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Development of the bent focusing mirror in HEPS from design to test

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Outline

Introduction

- **4th Synchrotron Radiation Source**

SIRIUS

APS-U

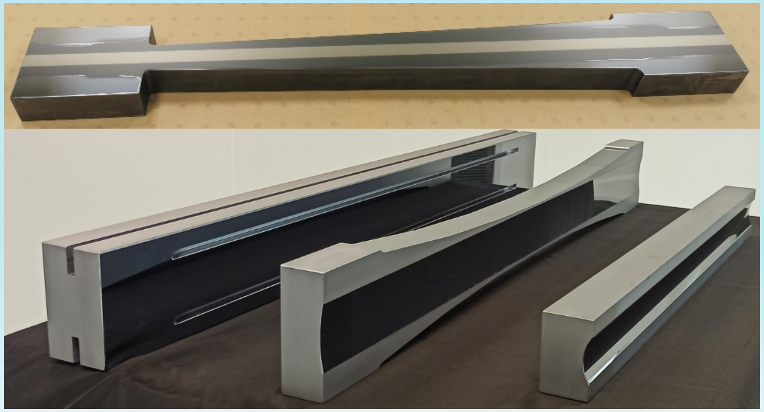
ESRF-EBS

Brilliance *and* **coherence** *are the main parameters.*

- **Bent Mirror**

HEPS

6GeV, 1364m, 34pm rad



Various bent mirrors in HEPS

Characteristics:

Adjust spot size;

Form secondary source;

Decrease errors.

One bent mirror

Design → Test

Progress *and* **Performance**

Outline

Design phase

- **Method**

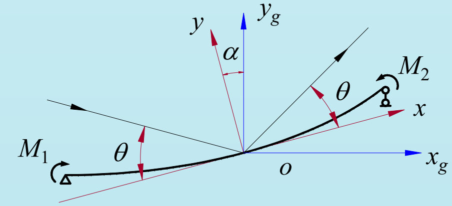
  - *Basic equation*

$$y=\frac{(p+q)\sin\theta}{(p+q)^2-(p-q)^2\sin^2\theta}\times\left\{2pq-\left[(p-q)\cos\theta\right]x-2\sqrt{pq}\sqrt{pq-(p-q)\cos\theta x-x^2}\right\}$$

Elliptical Eq.

$$K(x)=\frac{\sin\theta(p+q)}{2pq}\left(1-\frac{x^2}{pq}-\frac{x(p-q)\cos\theta}{pq}\right)^{3/2}$$

Curvature Eq.



  - *Gravity compensation*

$$M_g(x)=\frac{1}{2L_g}\left(x+\frac{L_g}{2}\right)C\int_{-L_g/2}^{L_g/2}(L_g-2x)b(x)dx-C\int_{-L_g/2}^{s}(s-x)b(x)dx$$

Moment by gravity

$$b(x)=\frac{\left(M(x)+M_g(x)\right)b_0}{EI_0K(x)}$$

Mirror width with gravity effect

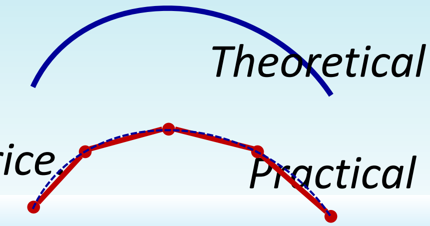
  - *Iterative method*

$$F(\xi)=EI_0K(x_g)\xi-\left(M(x_g)+\Phi(\xi)\right)b_0$$

$$\xi_{n+2}=\xi_{n+1}-F(\xi_{n+1})\frac{\xi_{n+1}-\xi_n}{F(\xi_{n+1})-F(\xi_n)},\quad n=0,1,2\cdots$$

The theoretical distribution of the mirror width is a ***curve****.*

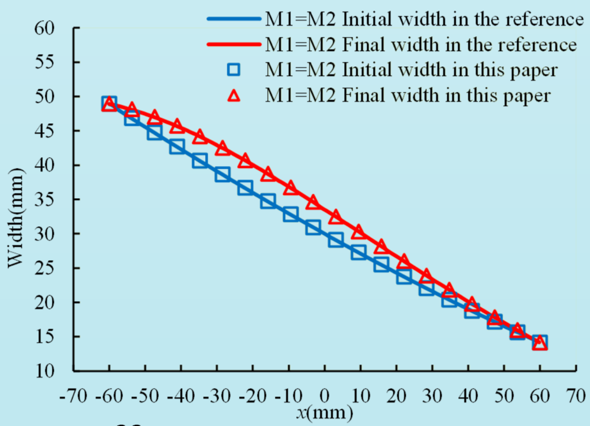
The practical distribution is fitted by a ***polyline*** *for sake of the price.*

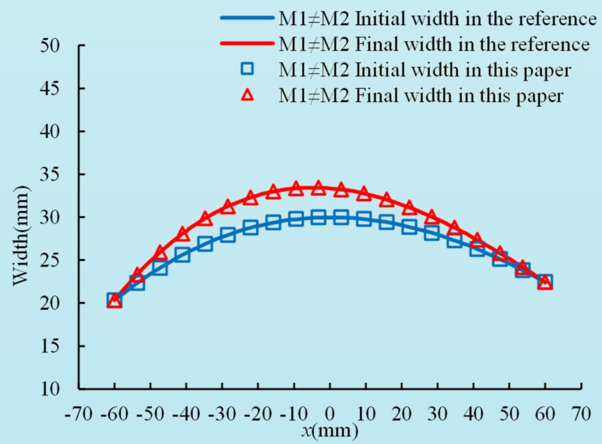


Design phase

- **Method***

  - *Validity*





The initial width and the final width are **well in coincidence** *with the reference for M1=M2 or M1≠M2.*

  - *Efficiency*

Iteration number	Residual slope error (nrad)	
	M_1=k•M_2, k=1	
	This paper	*Reference paper*
Initial width	*5.31×10^4*	*5.31×10^4*
1st iteration	*5.39×10^2*	*4.29×10^3*
2nd iteration	*46.68*	*3.79×10^2*
3rd iteration	*0.75*	*33.60*
4th iteration	*-*	*3.00*
5th iteration	*-*	*0.26*

Iteration number	Residual slope error (nrad)	
	M_1=k•M_2, k=0.2618	
	This paper	*Reference paper*
Initial width	*4.42×10^4*	*4.43×10^4*
1st iteration	*4.12×10^2*	*3.67×10^3*
2nd iteration	*20.91*	*3.25×10^2*
3rd iteration	*0.89*	*28.90*
4th iteration	*-*	*2.60*
5th iteration	*-*	*0.23*

The efficiency of the iteration of the solution is around **2 higher** *than the normal method.*

** Minwei Chen, Lidan Gao, Weifan Sheng, Peng Liu, Fugui Yang, Shaofeng Wang, Ming Li, "Efficient method on the determination of optimized width of bendable mirrors with gravity compensation", Results in Optics, 2021, 5, 100141.*

Design phase

- **Parameters**

Parameter name	Unit	Value
Active area	mm^2	605×20
Reflection direction	-	Face-down
Bent shape	-	Cylinder
Tangential slope error	μrad (RMS)	0.3
Object	m	∞
Image	m	4.5
Incident angel	mrad	1.7

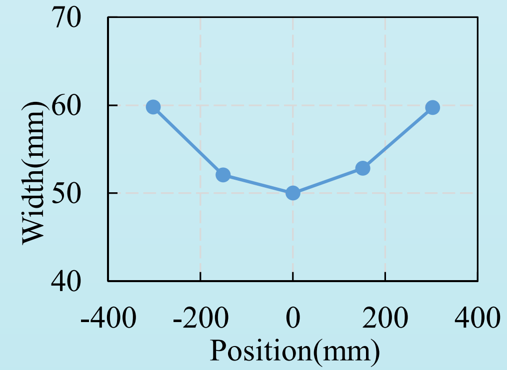
- **Design difficulties**
  - *Face-down reflection is a new challenge for us due to lacking of the experience;*
  - *The precision requirement is relatively high.*

Design phase

- **Results**

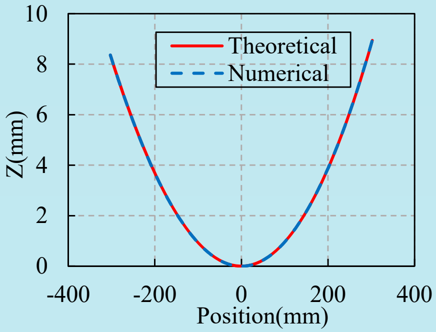
  - *Mirror width*

X(mm)	-302.5	-151.25	0	151.25	302.5
b(mm)	*59.78*	*52.07*	*50.00*	*52.81*	*59.73*

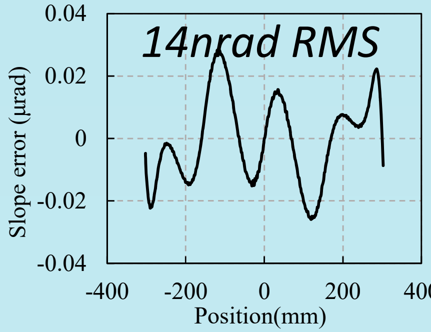


  - *Design error*

Height comparison



Slope error



Bent mirror	Theoretical	Material		
Item	Theory	Parameter %	Density uniformity ‰	E uniformity ‰
Requirement	Polyline	4.5	25.7	3.5
Slope error (nrad)	14	50	50	50

	Mechanism				Processing				
Item	Friction	Disp. resolution	Rolling	Yawing	Orientation	Shape μm	Height μm	Height uniformity μm	Parallelism μm
Requirement	*<1*	*81*	*25′*	*45′*	*3°*	*50*	*100*	*30*	*100*
Slope error (nrad)	*15*	*20*	*5*		42	14	7	25	11
Total error (nrad)	108								

  - *Manufacture error*

This error is equal to required error minus design total error.

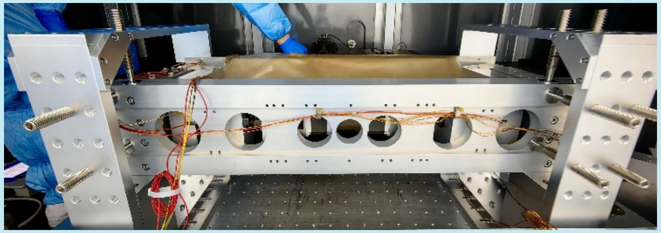
The suggested manufacture error is less than 0.2 μrad rms.

Outline

Off-line test phase

- **Test preparation**

  - *Component*



Bent mirror *Bender and horizontal LTP* *Sleeve with MoS_2 coating*

  - *Difficulties*

The reflection direction in the test **condition is different** *from that in the practical direction;*

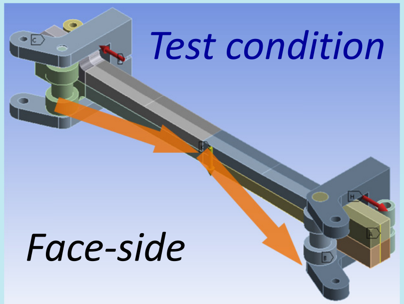
The results obtained by LTP must be superposed by the mirror **gravity**;

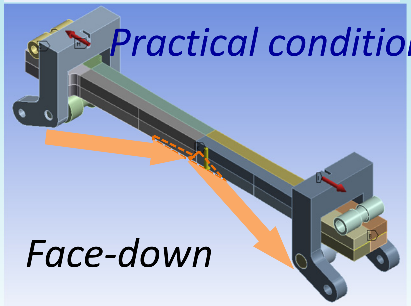
How to **adjust the actuator** *to reach the desired shape.*

  - *Solutions*

Consider the influence of the **gravity**;

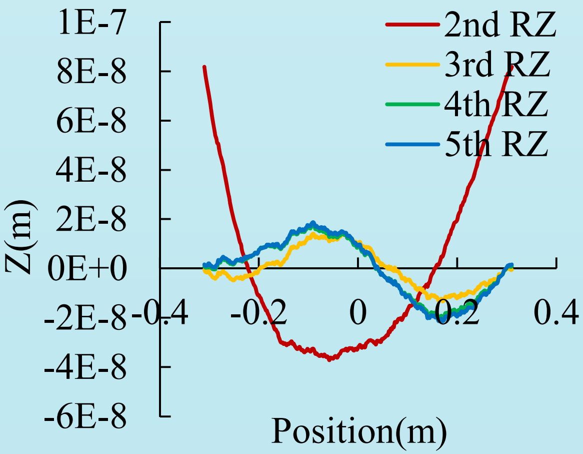
Iterate *between the inspection results and the numerical results.*

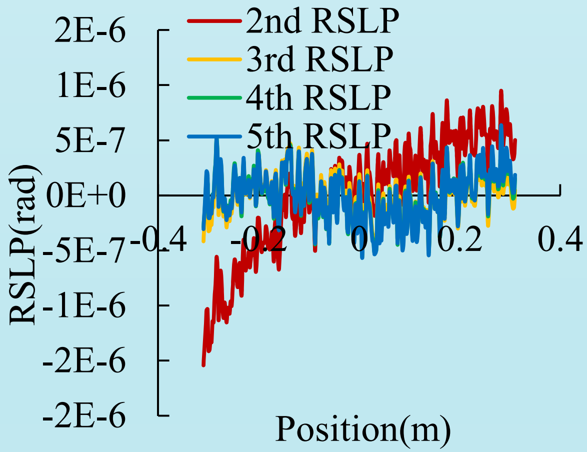




Off-line test phase

- **Test results**
  - *Height error and slope error*





Iteration number	Height error rms [nm]	Slope error rms [µrad]
1	*3310*	*27.0*
2	*47.7*	*0.63*
3	*13.2*	*0.28*
4	*14.4*	*0.25*
5	*12.1*	*0.22*

The height error and slope error both decrease as the the iteration number increasing; 4 or 5 iterations are enough to meet the requirement. The final slope error is converged to about 0.2 µrad rms, which exceeds the anticipation;

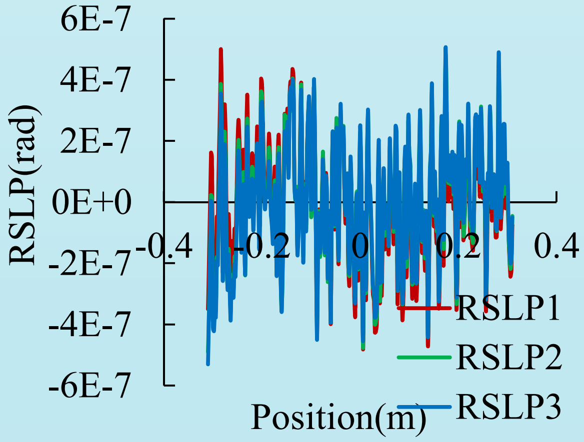
The result includes the error of the manufacture, bent mirror, mechanism and others, so the final error is good and acceptable.

Off-line test phase

- **Test results**

  - *Repeatability*

Number	Height error rms [nm]	Slope error rms [μrad]
1	*12.1*	*0.22*
2	*10.6*	*0.22*
3	*10.4*	*0.23*

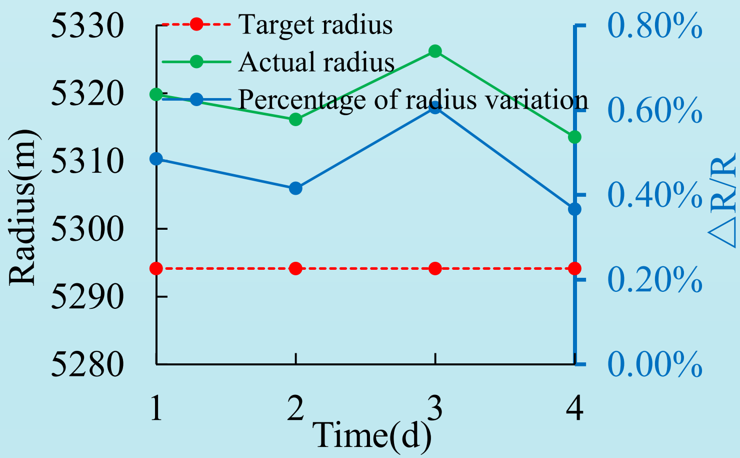


Test method: Release the force of the actuator, then reload the pervious value.

Results: The height error varies a little while the slope error nearly maintains the first value. Thus, the repeatability of the whole system is very good.

Off-line test phase

- **Test results**
  - *Stability*



Red dotted line: Target radius

Green solid line: Actual radius

Blue solid line: Percentage of radius variation

Evaluation criterion: The ratio of the variation of the curvature radius to the target radius, ΔR/R;

The test period lasts about 4 days. The interval of the actual curvature radius locates in about 5320m and the parameter ΔR/R corresponds to around 0.5%.

The stability is also acceptable for us.

Outline

Conclusion

The topic is related to the performance of the bent mirror system from design to off-line test. The detail is embodied in the followings.

- **Design phase**
  - *The method we use is not only proved to be correct but also to be efficient;*
  - *In the process of design, we consider lots of factors influencing the bent precision, such as theory, material, processing, mechanism and manufacture. All the errors summed meet the requirement.*
- **Off-line test phase**
  - *We solve the problem of the difference between the test condition and the practical condition after superposing the effect of the gravity;*
  - *After 4 or 5 iterations are enough to meet the requirement, and the slope error is converged to about 0.2 μrad rms that exceeds our expectation;*
  - *Repeatability and stability of the system are also been measured. From the view of the height error and the slope error, these parameters are verified to be excellent and acceptable.*

Thanks for your attention!

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