STABLE OPERATION OF HHG-SEEDED EUV-FEL AT THE SCSS TEST ACCELERATOR

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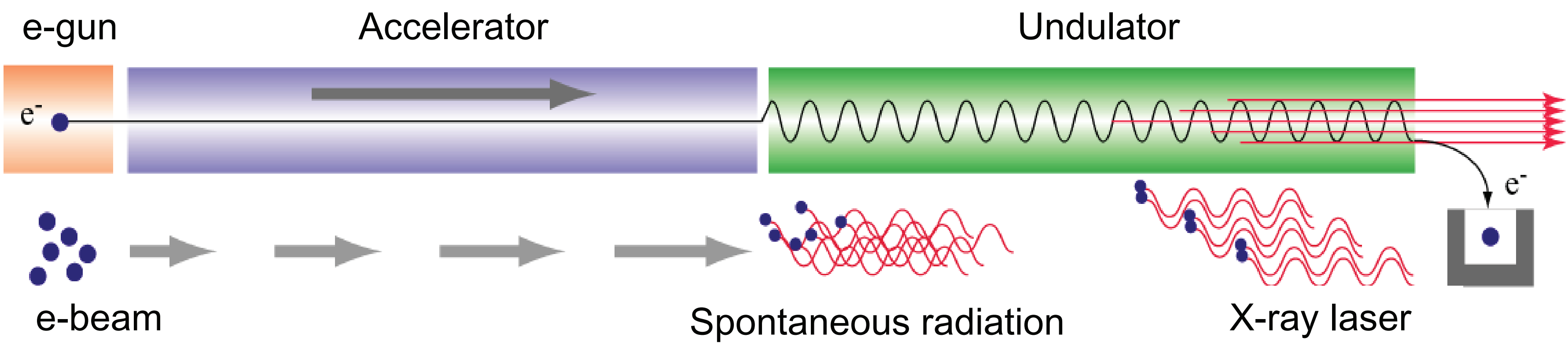
Outline

- Introduction of HHG-seeded FEL
- Seeded FEL with HHG (2010)
- Improvement of "effective" hit ratio of the seeded FEL operation by electro-optical sampling (2012)
- Summary

Self-amplification of spontaneous emission (SASE)



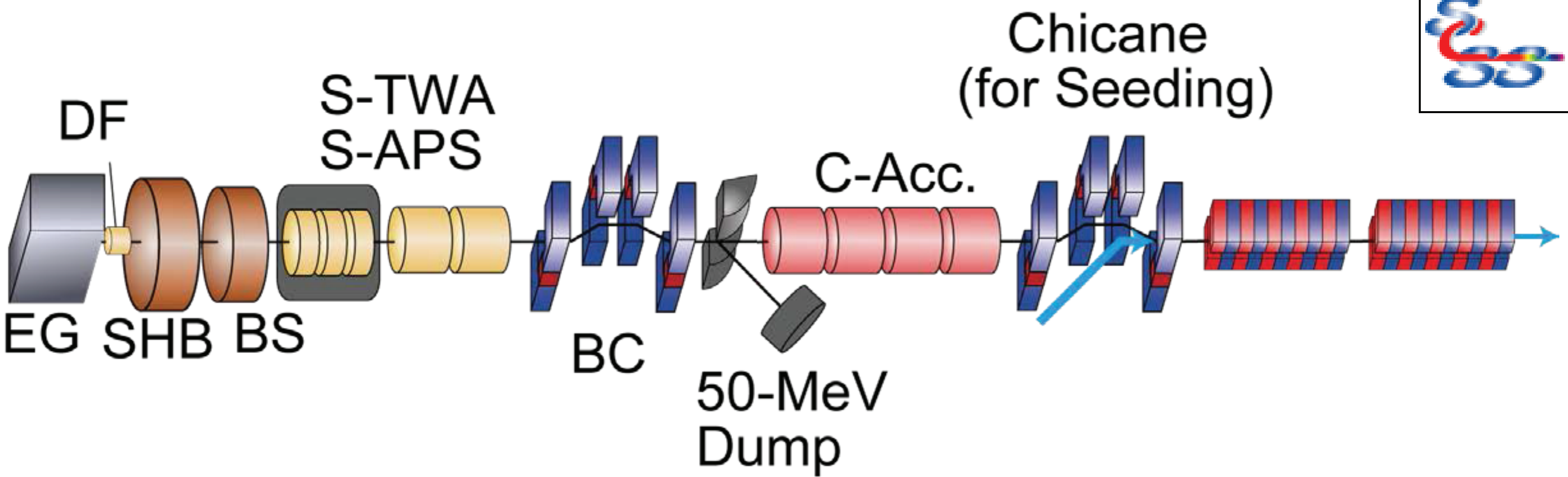
- ☺ Intense light pulse (μJ ~ mJ) *
- ☺ Wide wavelength range (THz ~ x-ray)
- ☺ Short pulse (10 fs ~ 1 ps)
- ☺ Spatial coherence
- ☹ Shot-to-shot fluctuation

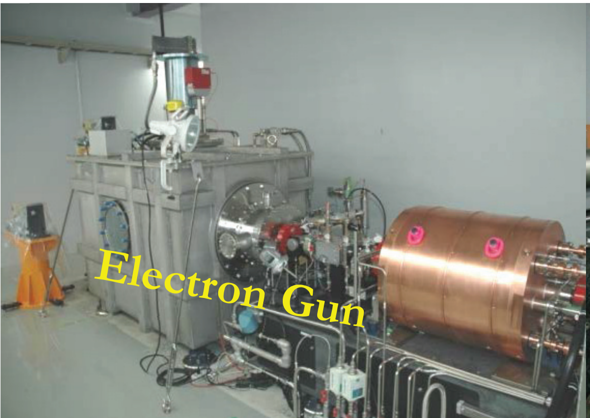
* FLASH (Germany), SCSS (Japan), LCLS (USA), SACLA (JAPAN), …

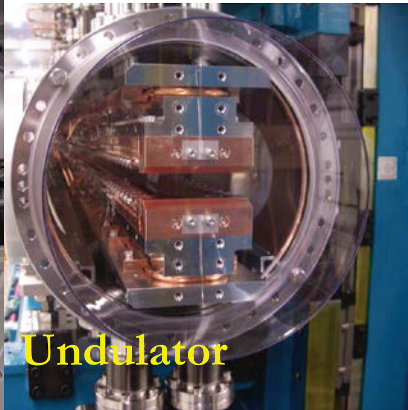
SCSS EUV-FEL Accelerator

- SCSS accelerator (*250MeV*, *50-60nm*)
  - 250 MeV Linac + In-vacuum undulator
  - Development & pilot user experiments of HHG-seeded FEL

SPring-8 Compact SASE Source





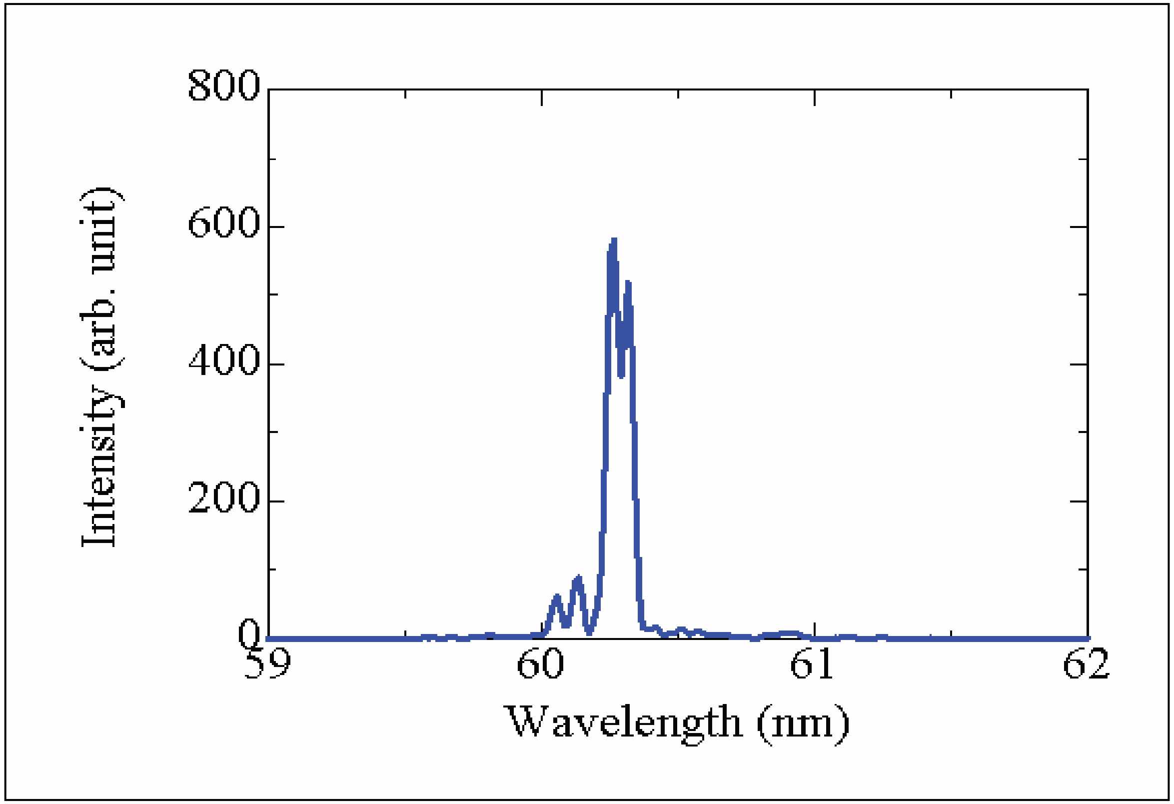


Fluctuating spectra – SASE operation at SCSS

SASE-FEL starts up from noise

Energy spectra and temporal profiles are fluctuating shot-to-shot!

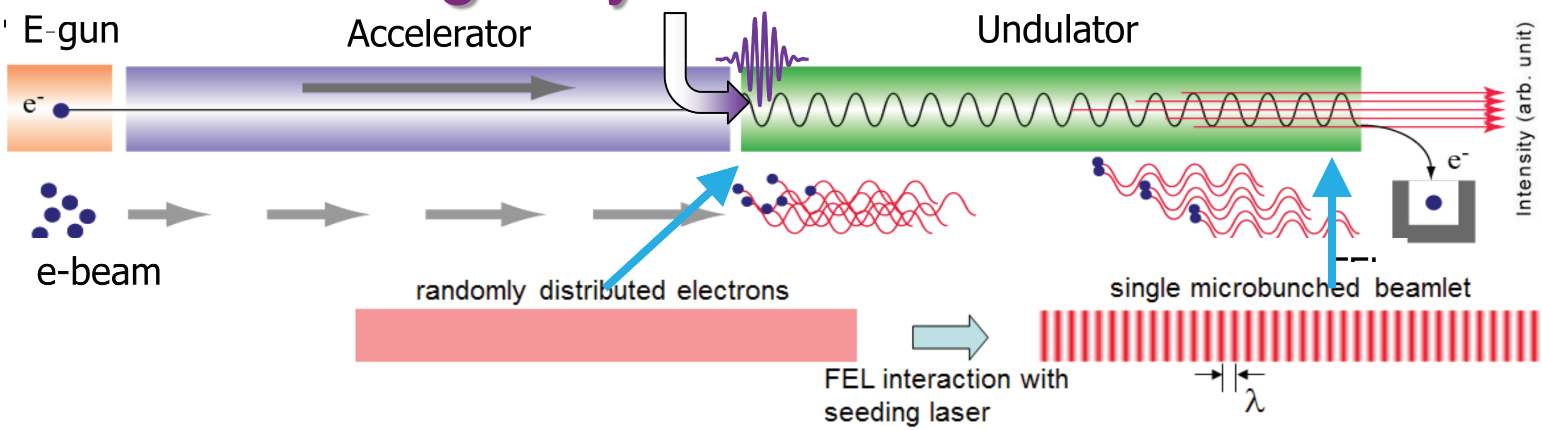
(originated from the SASE process)



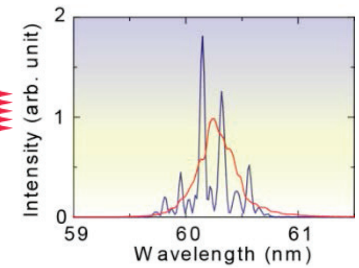
External seeding scheme is one of the solution to suppress shot-noise for reliable full-coherent light source (user operation).

Seeded FEL with HHG (Higher-order Harmonic Generation)

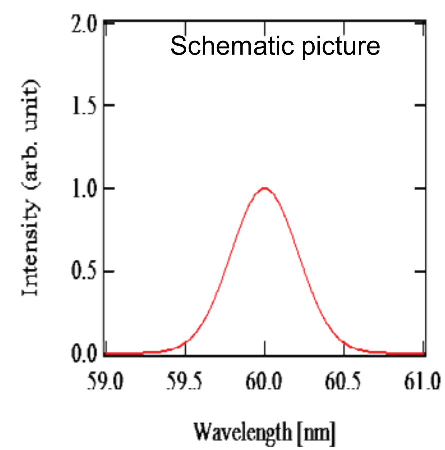
Coherent light by HHG



SASE-FEL



Seeded FEL

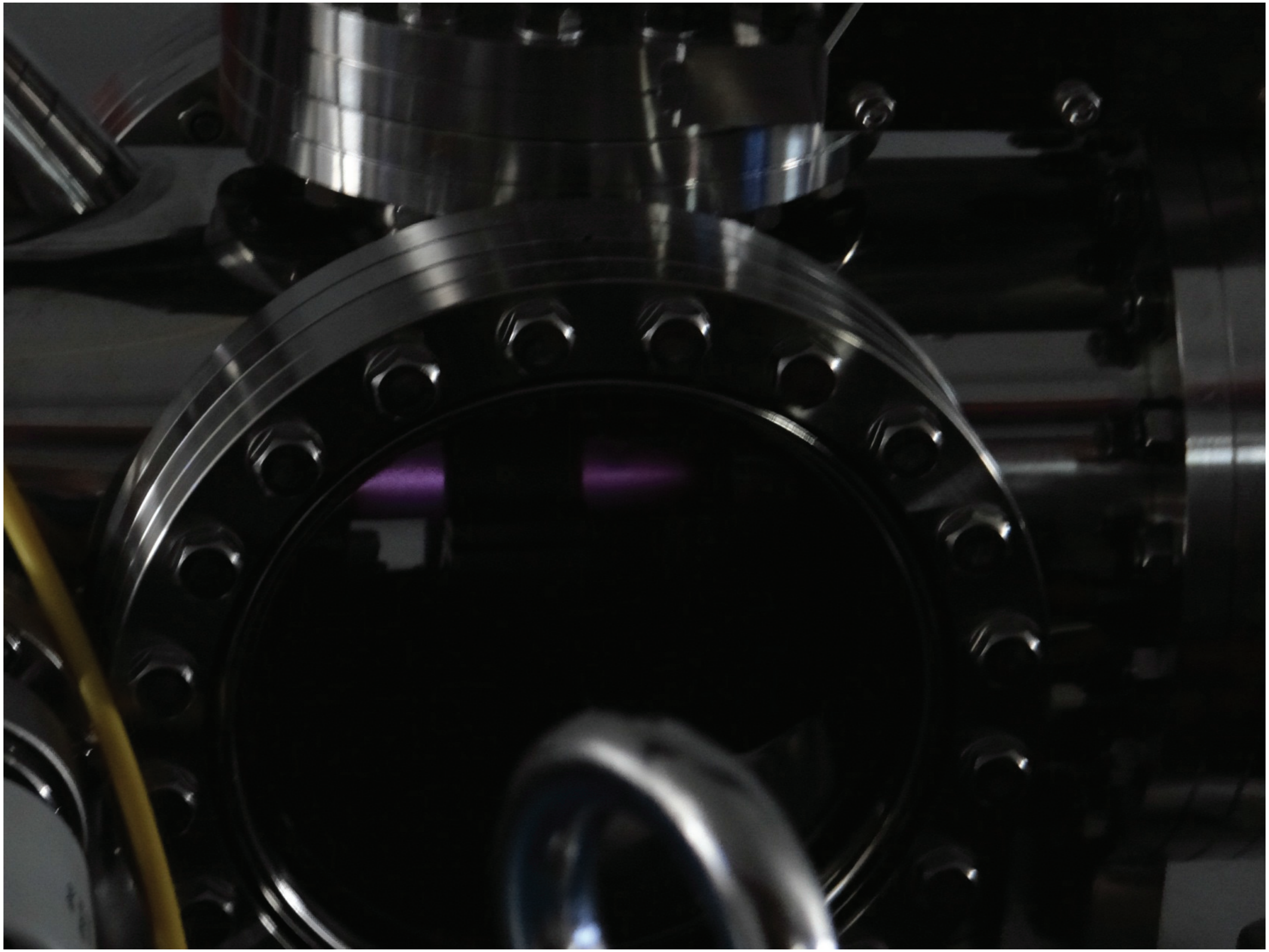


Difficulties of HHG-seeded FEL

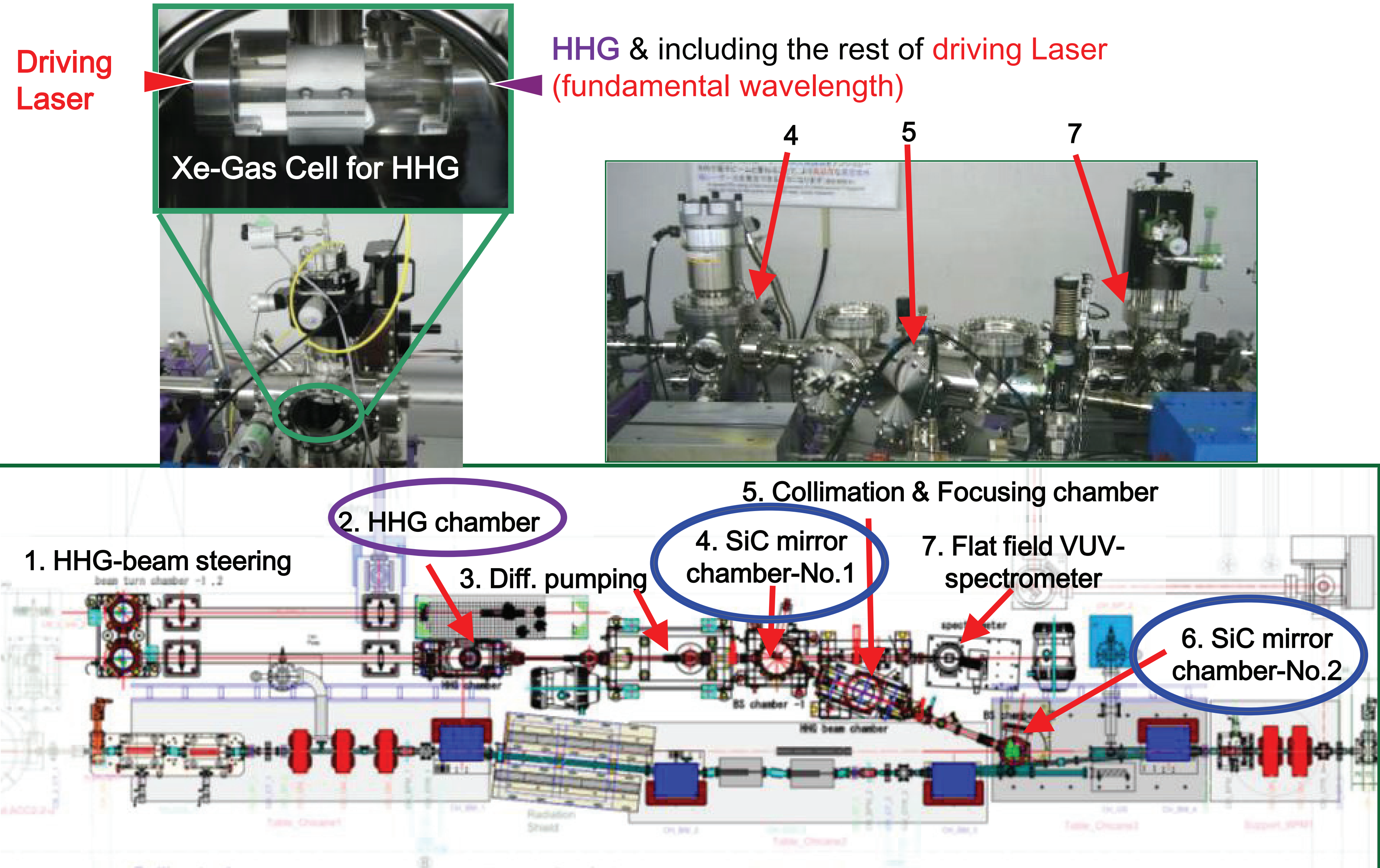
We have to synchronize independent pulse systems (HHG pulse & e-bunch).

Overlapping in 6D phase space under compressed both of HHG-pulse and e-bunch.

Higher-order Harmonic generation in Xe



HHG and its transport



6D phase space overlap for seeded FEL

	Size (x, y) FWHM	Time FWHM	Wavelength (Energy)
Electron bunch	~ 500 μm	300-600 fs	61.7 nm
HHG seed pulse	~ 1 mm	~ 50 fs	61.7 nm

To kill timing jitter, both pulse/bunch covers each other!

6D Phase Space

Centroid positions (Transverse size): X, Y

Momenta (Divergence): θx, θy

Time : t

Energy (Central Wavelength): E

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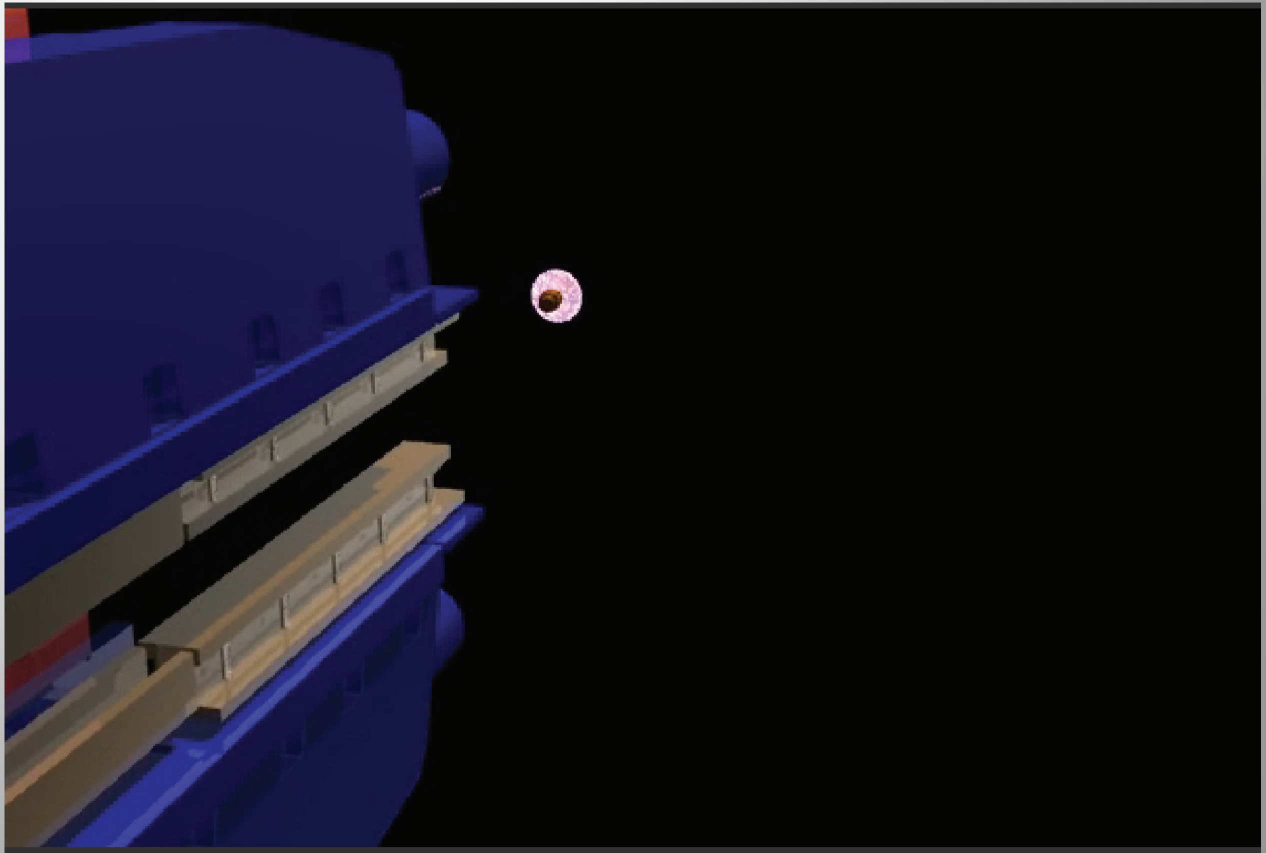

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6D Phase Space

Centroid positions (Transverse size): X, Y

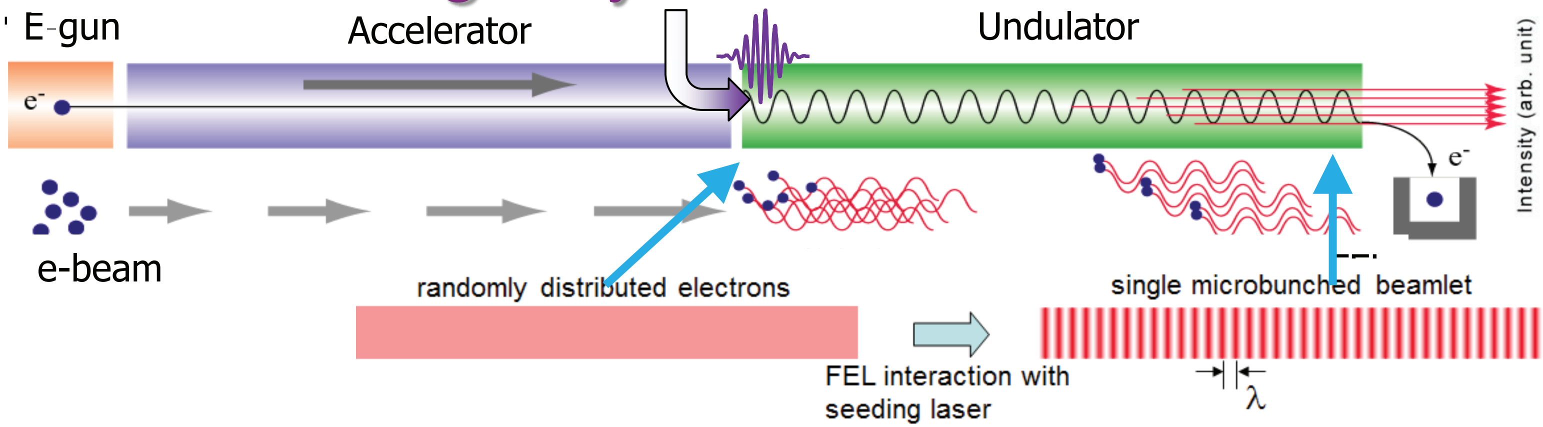
Momenta (Divergence): *θx, θy*

Time : *t*

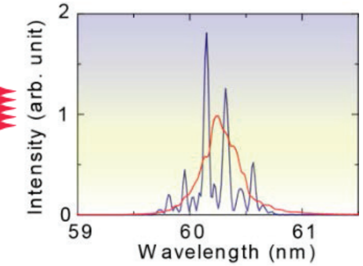
Energy (Central Wavelength): *E*

Seeded FEL with HHG

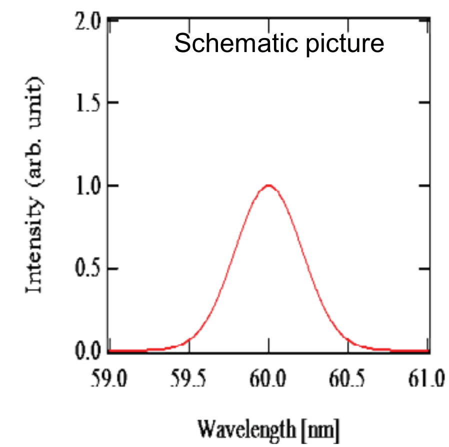
Coherent light by HHG



SASE-FEL



Seeded FEL



Advantage of Seeded FEL

- *Full (Temporal and Spatial) coherent*
- ***Monochromatic spectra***
- *Power stabilization*
- *Jitter free synchronization*
- *Compact undulator design*

Besides, higher contrast ratio (S/N) against SASE background noise!

Comparison of Seeded-FEL facilities

	USA LCLS SLAC	Japan XFEL/SPring8 RIKEN	Japan SCSS/SPrng8 RIKEN	FLASH DESY-II (sFLASH)	FERMI Itary
Electron Energy	14 GeV	14 GeV	0.25 GeV	1.25 GeV	10～20GeV
Wavelength	0.15 nm	0.06 ~ 0.15 nm	160 ~ 53nm, 30 nm (SHG)	30 nm	260 ~ 4 nm
Rep. Rate	120 Hz	10 Hz	30 Hz	10 Hz (Burst 1 MHz)	10 Hz (Burst 3 MHz)
Pulse energy	~ 200 μJ		~ 30 μJ	??	~ 10 μJ
Method	Self-seeding	Self-seeding	Direct HHG seeding	Direct HHG seeding	260 nm HGHG
Year of Seeding operation	2012	2013-2014??	2006	2012	2012

Sweden MAX-lab: HHG direct seed + HGHG
China SINAP: Shanghai DUV-FEL (EEHG)

Our history of HHG-Seeding Developments

Date	Event	Condition	Reference
June 2006	The first SASE amplification with our new machine concept	250 MeV, 49nm	
Dec. 2006	Seeding at **160 nm**	150 MeV, HHG 5th	G. Lambert et al., Nat. Physics 4, 296 (2008)
Sept. 2007	SASE saturation	250 MeV, 50~60nm	T. Shintake et al., Nat. Photonics. 2, 559 (2008)
Oct. 2010	Seeding at **61, 53 nm** Hit rate: ~0.3% Pulse energy : ~2 μJ	250 MeV, 300 fs HHG **13,15th**	T. Togashi, et al., Opt. Exp. 19, 317 (2011)
March 2011	The first test of Arrival time monitor (relative timing btw. e-bunch and HHG with EO sampling)		H. Tomizawa, BIW2012, Newport News, VA (2012)
July 2012	Seeding at **61 nm** with EO sampling **Hit rate: ~30%** Pulse energy : ~20 μJ	250 MeV, 600 fs HHG **13th**	H. Tomizawa, et al., LINAC2012, Tel-Aviv (2012)

Task force in our collaboration for HHG-seeding

Supports for this projects:

- RIKEN/JASRI XFEL project (SACLA)
- SCSS test accelerator operation team (Engineers)

Financial supports :

- RIKEN extreme photonics
- MEXT X-ray free electron laser utilization research (The University of Tokyo)
- Japan Atomic Energy Agency, Quantum Beam Science Directorate

A. Iwasaki

K. Ogawa, Y. Okayasu, H. Tomizawa, T. Togashi, T. Sato, S. Owada

T. Watanabe, E. J. Takahashi, S. Matsubara

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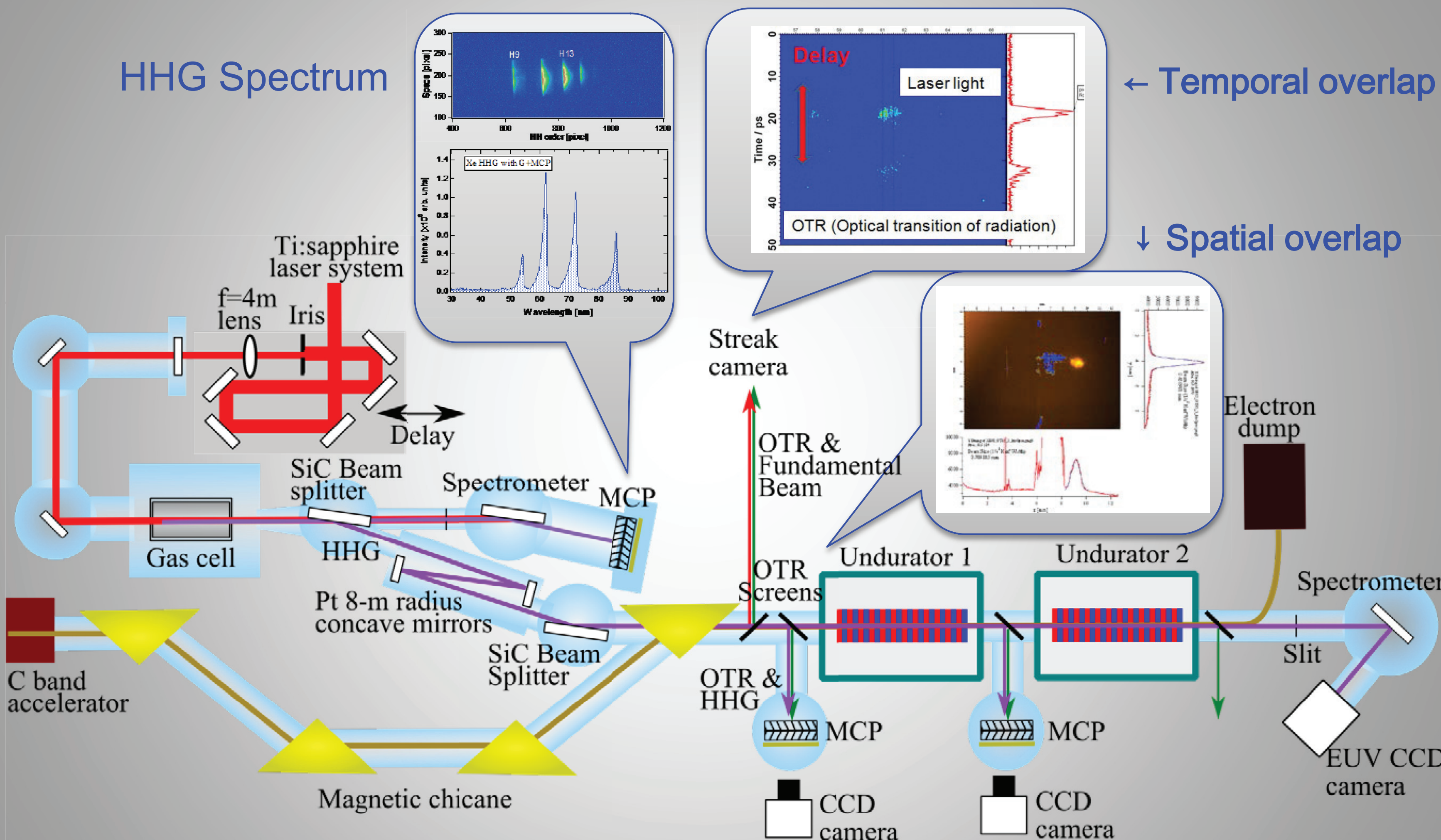
Seeding results at 61 nm in 2010

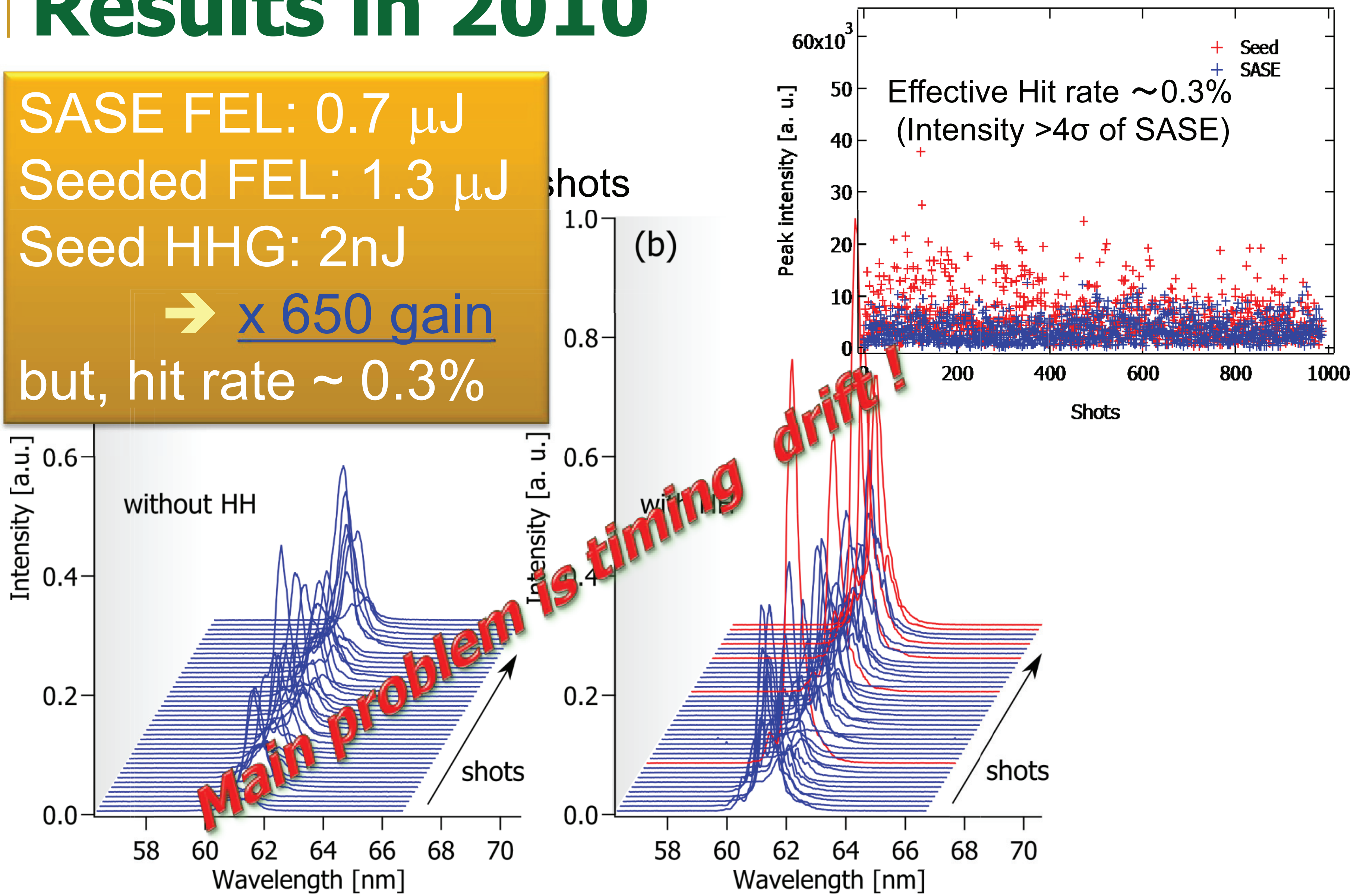


61nm-2nJ HHG @ Undulator

Results in 2010

SASE FEL: 0.7 μJ
Seeded FEL: 1.3 μJ
Seed HHG: 2nJ
➔ x 650 gain
but, hit rate ~ 0.3%

Trend graph of peak intensity



T. Togashi *et. al.*, Optics Express, **19** 317 (2011)

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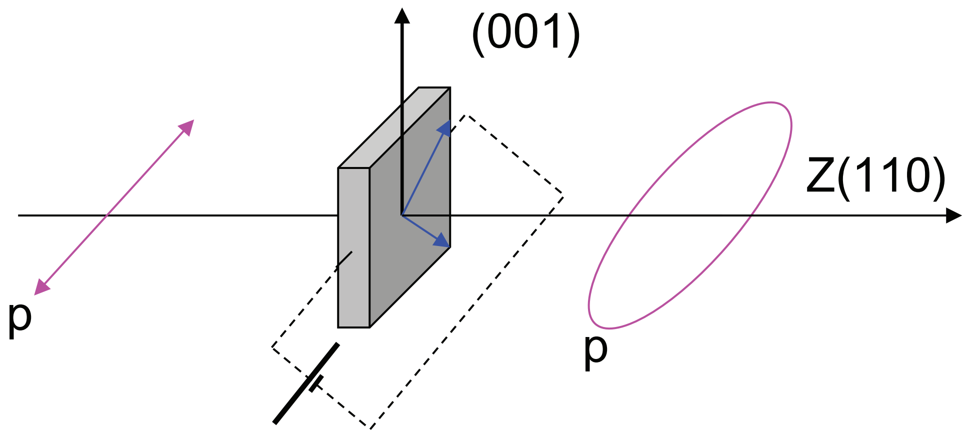
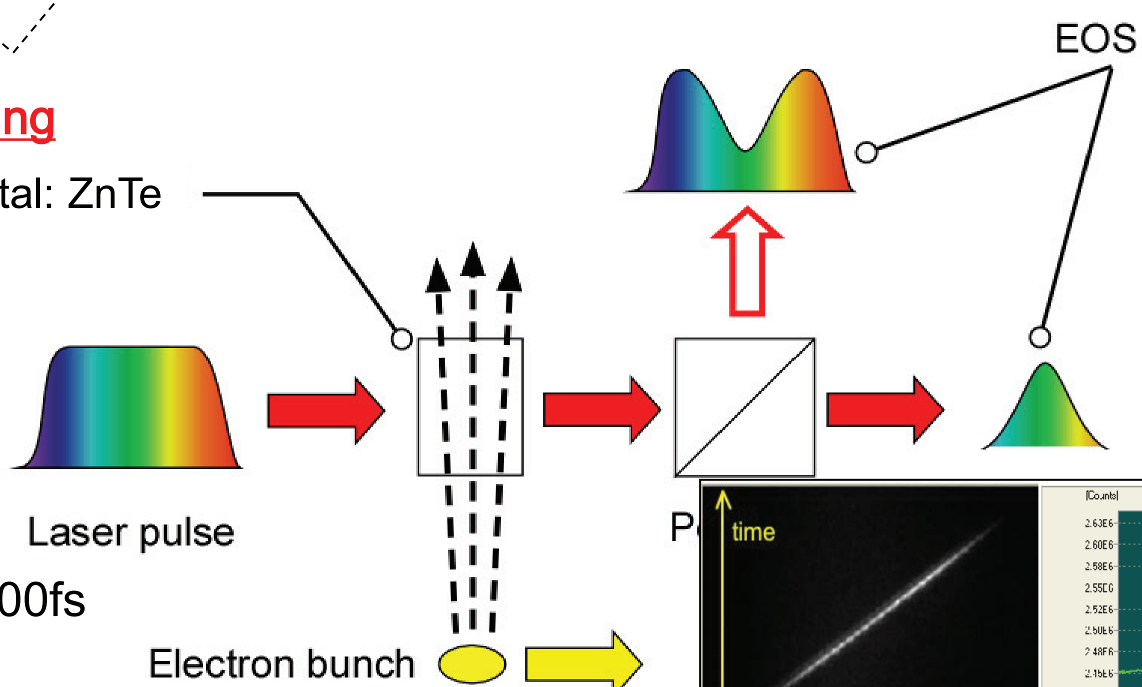
Principle of EOS (Electro-Optic Sampling)

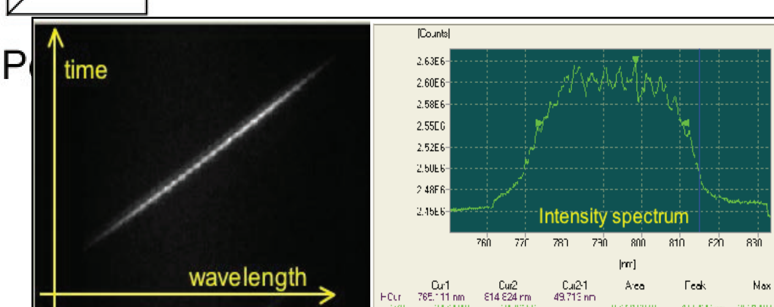
Pockel's effect (ZnTe)



By detecting the retardation (*Modulation of Polarization*) , we can know the temporal information of electron bunch (*Electric field*) .

Spectral Decoding



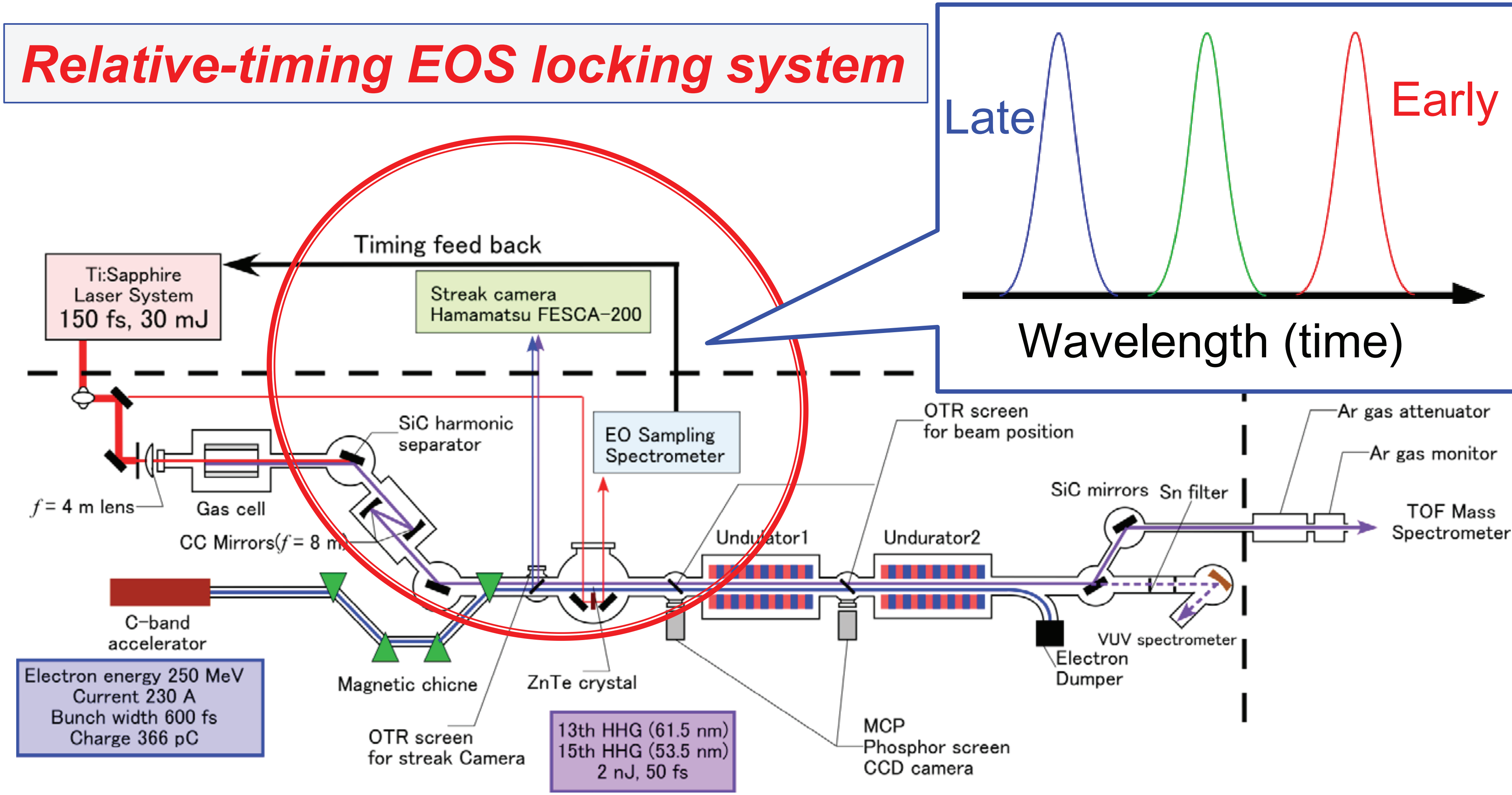


Electron bunch ～100fs

Electric field :
>100kV/cm @250MeV

Improvement of Hit Rate (~2012)

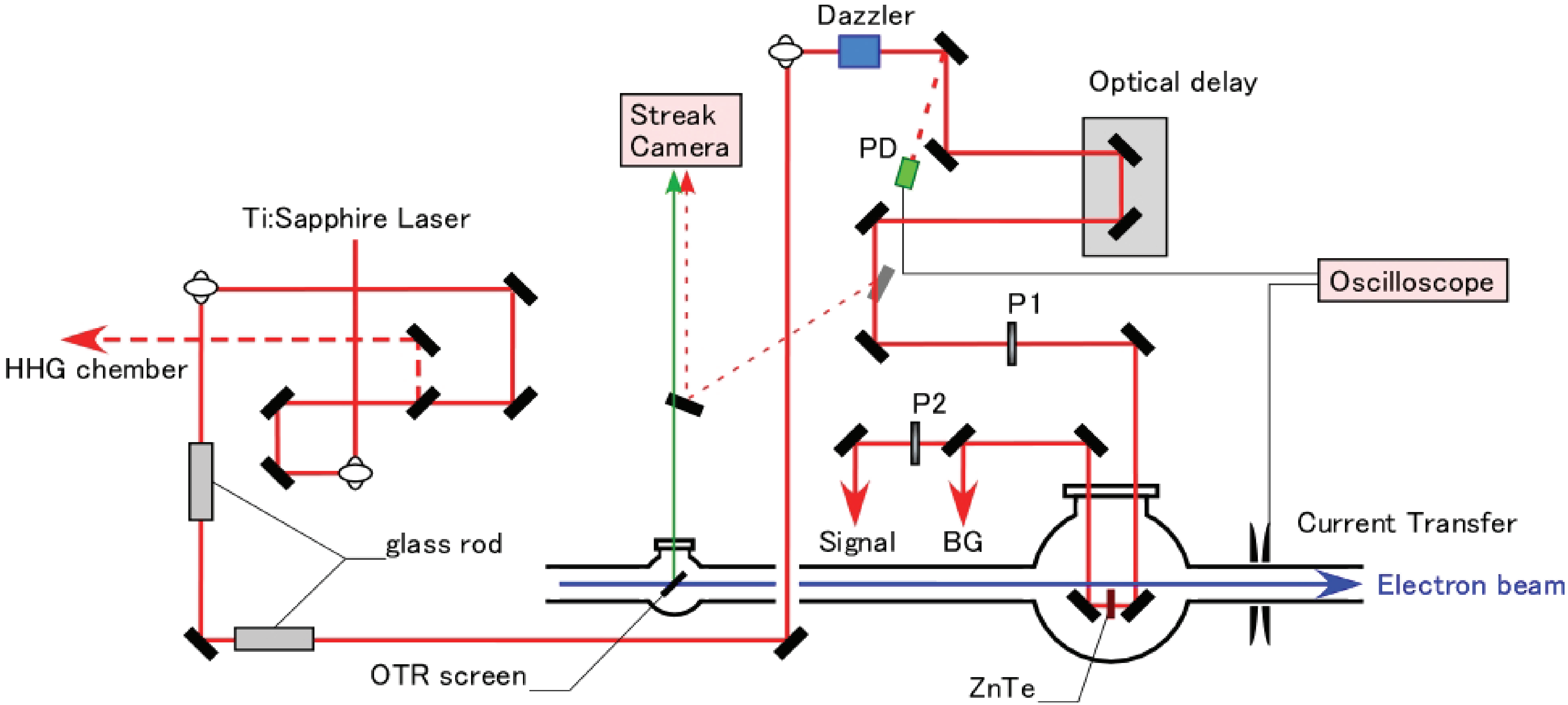
Relative-timing EOS locking system



61nm-2nJ HHG@Undulator

Measurement of arrival timing with EO-sampling for feedback (2012 April)

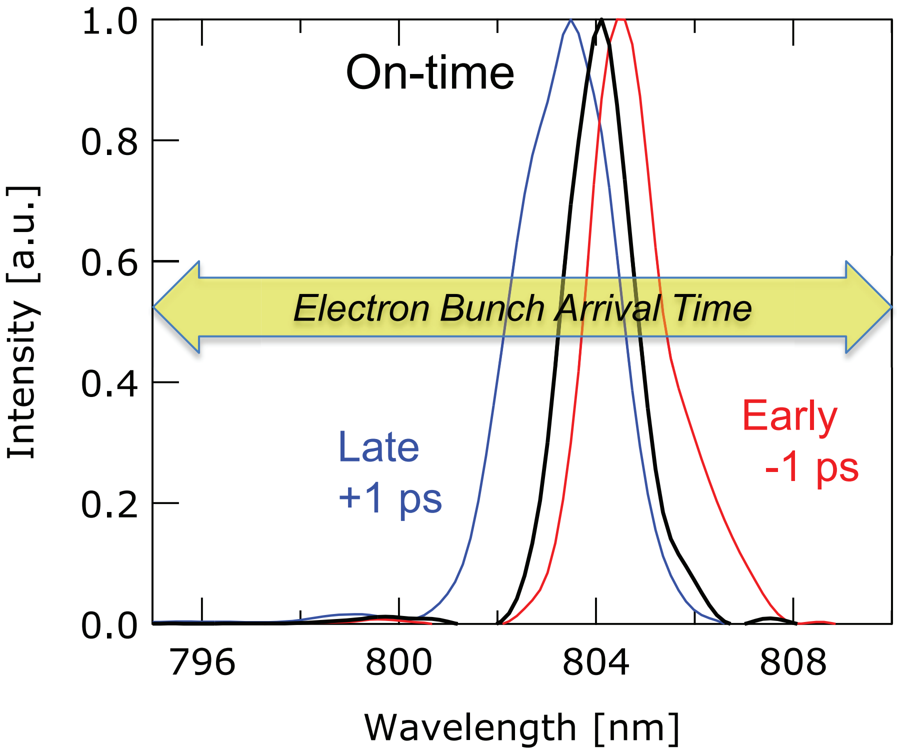
PD : photo diode
P1, P2 : polarizer (crossed Nicols)
OTR : optical transition radiation



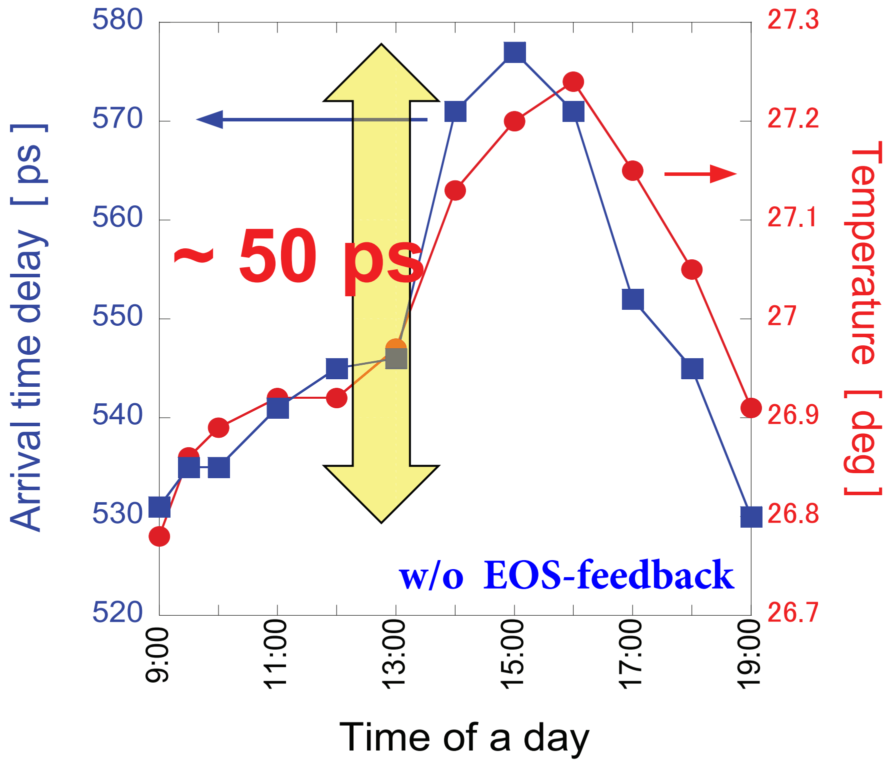
- EO prove laser was produced from HHG driving laser for seeding.
- High-dispersion glass-rod (n = 1.96, L = 20 cm)
  for a linear chirp pulse (175 fs → ~14 ps)

Relative timing-drift monitored by EOS

The spectra of EOS signal pulses decoded as the timing shifts from the best seeding condition (On-time)



"Relative" timing drift between the electron bunch and the laser pulse

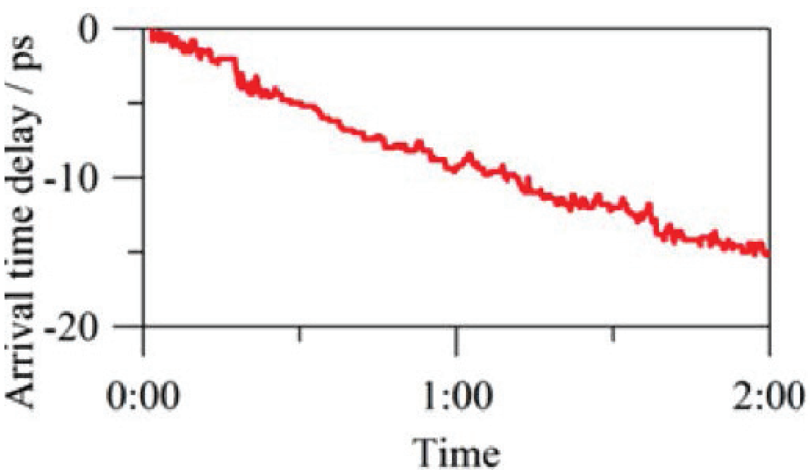


The arrival-time drift is calculated automatically with the computer program in terms of the peak position of the EOS signals.

The arrival-time drift of electron bunch : ***~50 ps for ½ day***

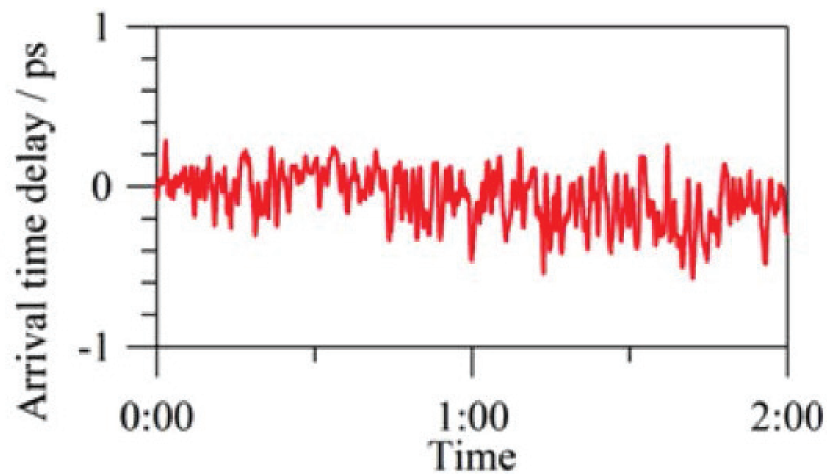
Performance of the Active feedback system for the timing jitter

Relative timing drift is actively compensated by using the EO signal



Timing drift > 15 ps

w/o EOS-feedback



Timing drift < 1 ps

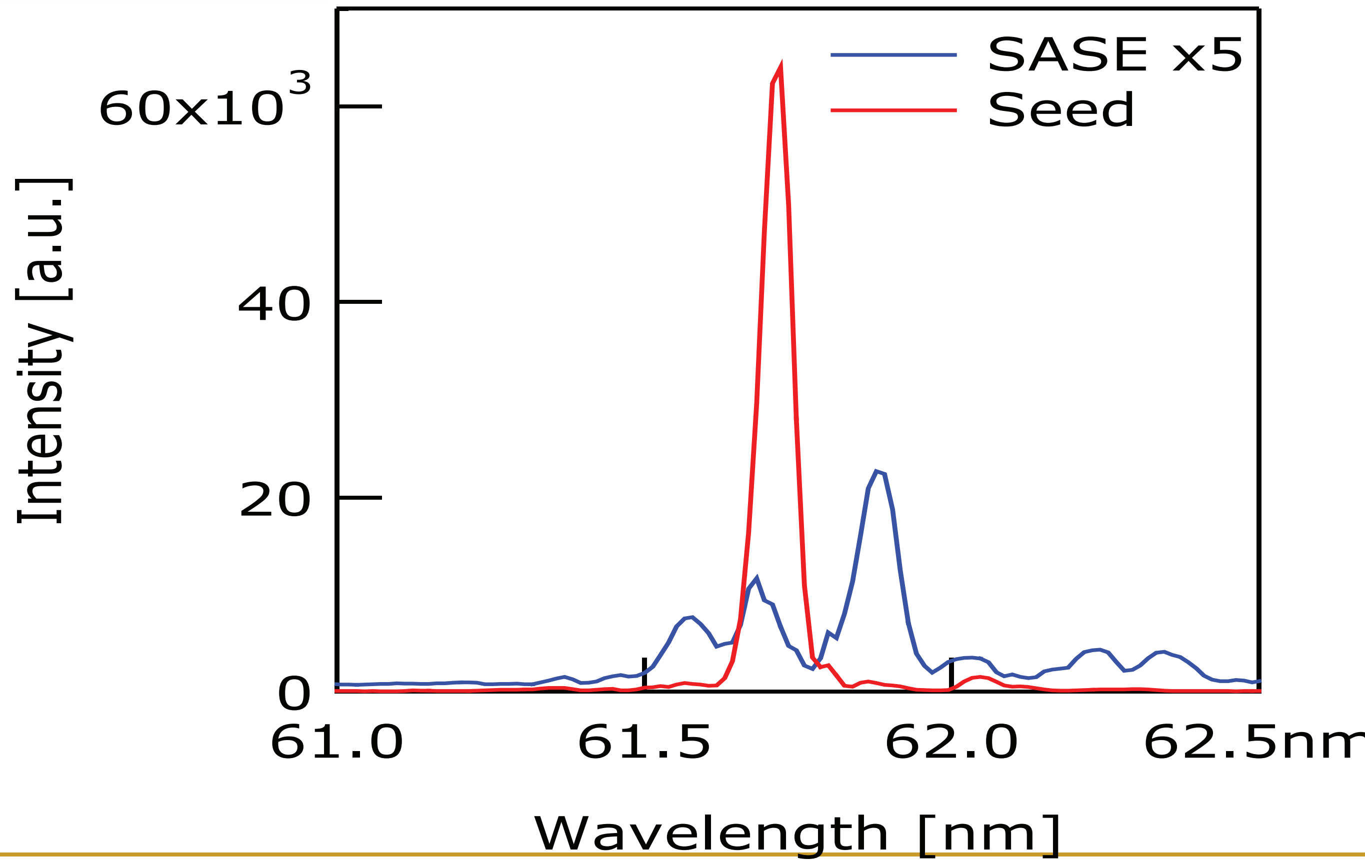
w/ EOS-feedback

A mode-locked oscillator (238-MHz) was synchronized to a 238-MHz master clock of SCSS by feedback locking of the cavity length.

Seeded FEL Performances (2012)
- Single shot spectrum -

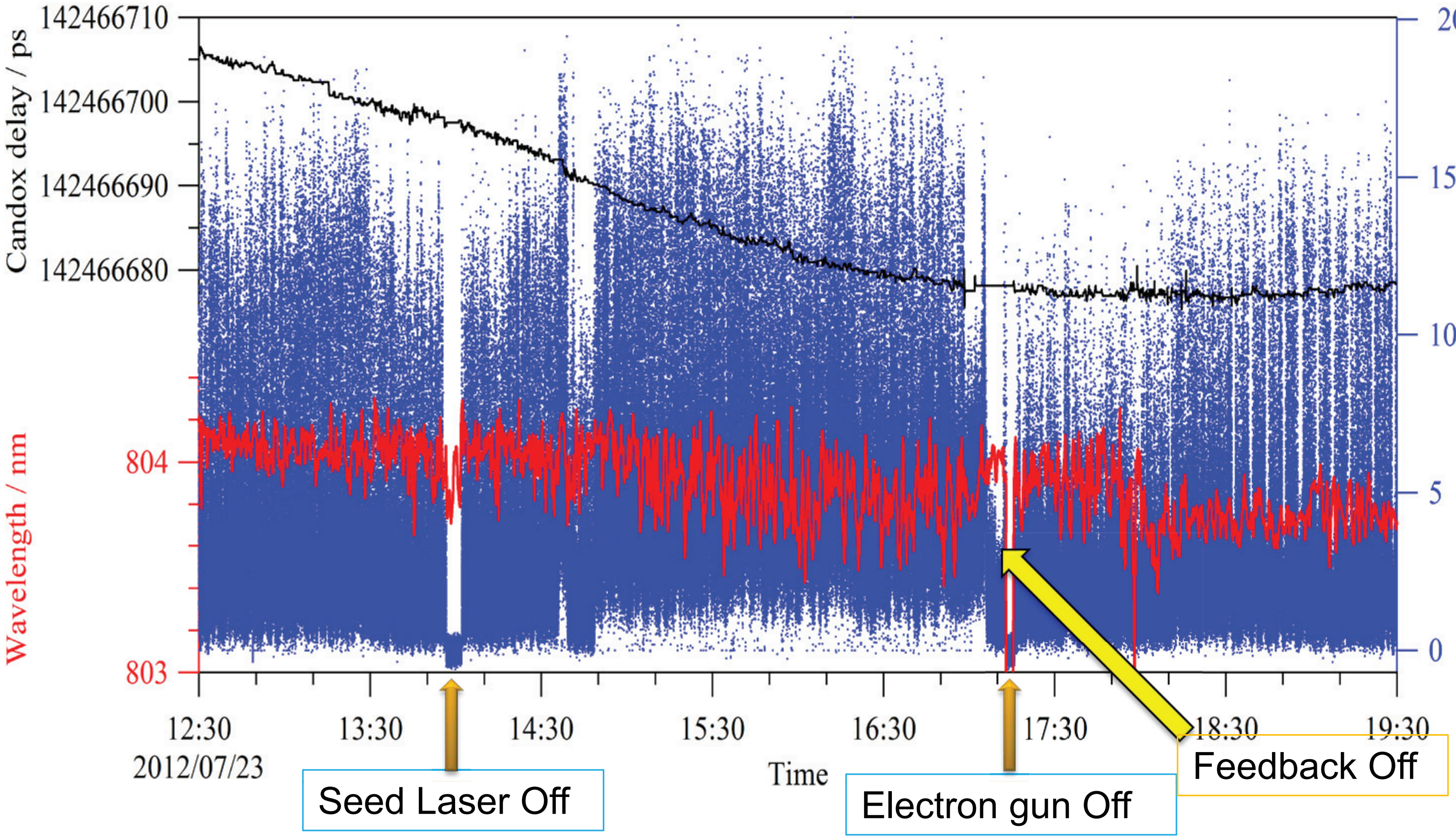
Spectra
Seeded vs. SASE FEL

The spectral bandwidth (FWHM) was **0.06 nm**.



Seeded FEL Performances (2012)

- Long term stability -



Seeded FEL Performances (2012)

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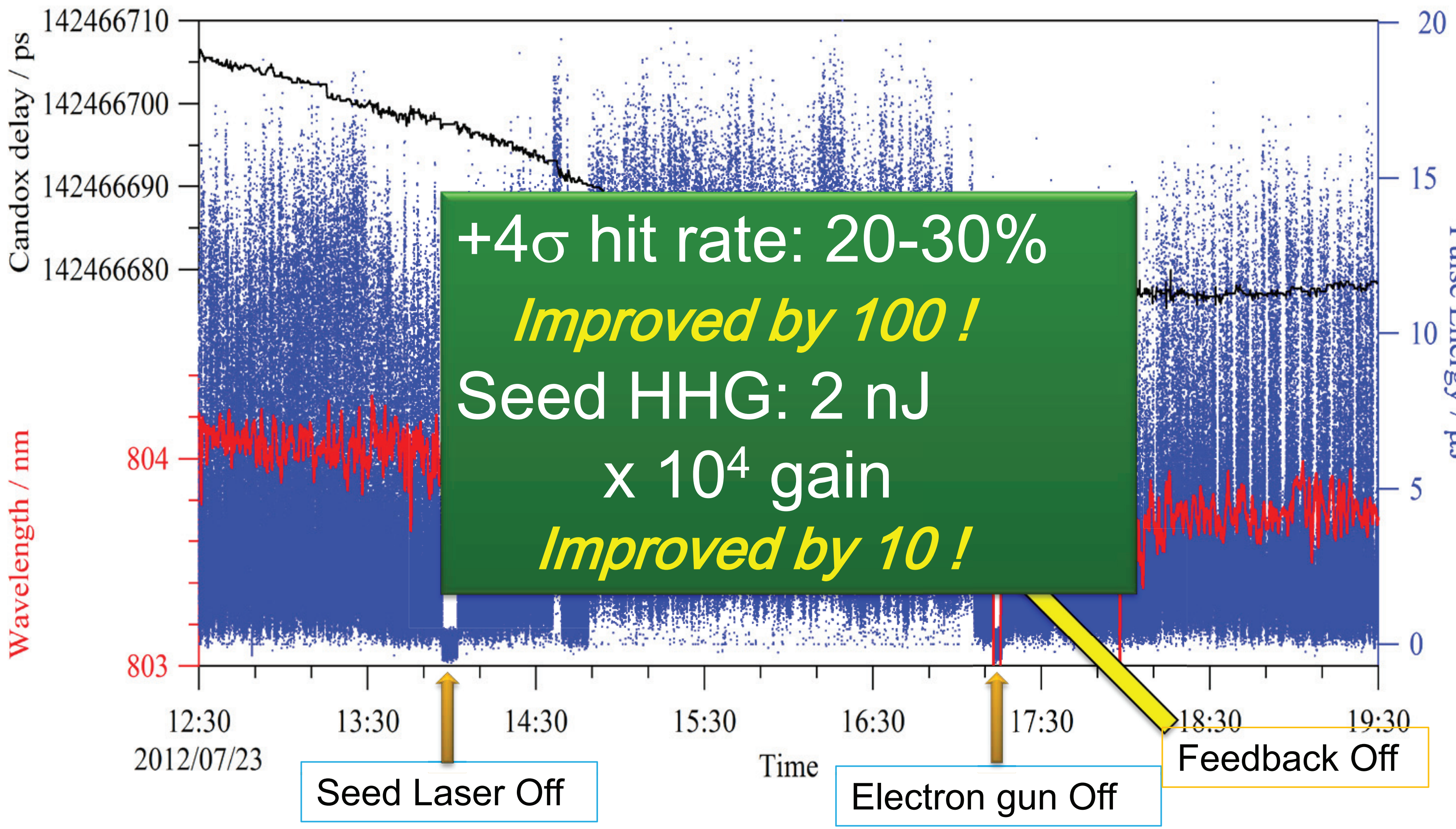
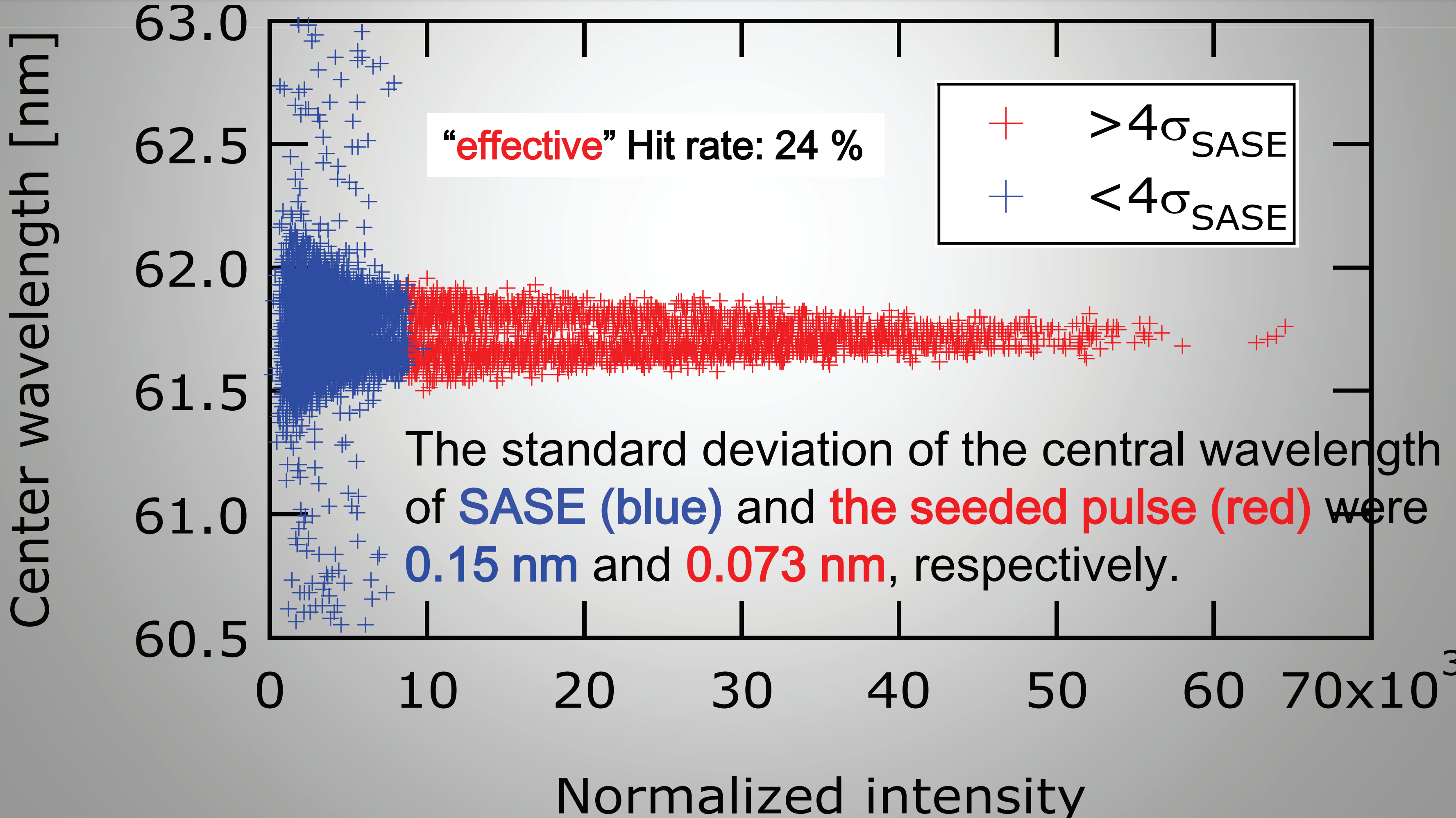


Seeded FEL Performances (2012)

The correlation data plot between the normalized intensity and central wavelength for 10,000 shot data

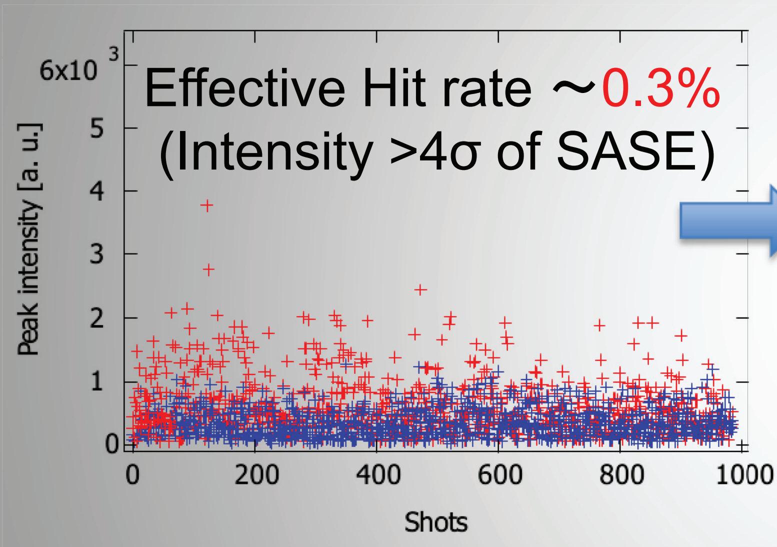


The standard deviation of the central wavelength of SASE (blue) and the seeded pulse (red) were 0.15 nm and 0.073 nm, respectively.

Improvements of FEL Performances (2010 → 2012)

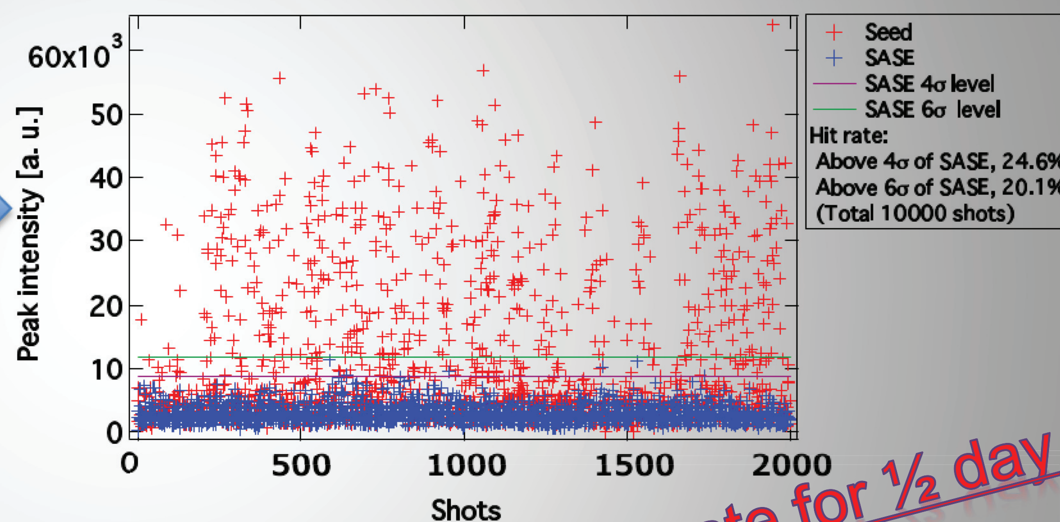
Previous result (2010)

w/o feedback



This result (2012)

w/ feedback



- Seeded FEL output was 1.3 μJ
- The seeding operation was only obtained less than 10 minutes.

~30% effective hit rate for ½ day
Up to 20 μJ

By using the EOS-based timing-drift system, the HH seeded FEL succeed to continuously operate about a half day which is the machine time of SCSS accelerator with 20-30% hit rate.

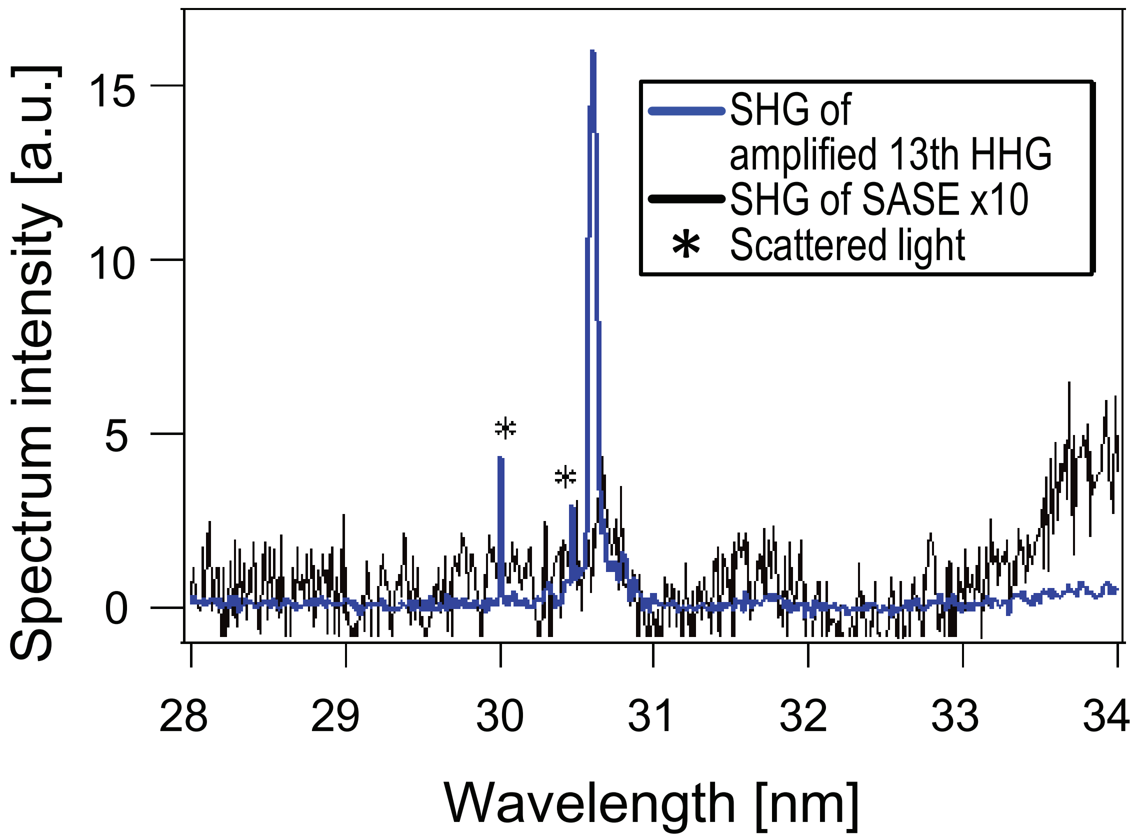
Summary

- Seeded at 61.5 nm (13th HH), 53.3 nm (15th HH)
- Introducing EOS-feedback, continual operation
- Dramatically improve seeding (2010)
- short term of timing drift or jitter < 1ps

	2010 (w/o feedback)	2012 (w/ feedback)
FEL pulse energy	1.3 μJ (max.)	20 μJ (max.)
Effective hit rate	0.3 %	20 – 30 %
FEL gain	x 650	x 10^4
Continual operation	< 10 min.	> 1/2 day

- We observed 2nd order seeded FEL (@30nm).

Spectrum of 2nd harmonic seeded FEL lased at 30.8 nm



Contrast ratio is significantly improved to 80 against SASE background.

Summary

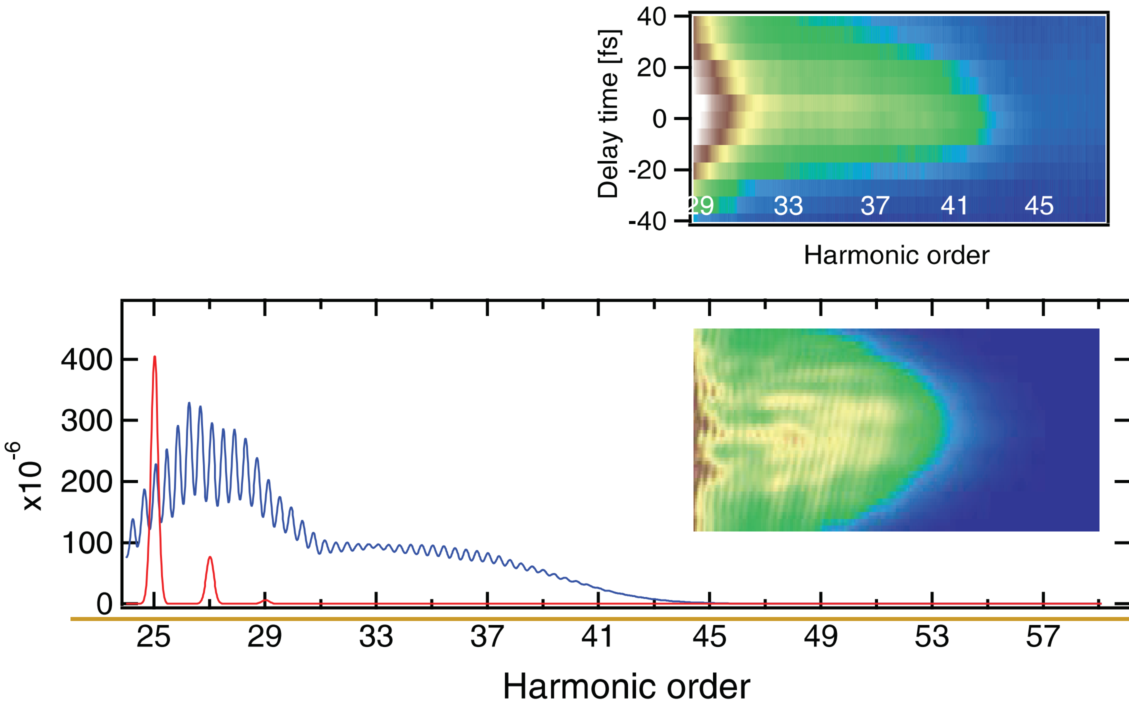
- We have succeeded a seeding effect of an FEL amplifier working in an EUV region with a wavelength of 61.5 nm(13th HH), 53.3 nm(15th HH).
- We improved output of 20 μJ with 20 – 30 % hit rate with timing control of EOS. Seeding condition have kept for half a day.
- Contrast ratio was improved more than 5 times (2010->2012).
- We are planning to generate shorter wavelength of seeded FEL (**13 nm - Water window**) at SACLA. Adjustability of FEL wavelength .

Tunable operation of seeded FEL

For tunable operation of seeded FEL,
a continuum HHG generated
by mixing multicycle two-color laser fields is proposed.
(Ti:S, 800nm + OPA, 1300nm)

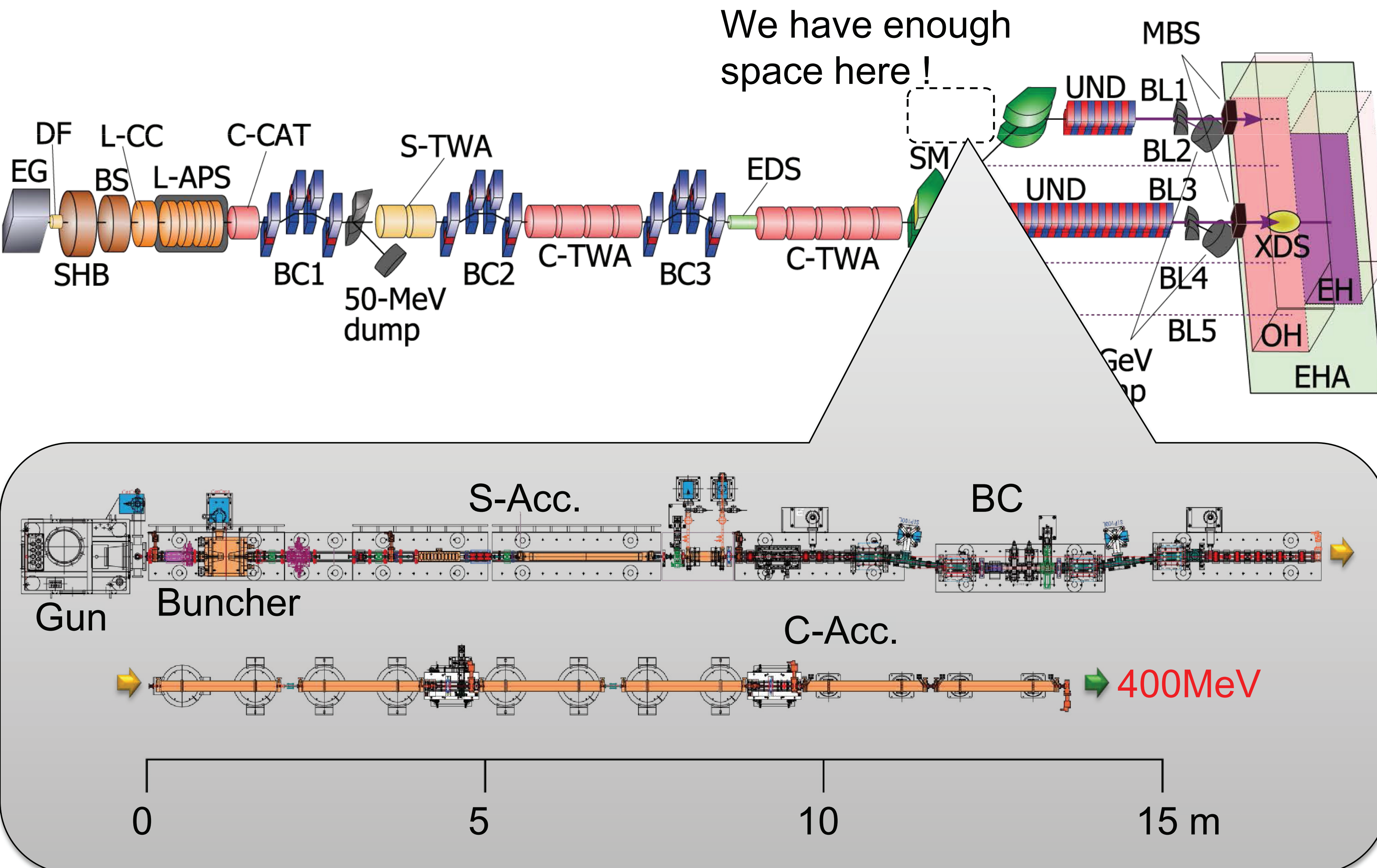
Eiji J. Takahashi, et al. PRA 104, 233901 (2010)

HHG Spectrum at cutoff region



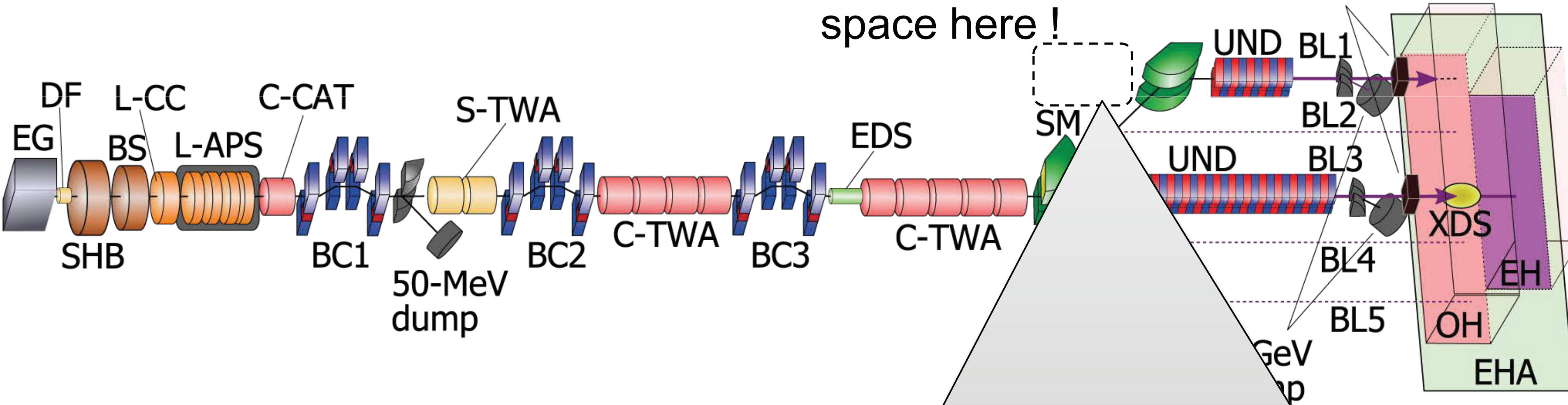
Red lines: One-color driving
Bule lines: Two-color driving
(a): Experiment
(b): Simulation

Machine Layout of SCSS+



Machine Layout of SCSS+

We have enough space here !



Accelerator components moving to BL1@SACLA (SCSS+)

- Dedicated beamline to EVU & SXR regions
- Start with 400 MeV & 30~50 nm, to be extended to 1.4 GeV & **3 nm**