FEL Activities at SINAP and FEL Stabilization Considerations

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On behalf of the FEL Team
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7th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI 2012), October 15-19, 2012, Shanghai

Acknowledgements

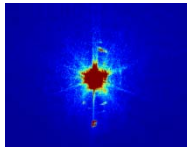
To the organizers of MEDSI for invitation to this fantastic workshop

To *the whole FEL team at SINAP*: *There are many NOT in the photos, my apology in advance.*

Outline

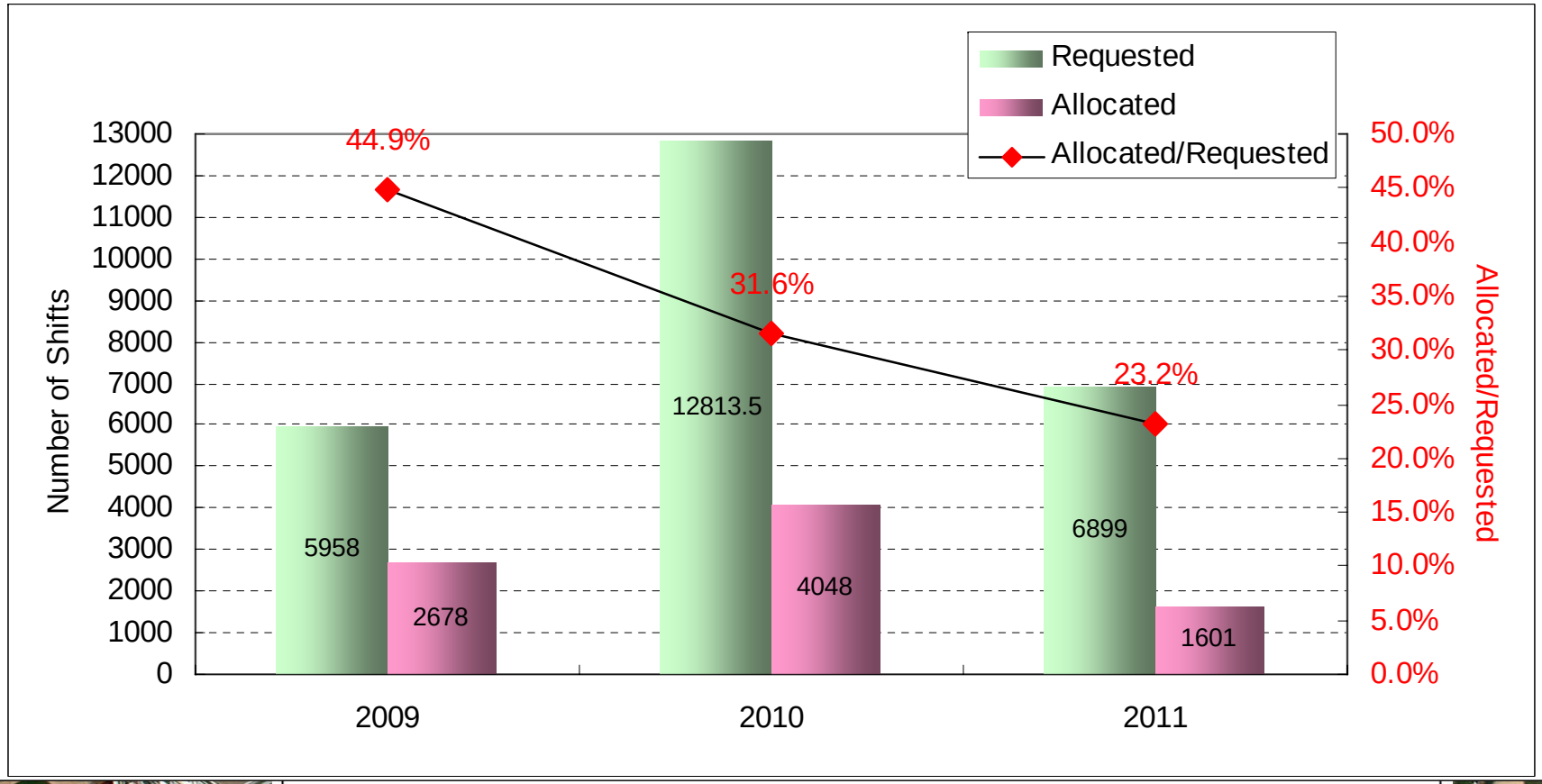
- Introduction to SINAP
- FEL activities at SINAP (limited to FEL projects and exps.)
  - SXFEL
  - SHXFEL
  - DCLS
  - SDUV-FEL
- FEL stabilization considerations (limited to orbit related issues)
  - Requirements
  - Countermeasures
- Summary and conclusions

SINAP: Transforming……

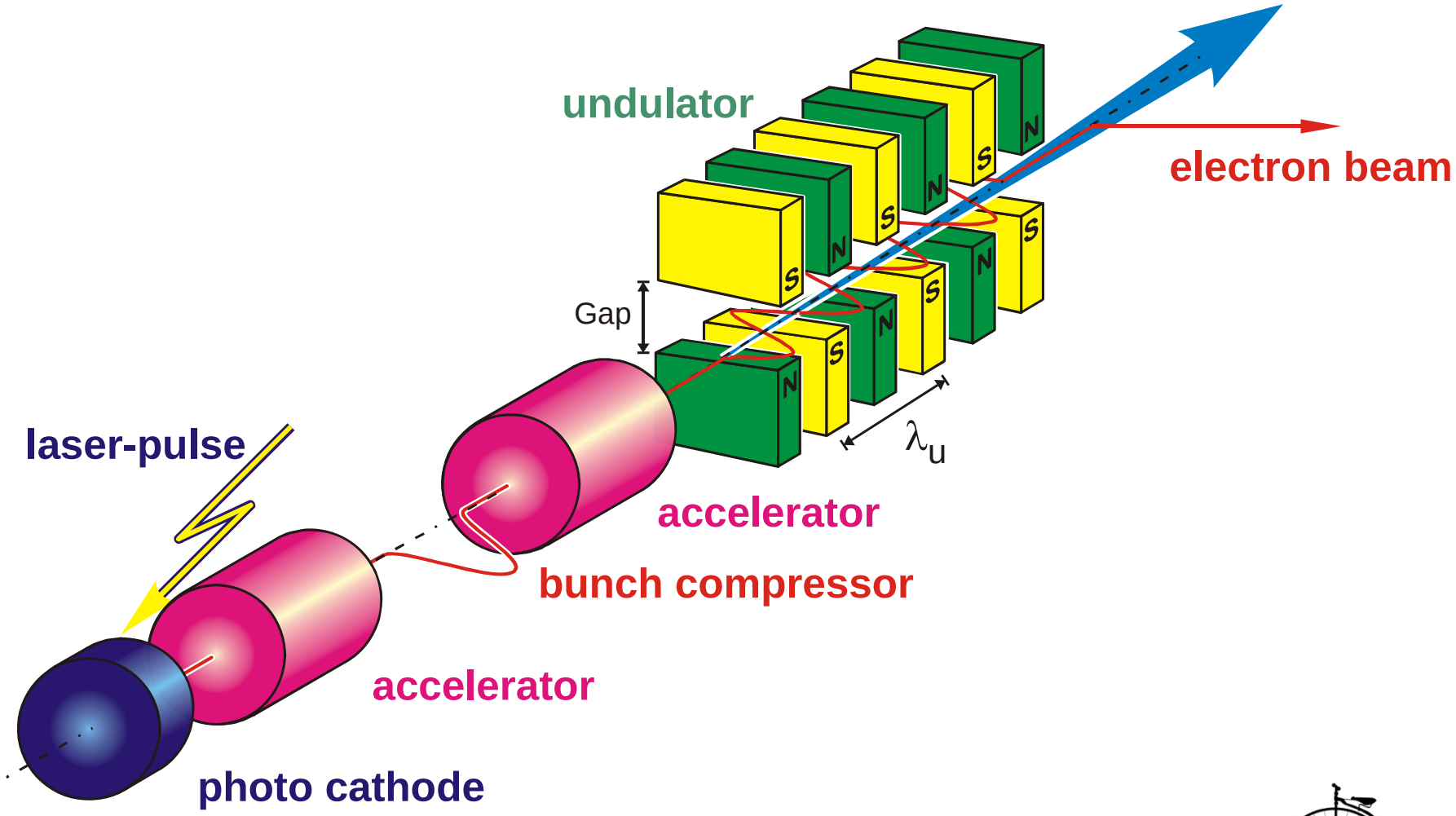


Shanghai Synchrotron Radiation Facility

A world leading intermediate-energy 3rd generation light source



What's Next?


undulator
electron beam
Gap
λ_u
laser-pulse
accelerator
bunch compressor
accelerator
photo cathode

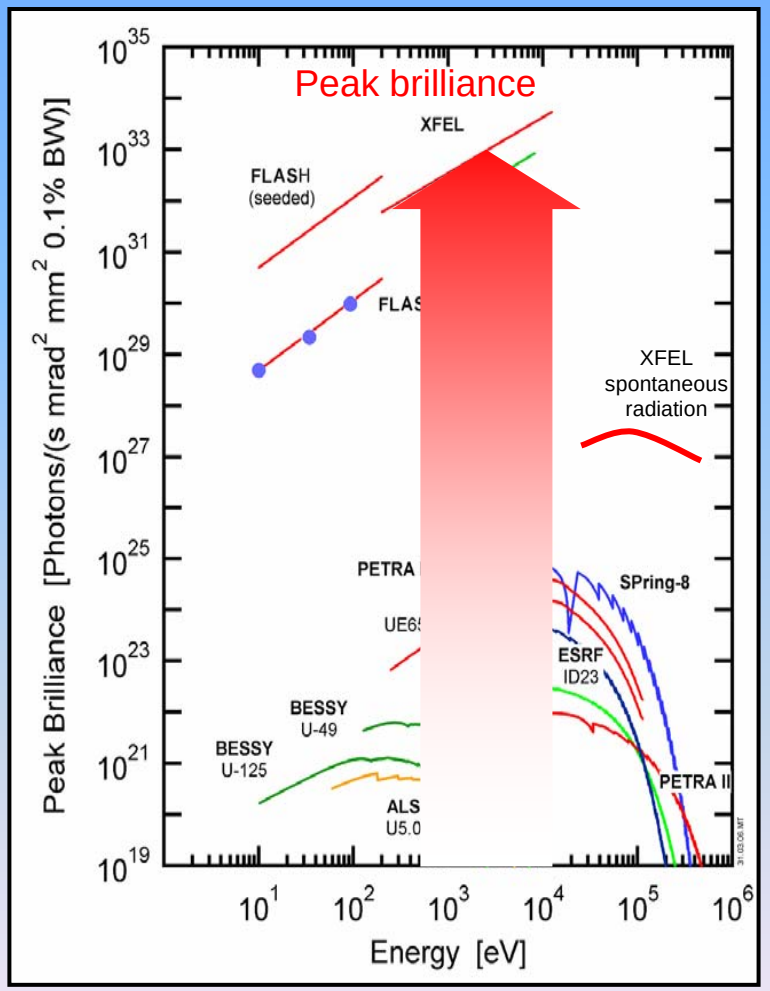
Properties of XFEL radiation

Compared to 3rd generation storage ring based synchrotron radiation facilities, the gain factors are:

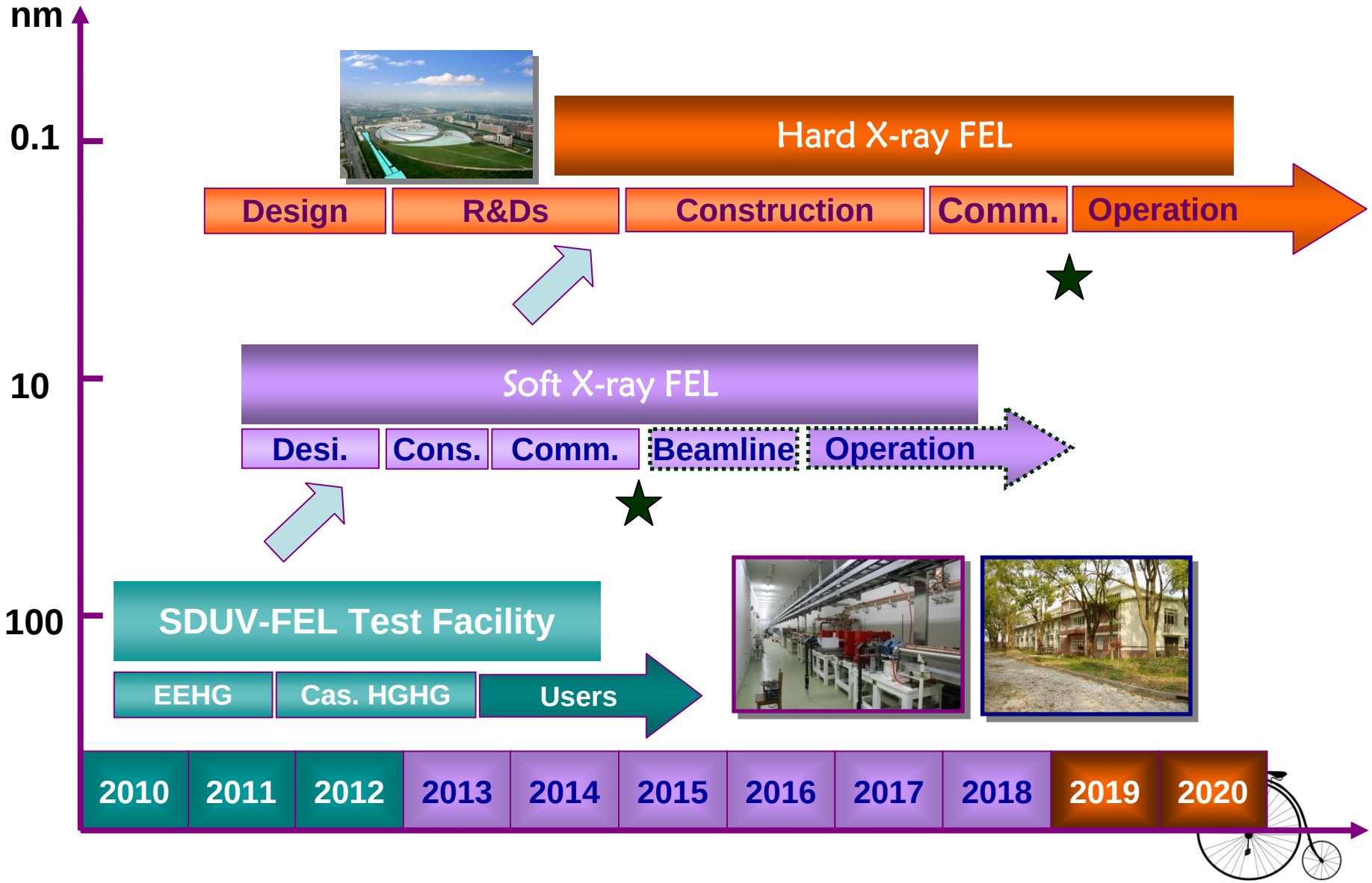
- peak brilliance: 10^9 at the FEL line
- average brilliance: 10^4 at FEL line (EUR)
- coherence: 10^9 at FEL line
- pulse duration: 10^{-3} at FEL line

With an FEL one gets in a pulse of ~25 fs duration as many X-ray photons as with a modern storage ring in 1 sec

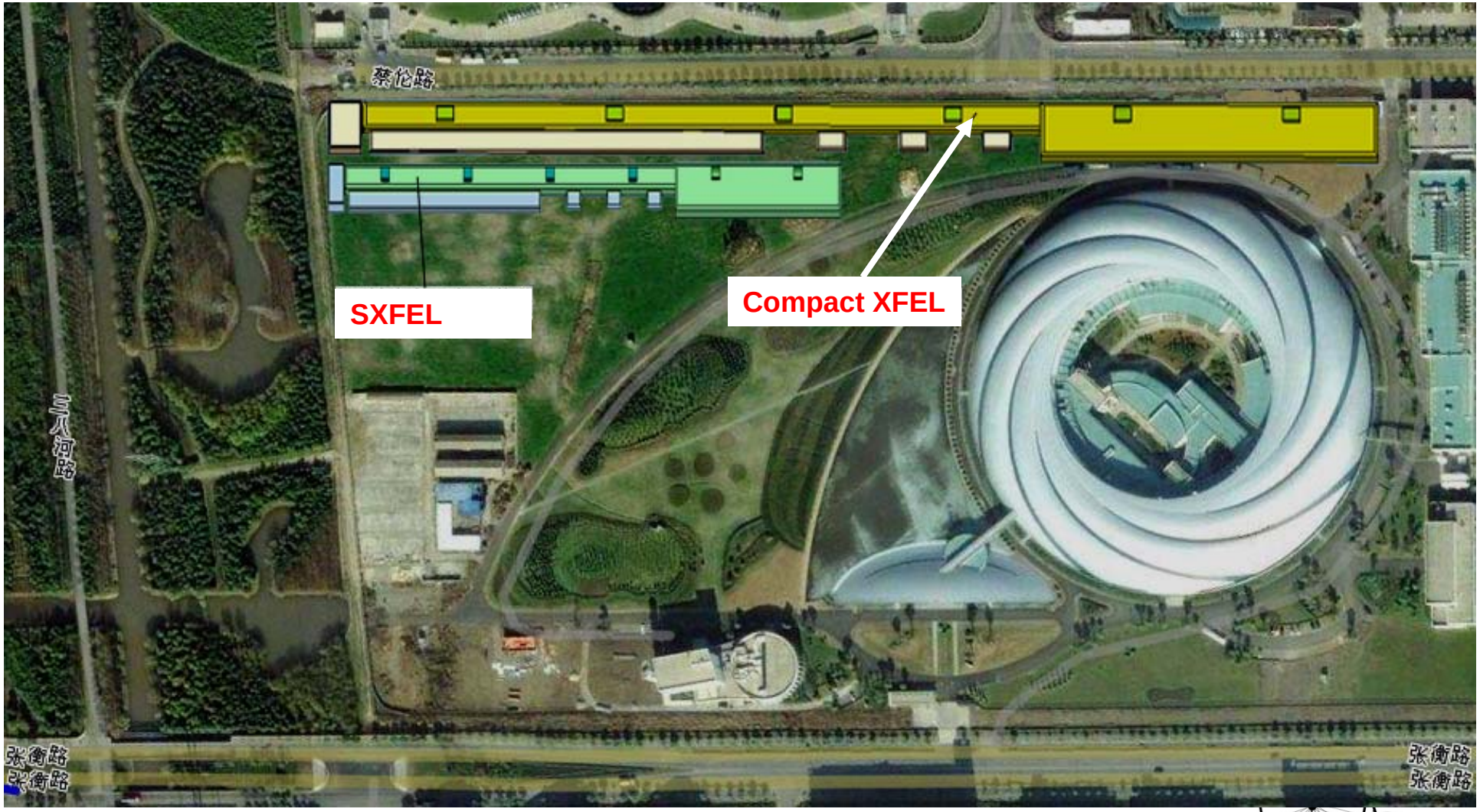
The XFEL will not replace the storage ring facilities,
it opens the door to new science



FEL strategy at SINAP



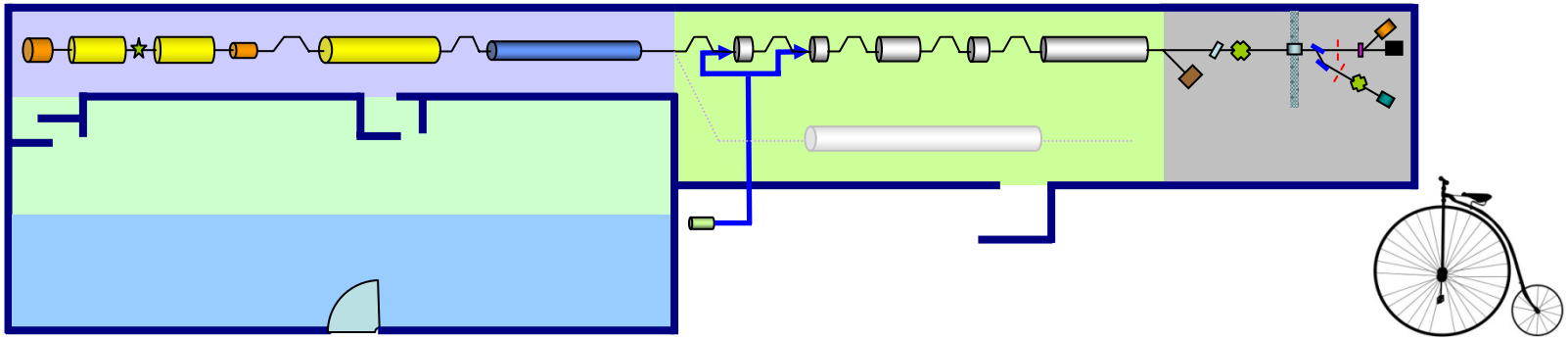
Shanghai photon science center



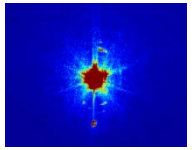
SXFEL in the SSRF campus

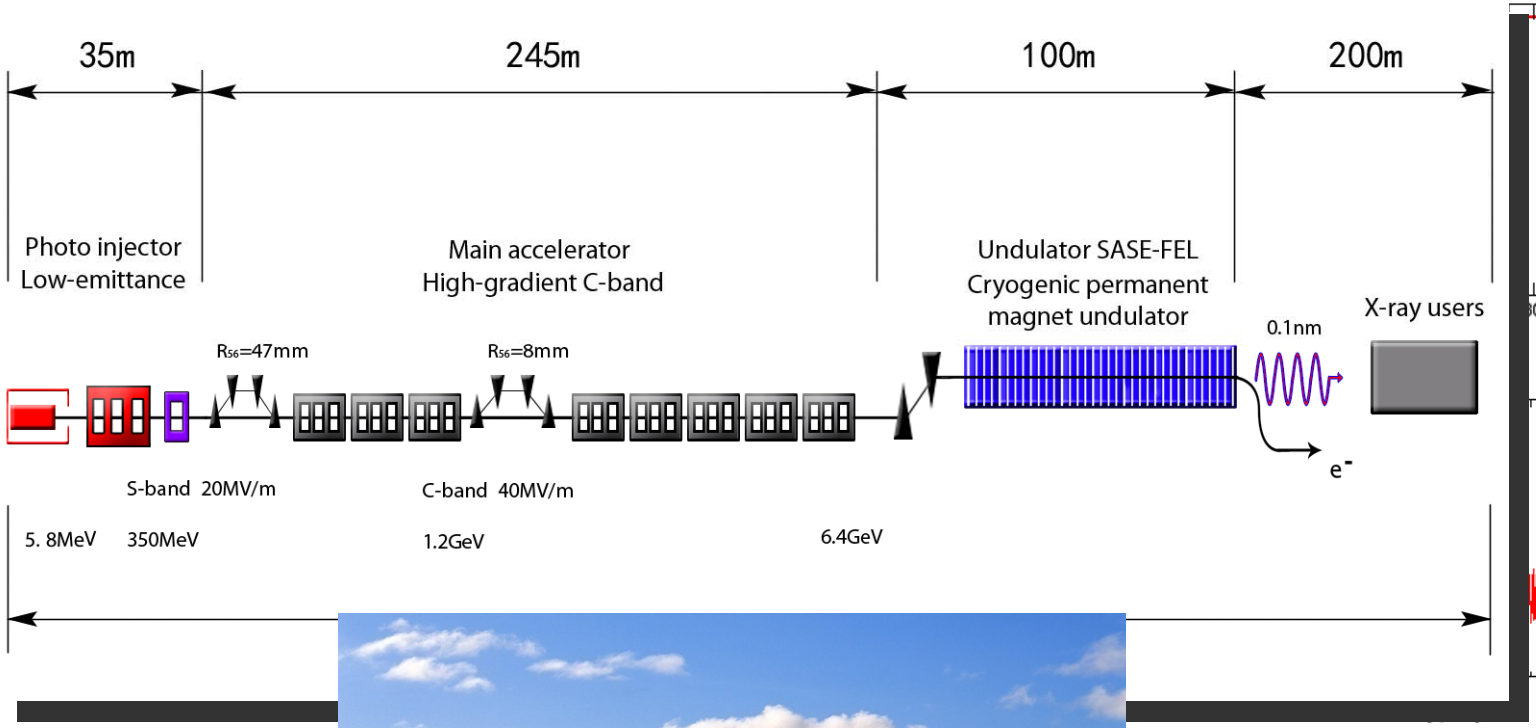
SXFEL Main Parameters

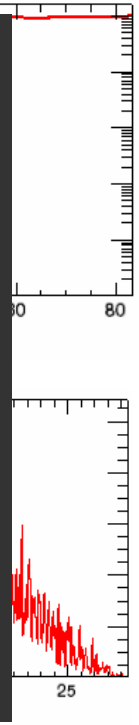
Parameters	HGHG	Upgrade	Unit
Output Wavelength	9	3	nm
Bunch charge	0.5~1	0.5~1	nC
Energy	0.84	1.2~1.3	GeV
Energy spread	0.1~0.15%	0.15%	
Energy spread (sliced)	0.02%	0.03%	
Normalized emittance	2.0~2.5	2.0~2.5	mm.mrad
Pulse length (FWHM)	1.	1	ps
Peak current	~0.5	0.5	kA
Rep. rate	1~10	1~10	Hz



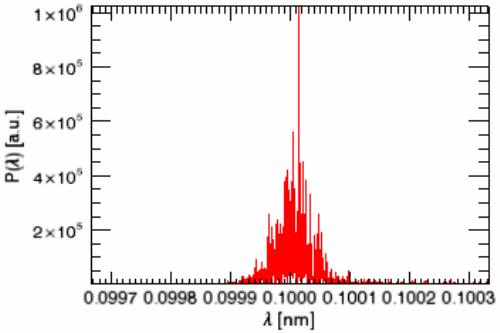
Shanghai Hard X-ray FEL

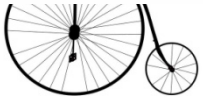




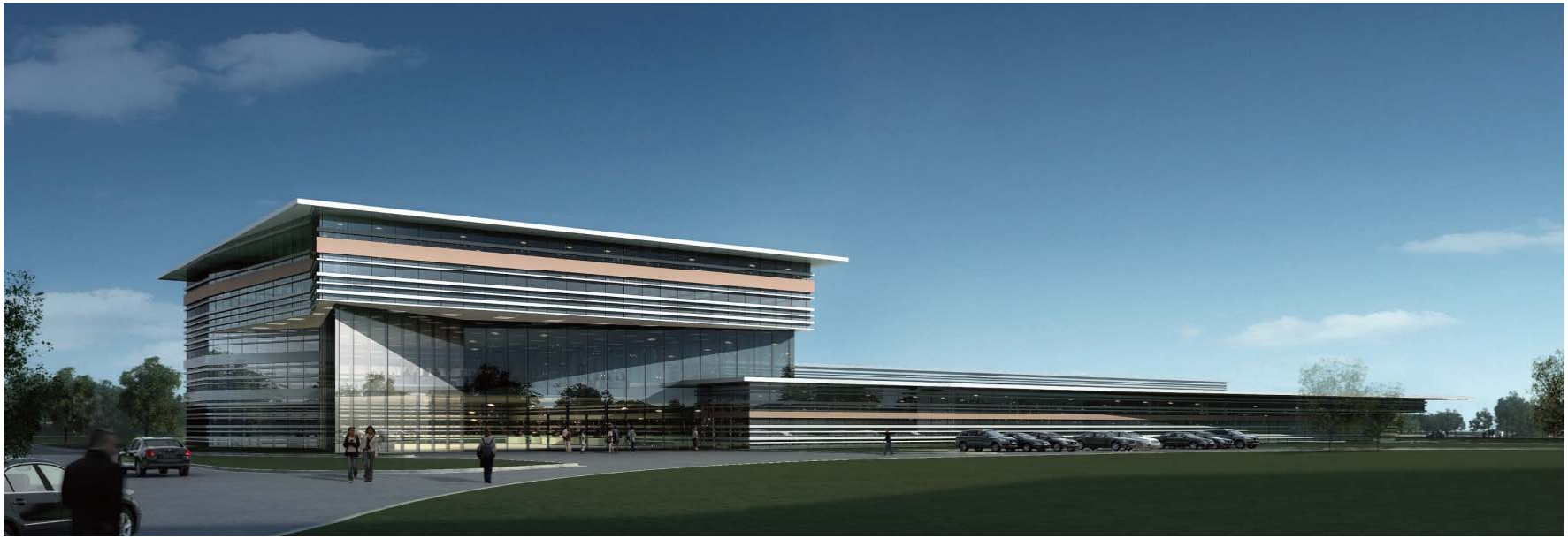


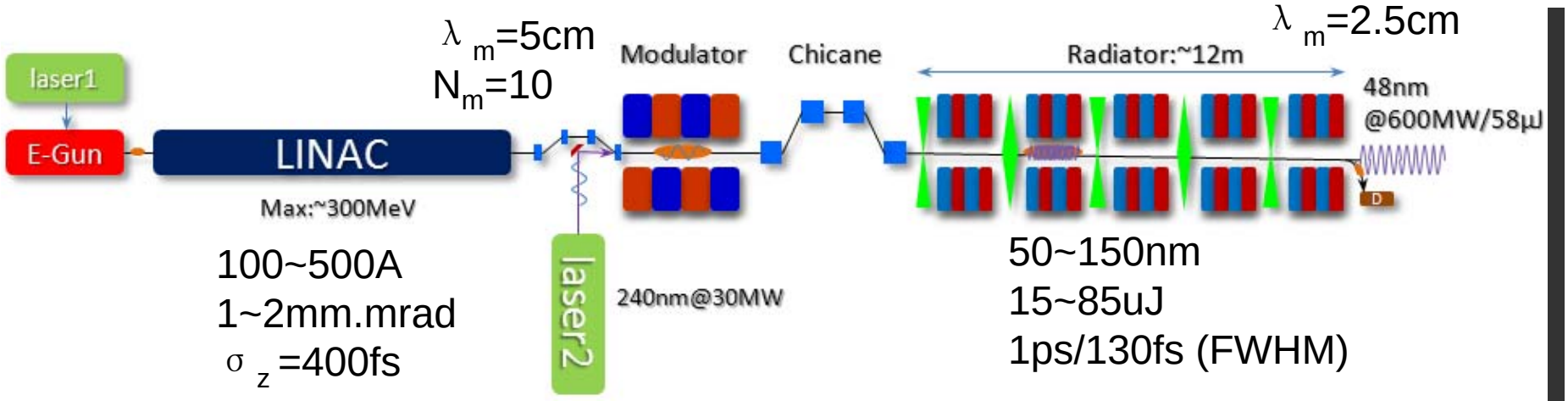
FEL parameter
Peak power
Peak brightness
3D gain length
Saturation length



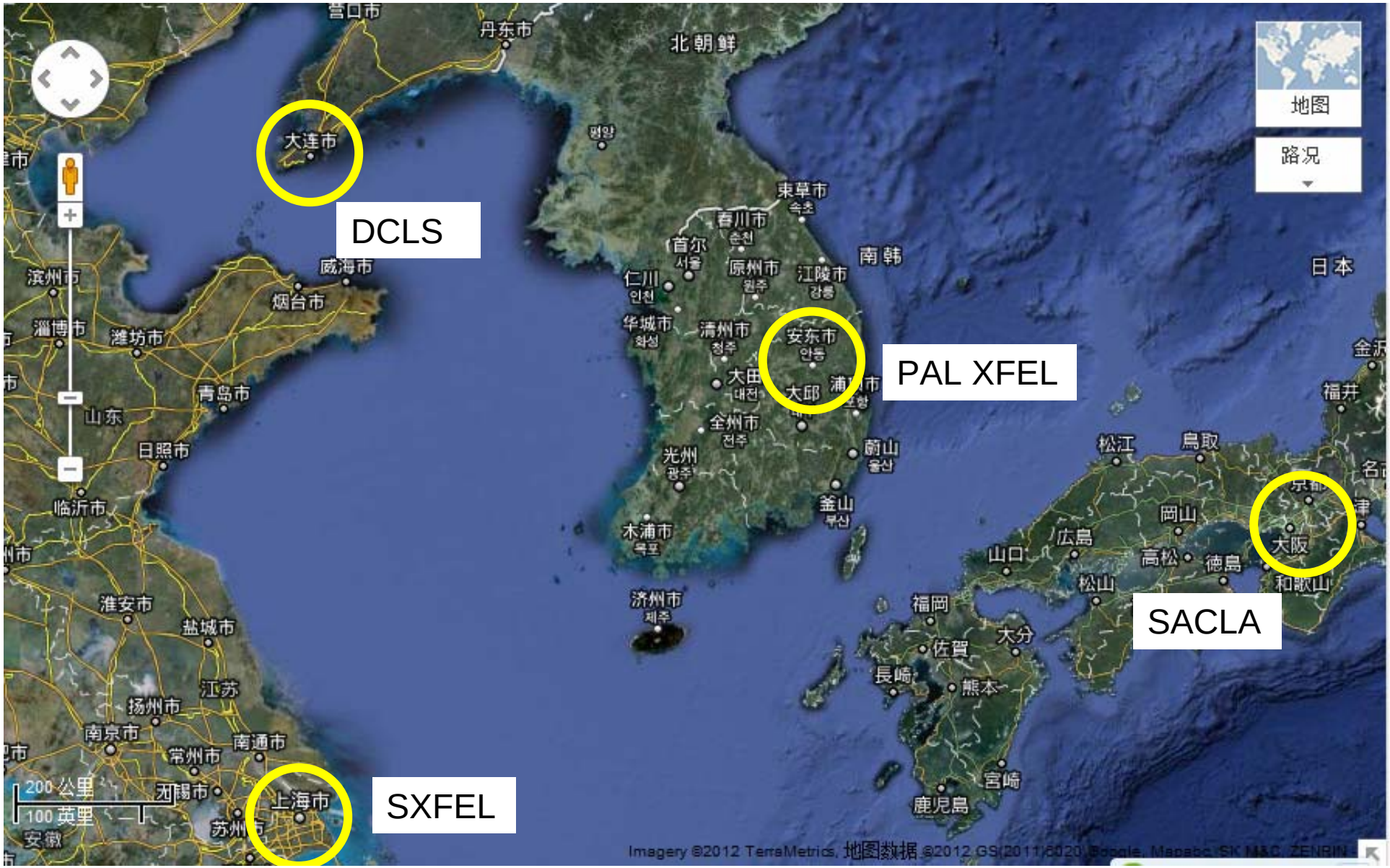


EUV FEL for DICP, CAS





FEL projects in Asia



SDUV-FEL Experiment Hall

Shanghai Deep UV FEL (SDUV-FEL)

SDUV-FEL Tests

- SASE
- HGHG
- EEHG
- Cascading

ODS=Optical Diagnostics Station

Milestones of FEL experiments

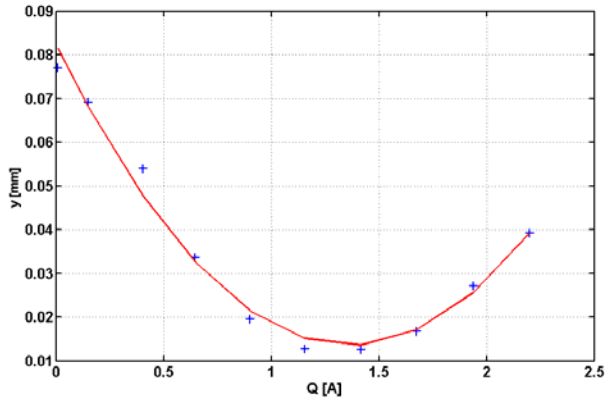
- 2009.04-08: Linac commissioning
- 2009.09-12: SASE experiment
- 2010.01-03: Seeded FEL Installations
- 2010.05: Seeded FEL experiments start
- 2010.05.17: HGHG signal
- 2010.05.22: First Echo signal (‘double-peak’)
- 2010.07-08: Install. for high harmonics EEHG
- 2010.12: HGHG saturation
- 2011. 04: EEHG amplification
- 2011.07-08: Cascaded HGHG experiments begin
- 2012.04: First cascaded HGHG signal

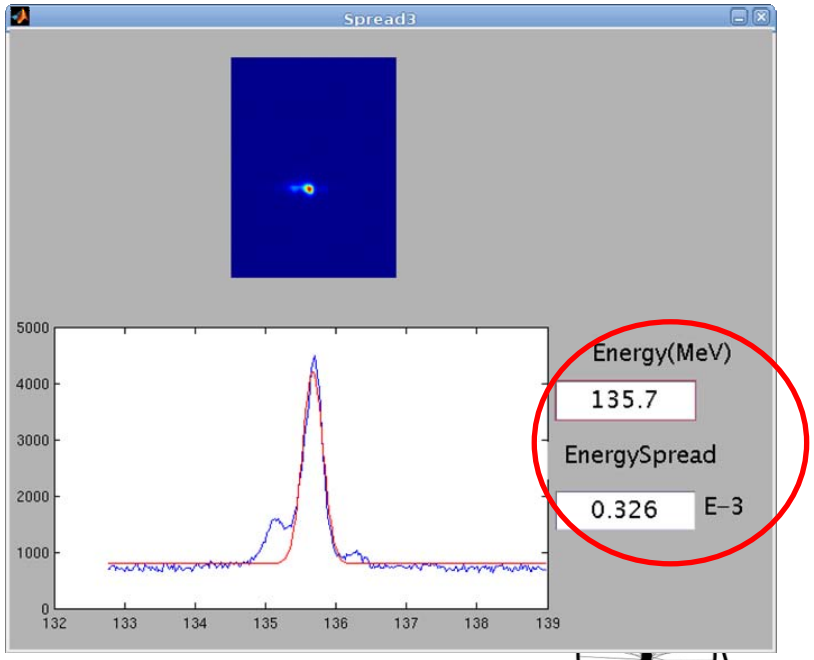
Main Parameters of SDUV-FEL Linac

Beam energy	100-150MeV
Beam energy spread (projected)	<0.03%
Normalized emittance	4~5mm-mrad
Bunch Length (rms)	1~3ps
Bunch charge	100~300pC

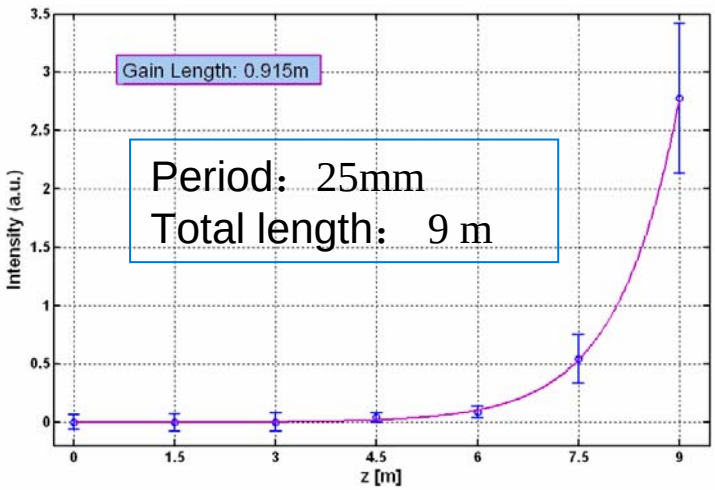
Linac Commissioning Results

- 100~150MeV
- 4~5mm.mrad
- ……

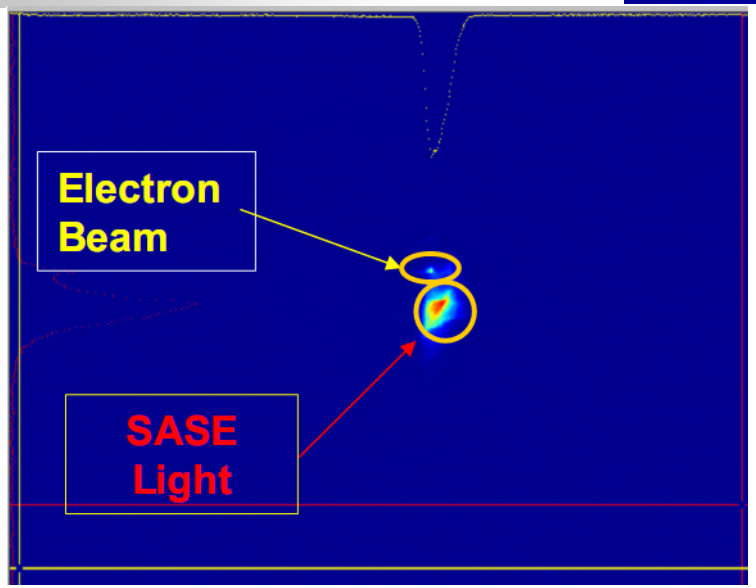




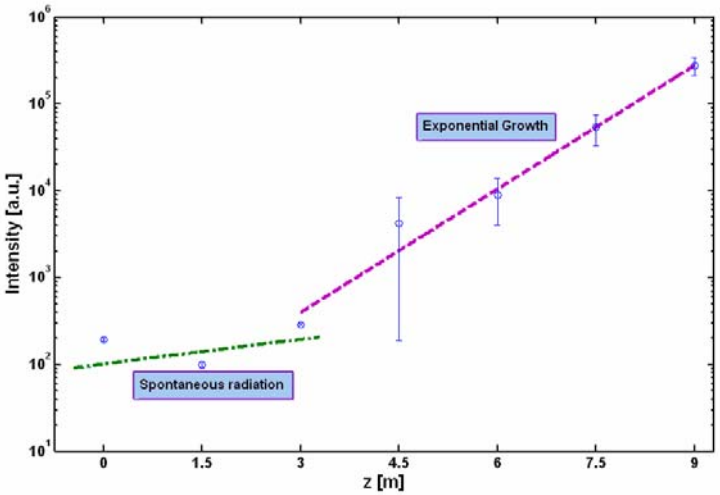
SASE Results (2009)

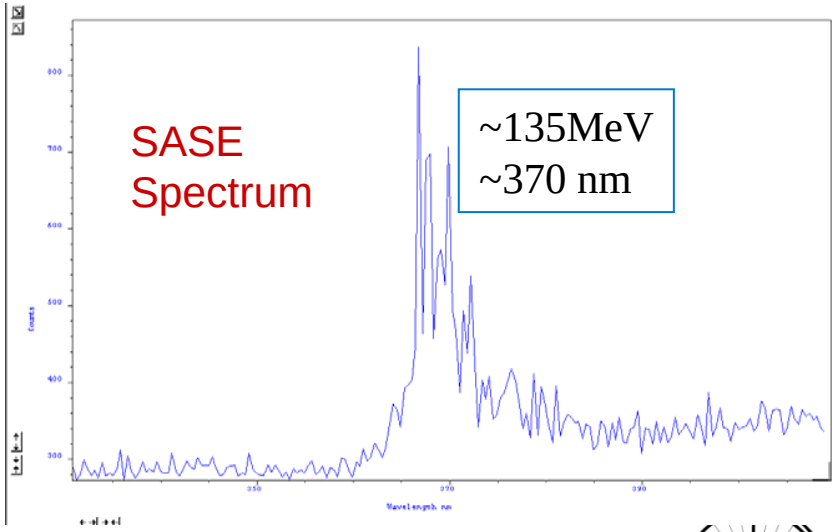


Period：25mm
Total length： 9 m



Gain length：~0.9m
Saturation length：~20 m

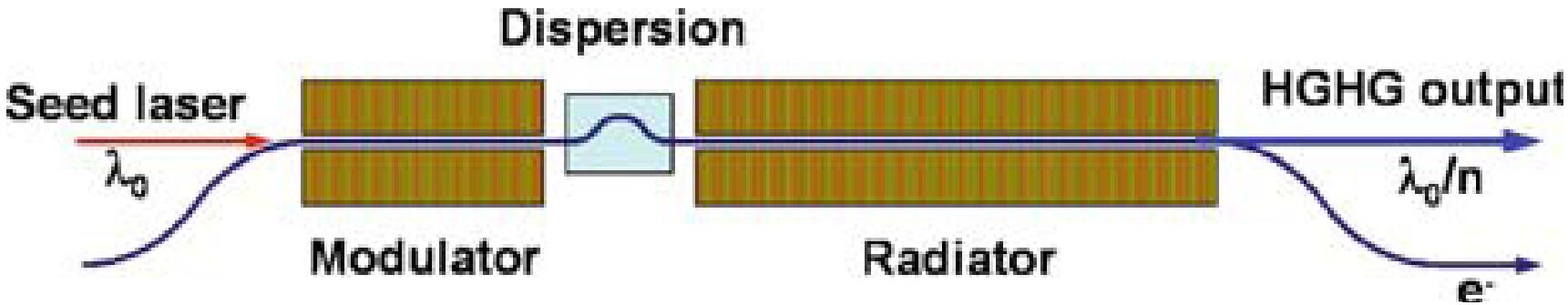


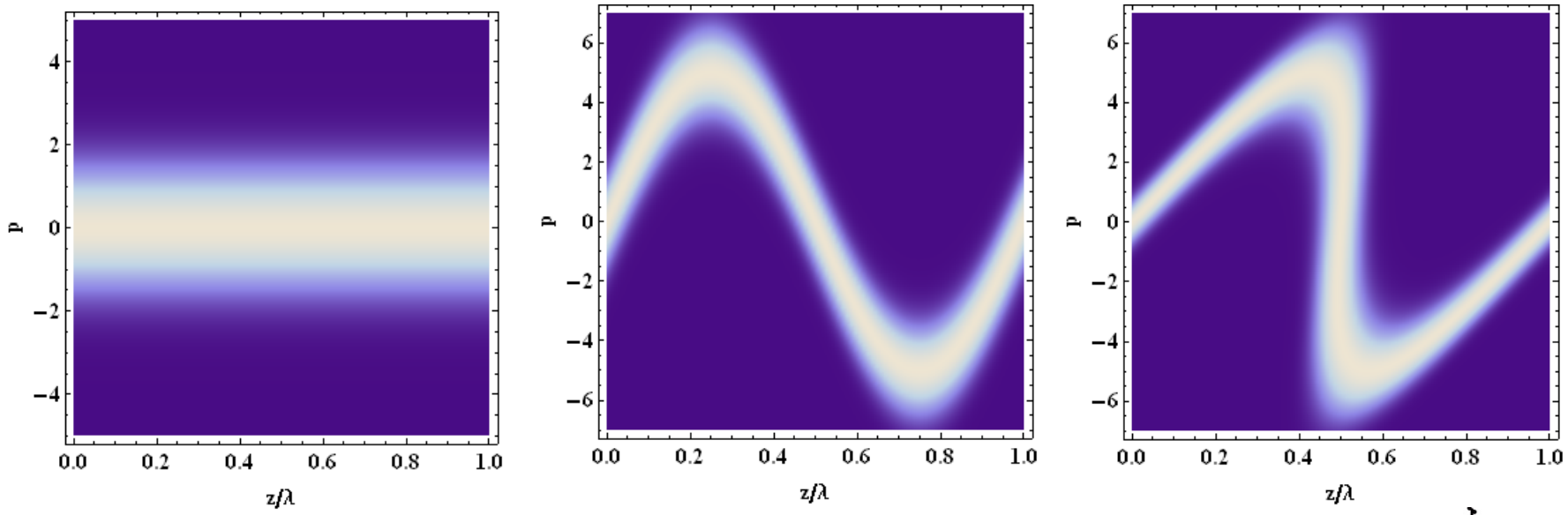


~135MeV
~370 nm

350 370 390 nm

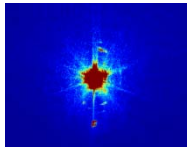
HGHG principle

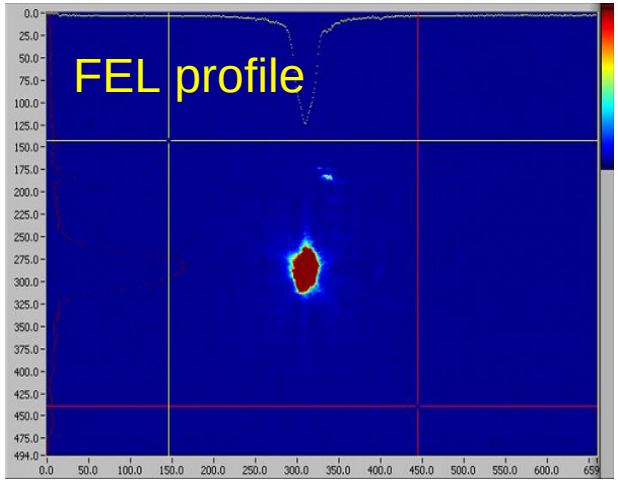


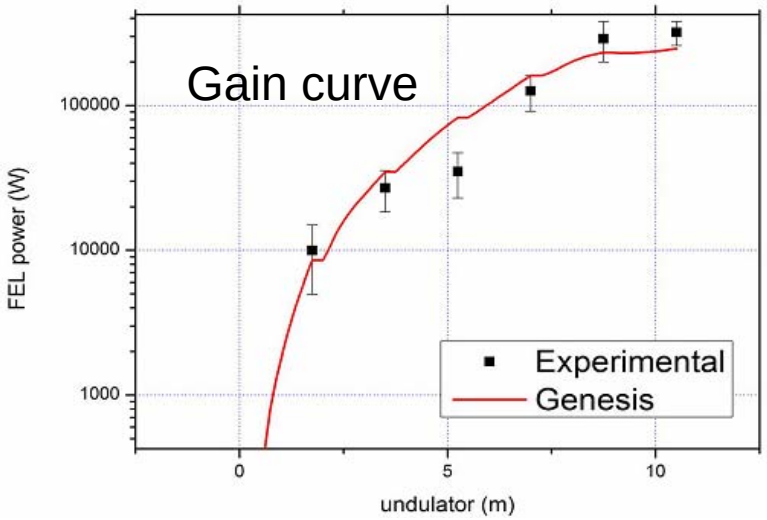


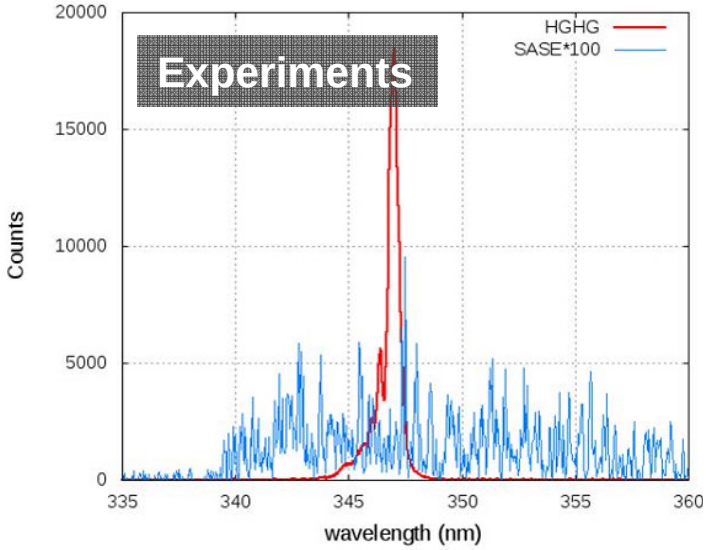
L.H. Yu, PRA 44, 5178 (1991)

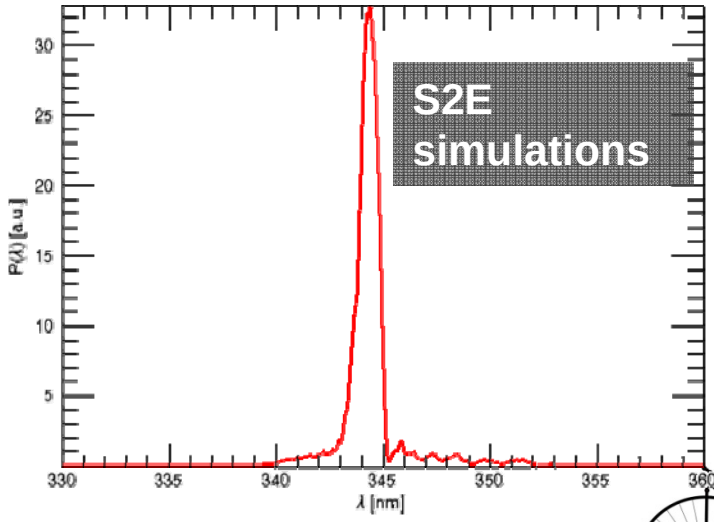
HGHG saturation, Dec. 2010

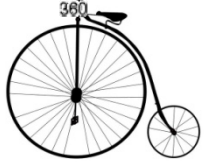




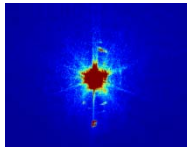


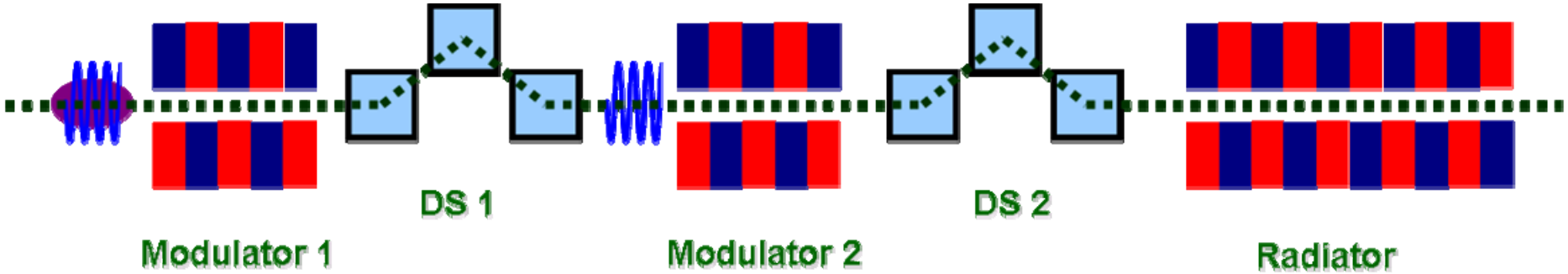


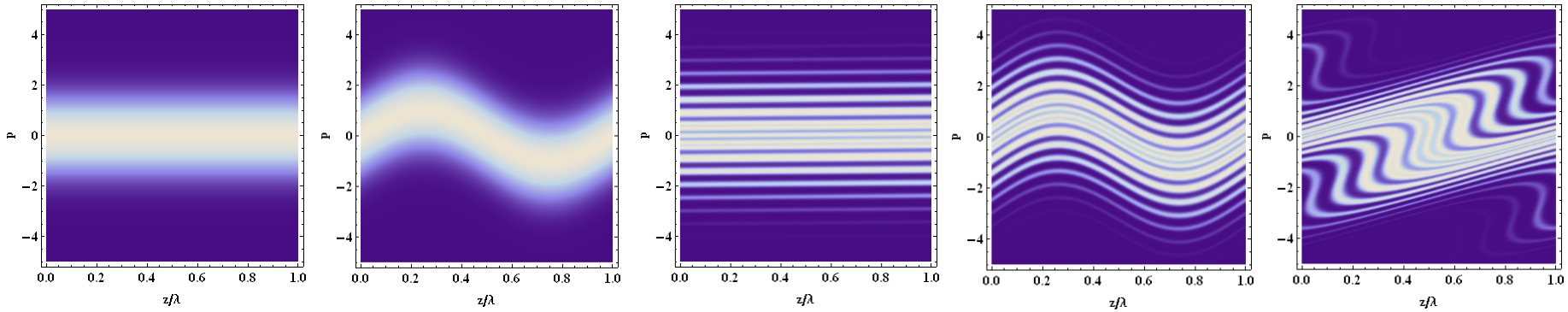


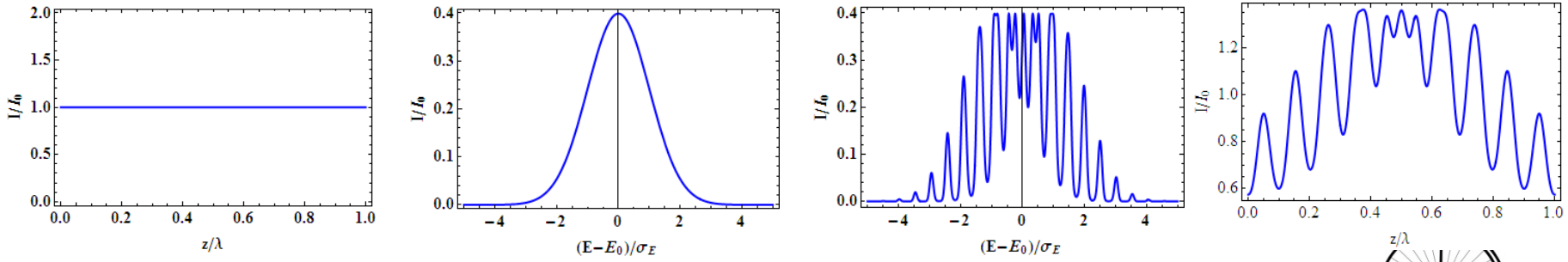


EEHG rationale



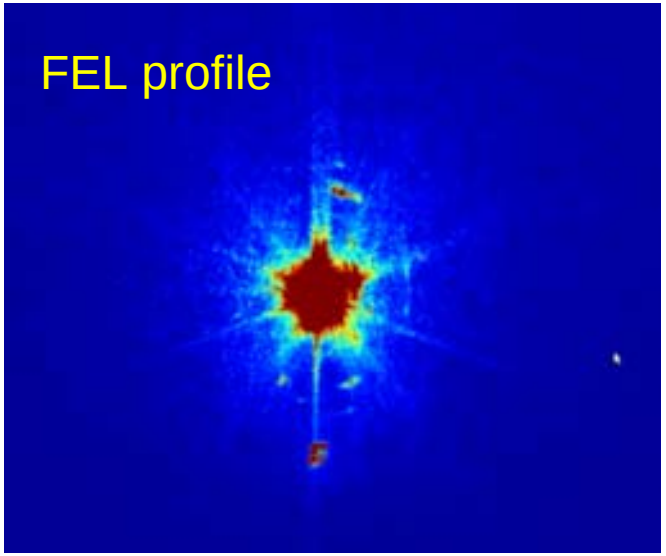


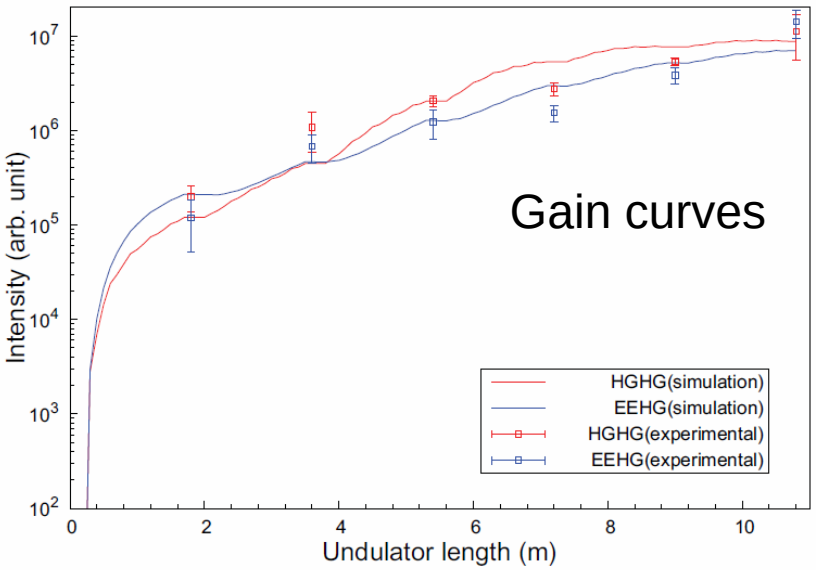


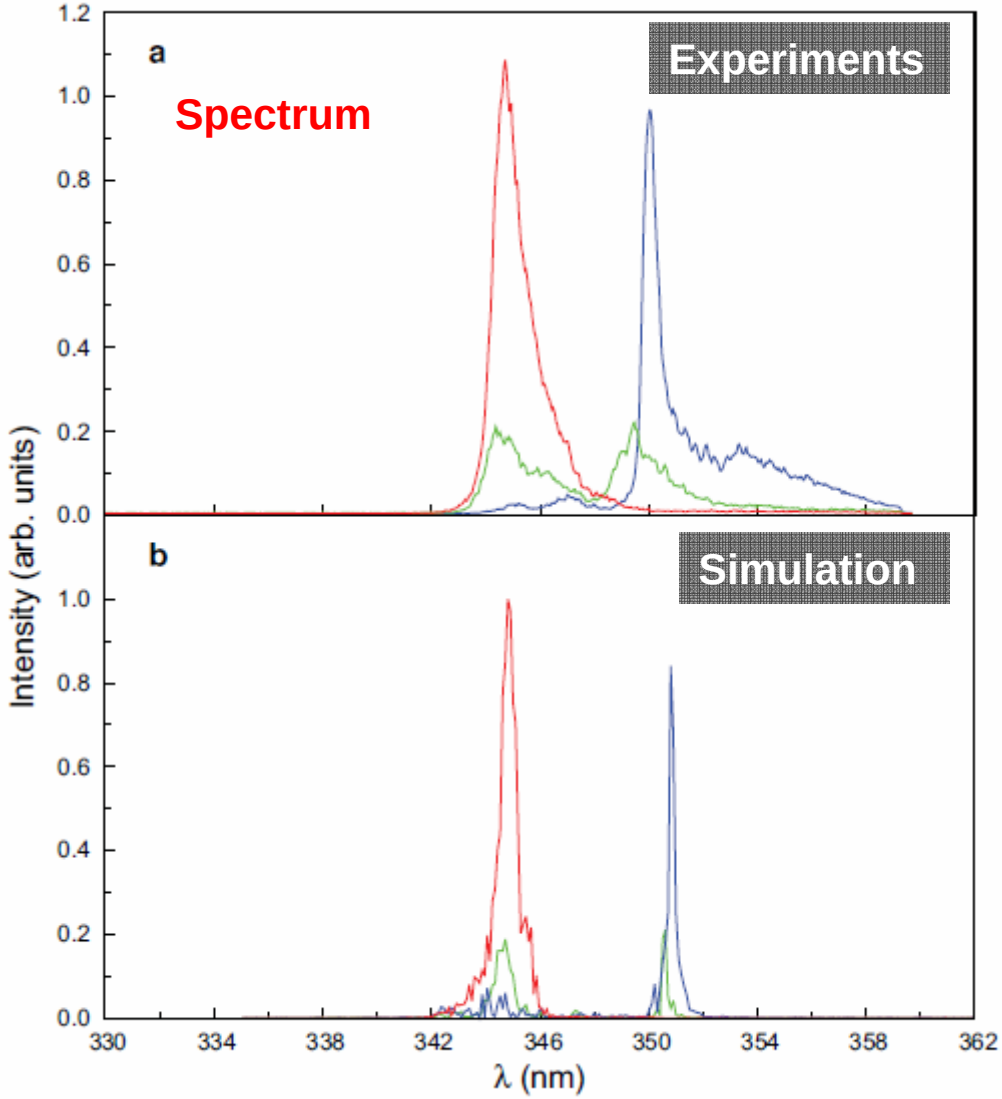


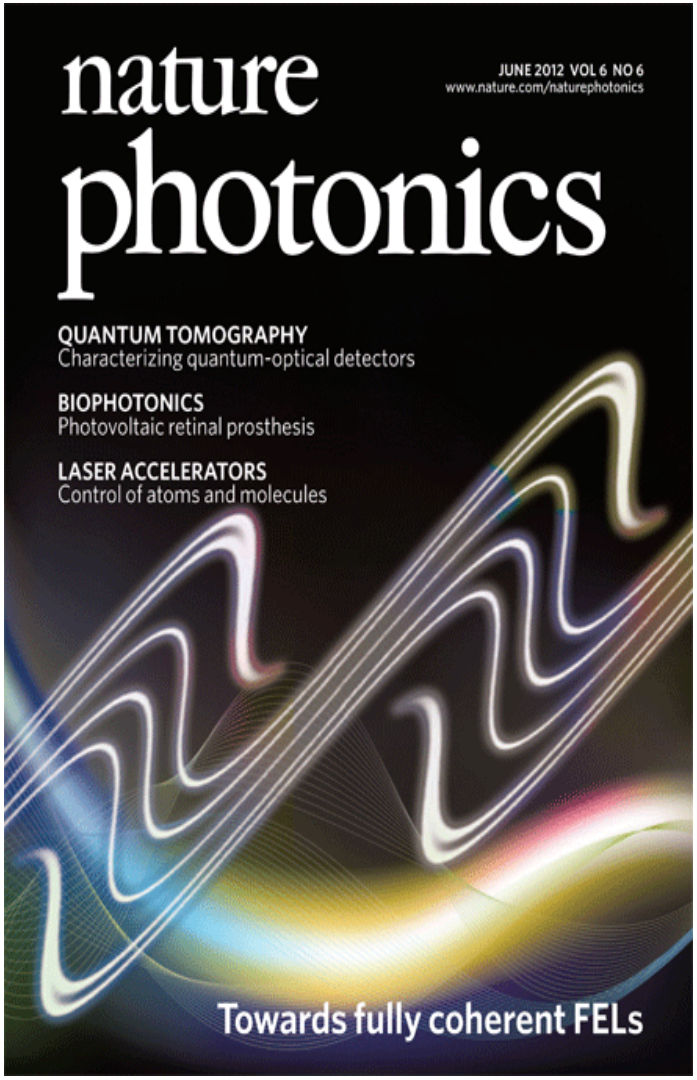
G. Stupakov, PRL 102, 074801 (2009)

First lasing of EEHG FEL, April 2011









LETTERS
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nature photonics

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

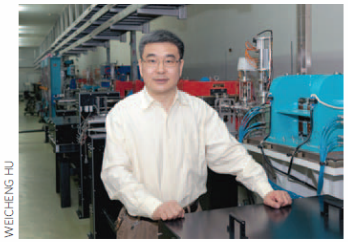
Z. T. Zhao[1]*, D. Wang[1], J. H. Chen[1], Z. H. Chen[1], H. X. Deng[1], J. G. Ding[1], C. Feng[1], Q. Gu[1], M. M. Huang[1], T. H. Lan[1], Y. B. Leng[1], D. G. Li[1], G. Q. Lin[1], B. Liu[1], E. Prat[2], X. T. Wang[1], Z. S. Wang[1], K. R. Ye[1], L. Y. Yu[1], H. O. Zhang[1], J. Q. Zhang[1], Me. Zhang[1],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

interview

Towards full-coherence FELs

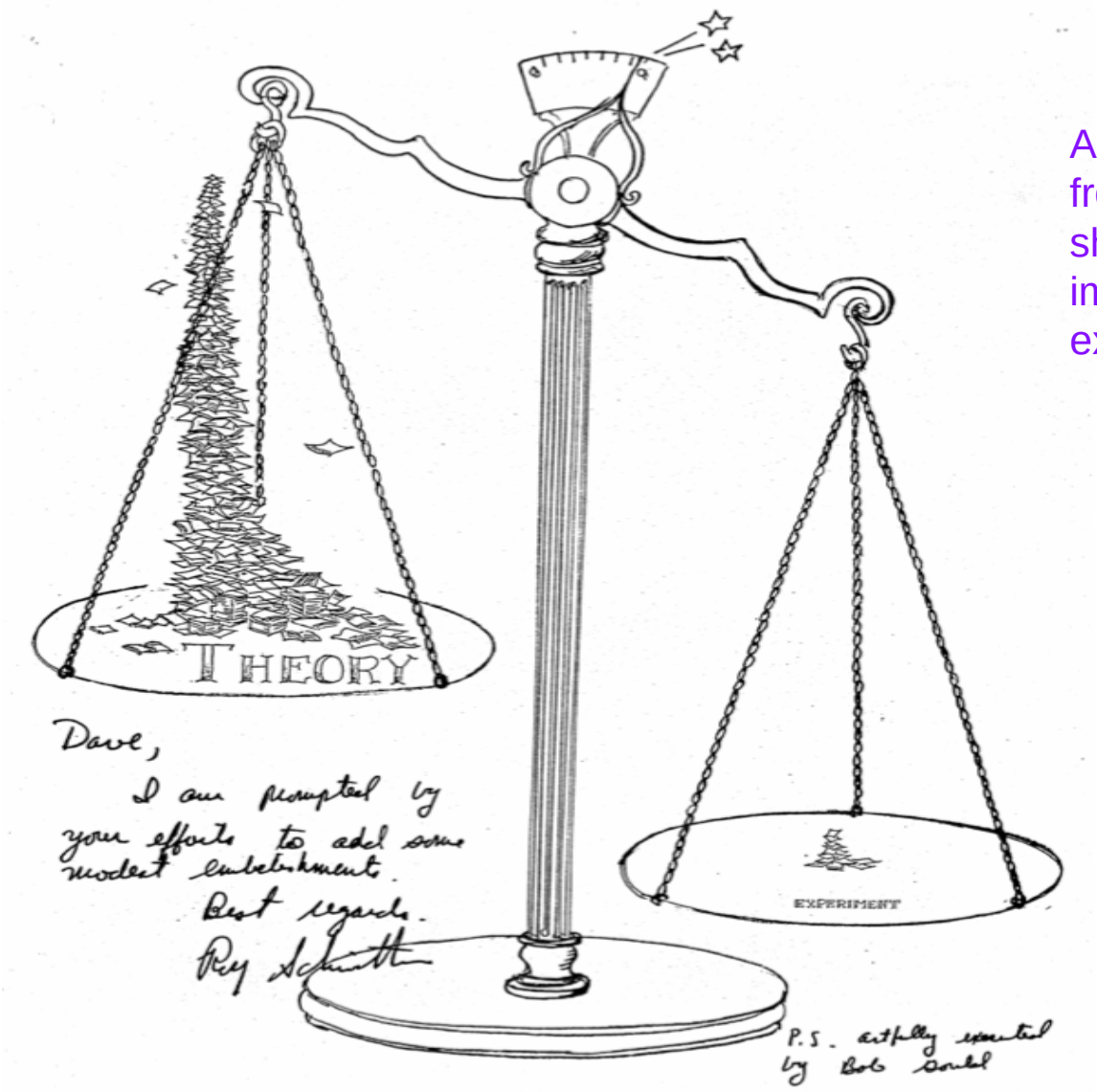
Zhentang Zhao from the Shanghai Institute of Applied Physics spoke with *Nature Photonics* about how he and his co-workers achieved first lasing in an echo-enabled harmonic generation free-electron laser.

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

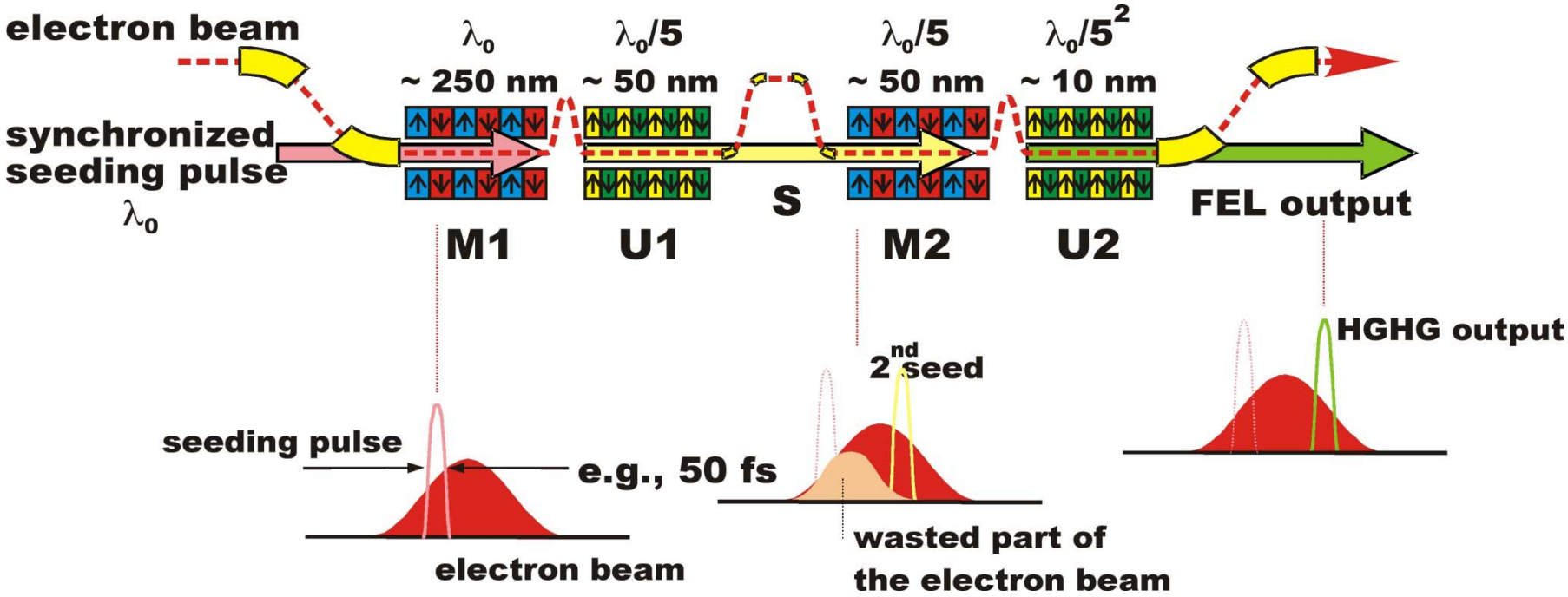
Zhentang Zhao inside the SDUV-FEL facility, where first lasing of the EEHG FEL scheme was demonstrated.

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



A famous drawing from the 1970's showing the relative importance of experiment vs theory

Cascaded HGHG



2-Stage cascade HGHG

The world first 2-stage cascaded HGHG FEL

1200nm

Seed-Laser λ

150MeV

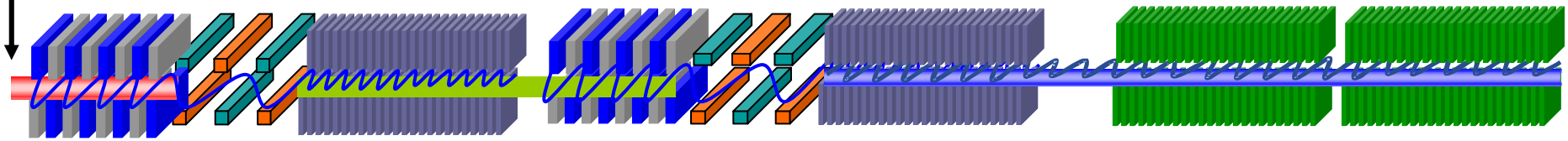
$$\lambda_1 = \frac{\lambda}{n}$$

600nm

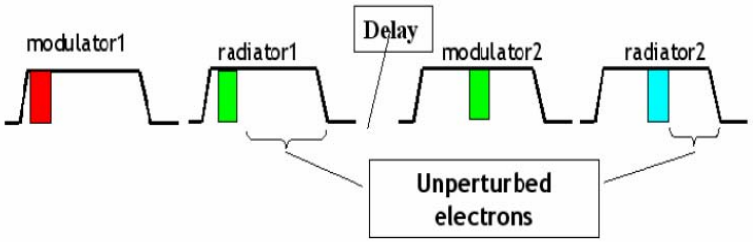
$$\lambda_2 = \frac{\lambda}{n \times m}$$

300nm

$$\lambda_f = \lambda_2$$

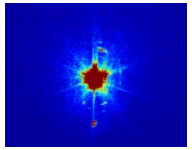


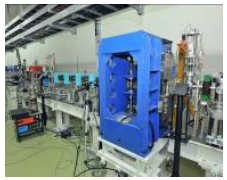
1st Stage **2nd Stage** **Final Amplifier**

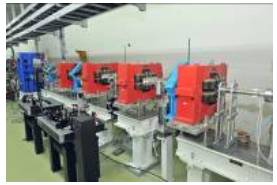


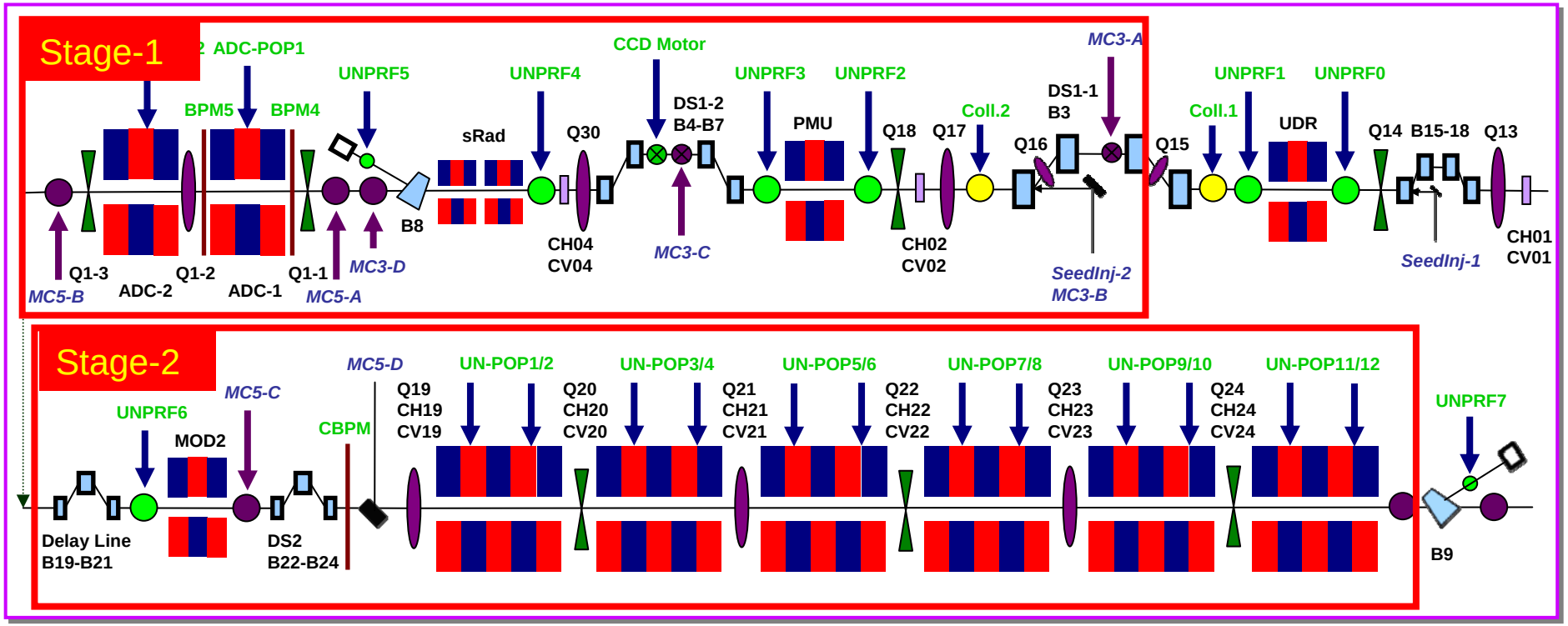
fresh bunch technique

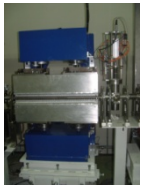
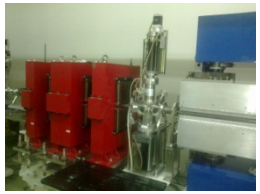
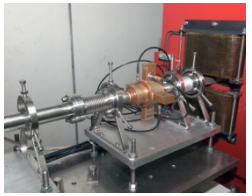
The two-stage cascaded HGHG FEL

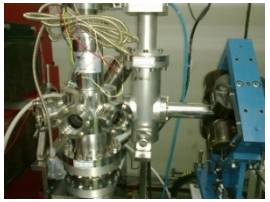
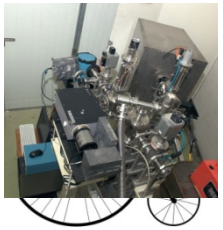




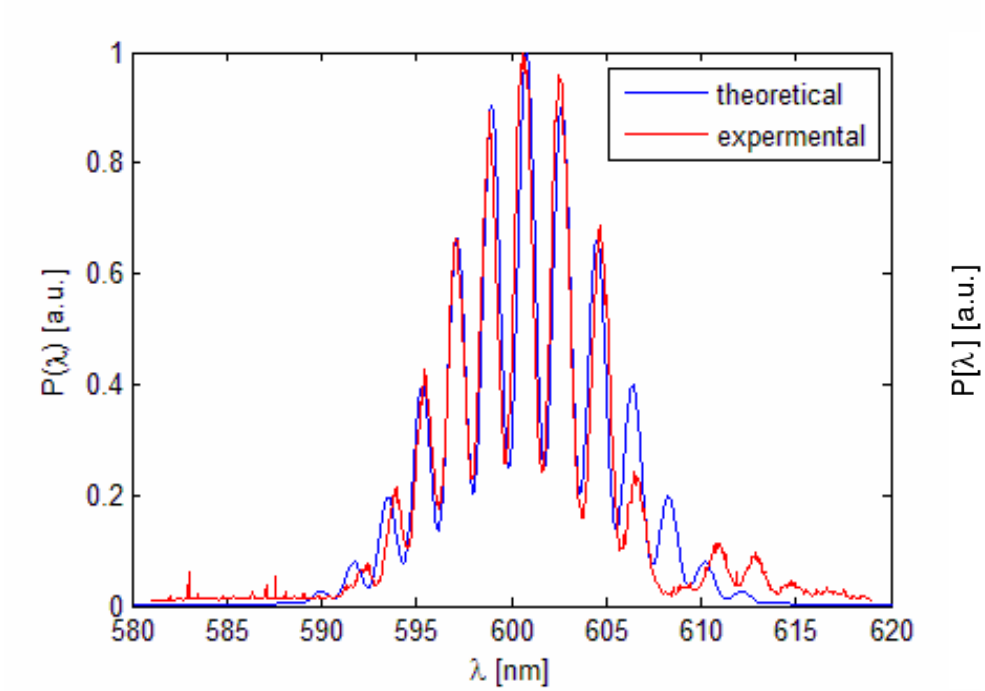


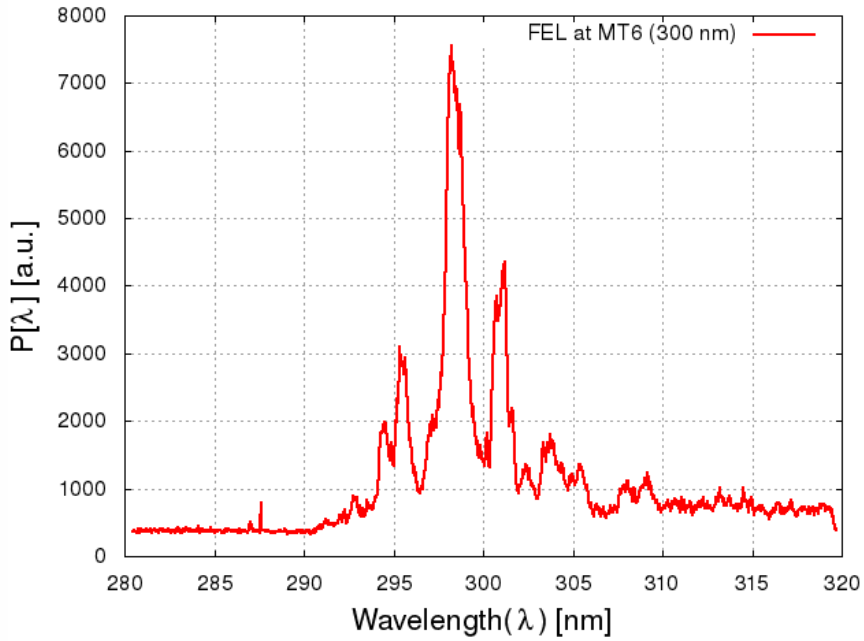


First results from a two-stage cascaded HGHG FEL



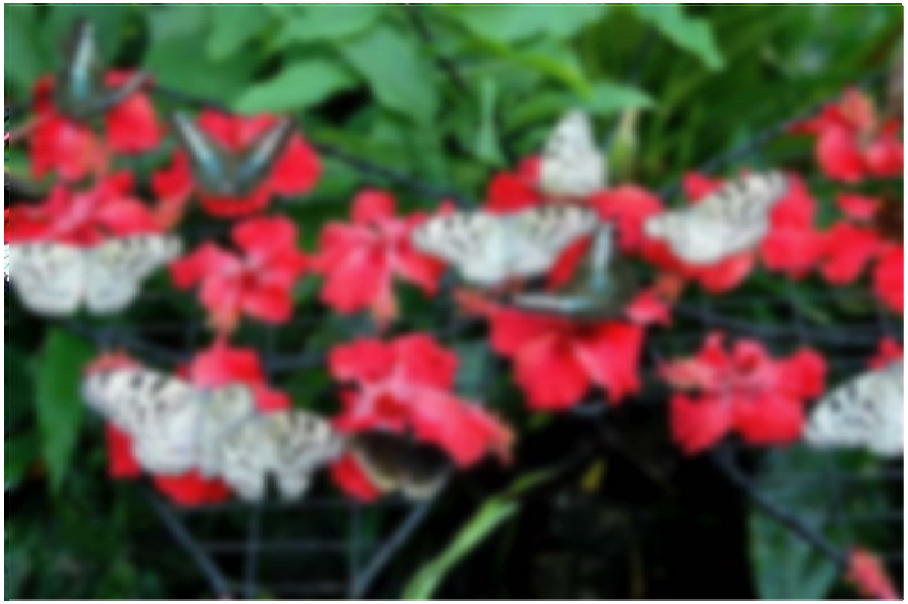


Paper in preparation

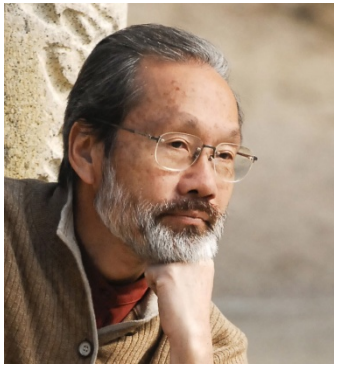
Stability can maximize the performance of a light source !

Courtesy of Hitoshi Tanaka

Stability can maximize the performance of a light source !



Courtesy of Hitoshi Tanaka



As **Shintake** urged in FEL'04, a linac-based light source is essentially unstable without an autonomous stabilization mechanism

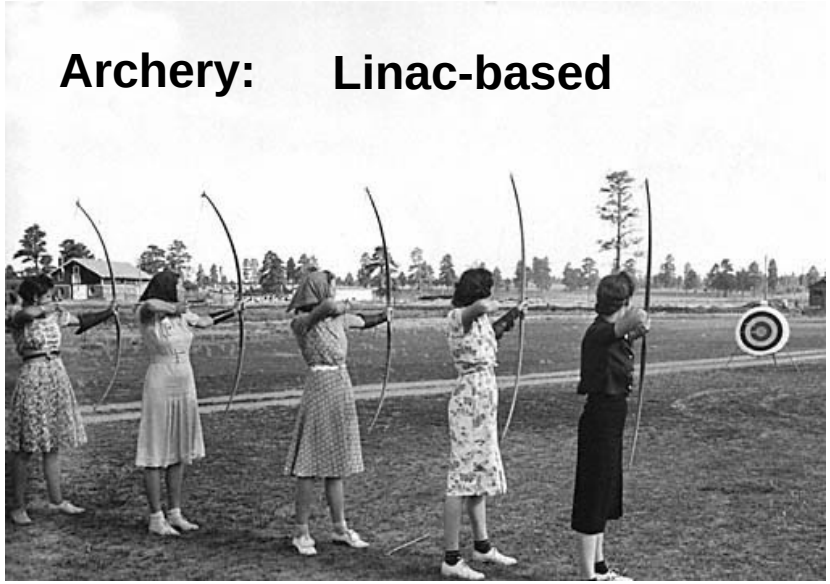
Strategy and efforts on the beam-stabilization is more crucial for **linac-based sources** rather than for ring-based ones.

Spinning-Top:

Ring-based

VS

Archery: **Linac-based**



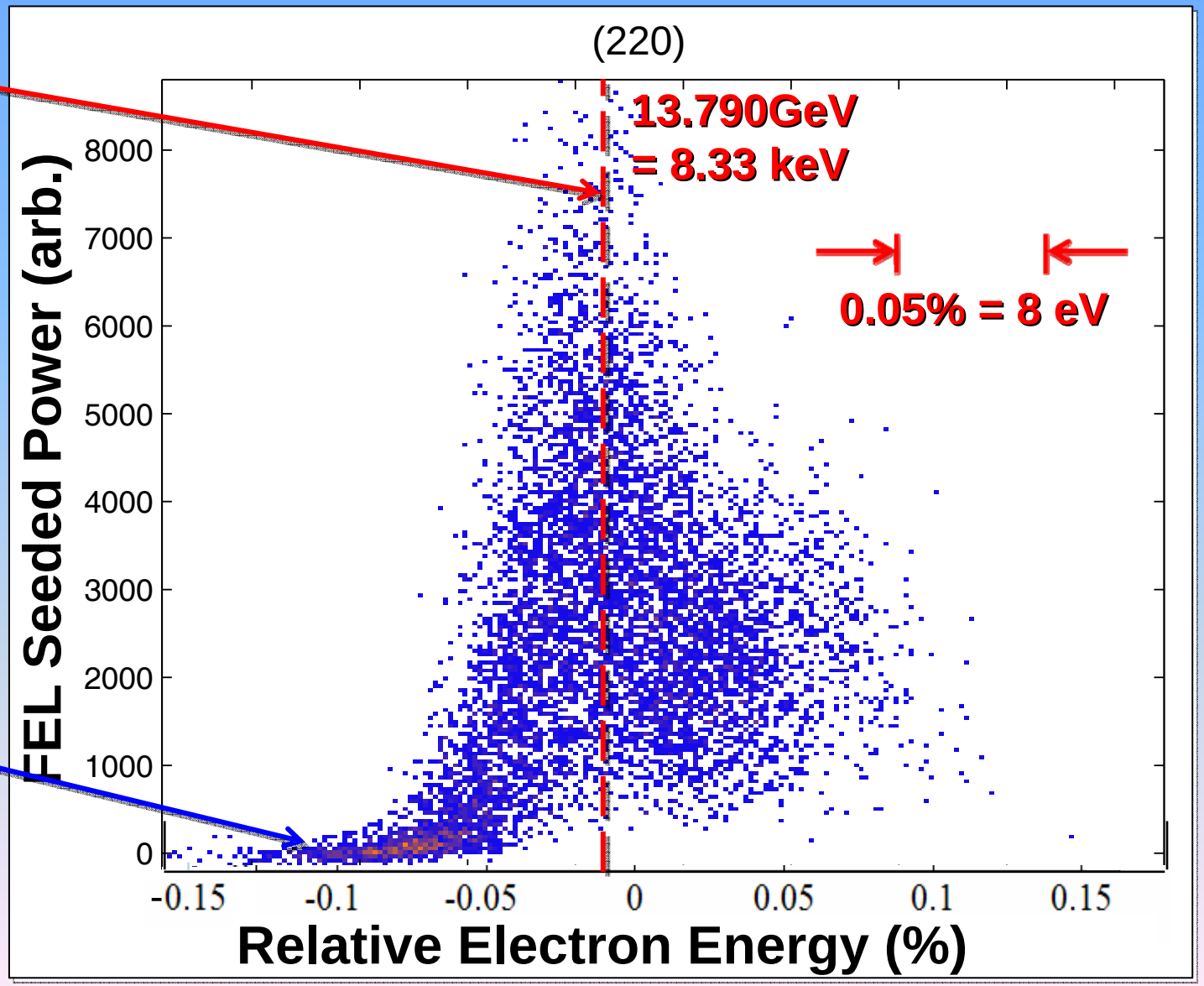
Courtesy of Hitoshi Tanaka

Seeded FEL Power Jitter vs. e^- Beam Energy Jitter

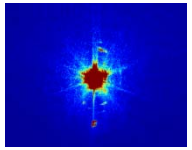
A. Lutman

>50% FEL power jitter even at fixed energy (20% best)… Expect ~10%

6% of shots **not** seeded due to e^- energy jitter (0.04% rms)



Electron-Beam Stability

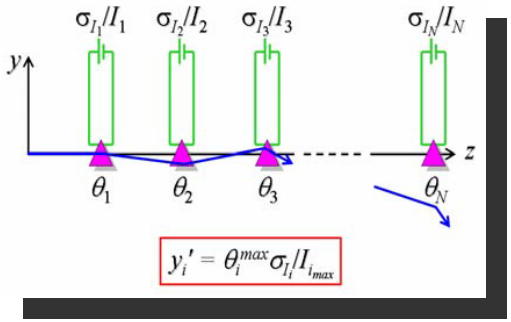


- Transverse stability
  - **Low energy (injector): transverse emittance dilution**
    (depends on the RF-frequency: X-band more sensitive than L-band)
  - **Beam break-up at high average current operation**
  - **High energy (undulator): gain reduction and wavelength jitter**

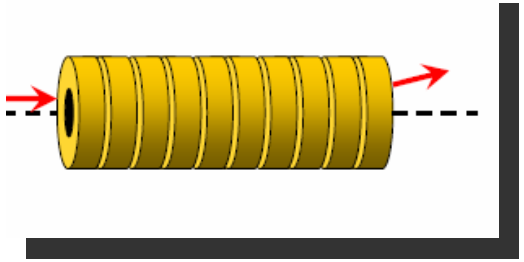
typically a (few) micron orbit accuracy

- Longitudinal stability (bunch / RF phase)
  - **Energy fluctuations**
  - **Current fluctuations → FEL gain fluctuations**
  - **Temporal jitter with synchronized sources**

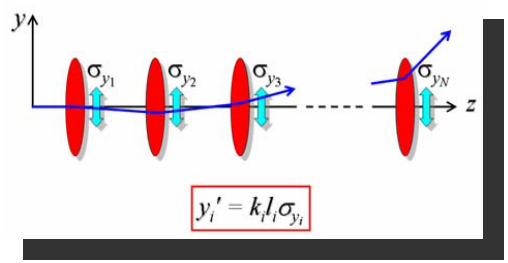
Noise sources: Transverse



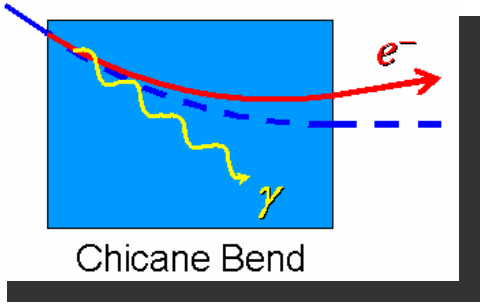
Steering coil current regulation



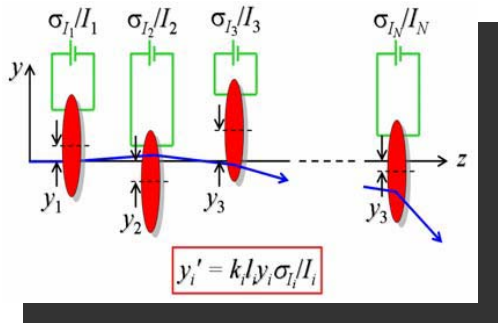
Wakefield kicks with charge jitter



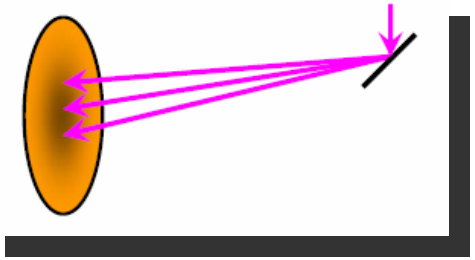
Quadrupole magnet transverse vibration



CSR kicks with charge or bunch length jitter



Quadrupole current regulation with misalignments



Drive laser pointing jitter

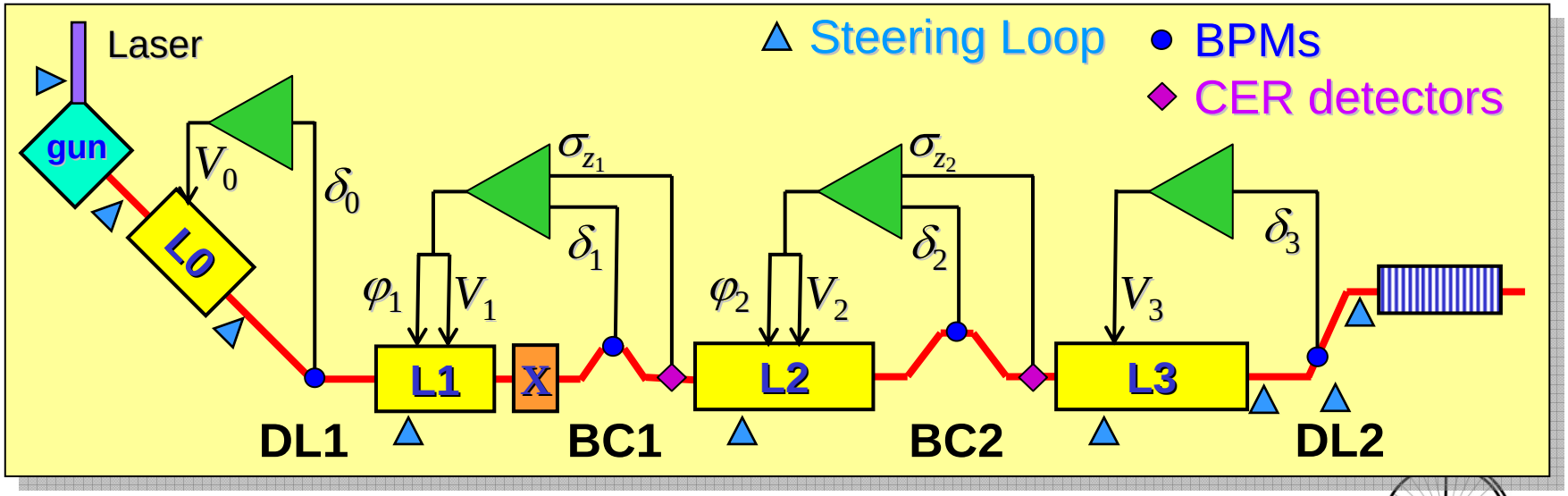
Laser & Electron-Based Feedback Systems

Transverse Loops Stabilize:

- Laser spot on cathode
- Gun launch angle
- Injector trajectory
- X-band cavity position
- Linac & LTU trajectory (5)
- Undulator trajectory

Longitudinal Loops Stabilize:

- DL1 energy
- BC1 energy
- BC1 bunch length
- BC2 energy
- BC2 bunch length
- Final energy



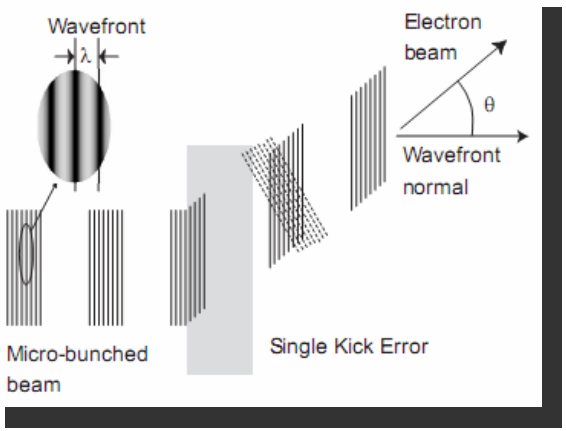
D. Fairley, J. Wu, LCLS@SLAC

Transverse Orbit / Undulator

- Electron beam orbit must be controlled over a few gain-lengths.
- Within this distance: gain reduction
  - → Reduction of radiation efficiency
  - → Smearing of microbunching

$$L_g^{'} = L_g / (1 - x^2)$$

$$x = \theta / \theta_c, \; \theta_c = \sqrt{\lambda / L_g}$$



- Over larger distances the overlap between optical field and the electron beam may disappear. In such a case, the micro-bunching will re-initiate the FEL process over a few undulator periods only.

T. Tanaka et al., NIM A 528 (2004) 172

LCLS Req. Specifications

- <2um over one gain length (~5m)

Table 1: Undulator and beam specifications for the most critical parameters (quadrupole magnet gradient is 60 T/m with mean quadrupole spacing of ~3.9-m).

Parameter Description	Value	Unit
Maximum BPM rms position resolution (x and y)	1	μm
Quadrupole magnet-mover x and y positioning repeatability	±2	μm
Initial rms uncorrelated quad and BPM alignment	100	μm
Initial rms correlated quad and BPM alignment	300	μm
Maximum BPM mean and rms calibration error	10, 3	%
Maximum quadrupole mean and rms gradient error	0.3, 0.3	%
Maximum quadrupole-mover mean and rms calibration error	5, 3	%
Maximum random rms undulator pole field errors	0.05	%
Incoming rms shot-to-shot trajectory jitter (% of rms beam size)	<20	%
Maximum uncertainty in knowledge of beam energy	2	%
BPM absolute read-back rms stability over one hour	2	μm
Minimum quadrupole-mover dynamic range	±500	μm
Earth's magnetic field compensated in undulator shimming	<0.05	G

Summary and conclusions

- FEL activities at SINAP
  - SXFEL: approved in Feb. 2011, design studies underway
  - DCLS: approved and funded, design studies underway, construction will begin late 2012
  - SDUV-FEL: nice test bed, however stability improvement highly desired

- FEL stabilization considerations
  - A lot of engineering challenges ahead

- *Your inputs are greatly appreciated.*

谢谢.