

FEL-I Beamline: Construction Progress and Commissioning Plan

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On behalf of the beamline design and engineering group

Tuesday, October 20, 2026

Outline

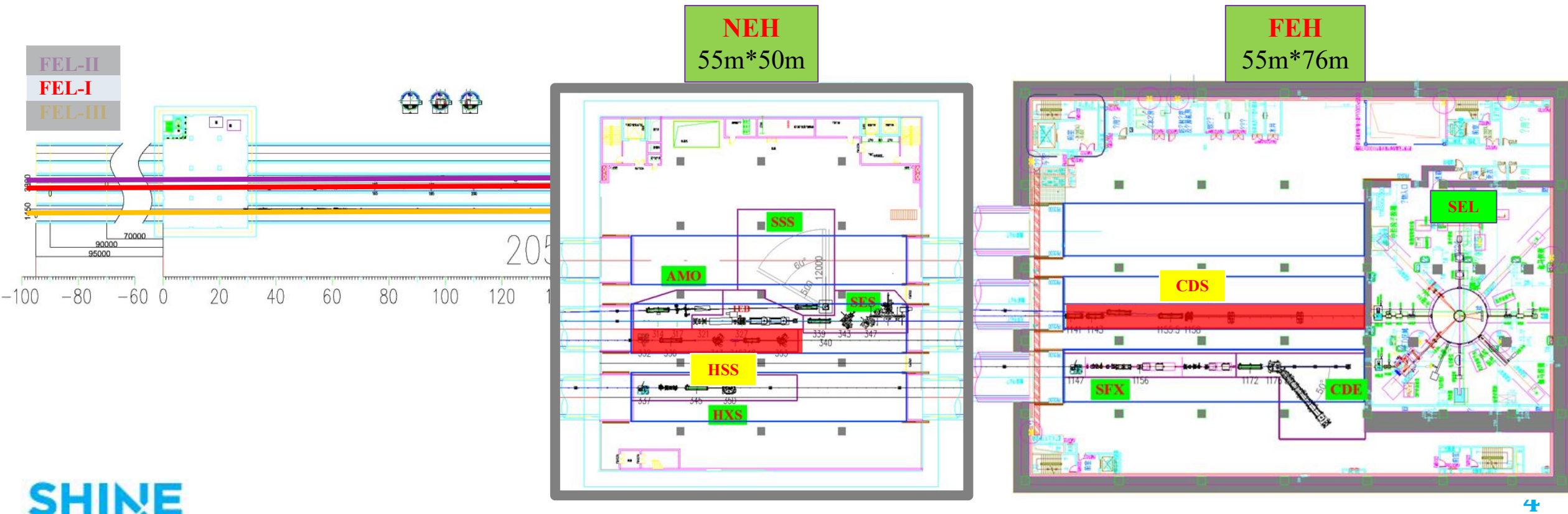
- **Introduction of FEL-I beamline**
- **Progress of the beamline**
- **Commissioning Plan**
- **Summary**

Introduction of FEL-I beamline

Introduction of FEL-I beamline

The FEL-I beamline will deliver 3–15 keV FEL pulses to three endstations:

- HSS: **H**ard X-ray **S**cattering and **S**pectroscopy Endstation
- CDS: **C**oherent **D**iffraction Endstation for **S**ingle Molecules and Particles
- SEL: **S**tation of **E**xtrême **L**ight

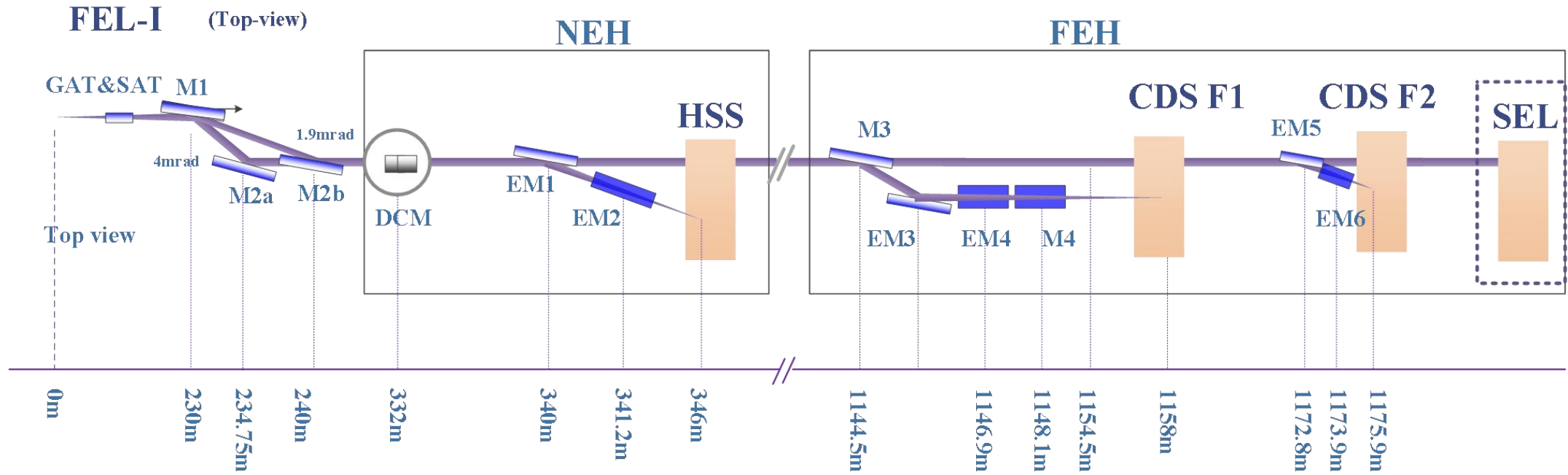


Introduction of FEL-I beamline: Requirements

parameter	Objective	Nominal
Energy range	3.0 – 15.0 keV	5.0 – 13.0 keV
Energy resolution($\Delta E/E$)	$2.0 \times 10^{-4} @ 8.9 \text{ keV}$	$2.0 \times 10^{-4} @ 8.9 \text{ keV}$
Efficiency of beamline	30% @ 7 keV (without monochromator)	15% @ 7 keV (without monochromator)
Spot size at sample	10 μm @ HSS 0.1 μm & 1 μm @ CDS	15 μm @ HSS

Achieving a focused beam size of **100 nm** will present the greatest **challenge** for the final acceptance test.

Introduction of FEL-I beamline: Layout

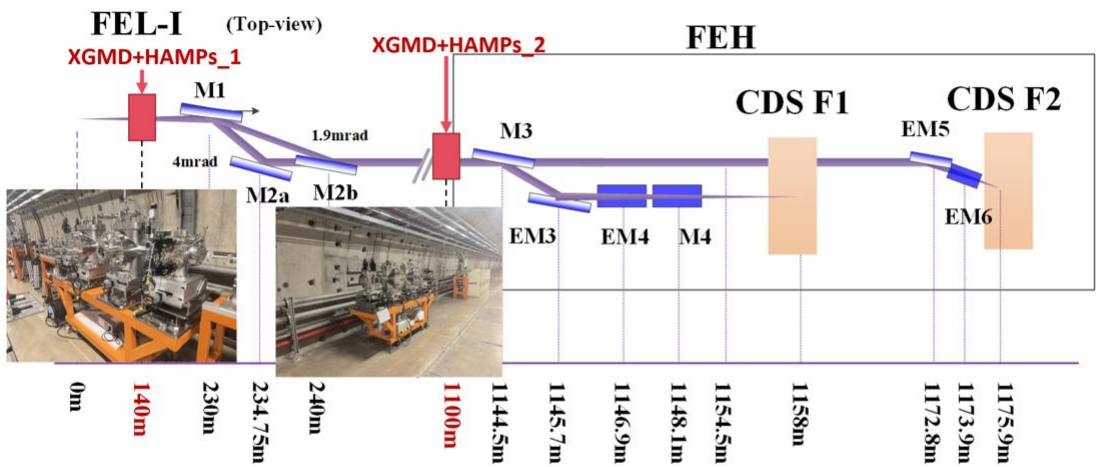


- Attenuators: GATT + SATT
- Three offset mirrors covering different photon energy ranges
- A cryo-cooling DCM for HSS endstation
- Benderable KB for HSS endstation
- Fixed shape micron and nano KB for CDS
- Diagnostics: pulse energy, pulse spectra, beam position and profile, beam loss monitor

Progress of the beamline

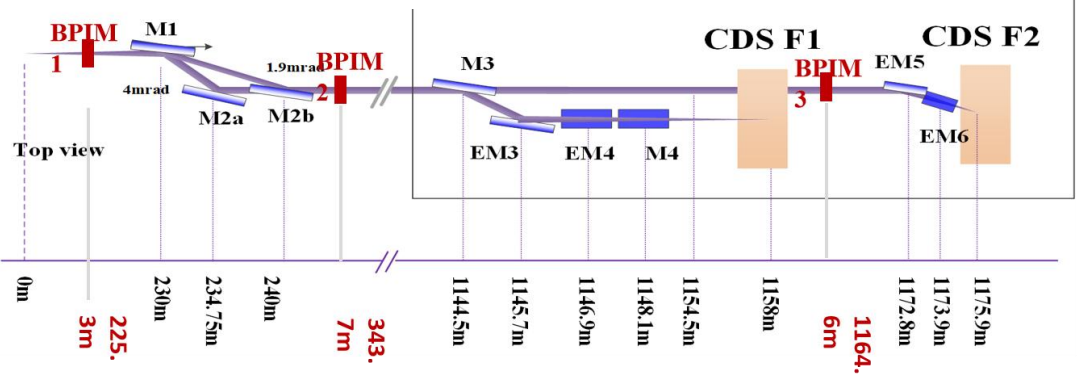
FEL-I diagnostics

XGMD&HAMPs



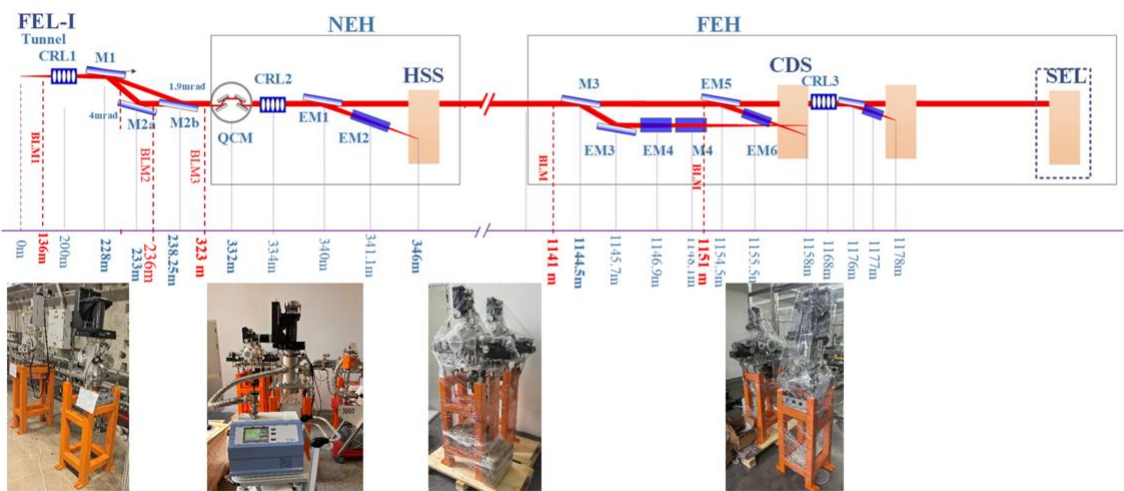
- Monitoring the pulse energy and position
- Measuring the reflectivity of mirrors
- Feedback M2 vibration

Beam Position and Intensity Monitor

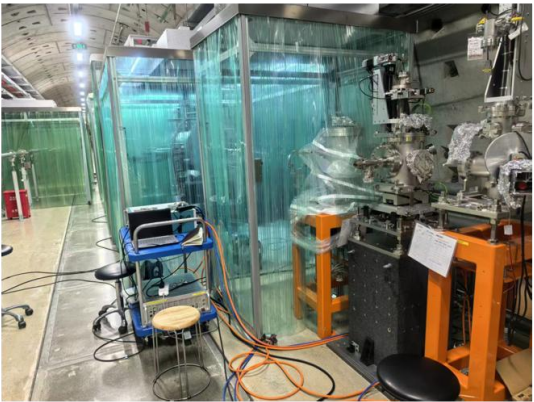


Beam Loss Monitor

on

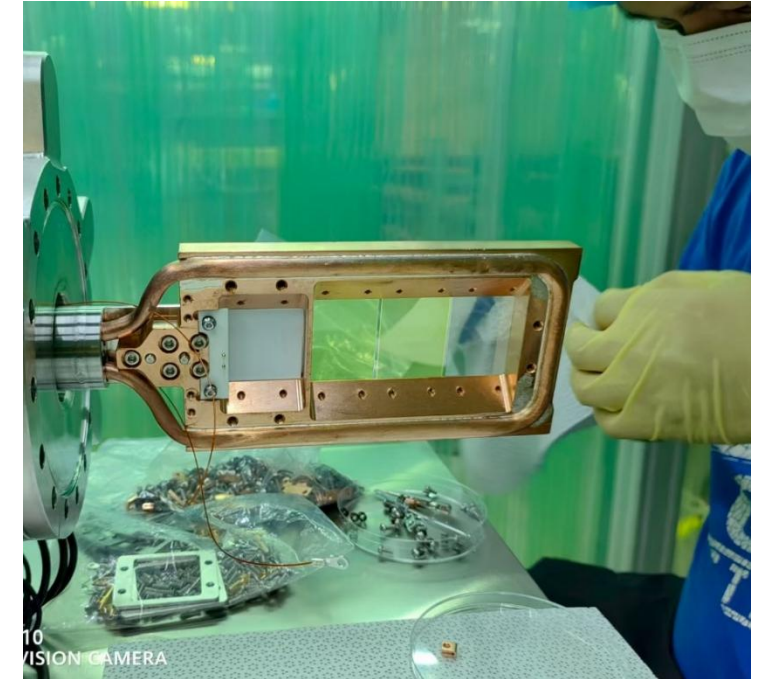


- Five BLMs are installed to monitor the possible lost photon beam in FEL-I in respective.



XGMD & HAMPs (2), BLM (2)
BPIM1 (1) has been installed on the beamline.

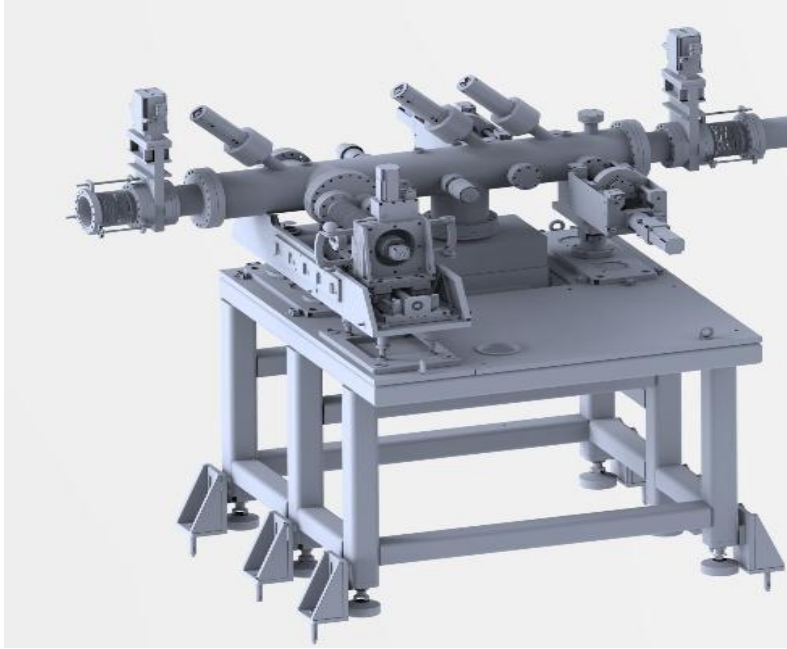
SHINE

[illegible]

9

FEL-I diagnostics

Single pulse spectrometer

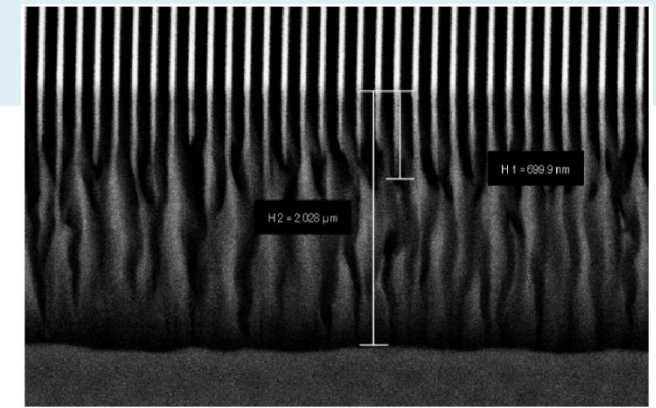


Grating and sample unit

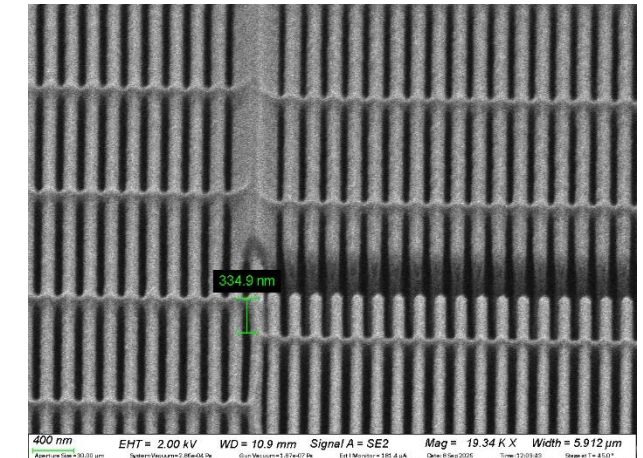


Crystal spectrometer

- Mechanical components have arrived.
- Crystals will be delivered in November.
- Gratings will be delivered in November, and there is a line wiggling problem.
- The in-house fabricated grating has been completed, but it has stitching errors.
- Scintillator based detector and Gotthard were purchased



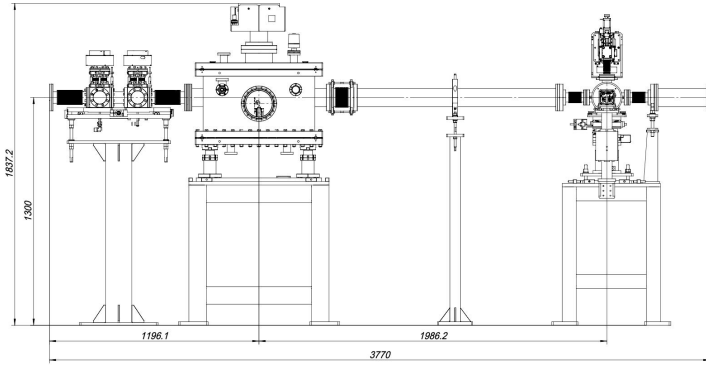
XRnanotech grating



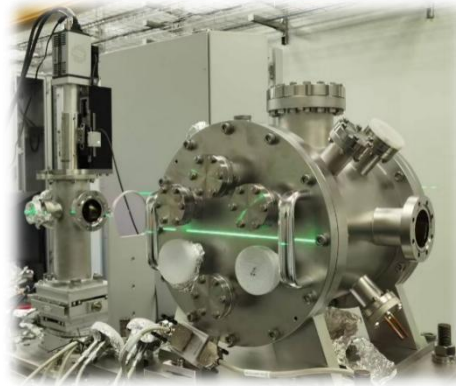
In-house grating

FEL-I diagnostics

Wavefront sensor

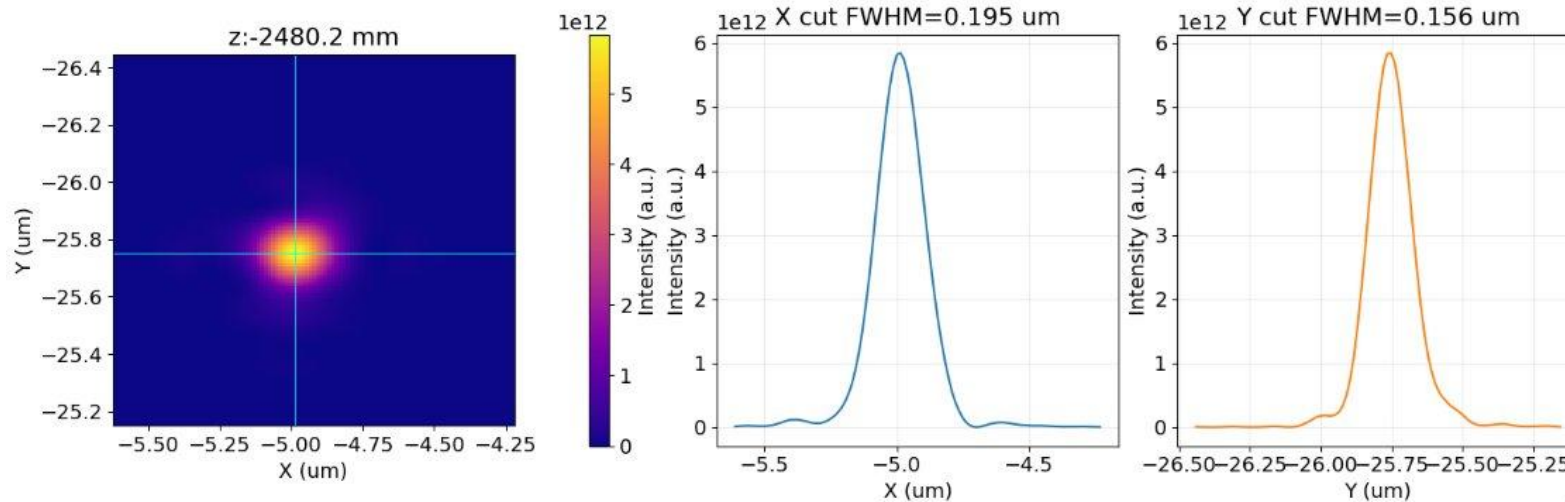


M2 wavefront sensor for the bender



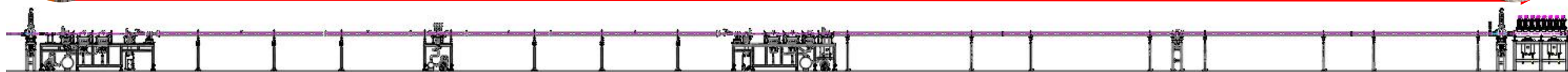
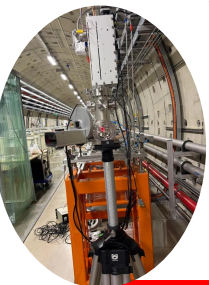
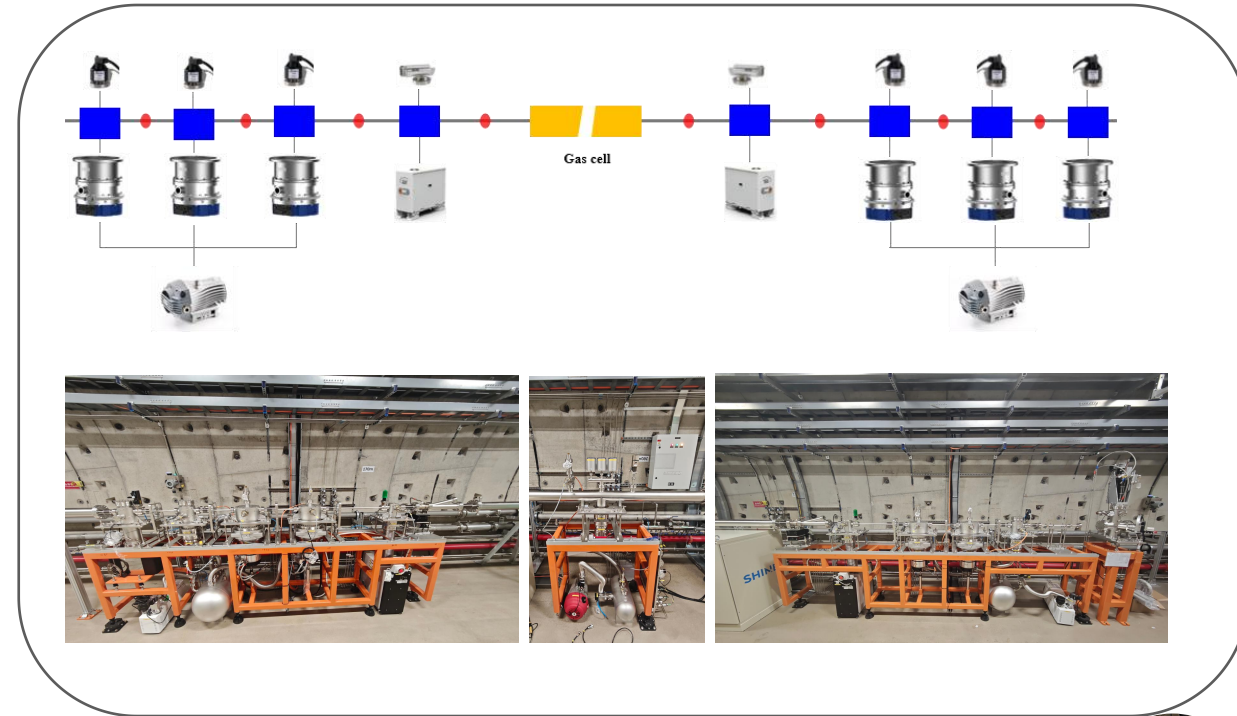
Wavefront sensor for Nano-focusing

- M2 wavefront sensor will be delivered by the end of October.
- The nano-focusing wavefront sensor has been completed and tested in a series of wavefront experiments



Gas Attenuator

- Up to 3 orders of magnitude
 - 20m attenuation path
 - Working gases N_2 and Ar
 - Pressure up to 16 Torr
- Full assembly of mechanical & vacuum components
 - Alignment calibration and laser propagation simulation completed
 - Vacuum leak detection passed
 - Water / electricity / gas utility routing finished
 - Integrated control commissioning in progress



Laser transmission over 52.8 m

Solid Attenuator

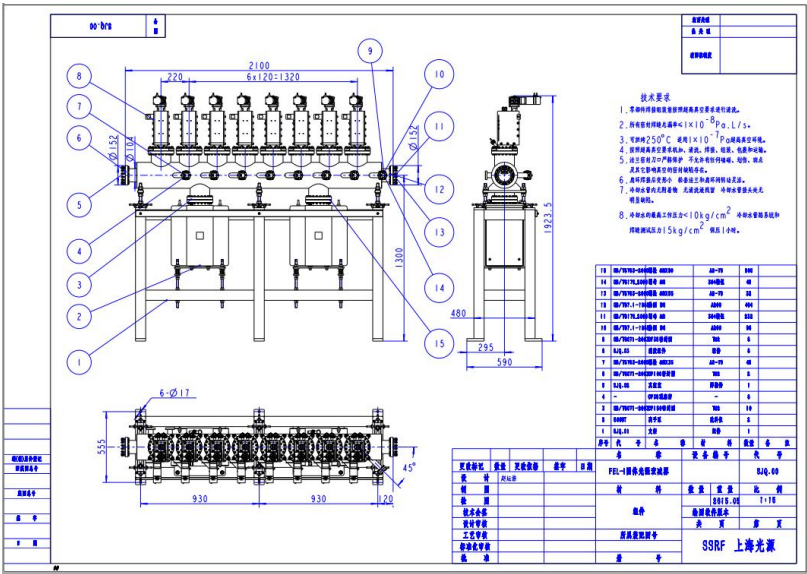
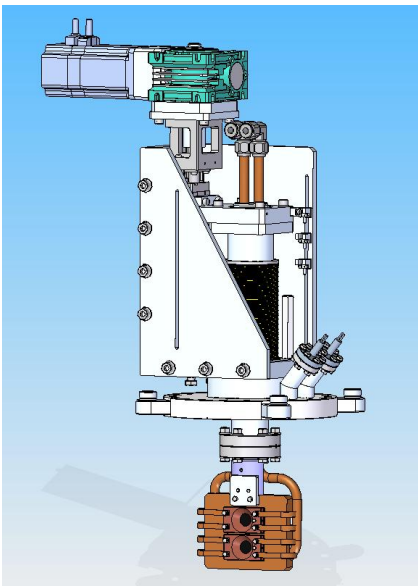
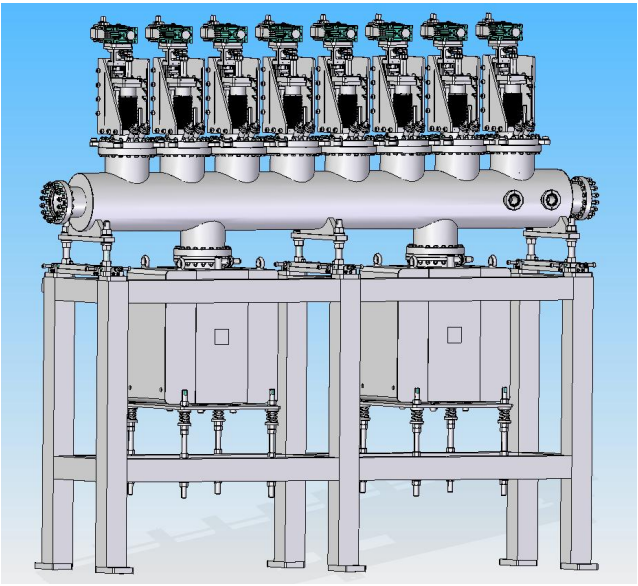
- Designed to attenuate by 6 orders of magnitude.
- Used in conjunction with gas attenuators at high repetition rates (0.1-1MHz). When the repetition rate is low (<0.1MHz), it can be used independently.
- Provide a motion repeatability accuracy of 10um.

The equipment was installed on the beamline in July 2026.

FEL-I Solid Attenuator Attenuation Plate Combination Design

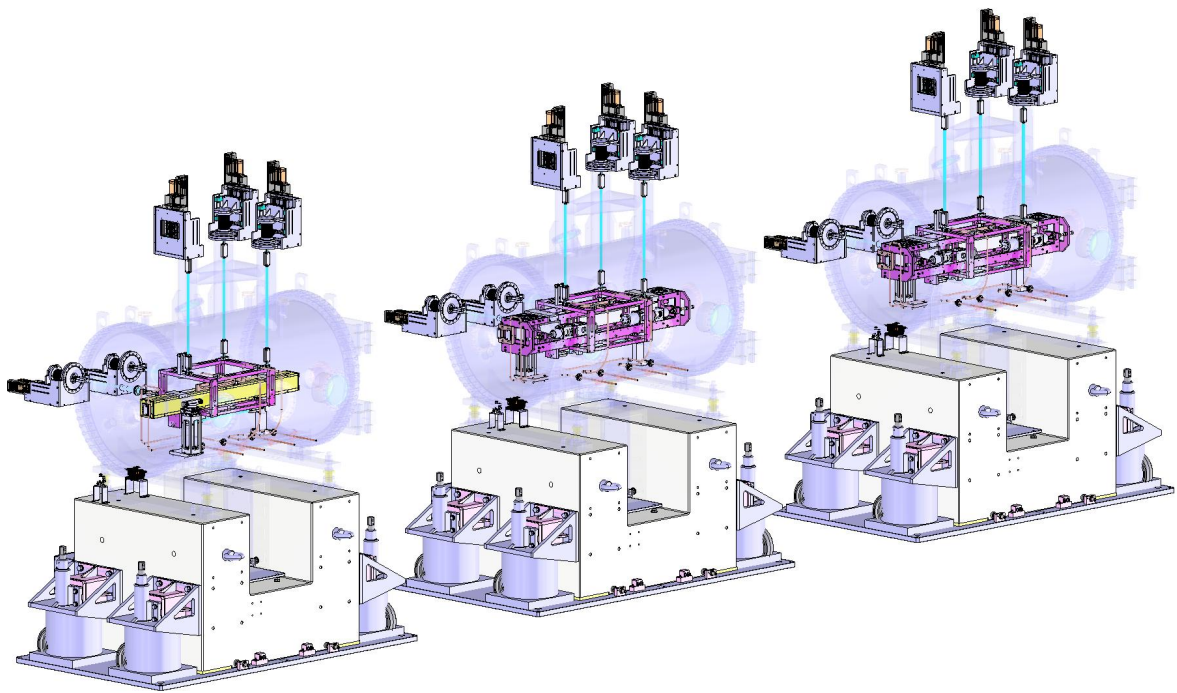
FEL-I 固体衰减器衰减片组合设计

Arm NO.			1	2	3	4	5	6	7	8
F E L - I	Positiong 位置 1	Material 材料	CVD	CVD	CVD	CVD	CVD	CVD	CVD	CVD
		Thickness 厚度 μm	40	80	160	320	640	1280	2560	5000
	Positiong 位置 2	Material 材料	Graphite	Graphite	Si	Si	Si	Si	Si	Si
		Thickness 厚度 μm	10000	20000	80	160	320	640	1280	2560
	Positiong 位置 3		-	-	-	-	-	-	-	-



Offset mirror

- 50nrad and 2nm RMS for M1
- 100nrad and 3nm RMS for M2a and M2b (after bending)
- Pitch stability < 50 nrad / 10min (RMS, <100Hz)
- Roll stability < 500 nrad / 30min (RMS, <100Hz)

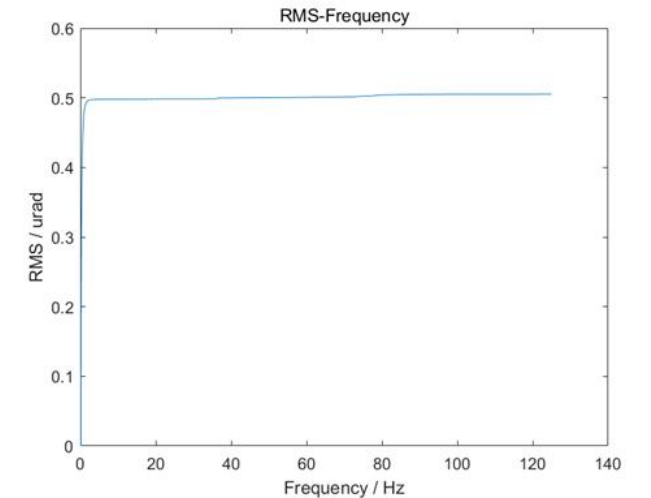
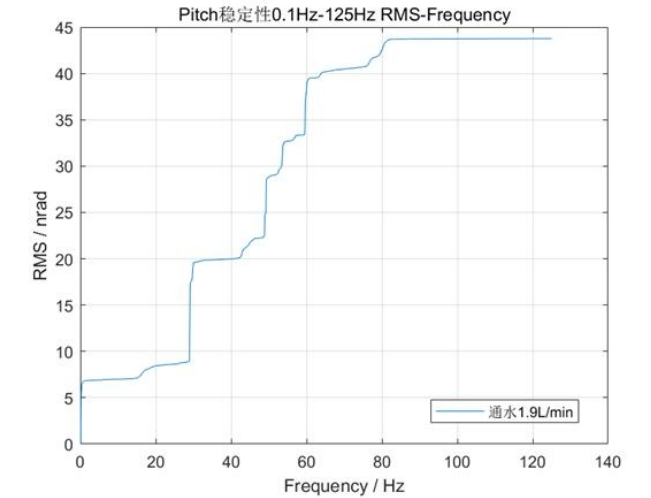
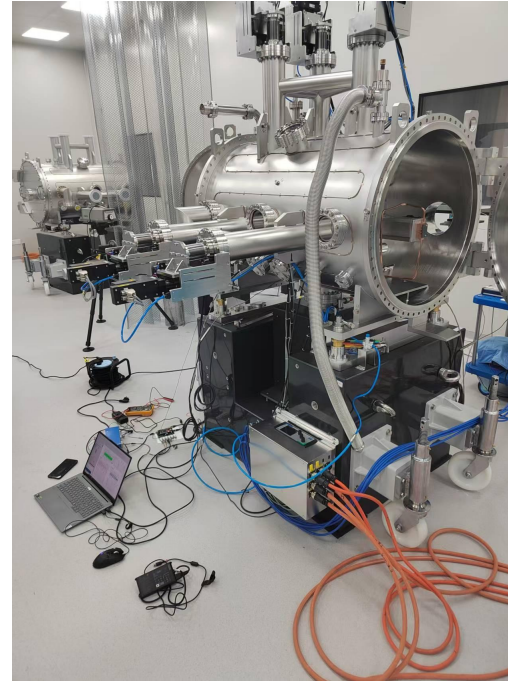
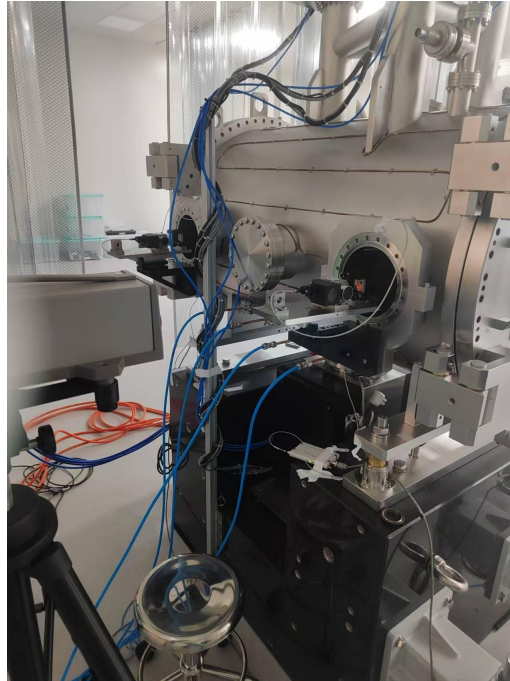
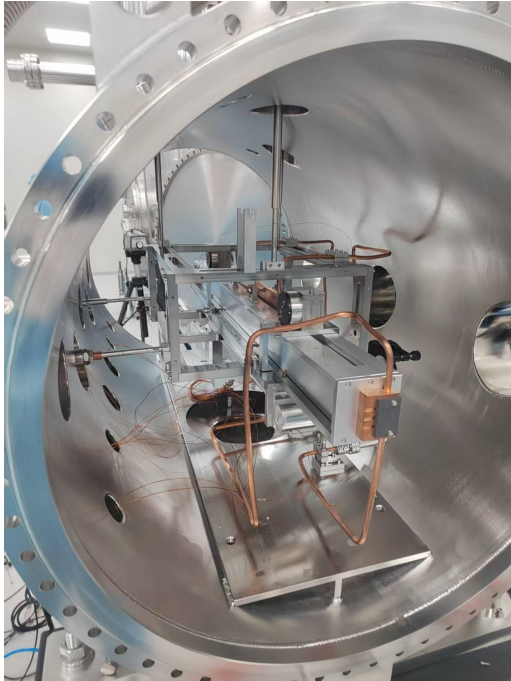


Axis		M1 mirror	M2a mirror	M2b mirror
X Vertical scan	Range	± 9mm	± 9 mm	± 9mm
	Resolution	≤10 μm	≤10 μm	≤10 μm
	Repeatability	≤50 μm	≤50 μm	≤50 μm
Z In/Out of beam	Range	± 9 mm	± 9 mm	± 9 mm
	Resolution	≤1 μm	≤1 μm	≤1 μm
	Repeatability	≤5 μm	≤5 μm	≤5 μm
Pitch	Range	± 0.3°	± 0.3°	± 0.3°
	Resolution	≤20 nrad	≤20 nrad	≤20 nrad
	Repeatability	≤60 nrad	≤60 nrad	≤60 nrad
Roll	Range	± 0.8°	± 0.8°	± 0.8°
	Resolution	≤10 μrad	≤10 μrad	≤10 μrad
	Repeatability	≤50 μrad	≤50 μrad	≤50 μrad
Yaw	Installation accuracy	200 μrad	200 μrad	200 μrad
Encoder	All axis with encoder			
	The effect of X and Z on Pitch must less than 1.0μrad			

Technical specifications for the adjustment system of the M1 and M2a/M2b mirrors

Offset mirror

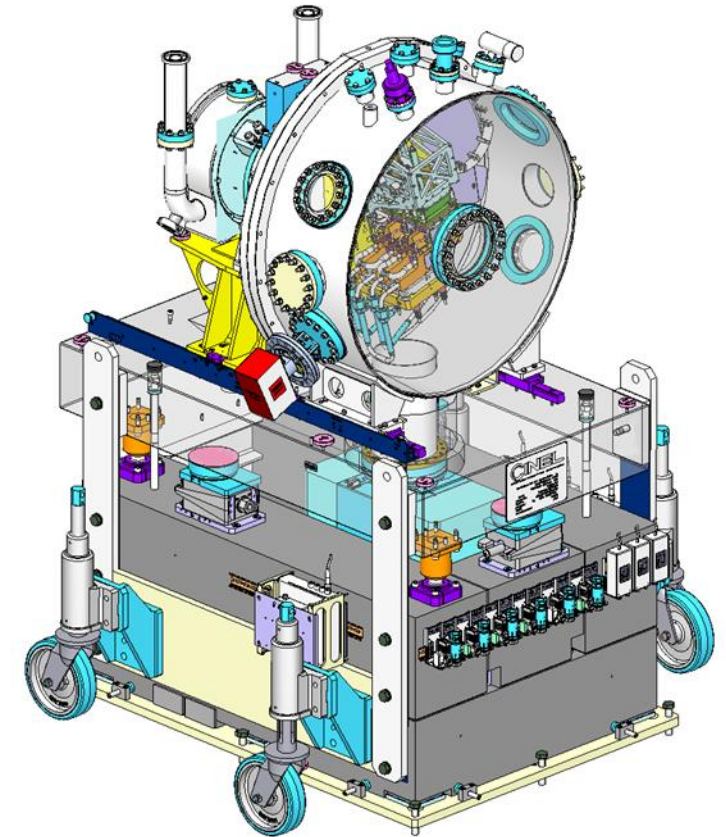
- M1 mirror chamber has completed offline testing, with all motion parameters meeting the requirements; and the stability results are as follows:
- Pitch stability = 44 nrad / 10min (RMS, 0.1~125Hz)
- Roll stability = 500 nrad / 20min (RMS, 0.1~100Hz)



Crystal monochromator

➤ Main Technical Parameters and Design Scheme

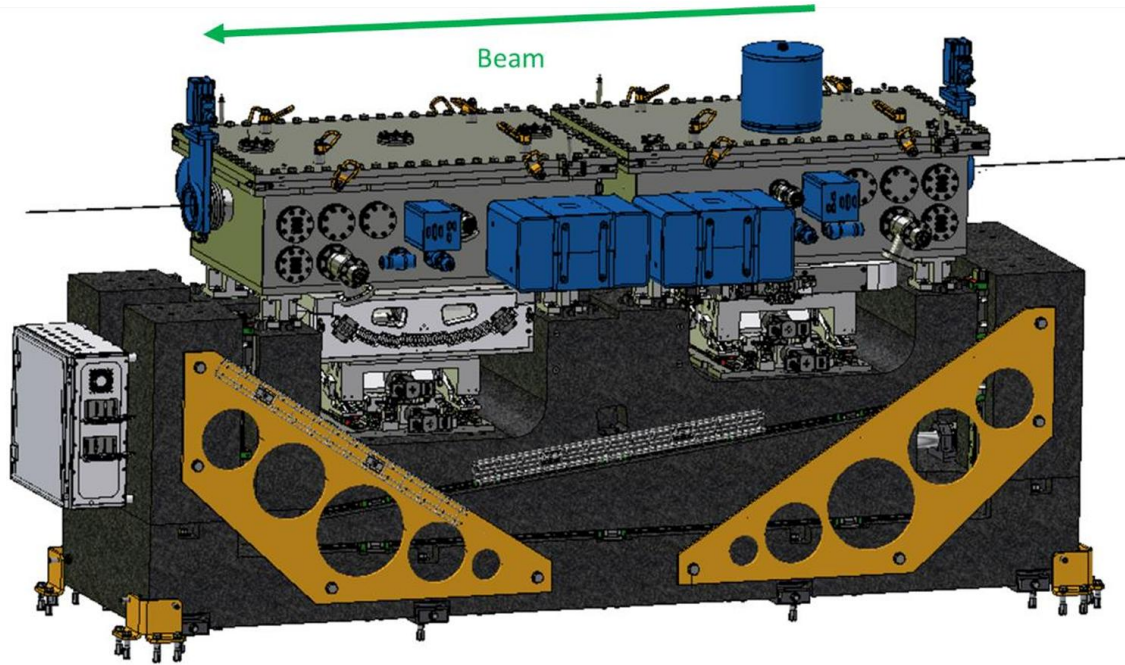
Parameter	Values
Crystal sets	Si(111), Si(311)
Energy range(keV)	3-15@Si(111) 5.6-15@Si(311)
Energy resolution	$<2 \times 10^{-4}$ @10 keV@Si(111) $<5 \times 10^{-5}$ @10 keV@Si(311)
Beam height	1300 mm
Beam vertical offset	15 mm
Bragg angle range	-5°-45°
Beam cross section at 1st crystal	4.8 mm(H)×4.8 mm(V)
RoC	Center of the first crystal
Maximum operational heat load	180W
Beam stability	50nrad/2 hours (RMS) (1~100Hz)
Cooling way	Cryo-cooling
Vacuum	$<1 \times 10^{-8}$ Torr, Particle free(ISO-6), Hydrocarbon free



It is expected to **arrive in March 2027**.
The installation **will be finished before June 2027**.

The Jtec crystal will arrive in July 2027.
The in-house crystal will be ready in December 2026.

HSS KB



HSS KB system:

- Bendable mirrors: two elliptical mirrors at 4 mrad with B4C & Ru coating

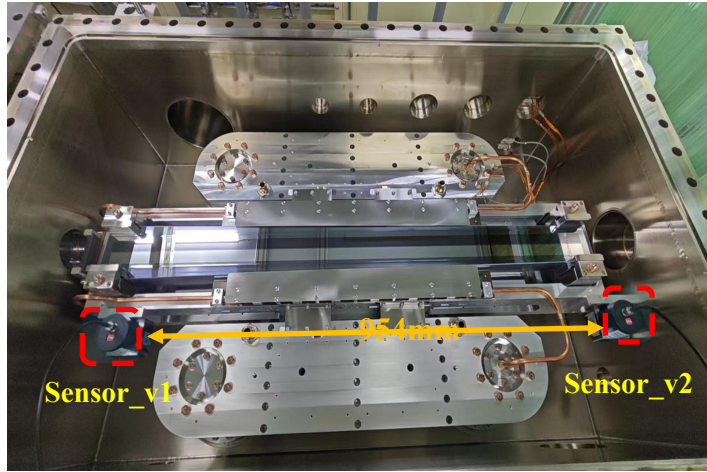
The installation has finished.

HSS KB-stability

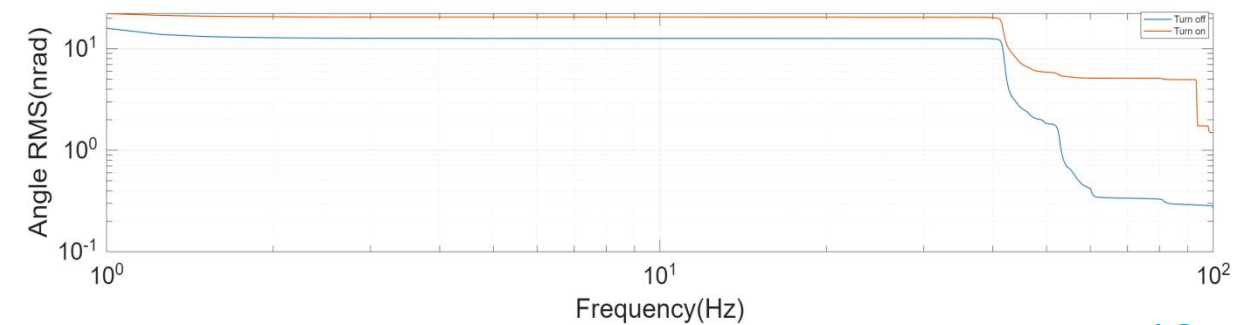
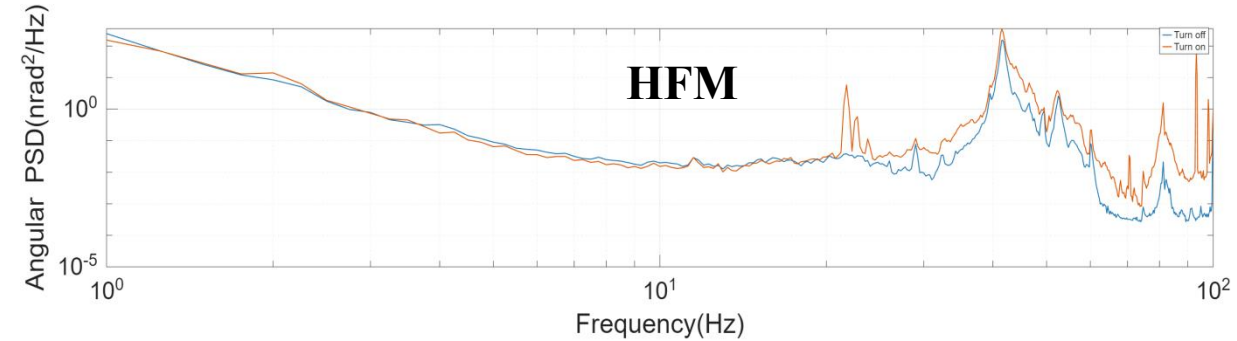
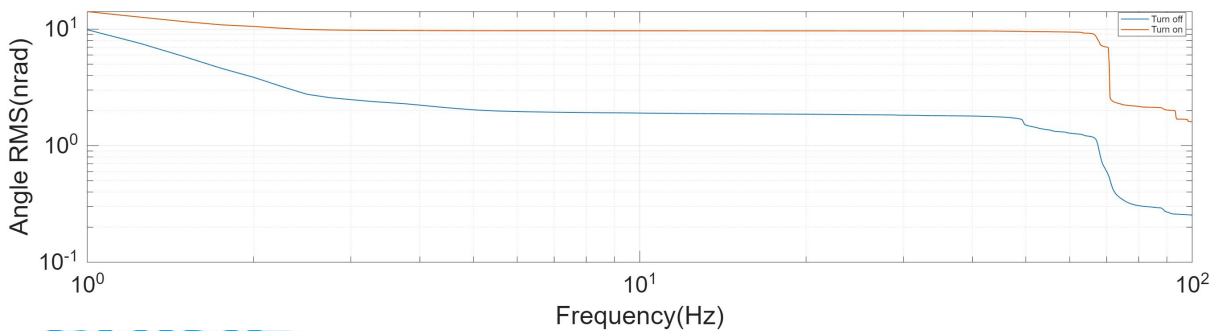
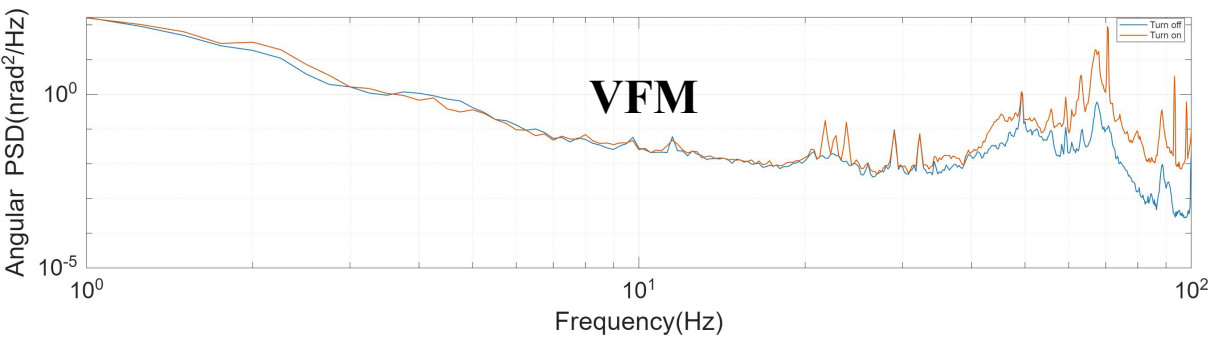
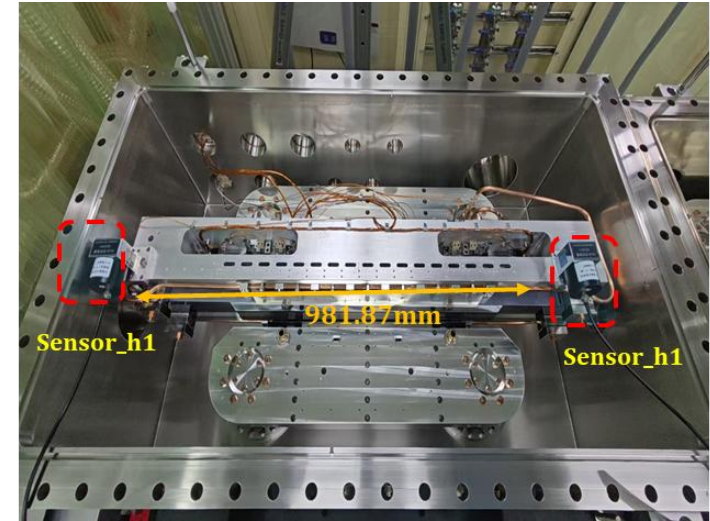


Rubber pads were added to suppress ambient vibration

HSS KB-stability



VFM: 15 nrad
HFM: 21 nrad

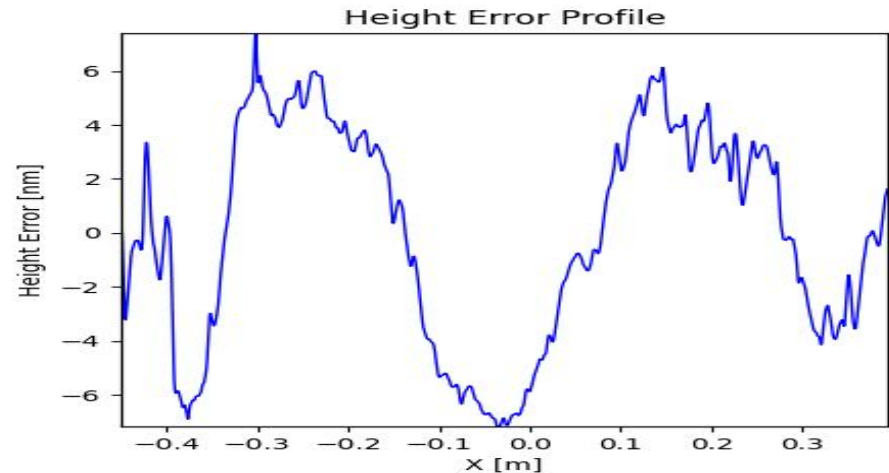
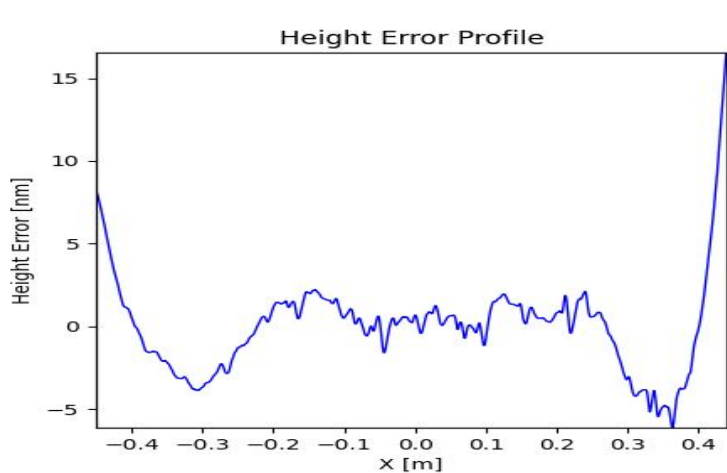


HSS KB-metrology result

	EM1	EM2
Mirror specification	0.5nm/2nm	0.5nm/2nm
Specification after bending	3nm/12nm@full aperture 1.5nm /6nm@400mm central part	3nm/12nm@full aperture 1.5nm /6nm@400mm central part
Mirror metrology result(SHINE)	2.18nm/9.7nm	6nm/36.4nm
Metrology result after bending (FAT)	2.62nm/9.97nm@full aperture 0.87nm /3.43nm@400mm central part	2.5nm/11nm@full aperture 0.9nm /4.24nm@400mm central part
Metrology result after bending (SAT)	2.99nm/22.2nm@full aperture 0.73nm /3.7nm@400mm central part	4nm/14.7nm@full aperture 1.63nm/7.5nm@400mm central part

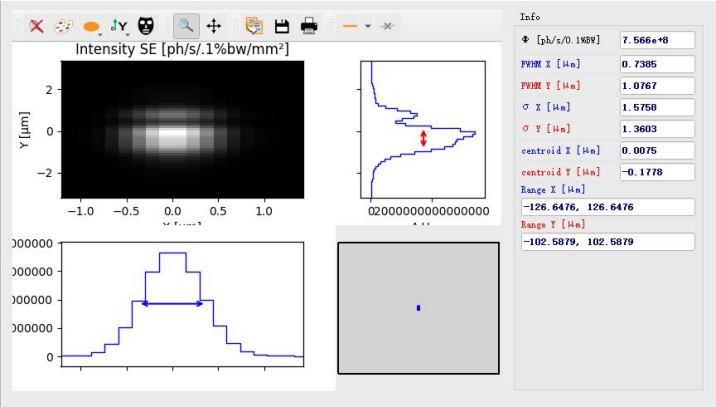
HSS KB-metrology result

Obvious side lobes appear in the vertical direction at the low-energy position of the focused spot.
No significant effect is observed on the horizontal focused spot.

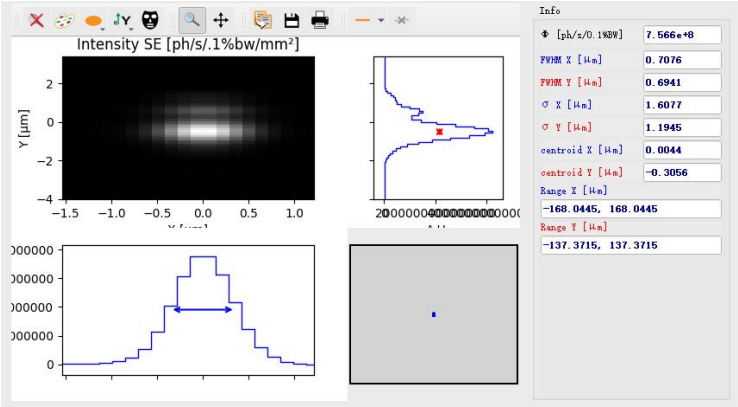


HFM

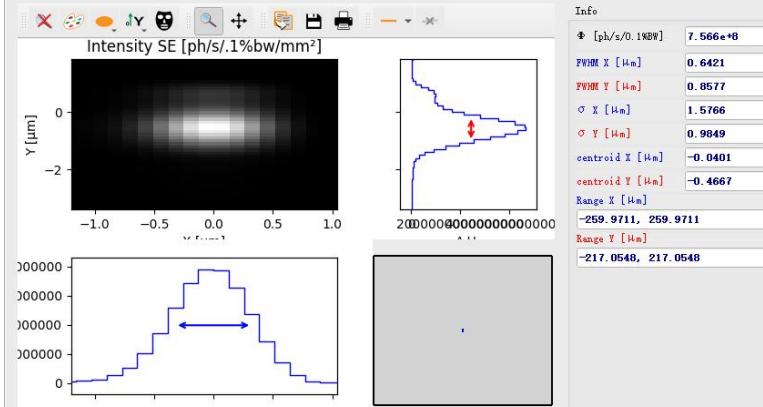
VFM



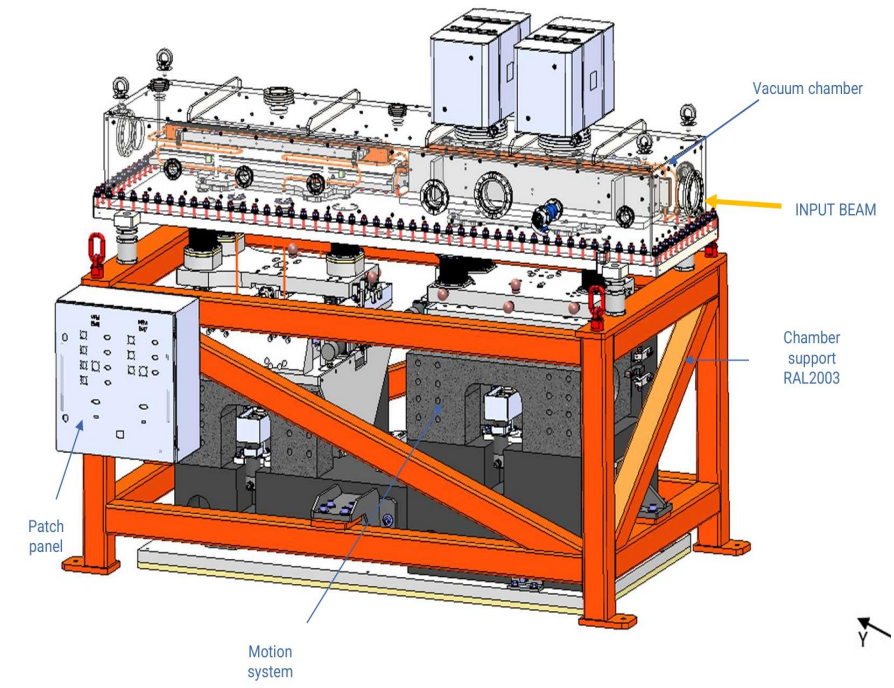
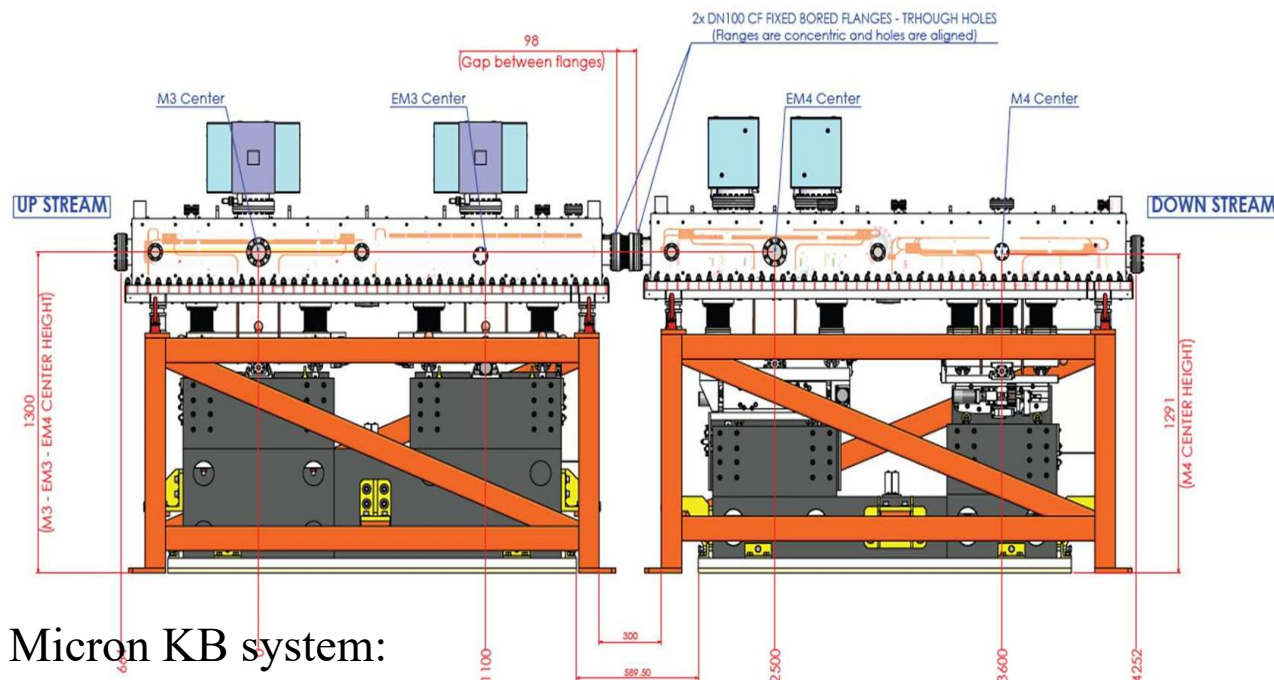
5keV



7keV



12keV



Micron KB system:

- Fixed shape, consisting of two plane mirrors and two elliptical mirrors with 4mrad, B4C & Ru coating
- Four bounces: one pair deflects in the horizontal plane and one pair in the vertical plane
- Face side, face-up and face-down

Nano KB system:

- Fixed shape, two elliptical mirrors with 7mrad, Ir coating

It arrived in Shanghai last week.

Mirror delivery is delayed. Only EM3 and EM7 have arrived.

FEL-I-CDS mirrors

腔体2



Mirror	M3	M4	EM3	EM4	EM7	EM8
Shape	plane	plane	ellipse	ellipse	ellipse	ellipse
Orientation	horizontal right	vertical up	horizontal left	vertical down	horizontal right	vertical up
Coating	B4C / Ru	B4C / Ru	B4C / Ru	B4C / Ru	Ir	Ir
Measurement	horizontal 3 support points	vertical up 3 support points	horizontal 3 support points	horizontal 3 support points	horizontal 3 support points	vertical up 3 support points
Gravity SAG	X	Δ	X	O	X	Δ

EEM 抛光，
需要2次
迭代（~1
个月）抛
光测量

接近完成，
大概2周
完成出厂
测量

已收货，
已测
需要同
JTEC
讨论支
撑方式。

基底出现瑕疵，需
要平移有效区域
（垂直方向），接
受目前状况。
30%折扣采购同一
参数反射镜

已收货，
待测

预计9月
份到货
（JTEC
自己镀
膜）

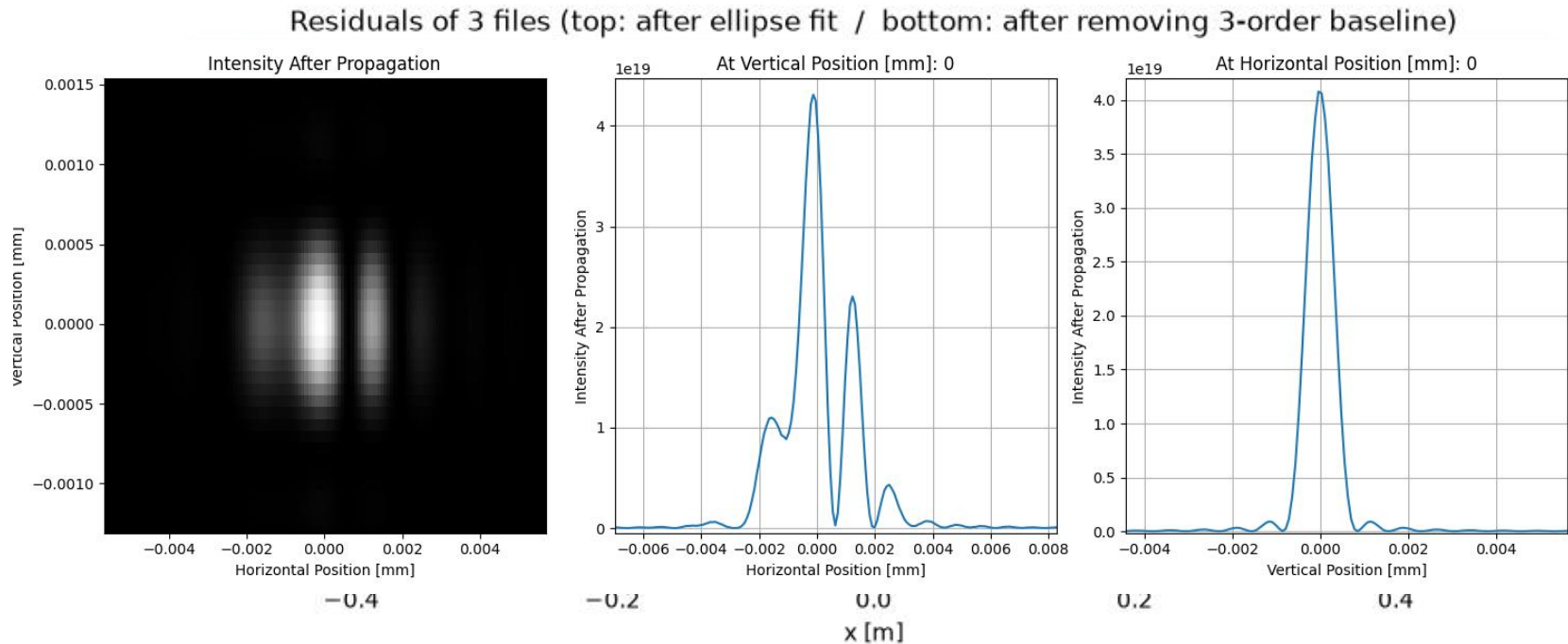
预约11月份 NTT 镀膜！
12月份发货

Deliver in December
2026

Deliver in January
2027

Deliver in
October
2026

CDS KB-Mirror metrology (EM3)



file	p	q	θ	PV_raw	RMS_raw	PV_cor	RMS_cor
EM3_HDX_raw_hei...	1145.5999	12.4000	-4.031e-03	19.309	4.235	13.609	2.394
EM3_Shanghai_ra...	1145.5999	12.4000	-4.025e-03	15.770	3.371	13.559	2.627
SHINE-CDS-EM3-B...	1145.6001	12.4000	-3.955e-03	40.870	9.862	28.423	7.166

- Only EM3 and EM7 have been delivered.
- EM3 (central radius ≈ 6 km) was characterized using SHINE stitching, HALF stitching and LTP metrology.
- The two stitching measurements agree well with each other but disagree significantly with LTP
- all measured results are bad.

Commissioning Plan

- **2027.9.15 First lasing FEL-I beamline**
- **2027.10.31 Start commissioning of FEL-I beamline**
- **2026.12.31 Complete the commissioning**

Summary

- **Most diagnostic tools have been installed.**
- **Offset-mirror installation is blocking the installation of T34**
- **The double crystal monochromator will be delivered later than planned.**
- **The HSS KB VFM failed to meet specifications during site acceptance testing.**
- **CDS KB mirrors are significantly delayed. For the delivered mirrors, only EM3 has been tested, and it does not meet specifications.**
- **Based on current plan, we have only two months for the commissioning of FEL-I beamline, including the endsations and beamline.**

Thank you for your attention!



Key milestones

