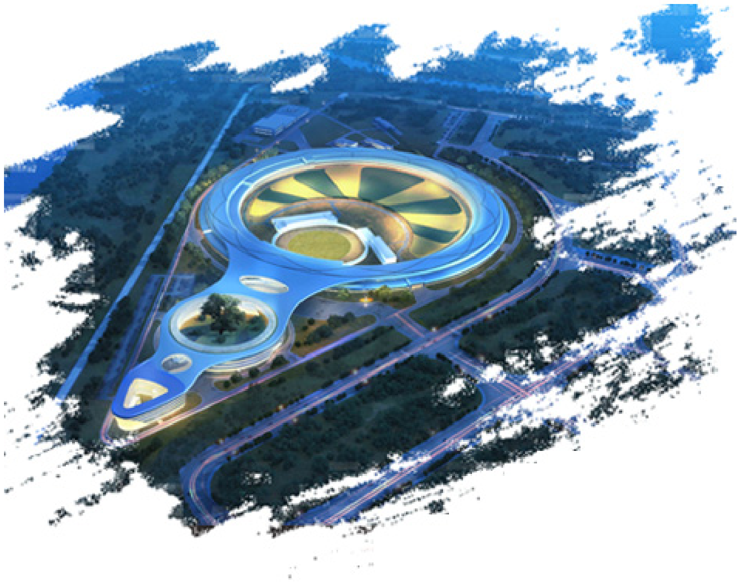
12th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI2023)

Thermal-deformation based X-ray active mirror development: Modulation and Metrology



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Institute of High Energy Physics

Nov. 7, 2023

Outline

1. BACKGROUND

① Fourth generation sources, diffraction-limited sources

② Challenges in beamlines

③ Final solution: active optics

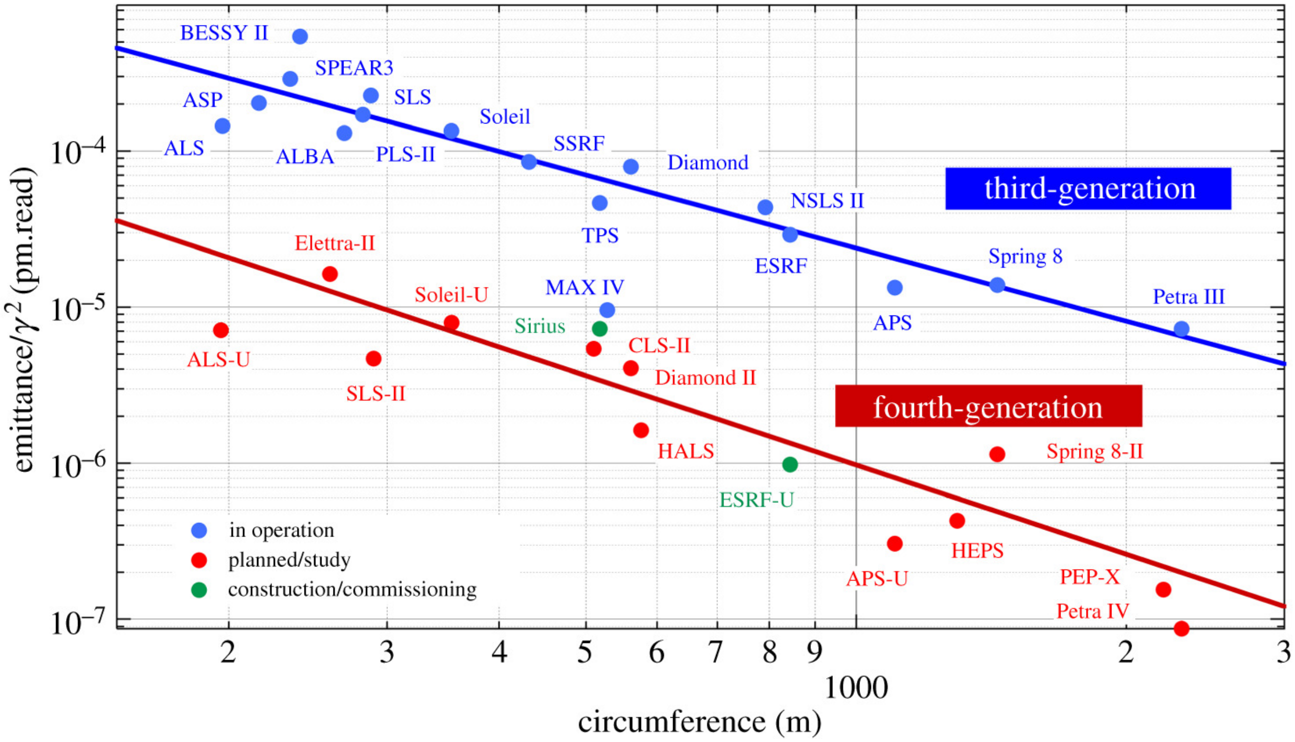
New Era for Large X-ray Source

The quest for more brilliance and coherence to the benefit of Science

- MAX IV Laboratory since 2016
- Accelerator: 7-BA, 20 periods
- 3 GeV Ring, Emittances: 339.4 pm rad

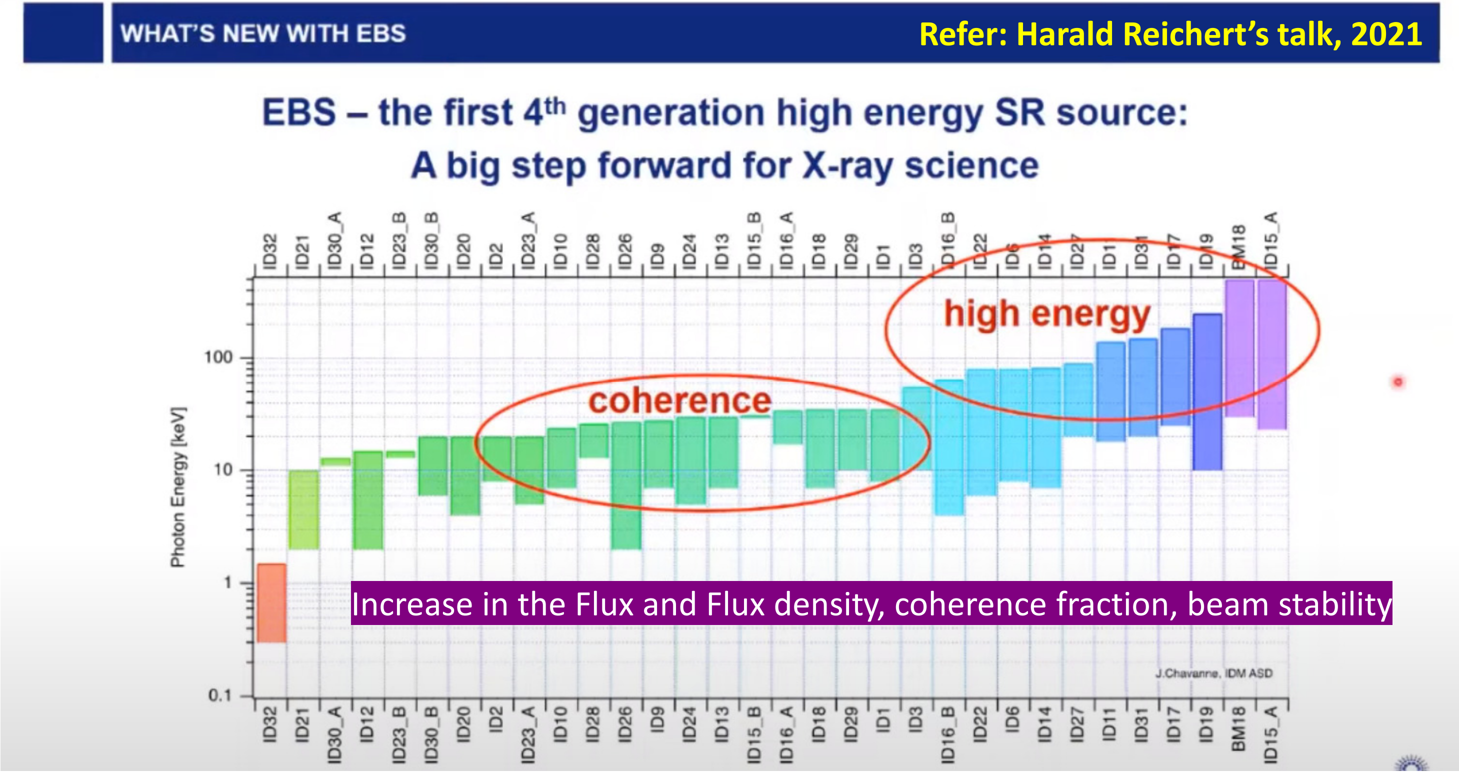
- EBS since 2020
- Accelerator: H-7-BA lattice design
- 6 GeV Ring, Emittances: 110 pm rad

New Era for Large X-ray Source

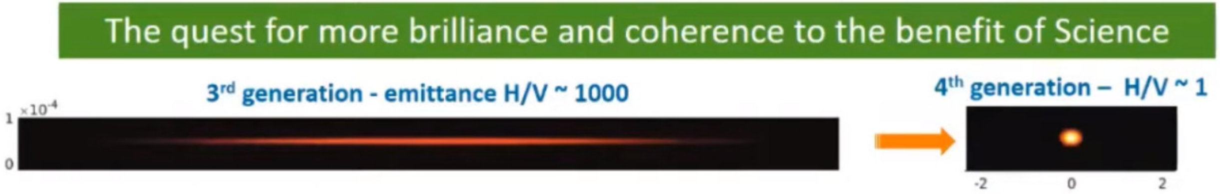


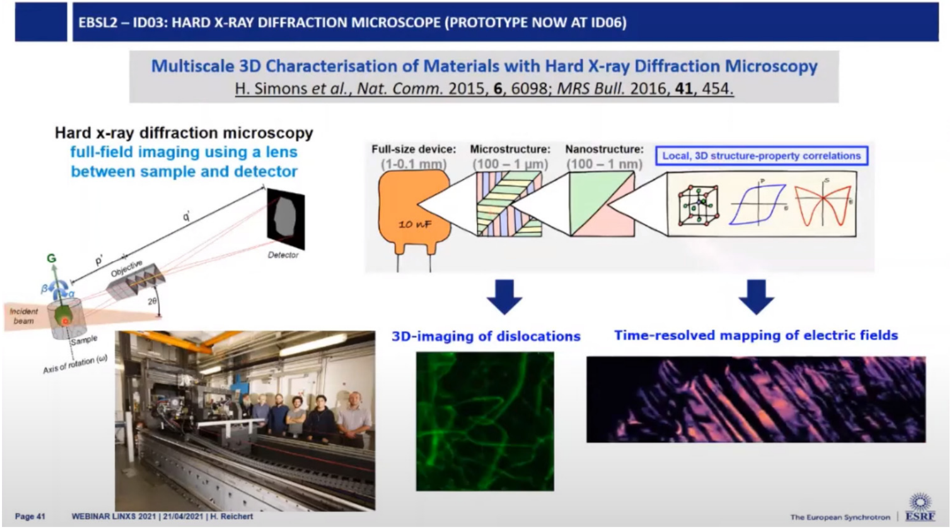
Reference: Liu L., Neuenschwander R. T. and Rodrigues A. R. D. 2019Synchrotron radiation sources in Brazil, Phil. Trans. R. Soc. A.3772018023520180235

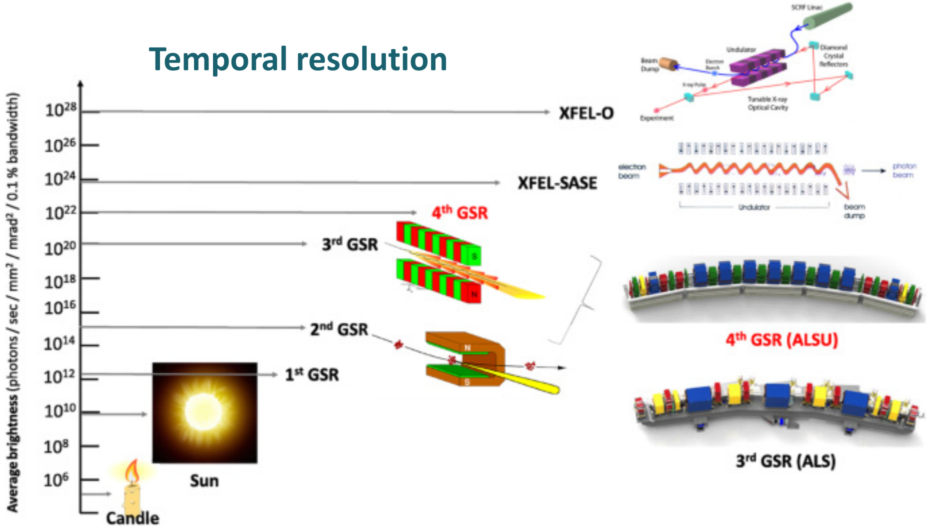
What is new with advanced light sources



Fourth generation source should be excellent







Fourth generation source should be excellent?

翻译：作为一个光源的建设者，我们需要问自己这么一个问题？

作为高能物理领域的一名研究人员，特别是在X射线光学方面的研究，您提出的问题非常重要。作为光源的建设者，我们需要不断审视和探讨以下问题：

1. 光源的性能需求：我们需要明确定义所需的X射线光源性能，包括波长范围、亮度、脉冲宽度等。这将直接影响实验的可行性和成果。
2.

CHAT- GPT told us, people in this meeting are very important !

3. 数值模拟和优化：借助数值模拟工具，您可以模拟光源的性能，优化光学系统，甚至进行虚拟实验。这有助于减少实际试验的成本和时间。
4. 机械设计和制造：光学仪器的机械设计需要考虑稳定性、精密度和环境因素。合适的机械结构对于确保光学系统的长期性能至关重要。
5. 自动化和人工智能：AI可以用于自动化实验控制、数据分析和优化过程。它在提高效率和提供实验结果的精确性方面发挥关键作用。
6. 实验验证：最终，您需要进行实验验证，以确保光源达到所需性能，并能够支持您的高能物理研究。

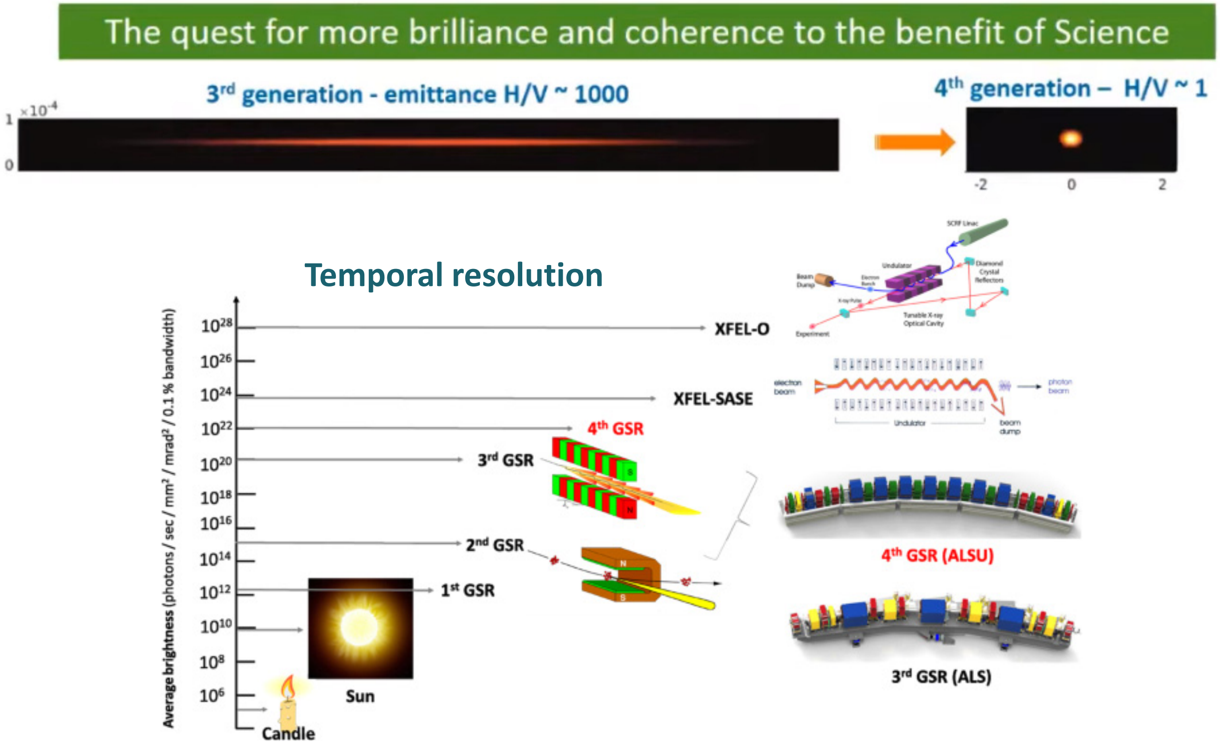
在您的研究中，不断关注这些问题并不断改进光源的设计和性能将对取得成功的实验和研究成果至关重要。 X射线光学是一个充满挑战的领域，但也充满了机会来推动科学的边界。

As a builder of light sources in the field of high-energy physics, particularly in X-ray optics, the question you've raised is of utmost importance. As light source developers, we need to continually examine and address the following questions:

- **Performance Requirements for the Light Source**: It is essential to precisely define the required performance of the X-ray light source, including wavelength range, brightness, pulse width, and other parameters. These specifications directly impact the feasibility and outcomes of experiments.
- **Optical Element Design**: The design of X-ray optical components is crucial. This encompasses the selection and optimization of lenses, reflectors, and other optical elements to ensure they meet the desired performance criteria.
- **Numerical Simulation and Optimization**: Utilizing numerical simulation tools allows ... d ... with
- **Mechanical Design and Manufacturing**: The mechanical design of optical instruments needs to consider stability, precision, and environmental factors. A suitable mechanical structure is crucial for ensuring the long-term performance of the optical system.
- **Automation and Artificial Intelligence**: AI can be employed for automating experiment control, data analysis, and optimization processes. It plays a crucial role in enhancing efficiency and ensuring the precision of experimental results.
- **Experimental Validation**: Ultimately, you need to carry out experimental validation to ensure that the light source meets the required performance and can support your high-energy physics research.

In your research, staying attentive to these questions and continually improving the design and performance of the light source will be vital for achieving successful experiments and research outcomes. X-ray optics is a challenging field, but it also offers opportunities to push the boundaries of science.

Fourth generation source should be excellent



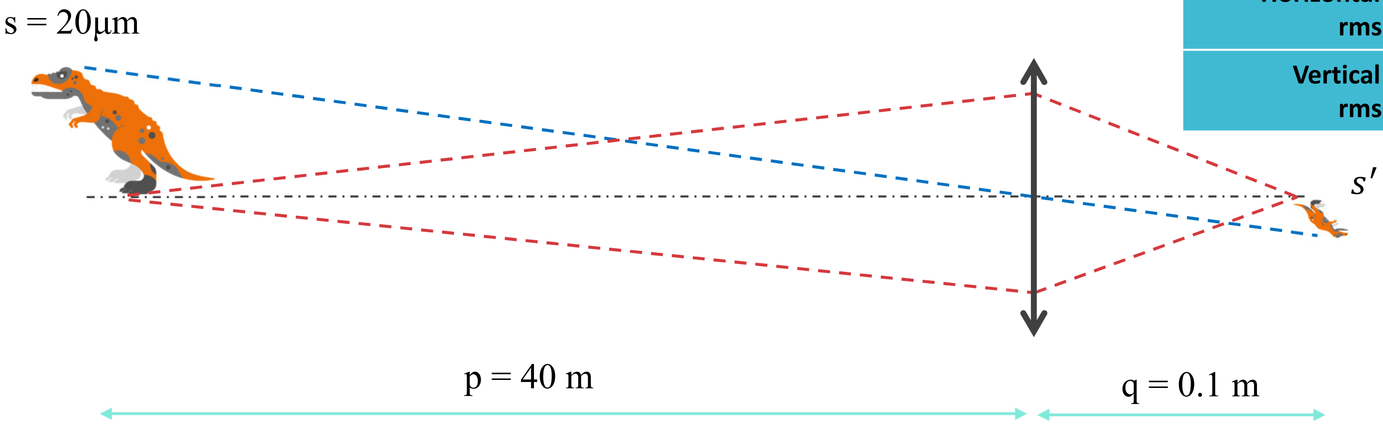
Taking HEPS for an example

1990s
ESRF\Spring-8\APS

2015 - now
EBS\APS-U\HEPS
\Spring-8 II
\PETRA-IV

Taking HEPS for an example

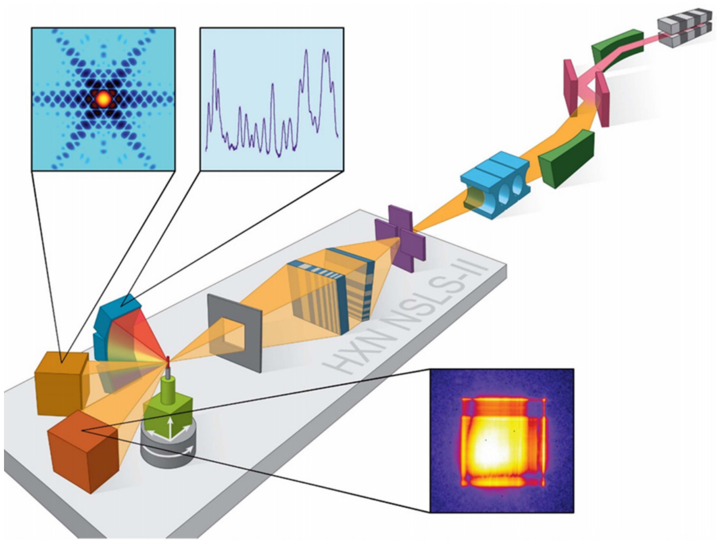
Beamlines	B4 @HEPS	P02 @PETRA-III
Horizontal Source size rms (μm)	10.0	141
Vertical Source size rms (μm)	5.2	6.0
Horizontal Diver. rms(μrad)	5.5	9.1
Vertical Diver. rms(μrad)	4.7	6.1



$$s' = s\frac{q}{p} = \mathbf{50\ nm}$$

It is very easy to achieve sub-micron spatial resolution in advanced sources with low-emittance theoretically.

Taking HEPS for an example



Hard X-Ray Nanoprobe (HXN) beamline @ NSLS-II,
Courtesy: Yan, Nano Futures (2018)

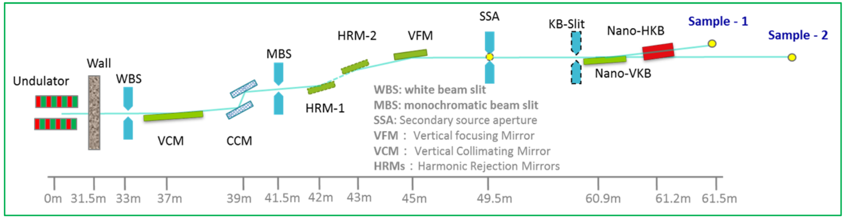
However, the real beamline is not so simple:

- Function: imaging, scattering, spectroscopy(energy scanning), diffraction, zooming spot
- Performance: large energy range, spatial resolution,

System setup includes:

- Source: Undulator, wiggler, bend magnet;
- Transport Optics: mirrors, monochromator, lens
- Sample: detector

Taking HEPS for an example



- **The focal spot size**

where,

$$\delta_{real} = \sqrt{\delta'^2_{ideal} + \delta'^2_{error}}$$

$$\delta'_{ideal} = s * M$$

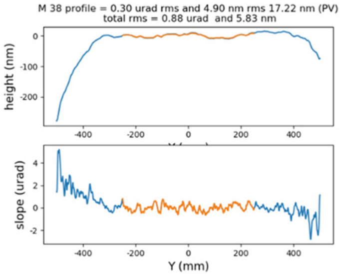
$$\delta'_{error} = q * Function(error)$$

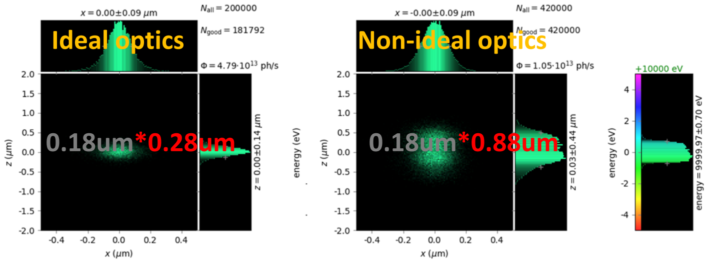
$$\delta_{real} = \sqrt{\delta^2_{ideal} + \delta^2_{diffraction} + \delta^2_{instability} + \delta^2_{shape\ error} + \delta^2_{heat\ load} + \delta^2_{alignment} + \delta^2_{chromat} + \cdots}$$

- The magnification M is not a problem even for sub-micron spot in HEPS

$$\delta_{real} = \sqrt{\delta'^2_{ideal} + \delta'^2_{error}} \sim \delta'_{error} \qquad \delta'_{error} = q * Function(error)$$

- **The performance of the system is affected by selection of optics (error) and the beamline design (q).**

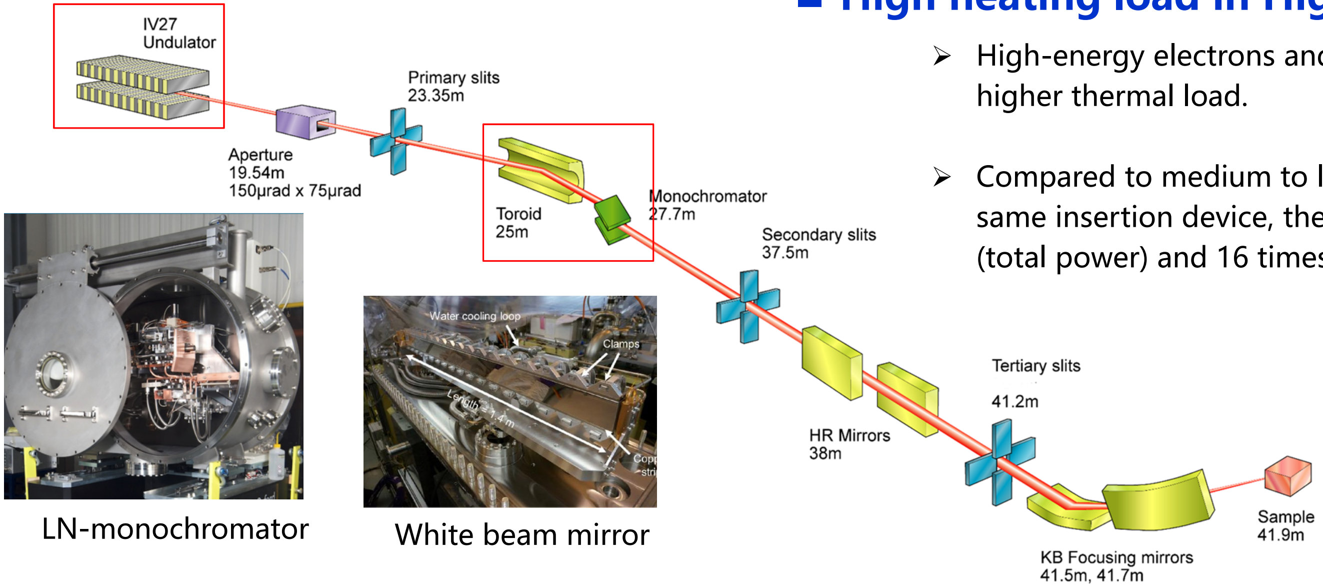




Taking HEPS for an example

■ High heating load in High energy source

- ➢ High-energy electrons and a high X-ray flux introduce a higher thermal load.
- ➢ Compared to medium to low-energy light sources, for the same insertion device, the thermal load issue is 4 times (total power) and 16 times greater (power density)



$$P[\mathrm{kW}] = 0.633 E^2[\mathrm{GeV}] \hat{B}^2[\mathrm{T}] L[\mathrm{m}] I[\mathrm{A}]$$

$$\frac{dP}{d\Omega}(0,0)[\mathrm{W/mrad^2}] = 10.84 \hat{B}[\mathrm{T}] E^4[\mathrm{GeV}] I[\mathrm{A}] N G(K)$$

LN-monochromator

White beam mirror

✓ **High Flux**： long ID N^2 、**High energy** E^2

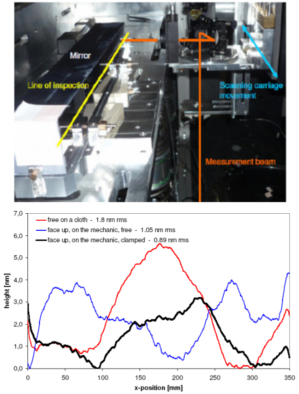
☐ **Heating load**： Long ID N-L、 High Energy E^4 - power density E^2 - total power

Taking HEPS for an example

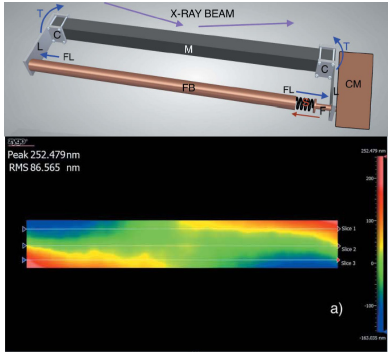
- Fabrication high quality X-ray optics(CRL\mirror\crystal) is not easy.
  - For mirror, only few venders can provide, but mass order around world
  - Key: Metrology and Fabrication
- Instrument integration: bender\mount\clamping\cooling

Static

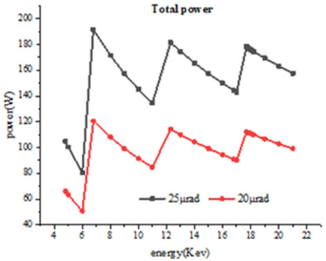
Dynamic

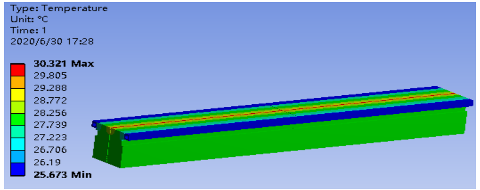


(Siewert, OE, 2012)



(Vannoni, JSR, 2016)



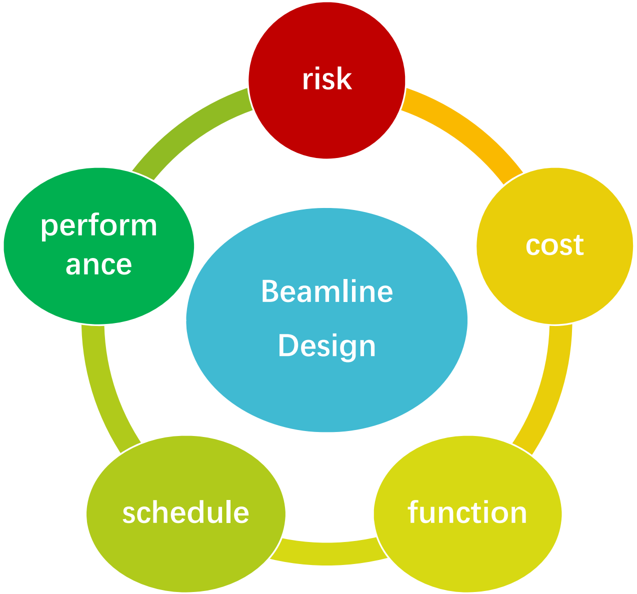


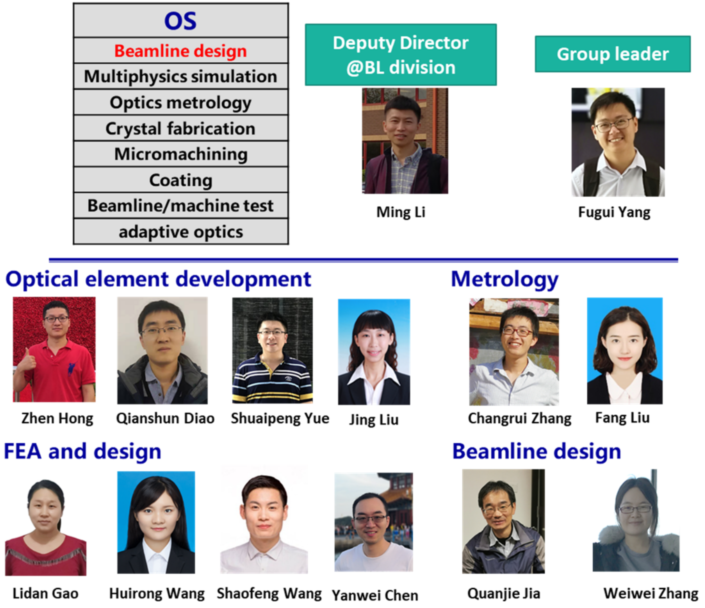
The challenges of the beamline is universal

光源与光束线建模 *Modeling partial coherence, optimizing design, and setting tolerances*	**source**
光学器件工艺 *Can a limited number of vendors meet worldwide demand?*	
热负载器件 *Can mirrors preserve wavefront quality under varying high power densities?*	**Optics devices and instruments**
X射线主动光学 Can stable, fast AXOs compensate the wavefront errors we expect ?	
器件污染 *Can we preserve mirror surface quality, and keep mirrors clean?*	
稳定性和准直 *Can mirrors be held to nanometers* and nrad *over time?*	
离线检测 *Can it keep up with demands for speed and accuracy?*	**Metrology and commissioning**
波前传感 Can we provide accurate feedback for adaptive correction in real time ?	
X射线监测与反馈 Can we adequately monitor the beam position and give feedback?	

6th DLSR Workshop, LBNL, October 2018
From Point view of OPTICS

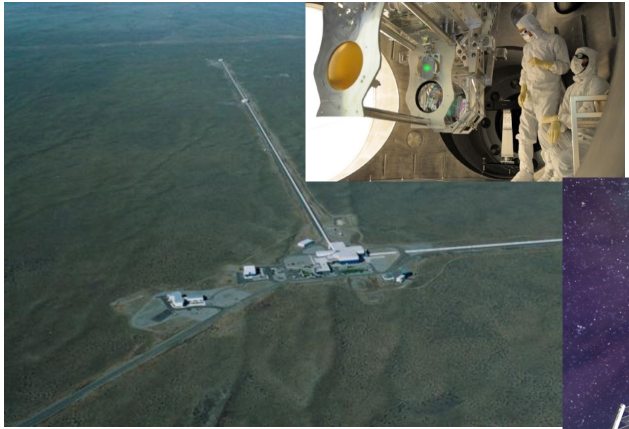
We have done something



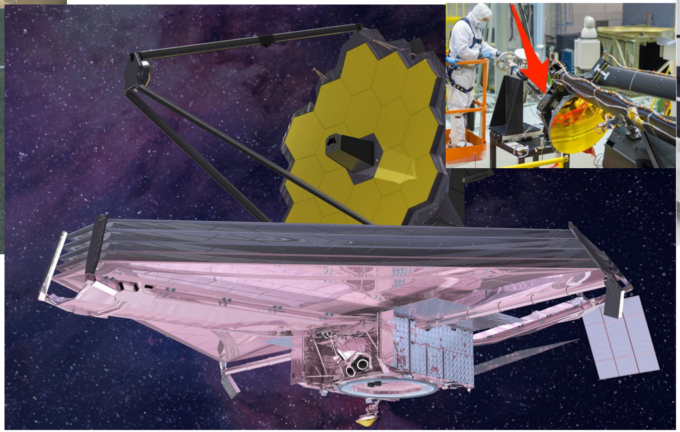


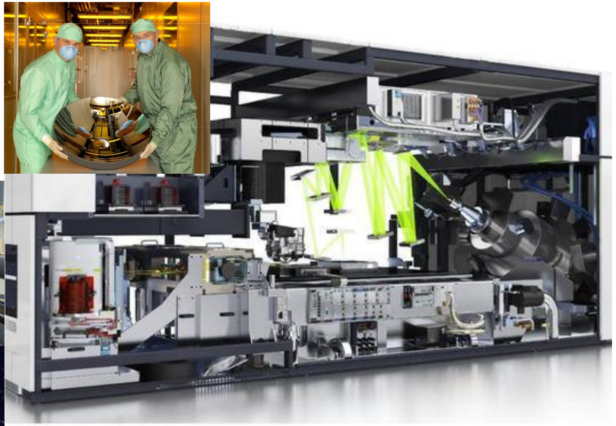
In the past several years, we dedicated ourself to serve for the physical design for beamlines and their instruments.

The challenges of the beamline is universal



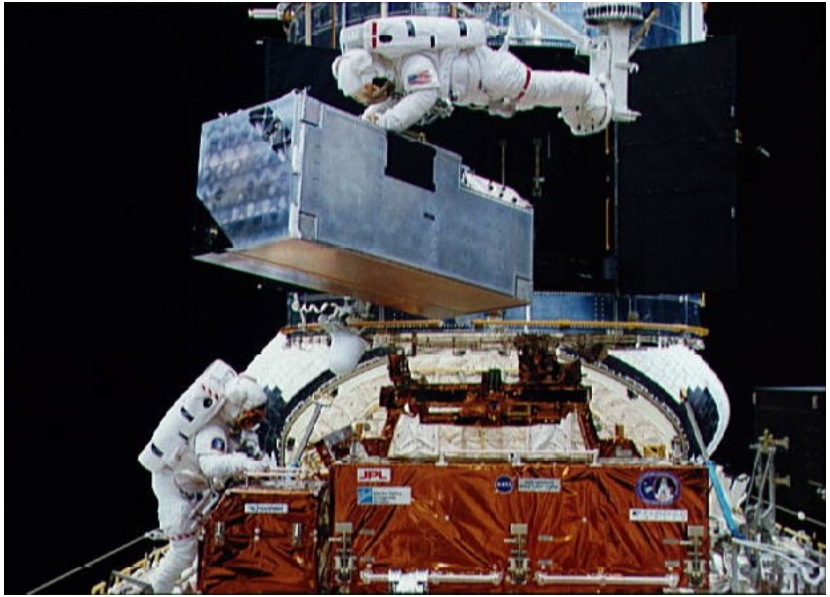
source - optics - detector





Fourth generation Facilities are precision optical systems

We conclude, active optics is ultimate solution!

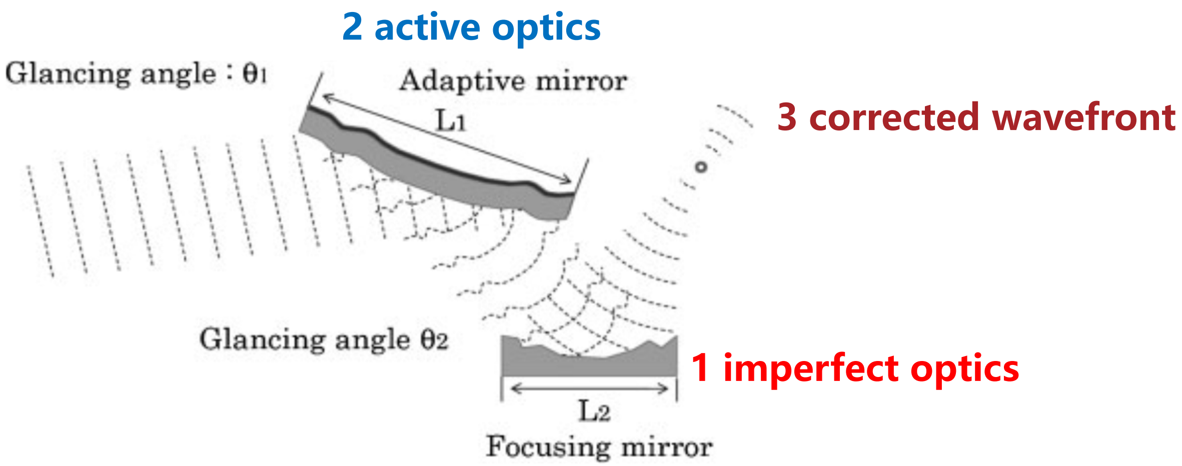


The **Corrective Optics Space Telescope** Axial Replacement (COSTAR) instrument for Hubble space telescope

If we admit it, then: active optics is the ultimate solution for engineering problem

We conclude, active optics is ultimate solution!

X-ray Wavefront Correction Scheme



In fact, the x-ray active optics has a long history

Invited Paper

R&D PROGRAM ON BIMORPH MIRRORS AT THE ESRF

J. Susini, D. Labergerie, and O. Hignette

European Synchrotron Radiation Facility,
BP 220, F-38043, Grenoble Cedex, France

ABSTRACT

The very low emittance of new synchrotron sources and the increasing number of micro-focussing applications make the production of highly stable and well defined beams increasingly necessary. The use of flexible mirrors whose curvature can be changed while maintaining a correct figure appeared to be a very attractive solution. For over two years, the ESRF has been developing a new approach which consists of making an X-ray mirror from an active material such as piezoelectric ceramics. With respect to conventional bender this concept, already used in astronomical and laser applications, has the advantages to be mechanics free, very compact and relatively cost effective. This paper presents the status of the ESRF's developments in this field. First, theoretical and technical descriptions of the system are given. Experimental tests of various configurations confirmed the potential of this concept. For example, two 150mm long bimorph mirrors set into a Kirkpatrick-Baez geometry gave a focused spot of 10µm (vertical) x 20µm (horizontal). Finally, the developments of in-situ control systems (strain gauges, optical devices), necessary to fully exploit the capabilities of these active optics, are discussed.

keywords: X-ray mirror, bimorph, piezoelectric materials, focussing optics, active mirrors, mirror benders.

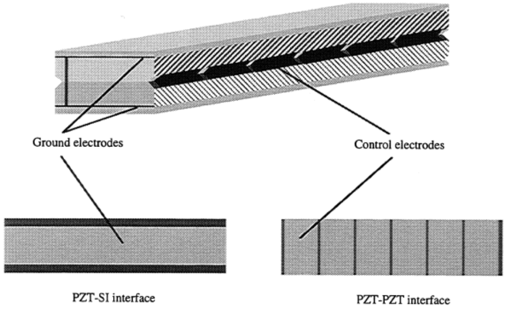


Figure 6 : New design of a 6-electrode bimorph mirror (see text for details)

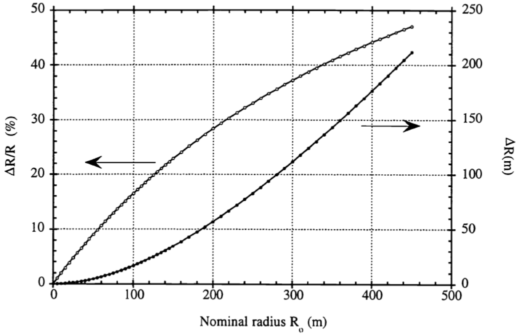


Figure 12 : Tuneability of the Radii of curvature of a curved polished bimorph for an arbitrary voltage of 1000V. The bimorph dimensions are 150x40x16mm^3.

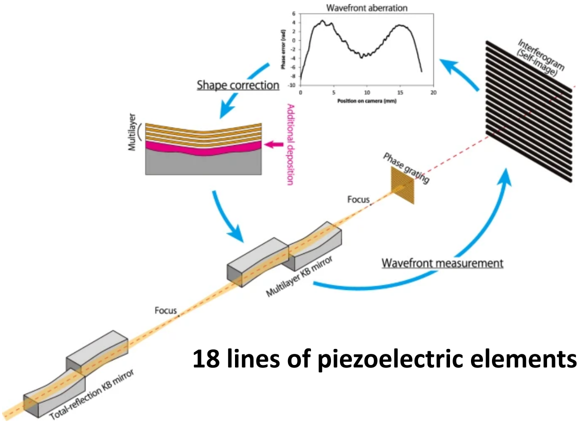
Reference: Susini J, Labergerie D R, Hignette O. R&D program on bimorph mirrors at the ESRF[C]//Optics for High-Brightness Synchrotron Radiation Beamlines II. SPIE, 1996, 2856: 130-144.

The performance is promising!

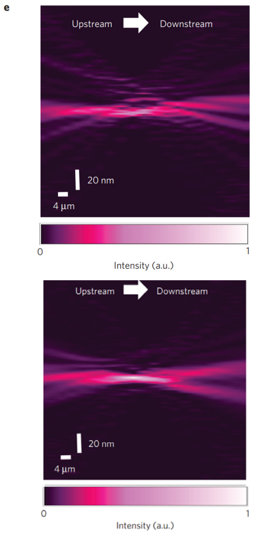
LETTERS
PUBLISHED ONLINE: 22 NOVEMBER 2009 | DOI: 10.1038/NPHYS1457
nature physics

Breaking the 10 nm barrier in hard-X-ray focusing

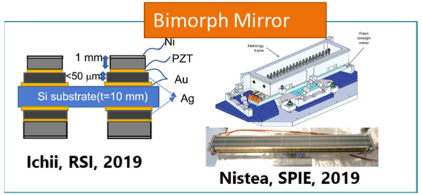
Hidekazu Mimura[1]*, Soichiro Handa[1], Takashi Kimura[1], Hirokatsu Yumoto[2], Daisuke Yamakawa[1], Hikaru Yokoyama[1], Satoshi Matsuyama[1], Kouji Inagaki[1], Kazuya Yamamura[3], Yasuhisa Sano[1], Kenji Tamasaku[4], Yoshinori Nishino[4], Makina Yabashi[4], Tetsuya Ishikawa[4] and Kazuto Yamauchi[1,3]

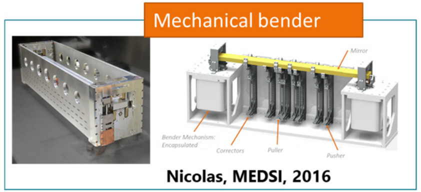


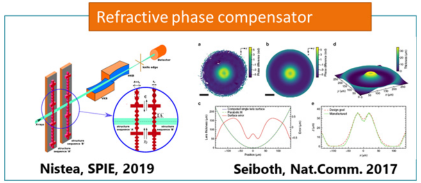
18 lines of piezoelectric elements

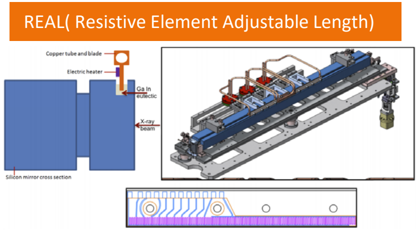


- There are several type of adaptive optics based on different effects, e.g. piezo-electric, mechanical, heating, and refractive









Diamond Light Source!

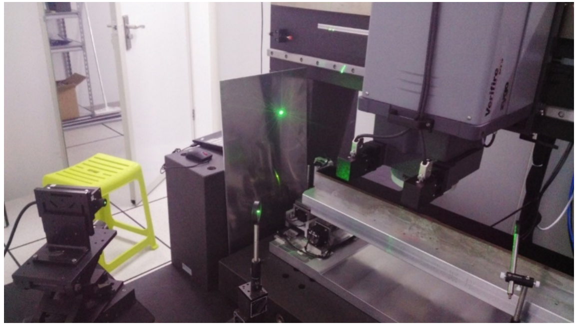
2. Surface Profile Modulation

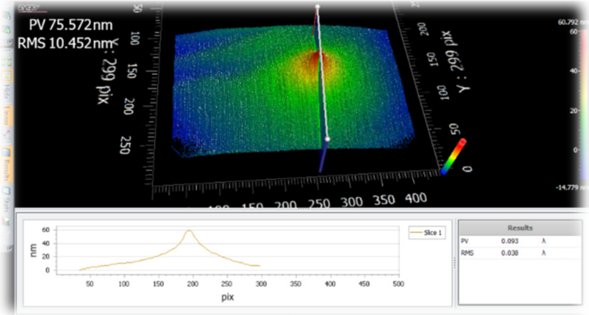
① Thermal heating performance verification

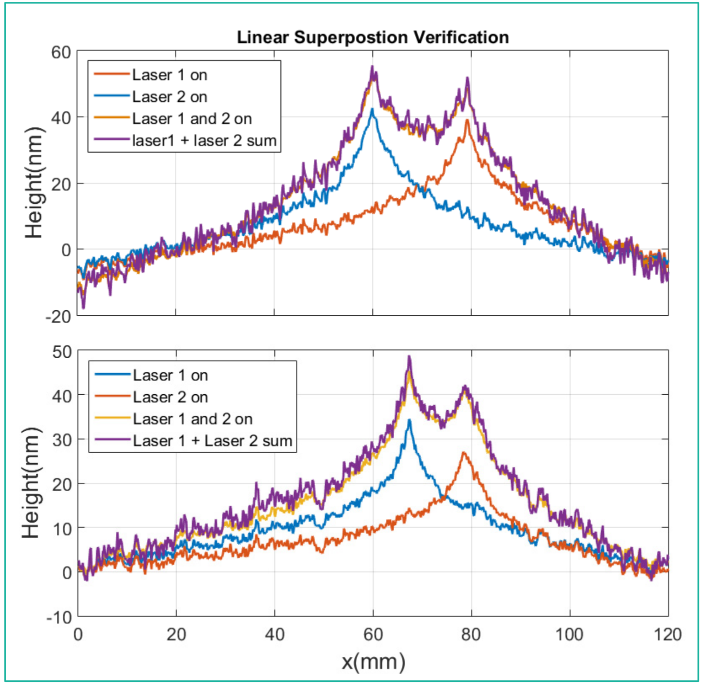
② Laser-heating scheme

③ Electric-heating scheme

Modulation Performance: linear superposition

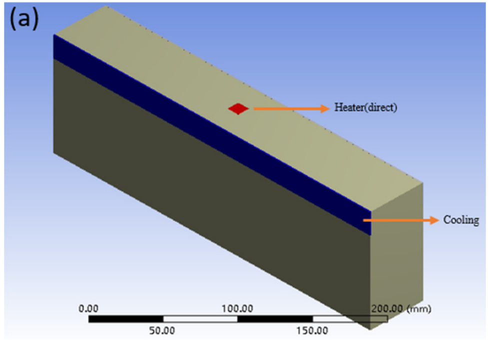




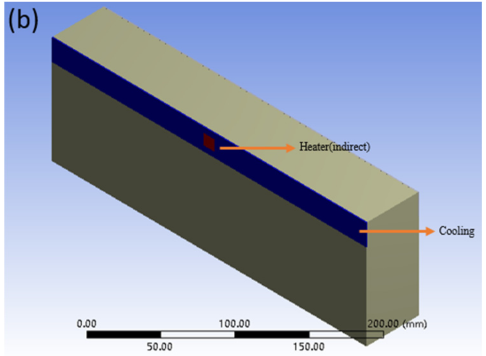


Through laser-heating measurement, the response is linear

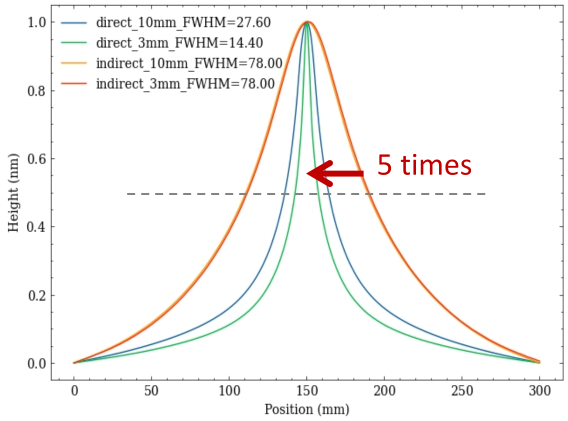
Modulation Performance: bandwidth and power



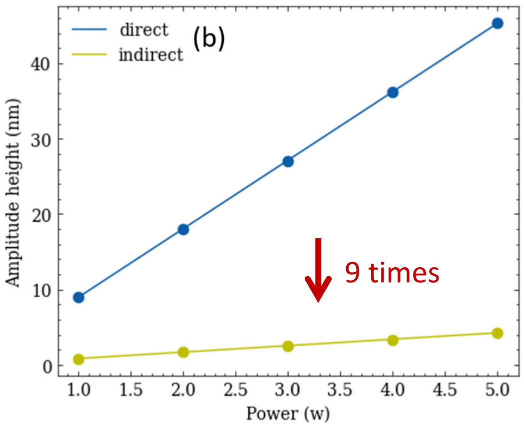
Surface-source-driving Scheme



Body-source-driving Scheme



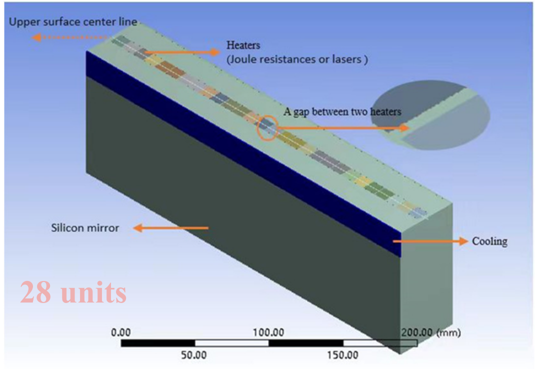
1. Width of the response comparison



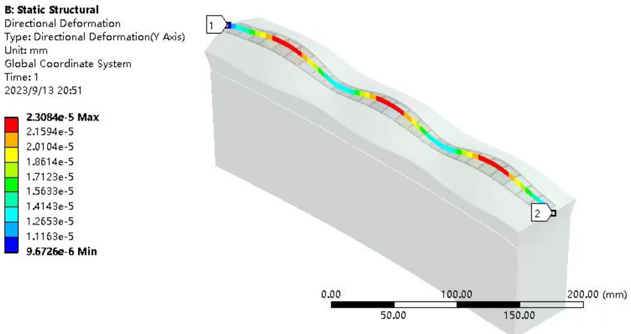
2. Driving power consumed

The surface driving feature has improved the modulation performance, including spatial bandwidth and efficiency.

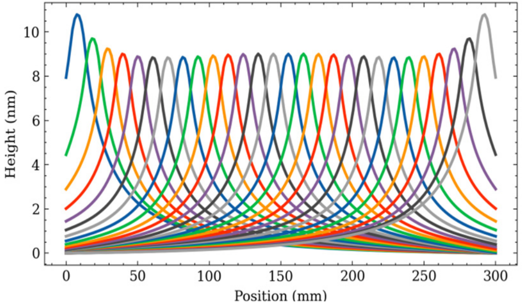
Modulation Performance: modulation



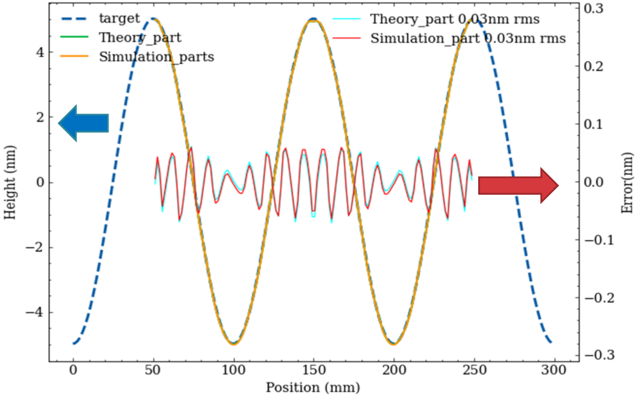
FEA model



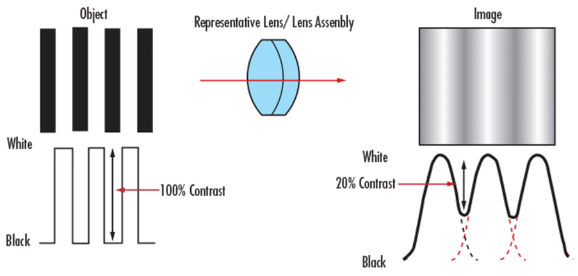
FEA results

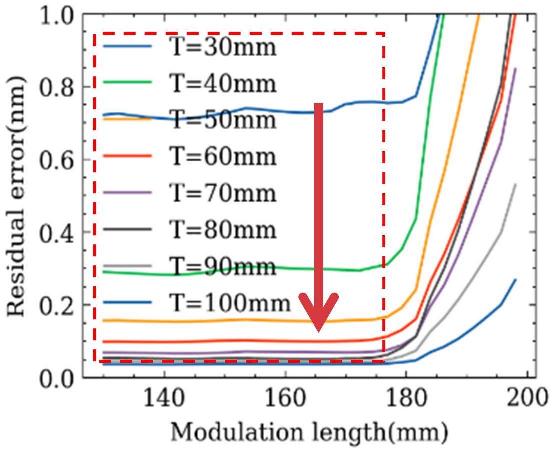


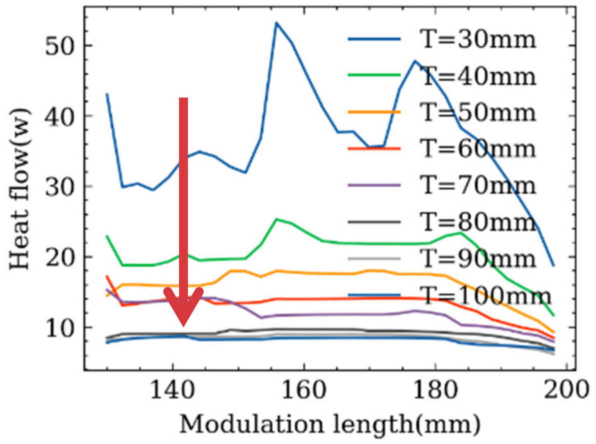
Response functions



Modulation Performance: modulation





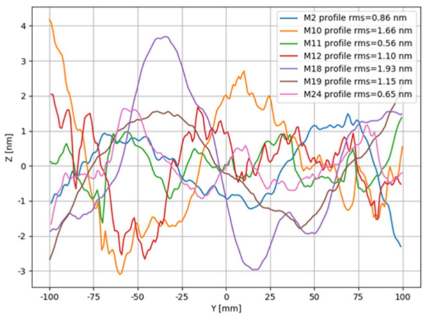


- Similar evaluation method used in optical imaging system

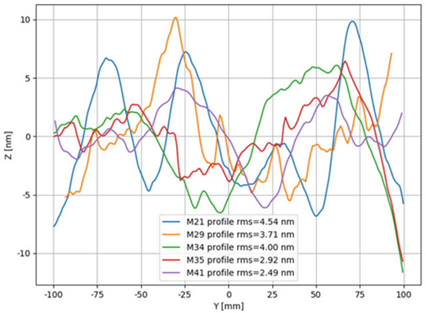
- **For target shape with different periods, the modulation performance has been proved.**
- **The low residual error and driving power can be achieved for low frequency error.**

Modulation Performance: mirror compensation

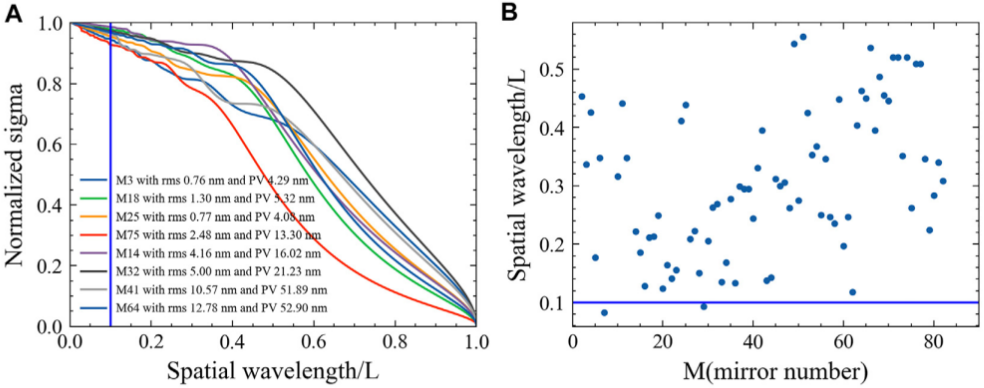
Good mirrors



Bad mirrors



Surface shape

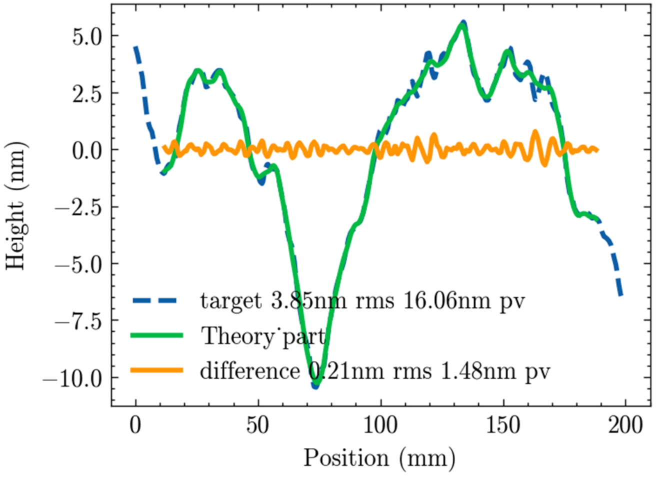


- **In our previous study, residual error at low spatial wavelength is shown to be the main contributor.**

  data from DABAM (Data Base for Metrology), ESRF

- Hu, W., Cui, X., Li, M., Sheng, W., Zhang, W., Jia, Q., & **Yang, F.** (2022). Study on the X-ray mirror quality specification in advanced light source. *Frontiers in Physics*, 801.

Modulation Performance: mirror compensation



Real mirror compensation example

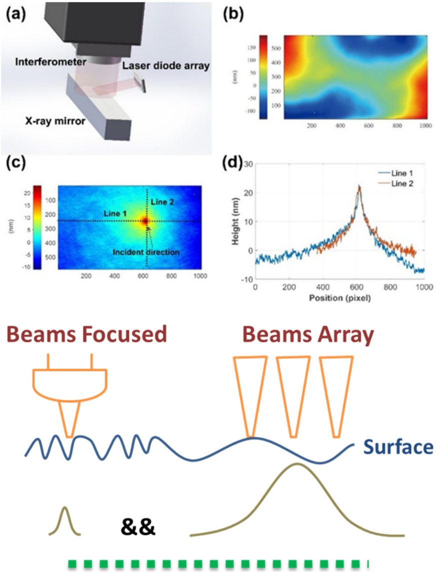
- **The fabrication error can be well compensated by the active optics, down to 0.5nm RMS**

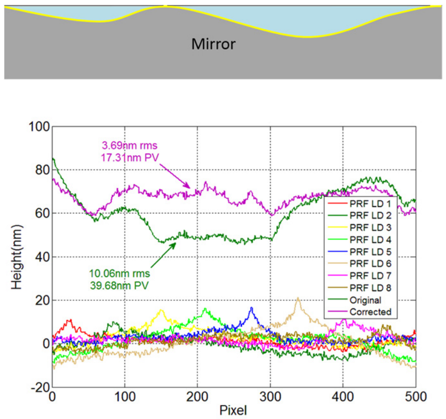
Mirror	length mm	Before correction		after correction		修正能力 rms比值	修正能力 PV比值	power
		rms	pv	rms	pv			
"16"	186	26.51	86.21	0.23	1.23	0.008676	0.014267	81.99
"17"	184	8.31	34.4	0.4	3.47	0.048135	0.100872	49.55
"18"	178	1.96	6.66	0.02	0.13	0.010204	0.01952	5.29
"19"	168	1.03	3.34	0.02	0.16	0.019417	0.047904	2.58
"22"	176	75.69	258.02	0.68	3.89	0.008984	0.015076	348.19
"25"	172	0.69	2.35	0.01	0.06	0.014493	0.025532	2.67
"26"	184	3.54	13.78	0.14	0.89	0.039548	0.064586	27.89
"27"	138	19.47	64.17	0.25	1.88	0.01284	0.029297	38.06
"28"	174	7.05	25.12	0.18	1.12	0.025532	0.044586	32.08
"30"	176	3.85	16.06	0.21	1.48	0.054545	0.092154	37.8
"31"	194	2.38	11.4	0.06	0.45	0.02521	0.039474	16.45
"32"	162	9.01	27.93	0.06	0.44	0.006659	0.015754	17.85
"33"	184	1.6	6.29	0.09	0.5	0.05625	0.079491	10.3
"34"	176	3.69	12.63	0.09	0.56	0.02439	0.044339	14.26
"36"	122	4.68	15.05	0.29	2.71	0.061966	0.180066	37.08
"37"	186	1.84	6.49	0.06	0.37	0.032609	0.057011	18.63
"38"	132	2.3	8.35	0.06	0.33	0.026087	0.039521	16.61
"39"	130	1.47	5.08	0.12	0.59	0.081633	0.116142	12.68
"40"	164	2	8.04	0.04	0.22	0.02	0.027363	15.45
"41"	148	2.79	10.25	0.1	0.58	0.035842	0.056585	94.3
"43"	192	6.8	24.84	0.12	1.22	0.017647	0.049114	62.65
"44"	174	15.72	63.87	0.16	0.73	0.010178	0.011429	130.97
"45"	190	1.68	7.97	0.04	0.26	0.02381	0.032622	8.93
"48"	152	1.05	4.1	0.04	0.2	0.038095	0.04878	7.89
"49"	186	2.65	10.16	0.24	1.9	0.090566	0.187008	27.88

Device-1: laser heating scheme

- **Laser-heating based deformable mirror**: it has been proposed in our lab.

(Fugui Yang, OL, 2016)





Advantages

★ Precise and real-time

★ High spatial resolution

★ Simple and low cost

But, Efficiency and safety for high power?

Device-2: electric heating scheme

① **Mirror layer**:
Reflect X-ray

② **Heater:** low resistance layer
Generate heat

③ **Substrate:** high resistance layer
Generate surface deformation

Thermal deformation – *X-ray mirror*

- **Mirror substrate material**
  - Figure of merit for thermal deformation: α / k
  - Other considerations: polishing quality, temperature, cost

Material	thermal expansion coefficient α 10^{-6}/°C	thermal conductivity k W/m/°C	figure of merit α/k 10^{-9} m/W	overall considerations
Aluminium	24	210	114	
Beryllium	11.5	216	53	
OFHC Copper	17	385	44	++
Invar	1.2	10	120	
Quartz (fused)	0.4	1.6	250	
SiC (CVD)	2.2	250	9	++
Silicon	2.6	148	18	+++

ThermoMechanics and applications
L. ZHANG, 1st edition on March 2011, Revised on March 2012

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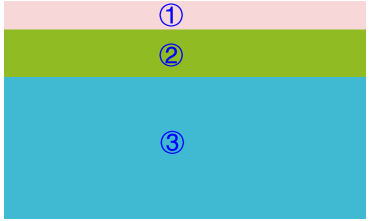
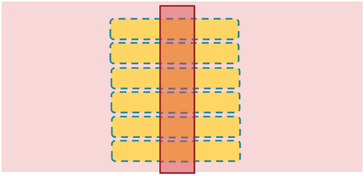
Side view



Top view



1. Material modification of Si substrate

Silicon Photonics

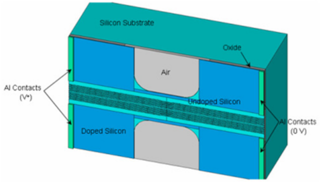
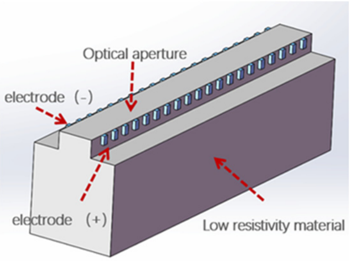


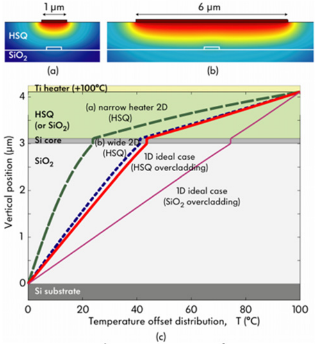
Fig. 4. Device design for thermo-optic device showing doped silicon (dark blue), undoped silicon (light blue), aluminum contacts (green), underlying oxide (dark gray) and air (light gray). Voltage applied across the device to drive current (device sectioned into four quadrants for ANSYS simulation).

(Tinker, OE, 2005)

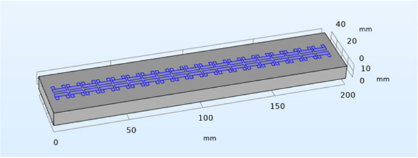


p/n-type doping in the top of the substrate

2. Thin film on the top of mirror

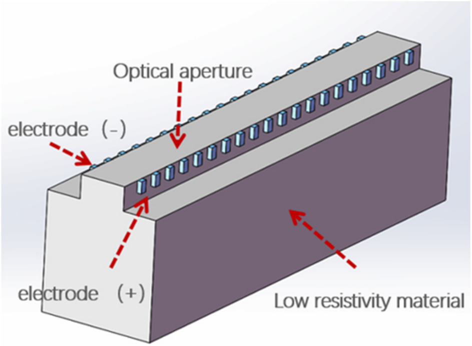


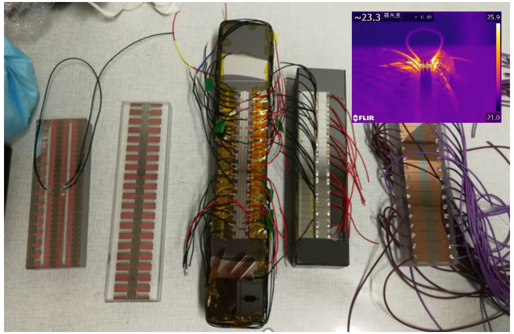
(Gan,2007)



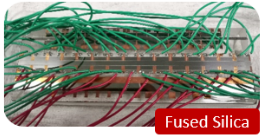
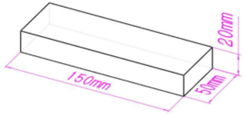
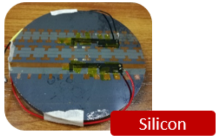
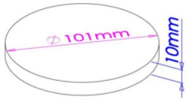
Coating film on the mirror

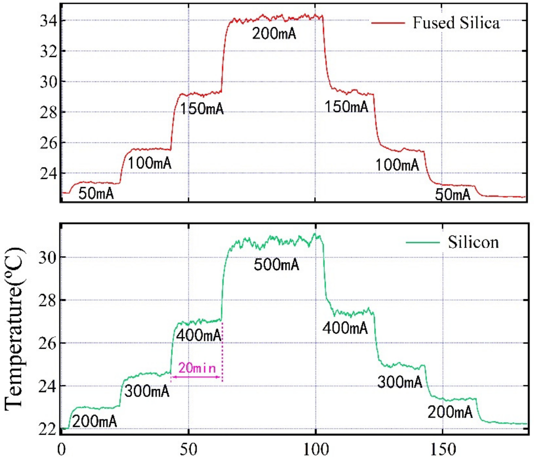
Preliminary Test:

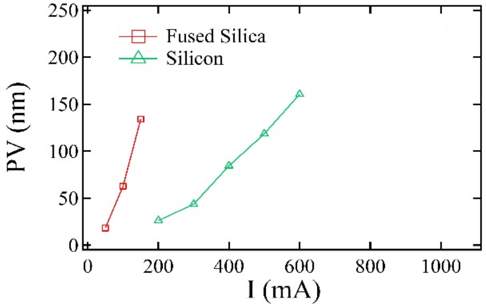




Samples (2020-now)

No.	Sample material and photos	Sample size
1	 Fused Silica	 150mm, 50mm, 20mm
2	 Silicon	 ϕ101mm, 10mm





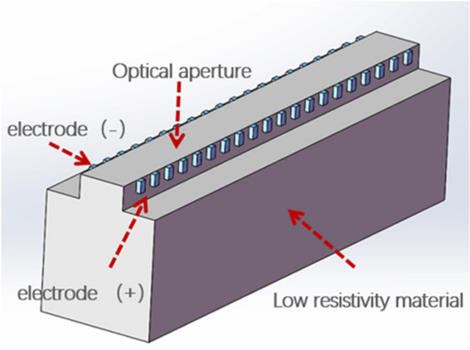
Comparison of samples' PV values

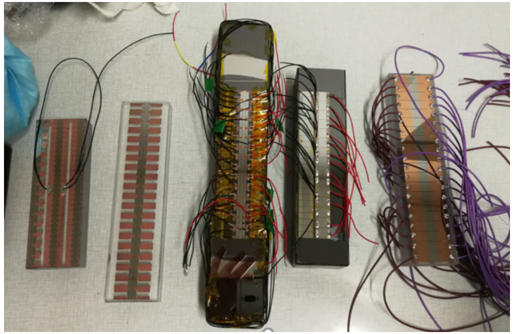
Absolute deformation:
Si < Fused Silica

In air, the stabilization time is about several minutes.

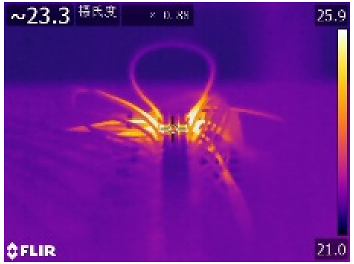
Preliminary Test:

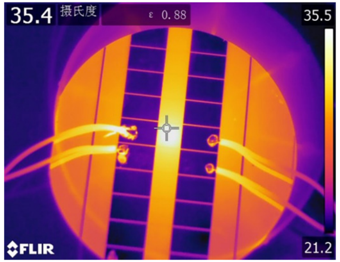
Collaboration with Le Kang and Zhijia Sun, Spallation Neutron Source Science Center, IHEP

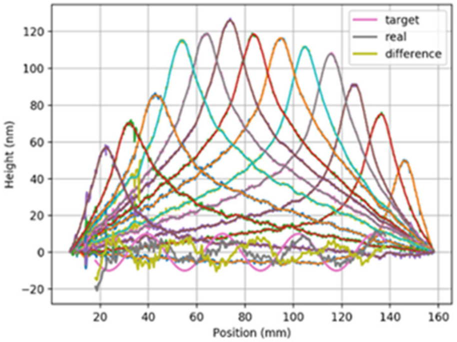


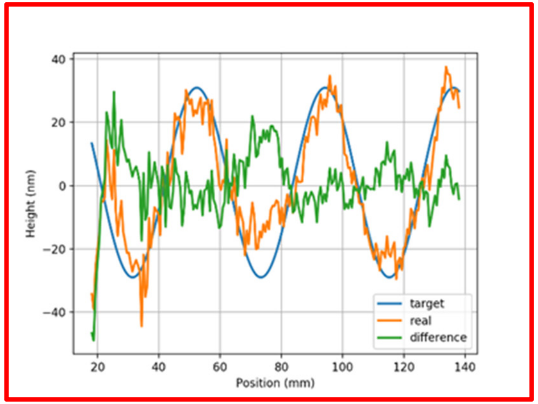


Samples (2020-now)









- **In experiment, the feasibility of the surface has been proved, but the measurement is not good.**

3. Surface Profile Metrology

① System development

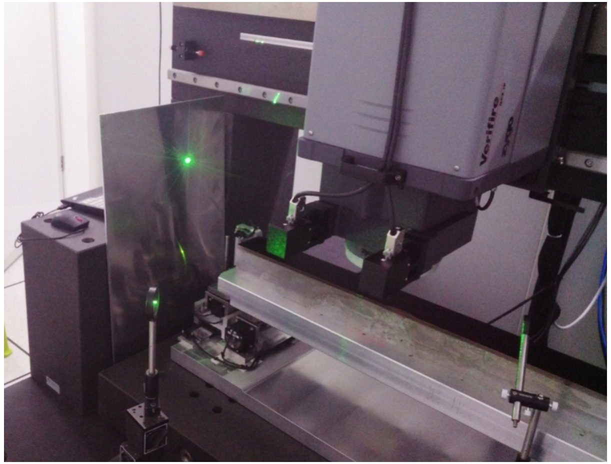
② Performance test

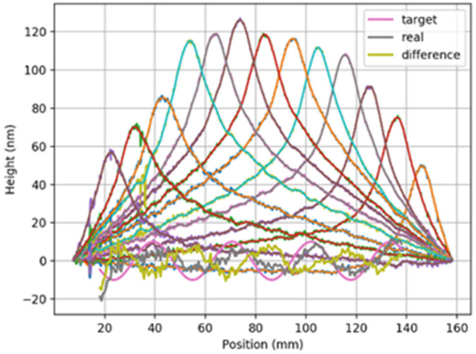
③ Ongoing experiment

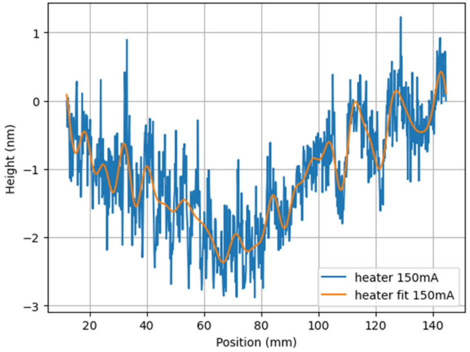
Metrology Issue:

□ Previous Interferometer measurements

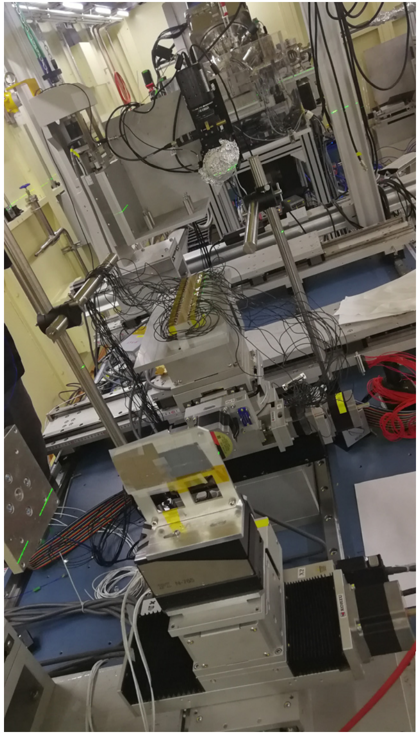
- Low repeatability due to temperature gradient
- Low precision due to instability of the environment



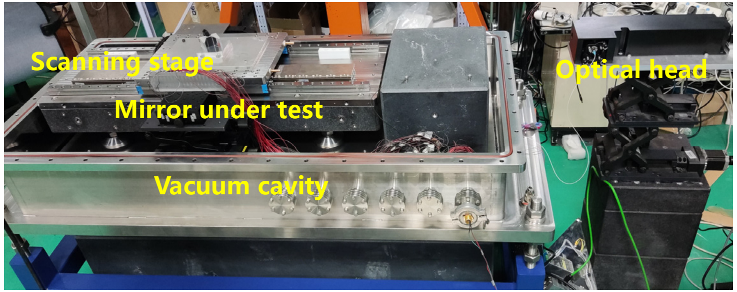


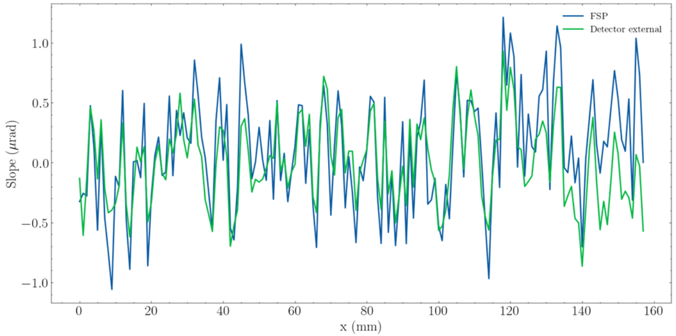


In – vacuum surface profile metrology system



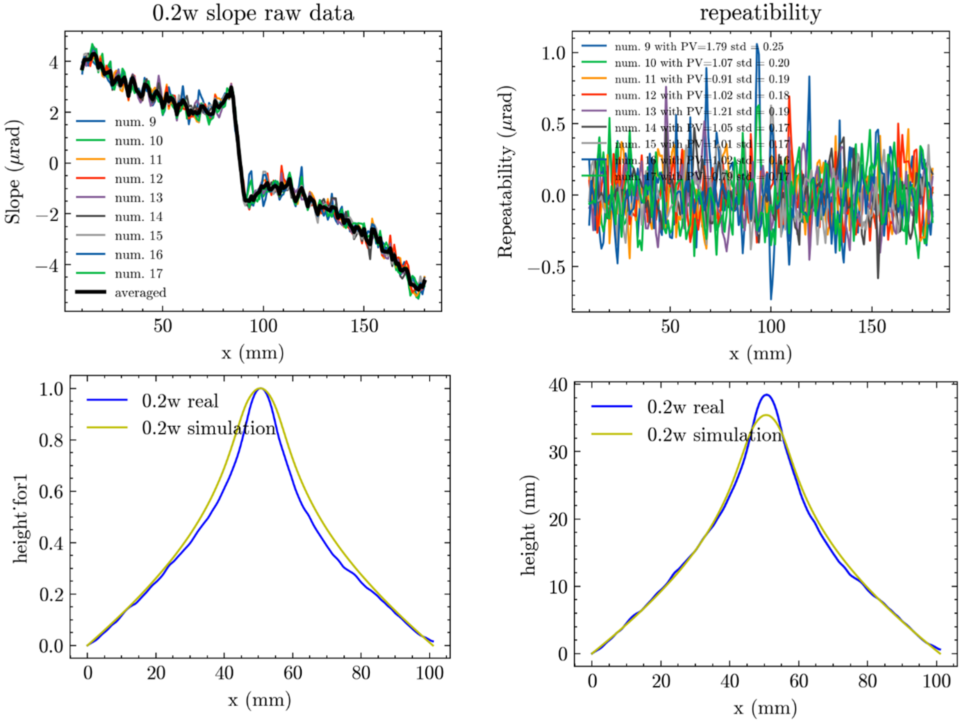
Test beamline @SSRF





In comparison test， the difference reaches 87nrad RMS

In – vacuum surface profile metrology system



In heating deformation test, the profile agree with FEA simulation well!

2023.10.26

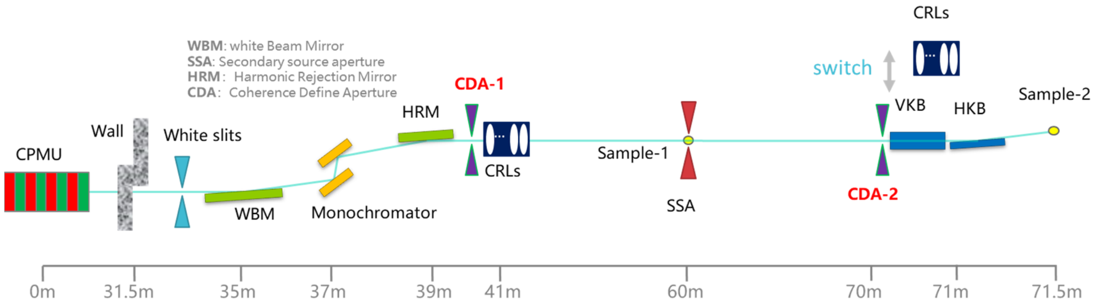
4. Summary and Outlook

Summary

- The fourth generation source challenges beamline techniques
- Active optics is the ultimate solution for 4th generation SR
- Thermal-deformation based X-ray active optics is effective:
  - High performance: spatial resolution
  - Low cost, low techniques issues
- The engineering implementation is currently in progress!
  - **Thanks for all your support**

Future

- Successful application of Active Optics will lower the cost and technique risk of the beamline
  - 40 beamlines, 1 million, we will have 40 million
  - For undulator, flux saved 10% will contribute 10% cost = 100 million
- In the following beamlines, we will consider the x-ray active optics more seriously, given the budget,…



Acknowledgements

- Optics group in HEPS and students (Dezhi Diao, Jun Han, Han Dong, Ye Zhu)

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- Raymond Barret, ESRF, EU
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