X-ray amplification with laser plasma and its applicability to EUV-FEL

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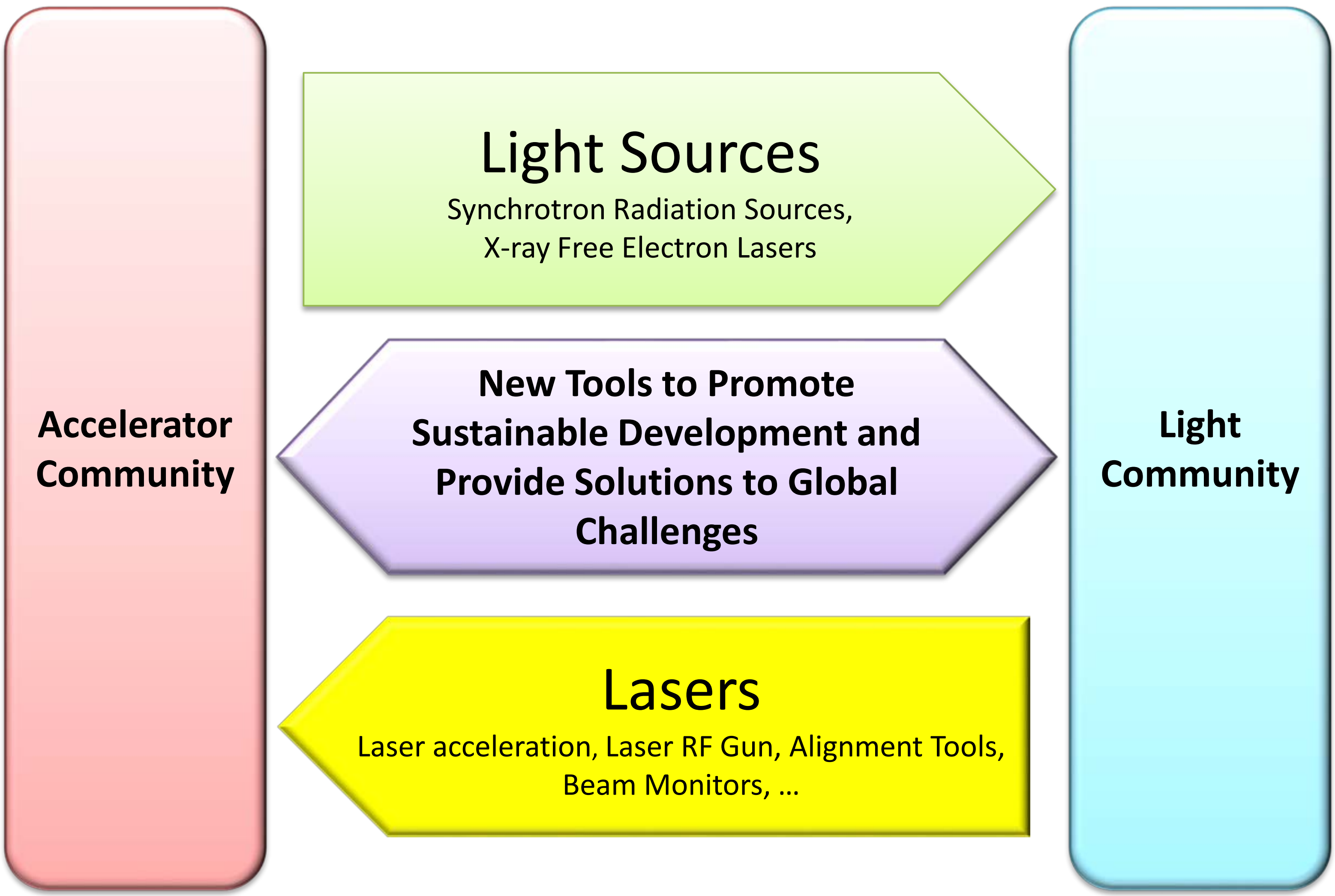
Plan

- Introduction
- SPring-8 Compact SASE Sources
- Inner-shell Laser with Two-Color SASE pulses
- XFEL Amplification with Laser Plasma
- Energy Recovery Bilinear Accelerator
- Concluding Remarks

Introduction

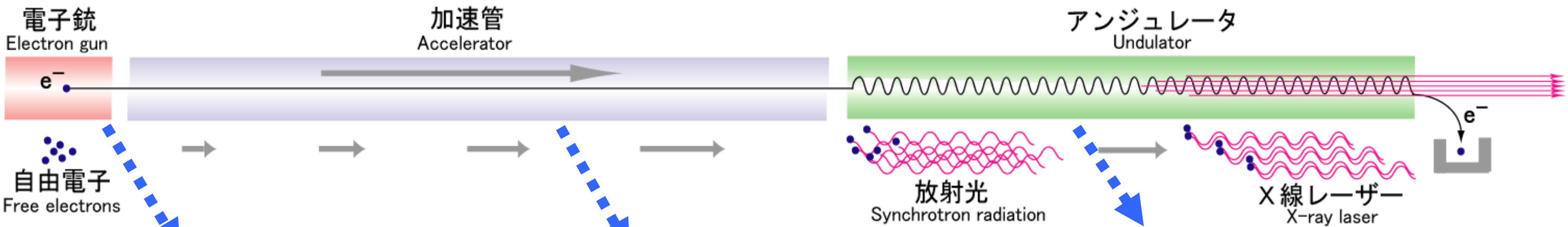
- Development of laser-based EUV sources for semiconductor lithography is ongoing.
- In addition, accelerator-based EUV sources are attracting attention regardless of their high cost.
- Appropriate combinations between laser and accelerator could reduce both size and cost of the light sources.
- Here we introduce the recent status of SACLA and recent results of XFEL amplification with laser plasma.
- If the above scheme could be used for EUV source, a complete new way of light source development may be envisaged.

Interdependence between Accelerator and Light Communities

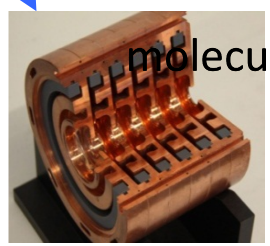


Compact SASE Source

- Short-period, in-vacuum undulators can reduce the electron energy to generate XFEL light with a certain photon energy.
- SPring-8 Angstrom Compact Laser (SACLA) is the world's first XFEL based on this 'compact' concept.

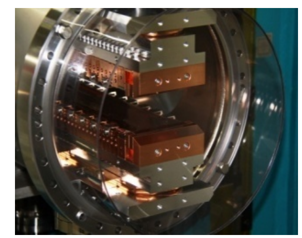


CeB6 thermionic e-gun

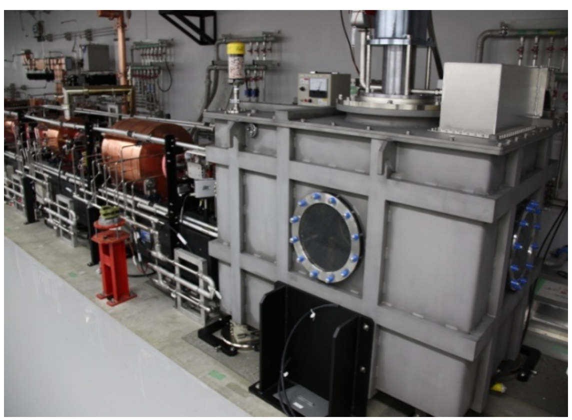


molecule

C-Band (5712 MHz) acceleration tube

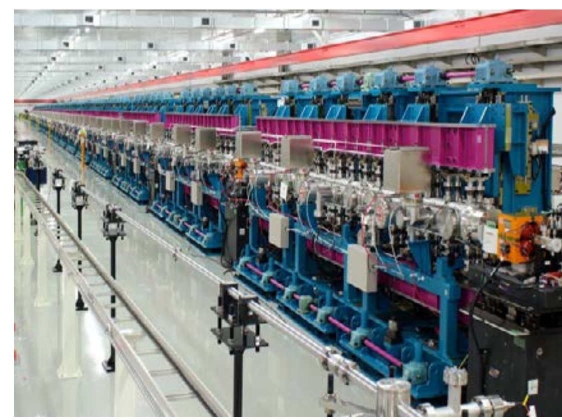


In-vacuum undulator



Thermionic e-gun to generate high-quality electron beam

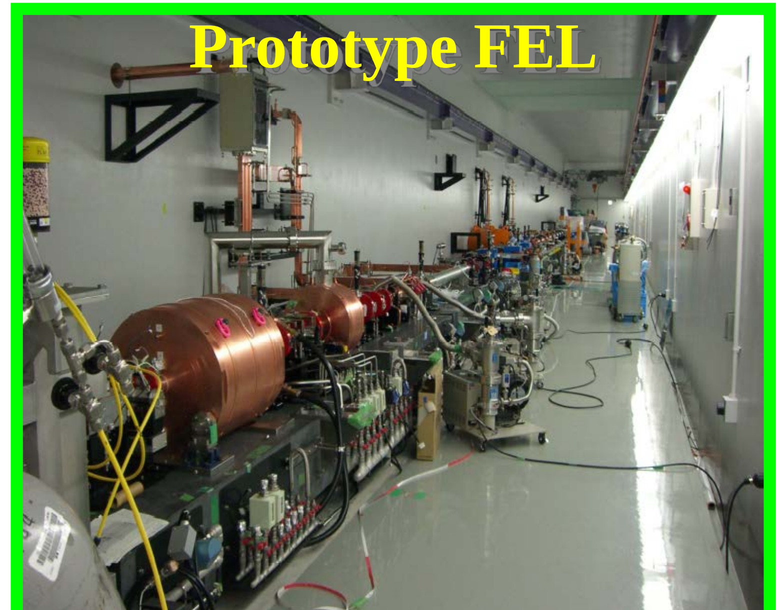
High-gradient C-band accelerator

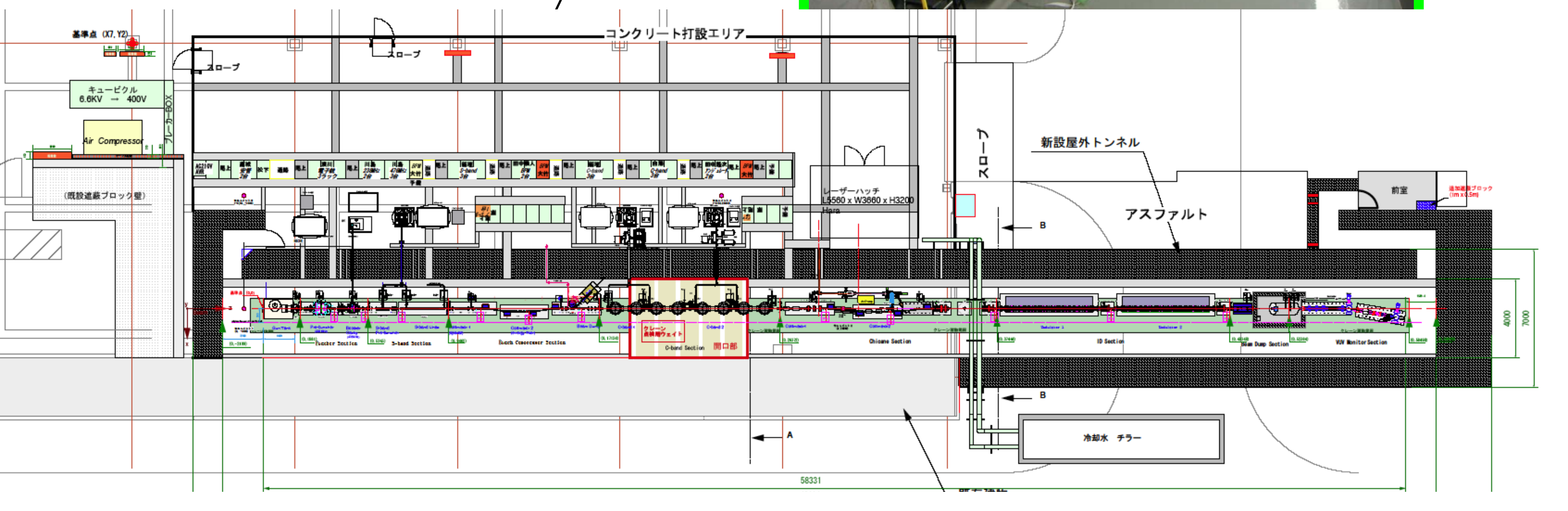


In-vacuum undulator to produce SASE FEL

SACLA Prototype Construction

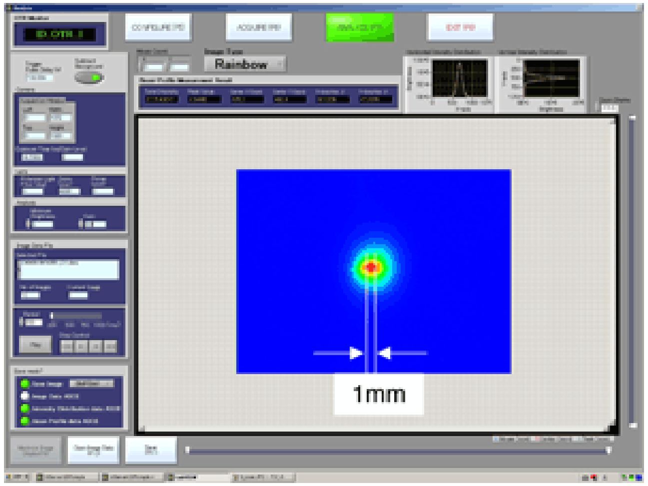
250 MeV Prototype, Total Length: 60 m, Target Wavelength: 60 nm



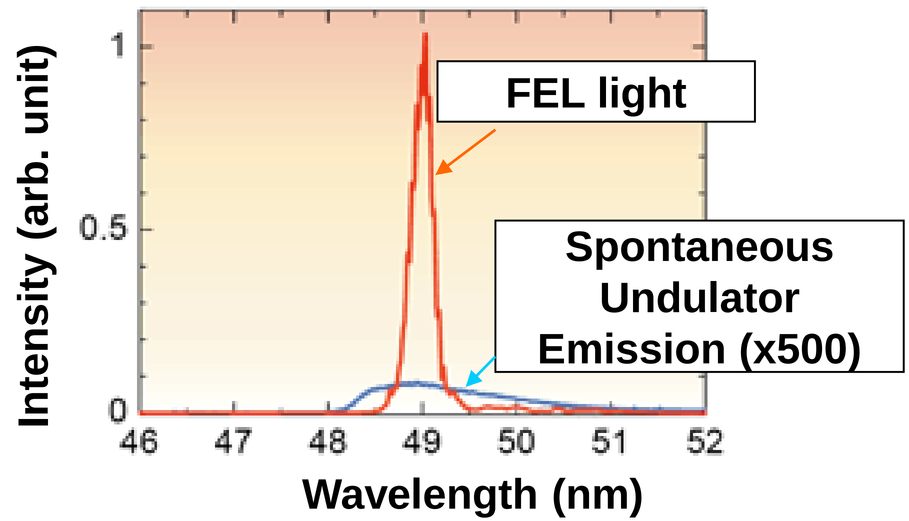


First Lasing at 49 nm (June 20, 2006)

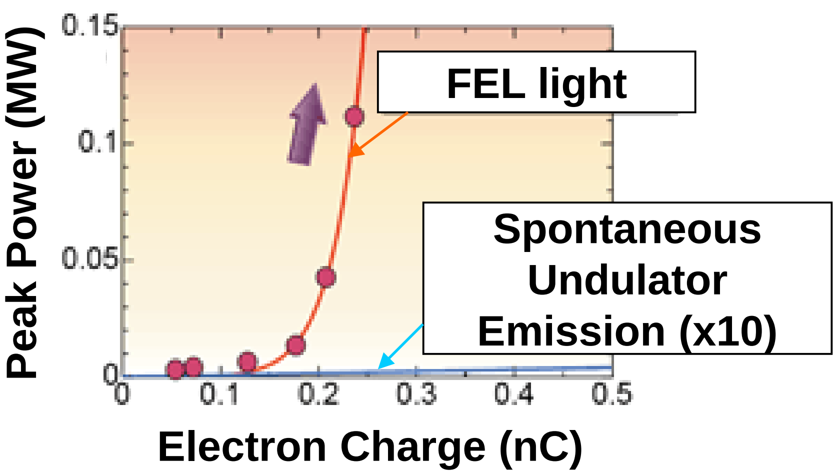
Electron Beam Profile



Spectrum



Charge Dependence



E = 250 MeV
Charge/Pulse ≤ 0.25 nC
Emittance ≤ 2πmm･mrad
Pulse Length ≤ 2 ps
Wavelength = 49 nm
Max. Power = 110 kW

SACLA

(SPring-8 Angstrom Compact free electron LAser)

X-Ray Free Electron Laser with 8 GeV electron Liniac
700 m length including experimental building
Completed in March 2011
Open for public users (domestic and international)

The first XFEL that collocate with a 3rd generation SR source.
The first "compact" XFEL to have a length of 700 meters.

General Information about SACLA

- **5,861 h** operation with **4,026 h** user time with **130 h** down time (~3.2% of user time) in 2016 FY
- MTBF: **67** min for **BL2/3**(2016 FY)
- **3** beam lines are in operation. **2** pending construction.
- **1188** visiting users in 2016 FY
- **151** proposals submitted, **77** approved (**51 %**) in 2016 FY
- User affiliation: **23.4%** from abroad, **26.0%** from national/public institutes, **42.8%** from universities, **7.8%** from industries
- Operation Budget: **5.79** BJPY in 2016 FY
- **274** publications (2012~) in refereed journals

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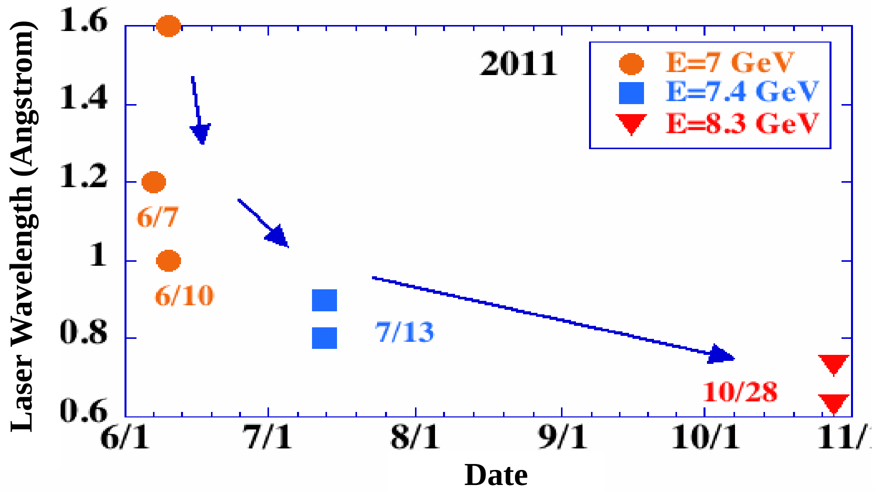
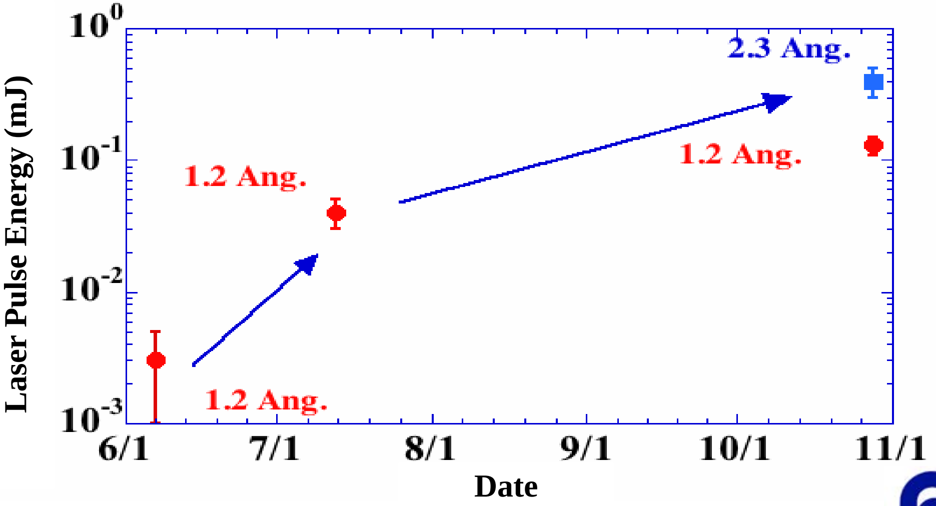
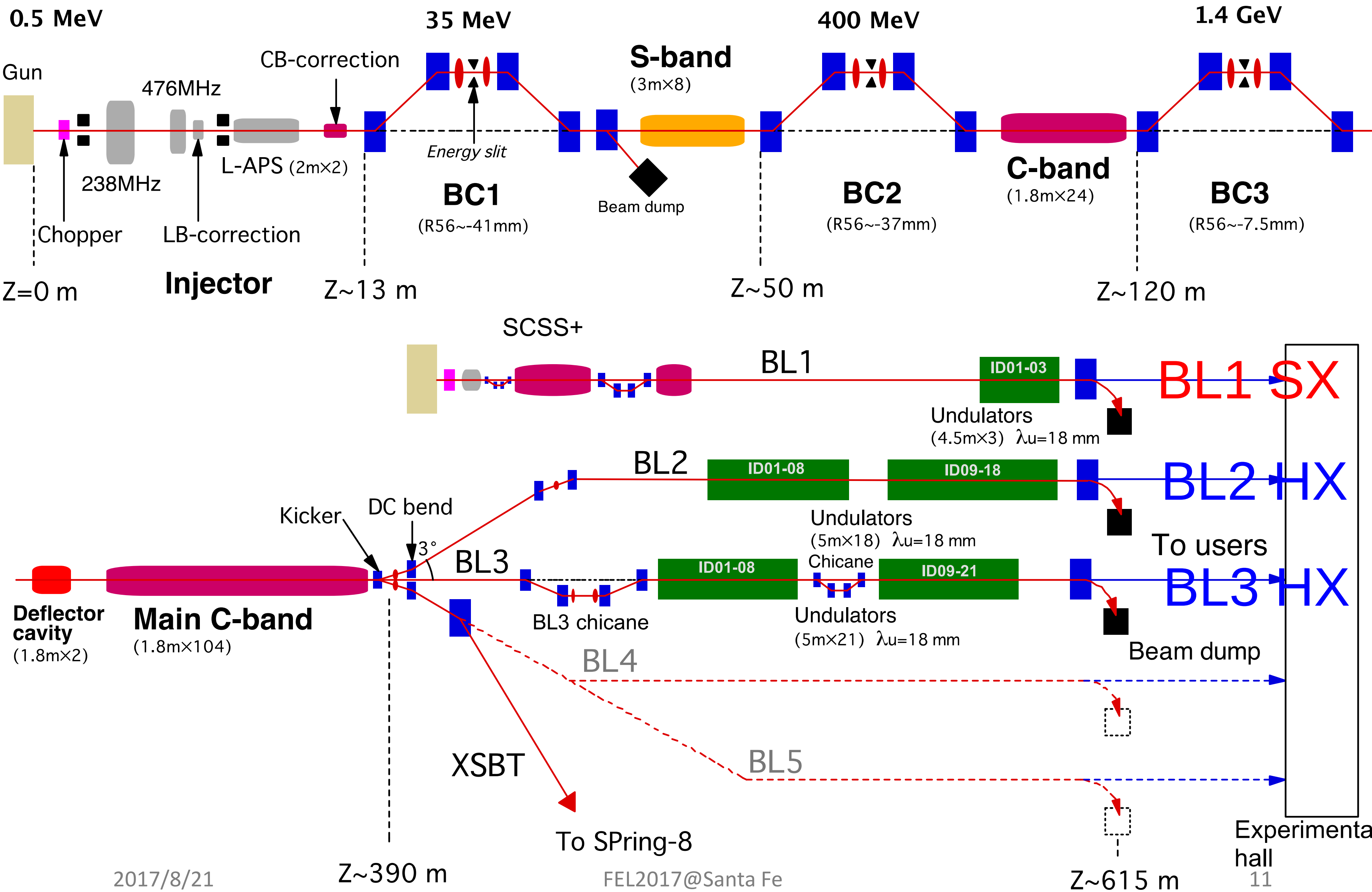
Laser Broke 1.0 Angstrom Barrier





3 FEL(2X+1SX) Beamlines Available



Help Promote Sustainable Development

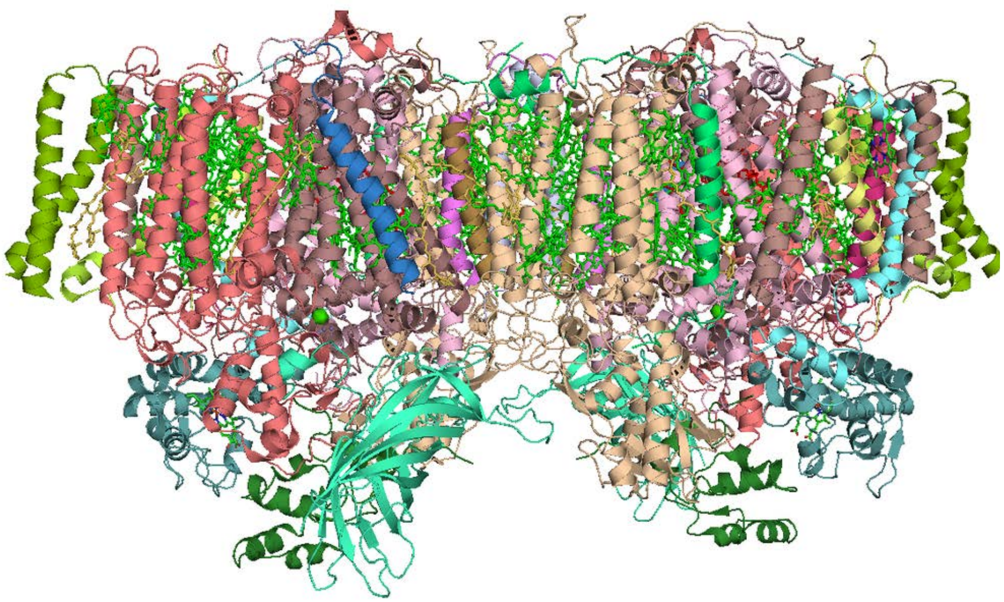
- PSII molecular structure was determined by using SPring-8 and SACLA
- Reaction dynamics is under investigation with SACLA
- The structure of reaction center help develop the artificial photosynthesis catalysts

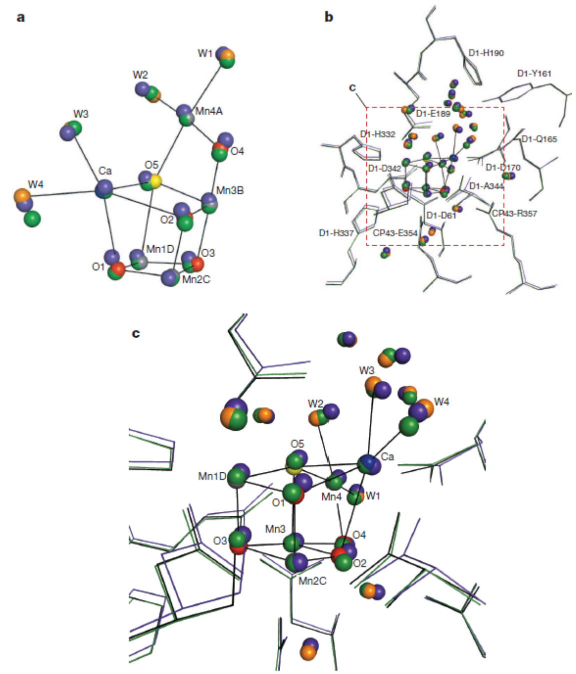
LETTER

doi:10.1038/nature13991

Native structure of photosystem II at 1.95 Å resolution viewed by femtosecond X-ray pulses

Michihiro Suga[1]*, Fusamichi Akita[1]*, Kunio Hirata[2,3], Go Ueno[2], Hironori Murakami[2], Yoshiki Nakajima[1], Tetsuya Shimizu[1], Keitaro Yamashita[2], Masaki Yamamoto[2], Hideo Ago[2] & Jian-Ren Shen[1]

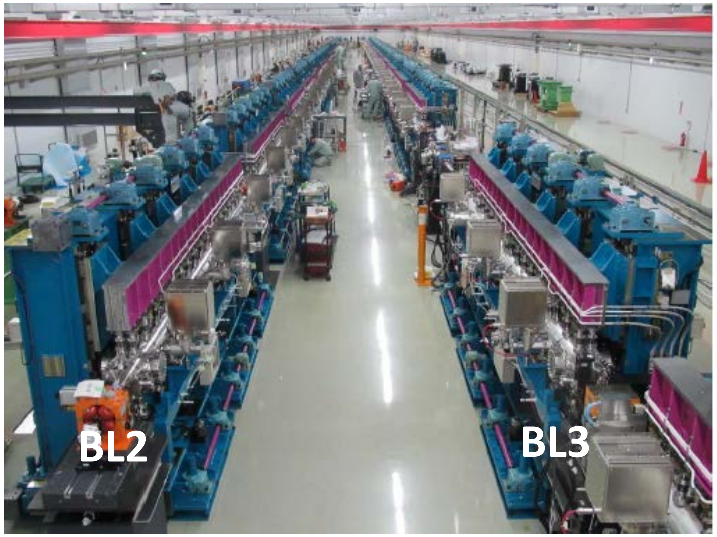




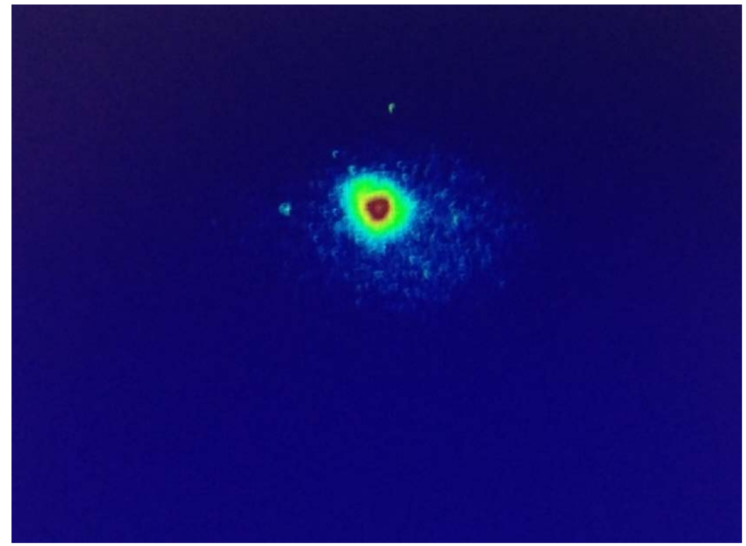
New beamline: BL2

Deficiency of beamtime severely limits research activities with XFEL

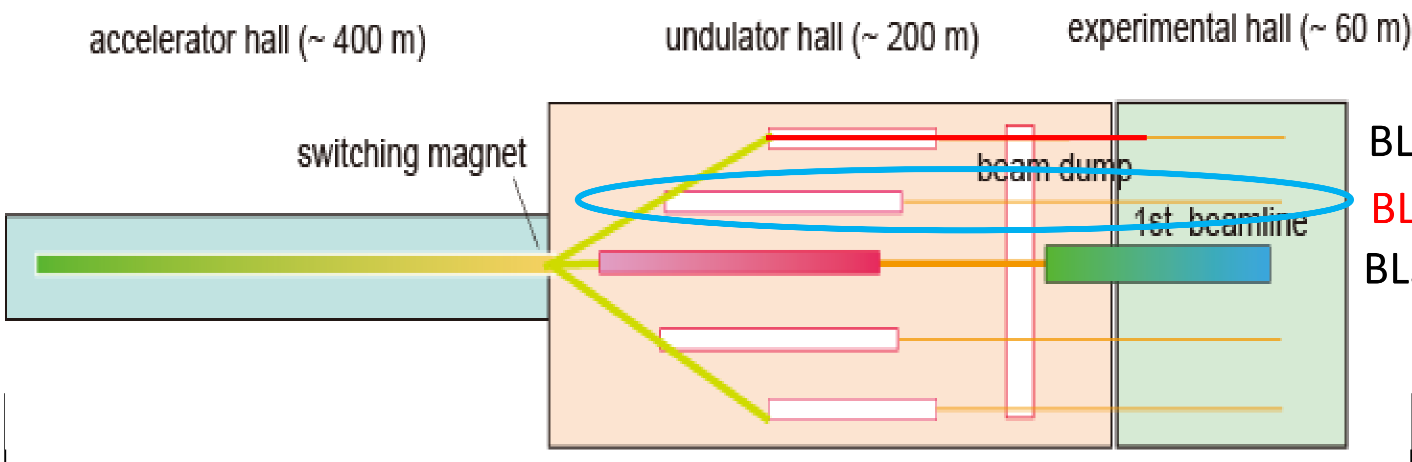
Construction of 2nd hard X-ray FEL beamline for increasing capacity



Undulators installed in summer 2014



First lasing on Oct 20th, 2014

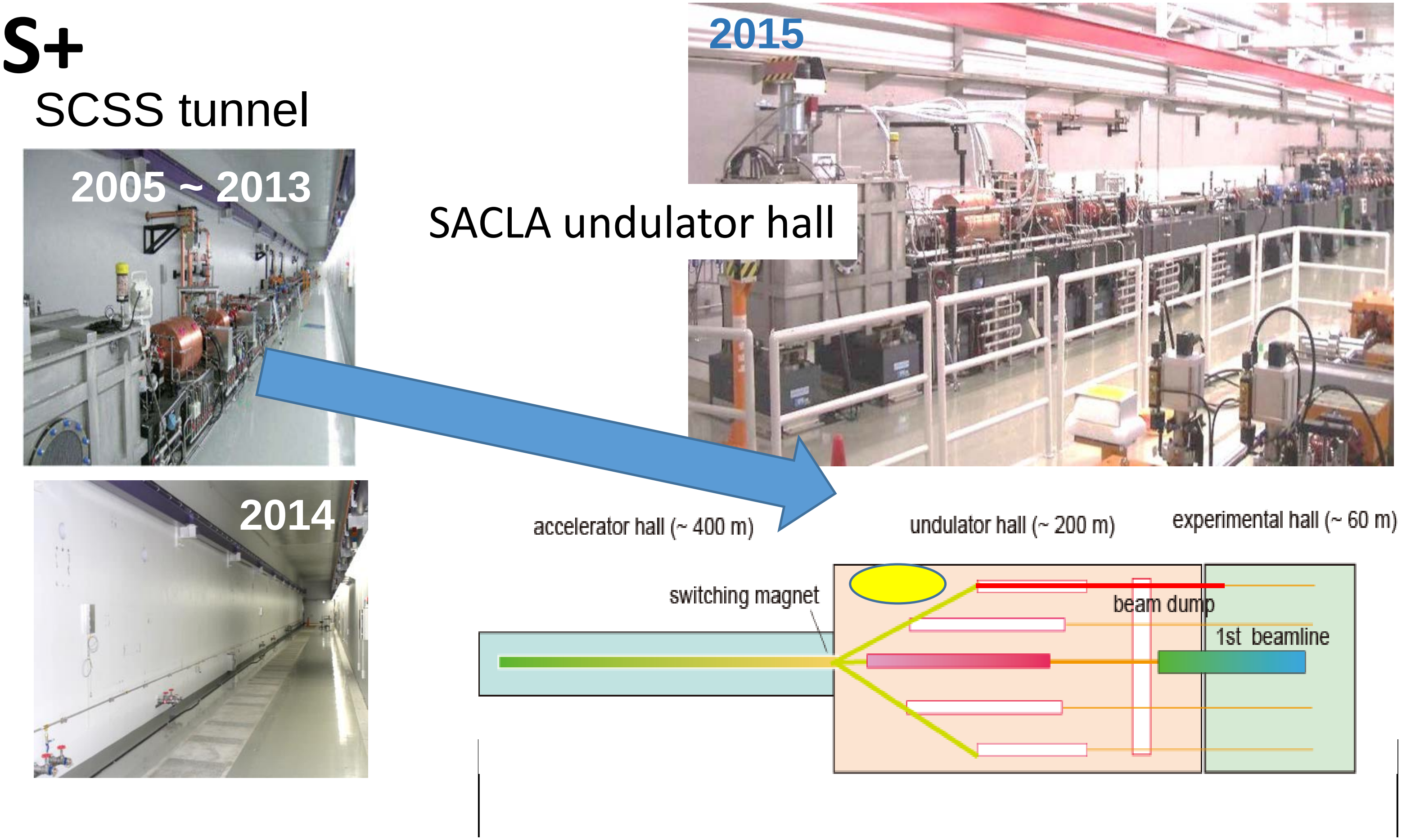


BL1 (SX spont)

BL2 (HXFEL)

BL3 (HXFEL)

SCSS+

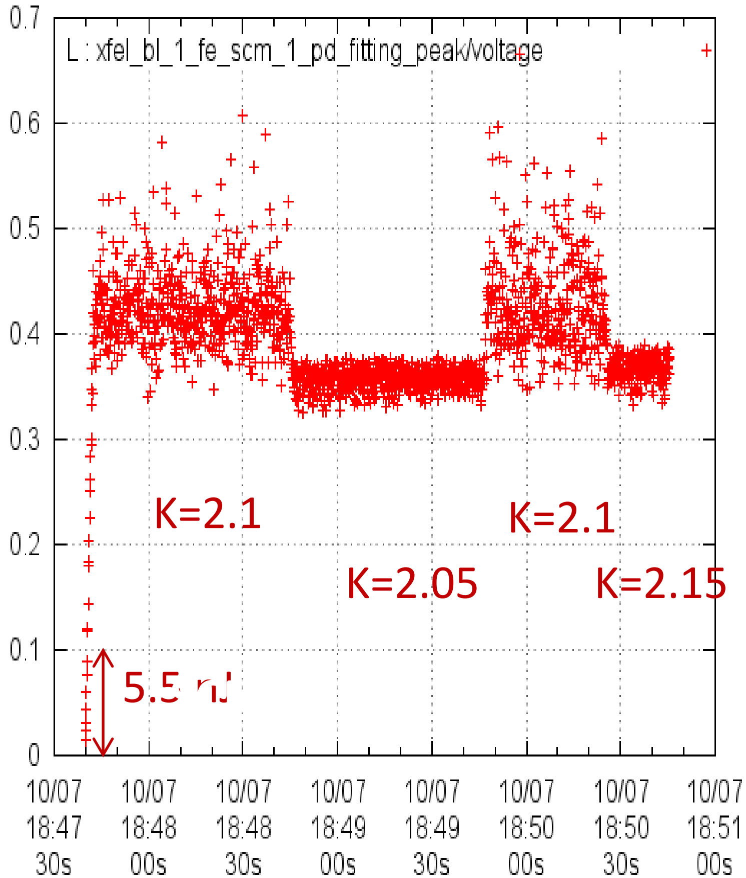


- Evacuate SCSS from the original tunnel, and relocate to SACLA undulator hall and connect to BL1
- E-beam driver for EUV/SX FEL generation, independent of the SACLA main linac
- Completed in 2015 summer with 450 MeV (λ~30 nm with λ_U=18 mm)

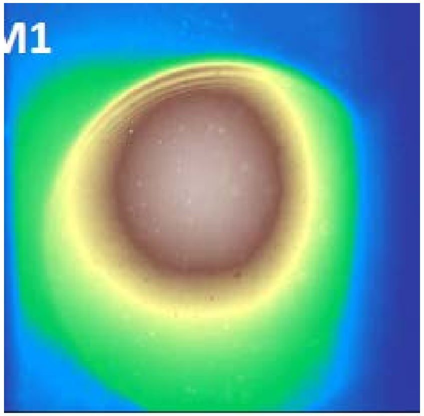
Commissioning: First SASE lasing on Oct 7, 2015

ID#1: K=2.1
ID#2: tuning K

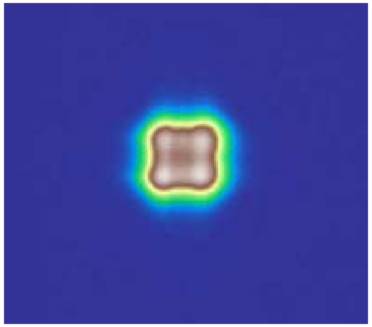
Pulse energy : 10~20 uJ



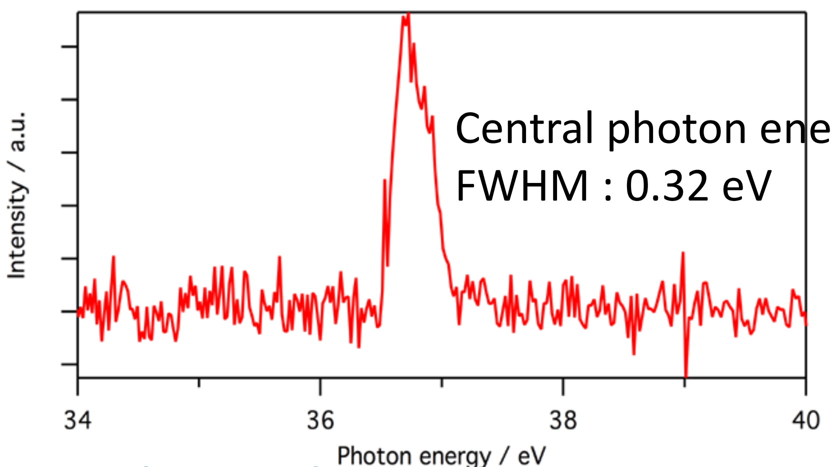
Beam profile



Interference pattern with small slit size



Spectrum



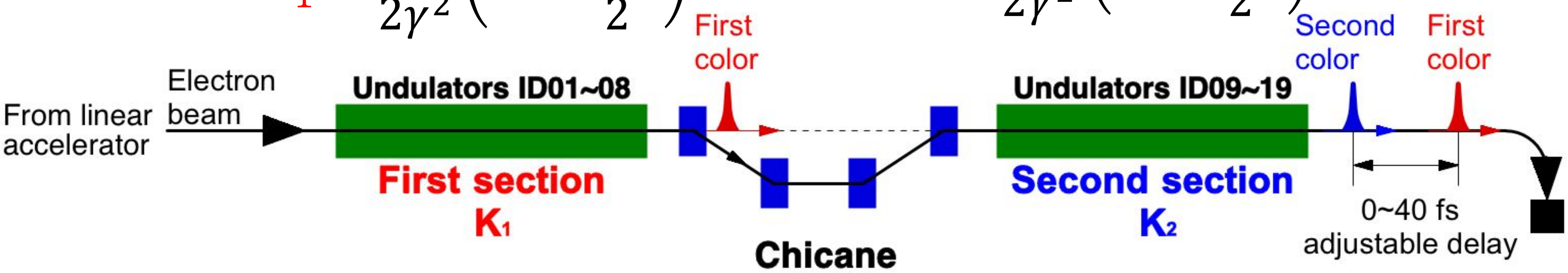
Continue commissioning

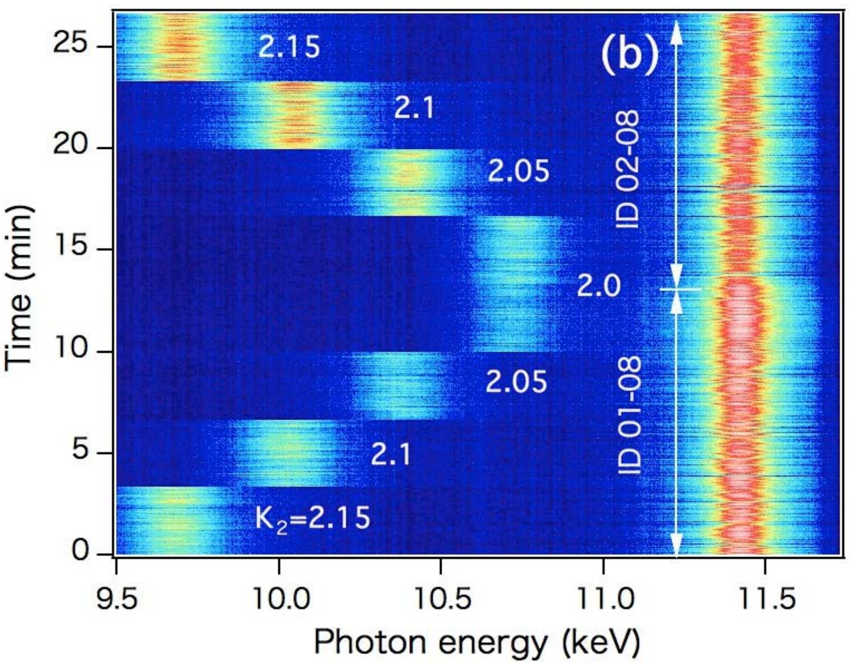
Test user operation starts in early 2016

Add a C-band unit in Aug 2016: up to 750 MeV (~ 10 nm)

Two-color operation with variable-gap undulators

$$\lambda_1 = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K_1{}^2}{2}\right) \qquad \lambda_2 = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K_2{}^2}{2}\right)$$





- Maximum photon energy separation: >30 %
- Time delay between two pulse can be adjusted between 0~40 fs with a sub-femtosecond resolution.

ARTICLE

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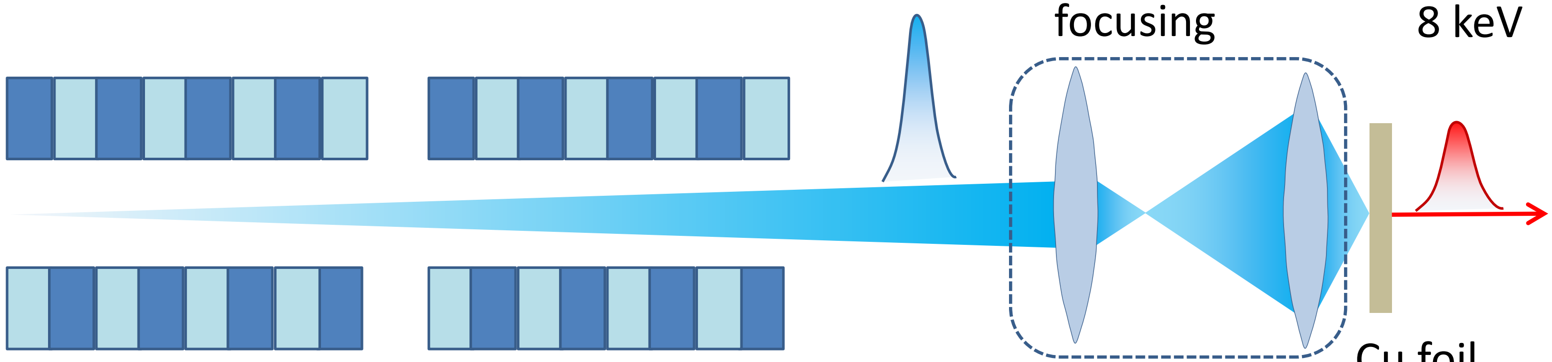
Two-colour hard X-ray free-electron laser with wide tunability

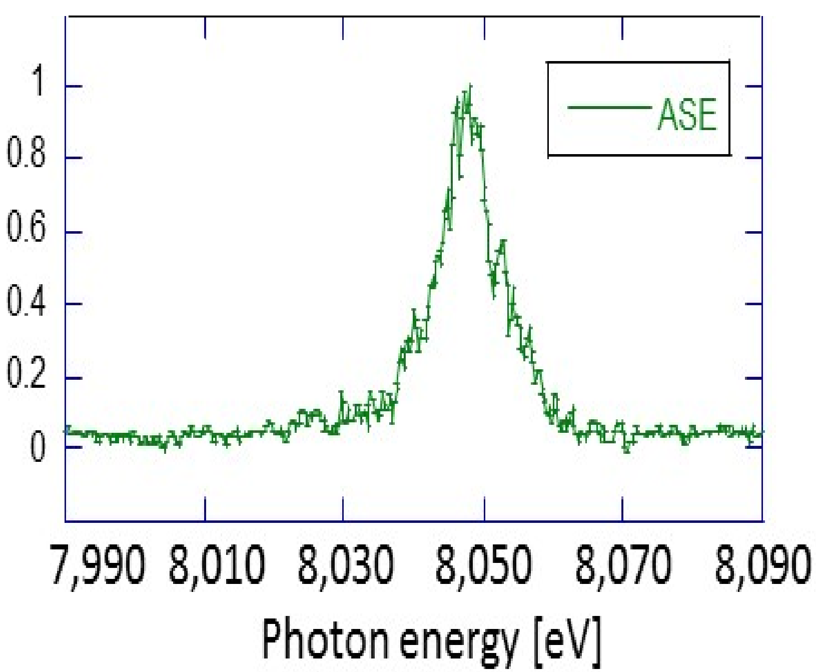
Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], Tadashi Togashi[2], Kazuaki Togawa[1], Kensuke Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

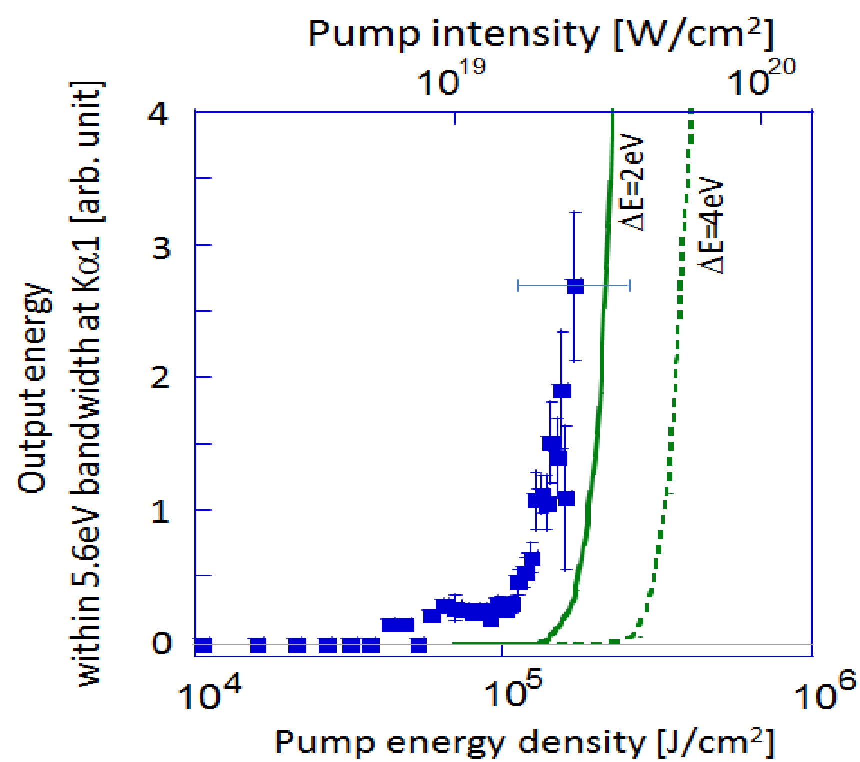
Hara et al, Nature Commun 2014

Achievement of Hard X-ray Cu-Ka atomic laser (ASE)

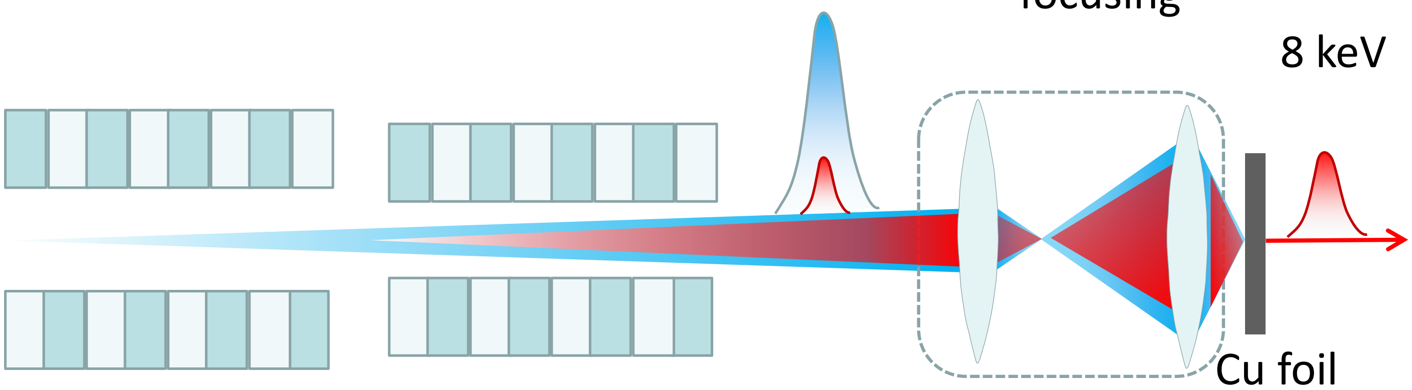


Yoneda *et al.*, *Nature*

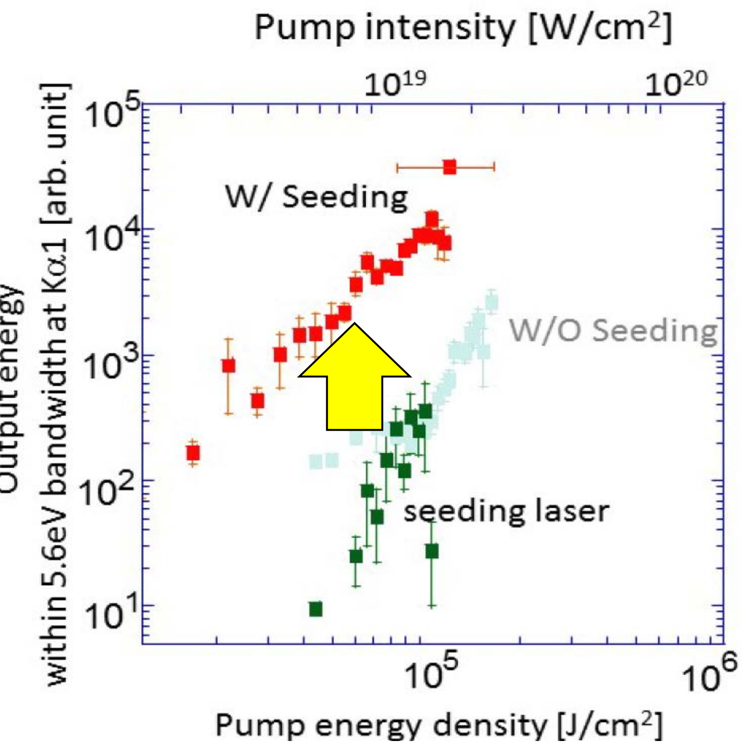


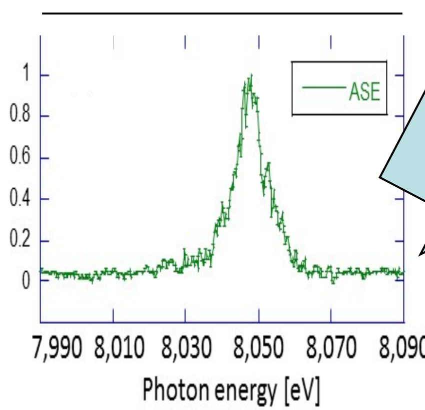


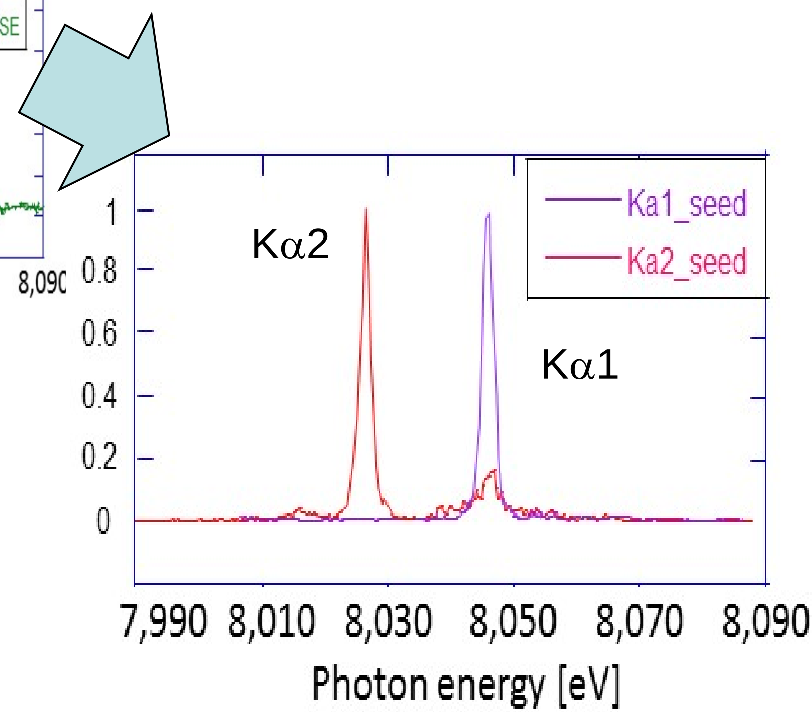
Achievement of Hard X-ray Cu-Ka atomic laser (seeding)



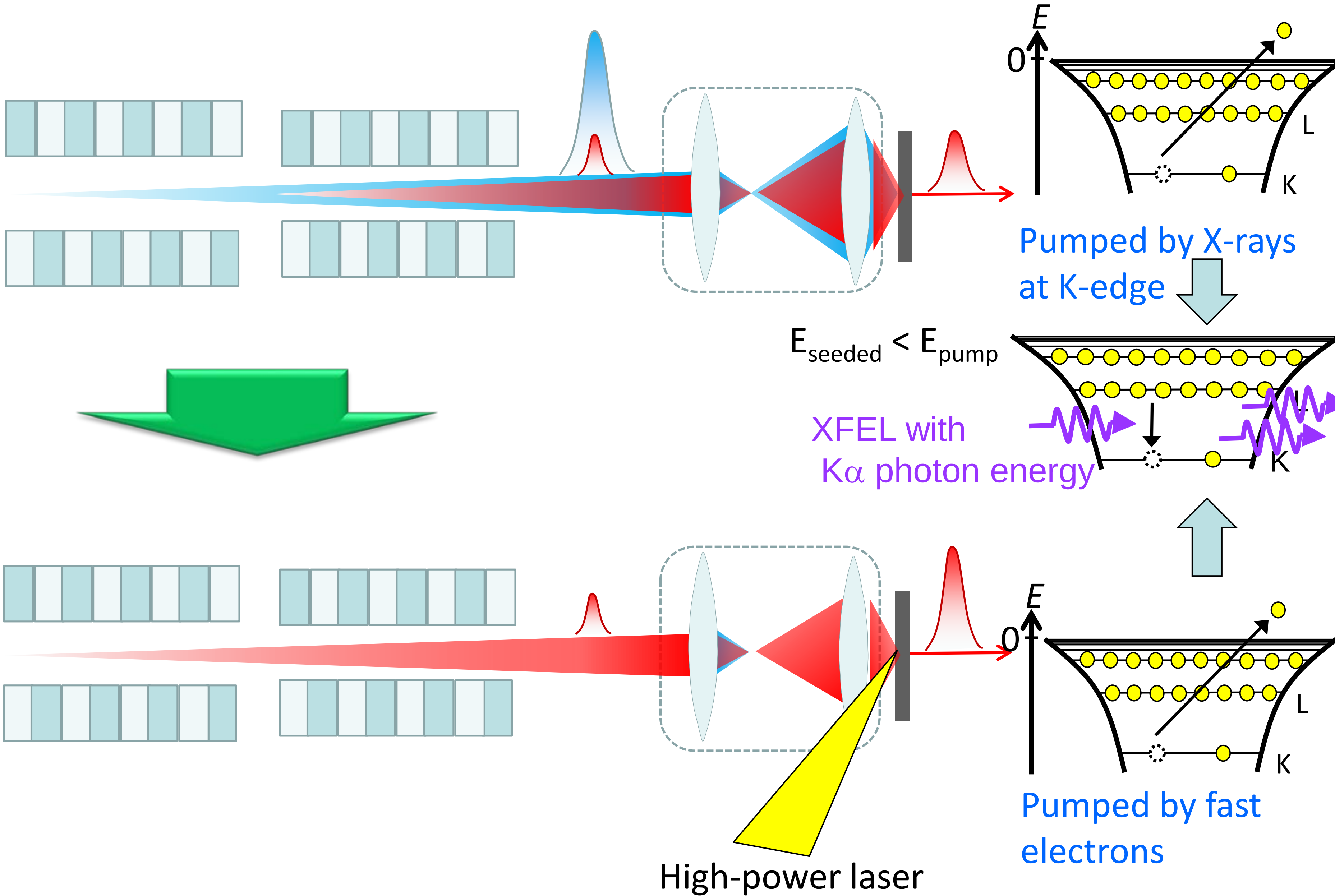
Yoneda *et al.*, *Nature*







Challenge for increasing XFEL pulse energy



Experimental setup

Inubushi et al., submitted

XFEL

Photon energy : 8.05 keV

Pulse energy : Max. 45 μJ

Duration : <10 fs

Focal spot : 10 μm

Ti:Sapphire laser (2 TW)

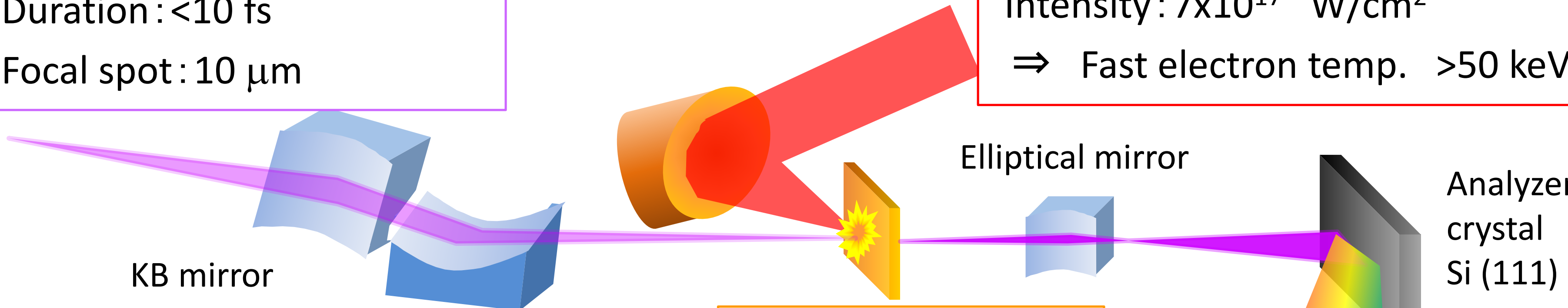
Pulse energy : 80 mJ

Duration : 50 fs

Focal spot : 10 μm

Intensity : 7×10^{17} W/cm^2

⇒ Fast electron temp. >50 keV

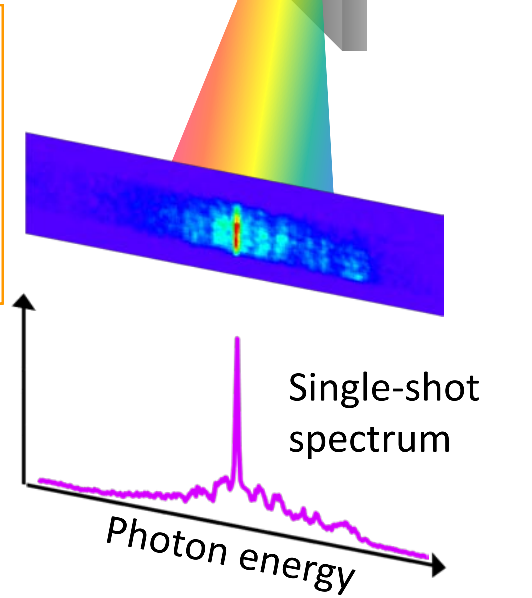


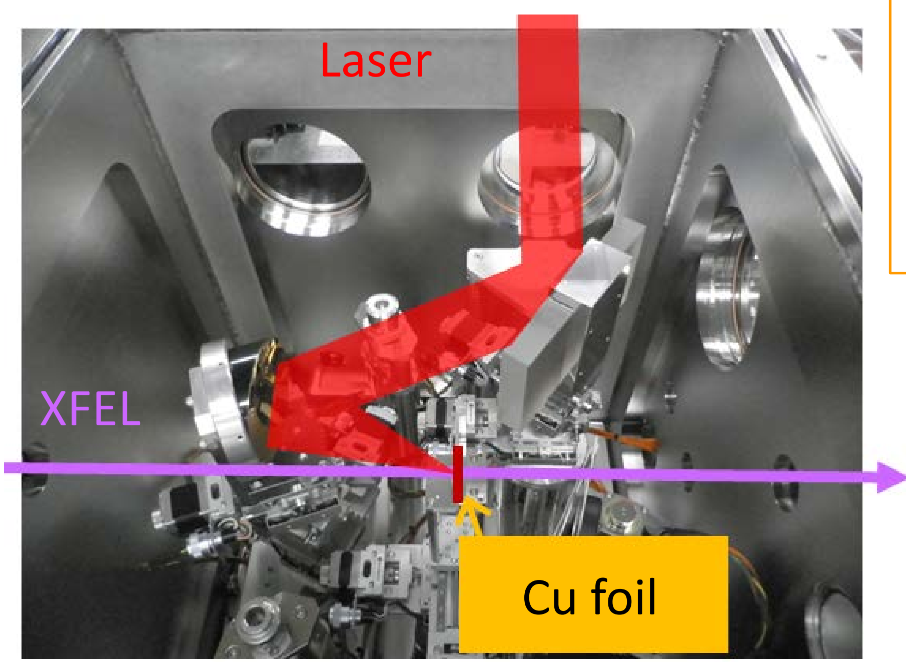
Cu foil

Thickness: 20 μm

K-edge : 8.98 keV

Cu-Ka : 8.05 keV

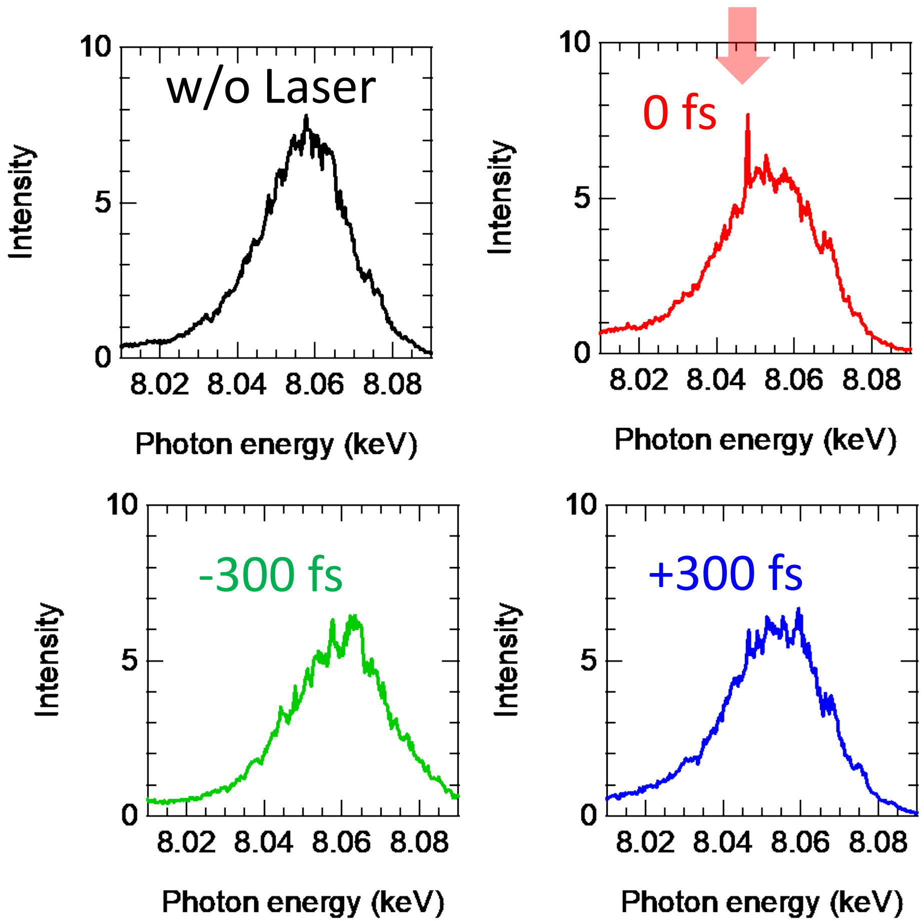




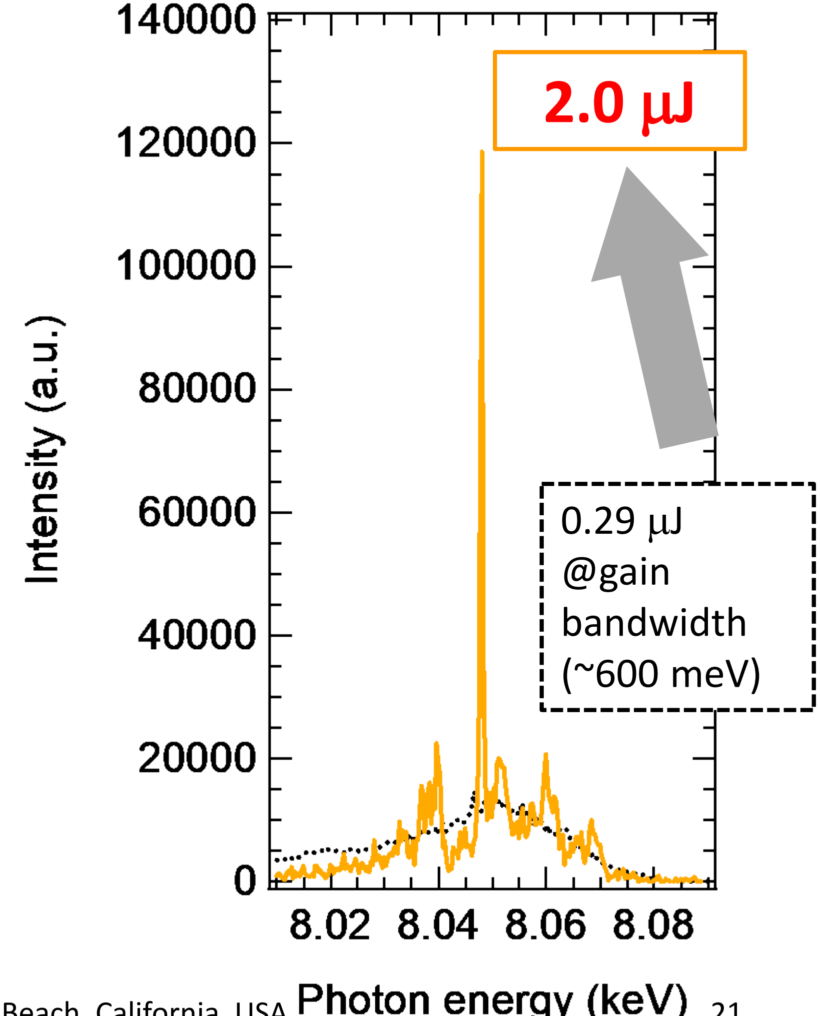
Results: Spectra of amplified pulses

Inubushi et al., submitted

150-shot averaged spectra



Single-shot spectrum



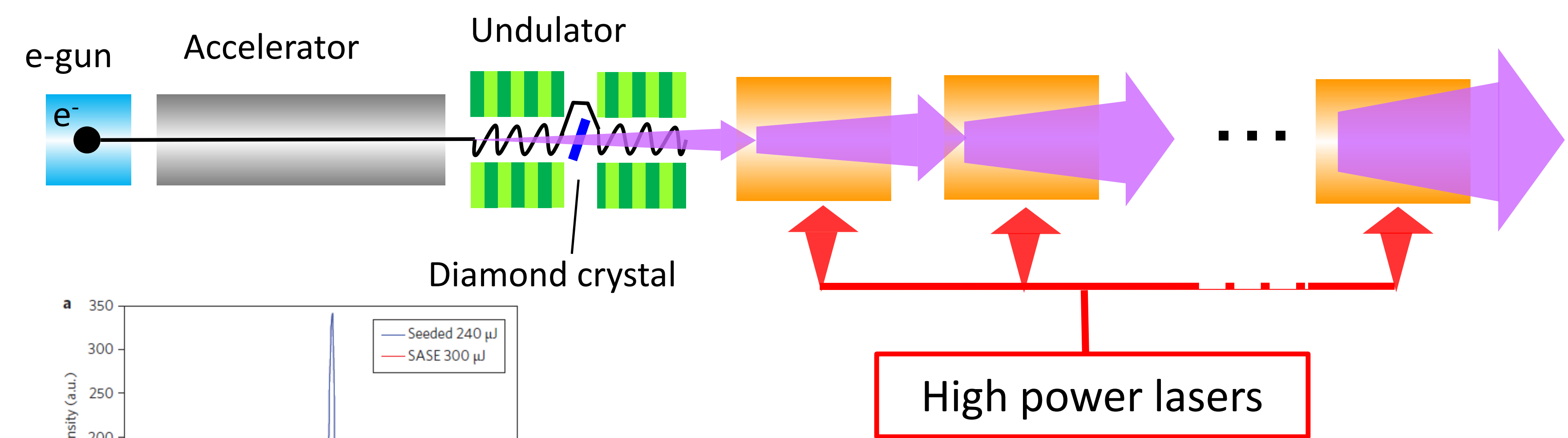
Hit rate of amplification: ~15%

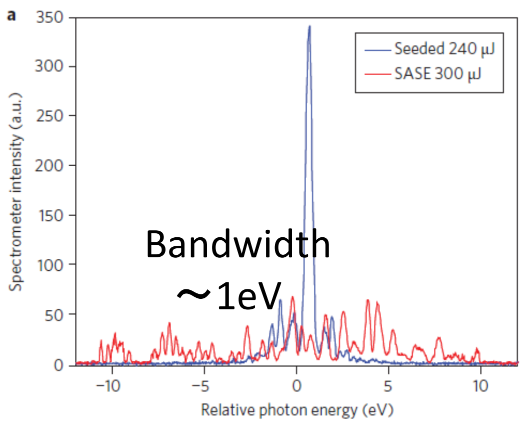
⇒ Timing jitter and fluctuation of XFEL

Multi-stage amplification: X-ray laser beyond TW level

Inubushi et al., submitted

Self-seeded XFEL ***Multi-stage amplifier***



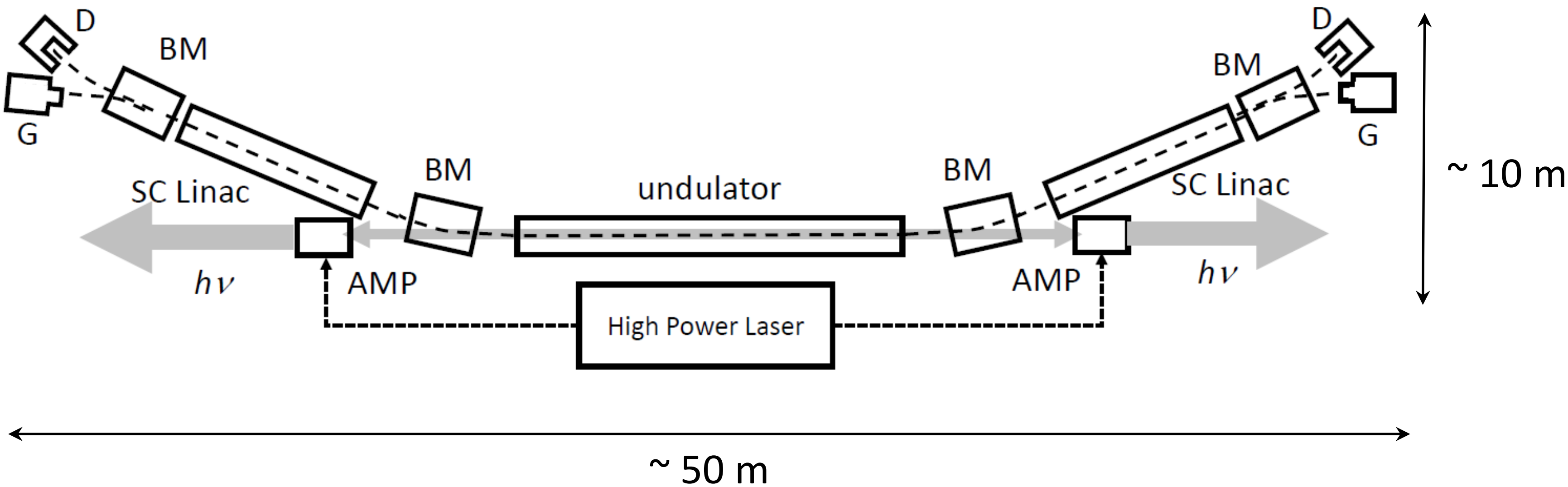


J. Amann *et al.*, *Nature Photonics* **6**, 693 (2012)

XFEL + High-Power Laser

New-generation, ultraintense X-ray laser

Bilinear Accelerator for ERL-EUV-FEL



Photon Wavelength	13.5 nm
Linac Energy	280 MeV
Repetition	10 MHz ~ 100 MHz
Pulse Energy	0.1 μJ (5th harmonics)
Undulator Period	20 mm
Undulator K-value	1.5
Amplification	x 100 ~ x 1000

ERL-Ring design (e.g. KEK)

~ 4,000 m^2 area is needed for 1 EUV line.

This design

~ 500 m^2 area is needed for 2 EUV lines.

x16 space efficiency

Concluding Remarks

- Atomic laser achieved by using SACLA's two color operation, and laser-plasma amplification of XFEL pulse were introduced.
- Possible application of laser-plasma amplification is 13.5 nm high-power EUV source. A bilinear accelerator FEL for this purpose has been proposed.
- In the SPring-8 site, there are some light sources which can emit moderate intensity 13.5 nm light (New-SUBARU SR and SCSS+ EUV-FEL).

Acknowledgement

All SACLA/SPring-8 Members (RSC, JASRI)

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Hidekazu Mimura

HERMES, high-power laser@SACLA

(Osaka U, RSC, JASRI, NIMS, Ehime U, Hiroshima U, Okayama U, Shimane U, Kobe U, JAEA, TOSHIBA/JST)

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UEC

Hitoki Yoneda

Thank you for your attention