Temporal diagnostics of femtosecond e-bunches via X-ray intensity interferometry

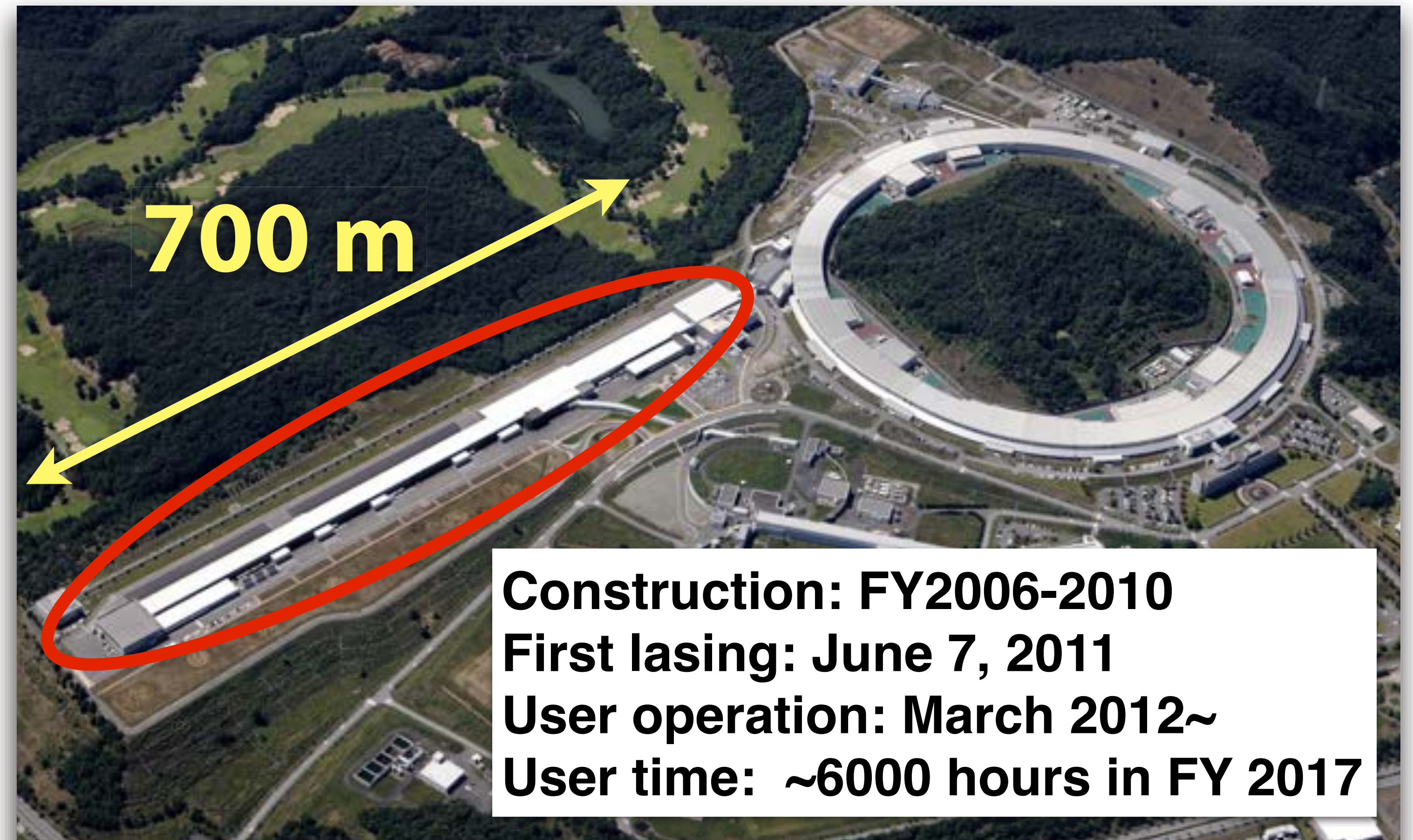
“Simple & cost effective way to measure attosecond/femtosecond e-bunch duration”

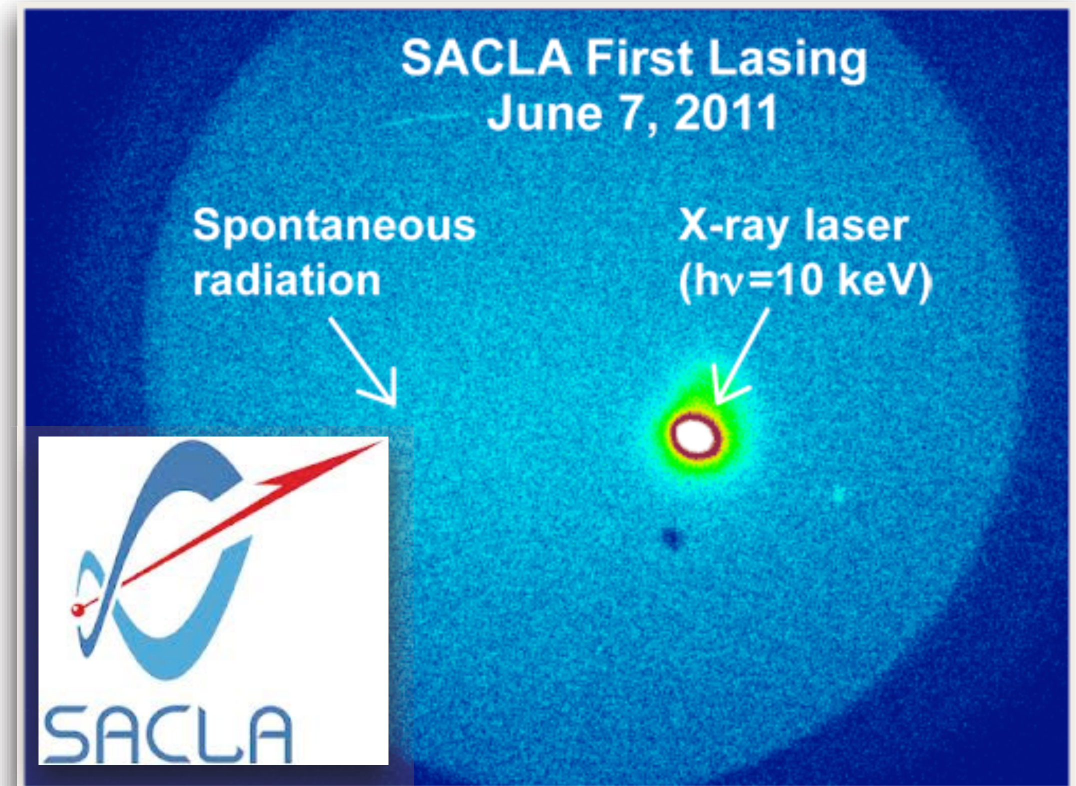
<u>Ichiro Inoue</u>, Toru Hara, Yuichi Inubushi, Hitoshi Tanaka, and Makina Yabashi

RIKEN SPring-8 Center / SACLA

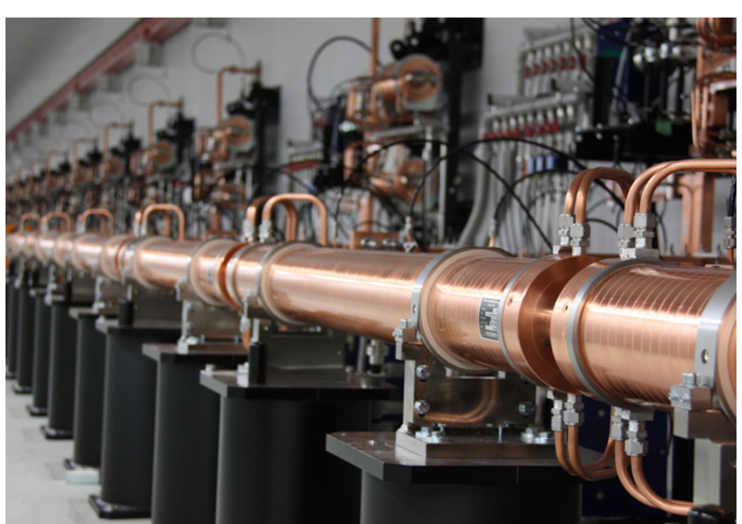
SPring-8 Angstrom Compact free-electron LAser

"SACLA"





High gradient C-band accelerator
(acceleration gradient: 35 MV/m)

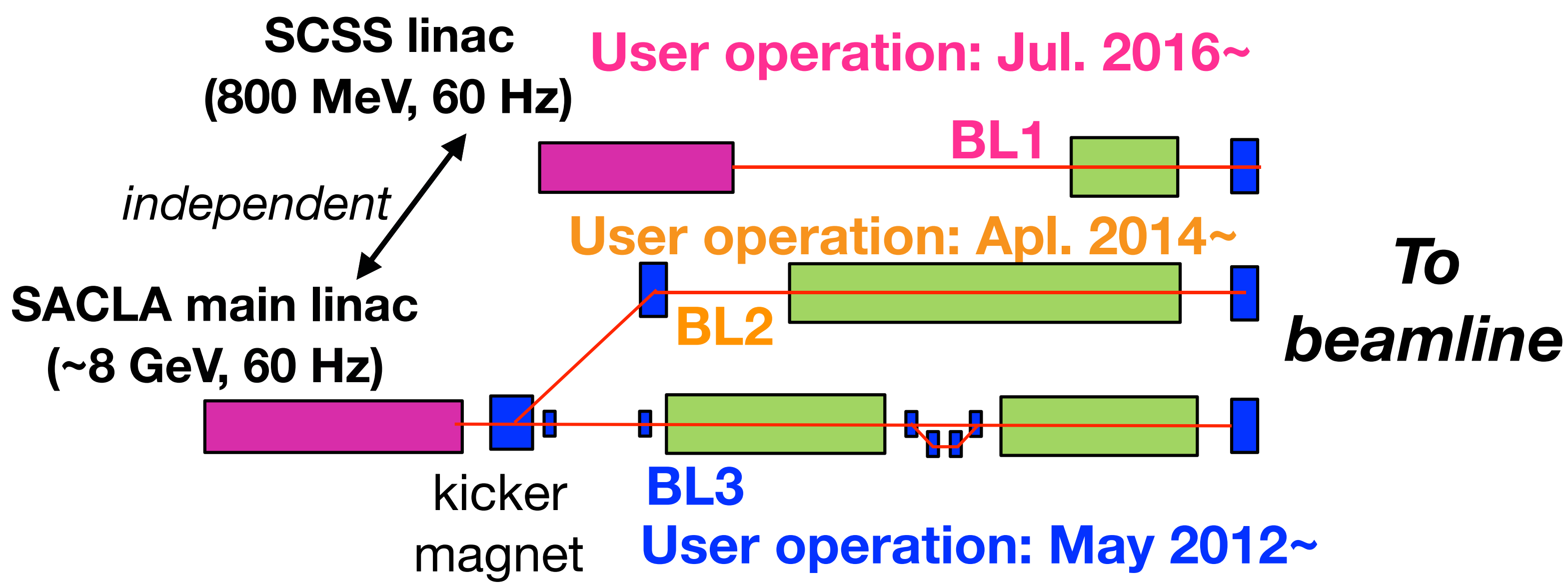


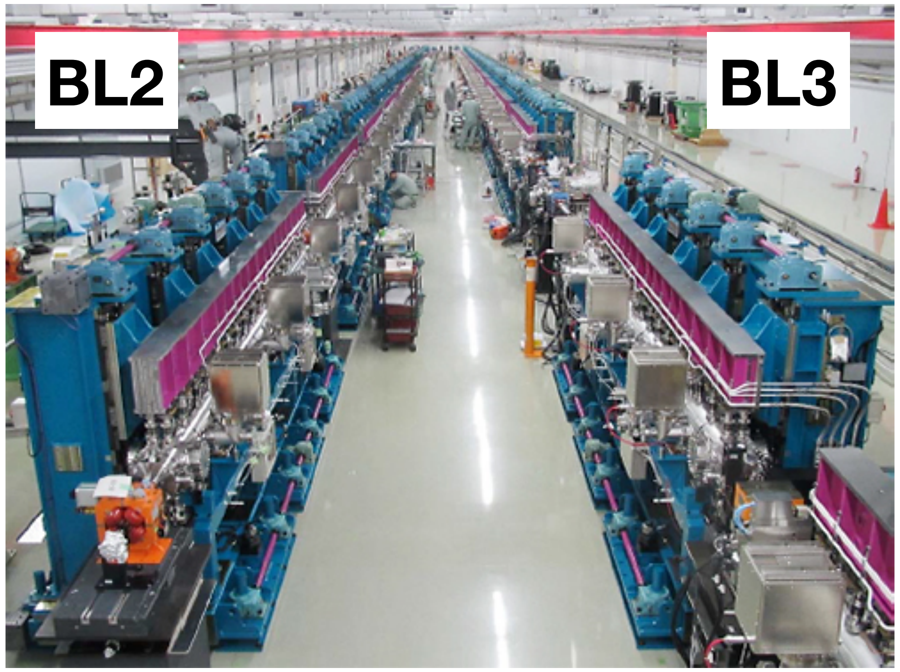
In-vacuum short period
undulator (λ_u=18 mm)

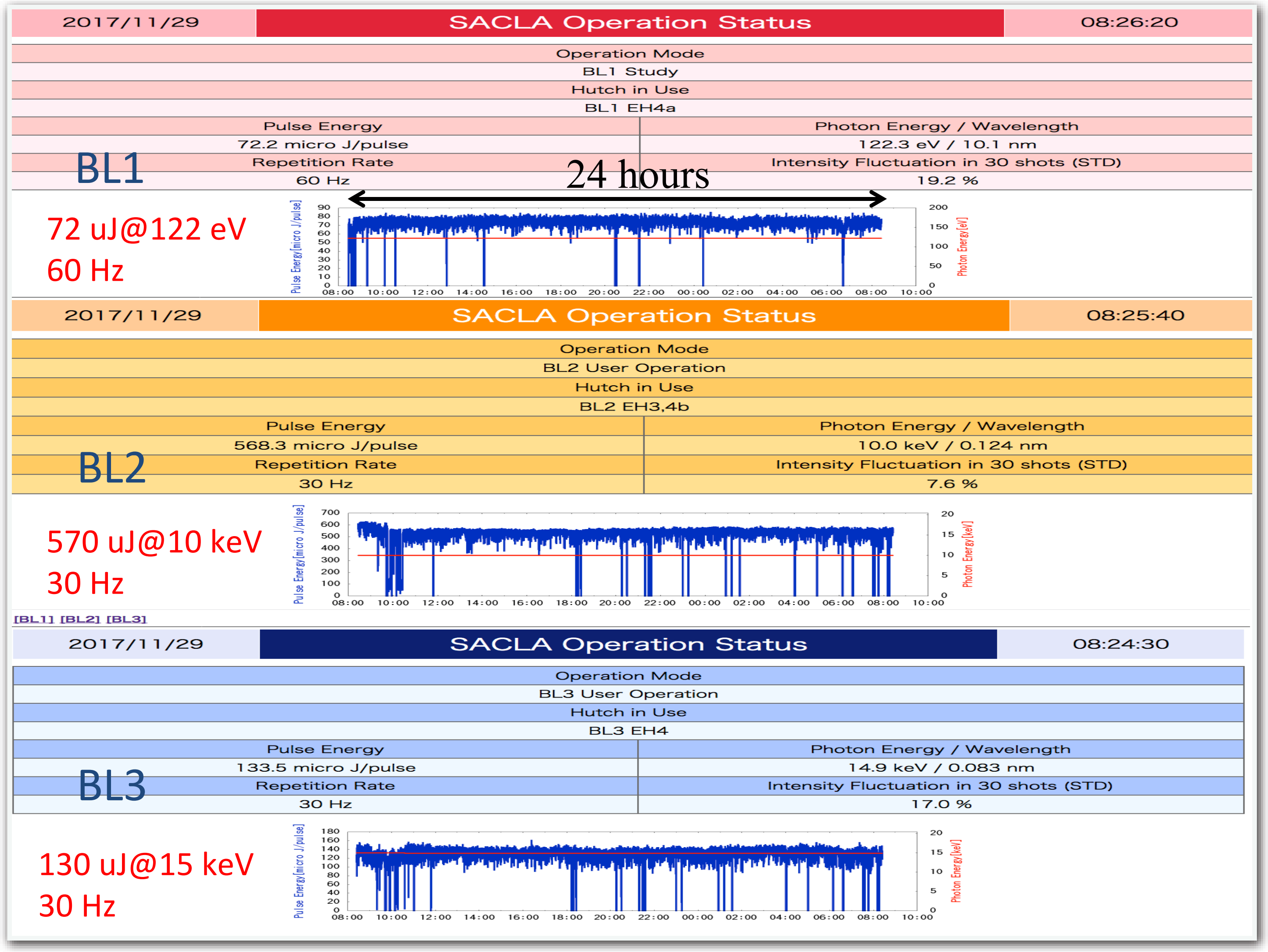
XFEL amplification can be achieved at a relatively short distance (~700 m)

Current layout of SACLA

Accelerator & undulator



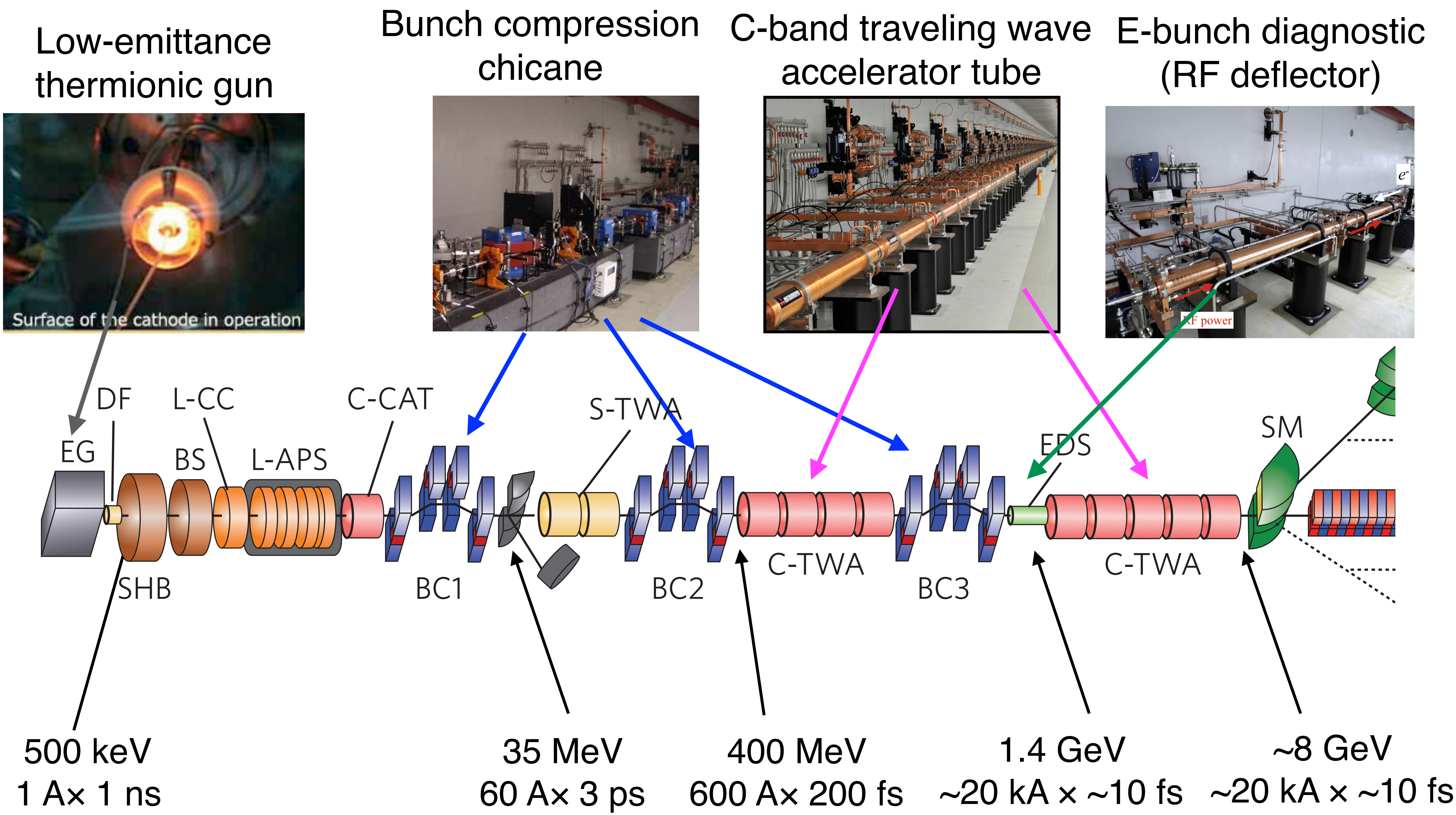




of undulators

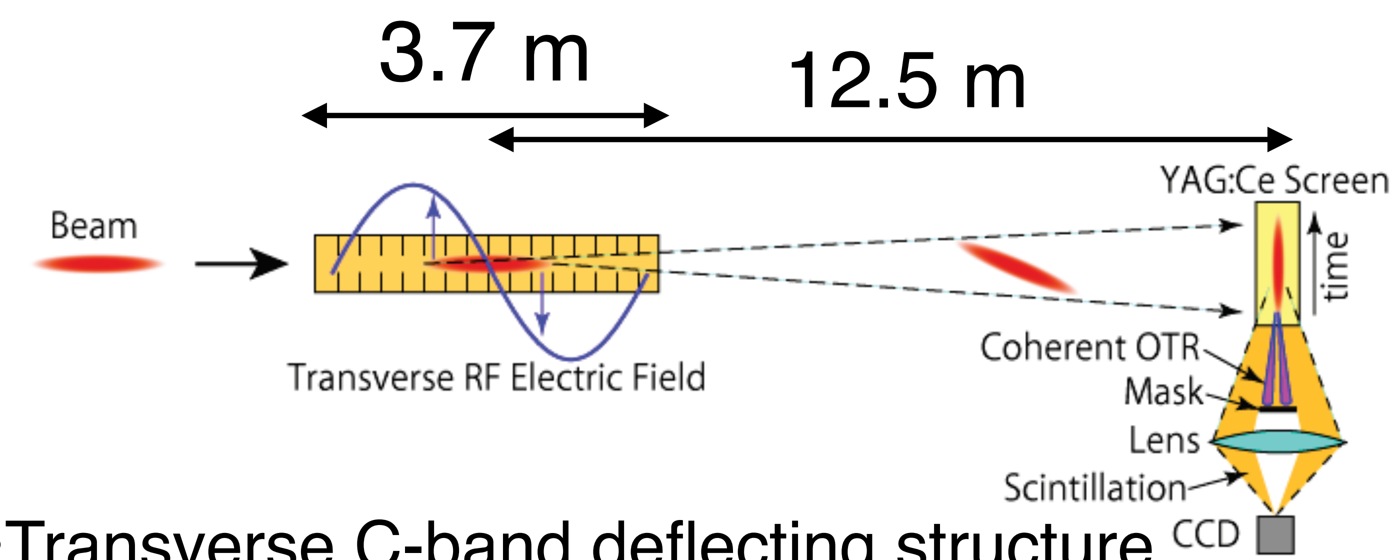
BL1: und. × 3
BL2: und. × 18
BL3: und. × 8 + und. × 13

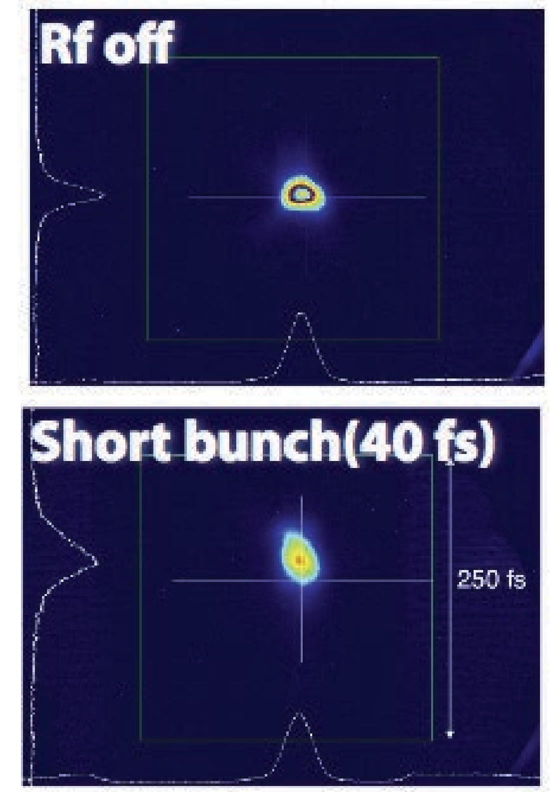
Configuration of SACLA accelerator



T. Ishikawa *et al.*, Nat. Photon. (2012).

Longitudinal diagnostic by RF deflector



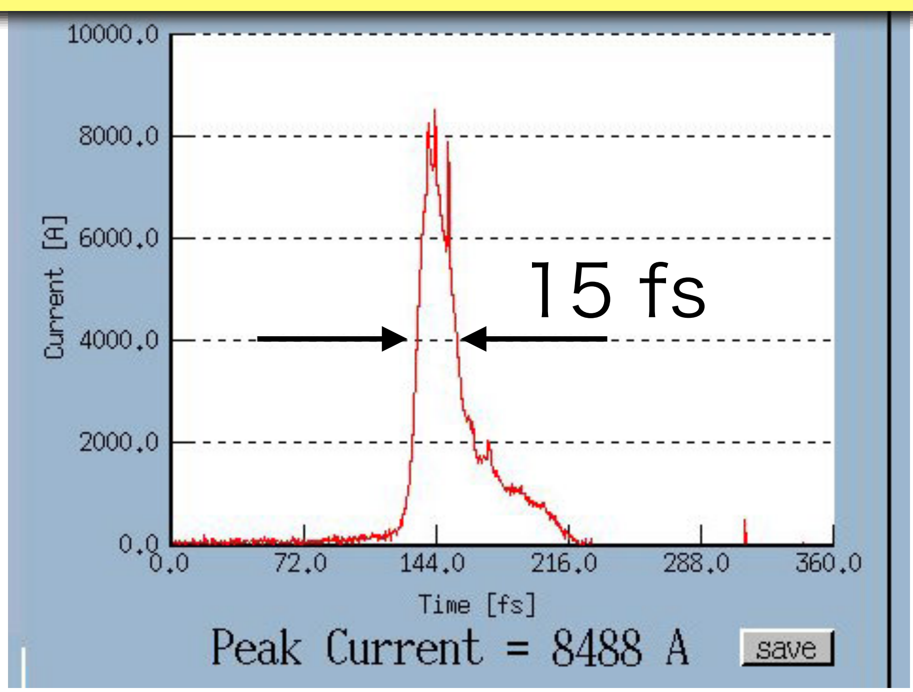


- Transverse C-band deflecting structure
- Deflecting voltage: ~60 MV
- Time resolution: 10-20 fs

  ←mainly determined by the projection size of e-beam

H. Ego *et al.*, *NIMA* **795**, 381 (2015).

Typical temporal profile of e-bunch measured by RF deflector

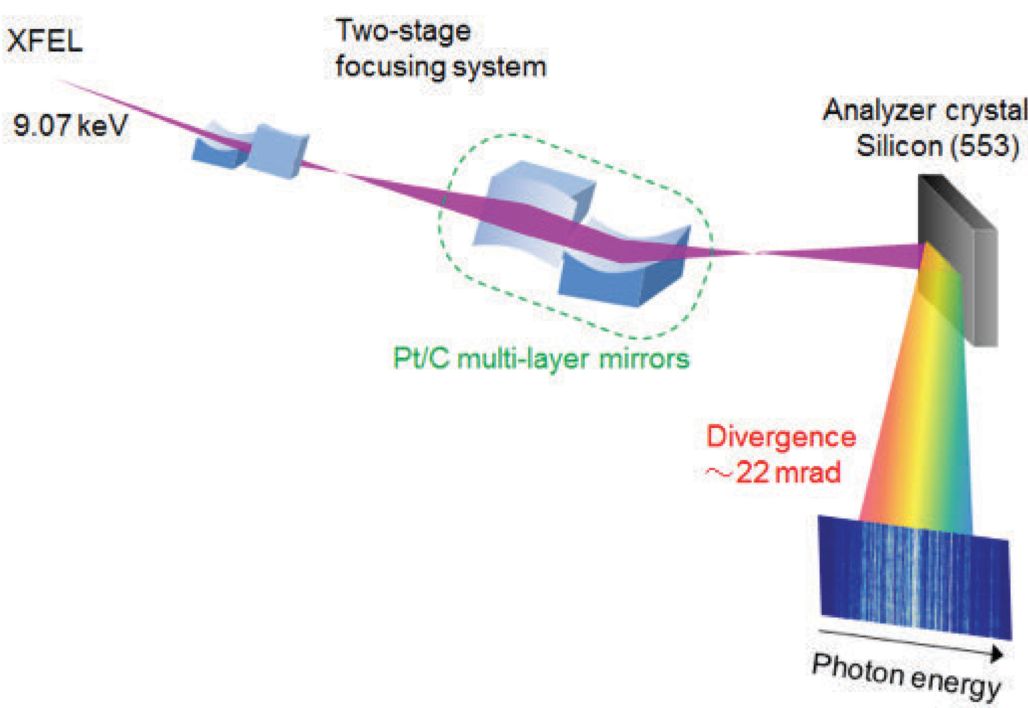


- Measured e-bunch duration is comparable to the time resolution of the deflector

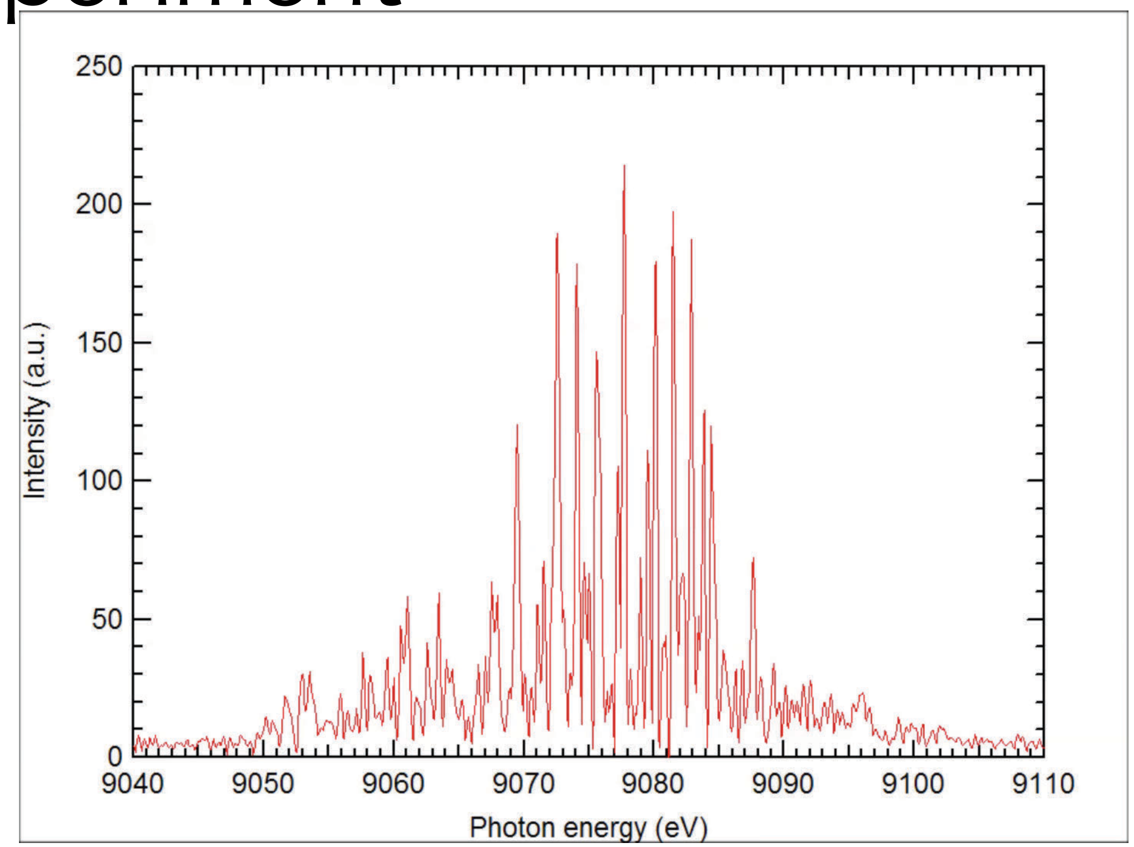
  →E-bunch duration is less than 15 fs

Measurement of XFEL duration @SACLA

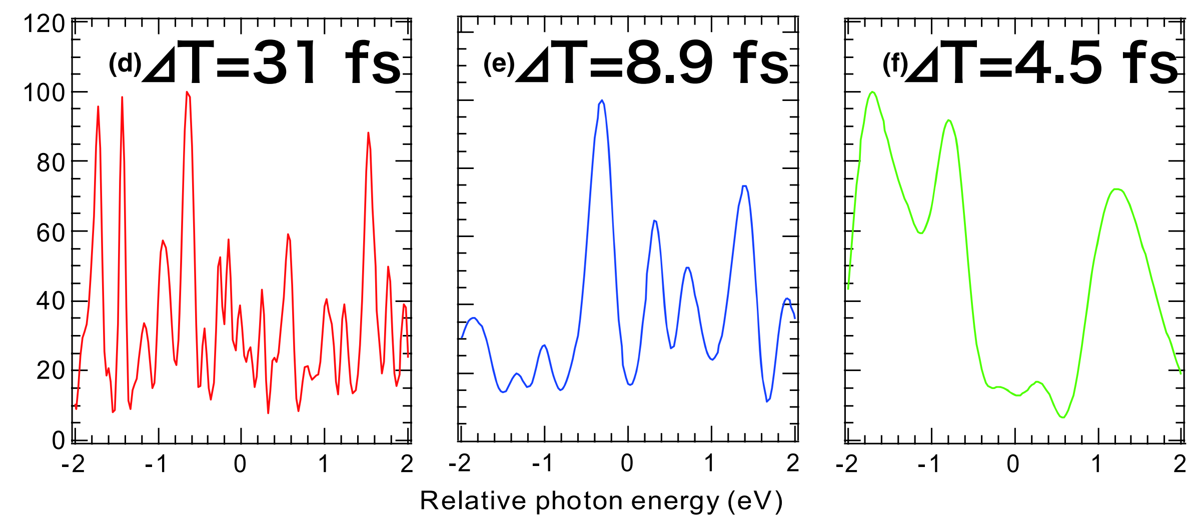
Single-shot spectrum + FEL simulation



Experiment



Simulation

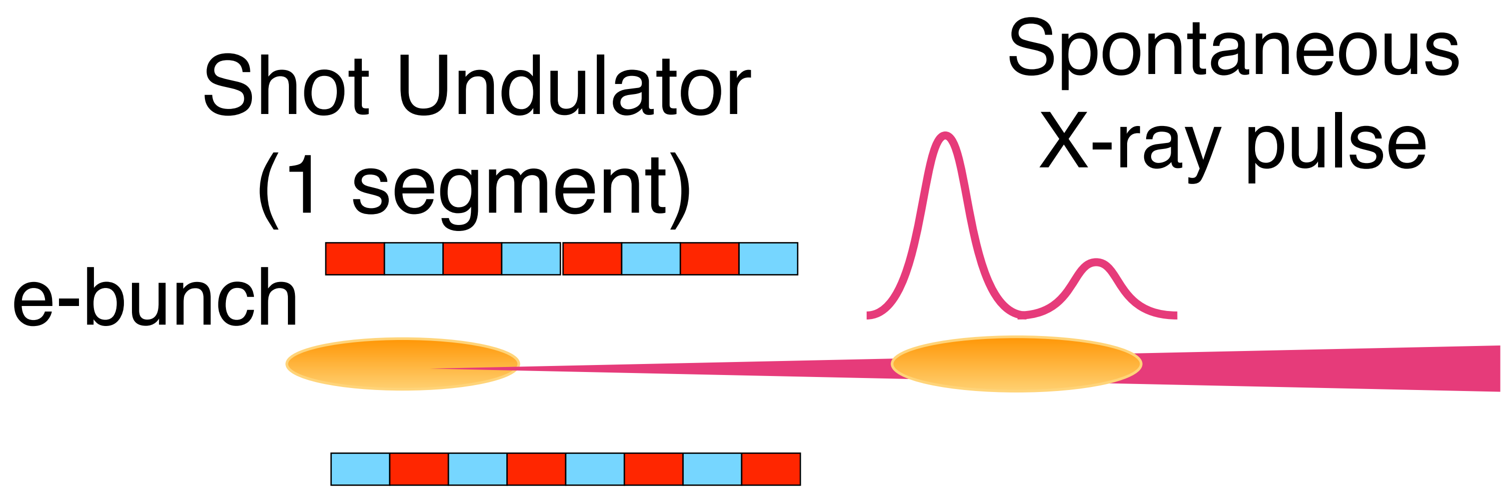


X-ray pulse duration@SACLA:
6-8 fs (FWHM)

E-bunch duration should be comparable or less than 10 fs

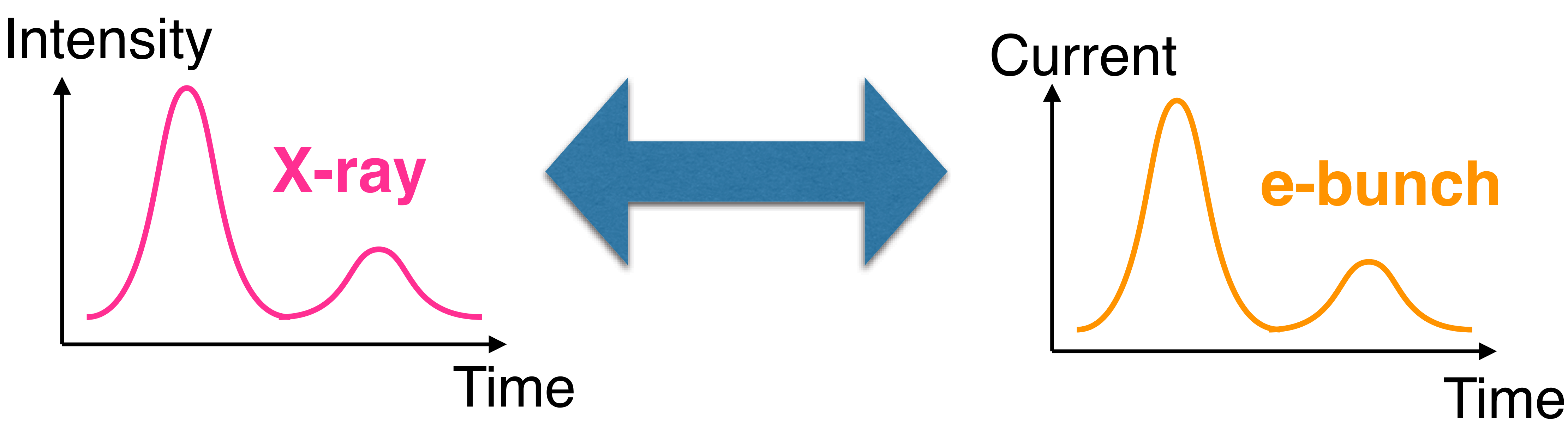
Inubushi, *PRL* (2012).
Inubushi, Inoue, *Appl. Sci.* (2017).

How to improve the resolution of longitudinal diagnostics ?



Temporal profile of the X-ray pulse

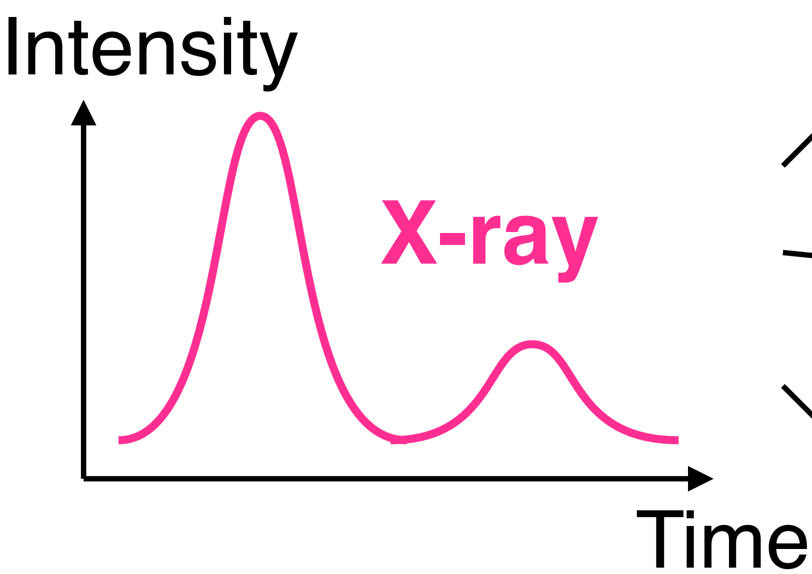
Current profile of the e-bunch



Shapes are almost identical

(slippage of e-beam is negligibly small: ~ a few tens of attoseconds)

Temporal diagnostic of X-ray beam



High speed camera

Photron

Max. frame rate:
~10^6 frame/s
(~1 μs/frame)

https://www.photron.co.jp/

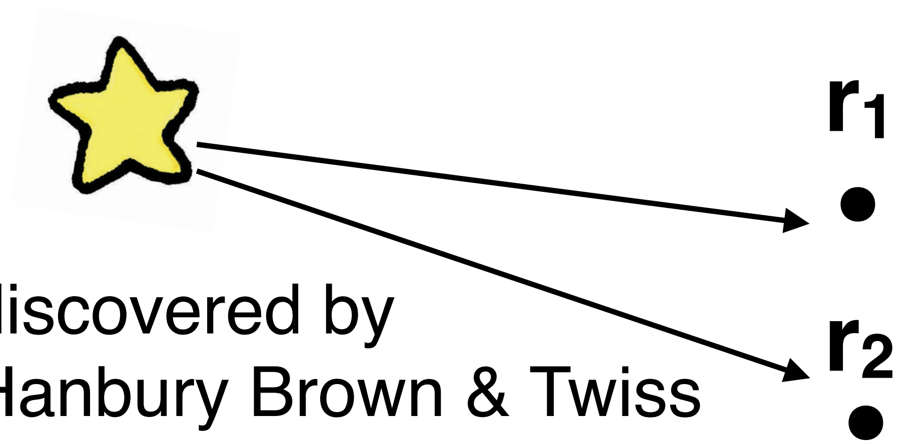
HAMAMATSU
PHOTON IS OUR BUSINESS

Max. time resolution:
500 fs

https://www.hamamatsu.com/

Intensity interferometry of
spontaneous X-rays from e-bunch

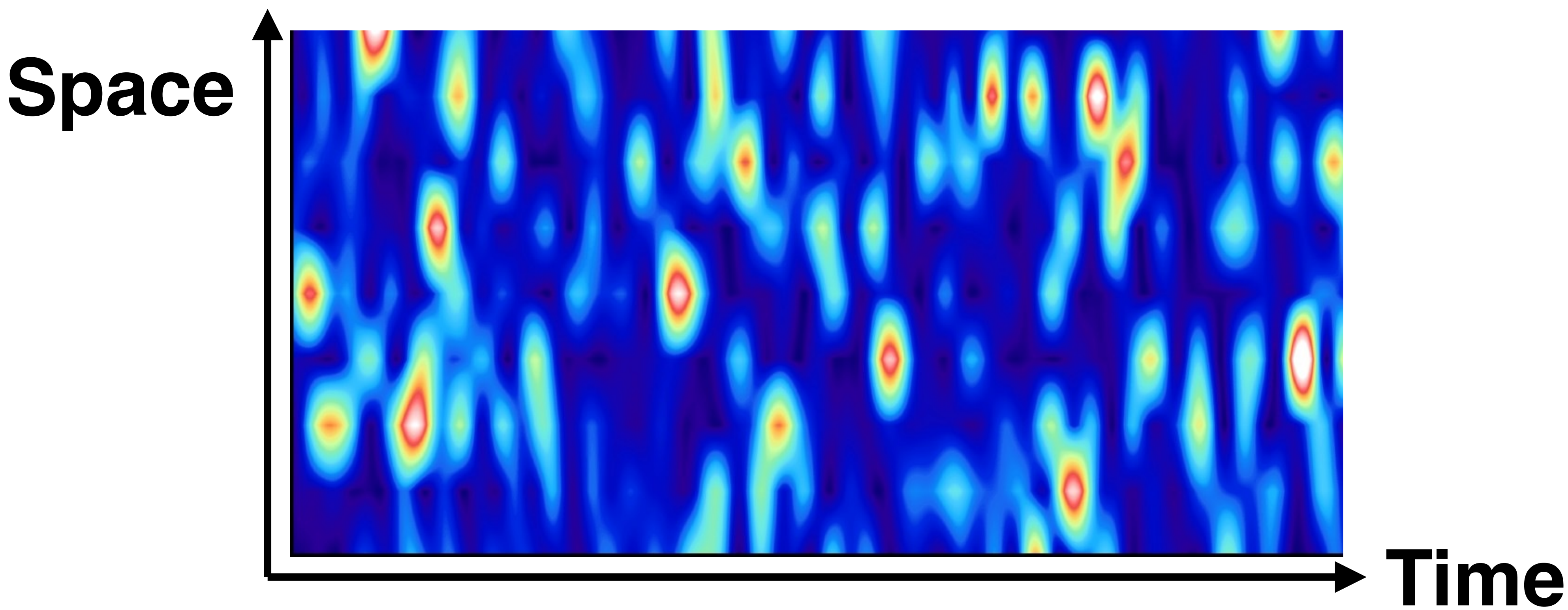
Intensity interference of chaotic light



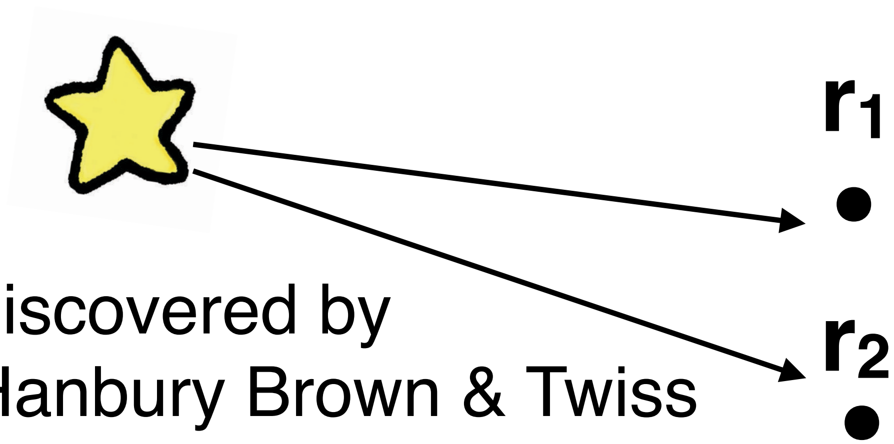
discovered by
Hanbury Brown & Twiss
in the mid 1950's

Intensities of chaotic light
within spatial and temporal coherence
lengths are correlated

"photons in chaotic light tend to be bunched"



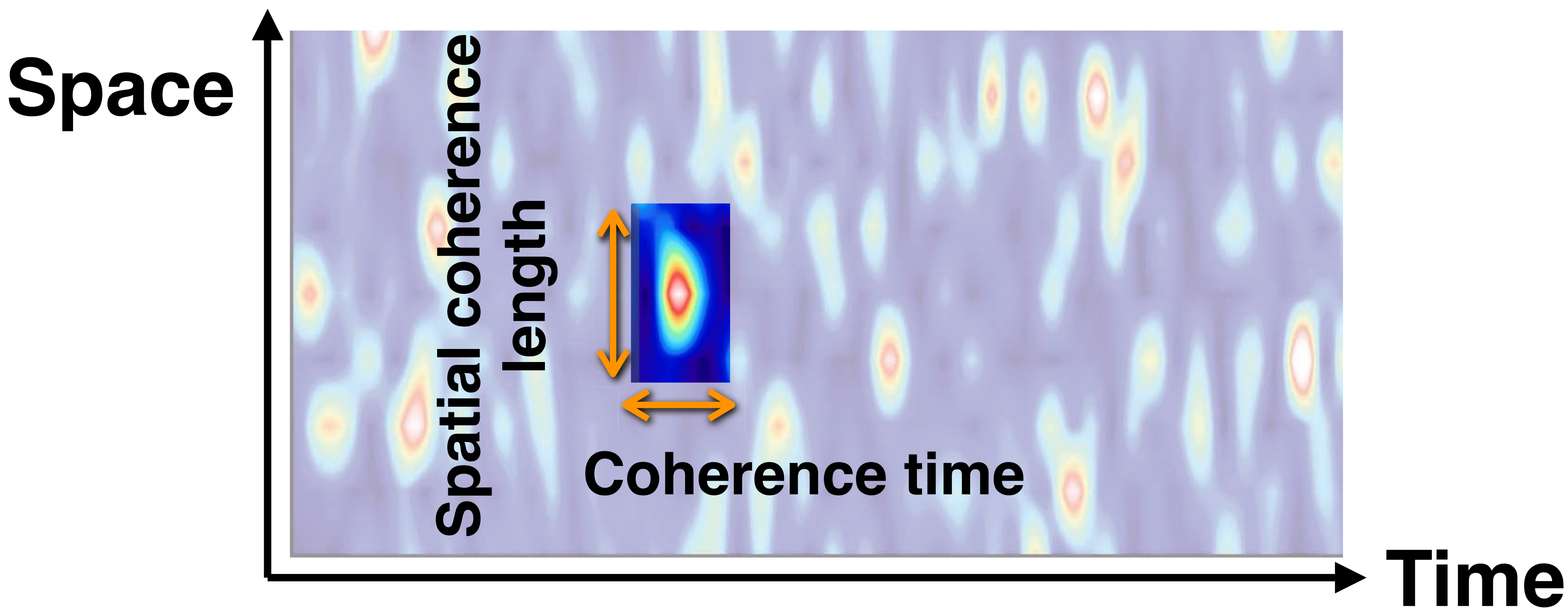
Intensity interference of chaotic light



discovered by
Hanbury Brown & Twiss
in the mid 1950's

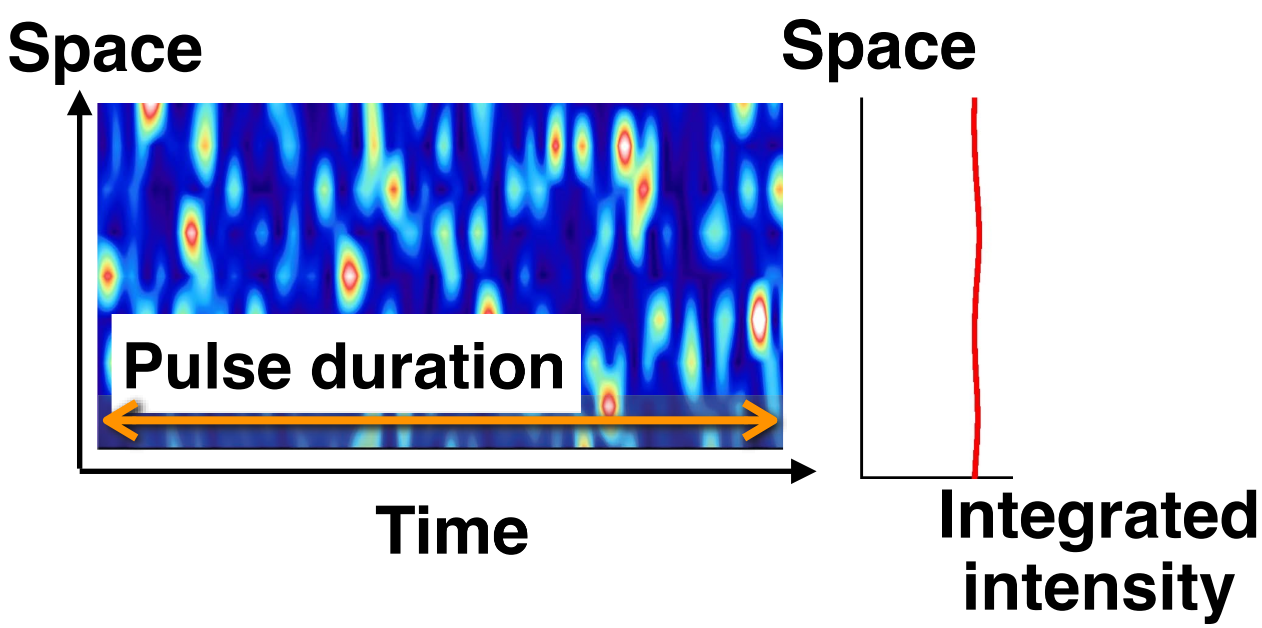
Intensities of chaotic light
within spatial and temporal coherence lengths are correlated

"photons in chaotic light tend to be bunched"



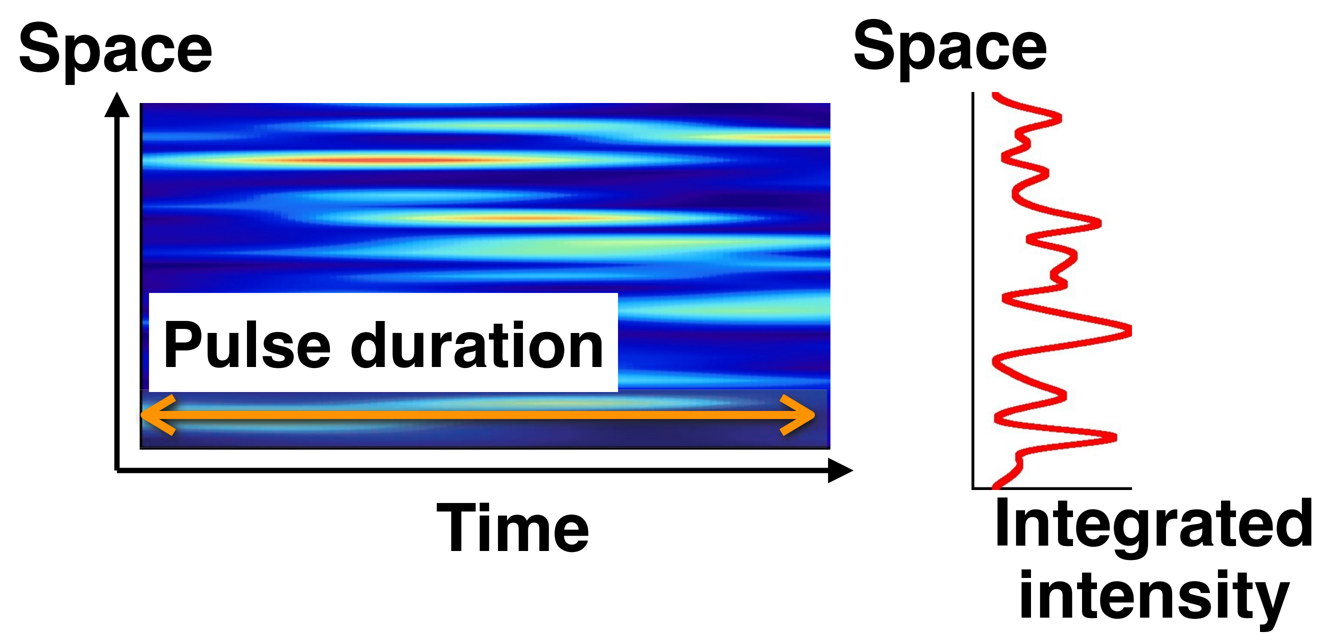
Time-integrated intensity interference in pulsed light

pulse duration > coherence time



No correlation of time-integrated intensities at separated positions

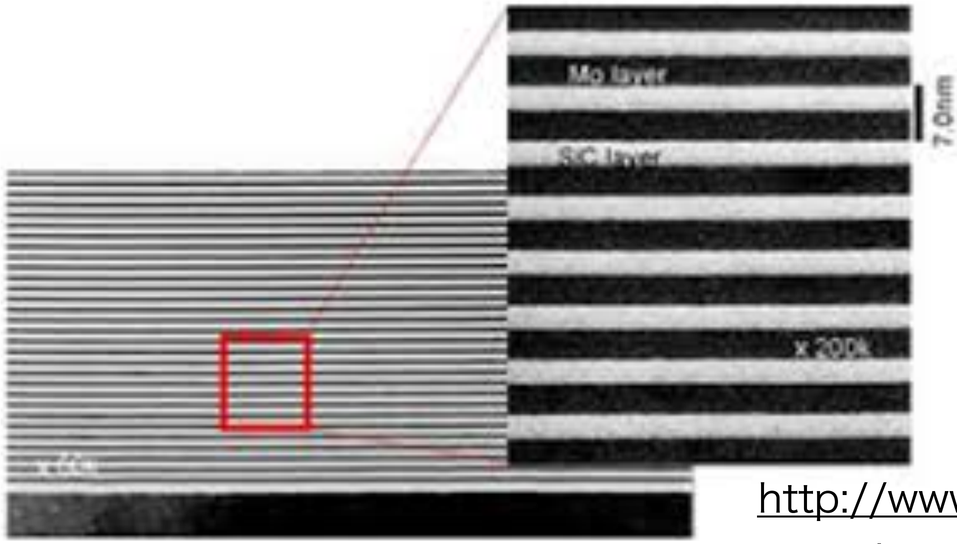
pulse duration $\simeq$ coherence time



Strong correlation of time-integrated intensities within spatial coherence length

By changing the coherence time of the optical pulse and measuring the degree of time-integrated intensity interference, we can determine the temporal intensity profiles of optical pulses.

Coherence time achievable by X-ray optical devices



http://www.ntt-at.com/product/multilayer/

Multilayer

$\Delta E/E = 10^{-2}$ - 10^{-3}

Coherence time : 10-100 as

SAINT-GOBAIN

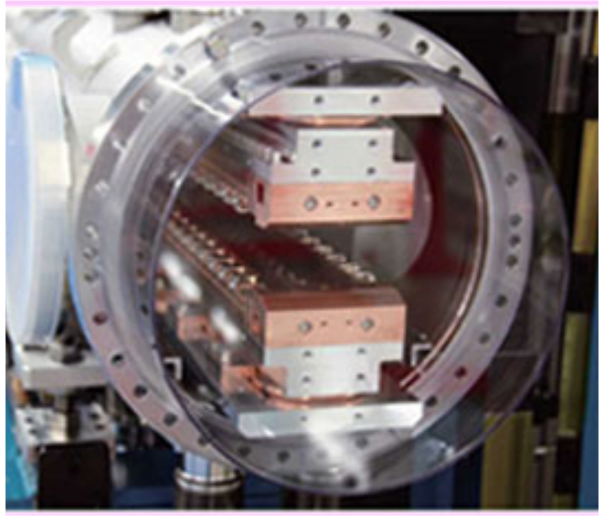
https://www.saint-gobain.co.jp/

Crystal monochromator

Si, Ge, SiO_2, InSb etc..

$\Delta E/E = 10^{-3}$-10^{-8}

Coherence time : 100 as-10 ps



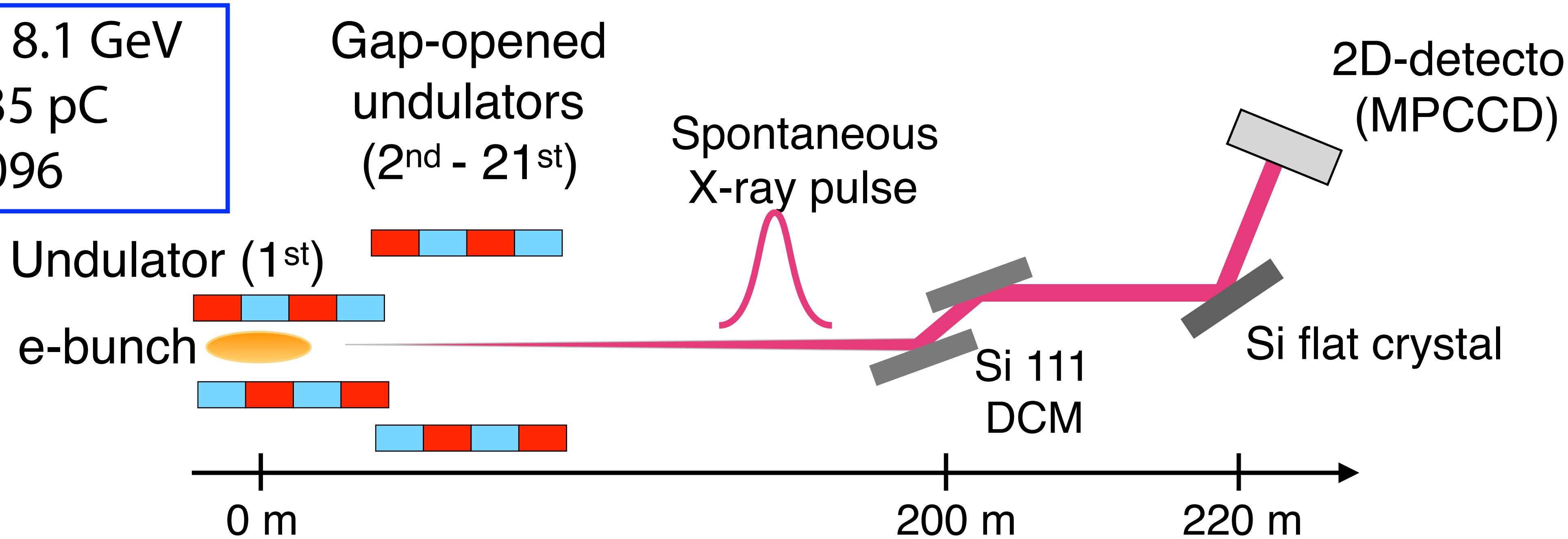
Undulator radiation itself

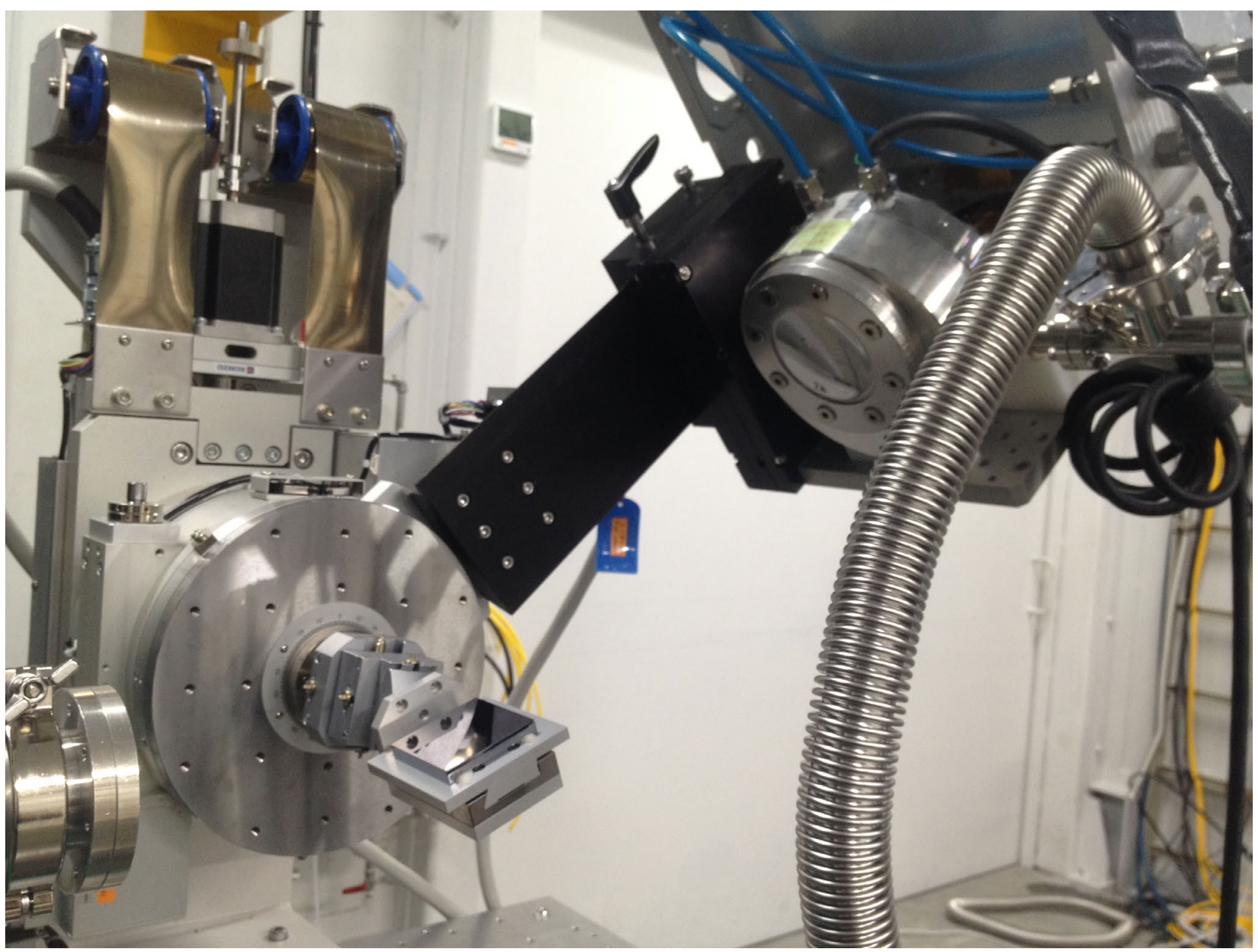
$\Delta E/E \sim 10^{-1}$-10^{-2}

Coherence time : 1 as-10 as

Intensity interferometry @SACLA BL3 (10.5 keV XFEL)

- e-beam energy: 8.1 GeV
- Total charge: 235 pC
- K parameter: 2.096





Reflective index	Coherence time
111	0.8 fs
220	1.3 fs
311	2.6 fs
440	7.7 fs
333	8.4 fs
444	14.8 fs
660	30.9 fs
555	46.4 fs

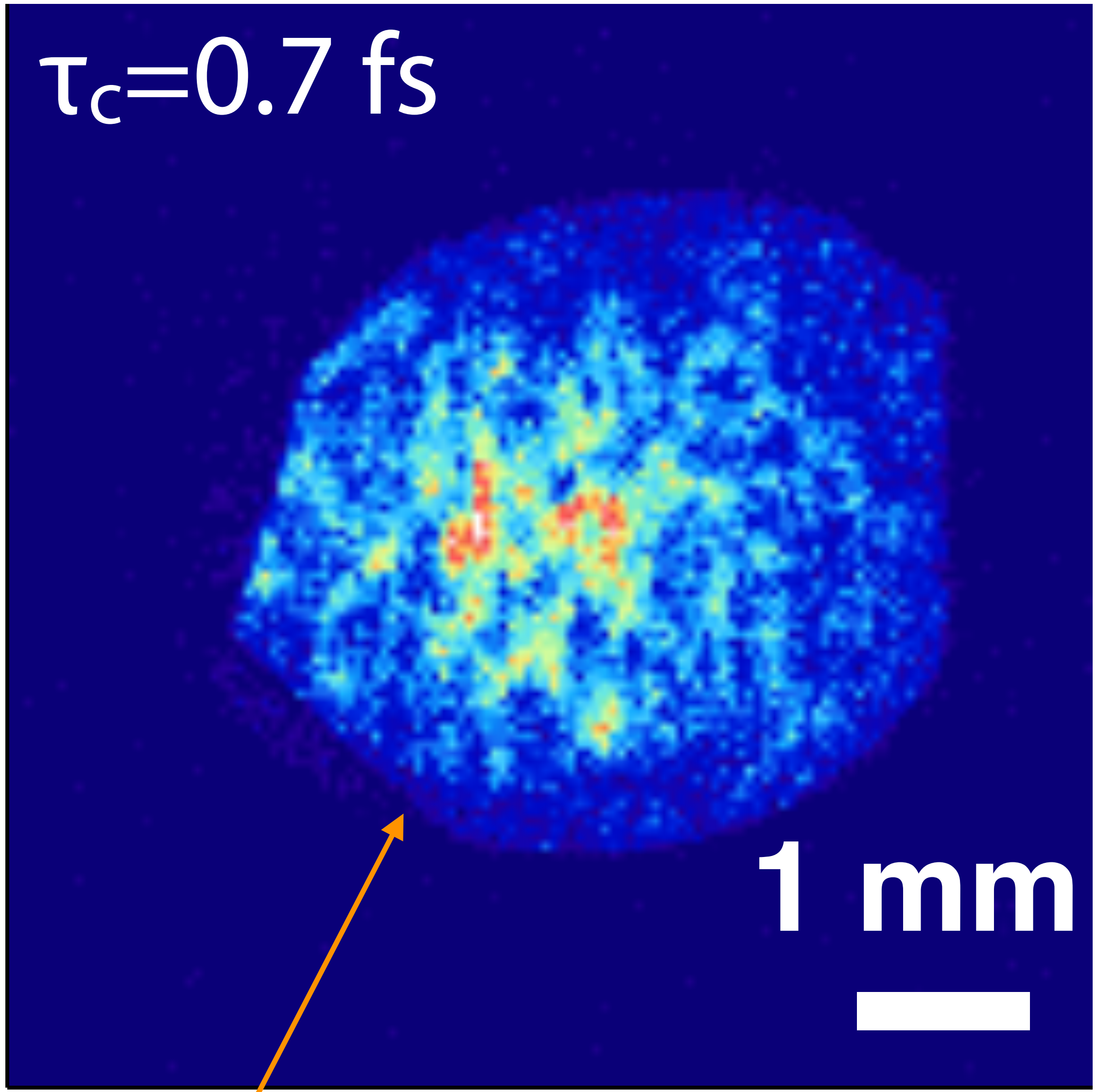
coherence time

$$\tau_c = 1/(2\sigma_\omega)$$

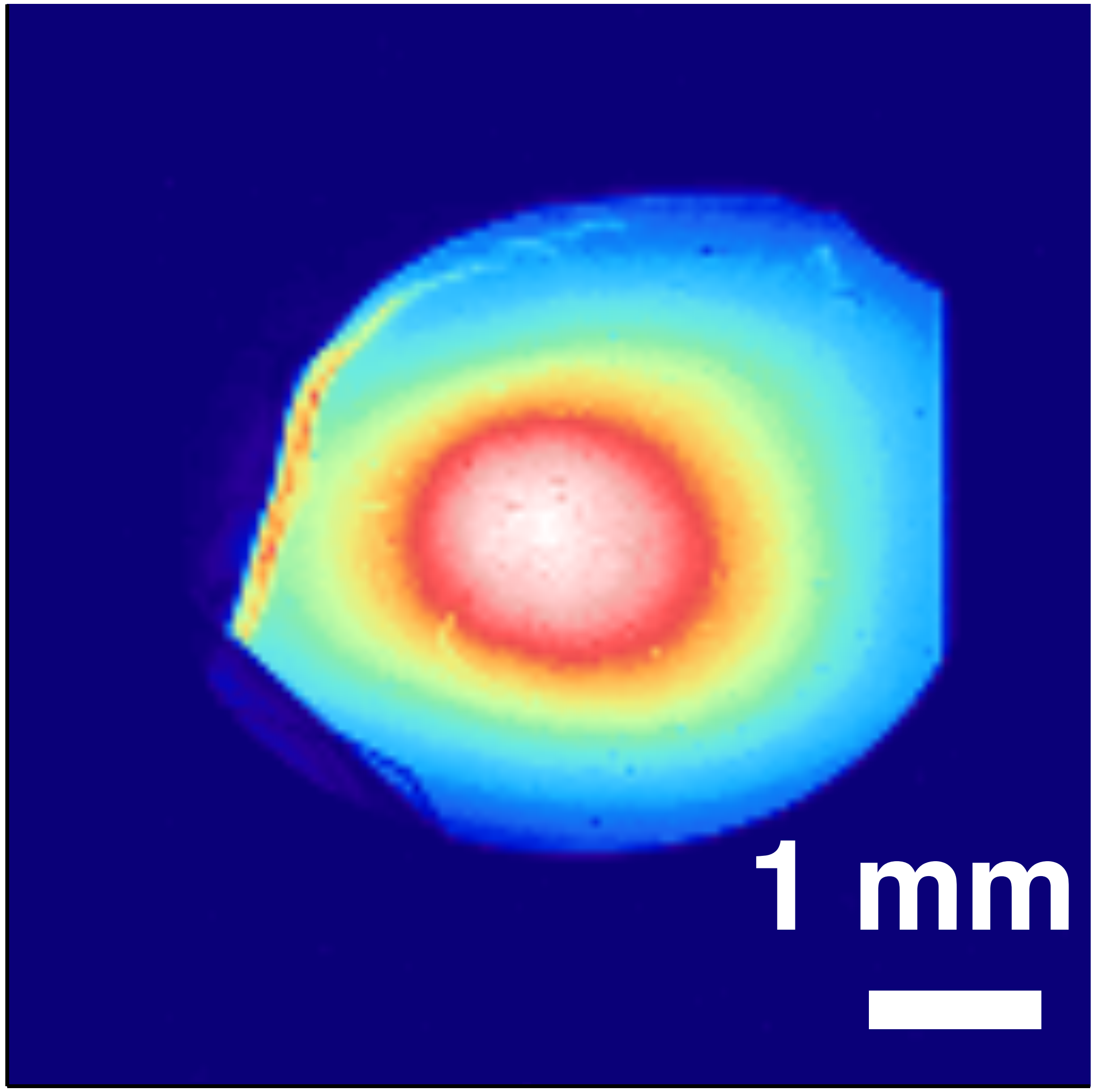
frequency spread
of X-ray beam
after monochromator

Single-shot image of spontaneous X-ray pulse

Spontaneous X-ray radiation monochromatized by Si 111 reflection



cf. Averaged image over multiple pulse



Some portions of the X-ray beam is cut due to the limited aperture of the beamline

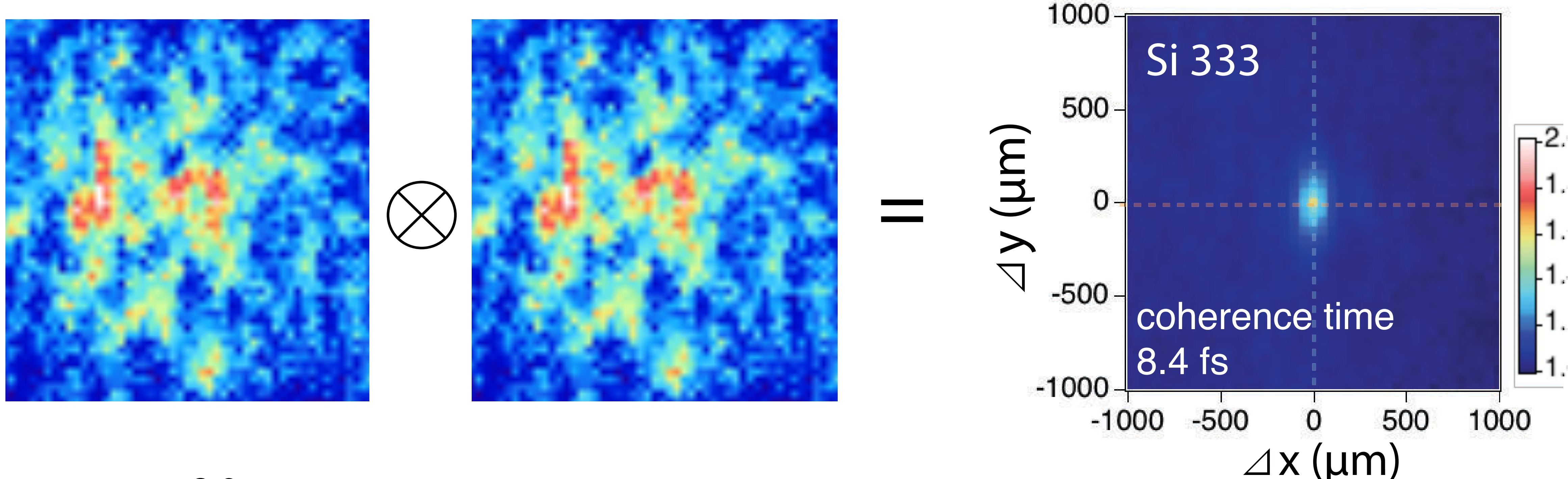
I. Inoue *et al.*, *PRAB* 21, 080704 (2018).

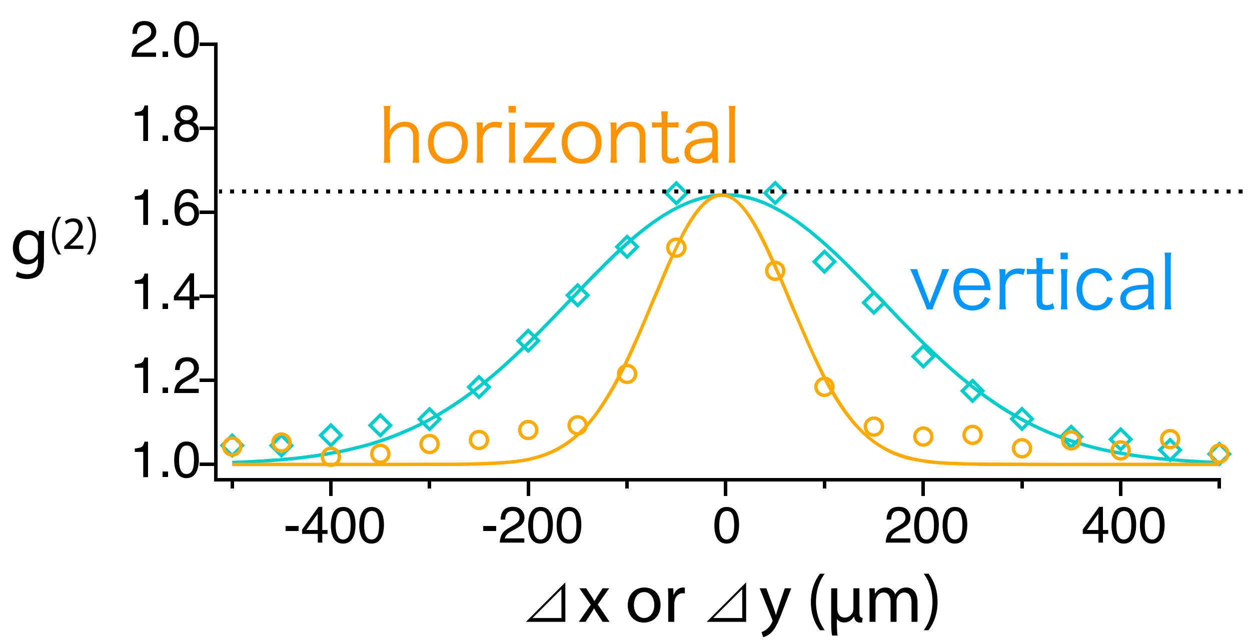
Quantitative analysis of intensity interference

Normalized intensity correlation functions (“2D autocorrelation”)

$$g^2 = \frac{\langle I^t(r_0) I^t(r_0 + \Delta r)\rangle}{\langle I^t(r_0)\rangle \langle I^t(r_0 + \Delta r)\rangle}$$

< >: average over different pulses

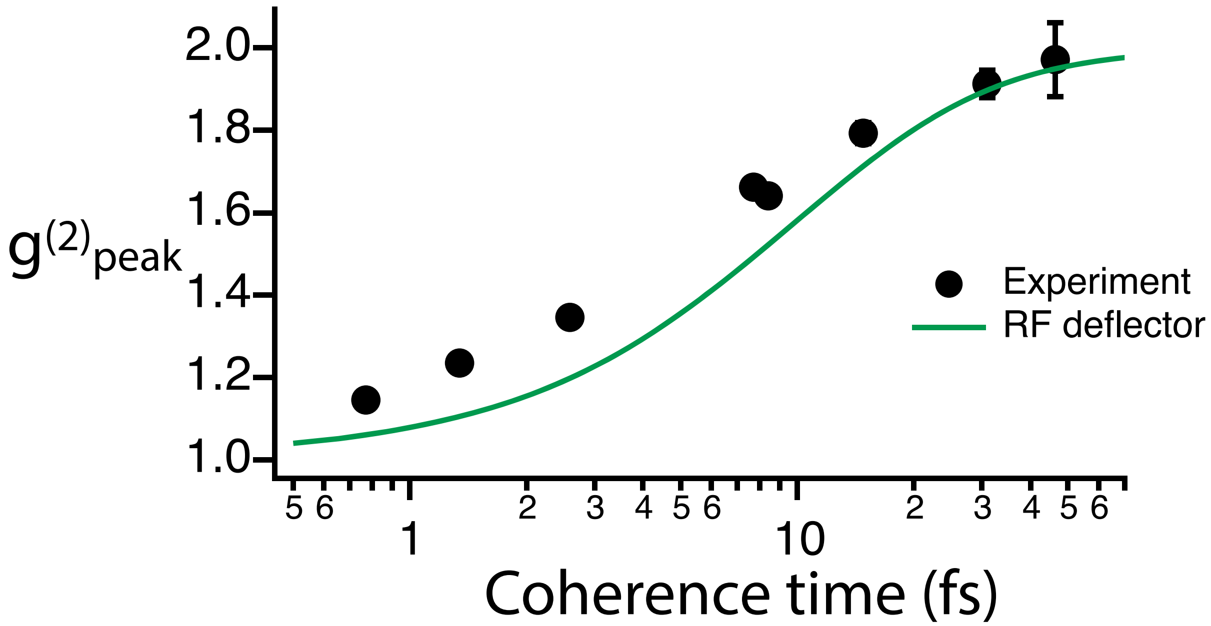


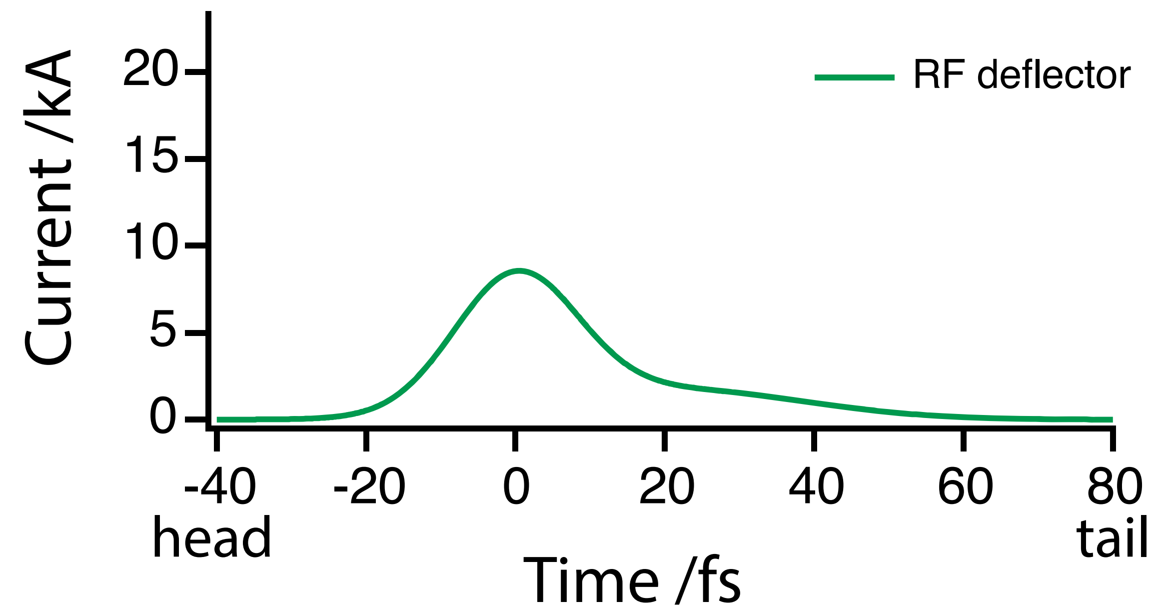


Width:
spatial coherence length

Peak value:
determined by magnitude relationship between coherence time and pulse duration

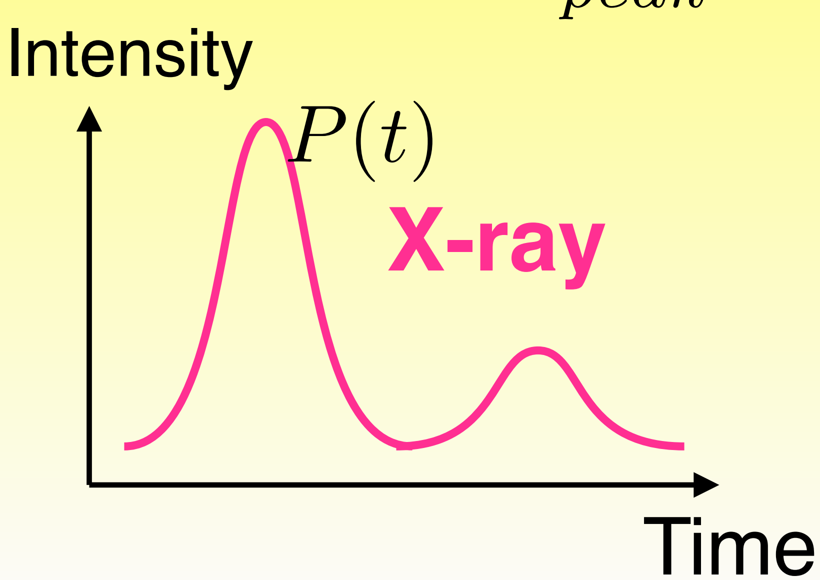
Determination of e-bunch profile by intensity interferometry





Relationship between g^2_{peak} and coherence time

$$g^{(2)}_{peak} = 1 + \int \Pi(\tau) \exp\left[-\left(\frac{\tau}{2\tau_c}\right)^2\right] d\tau$$



$$\Pi(\tau) = \int P(t)P(t+\tau)dt$$

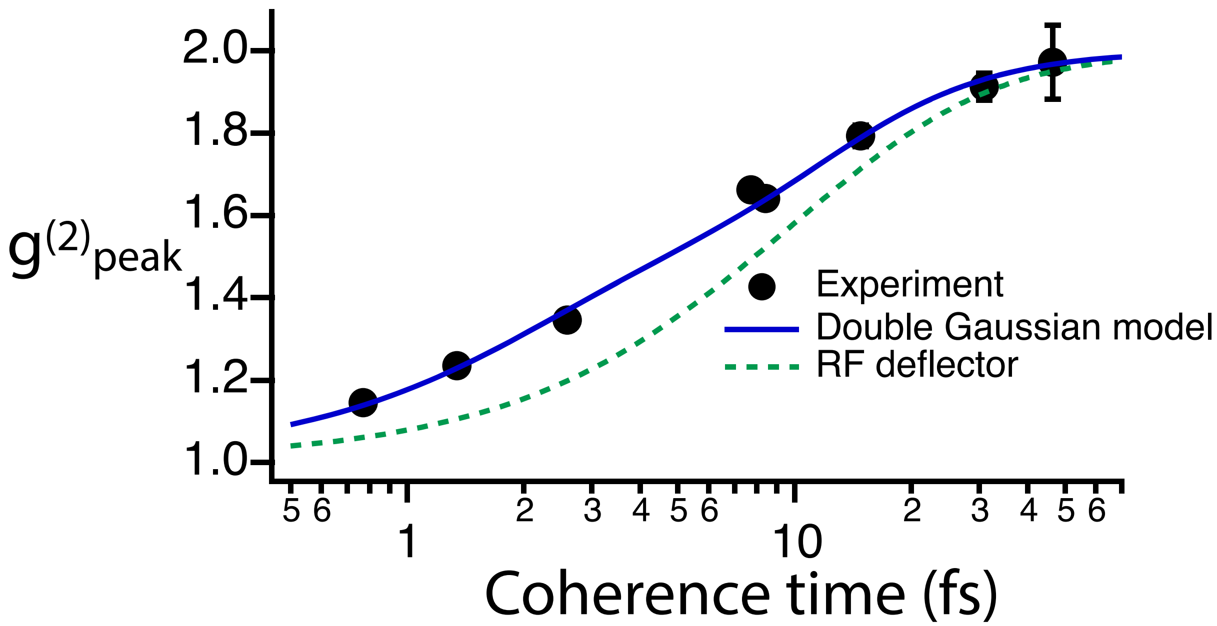
autocorrelation of temporal shape of X-ray pulse

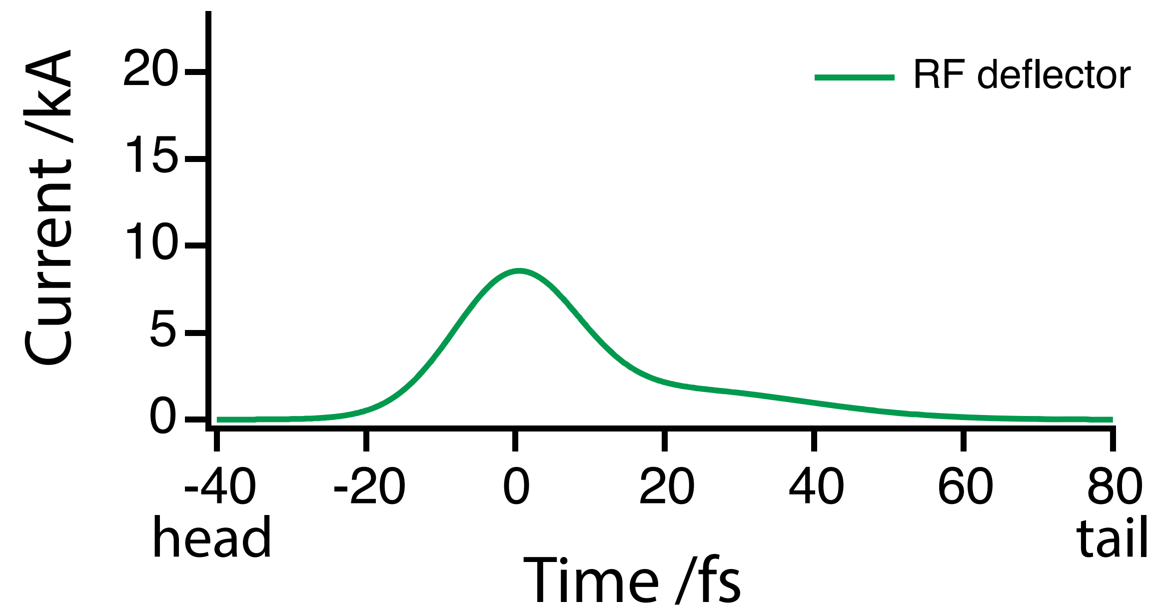
$$\tau_c = 1/(2\sigma_\omega)$$

coherence time of X-ray beam after monochromator

I. Inoue *et al.*, *PRAB* 21, 080704 (2018).

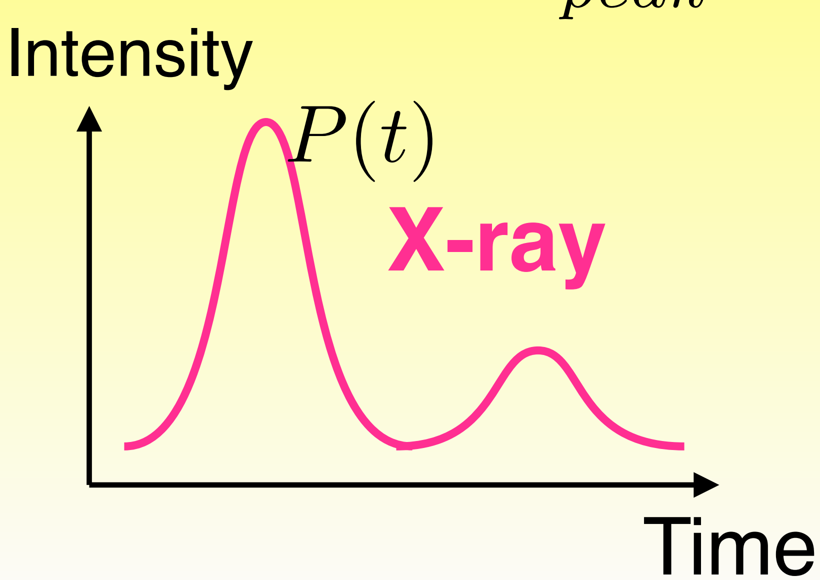
Determination of e-bunch profile by intensity interferometry





Relationship between g^2_{peak} and coherence time

$$g^{(2)}_{peak} = 1 + \int \Pi(\tau) \exp\left[-\left(\frac{\tau}{2\tau_c}\right)^2\right] d\tau$$



$$\Pi(\tau) = \int P(t)P(t+\tau)dt$$

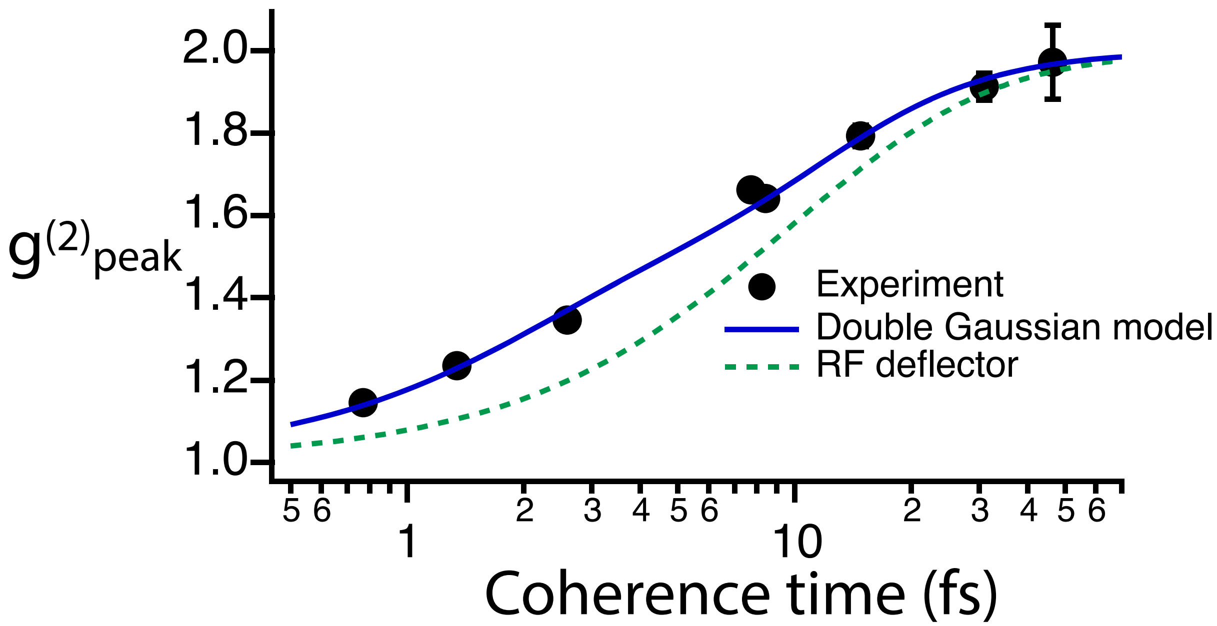
autocorrelation of temporal shape of X-ray pulse

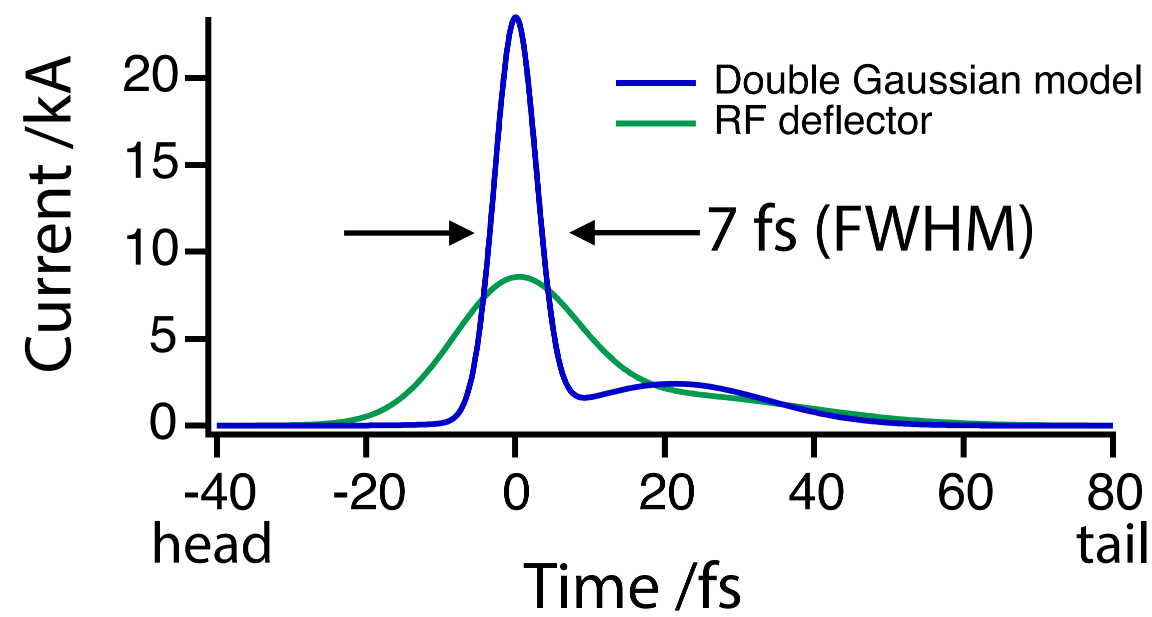
$$\tau_c = 1/(2\sigma_\omega)$$

coherence time of X-ray beam after monochromator

I. Inoue *et al.*, *PRAB* 21, 080704 (2018).

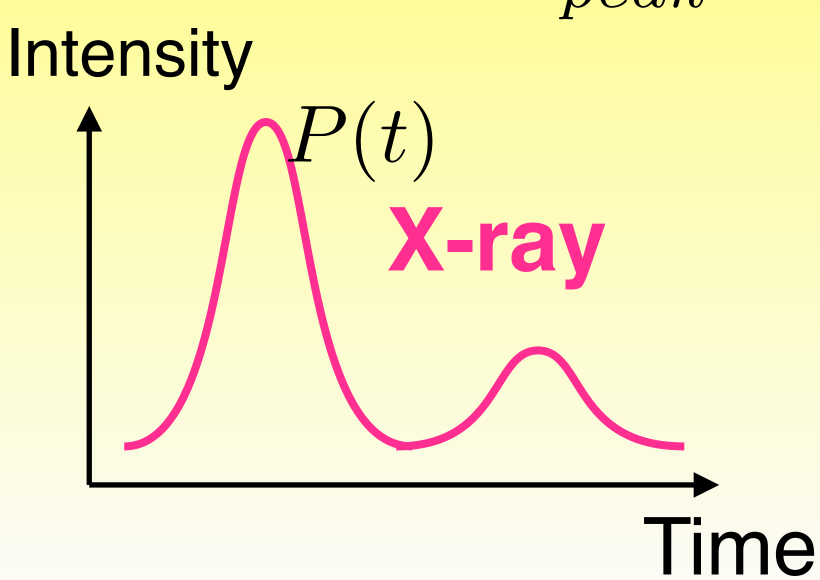
Determination of e-bunch profile by intensity interferometry





Relationship between g^2_{peak} and coherence time

$$g^{(2)}_{peak} = 1 + \int \Pi(\tau) \exp\left[-\left(\frac{\tau}{2\tau_c}\right)^2\right] d\tau$$



$$\Pi(\tau) = \int P(t)P(t+\tau)dt$$

autocorrelation of
temporal shape
of X-ray pulse

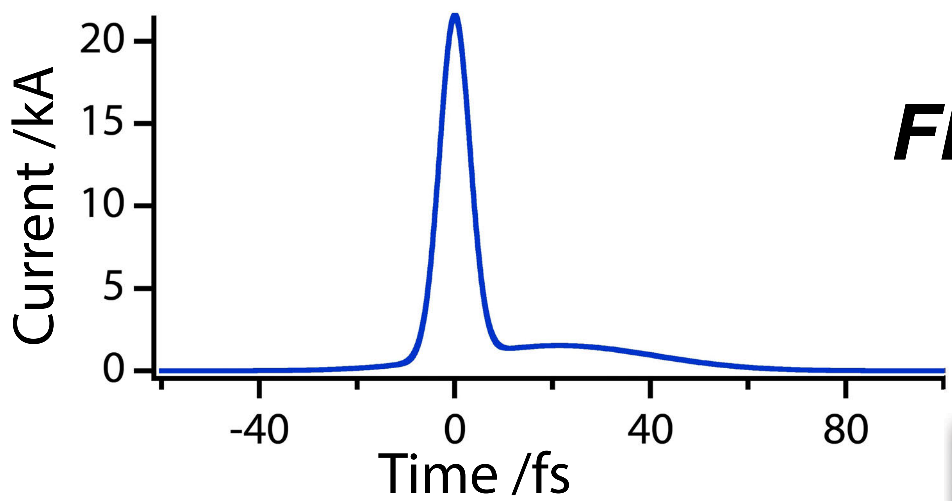
$$\tau_c = 1/(2\sigma_\omega)$$

coherence time of X-ray beam
after monochromator

I. Inoue *et al.*, *PRAB* 21, 080704 (2018).

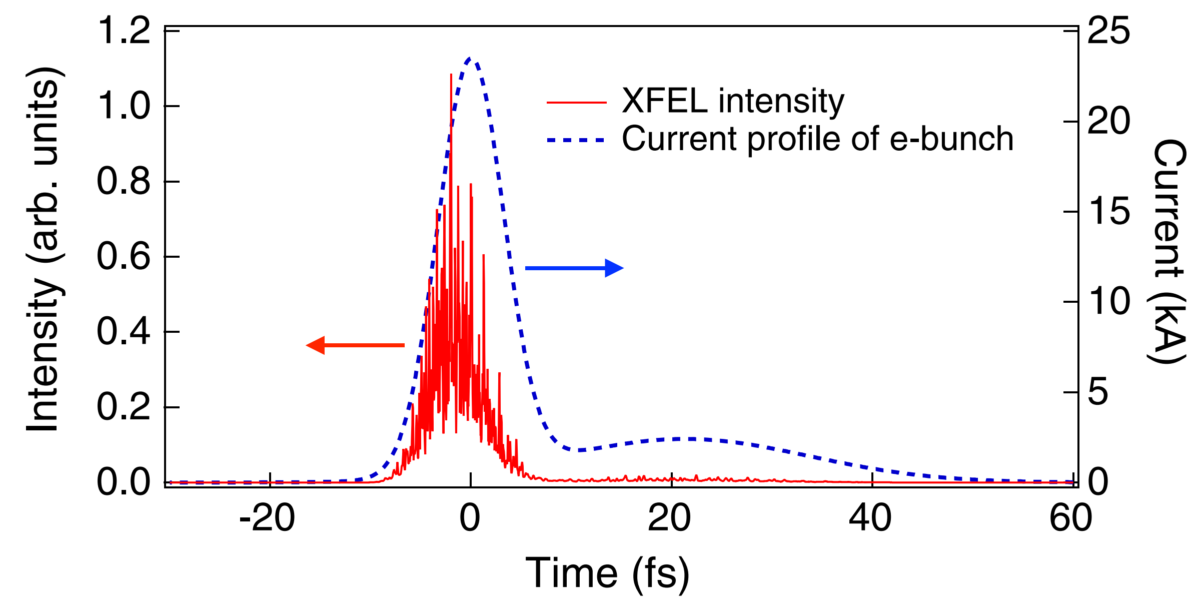
Evaluation of XFEL pulse duration

Temporal profile of e-bunch



FEL simulation (SIMPLEX)

Temporal profile of XFEL pulse (10.5 keV)



+Other parameters

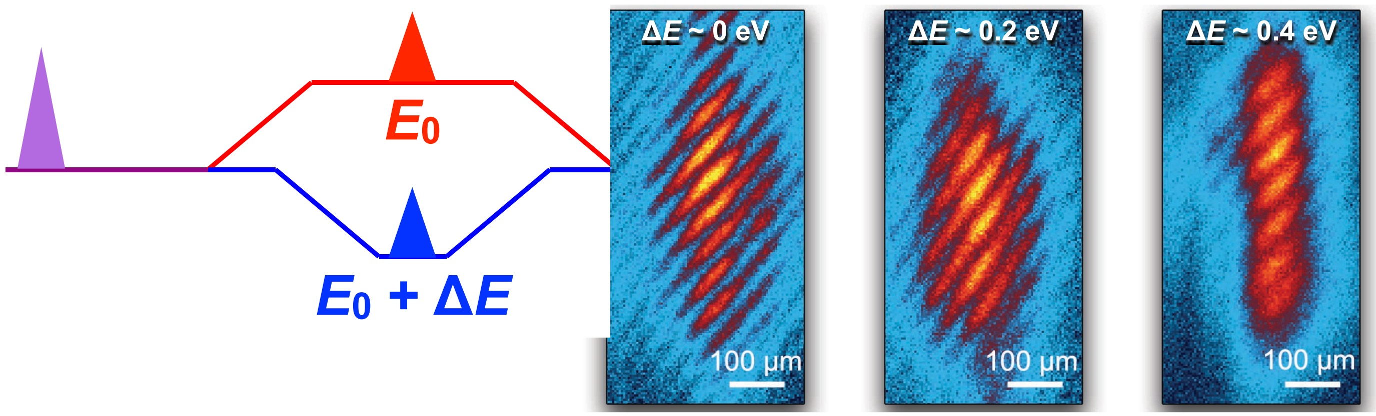
- emittance
- energy spread
- energy chirp
- betatron function

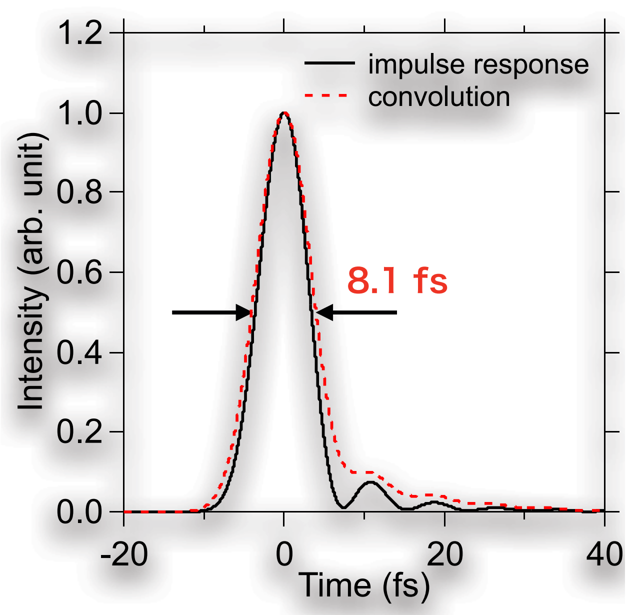
etc…

- ☑ High current region of e-bunch selectively emit intense X-rays
- ☑ XFEL duration is **~7 fs (FWHM)**

Comparison with other diagnostic methods

Interferometry of XFELs with different wavelengths

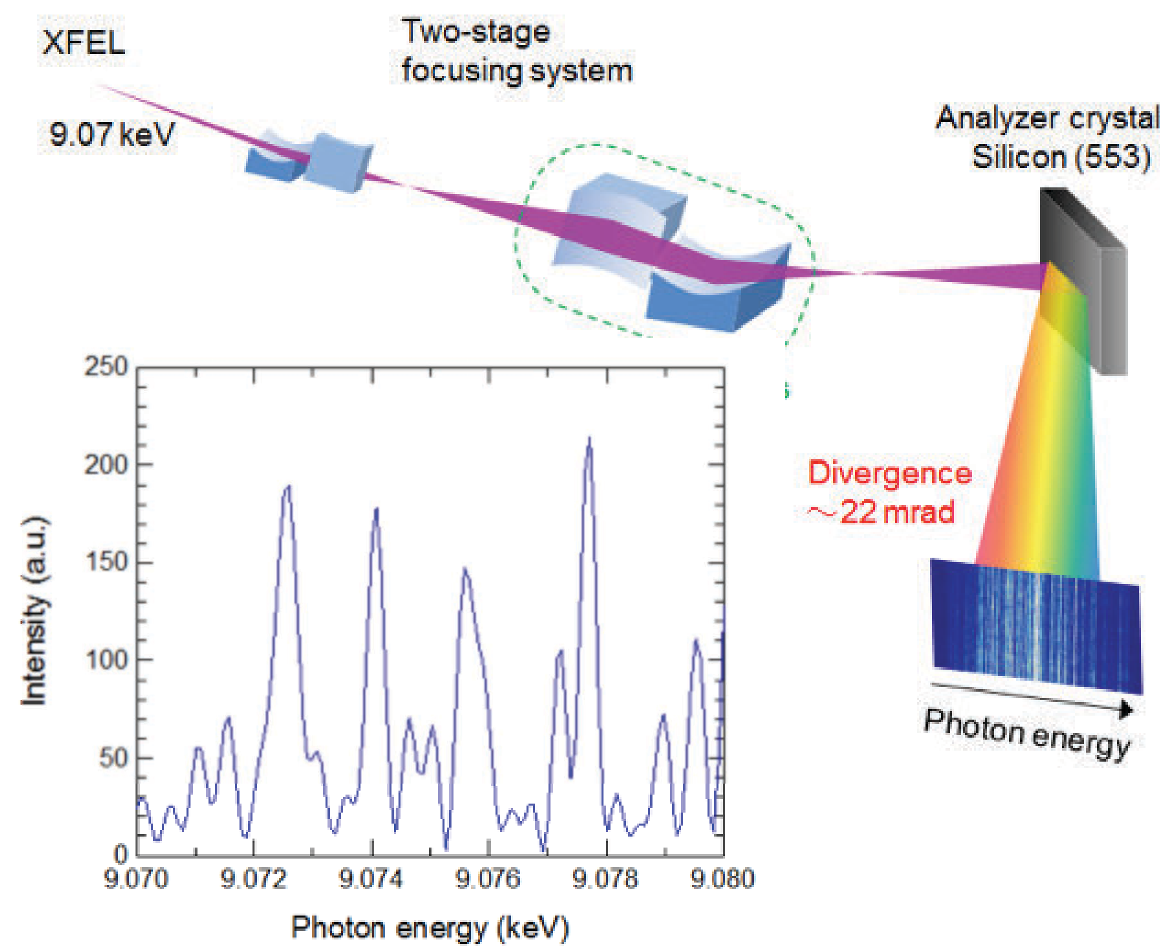




mono-XFEL pulse duration: ~8 fs (FWHM)

Osaka *et al.*, *in preparation.*

High-resolution spectrum



XFEL pulse duration: 6-8 fs (FWHM)

Inubushi, Inoue, *Appl. Sci.* (2017).

Summary

- ☑ Intensity interferometry for temporal diagnostic of e-bunch/XFELs has been proposed and demonstrated.

- ☑ Our scheme is applicable to much shorter e-bunches since the coherence time of X-rays can be controlled to attosecond region with X-ray optical devices.

- ☑ This scheme is cost effective and easily conducted.
  →should be useful for cross-checking with other diagnostic systems.

- ☑ Single-shot temporal diagnostic scheme based on intensity interferometry is under development.