Three way meeting between ESRF, APS and SPring-8
"Time-resolved science and technique"

Time-resolved x-ray SR experiments using synchronized femtosecond pulsed laser in SPring-8

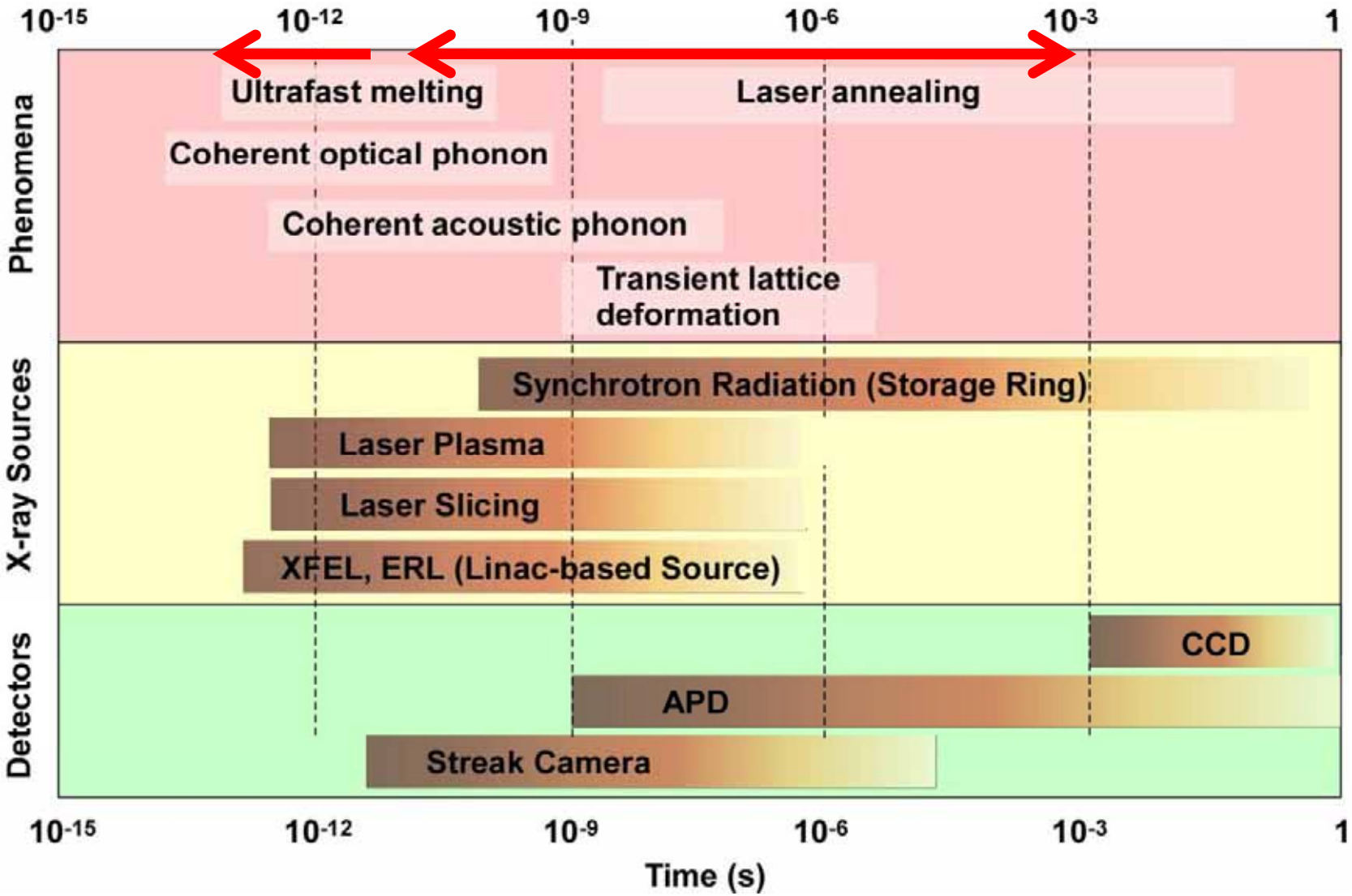
Yoshihito Tanaka

RIKEN/SPring-8 Center
JASRI/SPring-8
CREST, JST

--- Outline ---

1. Introduction

1.1. Typical time scales of phenomena



1.2. SR sources & the time structure

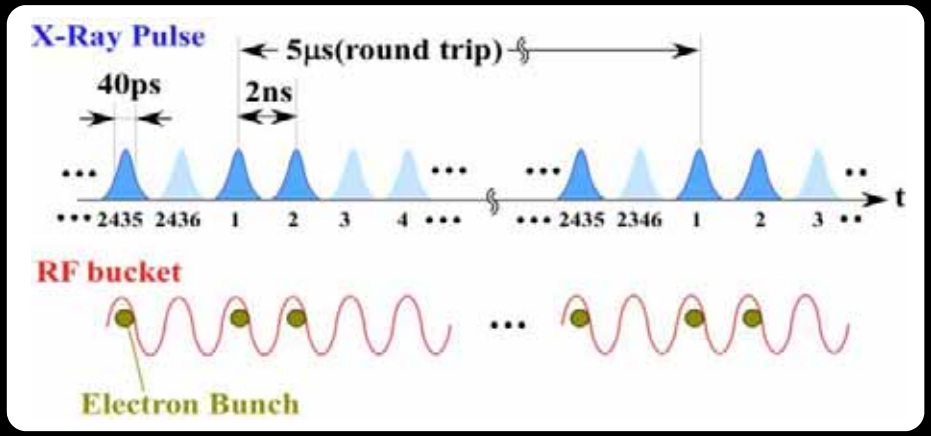
1. Storage ring SR sources

SPring-8

APS

ESRF

Pulse width:
40 ps (FWHM)
Rep. rate:
200 kHz-509MHz



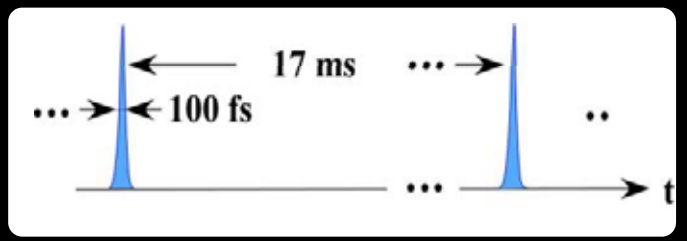
2. Linac-based SR sources (FEL)

SLAC LCLS

SCSS

EuroFEL

<<100 fs
60 Hz (FEL)

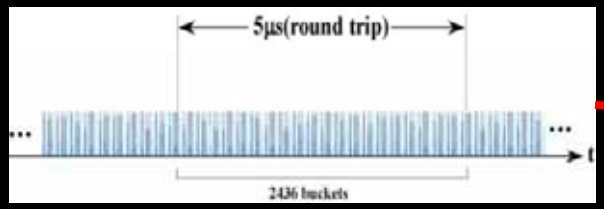


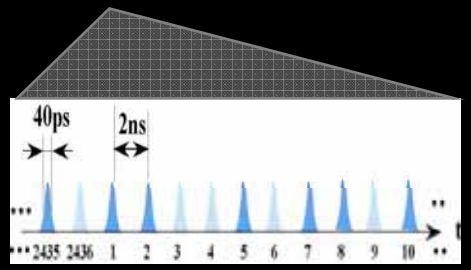
1.3. TR techniques at SPring-8

SR time structure

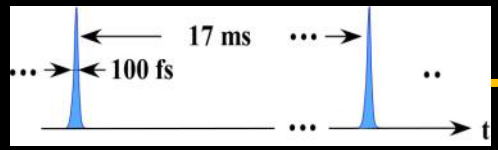
Time resolution & Method

Storage Ring





FEL



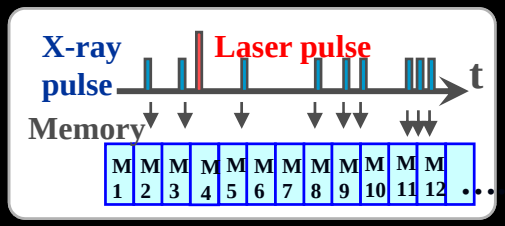
1 ms

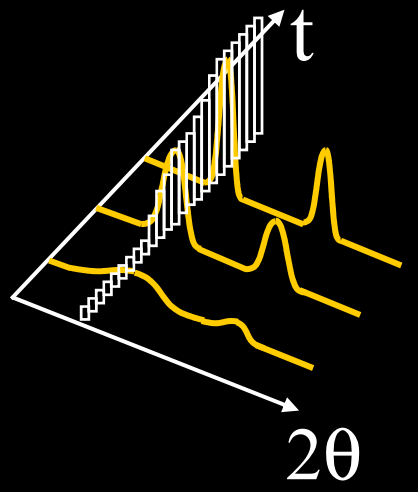
1 μs

1 ns

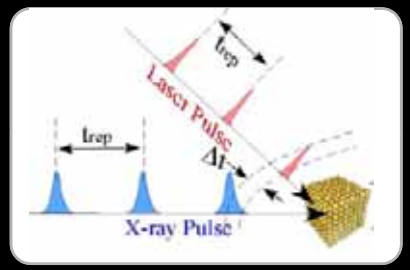
1 ps

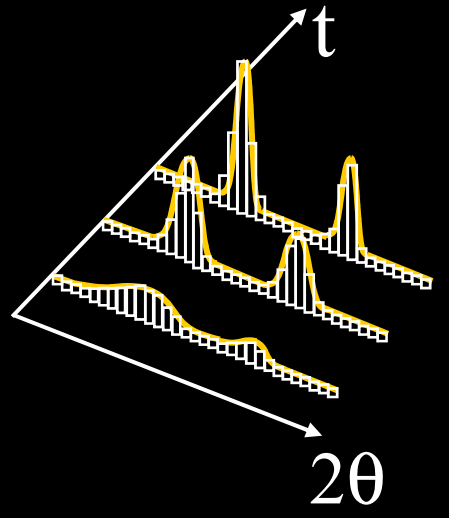
APD+MCS



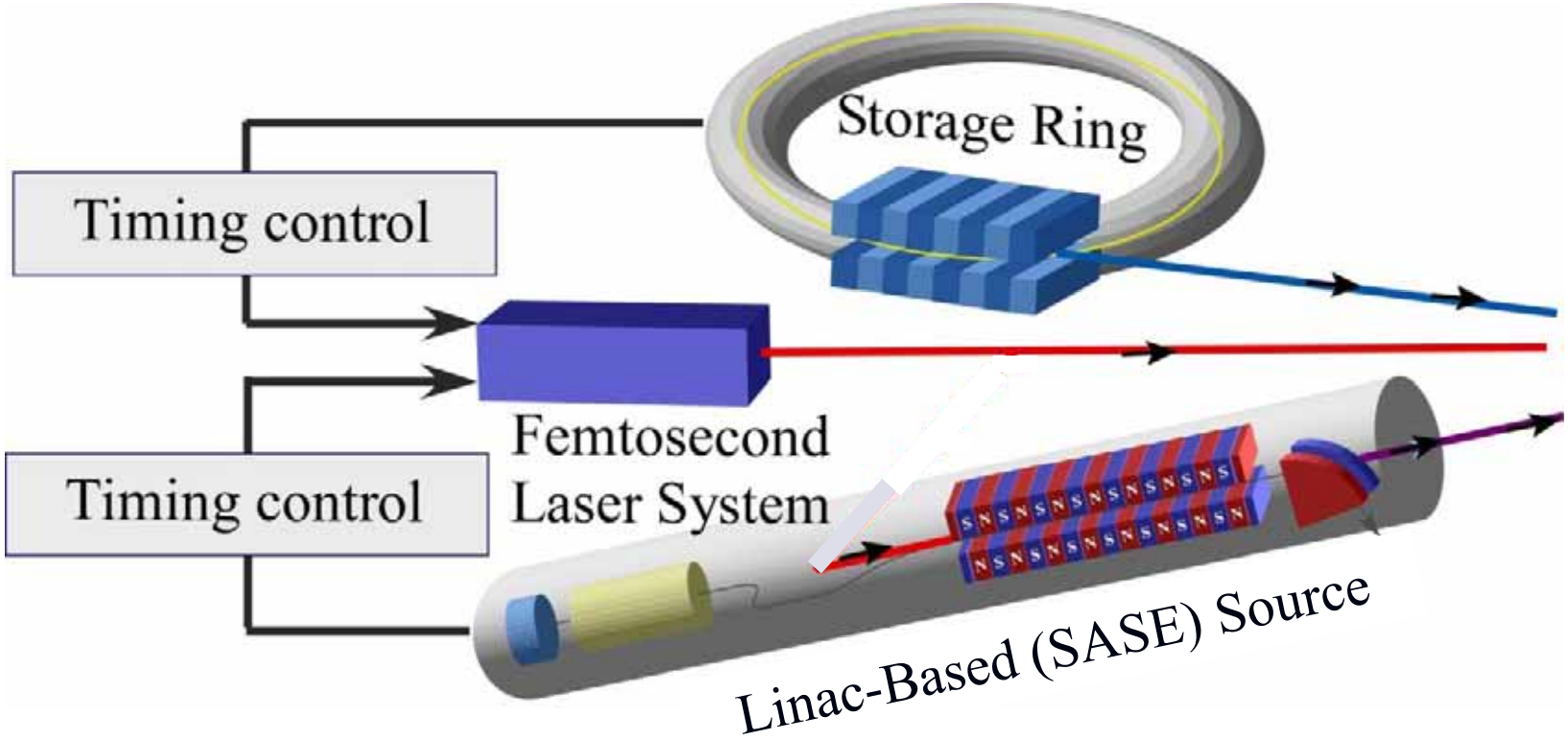


Pump-probe





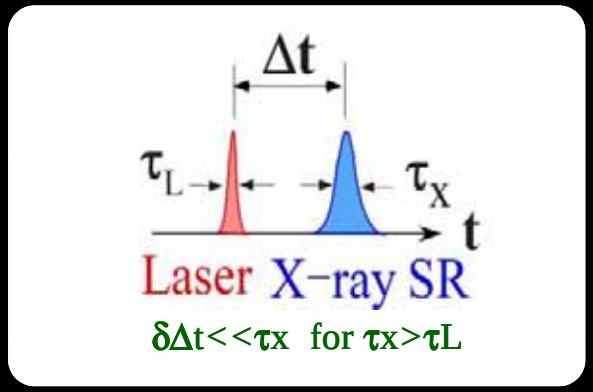
SR-laser synchronization



2. Key technology for SR-laser synchronization

2.1 Precise timing (phase) control

- Required precision
  << Pulse width
  40 ps for Ring
  100 fs for Linac

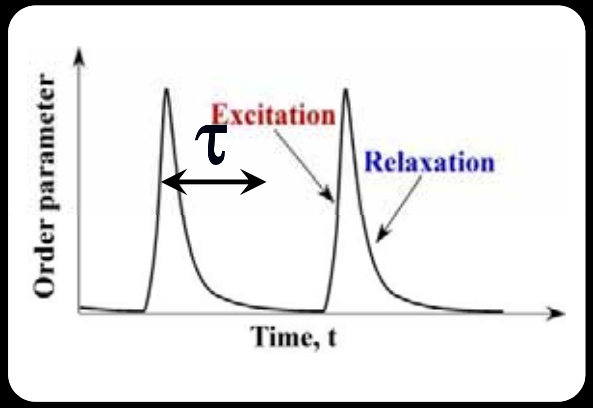


2.2 Repetition rate issue

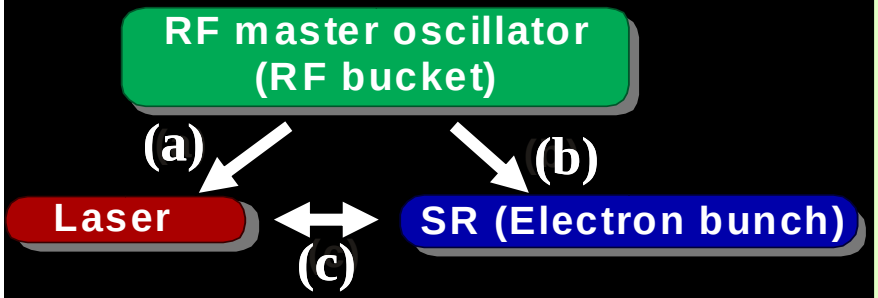
- Dependent on recovery time in target phenomenon

$1/f_{rep} > \tau$ ～1 ms

- Available averaged power of the pulsed laser



2.1 Precise timing (phase) control at storage ring



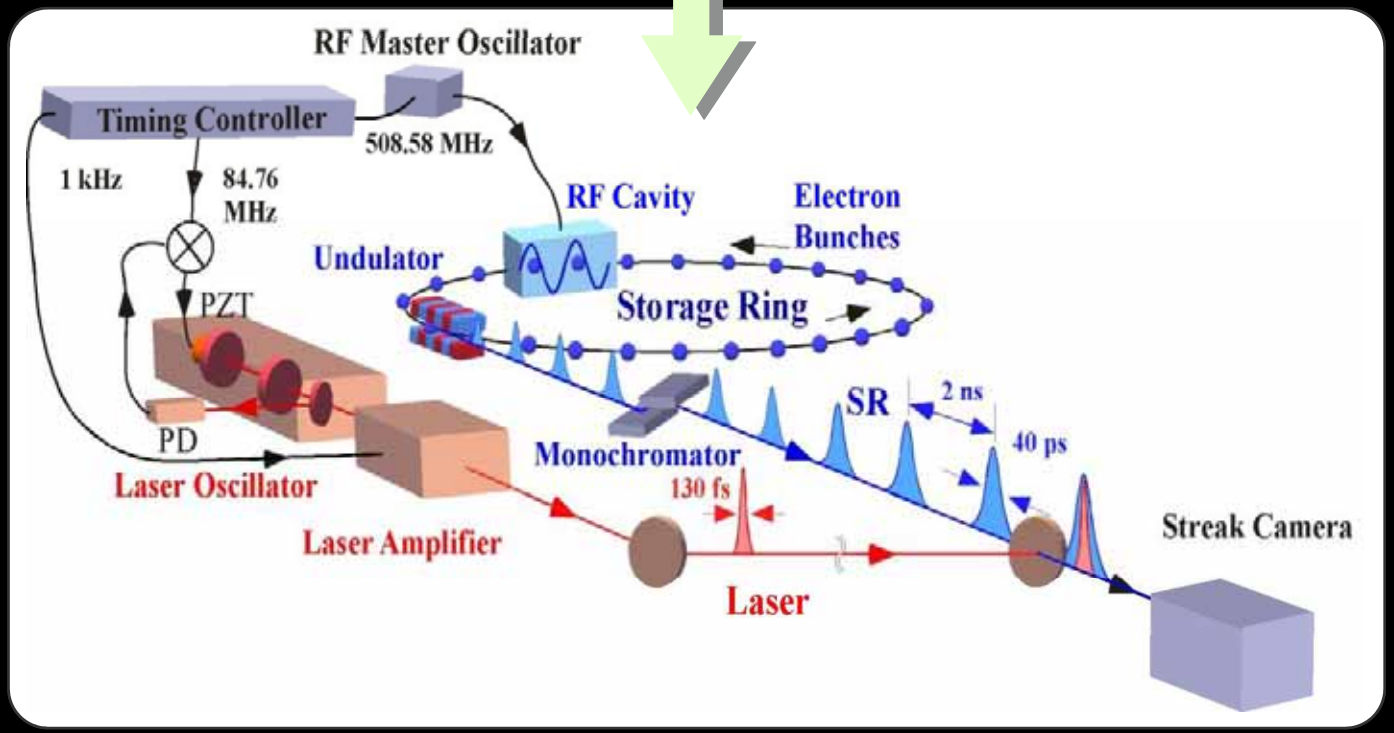
Synchronization scheme

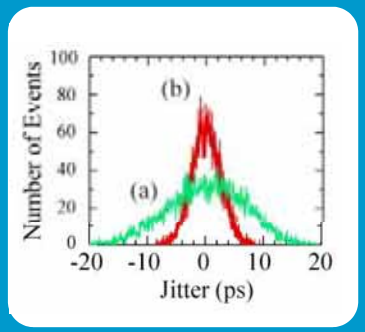
- **Mode-locked Ti:sapphire laser with external trigger from a RF master oscillator of the ring**

$$\text{Cavity length} = \frac{1}{2} \cdot \frac{c}{(f_0/6)}, \qquad f_0\text{: Frequency of RF master oscillator}$$

- **Output timing of amplified laser pulses is controlled with a counter and a delay pulse generator**

$$(\text{Repetition rate} = \frac{1}{2436 \times 209} f_0 \sim 1\ \text{kHz})$$

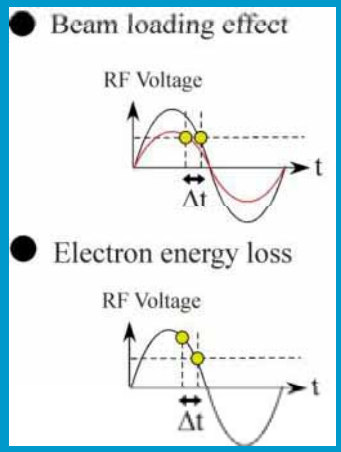




RF master oscillator (RF bucket)

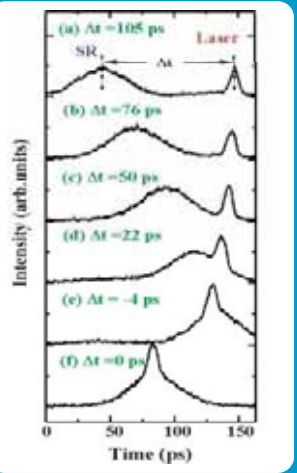
$\Delta t_{jitter} < 3$ ps

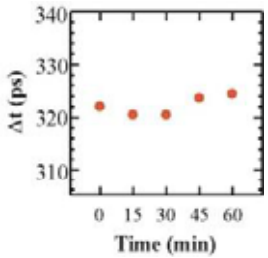
$\Delta t_{drif} < 5$ps



$\Delta t < 5$ ps

Laser ⟷ **SR (Electron bunch)**





Long-term stability
$< \pm 2$ ps

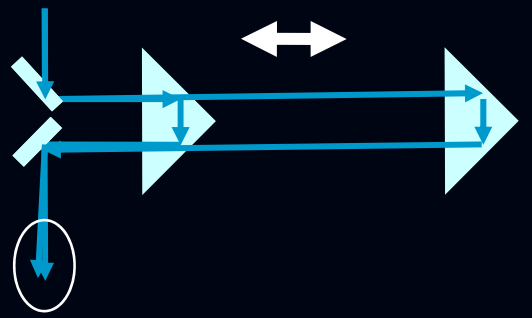
$\Delta t < 5$ ps

Y. Tanaka, T. Hara, H. Kitamura, T. Ishikawa, Rev. Sci. Instrum., 71, 1268 (2000)

Time(phase)-delay control

1. Optical Delay

- High precision delay
- Large delay may cause the misalignment at a sample



2. RF trigger delay (Continuous phase shifter)

- Compact, **Quick feedback**

$E(t)=\sin \omega t$

$A_1 \cos \omega t + A_2 \sin \omega t = \sin(\omega t-\alpha) = \sin(\omega(t-\tau)) = E(t-\tau)$

A_1: Q, A_2: I

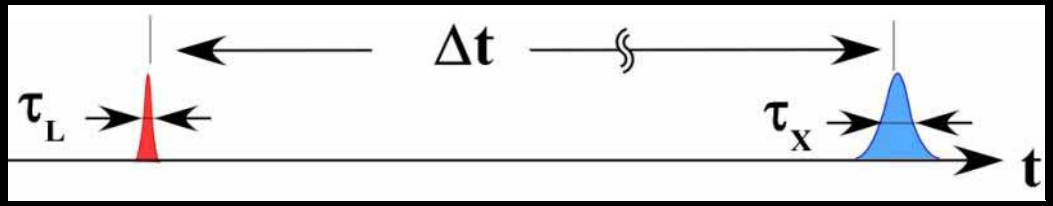
$A_1=-\sin \alpha$, $A_2=\cos \alpha$

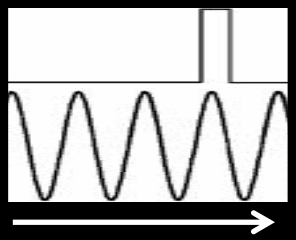
Phase $\alpha \gg 2\pi$ Time delay

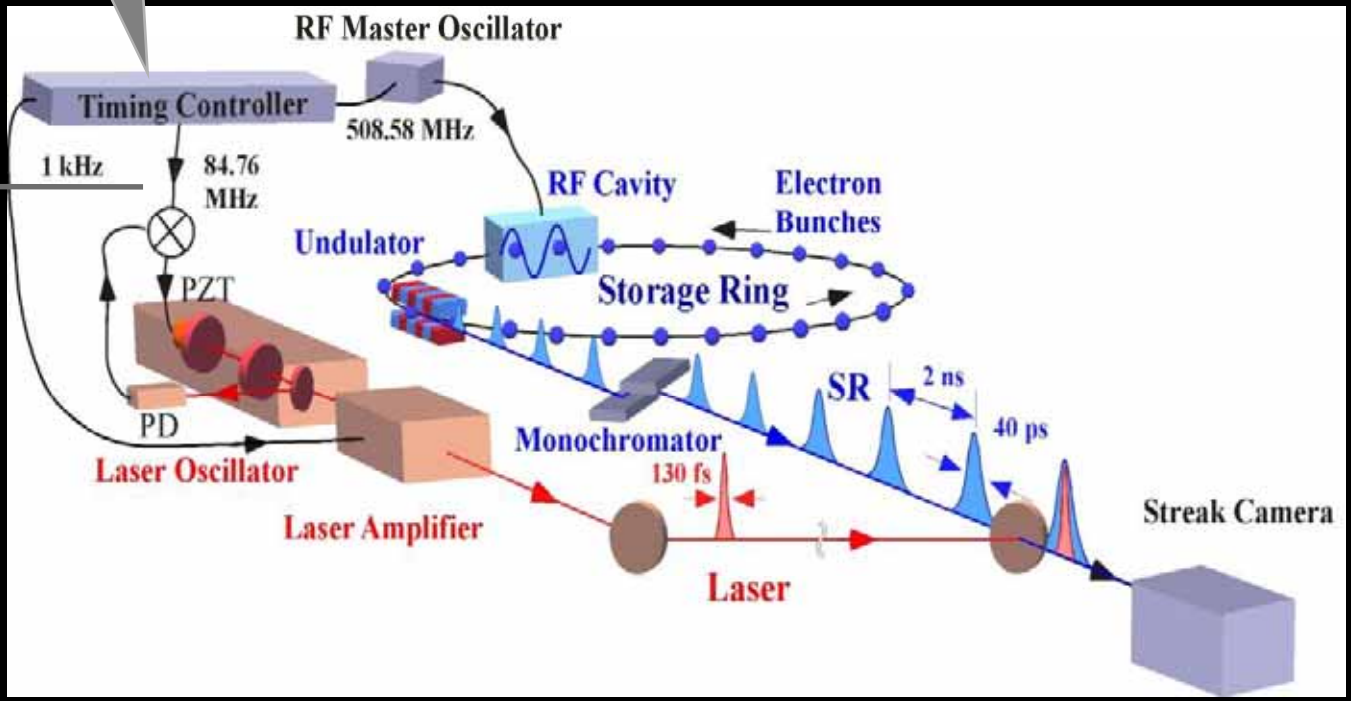
T. Ohshima, Y. Tanaka: Patent No. TOKUGAN2006-067346

Candox co.

Wide range with 5 ps precision timing control







2.2 Repetition rate

Extraction of X-ray pulses with low rep. rate

(a) Pulse selection by mechanical chopper

Gate > 400 ns

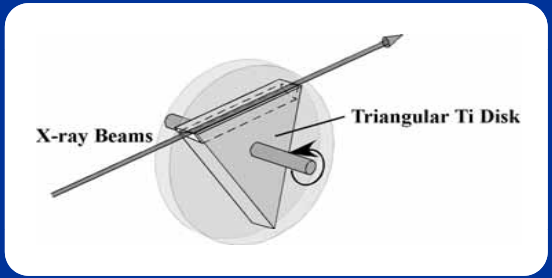
(b) Electronic gate

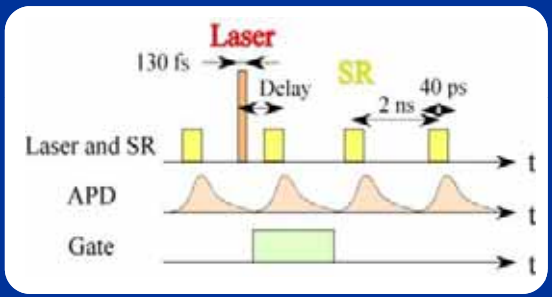
- Avalanche photodiode

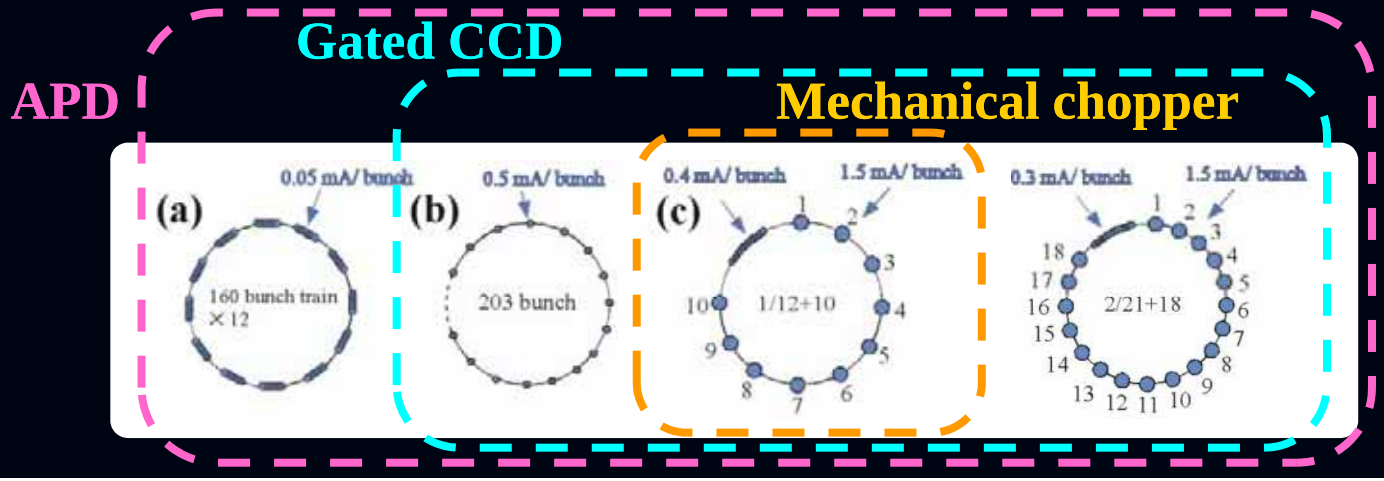
Gate > 5 ns

- Gated X-ray CCD camera

Gate > 100 ns



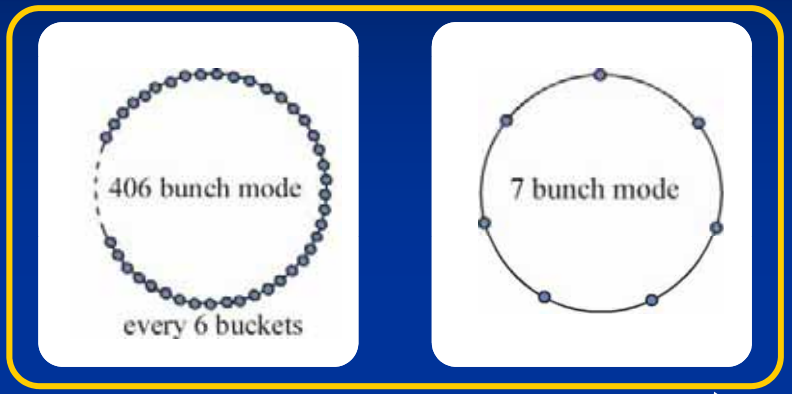


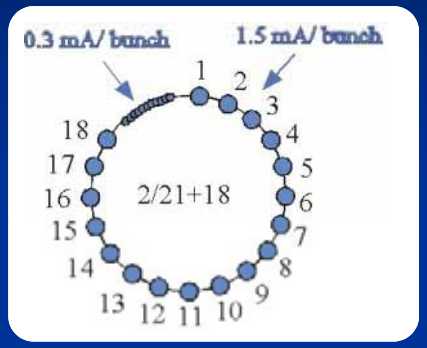


Pump &probe with high repetition rate (MHz)

(Fast decay phenomena by using focused beams)

SR





+X ray pulse selector

Laser

λ=800nm
τ = 80fs
E = 10nJ/pulse
f = 85 MHz

f = 1 MHz

Ti:S Oscillator

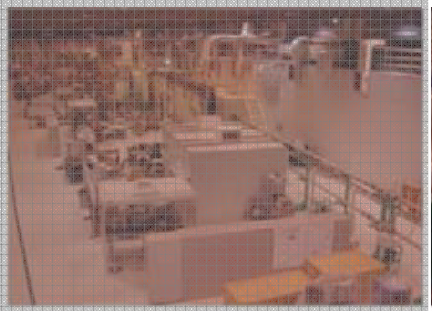
AO modulator

Regenerative Amplifier

λ=800nm
λ=400nm (SHG)
λ=266nm (THG)
τ = 130fs
E = 1mJ/pulse
f = 1 kHz

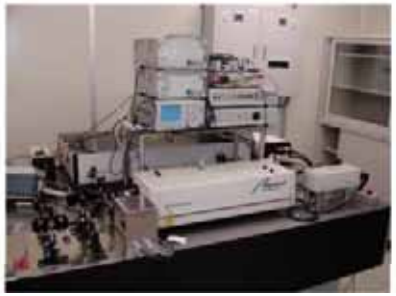
Synchronized femtosecond pulsed laser systems in SPring-8

① BL29XUL
1km-long beamline

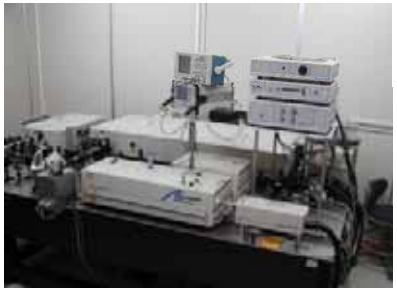


② BL19LXU
27m-long undulator

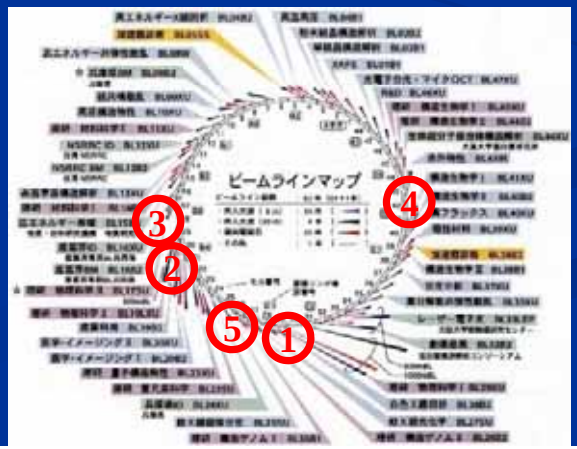
③ BL17SU
Soft x-ray beamline



④ BL40XU
CREST hutch



SCSS(FEL prototype accelerator)



⑤ BL25SU

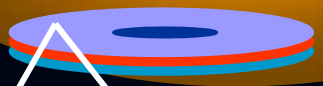
⋮

3. Experiments with TR technique with fs lasers

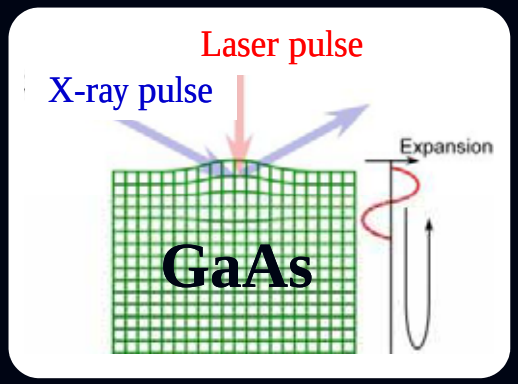
Acoustic echo in semiconductors

Phase change in DVD media

Laser seeding in FEL

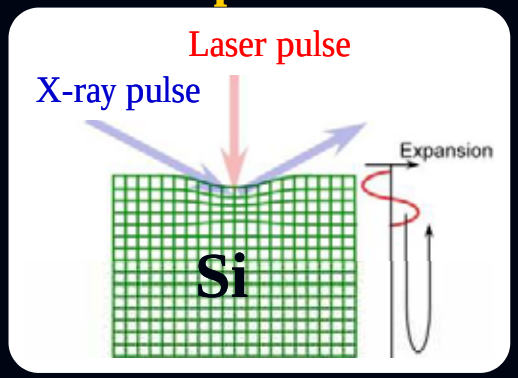


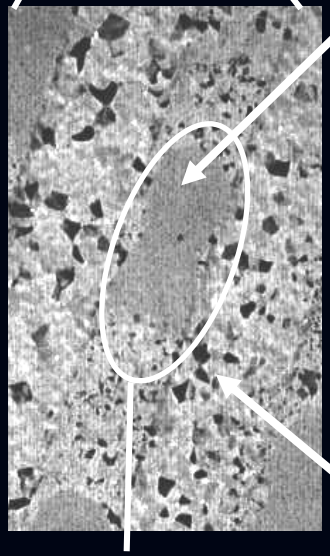
Expansion



0.1 ps - ns ?

Compression



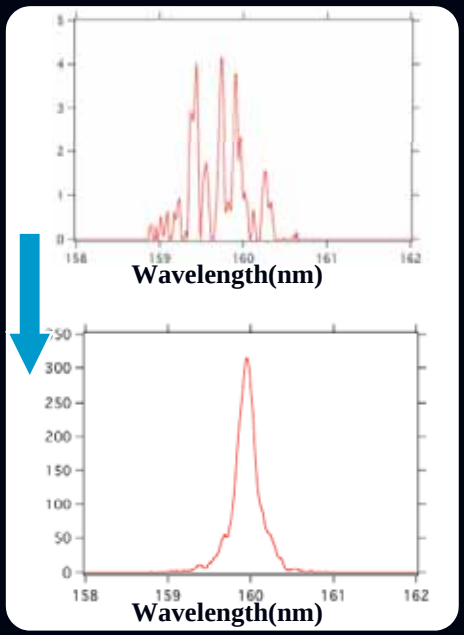


Recorded mark

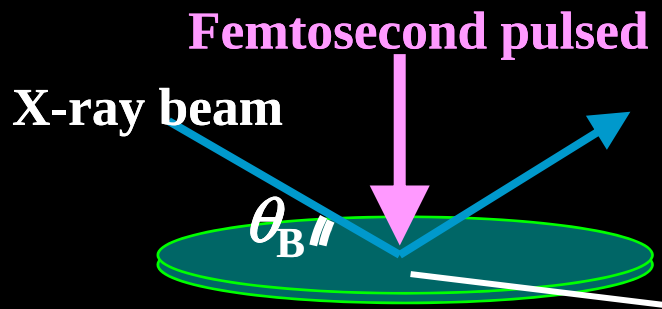
Amorphous

20-30 ns ?

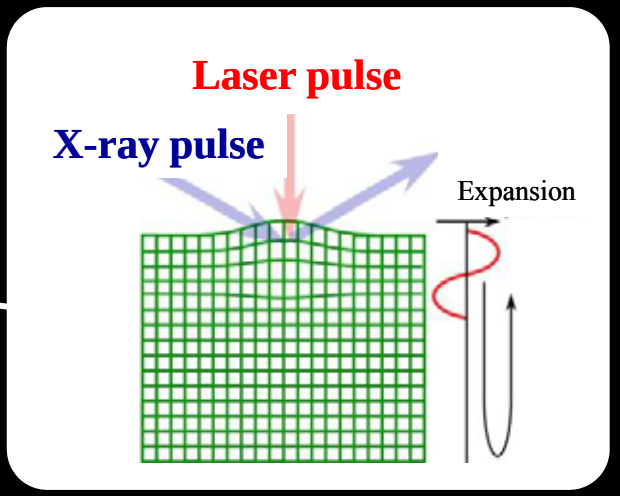
Crystal



3.1 Acoustic echoes in semiconductors

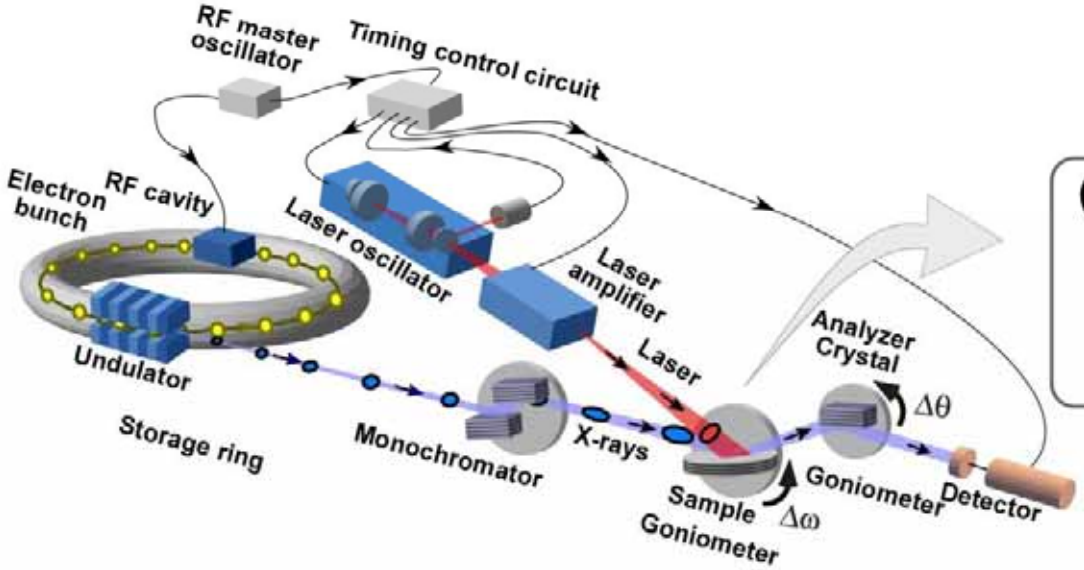


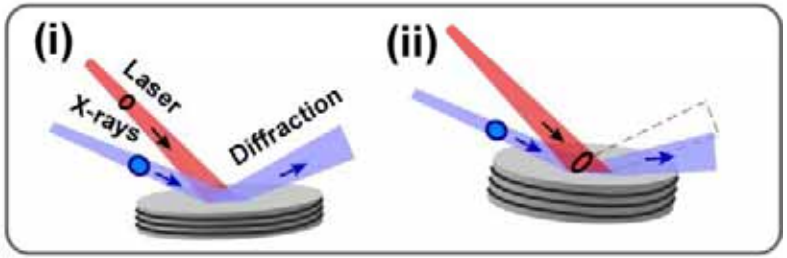
GaAs or Si single crystal wafer



$\lambda = 2d \sin\theta_B$: Bragg condition

$$\boxed{\Delta\theta = -(\Delta d/d)\tan\theta_B}$$

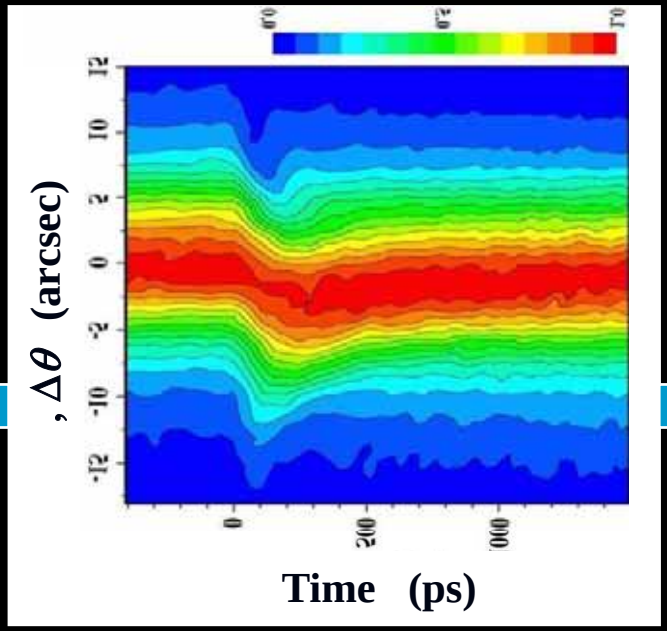


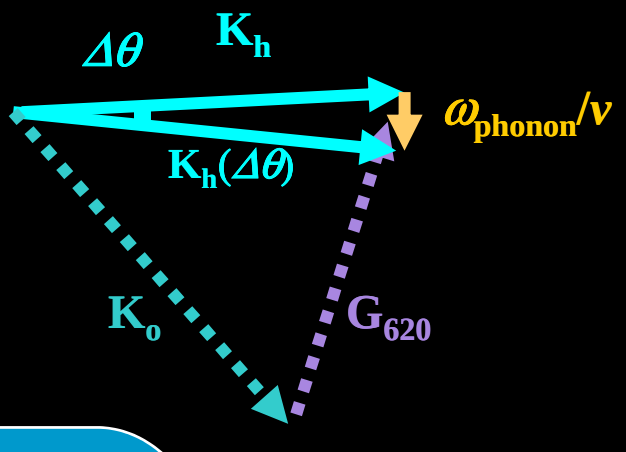


Fast lattice response by fs laser irradiation

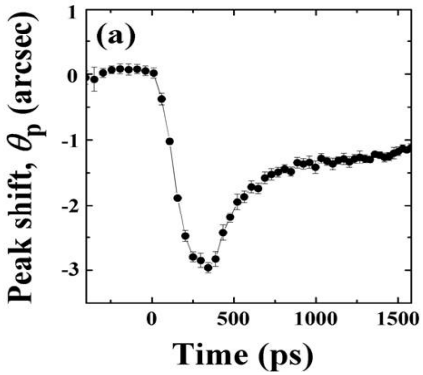
GaAs <100>

Lattice expansion

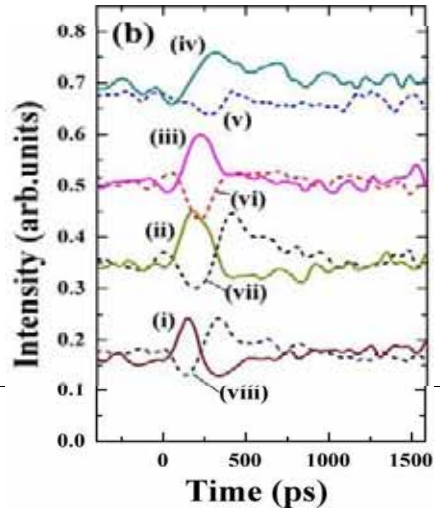


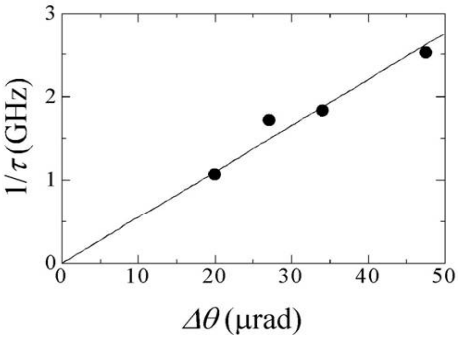


Acoustic phonon



$\Delta d_{100}/d_{100} \sim 2.4 \times 10^{-5}$
for 5mJ/cm^2-laser irradiation





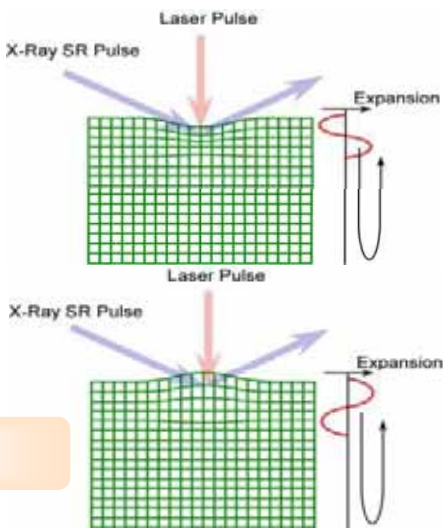
$\omega_{phonon}/v = K_h \cdot \Delta\theta$

$1/\tau_{phonon} = vK_h \cdot \Delta\theta/2\pi$
$= (v/\lambda)\,\Delta\theta$

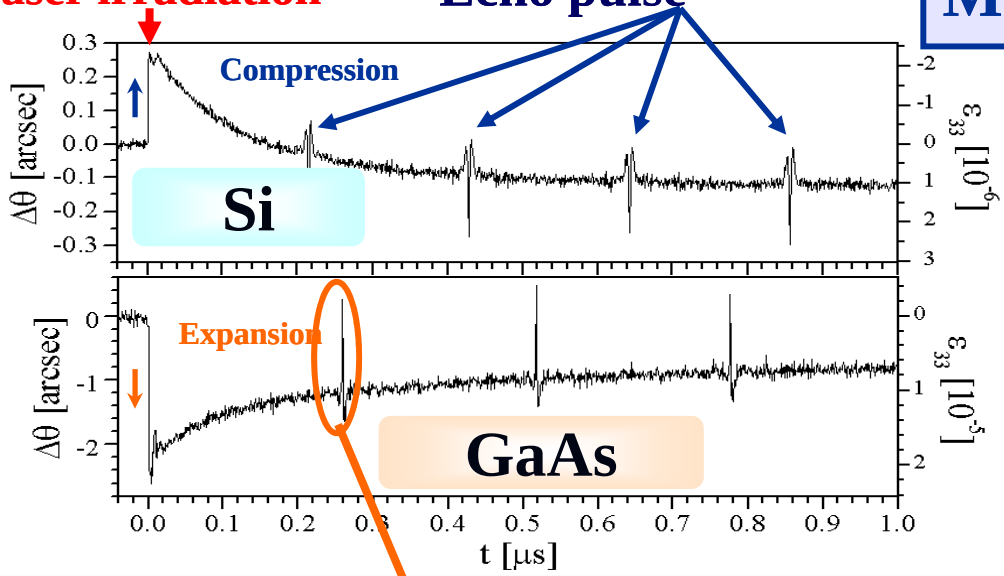
Pulse echoes in Si and GaAs

Si

GaAs



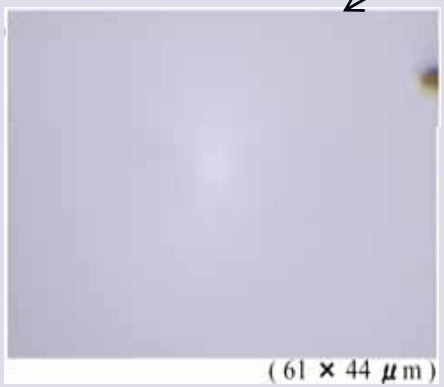
MCS

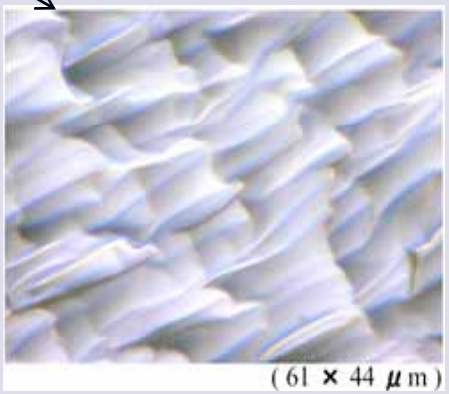


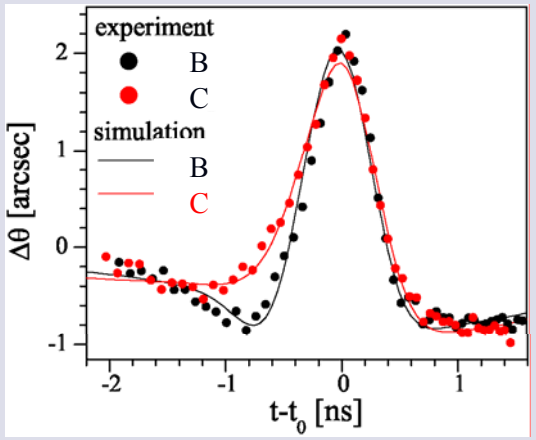
Pump-probe

Sample B : σ~1nm

Sample C : σ= 350nm

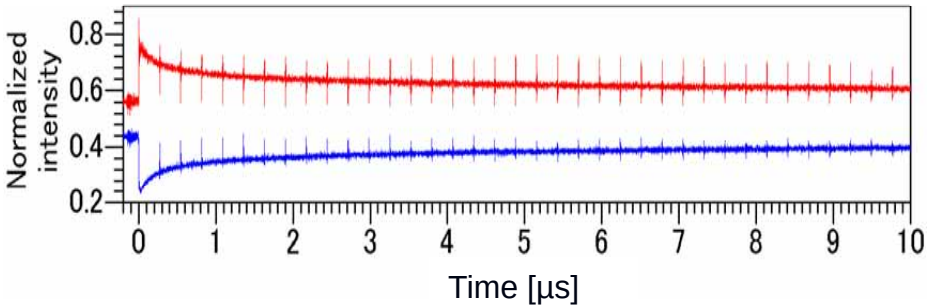






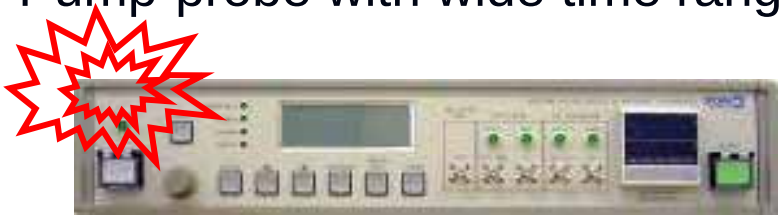
Y. Hayashi, Y. Tanaka, T. Kirimura, N. Tsukuda, E. Kuramoto, T. Ishikawa: Phys. Rev. Lett. 96 (2006) 115505.

Wide range with high resolution measurements

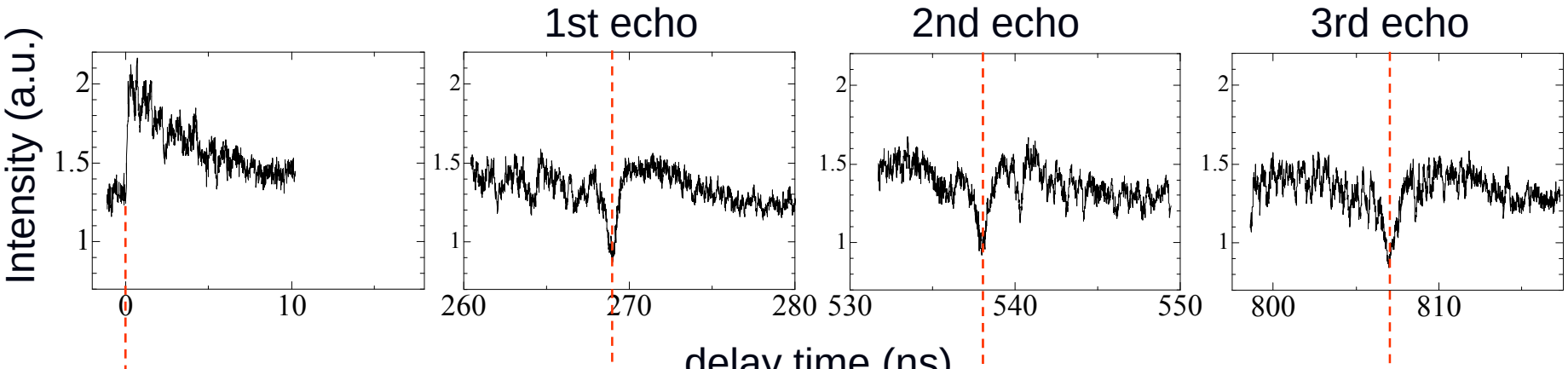


Acoustic pulse echoes measured with MCS

Pump-probe with wide time range



Scan range: 0 ~ 820 ns
Scan step: 10 ps



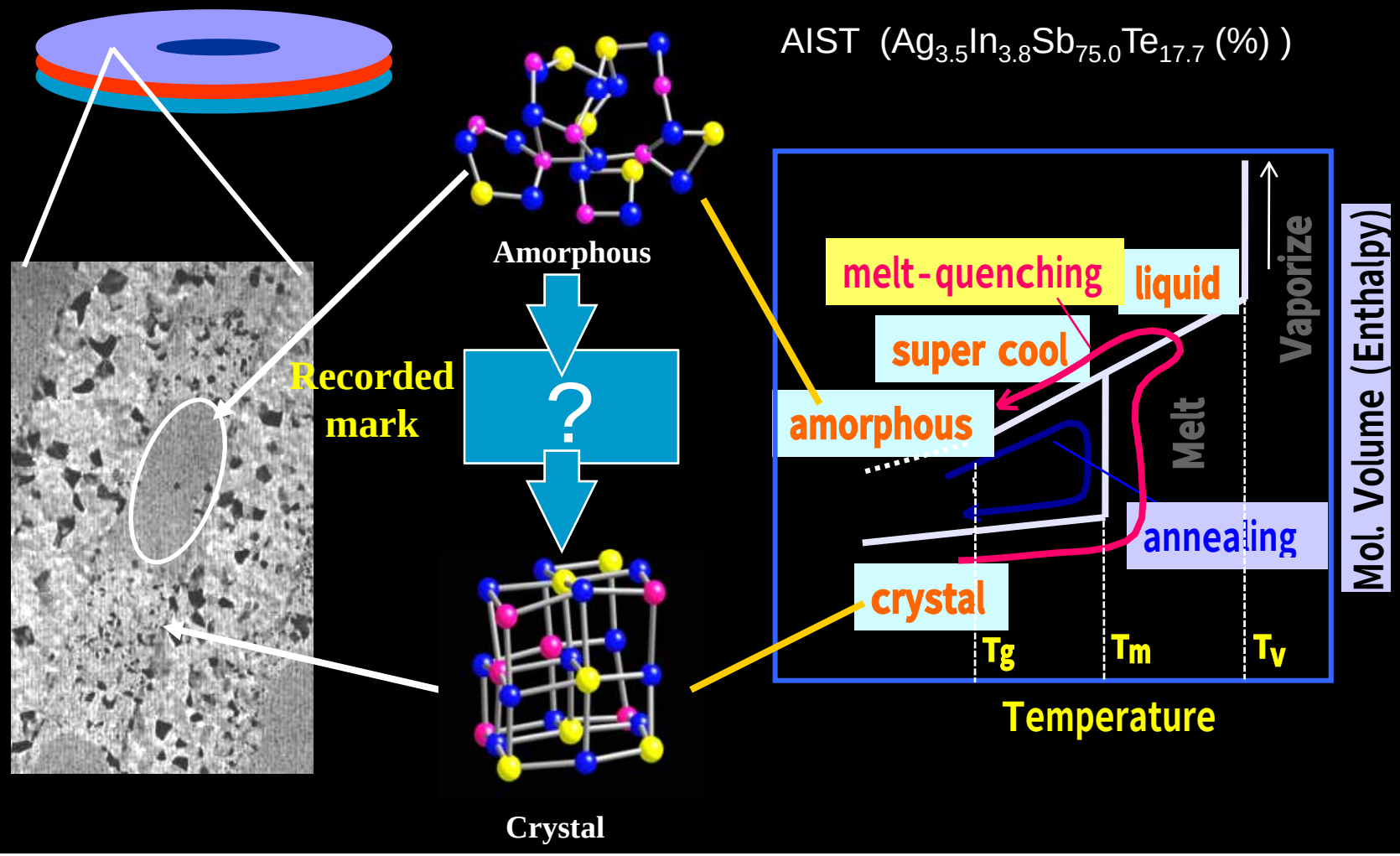
268.99±0.01 ns | 537.99±0.01 ns | 806.97±0.01 ns

$v = L/\Delta t$

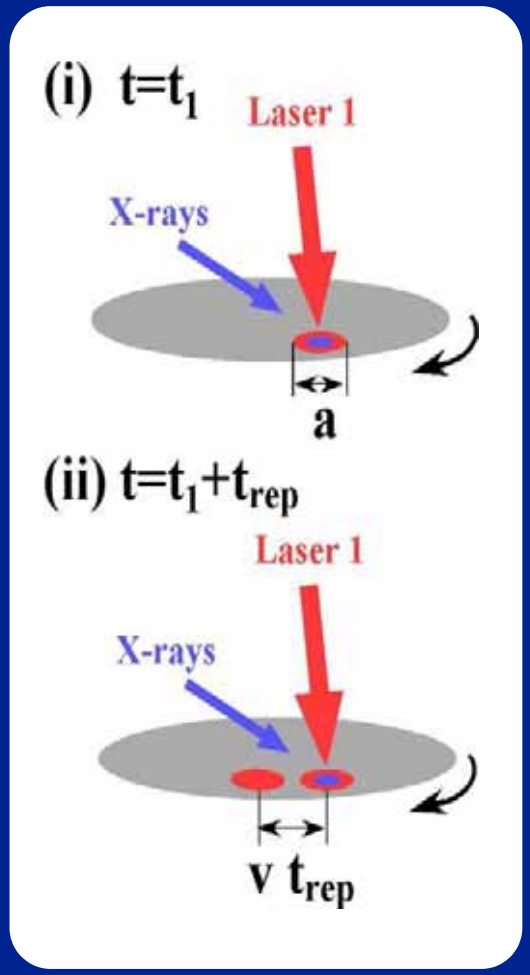
High precision measurement of sound velocity

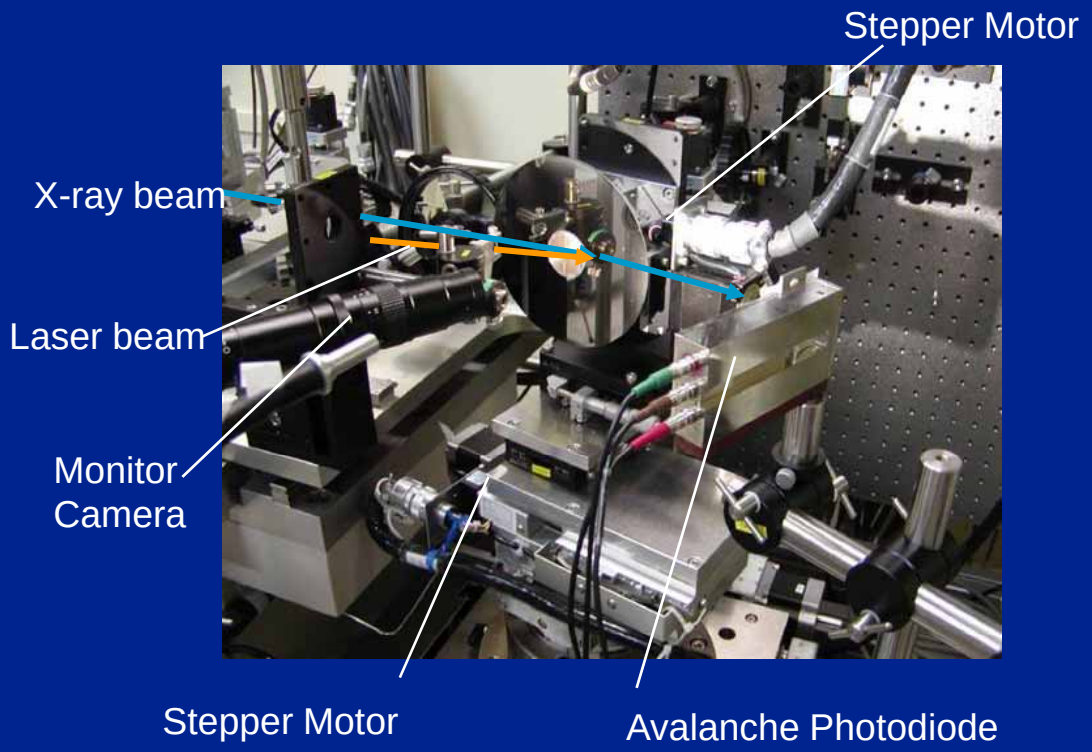
Rev. Sci. Instrum. Accepted in March 17.

3.2. TR-measurement for amorphous-crystal phase change in DVD media



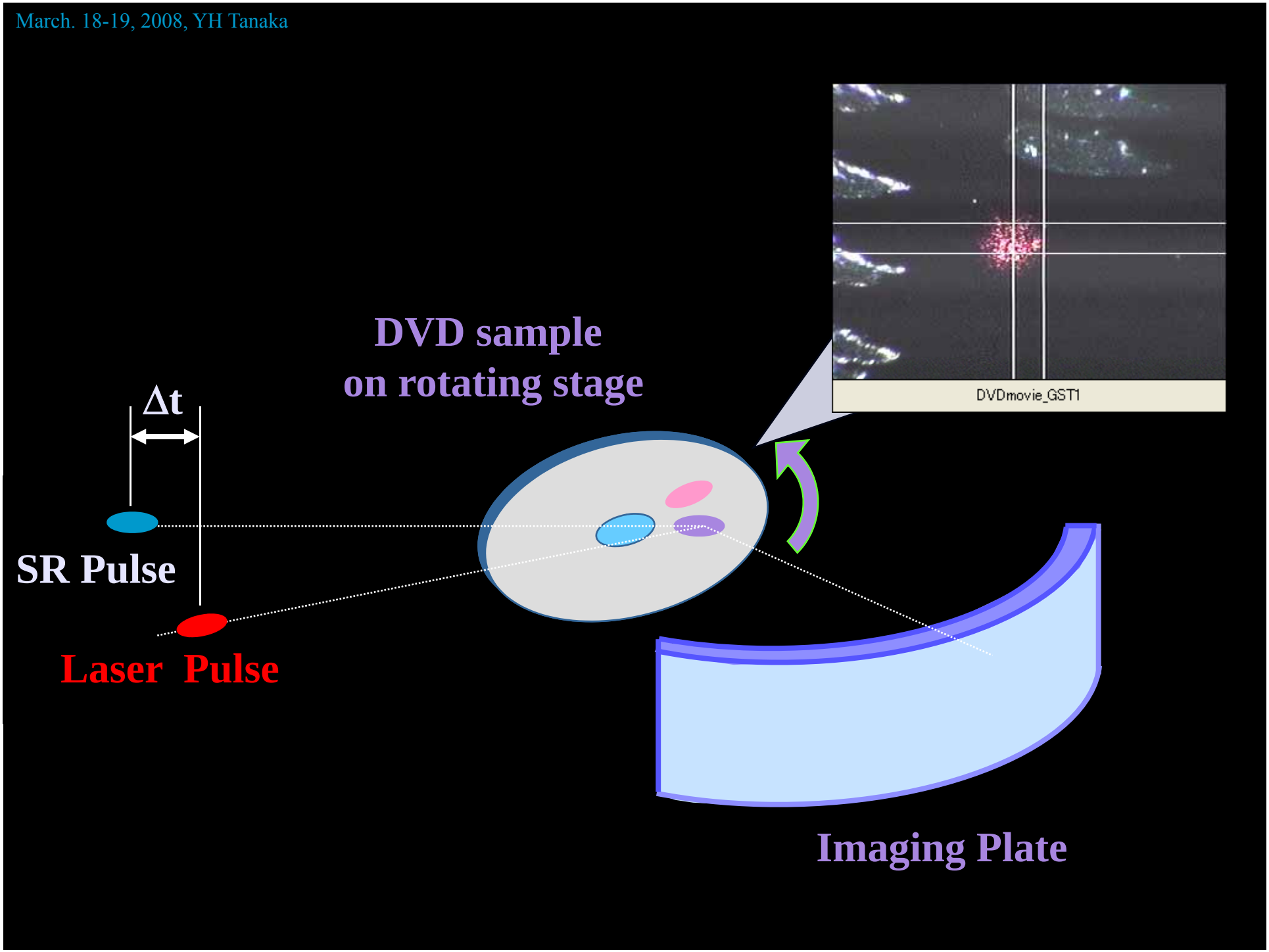
Measurement technique for non-reversible process





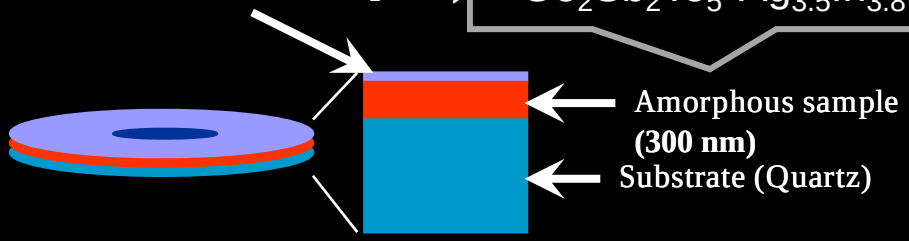
Sample is prepared on the rotating disk, so that the laser pulse always irradiates the fresh sample surface before transition.

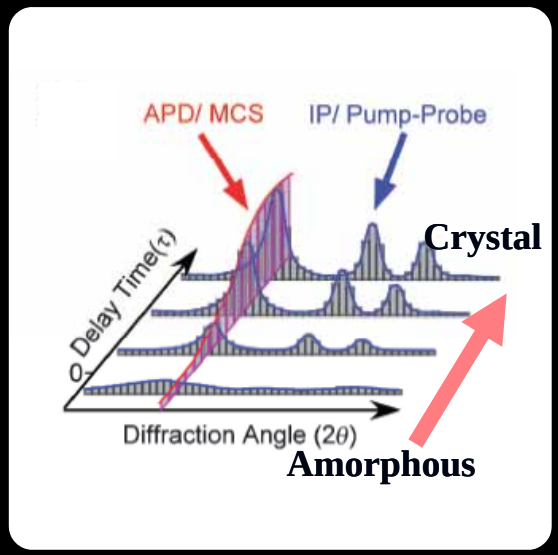
March. 18-19, 2008, YH Tanaka

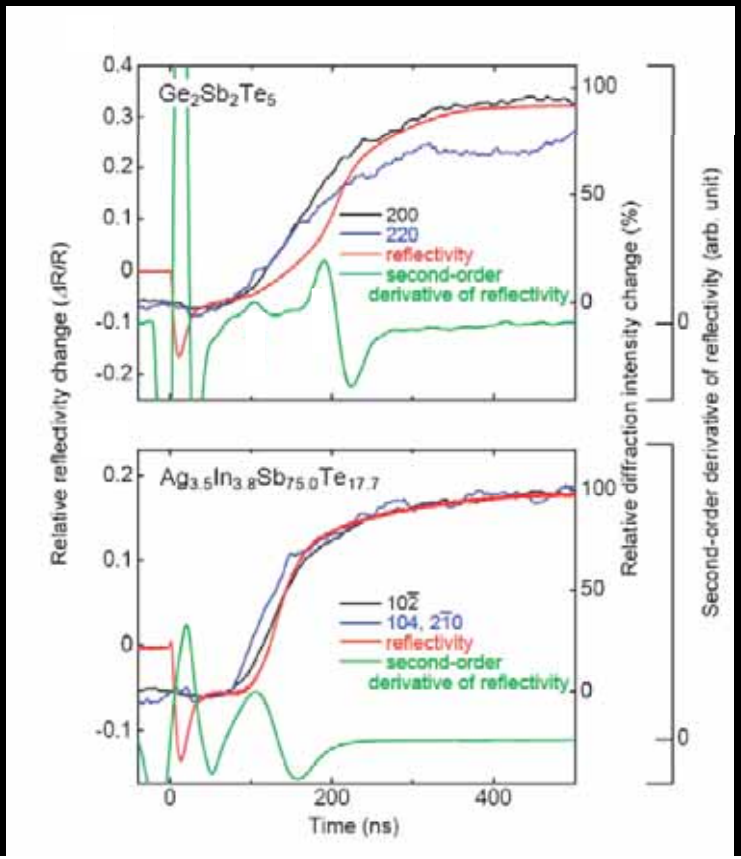


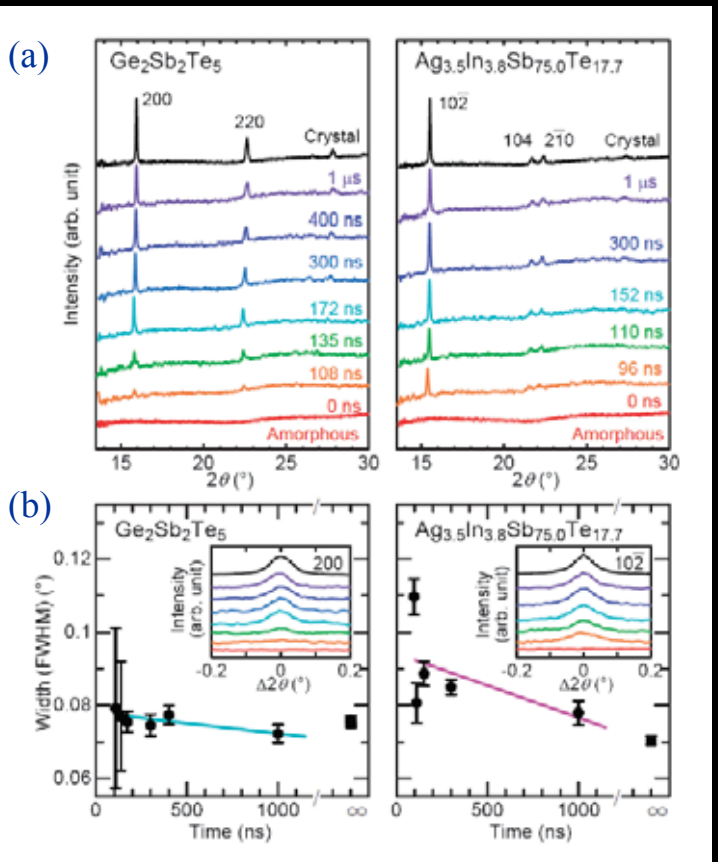
Measurement (MCS &Pump-Probe)

GST225 || $Ge_2Sb_2Te_5$ AIST || $Ag_{3.5}In_{3.8}Sb_{75.0}Te_{17.7}$ (%)

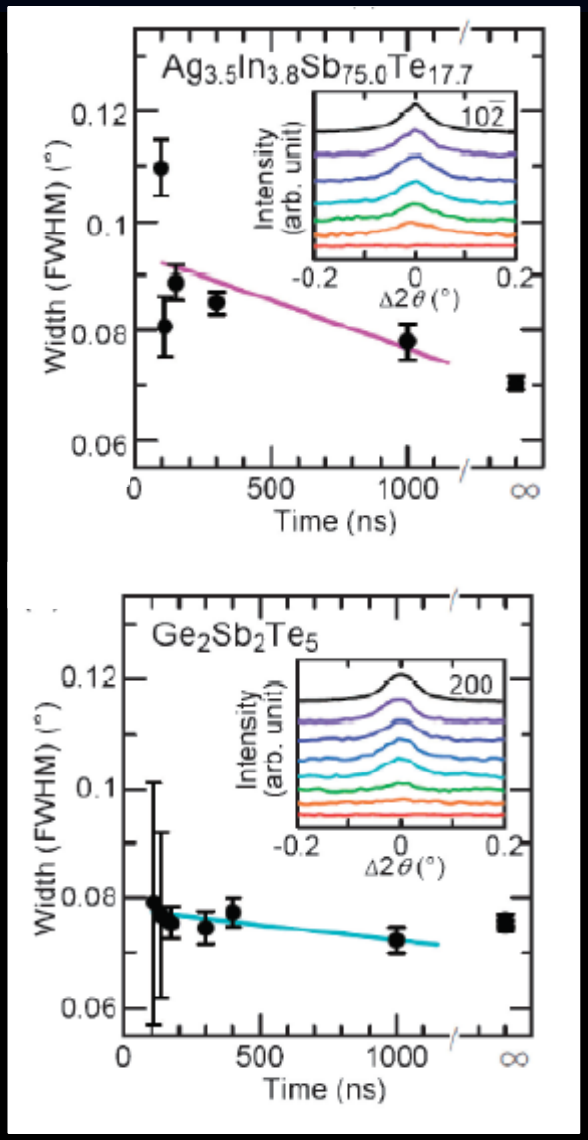


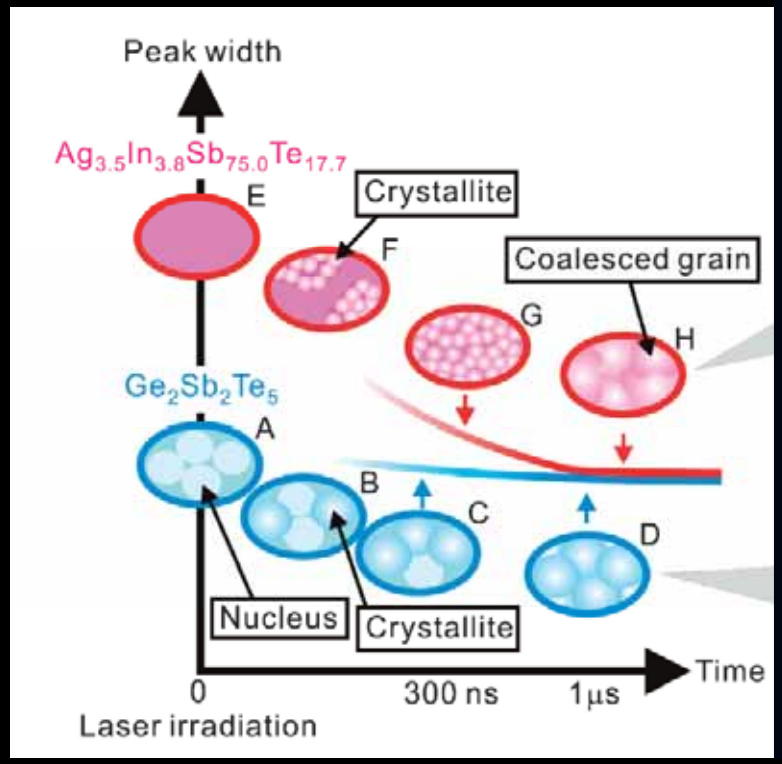






Results and discussion





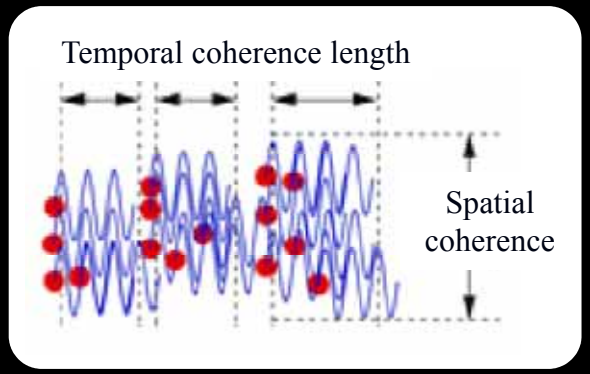
Different crystallization process

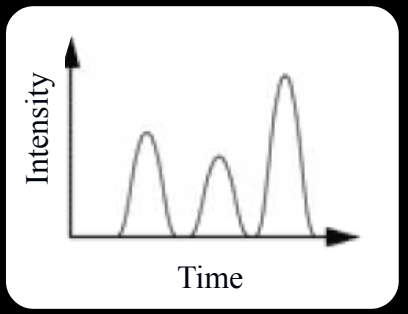
Applied Physics Express, 1, 045001 (2008).
Published in March 14.

3.3. Laser seeding in FEL

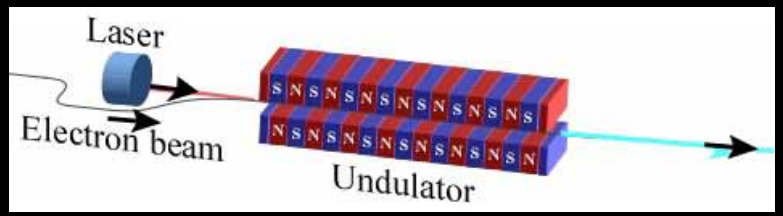
Improving the temporal coherence in single-pass FEL

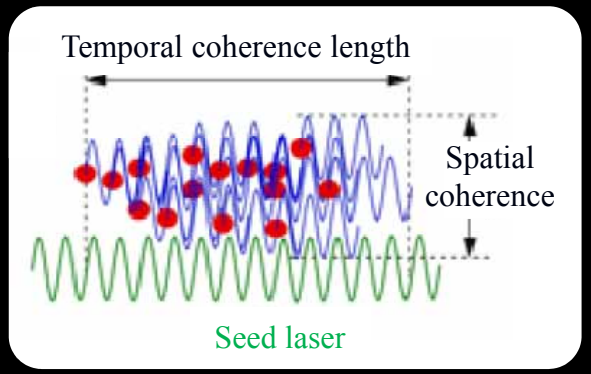
SASE (Self-Amplified Spontaneous Emission)

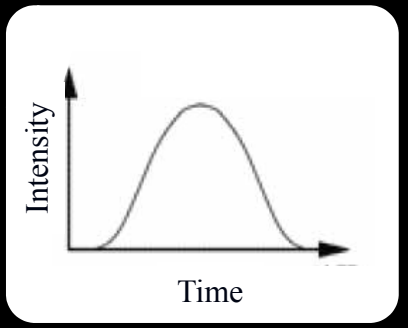




Laser-Seeded SASE





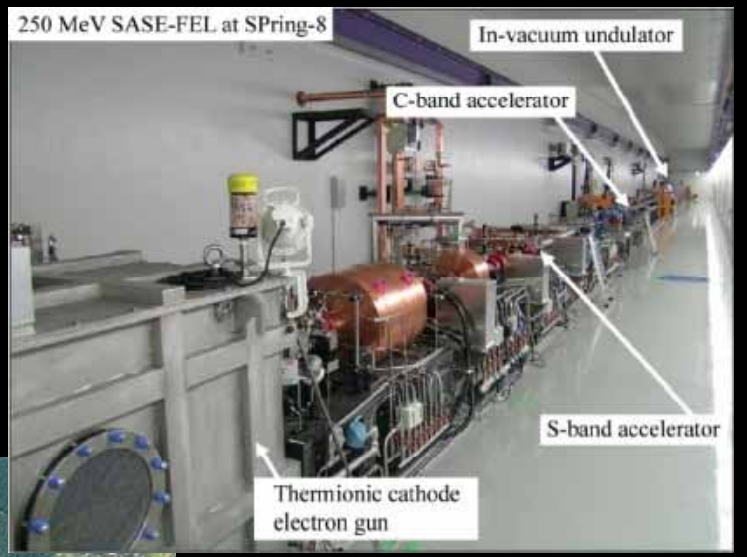


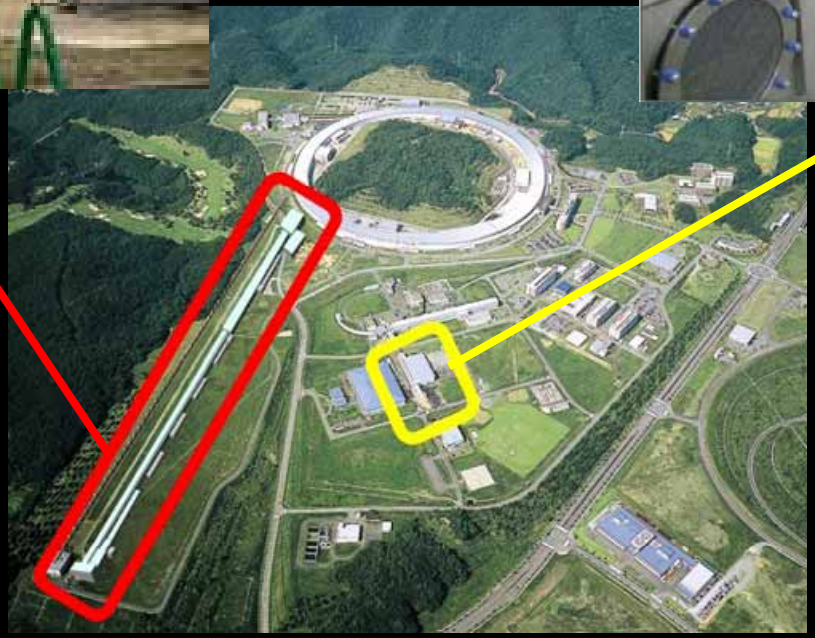
SCSS project in SPring-8

SCSS-XFEL

Under construction

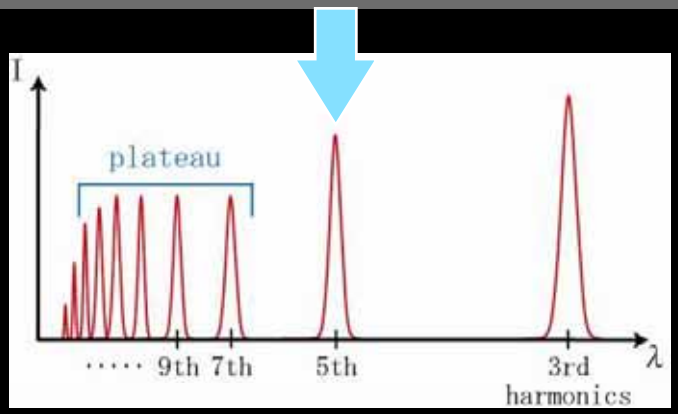
SCSS prototype accelerator



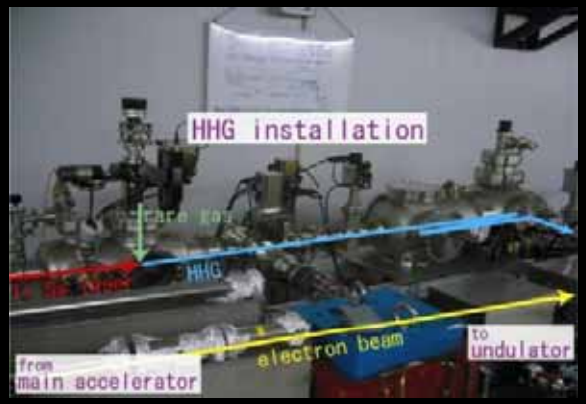


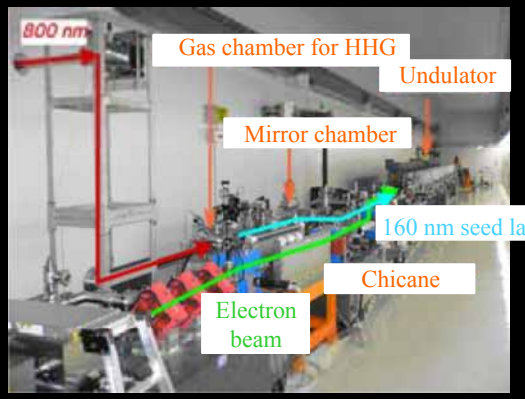
SPring-8 Campus

Seeding with Higher Harmonic Generation in Gas

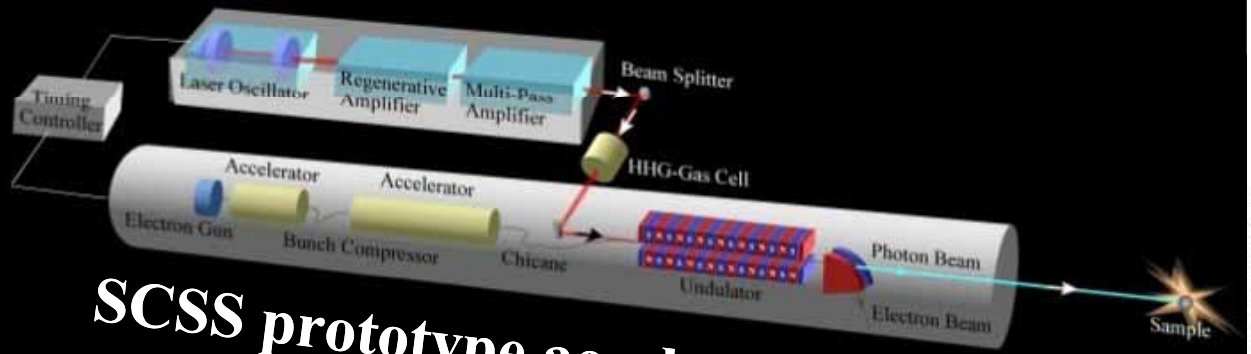


HHG

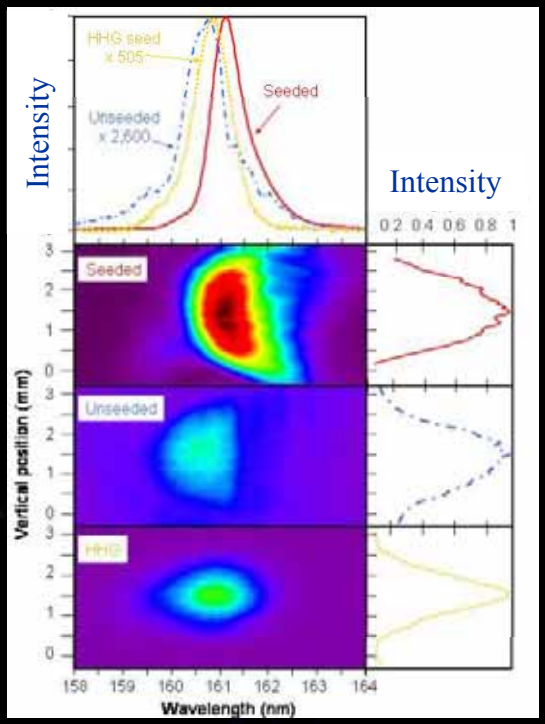




Demonstration in 160 nm

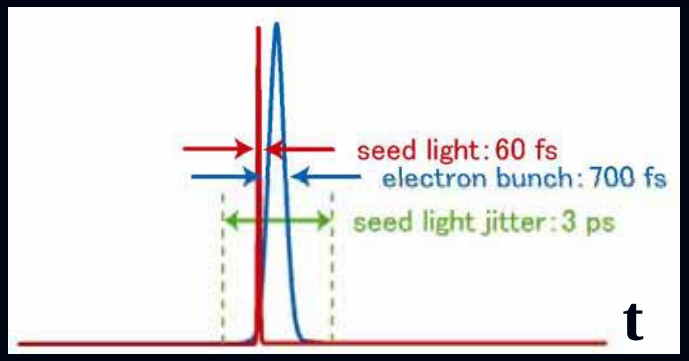


SCSS prototype accelerator

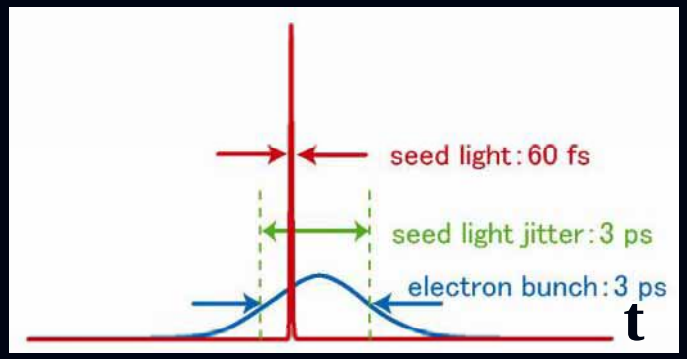


Nature Physics, Online published in March 9

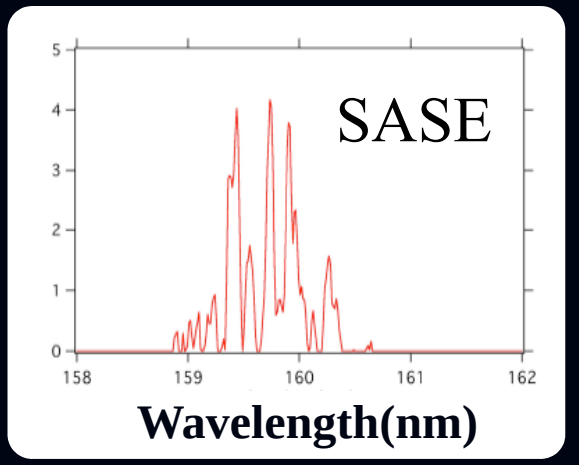
Debunching for stable temporal overlap

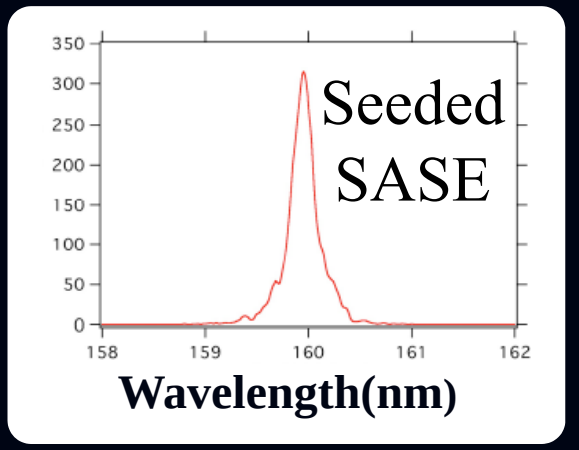


Debunching operation



Stable seeding





Seeded SASE pulse should perfectly be synchronized to the seed laser

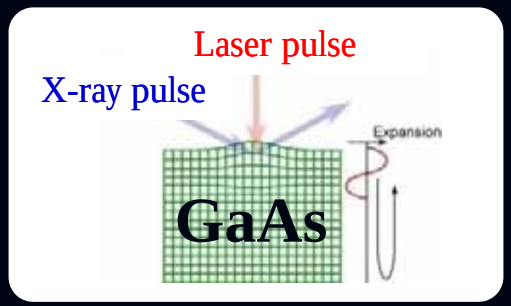
Seed laser pump- seeded SASE probe in femtosecond resolution

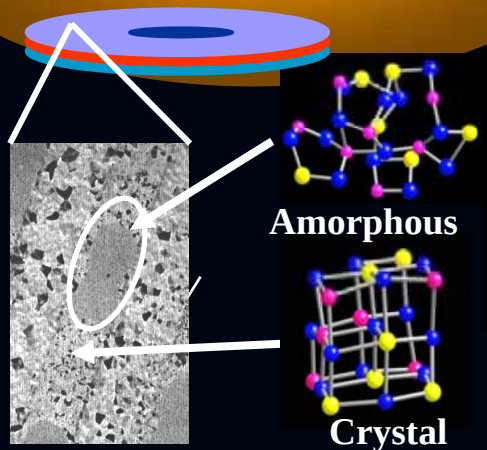
4. Summary of Exps with TR technique in SP8

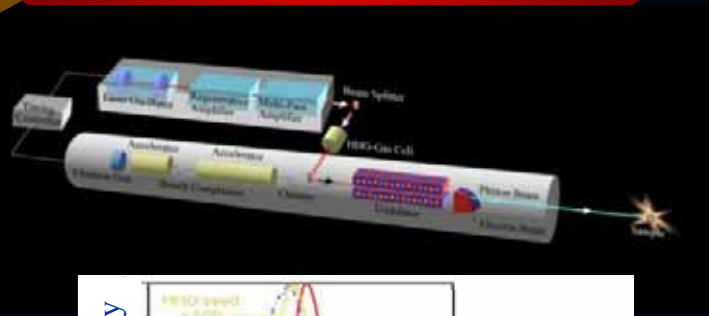
Acoustic echo in semiconduct

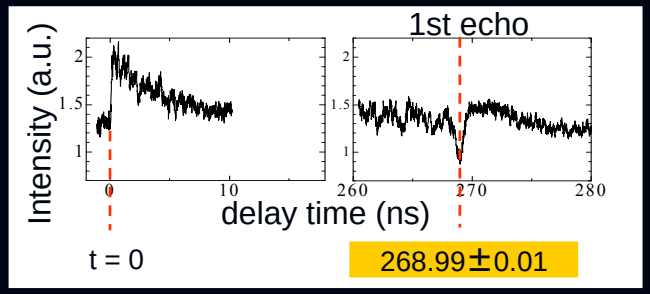
Phase change in DVD media

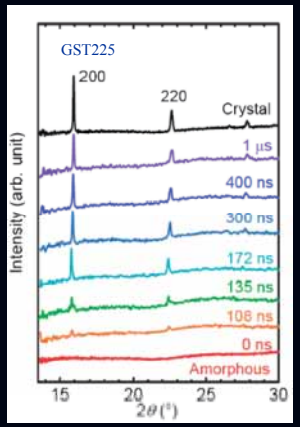
Laser seeding in FEL

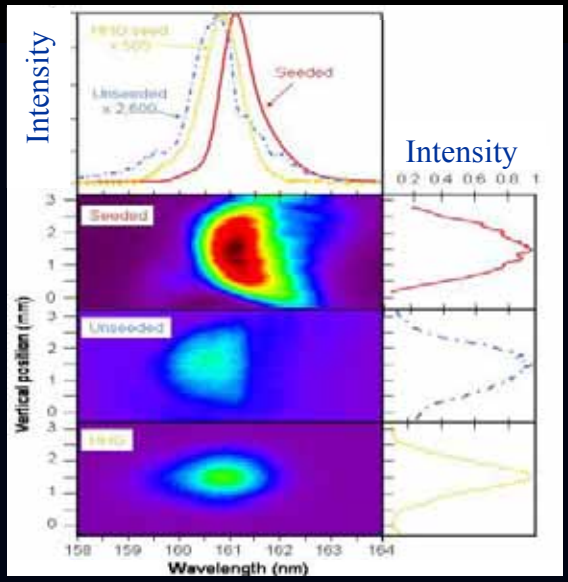












Phys. Rev. Lett. 96 (2006) 115505.
Rev. Sci. Instrum. Accepted on March 17.

Applied Physics Express, 1 (2008) 045001. Published on March 14.

Nature Physics, (2008), Online published on March 9,
DOI：10.1038/nphys88989

Future prospective on technical development

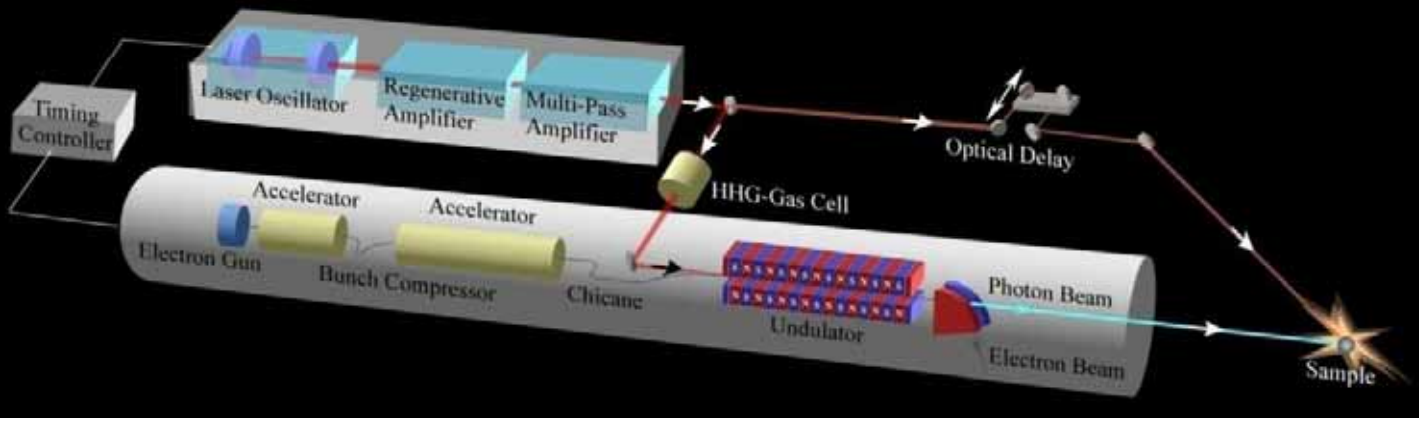
- Combination system with fs lasers in SP8
  - 40 ps resolution
  - Wide time range
  - 5 ps synchronization precision
  - For non-reversible phenomena

ps to fs

- Femtosecond resolution
  - Post processing
  - Jitter free system ?

High rep. rate

- Combination with X-ray microbeam
  - High repetition rate



Thank you

Acoustic pulse echoes in Semiconductors

Laser Seeding in FEL

Yujiro Hayashi (Hokkaido Univ., RIKEN)
Kazuhiko Tahara (Hyogo Univ., RIKEN)
Tetsuya Ishikawa (RIKEN)

M. E. Couprie (SOLEIL, France)
E. Guilllaume (CEA, France)
Toru Hara (RIKEN)
Hideo Kitamura (RIKEN)
Yoshihito Tanaka (RIKEN, CREST)
Yoshimitsu Fukuyama (JASRI, CREST)
Takashi Ohshima (RIKEN, CREST)
Nobuhiro Yasuda (JASRI, CREST)
Yutaka Moritomo (Tsukuba Univ. CREST)
Shigeru Kimira (JASRI, CREST)
Masaki Takata (RIKEN, CREST)
…

Phase change in DVD media