Beamline diagnostics

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On behalf of Beamline and Endstation Technical Department

October 23, 2025

Outline

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- **Motivation driven by experiments**
    - SES endstation: Spectrometer for Electronic Structure
    - AMO endstation: Atomic, Molecular and Optical physics
- **Diagnostics system for beamline and endstations**
    - Pulse energy diagnostic: GMD + HAMPs
    - Pulse arrival monitor (PAM)
    - Talbot Wavefront Sensor
    - Photoemission Spectrum (PES)
    - Beam loss monitor (BLM)
    - Imager
    - Energy resolution measurement
- **Commissioning plan**

SES-TAP Endstation: DAY 1 Experiment

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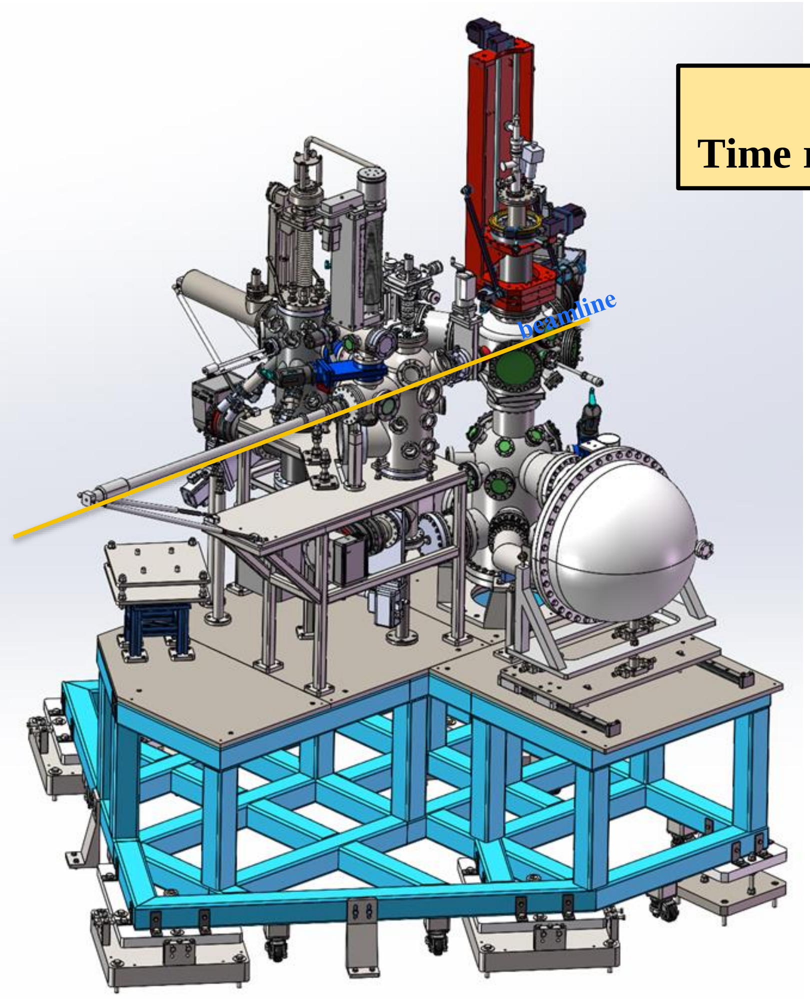
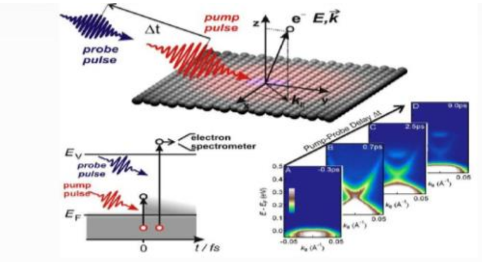
TAP Substation
Ultrafast Dynamics of Electronic Structures

Day 1 : Pump Probe Experiments
Dynamic of Electrical Structures in 2D materials

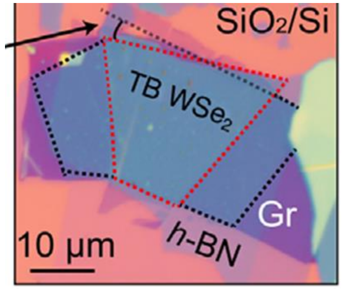


Specification
Time resolution: better than 60 fs



Fritz Haber Institute | Fritz Haber Institute of the Max Planck Society (mpg.de)

Twisted TMD



XFEL

- Energy range: 200eV
- Pulse energy: 1-10 μJ (GMD + HAMPs)
- Pulse duration: 40 ~ 50 fs
- Jitter: < 50 fs (PAM)
- Beam spot size: ~ 10 μm (Wavefront sensor)
- Energy resolution: ~150 meV (Energy resolution measurement)
- Repetition rate: 100 kHz

co-axis

Laser

- Wavelength: 1030 nm pump
- Repetition rate: 100 kHz
- Spot size: ~50 μm
- Pulse energy: 15-20 μJ
- Pulse duration: 30 ~ 40 fs

AMO Endstation: DAY 1 Experiment

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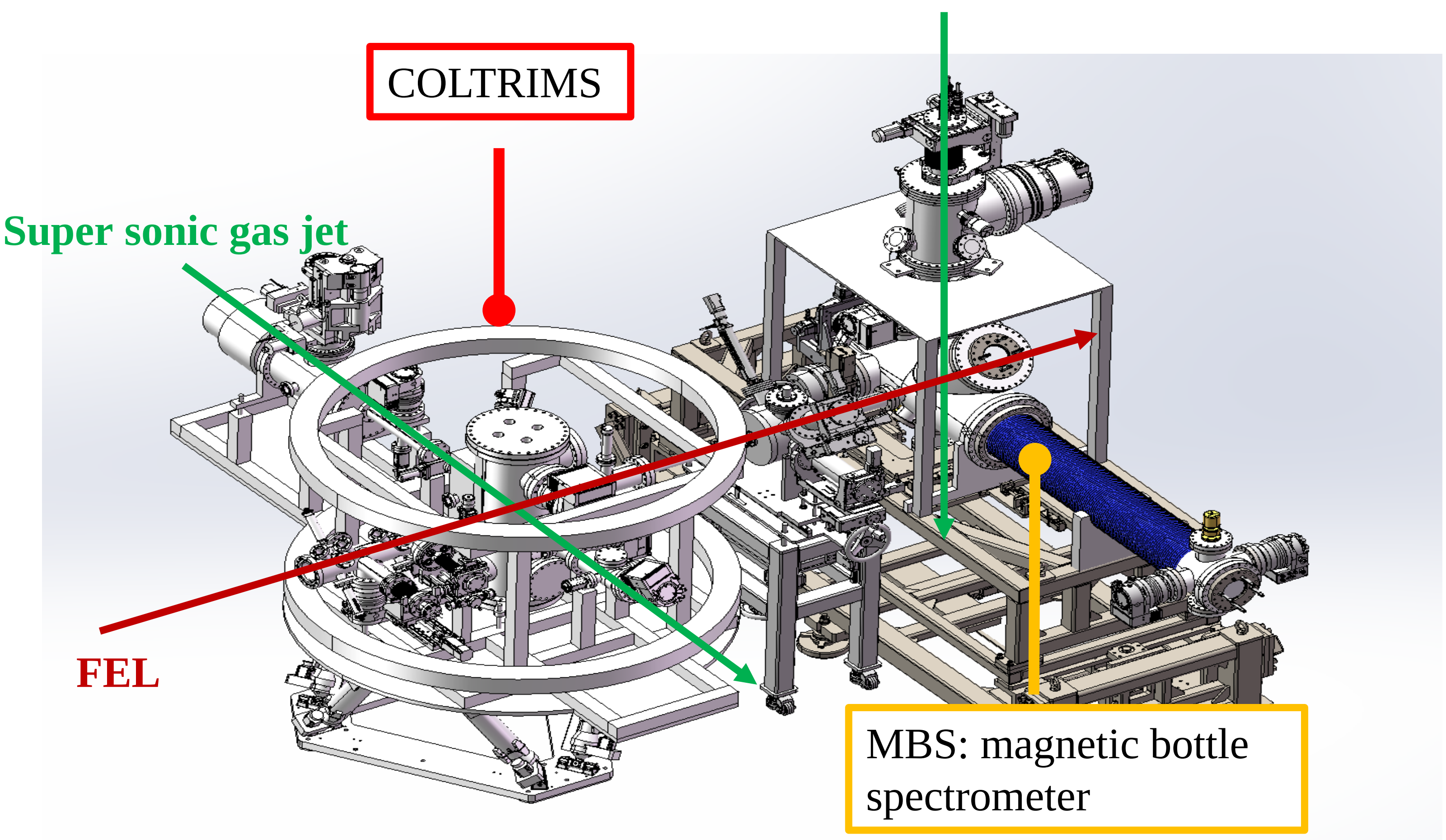
Momentum imaging of ions and electrons



Experimental parameters

XFEL

- Beam spot size: < 10 μm
- Pulse duration: 10 ~ 150 fs
- Jitter: < 35 fs
- Repetition rate: 100 kHz
- Pulse energy: 10-3000 μJ

Laser

- Wavelength: 266-3000 nm
- Repetition rate: 100 kHz
- Spot size: <100 μm
- Pulse energy: >100 μJ
- Pulse duration: 30 ~ 150 fs

Main diagnostic requests

- Beam position monitor: Imager
- Foci : Wavefront sensor
- Pulse flux: GMD + HAMPs
- Photon energy: PES
- Pump-probe jitter: PAM

Overview of FEL-II diagnostics system

	Diagnostic tool	Main Specification	Quantity	
1	Pulse energy diagnostic (GMD + HAMPs)	≤10%	3	(1 before M1, 2 before pink/mono KB)
2	Pulse arrival monitor (PAM)	15 fs RMS	2	(1 pink, 1 mono)
3	Talbot Wavefront Sensor	$\lambda/50$	4	(1 after M2, 3 after 3 endstations)
4	Photoemission Spectrum (PES)	0.5 eV	1	(before M1)
5	Imager	30 μm	14	(every limiting aperture)
6	Beam loss monitor (BLM)	Response time ≤ 10 μs	4	(after mirrors)
7	Energy resolution measurement	$E/\Delta E \geq 10{,}000$ @867eV	1	(after exit slit)

Pulse energy diagnostic: GMD + HAMPs

Experimental requirements: 1-10 μJ

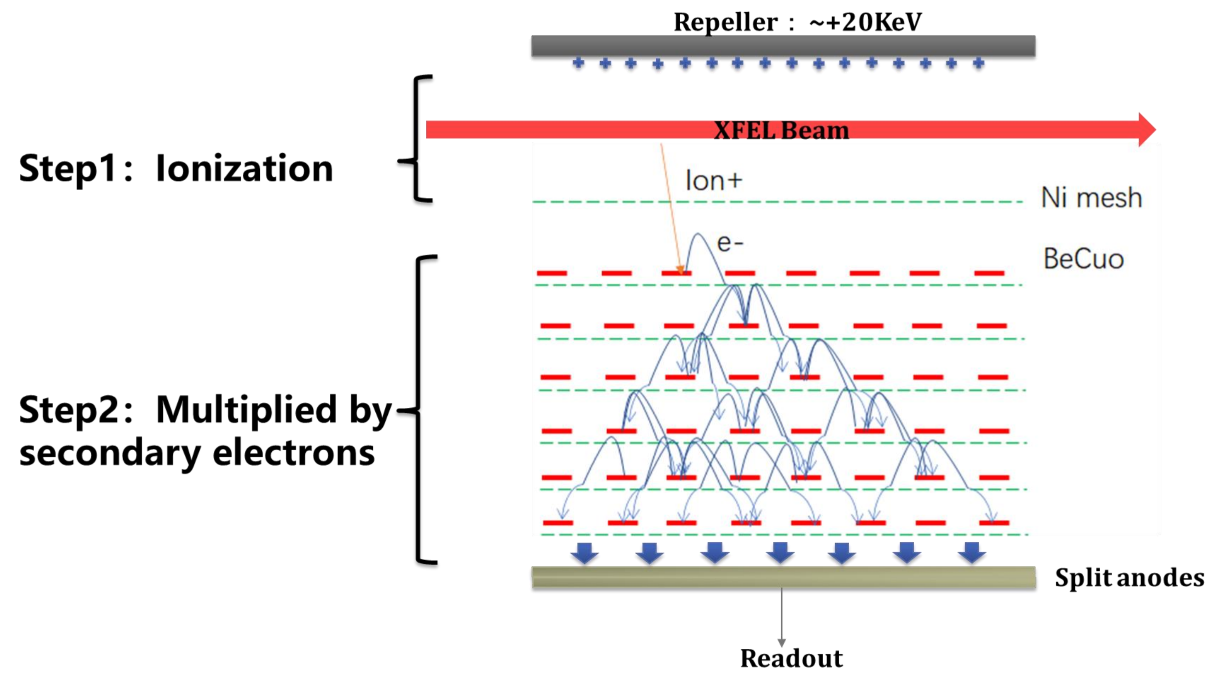
Function: pulse energy and position measurement

Specifications:

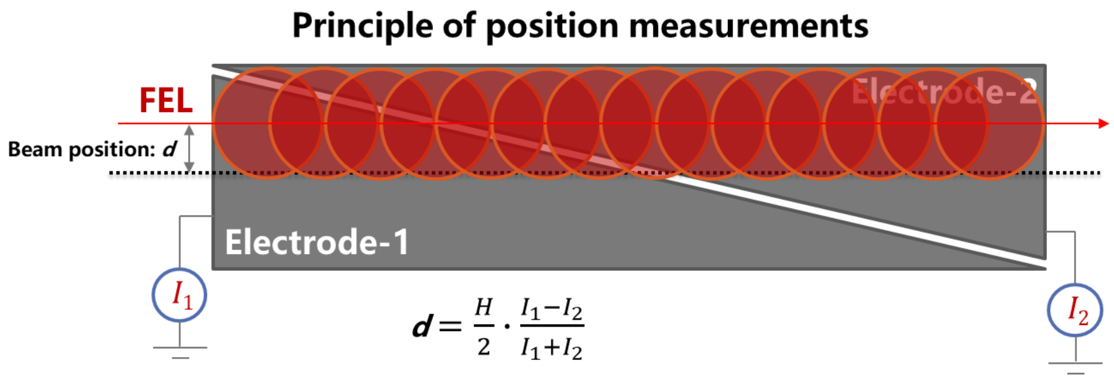
Pulse energy accuracy ≤10% (single-pulse measurement)

Pulse position accuracy ≤10% (multi-pulse average)

Pulse energy measurement with HAMPs

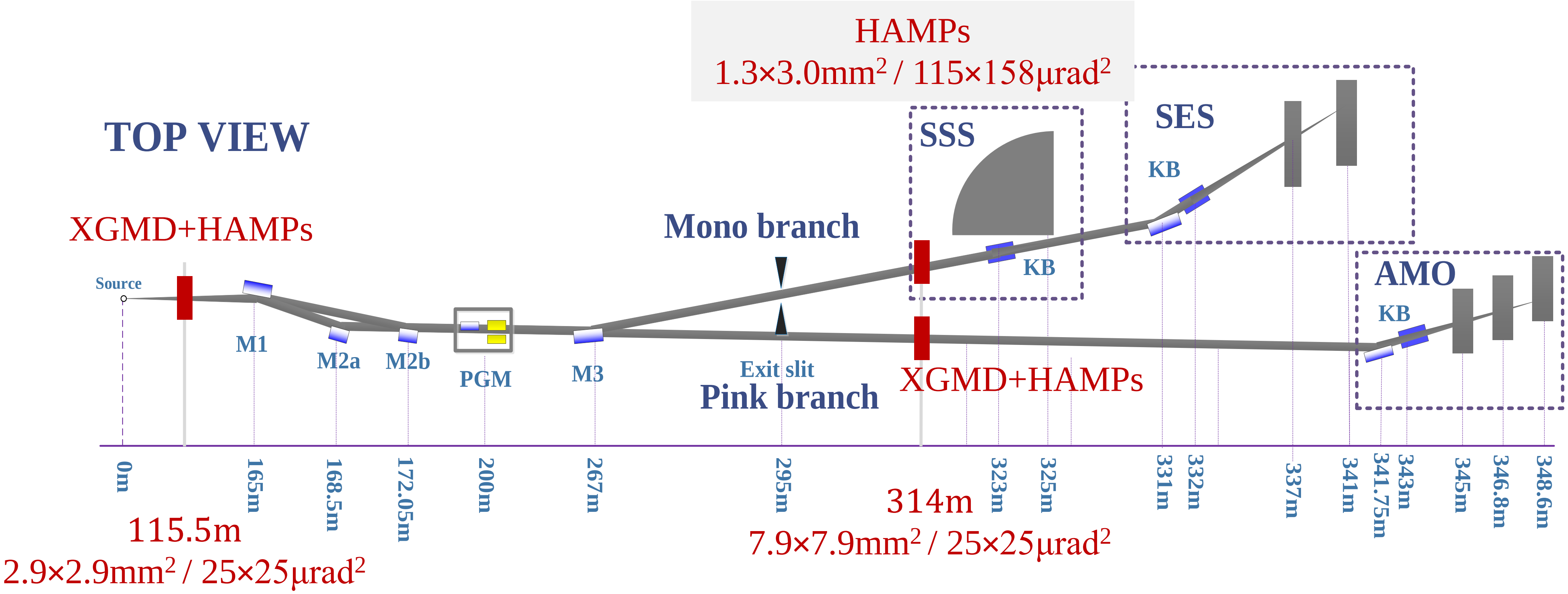


Beam position estimation with split anodes



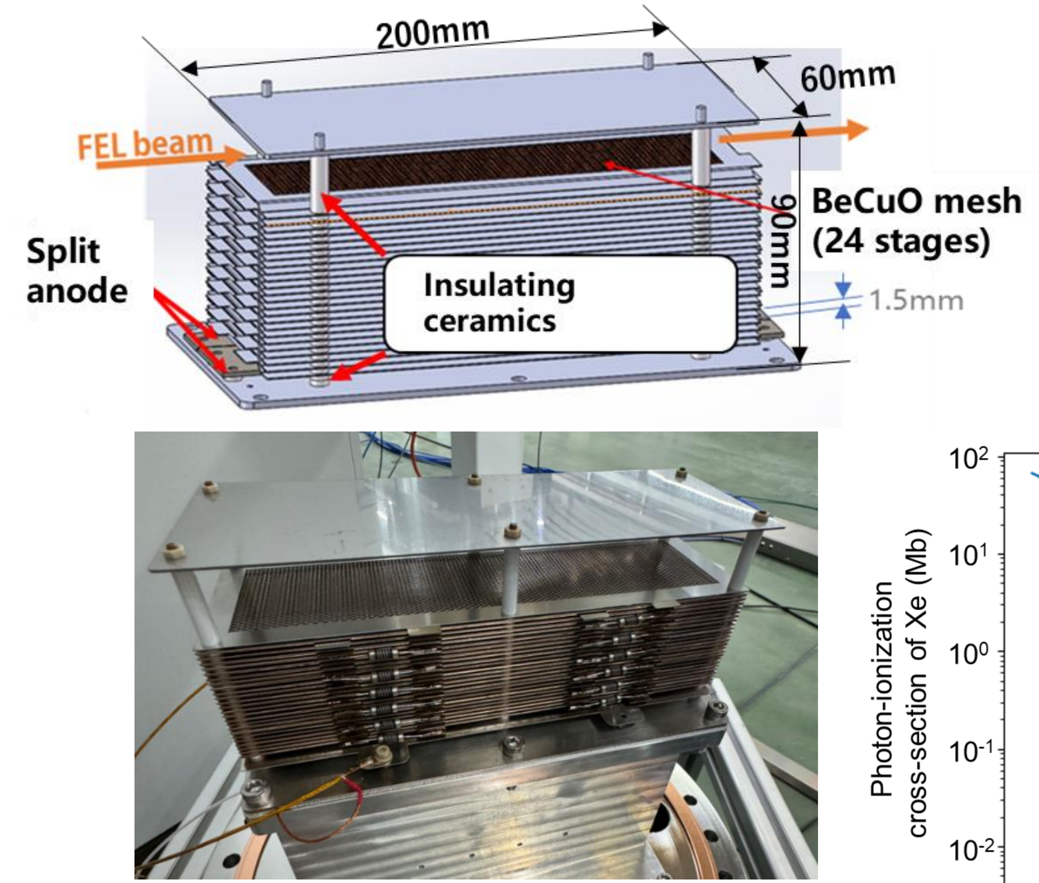
Ref.: Sorokin and Tiedtke*, *et al.*, J. Synchrotron Rad. (2019). **26**, 1092–1100

HAMPs： location



- Monitoring the pulse energy and position
- Measuring the reflectivity of M1 + M2 [+ M3] mirrors
- The HAMPs in pink branch is used to feedback M2 vibration

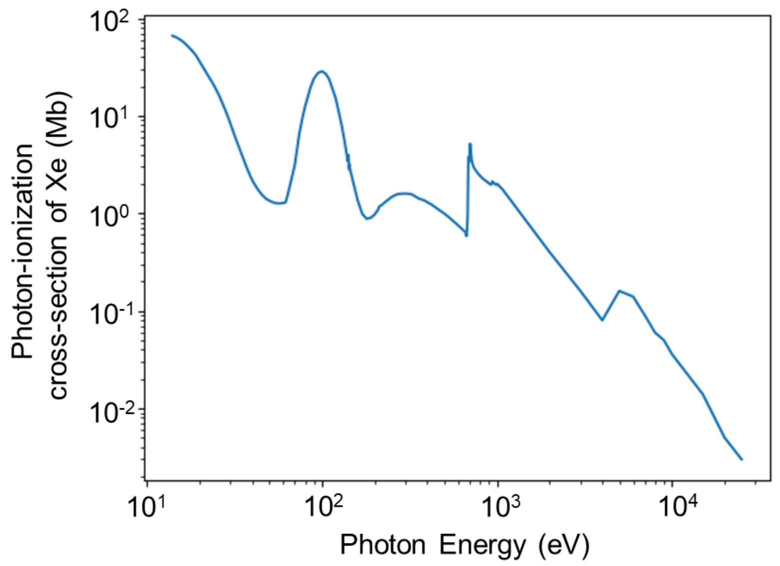
HAMPs： detector module



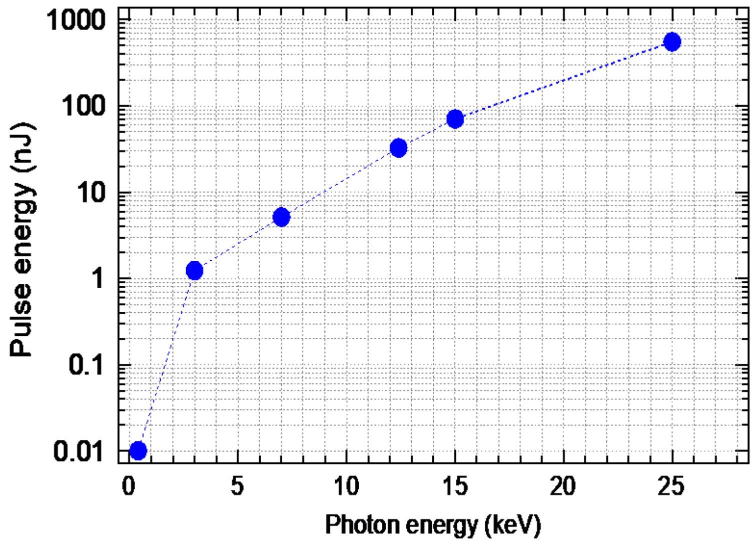
Calculation on detection threshold

Working gas: Xe

Number of ion generated by single pulse ≥ 1



$Q.E.(\hbar\omega)$ of Xe



detection threshold of Xe

Detector length: ~200mm
Number of stages: 24
Working voltage: 4kV-7kV
Working pressure: 5E-3Pa
Working gas: Xe, Kr, Ar...

Capable of detection of 1 μJ at 400eV

HAMPs： mechanical design

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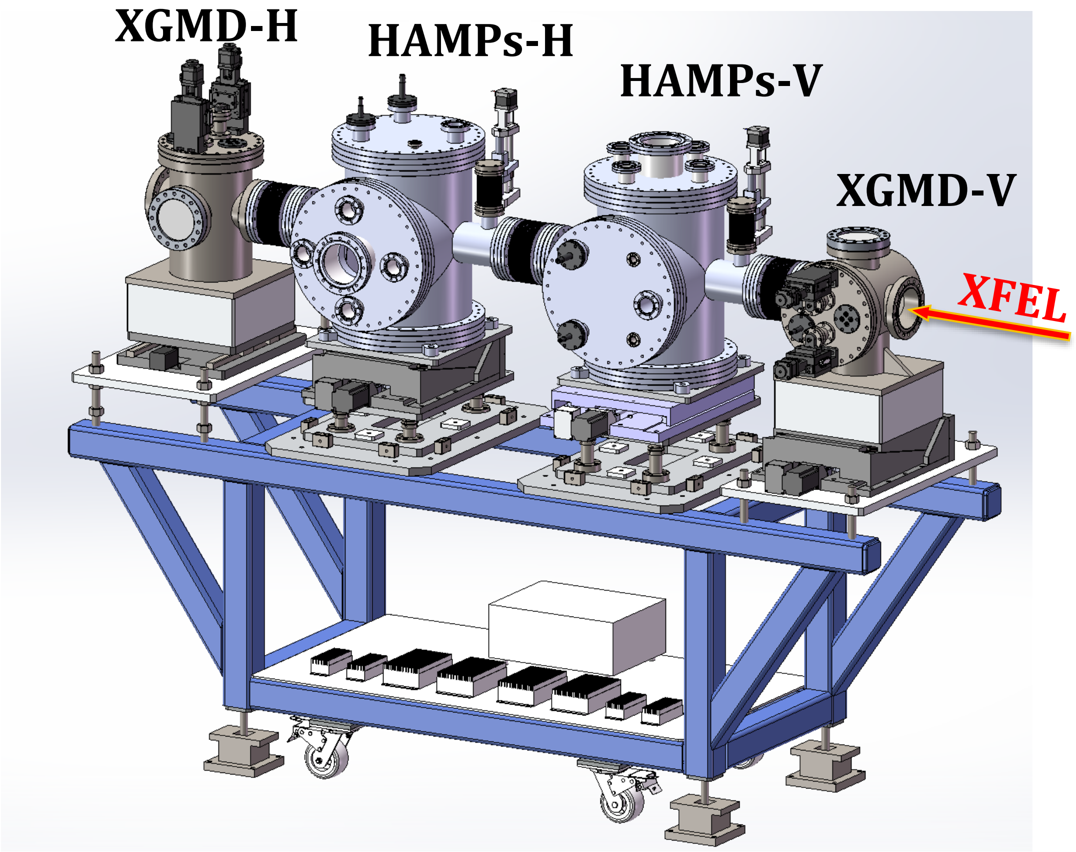


Differential pumping (300L TMP × 2)

Range: 5 orders (5E-3 Pa →5E-8 Pa)

Differential aperture: Φ8mm (Beam size : 2~5 mm@6σ)

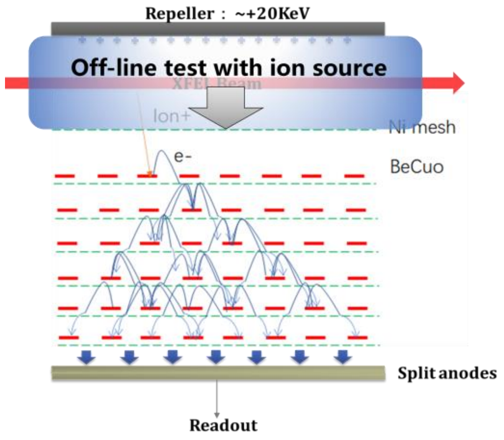
Positioning mechanic

XY motion range： ±10mm

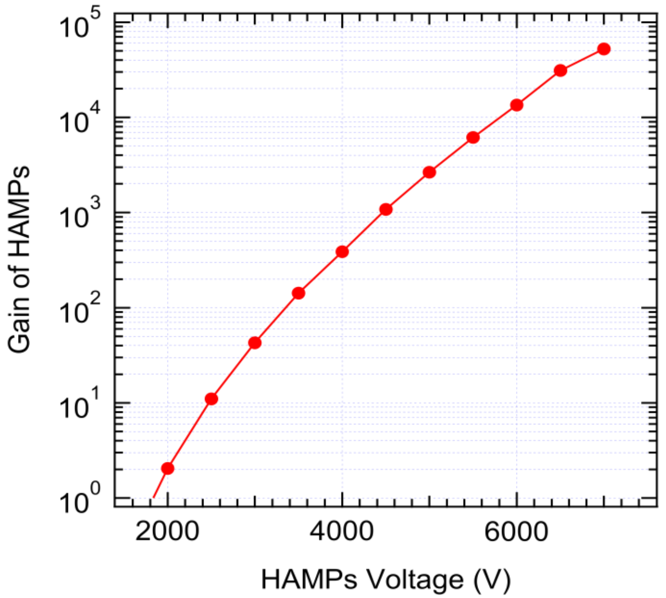
XY motion accuracy： 0.05mm

HAMPs: off-line test with ion source

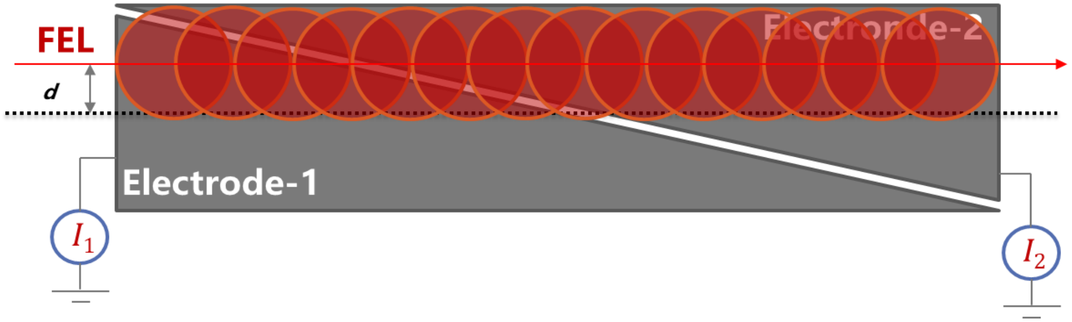
□ Testing with Ion source



Max Gain: 52000 (@7000V)

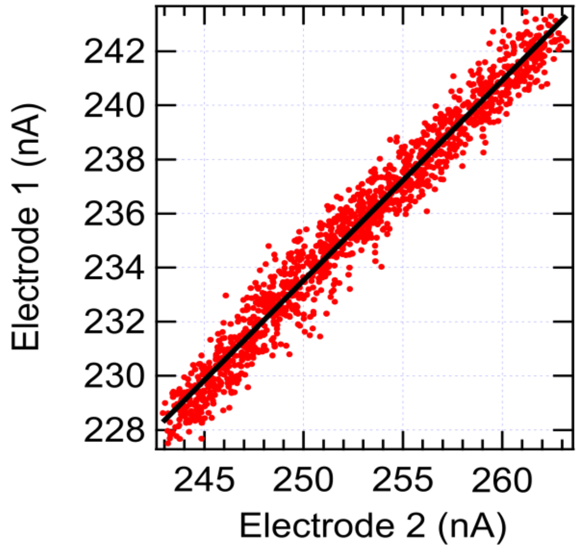


□ Self-correlation test with split anodes: Accuracy of the multiplier

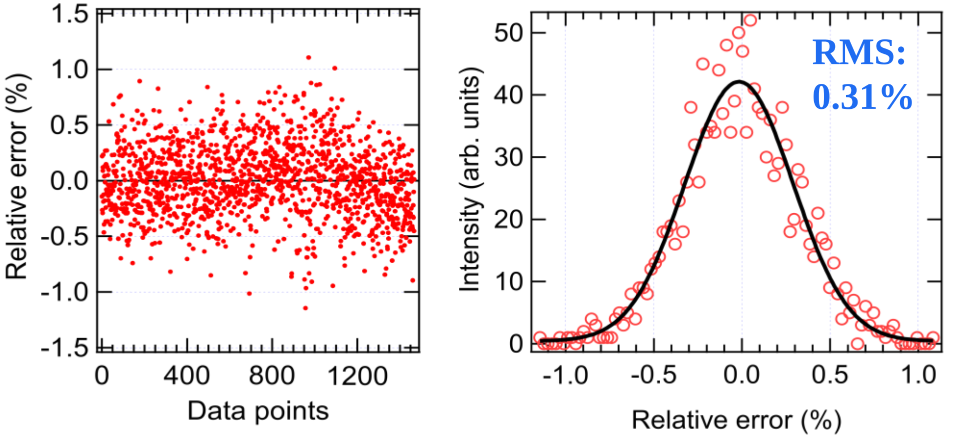


Ideally, the **ratio of the intensity from two electrode** should be 1:1 when XFEL beam pass through the center of detector, or a constant (off-center).

correlation between two electrodes



Error analysis



Conclusion (off-line test)

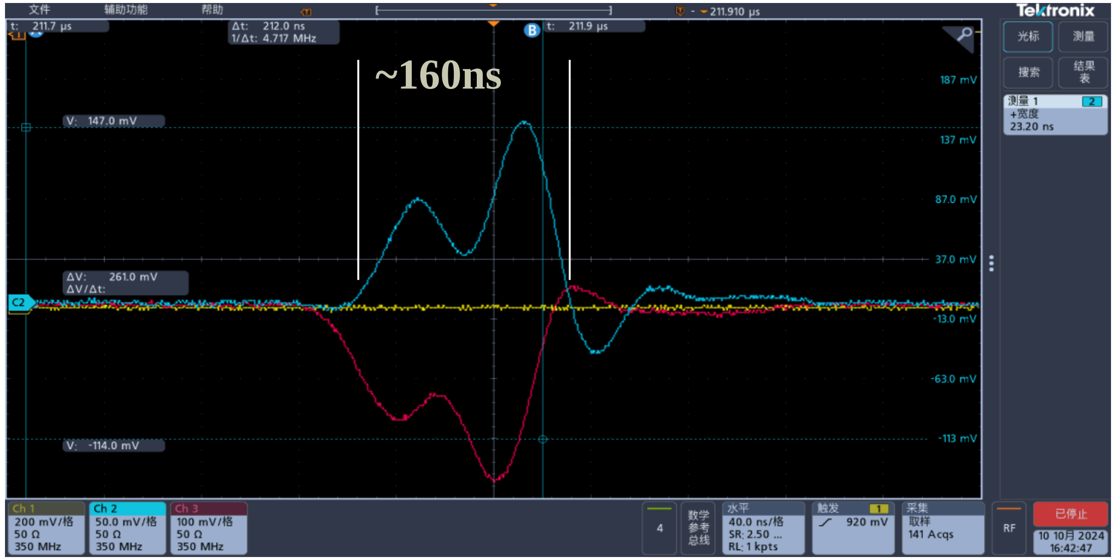
1. **Max gain > 4 orders**
2. **Accuracy ~0.31% (RMS) for DC signals.**

HAMPs: on-line calibration @SXFEL

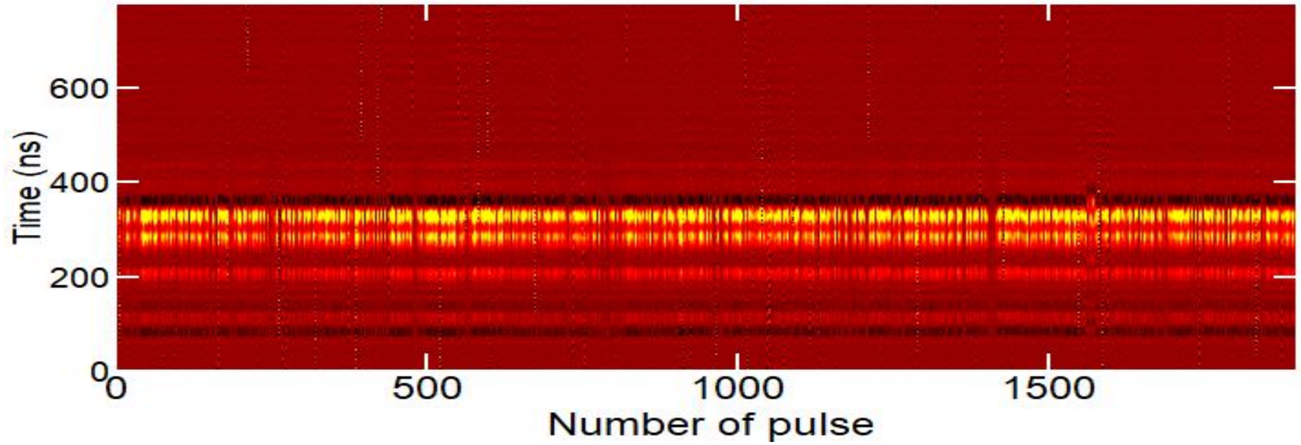
1. Wave form of multiplied signal

time duration ~160ns (capable for high repetition)

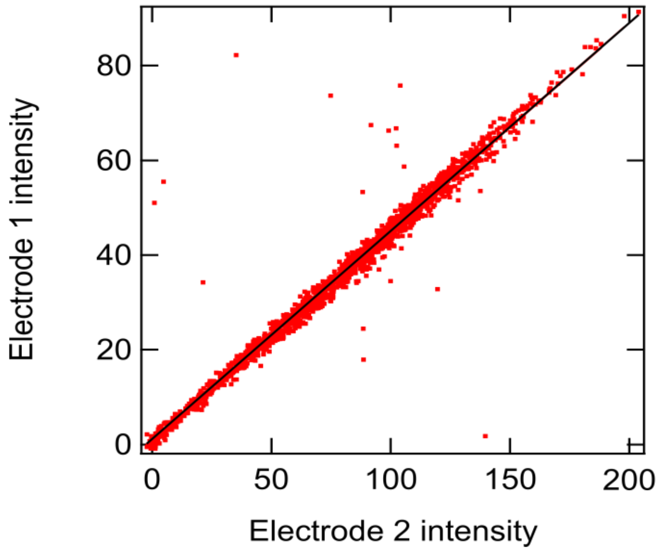
(Incident XFEL: 13.5 nm (92eV), 25Hz)



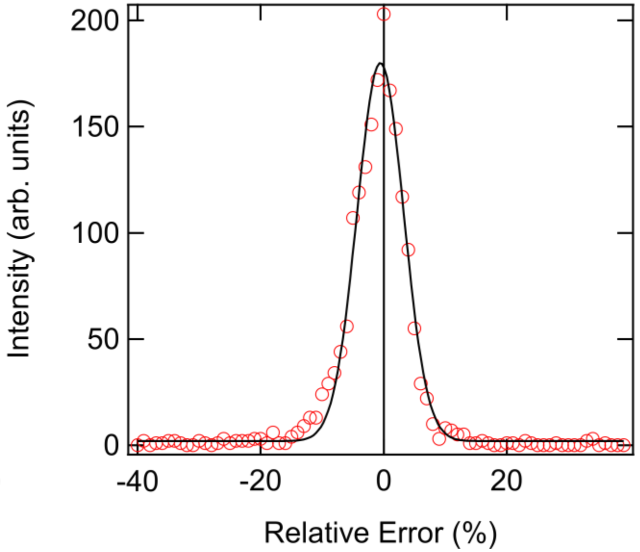
2. Pulsed signal acquisition with Fast ADC



correlation between two electrodes



Relative error: 3.8%(RMS)



Conclusion of on-line test:

1. **Time duration of each multiplied pulsed sigal: 160ns --> capable for high repetition (≥100kHz);**
2. **Accuracy test for pulsed signal: 3.8% (RMS), fulfill the commissioning specifications.**

Pulse position diagnosis：on-line test

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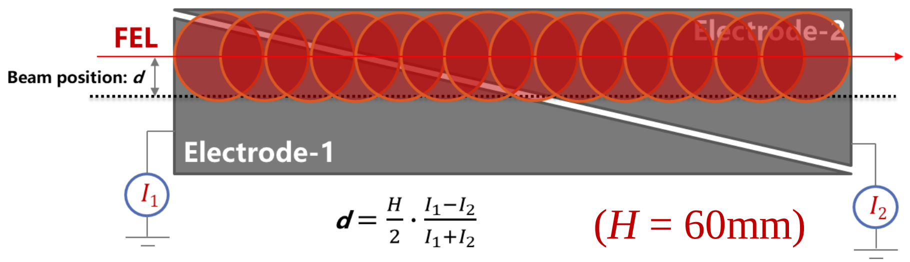
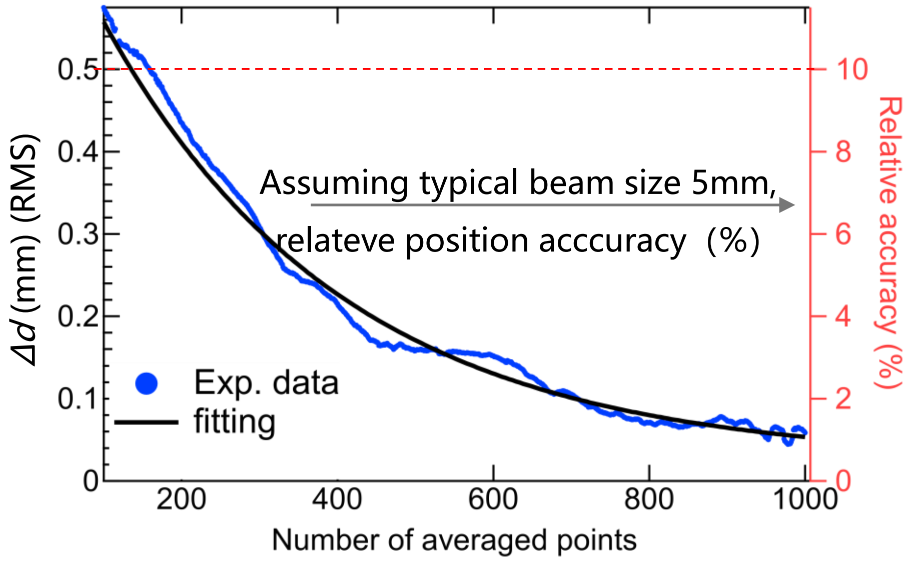
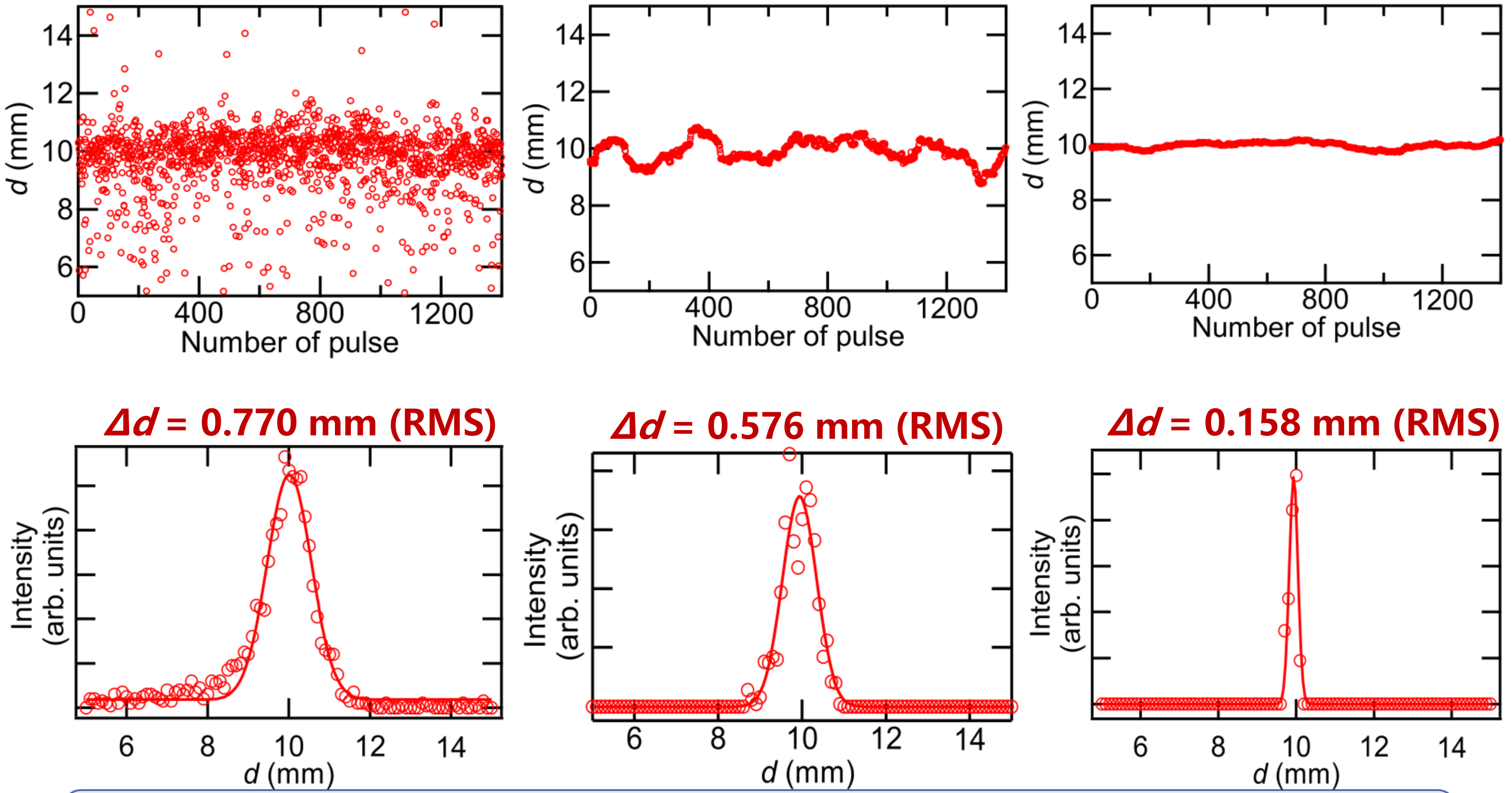
Principle of position measurements





Oginal data (no average) **Average of 100 points** **Average of 500 points**



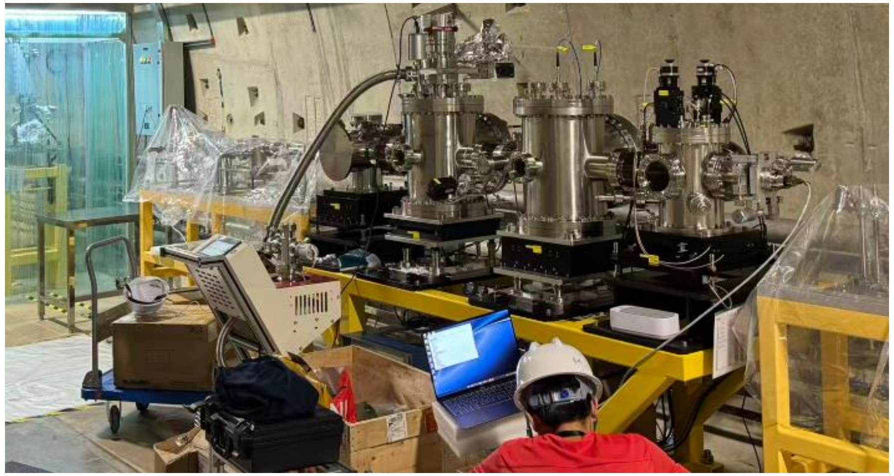
Conclusion of position diagnosis (multi-pulse average):

Position accuracy <0.5 mm @ avegage of >200 points

Fulfill commissioning specifications ≤10%, assuming typical beam size of 5 mm.

First GMD+HAMPs installed

FEL-II XGMD+HAMPs_1

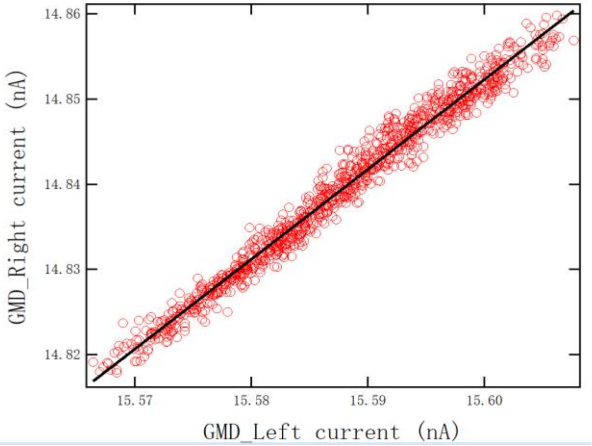


FEL-II XGMD+HAMPs_2

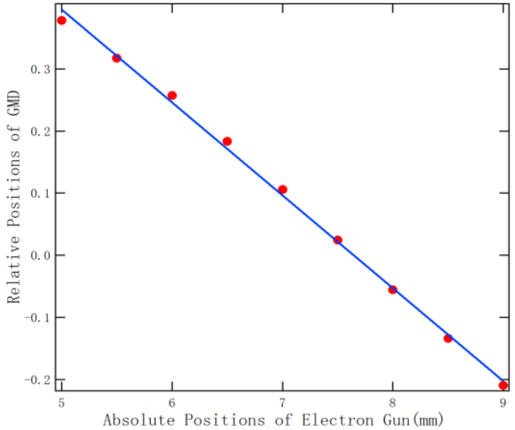
Rack installed, chamber will arrive in November

Offline test with ion source

Correlation of two anodes



Position calibration



FEL-II HAMPs_3

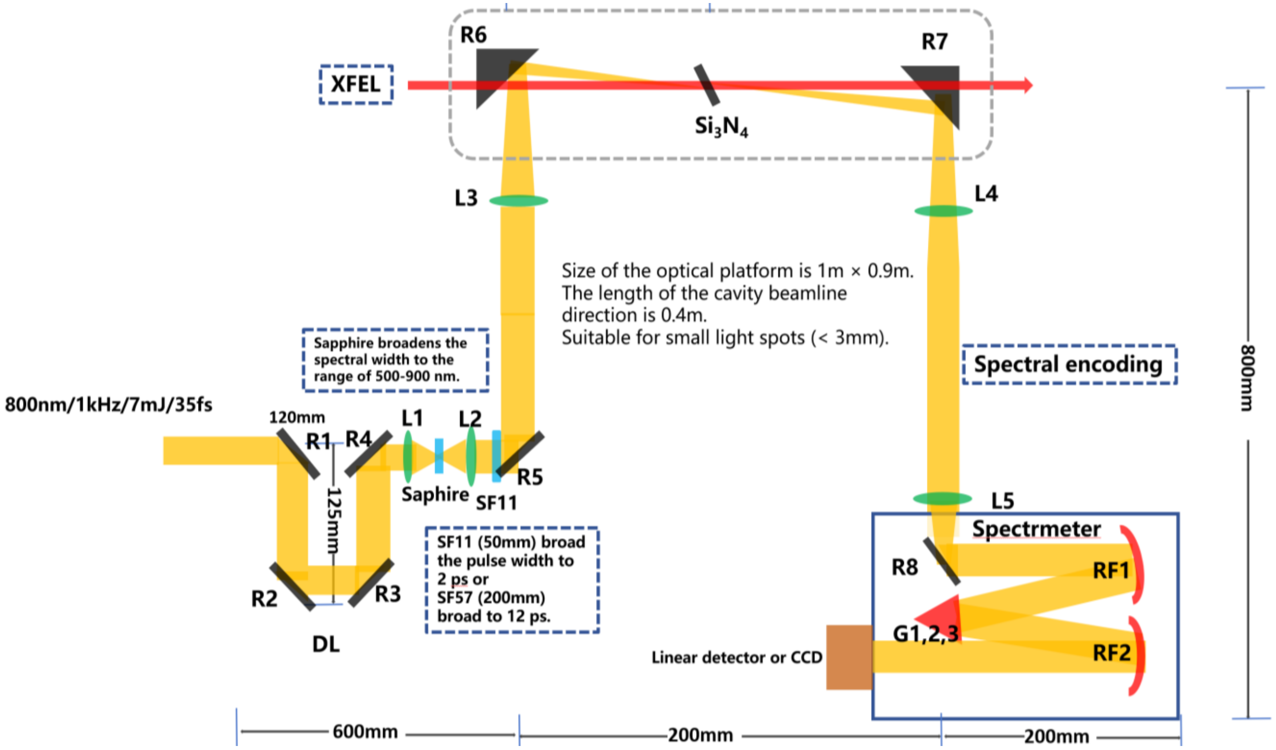
Rack arrived, waiting in installation queue

Pulse arrival monitor (PAM)

Experimental requirements: jitter < 50 fs

Function: pulse arrival time measurement.

Specification: accuracy < 15 fs (RMS)



Harmand, M., Coffee, R., Bionta, M. *et al. Nature Photon* **7**, 215–218 (2013)
PATRIK GRYCHTOL, DANIEL E. RIVAS, et al. Optics EXPRESS 29, 37429-37442 (2021)

PAM: location

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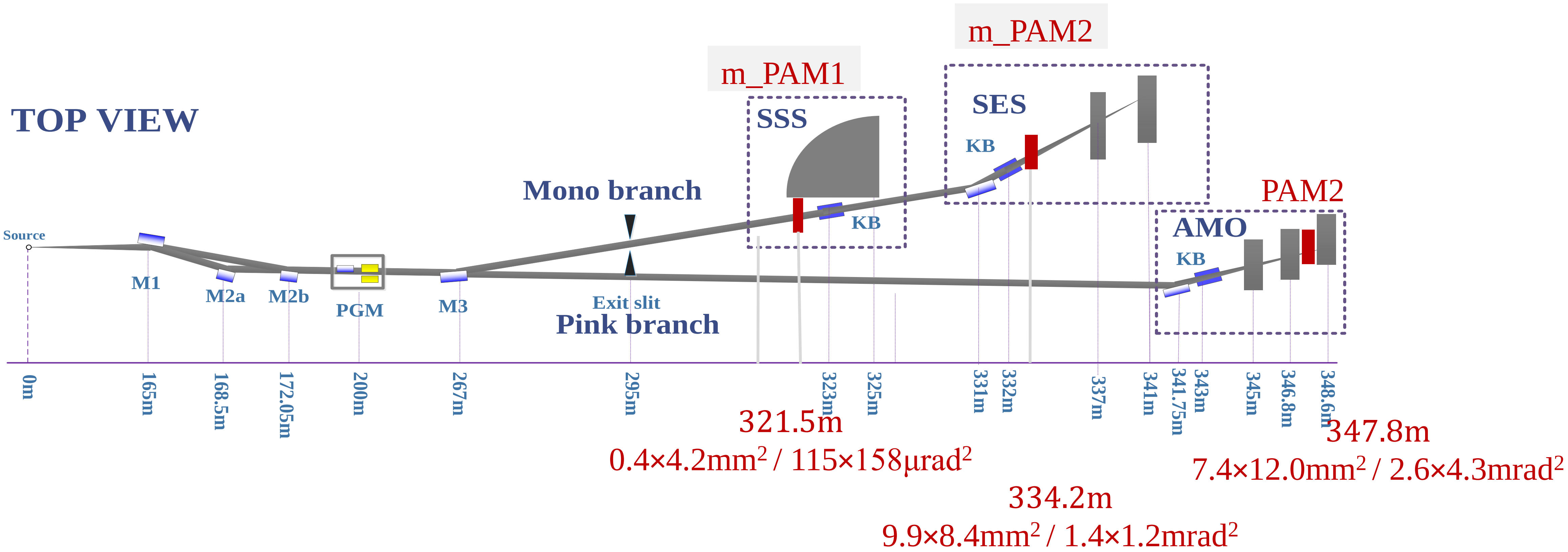
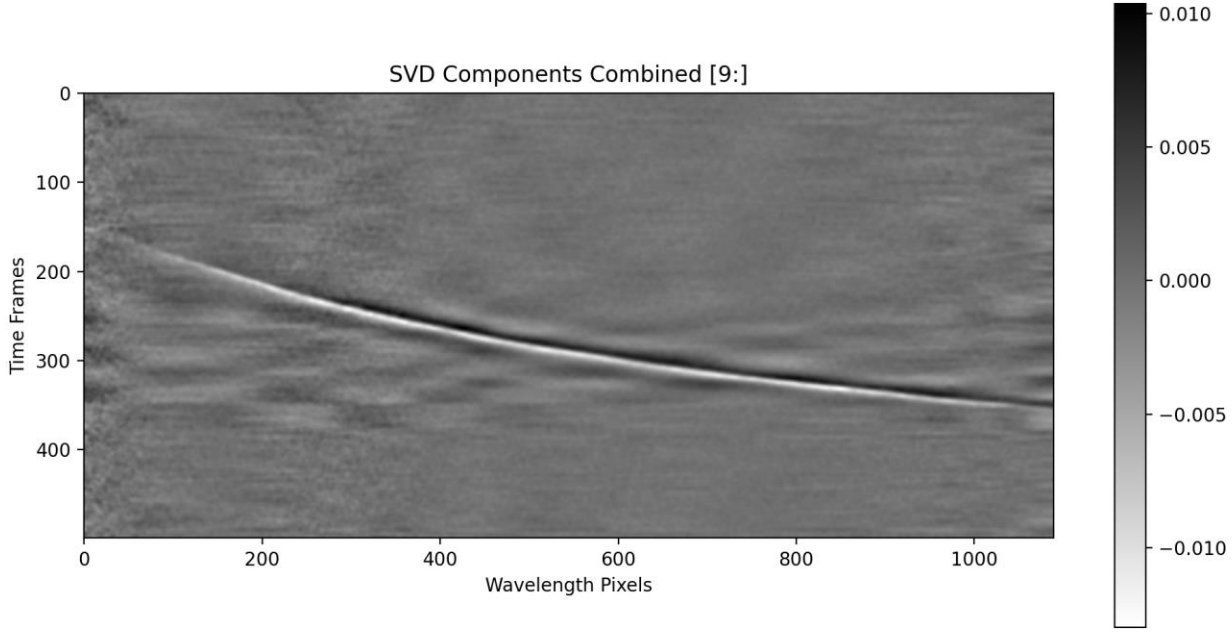


- Location after AMO endstation. Real time measurement of single pulse arrival time for gas sample.
- Each PAM installed before SSS and SES endstations with solid samples. Measurement of jitter and delay line before experiment.

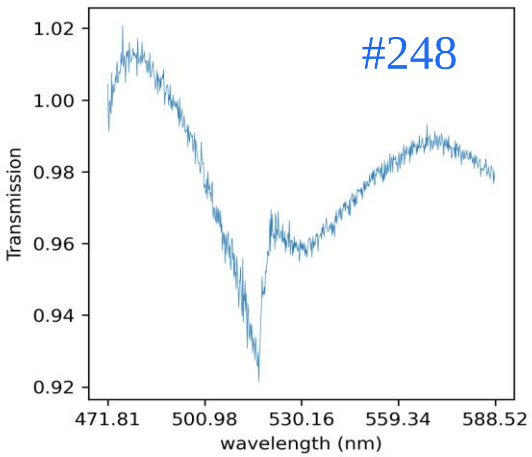
PAM：online test @SXFEL

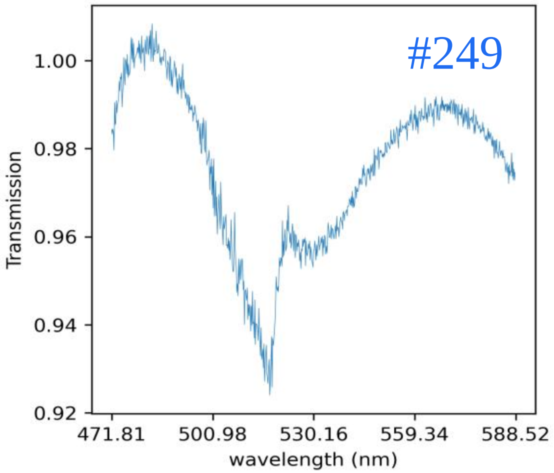
- **Laser: 800 nm/100 Hz**
- **FEL: 413eV (3nm), 10 Hz**
- **Sample: 1 μm-thick Si_3N_4**
- **Triggering signal: GMD intensity > threshold**

1. **Spatial Alignment**
   YAG + camera.
   Both FEL and laser are ~ 100μm.
2. **Temporal Alignment**
   PD + oscilloscope. ~90fs.
3. **Delay line scanning**
   Step size 10 μm.
   Measuring 50 pulses at each position.



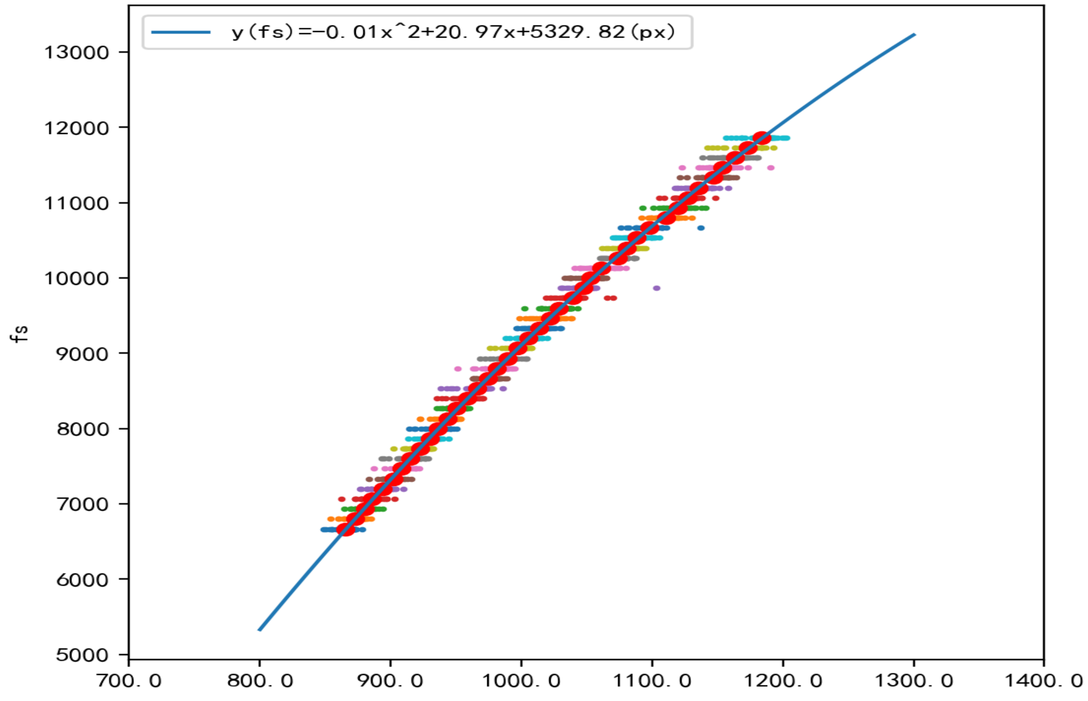
Example of Single-Pulse Spectrum



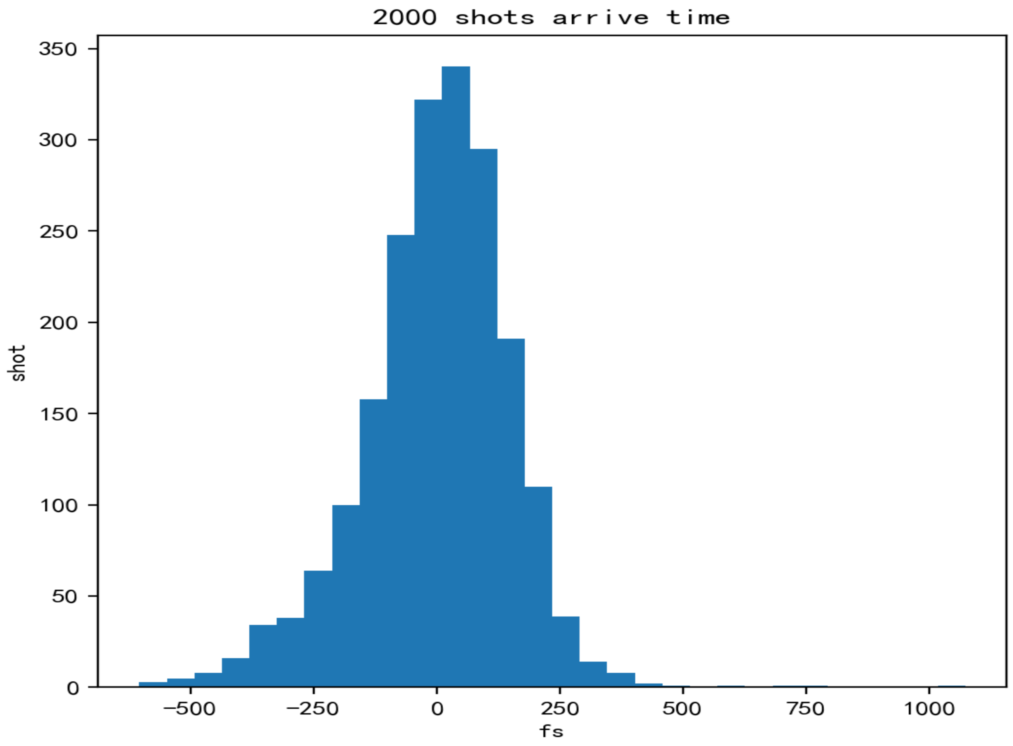


PAM： data processing

Arrival time data of 40 delay lines
(50 pulses for each delay line)

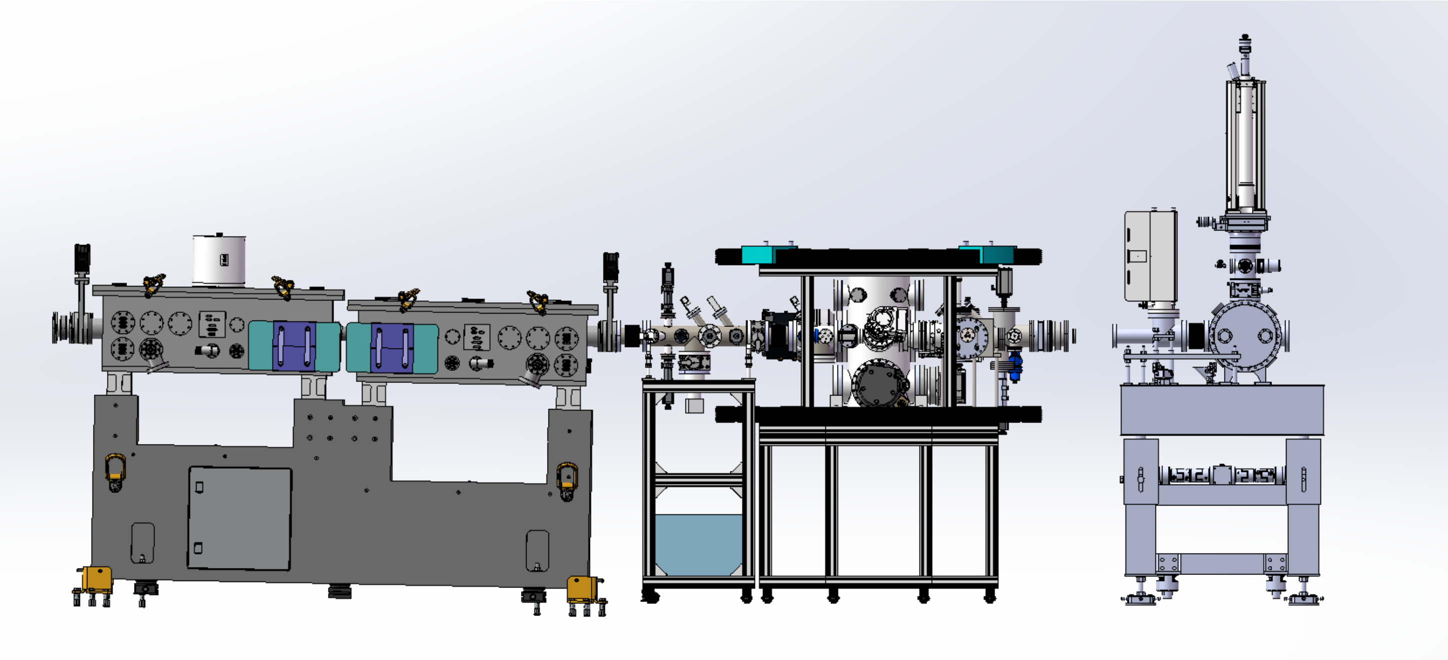


Standard deviation on 2000 pulses
jitter： 150fs rms



PAM： ready for installation

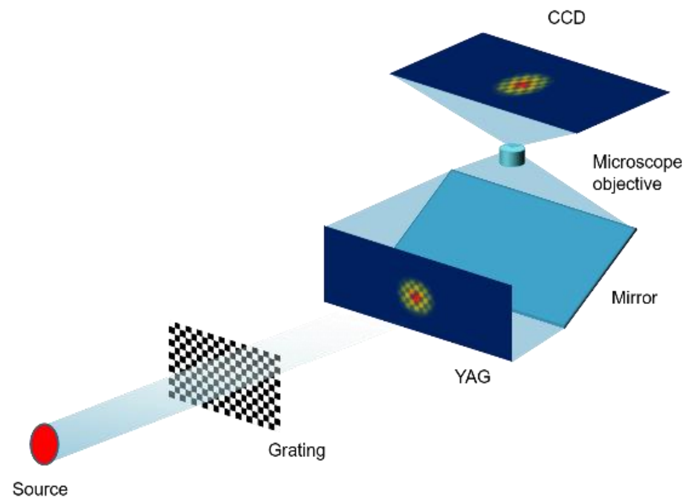
- The PAM will ben installed near the third focal point of AMO endstation.
- The PAM has been moved to Shaft #4, near AMO endstation.

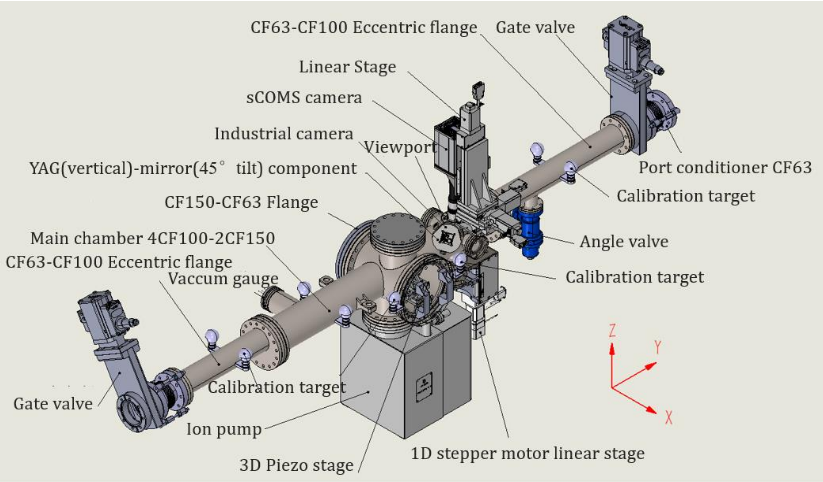


Wavefront Sensor

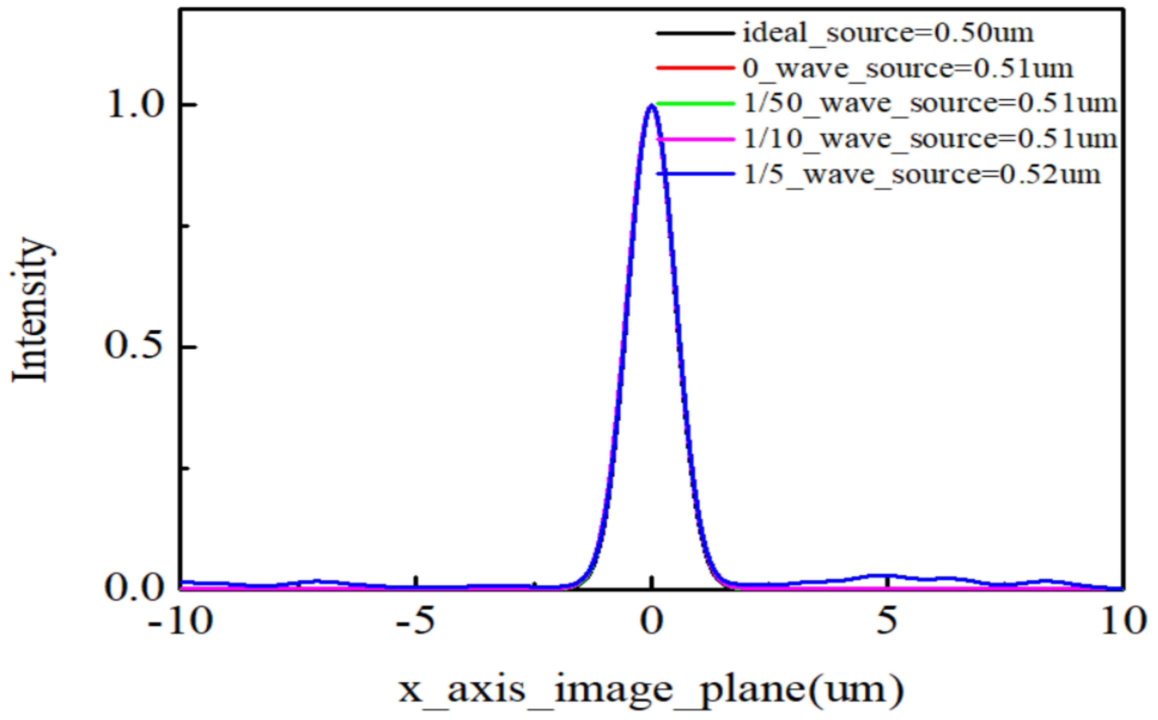
Experimental requirements: Measuring beam spot of ~ 10 μm

Repeatability: λ/50





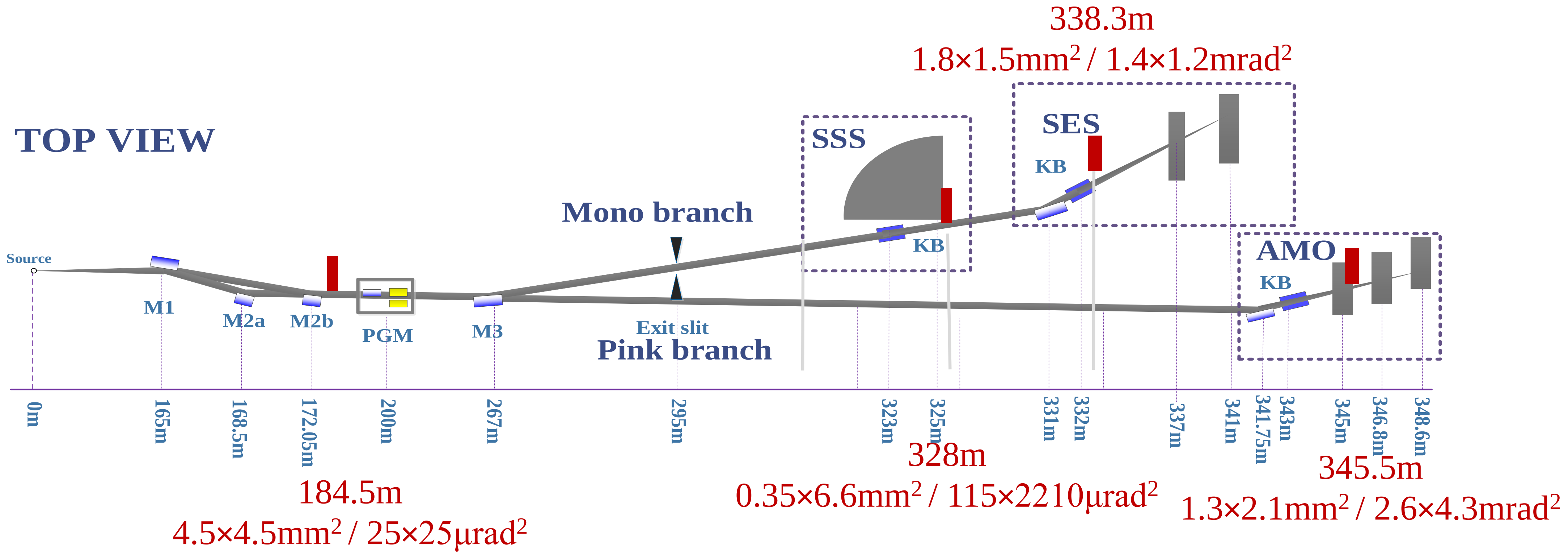
Simulation on beam reconstruction with wavefront errors



Wavefront measurement with λ/50 error is sufficient for 10μm spot

Yanwei Liu et al. Optica, 2018, 5, 967-975
Guillaume Baffou, J. Phys. D: Appl. Phys. 54 (2021) 294002

Wavefront Sensor： location



- Three wavefront sensors are installed after endstations in the beamline.
- First, KB alignment roughly with beam focal spot measurement using imager.
- Second, measurement using wavefront downstream of focal point.
- Reconstruction of focal spot for fine KB alignment.
- One wavefront sensor after M2 bending mirror with 12m distance. Measuring the wavefront to feedback the M2 bending.

Wavefront Sensor： thermal analysis

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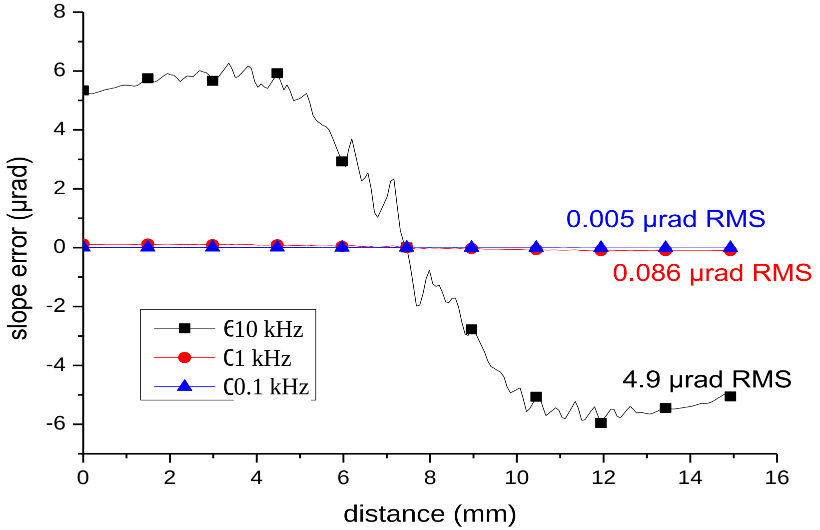
- Photon energy: 900eV
- Pulse energy: 600 μJ
- Silicon grating on Al frame

Wavefront sensor can work at no more than 600mW, which is also experimental requirement.

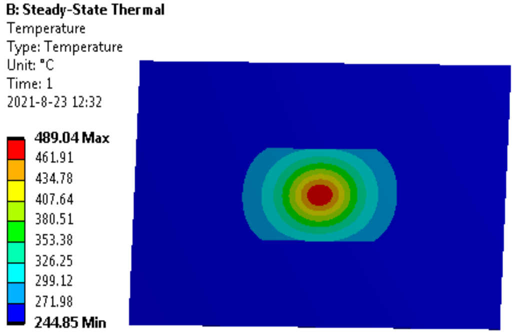


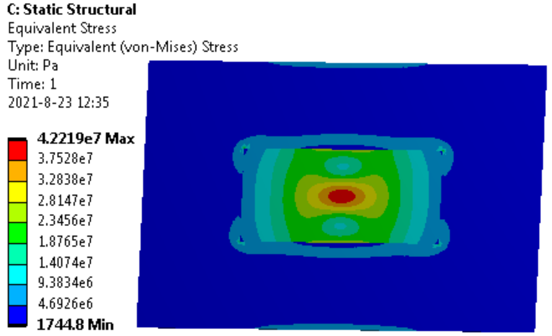
Grating slope error

Temperature: max 489°C

Stress: max 4.2E7 Pa

10 kHz

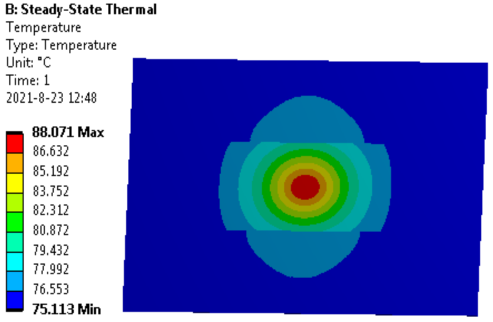


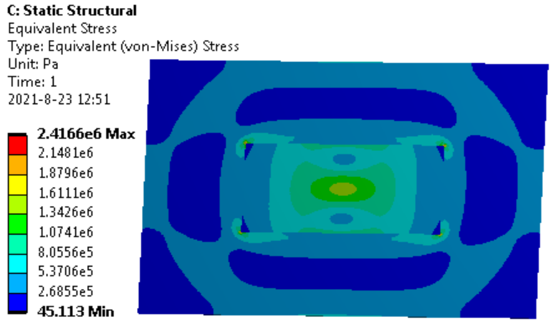


Temperature : max 88°C

Stress: max 2.4E6 Pa

1 kHz





Wavefront Sensor： on-line test @SSRF

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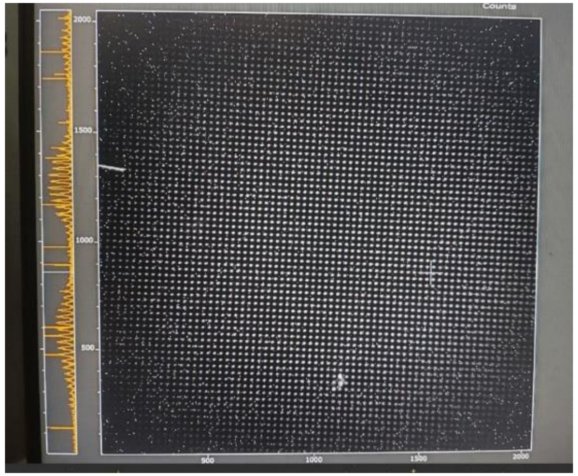
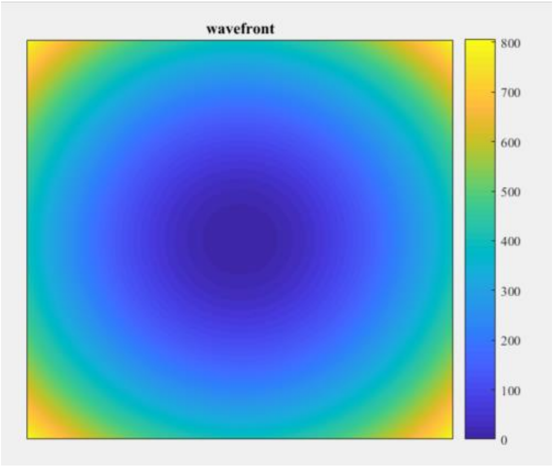
- Energy: 1000eV
- Grating period 18μm
- Pinhole size: 5μm
- Power after pinhole: 3.6nW， exposure time 30s

Experiment on pinhole calibration

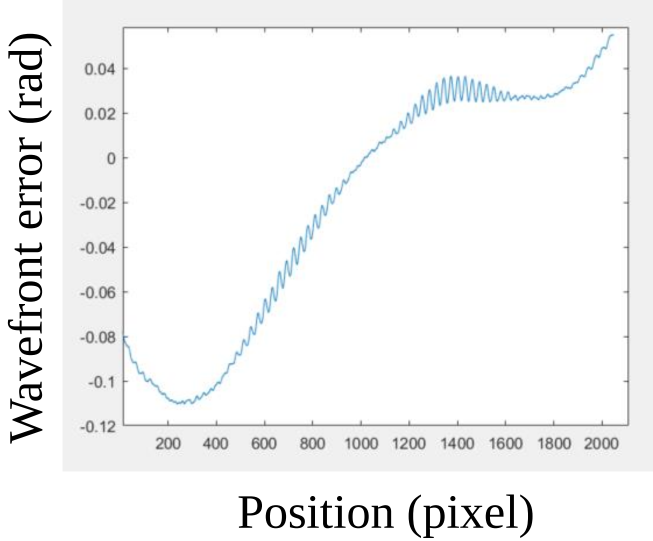
Grating self-image from pinhole



Wavefornt from pinhole



Wavefront measurement error： λ/100



Wavefront Sensor for 3 endstations

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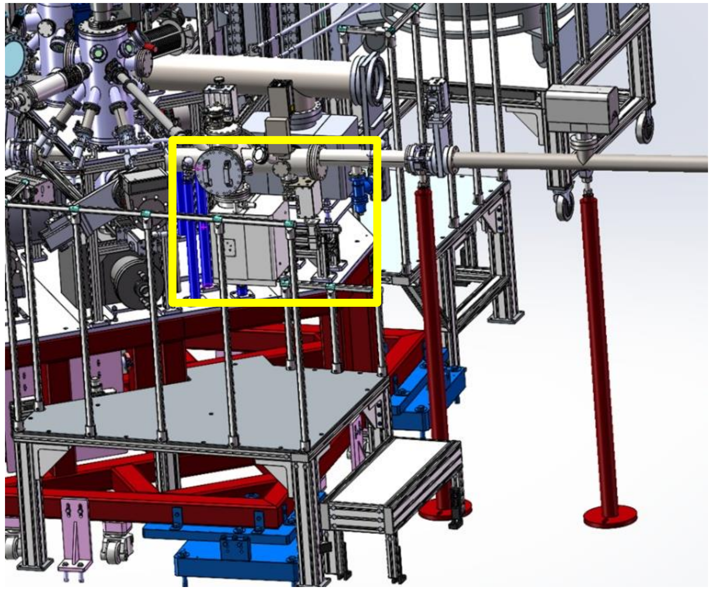
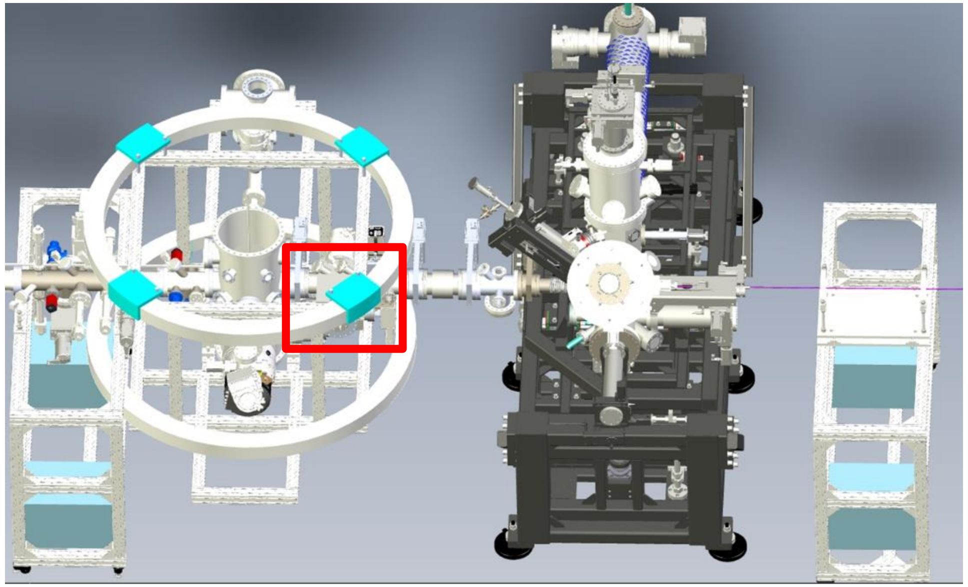
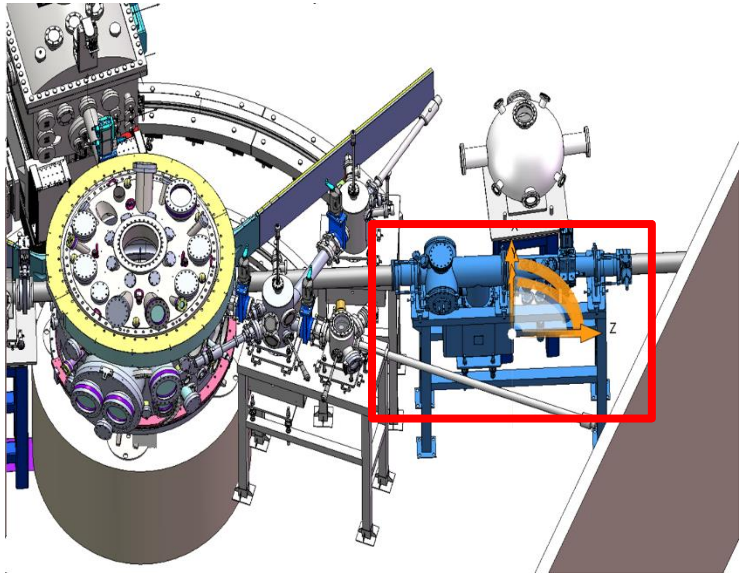
SES endstation



AMO endstation



SSS endstation



- The wavefront sensors will be installed in compact with endstations
- Wavefront sensor for SES： arrive at December
- Wavefront sensor for AMO： arrive at next January
- Wavefront sensor for SSS： arrive at February

Photoemission spectrum: PES

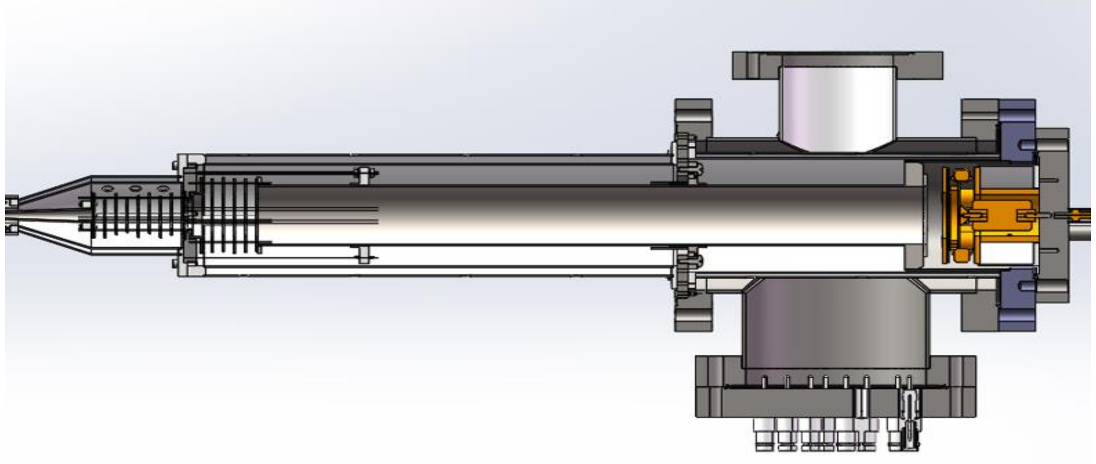
SHINE

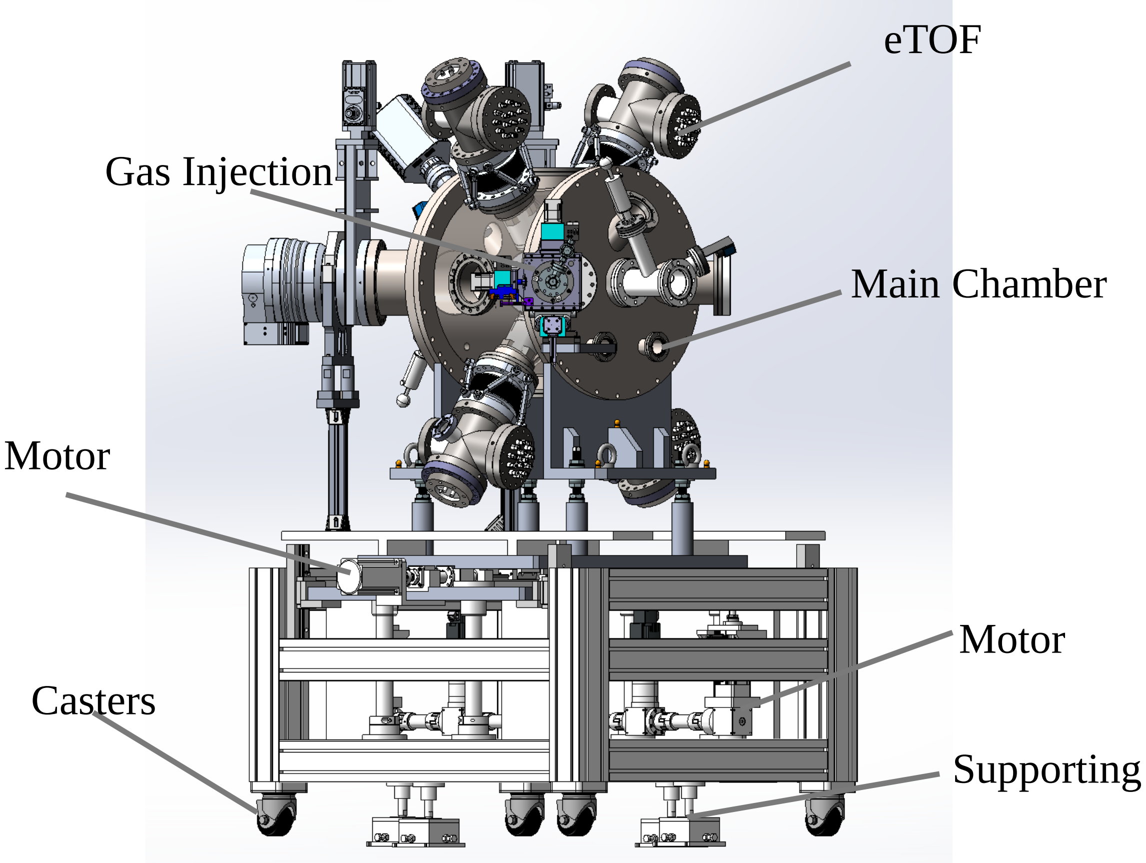
Function：Measure the spectrum of FEL light

Energy resolution: 0.5 eV

Principle: Utilizing eTOF to measure the kinetic energy of photoelectrons to get the FEL spectrum.

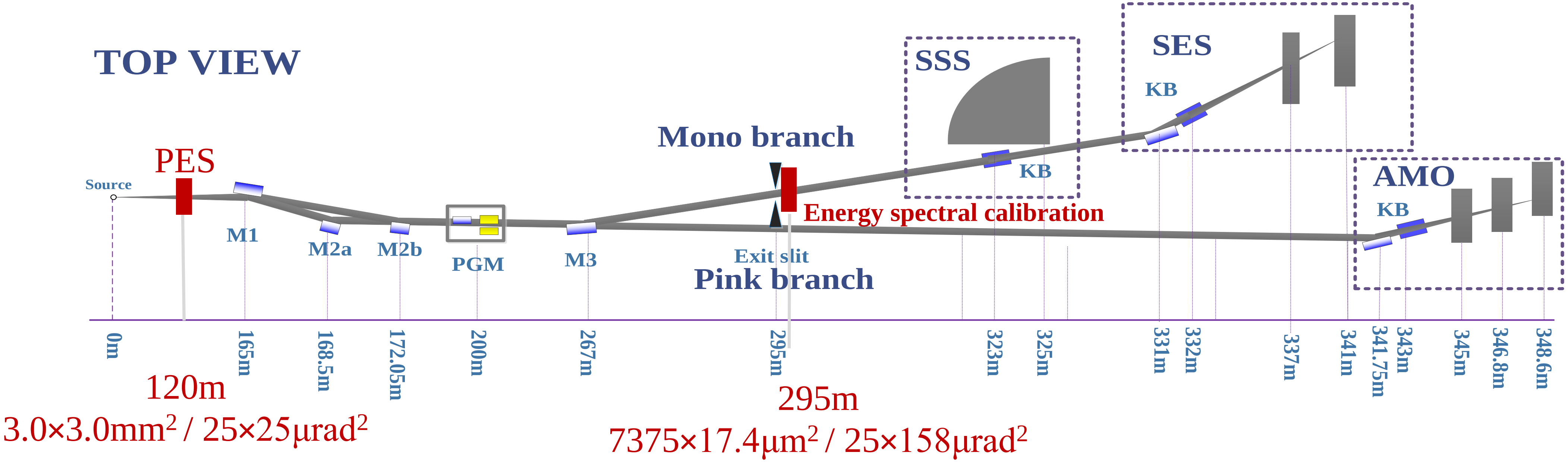
- 4 eTOF are installed in phase I for simplicity.
- Another 4 eTOF will be installed in the future to increase signal noise ratio.
- The eTOF consists of three parts: Nose, electrostatic lens and drift tube.





Markus Braune, et al, J. Synchrotron Rad. (2016). 23, 10–20
Peter Walter, et al, J. Synchrotron Rad. (2021). 28, 1364–1376
Alberto De Fanis, et al, J. Synchrotron Rad. (2022). 29, 755–764
J. Laksman et al., Appl. Sci. 14 (22), 10152 (2024)

PES: location



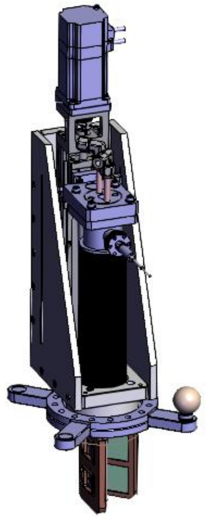
- The PES locates as upstream as possible to get small spot (4~10mm) to increase energy resolution
- Measure the average spectra of multiple pulses
- A YAG imager after the exit slit is used as a calibration tool

PES: online calibration

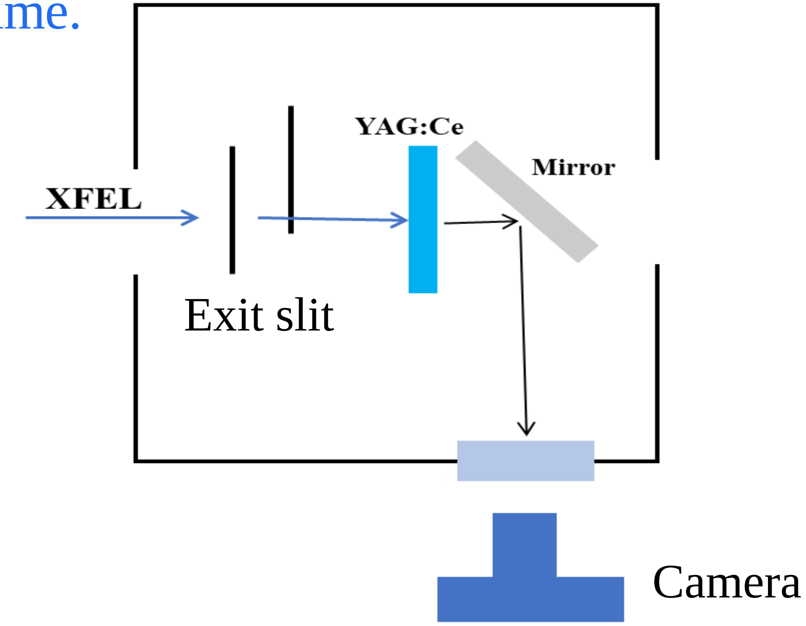
SHINE

- Calibrating monochromator
- Measurement of PES and calibration tool.
  Get a pair of energy and PES flight time.
- Change gap and energy, getting more pairs of energy and PES flight time.
- Calibrate PES parameters (P0~P4) using following equation

$$t_{\mathrm{TOF}} = P_0 + \frac{P_1}{(E_{\mathrm{kin}} + P_2)^{1/2}} + \frac{P_3}{(E_{\mathrm{kin}} + P_4)^{3/2}}.$$



Located after exit slit (within 60mm)

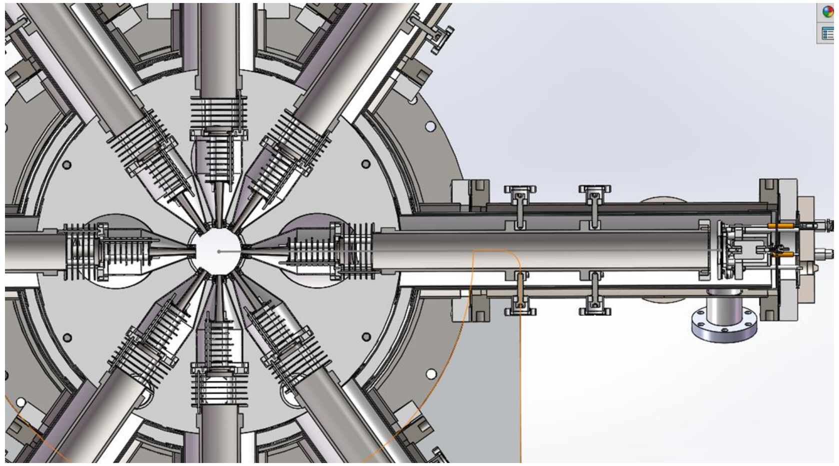


Spatial resolution: 7.8 μm
Field of view: 20mm × 16.8mm

PES: magnetic shielding

Specification: B ≤ 5mGs

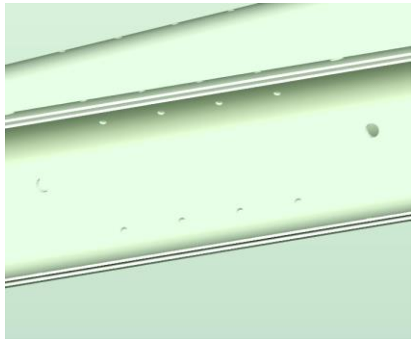
- Main chamber is made of stainless steel. eTOF is made of titanium alloy.
- Both main chamber and eTOF have two magnetic shielding layers.
- There are many Φ10mm holes on eTOF magnetic shielding layers for vacuum pumping.
- There is a magnetic shielding hat to cover the detector at the end of eTOF.
- The magnetic field in the eTOF is measured and meets the requirement.



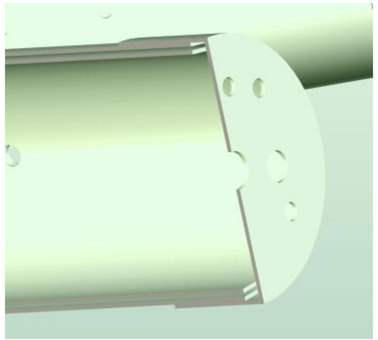
Magnetic field measurement inside eTOF

Axial position (mm)	0	50	100	150	200	250	300	350	390
Magnetic field (mGS)	100.65*	3.72 √	0.76 √	0.74 √	0.71 √	0.73 √	0.76 √	0.98 √	4.60 √

*Measurement was done without main chamber, so 0mm position is outside of eTOF.



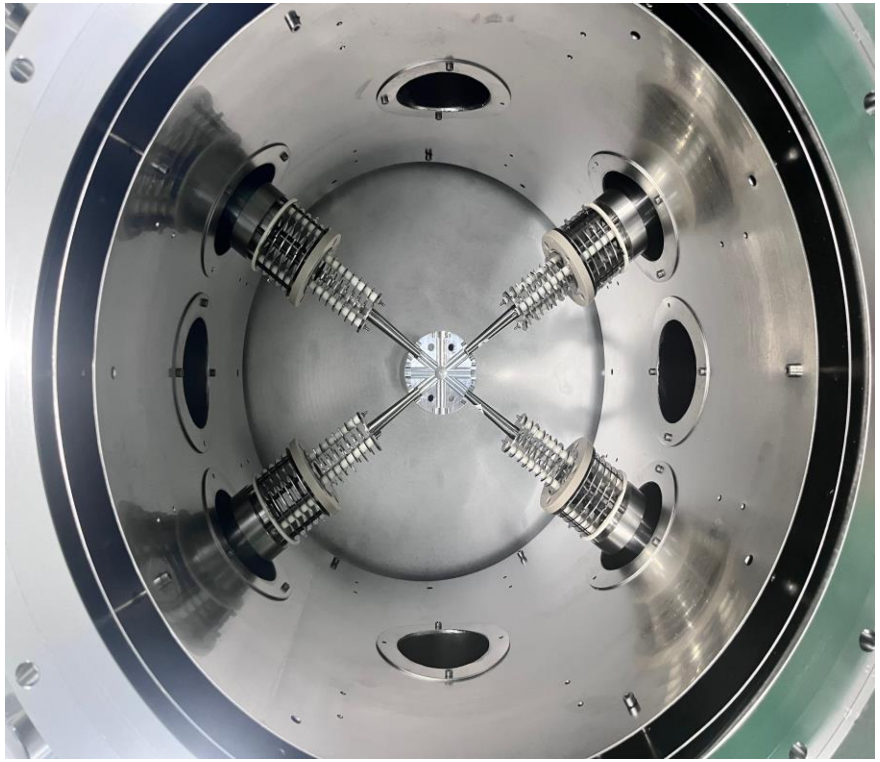
Φ10mm holes on eTOF shielding



Shielding hat at eTOF end

PES: test @SXFEL will be done

- The PES has arrived and installed at SXFEL.
- Online test will start in November, ~ 3days.

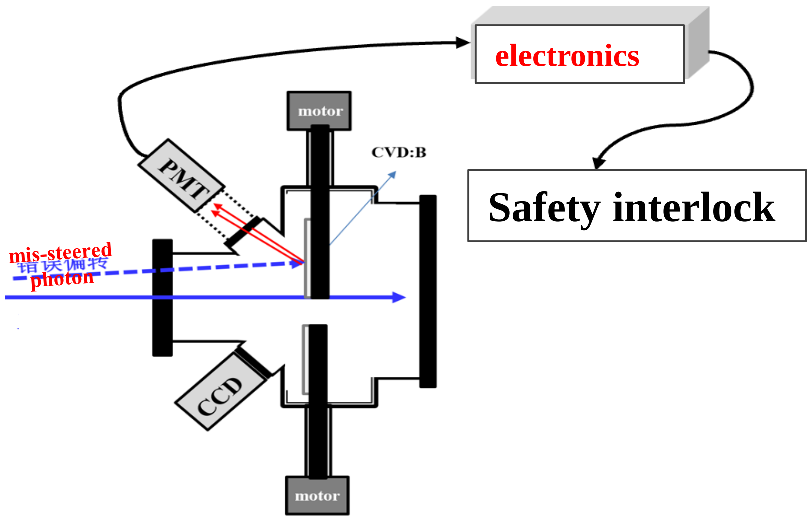


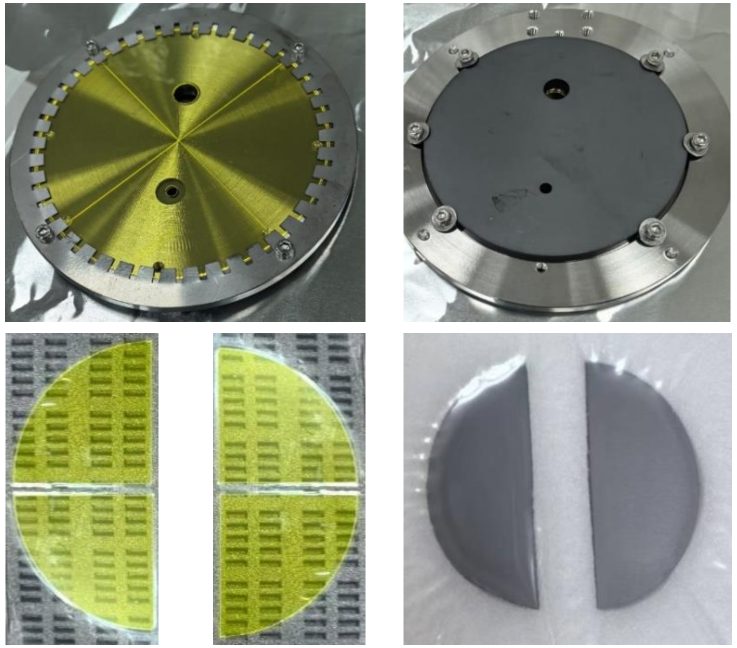
Beam Loss Monitor (BLM): Principle

SHINE

Function： Response on the lost photon beam and notify the machine protection system

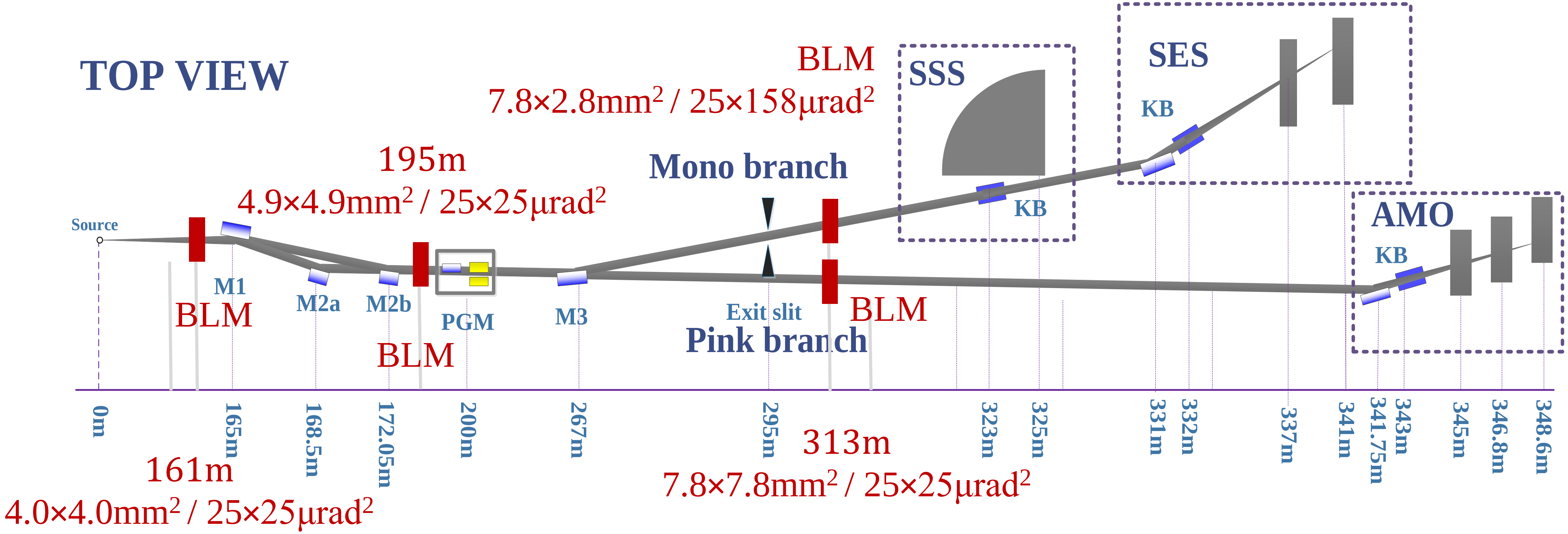
Response time: detecting fluorescence from diamond and response within 10μs





N. Gerasimova, H. Sinn, S. Dziarzhytski, R. Treusch, Proceedings of FEL2014, Basel, Switzerland, ISBN 978-3-95450-133-5

Beam Loss Monitor (BLM): Location



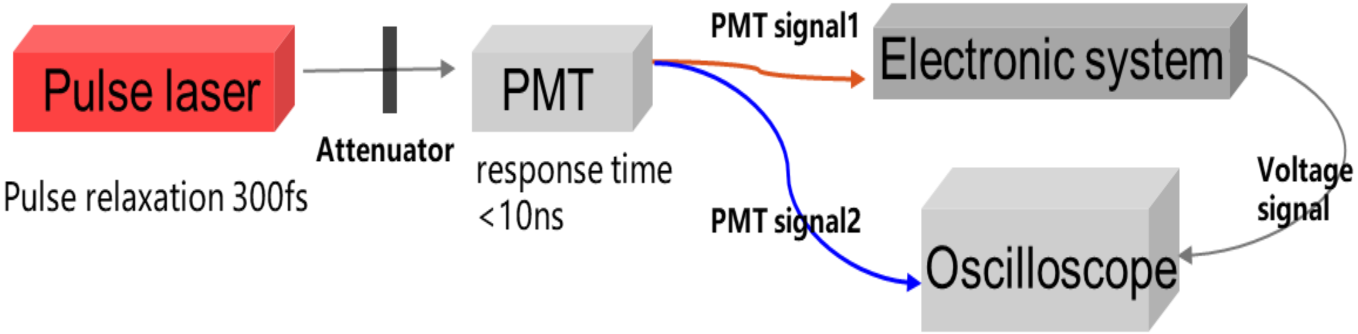
- Four BLMs are installed to monitor the possible lost photon beam
- The threshold will be measured during beamline commissioning

Beam Loss Monitor： Off-line test

SHINE

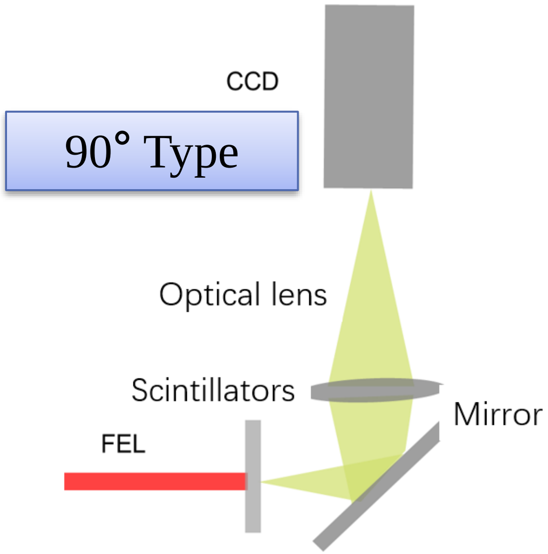
Testing with a 10kHz pulse laser

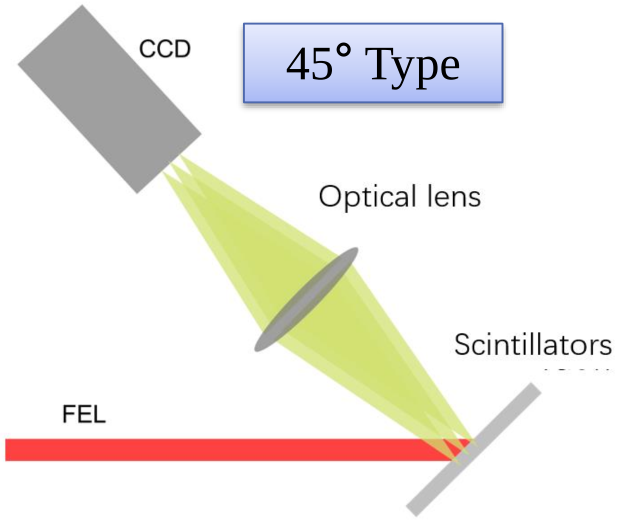
Test results: Delay time is [0.50 - 0.55] μs

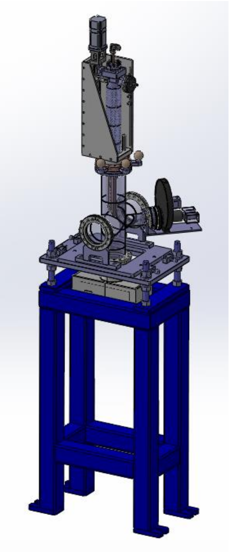


Imager：Principle

Function： Imaging the unfocused FEL light to characterize the beam shape







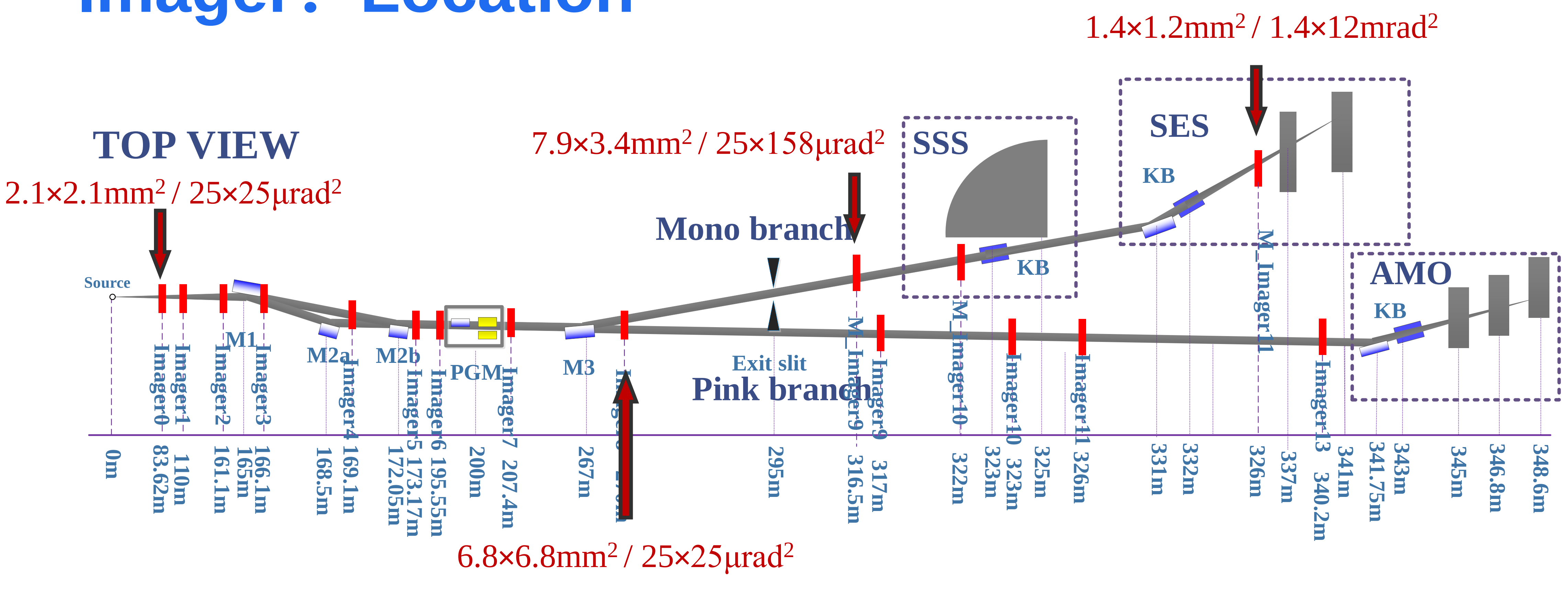
X-ray excitation of the scintillator generates visible photons, which are spatially resolved by the imager.

Two design schemes: 90°-based layout and 45°-based layout

Imager Type	Work distance/mm	Resolution	beamline-compatible
90° imager	200	High	FEL-II Mirror will be damaged in FEL-I
45° imager	210	Low	FEL-I&FEL-II

Andreas Koch, et al, J. Synchrotron Rad. (2019). 26, 1489–1495

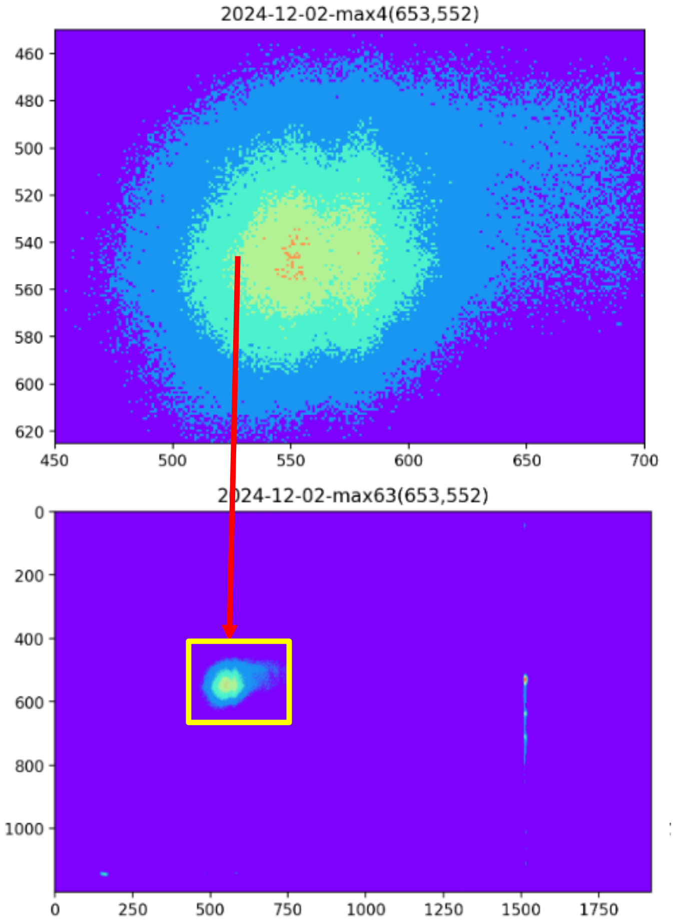
Imager： Location

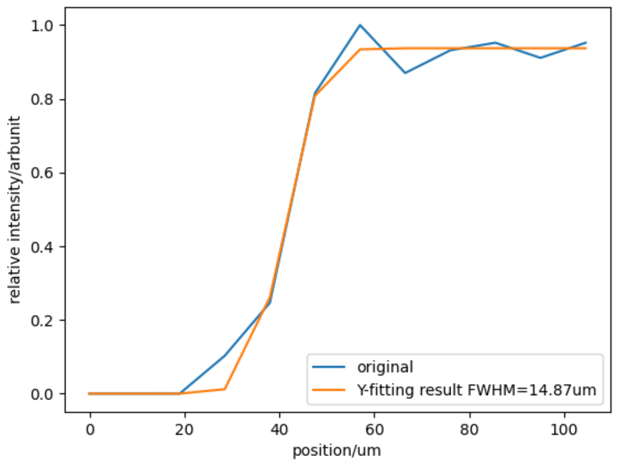


- There are 14 imagers in the beamline
- There is an imager after every mirror and aperture which may cut beam

Imager： online test @SXFEL

In-line measurement of Imager	
Work distance	210mm
Pixel size	5.86μm
Focal length	50mm
Photon Energy	410eV
Min Pulse energy	**0.85μJ**
Spot Size	**3.3mm × 2.8mm**
Average Pulse density	0.7μJ/cm^2



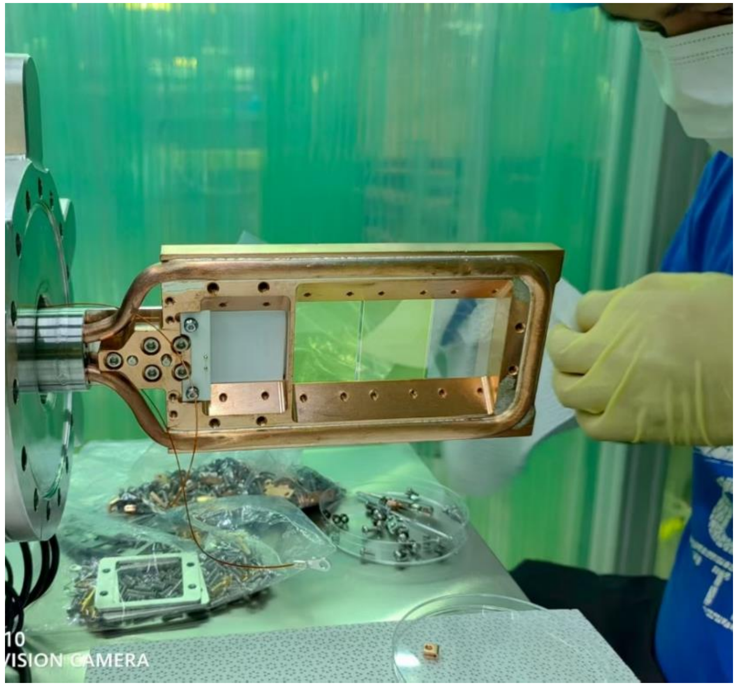


Edge FWHM: 14.9μm

Imager： Installation @ SHINE

SHINE

Installed @ FEL-II



Installing scintillator inside clean hutch

Scintillator type	Size (mm)	Thickness (mm)	Theoretical Light yield (/kev)
gagg： ce	30 * 42	0.2	50
yag： ce	30 * 42	0.2	15
diamond： B	30 * 42	0.2	10

- A rotating plate with 5 different filters is used for different pulse energy.
- Water cooling is used for diamond: B.

- There are totally 14 imagers in the beamline.
- Four imagers have been installed.
- Six imagers have been calibrated and tested for motion control.
- Three imagers are waiting for calibration and motion control test.
- One imager is under manufacture.

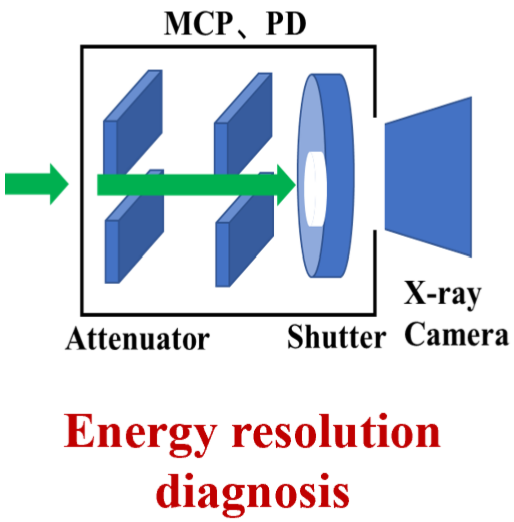
Energy resolution diagnosis

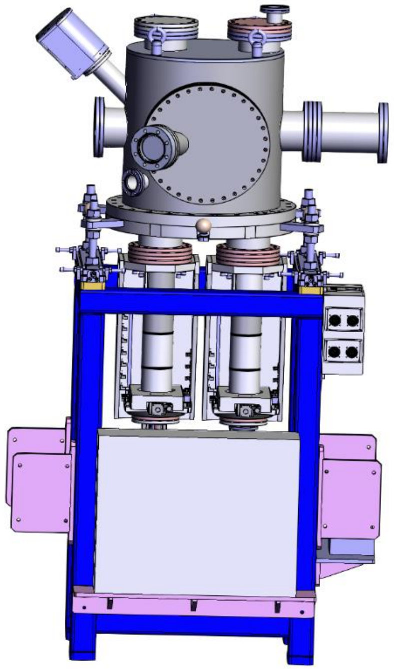
SHINE

Function： Measuring the beamline energy resolution

Specification： E/ΔE=10000@867eV

- Fill Ne gas (pressure~10.5 mTorr, length 20m, transmission~80%) into the gas attenuator
- Measure the Ne absorption spectra using MCP after the exit slit
- Fit the absorption spectrum to obtain energy resolution E/ΔE, assuming Ne natural width is 0.25eV





S. H. Park et al., Rev. Sci. Instrum. 89, 055105 (2018)

Installation plan

SHINE

- The installation of diagnostics system have been started since July 2025 and finished in next March.

Instrument	FE_Imager	Imager1	GMD+HAMPs 1	PES	BLM1	Imager2	Imager3	Imager4	Imager5	BLM2	Imager6	Imager7	Imager8	BLM3
Shippment to SHINE	arrived	2025/6/30	2025/7/25	2025/10/9	2025/7/10	2025/6/30	2025/6/30	2025/6/30	2025/6/30	2025/6/30	2025/6/30	2025/6/30	2025/6/30	2025/7/10
Assembling start	2025/7/28	2025/6/30	2025/8/11	2025/11/12	2025/7/11	2025/6/30	2025/7/14	2025/7/14	2025/6/30	2025/7/1	2025/6/30	2025/7/14	2025/7/14	2025/7/11
Assembling finish	2025/8/7	2025/7/18	2025/8/25	2025/11/20	2025/7/24	2025/7/16	2025/7/30	2025/7/30	2025/7/15	2025/9/15	2025/7/16	2025/7/30	2025/7/29	2025/9/20
Installation	8. 25–10. 11	9. 9–10. 13	8. 26–9. 23	11. 12–11. 20	8. 12–9. 22	8. 12–9. 22	8. 25–10. 10	8. 25–10. 10	8. 12–9. 22	8. 28–10. 13	8. 28–10. 13	8. 28–10. 13	8. 12–9. 22	9. 8–10. 20

Instrument	XGMD+HAMPs2	Imager10	Imager11	Imager13	SES-WFS	AMO-WFS	SSS-WFS	PES calibration tool	energy resolution	m_BLM3	m_HAMPs2	m_Imager10	m_Imager12
Shippment to SHINE	2025/9/22	2025/6/30	2025/6/30	2025/10/30?	2026/1/12	2026/1/1	2026/1/2	2025/8/20	2025/8/27	2025/6/30	2025/9/22	arrived	2025/6/30
Assembling start	2025/9/22	2025/7/14	2025/7/14	2025/11/3	2026/1/12	2026/1/1	2026/1/2	2025/8/21	2025/8/28	2025/7/1	2025/9/22	2025/7/28	2025/7/28
Assembling finish	2025/9/30	2025/7/29	2025/7/30	2025/11/19	2025/12/26	2026/1/27	2026/3/10	2025/9/10	2025/9/29	2025/9/25	2025/9/30	2025/8/14	2025/8/14
Installation	10. 1–10. 15	7. 30–9. 12	8. 14–9. 29	11. 20–1. 5	12. 27–1. 14	1. 27–2. 26	2. 26–3. 10	9. 11–10. 21	09. 30–10. 31	10. 9–11. 17	10. 1–10. 15	10. 9–11. 17	9. 4–10. 13

Commissioning plan (Phase-I: 200eV, 10μJ, 10Hz)

SHINE

Instrument	Period (day)	Commissioning contents
XGMD + HAMPs	6 (parallel)	● Wave form measurement: working gas Kr@5E-4mbar ● Anodes position alignment: Making the signals of two anodes equal ● Pulse energy accuracy : correlation between two anodes ≤10% ● Pulse position accuracy
PES	7 (parallel)	● Alignment: gas injector, 4 eTOFs and beam ● TOF spectrum measurement: trigger test, time alignment, ADC test.
BLM (4)	3	● Beam alignment ● PMT measurement test ● Electronics test: trigger threshold, working mode test
Pulse arrival monitor	10	● Beam alignment: position alignment, rough time alignment ● Time scan: find transmission jump ● Optimization to get better accuracy
Imager (14)	7	● Beam alignment ● Spatial resolution test
Wave front sensor (2)	10	● Beam alignment ● Wavefront test, reconstruction of focal spot ● Align KB mirror to get smaller focal spot
Total	**30**	

Summary

SHINE

- **There are 7 types of tools for diagnostics of pulse energy and time, beam position and size, energy spectrum and wavefront.**
- **The experimental requirements are satisfied by the diagnostics system.**
- **The installation of diagnostics system have been started since July 2025 and finished in next March.**

	Diagnostic tool	Experimental requirements	Main Specification
1	Pulse energy diagnostic (GMD + HAMPs)	Pulse energy: 1-3000 μJ	≤ 10%
2	Pulse arrival monitor (PAM)	Jitter: ≤ 35 fs	≤ 15 fs RMS
3	Talbot Wavefront Sensor	Beam size: ≤ 10 μm	≤ λ/50
4	Photoemission Spectrum (PES)		≤ 0.5 eV
5	Imager		≤ 30 μm
6	Beam loss monitor (BLM)		Response time ≤ 10 μs
7	Energy resolution measurement	ΔE: ~150 meV	ΔE ≤ 86.7meV @867eV

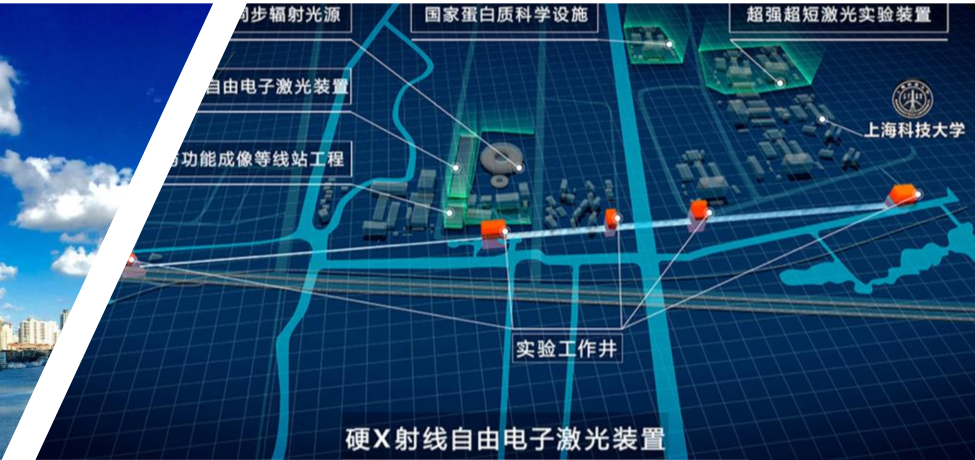
Acknowledgement

- **Team members**
  - PAM：Zhi Guo, Xiangzhi Zhang, Chi Zhang
  - Wavefront Sensor：Xiangyu Meng, Junchao Ren, Zhi Qiao, Yajun Tong
  - GMD + HAMPs: Mao Ye, Jishan Liu
  - Imager：Huachun Zhu
  - BLM: Haigang Liu
  - PES: Junqin Li, Yamei Wang
  - Energy resolution diagnosis: Huaina Yu, Fangyuan Zhu
- **Thank Engineer Department (Jiahua Chen, etc) and Experimental Assistant Department (Ping Huai, etc)**
  - Control, alignment, vacuum, etc.
  - Data management, network, etc.

Questions to the committee

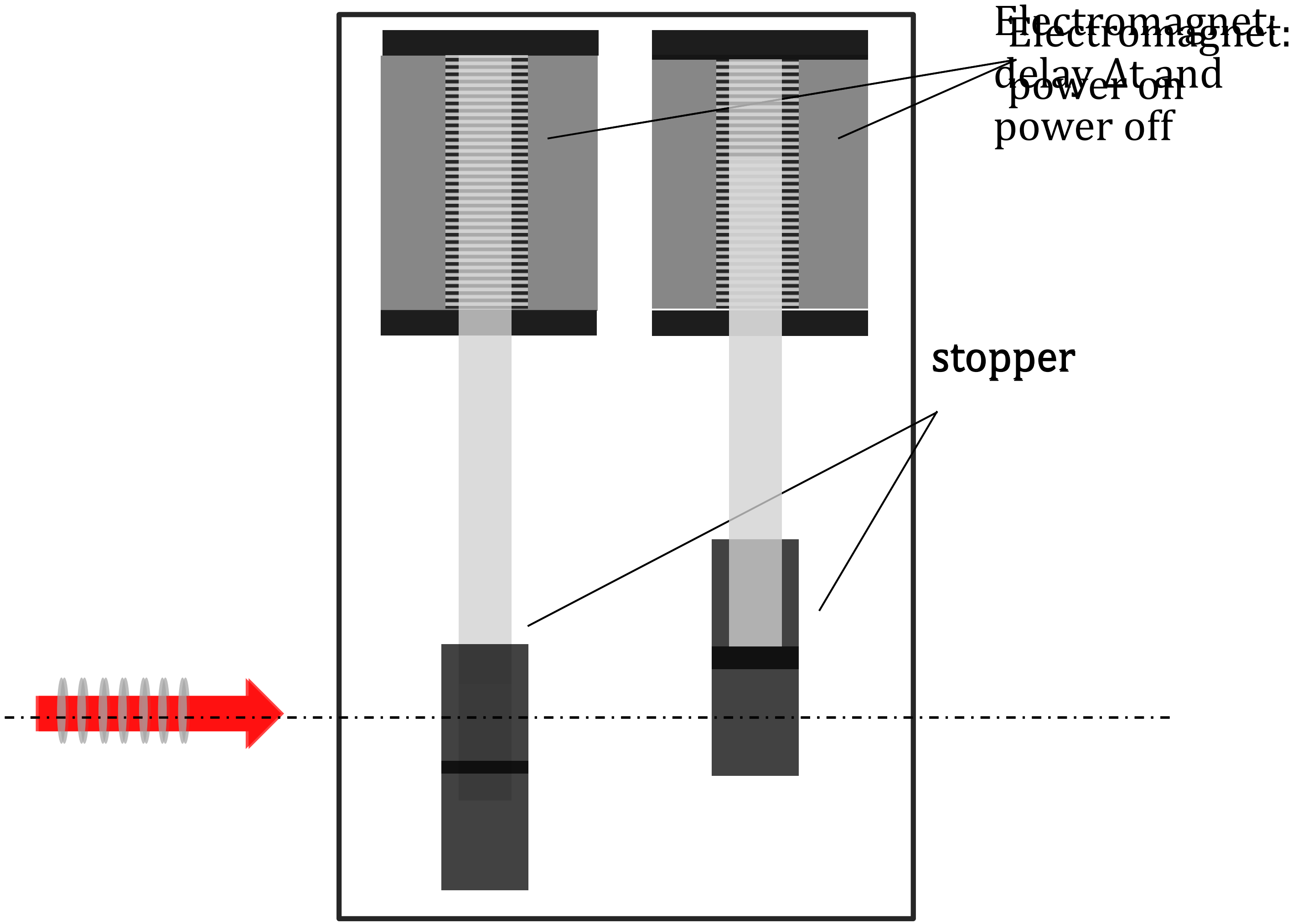
- In the wavefront sensor calibration, what's the best distance between the pin hole and the focal point? How to balance the damage risk and transmitted flux?
- How often to calibrate the HAMPs detectors? For example, every month/half-year/year?
- In pulse arrival time tool, how to selecte suitable samples at high repetition rate and low photon energy?

Thank you for your attention!

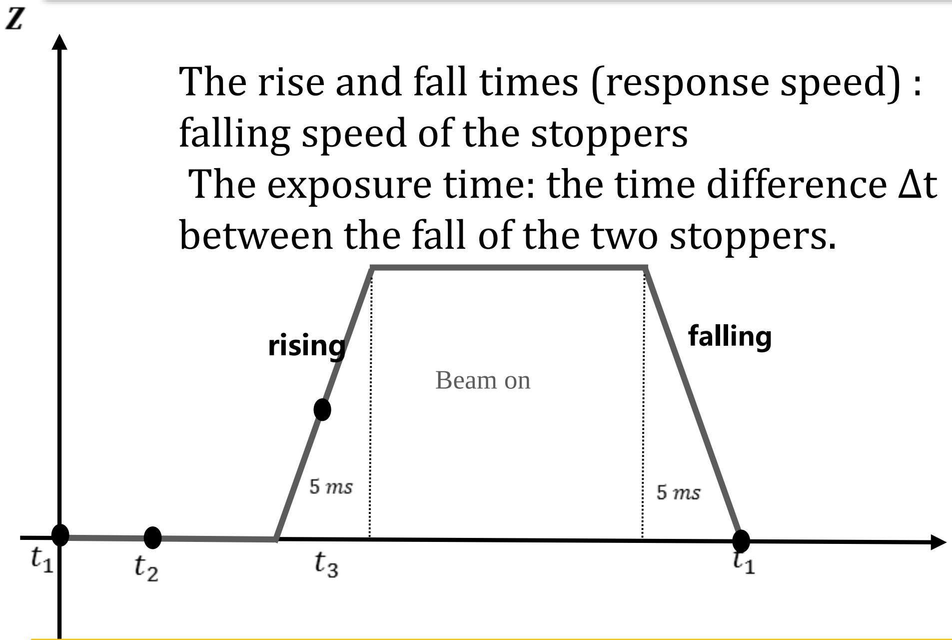


Wavefront Sensor Shutter: Physics

SHINE



Function: Absorbing partial pulse to reduce the power on the grating and YAG:Cr screen



Advantage

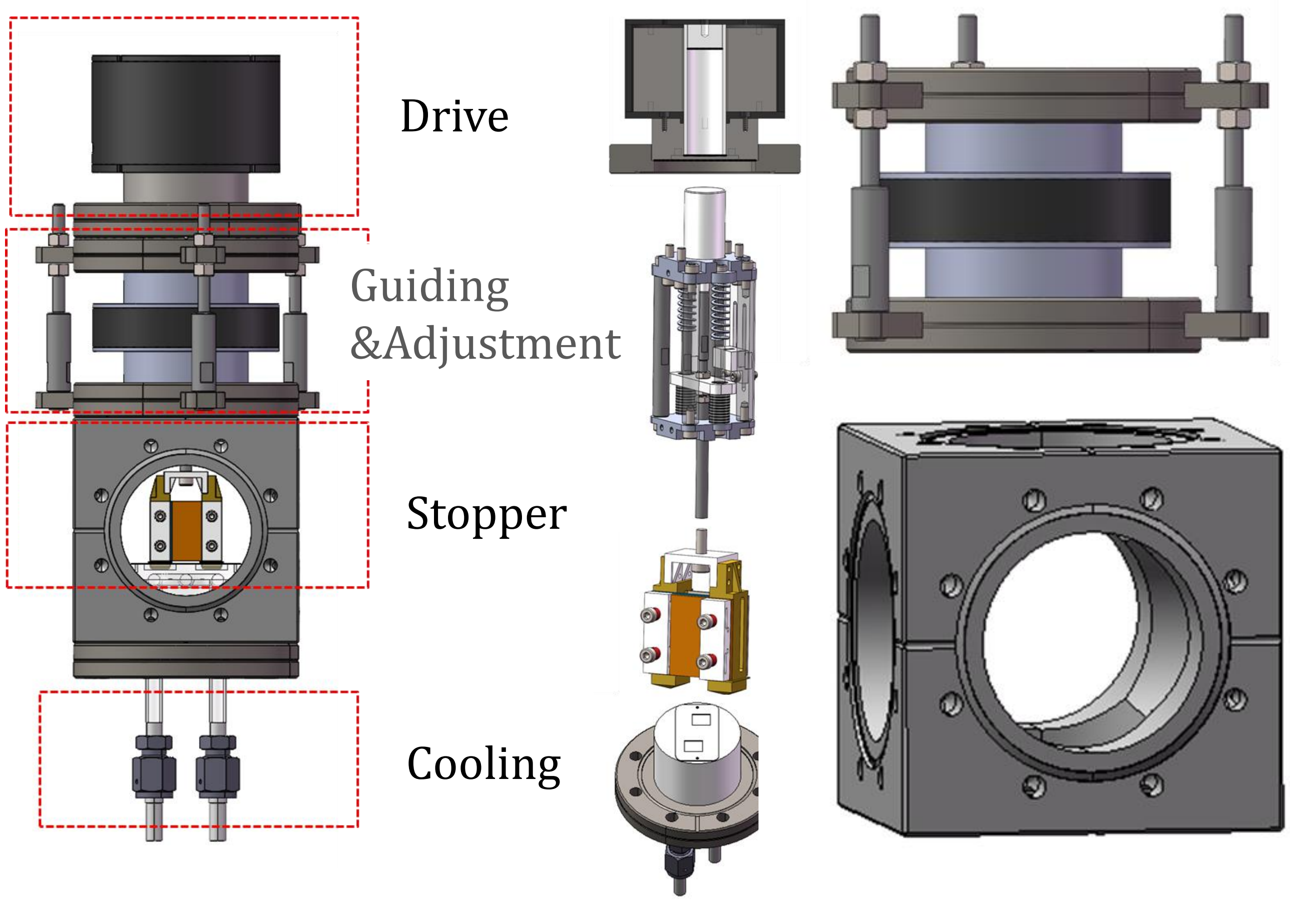
- **The exposure time is controllable Δt**
- **Cyclic exposure**
- **Exposure time Δt can be ~ms**

By allowing two stoppers to fall freely with a time difference of Δt, a light - transmitting window is created to control exposure. The stoppers are cooled to absorb most of the heat from the Free - Electron Laser (FEL).

Design Scheme - Main Structure

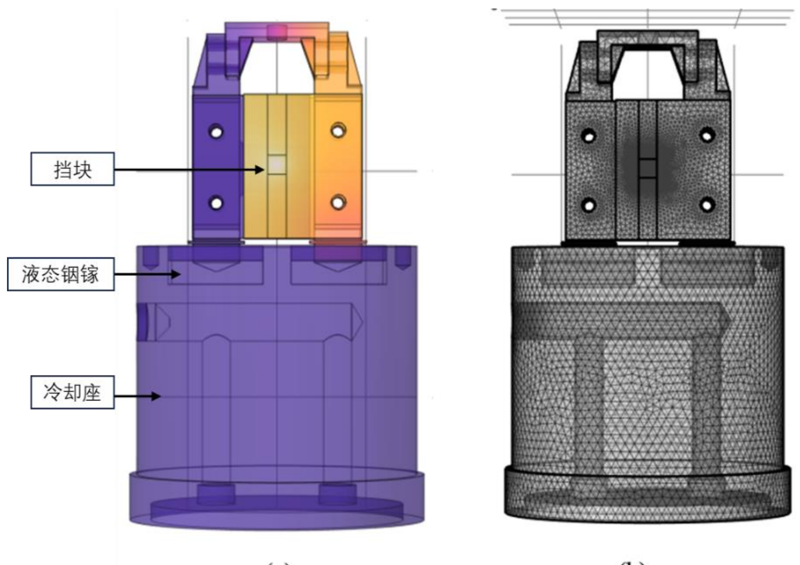
SHINE

- Drive Mechanism: A solenoid outside the vacuum is used to control the lifting of the stopper by energizing and de - energizing.
- Guiding and Adjustment: This is to ensure that there is no friction between the electromagnet core and the vacuum wall.
- Stopper: A composite structure of diamond and tungsten is adopted to absorb heat and block high - energy radiation.
- Cooling: A liquid InGa bath is used. The lower part of the stopper is immersed in the liquid InGa bath for heat exchange, and the liquid InGa bath is water - cooled.



Stopper Temperature Analysis

- With the InGa cooling method, average power below 50 W, the temperature of the stopper is less than 200 °C
- The stopper can handle an average power of less than 50 W properly.



(a) (b)