on Dec-2003: sudden change of focusing capability

Zhang L. et al., *Proc. of SPIE* (2004). **5539**, 48-58



FEA results:

Total absorbed power: **139 W** (-20% ?)

Cooling coefficient h_{eff}=0.005 W/mm²/°C

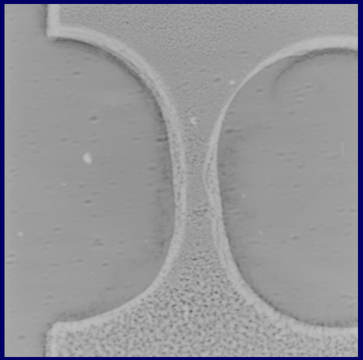
T_{max}=873 °C

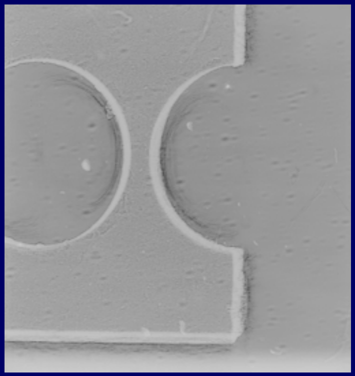
σ^{VM}_{max}=564 MPa → high stress, large plastic deformation

thermal fatigue failure

Phase contrast images

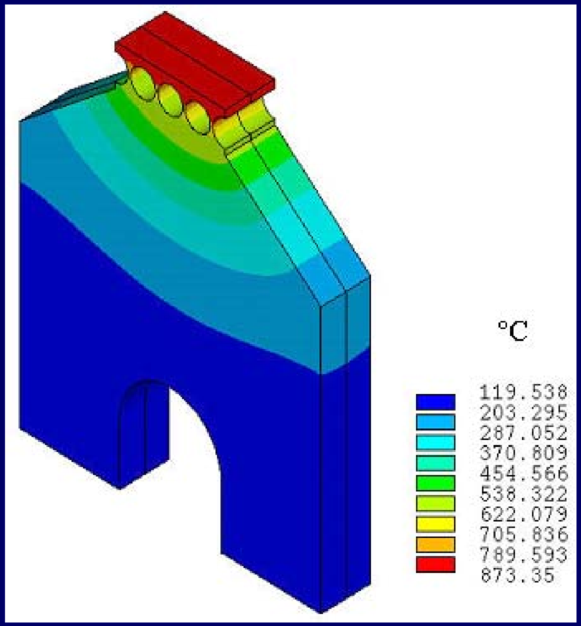
Damaged lens

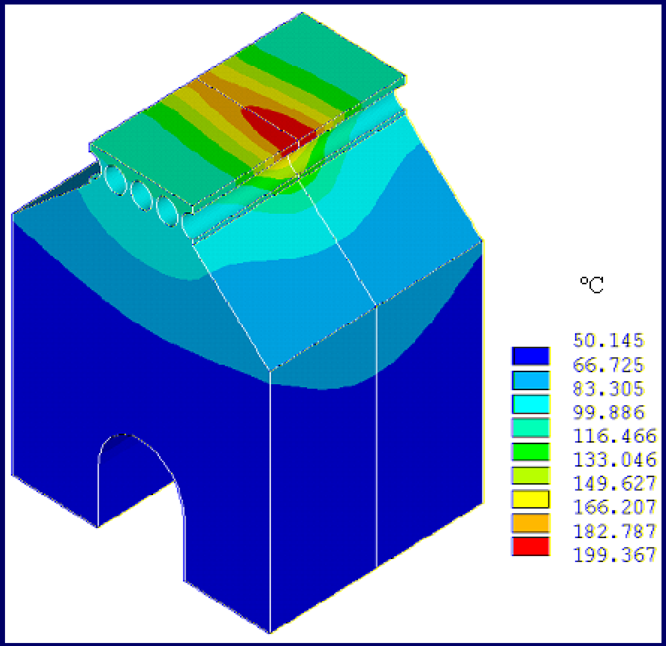




new lens

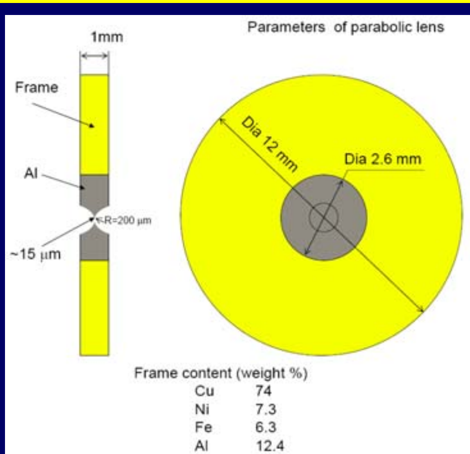
CRL - *Design optimization*

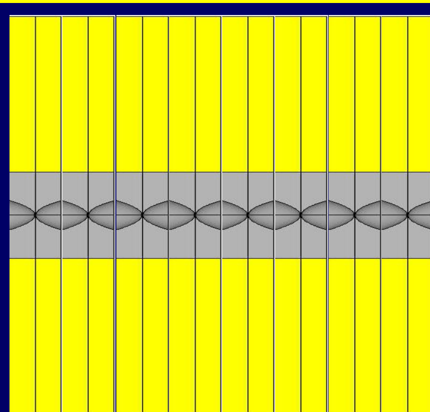




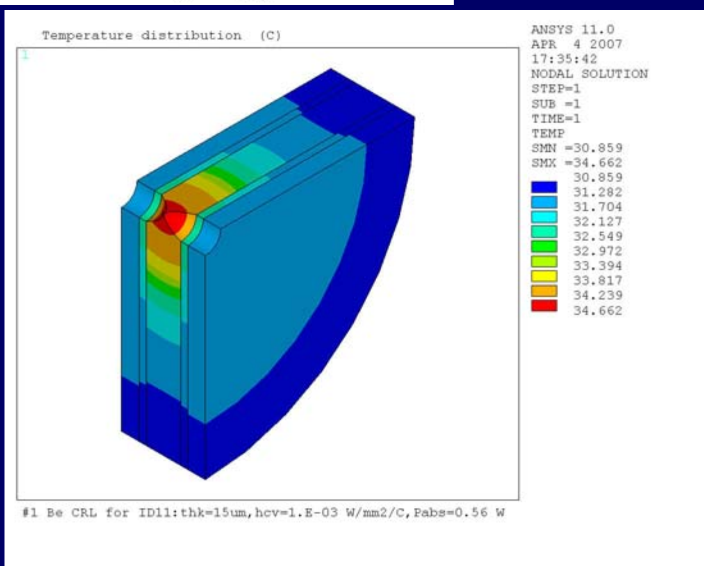
		present	optimized
width	*mm*	2	10
t_{thin}	*mm*	0.1	0.2
V_{bm}	*mm*	4	2
h_{eff}	*W/mm² /°C*	0.005	0.02
T_{max}	*°C*	873	199
σ^{VM}_{max}	*MPa*	564	205

CRL / Transfocator – *cooling design*

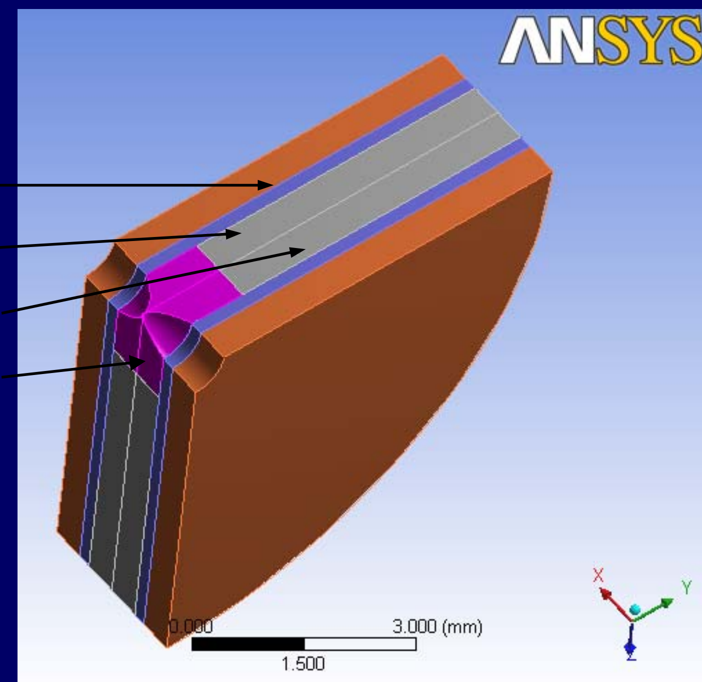


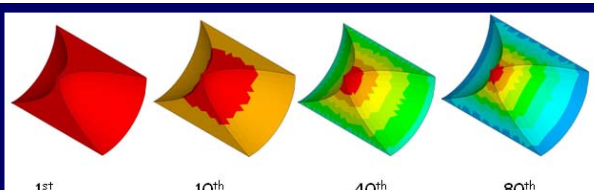


- N number of parabolic lenses (Be, Al, …, 15um, 0.56, 1.4W)
- Cooled or not cooled ?
- How cooled ?



- Copper plate
- Indium foil
- Bronze frame
- Be or Al lens



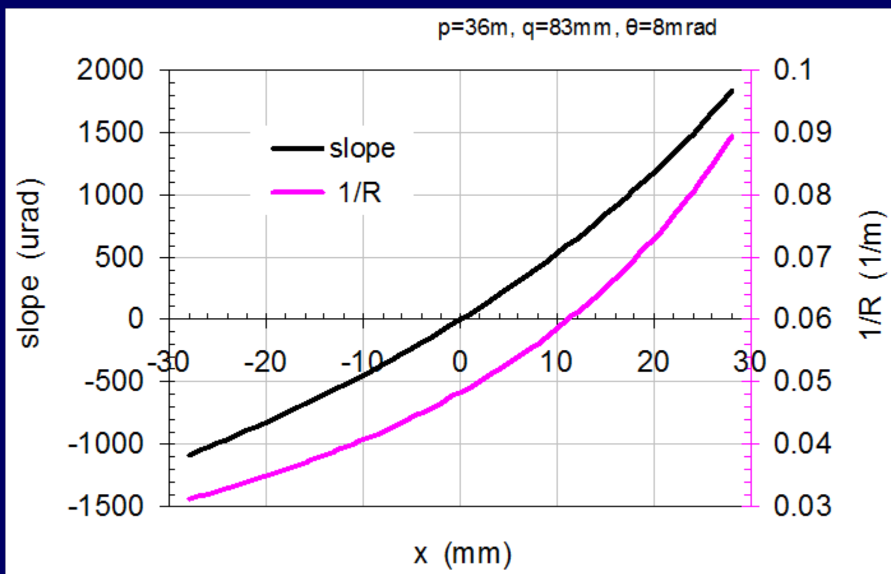


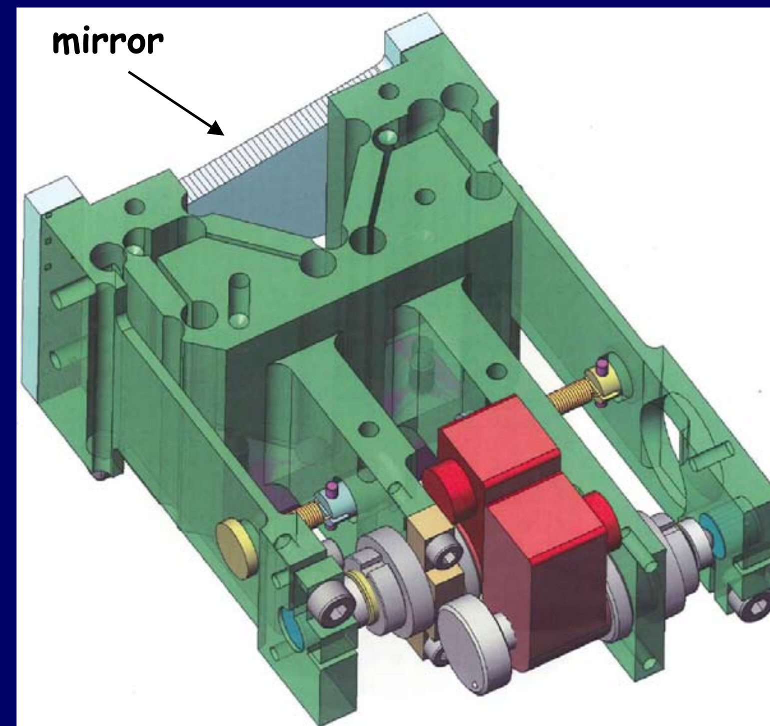
- **Outer ring cooling**

2007

KB mirror profile optimization

Grazing angle **θ=8mrad**



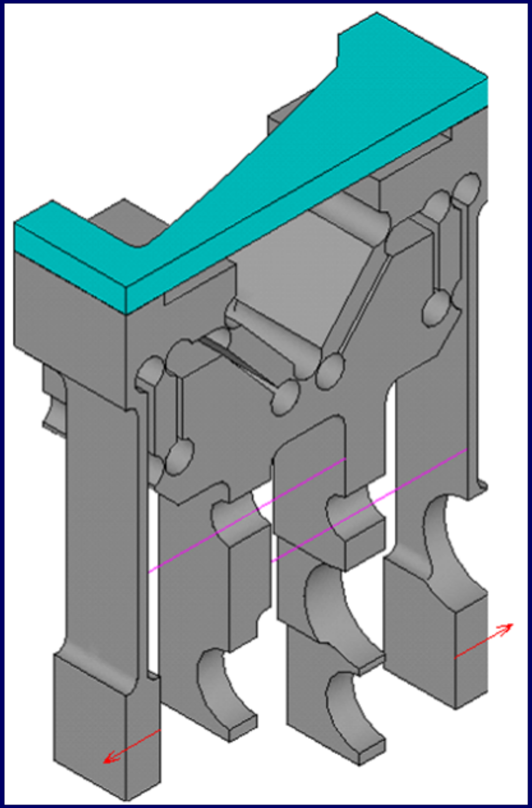


- **Aspheric shape: *R(x)* varies strongly with x**
- **Highly bent :**
  - Radius of curvature reaches R_{min}=11.2m at x=28mm
  - Slope of bent mirror in the range of a few of mrad

- **Which profile of the mirror ?**
- **How to determine the profile ?**

2008

KB mirror profile optimization - *algorithm*



From beam theory:

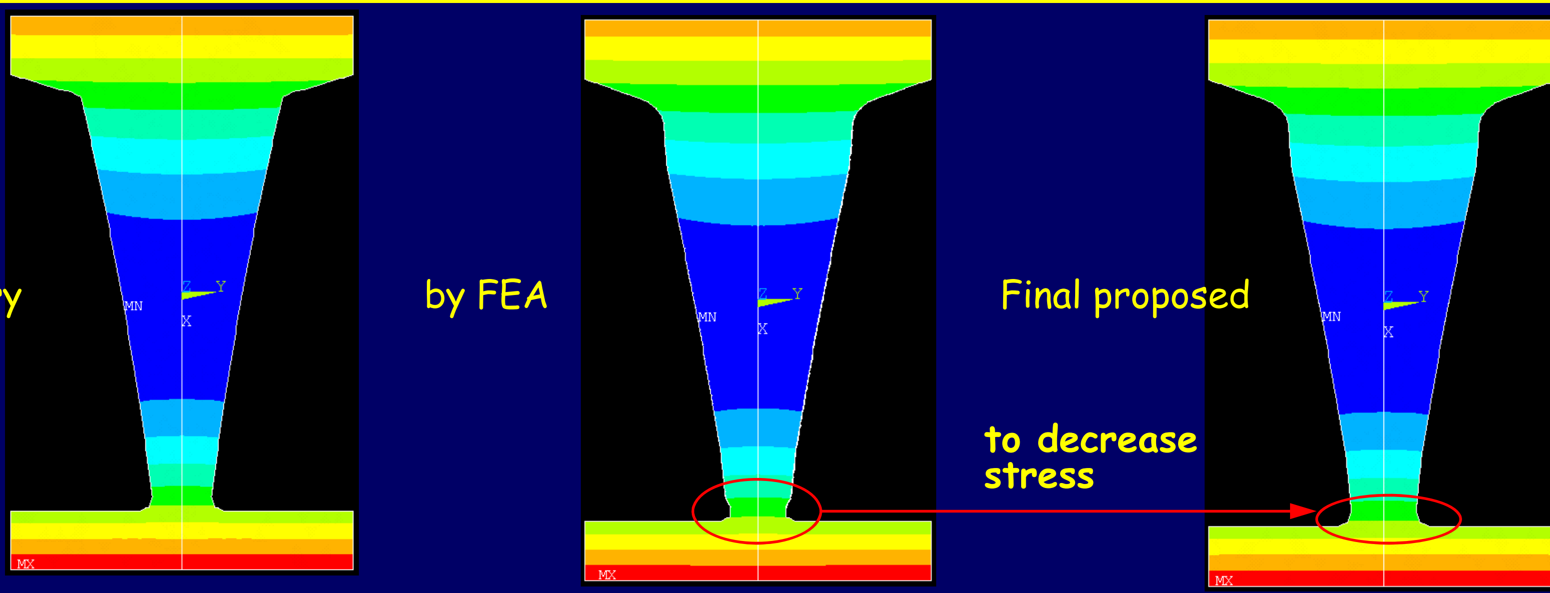
$$W(x) = \frac{\frac{1}{2}(F_1 * L_{arm-1} + F_2 * L_{arm-2}) + (F_2 * L_{arm-2} - F_1 * L_{arm-1}) * \frac{x}{L}}{\frac{1}{12} E * t^3 * \frac{1}{R(x)}} \qquad (A)$$

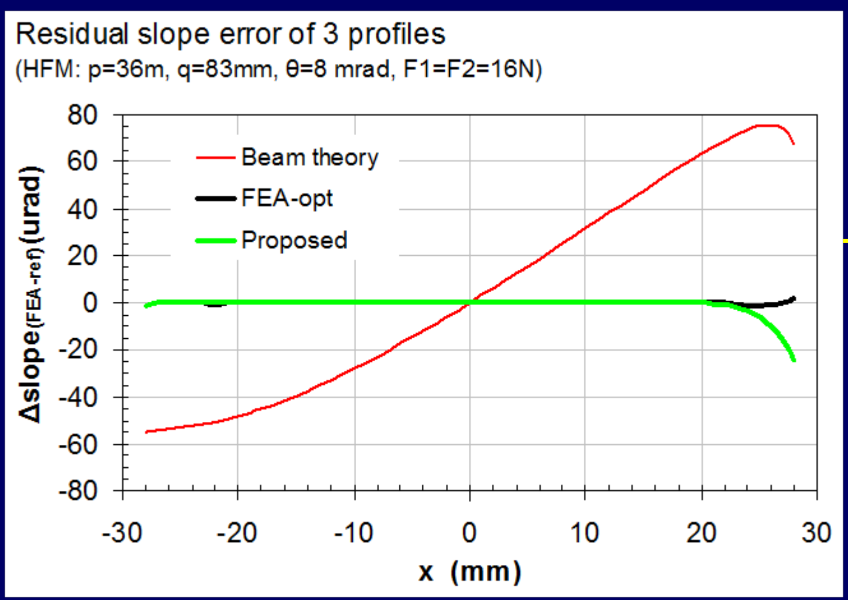
1. Initial width calculated by Eq.(A): $W_1(x)$
2. bent mirror shape calculated by FEA as well as curvature along the axis x on the mirror surface $f_n(x) = d^2U/dx^2$
3. Comparison with ideal shape $f_{ref}(x) = 1/R(x)$
4. Correction of the mirror width as :

$$W_{n+1}(x) = W_n(x) * \frac{f_n(x)}{f_{ref}(x)} \qquad (B)$$

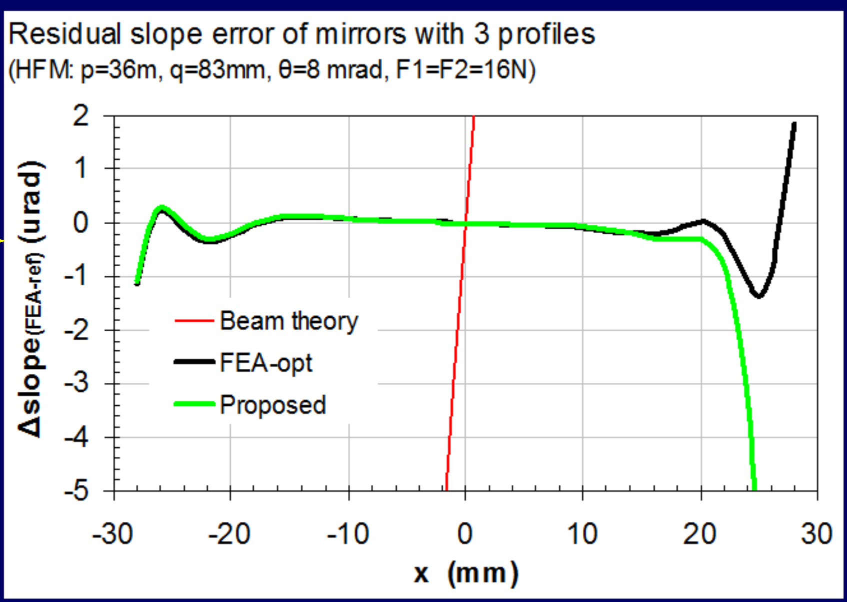
5. 4~5 iterations (repeat steps 2-4) give stabilized results

KB mirror profile optimization - *results*





zoom



KB mirror profile optimization - *summary*

FEA deals with following issues:

- Mirror width profile
- Residual slope error
- Sensitivity to the uncertainty of preload spring parameters
- Si crystal orientation
- Stress in the mirror
- Resolution requirement for the Pico motors
- Stress in the bender and glue layers
- Error analysis
- Mirror performance at different photon energy
- …

Summary

FEA

- Widely used in X-ray optic Design, manufacturing and operation
- Providing data for
  - Ray-tracing
  - Dynamic diffraction simulation