The 12th International Organization of Chinese Physicists and Astronomers Accelerator School

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FEL：Scientific Applications（EUV）——Dalian Coherent Light Source

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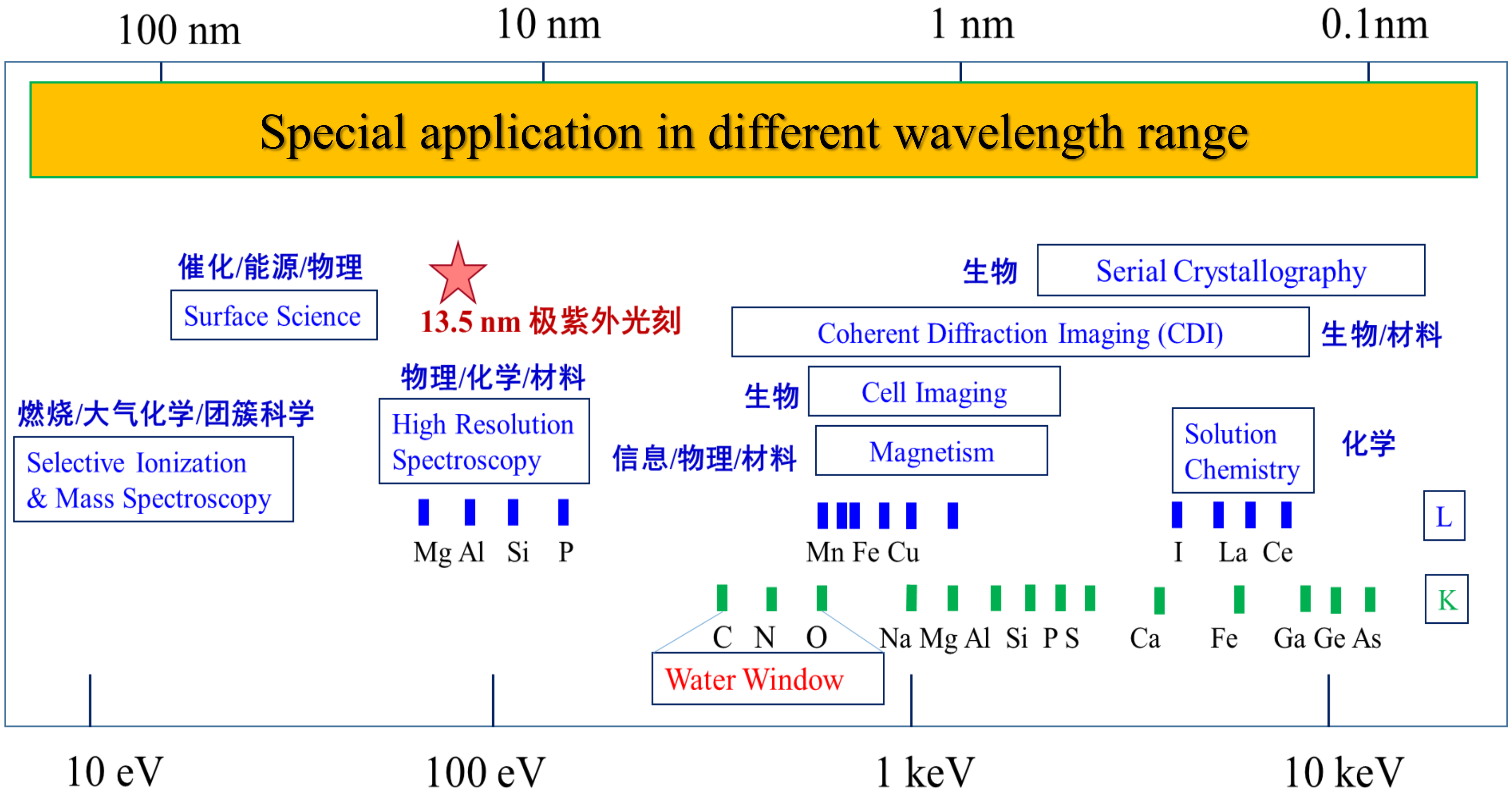
Scientific Application in General

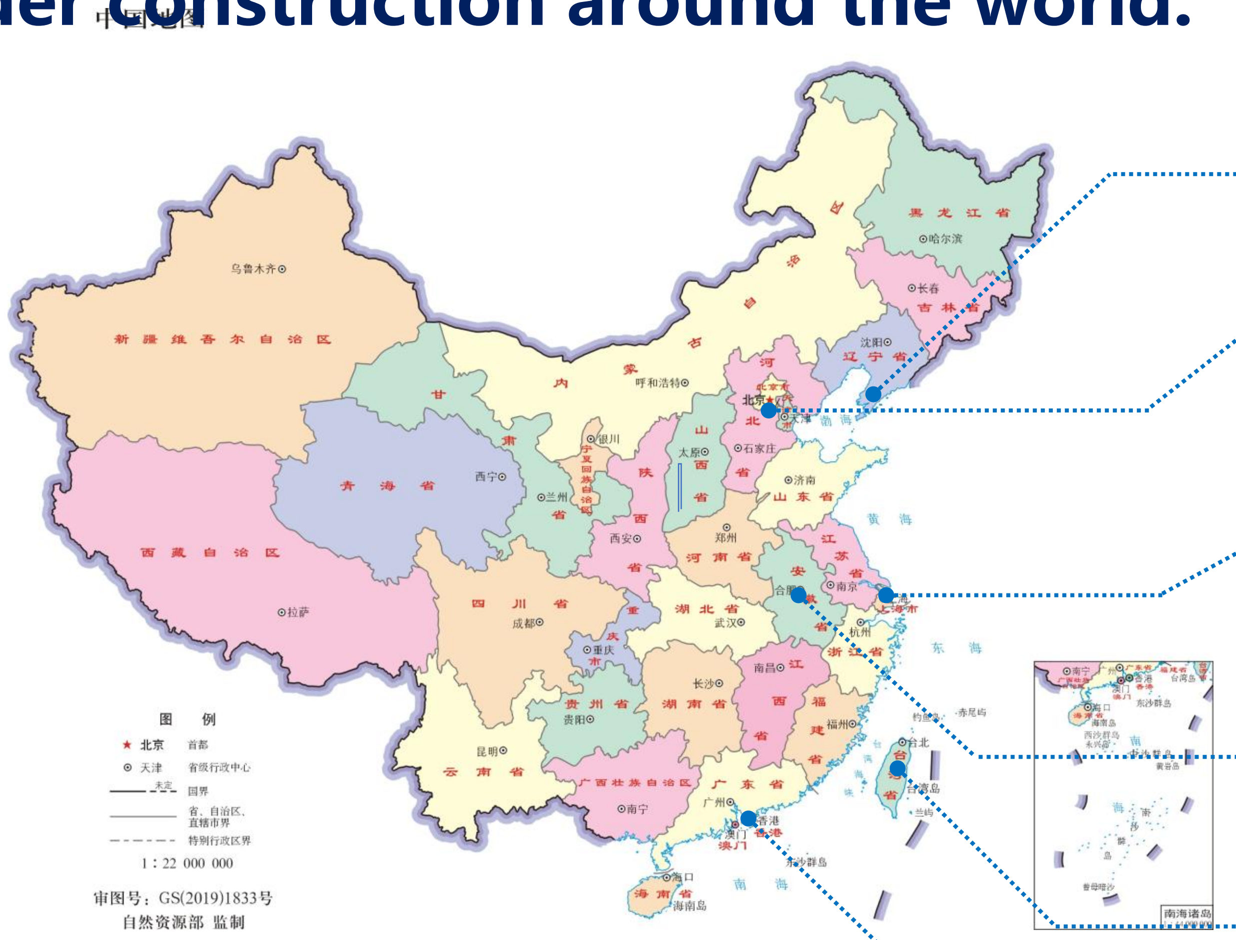


- Spectroscopy
- Diffraction
- Scattering
- Imaging

Meet the needs of multidisciplinary frontier research.

Advanced Light Sources

More than 60 SR and 10 high-gain FEL facilities in operation and under construction around the world.



SR
FEL

大连相干光源（2017）

北京同步辐射装置（兼用模式、1991）
<u>北京高能同步辐射光源</u>

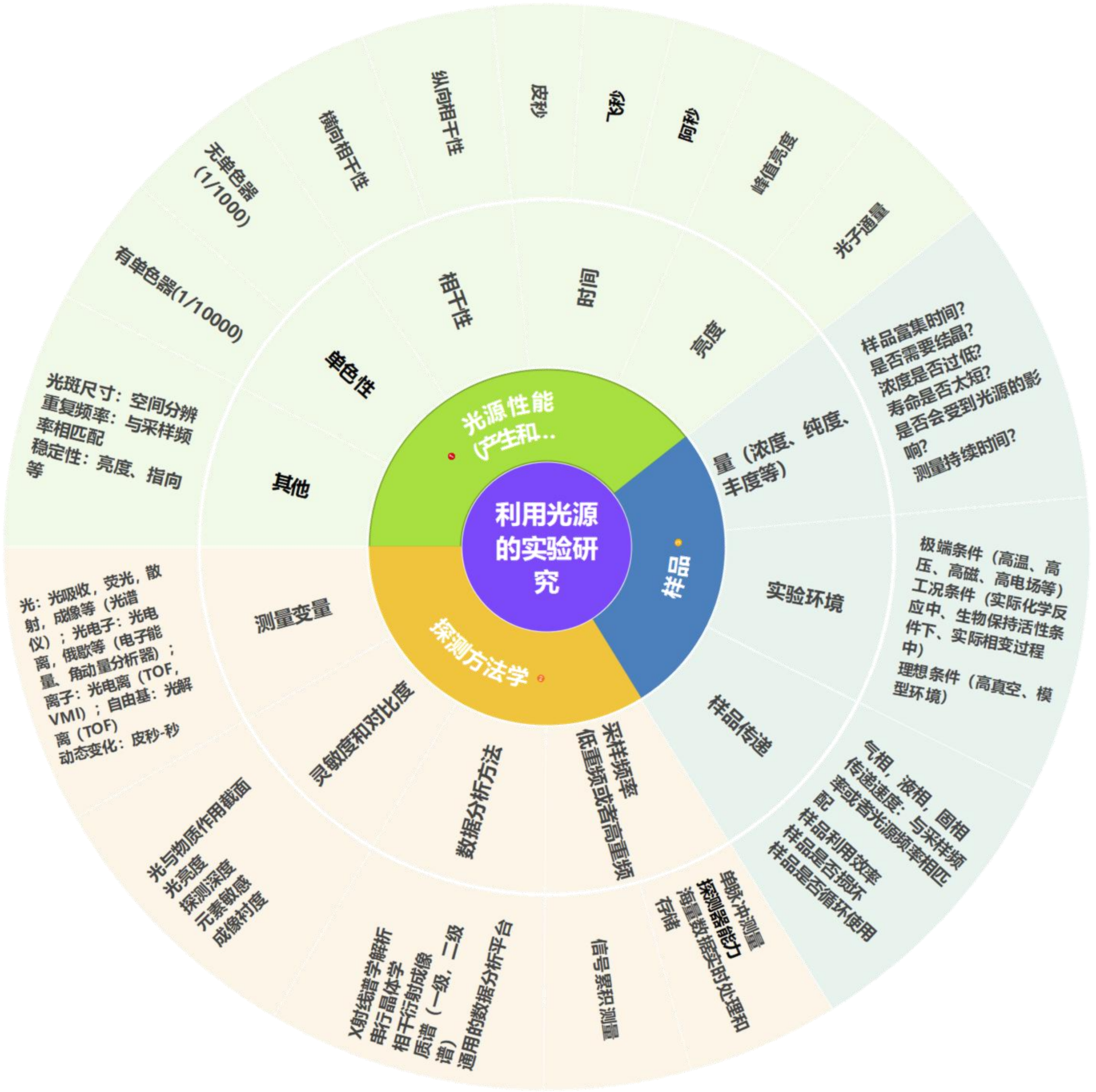
上海同步辐射光源（2009）
上海软X射线自由电子激光装置（2022）
<u>上海硬X射线自由电子激光装置</u>

合肥国家同步辐射装置（1991）
<u>合肥先进光源</u>

台湾光源（1993）
台湾光子源（2016）

<u>深圳中能高重复频率X射线自由电子激光装置</u>

Elements of Measurements in Advanced Light Sources



- **Bright source:**
  - Advanced accelerator technology
  - New radiation mechanism
- **X ray/EUV optics:**
  - Transportation
  - Manipulation
  - Diagnosis
- **Experimental measurement:**
  - Sampling
  - Detection
  - Time resolved
- **Data:**
  - Accumulation and storage
  - Analysis and utilization

Outline

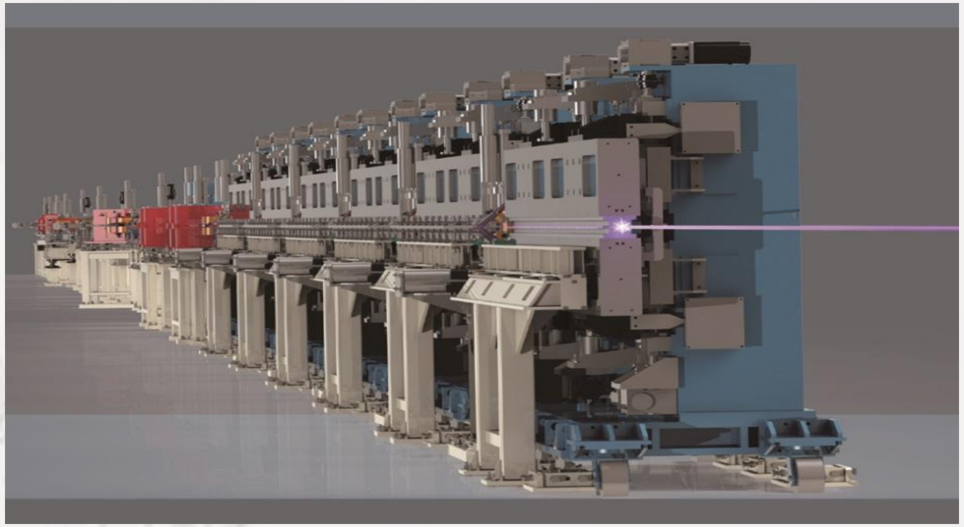
I. Introduction of DCLS

II. Experimental method

III. Scientific research

IV. Future plan

Overview of Dalian Coherent Light Source



Unique Free electron laser facility in the VUV and EUV range

- Tunable Wavelength： 50 – 150 nm
- Pulse Energy： >100 uJ (1 mJ)
- Pulse length： 100 fs /1 ps
- Bandwidth： Close to Fourier transform limit
- Jitter： <30 fs
- Rep Rate： 50 Hz

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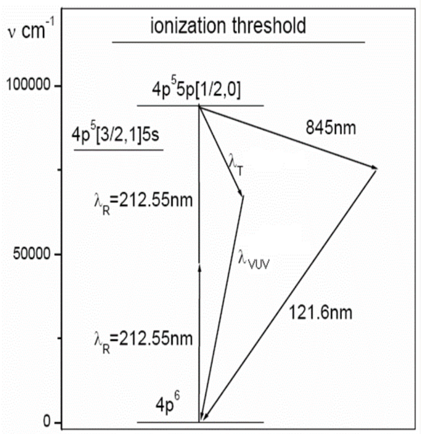
NSFC
国家自然科学基金委员会
National Natural Science Foundation of China

EUV Light Source（10–120 nm）

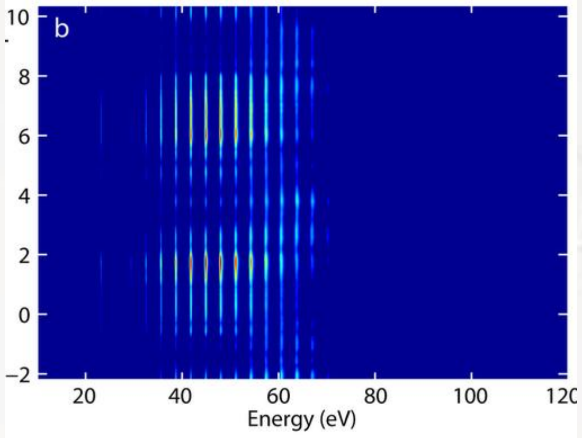
The material world is made of atoms and molecules. Molecule detection by ionizing is a essential method for studying the relevant systems. One photon ionization by Extreme ultraviolet light is the most effective way, combination with ultrashort.

Four wave mixing



Limited Wavelength tunability
~uJ pulse energy
~ns Pulse duration

High harmonic generation



Limited Wavelength tunability
~nJ pulse energy
~fs Pulse duration

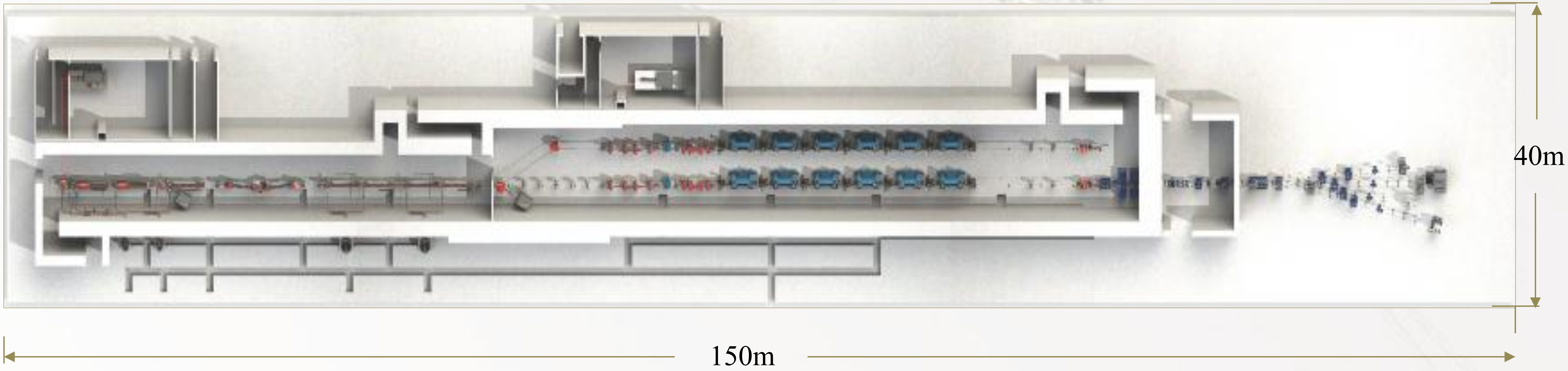
Synchrotron radiation

Wavelength tunability
~nJ pulse energy
~10ps Pulse duration

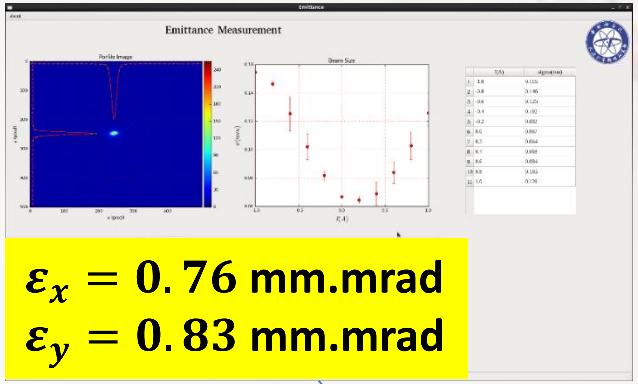
DCLS is a FEL user facility in EUV range that provides high-brightness, ultrashort-pulse, wavelength--tunable laser.

DCLS Layout

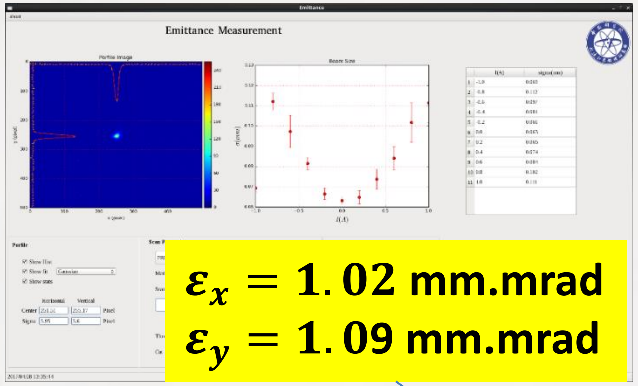
First lasing in December 2016



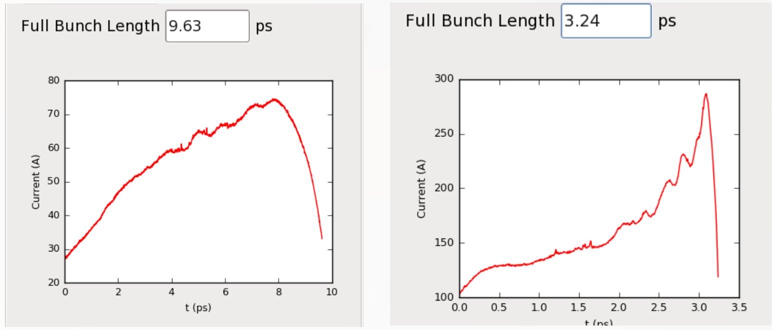
LINAC based on copper structure



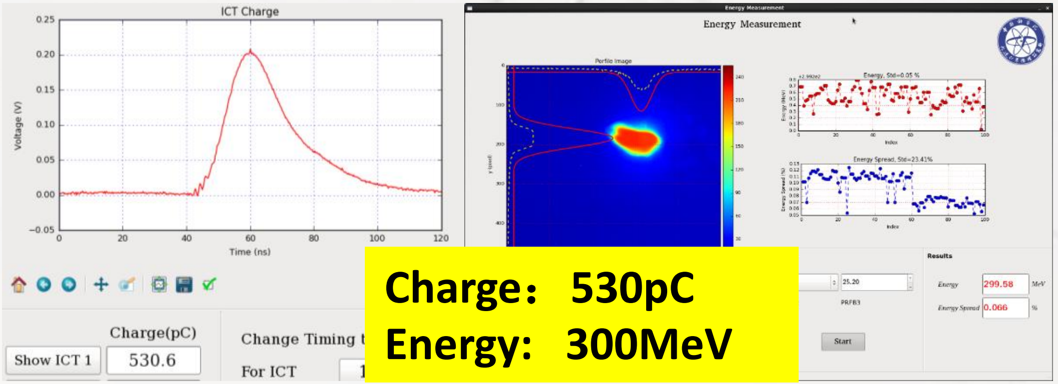
$\varepsilon_x = 0.76$ mm.mrad
$\varepsilon_y = 0.83$ mm.mrad



$\varepsilon_x = 1.02$ mm.mrad
$\varepsilon_y = 1.09$ mm.mrad

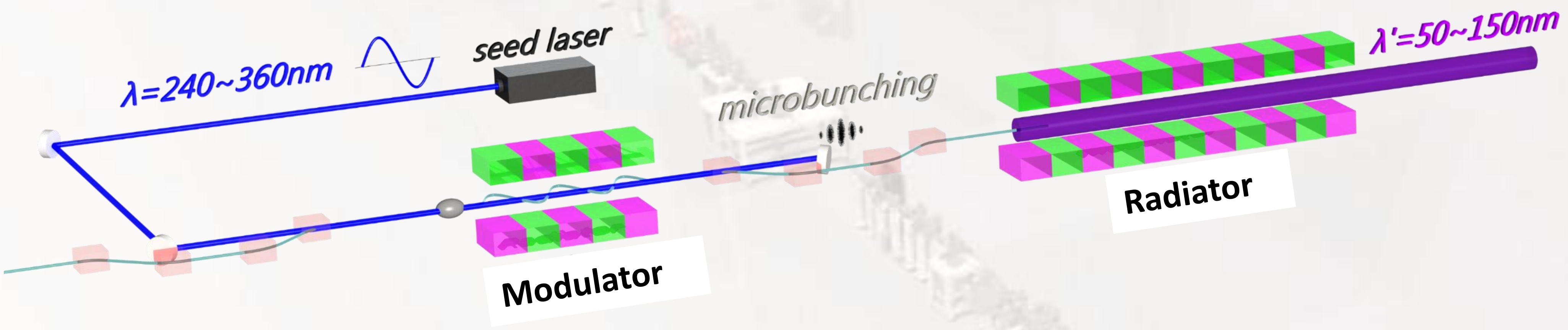


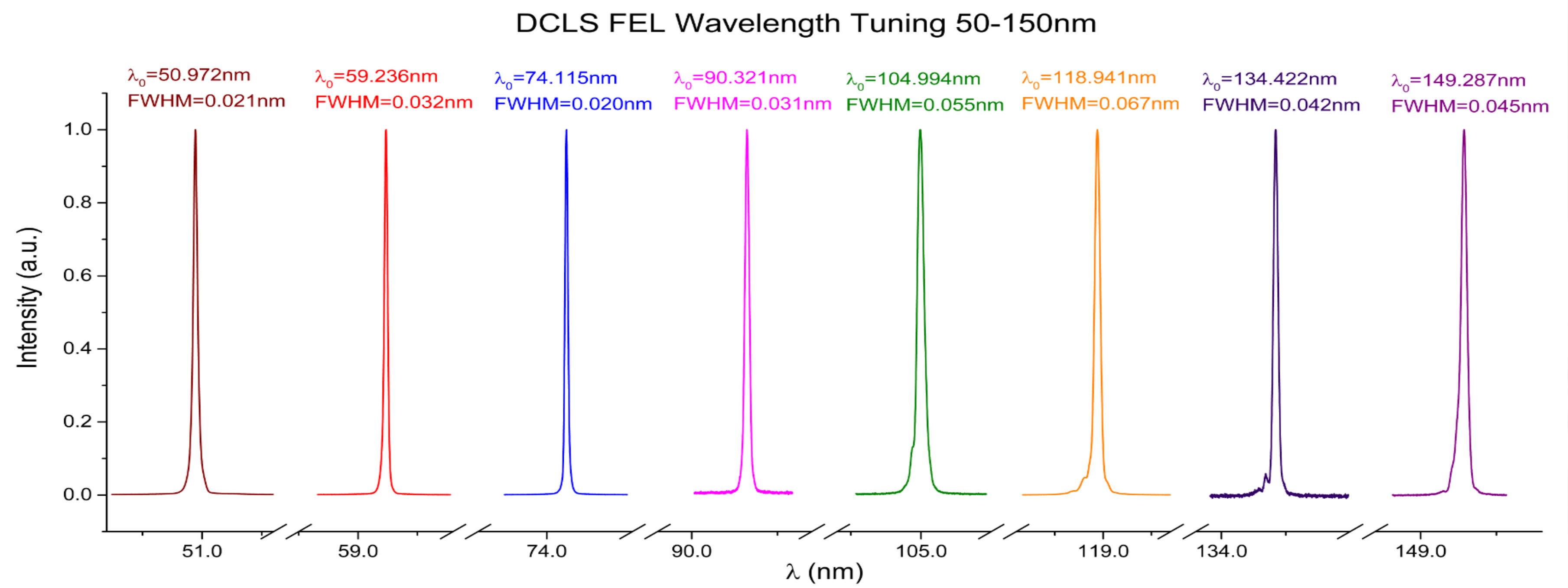
No compress : 9.63ps
After compress: 3.24ps



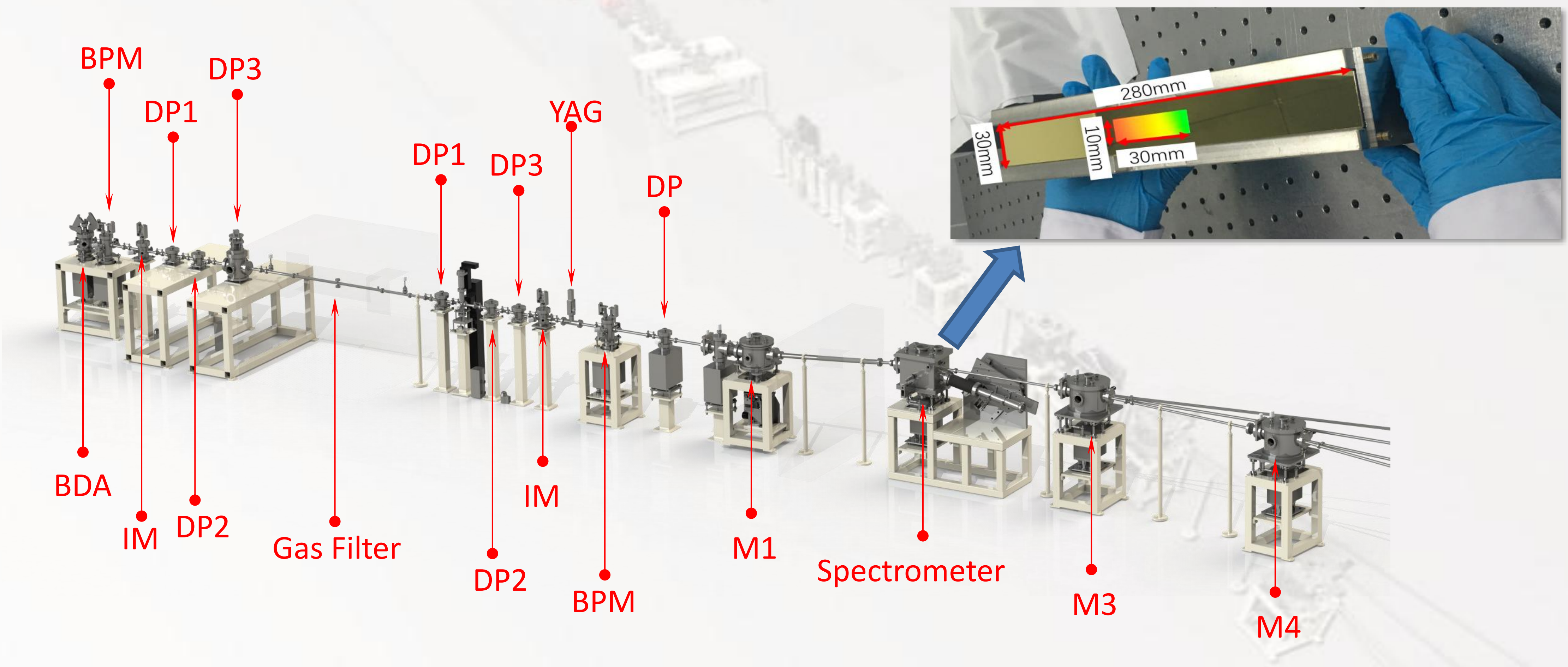
Charge： 530pC
Energy: 300MeV

Seeded FEL based on HGHG mode





Transportation and diagnosis of DCLS



Cooperation with Prof. Qiuping Wang at USTC

Milestone

2012.03 Starting of DCLS

2013.08 Review of TDR of DCLS

2013.12 Prototype of Undulator

2014.10 Starting of Construction

2016.04 LINAC installation

2016.09 Undulator spontaneous emission

2016.11 FEL SASE lasing

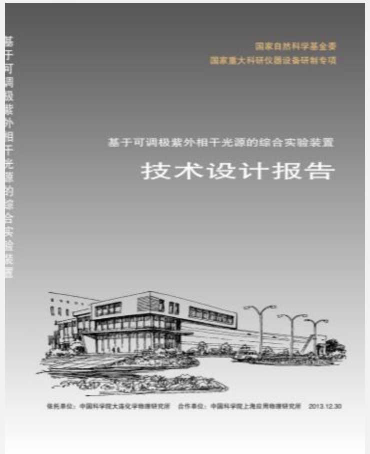
2016.12 FEL HGHG lasing

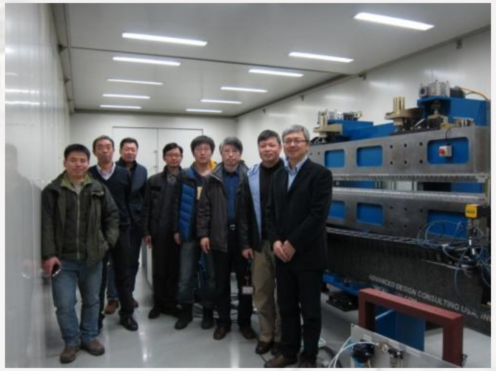
2017.06 First user experiment

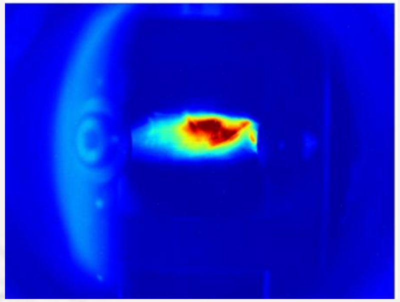
2018.07 Project acceptance and operation

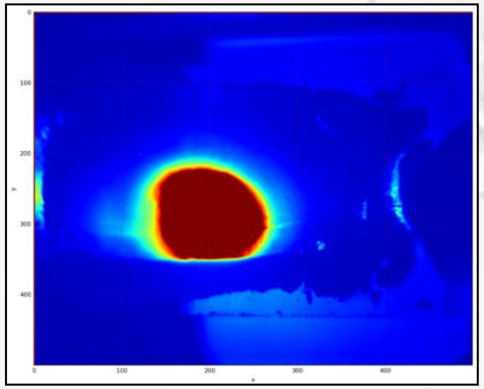
2020.12 2nd FEL line installation

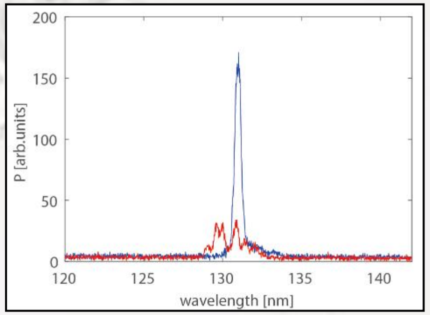
2021.08 First lasing of 2nd FEL line









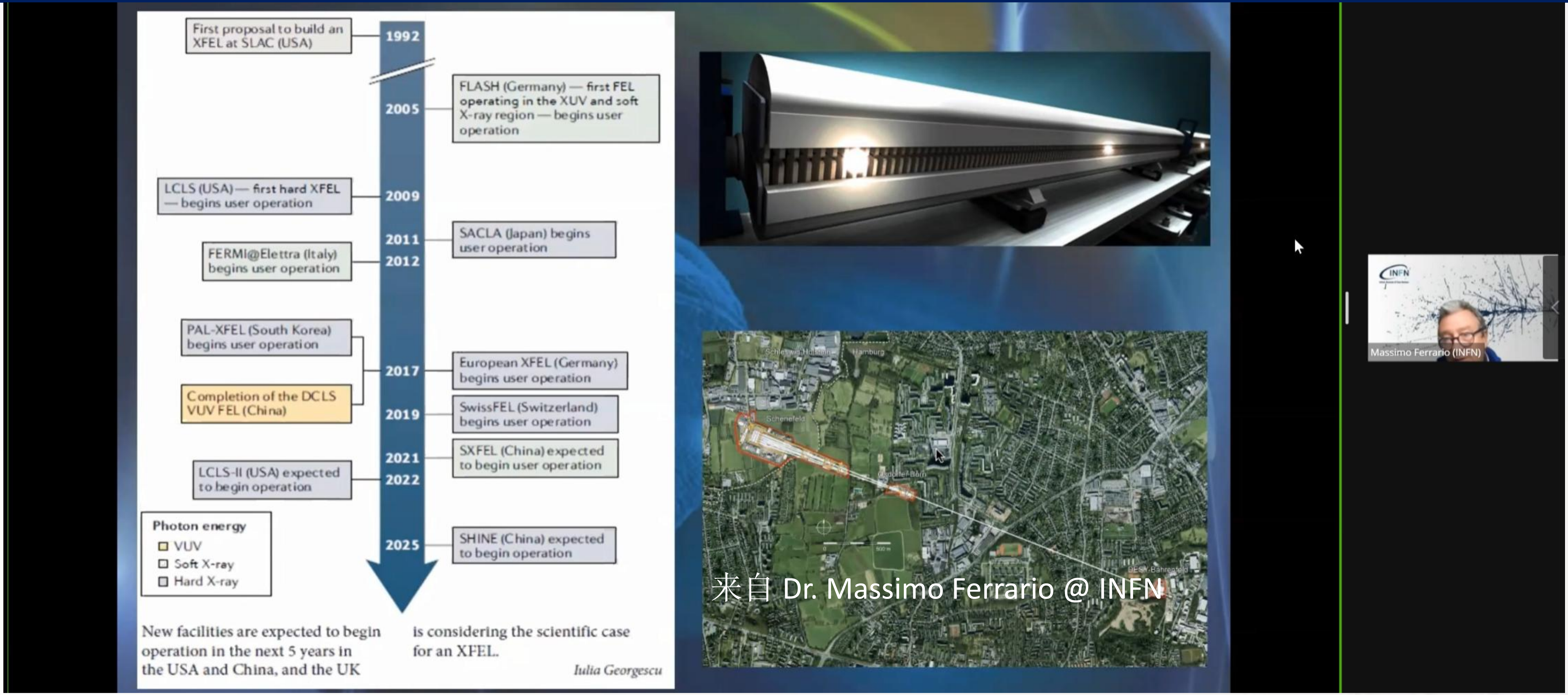


DCLS Operation Statistics

Year	Total beamtime	User beamtime	Percentage of user beamtime	Percentage of delivery
2019	5979.5	3428.6	57%	76%
2020	6319.2	5601.8	88%	94%
2021	5795.4	3028.5	52%	90%
2022	7380.2	5897.6	80%	93%
2023	7030.4	5968.6	85%	92%
2024 (planed)	6888.0	5304.0	77%	90%

FEL Facility (2022)	LCLS	FLASH	FERMI	SwissFEL	SACLA	PAL
User beamtime	4260	888	3408	2568	5916	4608
Total beamtime	6768	3096	5904	5472	——	5928

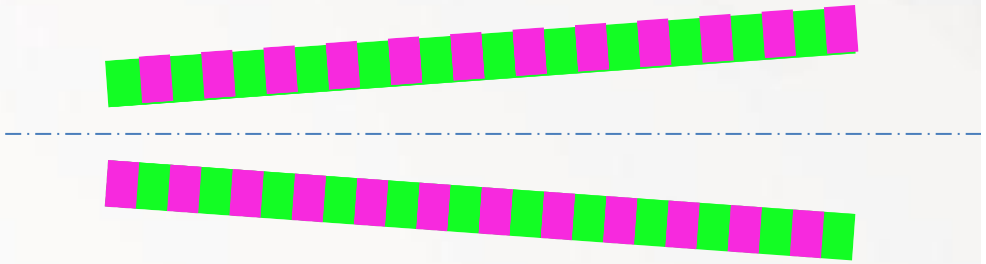
High gain FEL user facility in the word



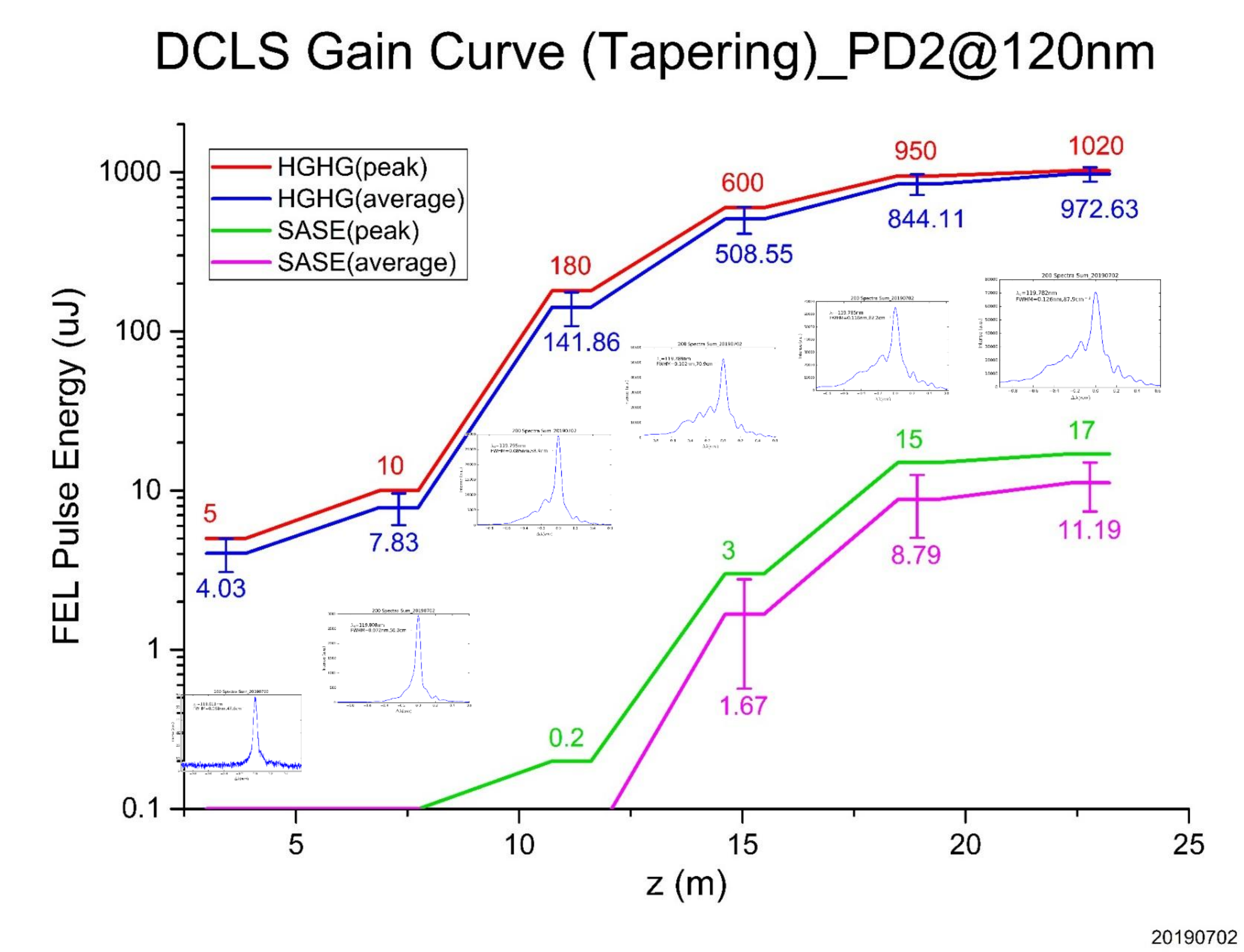
- The first high gain FEL user facility in China.
- Unique FEL user facility focusing in VUV-EUV range in the world.

Higher Pulse Energy

Tapering the undulators



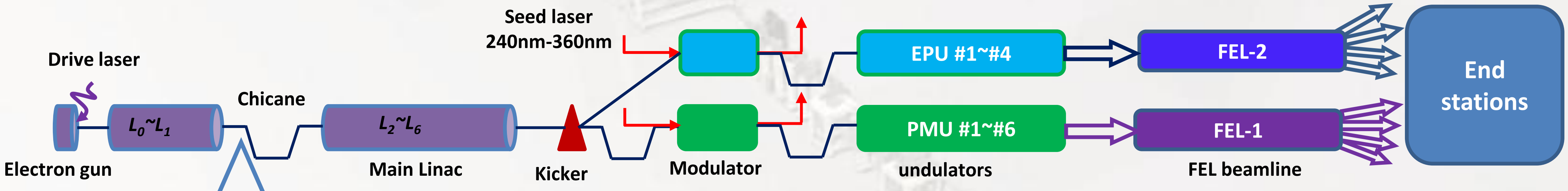
By slightly tapering the undulators, the magnetic field gradually become weaker so as to maintain the resonance condition with the electrons losing energy through FEL radiation. Compared with regular setup without tapering, the FEL pulse energy using tapered undulators can be enhanced by a factor of three.



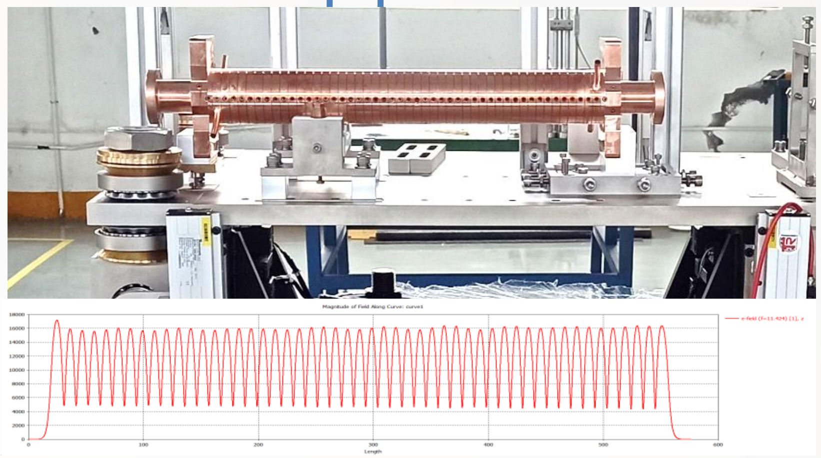
More than 5×10^{14} photons per pulse within 0.1% linewidth

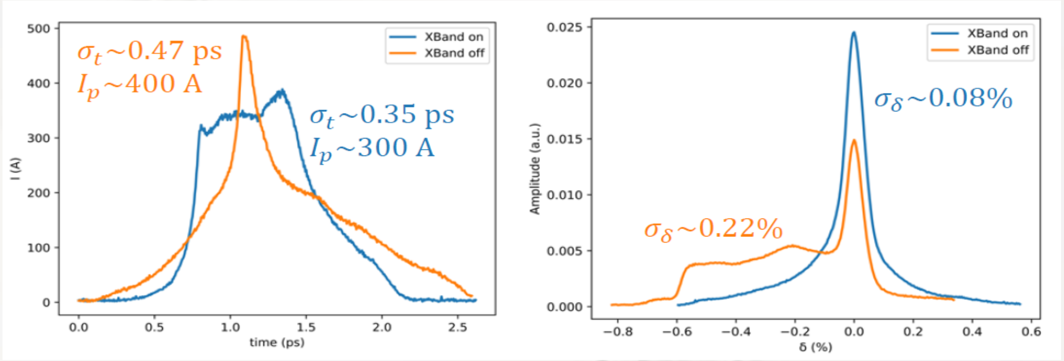
X-band linearizer

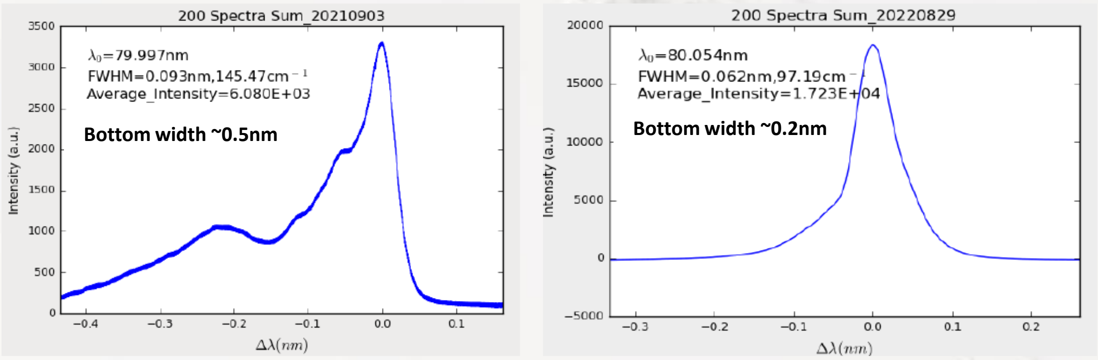
An X-band linearizer significantly improves the electron beam quality by making the current distribution more uniform as well as reducing the energy dispersion by 60%. The resultant spectral width has been reduced by a factor of two.



0.6m X-band linearizer







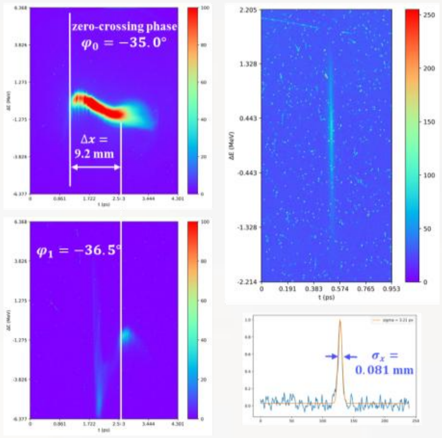
Temporal distribution diagnosis system

Time resolution:

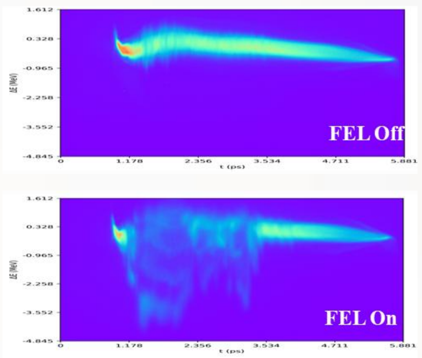
$$\Delta_t = \frac{E\sigma_{x0}}{\omega e V_{def} R_{12}} = \sqrt{\frac{\gamma\varepsilon_{n,x}}{\beta_d}} \frac{\lambda_{rf} m_e c^2}{2\pi c |eV_{def} \sin\Delta\mu|}$$

- **S-band frequency**
  $f = 2856\ \text{MHz}$
- **position-time conversion**
  $c_{x2t} = \frac{|\varphi_1 - \varphi_0|}{\Delta x \cdot 2\pi f} = 158\ \text{fs/mm}$
- **Resolution**
  $R = c_{x2t} \cdot \sigma_x = 12.8\ \text{fs}$

deflector on **deflector off**

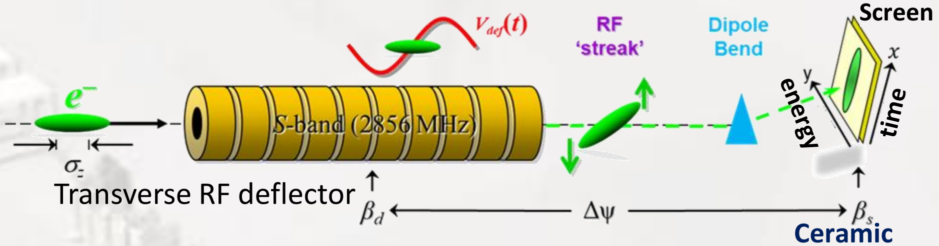


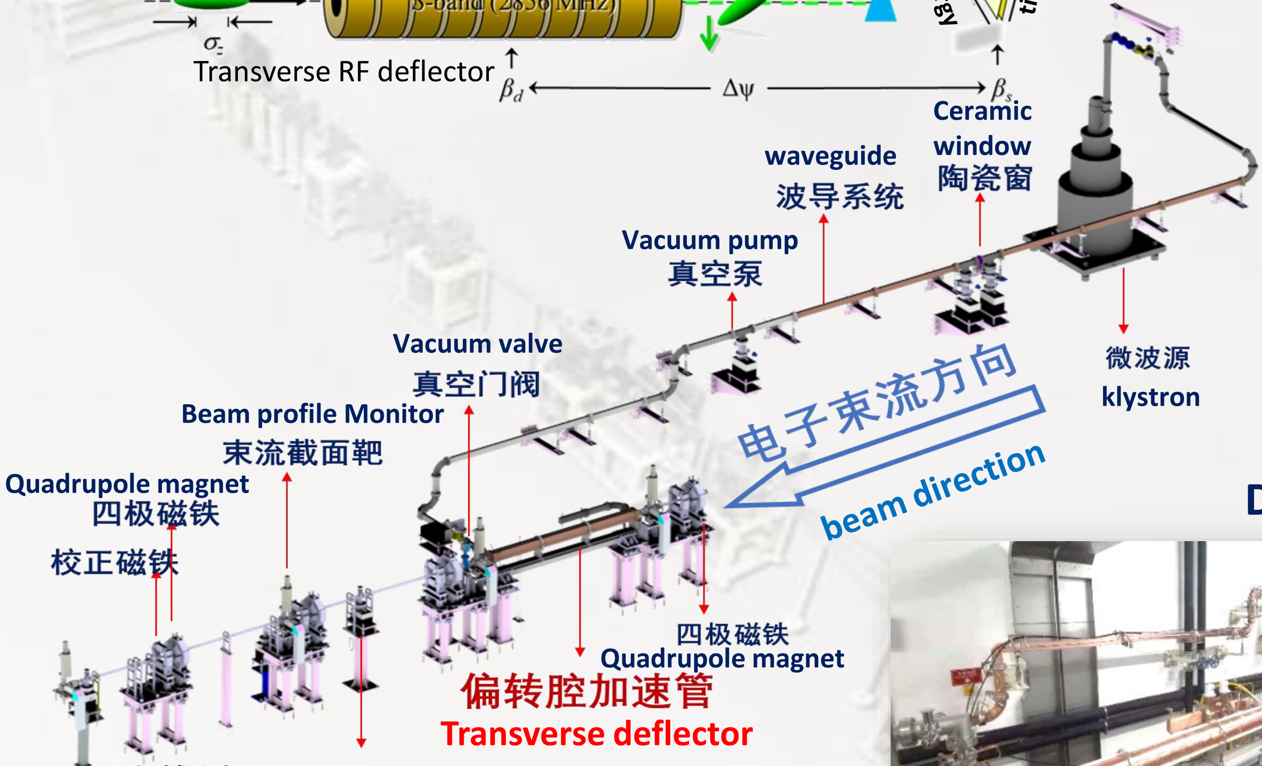
Electron beam



Temporal distribution diagnostics of FEL light@130nm

Principle diagram





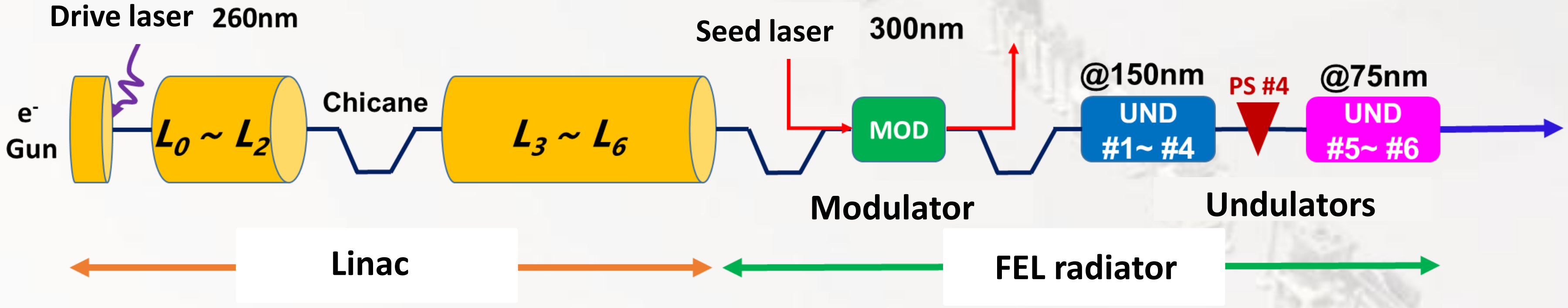
Deflector

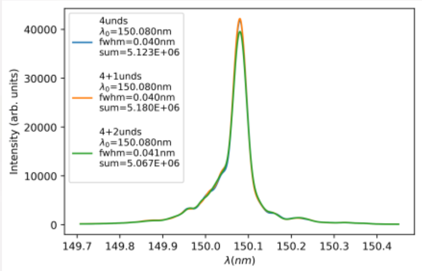
The time resolution is about 12fs

Two-color VUV FEL pulse with tunable delay

- **Seed laser: 300nm**
- **4 modulators @ 150nm**
- **2 modulaors @ 75nm**

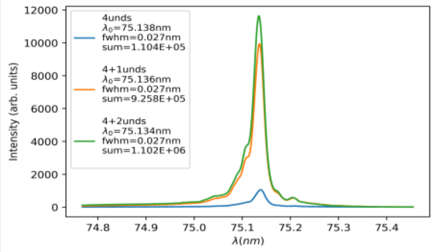
$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$





150nm: 77.8 μJ

75nm: 2.8 μJ

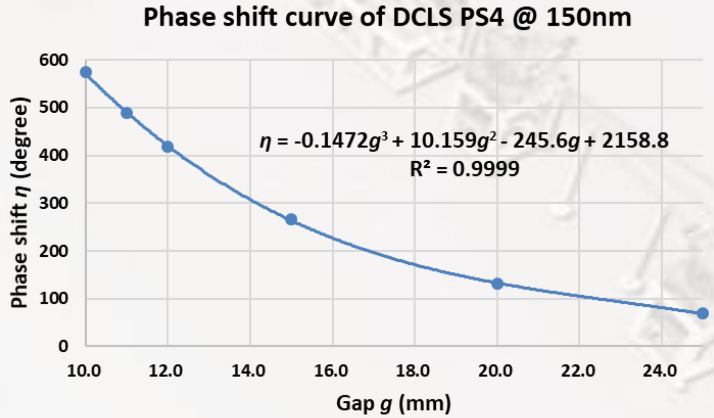


Realize the phase shift of two-color laser pulses with #4 phase shifter

$$E(t) = \sqrt{I_\omega(t)}\cos\omega t + \sqrt{I_{2\omega}(t)}\cos(2\omega t - \emptyset)$$

Phase shifter tunable range: $\emptyset \in [68^\circ, 490^\circ]$

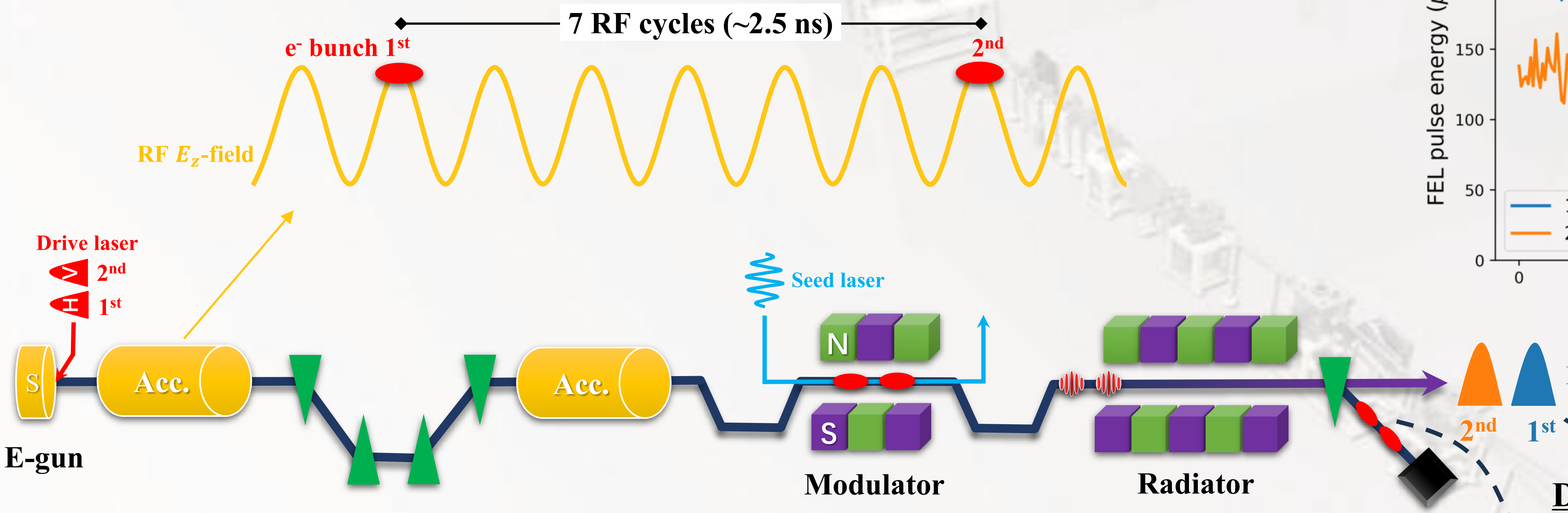
$1^\circ \sim 1.4as$ **@150nm**



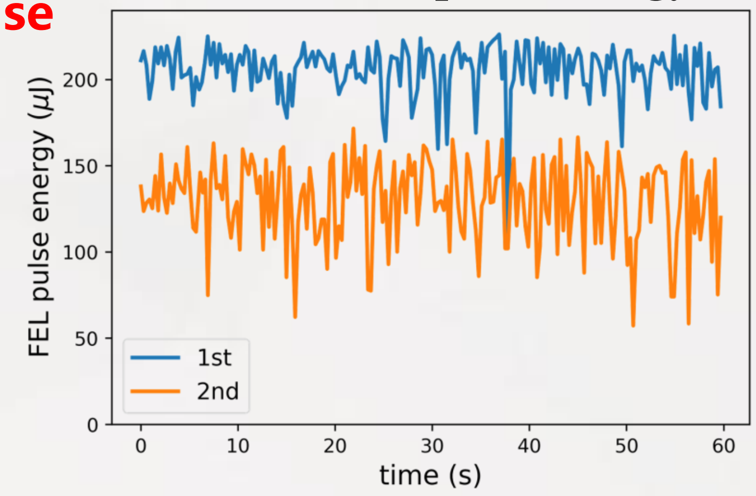
By tunning the phase shifter between the two undulator sections, the relative phase of the two-color VUV laser pulse can be precisely controlled, providing a new tool for atomic physics researches

Double pulse lasing

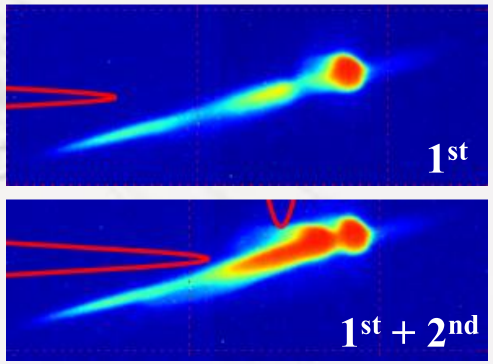
Double drive laser (H. & V.) → Double electron bunch → Double FEL pulse



Double FEL pulse energy



Double bunch energy distribution

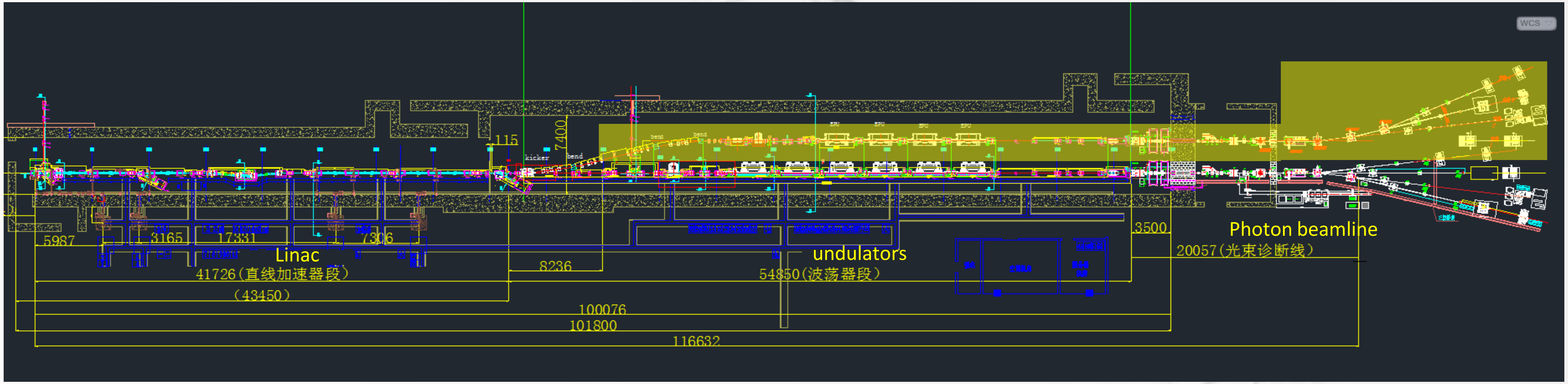


- A double pulse lasing experiment was conducted to enhance the FEL intensity by employing a double drive laser with a time separation of ~2.5 ns.
- Nearly identical configurations were collocated for these two laser/bunch/FEL pulses.
- A 1.6-fold enhancement in FEL intensity was achieved with the double pulse compared to the single pulse (~200μJ vs. 330μJ).

The 2nd FEL beamline with variable polarization

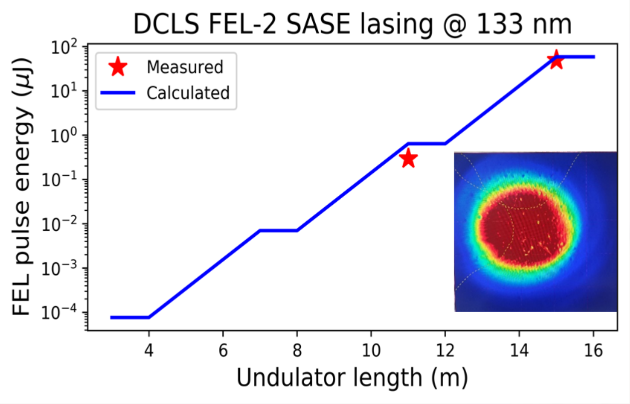
FEL-2 first lasing on 2nd August 2021

- FEL-1 &2 running simultaneously to serve more users
- Variable polarization，ultrashort VUV pulse ~100fs



Beam switchyard

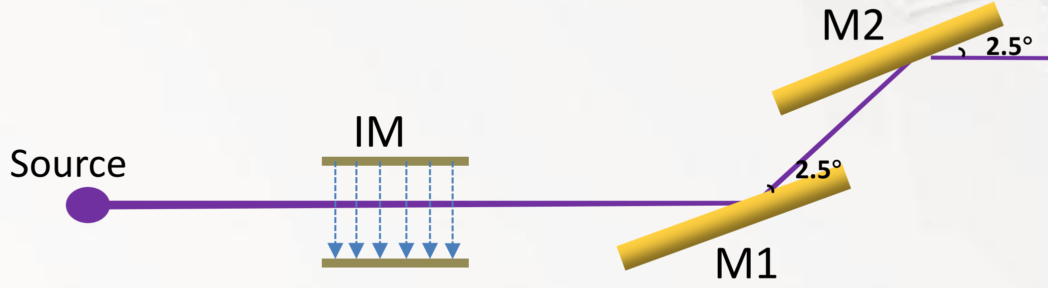
EPU

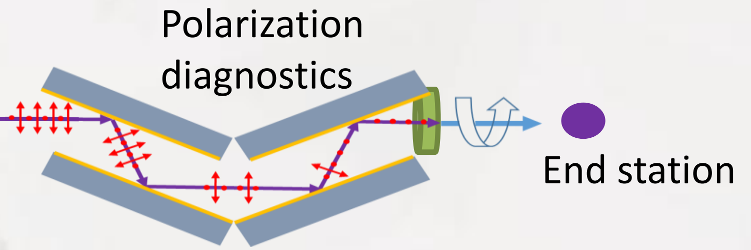


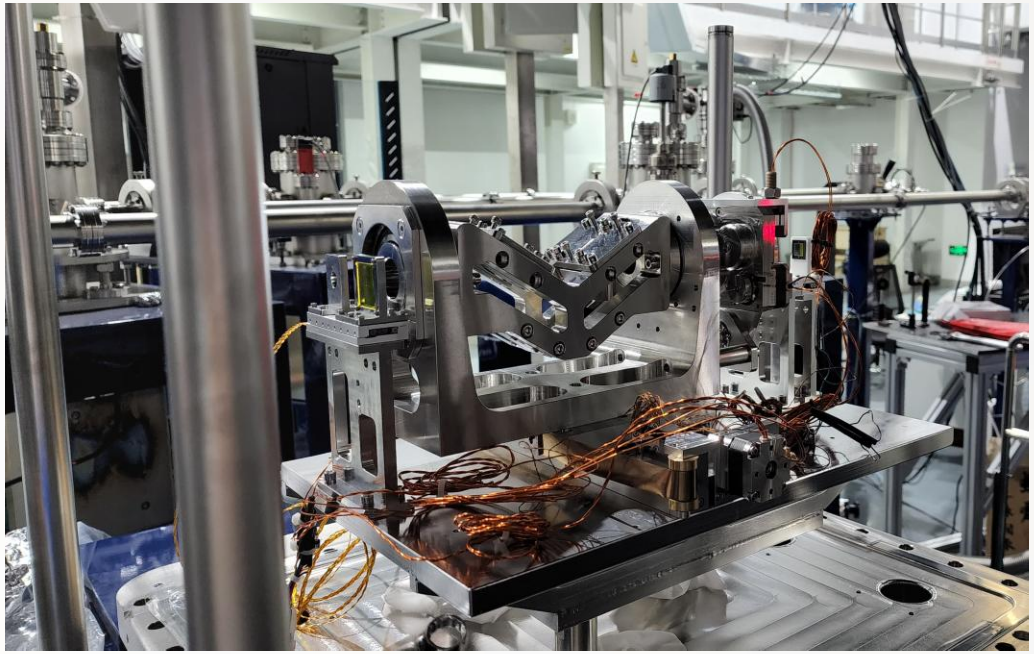
Lasing @133nm

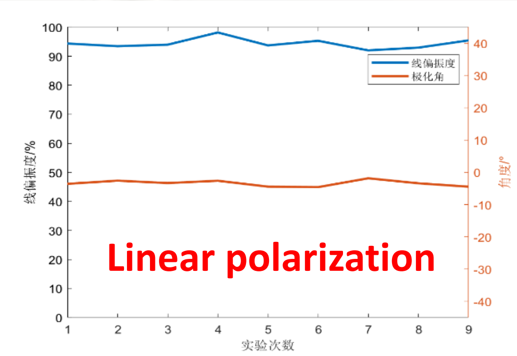
Polarization diagnosis of VUV FEL

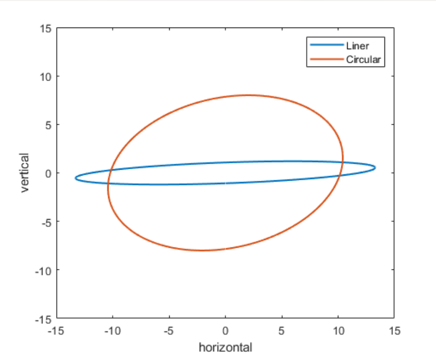
Based on the direct optical measurement technology, the polarization diagnosis system for DCLS covers the entire VUV range with high precision and services in routine operation.

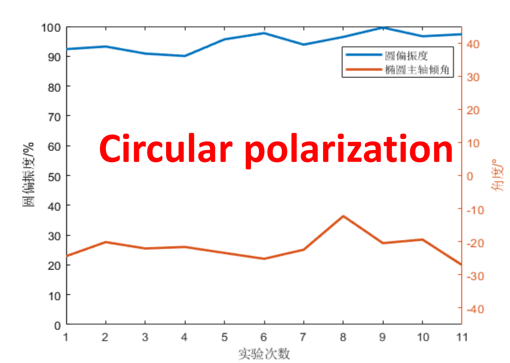








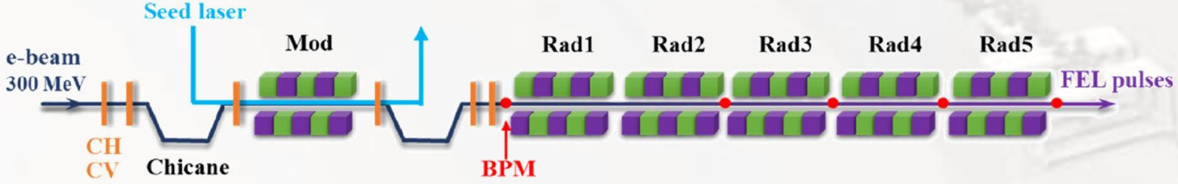




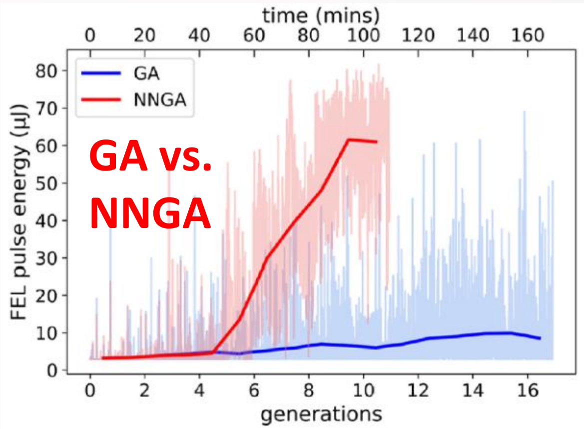
ψ	-3.42° ±0.955°
P_L	94.4%±1.79%
ψ	-21.65° ±3.87°
P_c	95%±3%

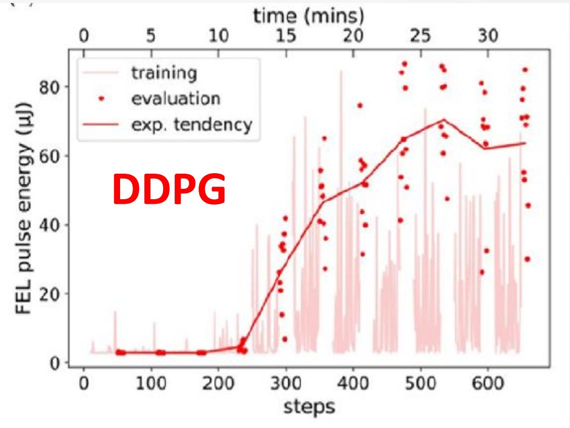
FEL optimization via machine learning

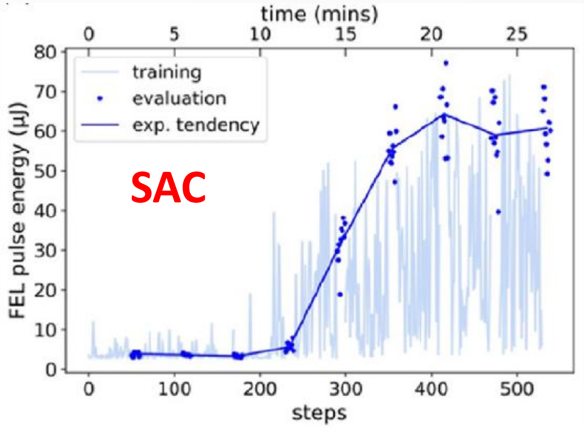
➢ **It only takes 20 minutes to automatically tune FEL energy from zero to saturation.**

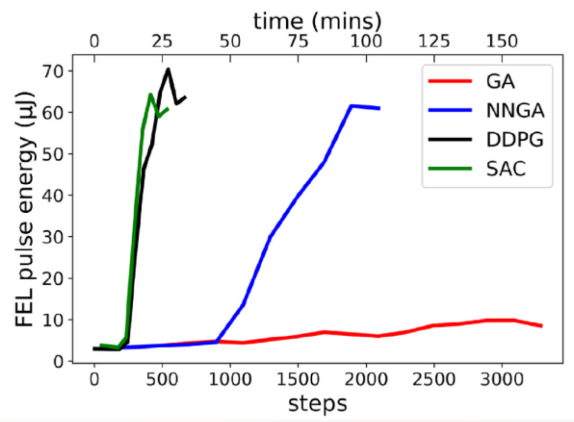


	Time consuming (min)	Steps	Optimized pulse energy (μJ)
GA	>>164	>>3400	9.86
NNGA	90	1800	61.57
DDPG	27	540	70.45
SAC	21	420	64.26









- **Four algorithms have been employed during the optimization, namely the standard generic algorithm (GA), the neural network based genetic algorithm (NNGA)， the deep deterministic policy gradient (DDPG) and the soft actor critic(SAC) reinforcement learning algorithms.**
- **DDPG and SAC have demonstrated much better performance where convergences were achieved in ~20 minutes**
- **Objective：FEL pulse energy**
- **Optimized variables：12 correctors between the linac and the radiator**
- **Optimized steps：adjusting the correctors and each data point obtained in the experiment was averaged over 10 shots.**

Outline

I. Introduction of DCLS

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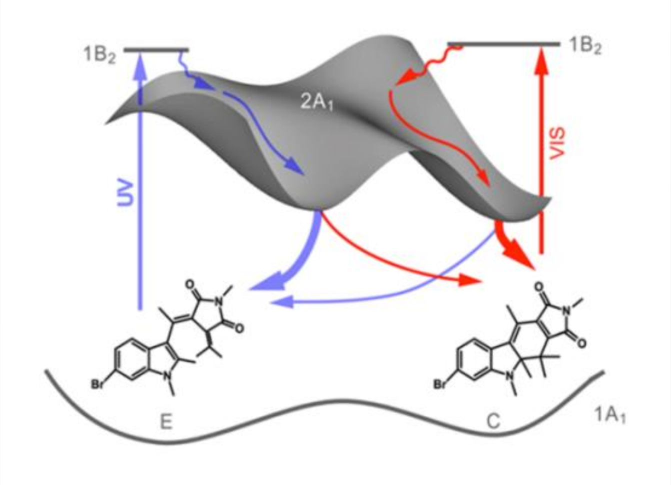
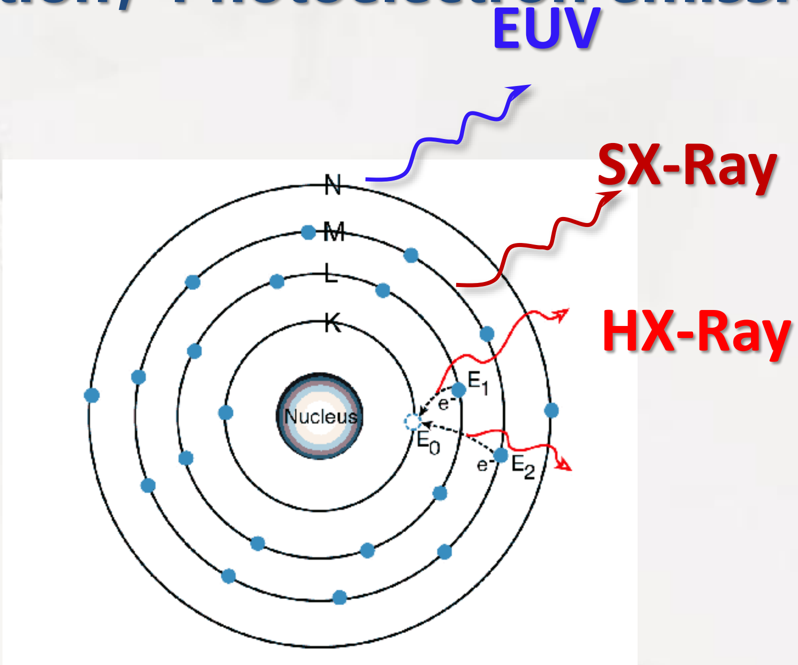
III. Scientific research

IV. Future plan

1. Spectroscopy and ionization

➢Spectroscopy: Electronic state excitation; Photoelectron emission





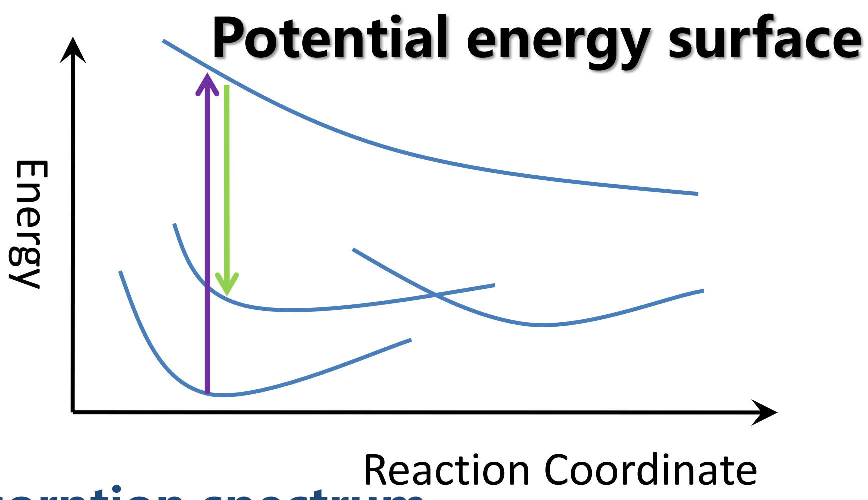
Molecule electronic state excitation

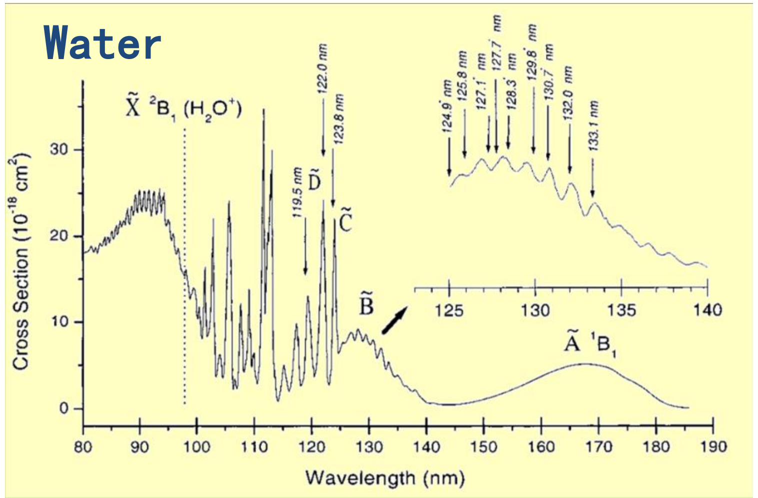
Atomic absorption

➢Photon ionization: detection with high sensitivity and selectivity

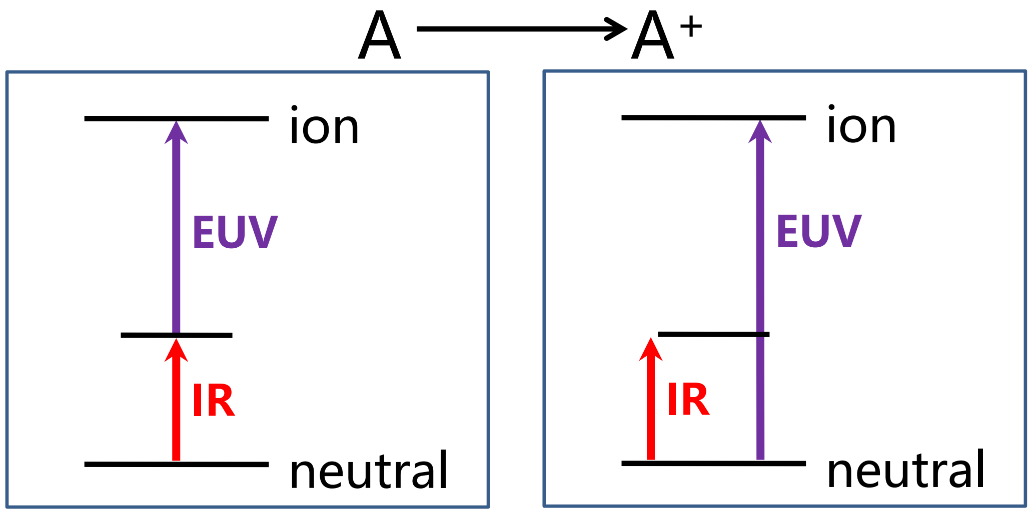
CH_3CHO	CH_3COOH	CH_3COCH_3	NH_3	C_6H_6	BF_3	CO	ClO_2	C_6H_{12}	CH_2NH_2	B_2H_6	$C_6H_4Cl_2$	$(C_2H_5)_2NH$
10.23	10.66	9.7	10.16	9.24	15.56	14.01	10.36	9.86	9	11.38	9.06	8.01

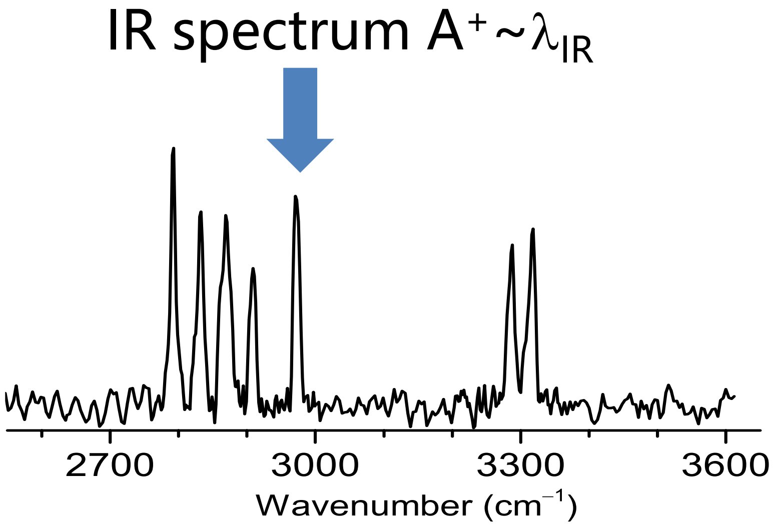
Spectroscopy





■ **Absorption spectrum**

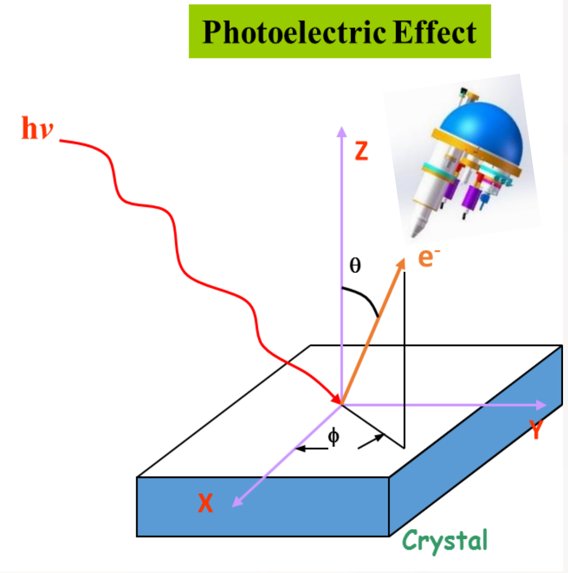




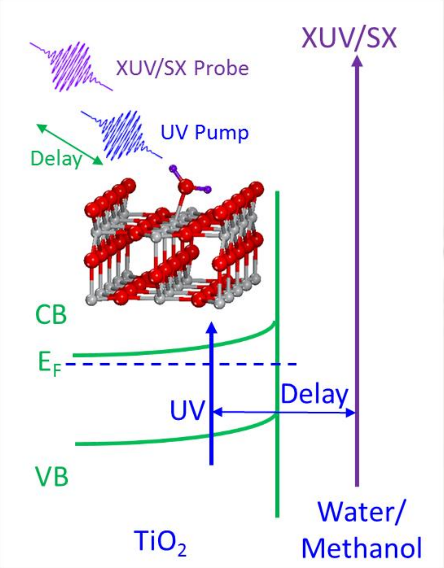
■ **IR+VUV spectrum**

Photoelectron emission

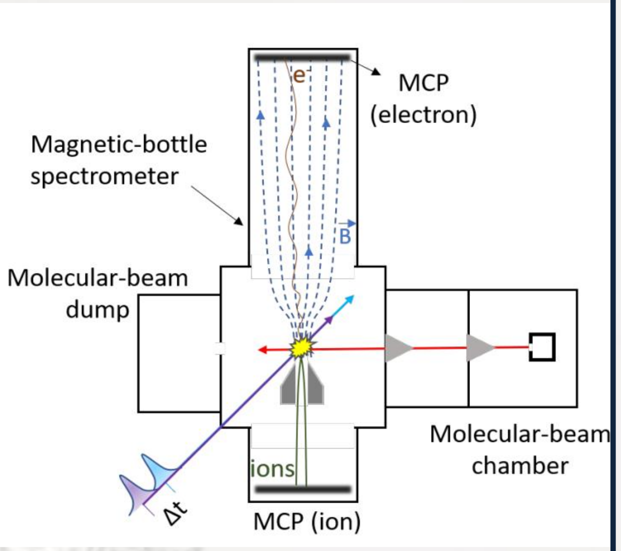
Interface



Optical Pump+XUV Probe



Gas phase



Energy reservation

$$E_B = \hbar\omega - E_{kin} - \phi$$

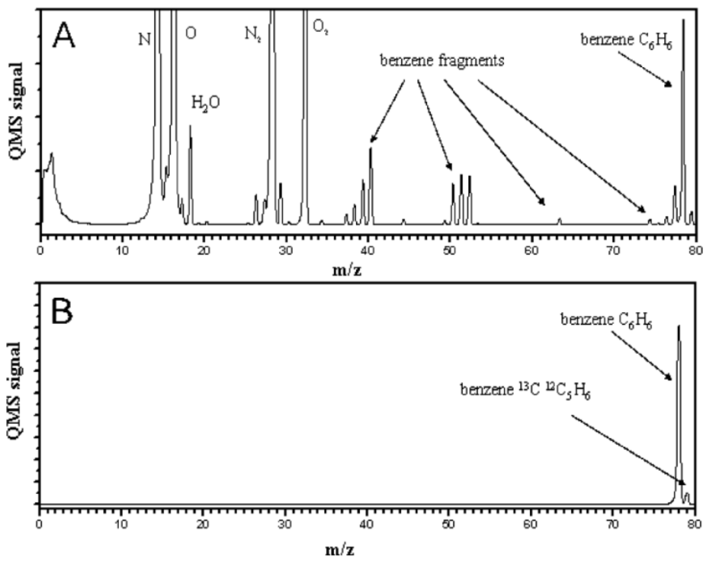
Momentum reservation

$$p_{//} = \hbar k_{//} = \sqrt{2mE_{kin}} \sin\theta$$

Photoelectron spectroscopy is one of the most direct experimental techniques for measuring the electronic structure of matter. Light sources in the extreme ultraviolet(10-40 eV) are suitable for the study of surface interface processes and gas-phase reactions due to the low energy of the spilled electrons, e.g., probing the molecular orbitals of adsorbates, the valence band structure of semiconductors and heterojunctions, and the structure of gas-phase molecules or clusters.

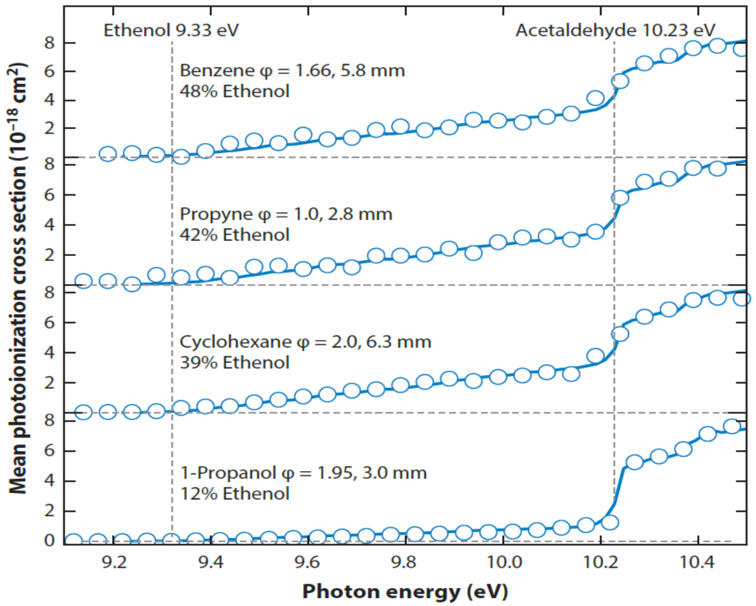
Detection by EUV one photon process

Ionization
Electron bombing vs one photon



1. Less fragment，easy to analysis
2. Short-live intermediates and radicals
3. Complex system—operando condition

Photon ionizing energy spectrum

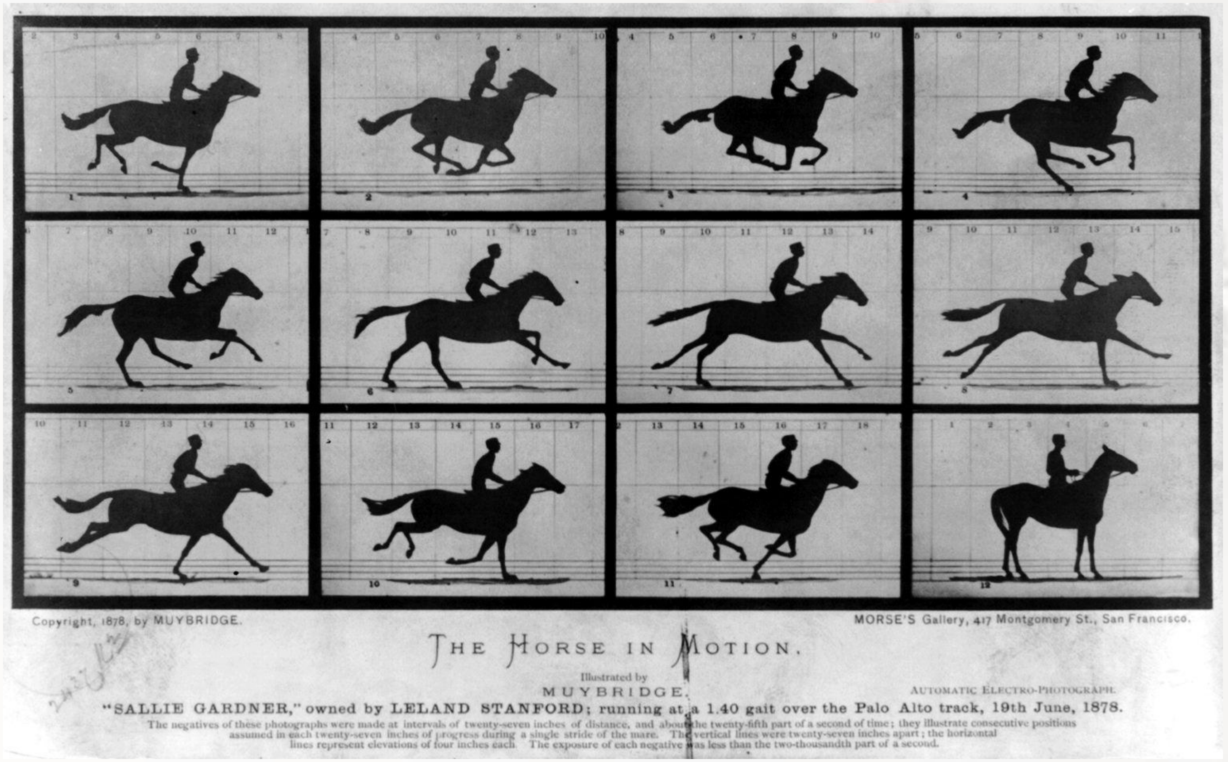


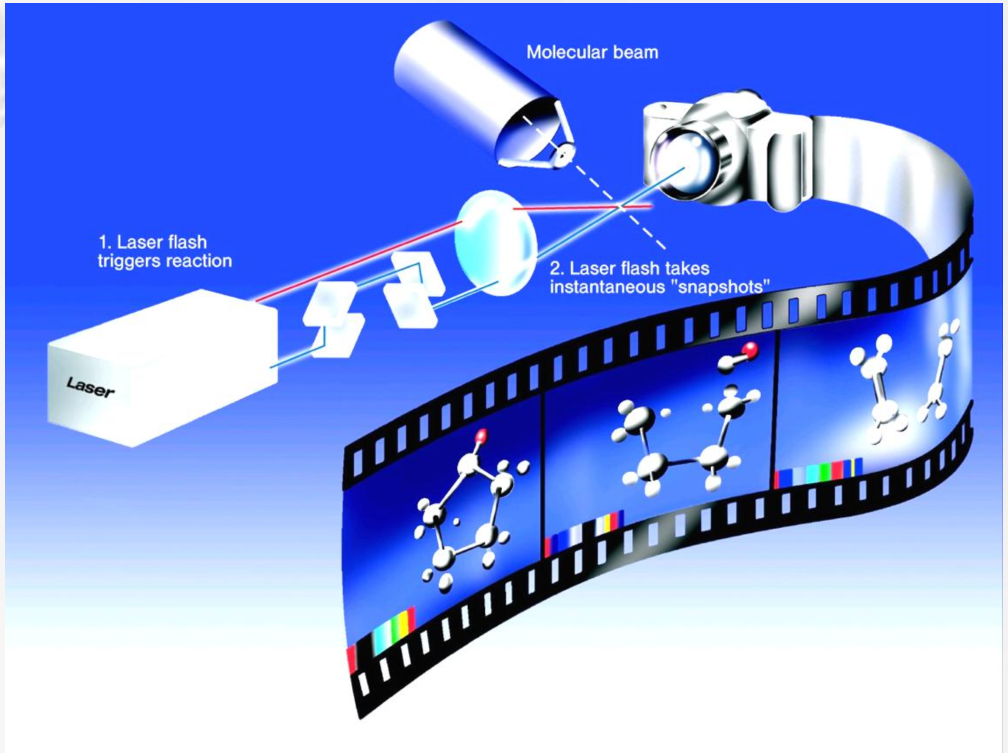
1. Selectivity，same mass with different PIE
2. Sensitivity，large cross section of ionization, pulsed sample with pulsed light, 10^{14} photons/pulse can detect single atom

Single Photon Ionization Detection: Highly Sensitive, Tracing Short-Lived Intermediates and Free Radicals in Chemical Processes

Anal. Chem. **77**, *2218-2226* (2005)

2. Ultrafast process

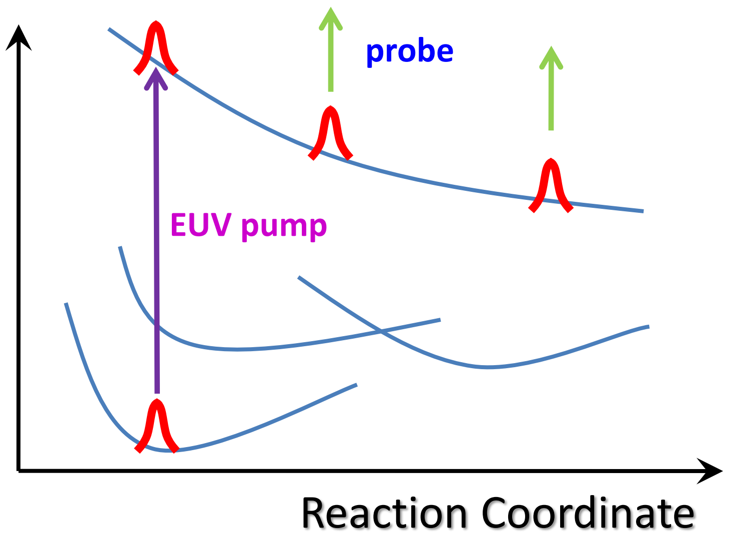




fs-ps pulse laser in EUV range at DCLS

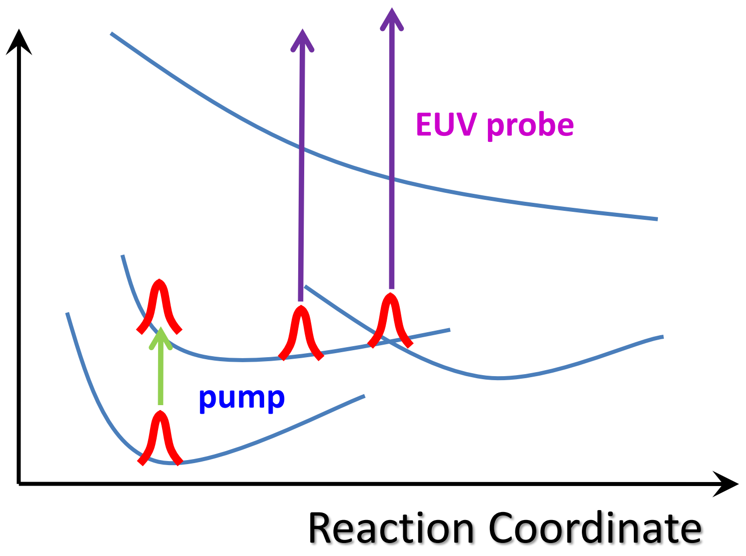
Ultrafast measurement in EUV range

Dynamics of molecule in highly excited electronic state



1. Single photon excitation of high electronic states with high efficiency
2. Continuously tunable wavelength to realize selective state excitation

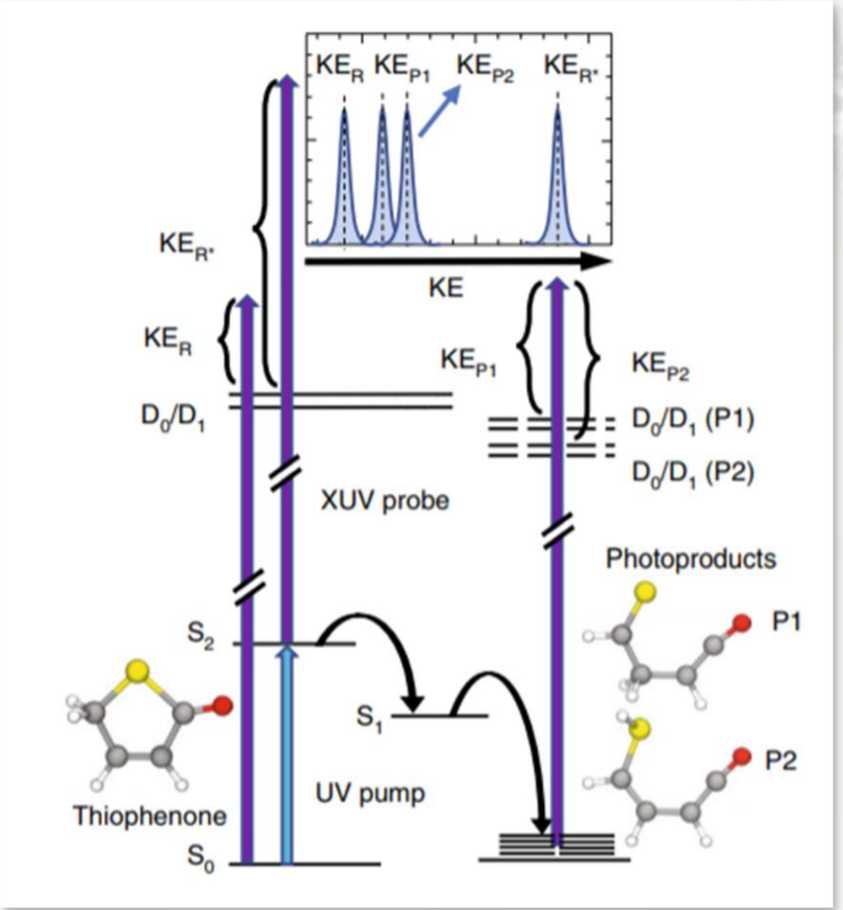
The whole PES observation

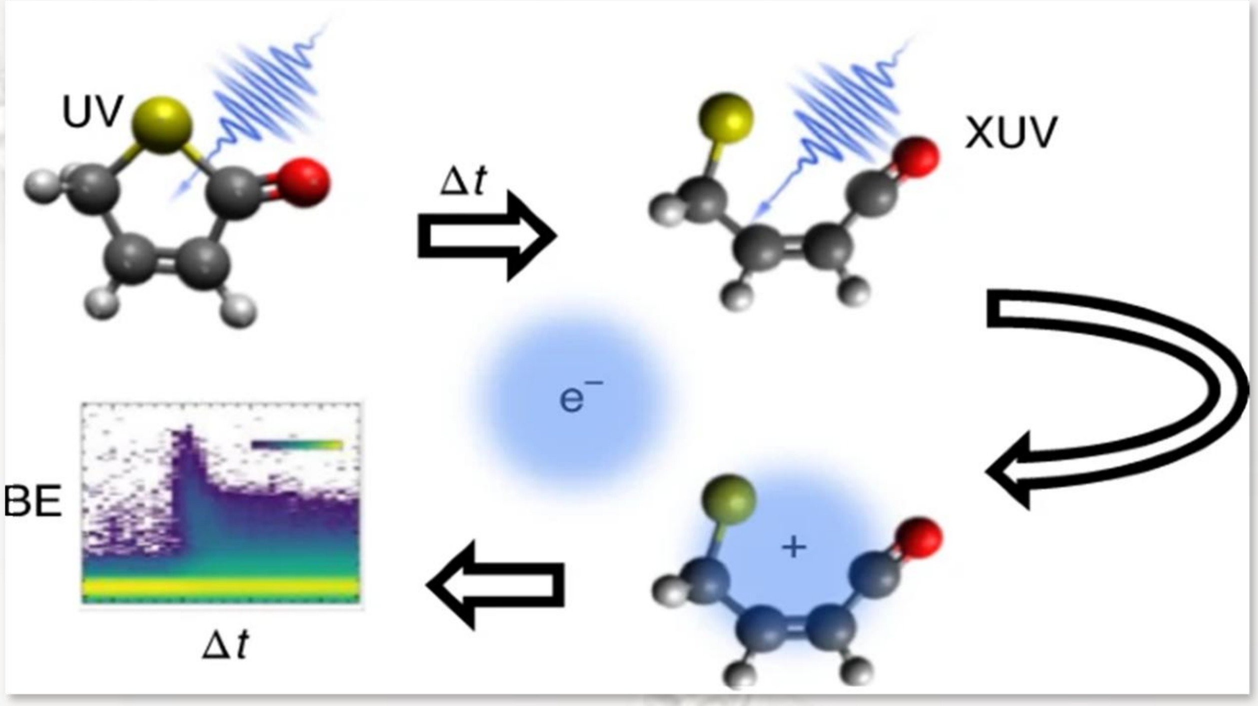


1. Continuously detect the potential energy surface.
2. EUV wavelength insensitive as long as photon energy greater than PIE

In conjunction with ultrafast infrared, visible, and ultraviolet lasers to study the dynamics of different excited states and molecular structure evolution processes

Example： ring opening observation





FERMI FEL

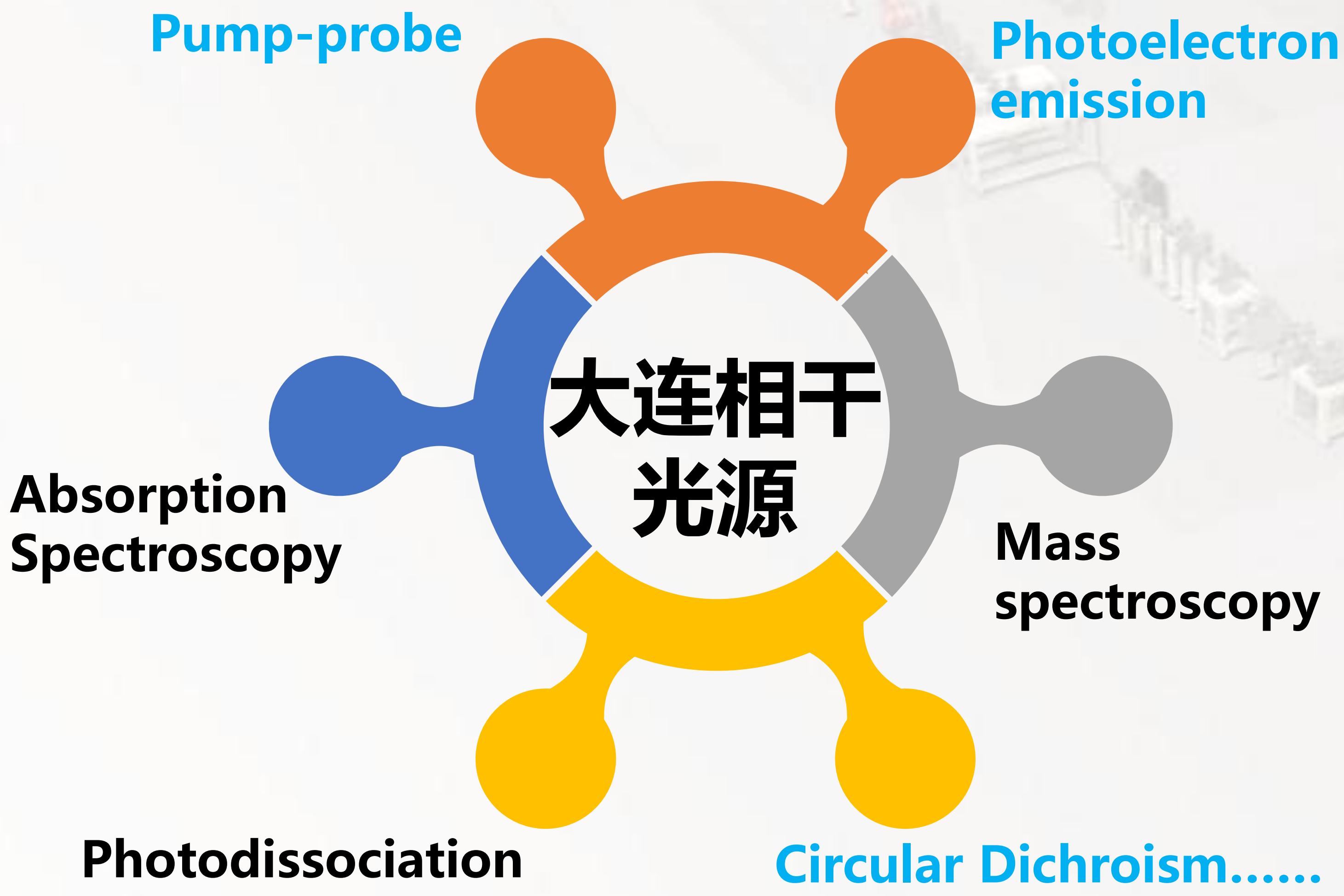
Pump: UV 265 nm

Probe: XUV 64.4 nm

The FEL photon energy is deliberately chosen to be well above the first ionization potential (IP) of the ground-state molecule (~9.7 eV) but below the IP of the helium carrier gas, ensuring that the electronic character of the target molecule can be traced throughout the complete structural evolution with only minimum background signal from the carrier gas.

Nature Chemistry (2020)
https://doi.org/10.1038/s41557-020-0507-3

Instrumentation at DCLS



Online:

- ☐ Molecule Photochemistry
- ☐ Neutral Cluster
- ☐ Free radical
- ☐ Aerosol
- ☐ Protein MS
- ☐ Molecular physics at interfaces end station（德国）

Planing:

- ☐ TR-PES
- ☐ SIMS

Take the advantage of high pulse energy by pulsed sampling

Outline

I. Introduction of DCLS

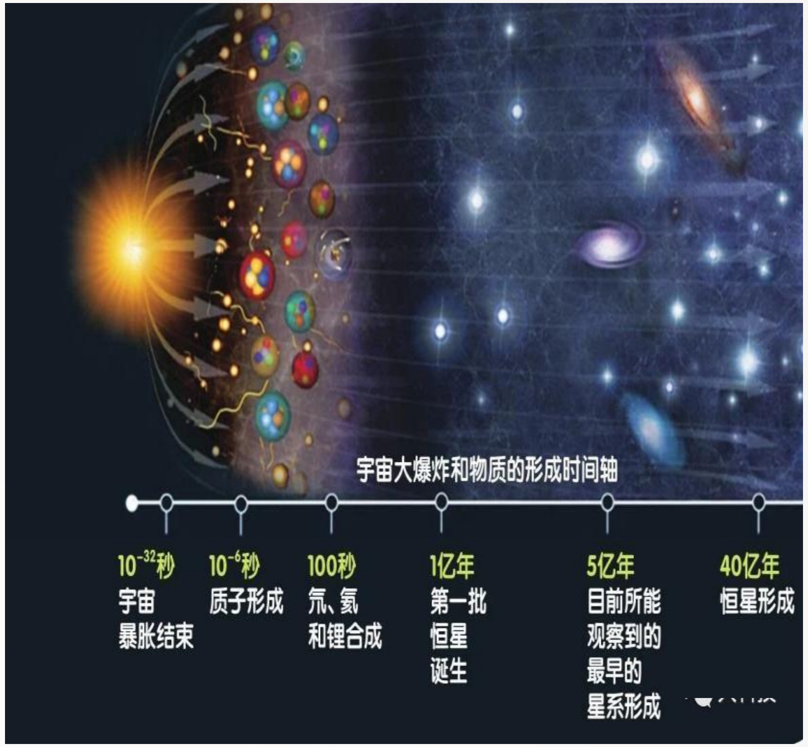
II. Experimental method

III. Scientific research

IV. Future plan

Scientific Case I:Molecular Photochemistry

Molecular photochemistry concerns the chemical evolution of atoms and molecules in the universe, determining the chemical compositions of the interstellar clouds and planets.



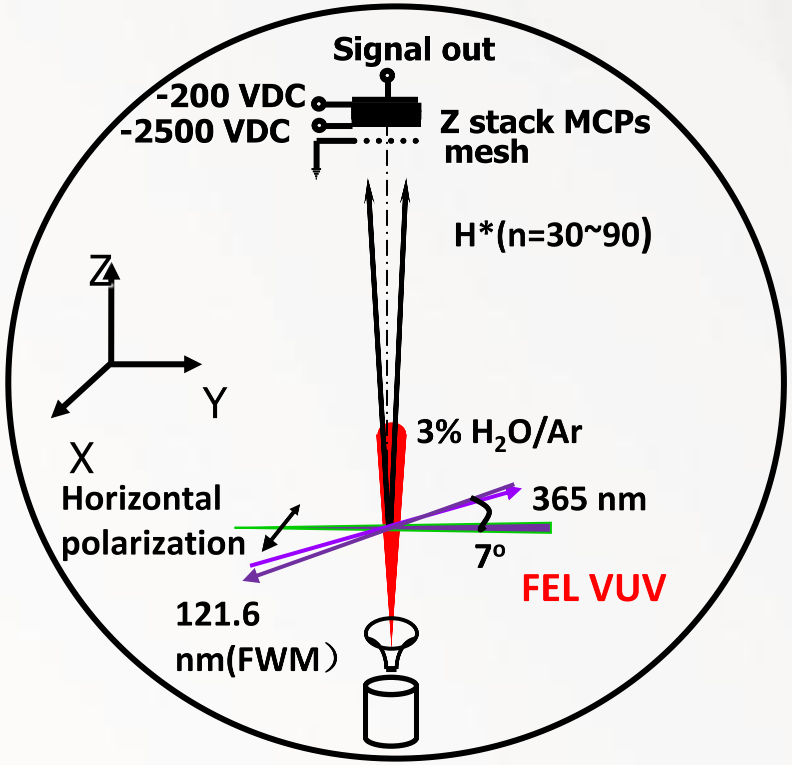
Several key scientific issues related to interstellar chemistry:

- ☐ Origin of Oxygen on the atmosphere of earth.
- ☐ Origin of water on the earth
- ☐ Origin of Interstellar amino acid
- ☐ Origin of life
- ☐ ……

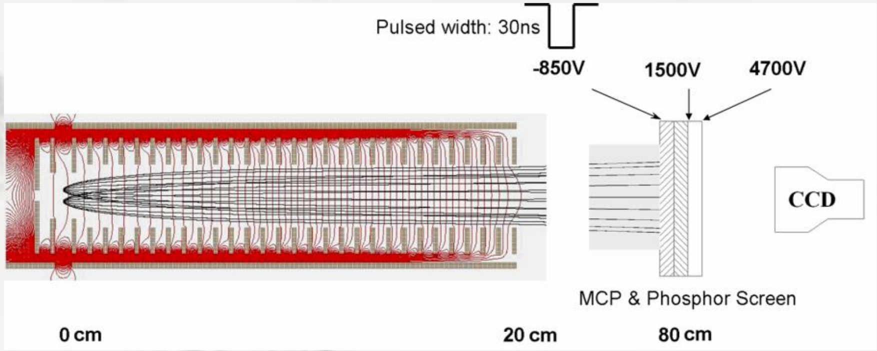
The VUV FEL laser is an unique tool to study molecular processes, which help us understanding the origin of life in the interstellar space.

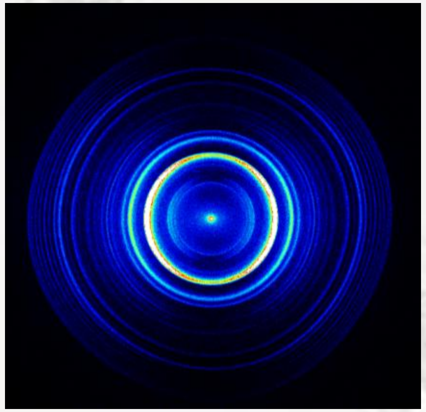
Molecular Photochemistry Instrumentation

Dissociation by VUV FEL and detection by table-top VUV source with four wave mixing or REMPI



<u>VUV FEL - HRTOF</u>





<u>Velocity imaging with REMPI</u>

Rev. Sci. Instrum. *89, 063113 (2018);*

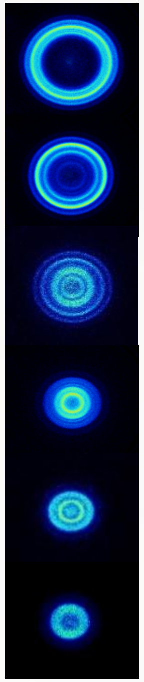
J. Chem. Phys. *148, 124301 (2018) (Editor's Pick)*

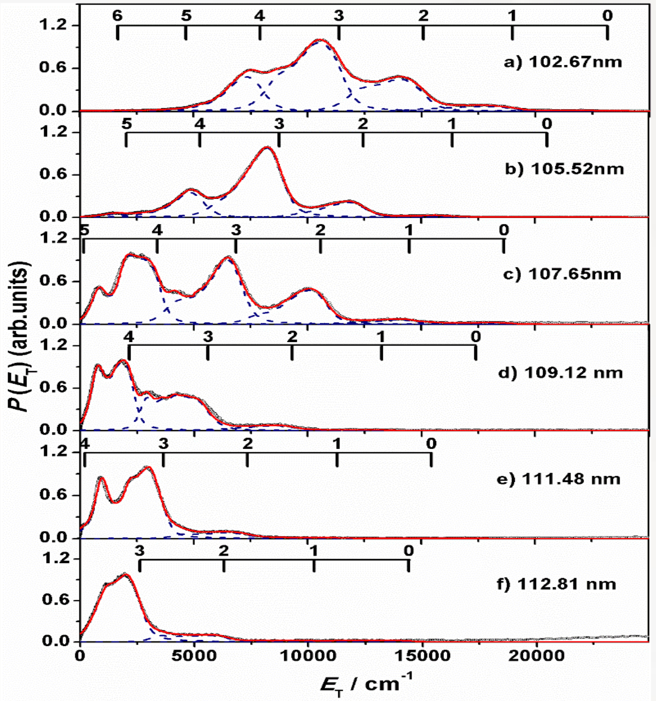
Prof. Kaijun Yuan, DICP

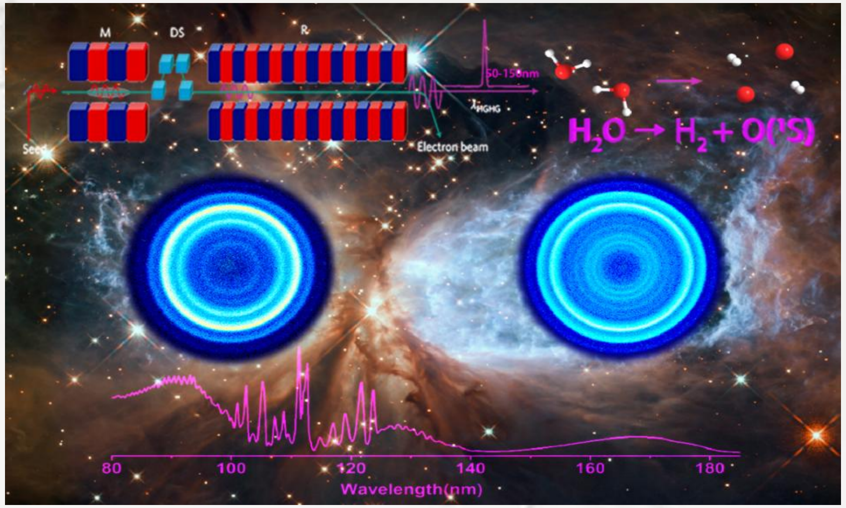
H_2O Photochemistry

Vibrational excited $H_2^*(v)$ has been detected in shock-heated gas and in photodissociation regions (PDRs) in space, which was formed by collisions and fluorescence excitation in PDRs.

VUV photochemistry of interstellar H_2O: H_2O + hv (102-112nm) → $O(^1S)$ + $H_2(v>0)$







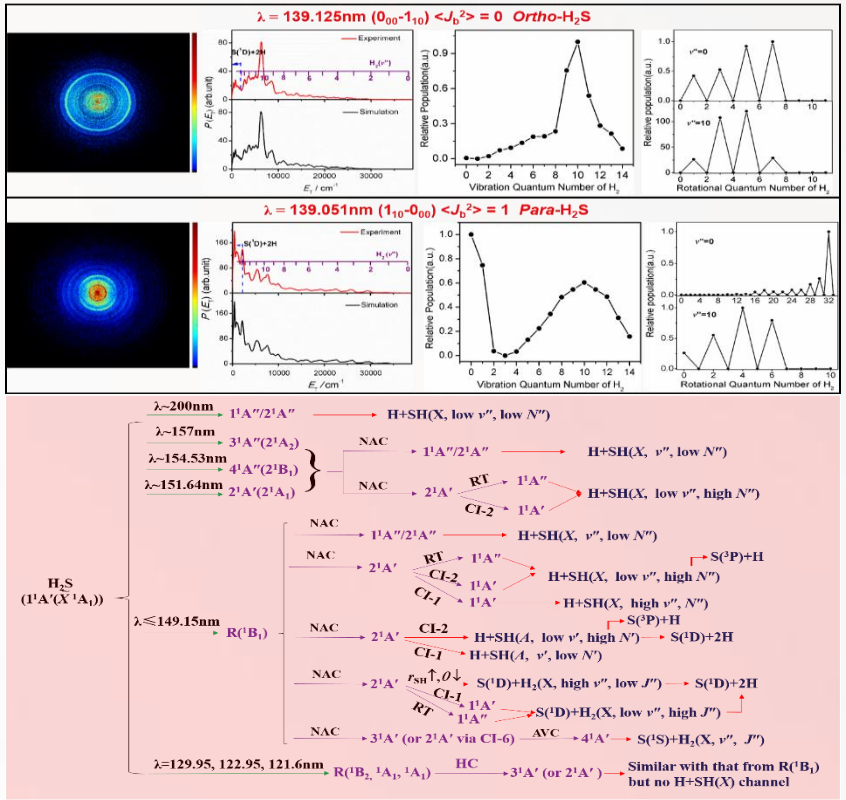
- All of the H_2 are vibrationally excited;
- **>90%** of H_2 fragments populate in a single vibrational state v=3 at 112.8 nm;

This process represents a further source $H_2^*(v)$ observed in the ISM, which should be recognized in appropriate interstellar chemistry models.

Nat. Commun., 12, 6303 (2021) (Featured Article); *J. Phys. Chem. Letts, 13,9786(2022)* .

H_2S Photochemistry

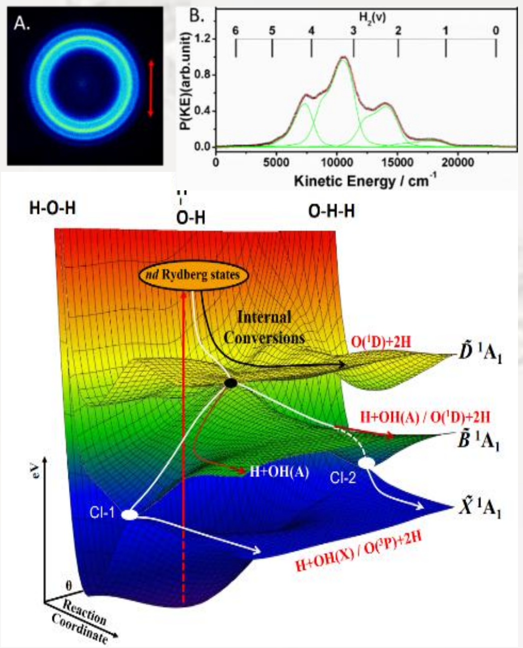
- H_2S is the most abundant S-bearing gas-phase species in the solar nebula. The S atom and SH radical densities in the ISM linked to H_2S photolysis. The measurements of all fragmentation channels in the whole VUV region are necessary for astrochemical modelling.

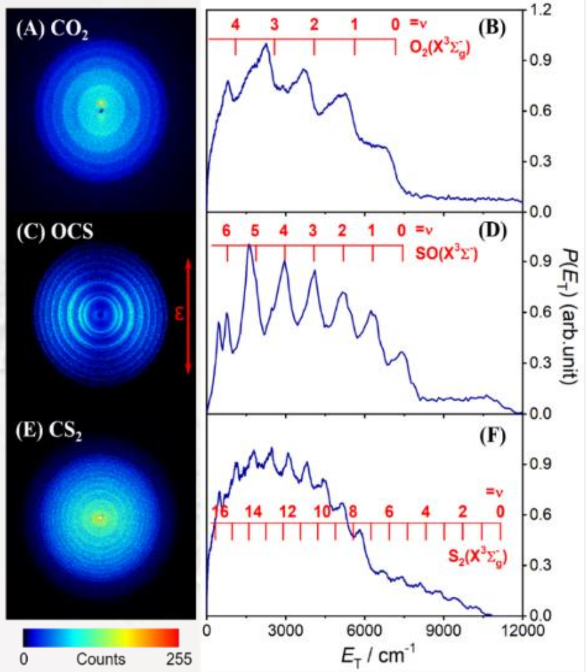


Chemical Science, 2023, 14, 2501 (back cover).

- The central atom decomposition channel for triatomic molecules is rarely reported. By using the VUV FEL, Such channel has been identified in several molecules, which deepens our understanding of the evolution of interstellar medium.

$H_2O + h\nu \rightarrow O + H_2$ $\quad$ $CO_2/OCS/CS_2 + h\nu \rightarrow C + O_2/SO/S_2$

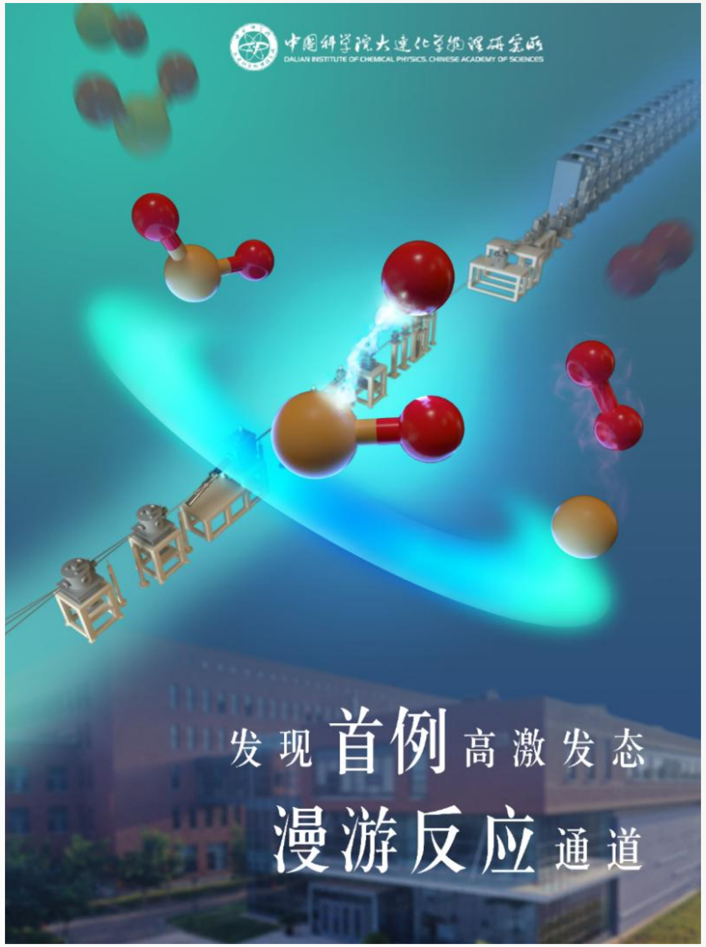




Nat. Sci. Rev., 2023, 10: nwad158;

JACS Au, 2023, 3, 2855 (Editor's Choice)

SO_2 Photochemistry



$SO_2(R) \rightarrow S(^1D) + O_2(a^1\Delta_g)$, 132-138 nm

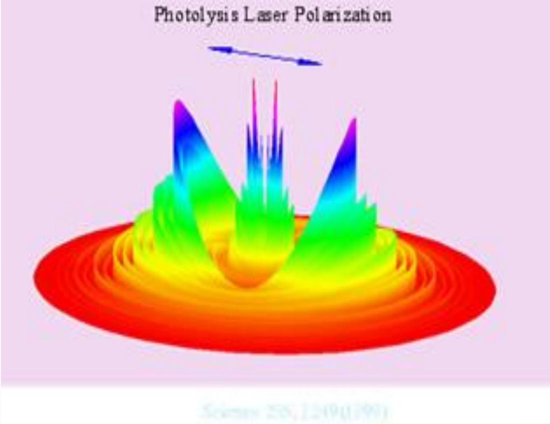
- **The first direct dynamical evidence of roaming for photodissociation of a triatomic molecule from a highly excited electronic state;**
- **Such roaming dynamics may well be the rule rather than the exception for molecular photodissociation via highly excited states;**
- **This study opens the door for roaming from a highly excited electronic state to produce electronically excited products, which react very differently in the atmosphere, space and in combustion.**

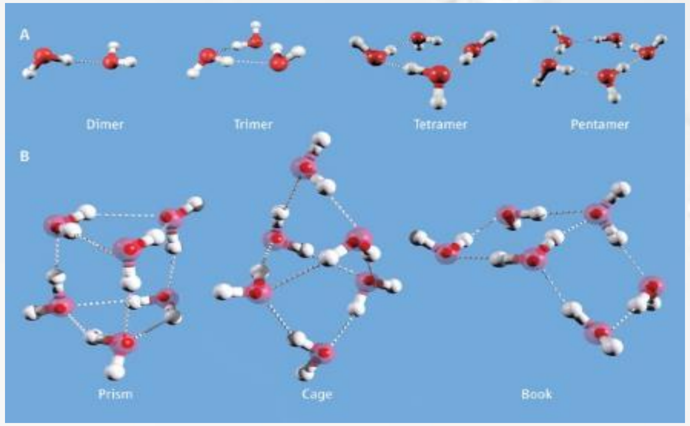
Science, 2024, 383, 746.

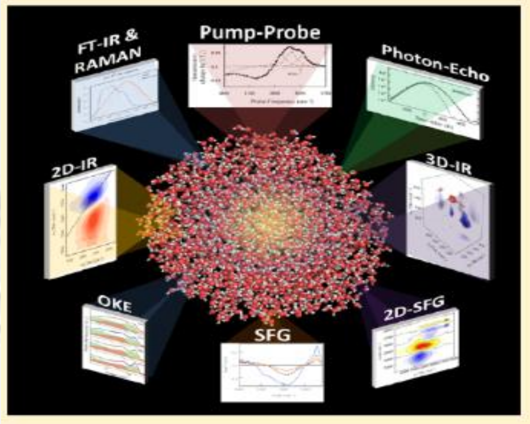
Scientific Case II：Cluster Science

Clusters bridge the gas and condensed phases and exhibit interesting size-dependent physicochemical properties.

For example: what is the structure of water?



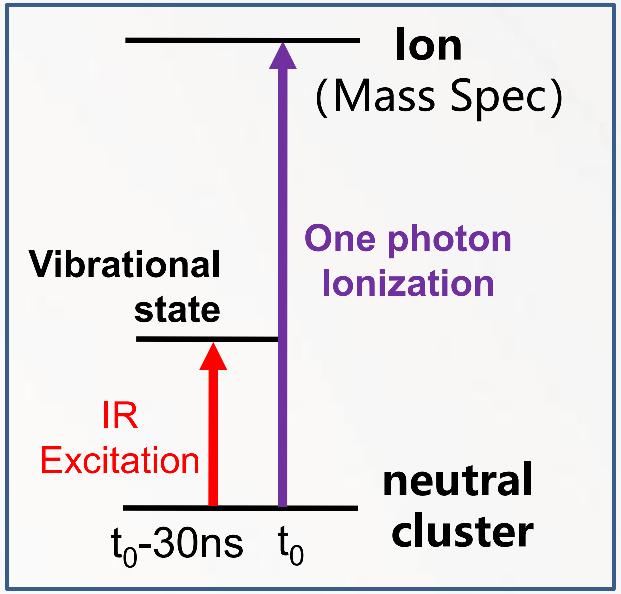


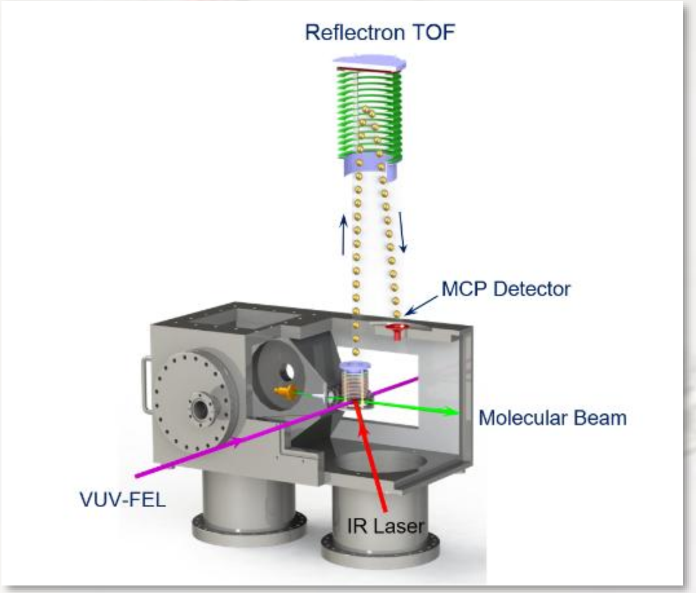


Water molecule | **Water clusters** | **Solvation effects**

However，neutral clusters have presented major experimental challenges, because the absence of a charge makes size selection and detection difficult.

IR spectrometer of neutral clusters at DCLS





Features:

1) Direct detection of confinement-free neutral complexes
2) Near-threshold ionization with high sensitivity and size-selectivity
3) Recording of well-resolved vibrational spectra of size-selected neutral clusters

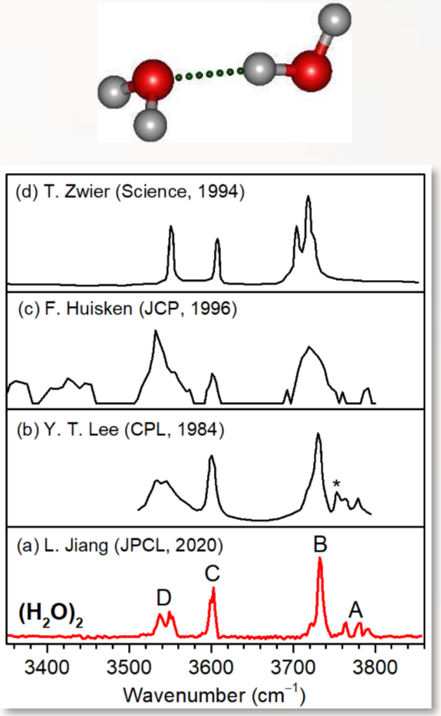
Presenting a new paradigm for the study of vibrational spectra of a wide variety of neutral clusters with the relevance of catalysis and atmospheric chemistry.

***Rev. Sci. Instrum.**, 91, 034103 (2020)*

Prof. Ling Jiang, DICP

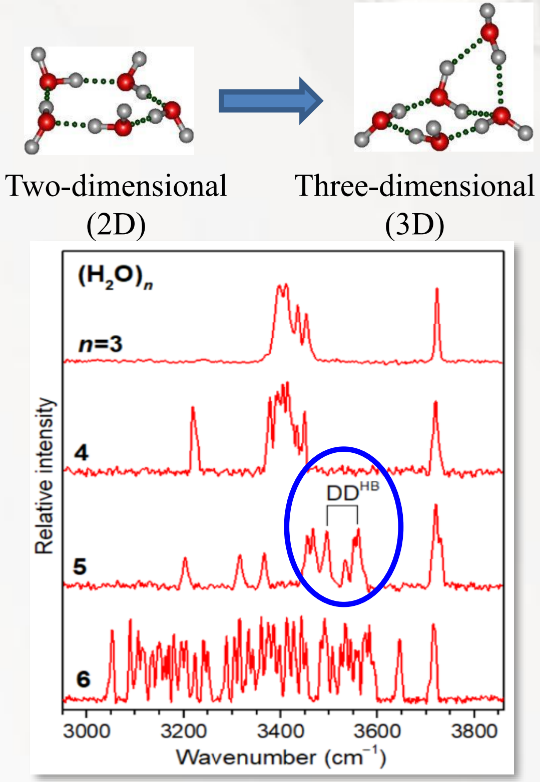
Water Cluster

Soft near-threshold ionization of $(H_2O)_2$ avoids extensive fragmentation



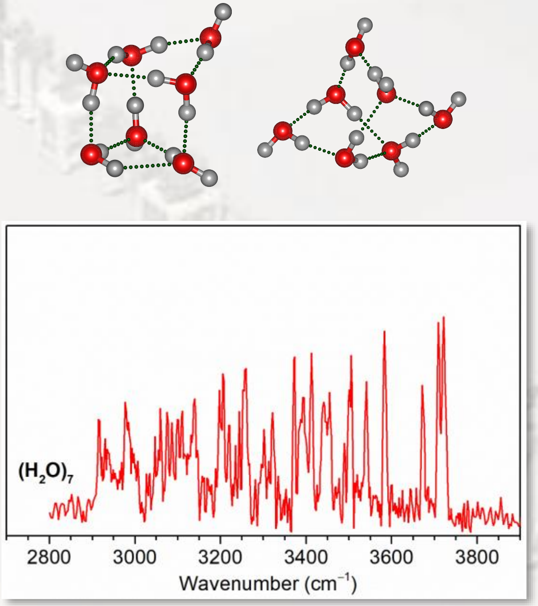
J. Phys. Chem. Lett., 11, 851 (2020)

Striking spectral change in the OH stretch region from tetramer to hexamer



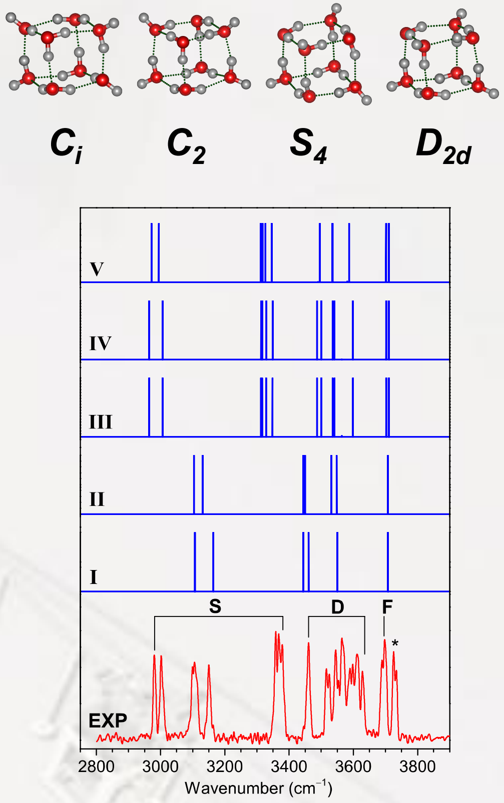
Proc. Natl. Acad. Sci., 117, 15423 (2020)

Structural complexity of ice-like clusters



J. Am. Chem. Soc., 144, 21356 (2022)
Cell Rep. Phys. Sci., 3, 100748 (2022)
Chin. Chem. Lett., 34, 107702 (2023)

Identification of new water octamer cubes



Nat. Commun., 11, 5449 (2020)

n=2 **n=3-6** **n=7** **n=8** **n=…**

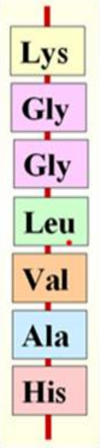
n: Number of water molecule in the cluster

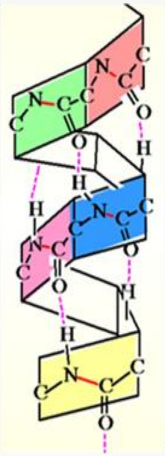
Scientific Case III: Precise Characterization of Protein Dynamic Structure

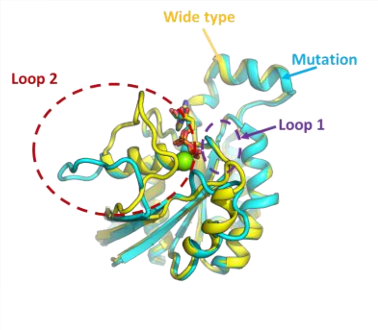
Challenge: precise characterization of non-covalently regulated dynamic structures and interactions

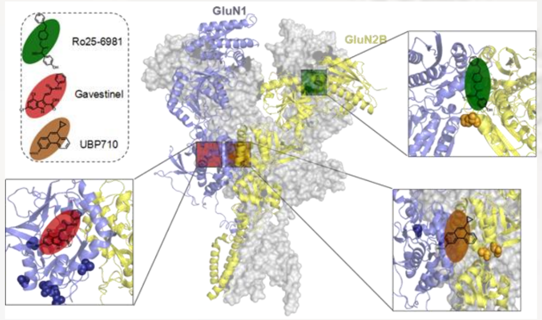
Existing Mass spectrometry (MS)

Primary Structure	Secondary Structure	Tertiary Structure	Quaternary Structure









Amino acid sequence	Local conformation	Overall protein fold	Protein complex

Covalent bonds determine protein sequence	Protein dynamic structure, and protein-protein, protein-ligand interactions are regulated by noncovalent bonds including hydrogen bonding, salt bridge, and hydrophobic interactions.

Technical Difficulties:
Highly dynamic, difficult in localization and quantification

Solution: XUV-FEL + MS

1) High photon energy, efficiently dissociating protein backbone covalent bonds

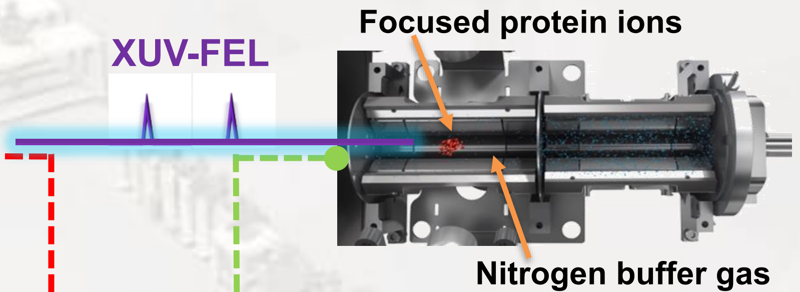
2) Ultrafast pulses, non-covalent bonds retained in photofragments

XUV-FEL Mass Spectrometry

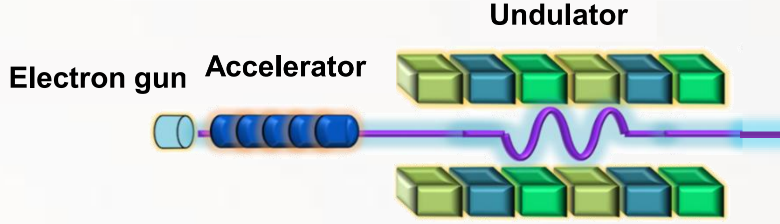
➢ **Introducing the XUV-FEL into commercial MS with modification by beamline scientist.**

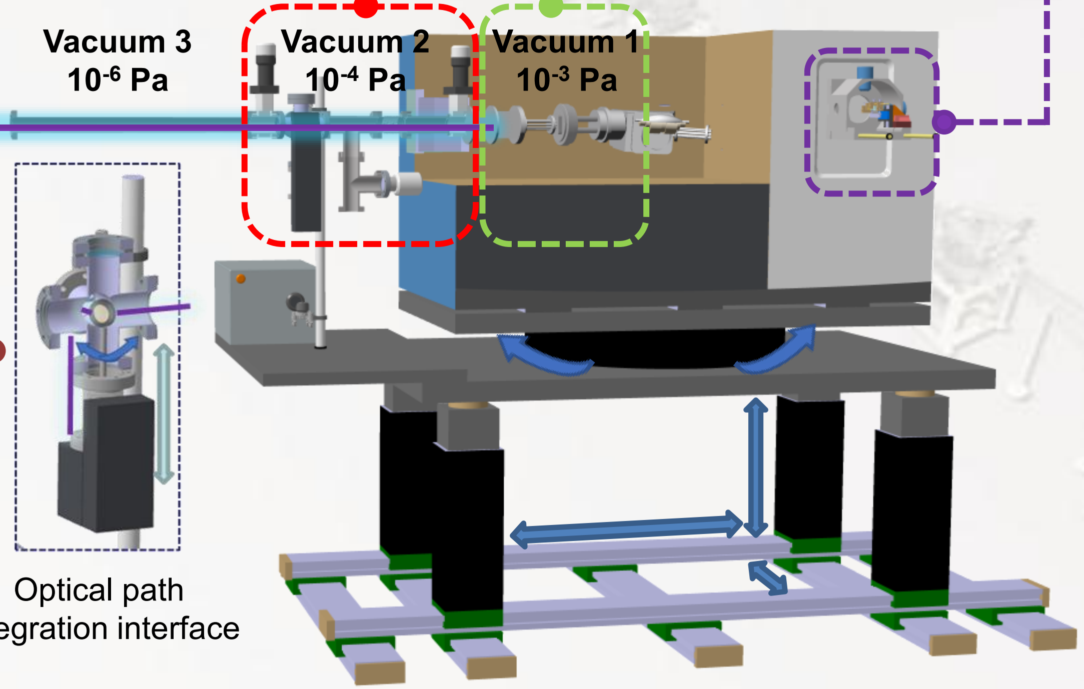
XUV-FEL mode 50-150 nm

MS-beam line adaptation device, three-level vacuum differential pumping system

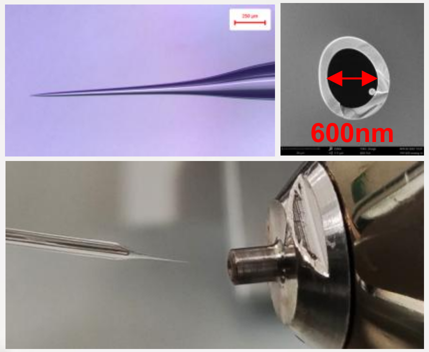


XUV, MS dissociation trap, protein ion trinity

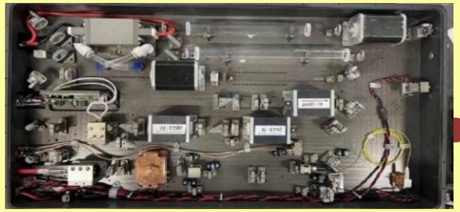




Nondenaturing static electrospray ionization source



desktop laser 120/130/157/193 nm

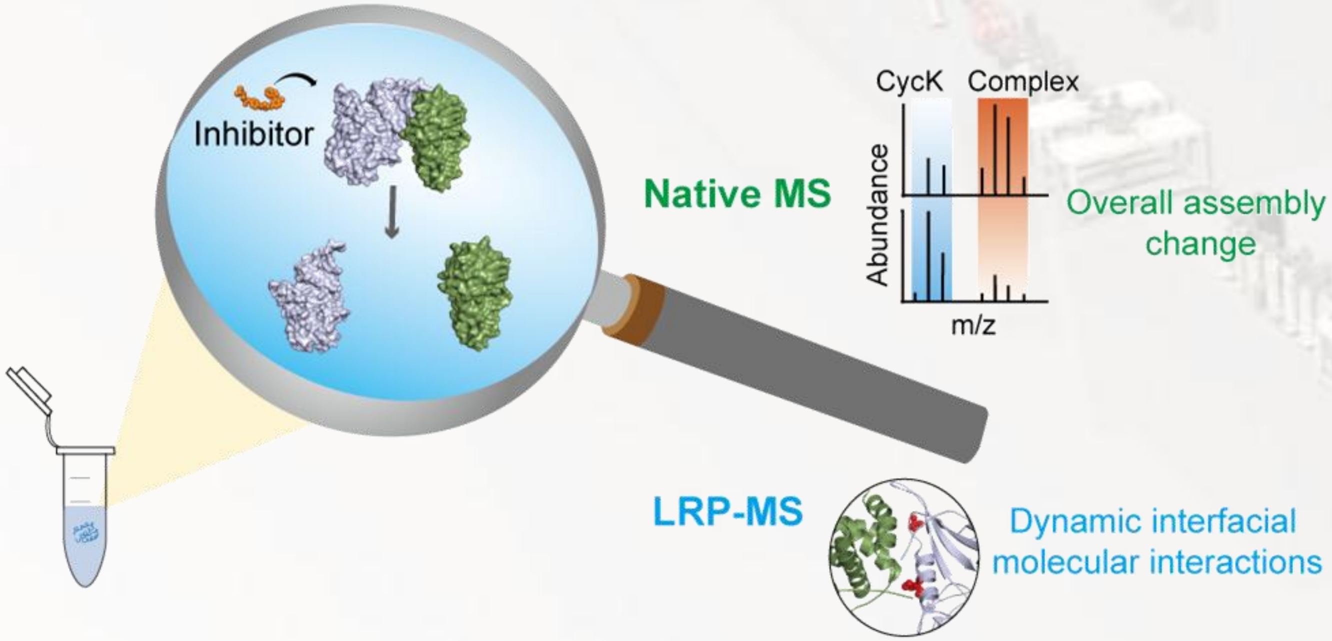


Excimer laser and XUV-FEL combined system, wavelength adjustable within the range of 50-200 nm, achieving wavelength-selective dissociation.

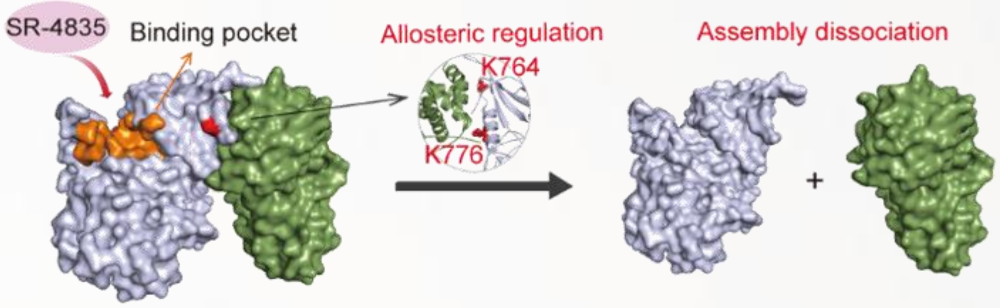
Precise optical platform with multiple degrees of freedom, with an accuracy of 30 μm.

Precisely control the nanoscale nozzle and nano-electrospray to reduce the interference of hydration peak and spray current thermal effect.

Allosteric activation of CDK-Cyclin K complex dissociation



Inhibitor SR-4835 binds to the ATP pocket and induces interfacial allostery of the complex and activates dissociation.

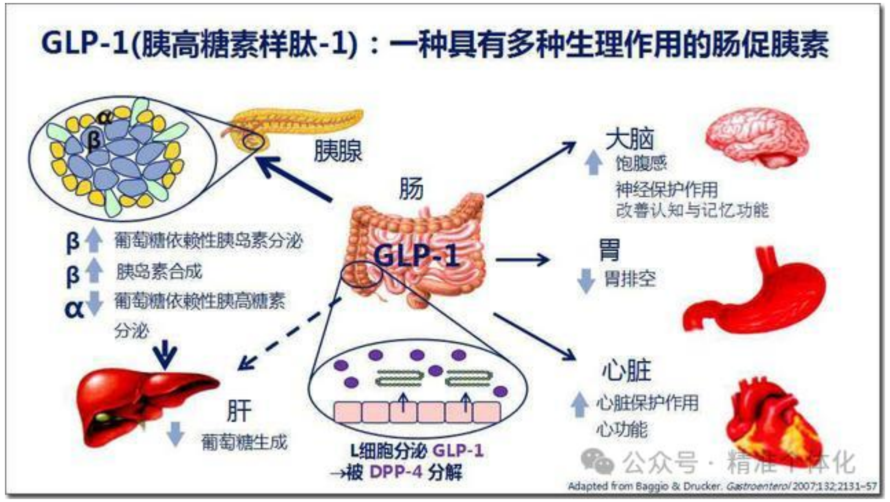


J. Am. Chem. Soc. 2023, *145*, 11477

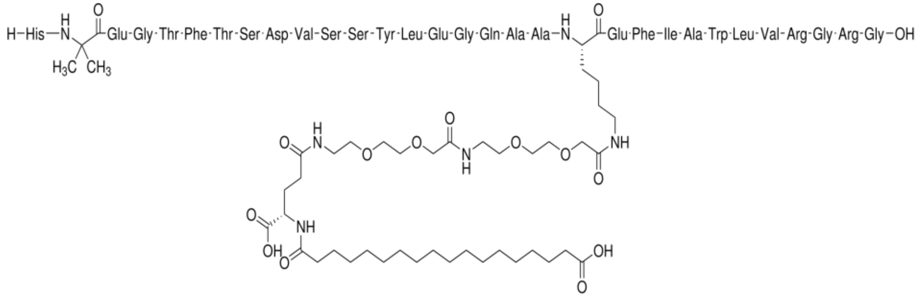
- Binding of CDK kinase to Cyclin K protein is closely related to mechanism of tumorigenesis, it is key to inhibit their binding for drug development;
- The method of high-throughput characterization of the molecular mechanisms of small molecule inhibition of dynamic interactions is missing, which limiting rational design of CDK12/CDK13 inhibitors;
- Utilizing XUV FEL- MS instrument, inhibitor SR4835 was discovered to activate complex's conformational dissociation, achieving inhibition of CDK-Cyclin K binding;
- This work has opened up new ideas for rational design of small molecule inhibitors.

Detection and Conformational Optimization of Non-Covalent Interactions in Disordered Peptide Drugs

The best-selling peptide drug “Semaglutide”： the total sales volume in 2023 has reached approximately 21.158 billion US dollars, approaching the revenue level of 21.2 billion US dollars of "the world's best-selling drug" Humira in 2022.



Semaglutide is obtained through GLP-1 peptide sequence modification



F. Wang*, C. Luo*, 2025, manuscript in preparation

Key Scientific Issues:

Lack of accurate characterization technology for dynamic conformations, making directional optimization difficult.

1) Extreme ultraviolet photodissociation mass spectrometry identifies key non-covalent interaction sites;

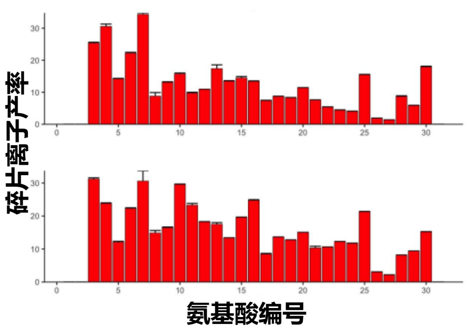
2) Endogenous metabolites are used for precise regulation of non-covalent interactions.

3) With the same hypoglycemic and weight-loss effects, the dosage is reduced by 75%.

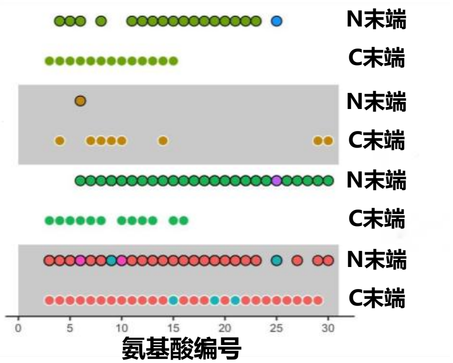
Analyze and optimize the spatial dynamic conformations of GLP1-like drugs such as the best-selling drug Semaglutide

Extreme ultraviolet laser dissociation to analyze conformational characteristics

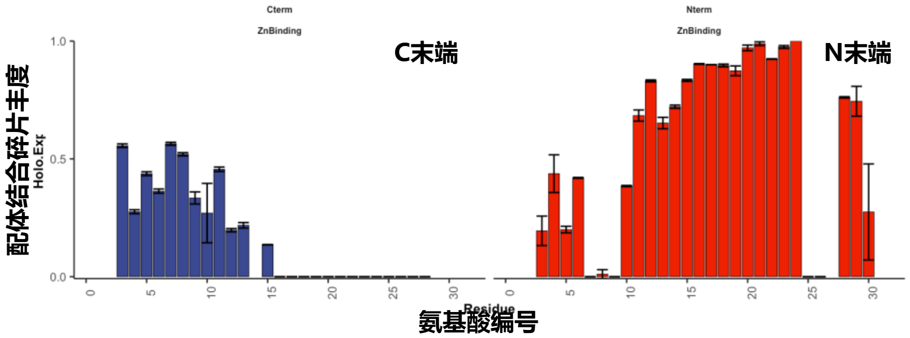
Conformational Difference Analysis



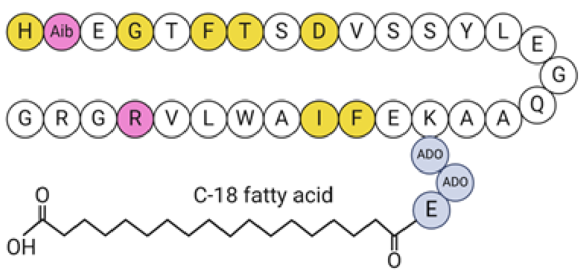
Ligand Binding Site Analysis



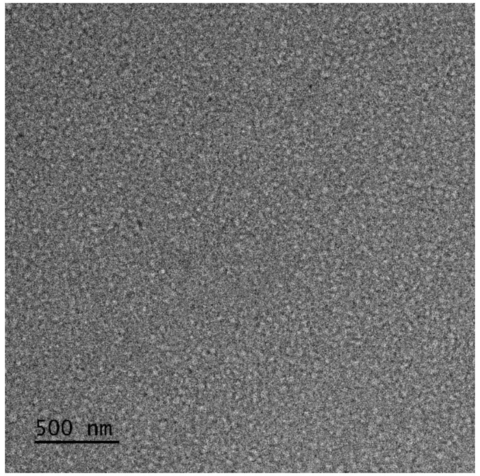
Analysis of Key Non-Covalent Interactions in Aggregated Conformations Endogenous Molecule Regulation of Assembly and Its Conformation



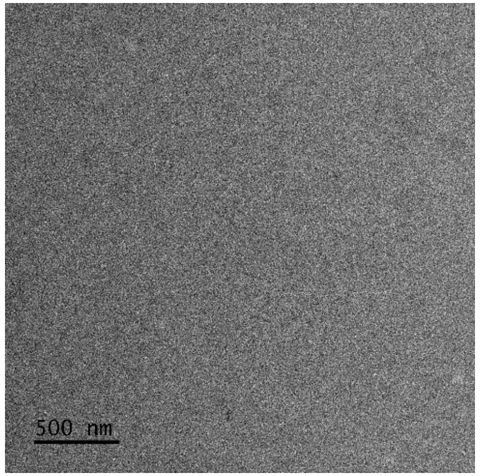
Regulate the self-assembly conformation of Semaglutide



司美格鲁肽plus

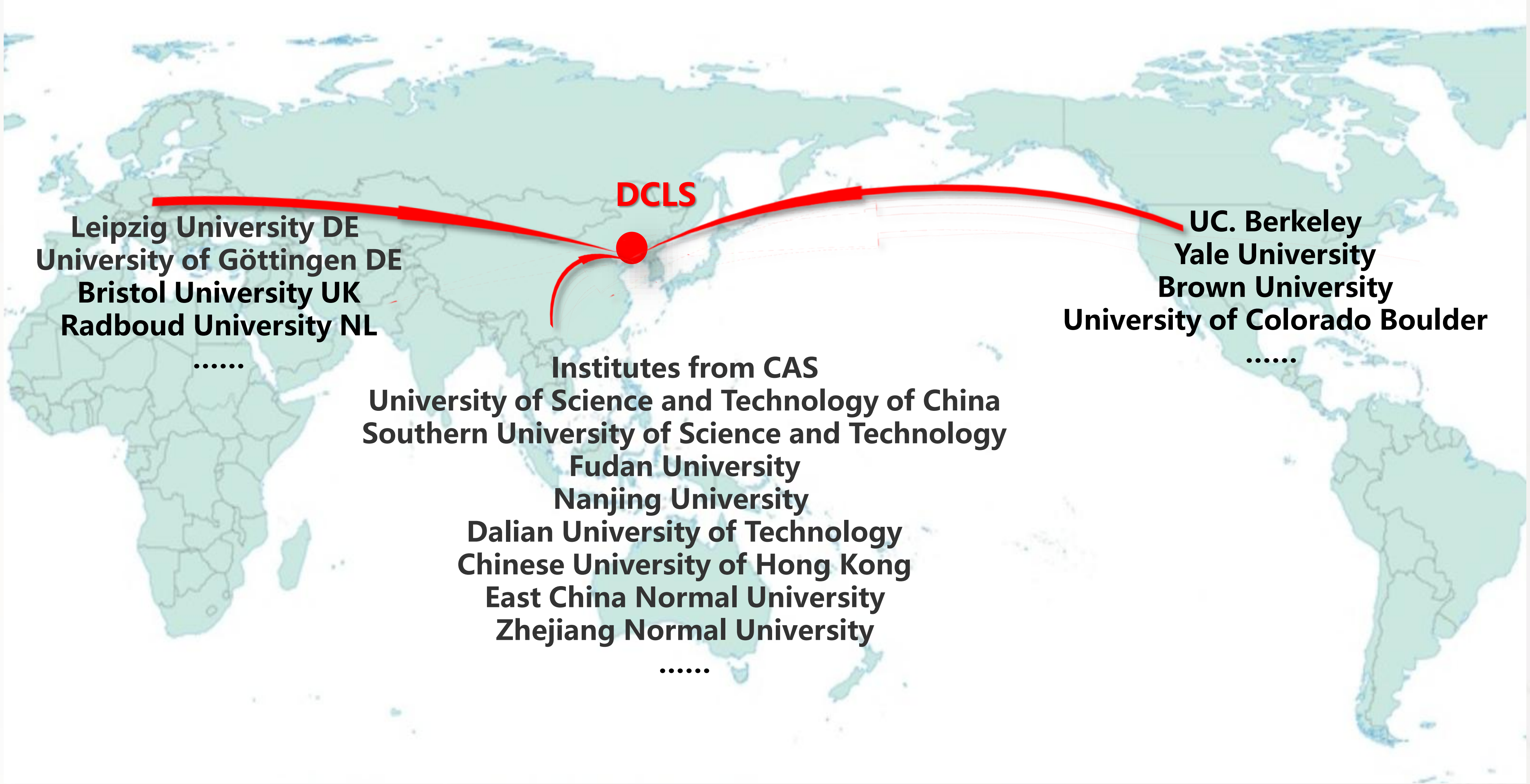


司美格鲁肽



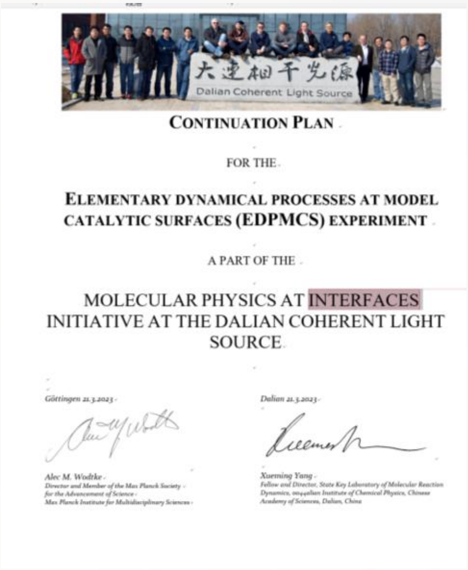
罗成、王方军、谢岑，专利申请号：202510730966.9

Cooperation： User from world



We are looking forward to have more users from the world

Instrumentation from Germany: Molecular physics at interfaces end station


大连相干光源
Dalian Coherent Light Source

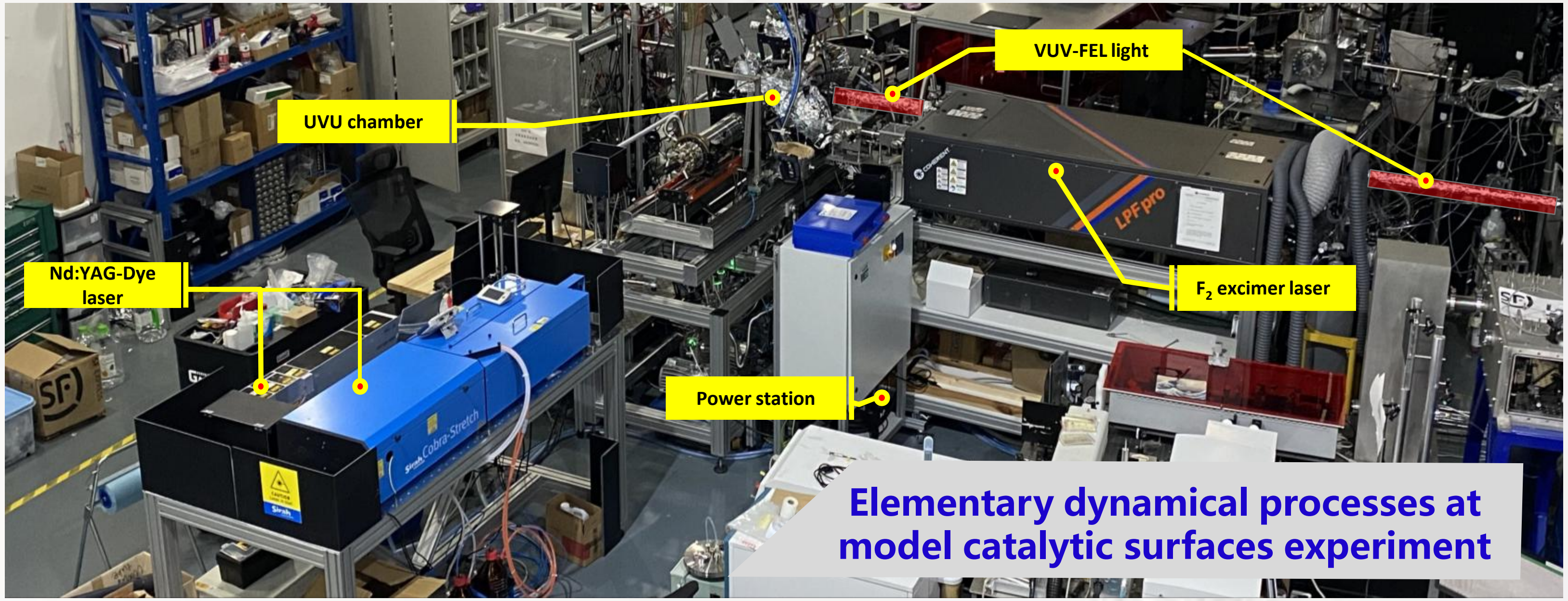
CONTINUATION PLAN

FOR THE

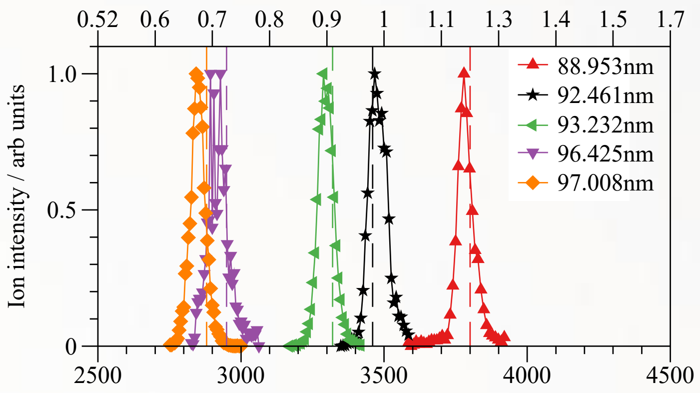
ELEMENTARY DYNAMICAL PROCESSES AT MODEL CATALYTIC SURFACES (EDPMCS) EXPERIMENT

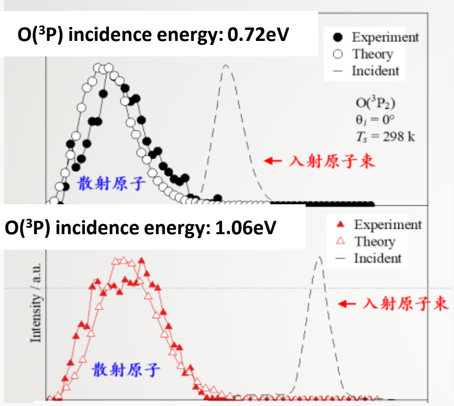
A PART OF THE

MOLECULAR PHYSICS AT INTERFACES INITIATIVE AT THE DALIAN COHERENT LIGHT SOURCE



Prof. Alec Wodtke
Max Planck Institute/
University of Göttingen





- Max Planck Institute invest to develop this experiment station
- First on-line experiment was conducted in May 2023. A super high speed Oxygen atom beam was obtained via the photolysis with VUV light of DCLS, and was used to conducted surface scattering experiments.

Outline

I. Introduction of DCLS

II. Experimental method

III. Scientific research

IV. Future plan

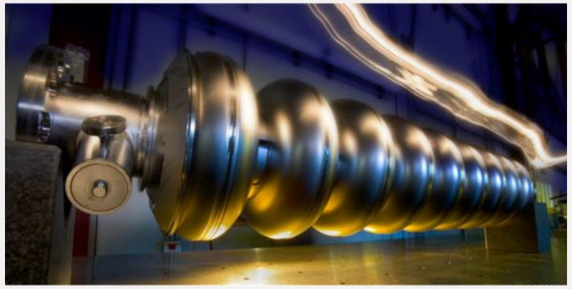
Future plan——FELs based on SRF

NCRF accelerator

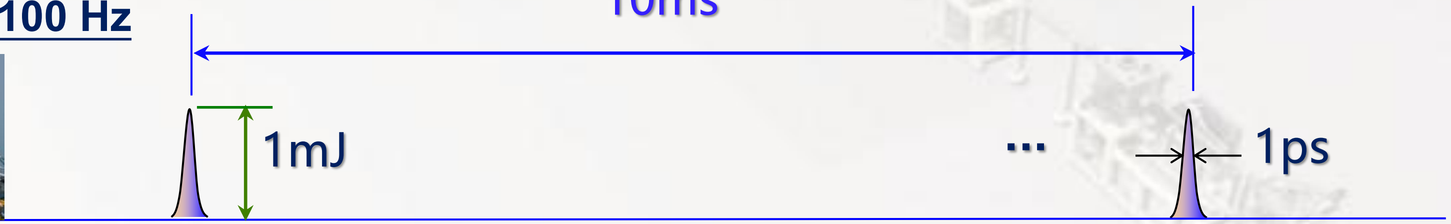
100Hz **repetition rate** 1,000,000Hz

10,000 times

SCRF accelerator

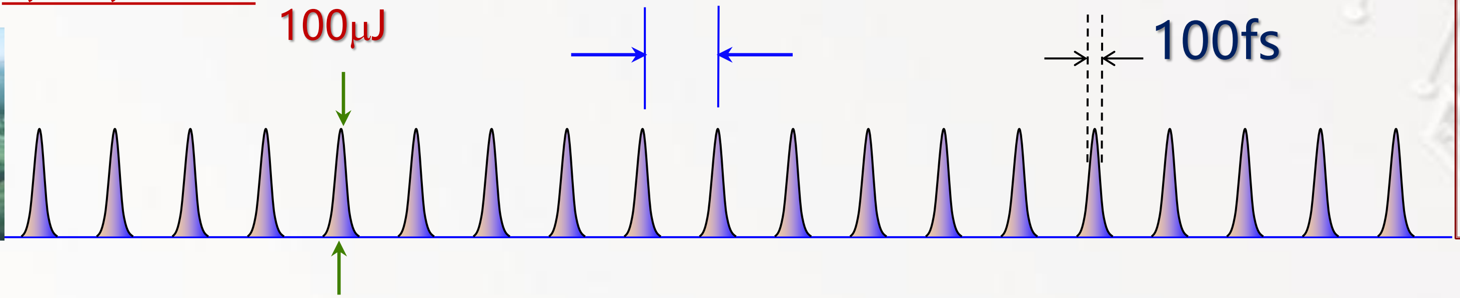


Low repetition rate FEL **100 Hz**



- Low repetition rate
- High pulse energy
- High time resolution
- High coherence
- Single on-line end station

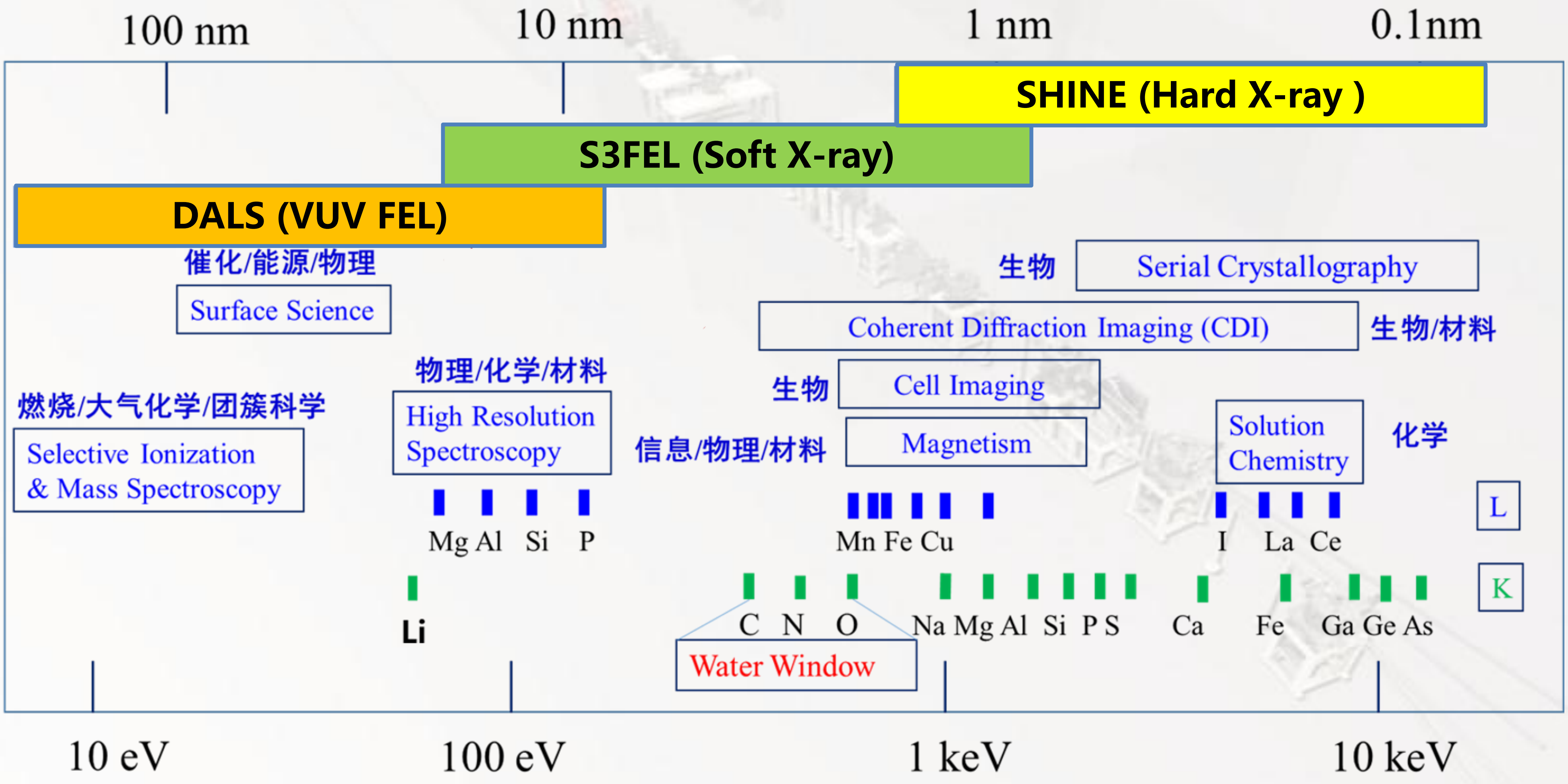
High repetition rate FEL **1,000,000 Hz**



- High repetition rate
- High pulse energy
- High time resolution
- High coherence
- Multiple on-line end stations

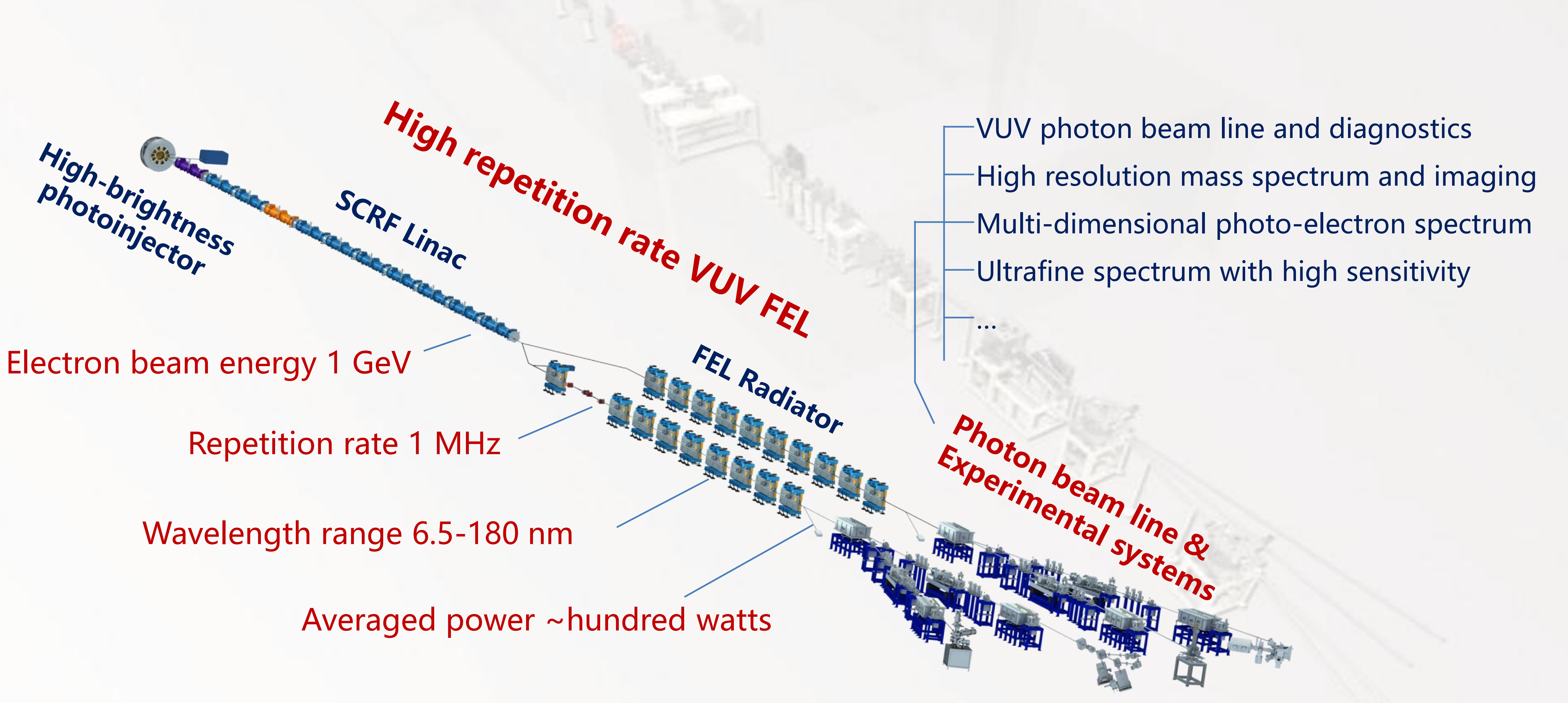
The FEL average power is 10000 times higher than the low repetition rate FELs!

Plans of high repetition rate FELs in China



These facilities have complementary photon energy for distinctive applications

High repetition rate VUV FEL (Dalian Advanced Light Source)

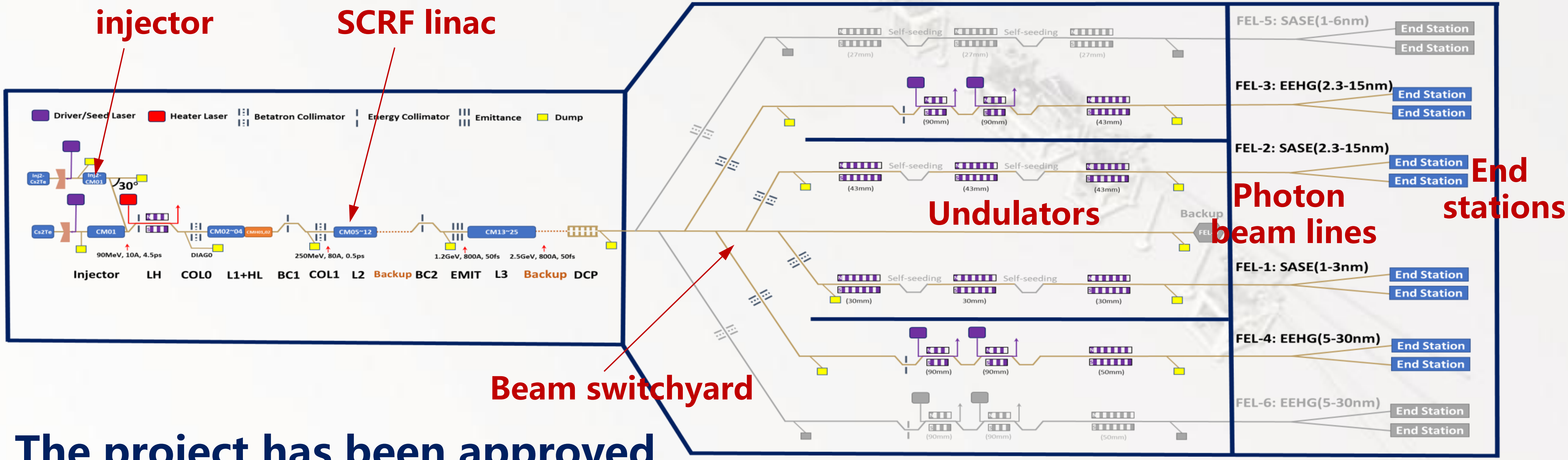


Shenzhen Superconducting Soft X-Ray FEL（S³FEL)

Project goal:

Generating 1MHz soft X-ray free electron laser light

Parameters	Objective
Electron beam energy	≥2.5GeV
Repetition rate	1MHz
Bunch charge	100pC
Photon energy	40-1200eV
Pulse energy	100μJ @ 1keV



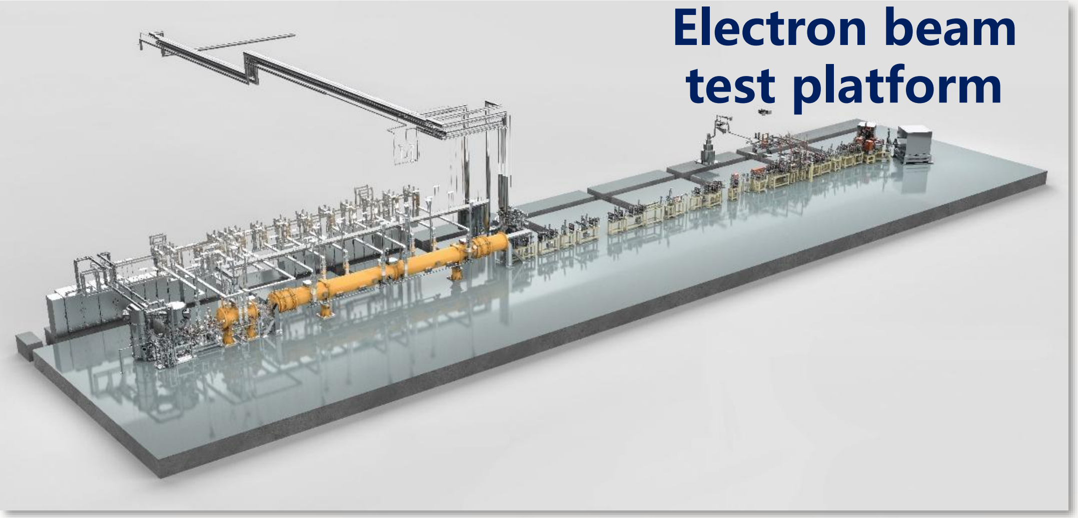
The project has been approved

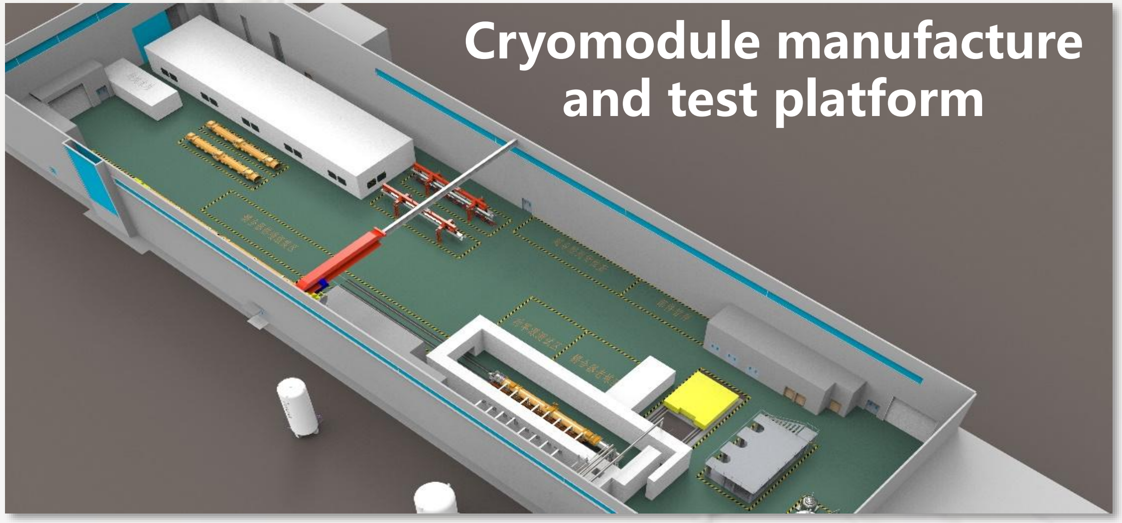
Length: 1.7km

Pre-research project of DALS

Key technologies

- Electron gun with photocathode
- Ultrafast laser
- Solid-state RF power source
- SCRF accelerator
- Cryo-technology

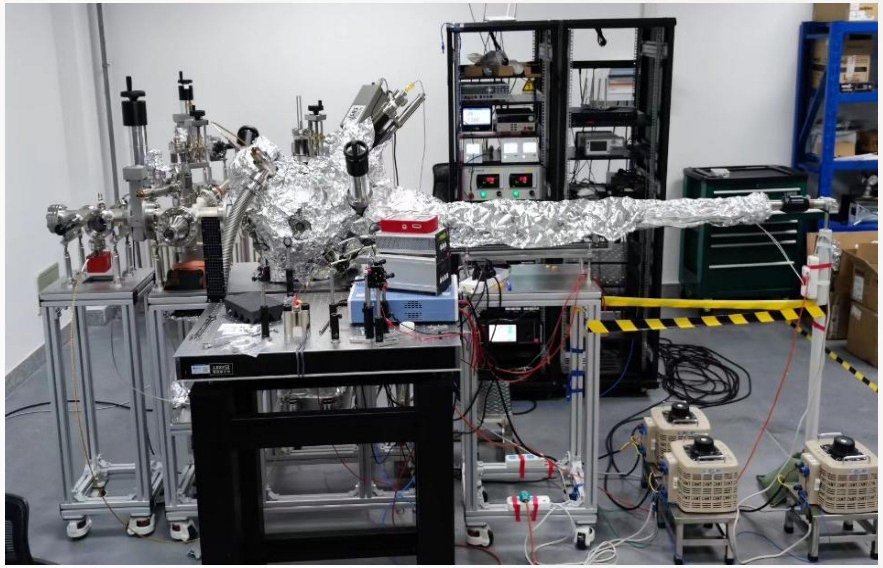




Goal: Demonstrating the key technologies of high repetition rate FEL based on superconducting accelerators

Production of High QE photocathode

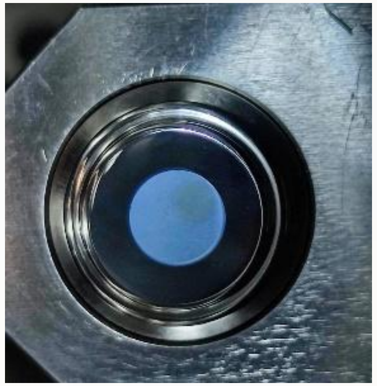
✓ Developed a Cs_2Te cathode production system successfully



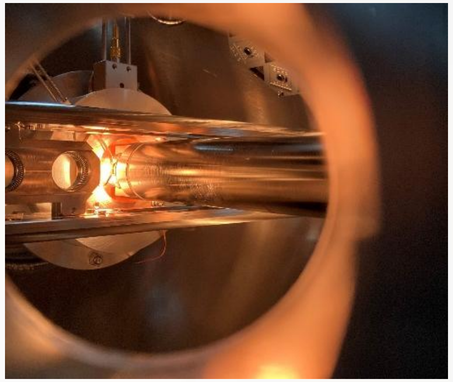
Cs_2Te preparation scheme

1. Load the substrate into vacuum chamber
2. Vent the preparation chamber to 1×10^{-8}Pa
3. Calibrate the vaporing rate of Cs and Te source
4. Heat the substrate to 80℃
5. Evaporate Te at 1.2nm/min for 15min
6. Evaporate Cs at 1nm/min
7. Monitor the photocurrent, and stop the evaporation when the appearance of the flat-top of the photocurrent.
8. Decrease the heating power, and make the substate cooling down to room temperature

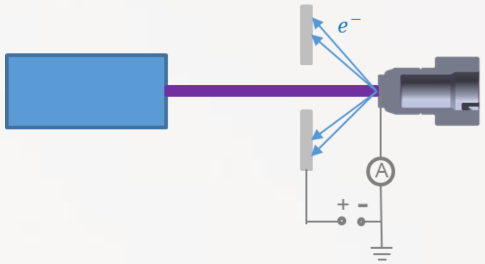
Cs_2Te photocathode



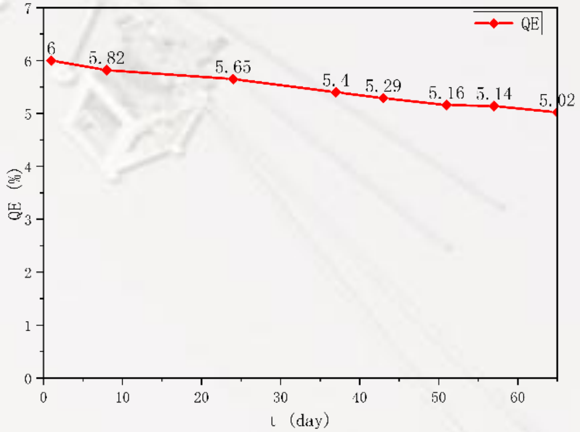
Film preparation



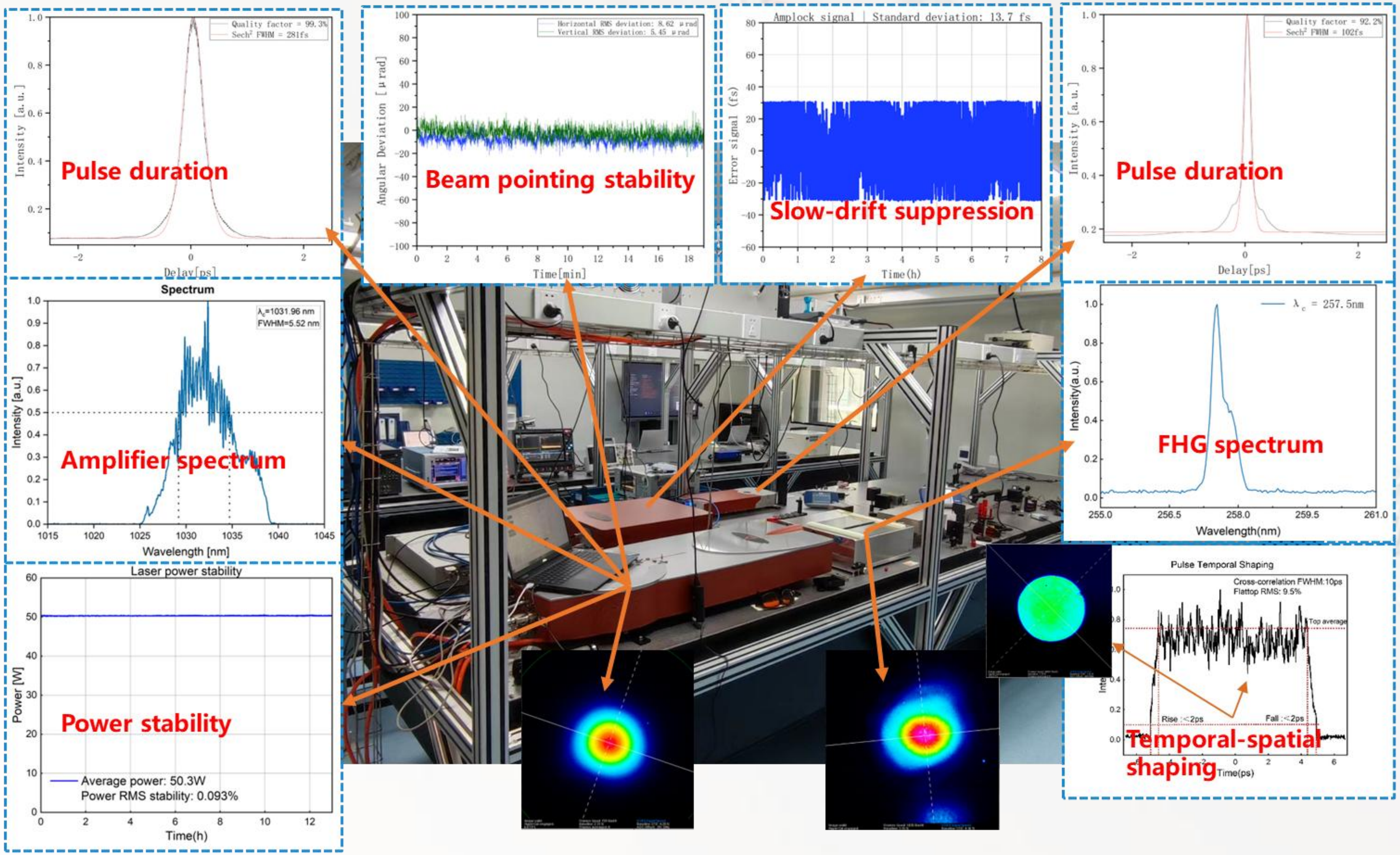
Schematic setup of the QE measurement



Curve of the dark lifetime



Drive laser system



Wavelength	257.5 nm
Repetition rate	1 Hz-1 MHz
UV laser power	2 W
Pulse energy stability (rms)	1.5%
Jitter between oscillator and RF reference (rms)	< 80 fs
Temporal profile	Flat-top / Gaussian shape
Pulse width(FWHM)	30-60 ps
Rising/Falling edge	<2ps
Transverse distribution	Flat-top
Spot size (FWHM)	0.2-2 mm
Pointing stability (rms)	10 µm

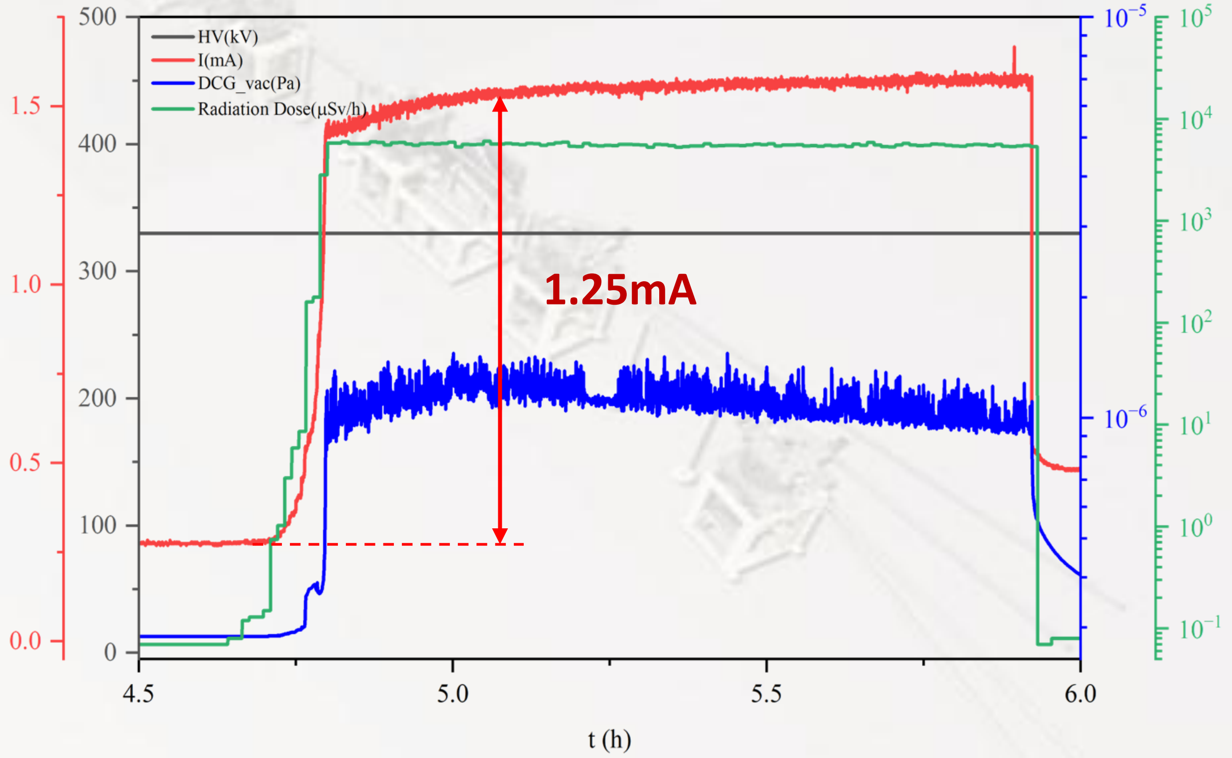
✓ **Development of drive laser system has been completed and all parameters meet requirements.**

DC high voltage electron gun

- ✓ **DC high voltage electron gun system has been operated at 330kV. Average current as high as 1.25mA has been obtained with single bunch charge of 100pC and bunch repetition rate of 12MHz.**

Gun system

1.25mA averaged beam current



1.3GHz cryomodule in collaboration with IHEP

The first high Q high gradient performance medium-temperature baking 1.3GHz cryomodule

Factory acceptance was completed in 8th July 2023

Parameters	Measurement	Specifications of DALS	Specifications of LCLS-II & SHINE	Specifications of LCLS-II HE	Best performance in LCLS-II/-HE
Total CW RF voltage (MV)	191.2	128	128	173	209
Average cavity CW gradient E_{acc} (MV/m)	23.1	16	16	20.8	25.1
2 K heat load of the cryomodule @128MV (W)	83.5	130	93	/	-
Average Q_0 @16MV/m	3.8×10^{10}	2×10^{10}	2.7×10^{10}	/	3.7×10^{10}
2 K heat load of the cryomodule @173MV (W)	133	/	/	137	115
Average Q_0 @21MV/m	3.6×10^{10}	/	/	2.7×10^{10}	3.27×10^{10}

✓ **The 9-cell cavities in the cryomodule achieved an unprecedented highest average Q_0 and accelerating gradient . The results significantly exceed the specifications of DALS and the other high repetition rate free electron laser facilities (LCLS-II, LCLS-II-HE, SHINE, S^3FEL).**

Electron beam test platform installation is in progress

Key devices have been delivered and the entire system is under integration

- Preliminary installation : mechanical supports, magnets, RF power source, vacuum system, beam diagnosis, beam dumps, cryo-distribution box, electrical supply and cooling water supply, etc.

Tunnel
(taken in March 2024)

Electrical and RF power source gallery
(taken in March 2024)

Installation of cryo-plant is in progress

Key devices have been delivered and the entire system is under integration. The system will be commissioned in July 2024.





Pre-research project of Dalian Advanced Light Source

Conceptual design in 2021

Birdview in June 2024

Electron beam with 1MHz, 100pC & 100MeV

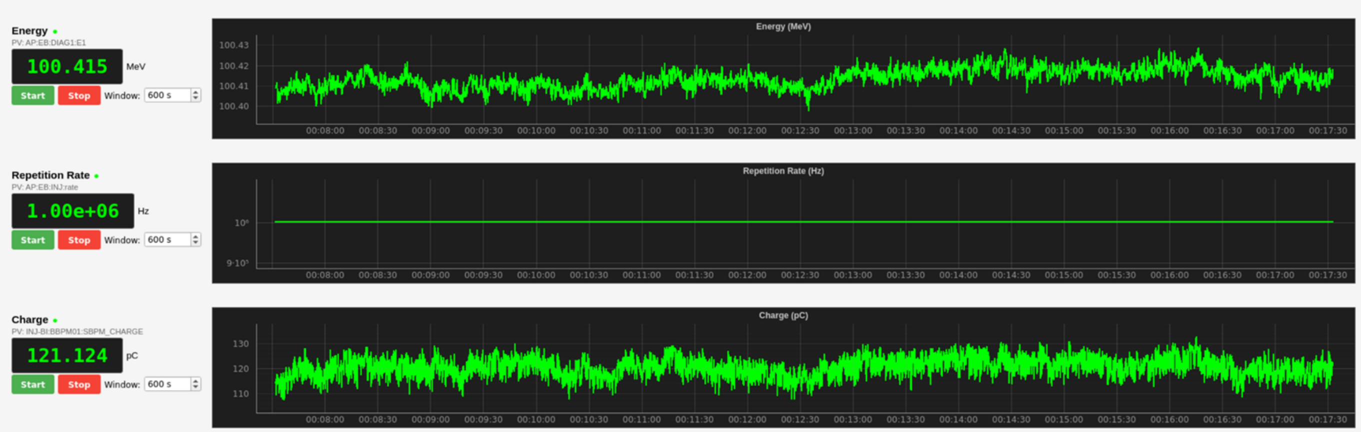
- The first high repetition rate beam test has been conducted on July 24, 2025.
- It successfully achieves electron beam with a 1MHz repetition rate, 100pC charge and 100MeV energy for more than 1 hour.
- The beam energy stability is better than 0.01% (RMS).

electron beam parameters

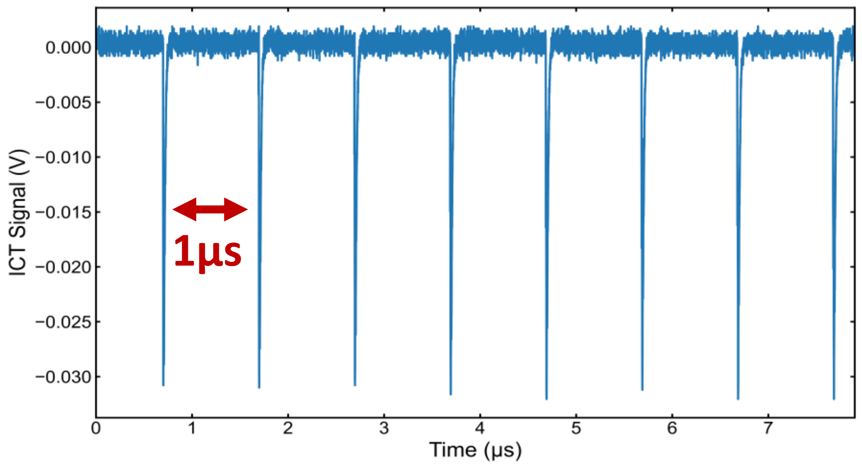
Energy

Repetition Rate

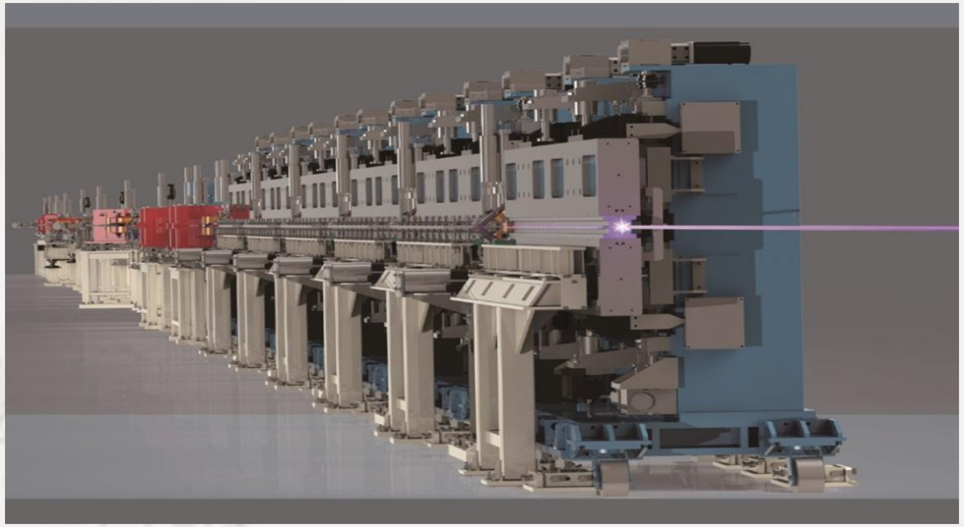
Pulse Charge



time interval of electron pulses



Overview of Dalian Coherent Light Source



Unique Free electron laser facility in the VUV and EUV range

- Tunable Wavelength： 50 – 150 nm
- Pulse Energy： >100 uJ (1 mJ)
- Pulse length： 100 fs /1 ps
- Bandwidth： Close to Fourier transform limit
- Jitter： <30 fs
- Rep Rate： 50 Hz

中国科学院大连化学物理研究所
DALIAN INSTITUTE OF CHEMICAL PHYSICS CHINESE ACADEMY OF SCIENCES

中国科学院上海应用物理研究所
SINAP
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

NSFC
国家自然科学基金委员会
National Natural Science Foundation of China

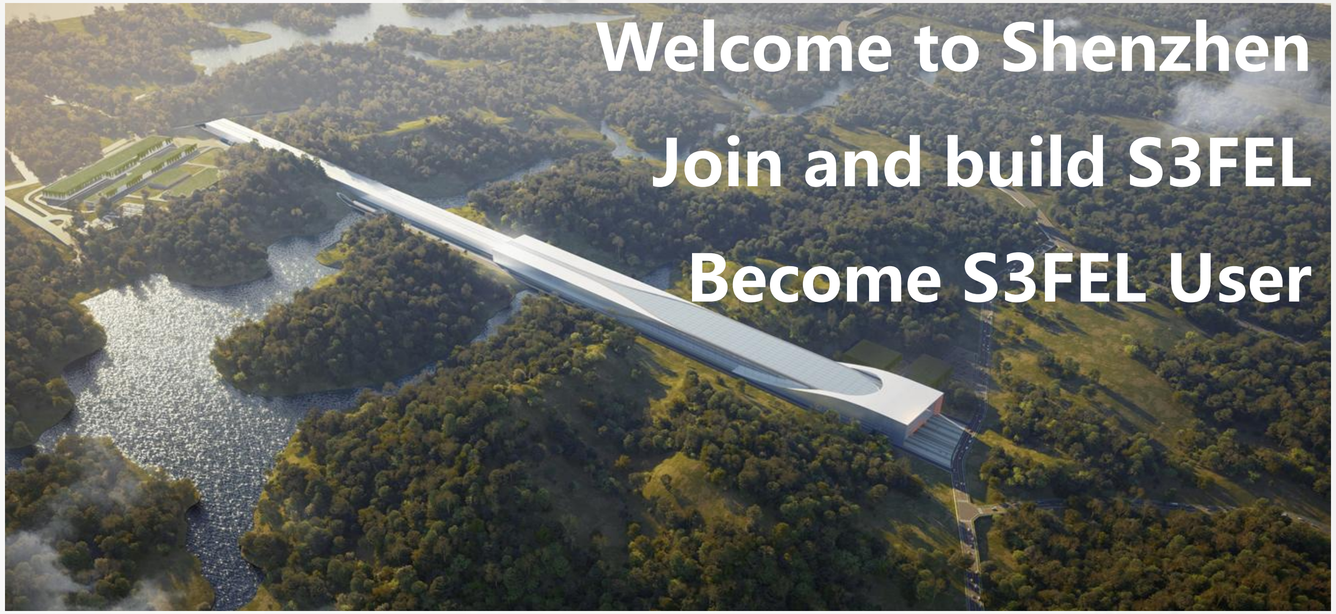
Thanks for attention

weiqingzhang@dicp.ac.cn

Welcome to Dalian

Become DCLS User

Join DCLS



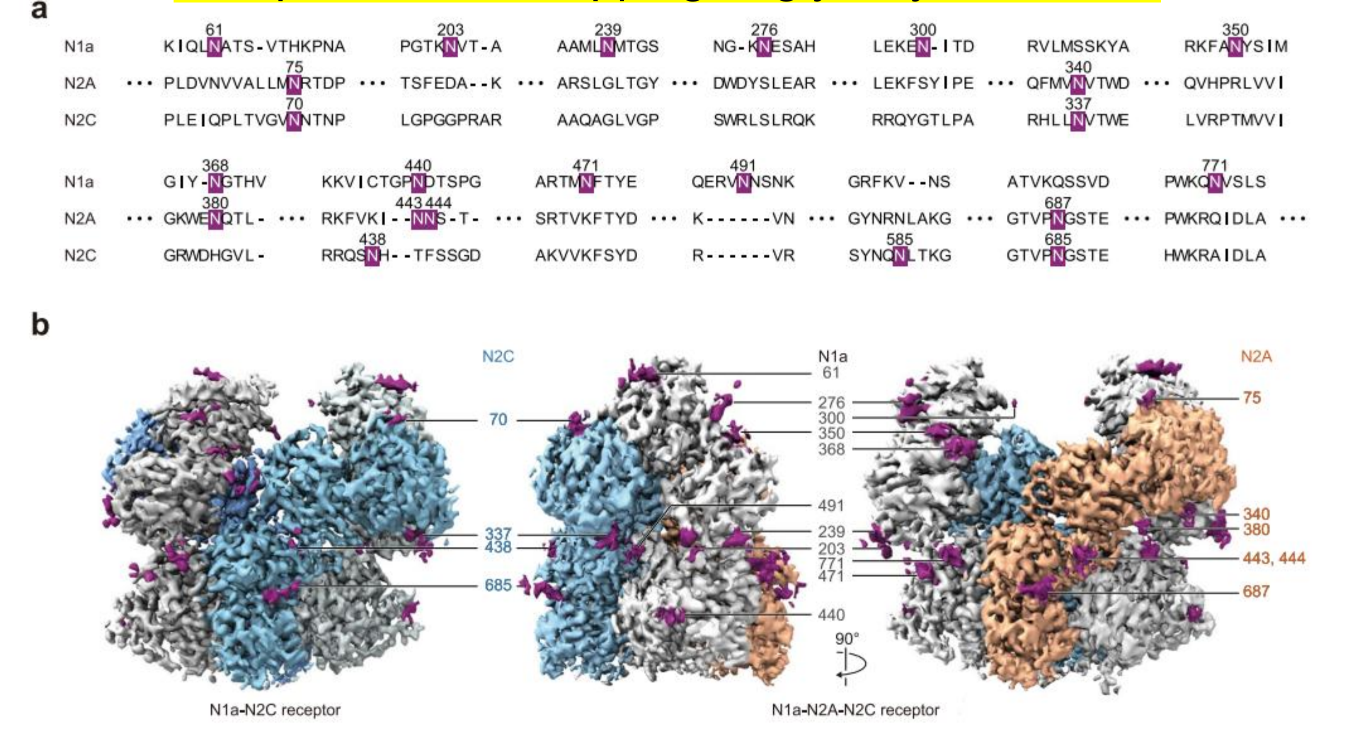
Thanks for attention

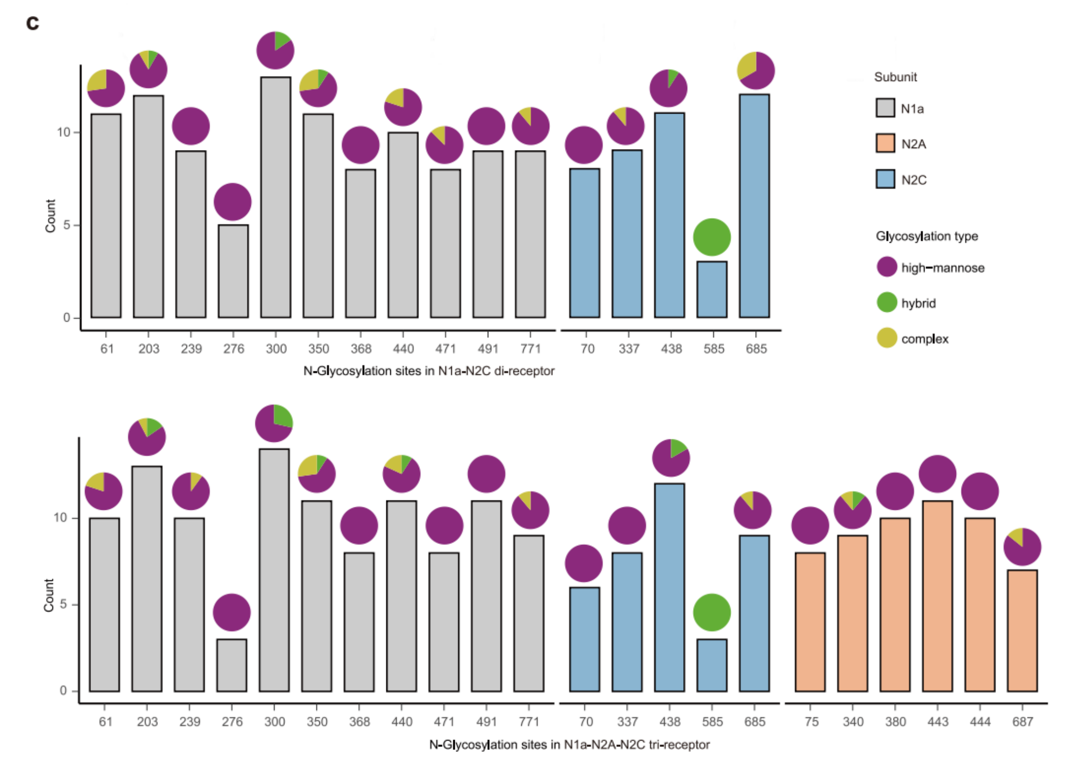
Representative Results 3: Precise Characterization of Protein Dynamic Structures and Interactions

Life and health

Precise characterization of glycosylation sites and glycoforms of NMDA

Comprehensive mapping of glycosylation sites





Assisted cryo-electron microscopy to resolve structures

Precise analysis of glycoform distribution

- **Deep and precise analysis of glycosylation sites and glycoforms;**
- **Theoretical basis for the structural analysis of different subtypes of NMDA receptors and the development of subtype-selective small molecule drugs.**

Nat. Struct. Mol. Biol. 2023, *30*, 629

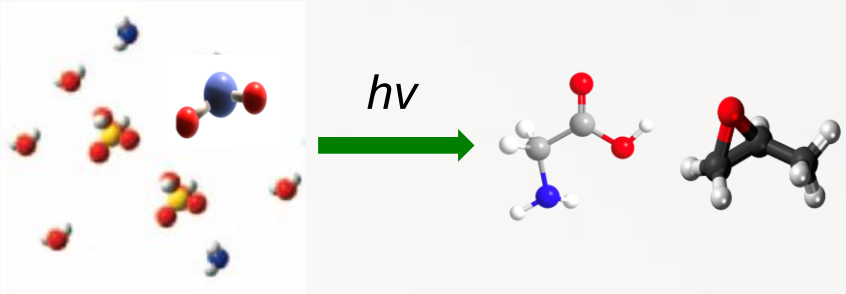
Photochemical reactions are main drivers for the evolution of interstellar living organic molecules

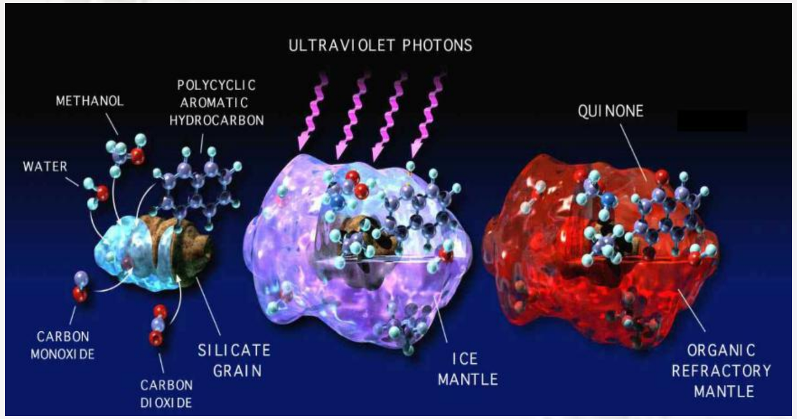
- **The chemical reactions of atoms and molecules driven by the interstellar radiation field (ISRF) play an important role in the forming of the interstellar clouds and planets.**
- **The initial living organic molecules (like amino acids) in the interstellar space may come from molecular photochemical reactions in gas phase or surfaces.**

Gas-phase and surface photochemical reactions

Small molecules

Amino acids

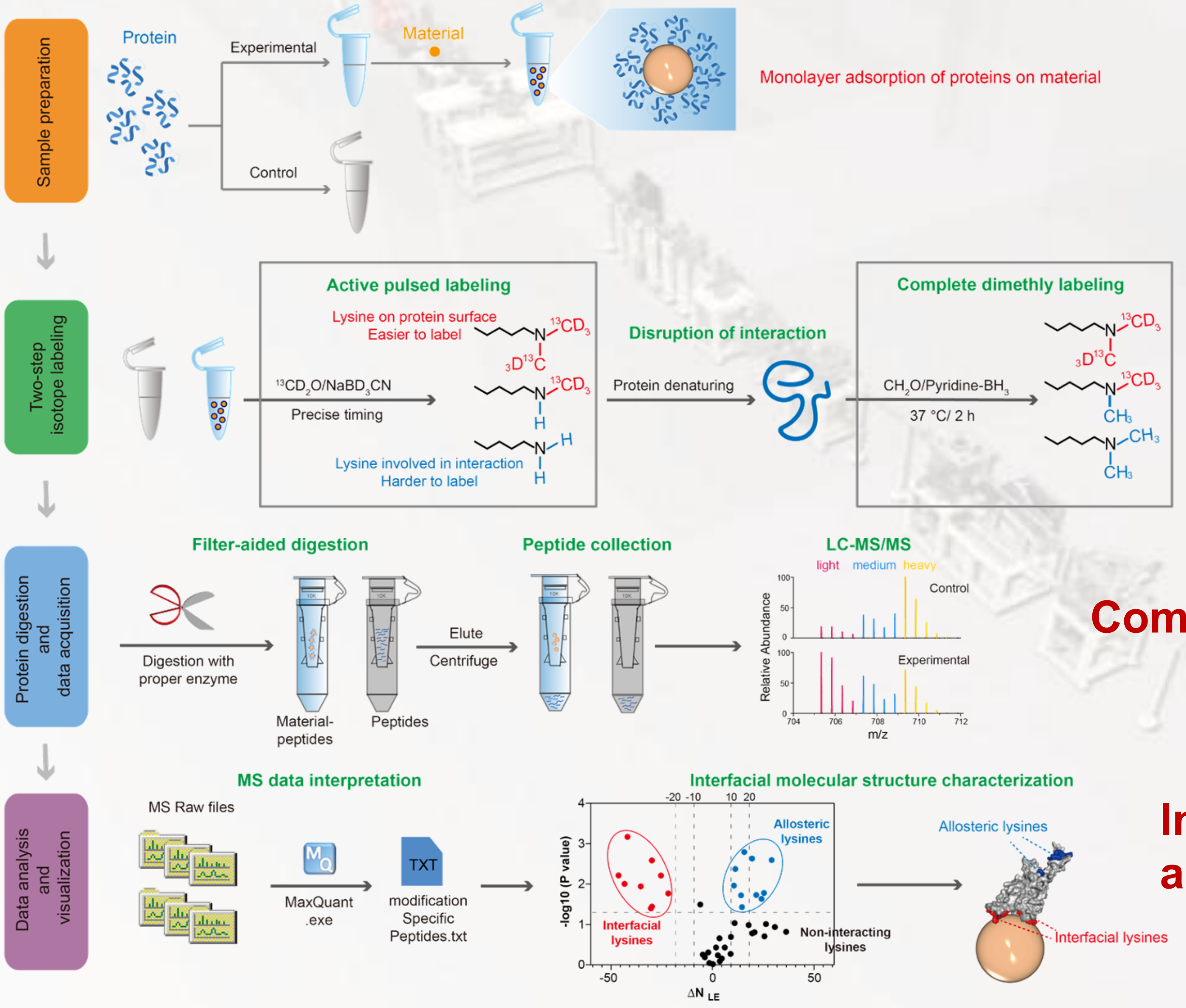




Nature, 2002

The VUV FEL laser is an unique tool to study molecular photochemical processes, both in gas-phase and surface, which help us understanding the origin of life in the interstellar space

Structural characterization of protein-material binding interface



1. Sample preparation — **Prepare material-protein complex**

2. Native labeling — **Decreased labeling levels on material-protein binding interface**

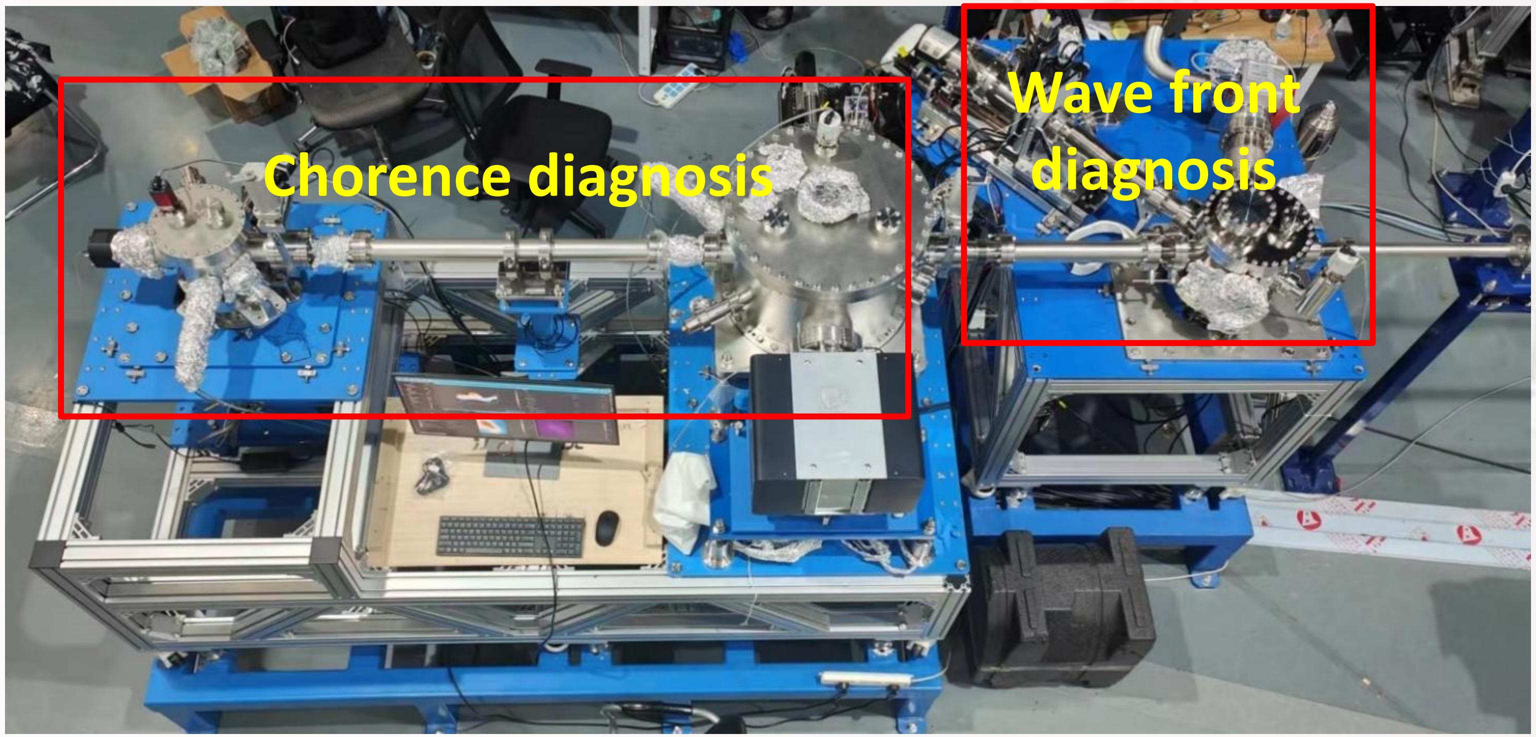
3. LC-MS/MS analysis — **Comprehensive characterization of lysine labeling levels**

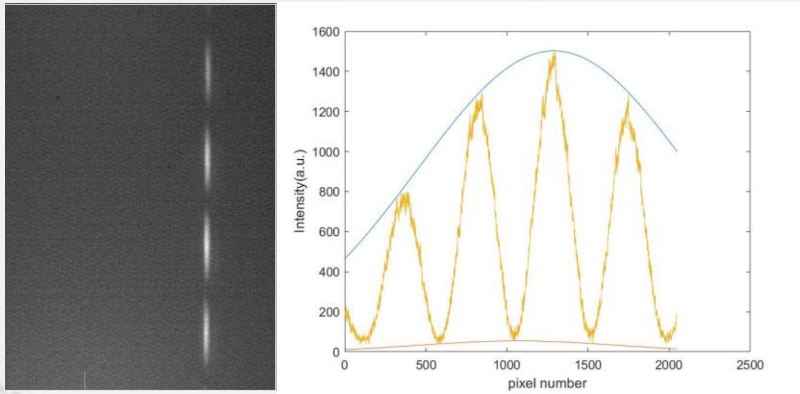
4. Data processing and interface analysis — **Interaction sequence regions and binding sites determined**

Nat. Protoc. 2023, *18*, 2600

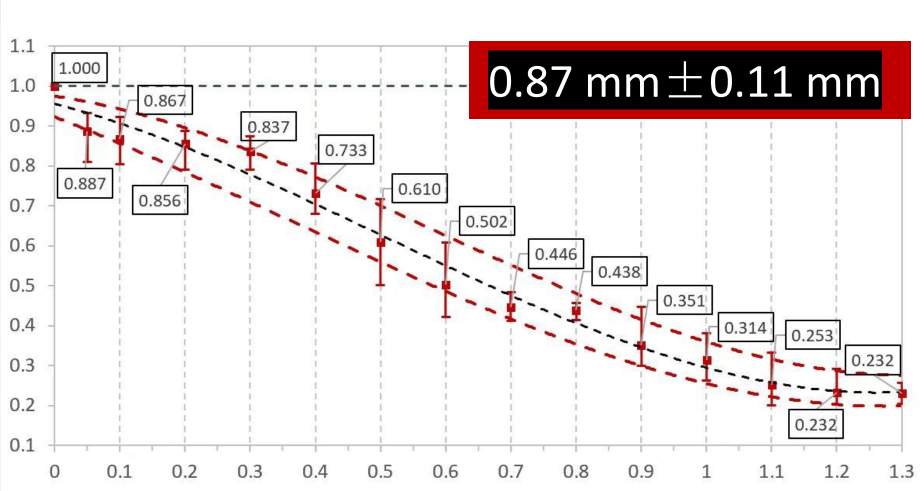
FEL wavefront and coherence diagnosis

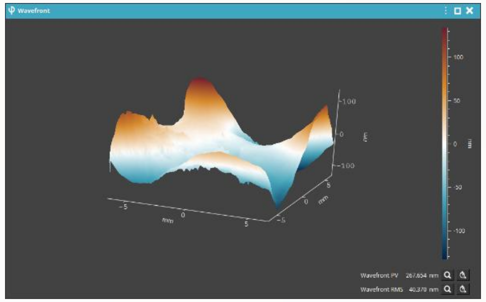
A wave front and coherence diagnostic system for DCLS has been developed and validated online.
It is shown that the variance of wave front is smaller than ±3nm and the transverse coherence length is 0.87mm.





Transverse coherence length measurement





Solid-state RF power sources

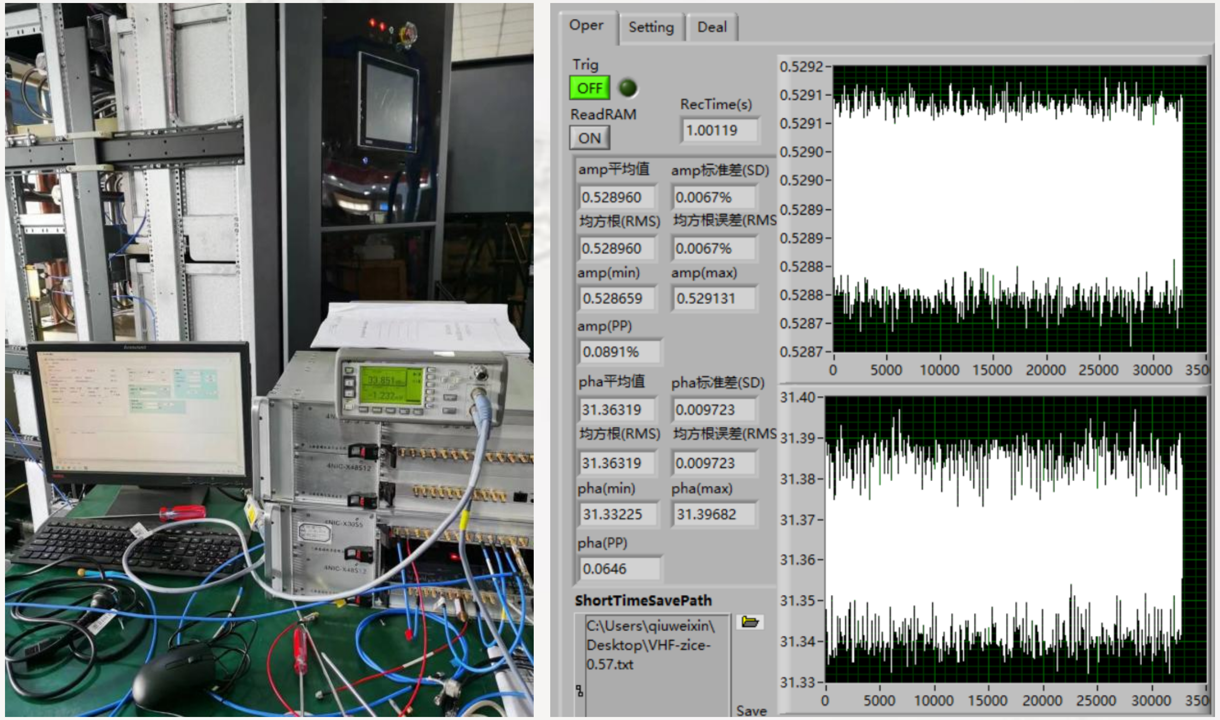
✓ Solid-state RF power sources have been manufactured and passed the acceptance inspection, and all parameters meet the requirements.

Parameters	Main Linac	Electron gun
Center frequency	1.3GHz	216.6MHz
Amplitude stability	0.1% p-p	0.1% p-p
Phase stability	0.1° p-p	0.1° p-p
Spur suppression ratio	-70dB	-70dB
Output power (1dB compression point)	5.5kW	60kW
Band width	1MHz	1MHz

1.3GHz power source

216MHz power source

216MHz factory acceptance measurements

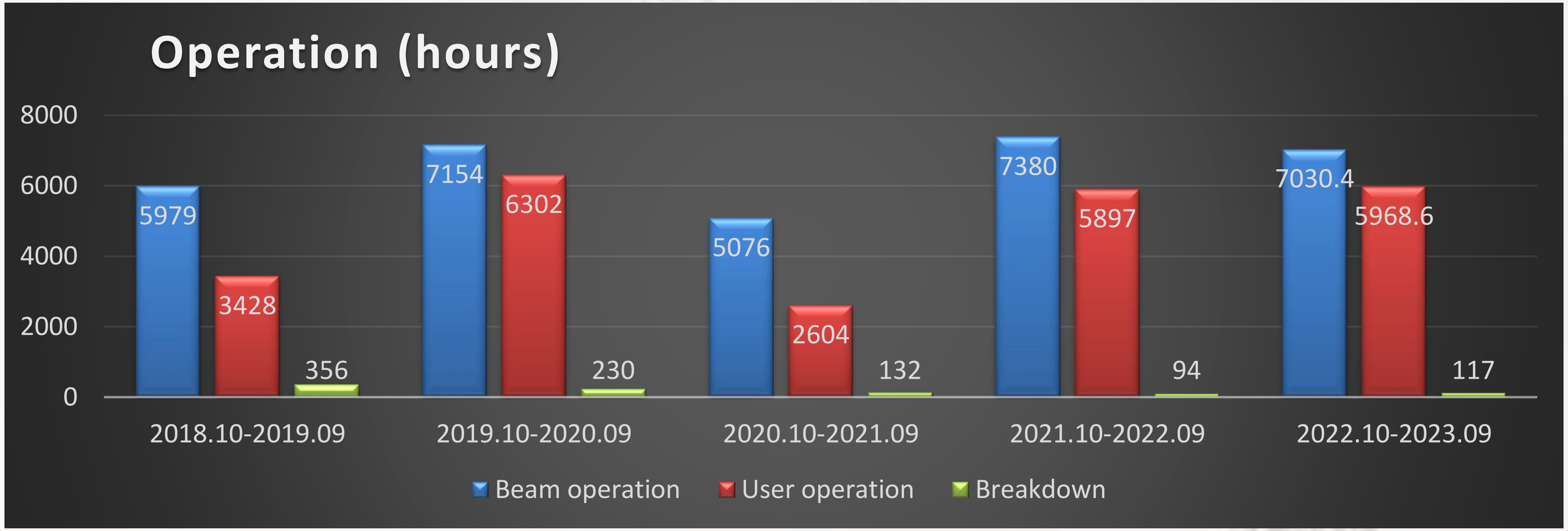


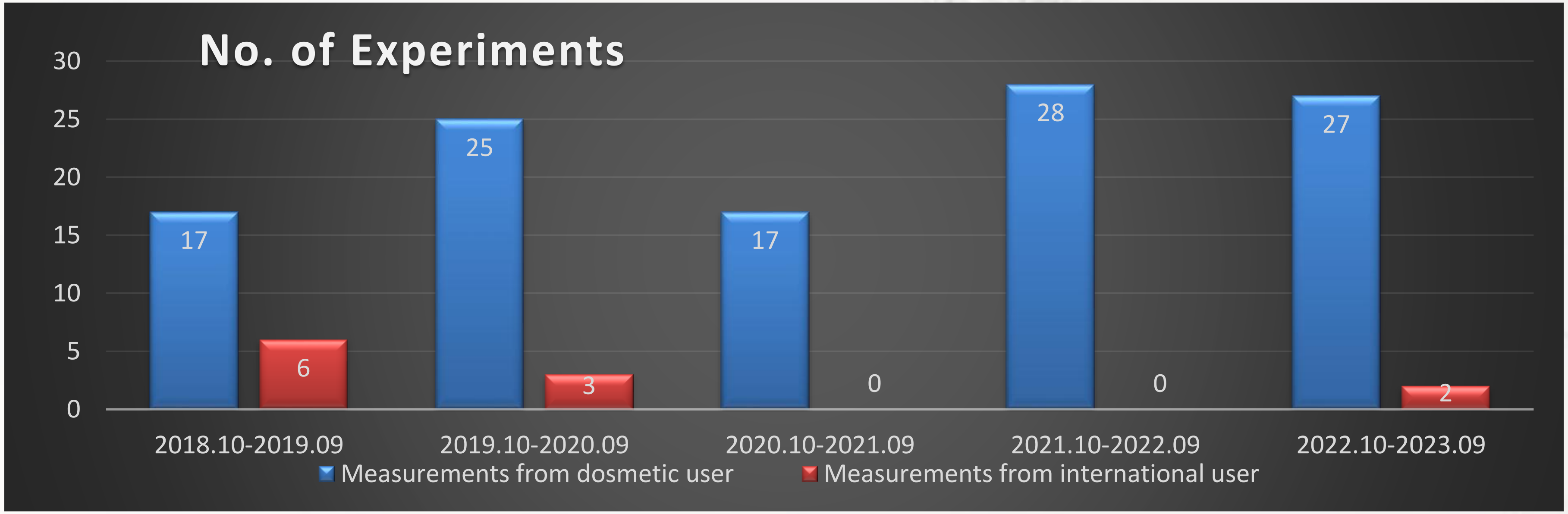
High gain FEL user facility

	Length （m）	E energy（GeV）	Wavelength (nm)
DCLS	150	0.3	50
SXFEL	300	1.0	8
Fermi	350	1.2	3
FLASH	400	1.2	3
SwissFEL	715	5.8	0.1
SACLA	750	8.0	0.06
PAL-XFEL	1100	10.0	0.1
LCLS	1500	14.5	0.15
LCLS-II	1500	4.0	0.25
Shanghai Hard X-ray FEL	3100	8.0	0.1
European XFEL	3800	17.5	0.08

VUV Soft X-ray Hard X-ray **SC FEL**

DCLS Operation Statistics





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