Seeded FEL Activities at SINAP

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Shanghai Institute of Applied Physics
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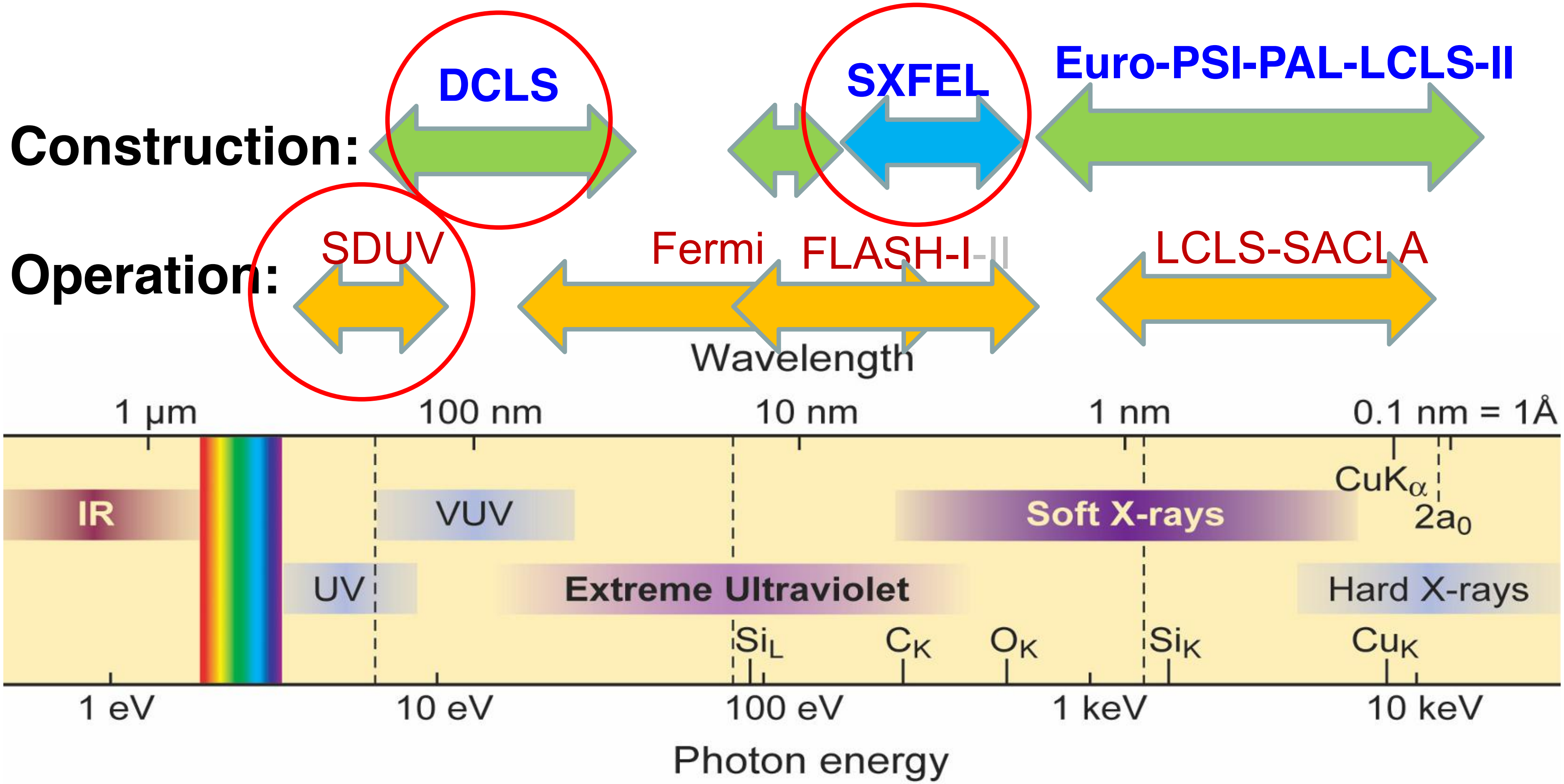
Seeded and self-seeding FEL workshop 2012
ICTP, Trieste, Italy
Dec.11, 2012

Outline

- Introduction: SINAP features seeded FEL
- SDUV seeded FEL experiments
- Dalian Coherent Light Source:
  a FEL user facility at VUV regime
- Shanghai Soft X-ray FEL
- Summary

Introduction

Existing High Gain FEL facilities:



FEL projects at SINAP

	SDUV-FEL	Dalian FEL	SXFEL	SXFEL-u
Type	Test facility	User facility	Test facility	User facility
Status	Operating	Construction	Design	Plan
FEL wavelength	150-350nm	50-150nm	9-50nm	1.2-6 nm
Overall length	65m	150m	300m	350m
Beam energy	100-200 MeV	300MeV	0.84 GeV	2 GeV
FEL principle	HGHG,EEHG	HGHG	HGHG,EEHG	HG,EE,SS
Injector	S-band RF	S-band RF	S-band RF	S-band RF
Linac	S-band	S-band	S-&c-band	S-&c-band
Undulator	Planar, OV	Planar, OV	Planar, OV	TBD
Completion	2009-15	2015	2015?	TBD
Location	Shanghai-J	Dalian-DICP	Shanghai-P	Shanghai-P

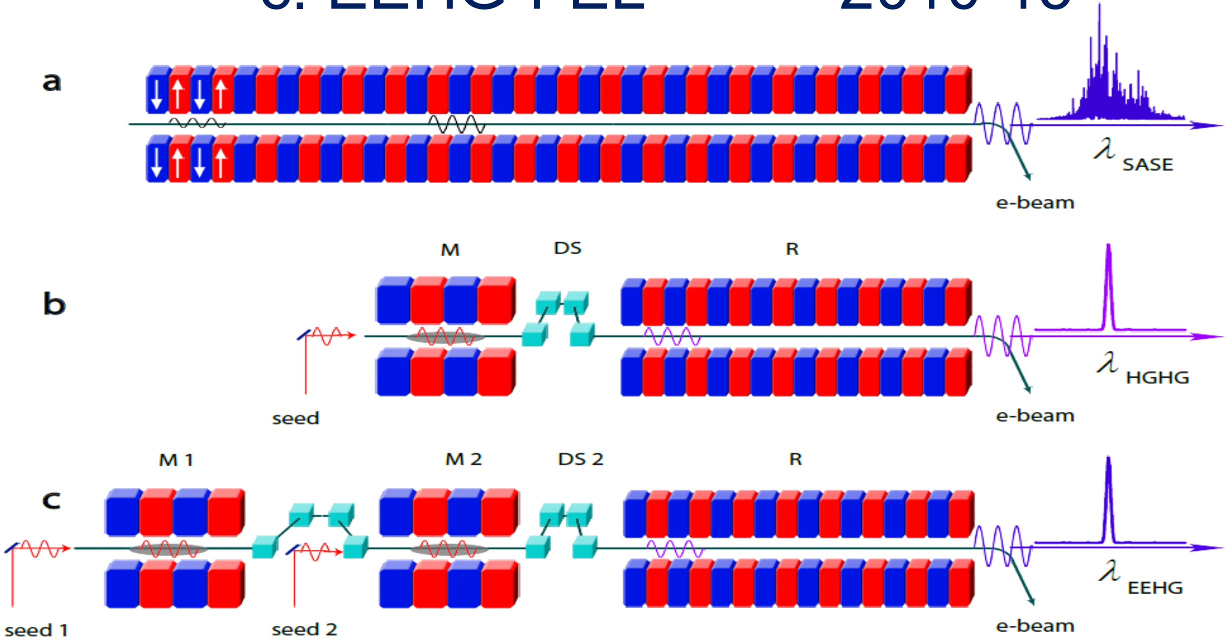
SDUV FEL

Shanghai Deep UV (SDUV) FEL at Jiading campus

a test bench for novel FEL principles

Various high gain FEL types at SDUV-FEL

a. SASE 2009
b. HGHG-FEL 2010-13
c. EEHG-FEL 2010-15

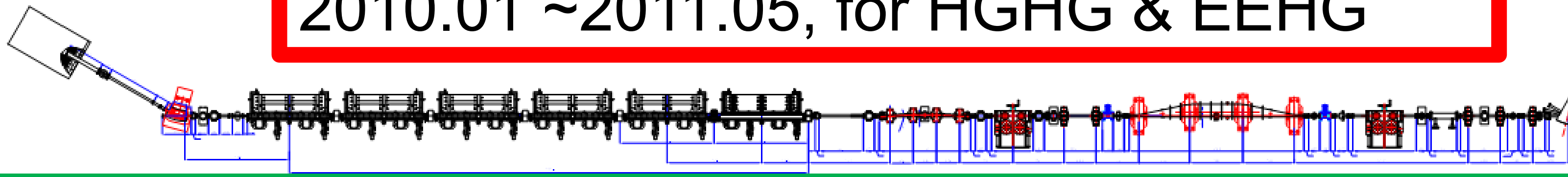


Milestones of FEL experiments

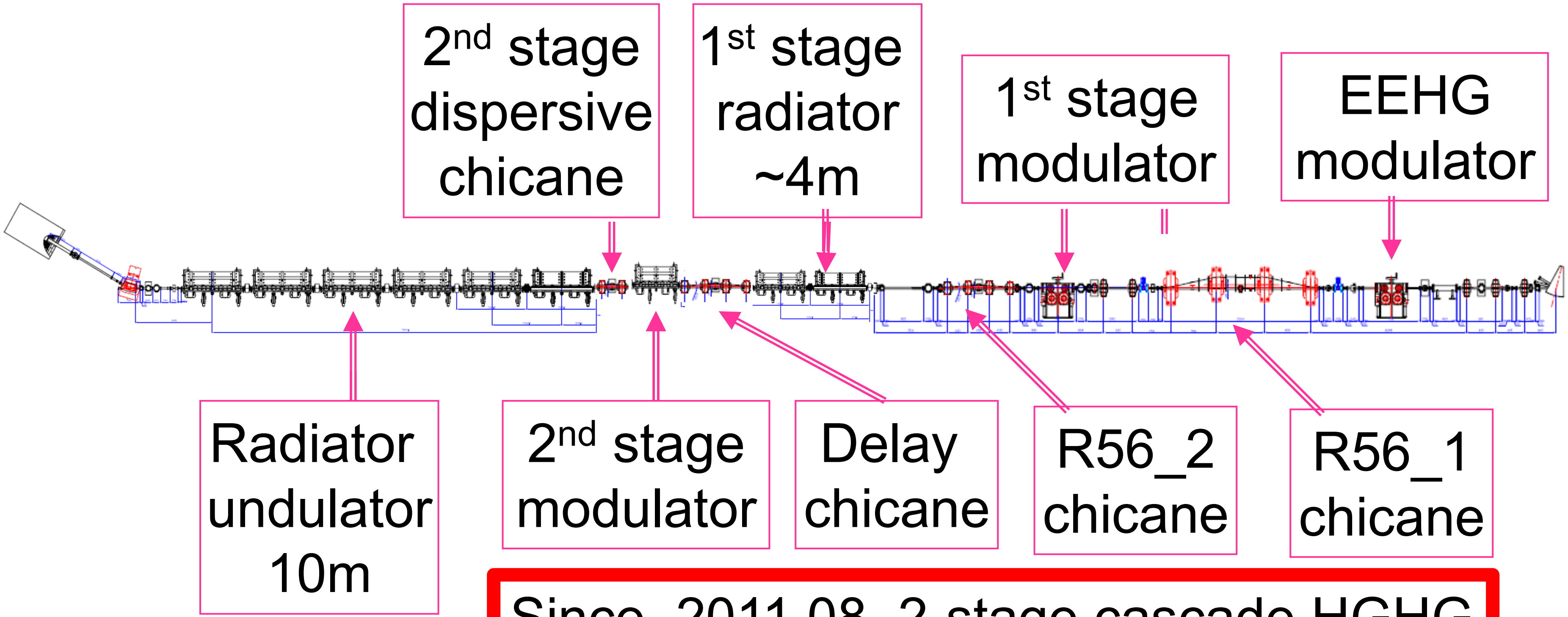
- 2009.04-08: Linac commissioning
- 2009.09-12: SASE experiments, gain curve obtained
- 2010.05: Seeded FEL experiments start
- 2010.05.17: HGHG signal
- 2010.05.22: Echo signal
- 2010.07-08: Installation for radiator undulators
- 2010.12: HGHG saturation (349nm)
- 2011.04: EEHG saturation (349nm)
- 2011.05-07: Cascaded HGHG installation
- 2011.8-12: 1st stage exp., Tunable HGHG with OPA
- 2012.1-4: cascade HGHG experiments, coherent signal from 2x2(1200-600-300) observed
- 2012.5: 80MW klystron removed,

Evolution of FEL layout at SDUV

2010.01 ~2011.05, for HGHG & EEHG



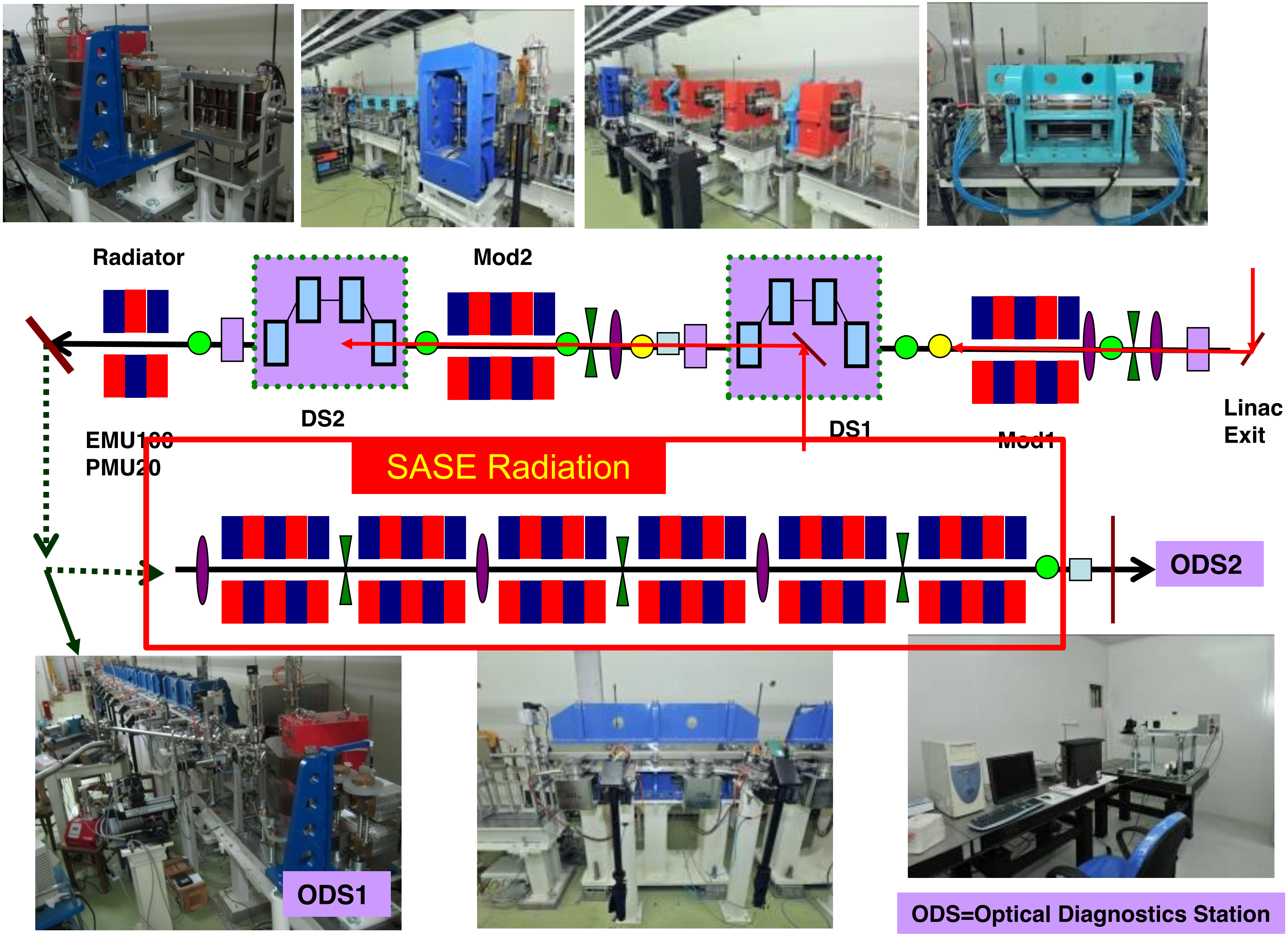
65m-long tunnel is fully occupied now.



Since 2011.08, 2-stage cascade HGHG

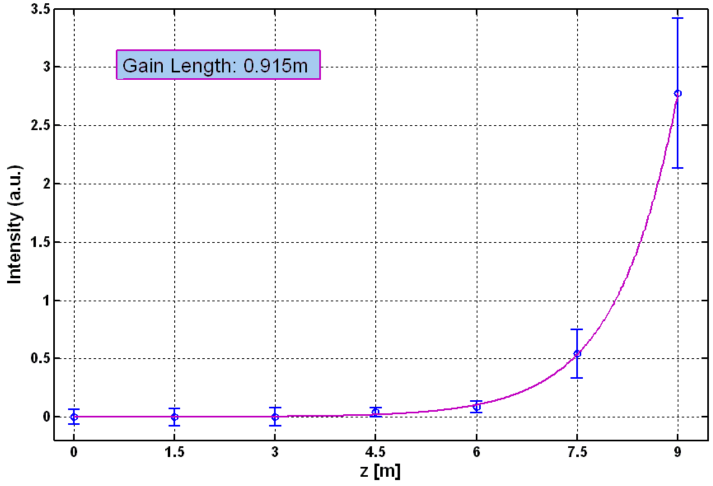
Parameters of SDUV

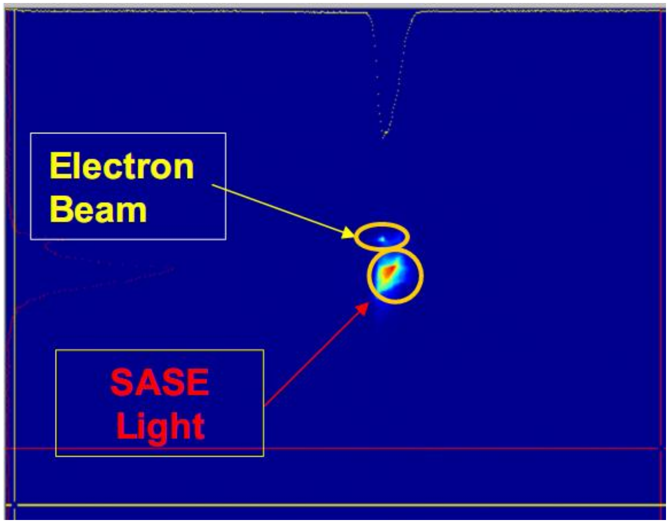
Beam energy	0~200MeV
Beam energy spread (projected)	0.1-0.2%
Normalized emittance	3~5mm-mrad
Bunch charge	100~300pC
Seed laser wavelength	1047nm(Nd-YLF) 800nm(TiS)/1200-2600nm(OPA)
Seed laser pulse length	8ps(Nd-YLF) /35fs/ 130fs/1ps
Seed laser power (1, 2)	~20MW(8ps)/~1GW(130fs)/100MW(OPA)
Modulator1_1 (EMU65)	10*6.5cm,
Modulator1_2 (PMU50)	10*5cm
Modulator2(PMU40)	10*4cm
R56 of dispersion section 1_1	<60mm
R56 of dispersion section 1_2	<10mm
R56 of dispersion section 2	<3mm
Radiator(1st stage):PMU40	2*40*4cm
Radiator(2nd stage): PMU25	6*60*2.5cm

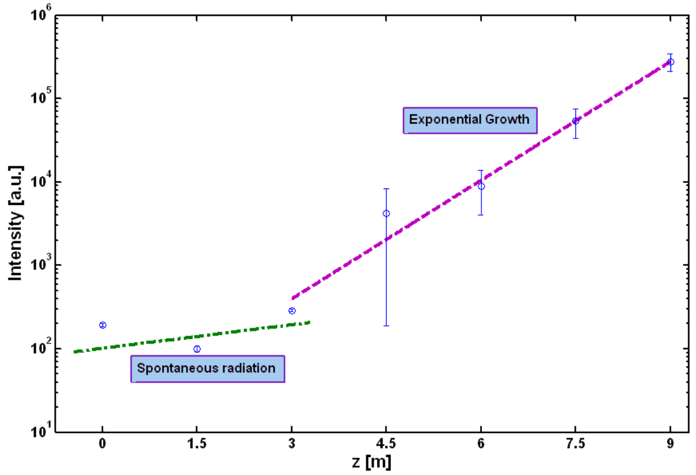


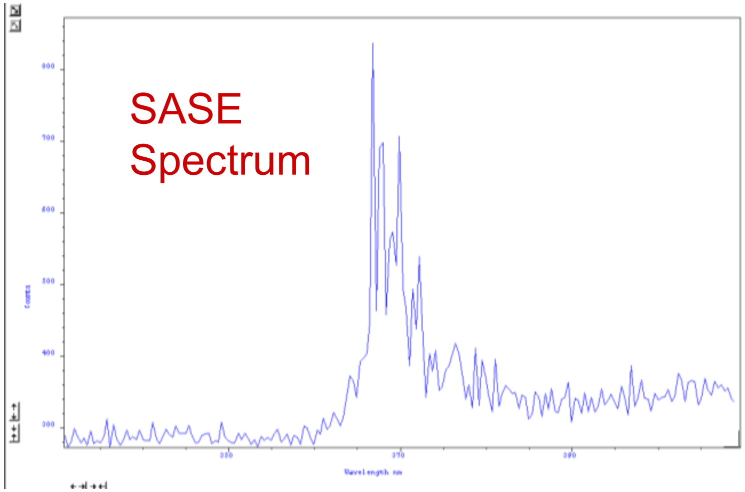
Radiator
Mod2
DS2
DS1
Mod1
Linac
Exit
EMU100
PMU20
SASE Radiation
ODS2
ODS1
ODS=Optical Diagnostics Station

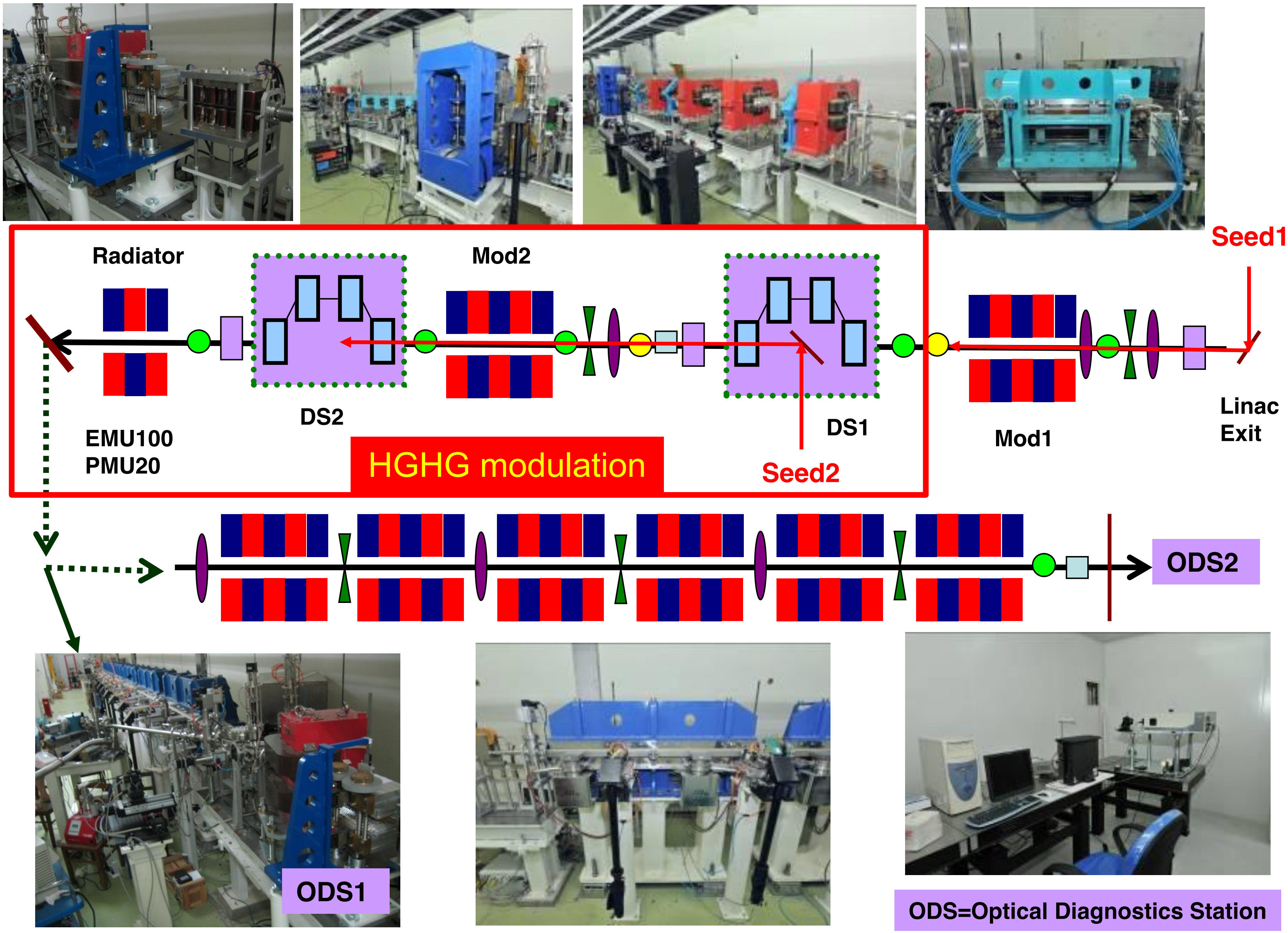
SASE Experimental Results (2009.09-12)







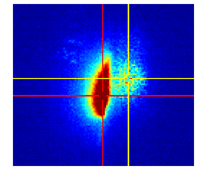




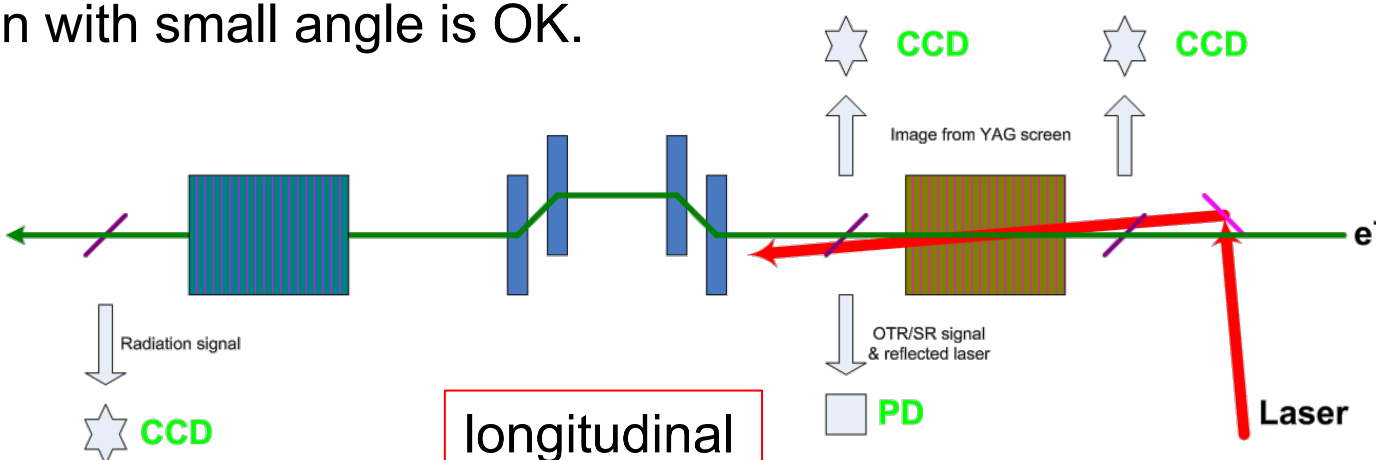
Seed1
Radiator
Mod2
DS2
DS1
Mod1
Linac
Exit
EMU100
PMU20
HGHG modulation
Seed2
ODS2
ODS1
ODS=Optical Diagnostics Station

Overlap of laser and electron beam

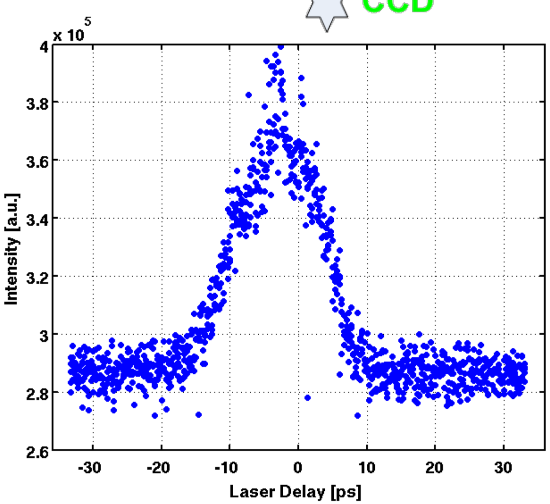
- Laser pulse: 8ps (FWHM)
- Electron bunch: 2 ~ 8ps
- Timing jitter is NOT an issue
- Injection with small angle is OK.

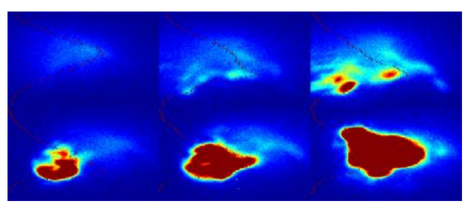


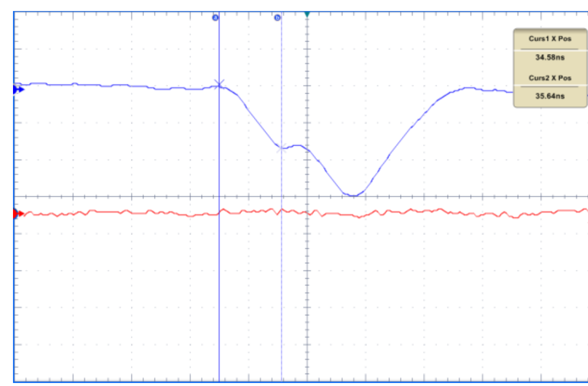
transverse overlap



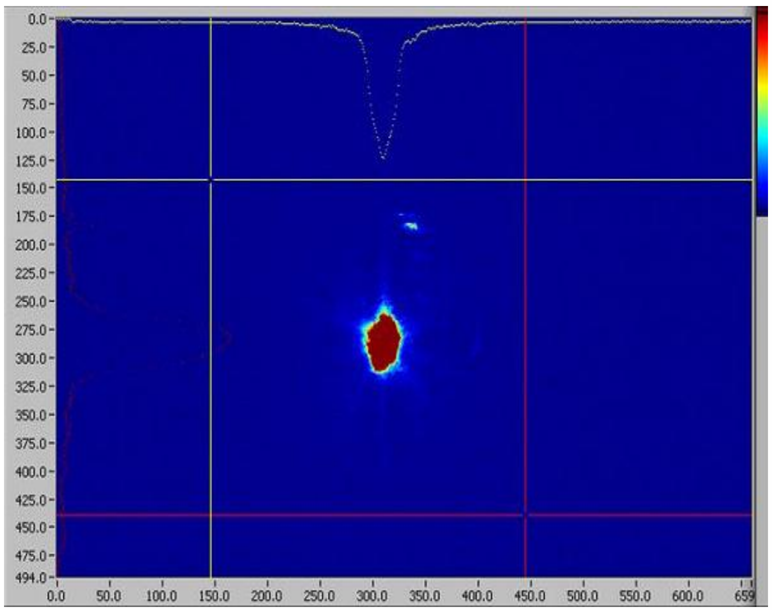
longitudinal overlap



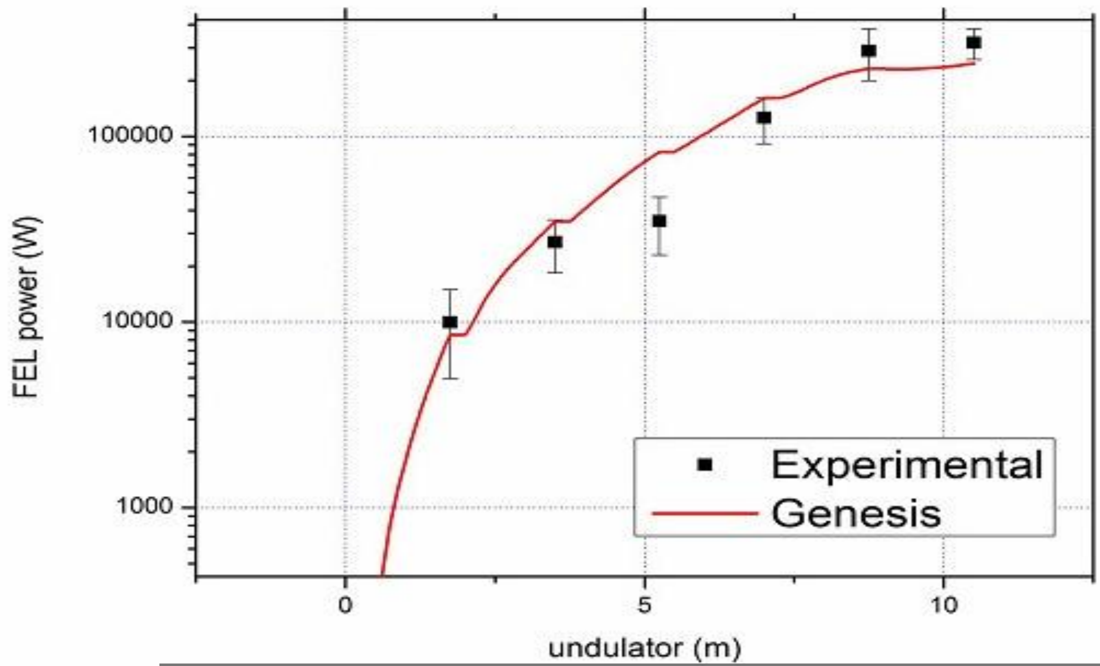




HGHG saturation at the 3rd harmonic of the seed laser

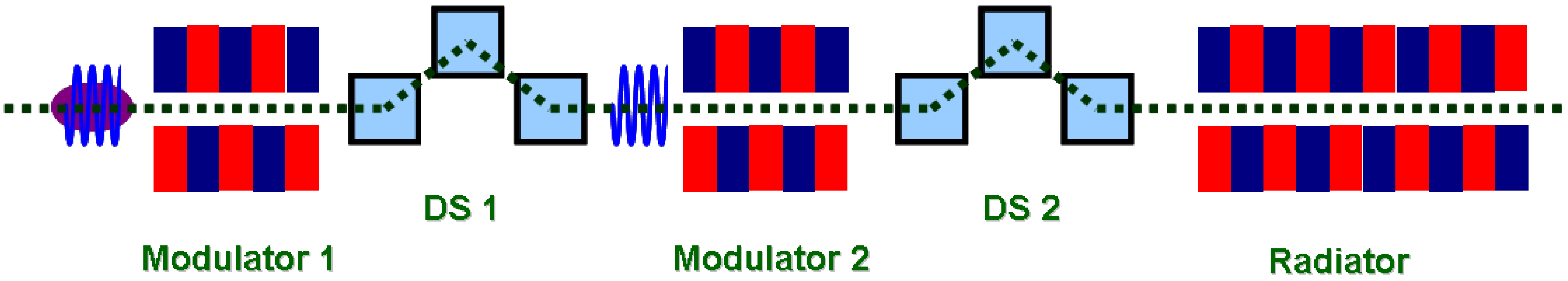


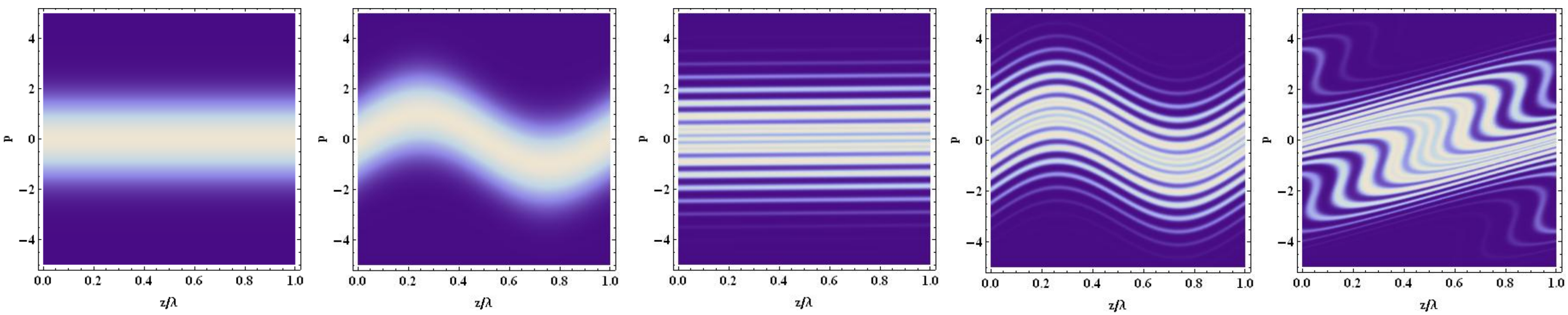
HGHG radiation at 349nm

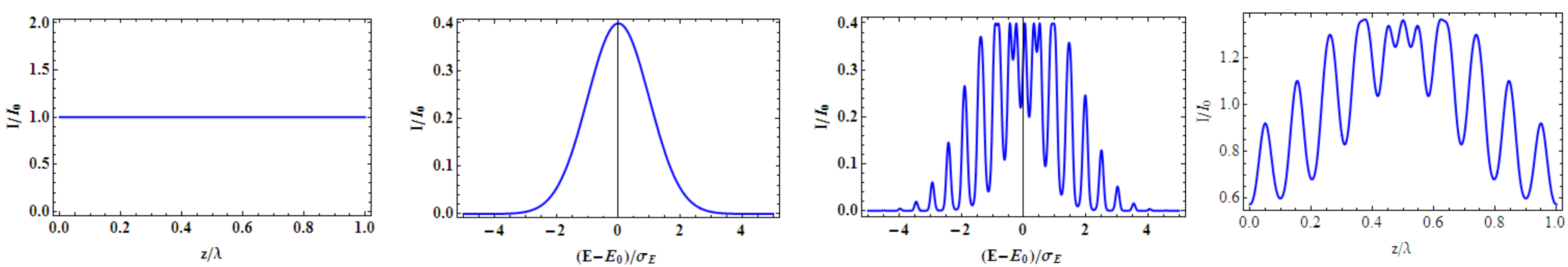


The average power of 3rd harmonic saturates after five undulator sections (8m).

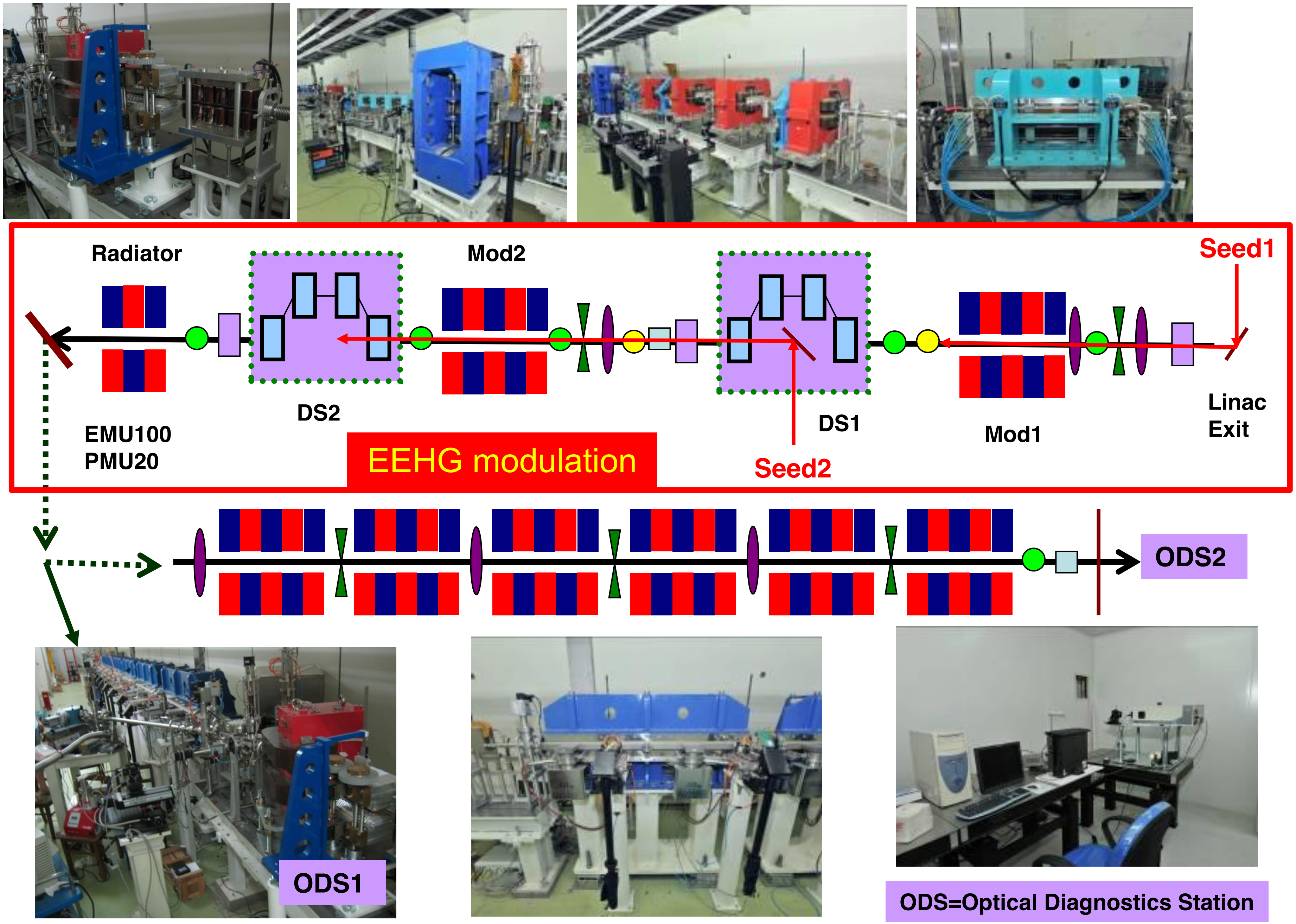
EEHG Principle







G. Stupakov, PRL 102, 074801 (2009)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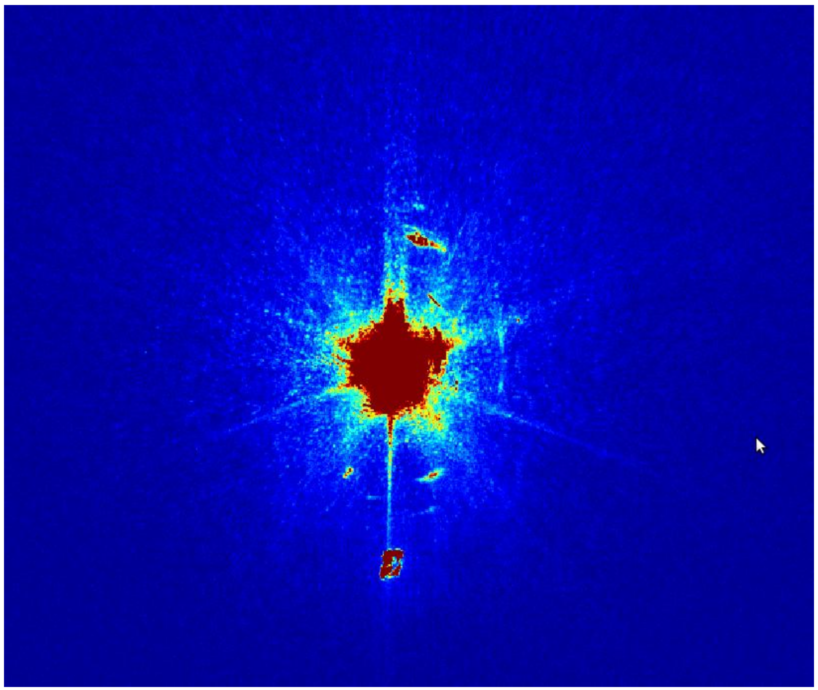
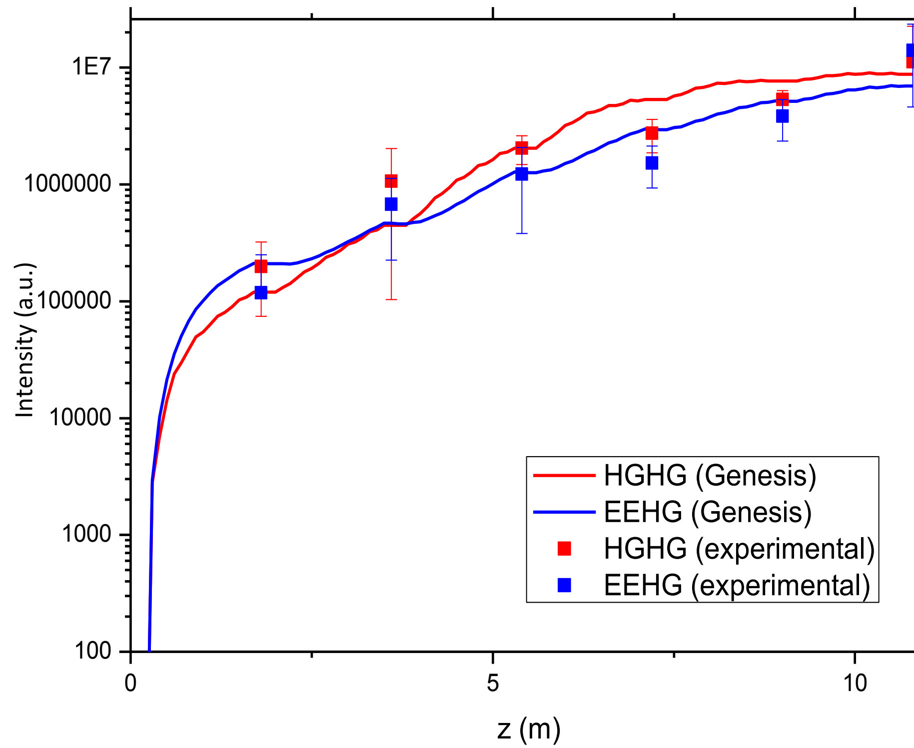
Mod1
EMU100
PMU20
EEHG modulation
Seed2
ODS2
ODS1
ODS=Optical Diagnostics Station

First lasing of EEHG FEL (3rd harmonic, 2011.4)

The EEHG signal have been successfully amplified by the long radiator of SDUV



The EEHG radiation



Gain curves of HGHG and EEHG

SINAP

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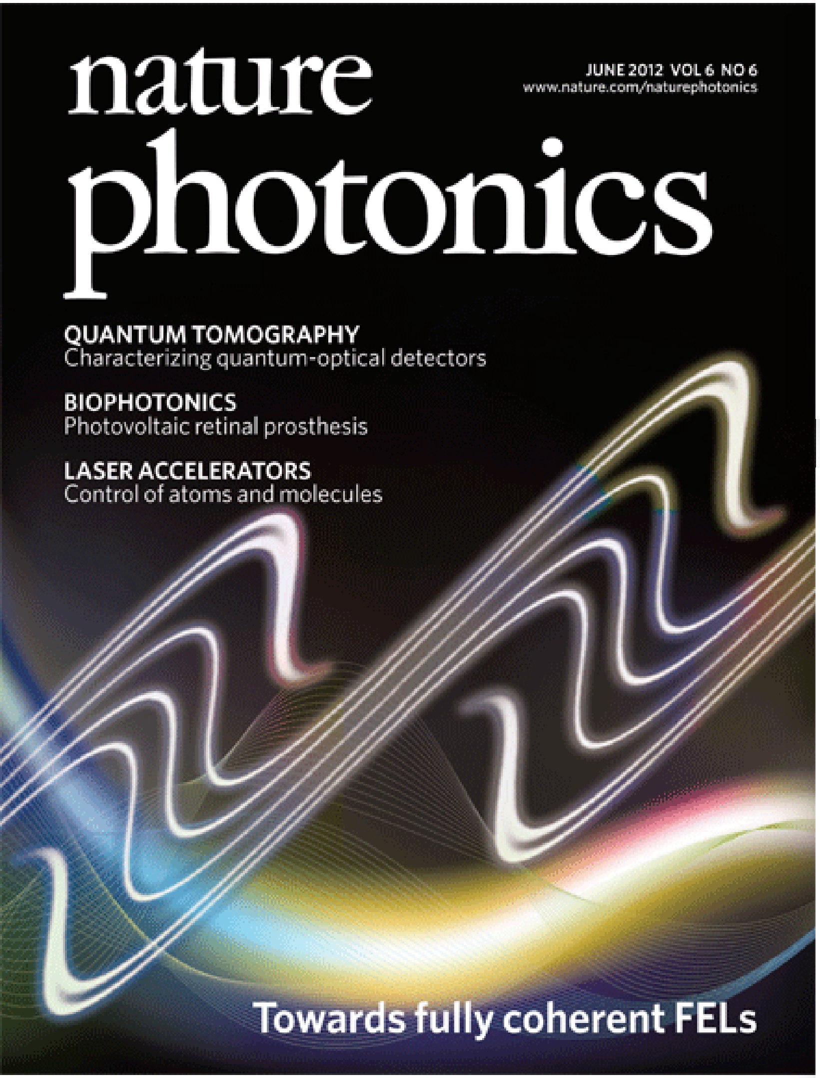

LETTERS
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nature photonics

First lasing of an echo-enabled harmonic generation free-electron laser

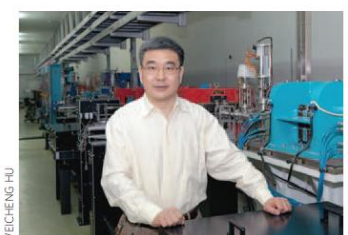
Z. T. Zhao[1]*, D. Wang[1], J. H. Chen[1], Z. H. Chen[1], H. X. Deng[1], J. G. Ding[1], C. Feng[1], Q. Gu[1], M. M. Huang[1], T. H. Lan[1], Y. B. Leng[1], D. G. Li[1], G. Q. Lin[1], B. Liu[1], E. Prat[2], X. T. Wang[1], Z. S. Wang[1], K. R. Ye[1], L. Y. Yu[1], H. O. Zhang[1], J. Q. Zhang[1], Me. Zhang[1], Mi. Zhang[1], T. Zhang[1], S. P. Zhong[1] and Q. G. Zhou[1]

interview

Towards full-coherence FELs

Zhentang Zhao from the Shanghai Institute of Applied Physics spoke with *Nature Photonics* about how he and his co-workers achieved first lasing in an echo-enabled harmonic generation free-electron laser.

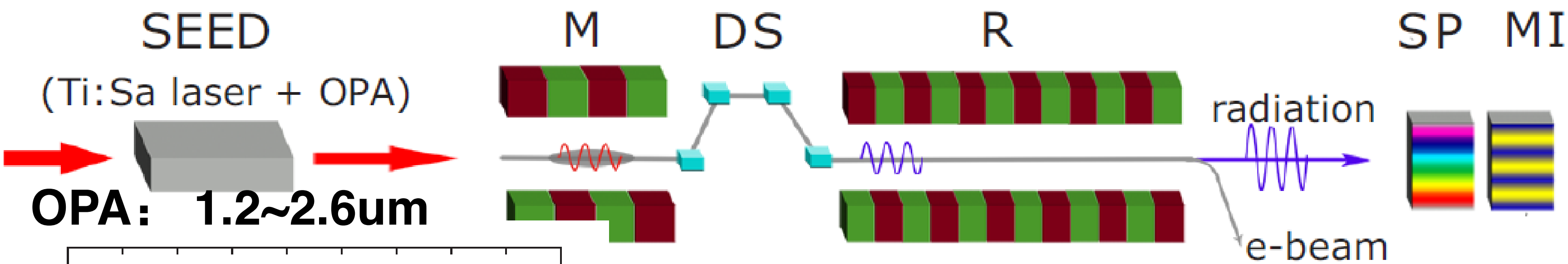
What is your work about?
We have experimentally demonstrated first lasing from an echo-enabled harmonic generation (EEHG) free-electron laser (FEL) — a feat that could lead to the development of full-coherence FELs with short wavelengths and very high intensities. We performed our work using the Shanghai deep ultraviolet free-electron laser (SDUV-FEL) at the Shanghai Institute of Applied Physics (SINAP), which consists of a 135.4 MeV electron accelerator and an amplifier composed of a series of undulator magnets. The EEHG concept was first proposed in 2009 by Gennady Stupakov, a distinguished accelerator physicist at the


WEICHENG HU

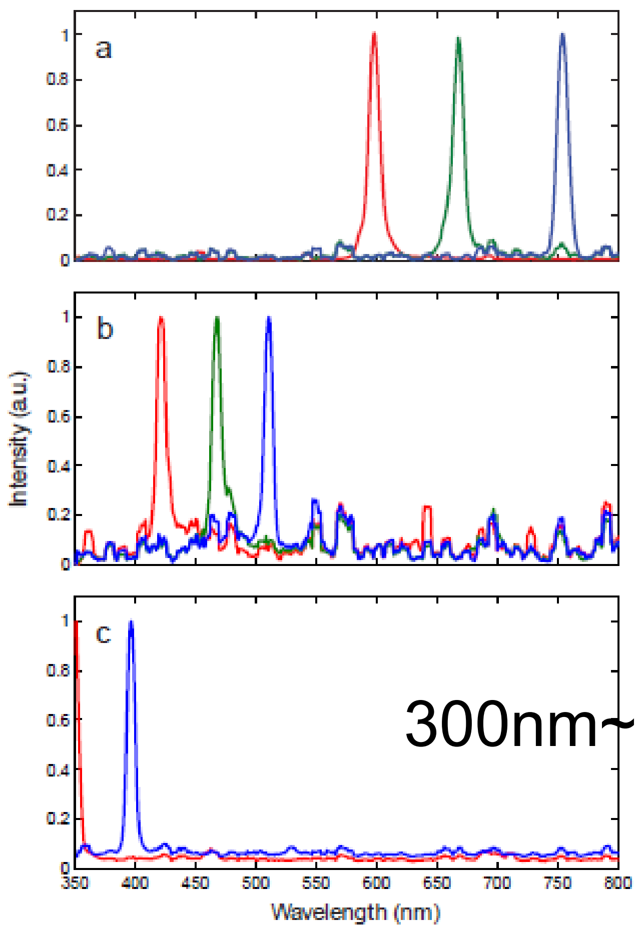
Zhentang Zhao inside the SDUV-FEL facility, where first lasing of the EEHG FEL scheme was demonstrated.

What are the potential applications and challenges of your technique?
Given its advantage of remarkable upconversion efficiency at higher harmonics, the EEHG scheme is promising for generating fully coherent radiation at soft-X-ray wavelengths from conventional lasers that have only a single seeding stage. Such full-coherence X-ray pulses will benefit many applications, including soft-X-ray resonant inelastic scattering, spectroscopic studies of correlated electron materials, and holographic, diffractive or lensless imaging. The challenges lie in demonstrating EEHG at very high harmonics, where its advantages over other

Wide tuning of wavelength of HGHG

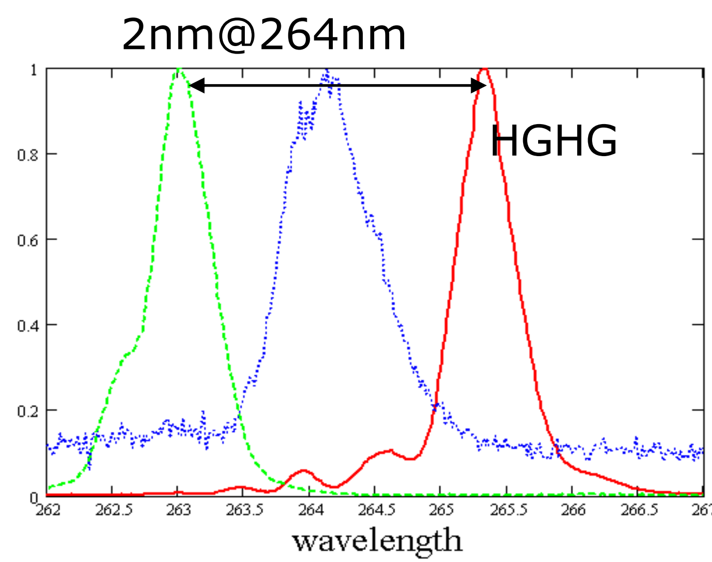


OPA： 1.2~2.6um



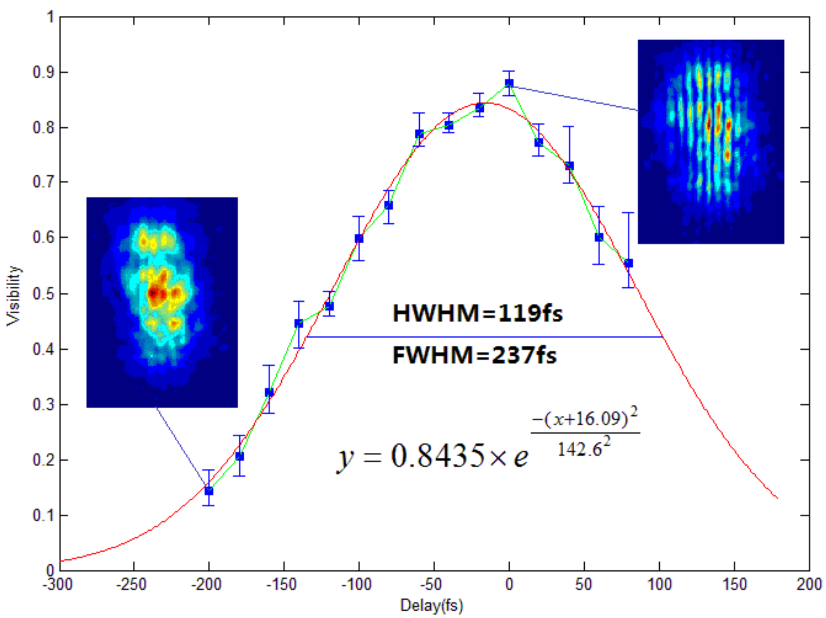
300nm~0.8um

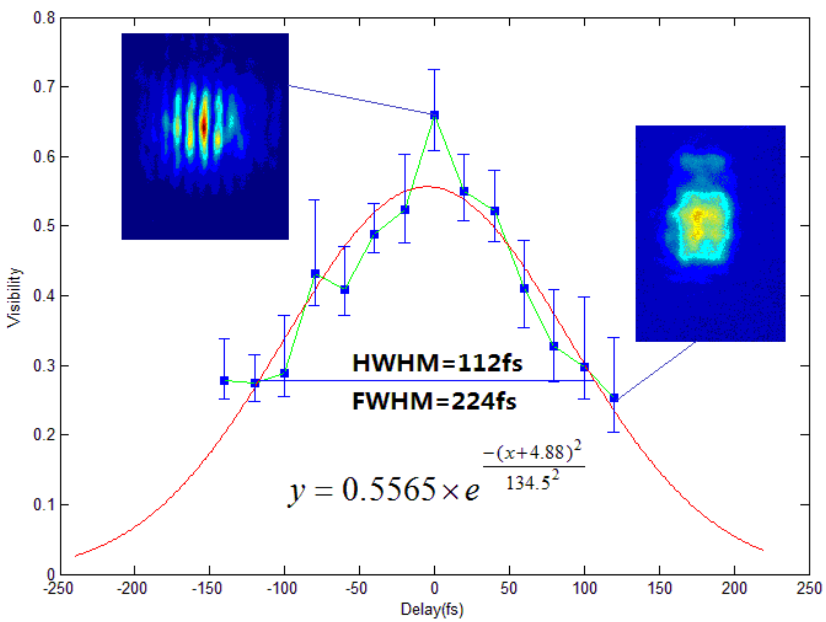
Before: BNL SDL FEL
w/beam chirp: + - 1nm only



Measurement of temporal coherence

Measurement of the temporal coherence of the FEL output (shown is the second harmonic) with double-slit interference ,
Lift: 600nm wavelength case, Right: 400nm wavelength case





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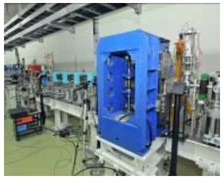
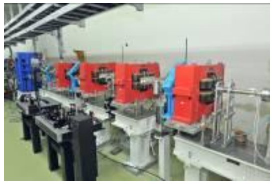
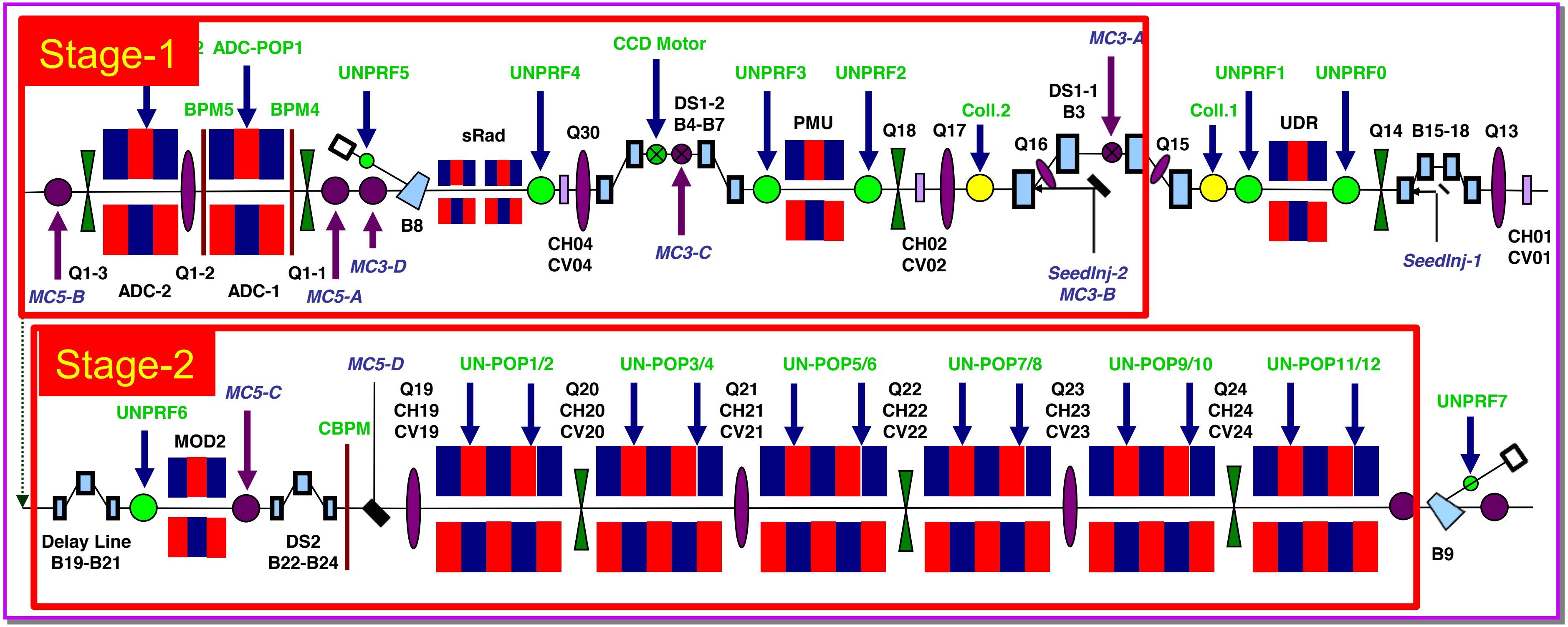
Shanghai Institute of Applied Physics, Chinese Academy of Sciences
SINAP

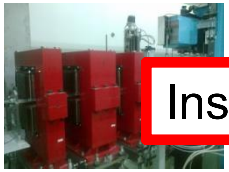
Cascaded HGHG Layout

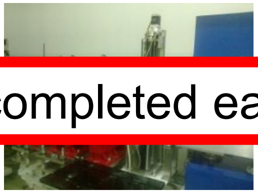




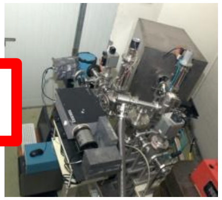




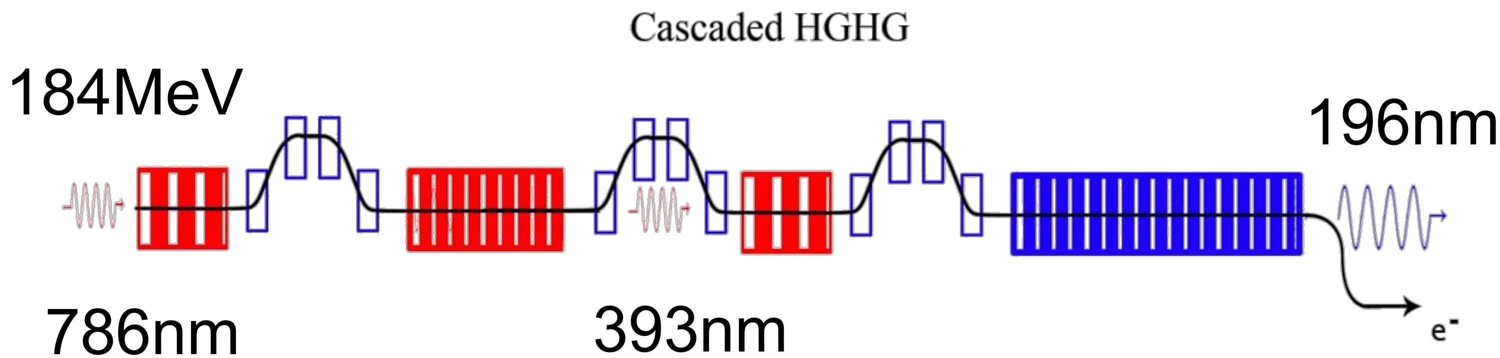






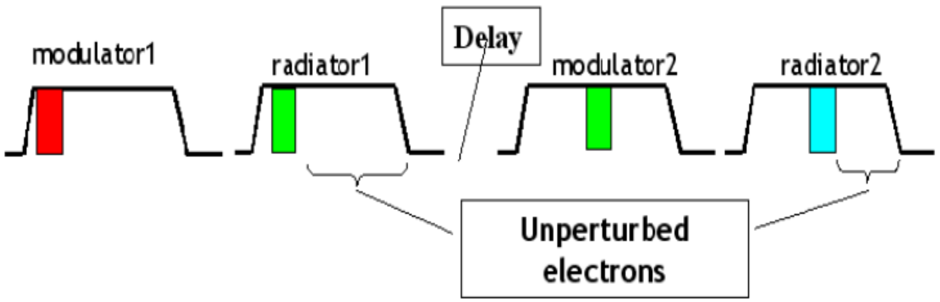
Installation completed early August, and experiments are ongoing.

Two-stage Cascaded HGHG at Upgraded SDUV-FEL



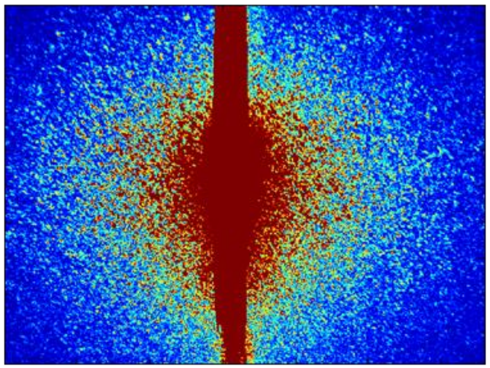
With OPA, now it is often 1200-600-300nm

Fresh bunch technique:

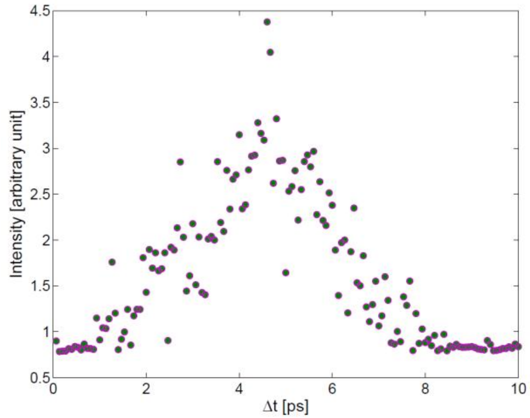


First Results

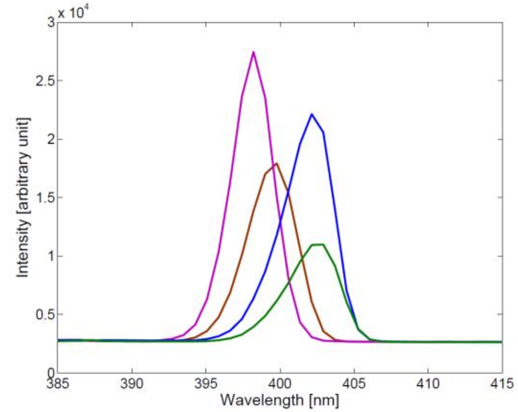
First stage



From CCD



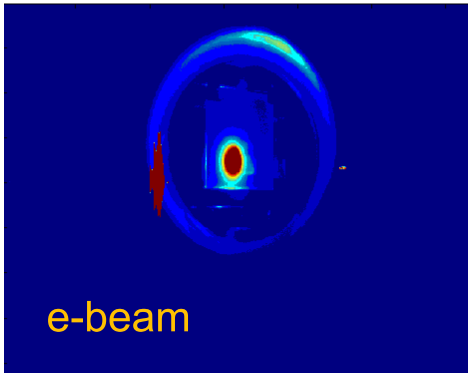
Timing scan

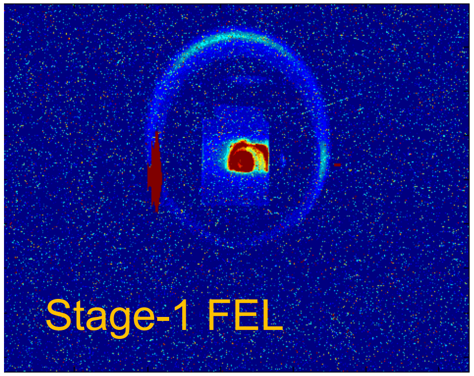


Spectrum: 390-400nm

2^{nd} Stage Modulation using first stage FEL radiation

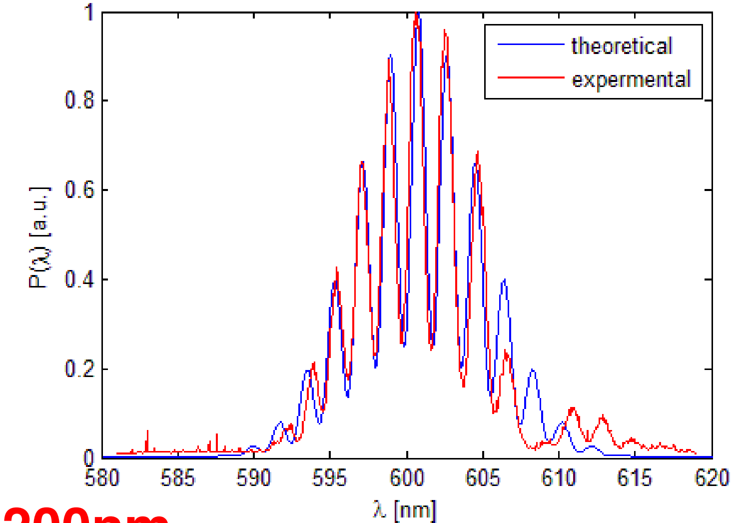
Transverse Overlaping

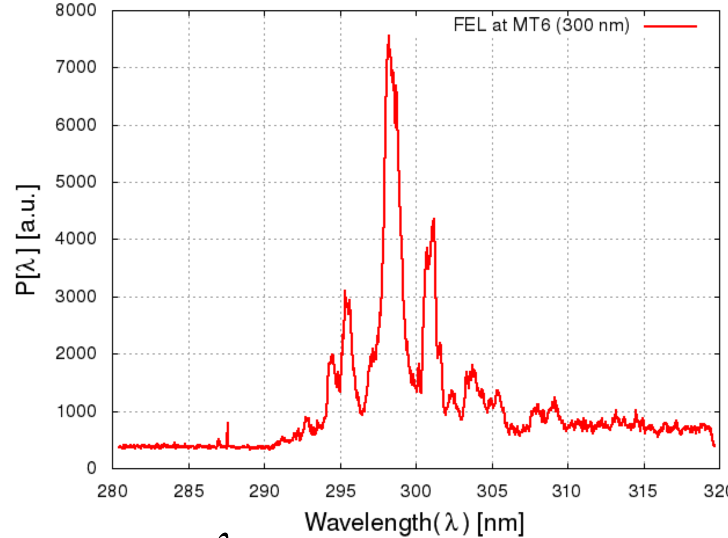




Beam spots before the modulator of the 2^{nd} stage

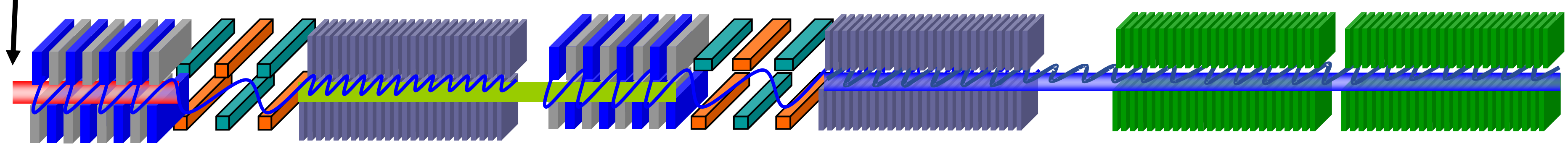
Cascade HGHG experiment





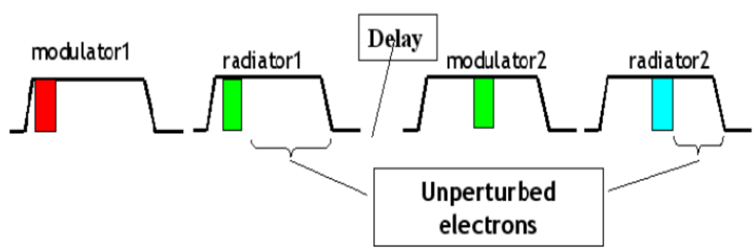
1200nm Seed-Laser λ $\lambda_1=\frac{\lambda}{n}$ **600nm** $\lambda_2=\frac{\lambda}{n\times m}$ **300nm** $\lambda_f=\lambda_2$

150MeV



1st Stage 2nd Stage Final Amplifier

fresh bunch technique



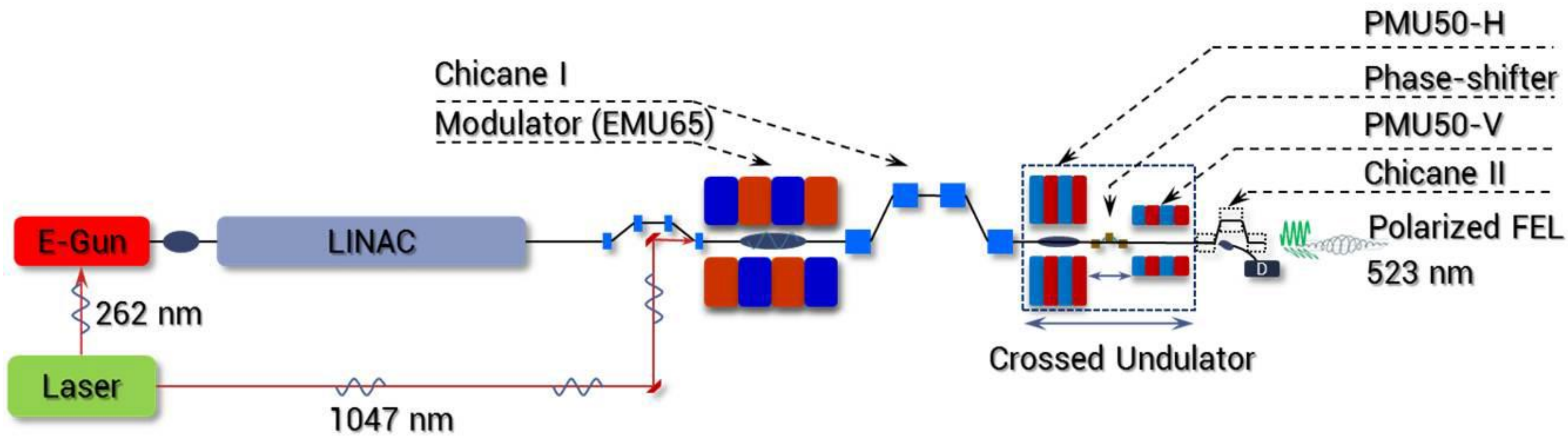
Plan for near future

- one major klystron (80MW) missing since June
- new klystron(50MW) may come next June
- new gun should come in 2 months

Next FEL experiments

- polarization control with crossing undulator
- cascade HGHG experiment with new gun
- EEHG modulation at 15-20th harmonics
- EEHG FEL amplification at 10th harmonic
- TGU for large energy spread?

Polarization control with crossed undulators

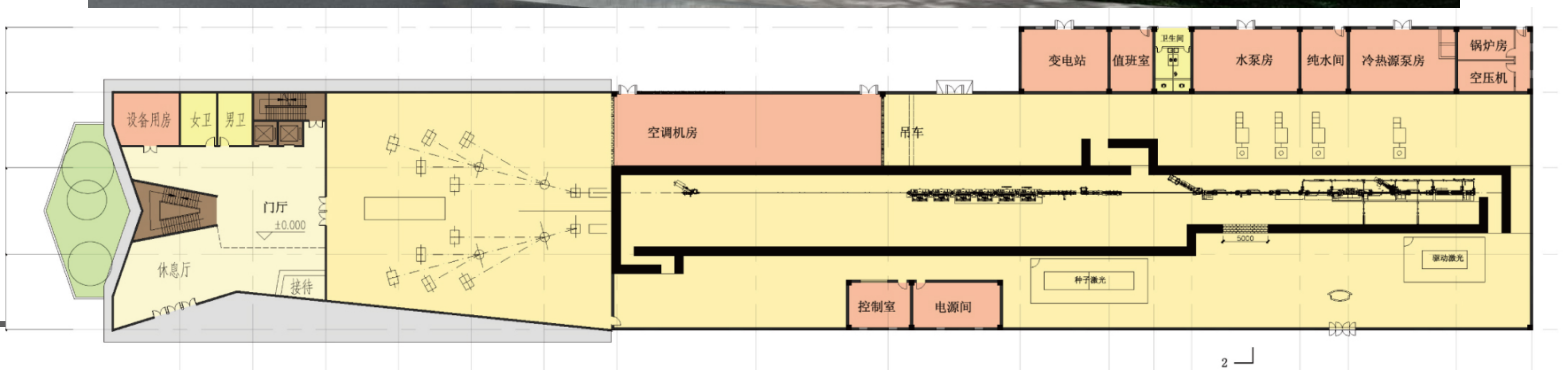


Dalian Coherent Light Source(DCLS):

Dalian EUV/VUV FEL

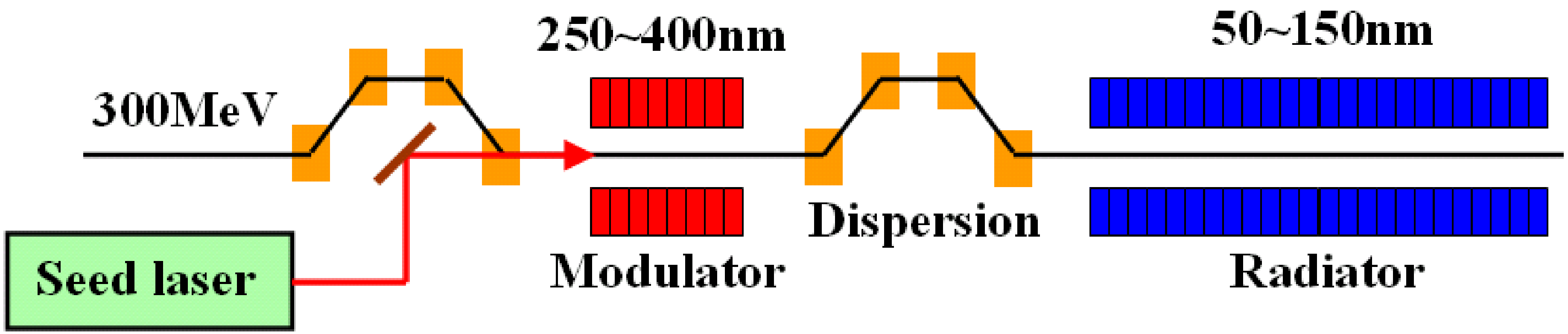
- Joint proposal by DICP-SINAP since 2009, **IR=>VUV**
- Funded by NSFC, December, 2011
- Carried out jointly by Dalian Inst of Chemical Physics, CAS (beam-line, experimental stations) and **SINAP, CAS (Free Electron Laser)**
- Seeded FEL(HGHG), 50-150nm tunable, 50Hz rep rate.
- fs-ps pulse lengths, GW peak power
- Scheduled for 2012-2015, in parallel to SXFEL, similar technology

DCLS: unique VUV source



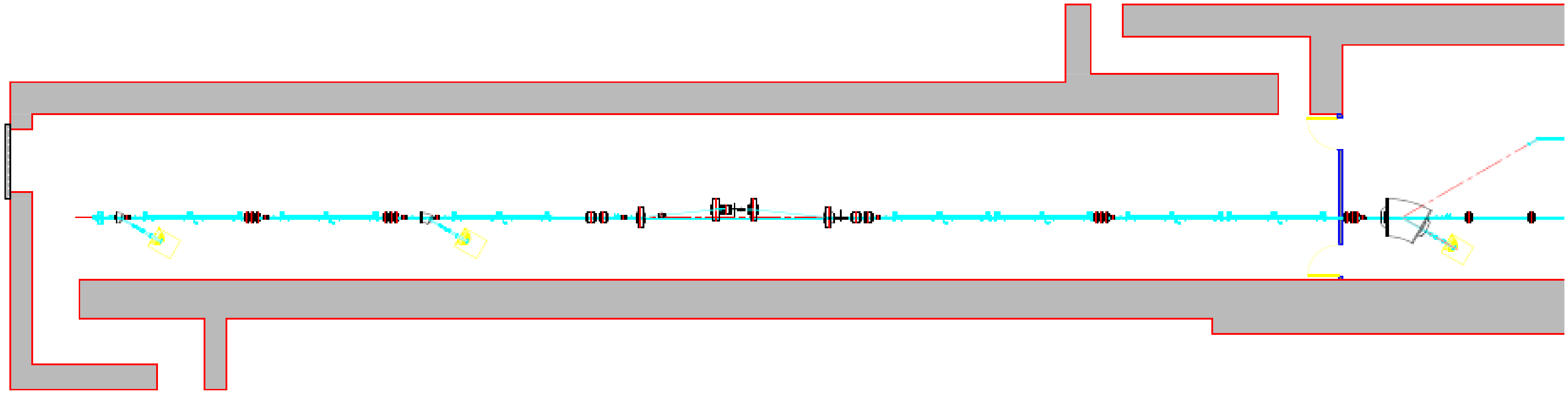
Seeding scheme: HGHG

- Choice of FEL scheme: high gain harmonic generation（HGHG）, **fully coherent, tunable and brilliant FEL**
- well proved, comfortable for laser seed at EUV



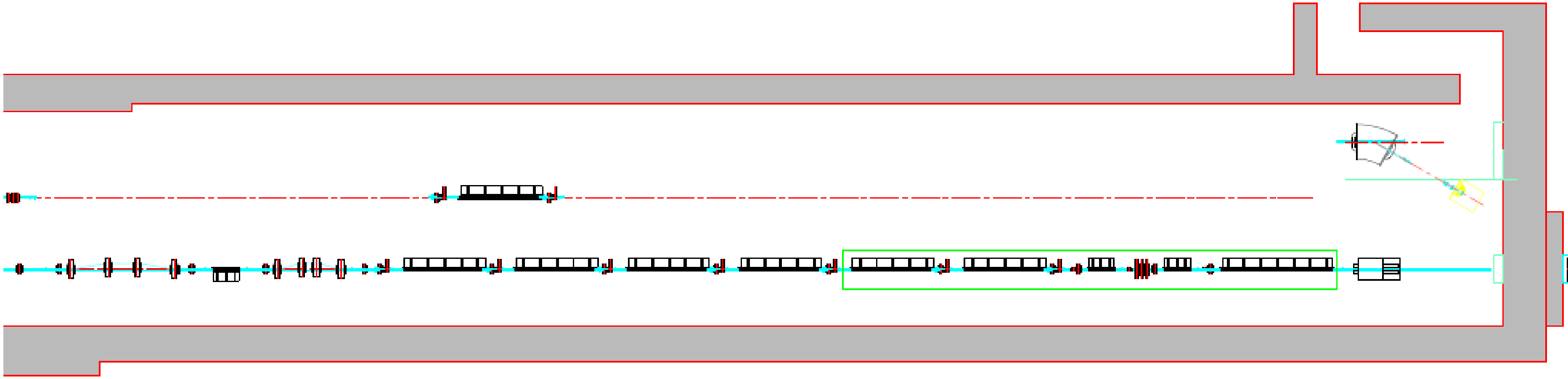
300 MeV linac + laser modulation + FEL radiator

DCLS：linear accelerator



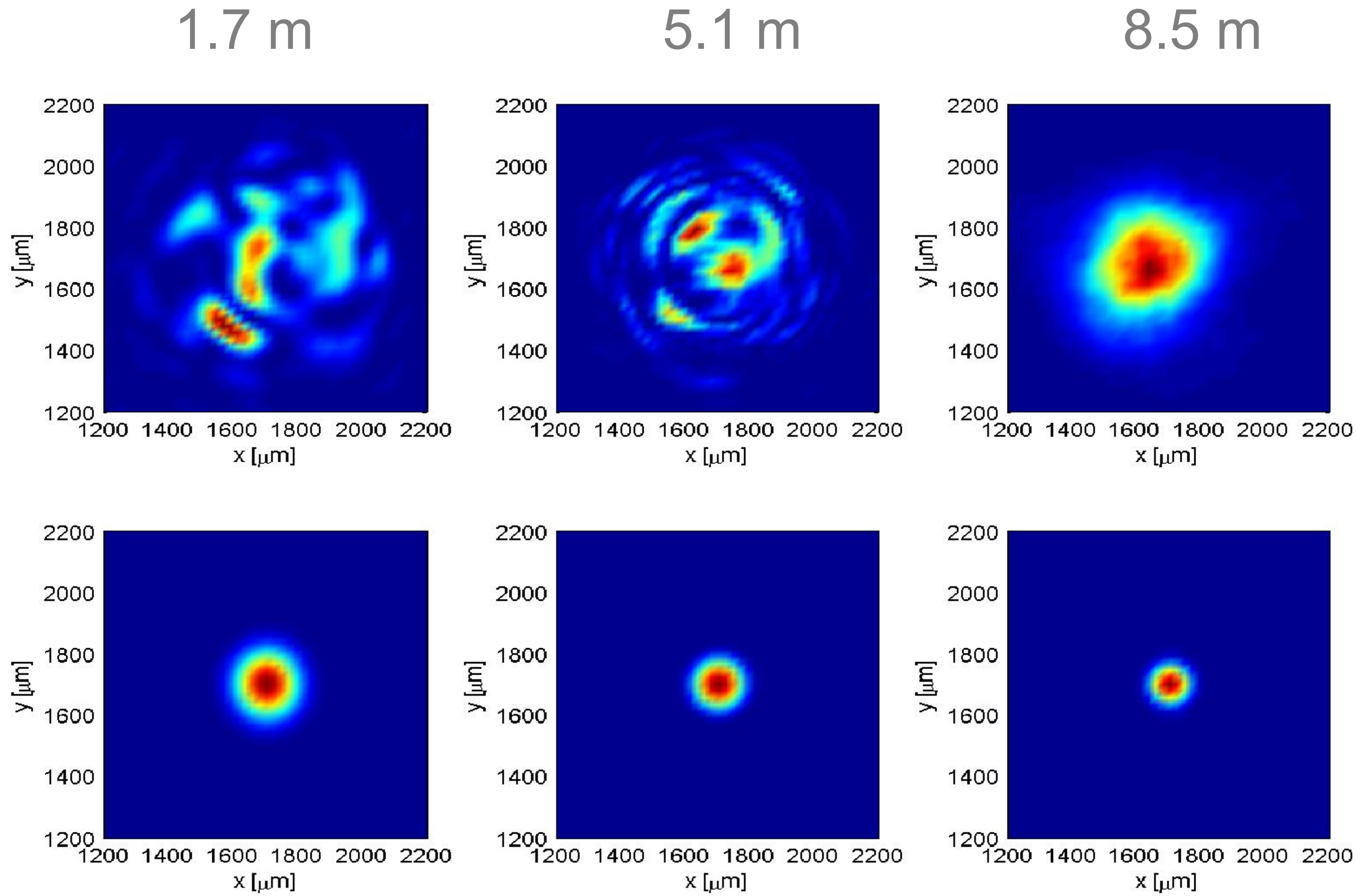
- 45m long, 300 MeV, copper structure
- photo-cathode gun + bunch compressor, X-band HC
- beam emittance：1-2mm.mrad,
- bunch charge：100-500 pC
- bunch length：200-2000 fs （FWHM）

FEL amplification



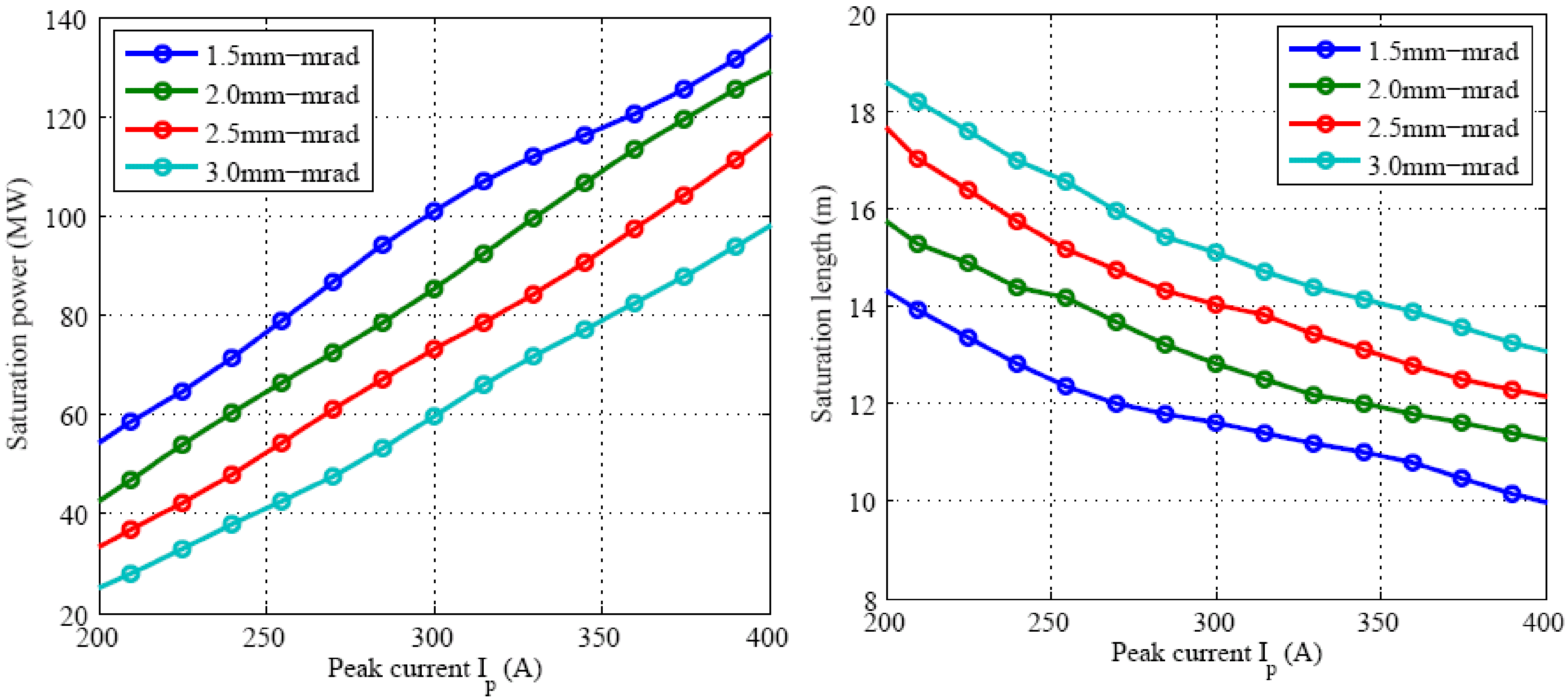
- 55m long: seeding + radiator(12m+6m) +pol.+ IR-THz source
- single-stage HGHG， UV seed, harmonic number：3-6
- tunable pulse-length， ultra-short + narrow-bandwidth mode
- undulators: planar, out-vacuum, lagre tapering
- second FEL line forseen

FEL performance



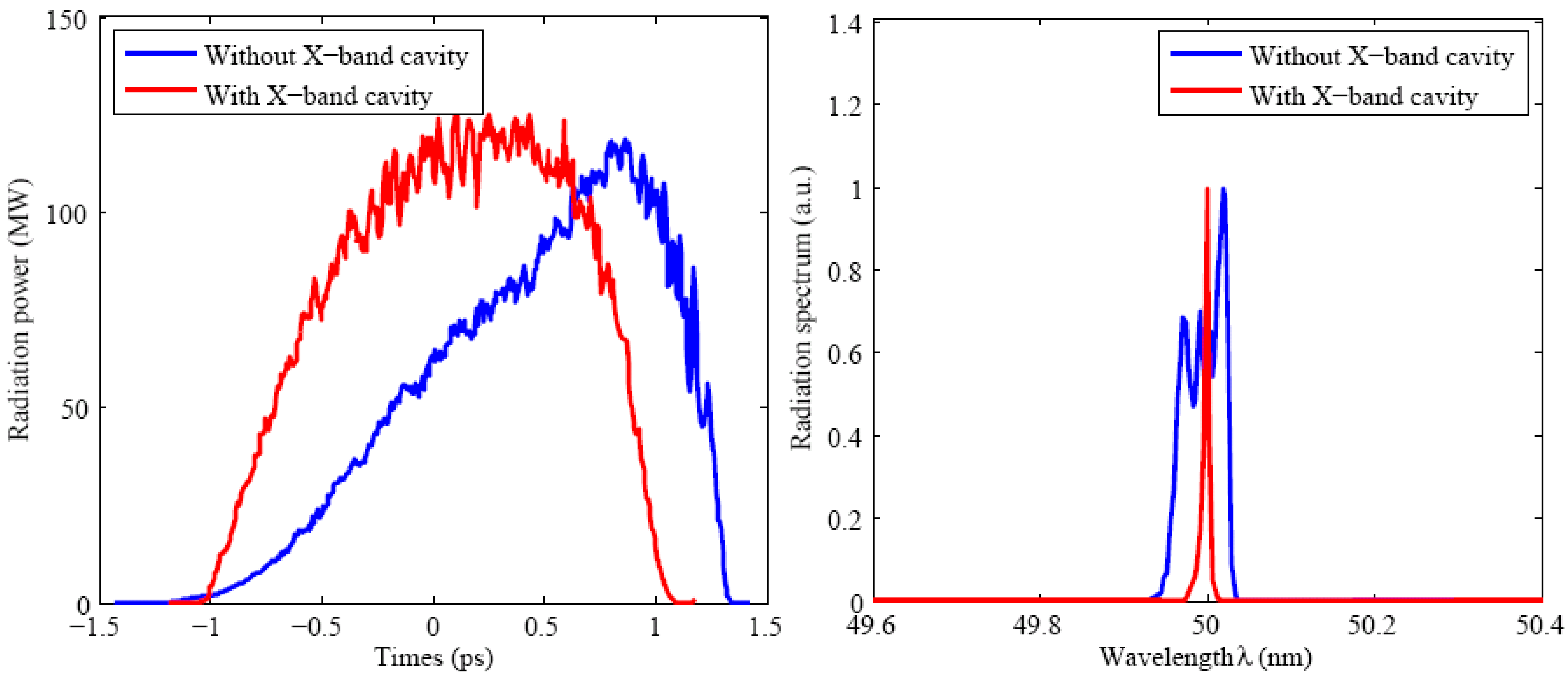
FEL property vs. peak current & emittance

☞ Saturation power and saturation length

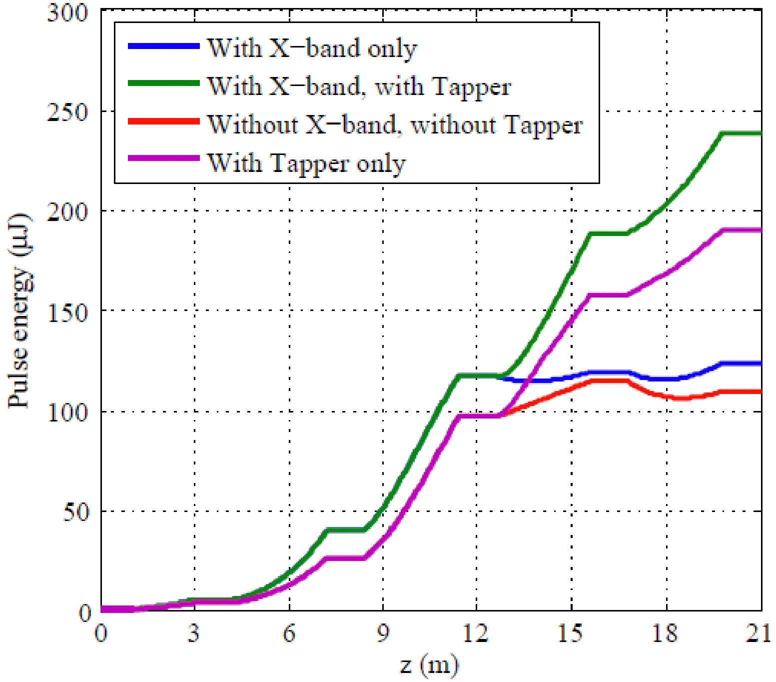


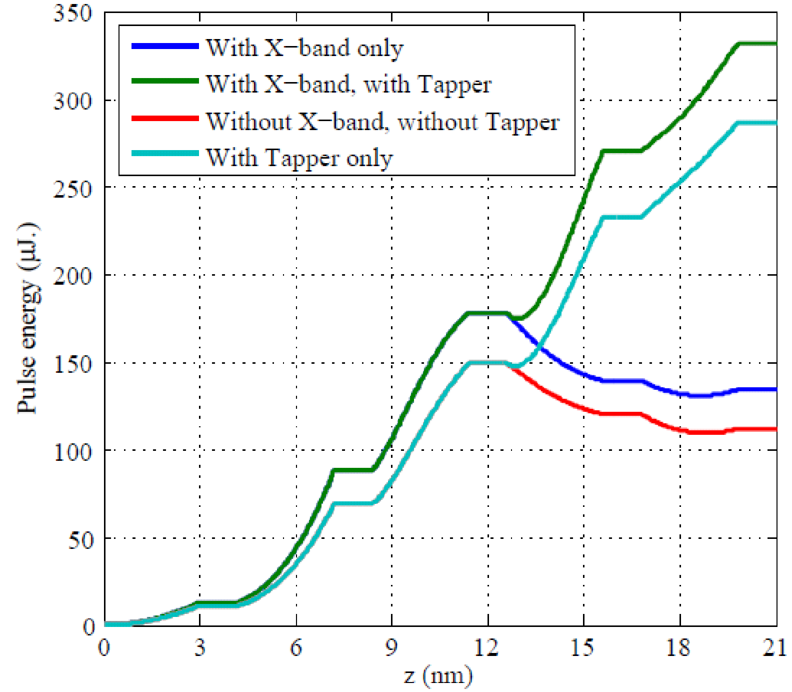
X-band: for better bandwidth

- x-band harmonic cavity, (FEL1 has no x-cav)



Start-to-end simulations



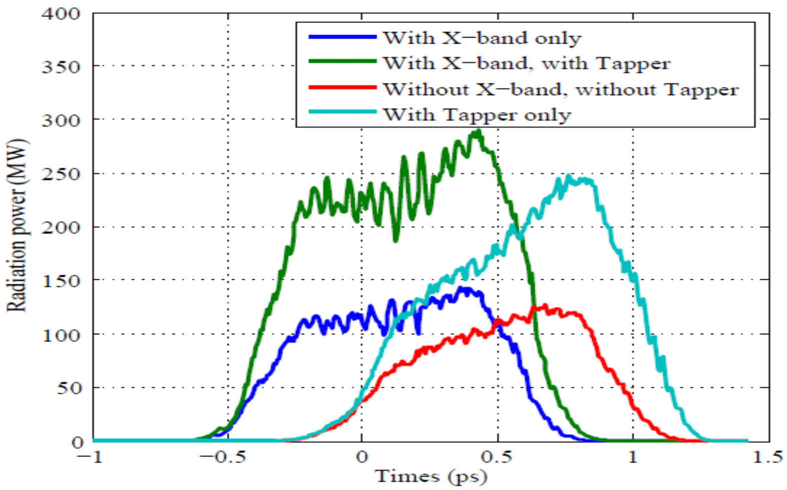


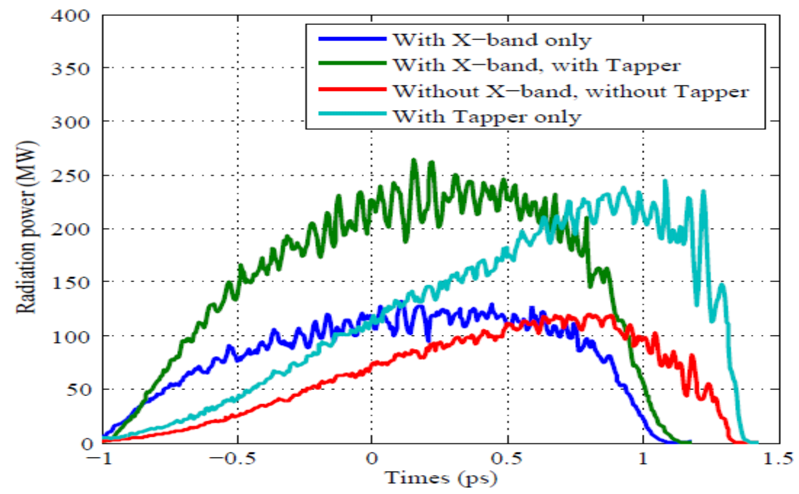
left, 1ps FWHM seed；

right, long seed

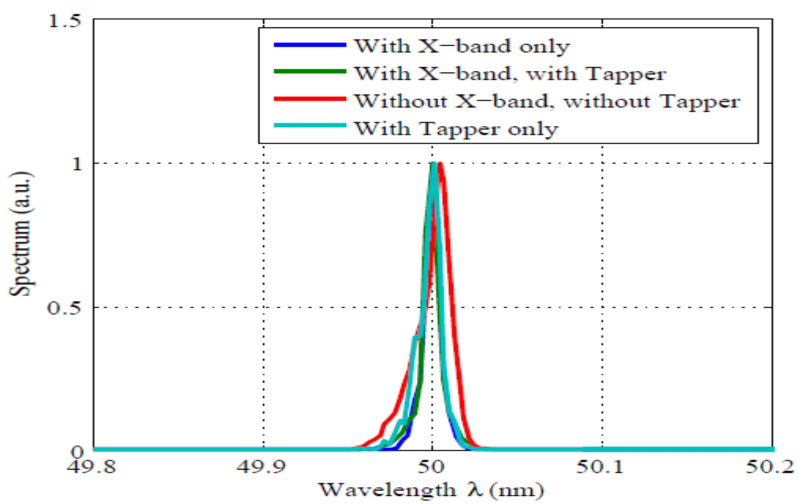
FEL output: 50nm. Longer wavelength should be similar or better.

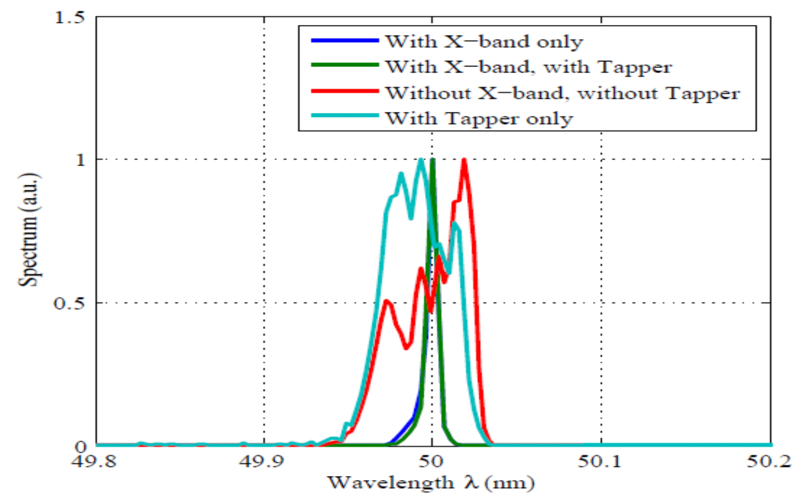
Observations: x-band harmonic cavity and tapering are quite beneficial





FEL radiation power and spectrum simulations.





DCLS FEL: technical issues

☞ advanced yet mature approaches

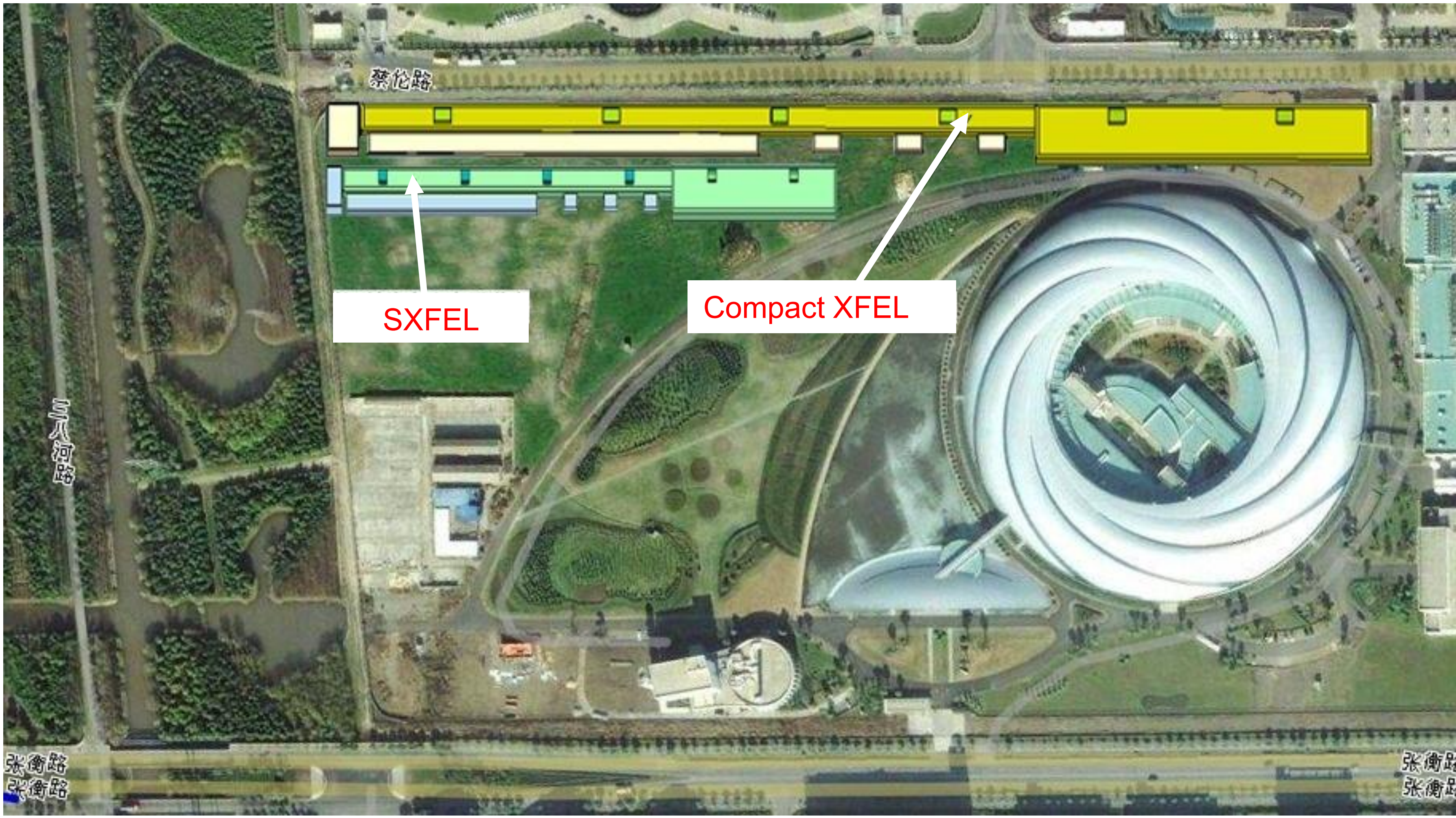
Gun ：	s-band Cu photo-injector
Accelerator：	s-band linac
FEL undulator：	planar, out-vacuum, variable gap
Beam instrument.：	cavity-BPM + profile monitor
Synchronization：	10 fs precision based on fiber laser techniques
Seed laser：	Ti-Sa system + OPA
Alignment：	moving quads + Beam-BA + Photon-BA

- most techniques tested on SDUV

Shanghai Soft- X-ray FEL:

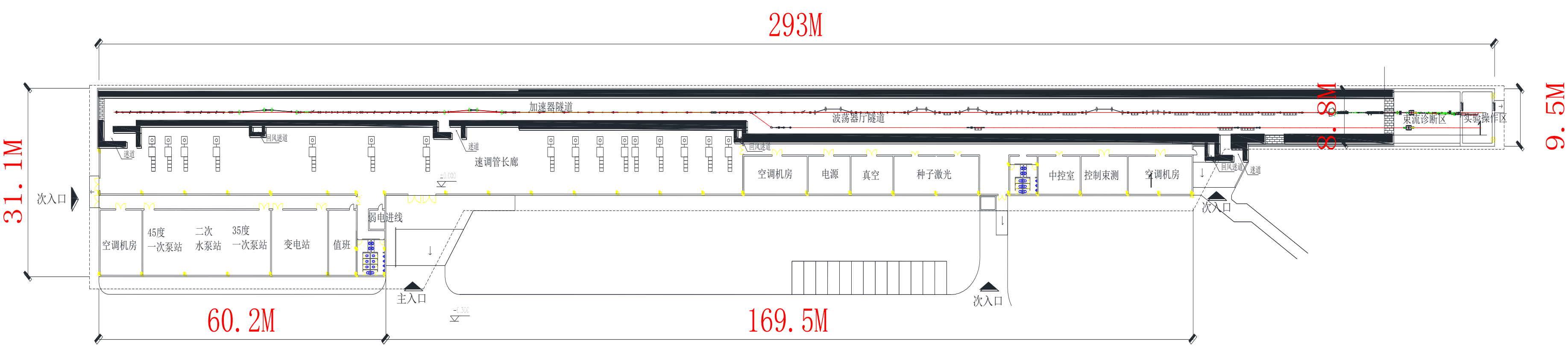
Shanghai Institute of Applied Physics(SINAP):
Accelerator-based Photon Science Center of China

SINAP future FEL projects



Shanghai soft X-ray FEL(SXFEL)

- approved in early 2011
- built at SINAP, 300m long， ~1GeV linac, 9nm FEL
- complete in 2015, FEL test facility

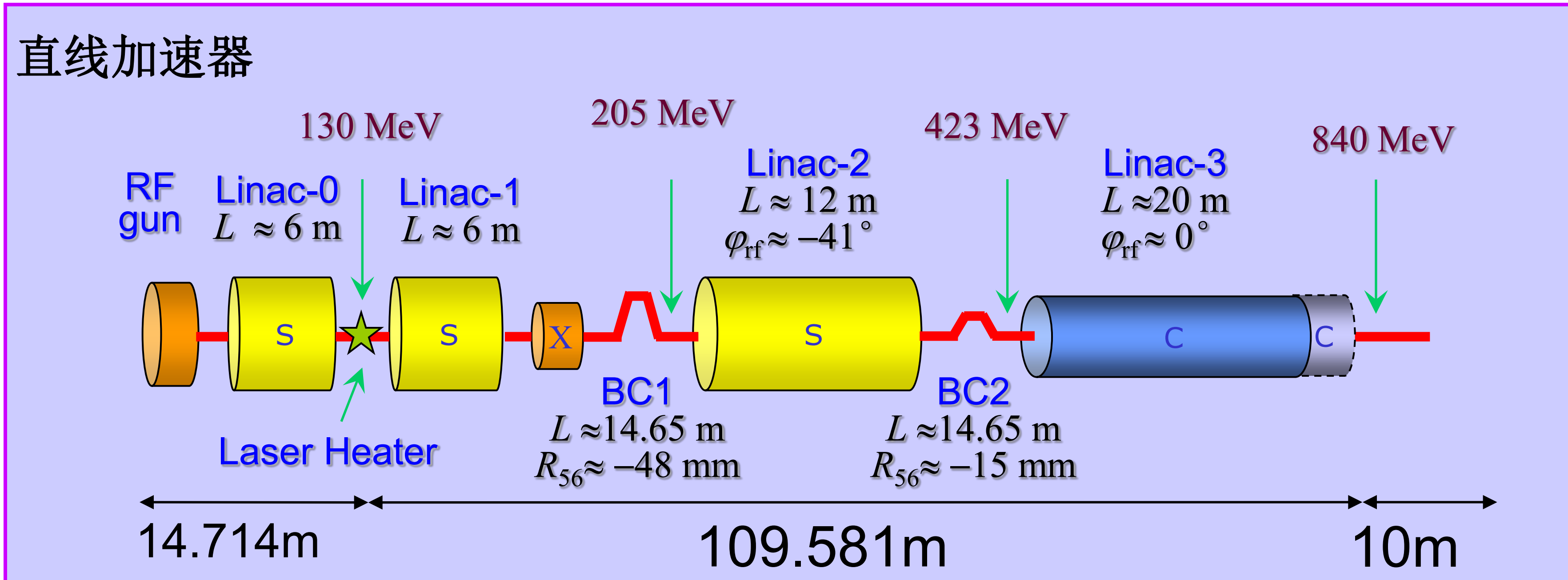


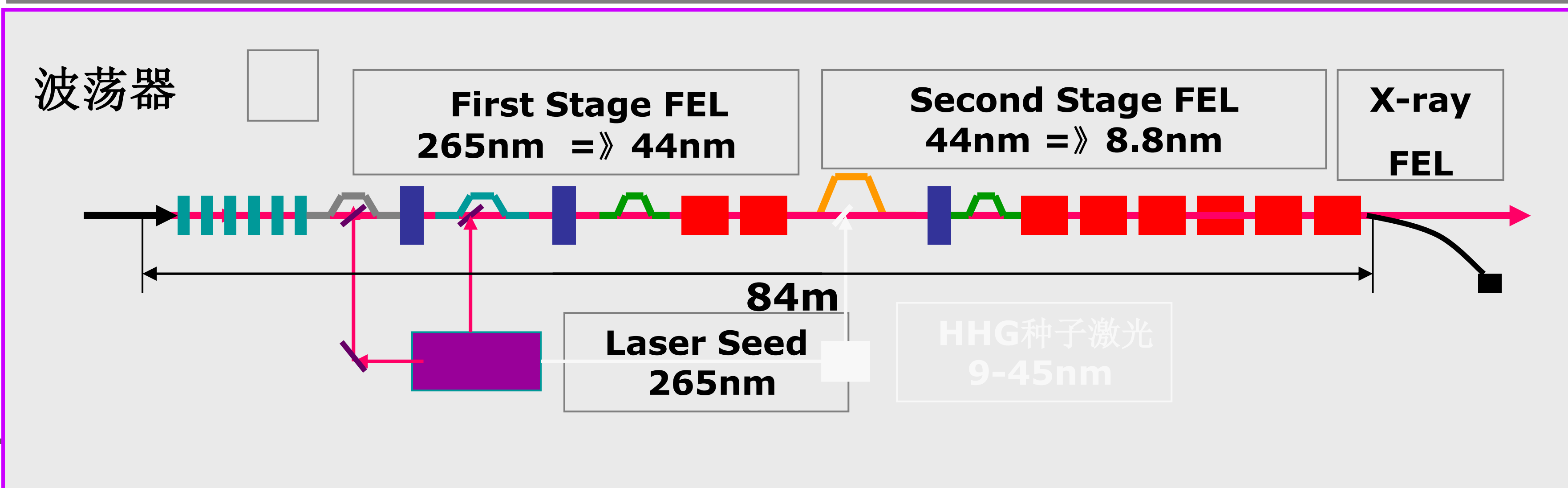
Main parameters

Parameters	Design value
Electron Energy	0.84 GeV
Normalized emittance	< 2.5mm.mrad
Slice energy spread	< 0.02%
Peak current/ bunch length/ charge	500 A /1ps/ 500pC
Wavelength of laser seed	~265nm
Scheme	HGHG，
Cascading scheme	265-44-9nm；
Modulator undulator	Tunable gap, hybrid planar
Radiator undulator	Hybrid planar
FEL peak power	>100MW
FEL wavelength	9 nm
FEL pulse length	100~150 fs (FWHM)

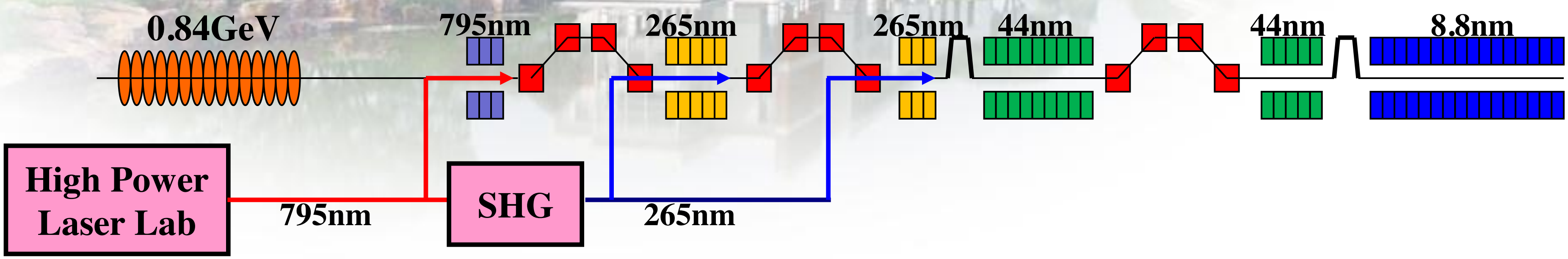
中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences
SINAP

Layout





New seeding options



- **0.84GeV, 600A, 0.6pC, 2mm-mrad, 150keV energy spread**
- **2 stage HGHG: 265nm to 8.8nm, baseline design**
- **3 stage HGHG: 795nm to 265nm + baseline design**
- **Echo-30: 265=>8.8nm FEL, with OPA at UV**
- **Echo-150: 1350=>8.8nm FEL, with OPA at IR**
- **HHG as seed: starting from 30-60nm**

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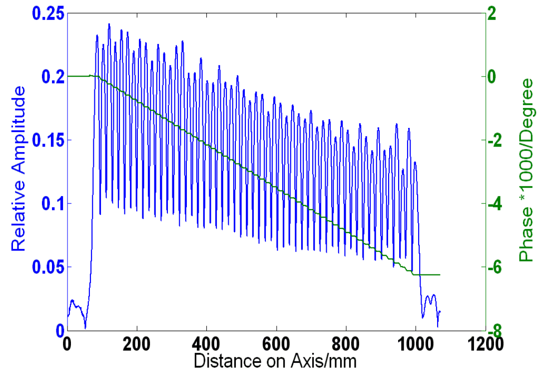
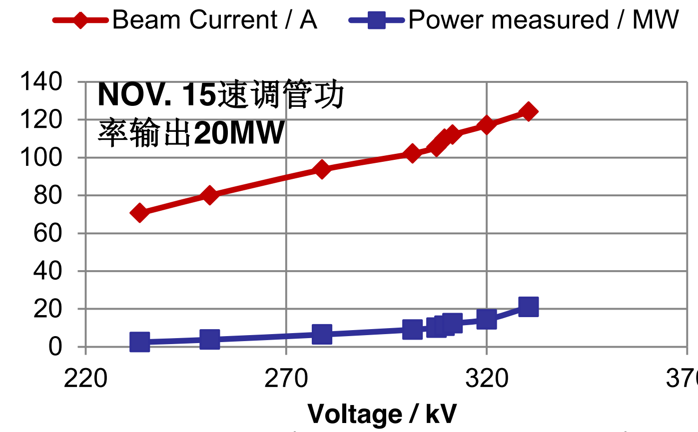
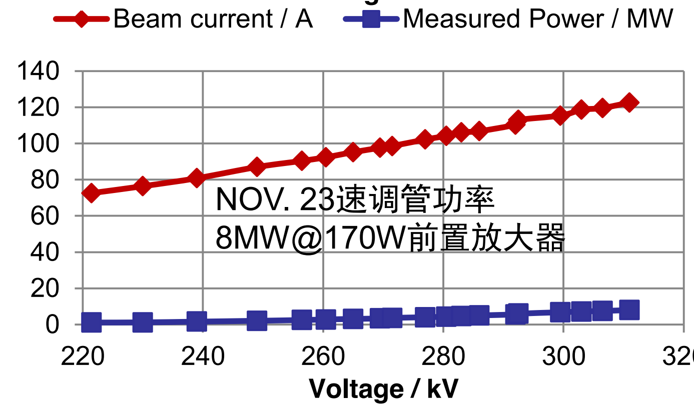
C-band high power test

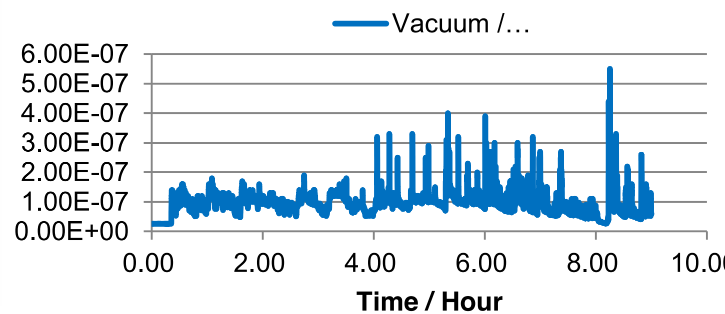
1.速调管测试实现20MW功率输出，可实现40MV/m梯度。

2. 加速结构测量实现8MW功率馈入，加速结构实现20MV/m。



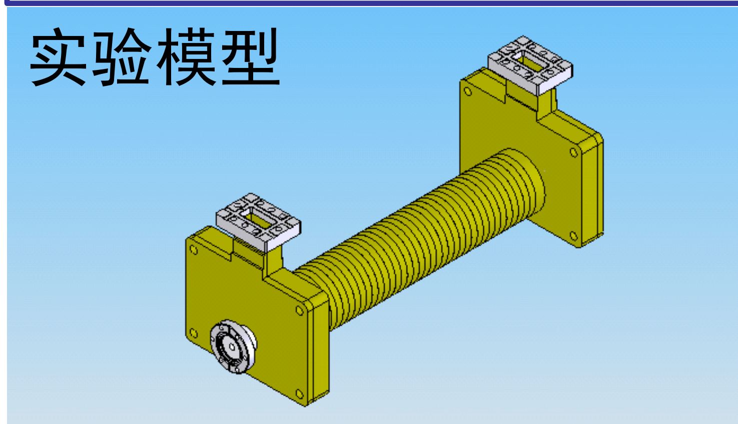


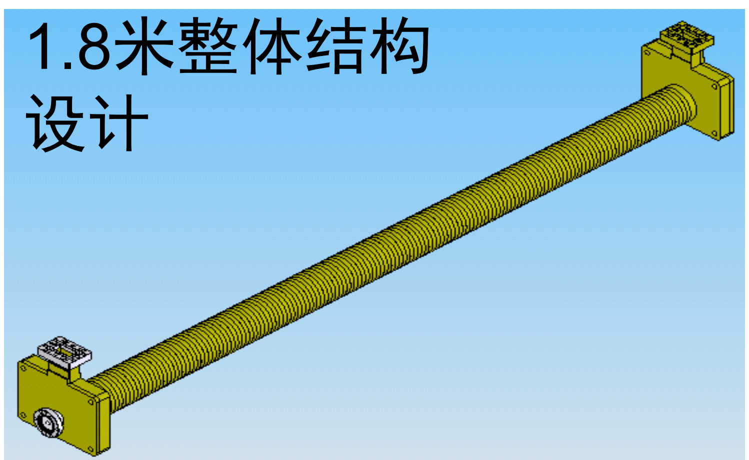


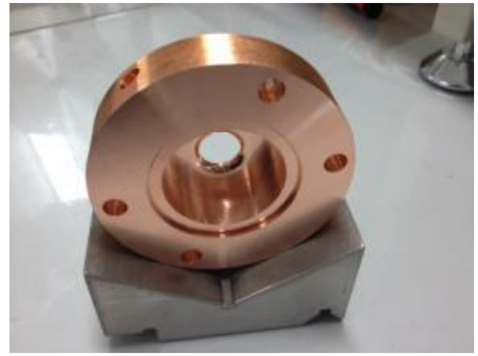


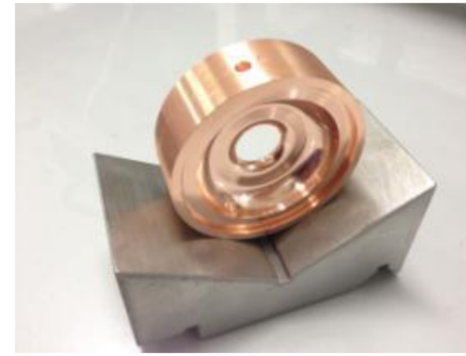
Structure optimization

1. 在第一根加速结构基础上，已经完成参数的全面优化。
2. 完成整体结构的初步设计。
3. 目前正在进行实验模型的加工和部分测试实验。

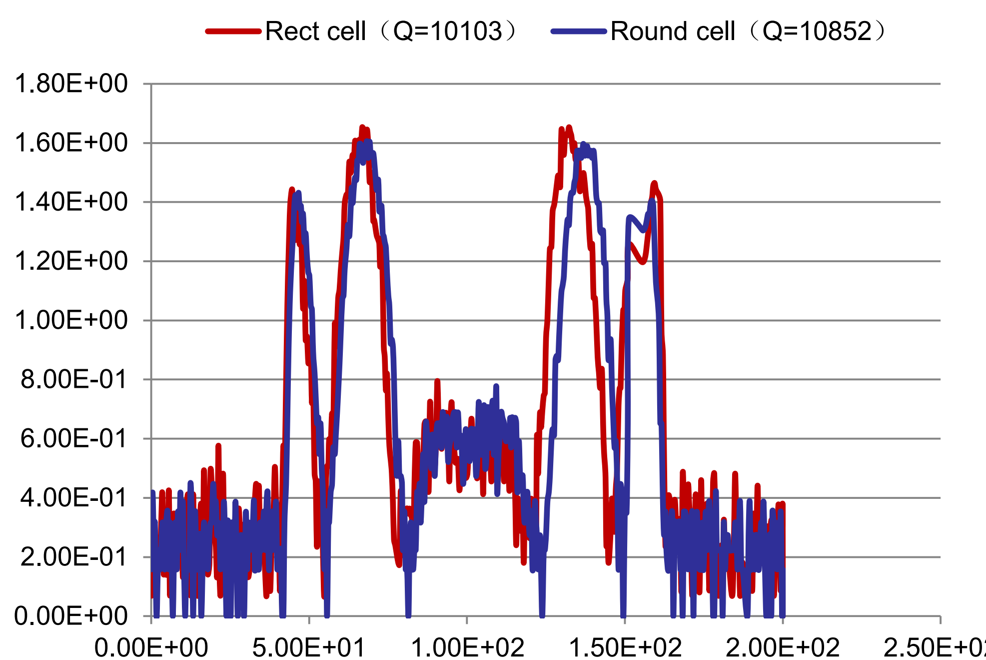




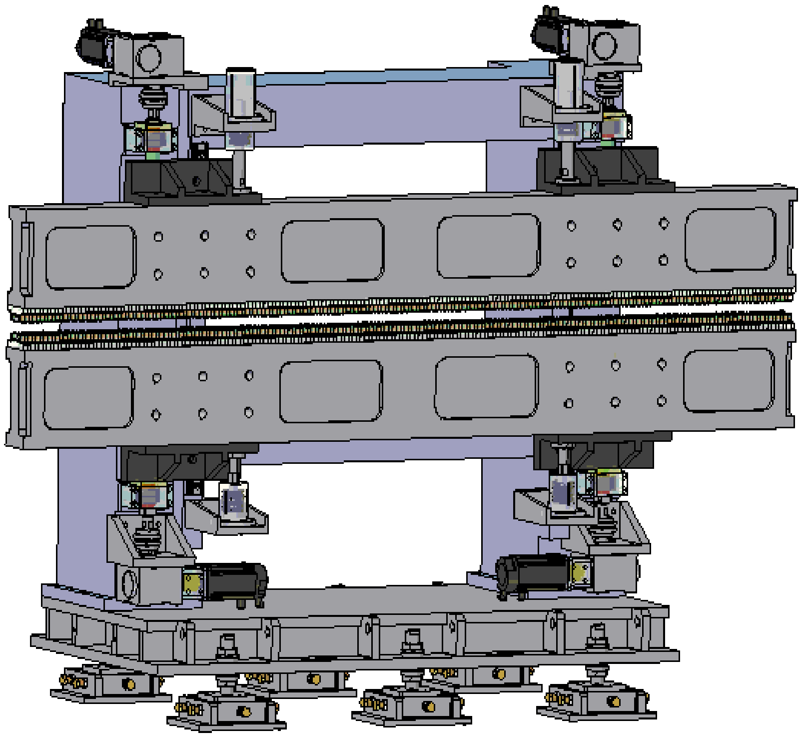


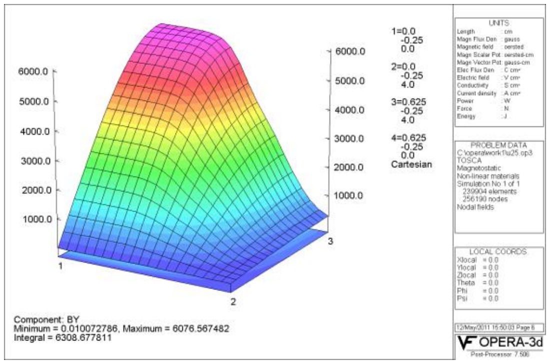


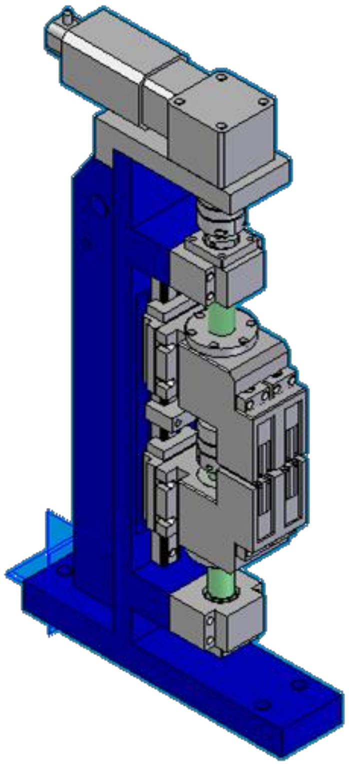
拱形腔和矩形腔分路阻抗Rs比较，拱形腔可以提供10%。



Undulator design



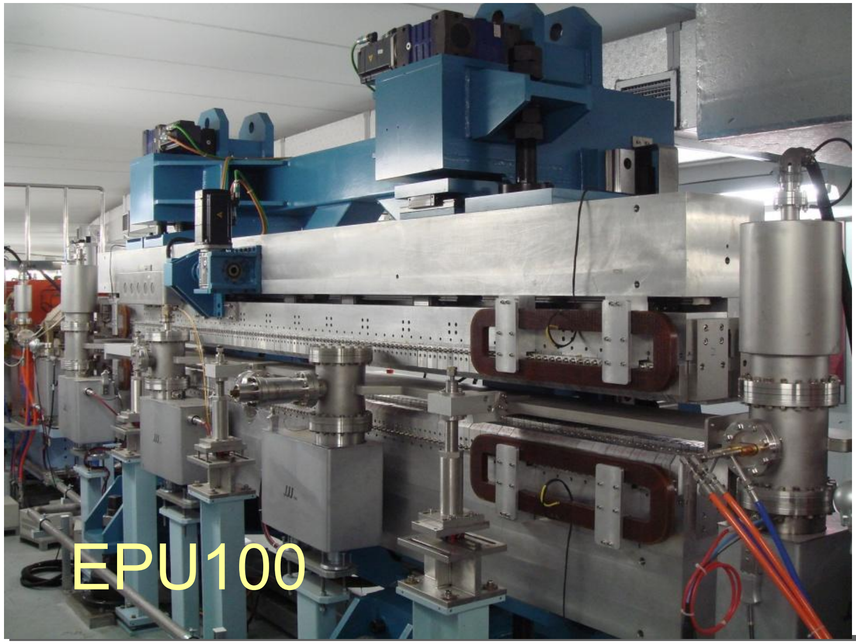




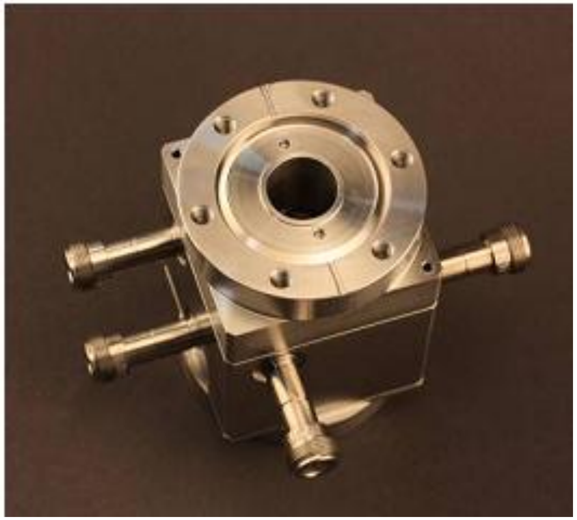
Undulators	λu (mm)	λres (nm)	K	Beff (T)	Length (m)
Modulator 1	80	240~280	5.806	0.920	1.5
Radiator 1	58	44	2.4919	0.460	2x3
Modulator 2	38	44	3.245	0.914	1.5
Radiator 2	25	8.8	1.35	0.576	6x3

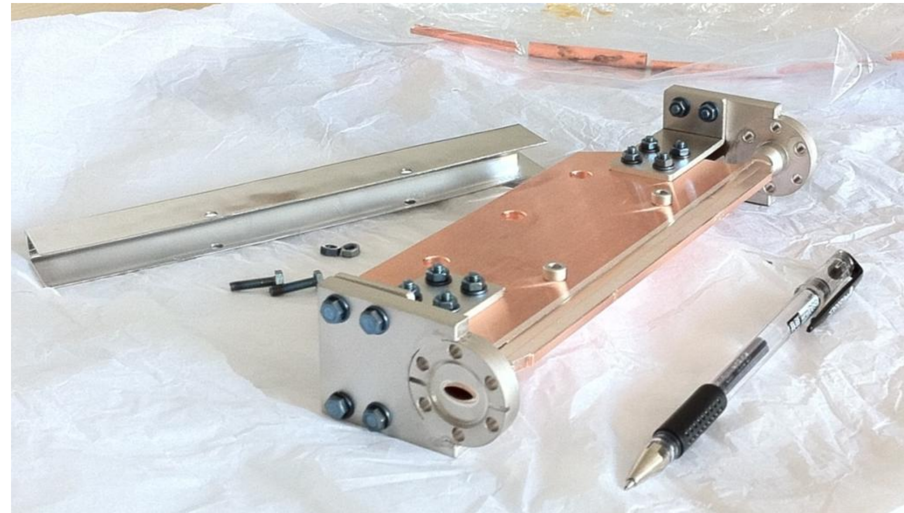
Insertion Devices at SINAP

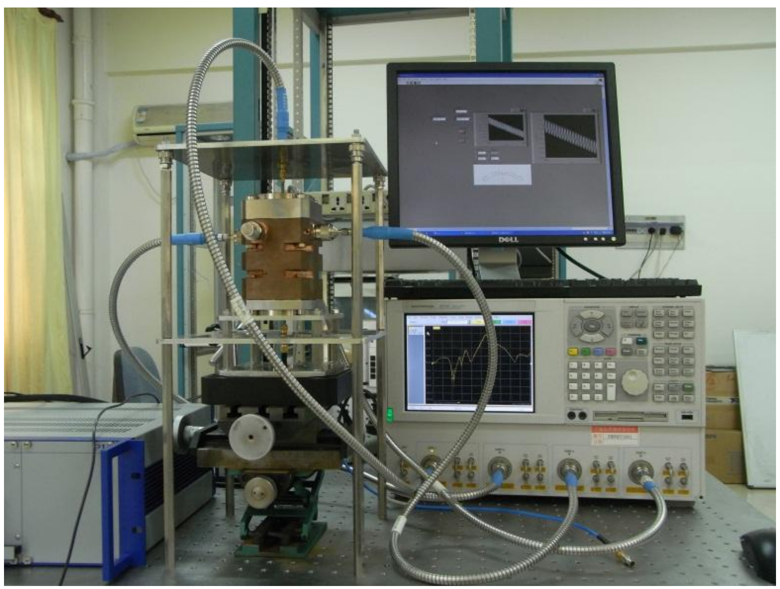
- mostly made in-house
- in-vacuum and out-vacuum
- planar and EPU

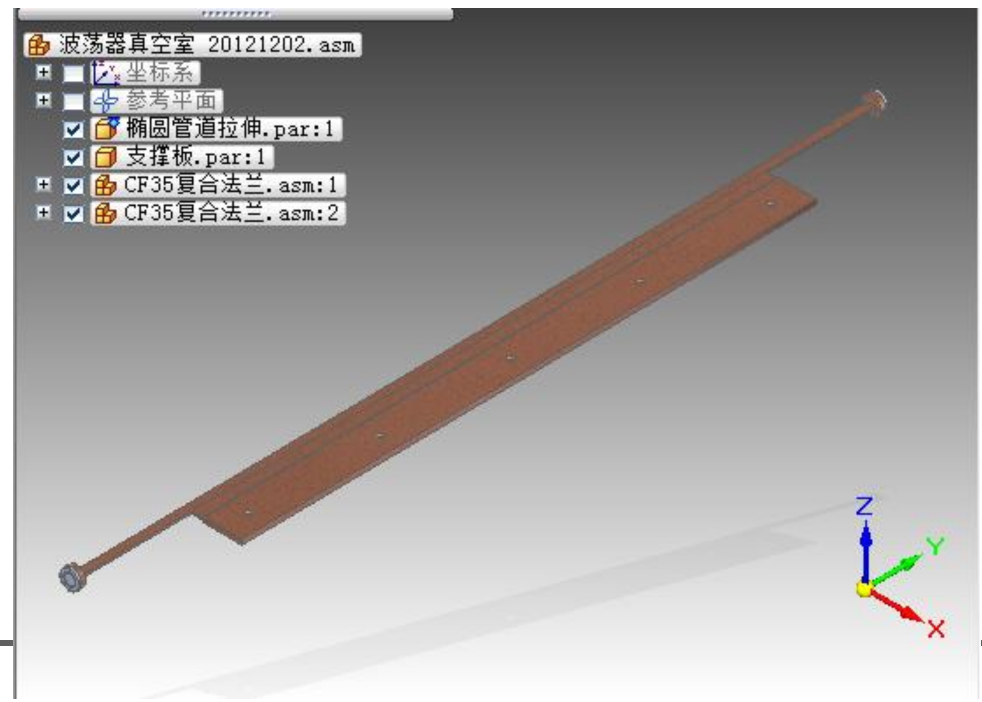


CBPM, Vacuum chamber









Summary

- SINAP, as the accelerator-based photon science center of China, is carrying out studies of a number of FEL facilities, all seeded-type.
- SDUV-FEL is focusing on FEL principle research on various topics for future FEL projects.
- DCLS is a nice user-driven FEL facility at VUV regime. The project is progressing as planned.
- SXFEL suffers from some delay. New directions for seeding under discussions.

Thanks for your attention!