Shenzhen Superconducting Soft-X-Ray Free Electron Laser (S^3FEL)

Weiming Yue （on behalf of Weiqing Zhang ）

S^3FEL team

深圳综合粒子设施研究院

Institute of Advanced Science Facilities, Shenzhen

Project overview

Project name	Shenzhen Superconducting Soft-X-Ray Free Electron Laser (S^3FEL)
Construction unit	Institute of Advanced Science Facilities, Shenzhen
	Shenzhen Guangming Science City Development and Construction Co., Ltd
Construction site	Guangming District, Shenzhen (Guangming science city, cluster of facilities)
Construction scale	Total area of ~220,000m^2
Construction period	6 years
Status	Approved on May 2023

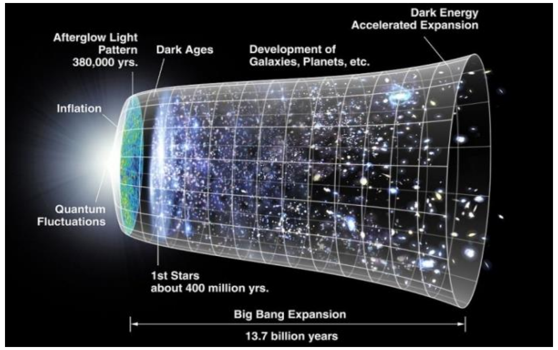
Importance of high-brightness advanced light source

- 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.

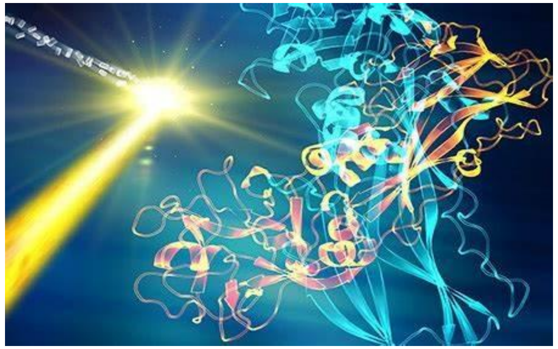
- High-brightness light source (such as laser technology) pave a way for the development of modern revolutionary technology.

Various scientific applications

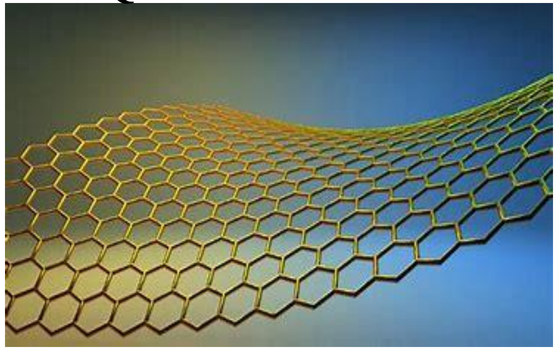
Interstellar science



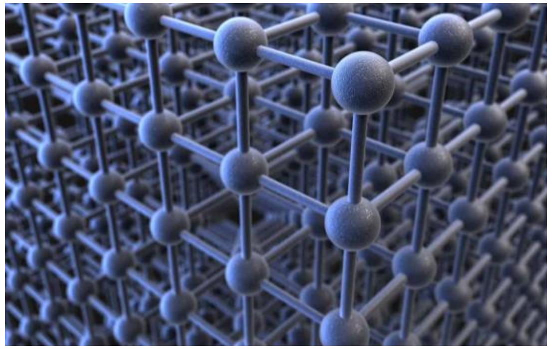
Biomedicine



Quantum materials



Information materials

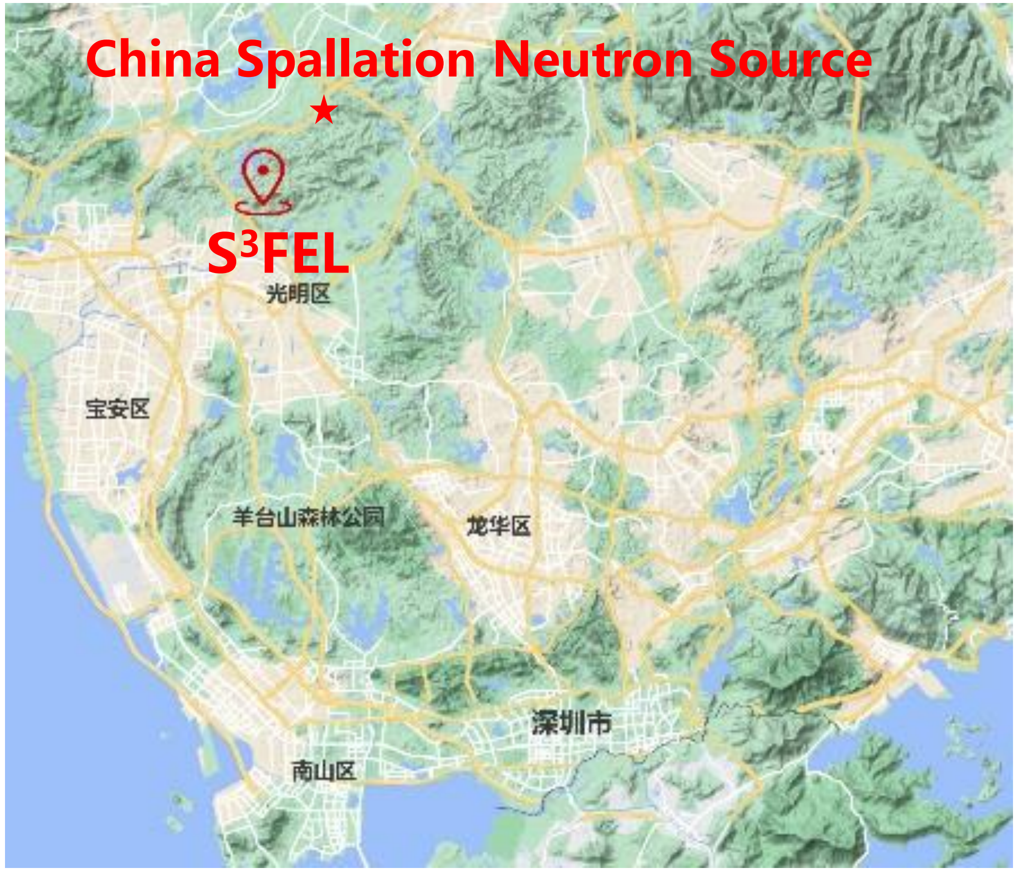


Worldwide FELs

Facility	Wavelength	Country	LINAC	Beam energy /GeV	Photon energy	Rep. rate/Hz	Staues
FLASH	Soft X-ray	DE	SRF	1.25	14 - 300 eV	5000	operation
European XFEL	Hard X-ray	EU	SRF	17.5	8.4 - 30 keV	27,000	operation
LCLS-II	Hard X-ray	US	SRF	4	0.2 - 5 keV	1,000,000	commissioning
SHINE	Hard X-ray	CN	SRF	8	0.4 - 25 keV	1,000,000	Under construction
S^3FEL	Soft X-ray	CN	SRF	2.5	0.04 - 1 keV	1,000,000	Approved

Where is Shenzhen?

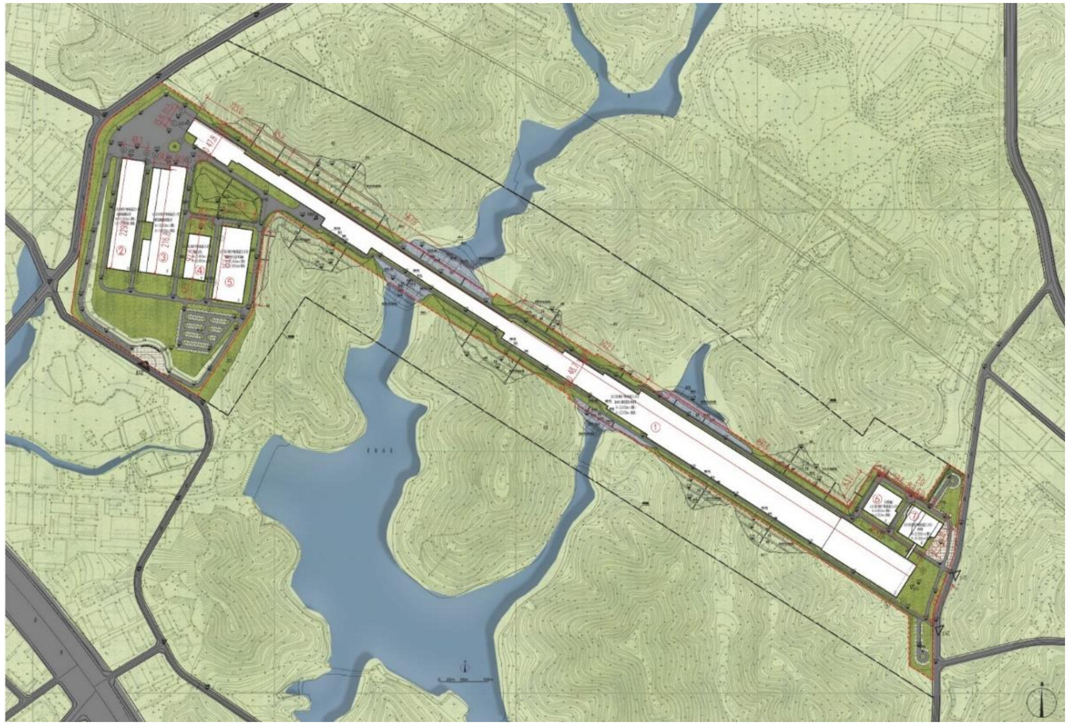
Guangming Science city

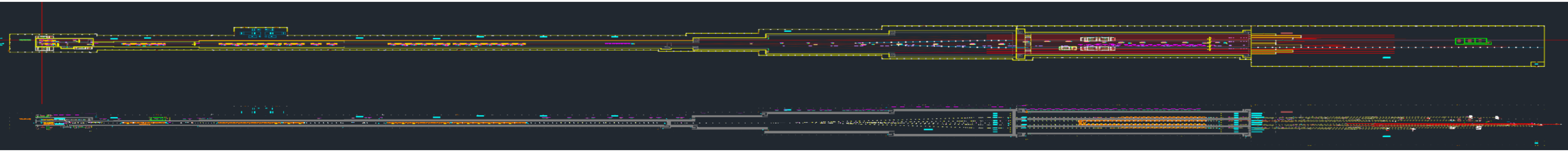


Guangming Science City, which is situated in the northwest of Shenzhen, is located at an important node of the Guangdong-Hong Kong-Macao Greater Bay Area and the Guangzhou-Shenzhen-Hong Kong-Macao Science and Technology Innovation Corridor. Bounded by Longda Expressway in the west, Guangming Science City reaches out to the boundary between Shenzhen and Dongguan in the north and the boundary of Guangming District in the southeast to occupy a planned area of 99 square kilometers.

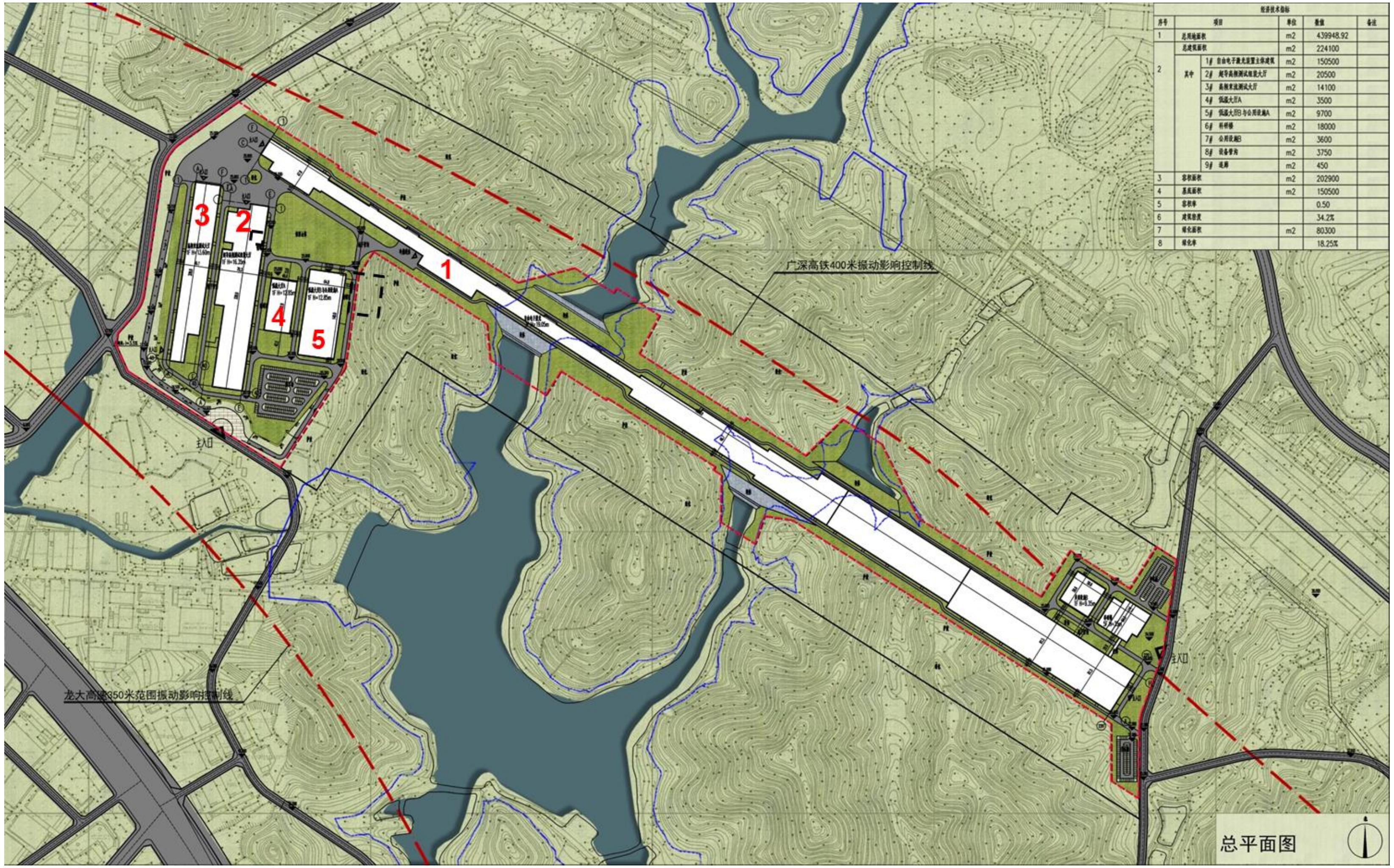
We will focus on building large-scale scientific facilities and establishing research institutes and institutions of higher education.

Location and Layout





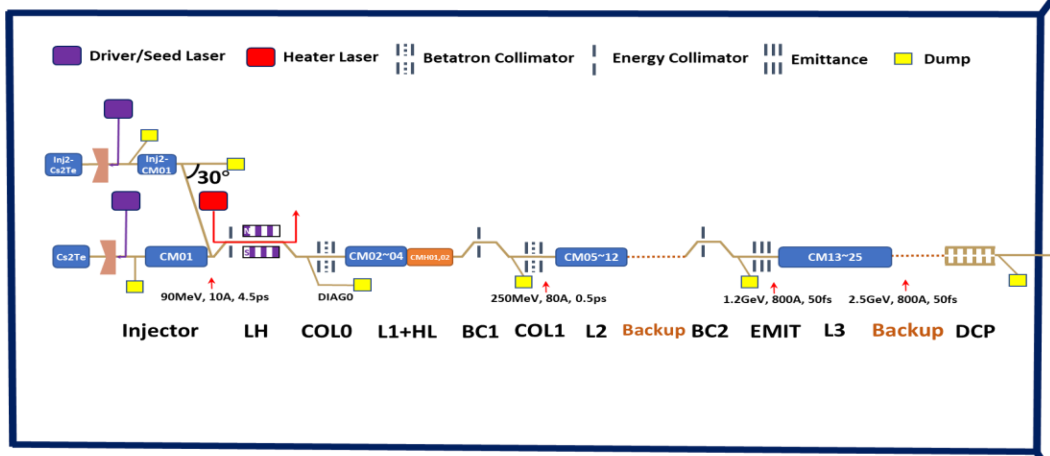
Campus overview

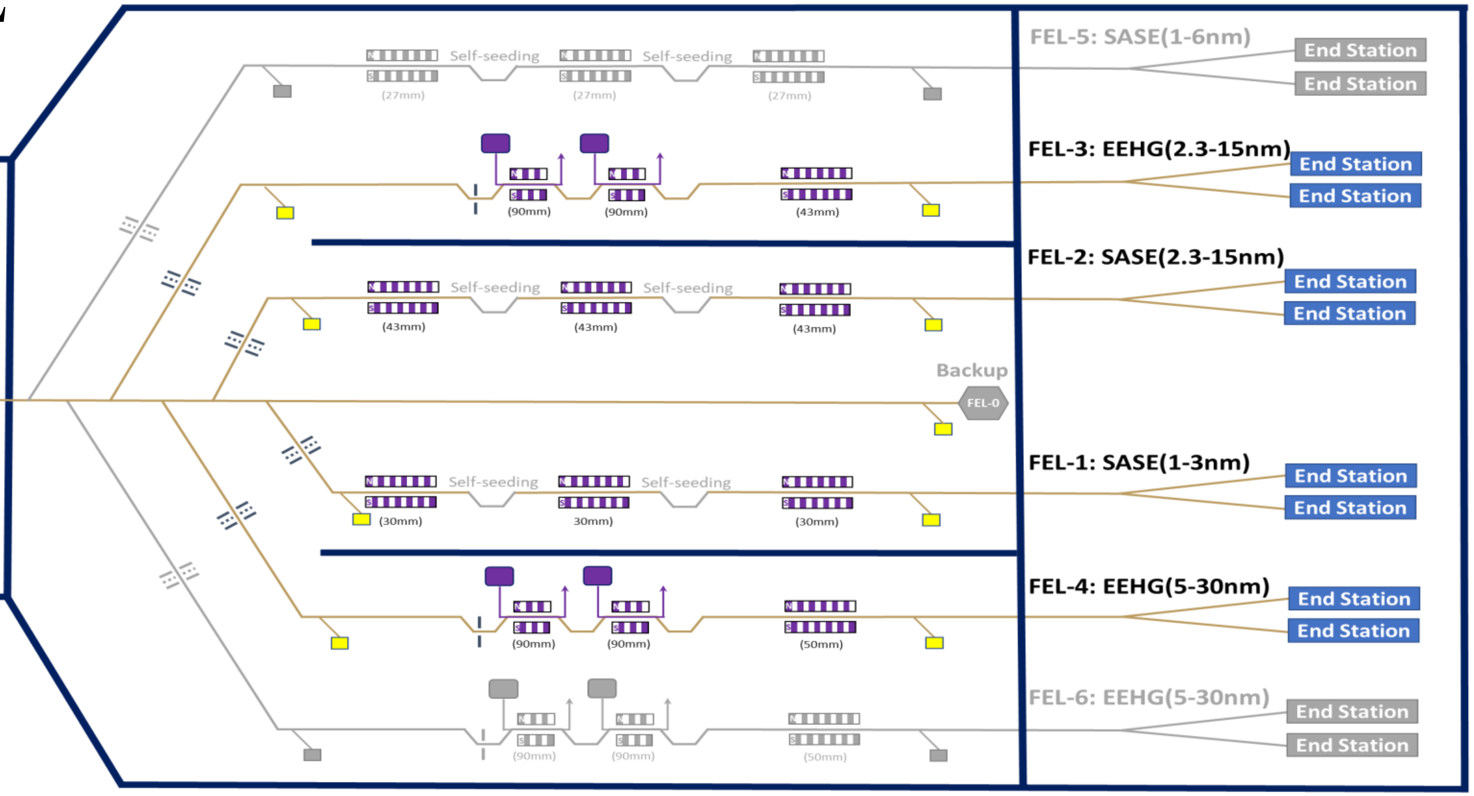


No.	Naming
1	S^3FEL hall
2	SMTF hall
3	PATF hall
4	Cryo-hall A (TFCP & PACP WCS)
5	Cryo-hall B (ACCP WCS)

S3FEL Layout

MHz repetition-rate soft X-ray FEL

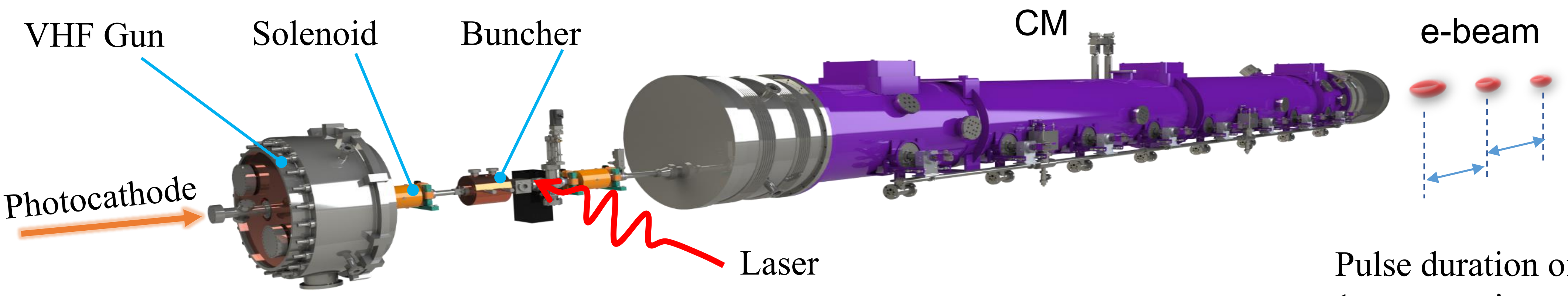




Parameter	Design
Beam energy/ GeV	2.5
Charge/ pC	100
Emittance/ mm-mrad	0.5
Rep. rate/ MHz	1
FEL wavelength/ nm	1-30

Injector

Function: Generate MHz repetition-rate, high quality and high brightness electron beam

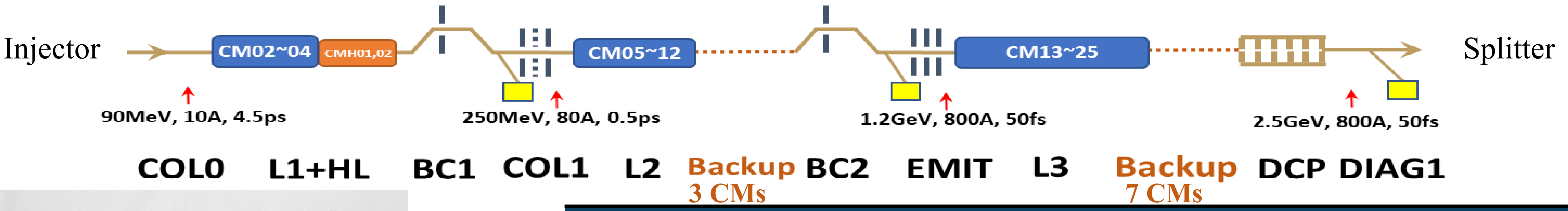


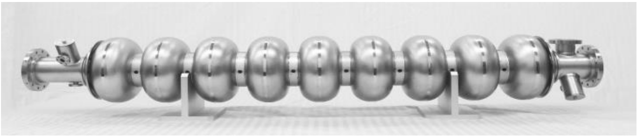
Pulse duration of ~10 ps with 1us separation

Parameter	Design	Range	Unit
Energy	90	70-120	MeV
charge	100	10-300	pC
bunch length （rms）	4.5	1-9	ps
Current	9	4-50	A
emittance	0.5	0.2-1.0	mm·mrad
energy spread	1	1-5	keV
repetition rate	1	0-1	MHz

LINAC design

Function: accelerate the electron beam, compress the beam length and increase the peak current intensity





1.3GHz cryomodule:
26 sets, energy acceleration

3.9GHz cryomodule:
2 sets, linear compression compensation

Parameter	Design	Range	Unit
energy	2.5	1.0-2.5	GeV
charge	100	10-300	pC
bunch length （rms）	50	10-100	fs
current	800	200-1000	A
emittance	0.5	0.2-1.0	mm·mrad
energy spread	400	250-500	keV
rep. rate	1	0-1	MHz

1.3 GHz CM Technical Requirements

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Parameter	Design Value	coment
Overall accelerate Voltage	≥ 128 MV	CW
Dark current	< 1 nA	
Static heat load	< 10W @ 2 K	
Dynamic heat load	< 110 W @ 2 K	@ 128 MV
Beam vacuum	1.3 × 10^{-8} Pa	@ 2 K
Insulation vacuum	1.3 × 10^{-4} Pa	@ 2 K
Remanence	< 5 mGs	
Operation frequency	1.3 GHz	
Operation temperature	2 K	
E_{acc}	≥ 16 MV/m	
Q_0	≥ 2.7 × 10^{10}	@ E_{acc} =16 MV/m
Misalignments (X、Z)	0.5 mm	internal
Q_{ext} of FPC	4.1 × 10^7	4.0 × 10^6 - 1.1 × 10^8
Max. Power	7 kW	CW
Tuning range of slow tuner	(exp/max) 250/450	With 1-2 Hz resolution
Tuning range of piezo	> 1 kHz	With 1 Hz resolution
Amp. stability	0.01% (RMS)	
Pha. stability	0.01 deg (RMS)	
BPM position resolution	200 µm	@10pC
BPM charge resolution	1 pC	

The deviation of the X/Y/Z directions of the internal components of the cryomodule relate to the cryomodule itself

Error Source	RMS error	unit
Cavity X,Y misalignments	0.5	mm
Quadrupole X,Y misalignments	0.5	mm
BPM X,Y misalignments	0.5	mm
Cavity Z misalignments	2	mm
Quadrupole Z misalignments	2	mm
BPM Z misalignments	2	mm

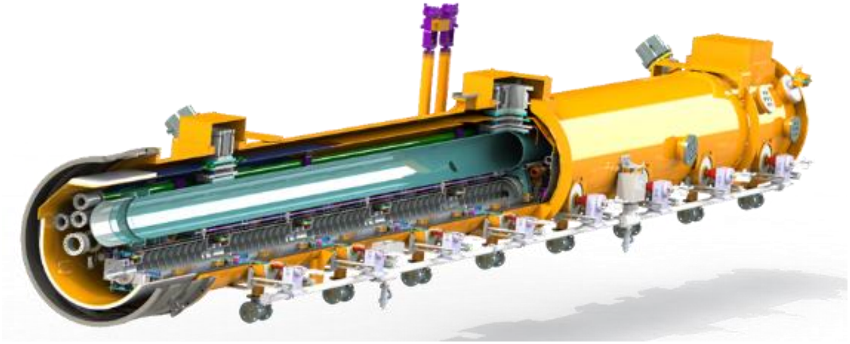
Cryomodule internal components XZ/YZ relative cryomodule tilt or axis deviation

Error Source	RMS error	unit
Cavity tilt misalignments	0.5	mrad
Quadrupole tilt misalignments	3	mrad
BPM tilt misalignments	3	mrad
Cavity roll misalignments	10	mrad
Quadrupole roll misalignments	3	mrad
BPM roll misalignments	3	mrad

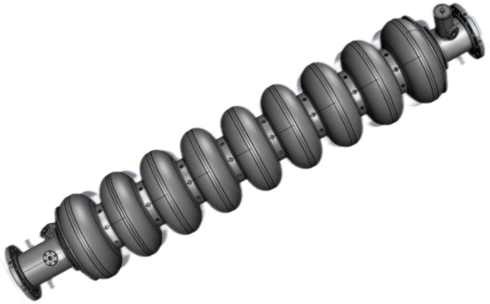
Cryomodule relative accelerator misalignment deviation, tilt or axis deviation

Error Source	RMS error	unit
Cryomodule X,Y misalignments	0.3	mm
Cryomodule Z misalignments	2	mm
Cryomodule tilt misalignments	0.05	mrad
Cryomodule roll	2	mrad

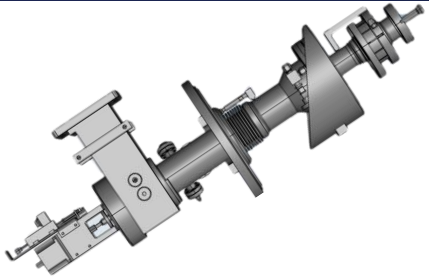
SRF cavity overview for S³FEL



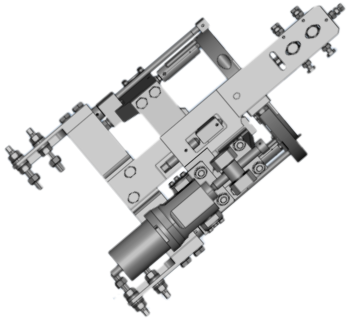
26 × 1.3 GHz CM



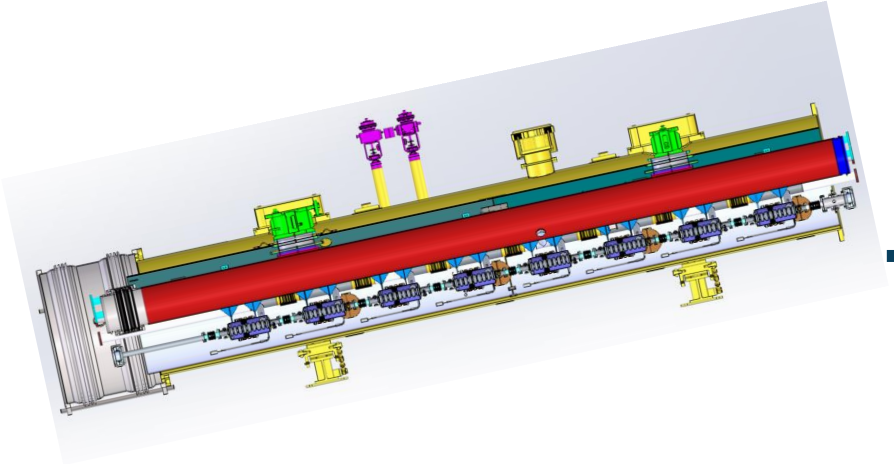
208 × 1.3 GHz Cavity



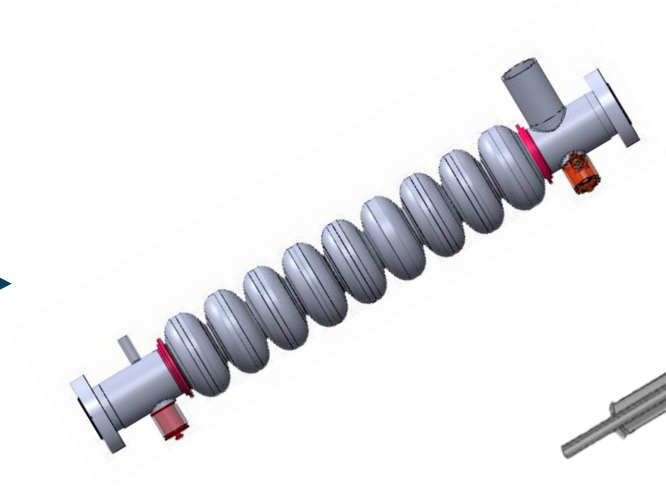
208 × 1.3 GHz Coupler



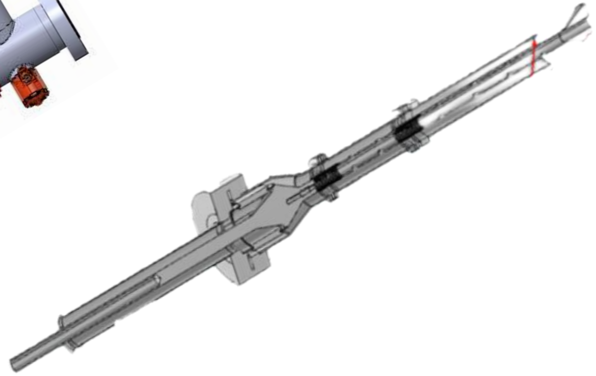
208 × 1.3 GHz tuner



2 × 3.9 GHz CM



16 × 3.9 GHz Cavity



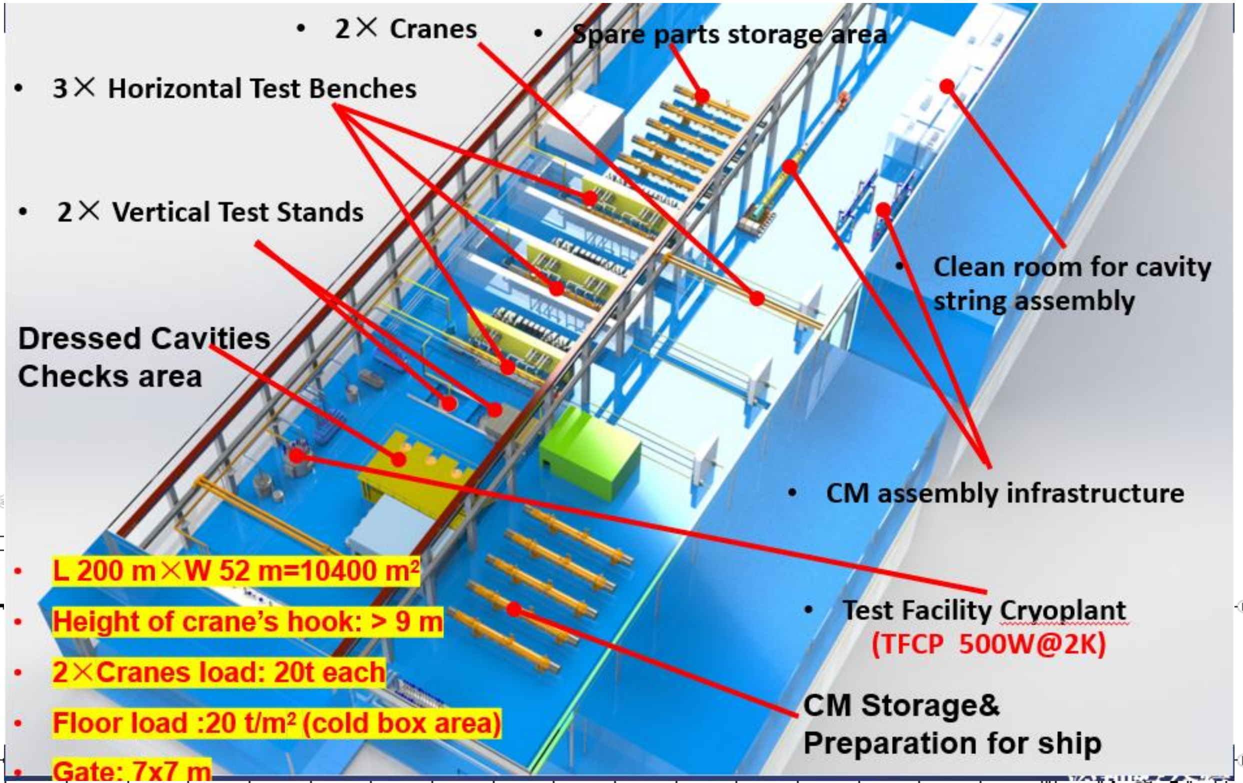
16 × 1.3 GHz Coupler

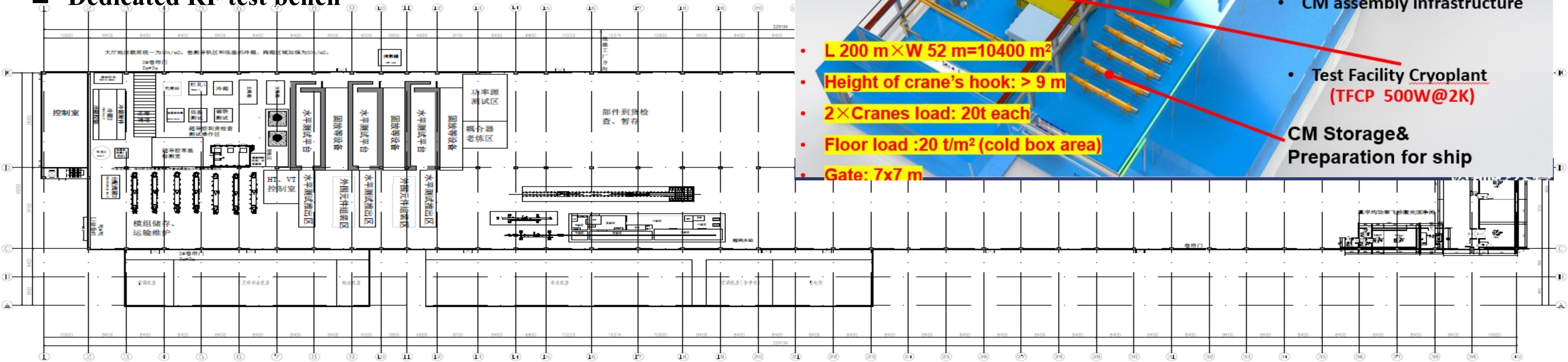
16 × 1.3 GHz tuner

HanLi (IASF), MOPMB080

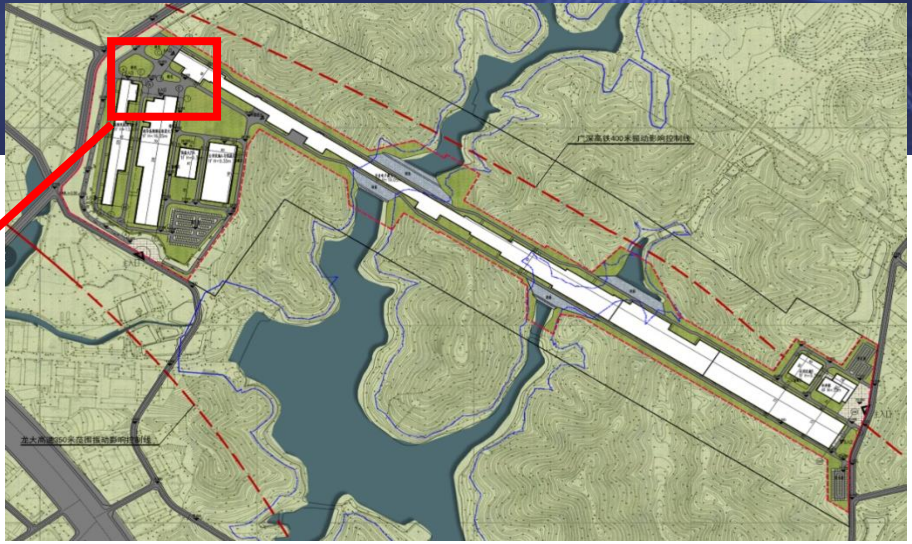
SRF Module Test Facility (SMTF)

- 2 × Vertical Test Cryostats (VTC)
- 3 × Cryomodule Test Benches (CMTB)
- 1 × Magnet test bench
- 1 × Clean room infrastructure
- 1 × Multipurpose cryo-test Facility
- Cryomodule assembly and integration bench
- Dedicated RF test bench





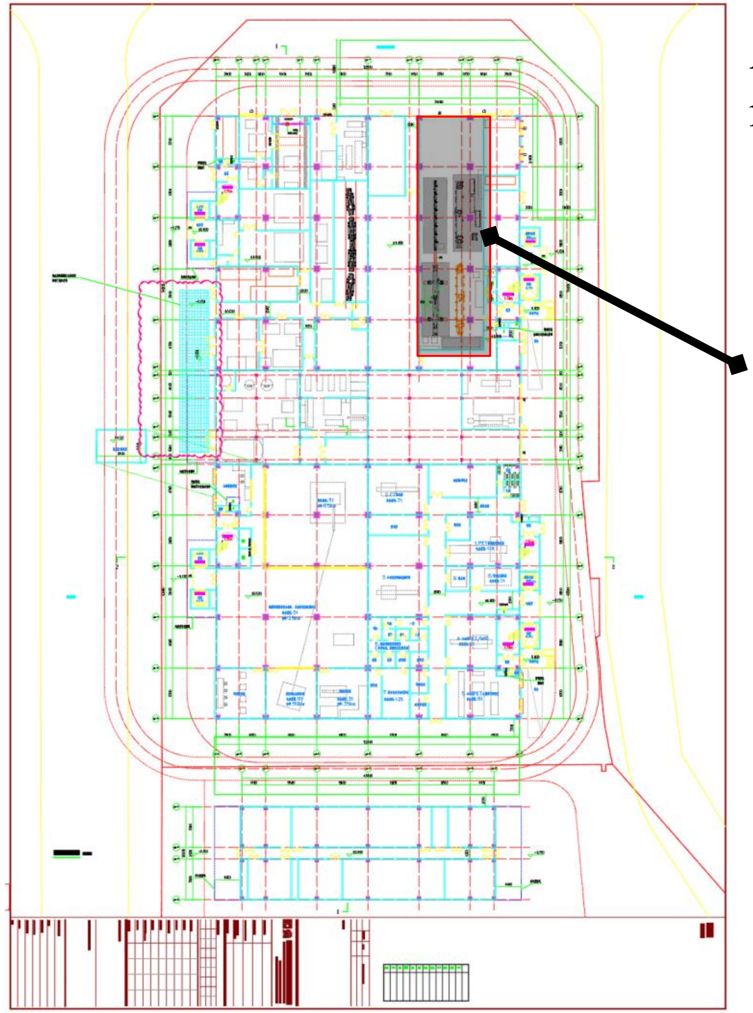
Current situation of S^{3}FEL



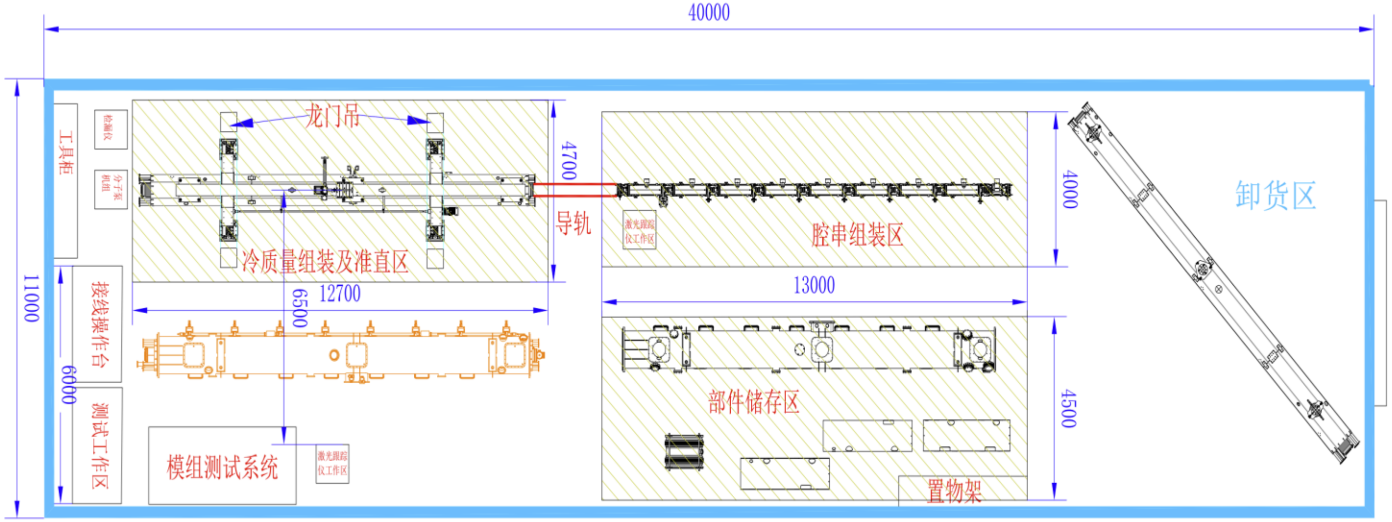
Construction of the first building (office) for S^{3}FEL is done in 09/2022.

Civil engineering construction for Linac will be started soon.

Temporary Lab for S^3FEL R&D work



A temporary experiment hall has been proved by Shenzhen government to support FEL related experiment before the readiness of SMTF.



~ 500 m²

International communication

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Institute of Advanced Science Facilities, Shenzhen

Preliminary Design Review (PDR)
S^3FEL Superconducting LINAC
15-16 June 2021

Summary of Recommendations

- Anticipate 3.9 GHz completion for enabling early injector operation
- Try to enable operation of injector before linac, enable cryo separation and provide a beam dump for its operation
- Provide an overall workflow from cavities to tested cryomodules, forecasting the necessary rework operations from previous projects, 100% success-oriented plans are bound to miss milestones
- Provide an integrated list of high-level machine parameters and derived acceptance criteria
- Ensuring R&D program for achieving reliable high-Q cavity performances in cavity VTs and cryomodule tests would be necessary before starting mass-production of cavities and cryomodules.
- Young staffs should actively join all of SRF works at IHEP, SHINE, IMP and PKU in the preparatory stage before completion of on-site infrastructures at Shenzhen.

Concluding Remarks

- **Shenzhen Laboratory should participate in the Tesla Technology Collaboration in the early stage, and the SRF activities for constructing S3FEL should be reported in order to obtain understanding and cooperation by the worldwide SRF community.**
- **Since several large SRF projects are under construction in China with limited talent pool and their own priorities, and considering the Shenzhen IASF a newly established accelerator lab and the tight schedule of S3FEL project, it is suggested to build as soon as possible an official collaboration frame with clear definition of the role of each partner institute/laboratory, in order to get more real support and resources.**

S^3FEL SRF accelerator preliminary design review, 15-16 June 2021

S^3FEL Cryogenic system preliminary design review, 2 May 2021

Report on the Preliminary Design Review
of the S3FEL Cryogenic System

P. Arnold, H.-S. Chang, G. Gistau-Baguer, W. Hees, E. Kako,
F. Millet, H. Nakai, D.S. Park, B. Petersen, S. Yoon, J. Weisend,

May 2, 2021

General Comments

The preliminary design review (PDR) of the S3FEL Cryogenic System was held April 27 -28, 2021.

The committee was very impressed by the quick progress made so far on the S3FEL project. The talks presented were clear and at an appropriate level of detail for a preliminary design review. There remains the need for separate detailed design reviews for many of the components, particularly the various valve and distribution boxes of the distribution system. The committee was only able to make high level evaluations of these components.

The schedule is aggressive in particular for the release of specifications. Thought should be given to staging the work in series rather than doing everything in parallel. Priority should be given to the TFCP and PACP with procurement of the CDS and ACCPs delayed until later.

The committee generally agrees with the design choices made, sees no significant technical issues, and believes that the project can move forward into procurement in an appropriately staged manner.

In terms of organization; having the cavity, cryomodule and cryogenics staff all in the same group is a good practice and a significant advantage. This approach should minimize interface and optimization problems.

The number of planned staff (50) is probably just enough assuming significant industry participation in the cavity and cryomodule production. Experienced people are required to follow the procurement of the cryoplants. Care should be taken not to underestimate the effort needed for proper controls development and integration.

There still many details to be worked out and the committee has made a number of recommendations. In particular, there are a number of details concerning the civil facilities that must be checked to ensure that the facilities are optimized to meet the needs of the cryogenic system.

Answers to Charge Questions

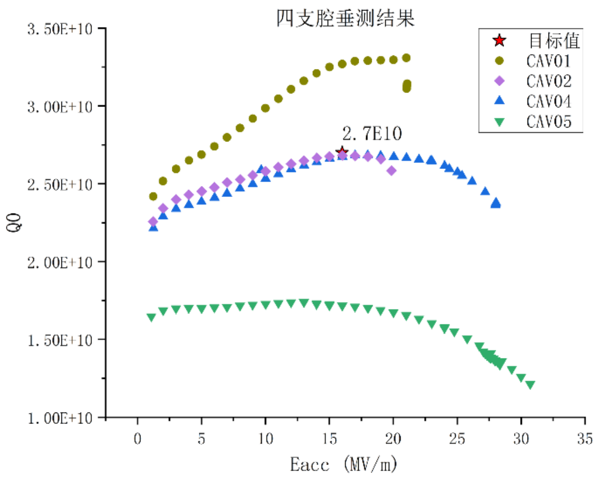
Are the interfaces between the cryoplants with their subsystems completed defined in term

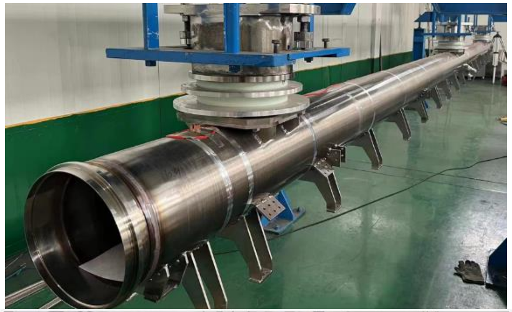
Important platform which providing extreme helpful advise and support!

Cryomodule technical cooperation

Cooperation with SHINE

- SHINE is responsible for assemble and test one 1.3 GHz cryomodule.
- Our group is responsible for developing key components. SHINE provides relevant technical guidance and test conditions.





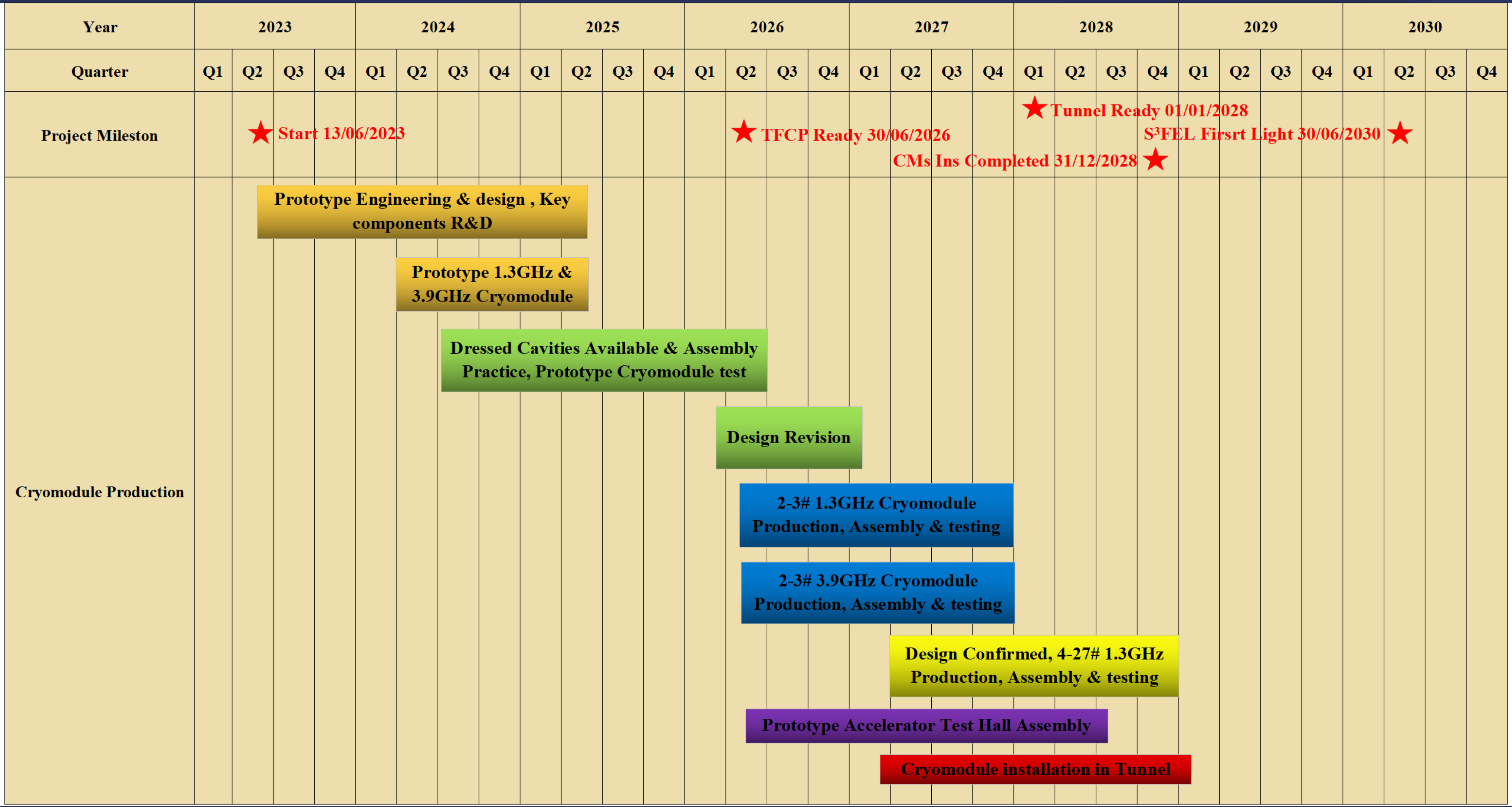
Cooperation with IHEP

Jiyuan Zhai (IHEP), WEPWB062

- IHEP made a 1.3 GHz cryomodule with 8 mid-T (medium-temperature furnace baking) 9-cell cavities for our project.
- Average usable gradient and Q_0 exceeds CW FEL projects and CEPC specs, and demonstrates excellent performance of mid-T cavities in a cryomodule for the first time.

Parameters	IHEP Mid-T CM	LCLS-II (SHINE, S^3FEL, DALS) Spec	LCLS-II-HE Spec	CEPC Booster Higgs mode Spec
Avg. usable CW E_{acc} (MV/m)	> 22	2.7×10^{10} @ 16 MV/m	2.7E10 @ 20.8 MV/m	3.0×10^{10} @ 21.8 MV/m
Avg. Q_0 @ 16 & 21 MV/m	3.6×10^{10}			

Project Schedule



Acknowledgements

We are here, it is by standing on the shoulders of yours!

Use existing designs and mature technologies Extremely beneficial from TTC and European XFEL, LCLS-II and SHINE projects

TESLA Technology Collaboration

Mission Statement

The mission of the TESLA Technology Collaboration (TTC) is to advance superconducting RF accelerator R & D and related accelerator studies across the broad diversity of scientific applications, and to keep open and provide a bridge for communication and sharing of ideas, developments, and testing across associated projects.

To this end the Collaboration supports and encourages free and open exchange of scientific and technical knowledge, expertise, engineering designs, and equipment.

Massive thanks for your help

Welcome to Shenzhen

Appendix

Soft X-ray light source as an important tool for material science

中能高重频X射线
自由电子激光
S^3FEL

↓

超高亮度、超快脉冲、强相干性
High brightness, ultra-short pulse and full coherence

↓

- 量子材料
  Quantum materials
- 催化
  Catalysis
- 生物大分子
  Biomolecules
- 雾霾成因
  Atmospheric chemistry
- 星际科学
  Interstellar chemistry
- 原子分子
  Atomic and molecular physics

↓

能源、环境、健康
新材料
Energy, environment, health and new material

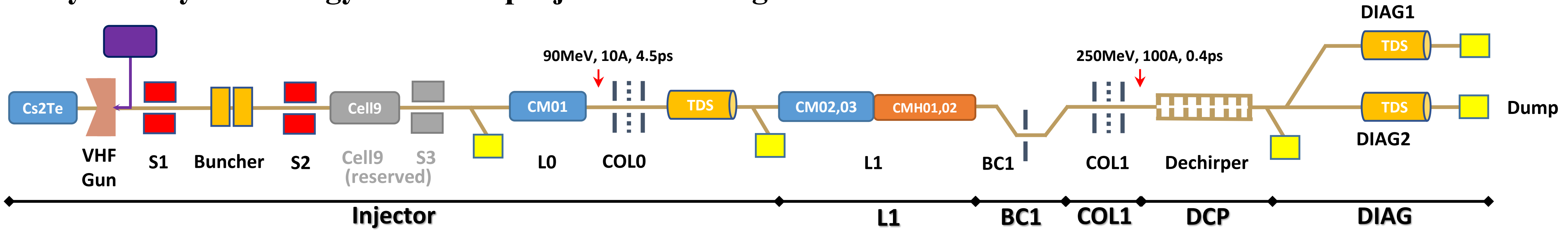
Advanced FEL facility

Femtosecond time resolution, high spatial resolution and Fourier-transform limit bandwidth

A transformative tool for basic science research and cutting-edge technology R&D

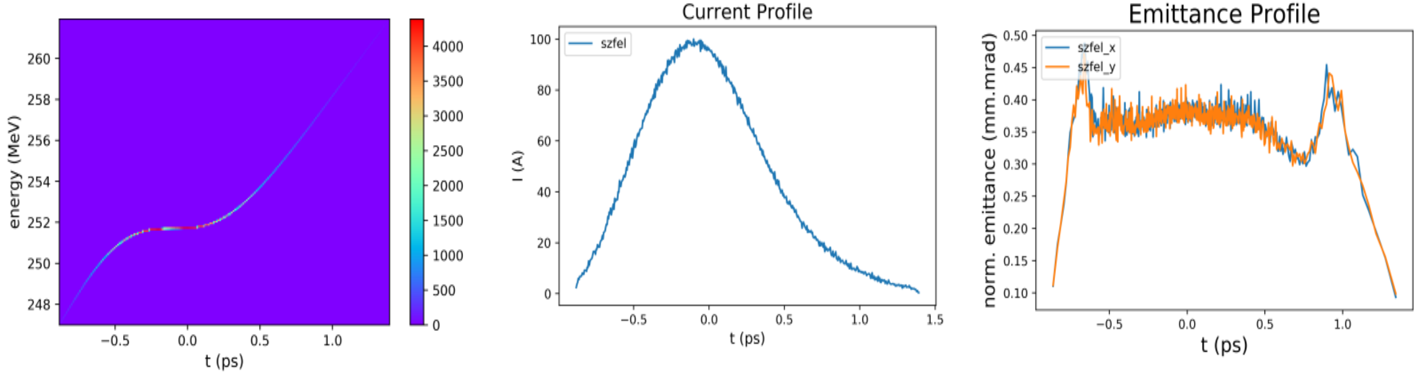
Prototype Accelerator Test Facility (PATF)

To verify the key technology of S³FEL project : including 3 × 1.3GHz CM +2 × 3.9GHz CM



Beam parameter

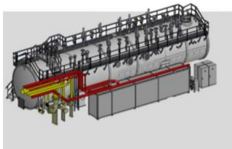
Parameter	Design Value	Operation Range	Unit
energy	250	100-300	MeV
charge	100	10-300	pC
bunch length (RMS)	0.4	0.1-5.0	ps
current	100	10-300	A
emittance	0.5	0.3-1.0	mm-mrad
rep. rate	1	0-1	MHz



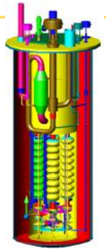
Physical simulation results meet the design requirement.

Cryogenic system infrastructure

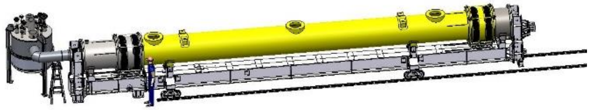
Test Facility Cryoplant (TFCP)



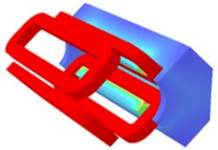
500W@2K



2 × (VTC)



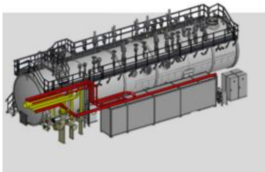
3 × (CMTB)



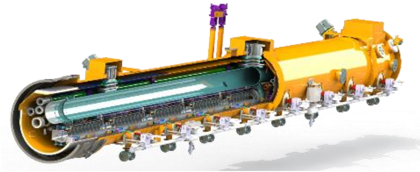
1 × (MTB)

1× (CTB)

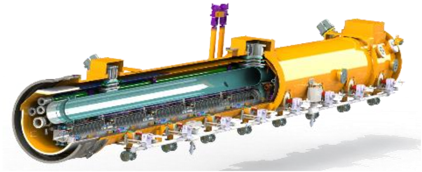
Prototype Accelerator Cryoplant (PACP)



1 kW@2K

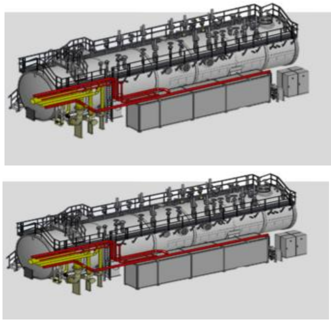


3 × 1.3GHz (CM)

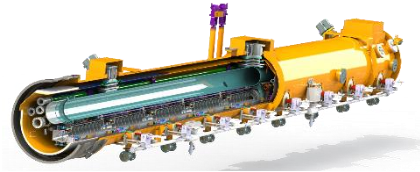


2 × 3.9GHz (CM)

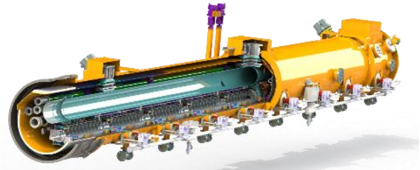
Accelerator Cryoplant (ACCP 1&2)



2 x 4 kW@2K



26 × 1.3GHz (CM)

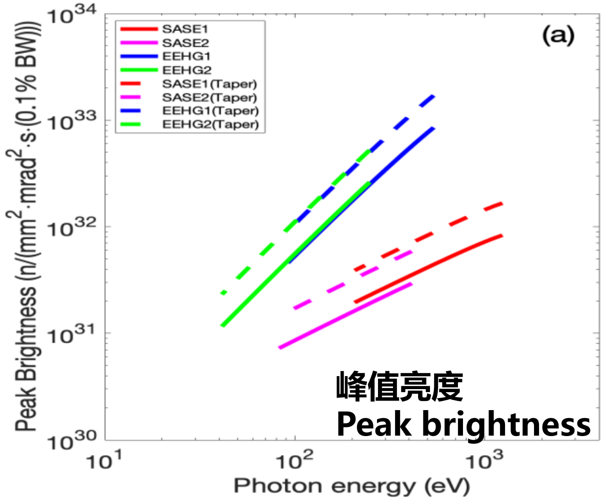


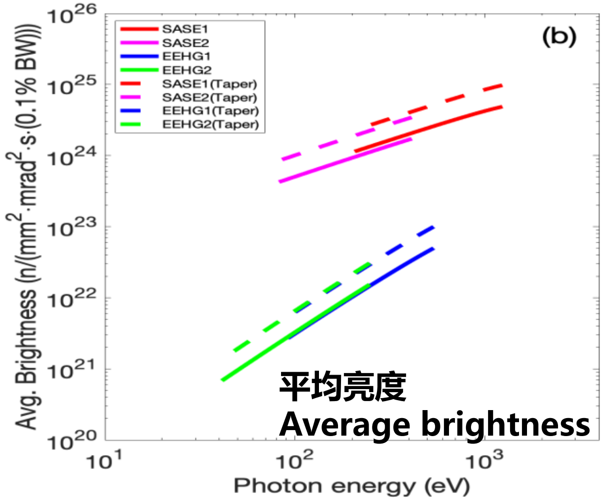
2× 3.9GHz (CM)

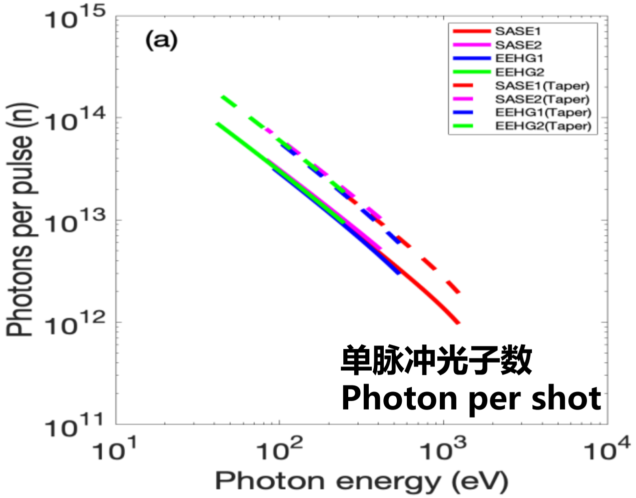
Cryogenic system capacity

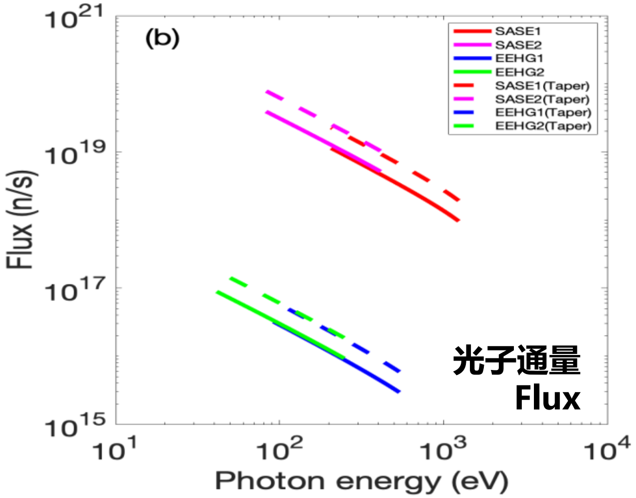
Cryogenic System	2K	4.5-8K	40-80K	User
TFCP	500 W	400 W	2500 W	SRF Module Test Facility
PACP	1000 W	500 W	4200 W	Prototype Accelerator Test Facility
ACCP1	4000 W	1700 W	16000 W	SRF LINAC
ACCP2	4000 W	1700 W	16000 W	

主要输出性能 Performance









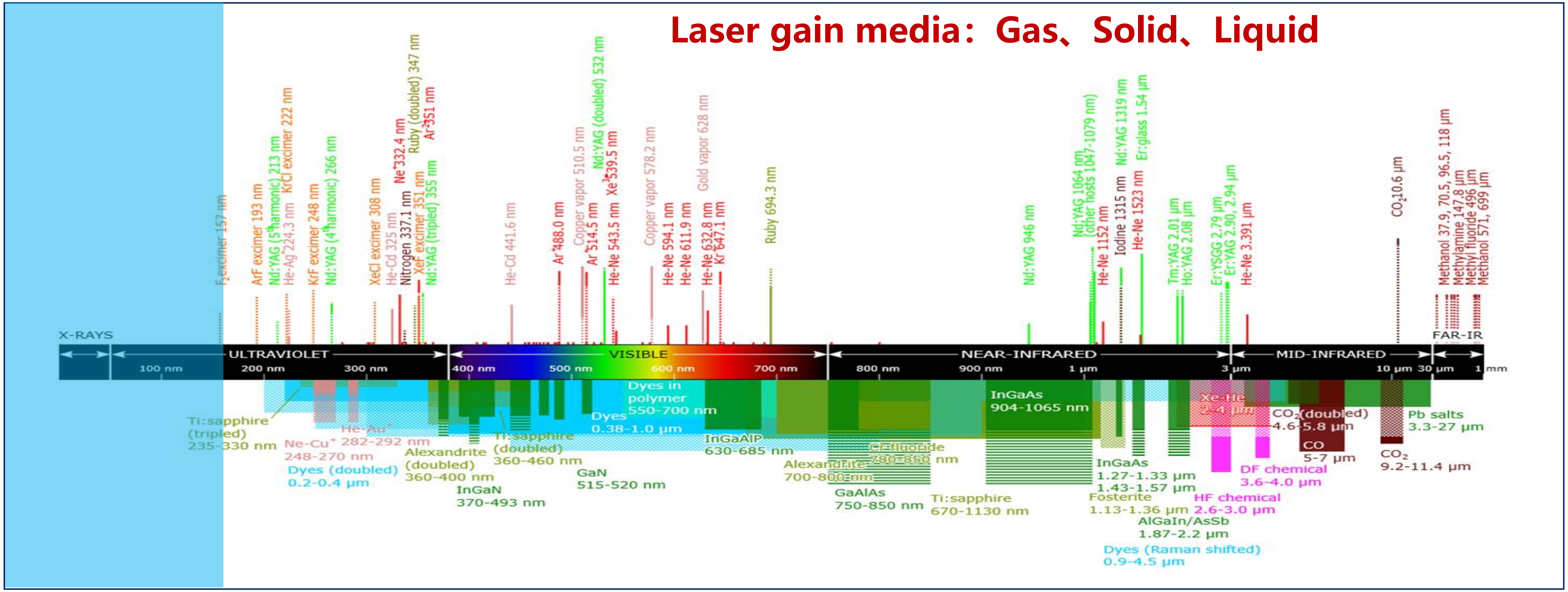
FEL主要输出性能 Performance

出光模式 Mode	EEHG	SASE
峰值亮度[a] Peak brightness	10^{33}	10^{32}
平均亮度[a,b] Average brightness	10^{22}	10^{24}
单脉冲光子数 (n) Photon per shot	10^{13}	10^{13}
光子通量 (n/s)[b] Flux	10^{16}	10^{19}

[a]亮度 brightness：光子 photon/mm²·mrad²·s·(0.1%BW)

[b]EEHG：1kHz；SASE：1MHz

激光技术发展的重要前沿 Frontiers of laser technology



科学研究，激光加工，通讯，医疗 Research, Processing, Communication, Medical treatment

SC 1.3 GHz cavity Requirements

ID	Name	Units	Min.	Nominal	Max.
1	Cavity type	TESLA			
2	Operating mode	CW			
3	Number of cavities per cryomodule	#		8	
4	Central frequency	GHz		1.3	
5	Operating temperature	K		2	
6	Shunt impedance	R/Ω		1036	
7	Accelerating gradient	MV/m		16	
8	RF coupler power handling	kW		3.8	
9	External quality factory		$4x10^6$	$4.1x10^7$	$1.1x10^8$
10	Unloaded quality factory			$2.7x10^{10}$	
11	Accelerating mode tuning range	kHz	-200		+200

- **Adjustable FPC**

SC 3.9 GHz cavity Requirements

ID	Name	Units	Min.	Nominal	Max.
1	Cavity type	TESLA			
2	Operating mode	CW			
3	Number of cavities per cryomodule	#		8	
4	Central frequency	GHz		3.9	
5	Operating temperature	K		2	
6	Shunt impedance	R/Ω		760	
7	Accelerating gradient	MV/m		14	
8	RF coupler power handling	kW		2	
9	External quality factor			$2.3x10^7$	
10	Unloaded quality factor			$2x10^9$	
11	Accelerating mode tuning range	kHz		750	

- Fixed FPC