中国科学院高能物理研究所
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R&D of Mirror Bending Techniques in HEPS

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- Zoom capability and it's optimized design
- Conclusion

Mirror Bending Theory

- Basic Theory:
  - Pure Bent Beam curvature

$$y''(x) = {M(x)}/{E\,I(x)}$$

y - deflection

x - position on mirror

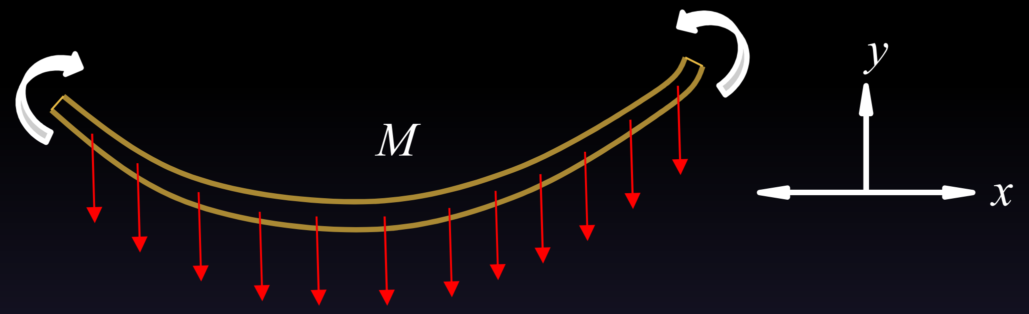
M - Bending Moment on cross-section

E - Young's modulus

I - Moment of Inertia of cross-section

Mirror Bending Theory

- Basic Theory:
  - Pure Bent Beam



$$y''(x) = {M(x)}\Big/{E\,I(x)}$$

When the moment is applied to both ends :

$$M_b(x) = M_0(1 + k_M x)$$

For a vertical focusing mirror, the extra moment from gravity:

$$M_g(x) = \frac{g\rho_m T}{4L}\left(-4L\int_x^{\frac{L}{2}}(u-x)W(u)du + (L-2x)\left(L\int_{-\frac{L}{2}}^{\frac{L}{2}}W(u)du + 2\int_{-\frac{L}{2}}^{\frac{L}{2}}uW(u)du\right)\right)$$

g – Acceleration of gravity, ρ_m - Mass density, T – Mirror Thickness, L- Mirror length, W- Mirror width

Mirror Bending Theory

- Elastic mechanics correction 1:
  - Extra transverse shear deformation:

$$y'(x) = s(x) - s(0)$$

s from bending moment:

$$s_b(x) \equiv \frac{-M_0 k_M}{W(x) * TG}$$

s from gravity (For a vertical focusing mirror) :

$$s_g(x) \equiv \frac{g\rho_m\left(\int_x^{\frac{L}{2}} \left(-\frac{L}{2} + u\right) W(u)\, du + \int_{-\frac{L}{2}}^{x} \left(\frac{L}{2} + u\right) W(u)\, du\right)}{GLW(x)}$$

G - transverse shear modulus

Mirror Bending Theory

- Elastic mechanics correction 2:
  - Extra axial shear deformation:

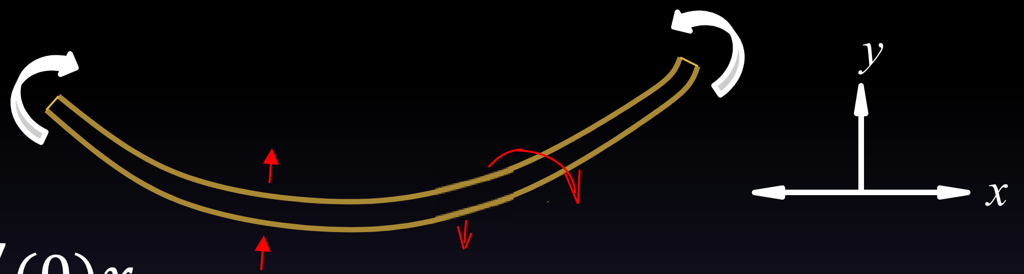
$$y'(x) = s(x) - s(0)$$

$$s_a(x) \equiv -\frac{M'(x)}{W(x)}\frac{6}{5G_aT}$$

G_a - axial shear modulus

Mirror Bending Theory

- Elastic mechanics correction 3:



  - Extra transverse deformation:

$$y_c(x) = h_c(x) - h_c(0) - h_c{}'(0)x$$

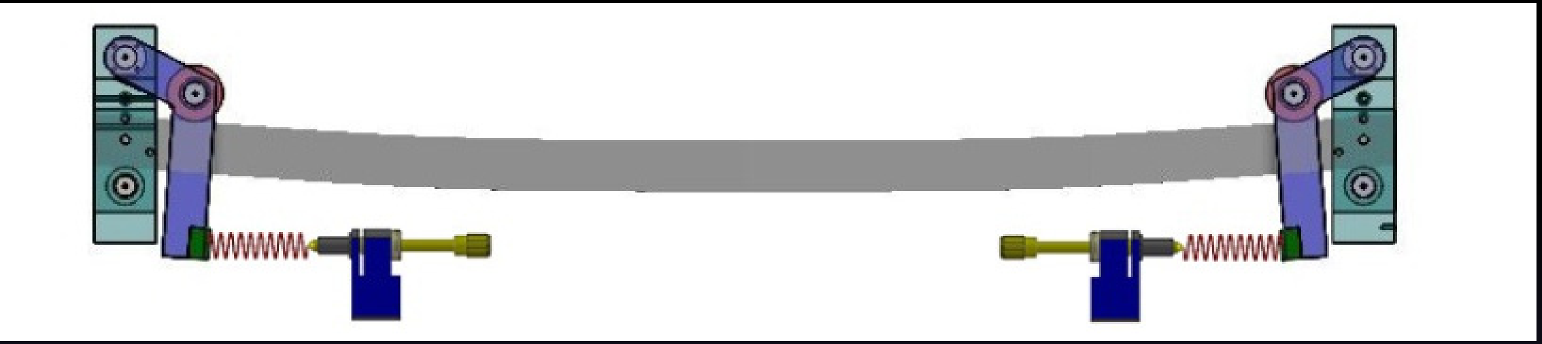
$$h_c(x) \equiv \frac{T^2\,\nu}{12}\,\frac{M(x)}{E\,I(x)}$$

  - Curvature (including Influence of saddle deformation):

$$y''(x) = \frac{-2\times 5^{2/3}\,E^{2/3}T^{8/3} + 2\times 5^{1/3}\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)^{2/3}}{W(x)^2\nu\left(ET\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)\right)^{1/3}}$$

Bending Design

Concept

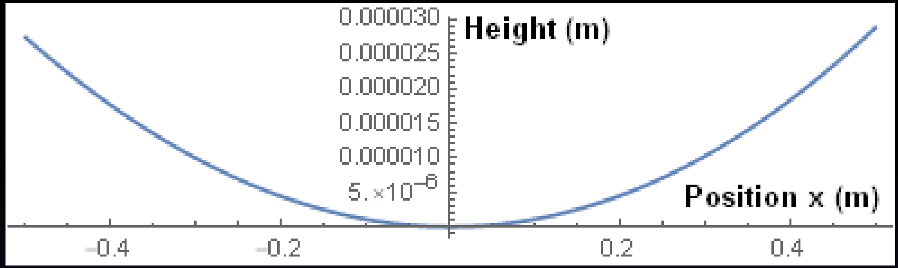


- Key points
  - Elliptical Bending
  - Two Independent Moments
  - Special Designed Torpedo Mirror
  - No Gravity Compensation System, simple and stable
  - Actuator spring – high resolution, high stability
  - New high elastic materials, Such as: BeCu

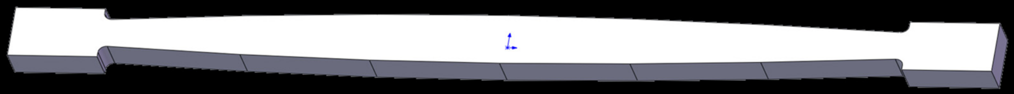
Mirror Design

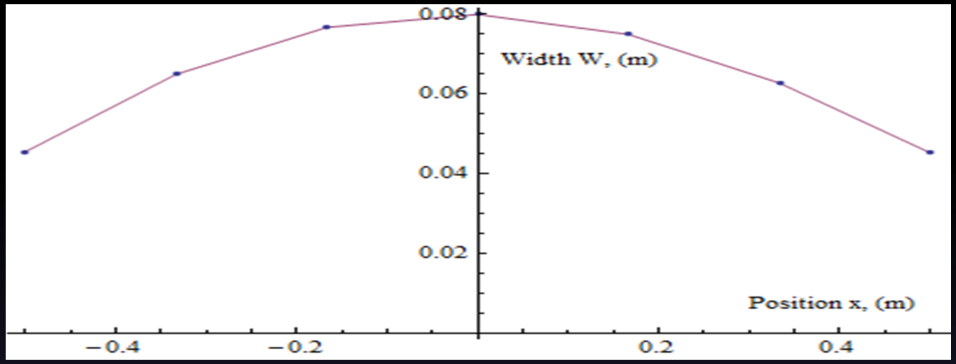
Bending Ellipse:

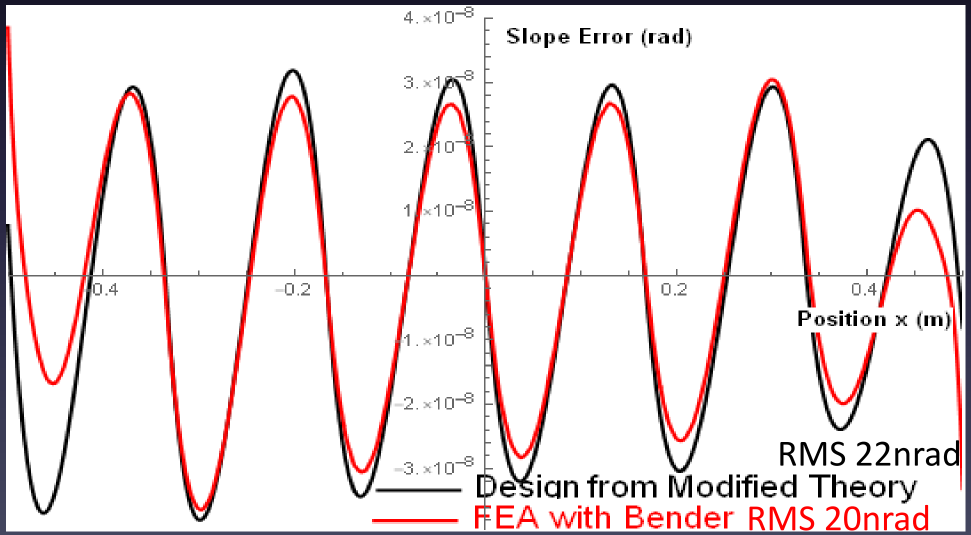
p=40m q=8m θ=3mrad



1260mm (1000mm)×80mm(max)×50mm



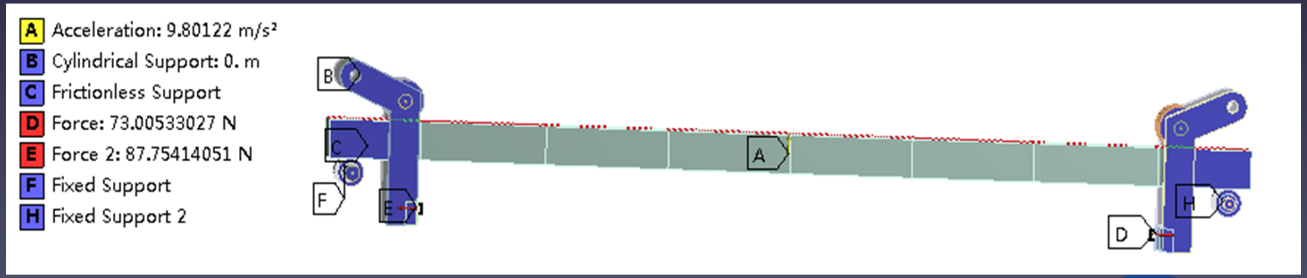




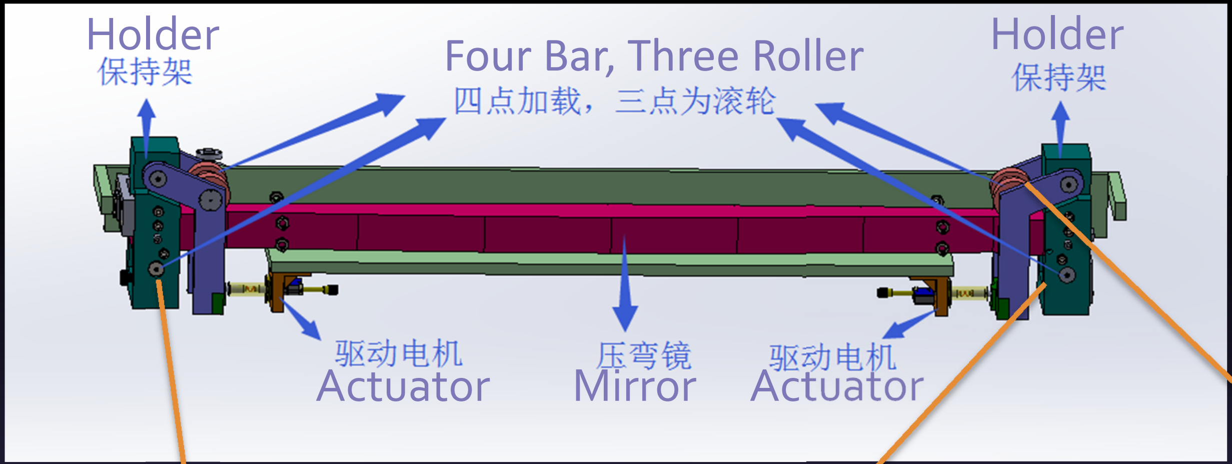
Anisotropy:

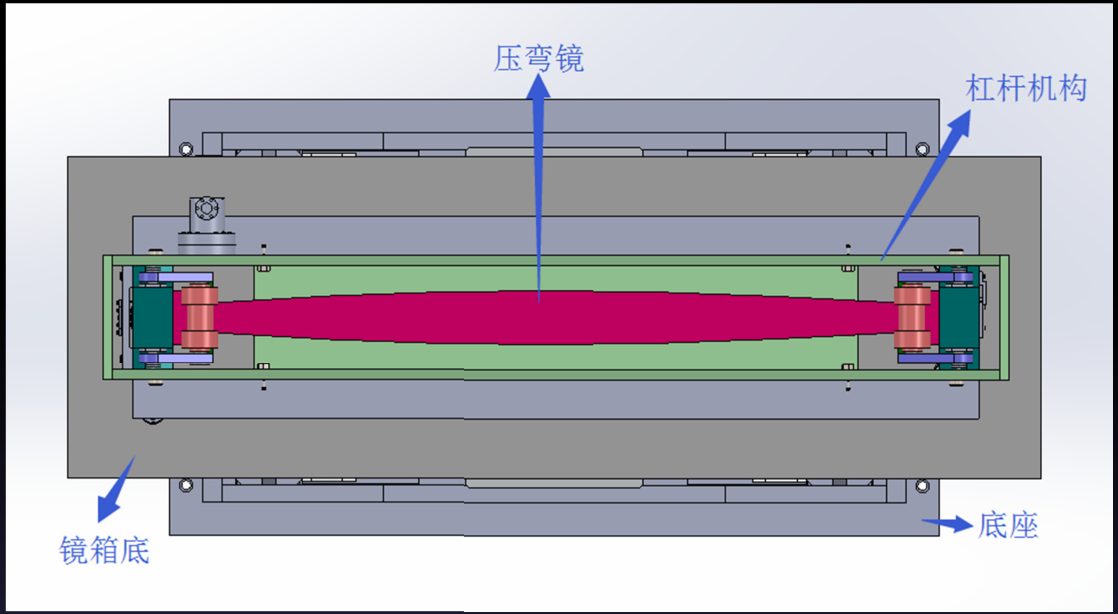
stiffness matrix: Length <1,0,0>, Width<0,1,1>, Height<0,-1,1>

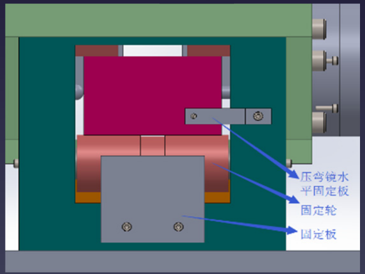
$$\begin{bmatrix} 165.7 & 63.9 & 63.9 & 0 & 0 & 0 \\ 63.9 & 194.4 & 35.2 & 0 & 0 & 0 \\ 63.9 & 35.2 & 194.4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 50.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 79.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 79.6 \end{bmatrix} \text{GPa}$$



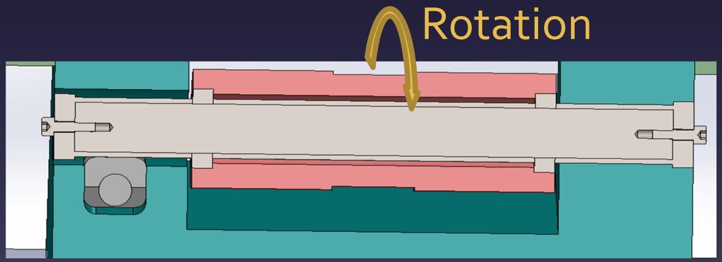
Bender design



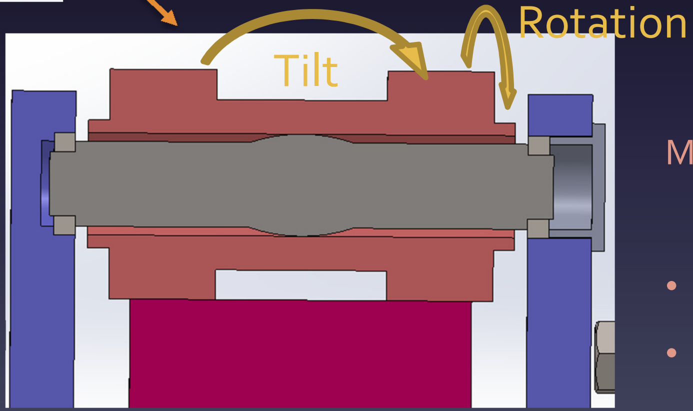




lower Fixed Bar



lower Roller



Upper Roller

Material of roller:

beryllium bronze

- Lower E -> Low Stress Concentration
- Higher σe -> Low Yield Deformation

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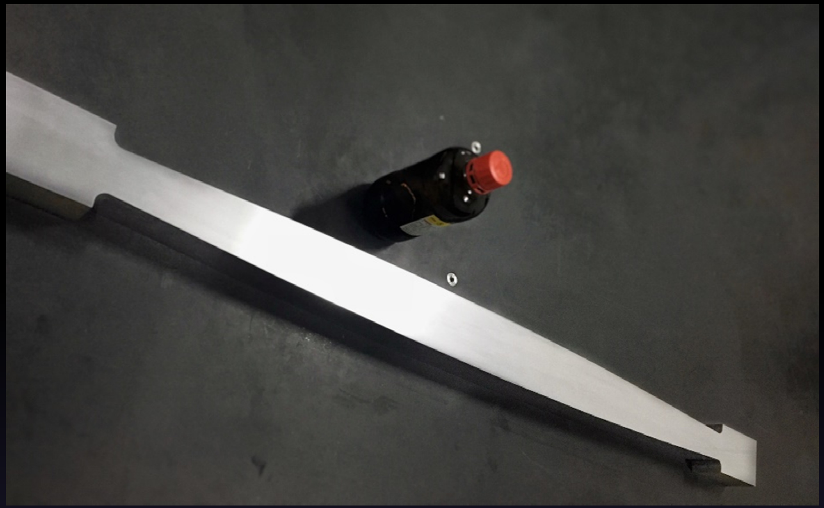
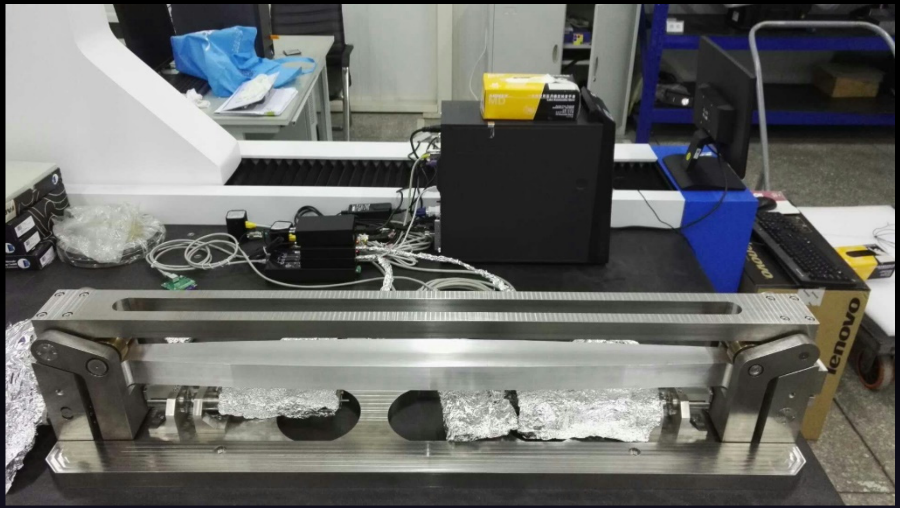
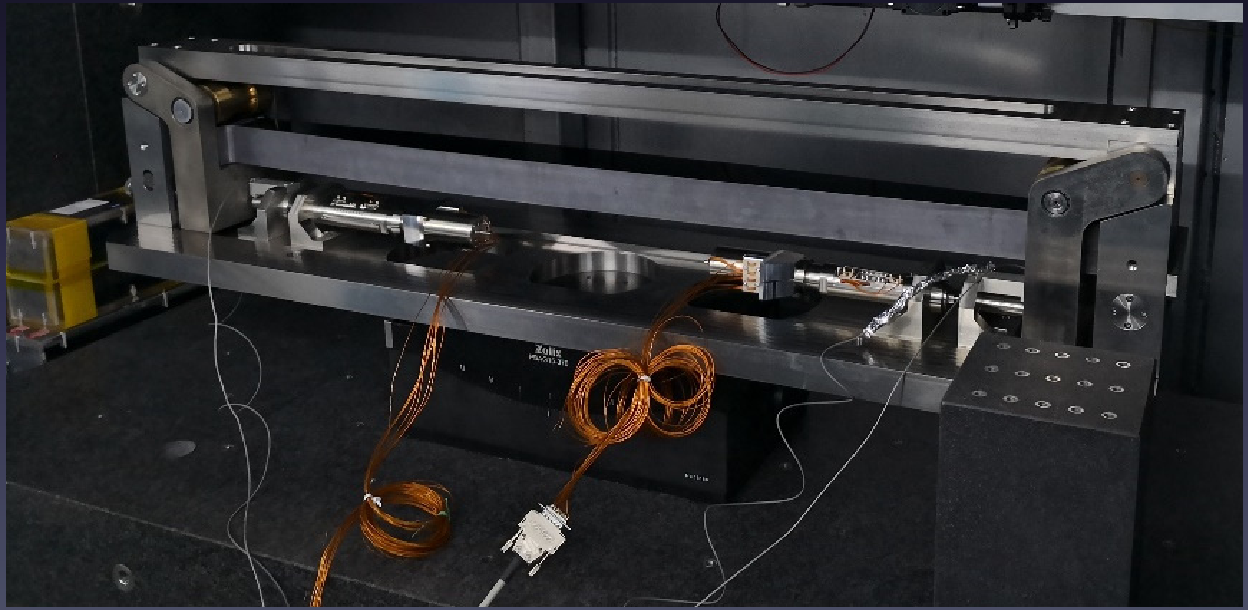
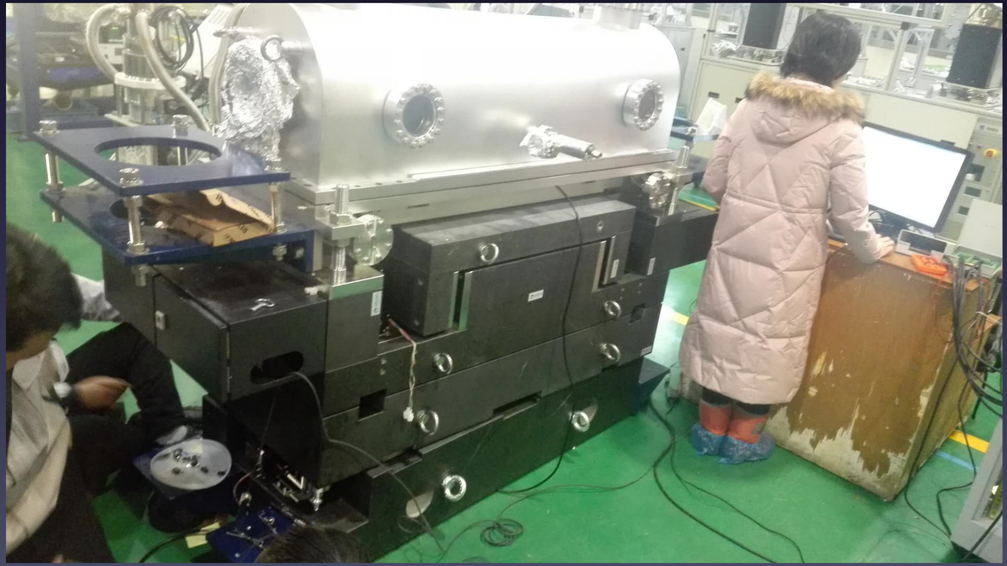
Physical processing









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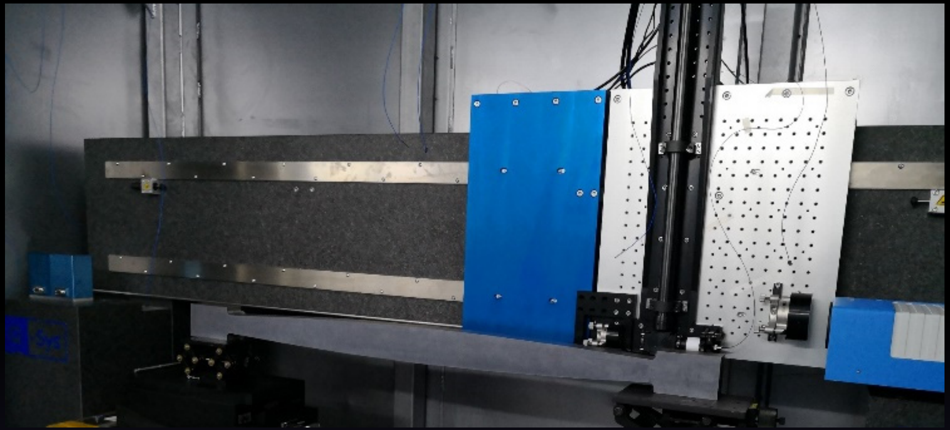
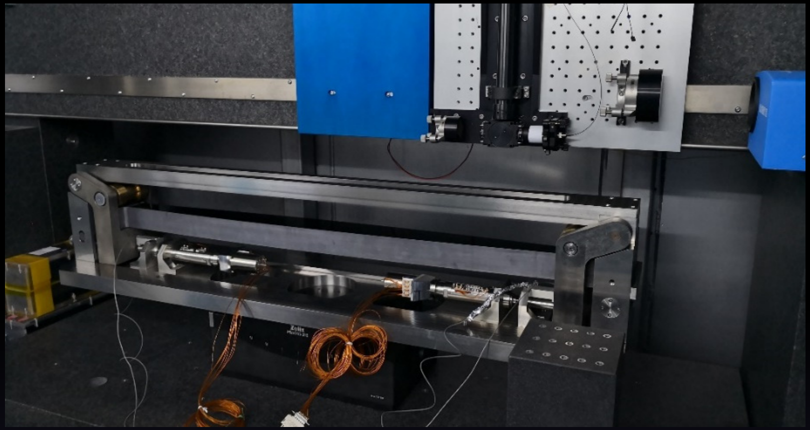
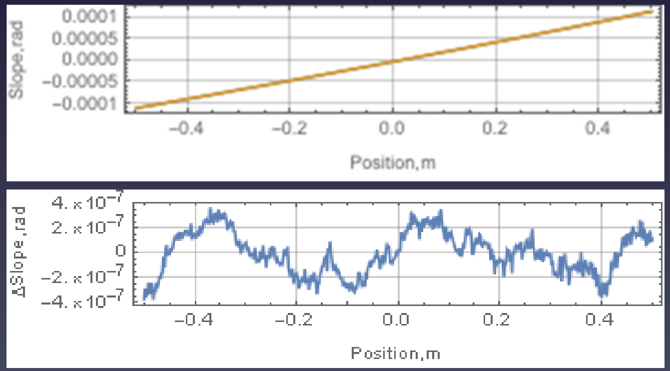
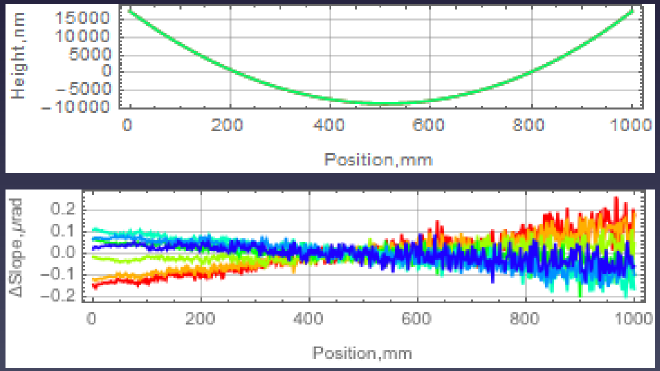
Measurement on FSP (Flag-type Surface Profiler)





	Measuring Results
effective length	1000mm
Bending Shape	Designed Ellipse
Bending shape accuracy (Bent mirror shape – Bare mirror shape – Designed ellipse)	0.17μrad (Vertical focusing)

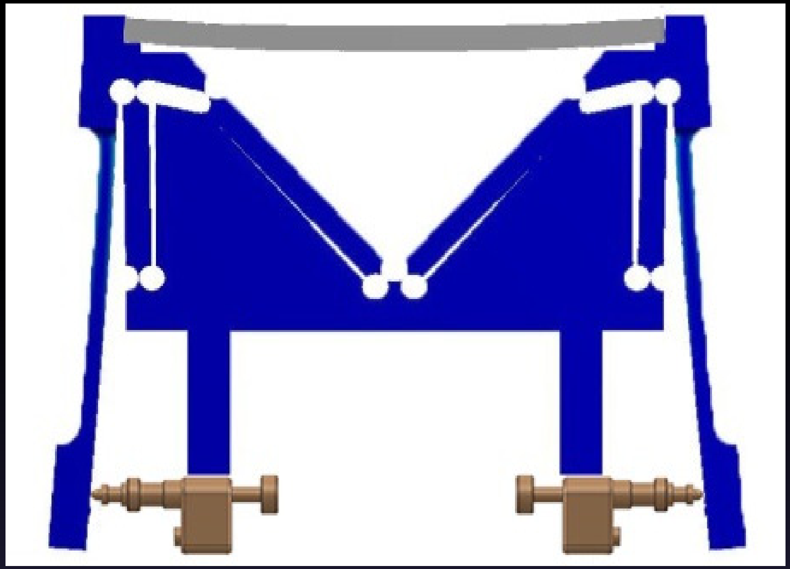




Bending shape accuracy RMS 0.17μrad

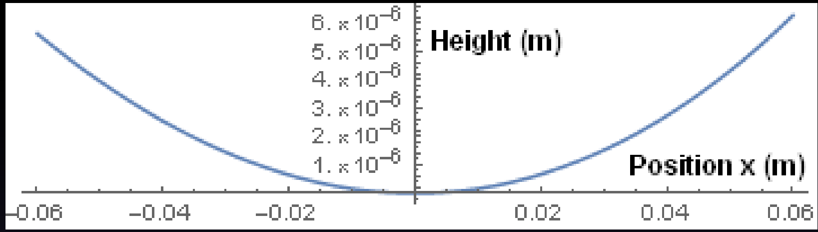
Stability: 72h, **deformation 66nrad RMS**

K-B Mirror Design

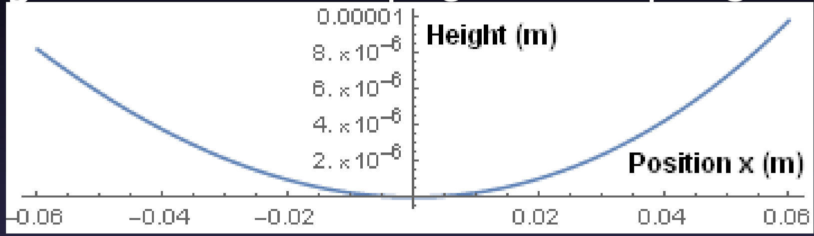


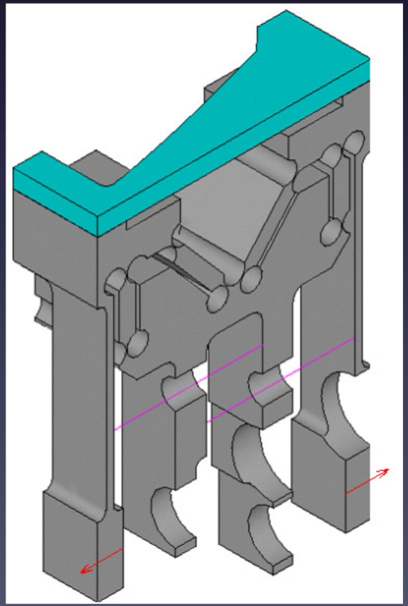
Bending Ellipse: Mirror Length: 146mm (120mm)

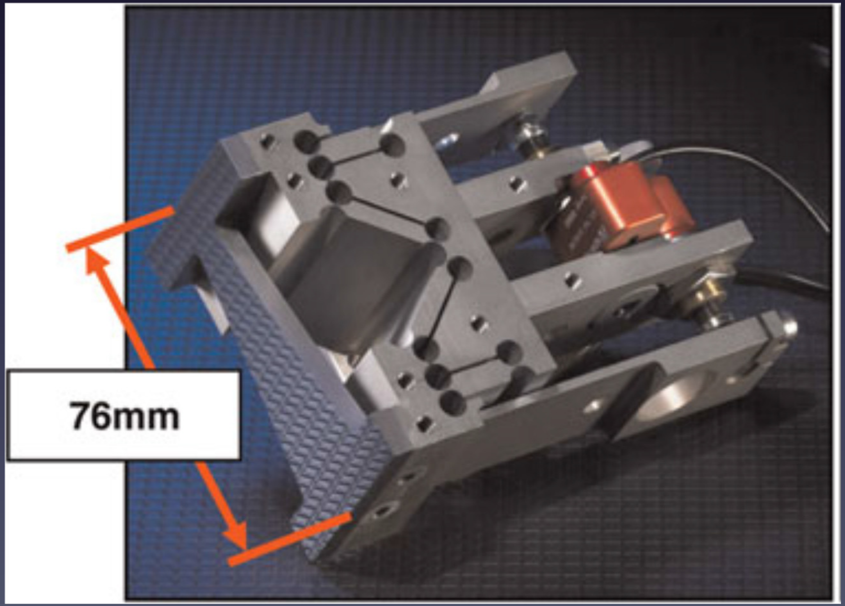
Vertical Focusing Mirror (VFM) : p=5m, q=0.5m, θ=3mrad



Horizontal Focusing Mirror (HFM) : p=5.18m, q=0.32m, θ =3mrad



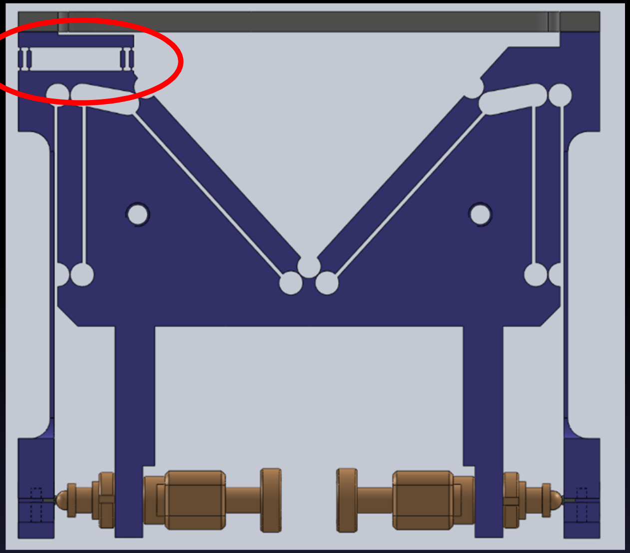




Original Design Idea From:
Lin Zhang et al. (2010) ESRF
R. Baker et al. (2010) ESRF

K-B Mirror Design

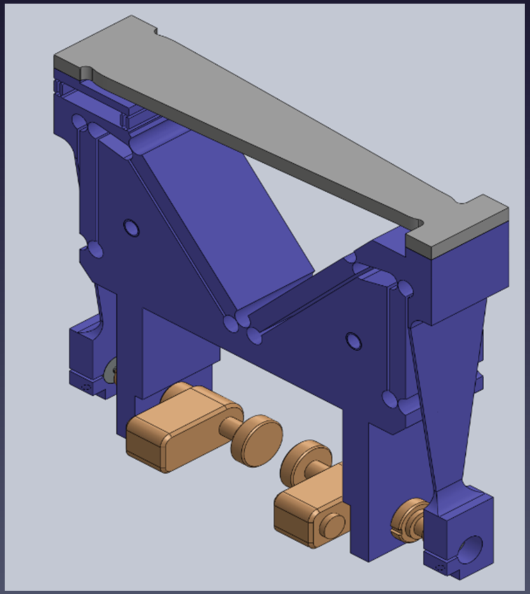
New Design: add Translation Flexure Hinge (TFH)

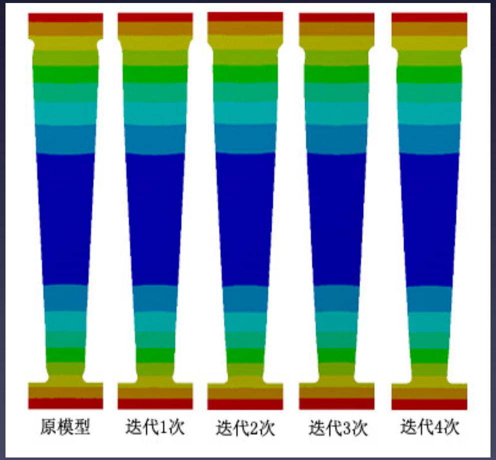


Machining Error of Flexure Bender
Bonding Error between Bender and Mirror
} → Bending Shape Error

Translation Flexure Hinge
- Reduce the Sensitivity of Bending Shape to Bender Errors.

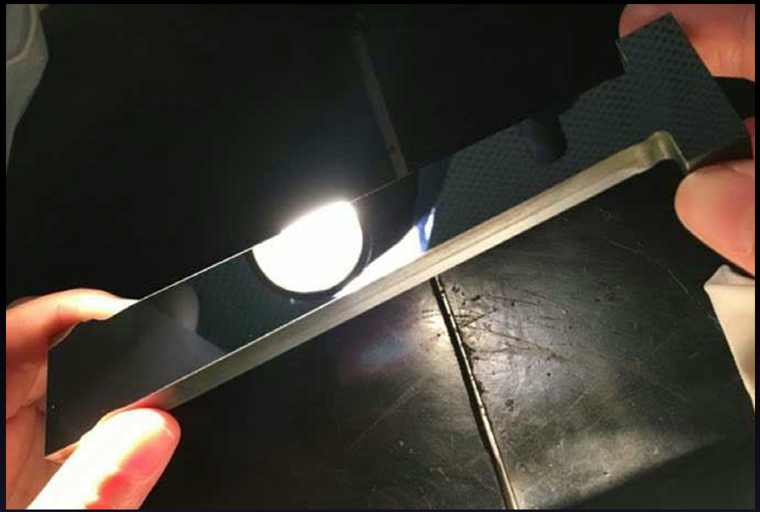
	VFM Without TFH	VFM With TFH	HFM Without TFH	HFM With TFH
Total Axial Stress F （N）	2.1	0.19	5.1	0.43
ΔF caused by 30μm Thickness Error of Glue Layer （N）	0.23	0.023	1.16	0.13
ΔF caused by 30μm Machining Error of Flexure Bender （N）	0.32	0.032	1.6	0.09

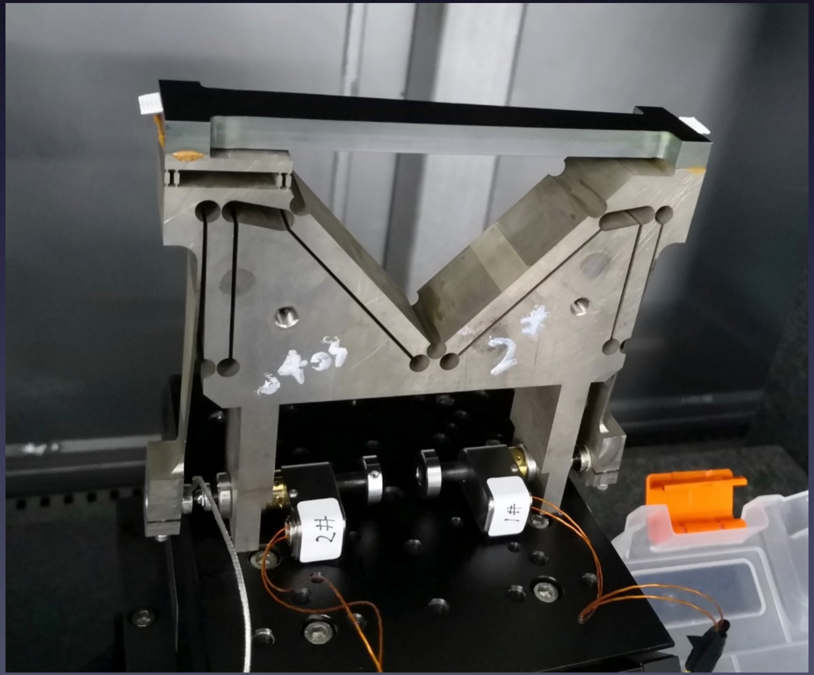


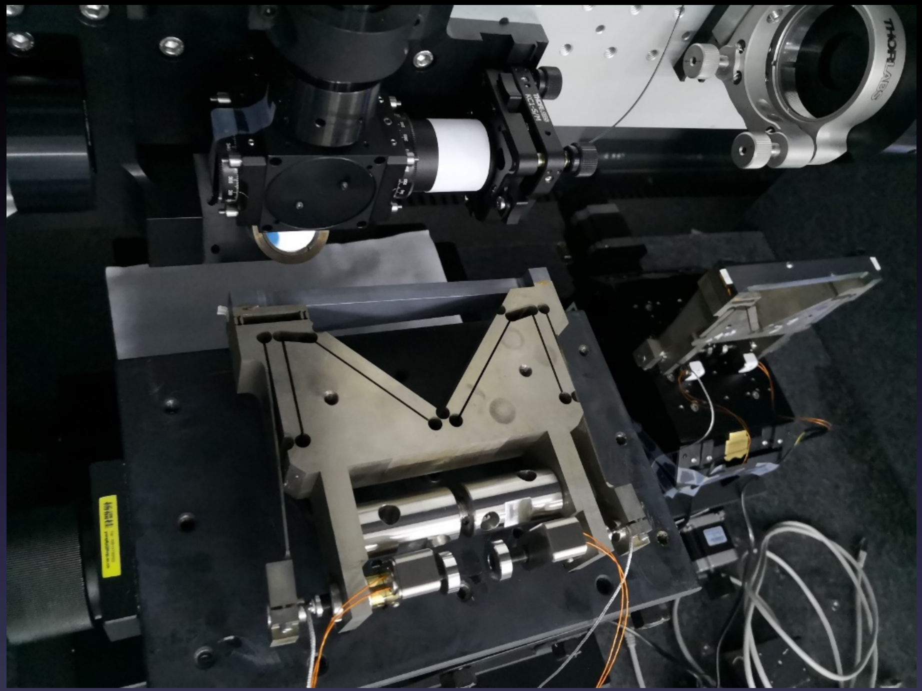


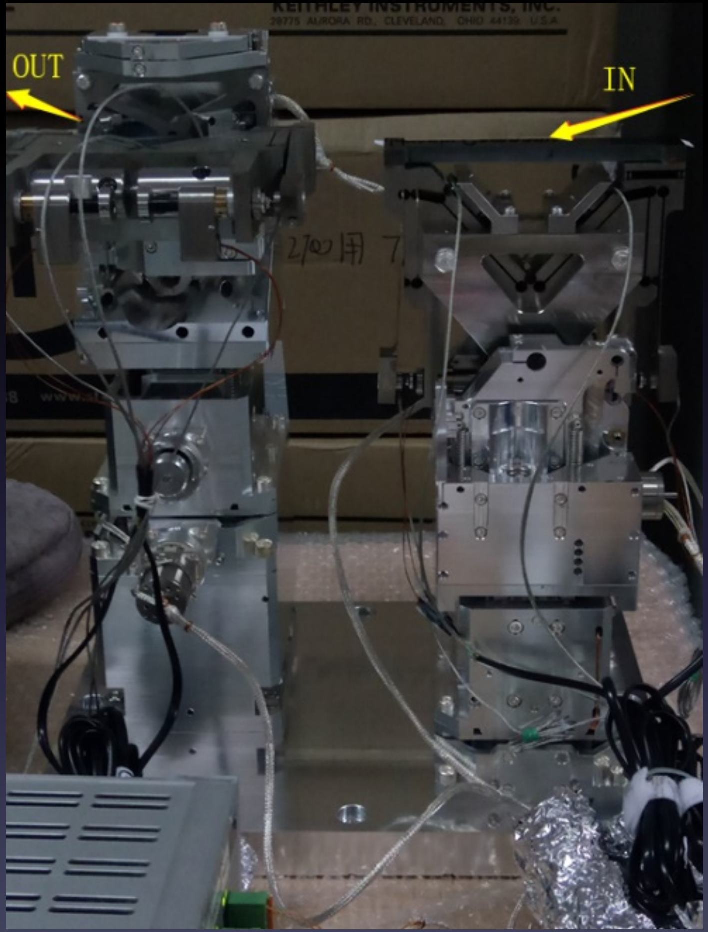
Mirror Profile Iteration by FEA

Physical processing

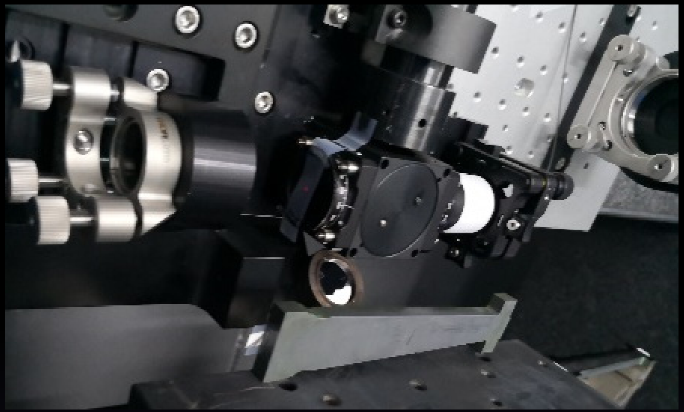


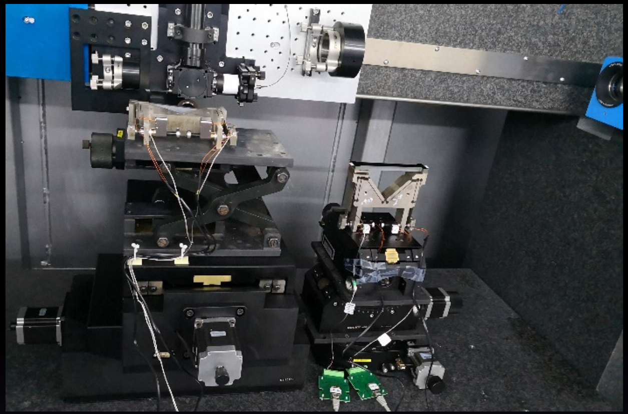




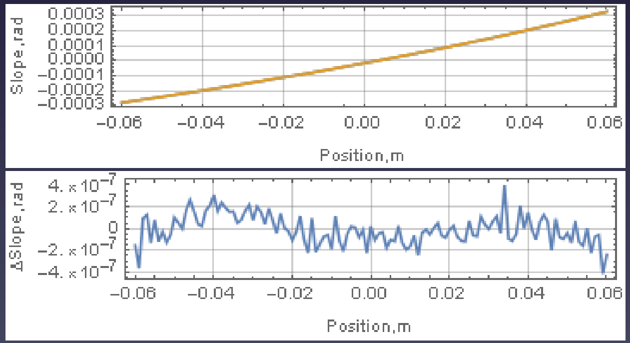


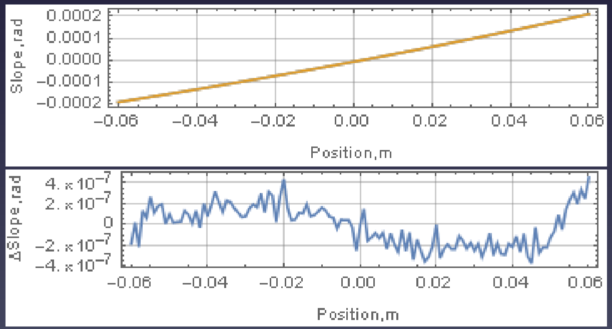
Measurement on FSP (Flag-type Surface Profiler)

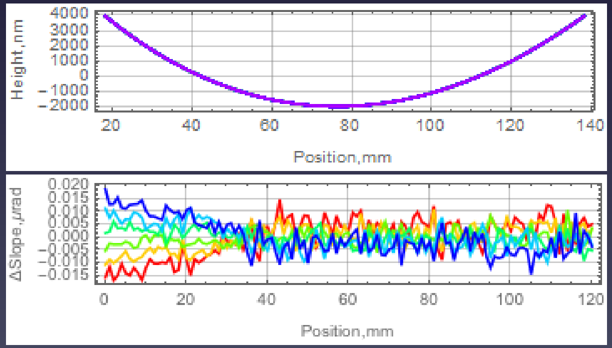




	Measuring Results
effective length	120mm（146mm total）
Bending Shape	Designed Ellipse(40m, 120mm, 3mrad)
Bending shape accuracy (Bent mirror shape – Bare mirror shape – Designed ellipse)	0.13μrad(HFM) 0.19μrad (VFM)







Bending shape accuracy RMS 0.13μrad & 0.19μrad

Stability：72h, **transformation** 6nrad RMS

Next Bending Techniques in HEPS

—— Zoom capability and optimized design

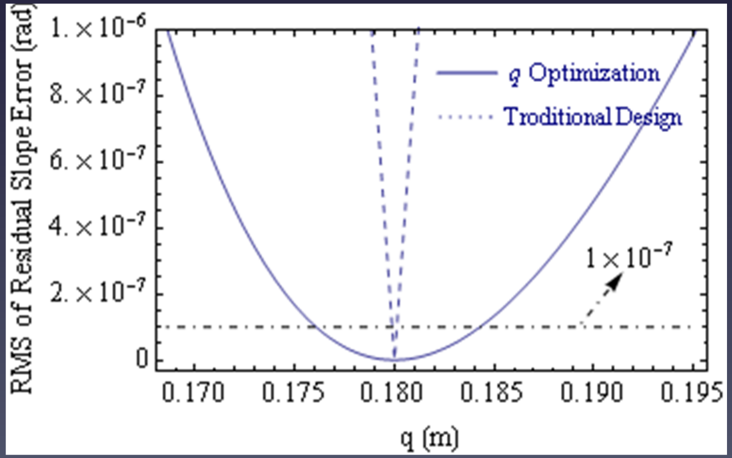
Zoom Variation Capability is new important requirement for Beam-lines

Whether Pure Bent Beam Theory or Elastic Mechanics,
For any *M(x)*, we can find matched *I(x)* to get Perfect Designed Elliptical Bending

$$y''(x) = {M(x)}/{E\,I(x)}$$

But for different *M(x)* design, typically different M1 and M2 -> different k_M design
the Zoom Variation Capability of bent mirror is different.

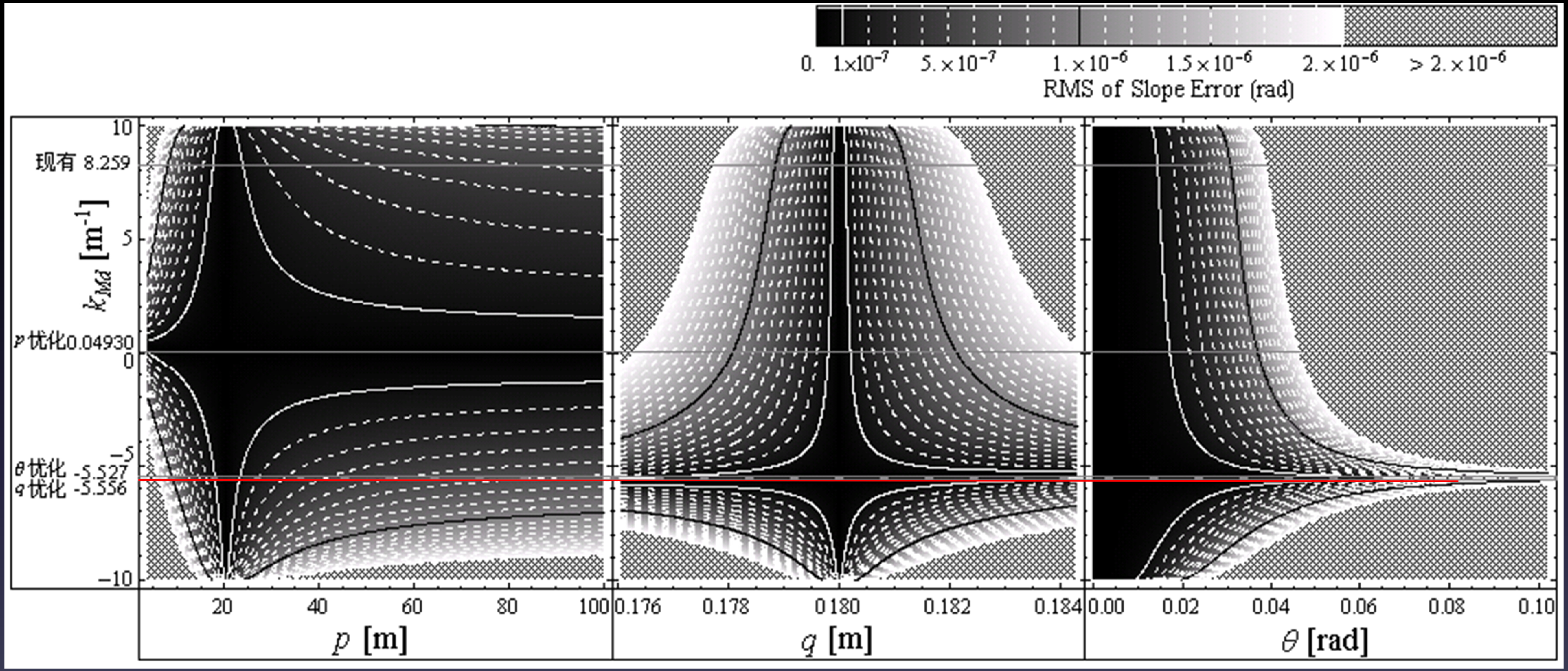
For example: p=20.3m， q=0.18m， L=0.2m， θ= 2.2mrad



Next Bending Techniques in HEPS

—— Zoom capability and optimize design

For example: p=20.3m，q=0.18m，L=0.2m，θ= 2.2mrad HFM



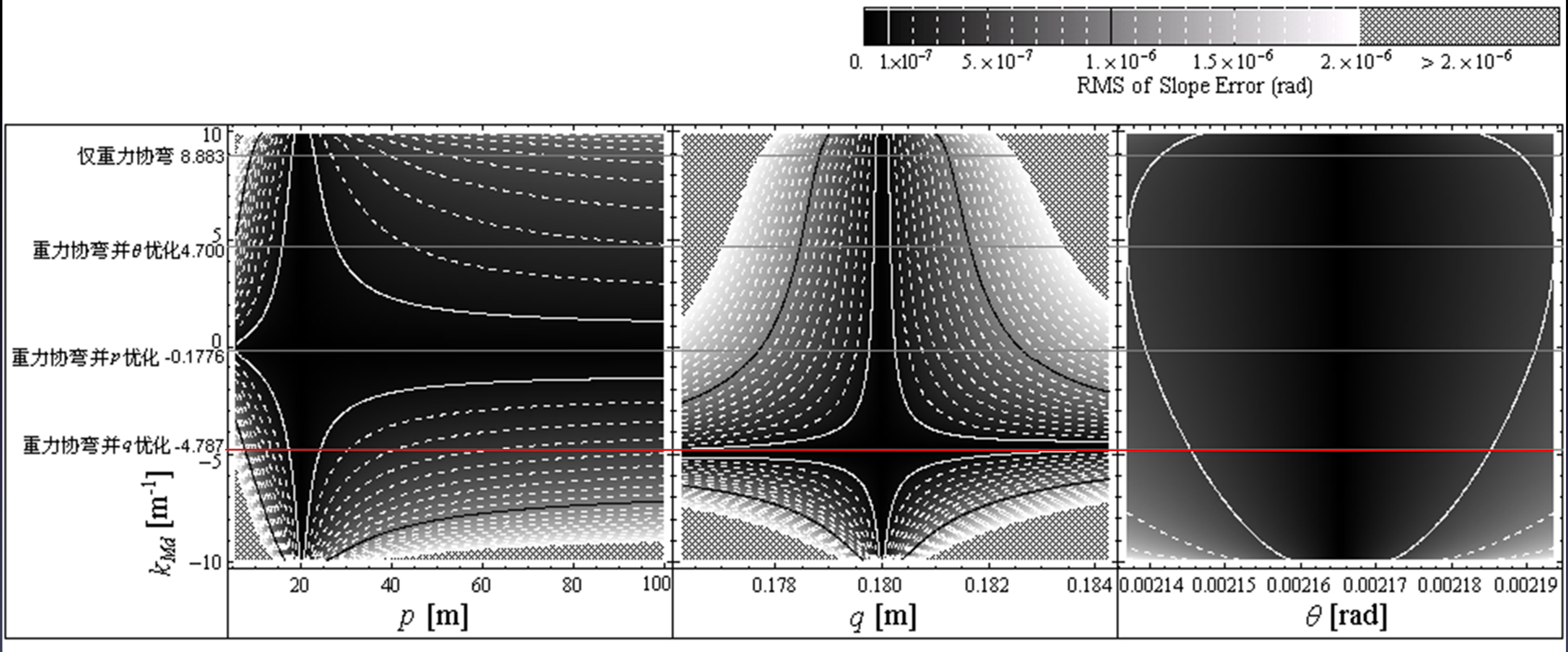
$$k_{Md} \doteq -\frac{\cos\theta_d}{q_d} - \frac{\sin\theta_d \tan\theta_d}{p_d} \approx -\frac{1}{q_d}$$

Subscript “d” means design value.

Next Bending Techniques in HEPS

—— Zoom capability and optimized design

For example: p=20.3m，q=0.18m，L=0.2m，θ= 2.2mrad， T=5mm VFM



Subscript "d" means design value.

Conclusion

- Elastic mechanics corrections on bending theory
- Long Bent Mirror and K-B Bent Mirrors are R&D, sub-200nrad bending accuracy is got with high stability.
- Zoom capability optimized bending design is discussed.

Thanks!

Our Team:

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- Fugui Yang
- Xu Liu
- Chunxia Yin
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