Progress of Free Electron Laser (FEL) - Spectrometer for Electronic Structure (SES) End-station

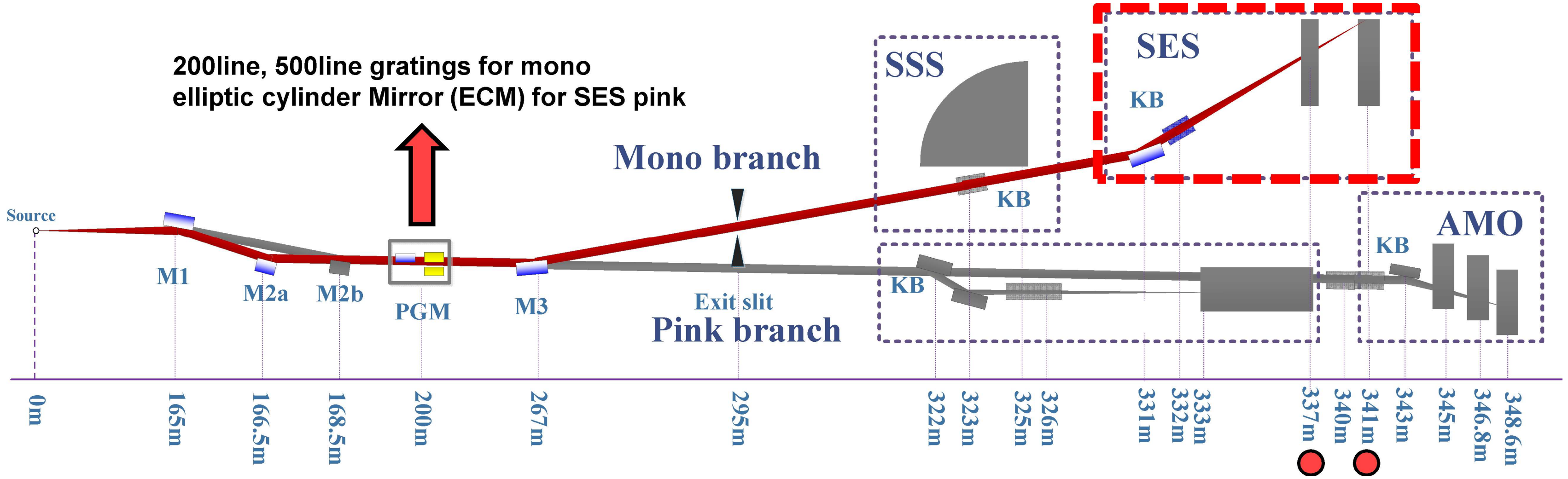
Meixiao Wang

2025-09-19

SHINE

SES

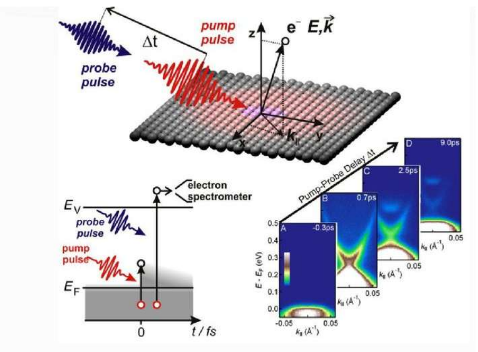
FEL-II beamline in SHINE



Range of Optimized Photon Energy: 0.20 ~ 3eV

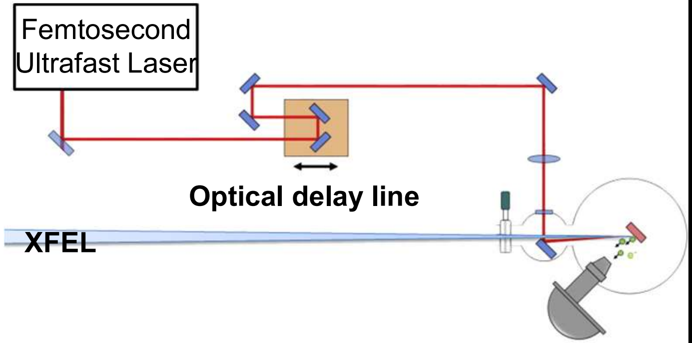
SES Endstation: Construction Plan

Ultrafast electronic dynamics subsystem (TAP)

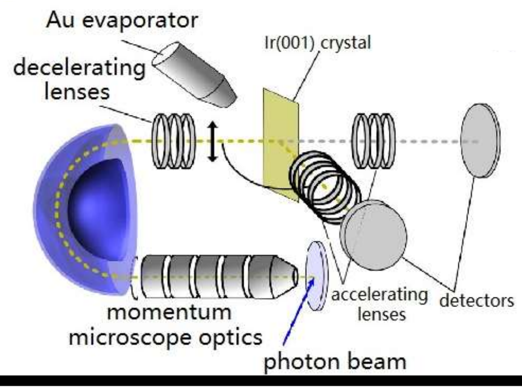


Fritz Haber Institute | Fritz Haber Institute of the Max Planck Society (mpg.de)

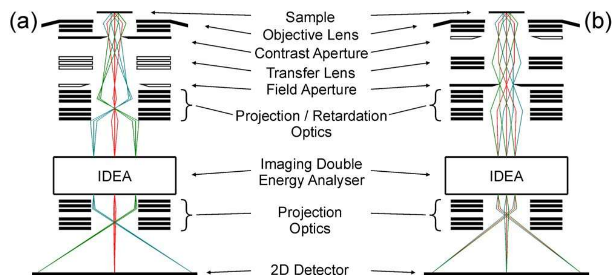
Femtosecond Ultrafast Laser + High repetition X-ray Free electron laser



High efficiency 2D Spin detector



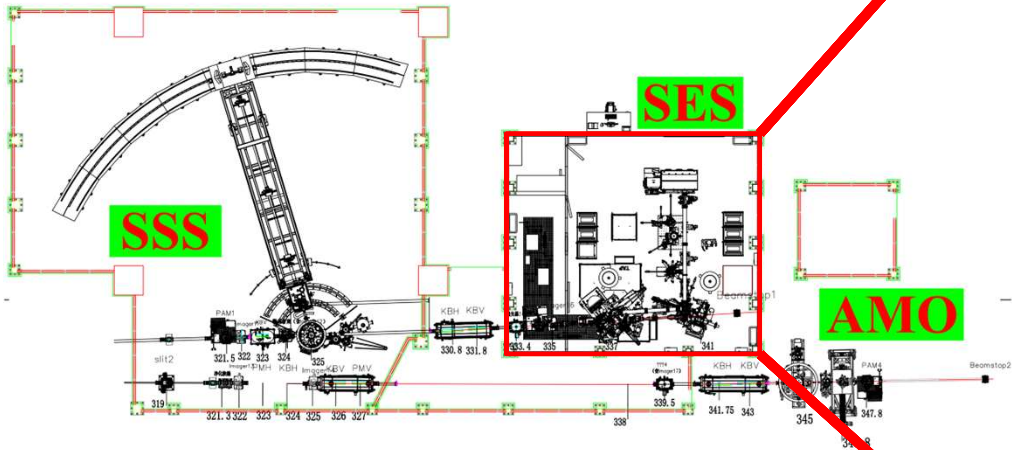
dual mode photoelectron microscopy subsystem (PEM)



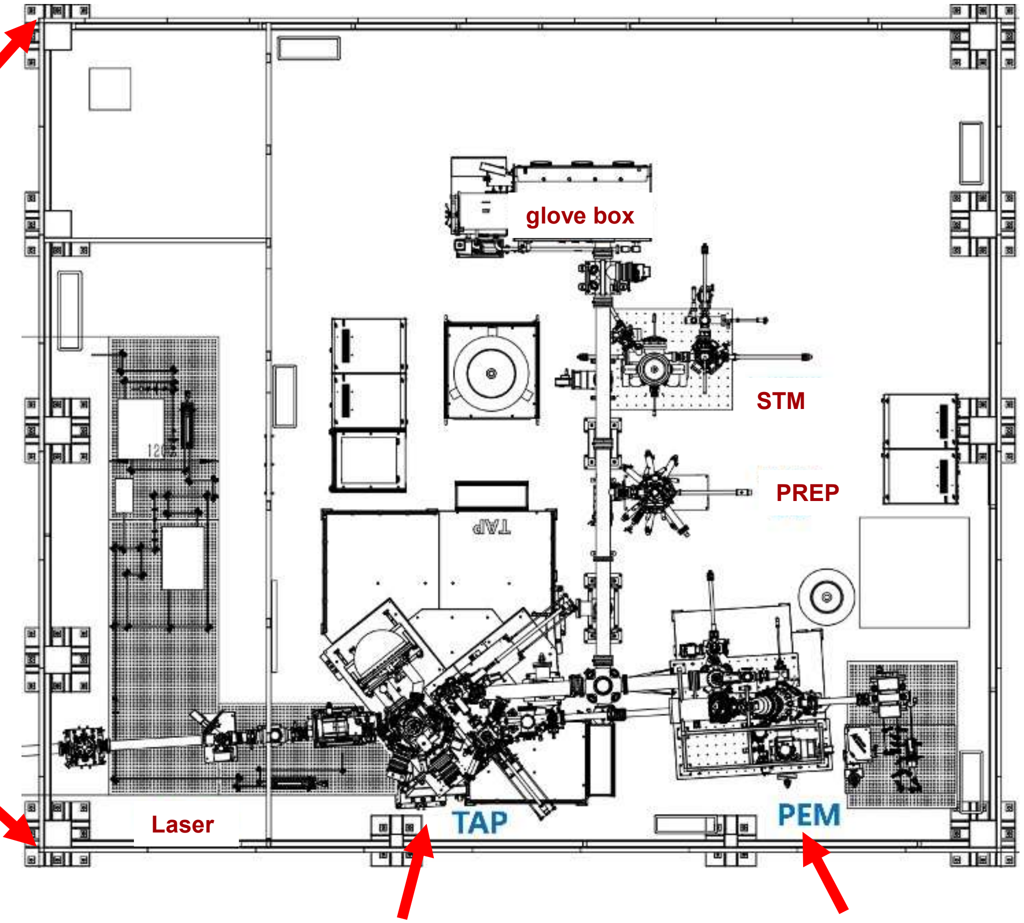
Ultramicroscopy 130 (2013) 70–76

Location and Layout of SES endstation

FEL-II endstations in
4# experimental hall



SES and AMO endstations will be online in May 2026



TAP subsystem
@ 337m
Finish in 2025 Q4

PEM subsystem
@341m
Finish in 2027 Q2

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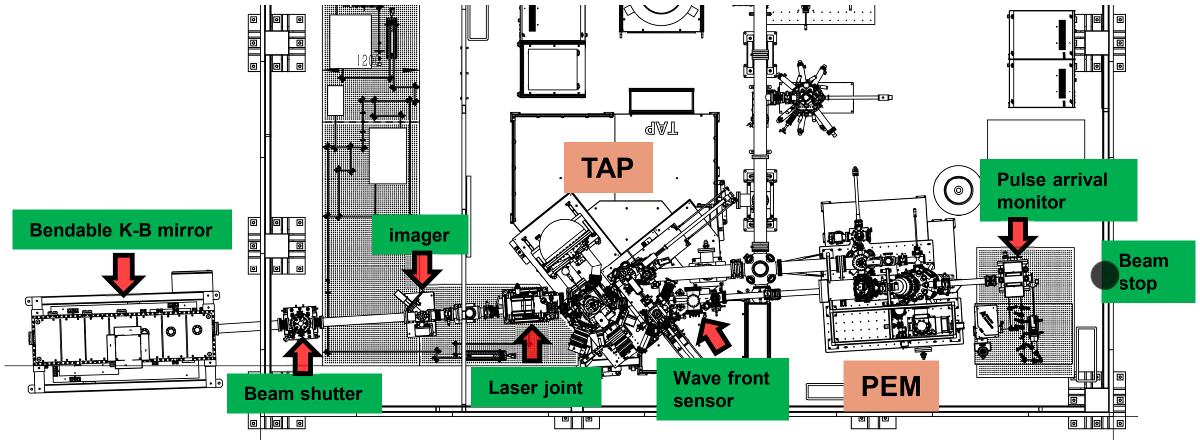
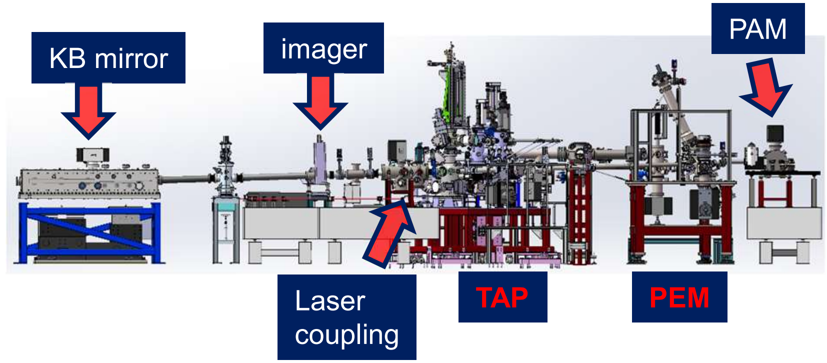
Layout of the Beamline & SES Endstation

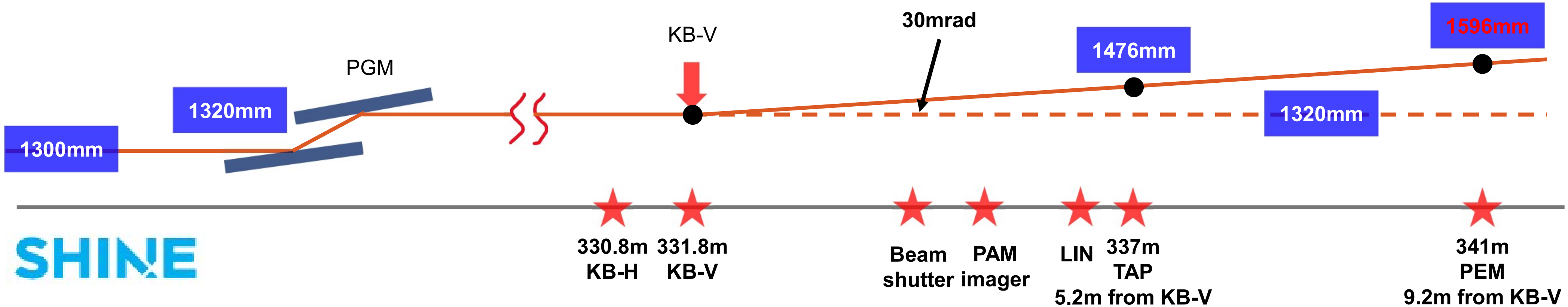
Online facilities arrangement in SES endstation



Side view



Design of the beamline layout (schematic in sideview)



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Specification for FAT in SES endstation

	Spec. of Design	Spec. of Final Acceptance Test (FAT)	Method for FAT	Position for FAT
Time Resolution (fs)	60	80	Measure the step width of the optical delay line using a laser Interferometer. The measuring results should keep no larger than 24μm (speed of light × 80fs) within ten minutes.	TAP
Spatial Resolution (nm)	100	500	The image of the a cheakerboard sample in 500 nm × 500 nm should be clearly resolved in the measured images.	PEM

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Required Optical Parameters of SES endstation

No.	parameter	SES endstation
1	Energy range	0.2~3keV
2	Optimized energy or range	0.4~1.7keV
3	Energy resolution power	≥40000@0.4keV&0.93keV
4	Transmission efficiency of single pulse	/
5	Content of high order harmonic	/
6	Focus beam spot（H×V）（FWHM)	< 10μm×10μm， double focus point @0.4keV
7	Divergence angle（FWHM)	/
8	Stability of beam（RMS)	≤4μm
9	Working distance of the K-B mirror	5.2 m(PEM) and 9.2 m(TAP) To the center of the mirror chamber
10	Width of single pulse	/
11	Attenuation requirement	4-6 order of magnitude, adjustable

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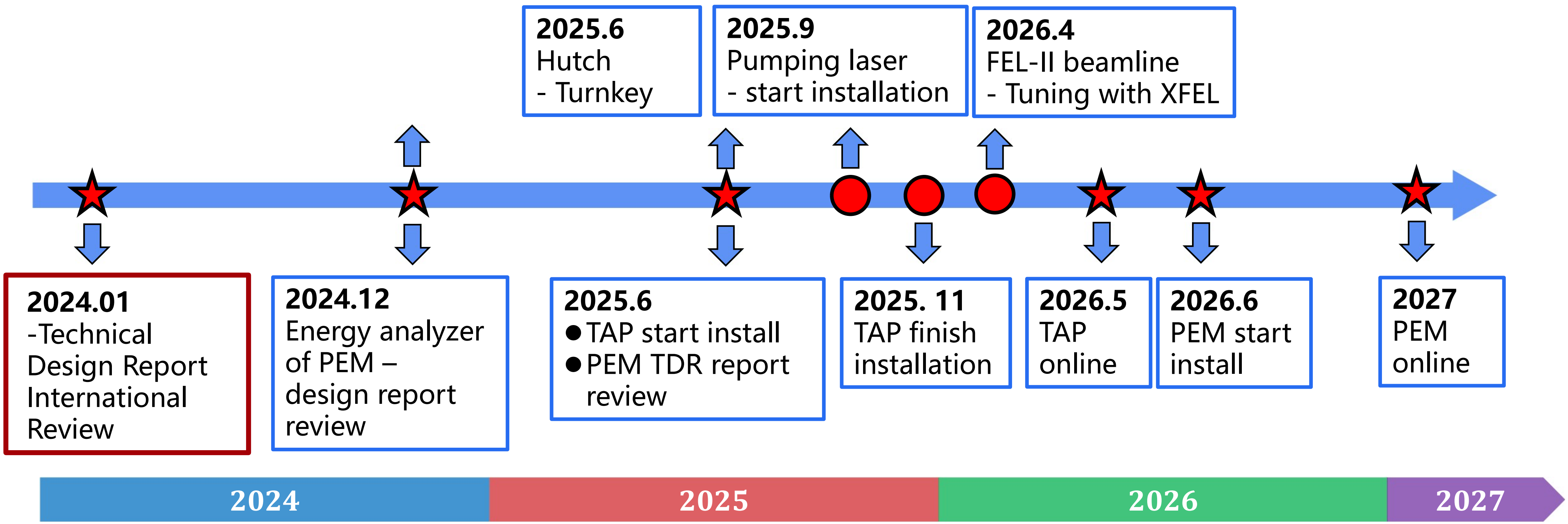
CPM plan of Construction the SES Endstation



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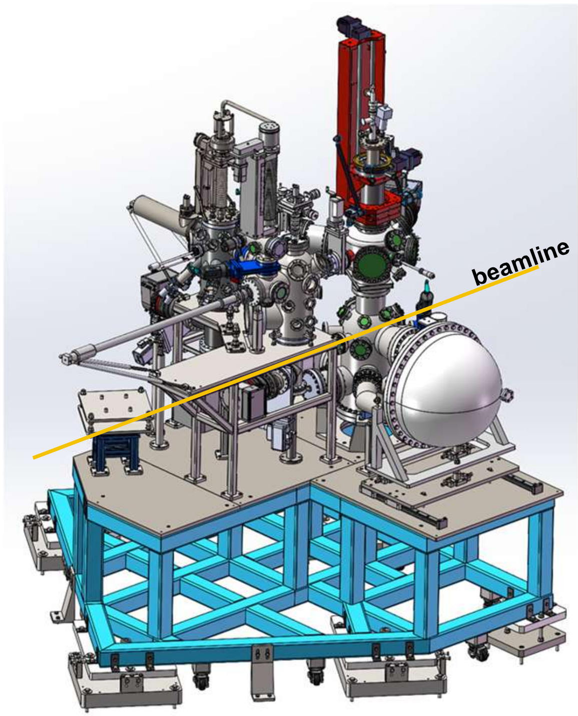
SES-TAP Endstation: DAY 1 Experiment

TAP Substation
Ultrafast Dynamics of Electronic Structures



Specification in design:
Time resolution: better than 60 fs

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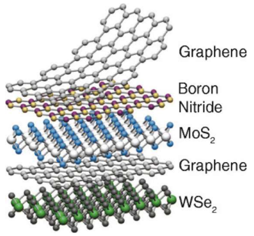
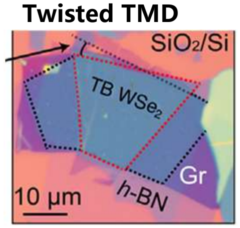
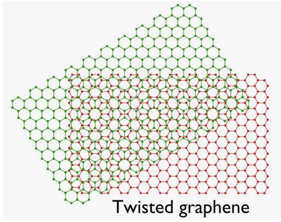
Day 1 : Pump Probe Experiments
Dynamic of Electrical Structures in 2D materials







Main Experimental Conditions:

XFEL

- Beam spot size: ~ 10 um ⇒ Imager & WFD
- Pulse duration: 40 ~ 50 fs
- Jitter: < 50 fs ⇒ PAM
- Energy resolution: ~150 meV @ 200 eV ⇒ PES
- Repetition rate: 100 kHz
- Pulse energy: 1-10 uJ

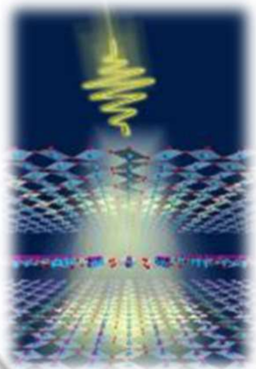
co-axis

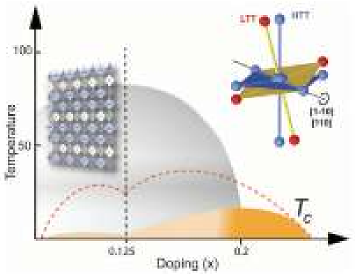
Laser

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

Scientific Cases of SES Endstation

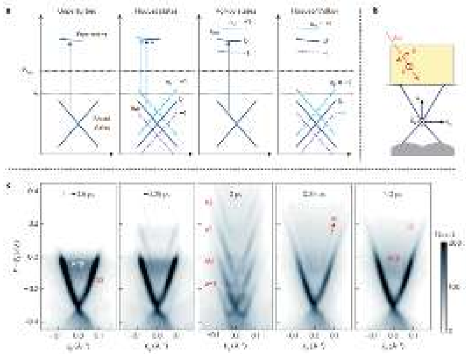
Unconventional Superconductivity





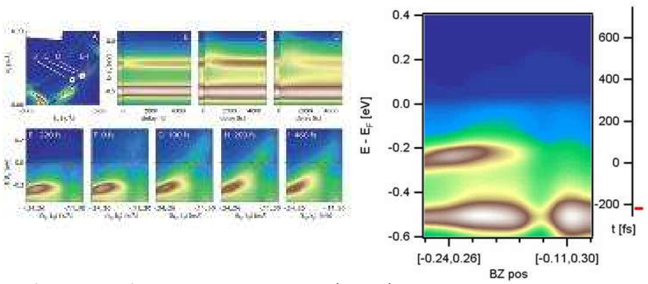
D. Fausti *et al.*, Science **331** 189 (2011)

Unusual topological states



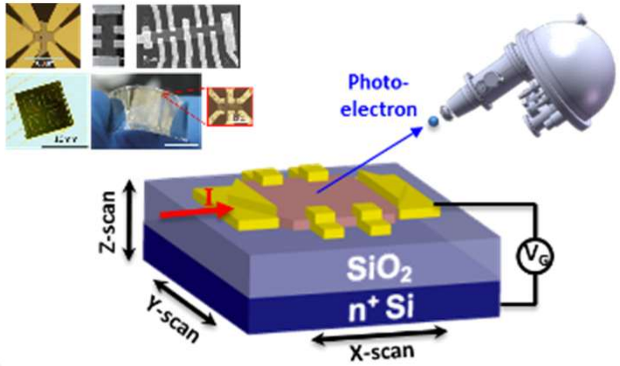
Y. H. Wang et al., Science, 342, 453 (2013)

Control of quantum phase transitions



F. Schmitt *et al*., Science, **321**, 1650 (2008)

Dynamics of functional devices

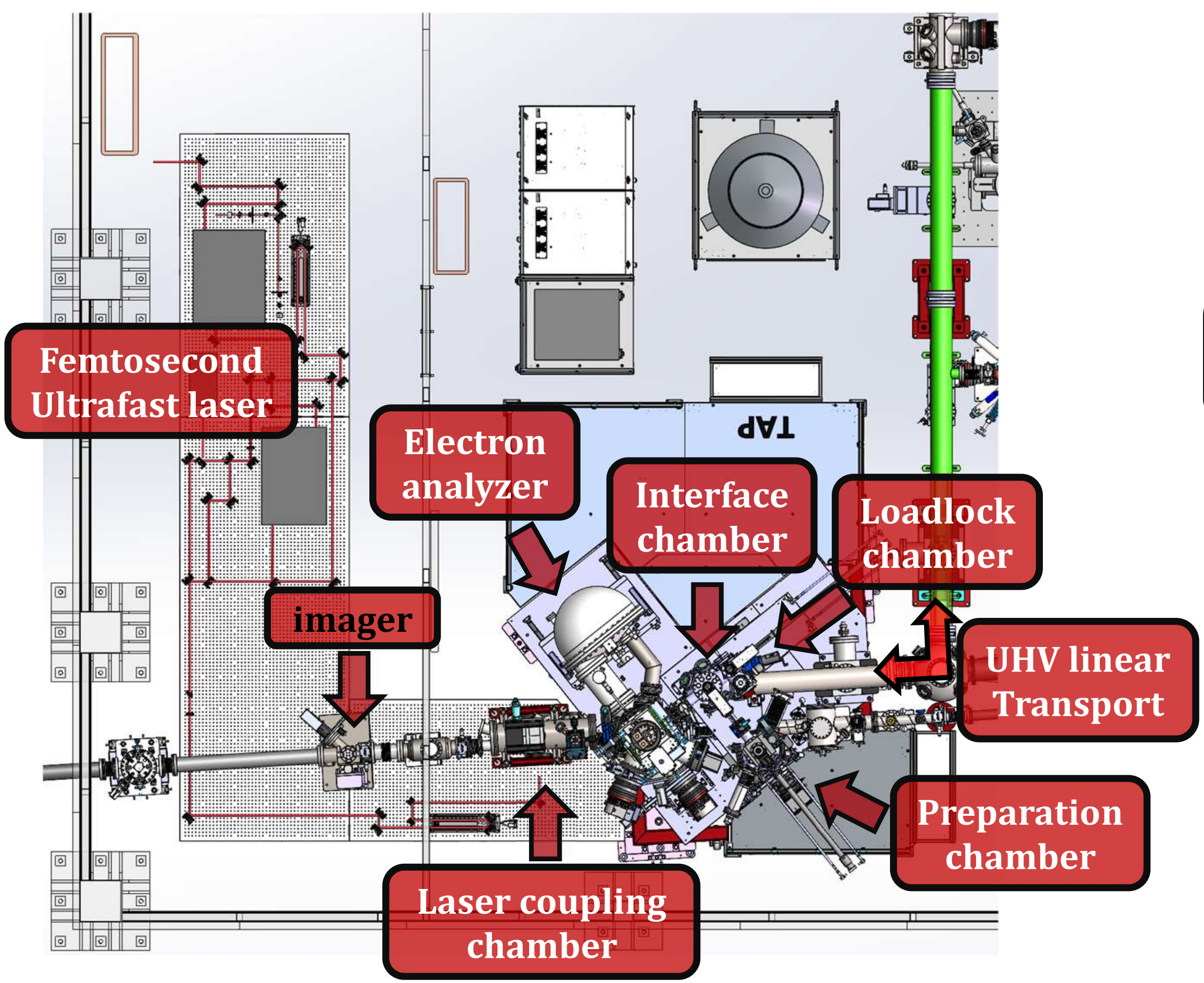


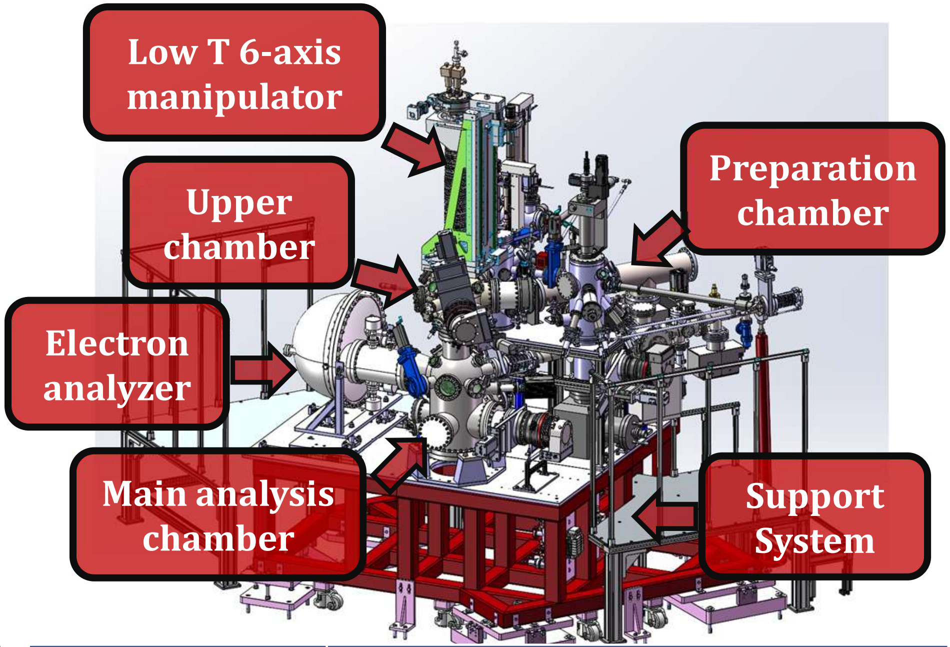
SES Scientific Cases:

- Ultrafast dynamics of moiré superstructures
- Ultrafast phase transition of CDW in TMD materials
- Strong light – matter interaction and related phenomena
- Terahertz (THz) tuned/induced quantum phase transitions

Ultrafast Electronic Dynamics (TAP)

Design of the layout of TAP subsystem





	Specification
Base pressure of Main Chamber	≤ 1×10^{-10} mbar
Range of sample temperature	7 - 350 K
Time Resolution	≤ 60 fs in design (≤ 80 fs for FAT)
Energy resolving power	E/ΔE ≥ 2×10^{4} @ photon flux ~ 10^{14} ph/s

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TAP subsystem – Energy Analyzer

Model: DA30-L
Manufacturer：
ScientaOmicron AB (Sweden)

items	specification
Energy resolution	≤ 1.8 meV FWHM @2eV passing energy (12 eV kinetic energy).
Detection of photoelectron energy range	Angle integration mode: 0.5-1500 eV; Angular resolution mode: 3-1500 eV; **Deflection mode: 3-800 eV.**
Pass energy	2, 5, 10, 20, 50, 100, 200 eV.
Receiving Angle of Angle resolution mode	± 7°, ± 15°, receiving Angle of Angle integral mode: ± 19°
deflection model Angle range: linear sweep	x: ± 3.5°, ± 7°, ± 15°, y: ± 3.5°, ± 7°, ± 15°.
Angular resolution	<0.1°@ spot size 0.1mm
spin detector upgradable	YES

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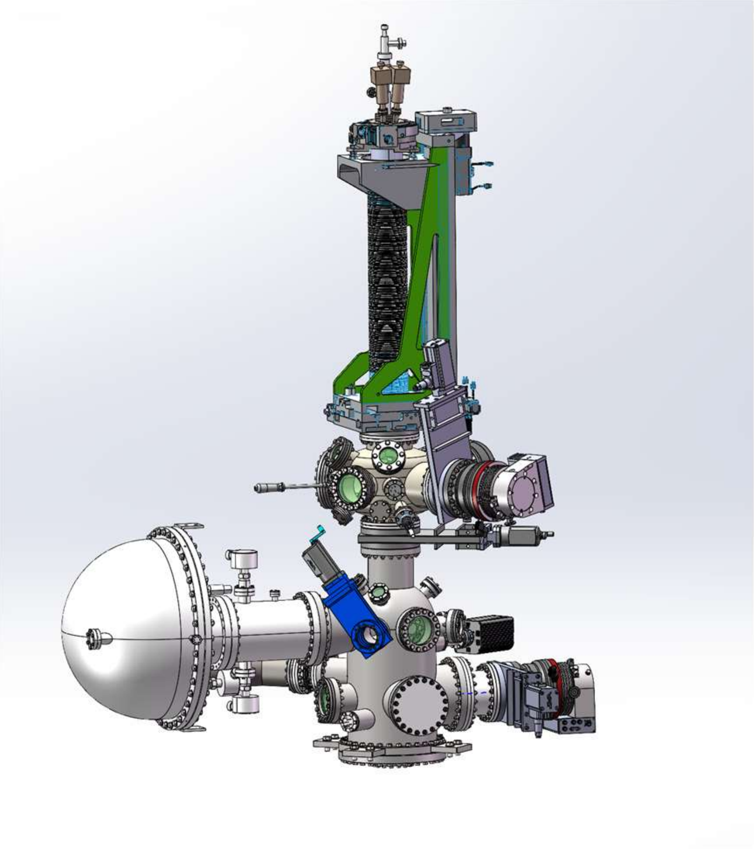
TAP subsystem – Main Analysis Chamber

Tr-ARPES Endstation with Classic Geometry



Specification of the Analysis main chamber

items	specification
Ultimate base pressure	1 × 10^{-10} mbar
Material for production	Outer: Stainless Steel 316 Inner：**double μ-metal shielding**
Residual magnetic field	< 5 milli-gauss (0.5 μT)
Dimensions	Diameter: 350 mm Height: 780 mm

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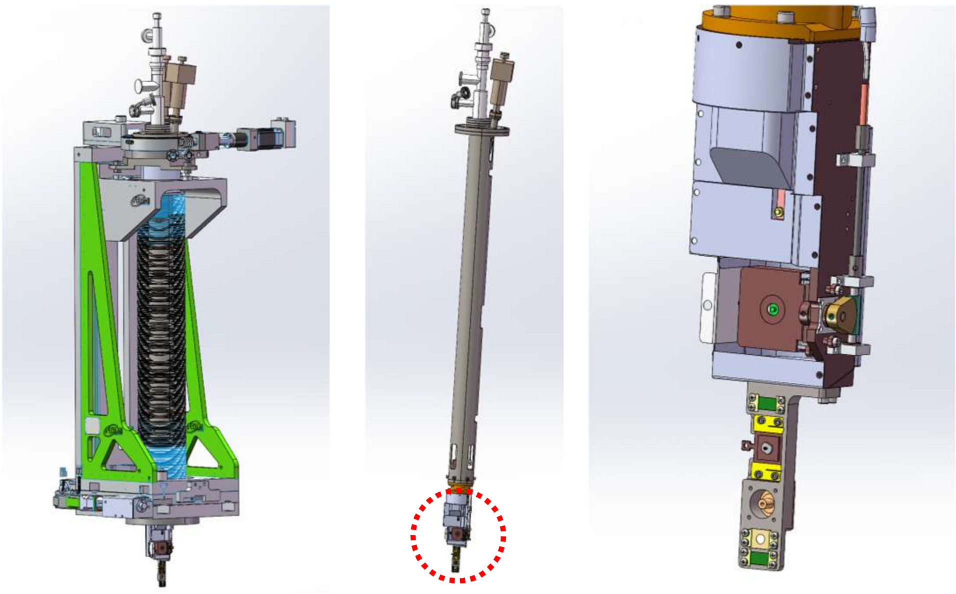
TAP subsystem – Low temperature multi-axis manipulator

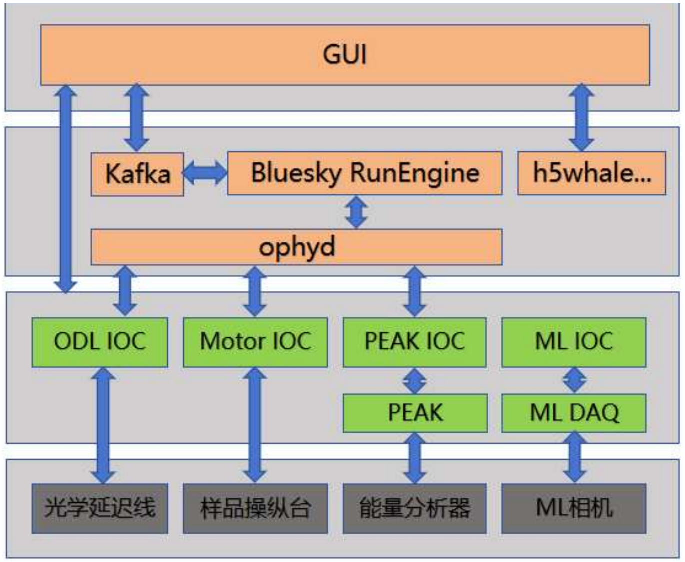


- Homemade
- Assembled with the temporal and spatial diagnosing tools (will discussed later) for both XFEL and pumping laser at the sample point.

items	specification
Lowest sample temperature	< 5.5K
Sample temperature range	7 – 350K
liquid helium consumption (open loop)	< 1.0 L/h @ 7K < 0.5 L/h @ 10K
Close LHe Loop upgrade	Yes
Motorized moving range (3T+3R)	10 mm for X & Y 650 mm for Z 180° for R1 rotation ± 15° for tilt ± 90° for azimuthal
Moving accuracy	< 2 microns in X, Y & Z < 0.1° accuracy and backlash
Shaking of the manipulator	Open loop: < 1 - 2 microns (simulated) Close loop: To be simulated

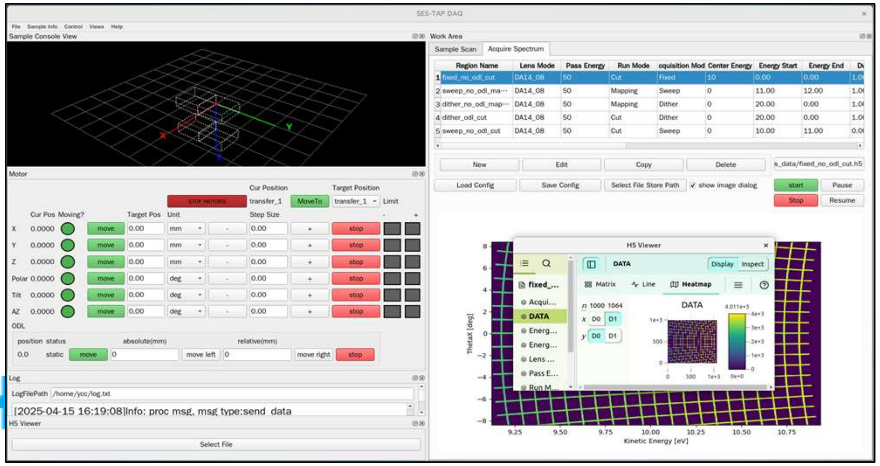
1 μm ↔ 3 fs

Software for TAP data acquisition (provided by software group)



- **GUI Layer:** PyDM-based user interface.
- **Application Layer:** Implements experimental logic based on the Bluesky framework, enables HDF5 data visualization via h5whale, and communicates with the GUI via Kafka.
- **IOC Layer:** Provides real-time control interfaces for hardware devices based on EPICS IOC.
- **Hardware Layer:** Physical devices, such as sample manipulators, hemispherical energy analyzers, etc.

Graphical User Interface

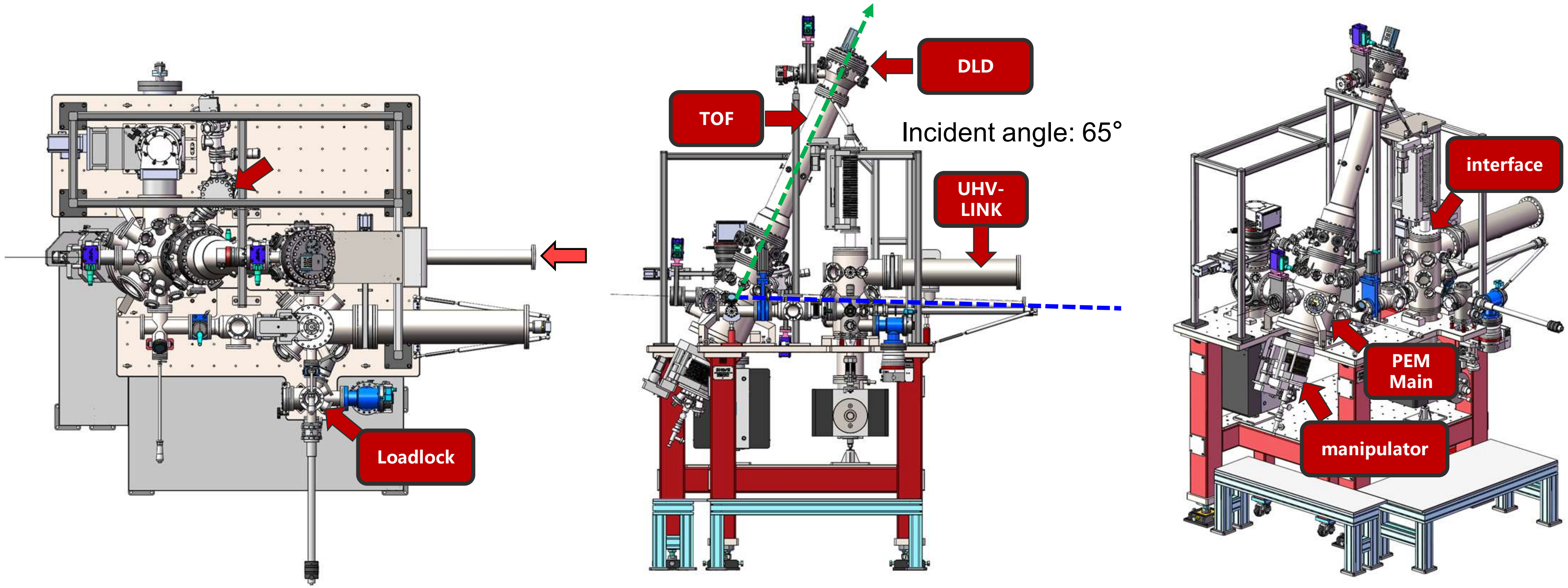


Functional modules:

- Sample surface scanning
- ARPES data acquisition
- Control of devices such as sample manipulators, energy analyzer, etc.
- 3D visualization of the sample manipulator
- H5 data visualization
- Log information and devices status display module

Dual mode photoelectron microscopy (PEM)

Layout of the PEM subsystem



PEM sample height 1596 mm

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Main specification of PEM subsystem

	Specification	Method for FAT
Base pressure of Main Chamber	≤ 1×10^{-10} mbar	Vacuum gauge installed on main chamber
Range of sample temperature	15 - 400 K	Thermo-diode on the back of the sample stage of the low temperature manipulator
Spatial Resolution	**≤ 100 nm (≤ 500 nm for FAT)**	The image of the a chessy sample in 500 nm × 500 nm should be clearly resolved in the measured images.
Energy Resolution	≤ 50 meV	Under kPEEM mode, fit the fermi edge of the standard sample (such as Au foil)
Momentum Resolution	≤ 0.005Å^{-1}	Under kPEEM mode, fit the MDC of the standard sample such as Au(111) surface states

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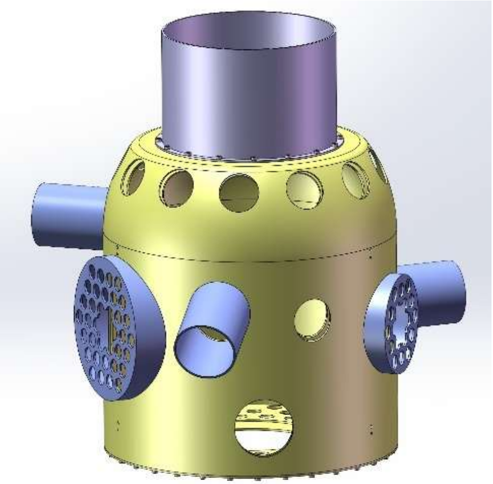
PEM subsystem – main components

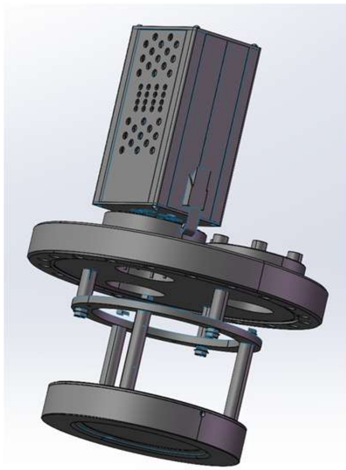
Main chamber

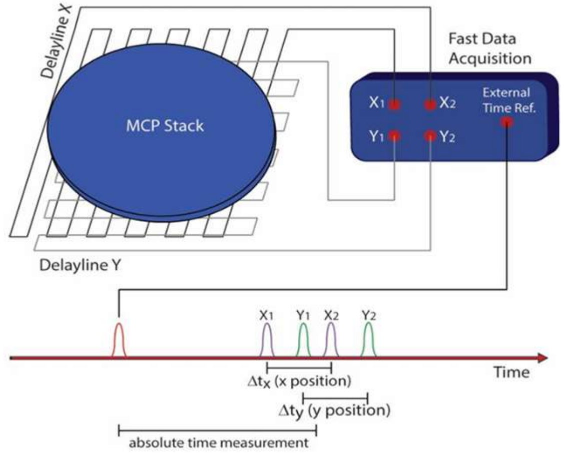


- Top flange CF200， bottom flange CF300， Heigh 510mm
- Outer: 316L stainless steal
- Inner: double mu-metal layers

items	specification
Ultimate base pressure	1×10^{-10} mbar
Leak rate	$< 1\times10^{-11}$ mbar·l/s。
Material for production	Outer: Stainless Steel 316 Inner： double μ-metal shielding
Residual magnetic field	< 5 milli-gauss

TOF+DLD



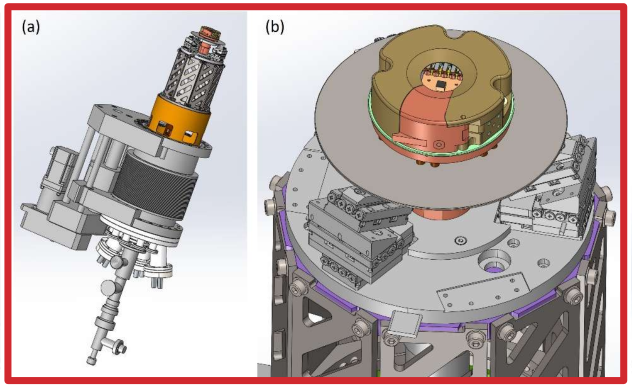


➢ The 1MHz XFEL pulse make SHINE compatible with TOF analyzer, which can increase the data taking efficiency by an additional factor of 10^2!

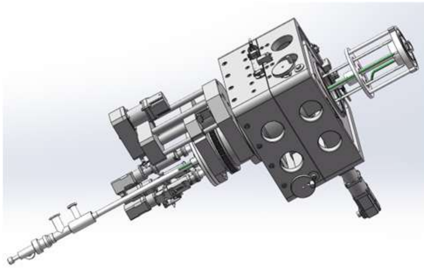
PEM manipulator

Commercial versions

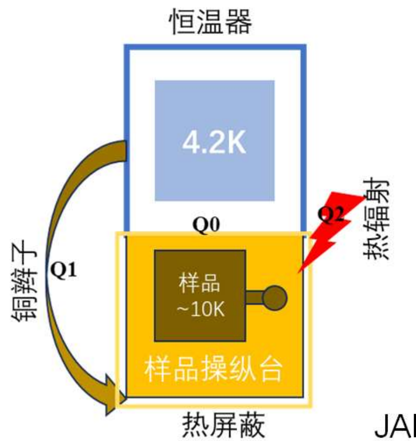
Our design: **PEM 1000**



Plan B: Backup
Fully new designed mechanical manipulator



	Scienta Omicron	SPECS	Surface Concept	**PEM 1000**
Moving	Piezo Hexapods	Piezo Hexapods	mechanical	Piezo Hexapods
Temperature range(K)	10-400	9	15-400	10-400
Fine moving range	X,Y, Z 5mm	X,Y, Z 6mm		X,Y, Z 6mm
tilt	5°	2°		5°
Azimuth	60°	60°	90°	60°
Sample stage fully retract	NONE	NONE	NONE	Retract 100mm



JANIS cooling head

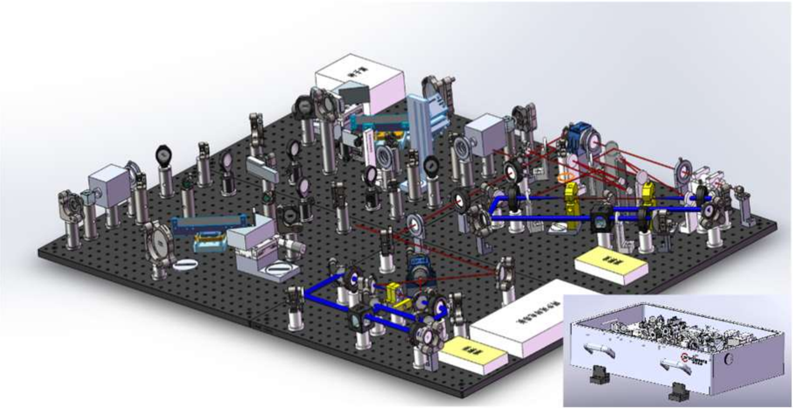
Silicon diode
1.4K-500K

LakeShore thermometer

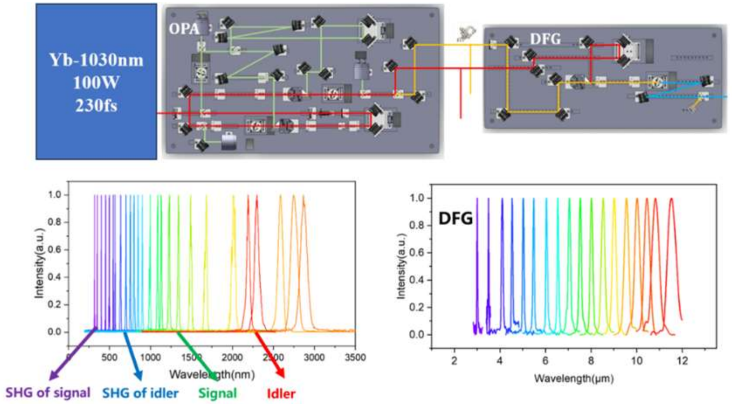
High-repetition-rate Laser for SES

☐ Self-developed high-repetition-rate laser

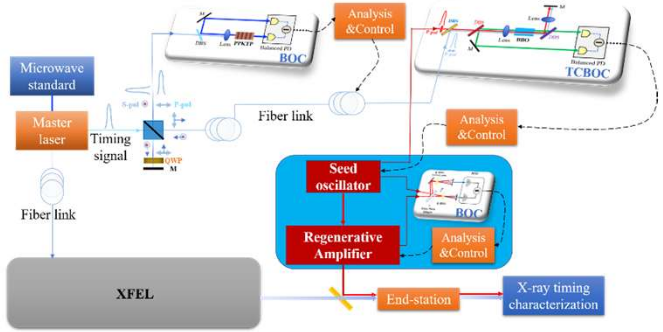
- **Fundamental laser parameters:** 1030nm, 100W @ 100kHz, <50fs
- **Frequency conversion units:** UV to IR by OPA (315nm~12μm); Harmonic Generator (SHG/THG/FHG)
- **Time synchronization:** The scheme based on pulse link has been determined



Technical design



Spectral tuning curve of OPA



Synchronization scheme

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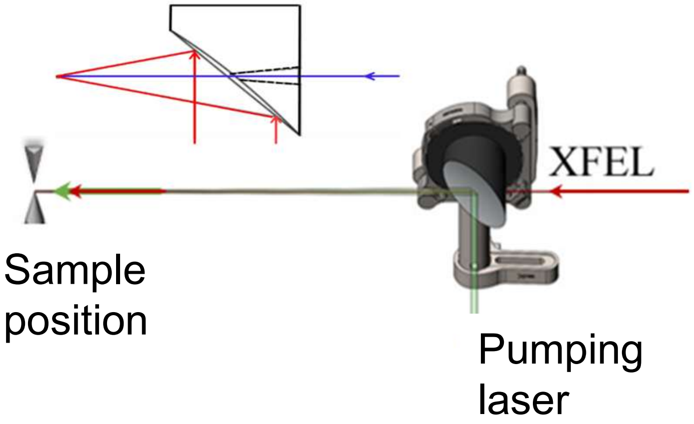
High-rep-rate laser system for SES will be completed and installed in this October.

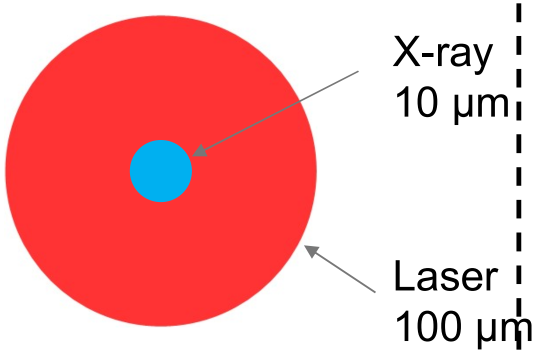
Coupling pumping laser with XFEL-Spatial Overlap

Spatial Coupling & Temporal Coupling

Coupling method



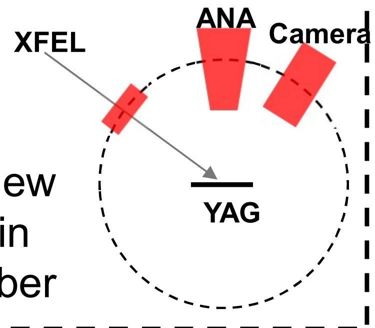
Spatial coupling



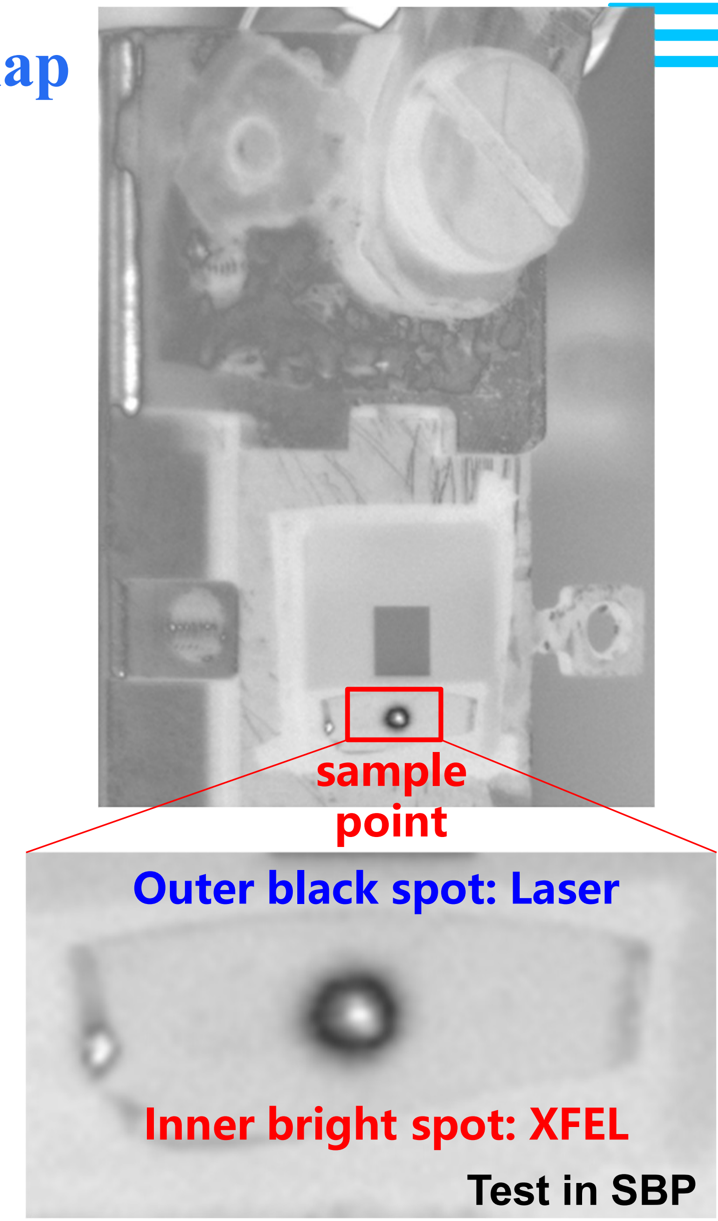
Co-axis transmission

	H	V
	sigma	sigma
400	0.23282957	0.195045729
600	0.260868295	0.218534299
900	0.183840295	0.154006488
1200	0.142444729	0.119328641
1600	0.114614808	0.09601499
2000	0.100266823	0.083995412
max	1.439516129	1.3125

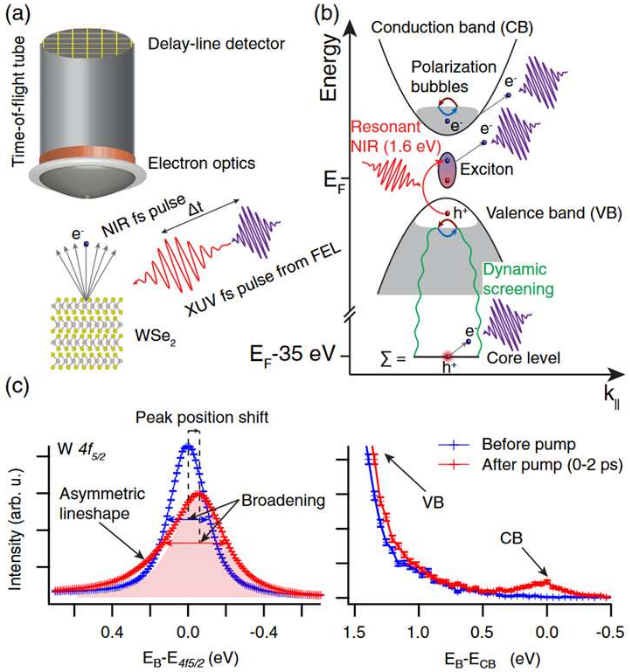
Top view of Main chamber



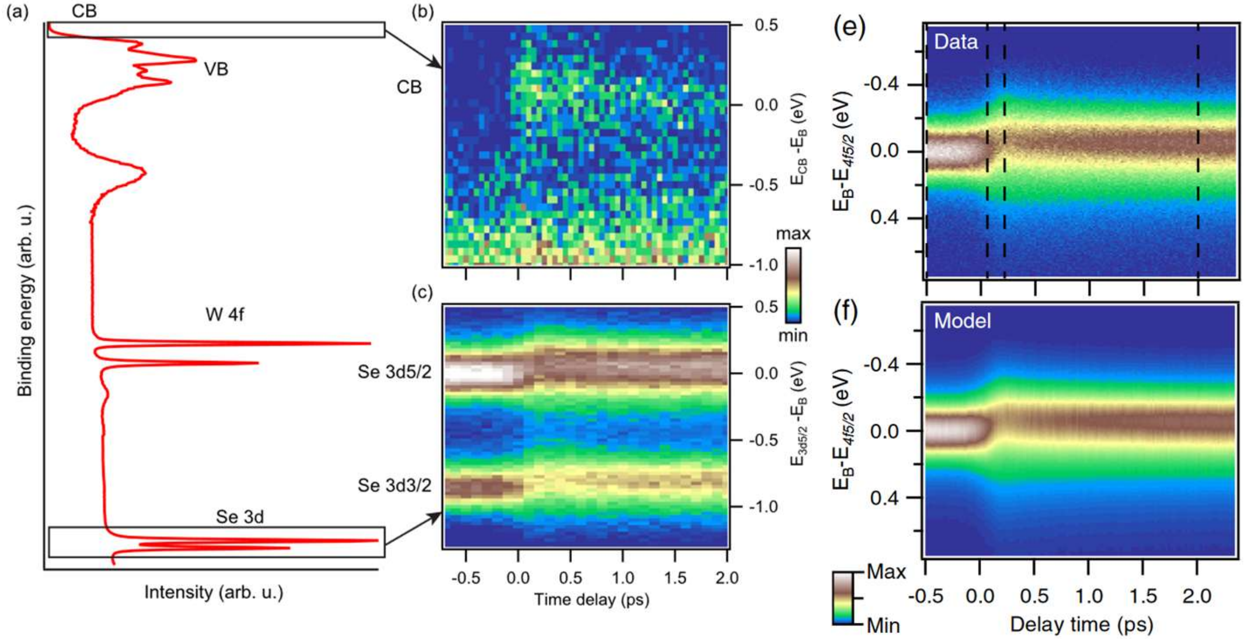
Hole in Beam Combiners： 2 mm



Coupling pumping laser with XFEL - temporal Overlap



Principle：exciton is formed by the pumping laser and holes are formed at the maximum of valance band, dynamic screening effect causes the move of fermi level or the core levels and the change of the spectrum.



Sample：WSe_2

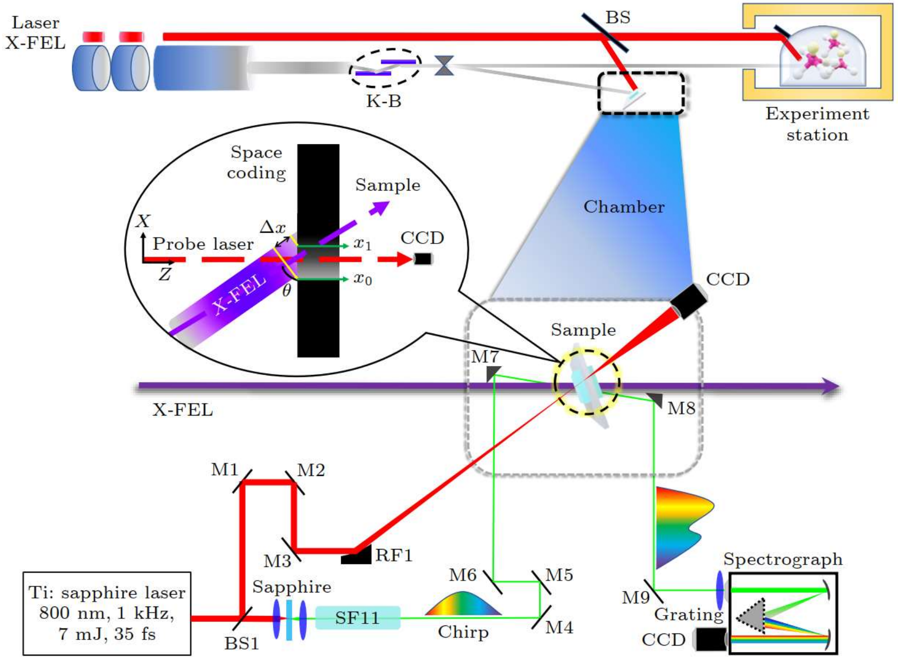
scanning the delay line stage，observe the move of the fermi level or the core levels.

Phys. Rev. Lett. 125, 096401 (2020)

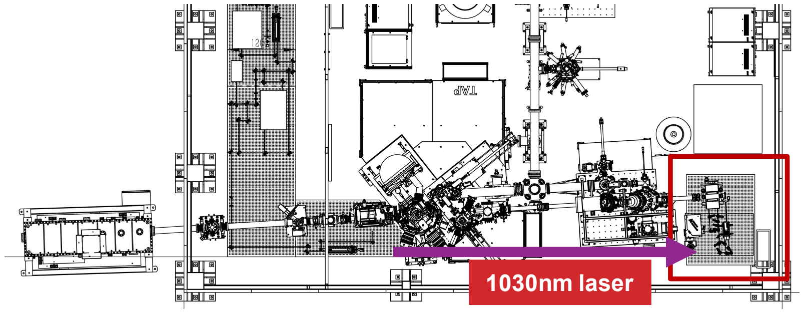
Rev. Sci. Instrum. 91, 013109 (2020)

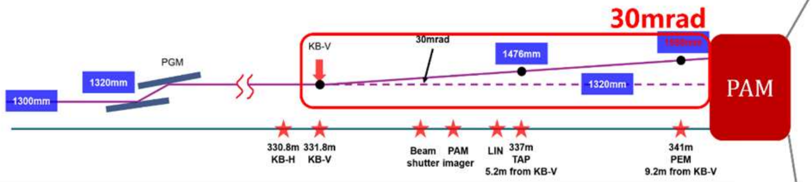
Pulse Arriva Monitor (PAM) of XFEL

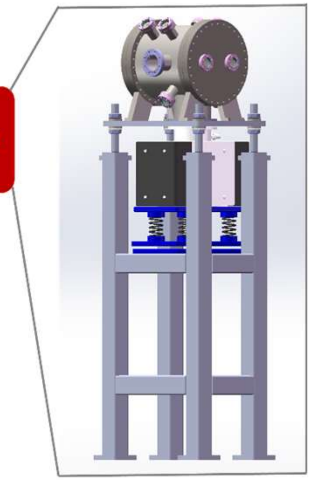
Method for PAM：
spectrum encoding and spatial encoding

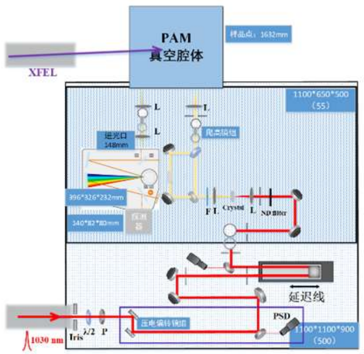


Acta Phys. Sin. 72,10 (2023)









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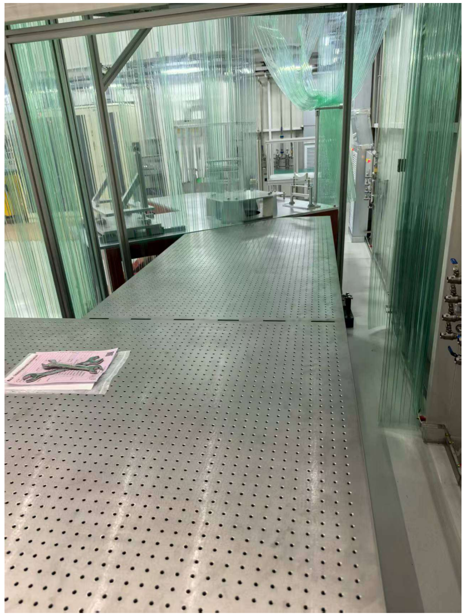
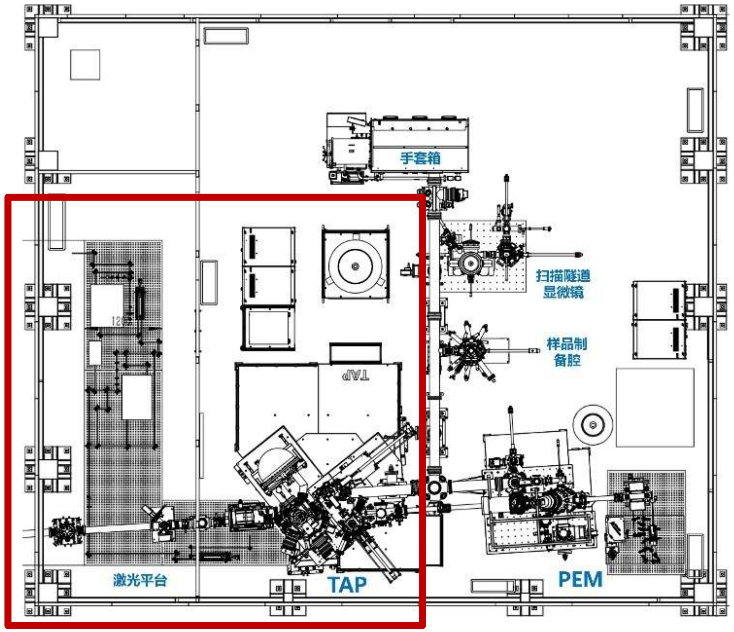
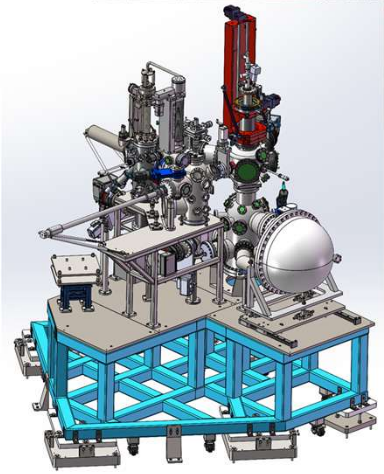
*SES PAM is designed and will be installed by **Laser Group** in SHINE

Current Status of the TAP subsystem







SHINE

- ✓ Most of the components of TAP have been assembled
- ✓ Laser system has started its installation

2025.Q4

- TAP finish installation
- Pumping laser finish

2026.Q1

- TAP control/motion/data acquisition test

2026.Q2

- Ready for initial test with XFEL

Summary

- SES endstation is the photoelectron spectroscopy endstations in FEL-II mono branch in SHINE
- Two subsystems: TAP (Tr-ARPES) and PEM (dual mode PEEM) will be established in SES
- First batch of user experiments: started in May 2026
- PEM subsystem is fully self-designed version, based on TOF+DLD to acquire the PEEM images

Acknowledgement

SES Team Members

From left to right:

- Binghui Yan (颜丙慧)
- Shucheng Shi (石书丞)
- Lei Chen (陈磊)
- Feng Wang (王峰)
- Meixiao Wang （王美晓)
- Yong Han (韩永)
- Jishan Liu (刘吉山)
- Peng Liu (刘鹏)

Thanks for your attention!

SHINE

Outline

- Brief Introduction of FEL-II beamline in SHINE
- Target for Building SES and the CPM plan
- Introduction of the two subsystems in SES
- Scientific scopes in SES
- Summary

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*Pumping Laser system for SES

- **High-repetition and high-power laser**
  central wavelength: 1030nm,
  pulse width: 25 - 40 fs,
  Average power: 100W,
  repetition rate: > 100kHz

	For SES Endstation	Note
Wavelength	OPA: 240nm~15um SHG/THG: 400nm/267nm	Optimize: 755-850nm
repetition rate	> 100 kHz using 1030 nm laser	
Pulse width	25~35 fs	
Spot size at sample point ($1/e^2$ in dia.)	20 -100 μm	
Laser power density at sample point (or energy density)	$10mJ/cm^2$	Normal
	1mJ/pulse	HHG upgrade
delay-line accuracy	0.5 fs	
delay-line range	-5-1000 ps	

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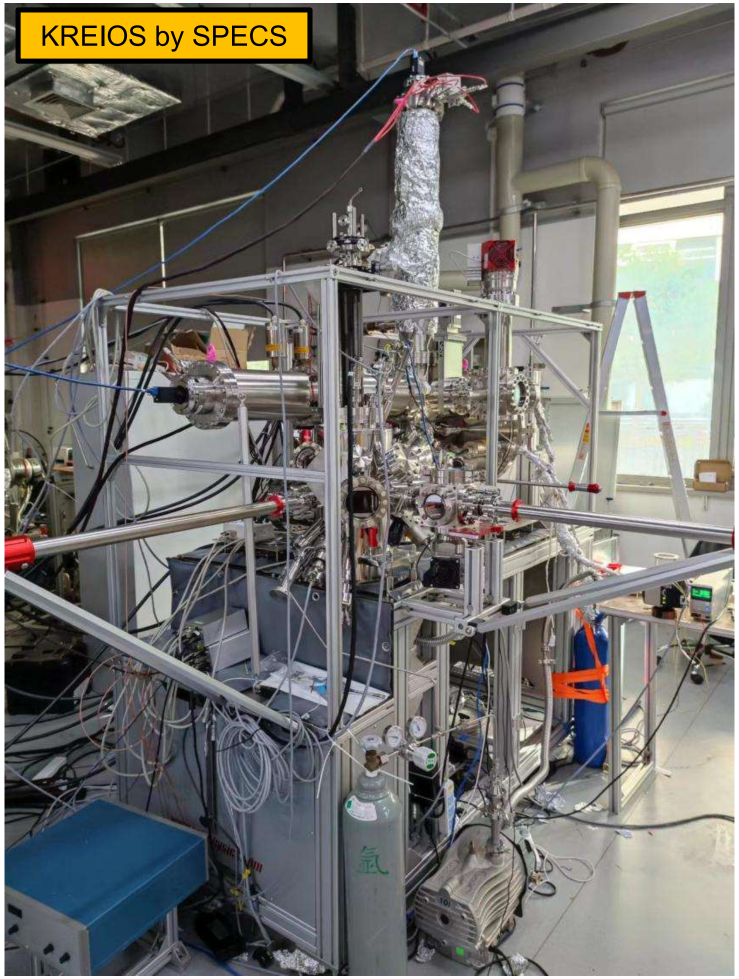
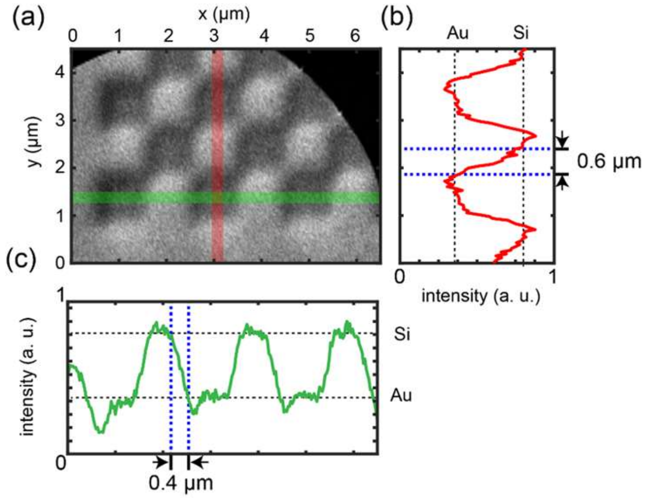
*Pumping laser system is provided by **Laser Group** in SHINE

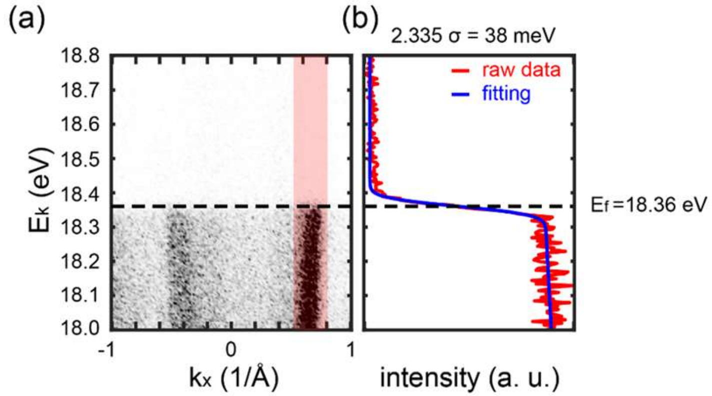
Test system for dual mode PEM subsystem



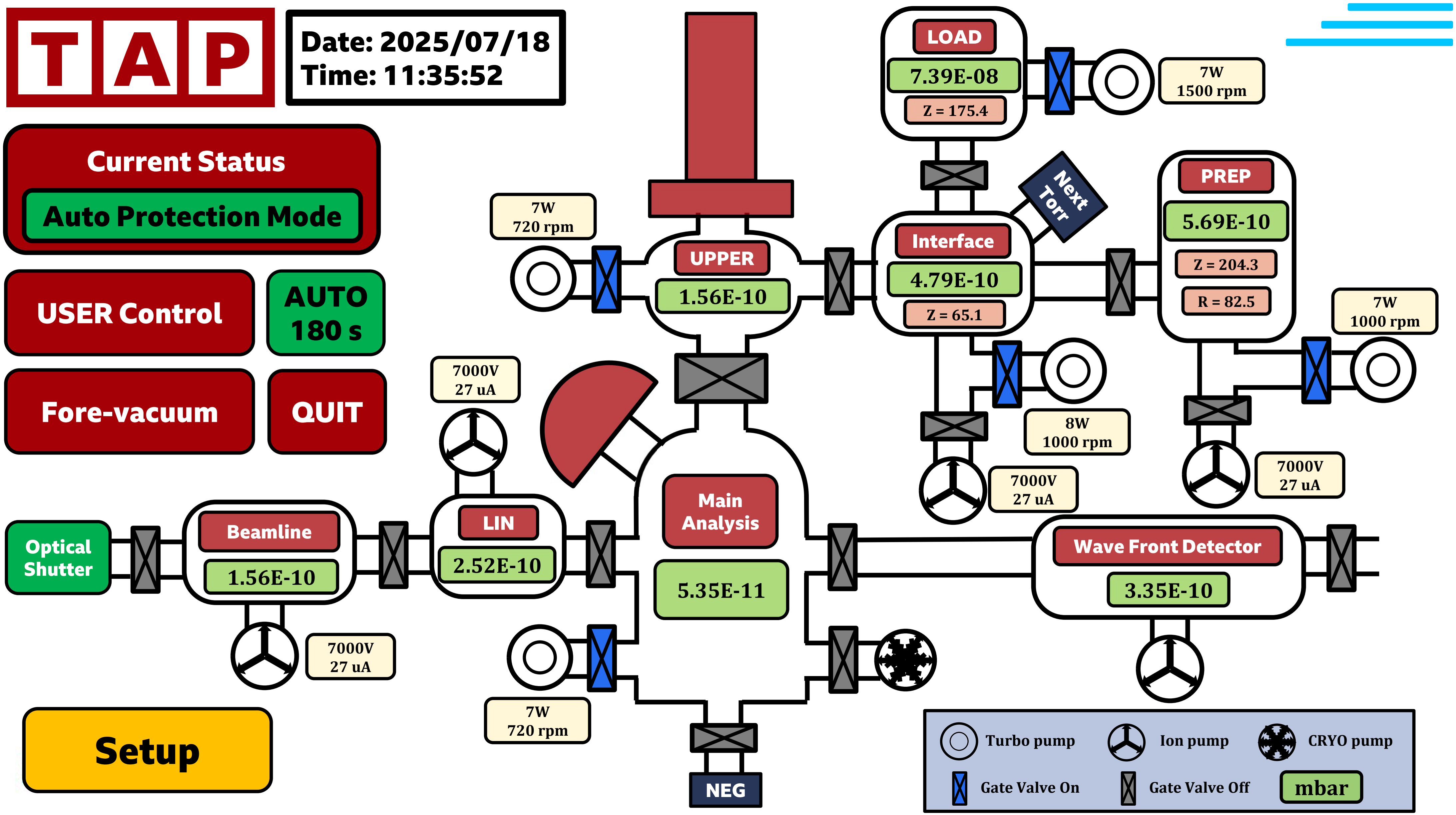


Sample: Au chessy

Test Result: 0.4μm (H) and 0.6μm (V)

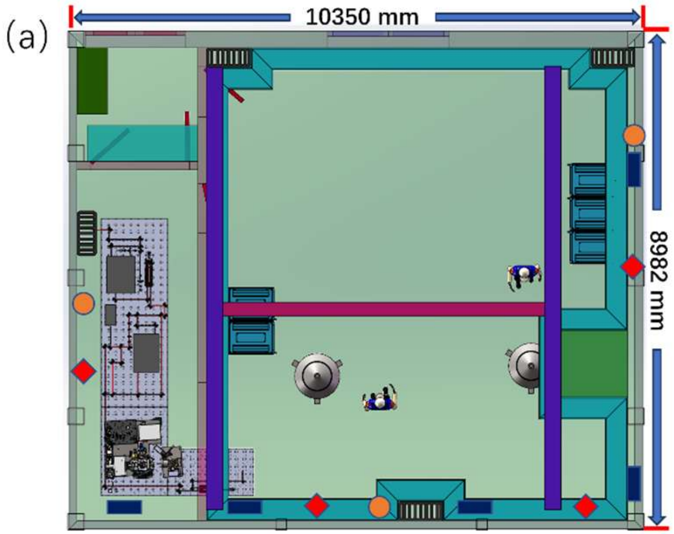


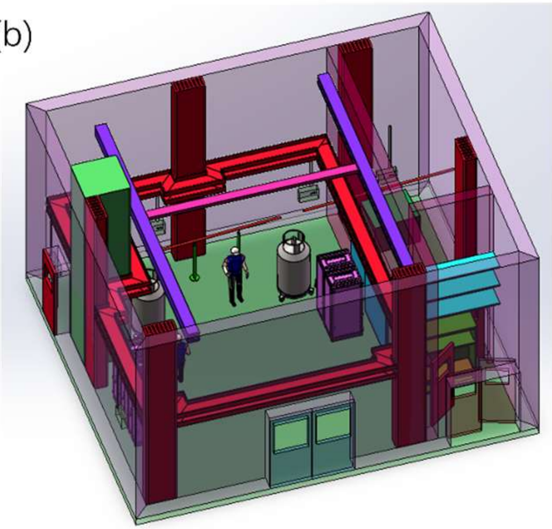
Energy resolution: ~ 38 meV



TAP
Date: 2025/07/18
Time: 11:35:52
Current Status
Auto Protection Mode
USER Control
AUTO
180 s
Fore-vacuum
QUIT
Setup
Optical Shutter
Beamline
1.56E-10
7000V
27 uA
LIN
2.52E-10
7000V
27 uA
7W
720 rpm
UPPER
1.56E-10
Main Analysis
5.35E-11
7W
720 rpm
NEG
LOAD
7.39E-08
Z = 175.4
7W
1500 rpm
Next Torr
Interface
4.79E-10
Z = 65.1
8W
1000 rpm
7000V
27 uA
PREP
5.69E-10
Z = 204.3
R = 82.5
7W
1000 rpm
7000V
27 uA
Wave Front Detector
3.35E-10
Turbo pump
Ion pump
CRYO pump
Gate Valve On
Gate Valve Off
mbar

Hutch of SES endstation





items	specification
Area (mm)	93.09 m^2 [10350 (W) × 8982 (H)]
Total Electric power	60 kW Three levels of power supply
Crane	1 ton in weight > 4.2 m in height
temperature stability	(24-26) ± 0.5℃ in 24 hours (max heating power: < 7.5 kW)
Speed of wind	< 0.1 m/s
cooling water	Speed: 18 ~ 20 l/min Pressure of outlet: 6 ~ 8 bar Temperature: 20 ± 0.5℃ At least 4 sites
Cable bridge	double layer

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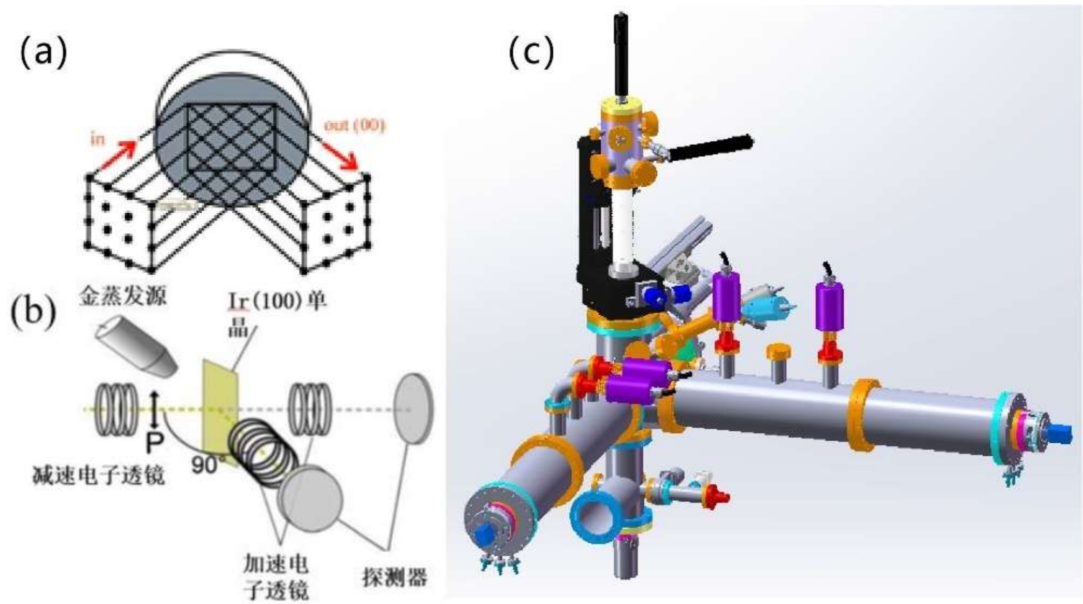
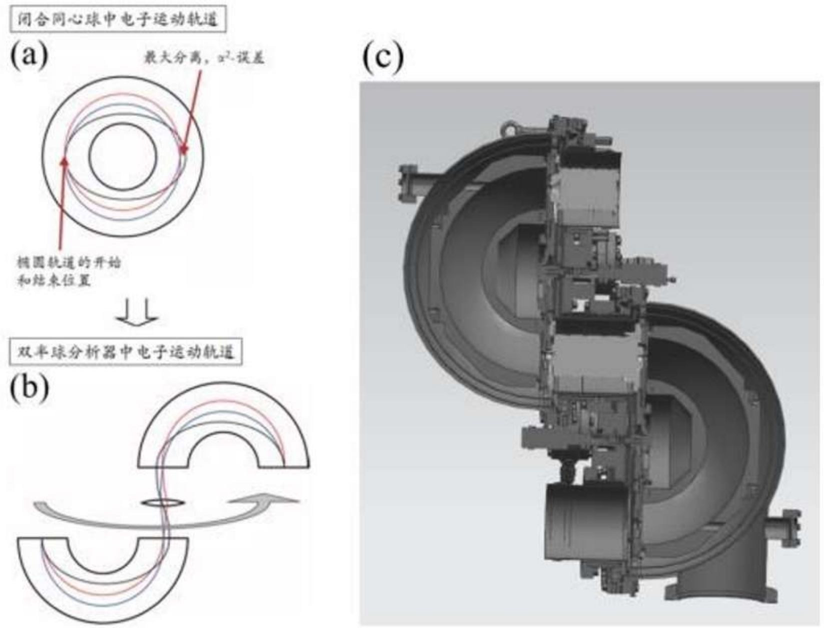
PEM—2D spin detector & double hemisphere analyzer



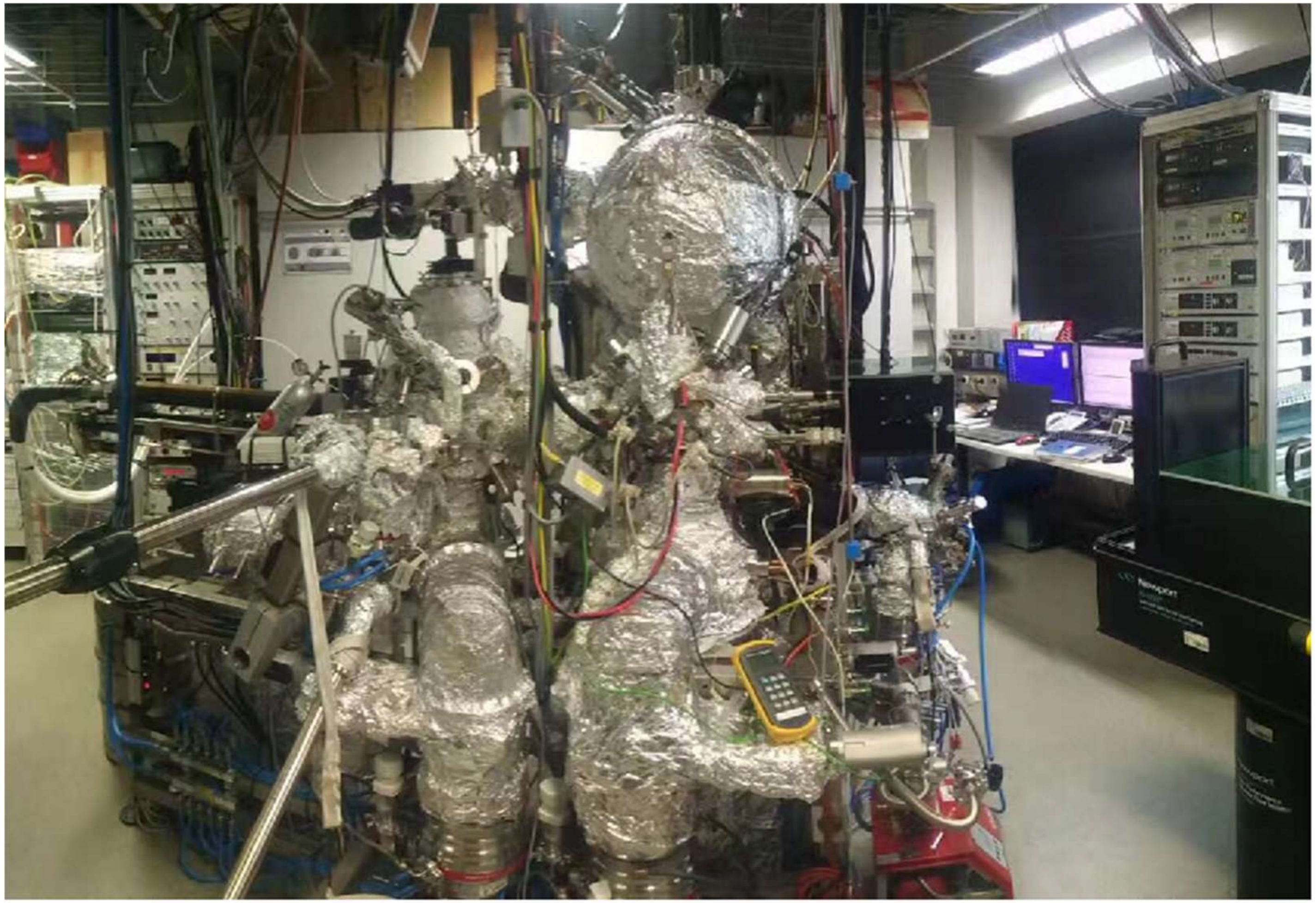
2D spin detector



double hemisphere analyzer

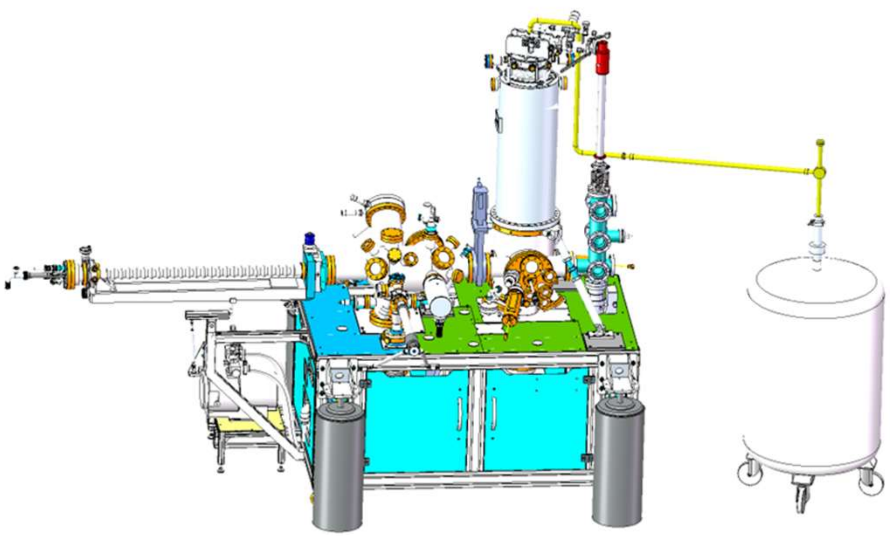
SHINE

PEEM in MPG

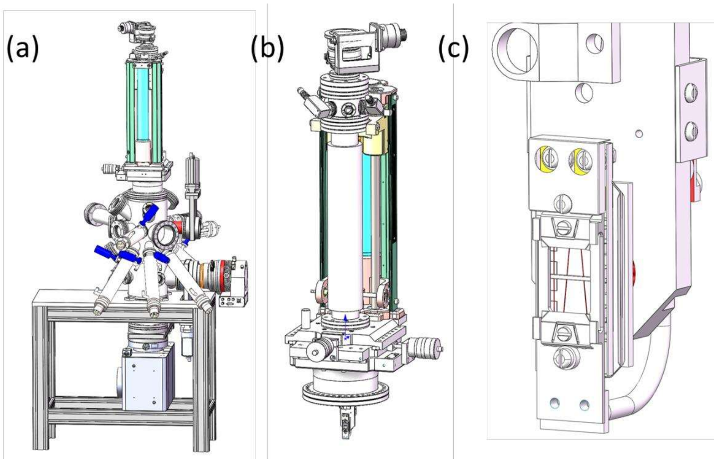


SHINE

STM with MBE thin film growth system



	Specification	Method for FAT
Base pressure of Main Chamber	≤ 1×10^{-10} mbar	Vacuum hot-gauge installed on main chamber
Range of sample temperature	< 5 K @ Lhe < 1.2 K with JT cooling	Thermo-diode on the back of the sample stage inside the STM scanning head.
Energy Resolution	≤ 0.2 meV	Fit the superconducting gap of Pb sample.
Noisy in Current	≤ 150 fA @ 5K	Frenquency Spectrum in current channel given by Nanonis controller.



MBE thin films fabrication chamber:

- Base pressure: < 2×10^{-10} mbar
- Sample manipulator: XYZ translation +R1
- Cooling with LN2, heating with DC current/E-beam, sample substrate: 140K~1800K

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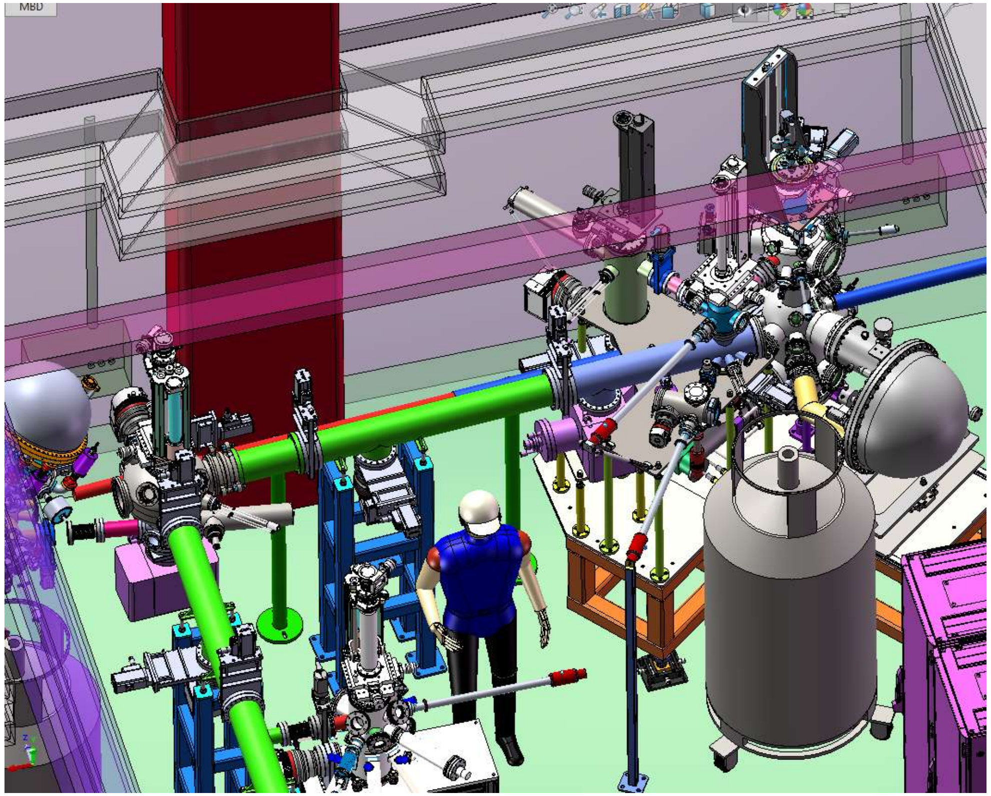
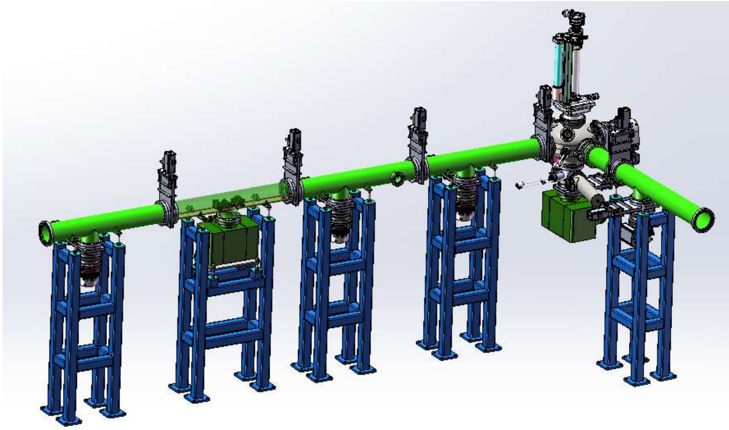
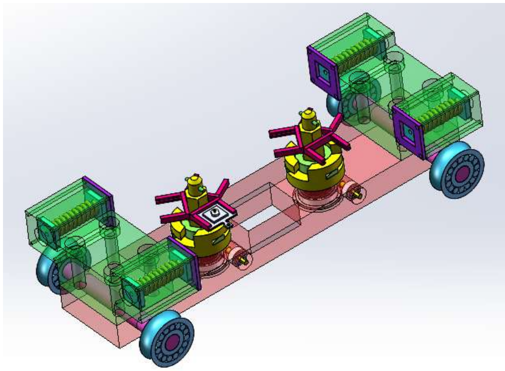
UHV sample transfer system


Realize sample transferring in UHV
between TAP, PEM, STM, and sample preparation system.

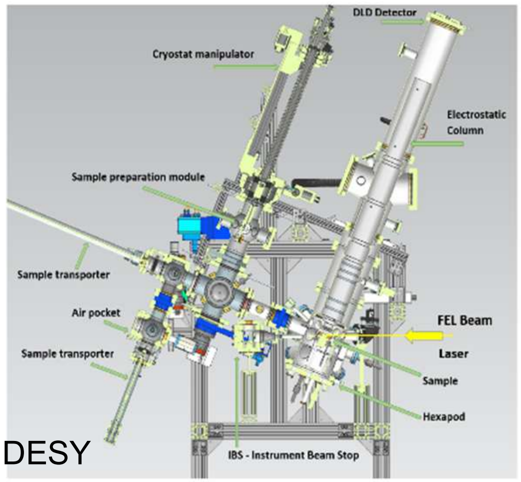


Figure 3: Central section of the TR-XPES experiment.