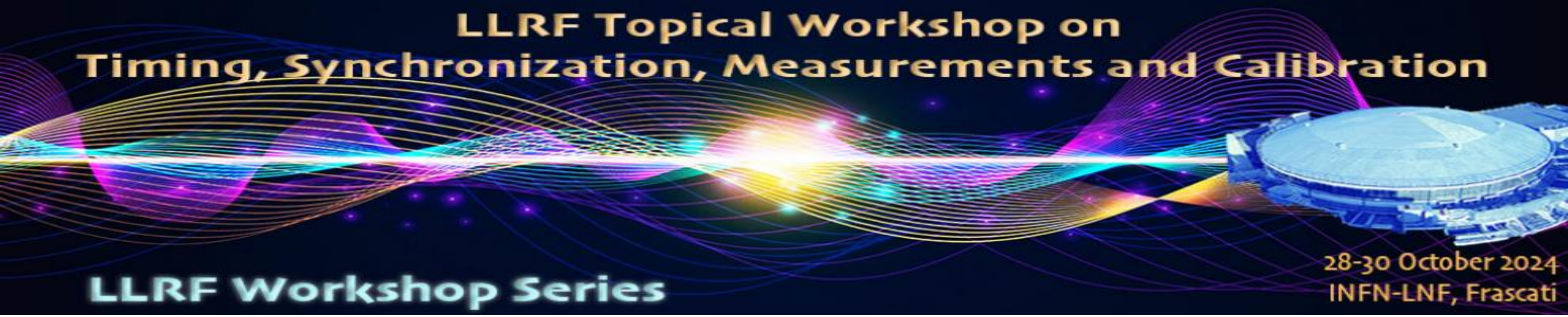


Femtosecond Synchronization System for Free Electron Laser

Zhichao Chen

(on behalf of Synchronization team)

Dalian Institute of Chemical Physics, CAS

Institute of Advanced Science Facilities, Shenzhen

2024/10/30

Outline

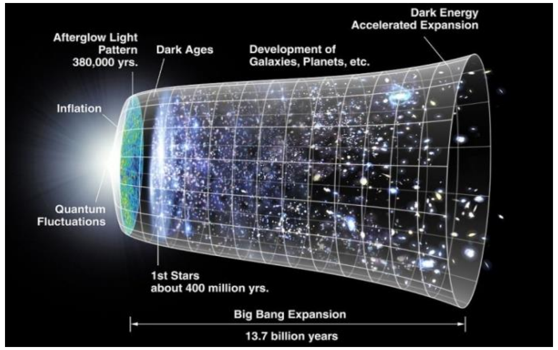
- **Introduction**
- **Synchronization Methods**
- **FEL projects & Fs-Synchronization Systems**
- **Acknowledgment**

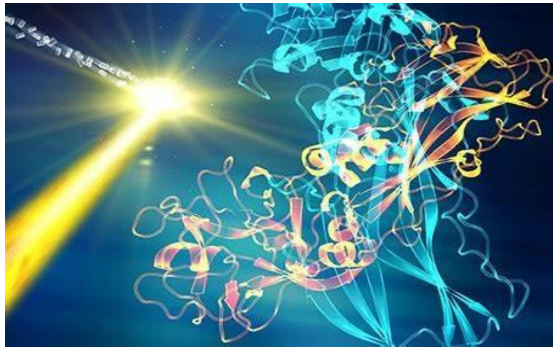
Introduction

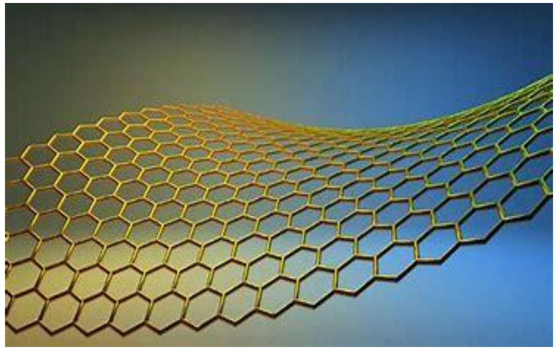
Importance of high-brightness advanced light source

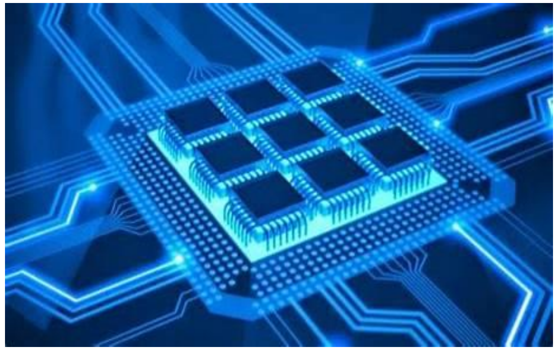
- The highly sensitive detection method based on the high-brightness light source is the most important driving force to promote the scientific research of matter and materials.
- High-brightness light source (such as laser technology) pave a way for the development of modern revolutionary technology.

Various scientific applications

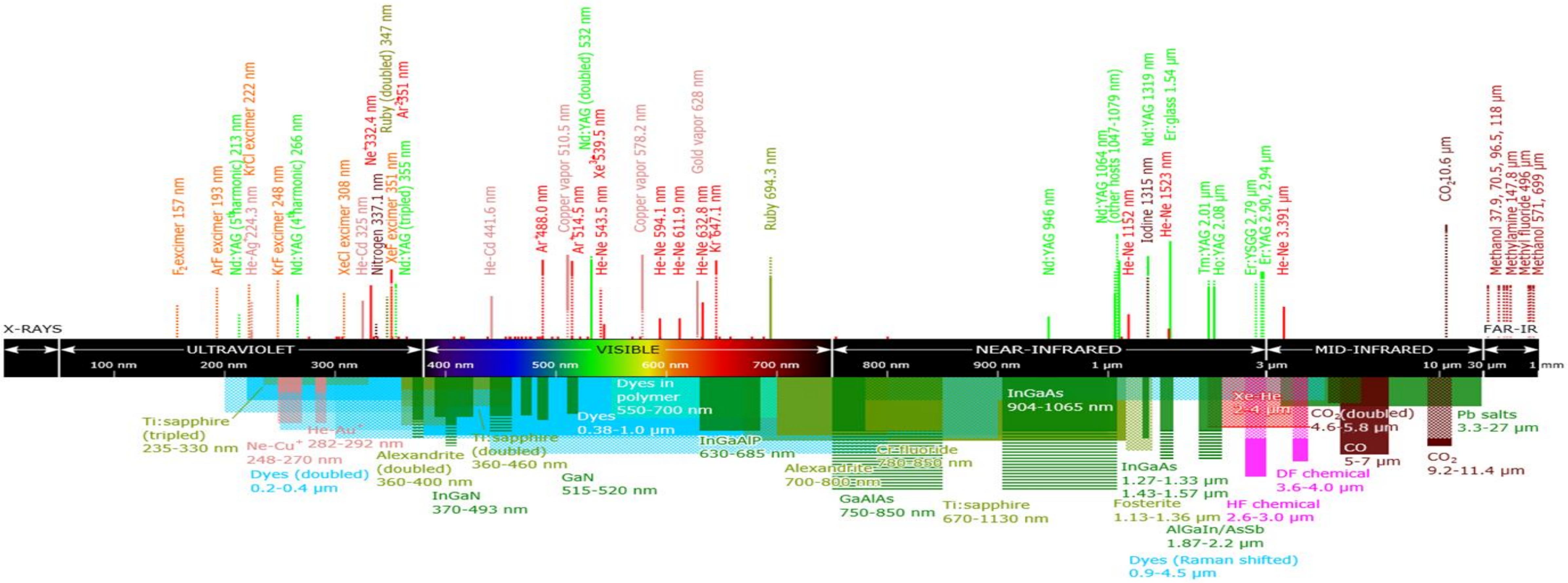








Introduction



X-ray and VUV light sources are not available easily!

Introduction

Development of Free Electron Laser

Milton et al, SCIENCE 292, 2037(2001)

Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser

S. V. Milton,[1*] E. Gluskin,[1] N. D. Arnold,[1] C. Benson,[1] W. Berg,[1] S. G. Biedron,[1,2] M. Borland,[1] Y.-C. Chae,[1] R. J. Dejus,[1] P. K. Den Hartog,[1] B. Deriy,[1] M. Erdmann,[1] Y. I. Eidelman,[1] M. W. Hahne,[1] Z. Huang,[1] K.-J. Kim,[1] J. W. Lewellen,[1] Y. Li,[1] A. H. Lumpkin,[1] O. Makarov,[1] E. R. Moog,[1] A. Nassiri,[1] V. Sajaev,[1] R. Soliday,[1] B. J. Tieman,[1] E. M. Trakhtenberg,[1] G. Travish,[1] I. B. Vasserman,[1] N. A. Vinokurov,[3] X. J. Wang, G. Wiemerslage,[1] B. X. Yang[1]

Self-amplified spontaneous emission in a free-electron laser has been proposed for the generation of very high brightness coherent x-rays. This process involves passing a high-energy, high-charge, short-pulse, low-energy-spread, and low-emittance electron beam through the periodic magnetic field of a long series of high-quality undulator magnets. The radiation produced grows exponentially in intensity until it reaches a saturation point. We report on the demonstration of self-amplified spontaneous emission gain, exponential growth, and saturation at visible (530 nanometers) and ultraviolet (385 nanometers) wavelengths. Good agreement between theory and simulation indicates that scaling to much shorter wavelengths may be possible. These results confirm the physics behind the self-amplified spontaneous emission process and forward the development of an operational x-ray free-electron laser.

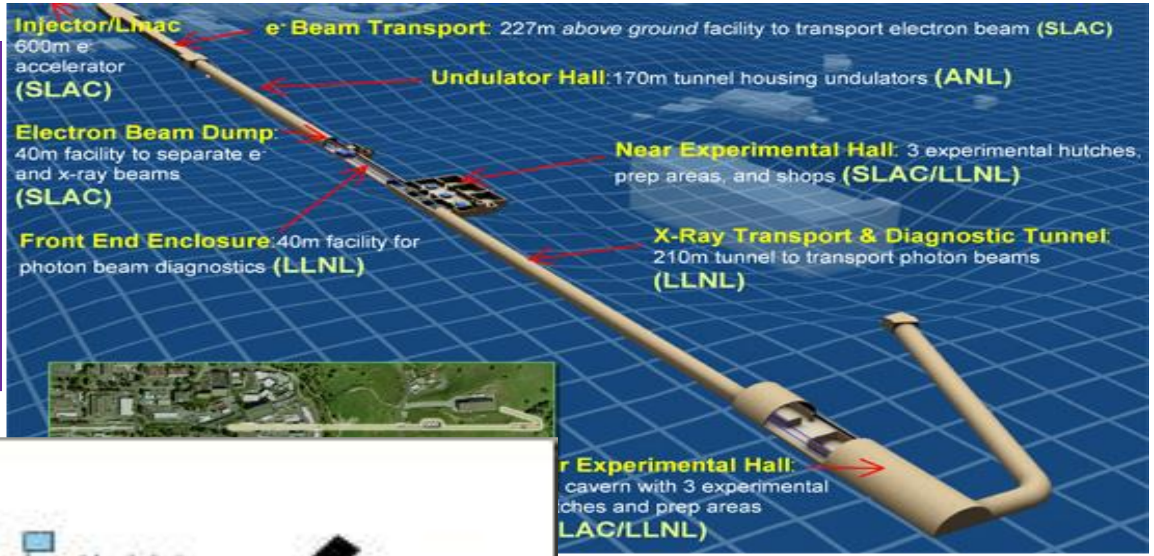
Yu et al. SCIENCE 289, 932(2000)

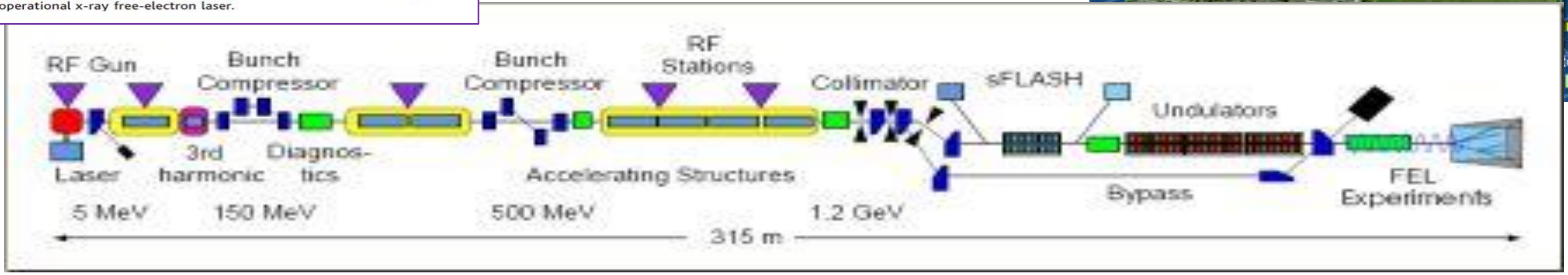
High-Gain Harmonic-Generation Free-Electron Laser

L.-H. Yu,[1*] M. Babzien,[1] I. Ben-Zvi,[1] L. F. DiMauro,[1] A. Doyuran,[1] W. Graves,[1] E. Johnson,[1] S. Krinsky,[1] R. Malone,[1] I. Pogorelsky,[1] J. Skaritka,[1] G. Rakowsky,[1] L. Solomon,[1] X. J. Wang,[1] M. Woodle,[1] V. Yakimenko,[1] S. G. Biedron,[2] J. N. Galayda,[2] E. Gluskin,[2] J. Jagger,[2] V. Sajaev,[2] I. Vasserman[2]

A high-gain harmonic-generation free-electron laser is demonstrated. Our approach uses a laser-seeded free-electron laser to produce amplified, longitudinally coherent, Fourier transform–limited output at a harmonic of the seed laser. A seed carbon dioxide laser at a wavelength of 10.6 micrometers produced saturated, amplified free-electron laser output at the second-harmonic wavelength, 5.3 micrometers. The experiment verifies the theoretical foundation for the technique and prepares the way for the application of this technique in the vacuum ultraviolet region of the spectrum, with the ultimate goal of extending the approach to provide an intense, highly coherent source of hard x-rays.

LCLS—LINAC Coherent Light Source





FLASH (*Free-Electron Laser* in Hamburg)

FEL promotes the revolution of laser technology from THz to hard X-ray.

Introduction

Some Free Electron Laser Facilities

Facility	Country	LINAC	Beam energy/GeV	Photon energy/keV	Rep. rate/Hz	Length/m	Status
LCLS-I	USA	RF	14.3	1-15	120	3100	Operation
SACLA	Japan	RF	8	0.44-20	60	750	Operation
FERMI	Italy	RF	1.5	0.0124-0.3	50	350	Operation
PAL XFEL	Korea	RF	10	0.124-12.4	60	1100	Operation
SXFEL	China	RF	1.5	0.1-0.6	10	532	Operation
DCLS	China	RF	0.3	0.007-0.041	50	150	Operation
SwissFEL	Swizerland	RF	5.8	0.25-12.4	100	715	Operation
FLASH	Germany	SRF	1.25	0.014-0.31	5000	315	Operation
Eu-XFEL	European	SRF	17.5	8.4-30	27,000	3400	Operation
LCLS-II	USA	SRF	8	0.2-5	1,000,000	3200	Operation
SHINE	China	SRF	8	0.4-25	1,000,000	3110	Under construction
S^3FEL	China	SRF	2.5	0.04-1	1,000,000	1700	Under construction
DALS	China	SRF	0.1 / 0.6	- / 0.007-0.19	1,000,000	60/750	Under construction

Introduction

Fs-Synchronization System manages FEL timing with fs-level.

Task:

- Providing femtosecond level stable Master clock ~Laser & RF
- Distributing Master clock to clients of Laser, LLRF, and Diagnostic
- 10 fs-additive jitter locking clients to the Master clock

Function:

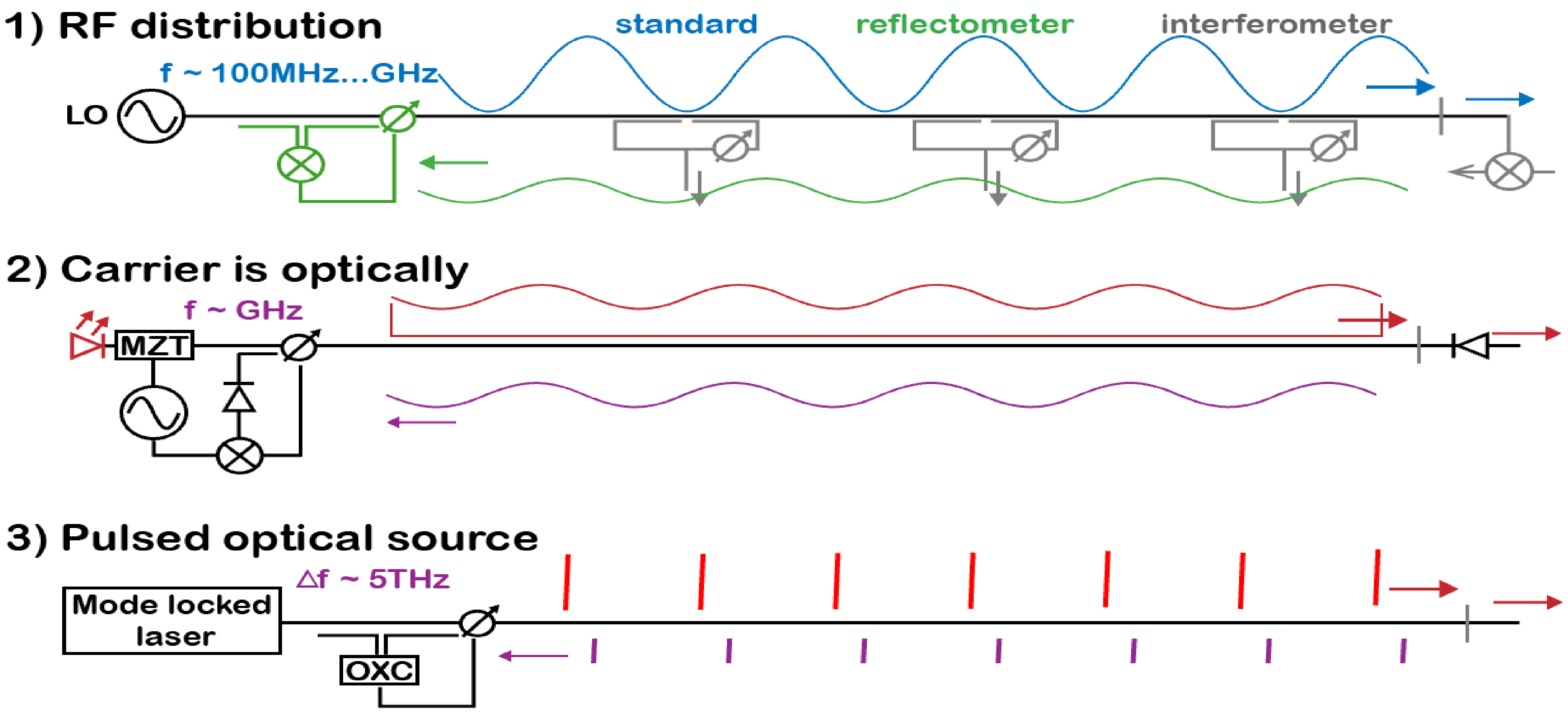
FEL can work and be stable

Research ability especially for Time-Resolved experiment

Outline

- Introduction
- **Synchronization Methods**
- FEL projects & Fs-Synchronization Systems
- Acknowledgment

Synchronization Methods



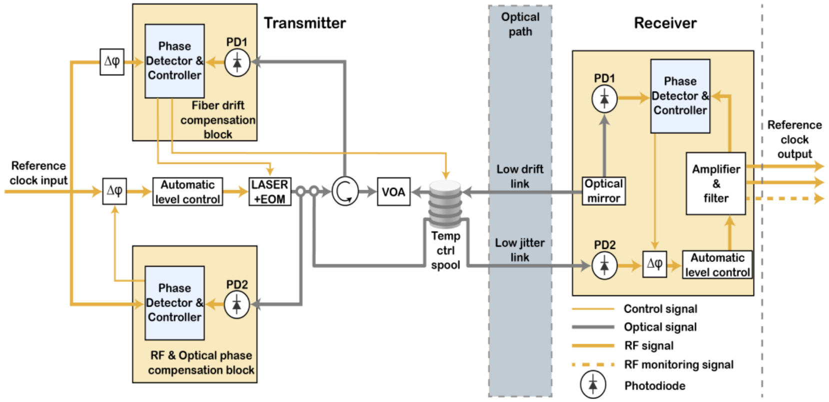
Adapted from Dr. Holger Schlarb slide

Synchronization Methods

Various synchronization methods have been developed

Approach		Developed by	Jitter fs[10Hz,10MHz]	Drift fs/24h/km	Advantage	Disadvantage
Fiber Link	Pulsed laser + PMF	MIT-CFEL DESY	<0.5	~5	Lowest jitter Drift free Large distance	Expensive
	CW laser + SMF	PSI LBNL	<20	~40	Low jitter Long distance	Certain drift
RF Link	Temperature stabilized RF	PAL SACLA	<10	>250	Stable	Large drift


European XFEL



SwissFEL


PAL XFEL

Synchronization Methods

Hybrid SYNC with pulsed laser link as the backbone has become the mainstream design of large-scale FELs.

Facility	RF	CW Laser Link	Pulsed Laser Link
LCLS	●		●
SwissFEL	●	●	●
FERMI	●	●	●
PAL XFEL	●	●	
SACLA	●	●	
SXFEL	●	●	●
DCLS	●		●
LCLS-II	●	●	●
FLASH	●		●
EuXFEL	●		●
SHINE	●		●
S^3FEL	●	●	●
DALS	●	●	●

Outline

- Introduction
- Synchronization Methods
- **FEL projects & Fs-Synchronization Systems**
- Acknowledgment

FEL projects & Fs-Synchronization Systems

Dalian

- ➢ **Dalian Coherent Light Source (DCLS)**

  Operation since 2017

- ➢ **Dalian Advanced Light Source (DALS)**

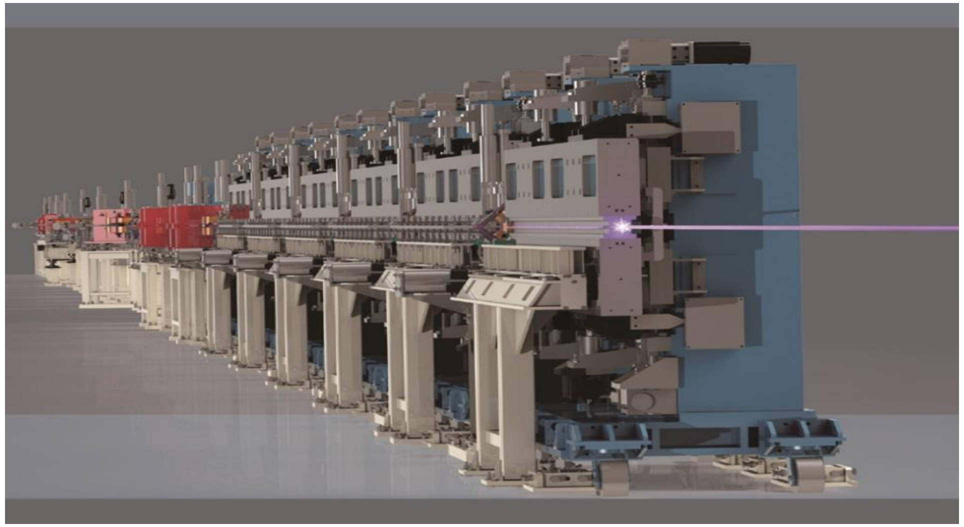
  Building, Pre-study project

Shenzhen

- ➢ **Shenzhen Superconducting Soft-X-ray Free Electron Laser (S³FEL)**

  Designing

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 [10 Hz, 10 MHz]**
- **Rep. Rate: 50 Hz**

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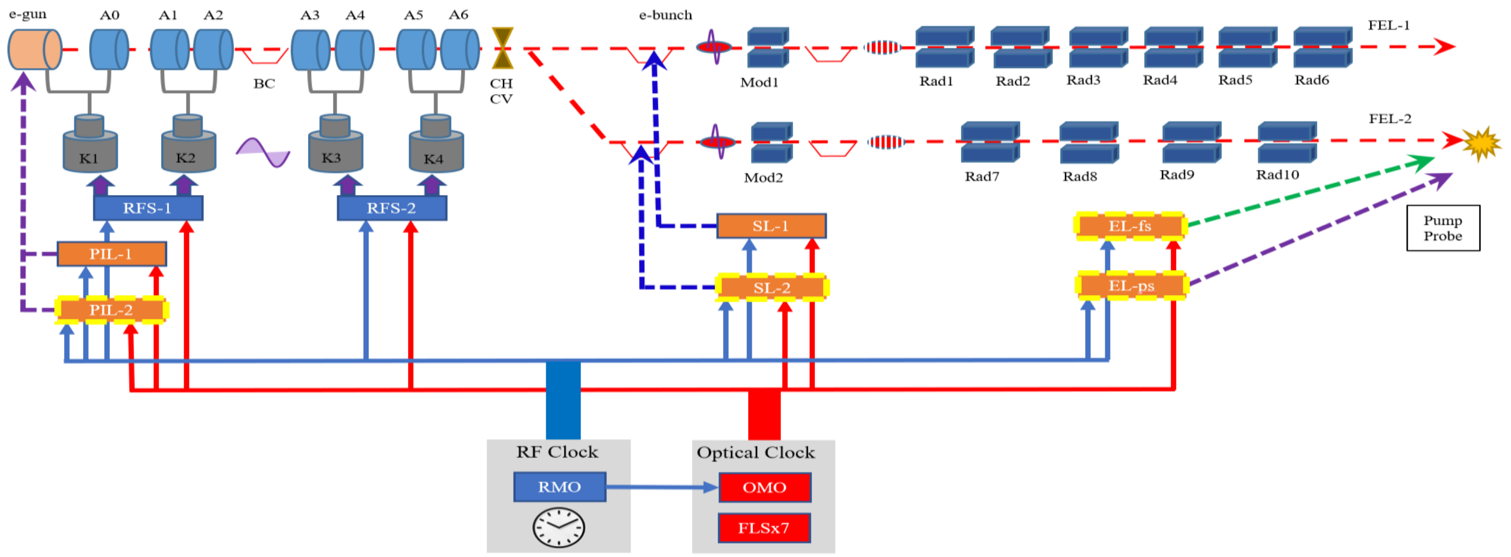
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

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

DCLS 30-fs Synchronization System



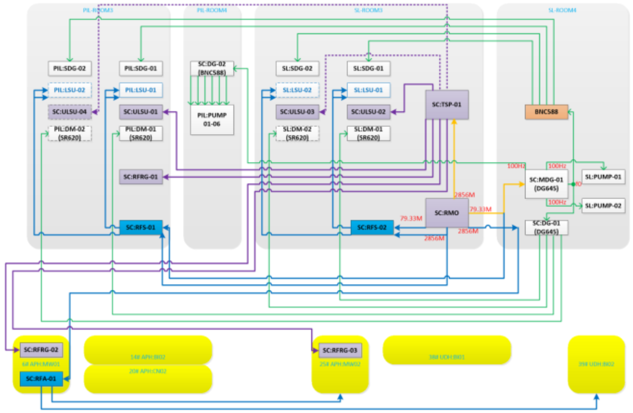
Pulsed Laser Synchronization System ~ 30 fs

RF Synchronization System ~ 50 fs

Item		Property	Requirement	Pulsed Laser/fs	RF/fs
Master clock	RF Master Oscillator (RMO)（2856 MHz）	Jitter	<30 fs [10 Hz, 10 MHz]	30	
	Optical Master Oscillator (OMO)（238 MHz）	Jitter	<10 fs [1 kHz, 10 MHz]	1	
Link	Fiber / RF cable	Jitter & Drift	<10 fs [35 μHz, 10 MHz]	5.5	2000
Client	Photoinjector Laser（79.33 MHz）	Jitter & Drift	<100 fs [35 μHz, 10 MHz]	15	50
	Seed Laser（79.33 MHz）	Jitter & Drift	<20 fs [35 μHz, 10 MHz]	15	50
	LLRF（2856 MHz）	Jitter & Drift	<30 fs [35 μHz, 10 MHz]	25	30
	BI (2856 MHz)	Jitter	<200 fs [10 Hz, 10 MHz]		30
Function				Operation	Backup

Scientific Customer → FEL → Synchronization System → Sub-system

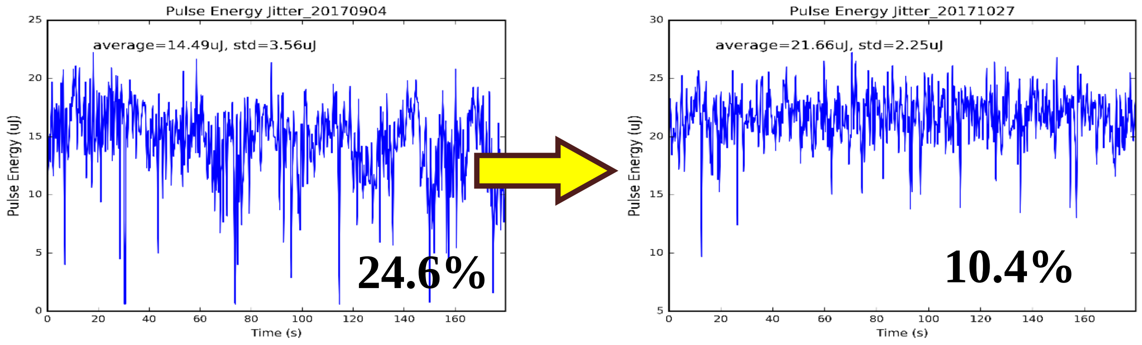
DCLS 30-fs Synchronization System



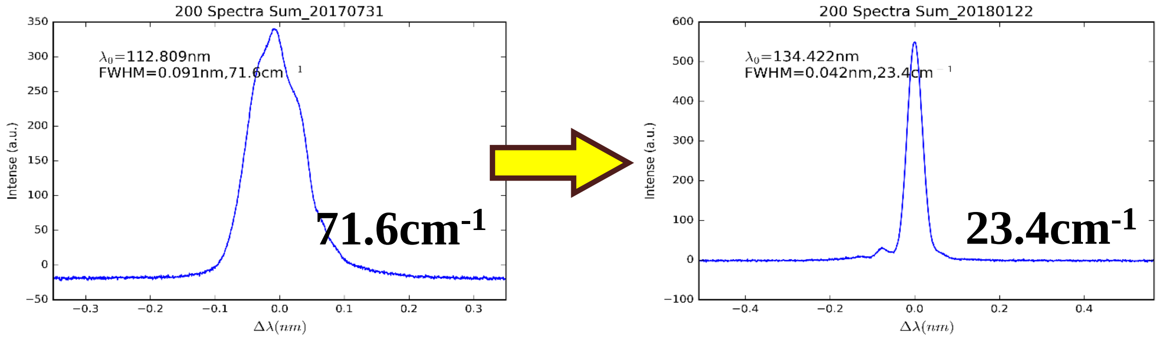
30 fs-Pulsed Laser Synchronization System Cooperation with Cycle

50 fs-RF Synchronization System Cooperation with SINAP

Energy stability

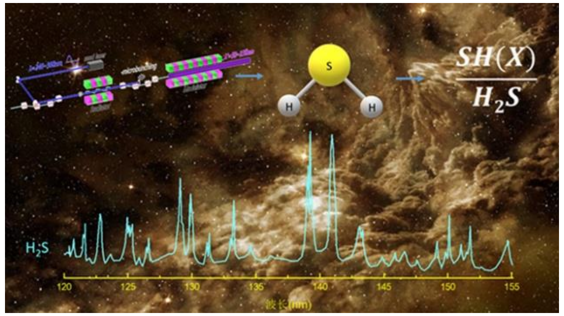


Spectra Stability



Scientific Research at DCLS   User drive project!

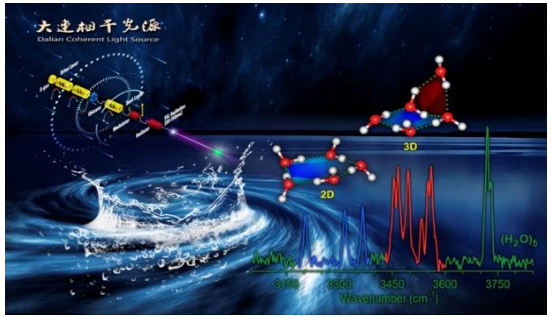
Photodissociation of small molecule in VUV range



Nat. Commun., 11,1547(2020)
Nat. Commun., 12, 2467 (2021)
Nat. Commun., 12, 4459 (2021)
Nat. Commun., 12, 6303 (2021)
Science Advances, 7, eabg7775 (2021)
Chem. Sci. 14, 2501(2023)
Nat. Sci. Rev. nwad158(2023)
Chem. Sci. 14, 2501 (2023)
Science, 383, 746 (2024)

Deep understanding of interstellar photo-chemistry process

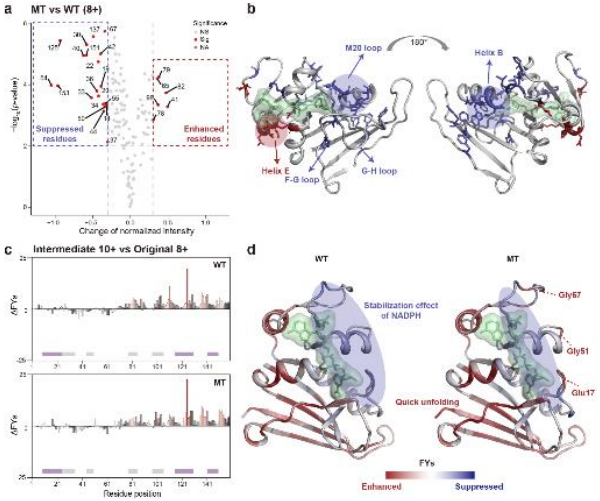
The structure of neutral water cluster



PNAS, 117, 15423(2020)
Nat. Comm., 11, 5449 (2020)
Nat. Catal., 4, 959 (2021)
J. Phys. Chem. Lett., 12, 472(2021)
J. Phys. Chem. Lett., 13, 5654(2022)
Cell Rep. Phys. Sci., 3, 100748(2022)
J. Am. Chem. Soc., 144, 21356 (2022)
J. Phys. Chem. Lett., 14, 3878 (2023)

Pentamer is the smallest water droplet. Octamer is the smallest ice cube.

Protein structure by MS



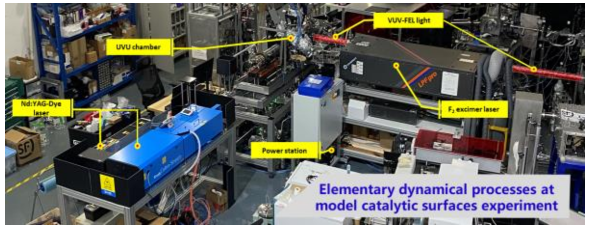
Nat. Protoc. 18, 2600 (2023)
Nat. Struct. Mol. Biol. 30, 629 (2023)
Nat. Nanotechnol. 17, 993 (2022)
Nat. Catal. 4, 607 (2021)
J. Am. Chem. Soc. 145, 1285 (2023)
J. Am. Chem. Soc. 145, 11477 (2023)
J. Am. Chem. Soc. 146, 8832 (2024)

Characterization of intramolecular hydrogen bonds of proteins

International Collaboration on surface scattering

Alec Wodtke
MPI from Germany

Xueming Yang
DICP from China

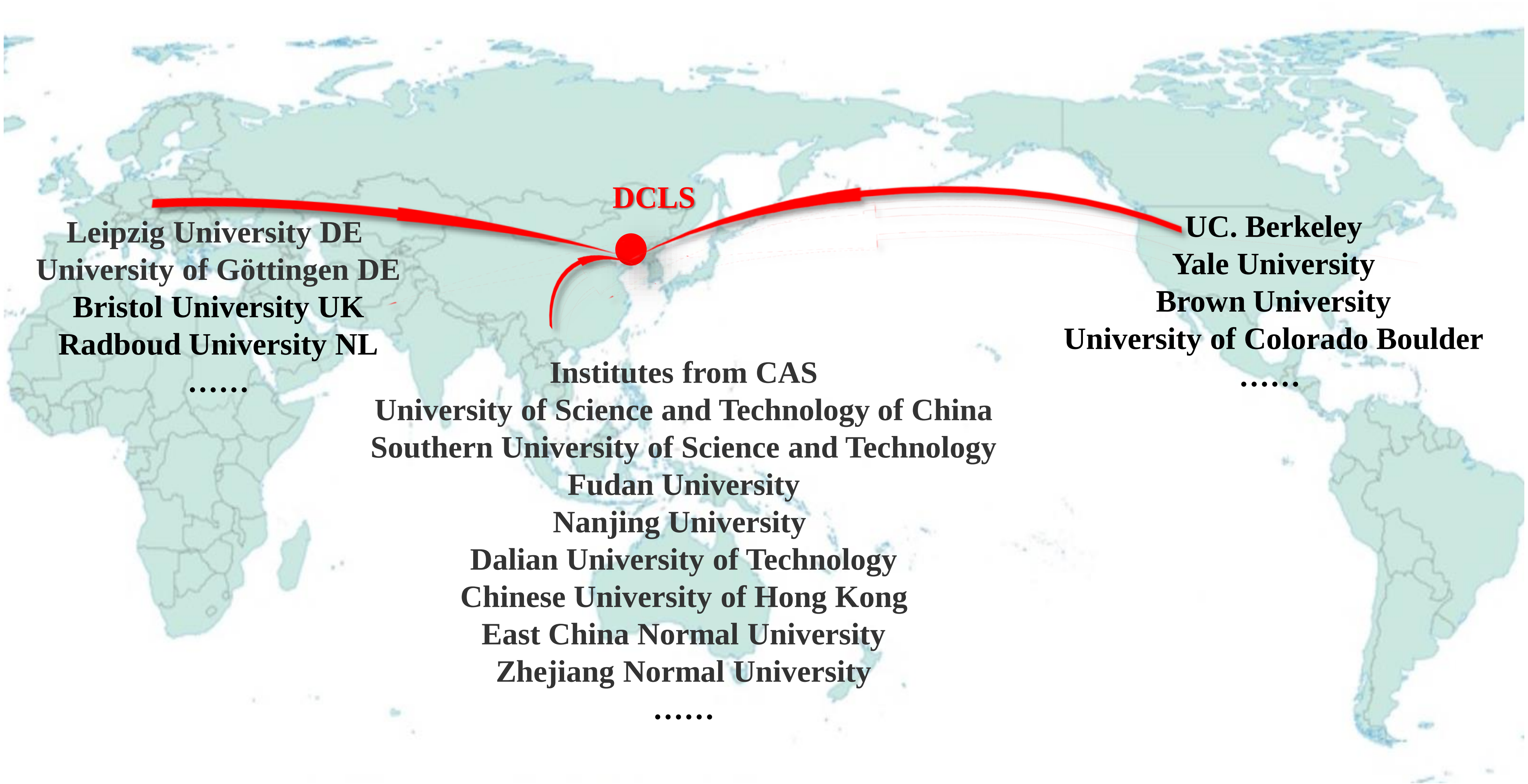


中国科学院大连化学物理研究所
DALIAN INSTITUTE OF CHEMICAL PHYSICS, CHINESE ACADEMY OF SCIENCES

Max Planck Institute for Biophysical Chemistry

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

World-wide Users

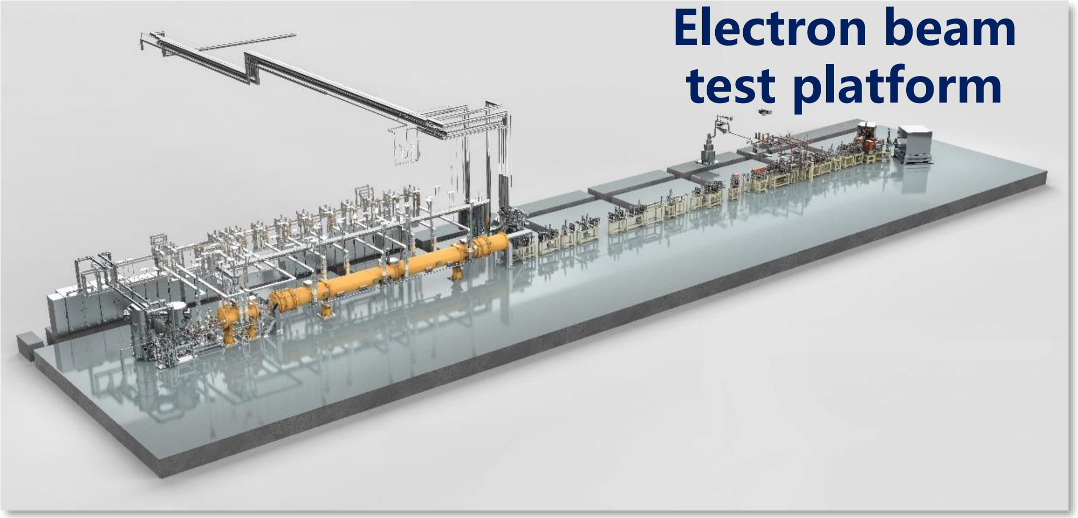


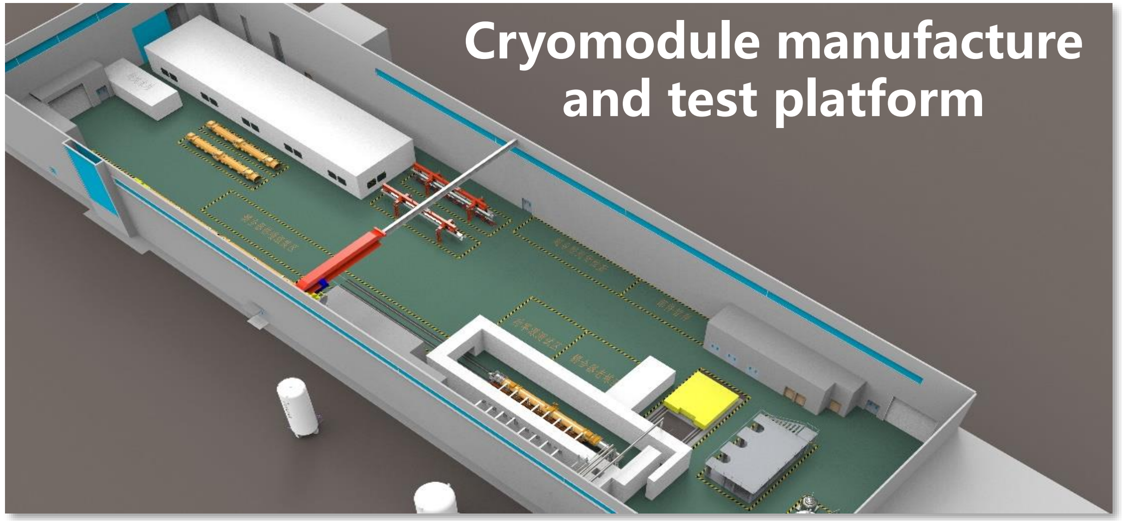
We are looking forward to have more users from the world!

Dalian Advanced Light Source (Pre-study project)

Key technologies for High rep. rate FEL

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





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

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

Electrical and RF power source gallery

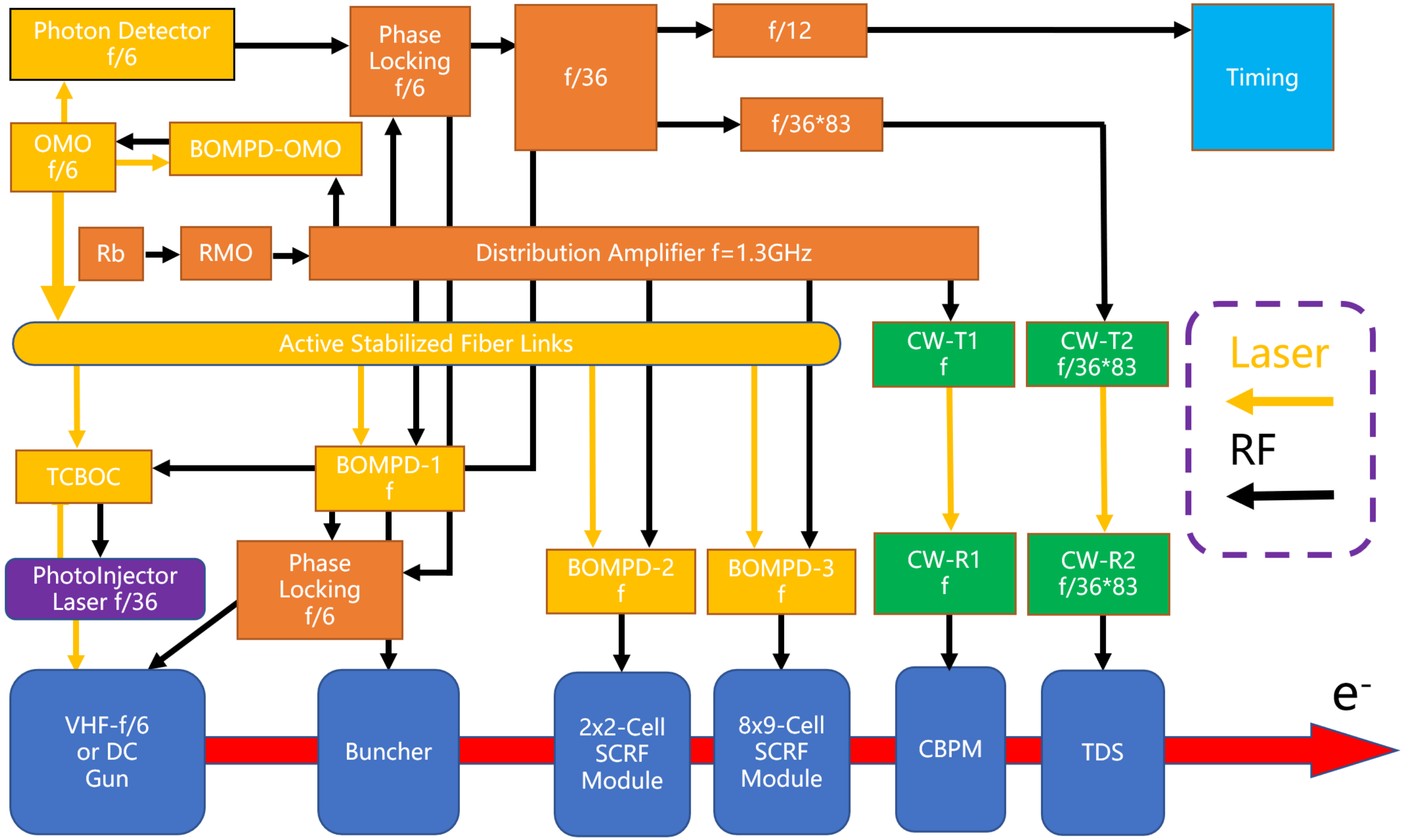
Pre-study project at DALS

Conceptual design in 2021

Birdview in June 2024

DALS 20-fs Synchronization System

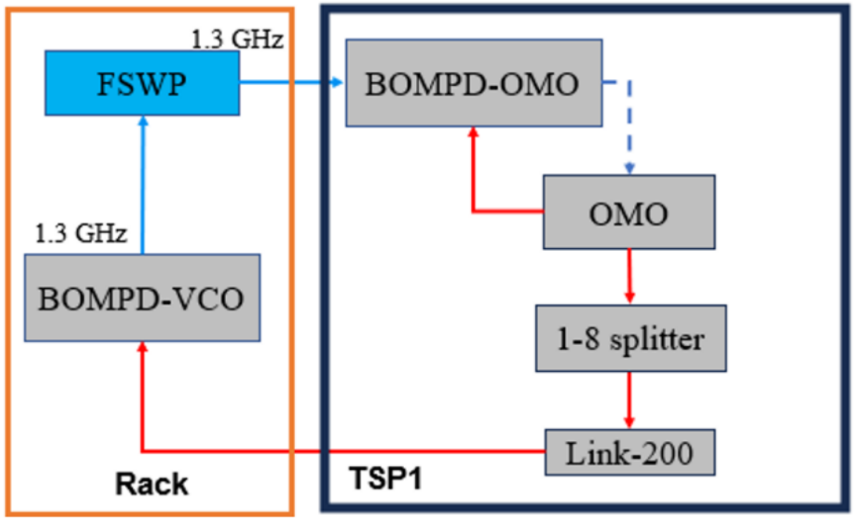
Requirements & Design



System	Device	Reference Mode	DALS	
			f=1300 MHz	Jitter & Drift (fs)
Laser	Photo injector Laser	Pulsed Laser	f/36	<80[35 μHz, 10 MHz]
	Heat Laser	Pulsed Laser	f/36	<100[35 μHz, 10 MHz]
	Seed Laser	Pulsed Laser	f/18	<20[35 μHz, 10 MHz]
	Experimental Laser	Pulsed Laser	f/18	<20[35 μHz, 10 MHz]
LLRF	VHF Gun	CW RF	f/6	<180[10 Hz, 10 MHz]
	Buncher	CW RF	f	<30[10 Hz, 10 MHz]
	1.3GHz SCRF Module	CW RF	f	<30[10 Hz, 10 MHz]
	3.9GHz SCRF Module	CW RF	f*3	<30[10 Hz, 10 MHz]
Diagnostics	BAM/BLM/LAM	Pulsed Laser	f/6	<10[35 μHz, 10 MHz]
	TDS band	CW RF	f/36*83	<60[10 Hz, 10 MHz]
	CBPM	CW RF	f	<100[10 Hz, 10 MHz]
Timing	Network switch	CW RF	f/12	<10 ps

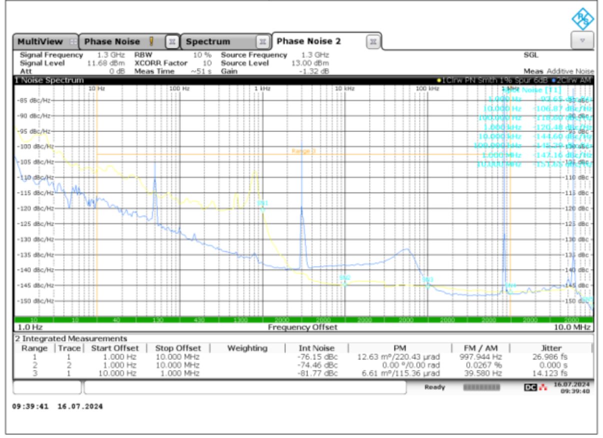
DALS 20-fs Synchronization System On the way!

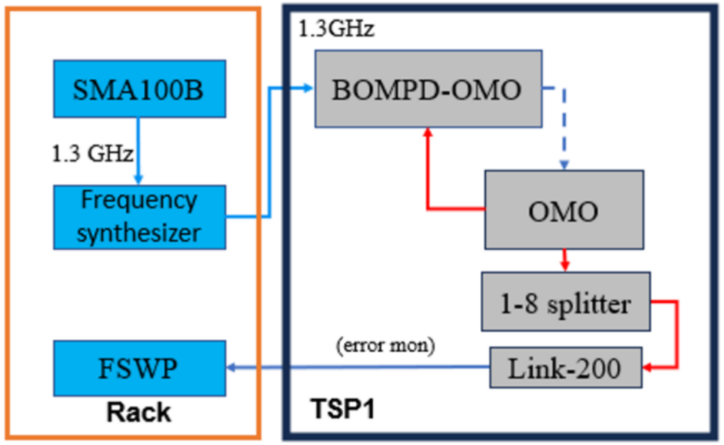
Cycle System & Some measurement



BOMPD RF (SN: 423)

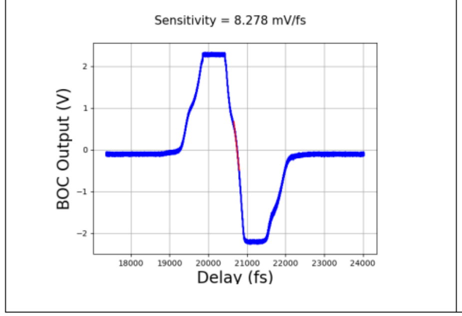
Jitter: 14.123 fs	**Amplitude noise:** 0.0267%

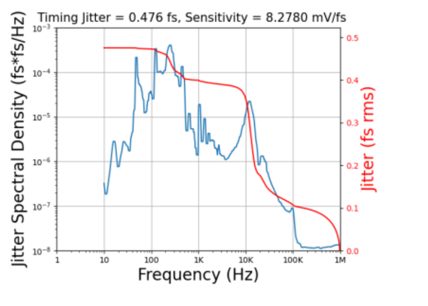




Link-020 (SN:465)

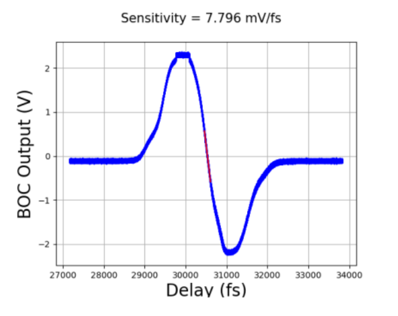
Timing sensitivity: 8.278 mV/fs	**Jitter:** 0.476 fs

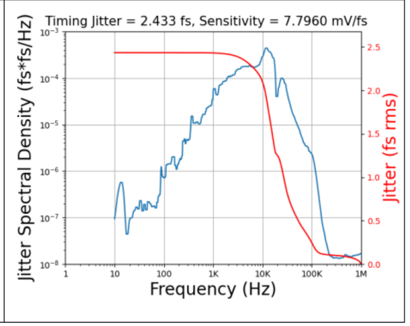




Link-200 (SN:466)

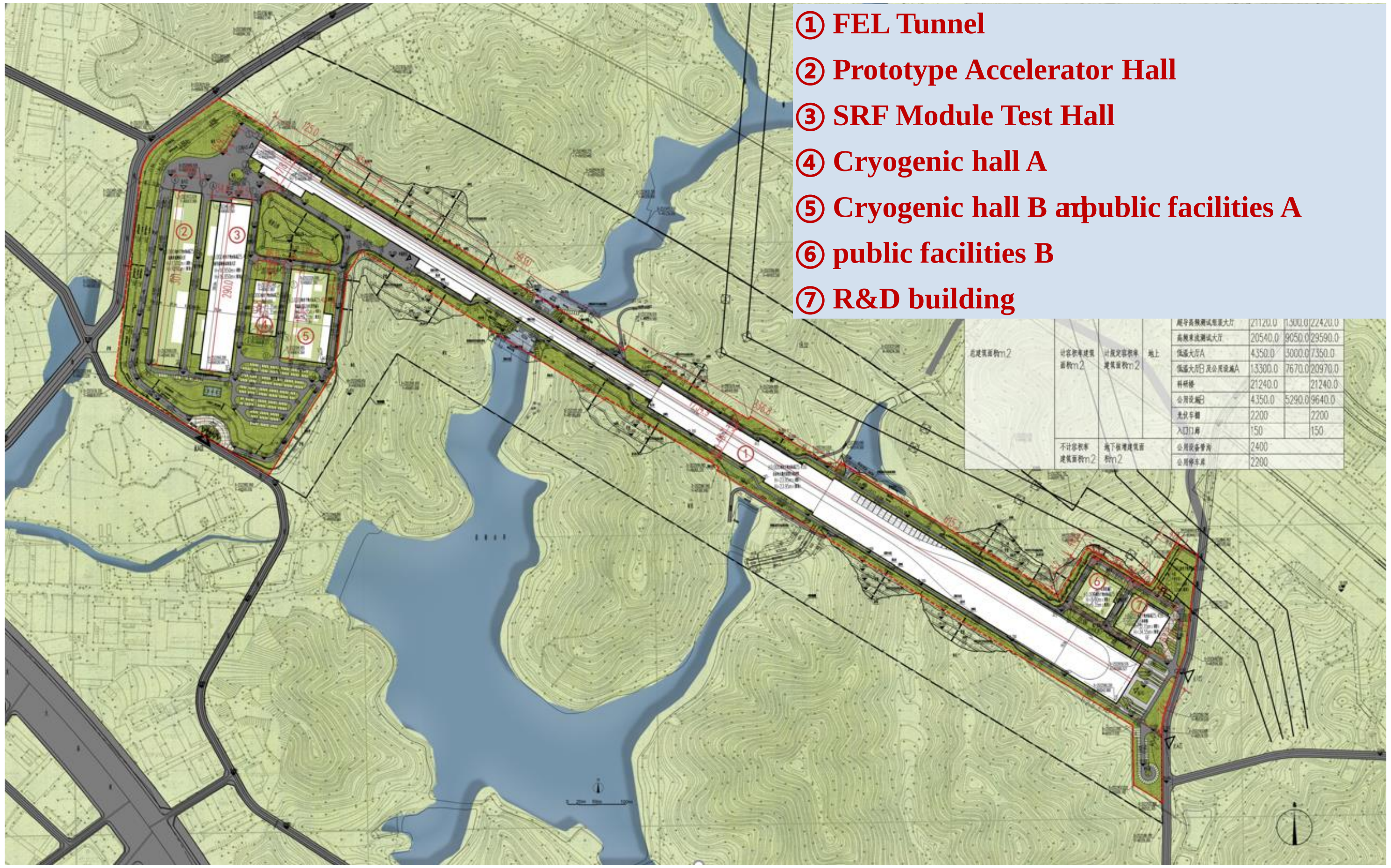
Timing sensitivity: 7.796 mV/fs	**Jitter:** 2.433 fs





Shenzhen Superconducting Soft-X-ray Free Electron Laser

Planning



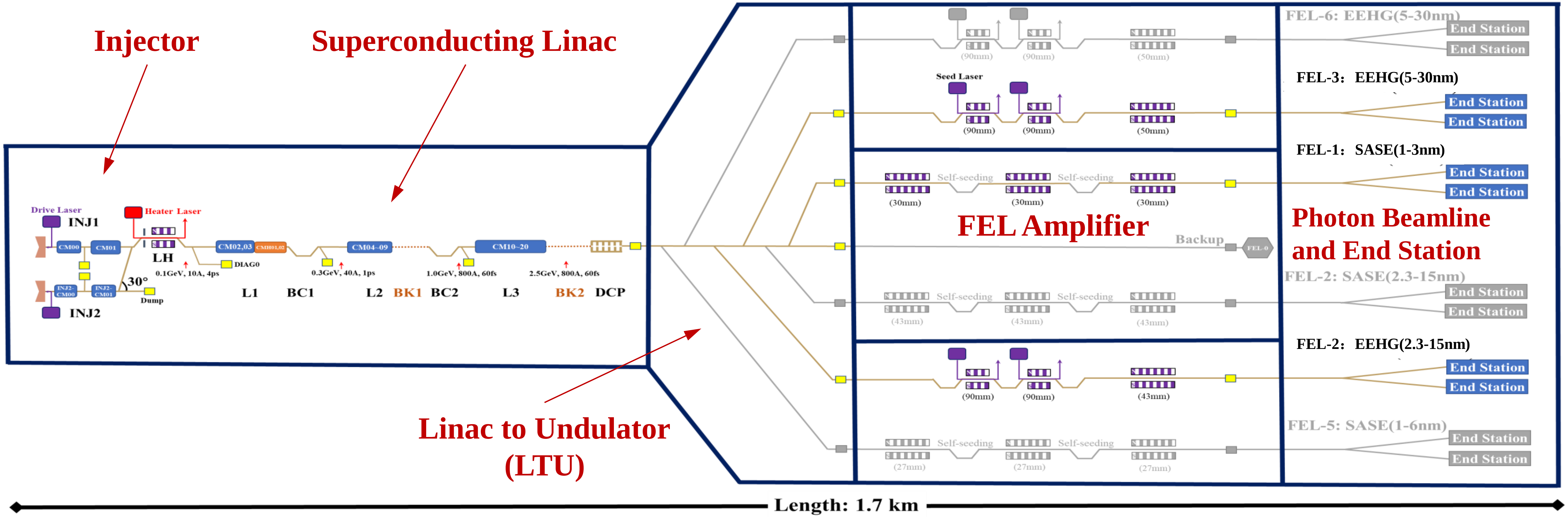
NO.	Name	Purpose
1	FEL Tunnel	Including injector, linac, undulator, beamline and endstaion
2	Prototype Accelerator Hall	linac component test with e beam
3	SRF Module Test Hall	R&D for SCRF
4	Cryogenic hall A	Cryogenic production and distribution
5	Cryogenic hall B And public facilities A	Cryogenic production and distribution Civil electricity, cooling water and fire control
6	R&D building	Experiment preparation
7	Public facilities B	Civil electricity, cooling water and fire control

It has been proposed in the city of Shenzhen and approved in 2023.

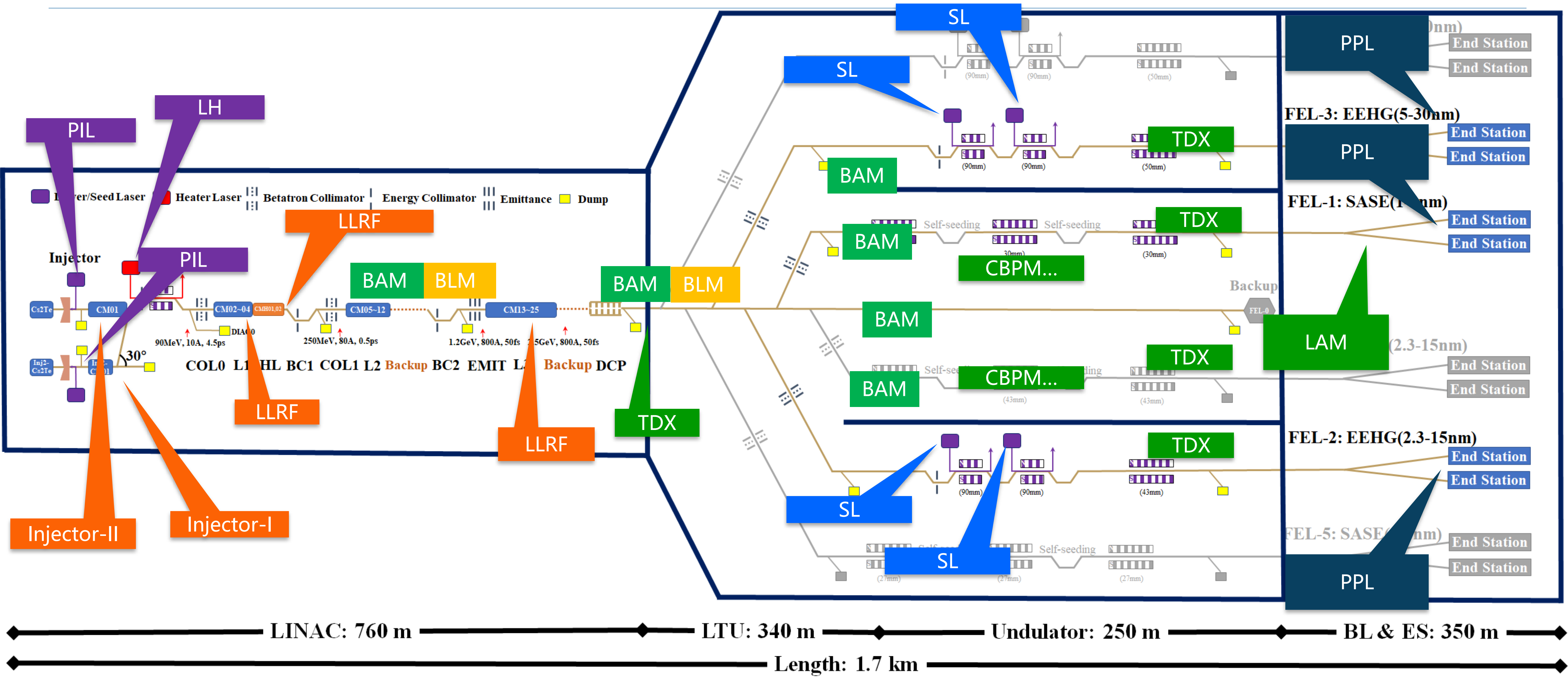
S3FEL Schematic Layout

Design and construction of a **superconducting CW-FEL facility** with a pulse repetition rate of **1 MHz** in the soft X-ray region (**1-30 nm**) to serve the scientific community.

Parameters	Objective	Units
Final electron energy	2.5	GeV
Bunch repetition rate	1	MHz
Bunch charge	100	pC
Undulator lines	3+3	-
FEL wavelength	1-30	nm
FEL pulse energy	~100	μJ



S³FEL Schematic Layout



1.7 km facility-wide, 10 fs-level synchronization of FEL devices including lasers, low level RF system, diagnostics and control system.

S³FEL synchronization requirements

System	Device	Reference	S³FEL / 479 units		
			f=1300MHz	Jitter & Drift (fs)	Units
Laser	Photo injector Laser	Pulsed Laser	f/36	<80[35μHz, 10MHz]	2
			f/18	<80[35μHz, 10MHz]	1
	Heat Laser	Pulsed Laser	f/36	<100[35μHz, 10MHz]	1
	Seed Laser	Pulsed Laser	f/18	<20[35μHz, 10MHz]	5
	Experimental Laser	Pulsed Laser	f/18	<20[35μHz, 10MHz]	4
LLRF	VHF Gun	CW RF	f/6	<180[10Hz, 10MHz]	2
	Buncher	CW RF	f	<30[10Hz, 10MHz]	2
	1.3GHz SCRF Module	CW RF	f	<30[10Hz, 10MHz]	26x8
	3.9GHz SCRF Module	CW RF	f*3	<30[10Hz, 10MHz]	2x8
Diagnostics	BAM/BLM/LAM	Pulsed Laser	f/6	<10[35μHz, 10MHz]	11
	TDS band	CW RF	f/36*83	<60[10Hz, 10MHz]	4
	TDX band	CW RF	f/9*83	<60[10Hz, 10MHz]	5
	CBPM	CW RF	f	<100[10Hz, 10MHz]	218
Timing	Network switch	CW RF	f/12	<10 ps	1

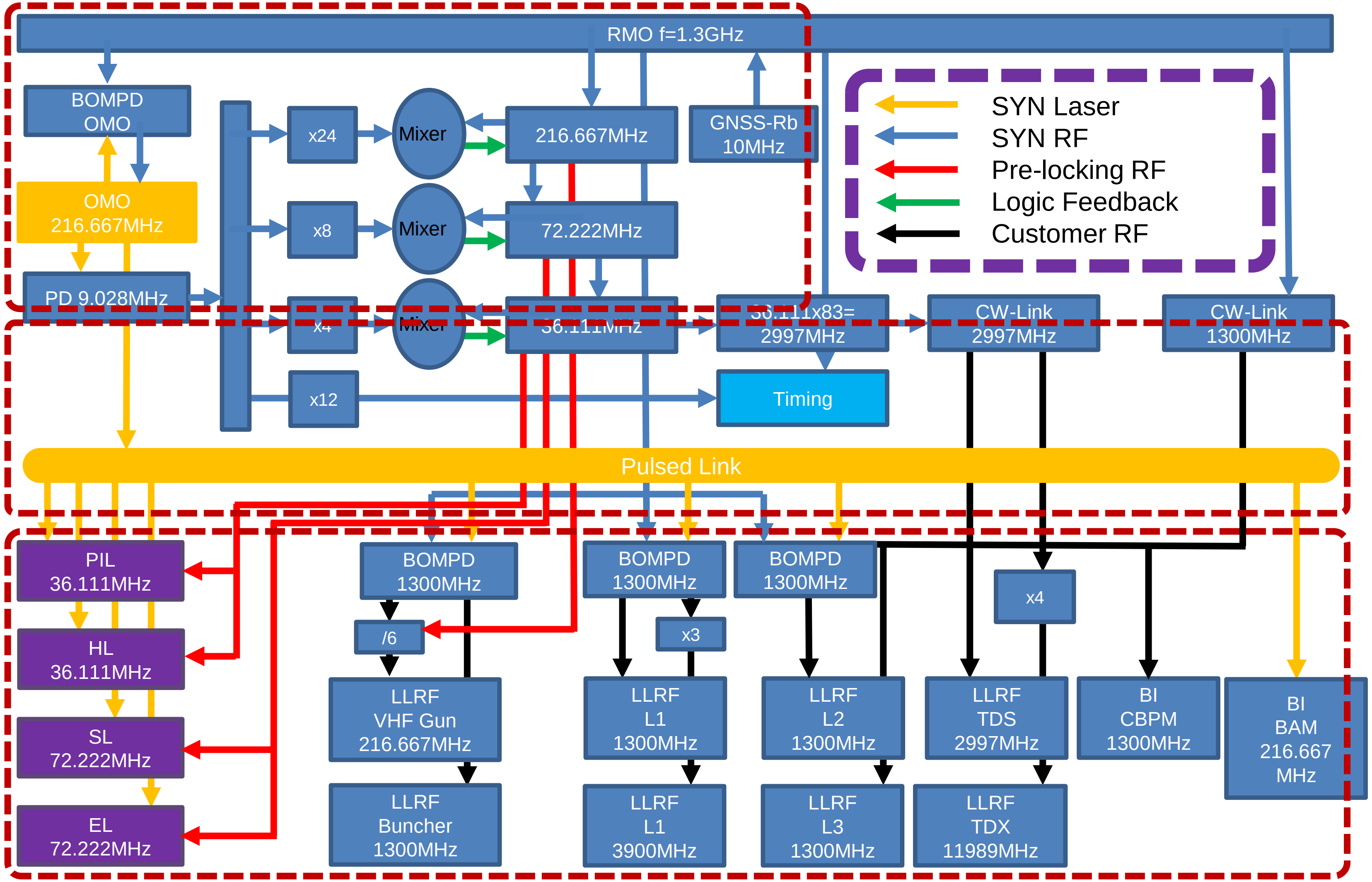
Design of S³FEL Synchronization system

Hybrid SYNC design including pulsed laser link, CW laser link, and temperature stabilized RF link.

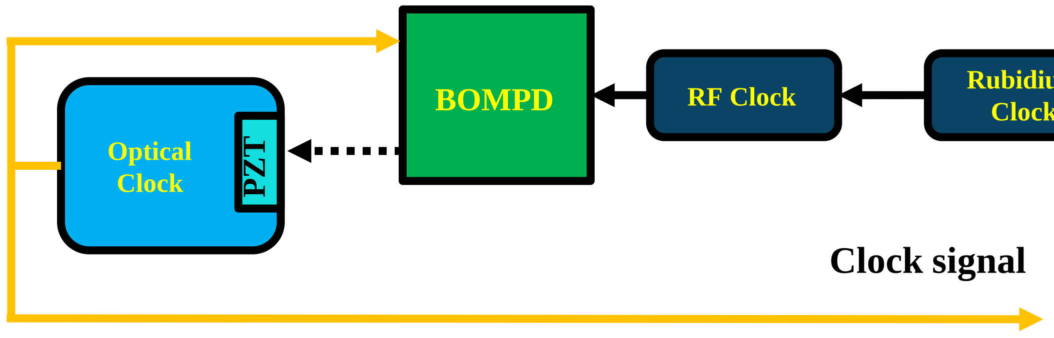
Master clock
Optical clock (OMO)
RF clock (RMO)
GNSS disciplined rubidium clock (GNSS-Rb)

Stabilized reference distribution
Pulsed laser link (PL-Link)
CW laser link (CW-Link)
Temperature stabilized RF link (TS-Link)

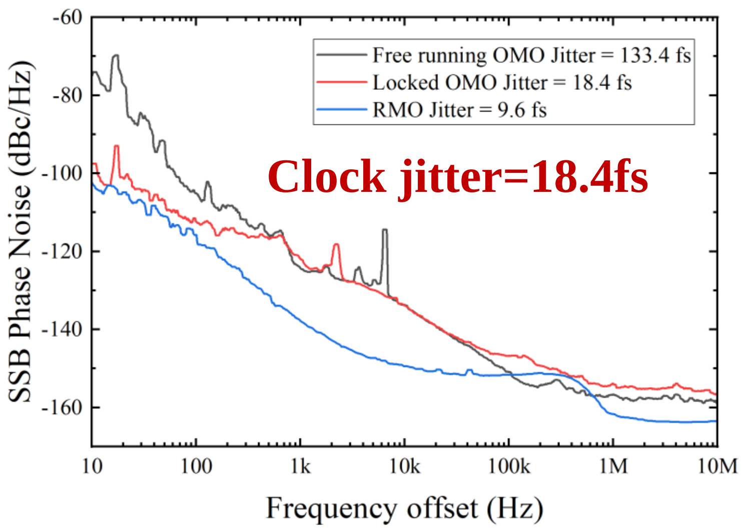
Locking of lasers and RF devices
Laser-to-laser lock (L2L)
Laser-to-RF lock (L2RF)



Master clock



Architecture diagram



Optical Clock

- Commercial osc.
- 216.667 MHz →1.3 GHz/6
- Ultra-low phase noise
- 1550 nm
- 24/7 operation

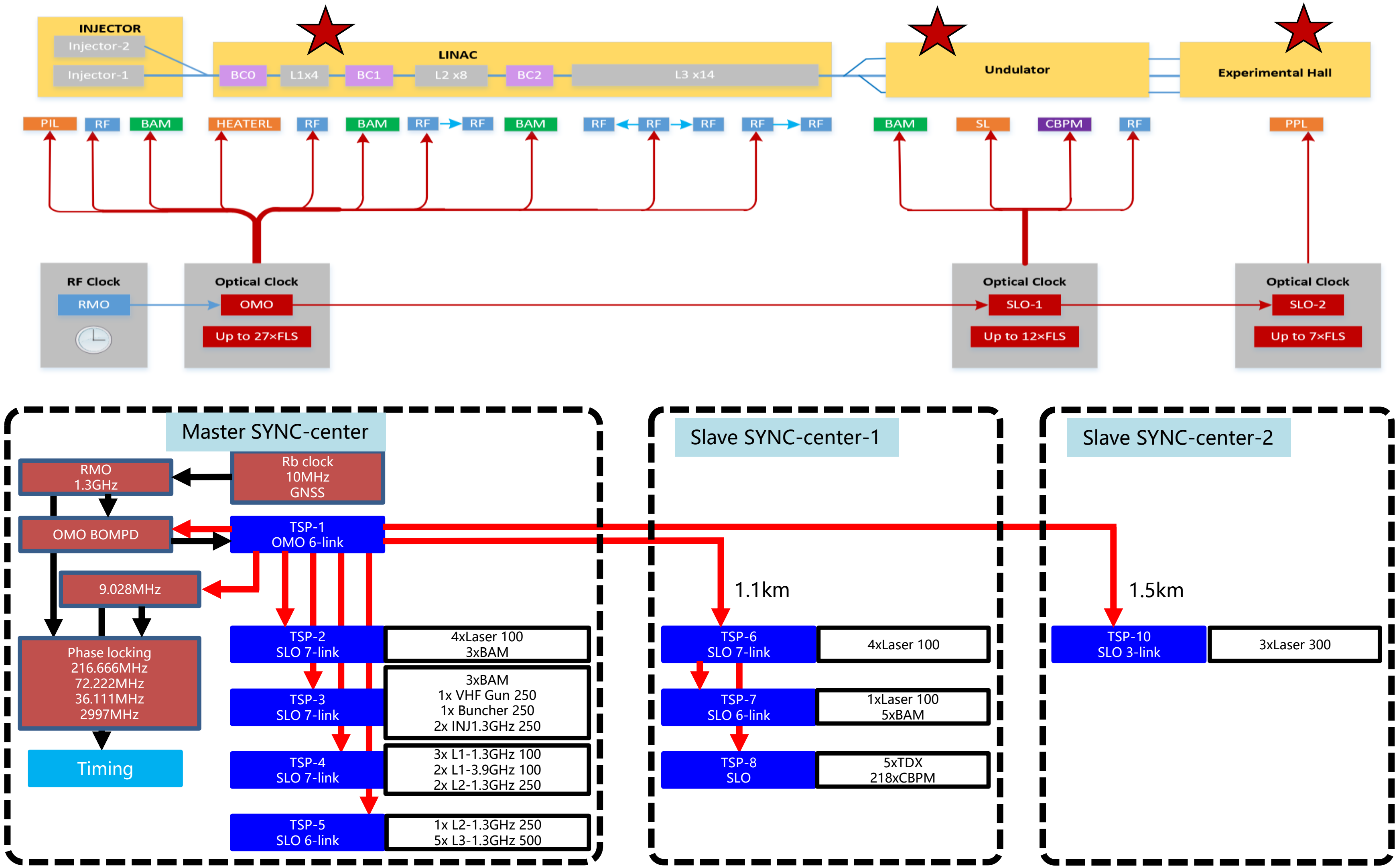
RF Clock

- Commercial osc.
- 1.3 GHz
- Ultra-low phase noise
- 24/7 operation

Master clock has been built with jitter better than 18.4 fs.

Stabilized reference distribution

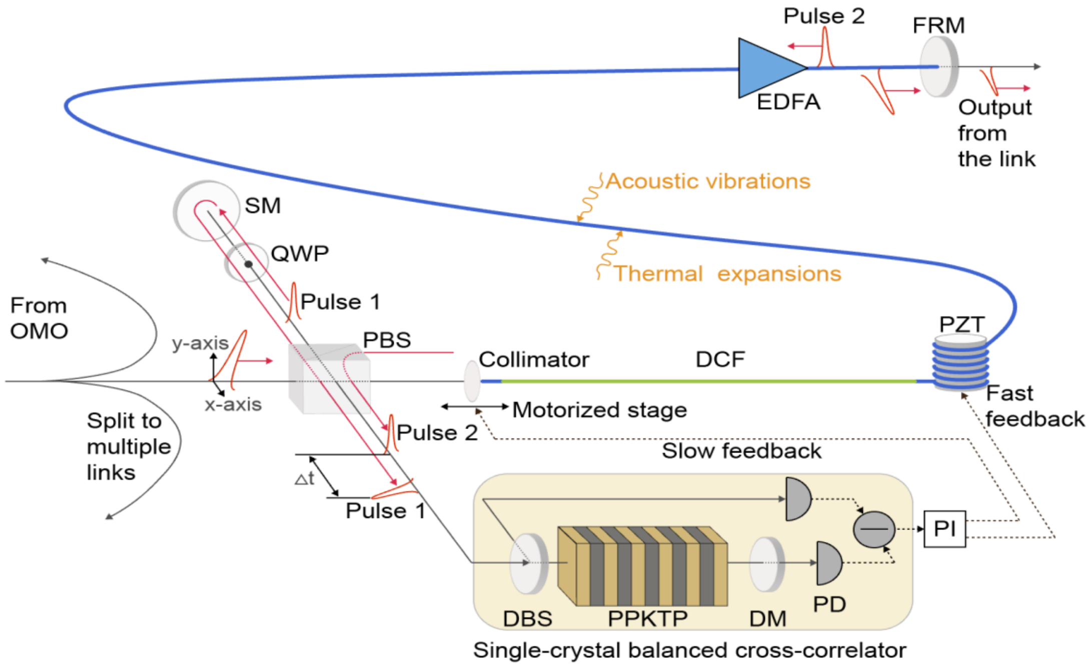
The topological structure of SRD network based on pulsed laser link.

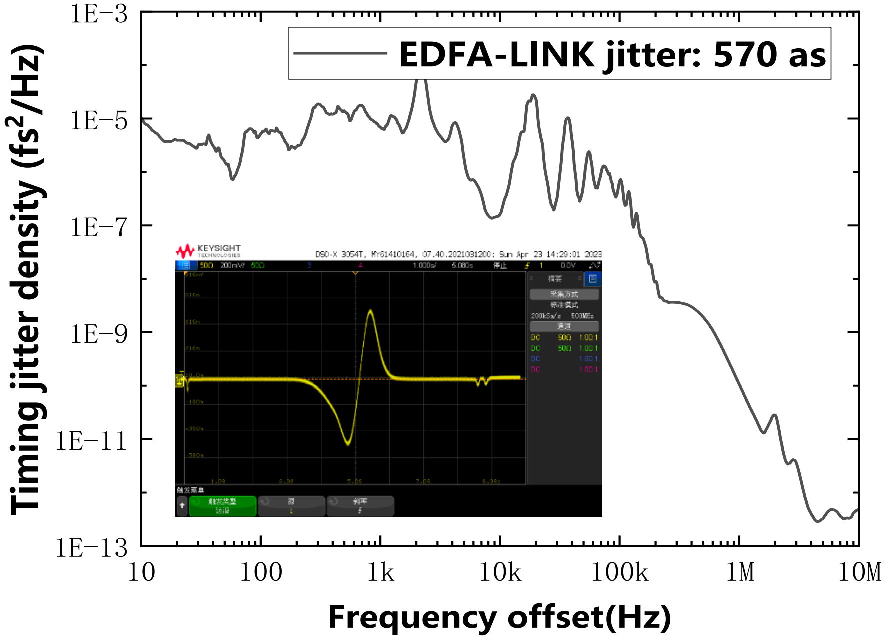


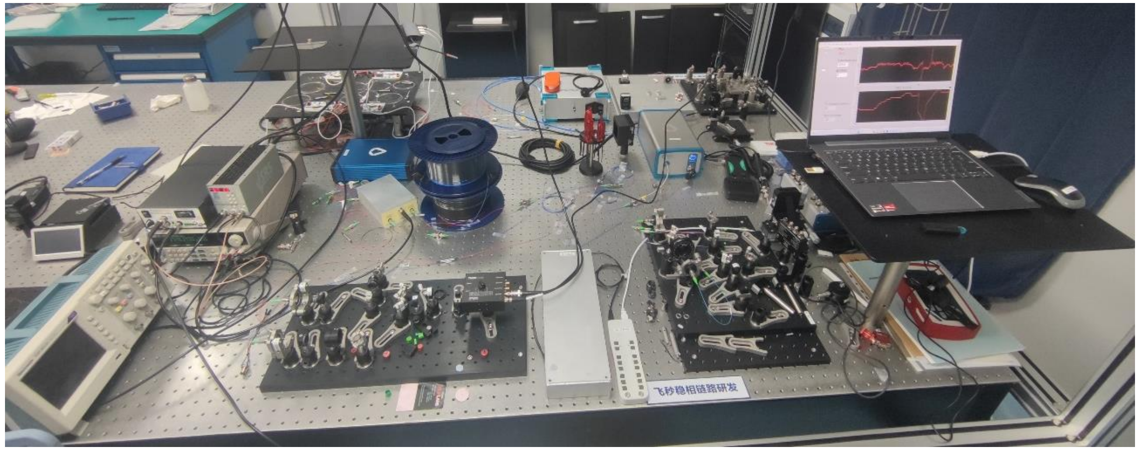
Pulsed laser link

Timing error detection & correction

- Balanced optical cross-correlation(BOC)
- Insensitive to laser pulse fluctuations
- Slope 15 mV/fs
- Piezo-based fiber stretcher BW~5 kHz





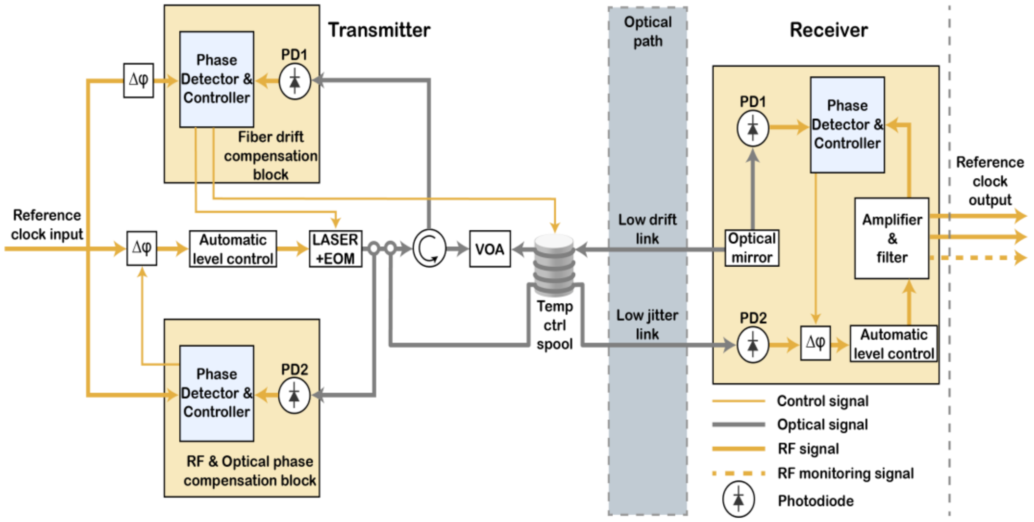


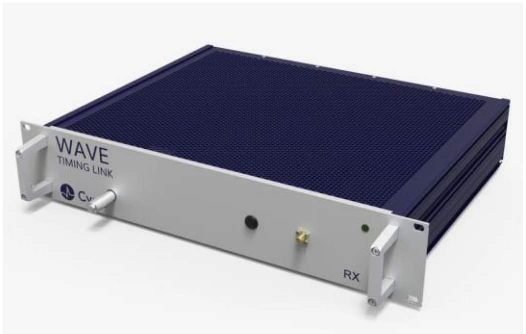
Demo PL-Link has been built with sub-fs jitter (in loop) & a few fs drift per day.

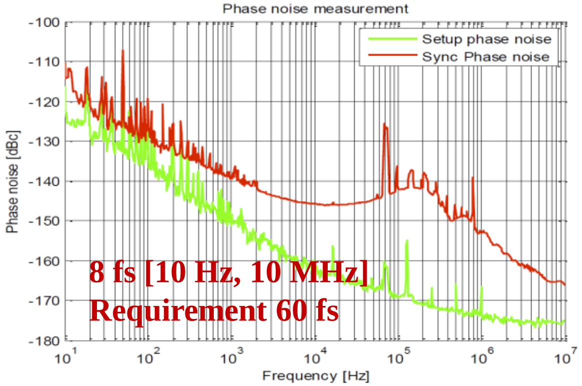
CW laser link

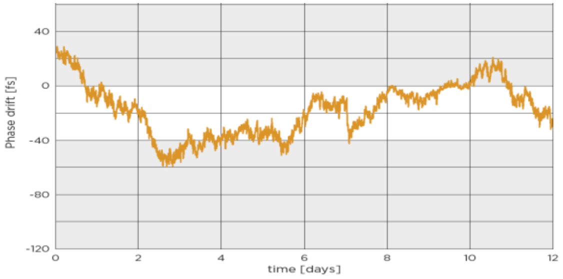
CW laser link

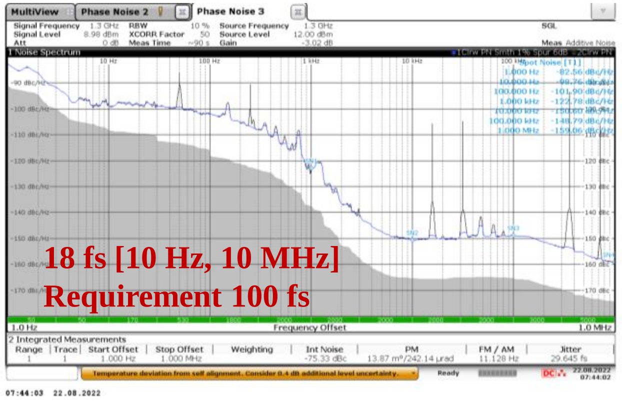
- Commercial CW laser link
- Low additive jitter & drift
- SYNC3 @ 2.6 GHz for TDS & TDX
- Wavelink @ 1.3GHz for CBPM

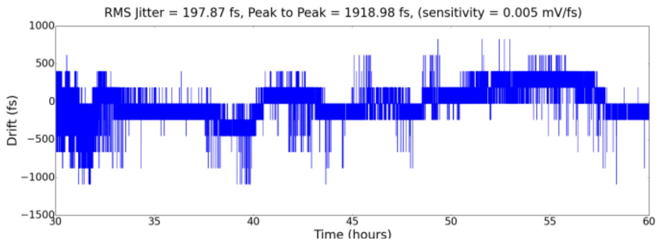










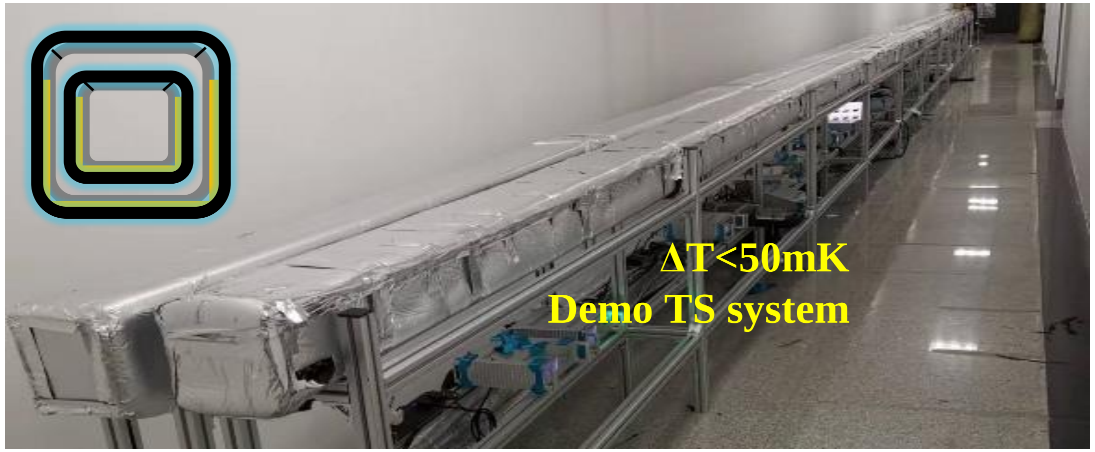


CW-Links are tested by companies and meet requirements of some of the devices of S^{3}FEL.

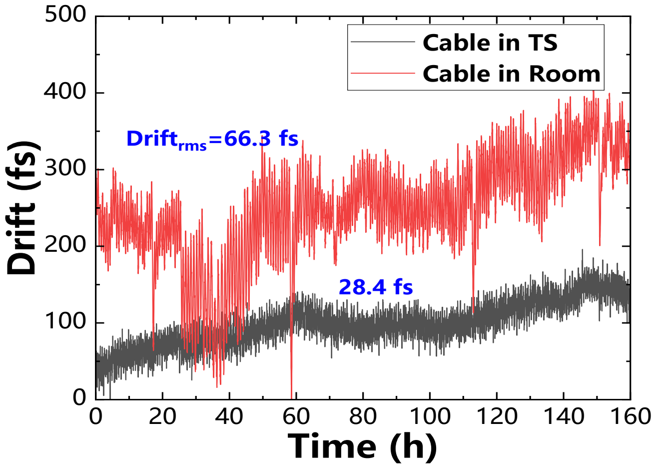
Temperature stabilized RF link

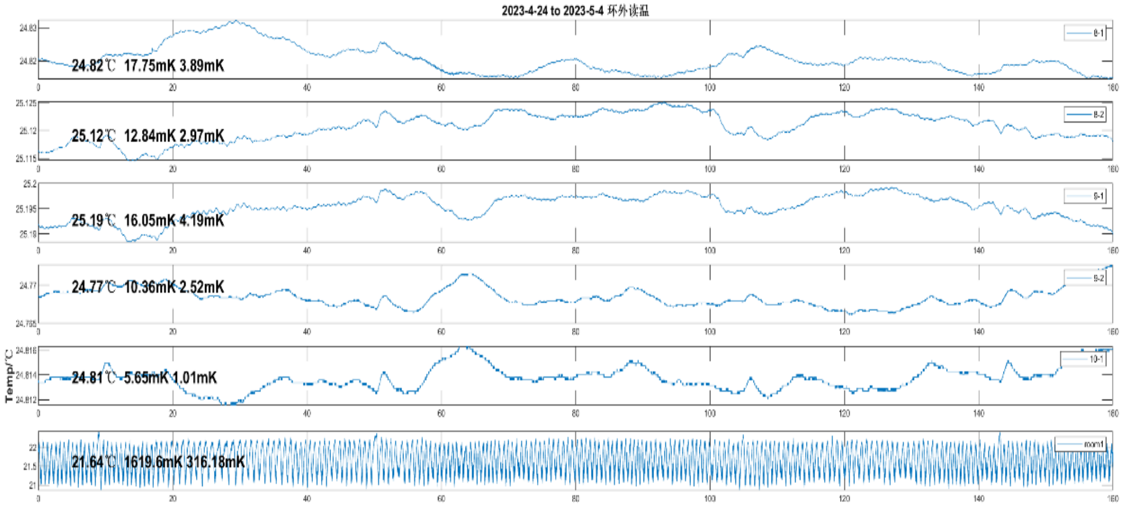
Temperature stabilized system

- 0.1 mK sensitivity
- PID feedback
- Double-layer thermal control system
- Internet setting, monitor, and data recording



TS-Link with 10-meter cable



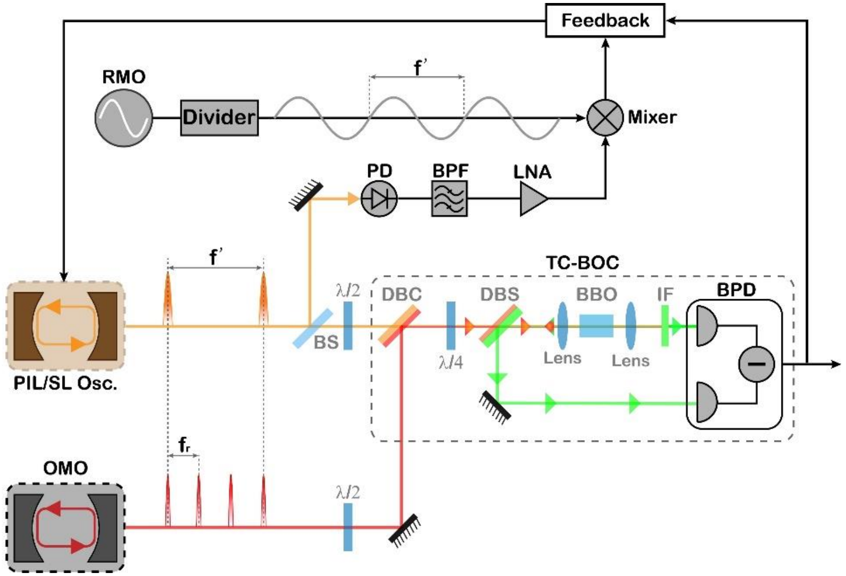


RF reference is distributed over TS-Link with less than 30 fs drift .

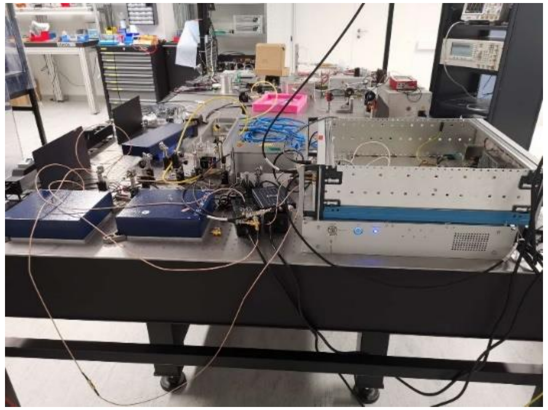
Synchronization of lasers

Laser-to-Laser Lock

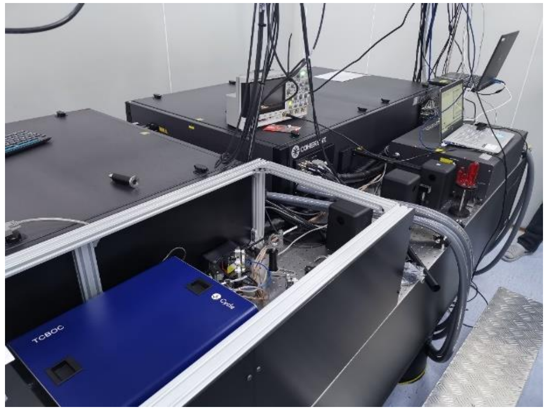
- Two-color balanced optical cross-correlation(TCBOC)
- RF Pre-lock function
- Insensitive to laser pulse fluctuations
- Slope 10 mV/fs
- Piezo-based feedback BW~5 kHz

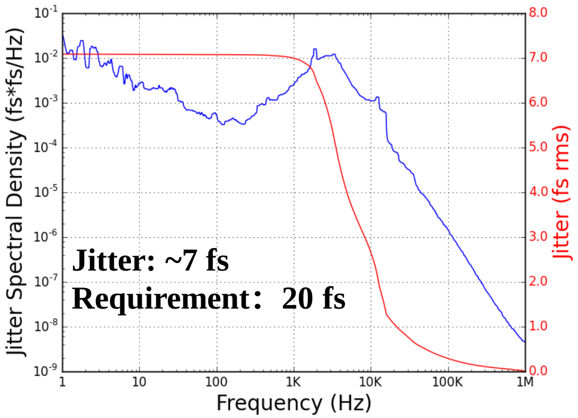


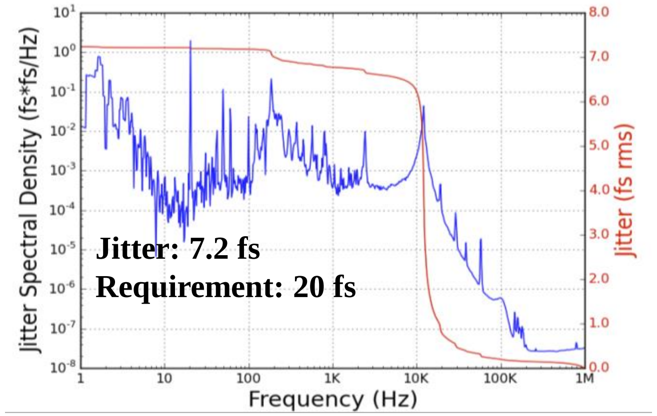
Mode-Locked fiber laser @1030nm



Mode-Locked Solid-State laser @800nm





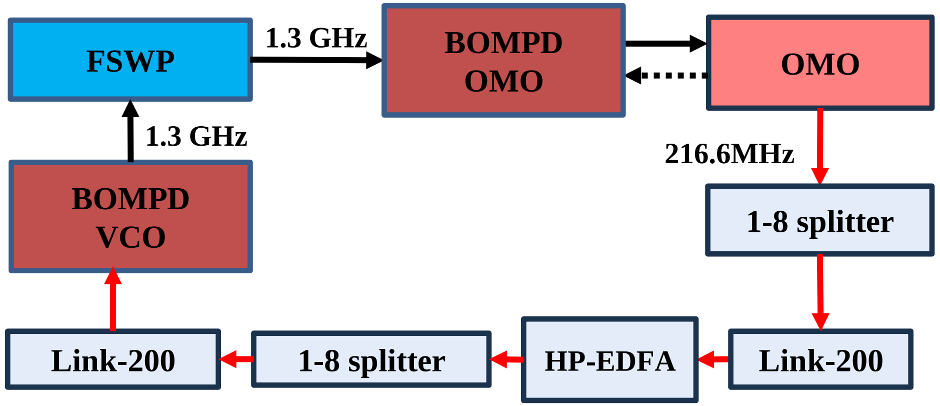


Locking of lasers has been tested and meet PIL, HL, SL, and PPL requirements.

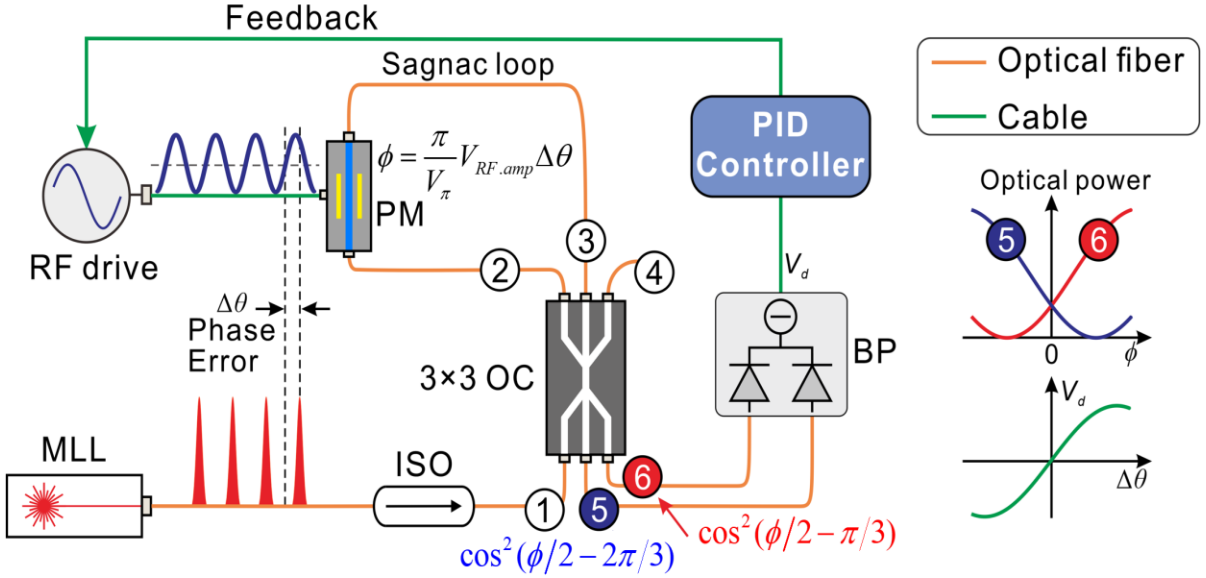
Synchronization of RF clients

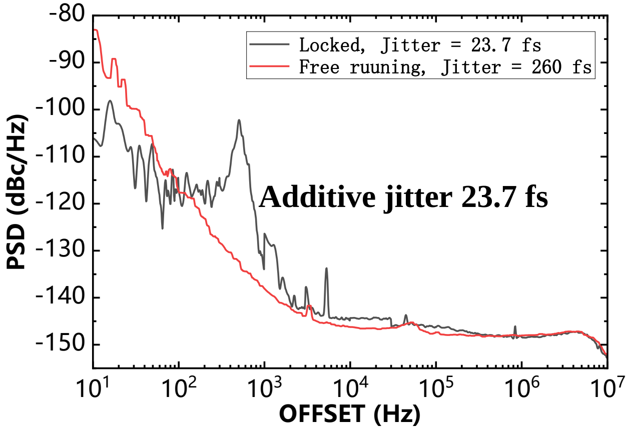
Laser-to-RF Lock

- Balanced optical-microwave phase detector (BOMPD)
- Insensitive to laser pulse fluctuations
- Slope 1 mV/fs
- Locking BW~5 kHz



Additive noise testing

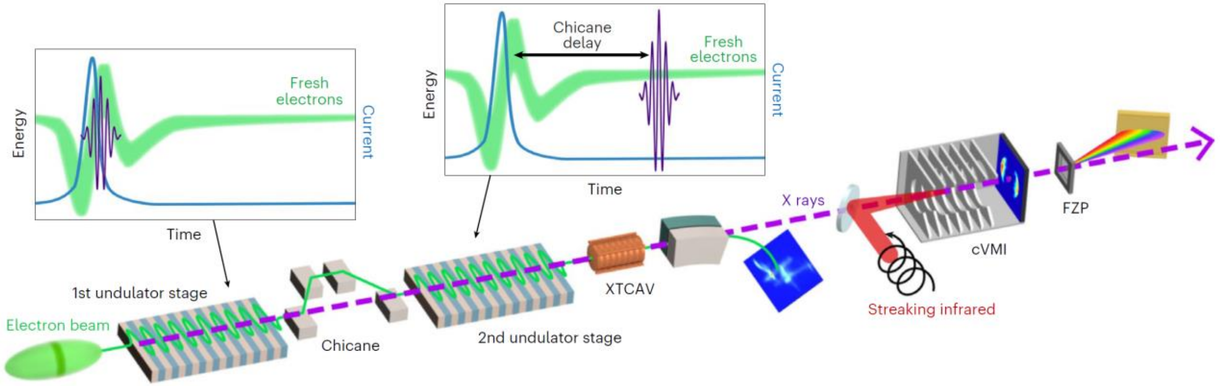




Locking of RF devices has been built and its performance is better than requirements.

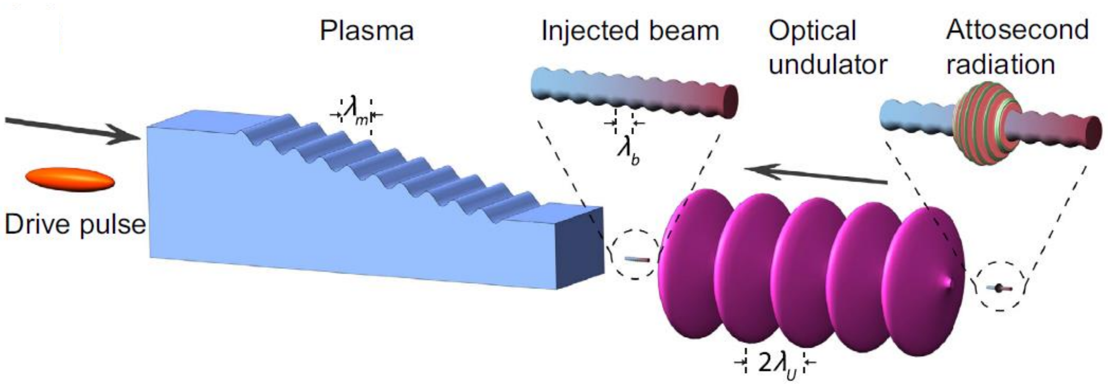
Requirement of 1 fs/ sub-fs Synchronization System

Terawatt-scale attosecond X-ray pulses from a cascaded superradiant free-electron laser



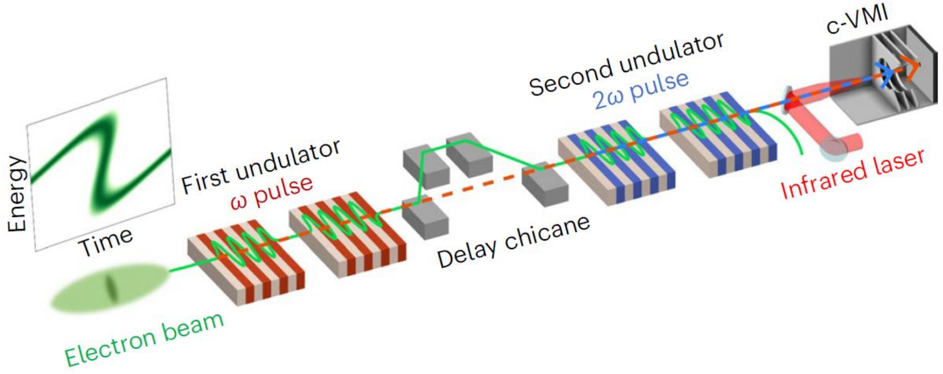
P. Franz et al. Nature Photonics 18, 698 (2024).

Attosecond x-ray free-electron lasers utilizing an optical undulator in a self-selection regime



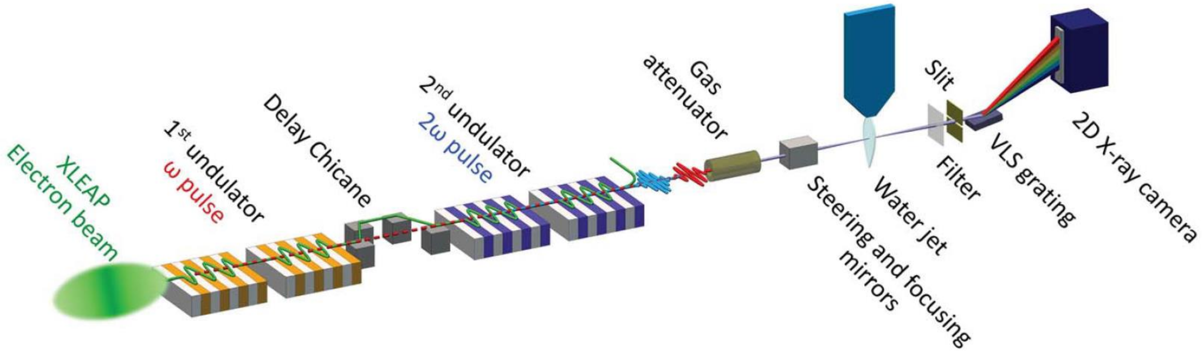
X. Xu et al. Phys. Rev. Accel. Beams 27, 011301 (2024).

Experimental demonstration of attosecond pump–probe spectroscopy with an X-ray free-electron laser



Z. Guo et al. Nature Photonics 18, 691 (2024).

Attosecond-pump attosecond-probe x-ray spectroscopy of liquid water



S. Li et al. Science 383, 1118 (2024).

Requirement of 1 fs/ sub-fs Synchronization System

Synchronization ability

1 ps	100 fs	10 fs	1 fs ?
2000	2010	2020	2030

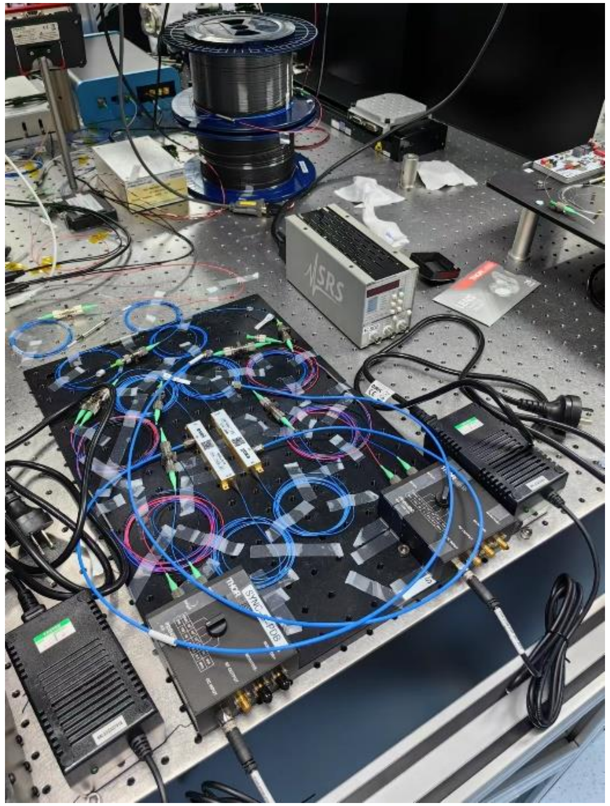
$$Total\ Jitter = \sqrt{Jitter^2 + Drift^2}$$

Jitter~ 1 fs [10 Hz, 10 MHz], OK

Drift ~10 fs [35 uHz, 10 Hz], (40 fs/m/℃)

Technology Strategy

- Temperature stabilization with ~mK level
- Micro-optics design / Optical chip
- Cross-system coupling: LLRF-SYNC, Laser-SYNC



A Big Challenge with Exciting Future !

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Thanks for attention

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