Yong Woon Park, Ph. D.
Pohang Accelerator Laboratory

On be half of PAL-XFEL team.

포항가속기연구소
POHANG ACCELERATOR LABORATORY

MPK
막스플랑크 한국 / 포스텍 연구소
Korea Foundation for Max Planck POSTECH
Korea Research Initiative

Location of Pohang

Pohang Accelerator Laboratory(PAL)

Pohang Accelerator Laboratory

1988: Foundation
1995: Pohang Light Source (PLS) construction
2011: Upgrade of PLS to PLS II
2015: PAL-XFEL construction

# of regular staff: 189 (total ~ 300)

Director: Dr. In Soo Ko

Future project: 4th generation storage ring

Outline

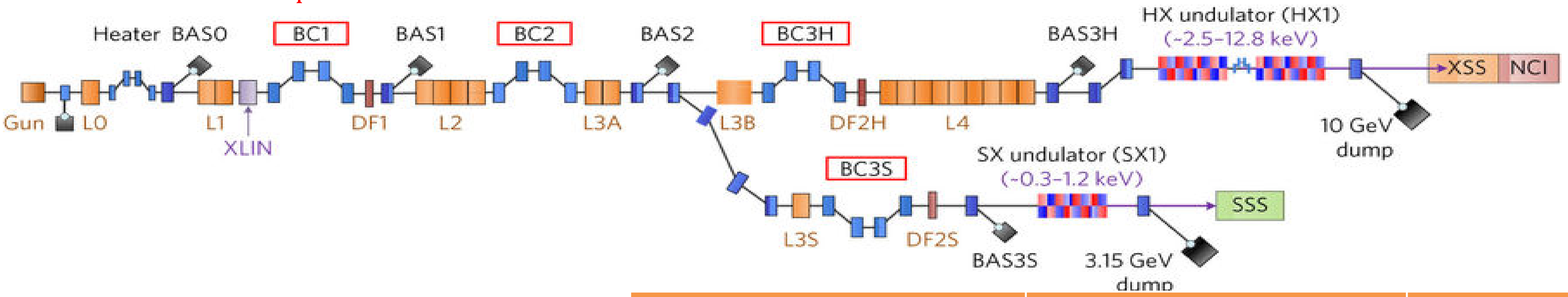
- PAL-XFEL: past
  - Construction process
  - Commissioning results
- PAL-XFEL: present
  - Self seeding
  - 20 fs timing jitter
- PAL-XFEL: future
  - Attosecond FEL beamline
  - Artificial Intelligence application
- Summary

Construction

Nov. 2012

Dec. 2013

PAL-XFEL Parameters



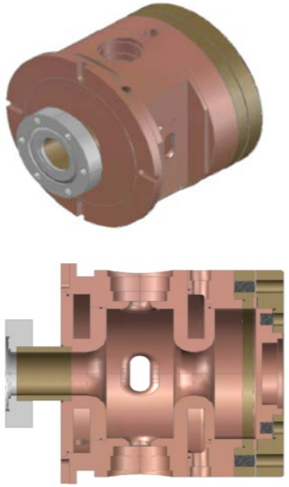
Main parameters

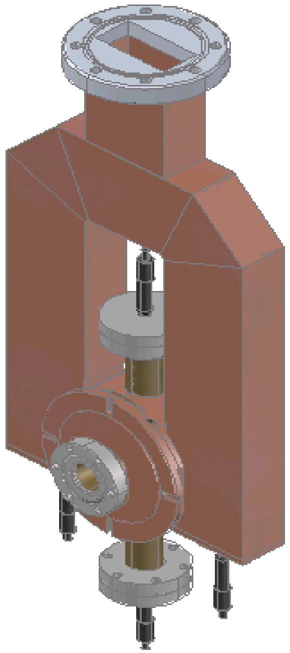
e^- Energy	10 GeV
e^- Bunch charge	20-200 pC
Slice emittance	0.5 mm mrad
Repetition rate	60 Hz
Pulse duration	5 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

Undulator Line	HX1	SX1
Wavelength [nm]	0.1 ~ 0.6	1 ~ 4.5
Beam Energy [GeV]	4 ~ 10	3.15
Wavelength Tuning [nm]	0.6 ~ 0.1 (energy or gap)	4.5 ~ 3 (energy) 3 ~ 1 (gap)
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0
Undulator parameter K	1.9727	3.3209

Photocathode RF gun in PAL-XFEL

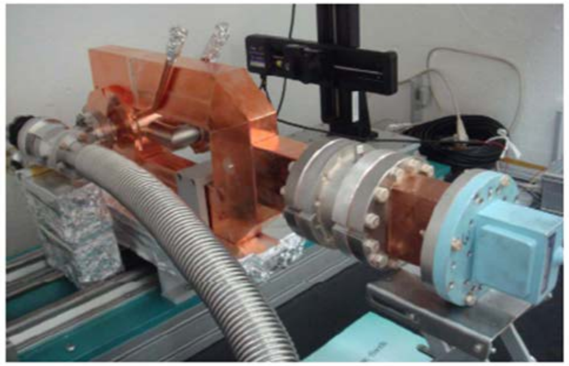
RF gun

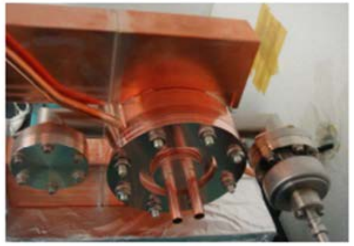




RF gun+Wave guide

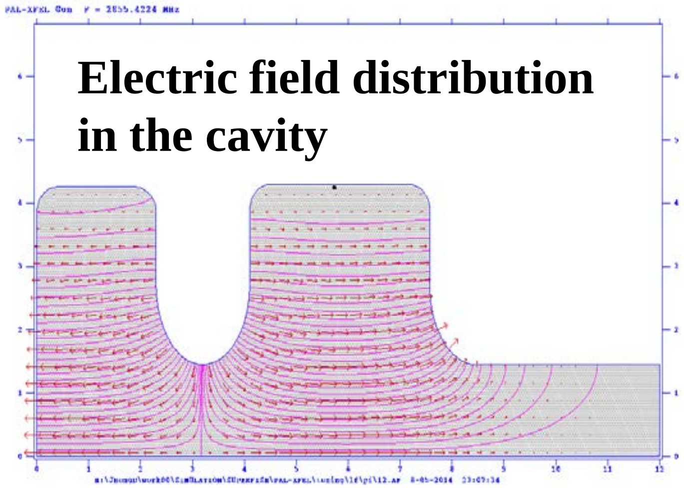
Cold model test





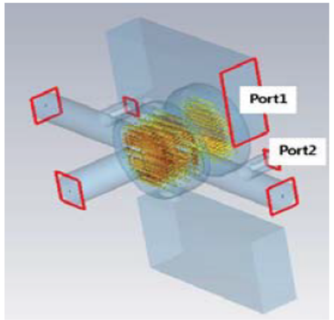
Cathode side

PARMELA simulation



CST 3-D Simulation

Modeling



Results

Parameter	Value	Unit
Operating Frequency	2856	MHz
Mode Separation	16	MHz
Coupling Coefficient	1.5	
S21	-80	dB

Requirements:

Vacuum : < 5×10^{-10} torr

Operating frequency: 2.856 GHz

Field balance($^{*}E_h/^{**}E_f$)of π mode: ~1

Mode separation($f_\pi - f_0$): ~10 MHz

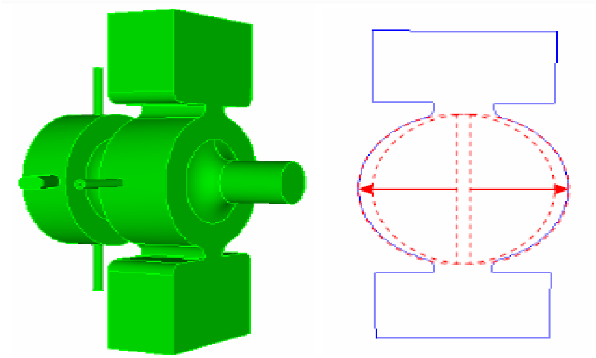
Coupling factor : ~1

Pulse repetition rate: >30 Hz

Jpn. J. Appl. Phys, 49, p. 086401 (2010) (coauthor)

JKPS, 58, p. 198 (2011) (corresponding)

SLAC Design



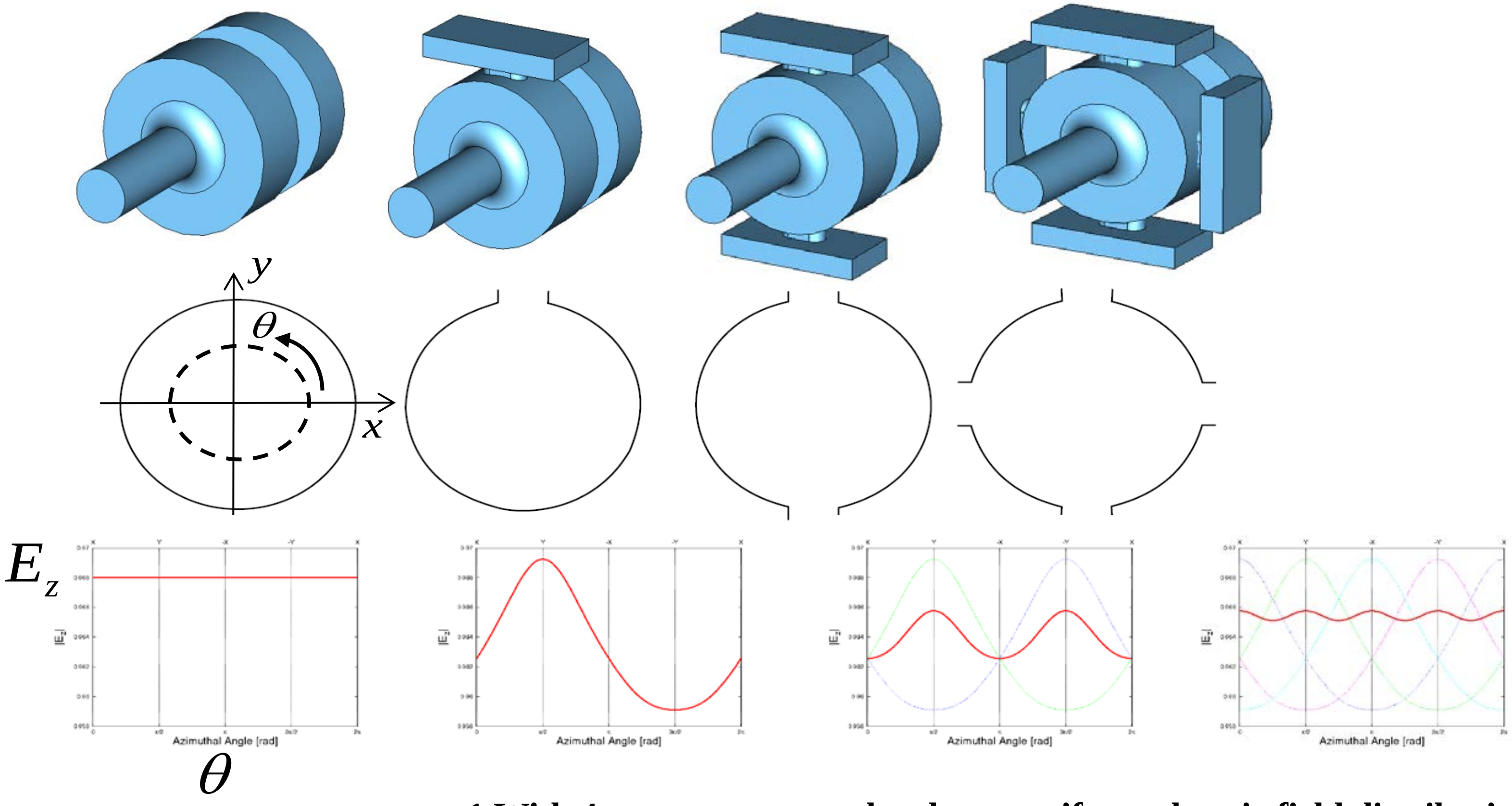
Race track shape

Electron gun is designed with race track shaped cavity to make unformity in the electric field distribution.

This design has a difficulty in the fabrication process.

Collaboration job with Prof. C. X. Tang in Tsinghua University.

PAL Design



1.With 4 ports, we can make almost uniform electric field distribution.
2. This model is easy to fabricate.
3. Four ports is helpful to maintain the vacuum level.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 104203 (2011)

Emittance growth due to multipole transverse magnetic modes in an rf gun

M. S. Chae,[1] J. H. Hong,[1] Y. W. Parc,[1,*] In Soo Ko,[1] S. J. Park,[2] H. J. Qian,[3] W. H. Huang,[3] and C. X. Tang[3]
[1]*Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea*
[2]*Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang 790-784, Korea*
[3]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*

(Received 25 March 2011; published 28 October 2011)

Linac

Klystron gallery

Undulator Hall

Hard X-ray Experimental Hall

Appl. Sci. **2017**, *7*, 479; doi:10.3390/app7050479

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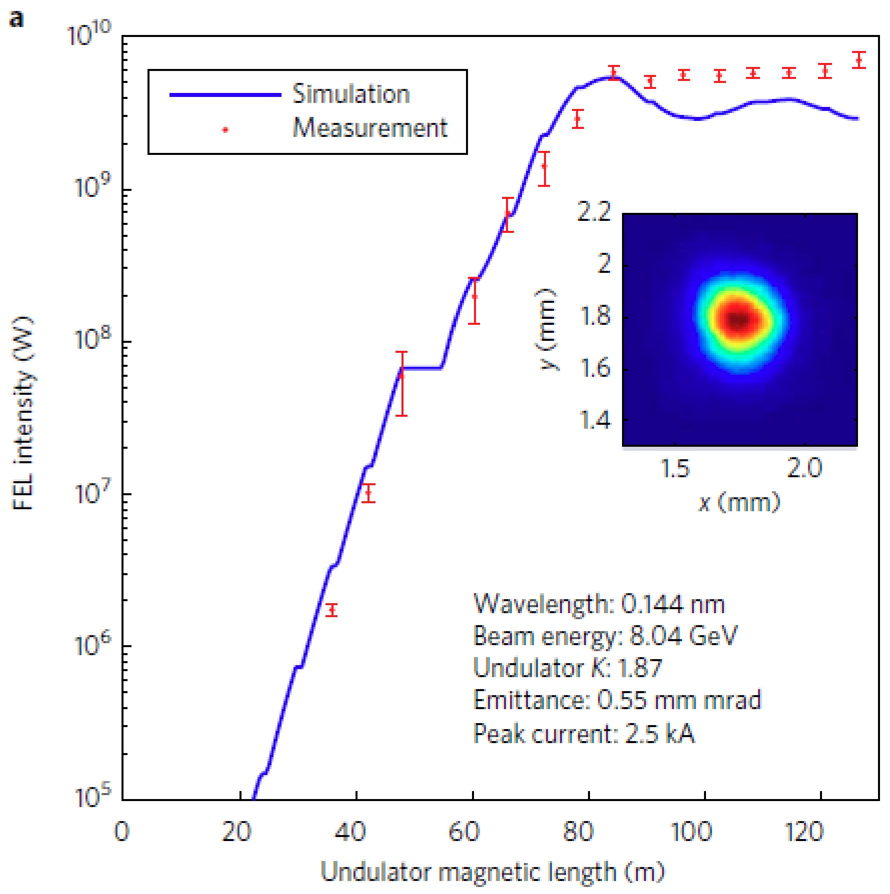
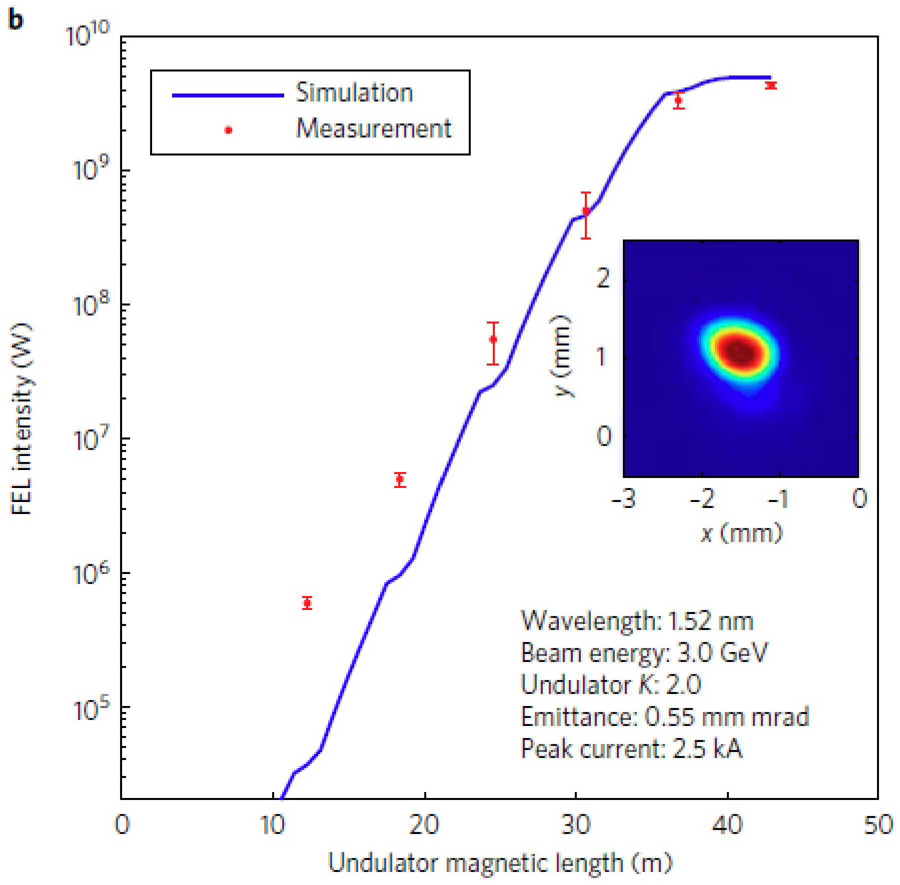
Brief Timeline

• April 2011:	PAL-XFEL project started
• Sep. 2012:	Construction started
• Jan. 2015:	Building completed
• Dec. 2016:	Installation completed
• April 12, 2016:	Commissioning started
• June 14, 2016:	First SASE lasing at 0.5 nm
• Oct. 28, 2016:	Lasing at 0.15 nm
• Nov. 27, 2016:	Saturation of 0.15 nm (project completed)
• March 16, 2017:	Saturation of 0.1 nm (design goal achieved)
• June 7, 2017:	First User Service
• May 30, 2018:	Self-Seeding Test
• Nov. 2018:	Permission granted to operate up to 11 GeV

Saturation curve



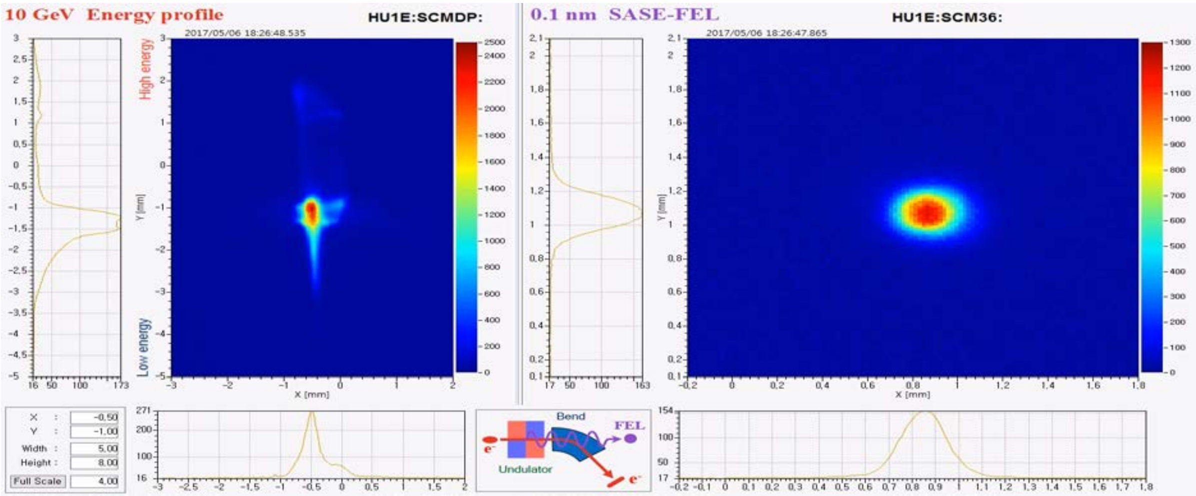
Hard X-ray



Soft X-ray

NATURE PHOTONICS | VOL 11 | NOVEMBER 2017 | 708–713 |

PAL-XFEL Status



- FEL position stability: 8~9% of beam size
- FEL power stability: ~ 4.0% RMS
- E-beam energy jitter: < 0.02 %
- E-beam arrival time jitter: < 20 fs
- FEL pulse energy: >1 mJ at 9.7 KeV

First Publication by First User

Science AAAS

Draft Manuscript: Confidential 18 August 2017

Title: Maxima in the Thermodynamic Response and Correlation Functions of Deeply Supercooled Water

Authors: Kyung Hwan Kim[1†], Alexander Späh[1†], Harshad Pathak[1], Fivos Perakis[1], Daniel Mariedahl[1], Katrin Amann-Winkel[1], Jonas A. Sellberg[2], Jae Hyuk Lee[3], Sangsoo Kim[3], Jaehyun Park[3], KiHyun Nam[3], Tetsuo Katayama[4], and Anders Nilsson[1,*]

Affiliations:

[1]Department of Physics, AlbaNova University Center, Stockholm University, SE-10691 Stockholm, Sweden

[2]Biomedical and X-Ray Physics, Department of Applied Physics, AlbaNova University Center, KTH Royal Institute of Technology, SE-10691 Stockholm, Sweden

[3]Pohang Accelerator Laboratory, Pohang, Gyeongbuk 37673, Republic of Korea

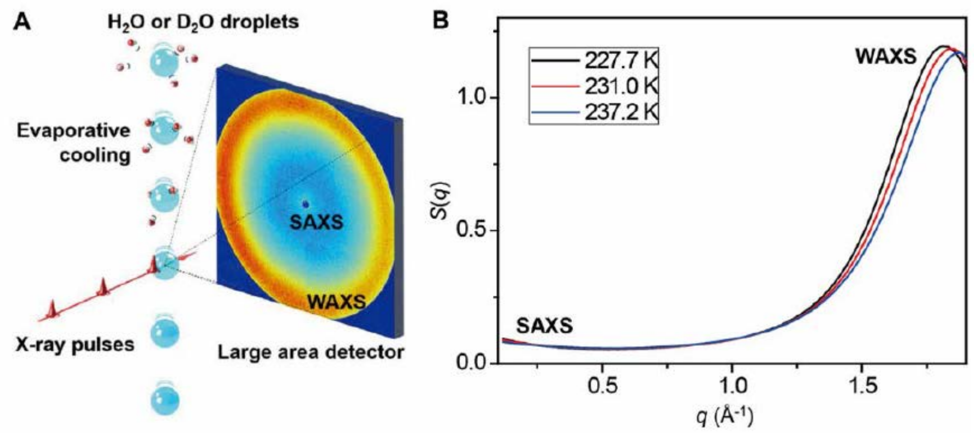
[4]Japan Synchrotron Radiation Research Institute, Kouto 1-1-1, Sayo, Hyogo 679-5198, Japan

*Corresponding author. E-mail: andersn@fysik.su.se

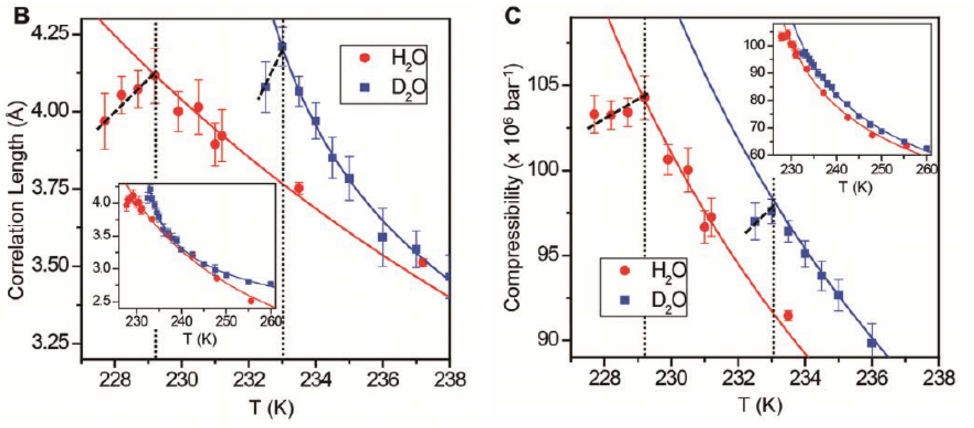
[†]These authors equally contributed to this work.

Abstract:

Femtosecond x-ray laser pulses were used to probe micron-sized water droplets cooled down to 227 K. From the x-ray scattering at the low momentum transfer region the isothermal compressibility and correlation length were extracted and the temperature dependence shows maxima at 229 K for H_2O and 233 K for D_2O. In addition, from the first diffraction peak it was observed that the liquid undergoes the most rapid growth of tetrahedral structures at similar temperatures. These observations point to the existence of a Widom line, defined as the locus of maximum correlation length emanating from a critical point at positive pressures deeply in the supercooled regime. The difference in maximum value of the isothermal compressibility between the two isotopes shows the importance of nuclear quantum effects.

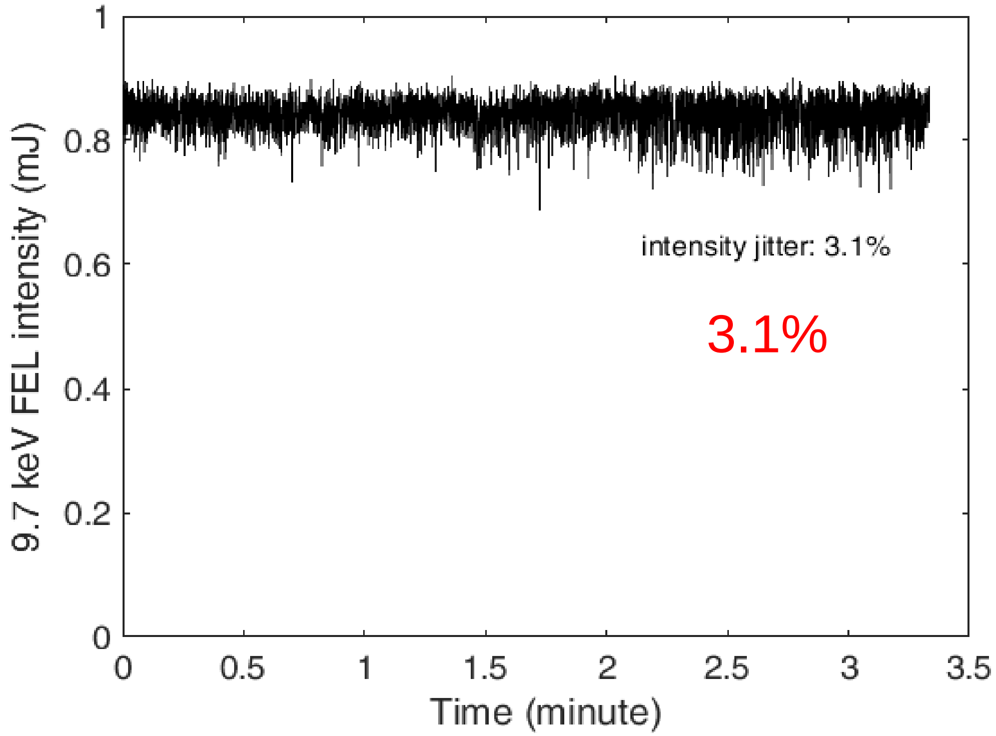


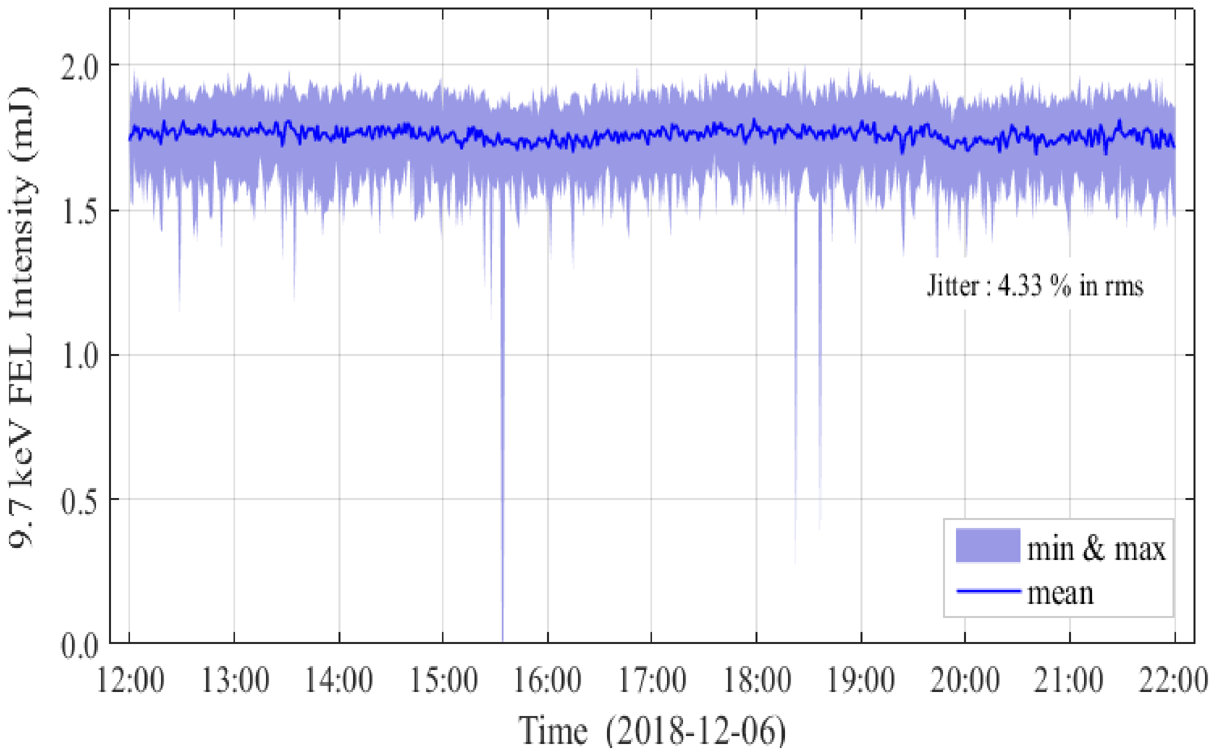
Confirmation of the Existence of the Widom Line !



Science, Vol. 358, p. 1589 (Dec. 22, 2017)

FEL Intensity Stability

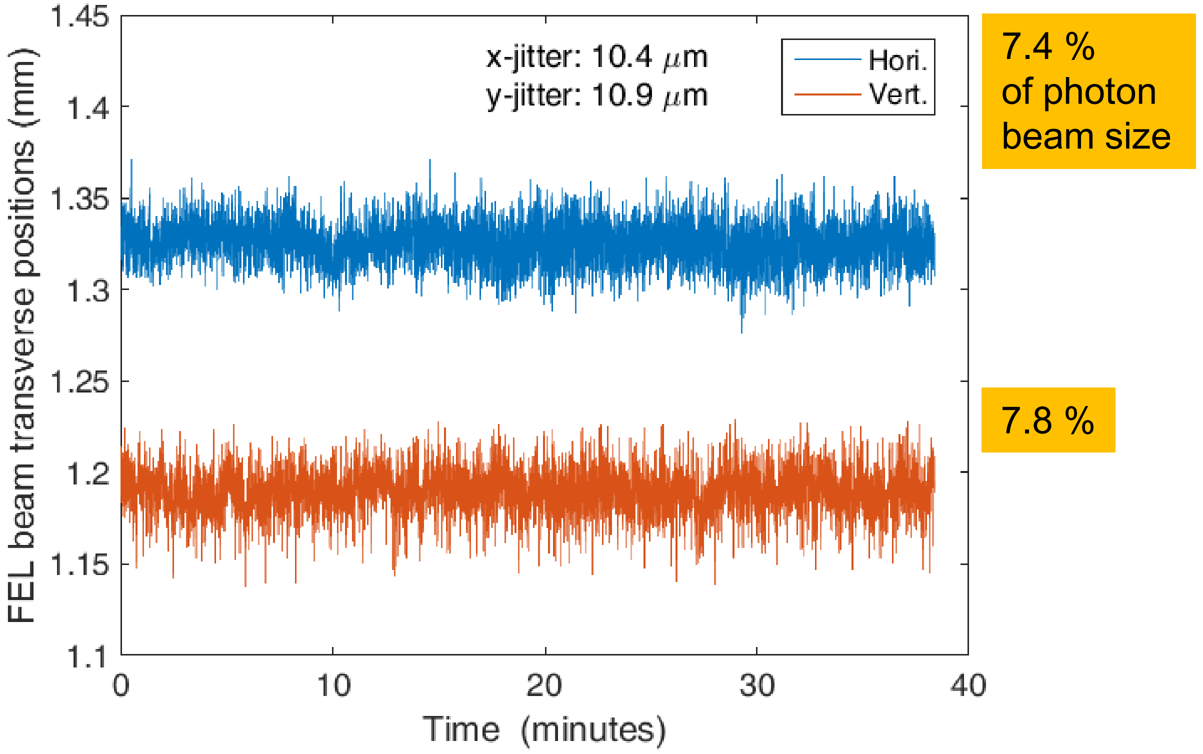


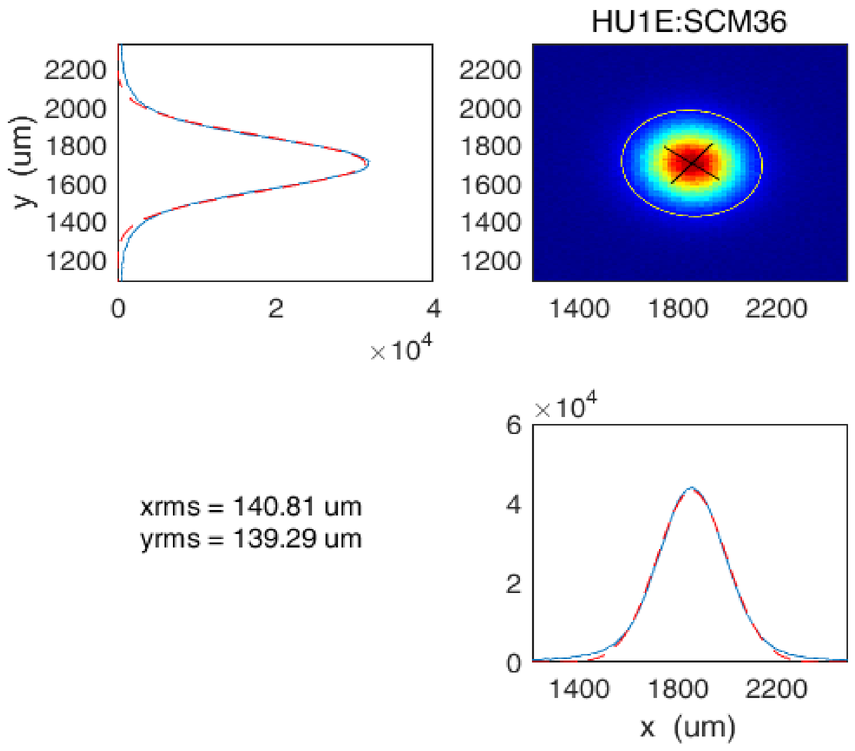


QBPM sum data calibrated by e-loss measurement

FEL Beam Position Jitter

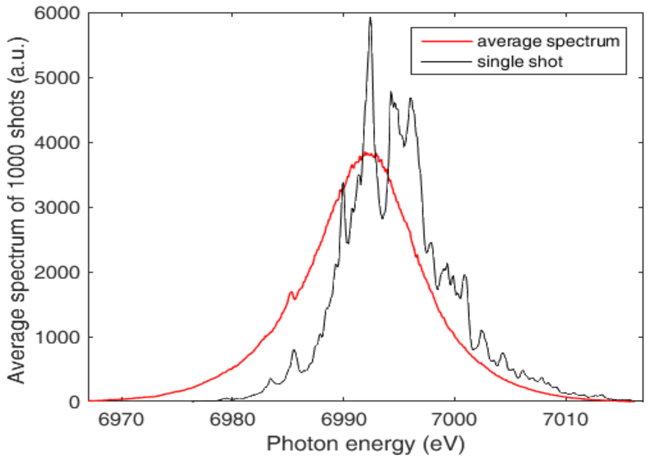
(measured at a 40-m downstream YAG-screen from last undulator)

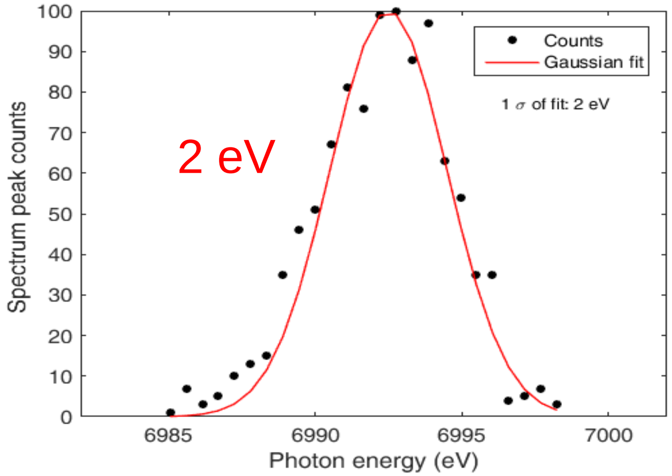




- FEL beam divergence angle: 1.6 μrad
- Angle jitter: 0.14 μrad in rms

Central Wavelength Jitter



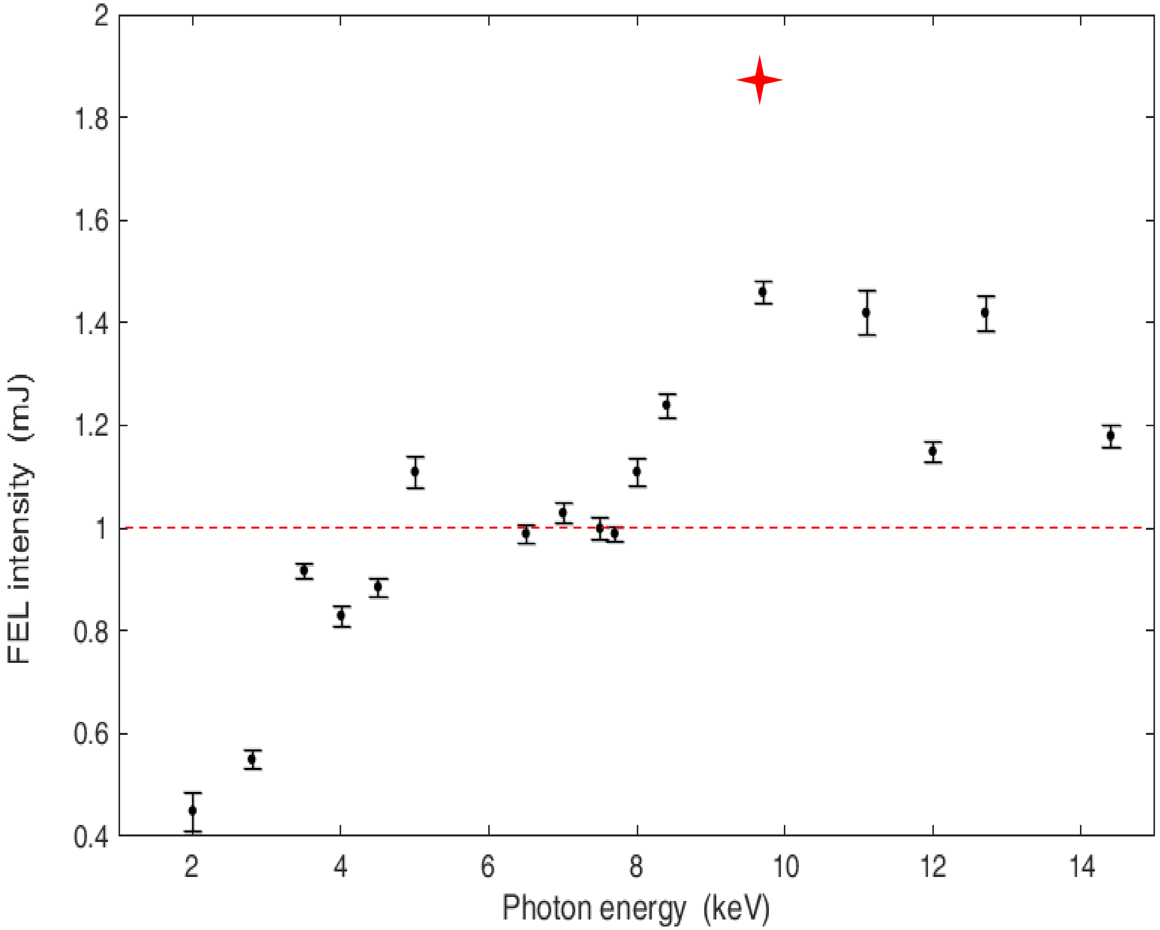


- SASE central wavelength jitter: 2.9 E-4

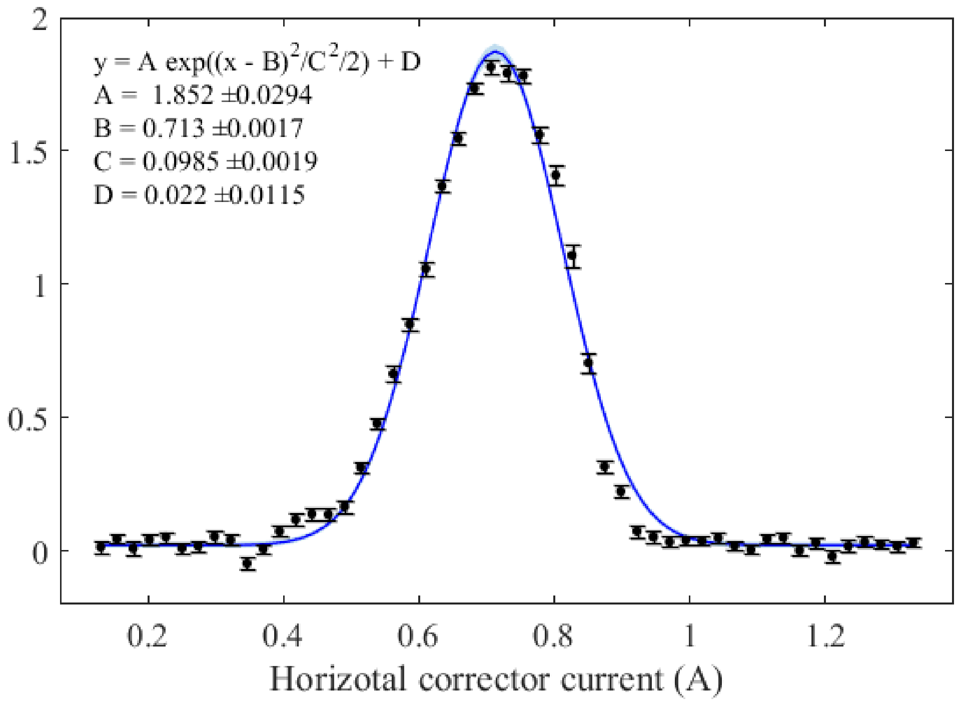
  (= 2 eV / 6.99 keV) < FEL parameter (5.0 E-4).

May 30, 2018

HX FEL Intensity



1.85 mJ at 9.7 keV



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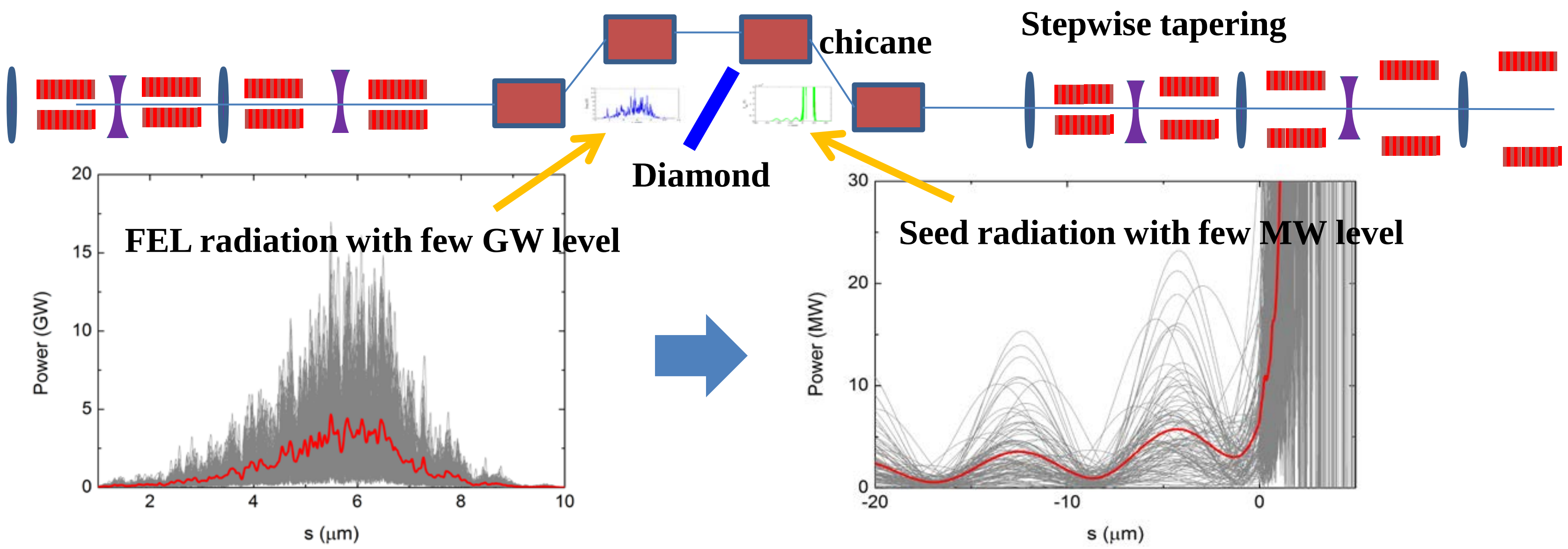
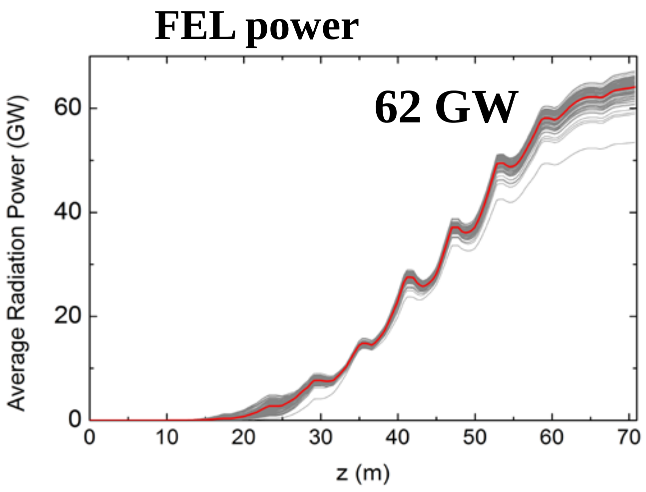
Self Seeding for Hard X-ray

Collaboration job with Dr. J. Wu in SLAC.

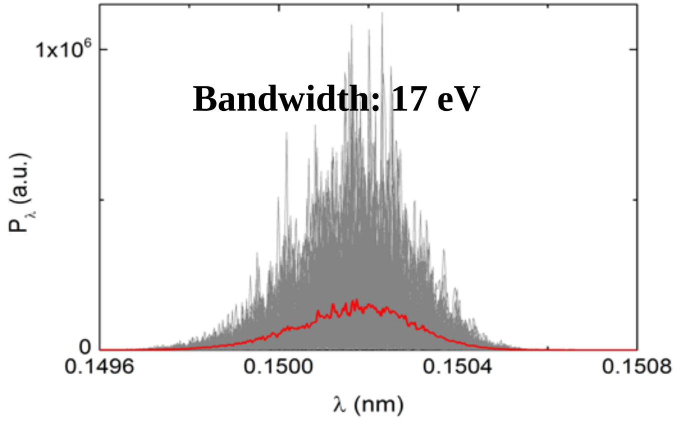




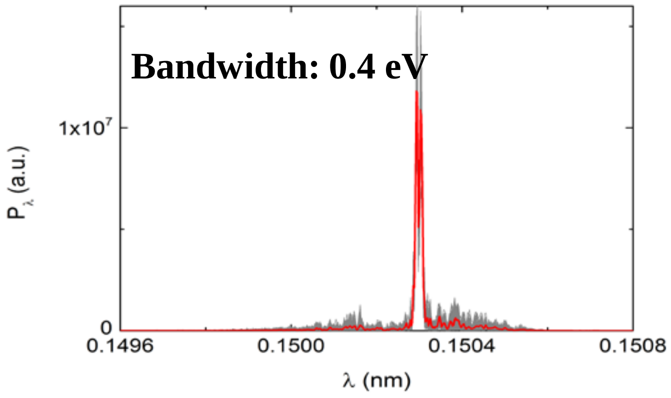
FEL power is increased by the seeding.

FEL bandwidth is decreased by the seeding.

Parameter	Unit	Value
Electron energy	GeV	8.126
Radiation wavelength	nm	0.15
Total charge	pC	100
Peak current	kA	4
Undulator period	mm	26
Undulator parameter K		1.96
Normalized transverse emittance (rms)	mm-mrad	0.15



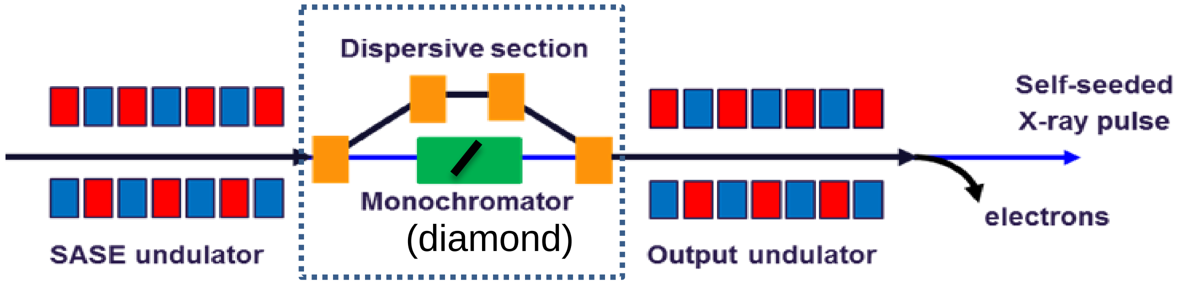
Without self seeding

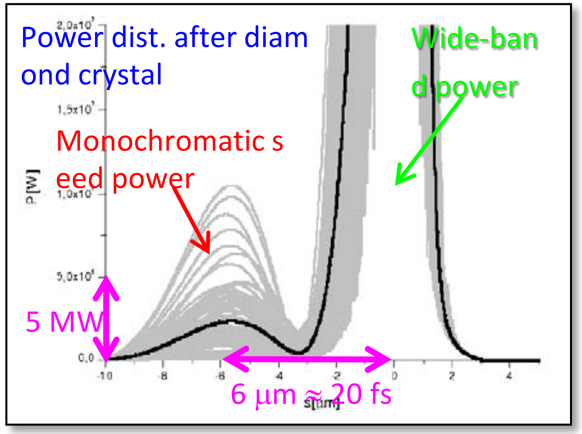


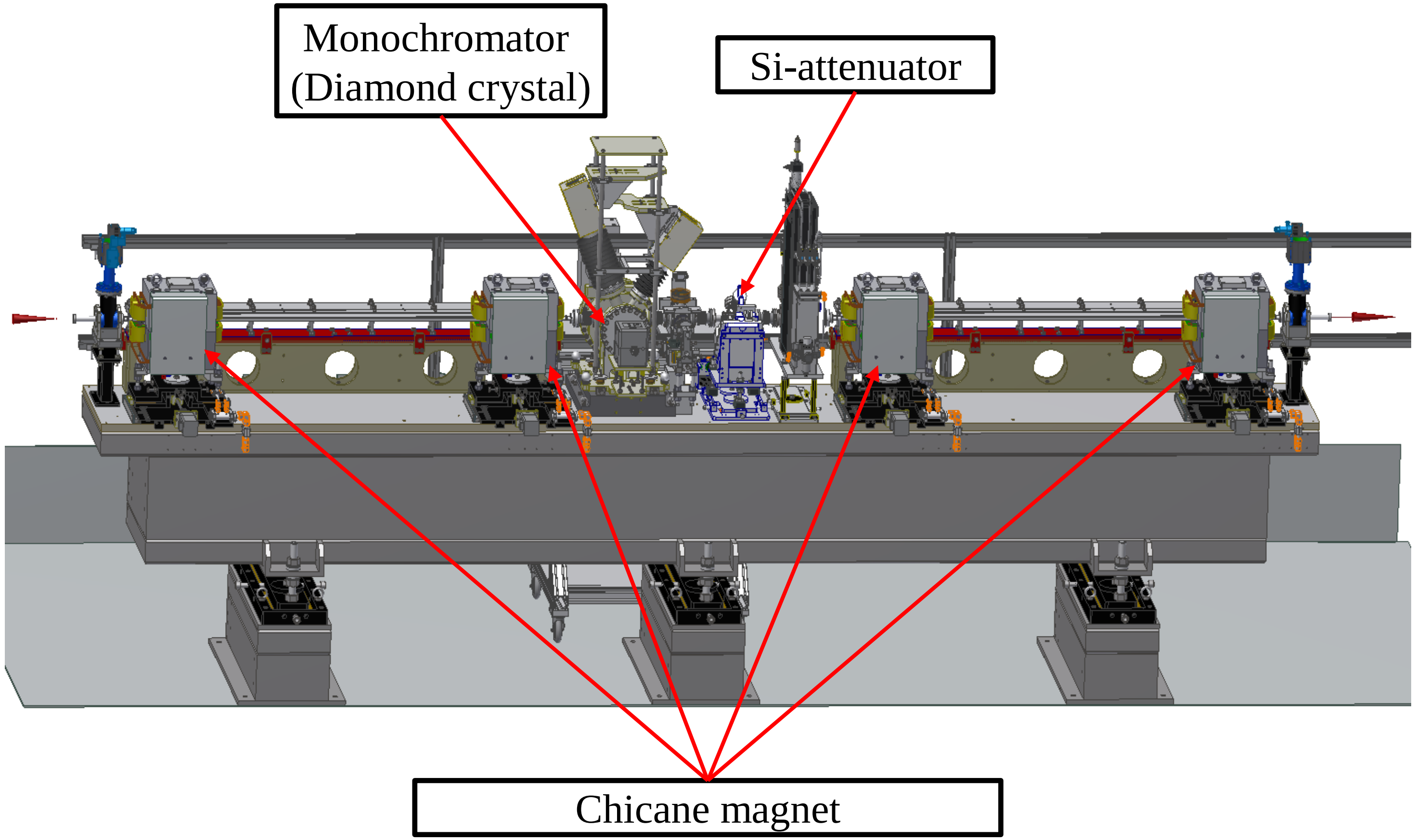
With self seeding

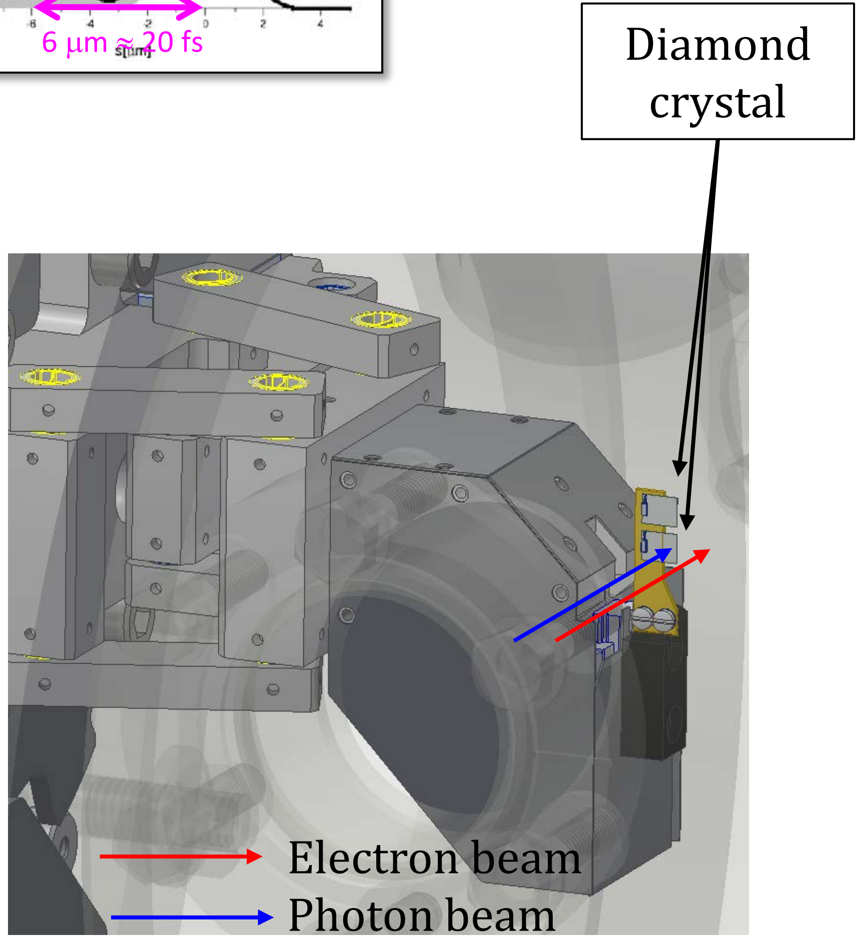
Nucl. Insrt. And Meth. A 798, p 162 (2015)

Self-seeding fat PAL-XFEL

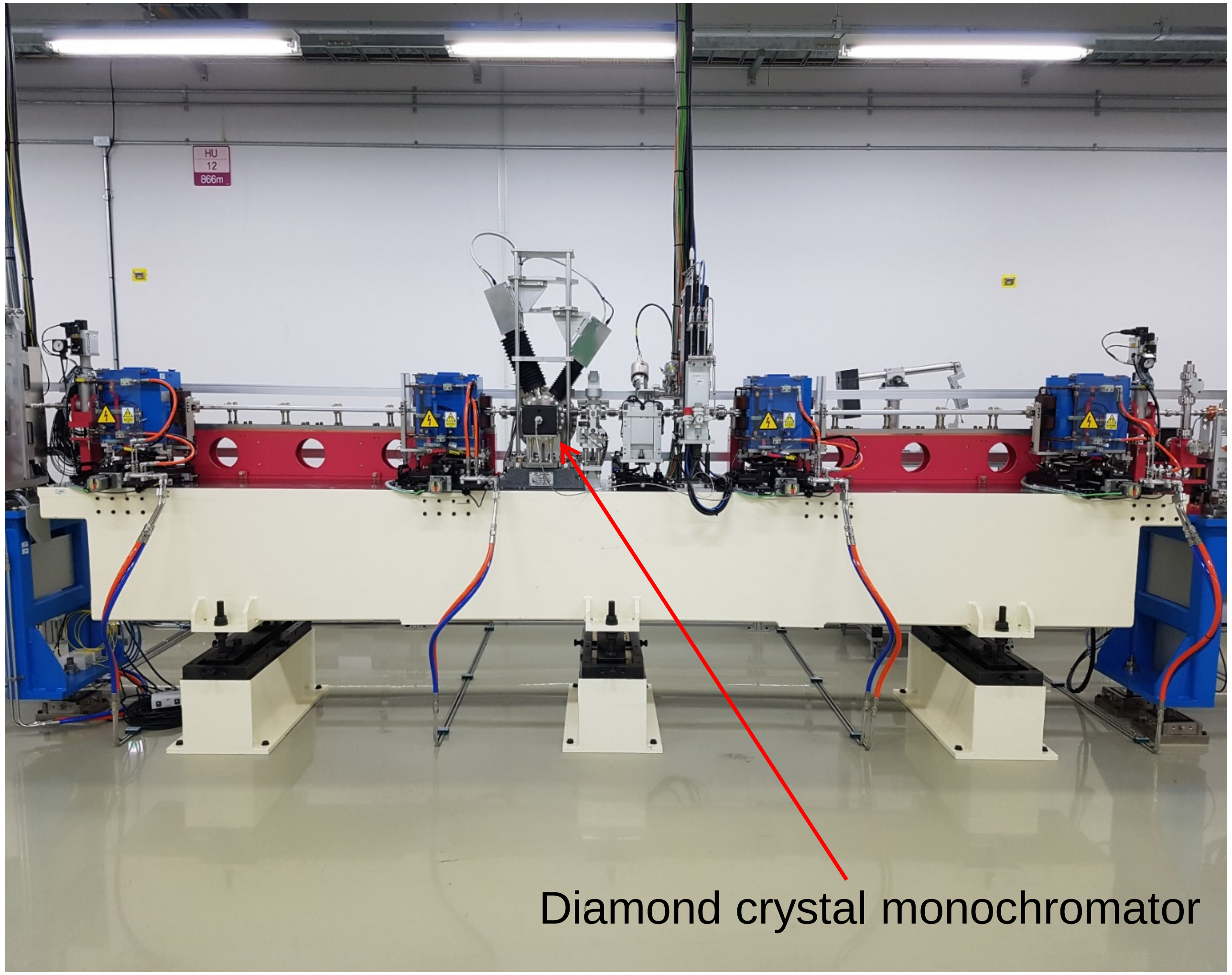


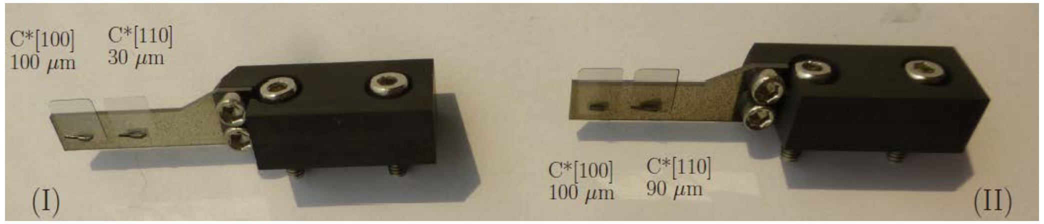






Self-seeding Section

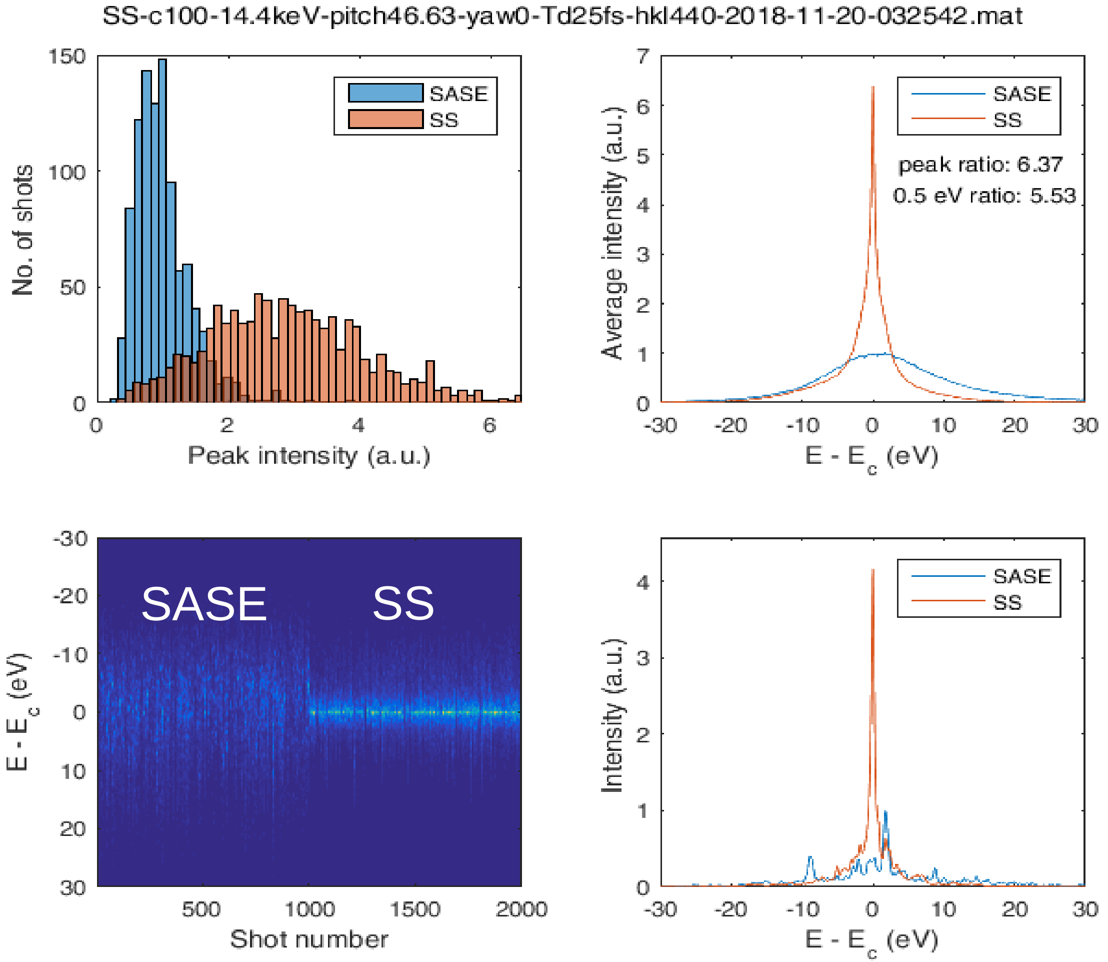




Diamond (100), 100 um : Photon energy: 7~10 keV
Diamond (110), 90 um : Photon energy: 5~7 keV
Diamond (110), 30 um : Photon energy: 3.3~5 keV

Result of Self-seeding Test #2 (Nov. 20, 2018)

180 pC charge, C100 (100um)
Crystal plane: [4 4 0]



- Pitch angle: 46.63, Yaw angle: 0
- e-Beam time-delay with respect to SASE: 25 fs
- Peak intensity ratio of SS and SASE: 6.37
- A fraction of 1-eV BW over entire spectrum
  - SASE: 0.047
  - SS : 0.226

- BW reduction: ~ 35 times
  - SASE: 16.9 eV
  - SS: 0.49 eV

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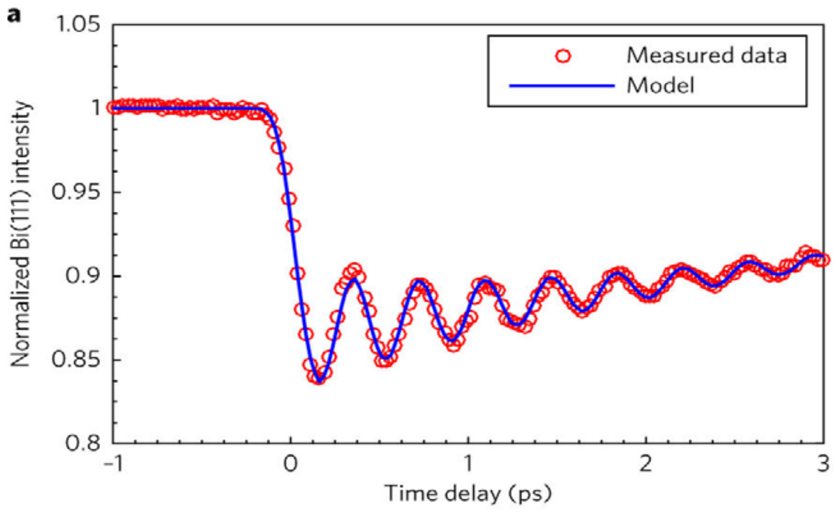
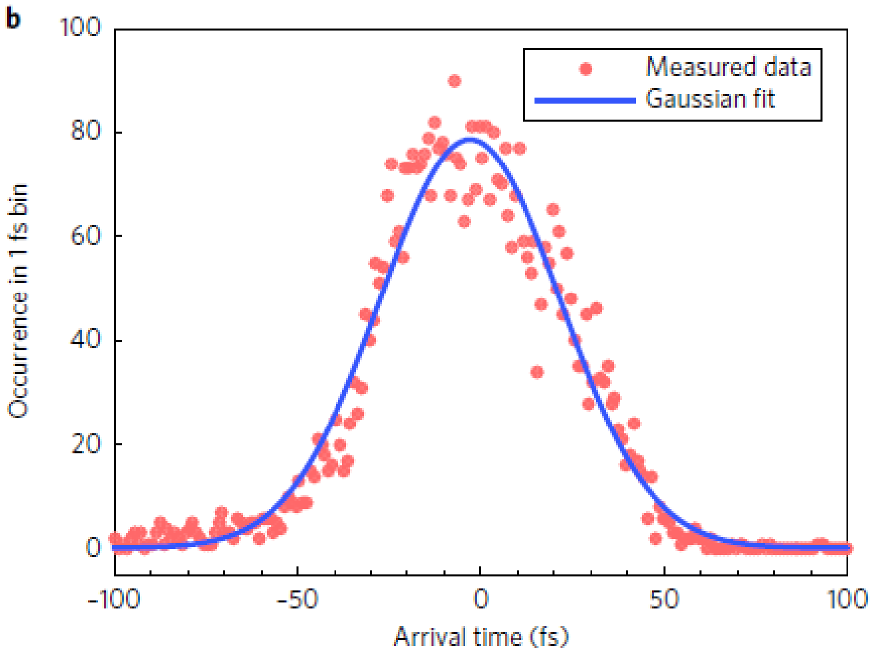
20 fs timing Jitter

Bi(111) Bragg diffraction intensity modulation





20 fs jitter without additional jitter correction

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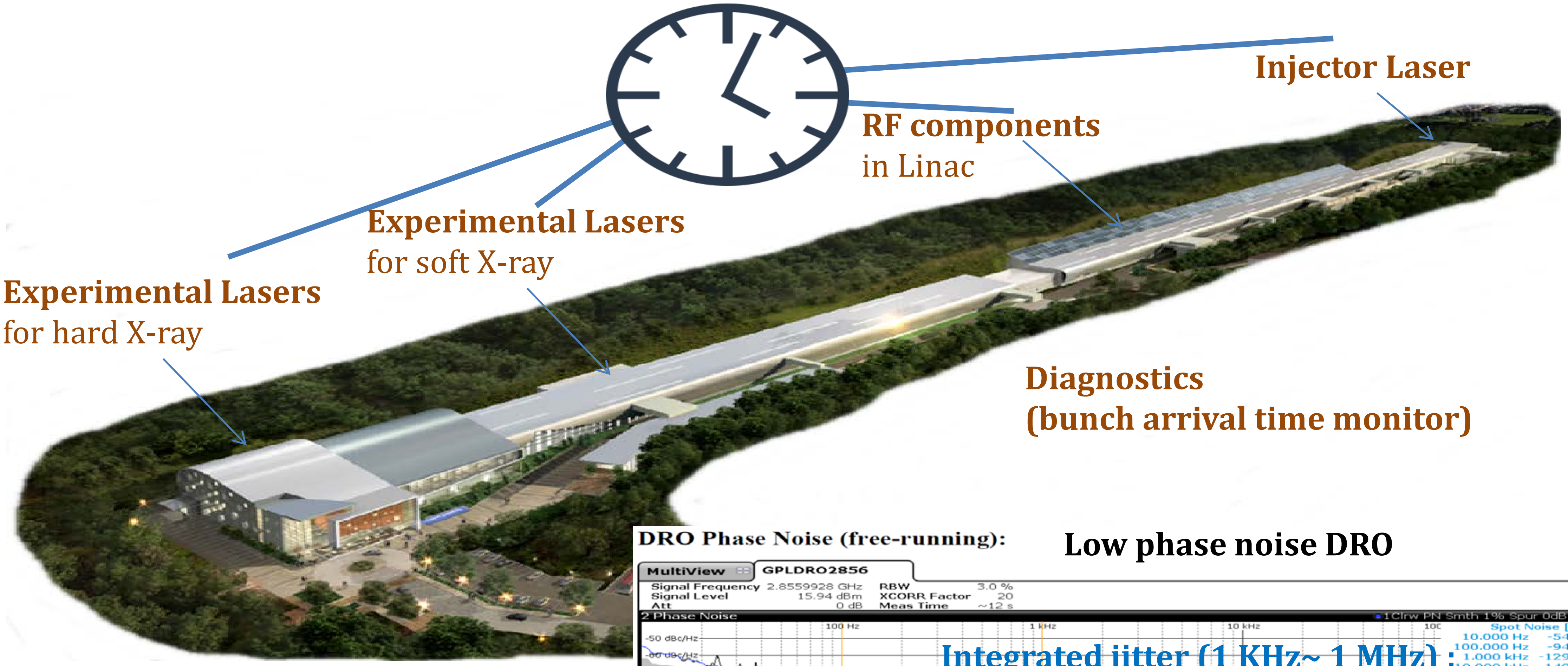
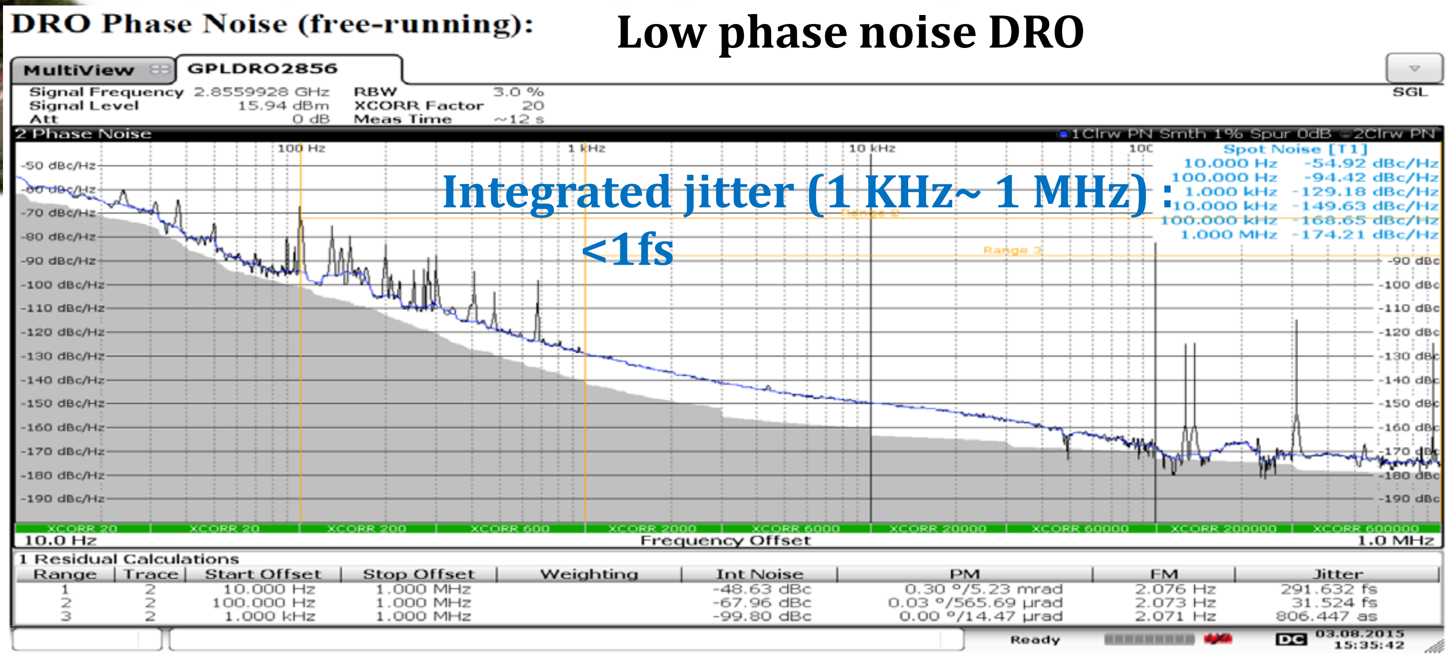
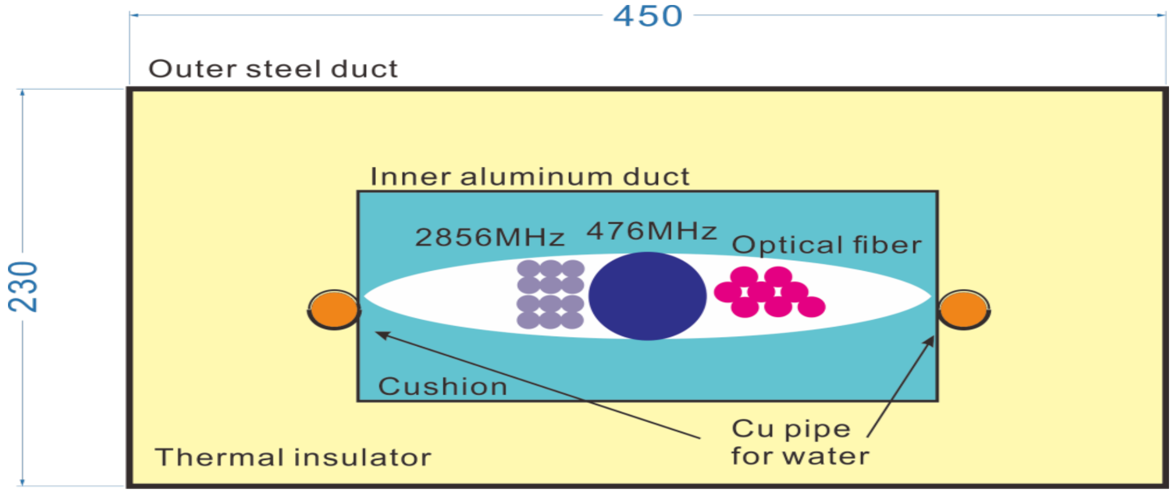




Presented at IPAC18 by Dr. Min

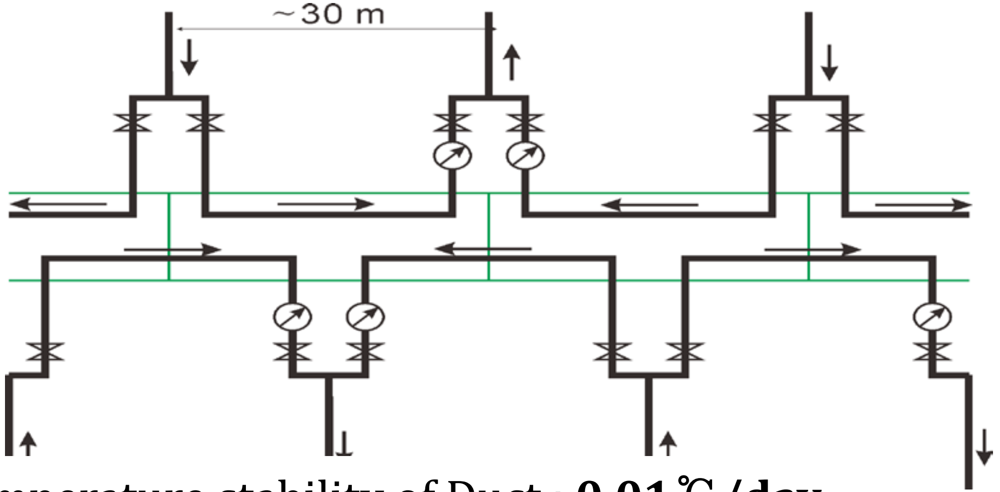
Temperature stabilization of RF Cables

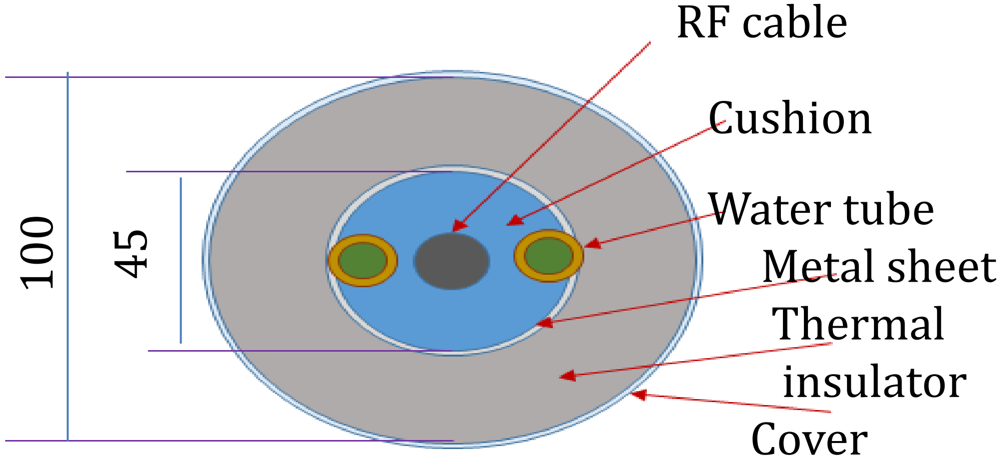
Duct cross-section



With cover open

LCW flow diagram

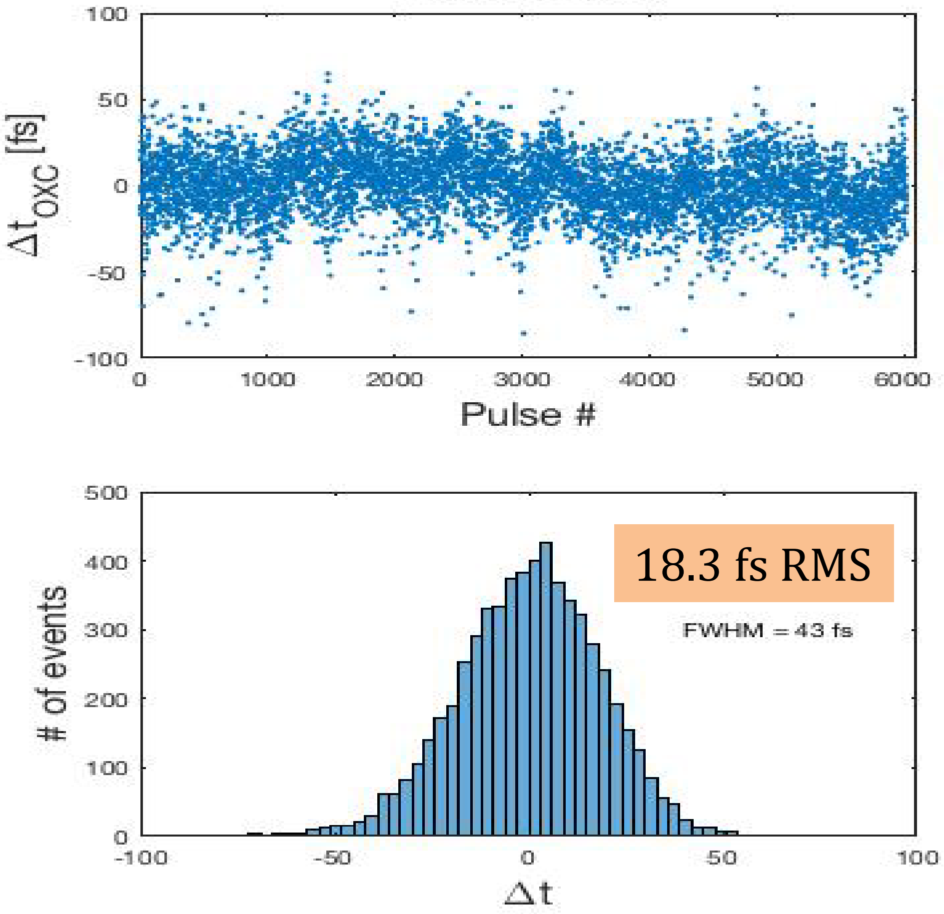




Temperature stability of Duct : **0.01℃/day**

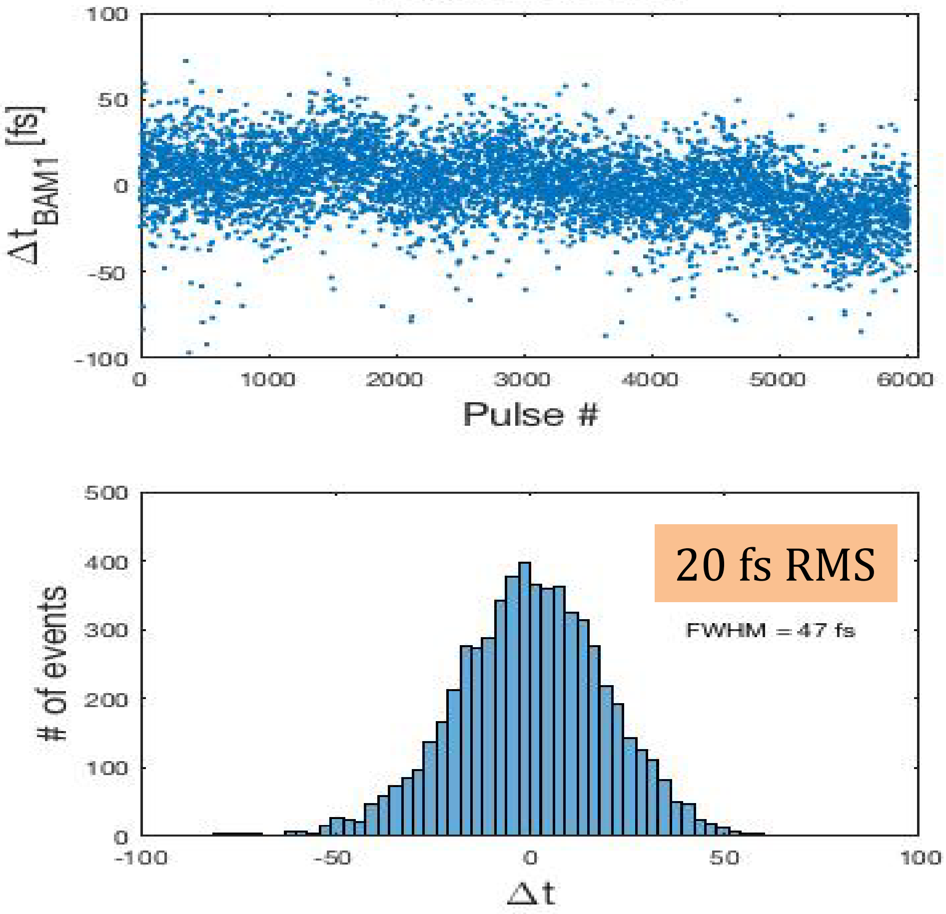
FEL timing jitter

FEL/optical laser cross-correlation



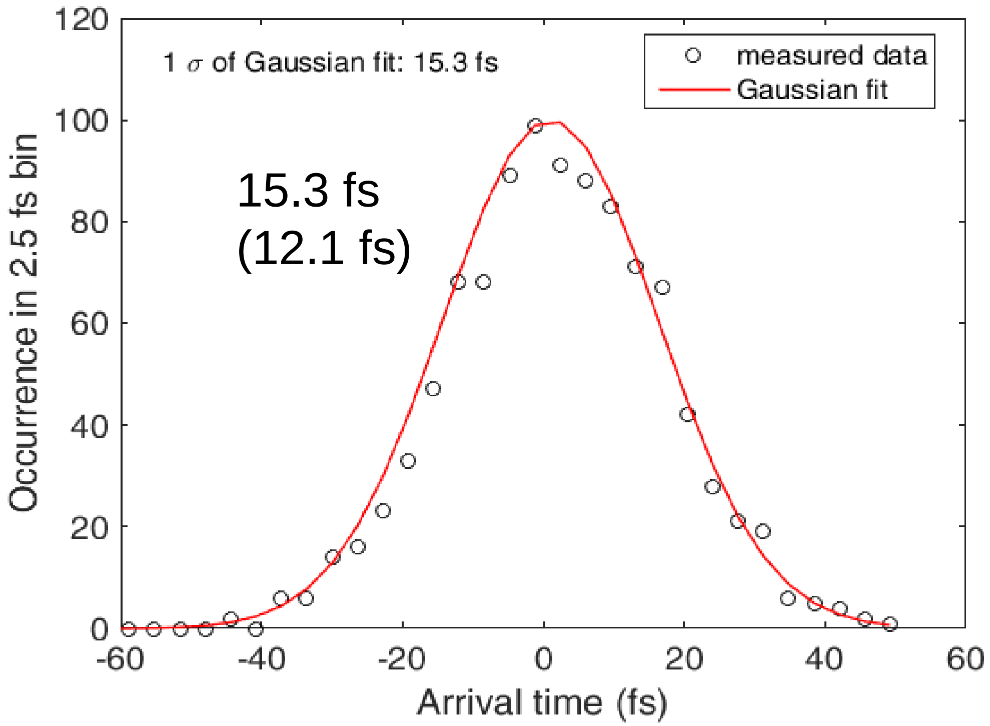
Optical laser synchronization jitter
Added ~10 fs

e^- bunch arrival time at undulator end

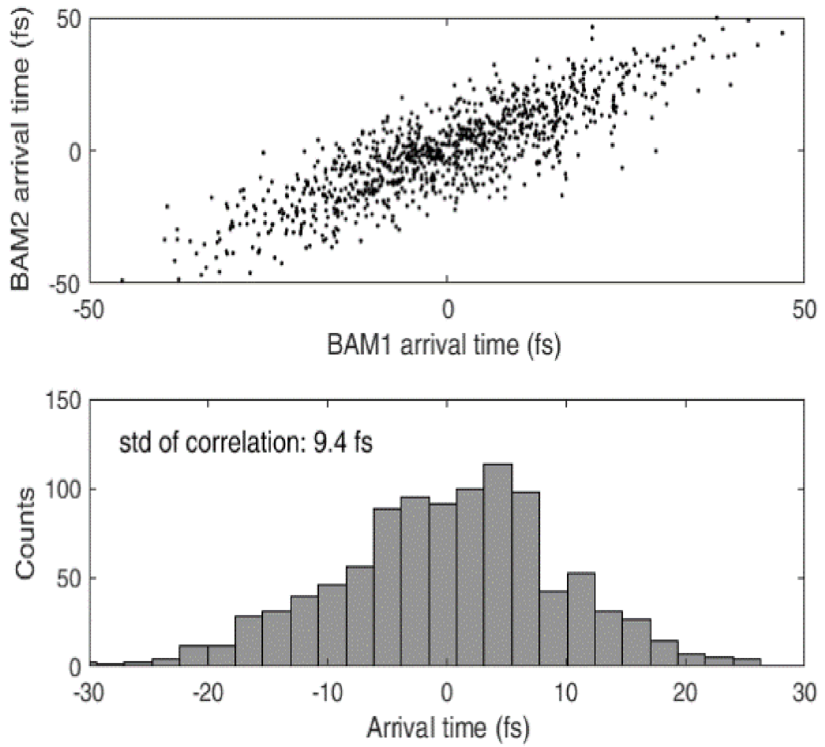


BAM instrumental jitter
Added >10 fs

Improvement of Arrival Time Jitter



Systematic error of the measurement system



- The measured arrival time before December 2017 is as good as 18.8 fs r.m.s. and the deconvoluted jitter of the electron bunch arrival time is 15.1 fs.
- The arrival time jitter is improved to 15.3 fs in April 2018. By counting the systematic error of 9.4 fs in (b), the actual arrival time jitter is as small as 12.1 fs in rms

MPS in Klystron is improved.

Statistics

Annual Plan of Operation: 12-hour operation per day mostly

	2017	2018	2019
Maintenance	109	102	98
Turn-on/Tuning	123	110	73
Machine Study			21
User Beamtime	**120**	**140**	**160***
No Operation	13	13	13

* 20 days of Director's beamtime included.
Reviews will be done by PAL internally.

User service

		Applied	Approved	Days of Service
2017	June 2017~Jan. 2018	82	**26**	95
2018	March 2018~Dec. 2018	84	**45**	128
2019 (1/2)	Jan. ~ June	70	**26****	

** One Director's beamtime not included

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PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

MPK 막스플랑크 한국 / 포스텍 연구소 Korea Foundation for Max Planck POSTECH Korea Research Initiative

Why attosecond hard X-ray ?

Single molecule imaging

PRL **106,** 105504 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

Single-Molecule Imaging with X-Ray Free-Electron Lasers: Dream or Reality?

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[1]*PRIMALIGHT, Faculty of Electrical Engineering; Applied Mathematics and Computational Science, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia*

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(Received 12 October 2010; published 9 March 2011)

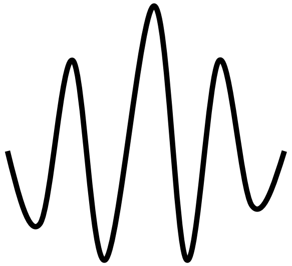
X-ray free-electron lasers (XFEL) are revolutionary photon sources, whose ultrashort, brilliant pulses are expected to allow single-molecule diffraction experiments providing structural information on the atomic length scale of nonperiodic objects. This ultimate goal, however, is currently hampered by several challenging questions basically concerning sample damage, Coulomb explosion, and the role of nonlinearity. By employing an original *ab initio* approach, we address these issues showing that XFEL-based single-molecule imaging will be only possible with a few-hundred long attosecond pulses, due to significant radiation damage and the formation of preferred multisoliton clusters which reshape the overall electronic density of the molecular system at the femtosecond scale.

XFEL-based single molecule imaging will be only possible with attosecond pulses

How to generate the TW-as X-ray pulse in XFEL?

Marriage of
state-of-art laser technology and
state-of-art accelerator technology

CEP-stabilized
Few-cycle laser



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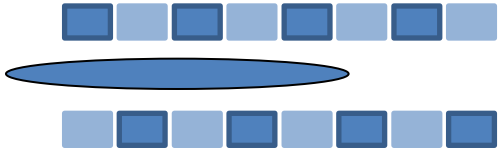


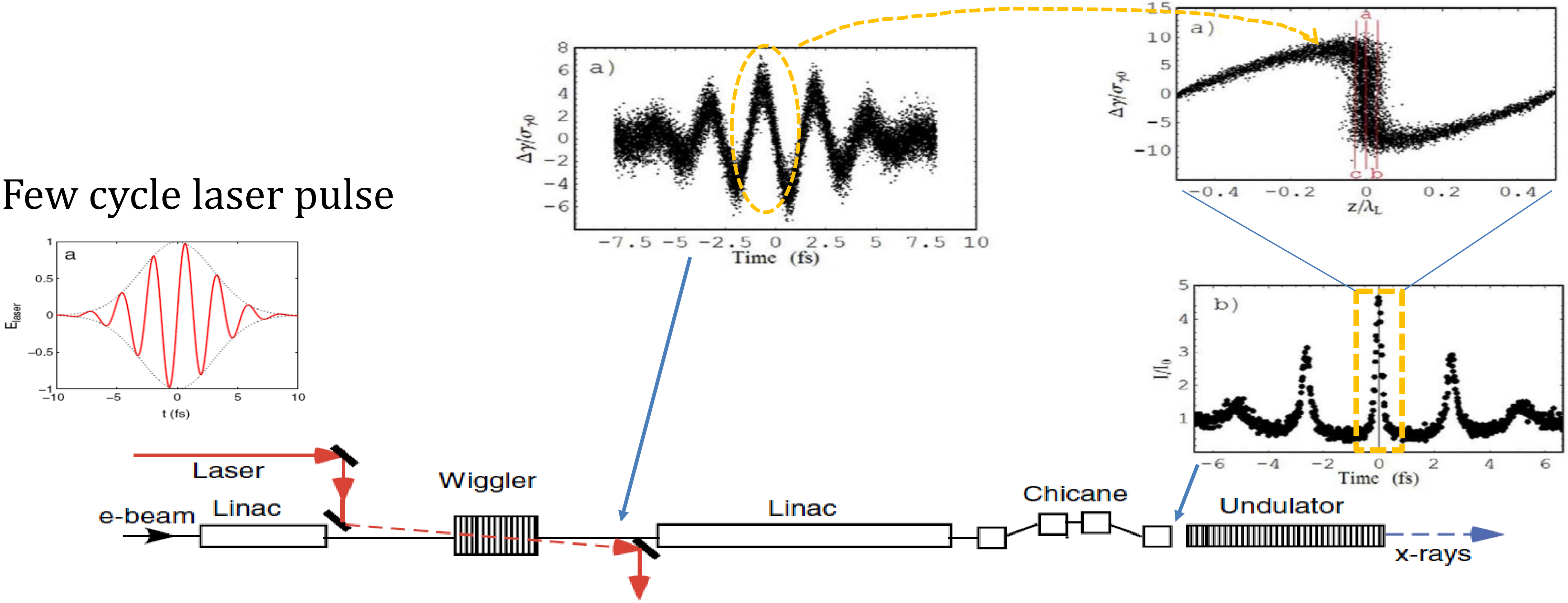
Low emittance e-beam and undulator

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 040701 (2005)

Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers

E-SASE scheme

Alexander A. Zholents
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA
(Received 21 May 2004; published 12 April 2005)

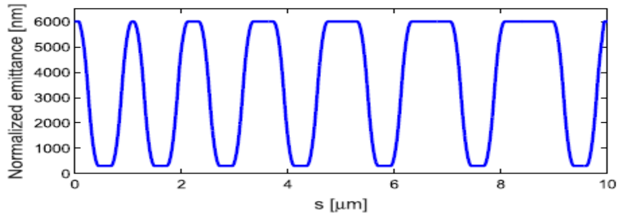


Energy modulation is converted to density modulation.

Recent progress in the generation of the TW-as XFEL

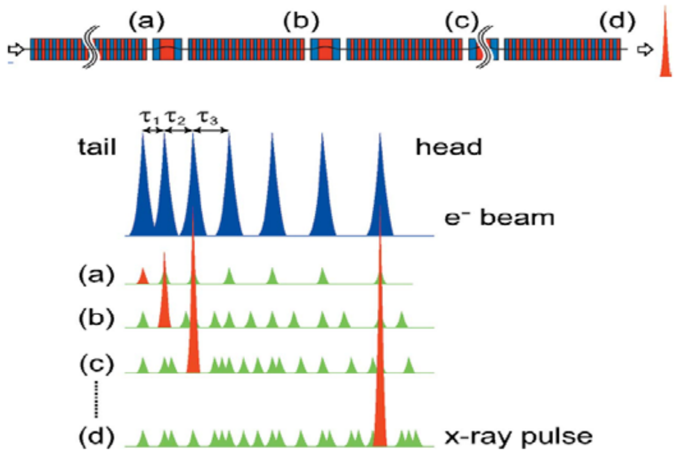
Tanaka, T. “**Proposal for a Pulse-compression scheme in X-Ray free-electron lasers to generate a multiterawatt, attosecond X-Ray pulse.** ” *Phys. Rev. Lett.* **110,** 084801 (2013)

Prat, E. & Reiche, S. “**Simple method to generate terawatt-attosecond X-Ray free-electron-laser pulses**”. *Phys. Rev. Lett.* **114,** 244801 (2015).

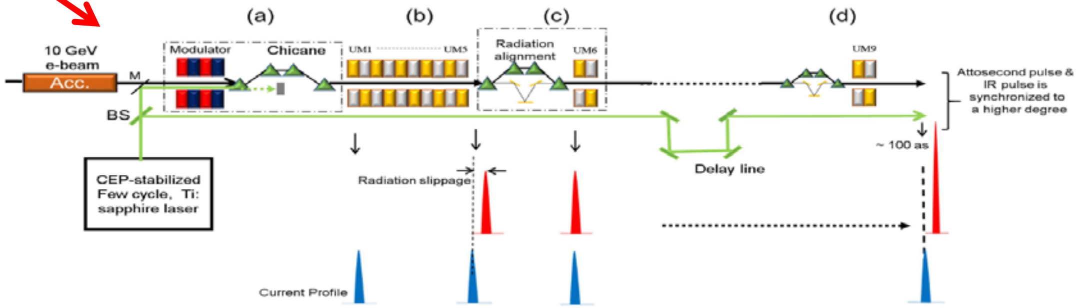


Takashi Tanaka, Yong Woon Parc, Yuichiro Kida, Ryota Kinjo, Chi Hyun Shim,
In Soo Ko, Byunghoon Kim, Dong Eon Kim, and Eduard Prat . **"Using irregularly spaced current peaks to generate an isolated attosecond X-ray pulse in free-electron lasers,“**
J. Synchrotron Rad23, 1273–1281 (2016).

Zhen Wang, Chao Feng and Zhentang Zhao, **"Generating isolated terawatt-attosecond x-ray pulses via a chirped-laser-enhanced high-gain free-electron laser,”** Phys. Rev. AB 20, 040701 (2017)



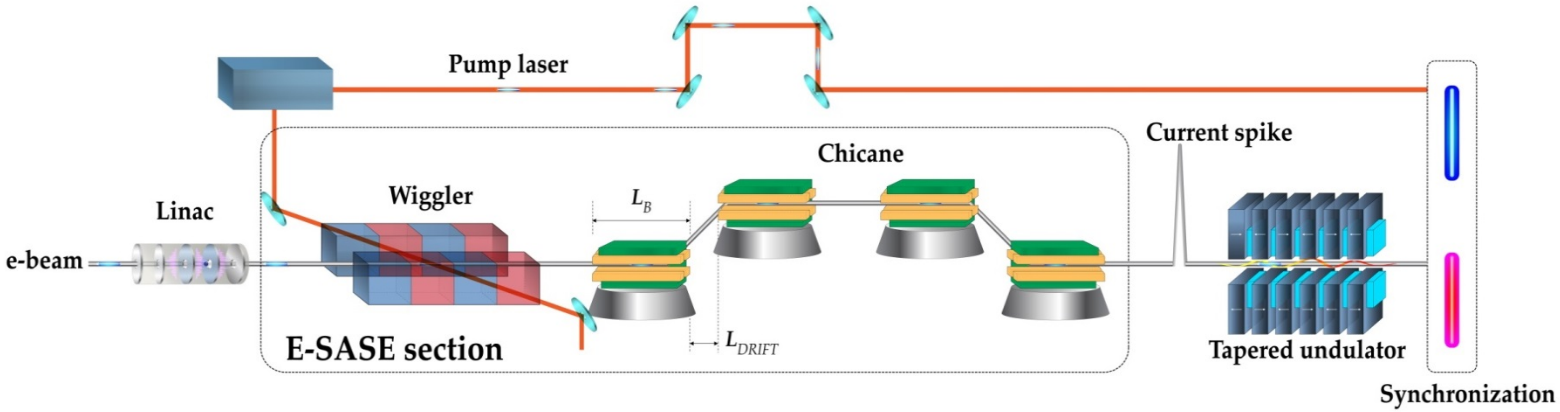
Sandeep Kumar, Yong Woon Parc, Alexandra S. Landsman, Dong Eon Kim
"Temporally-coherent terawatt attosecond XFEL synchronized with a few cycle laser"
Sci. Rep. 6, 37700 (2016)

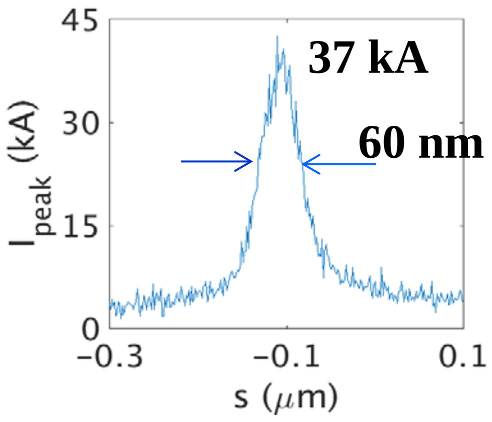


Single current method

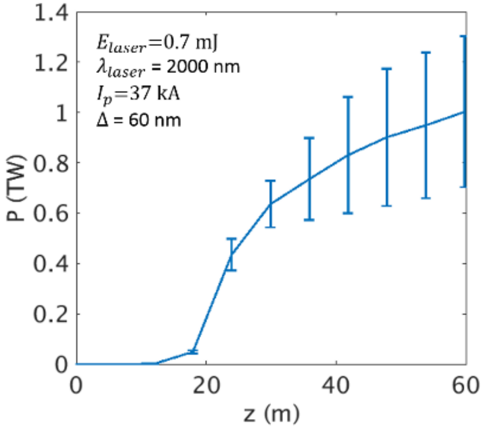
Collaboration job with Dr. C. H. Shim in PAL.

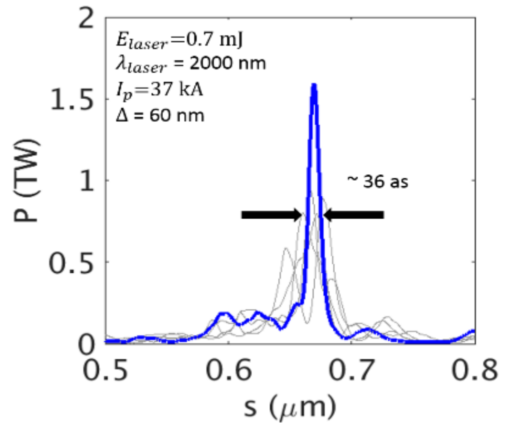
Collaboration job with Prof. D. E. Kim in POSTECH.





1) how short should the current spike be?
2) how much high peak current do we need and can we make it?
3) how high power of a modulation laser do we need?
4) what is the best wavelength for the modulation laser?



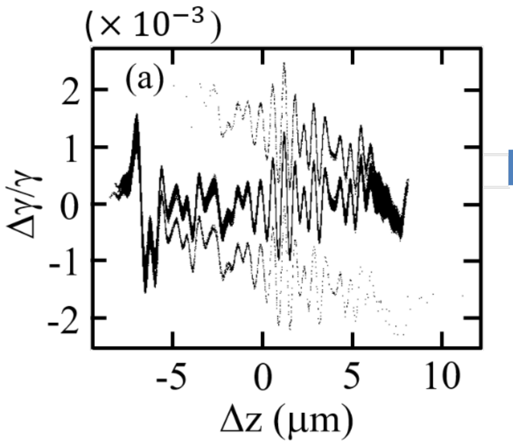


Optimization results with PAL-XFEL parameters.
Laser wavelength: 2 μm
Laser energy: 0.7 μJ at the wiggler

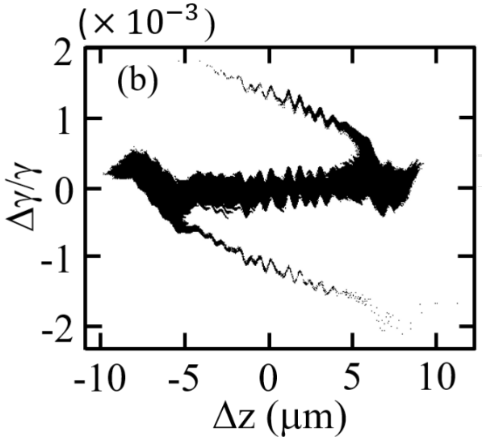
A single peak X-ray pulse with over 1 TW peak power and less than 100 as pulse width can be generated from a single current spike.

Sci. Report 8, p.7463 (2018) (corresponding)

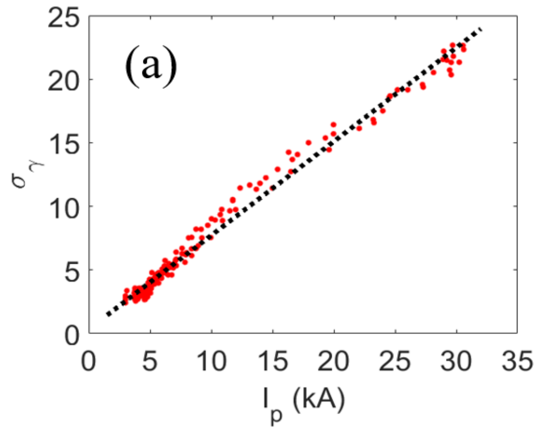
Micro-bunching effect

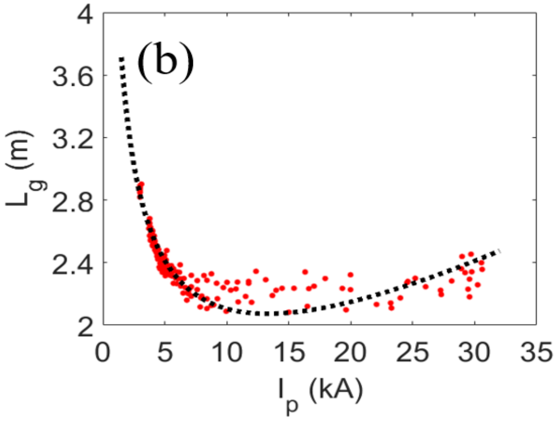


laser heater

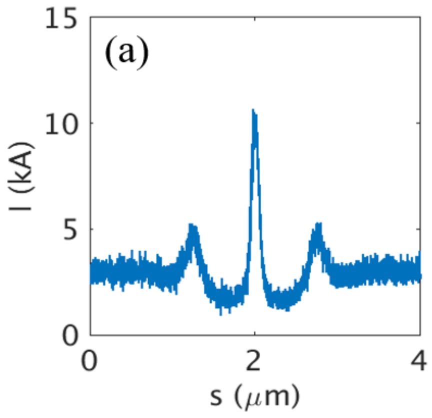


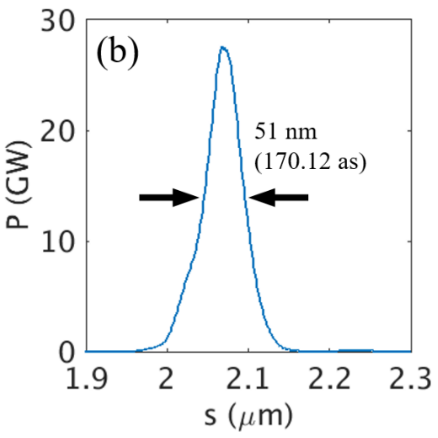
Slice energy spread is high



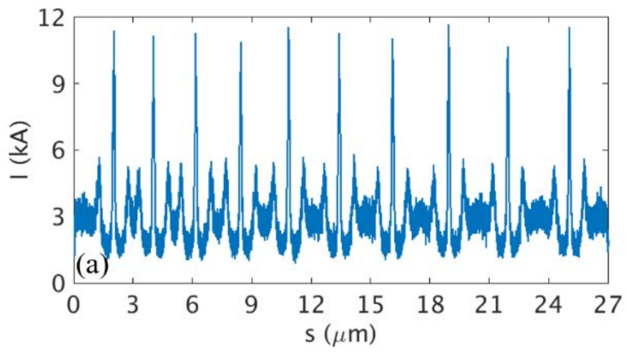


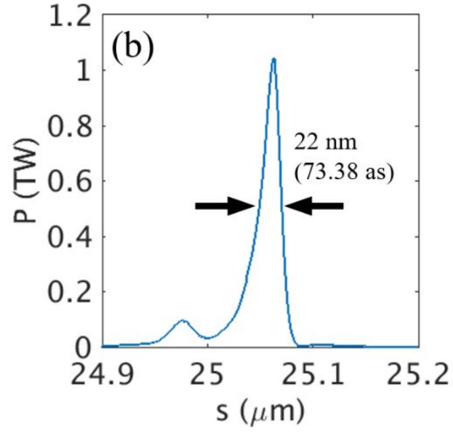
10 kA is an optimum.





Single current method

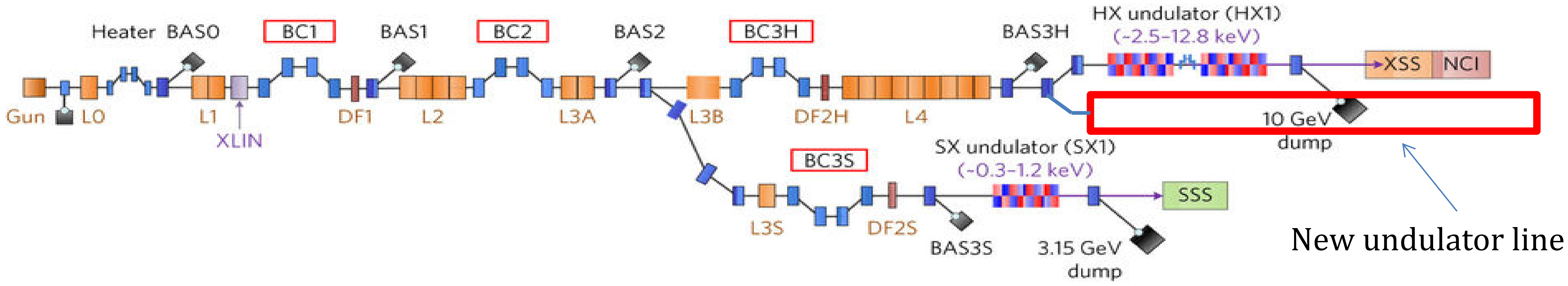




Multi current method

To be submitted to some journal

Plan for new undulator line



New undulator line will be devoted to the attosecond science.

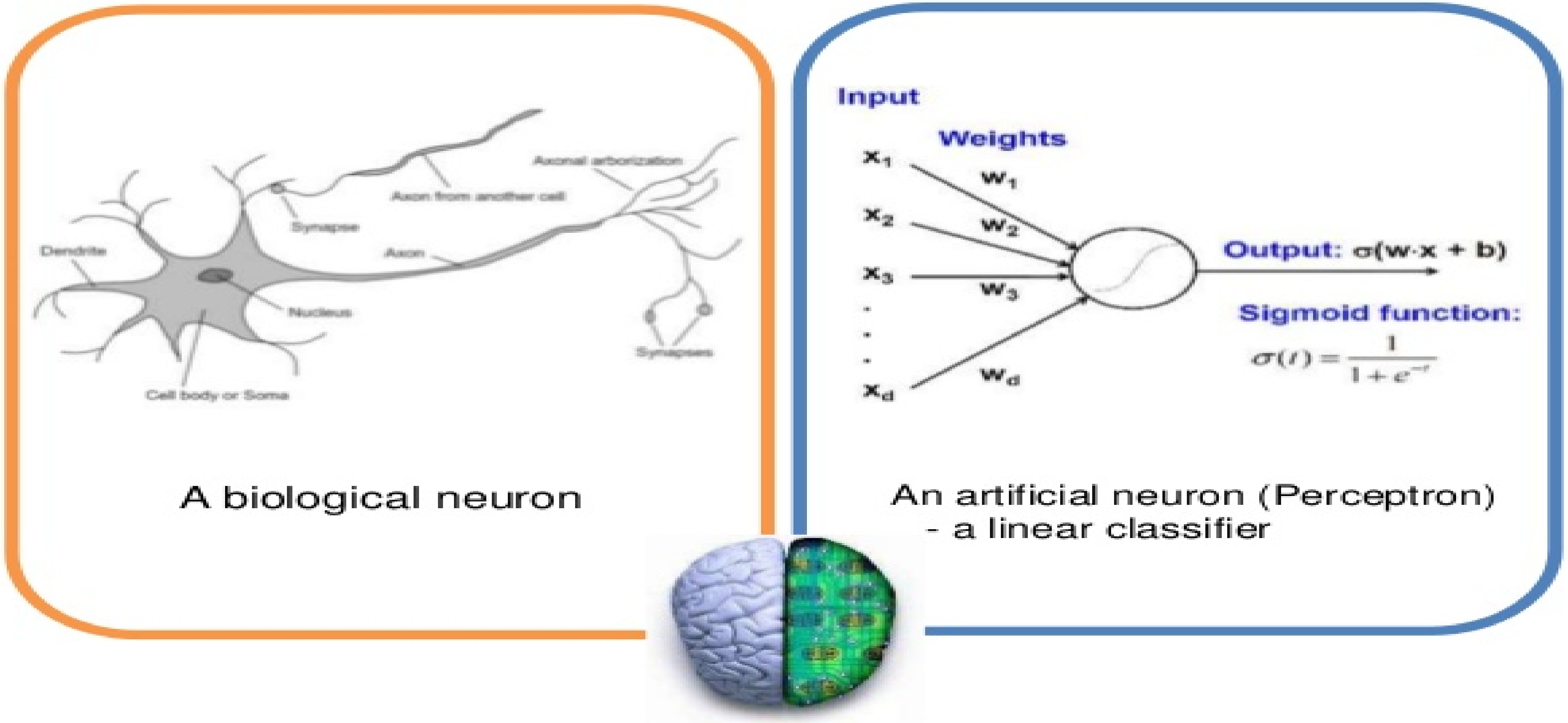
Problem: If we insert the delays between the undulator modules, there will be power drop for normal SASE operation.

Outline

- PAL-XFEL: past
  - Construction process
  - Commissioning results
- PAL-XFEL: present
  - Self seeding
  - 20 fs timing jitter
- PAL-XFEL: future
  - Attosecond FEL beamline
  - Artificial Intelligence application
- Summary

Perceptron

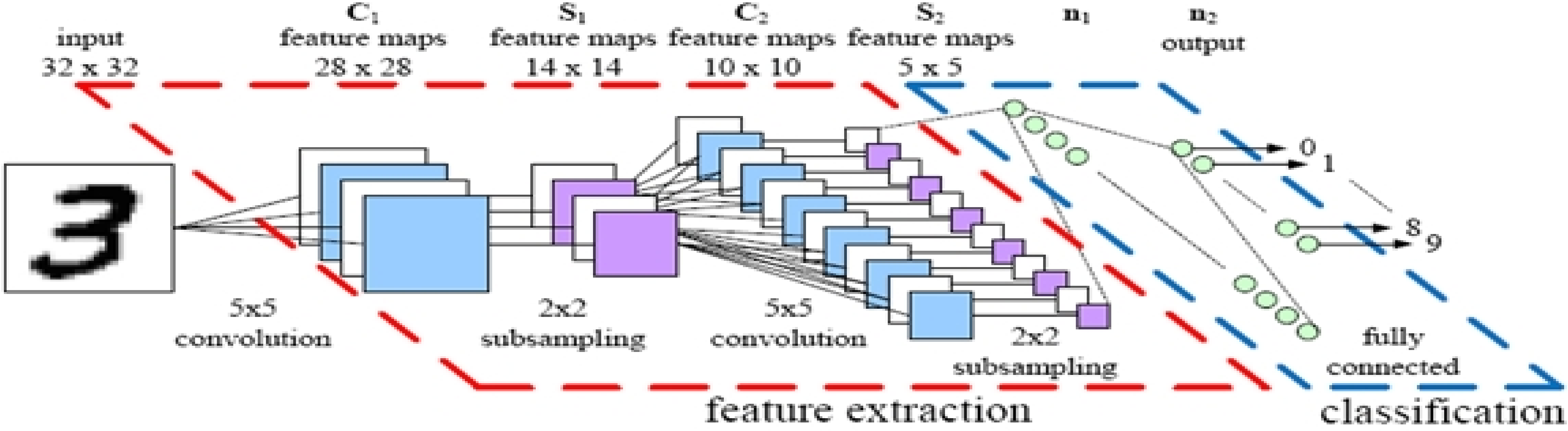
Biological neuron and Perceptrons



A biological neuron

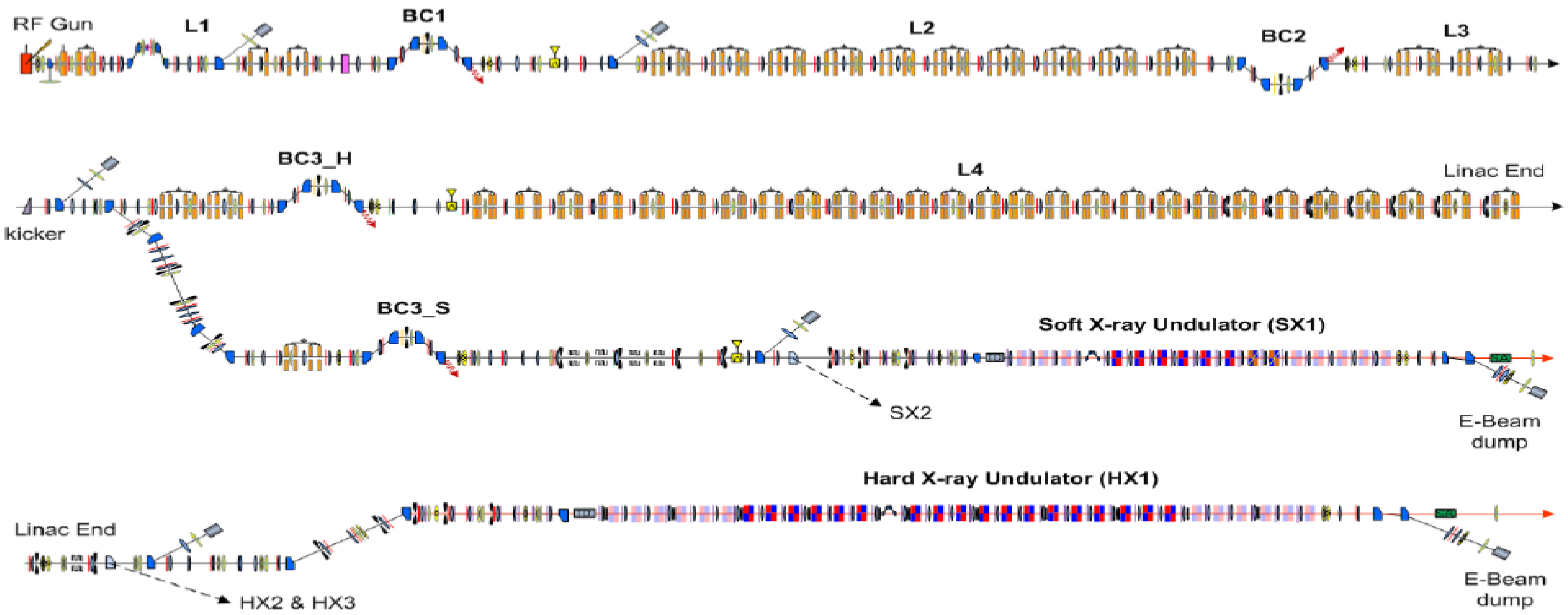
An artificial neuron (Perceptron)
- a linear classifier

Convolutional Neural Networks



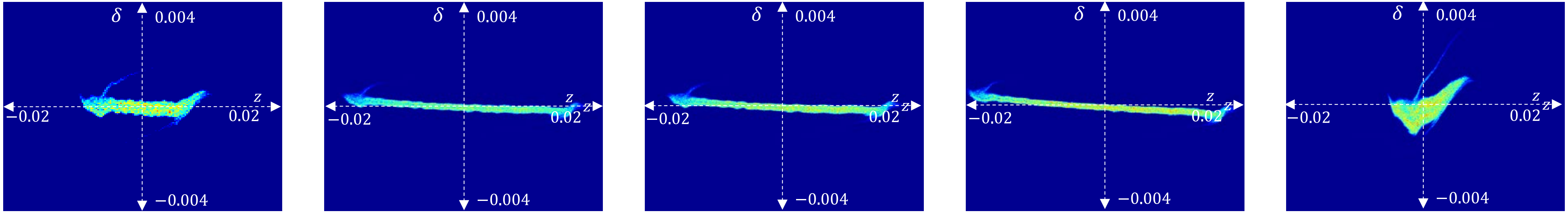
- Composing upper Feature by repeating convolution and Pooling (Subsampling)
- Convolution means process that gets some certain feature in local area.
- Pooling means process that gets Translation-invariant feature, while reducing dimension

PAL-XFEL Application

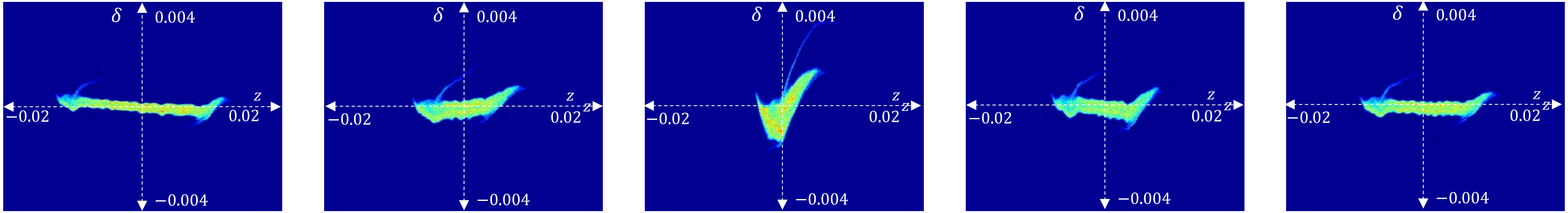


- Lattice : Merger, 5 RF cavity, dump magnet, arc, C type chicane, matching section
- Nominal operation : single-bunch mode. 40 pC charge, 630 A Peak Current
- 28800 ELEGANT simulation with LSC, CSR, Wake and other effects
- Option : $N_p = 2 * 10^5$,
- 1st training includes no measurement errors.

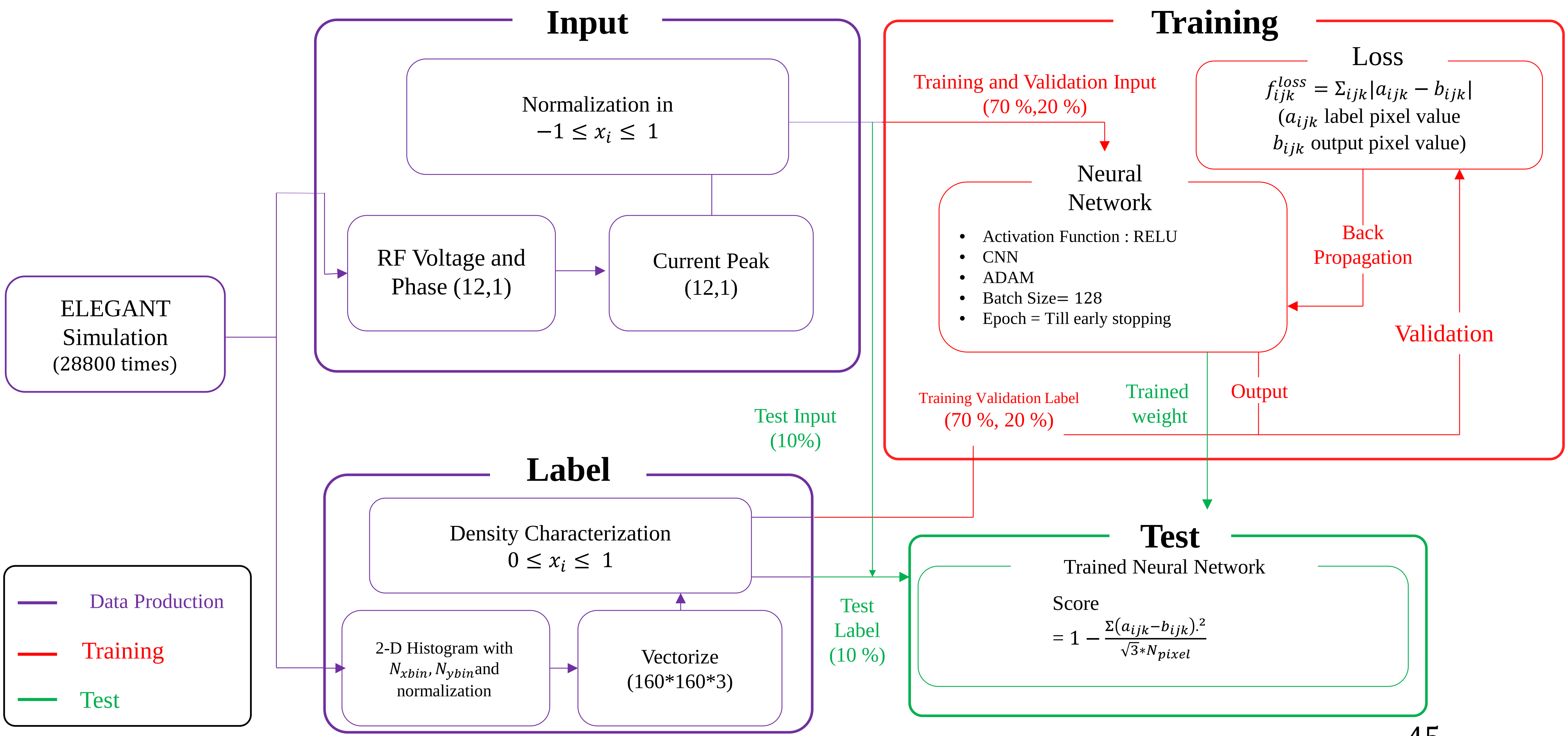
Deviations with 1% variation (S-band linac)



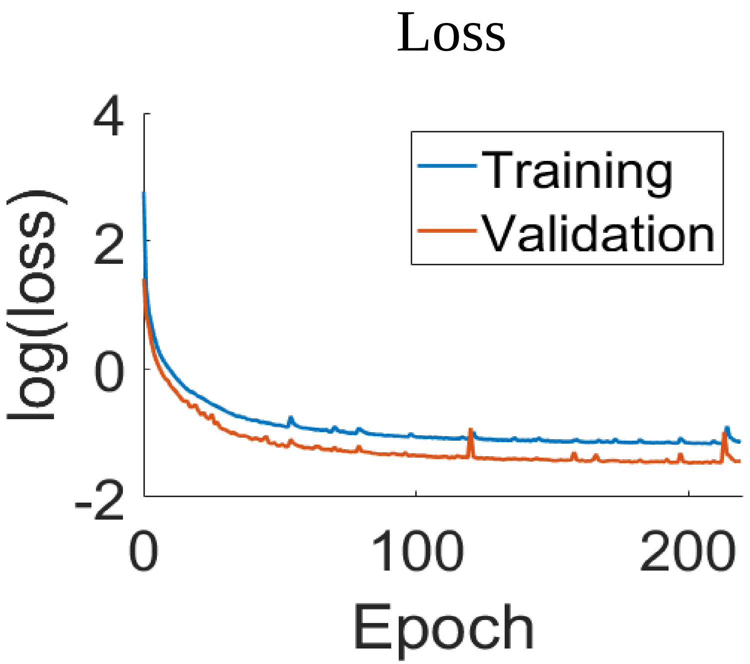
Normal Operation

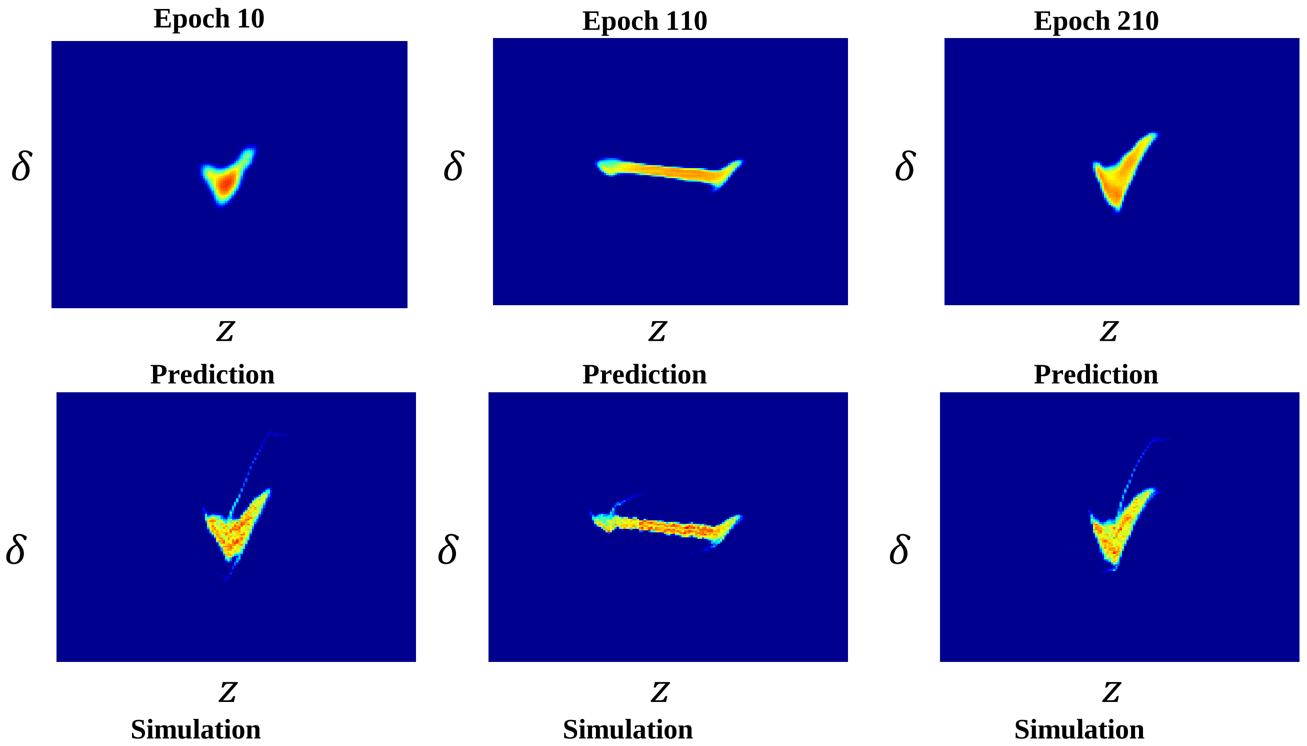


Training Scheme



Prediction Result





- Early Stopping method is applied to prevent model from overfitting.
- Time spending is as large as ten times due to increase of input and data.
- Despite of low epoch, it evolve toward simulation shape.

Summary

- 1. PAL-XFEL can supply upto 14.4 keV with self seeded light.
- 2. The timing jitter is less than 20 fs.
- 3. New attosecond beamline will be constructed soon.
- 4. Virtual diagnostics with artificial intelligence will be tried soon.

https://www.lasphys.com/workshops/lasphys19/

28th Annual International

LPHYS'19

Laser Physics Workshop

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(Gyeongju, July 8-12, 2019)

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Thank you
for your attention