Linac-Based Free Electron Lasers in China

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Outline

- Introduction
- SDUV-FEL Program
- DCLS User Facility
- SXFEL Projects
- HXFEL Plan
- Summary

Introduction

FEL Development in China

- Linac-based FELs have been being developed in China since mid-1980s, when the BFEL was proposed and built lately as the FEL first lased in Asia;
- Later on in late 1990s, a high-gain FEL program called SDUV-FEL was initiated; It started the FEL tests (SASE, HGHG and ECHO), from 2009;
- In mid-2000s, a soft X-ray FEL test facility (SXFEL) was proposed and began its construction in 2014; Its user facility project just founded and started this year;
- In early 2010s, an EUV-FEL, DCLS, was initiated and funded in 2013, it is in the commissioning now;
- In addition, a hard X-ray FEL facility was proposed and listed in the next 5-year plan of China's large scientific infrastructures to be built.


Free Electron Lasers in China
Low gain FEL
High gain FEL
CHINA
DCLS-FEL
IR FEL
IR FEL
IR FEL@USTC
SDUV-FEL
SXFEL
北京
朝鲜
韩国
日本
日本海
中国
成都
重庆
武汉
上海
东海
南海
广州
香港
澳门
缅甸
老挝
泰国
越南
孟加拉国
新德里
New Delhi
加尔各答
Kolkata
海得拉巴
Hyderabad
勒克瑙
Lucknow
斋浦尔
Jaipur
河内
Hà Nội
马尼拉
Maynila
那霸
大阪
东京
名古屋
札幌
青森
秋田
盛岡
仙台
新潟
金沢
長野
福島
静岡
広島
山口
松山
福岡
長崎
熊本
鹿児島
鳥取
蒙古
乌兰巴托
Улаанбаатар
阿拉木图
Алматы
新西伯利亚
Новосибирск

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

High Gain FELs in China

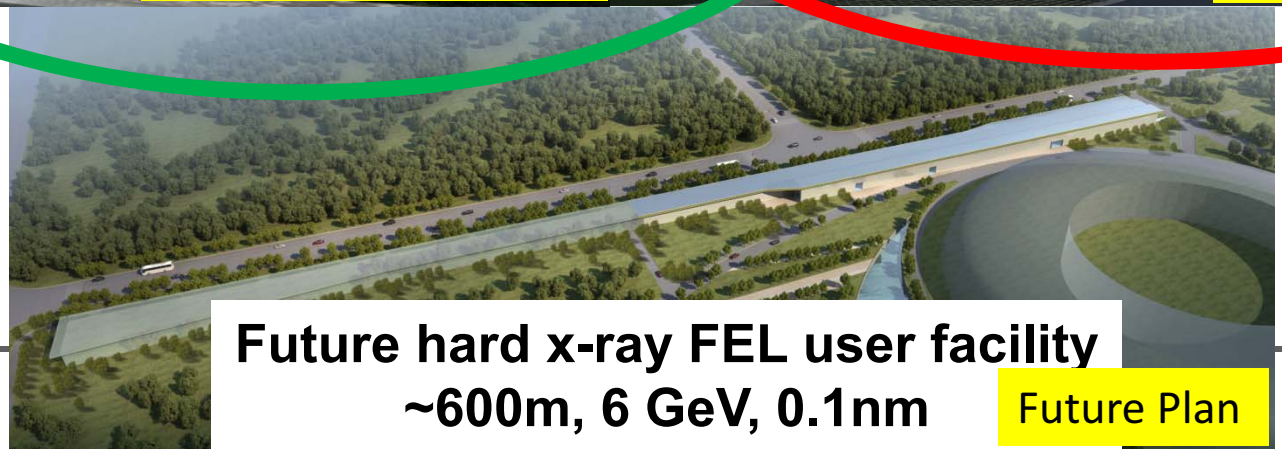
Shanghai DUV FEL,
65m, 180MeV, 250-350nm

Dalian VUV FEL
150m, 300MeV, 50-150nm

Under commissioning

Shanghai X-ray FEL Facility
300m, 840MeV, 9-40nm
530m, 1.6GeV, 2-10nm

Under construction



Future hard x-ray FEL user facility
~600m, 6 GeV, 0.1nm

Future Plan

High-gain FELs Constructed and Planned in China

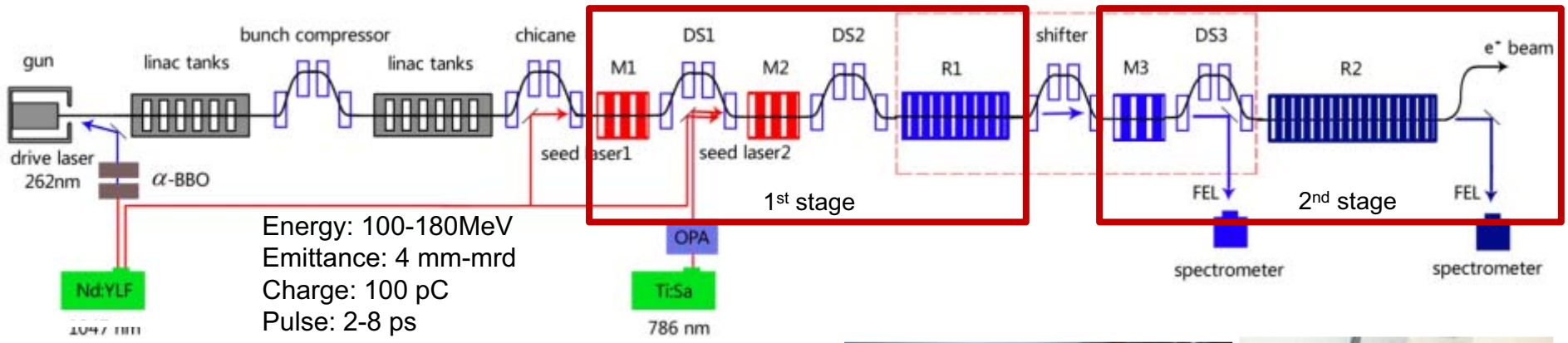
	SDUV-FEL	DCLS	SXFEL	HXFEL
	Test facility	User facility	Test/User	User
Status	Operating	Commissioning	Construction	Plan
Wavelength	150-350nm	50-150nm	2-40nm	0.1nm
Length	65m	150m	300-530m	530m
Main linac	S-band	S-band	C-band	C/X band
Beam energy	100-180MeV	300MeV	0.84-1.6GeV	6.0GeV
FEL principle	HGHG, EEHG	HGHG	HGHG, EEHG	SASE **ECHO Cascade**
Location	Shanghai	Dalian	Shanghai	Shanghai
First lasing	2009.09	2016	2017	**?**

SDUV-FEL Program

SDUV-FEL Program

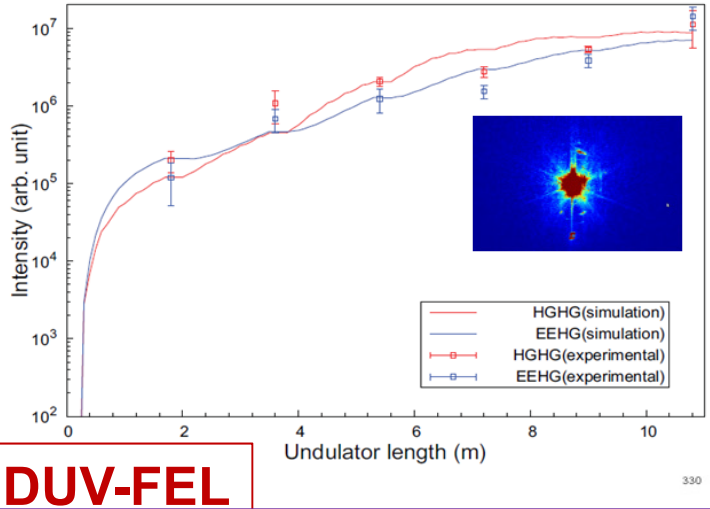
- Shanghai Deep Ultra-Violet Free-Electron Laser (SDUV-FEL) is a ~180MeV linac based seeded FEL test facility.
- Funding partially supported by
  - Chinese Academy of Sciences / CAS
  - Ministry of Science and Technology of China / MOST
  - National Natural Science Foundation of China / NSFC
- Collaborating institutes include USTC, IHEP, THUB and SINAP
- Be a test bed of the key technologies for high gain FELs

SDUV-FEL layout



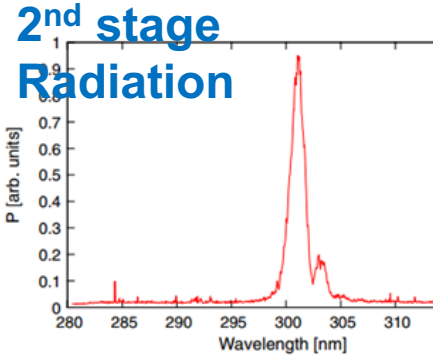
Energy: 100-180MeV
Emittance: 4 mm-mrd
Charge: 100 pC
Pulse: 2-8 ps

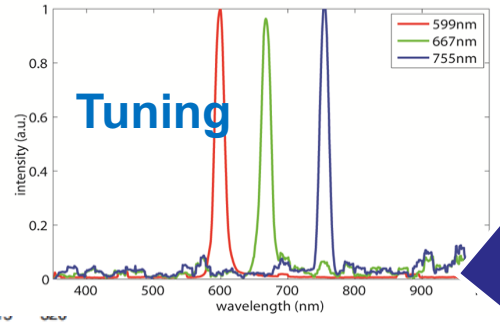
SDUV-FEL：seeded FEL Experiments



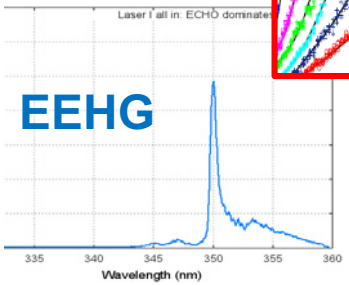
SDUV-FEL

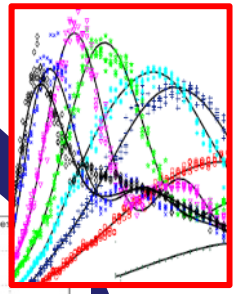
A preparation for XFEL





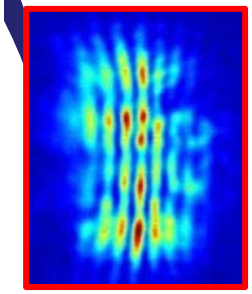
DCLS、SXFEL、HXFEL





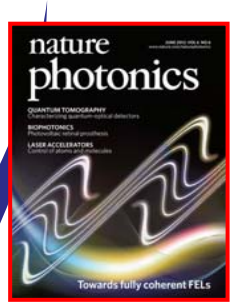
keV sliced energy spread measurement

Phys. Rev. ST-AB 14, 090701 (2011)



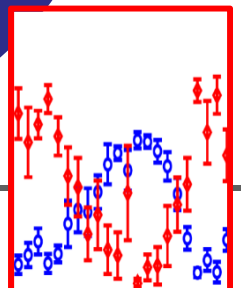
HGHG & cascaded HGHG

Phys. Rev. ST-AB 17, 020704 (2013)



First lasing of Echo-FEL

Nature Photonics 06, 360 (2012)



Crossed-planar undulator demonstration

Phys. Rev. ST-AB 16, 020704 (2014)

FEL Experiments @ the SDUV-FEL

- 2009.09: SASE lasing
- 2010.05: First echo signal observed
- 2010.12: HGHG saturation
- 2011.04: **EEHG-FEL lasing**
- 2011.12: HGHG tunability based on OPA
- 2012.04: **Cascaded HGHG signal Oberserved**
- 2013.08: EEHG@10th harmonic obtained
- 2013.11: **Crossed undulator polarization control**
- 2014.04: **FEL control with corrugated structure**
- on going: CPA and PEHG demonstration

- C. Feng, et al., Phys. Rev. ST Accel. Beams, **14** (2011) 090701.
- Z.T. Zhao, et al., Nat. Photonics, **6** (2012) 360-363.
- B. Liu, et al., Phys. Rev. ST Accel. Beams, **16** (2013) 020704.
- H. Deng, et al., Phys. Rev. ST Accel. Beams, **17** (2014) 020704.
- H. Deng, et al., Phys. Rev. Lett, **113** (2014) 254802.
- Z.T. Zhao and D. Wang, IEEE Trans. on NS, Vol: 63, No: 2, 930-938, (2016)

SDUV-FEL Parameters

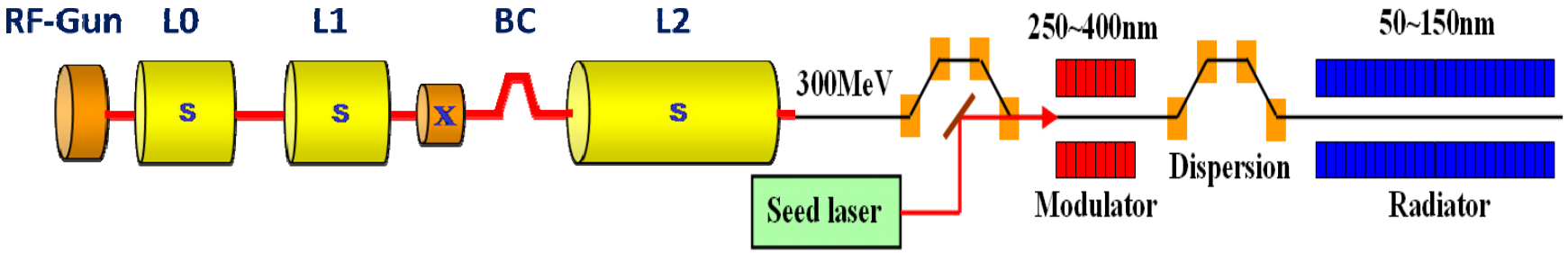
Parameters	Design	Achieved	Unit
Output Wavelength	266	250~400	nm
Bunch charge	1	0.1	nC
Energy	150	100~180	MeV
Energy spread	0.2	0.2	%
Energy spread (sliced)	-	0.005	%
Normalized emittance	4	2~3	mm.mrad
Pulse length (FWHM)	3	~3	ps
Peak current	300	~30	A
Rep. rate	2	2	Hz

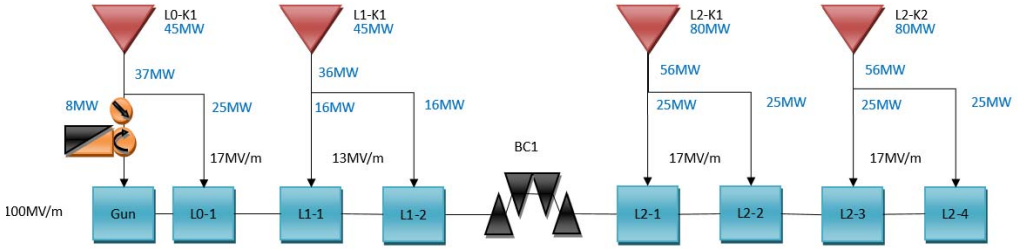
DCLS User Facility

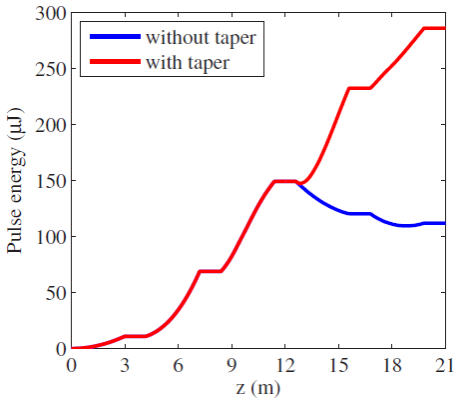
DCLS User Facility

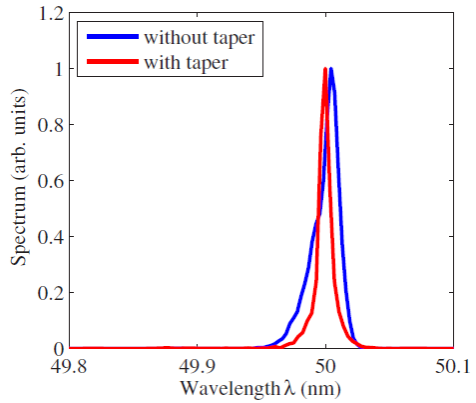
- Dalian Coherent Light Source (DCLS) is a single stage HGHG-FEL in the wavelength range of 50 – 150 nm for chemical dynamics research;
- DCLS is based on a S-band NC linac of 300MeV with a rep-rate of 1-50Hz, providing full coherent radiation with fs-ps pulse length;
- The building and facility construction started in 2014, and the beam commissioning started in September 2016.
- The project was founded by, its design and construction were made by SINAP, DICP &USTC ;

DCLS Layout and Parameters









FEL wavelength	150-50nm
FEL pulse energy	>100uJ@120nm
FEL rep. rate	1-50Hz
Modulator period	50mm
Modulator length	1.0m
Dispersion	0-2mm
Radiator period	30mm
Radiator length	18.0m
Beta function	6-8m

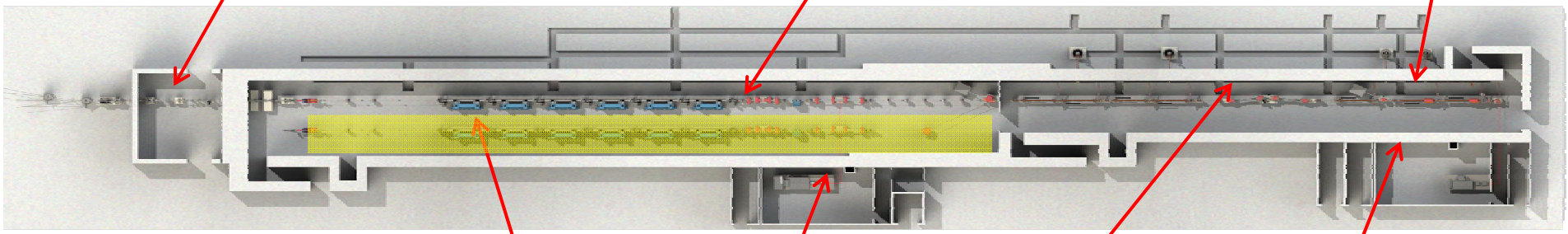
Start-to-end results: 50nm HGHG

DCLS Layout

Beamline & Endstation

FEL line1

Photo Injector



Space for FEL line2

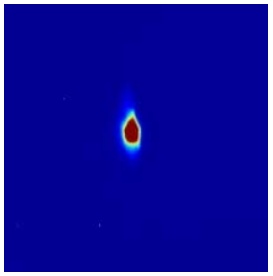
Seed laser

LINAC

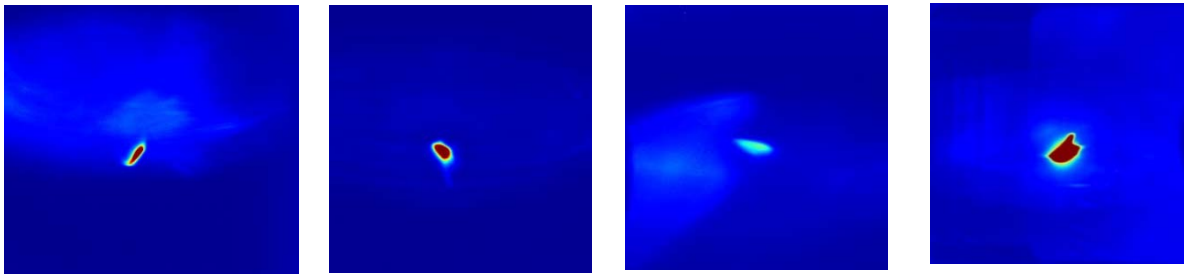
Injector Laser

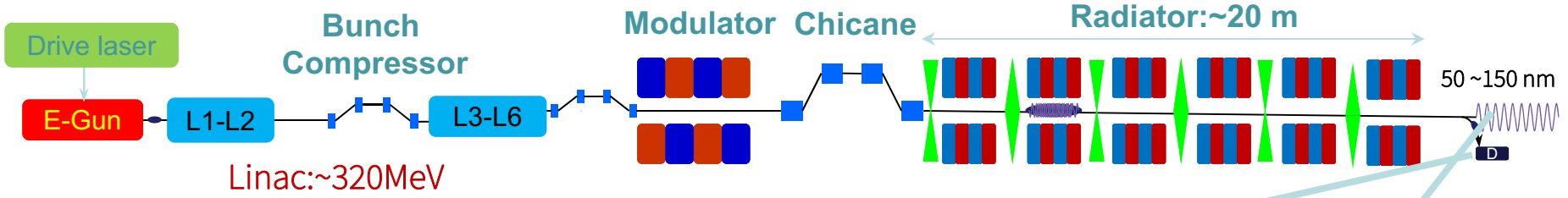
First FEL commissioning results

Electron beam at the exit of the linac



Electron beam in the undulators

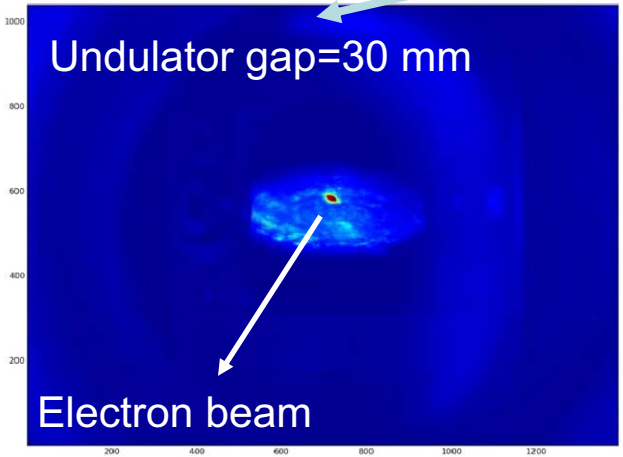


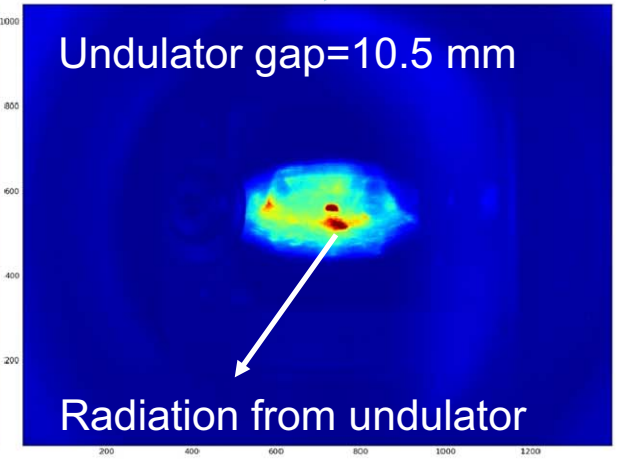


Commissioning started in mid-September 2016

Electron at the exit of the linac:

- Energy: 327 MeV
  @after bunch compression
- Energy spread: 0.12% (projected)
- Emittance-x: ~1.7mm·mrad @500 pC
- Emittance-y:~1.7mm·mrad @500 pC





DCLS-FEL Commissioning Progress

Parameters	Design	Achieved	Unit
Output Wavelength	50~150	-	nm
Bunch charge	0.5	0.52	nC
Energy	0.3	0.33	GeV
Energy spread	0.15	0.12	%
Normalized emittance	2	~1.6	mm.mrad
Bunch length (FWHM)	2	~2	ps
Peak current	300	~250	A
Rep. rate	10-50	10	Hz

SXFEL Projects:

SXFEL-TF and SXFEL-UF

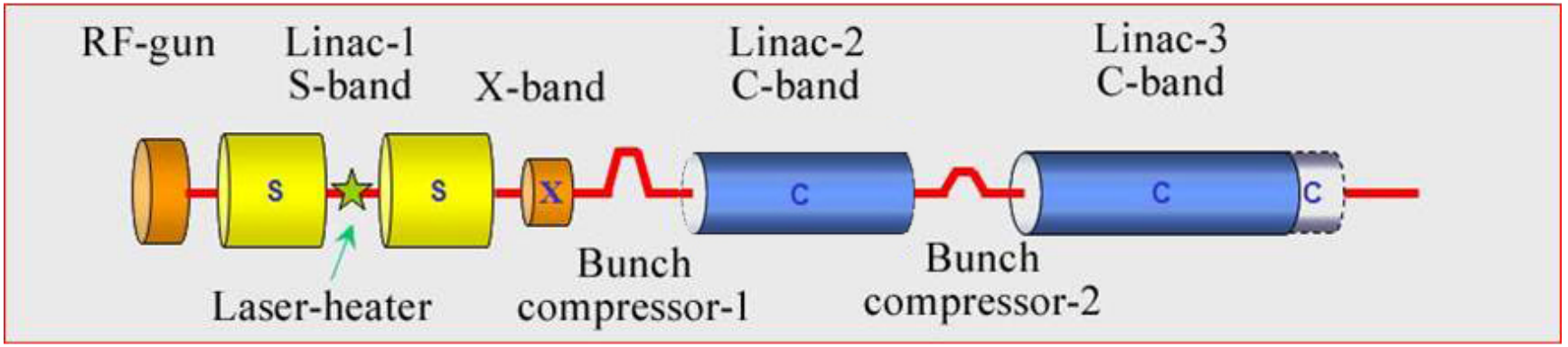
SXFEL Facility: TF +UF Projects

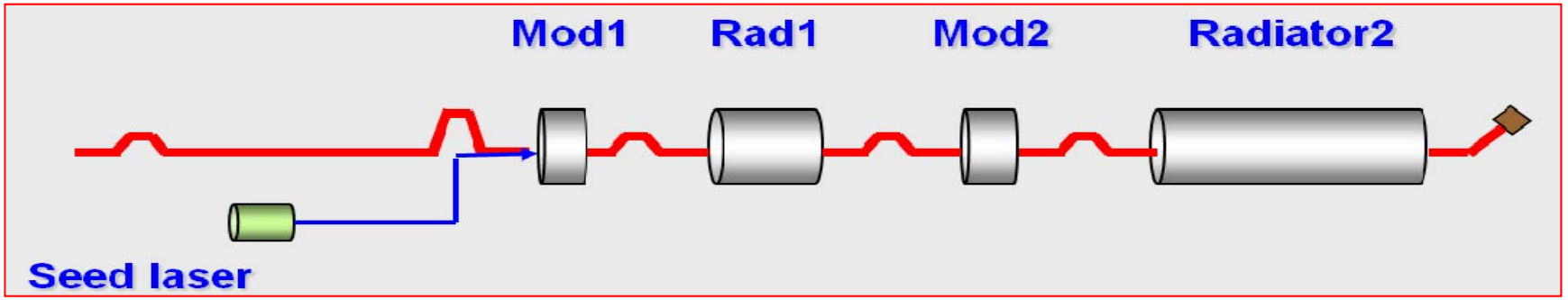
- **SXFEL facility** consists of two projects independently funded, **SXFEL test facility + SXFEL user facility**, with a total budget of ~155M$;
- **SXFEL test facility** was initiated in 2006 and founded in 2014, its ~300m long building was completed in April 2016, its 0.84GeV linac and undulators are in installation now, aiming at lasing in early 2017;
- **SXFEL user facility** was just founded to upgrade the linac energy to 1.6GeV for building two undulator lines with 5 experimental stations in the water window region, aiming at serving users in 2019.

SINAP, THUB and ShanghaiTech are collaborating in the design and construction of the SXFEL facility

Test Facility: SXFEL-TF

- A seeded FEL with two-stage HGHG or EEHG +HGHG based on an 0.84GeV linac and located in the campus of SSRF, closing to its synchrotron;





SXFEL-TF Parameters

Injector beam parameters

Bunch charge (nC)	0.5
Beam energy (MeV)	129.4
Pulse length (ps, FWHM)	9
Norm. emittance (mm.mrad, rms)	0.95
Energy spread (rms)	< 0.14%
Rep-rate (Hz)	1-10

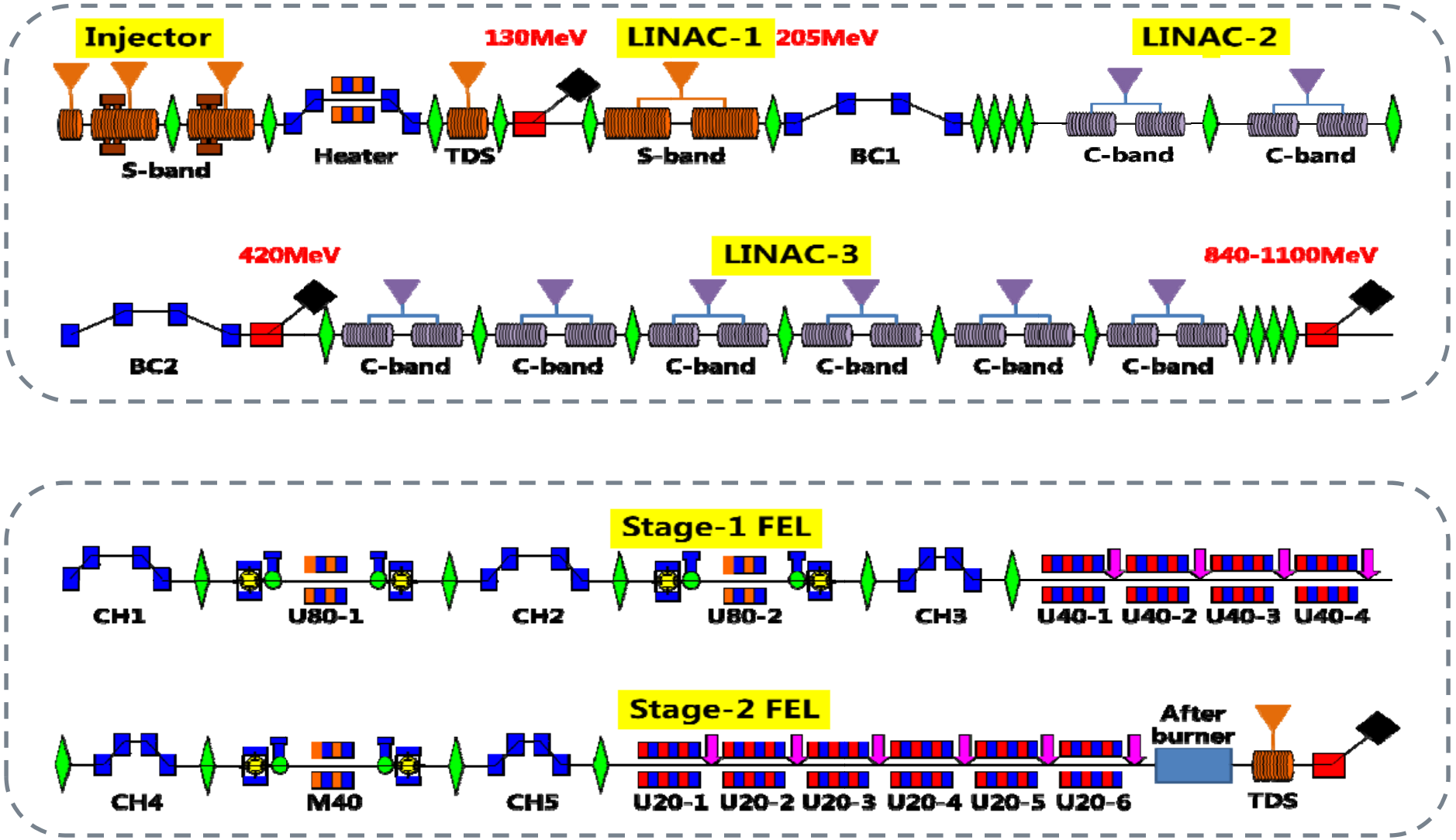
Main linac beam parameters

Bunch charge (nC)	0.5
Beam energy (GeV)	0.84
Bunch length (ps, FWHM)	≤ 1.0
Norm. emittance (mm.mrad)	< 2.0
Energy spread (rms)	< 0.15%
Rep-rate (Hz)	1-10
Peak current (A)	≥ 500

FEL parameters

	Baseline I (8.8nm)		Baseline II (6.3nm)
Scheme	HGHG-HGHG	EEHG-HGHG	HGHG-HGHG
Harmonics	6 × 5	6 × 5	7 × 6
Beam energy	730MeV	730MeV	840MeV
FEL wavelength	8.83nm	8.83nm	6.3nm
FEL pulse	< 100fs	<100fs	< 100fs
FEL power	>100MW	>100MW	>100MW

SXFEL-TF Layout

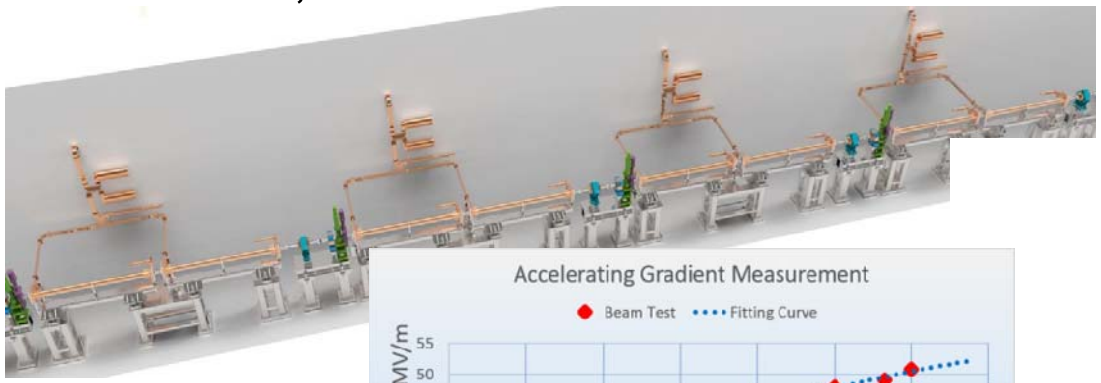


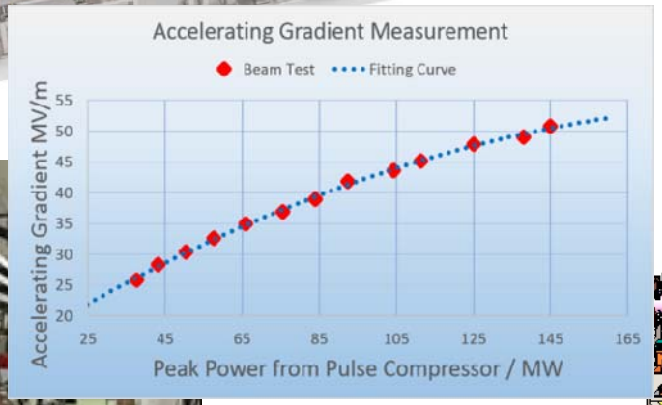
SXFEL-TF: Building

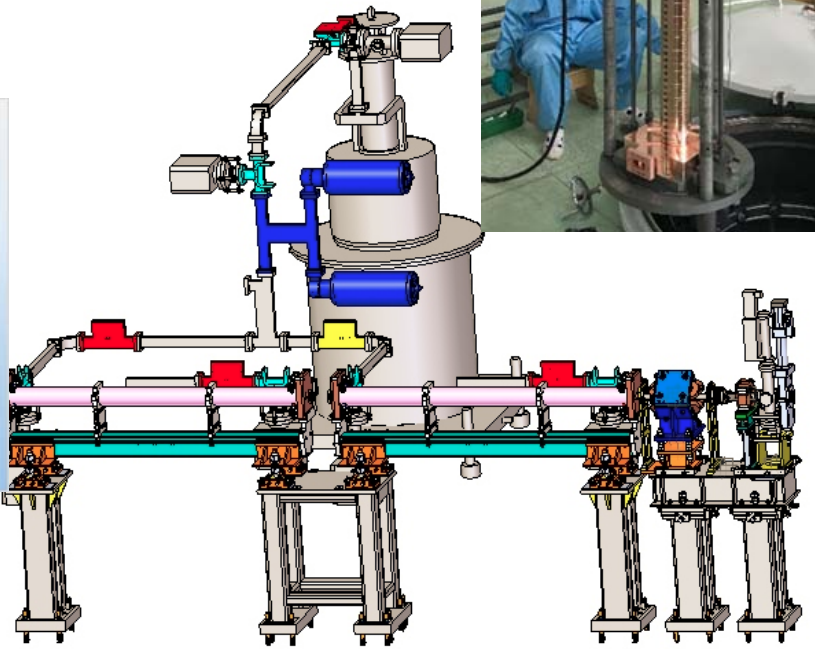
Technical hall and Accelerator tunnel

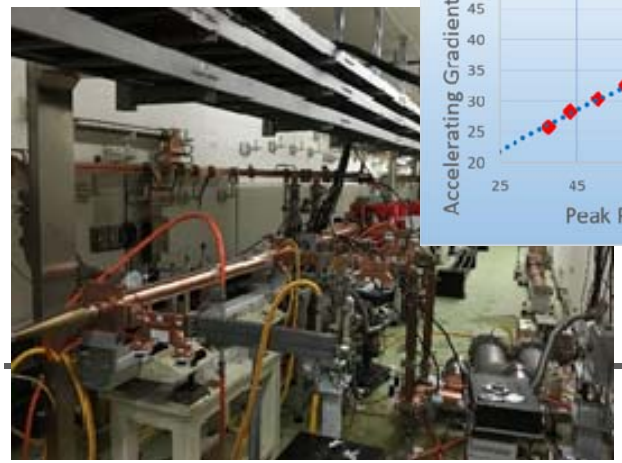
Case 1:C-band Linac System

- Technical R&Ds and prototypes were made, including RF, undulator, BI,…
- 1.8m C-band structure was successfully developed at SINAP;
- Its accelerating gradient reaches 50MV/m with beam;

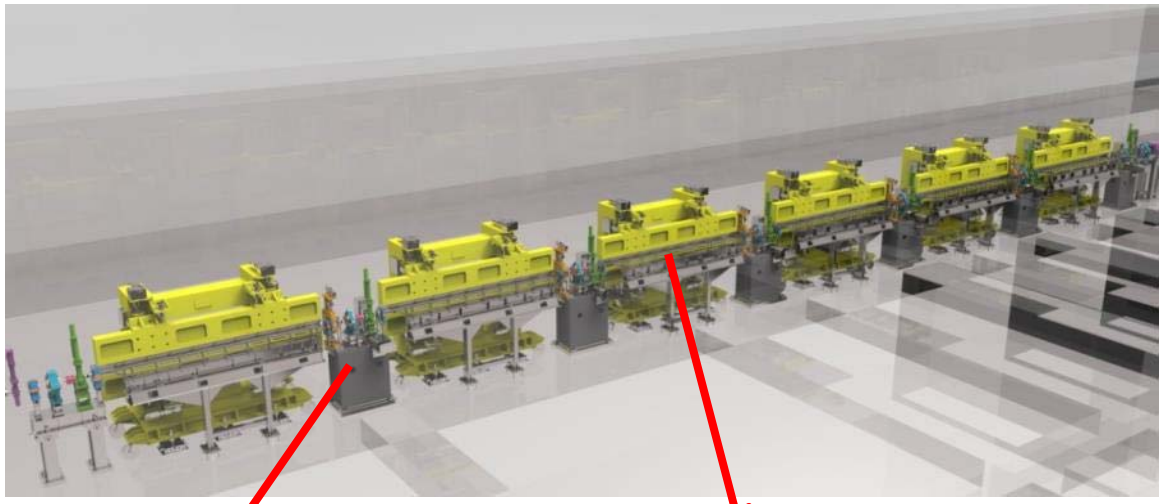




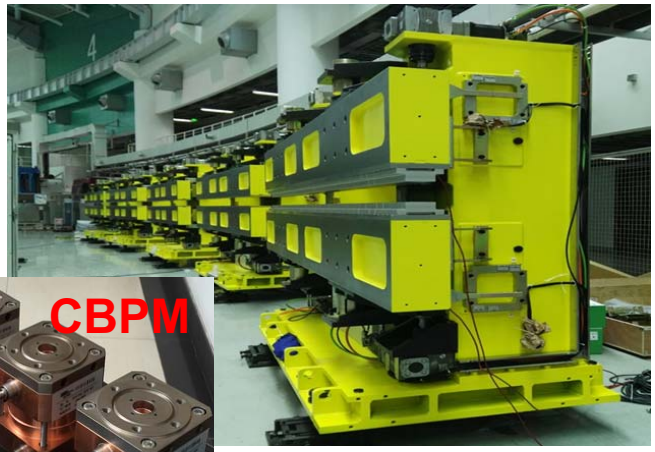




Case 2: Undulator System

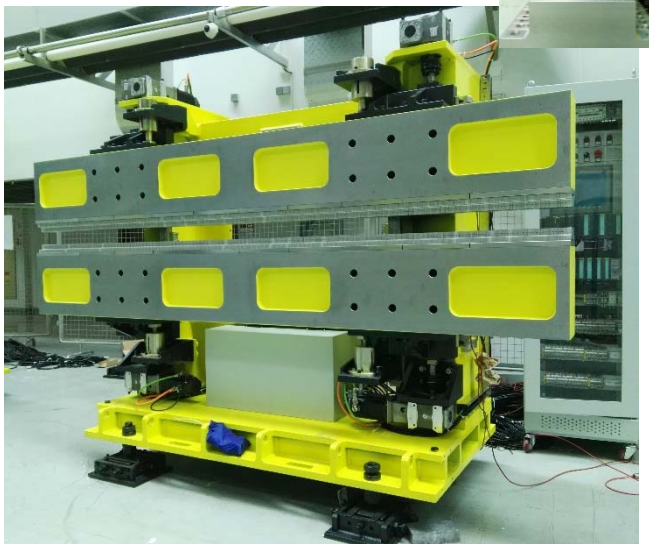


Undulators and Vacuum Chamber



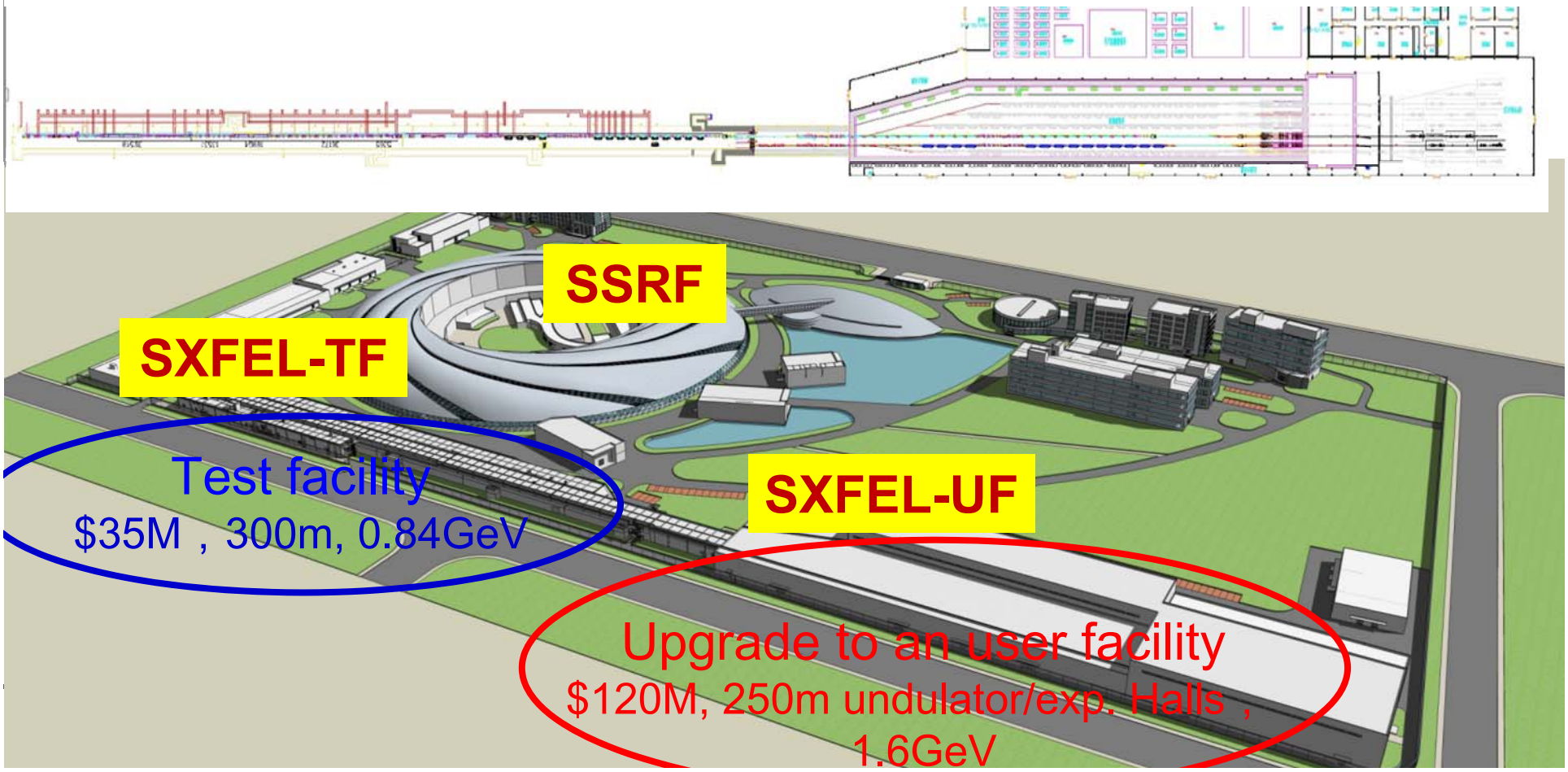
CBPM

- **3m undulator**

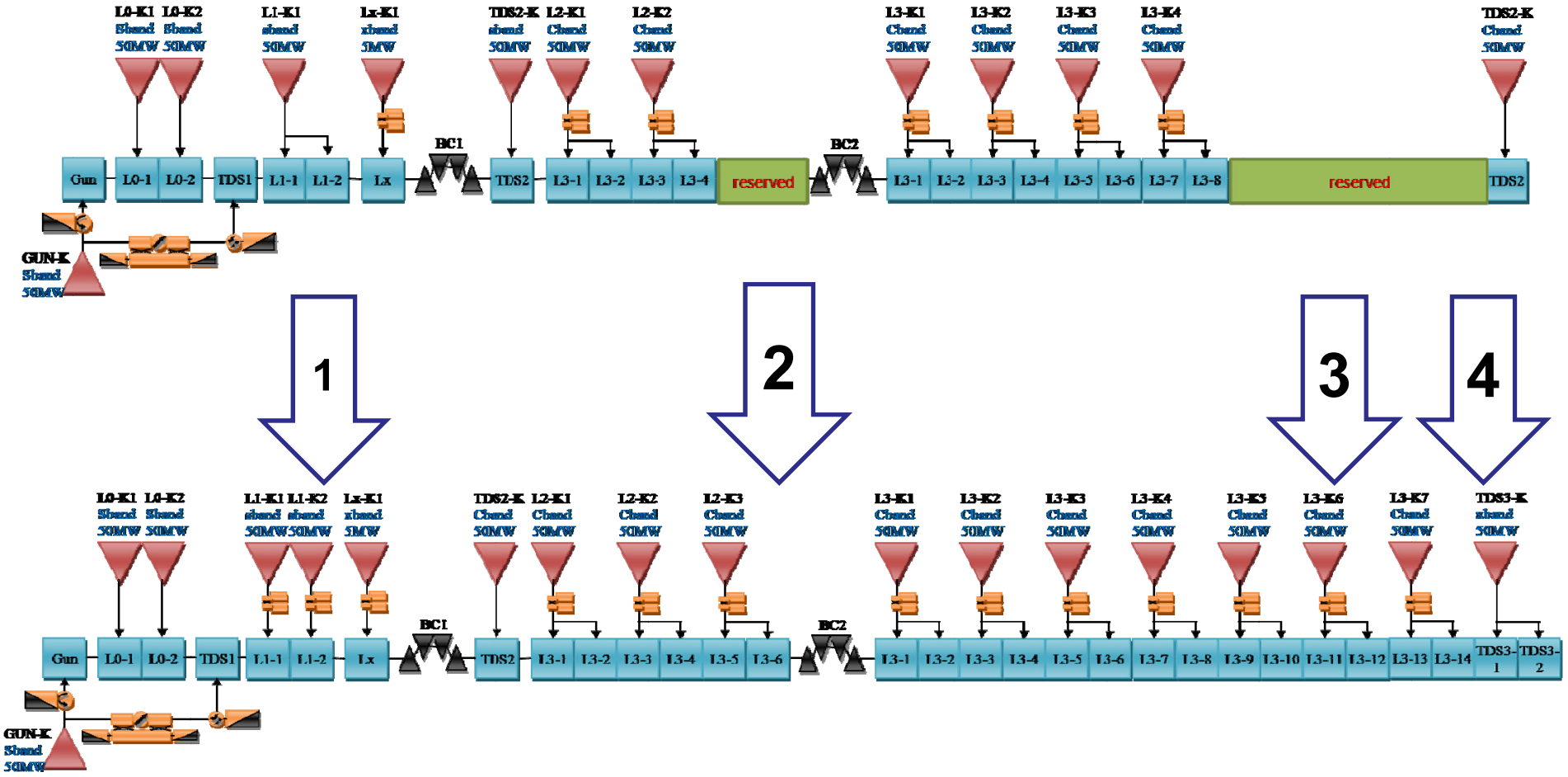


User Facility: SXFEL-UF

- A soft X-ray FEL user facility based on SXFEL-TF with two undulator line, a seeded FEL line and a SASE FEL line, is founded mainly by Shanghai local government, aiming at opening to users in 2019



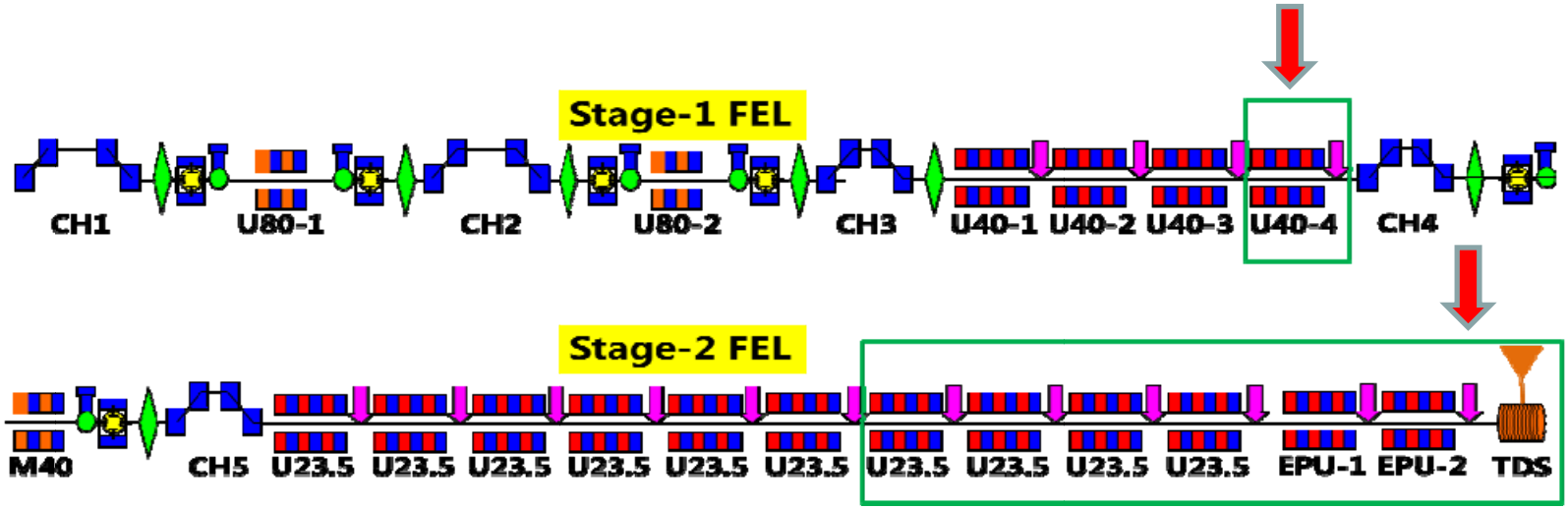
Linac energy upgrade：~1.6GeV



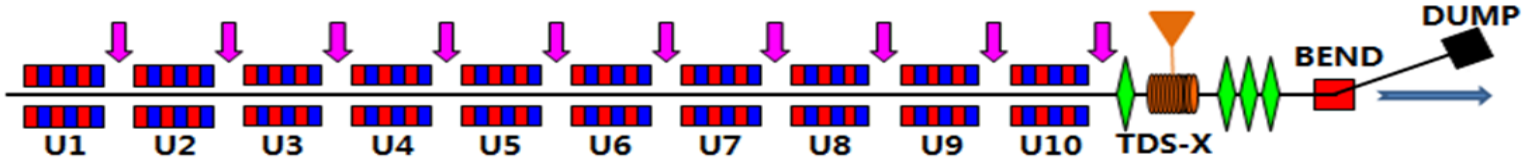
Adding:

- **1**) 1 S-band klystron and 2 SLEDs
- **2**) 1 C-band RF unit
  3) 3 C-band RF units
- **4**) 1 X-band deflecting structure

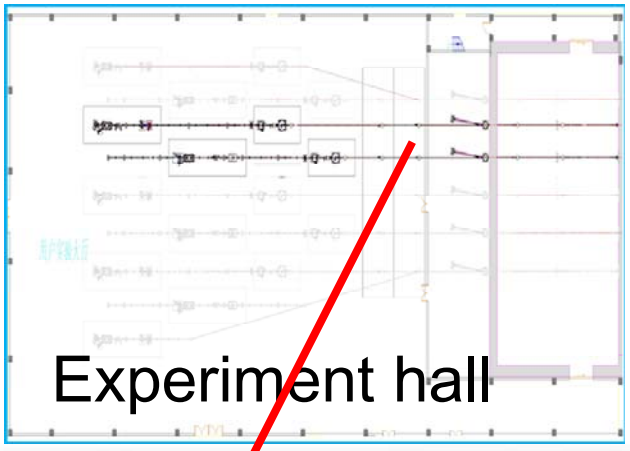
- FEL1: Seeded FEL line: add 7 undulator units

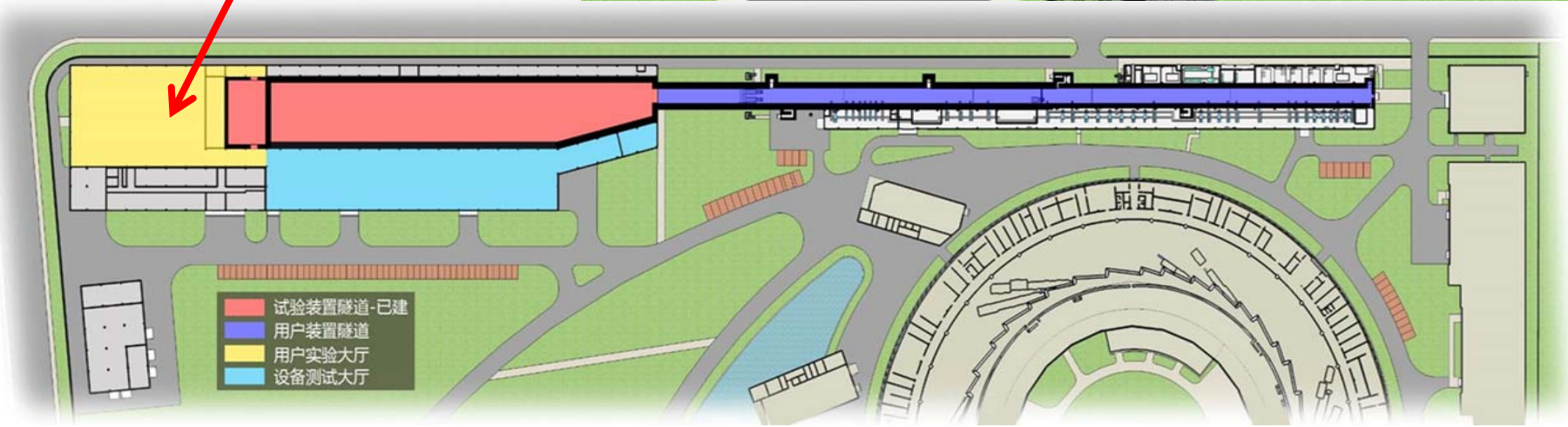


- FEL2: SASE FEL line: build 10 in-vacuum undulator sections



- 5 experimental stations:CDI, AMO, Ultrafast physics, Surface chemistry, Photon-electron;





SXFEL Facility Parameters

Parameters	Test Facility	User FEL1	User FEL2	Unit
Output Wavelength	9	3-10 (design) 2-40 (goal)	2-10 (design) 1.2-10 (goal)	nm
FEL type	HGHG EEHG	HGHG EEHG	SASE	
Bunch charge	0.5~1	~0.5	~0.5	nC
Beam Energy	0.84	1.0-1.6	1.0-1.6	GeV
Energy spread	0.1~0.15%	0.1~0.15%	0.1~0.15%	
Energy spread (sliced)	0.02%	0.02%	0.02%	
Normalized emittance	<2.0	<1.5	<1.5	mm.mrad
FEL Pulse (FWHM)	~0.5	0.03 -0.7	~0.7	ps
Peak current	~0.5	0.7	0.7	kA
Rep. rate	1~10	10-50	10-50	Hz

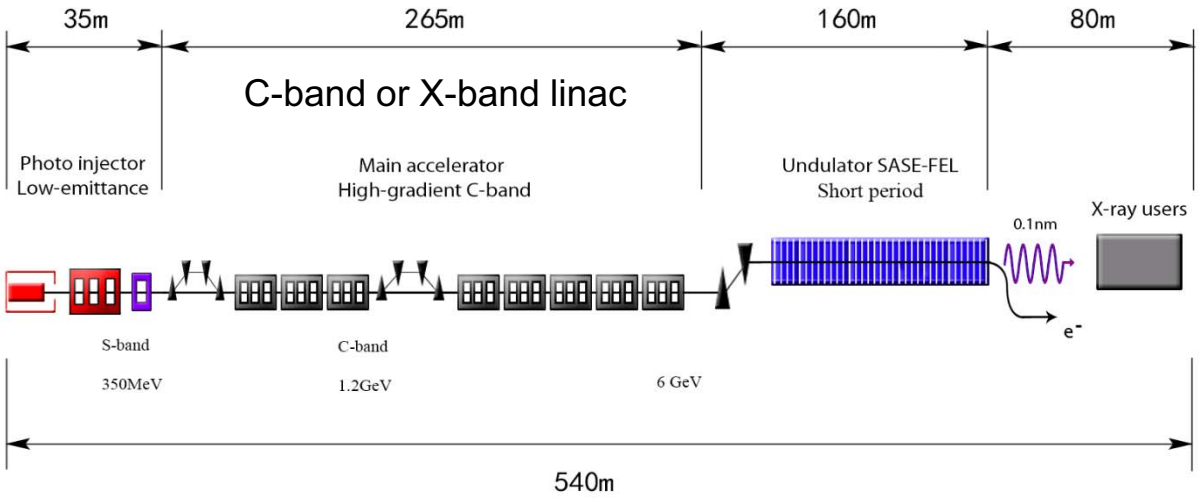
A Hard X-ray FEL Facility Plan

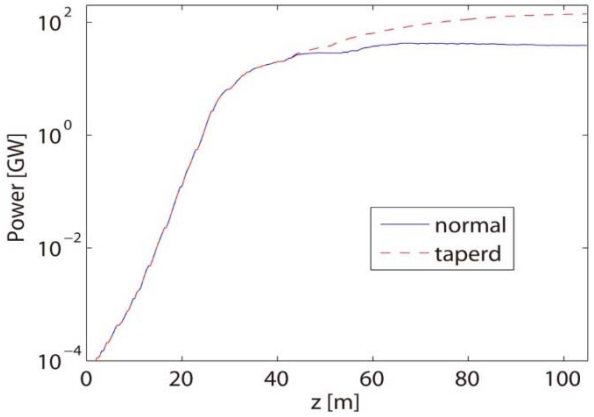
(HXFEL)

A Compact Hard X-ray FEL @ SSRF campus

- A high gradient linac (C-band or X-band) based hard X-ray FEL has been planned in the same building of SXFEL
- A two beam based seeded scheme of ECHO is considered for building a fully coherent hard X-ray light source

HXFEL baseline (SASE)

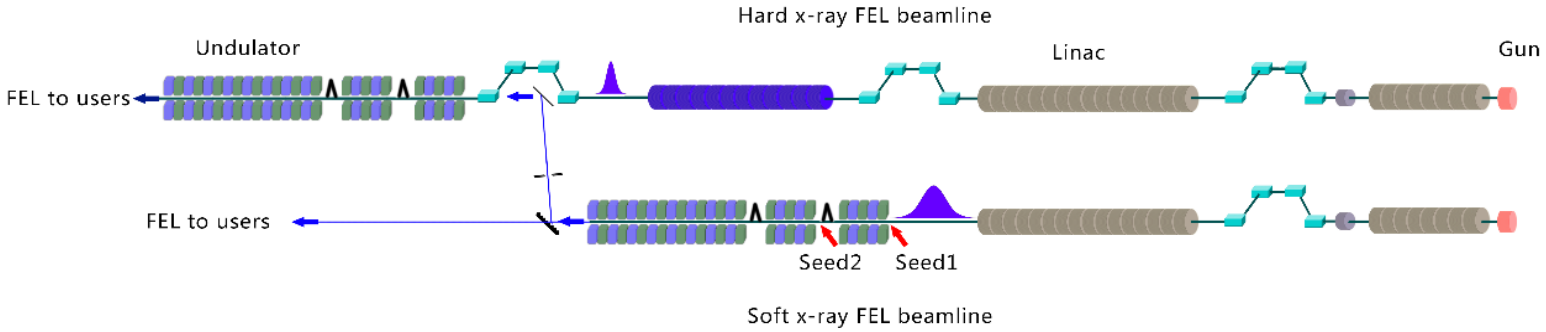


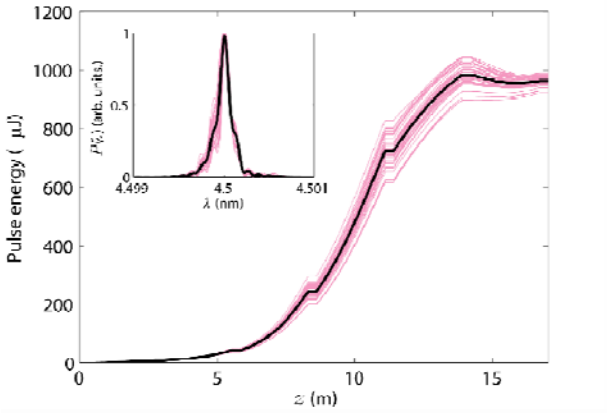


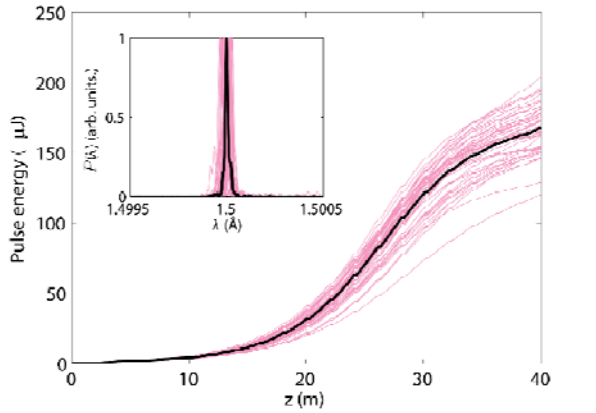
Electron beam	
Beam energy	6 GeV
Peak current	3 kA
Bunch charge	200 pC
Normalized emittance	0.4 mm·mrad
Bunch length	100 fs
RMS slice energy spread	1e-4
Repetition rate	50 Hz

Undulator	
Period	15 mm
Undulator length	100 m
FEL	
FEL wavelength	~0.1 nm
Output power with taper	100 GW
Photons/pulse	10^{13}
Saturation length	40 m

A New HXFEL Scheme (EEHG cascade)







Soft x-ray beamline: 1.6 GeV
Output wavelength: 4.5 nm

Hard x-ray beamline: 6 GeV
Output wavelength: 0.15 nm

Zhao Z, Feng C, et al, Two-beam based two-stage EEHG-FEL for coherent hard X-ray generation. Science Bulletin 61(9): 720-727 (2016) .

Summary

- Linac-based FELs have been developed slowly in China over the last 20 years, SDUV-FEL and DCLS have led a complete R&D for the follow-up projects;
- The SXFEL projects, which consisting of the SXFEL-TF and the SXFEL–UF，is underway in two phases, aiming at opening to user experiments in 2019;
- A hard X-ray FEL facility has been proposed and listed in the 5-year plan of China's large scientific infrastructures from 2016 to 2020;
- In the mean time, a SRF linac based XFEL is also under consideration in China.


Thank you for your attention
谢谢！
AURORA