June 25, 2004
Advanced Accelerator Concepts Workshop 2004

Femtosecond Beam Sources and Applications

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University of Tokyo,

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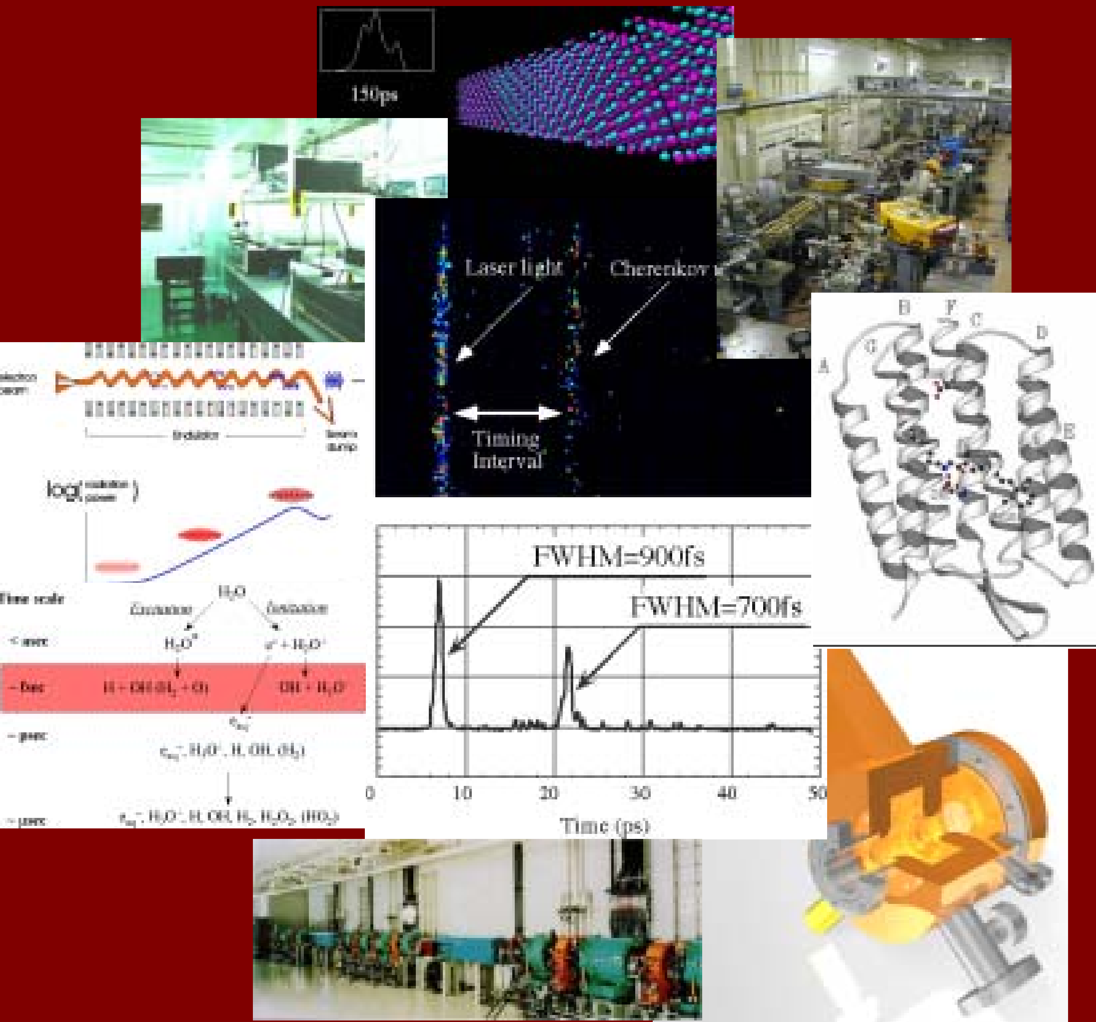
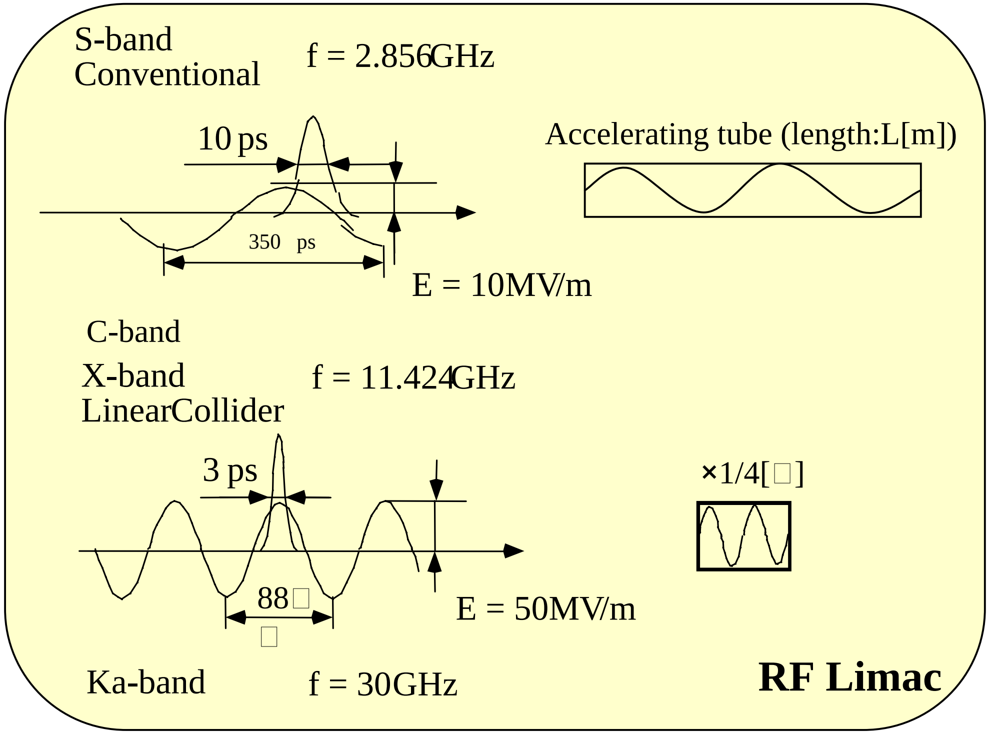
Femtosecond Beam Science

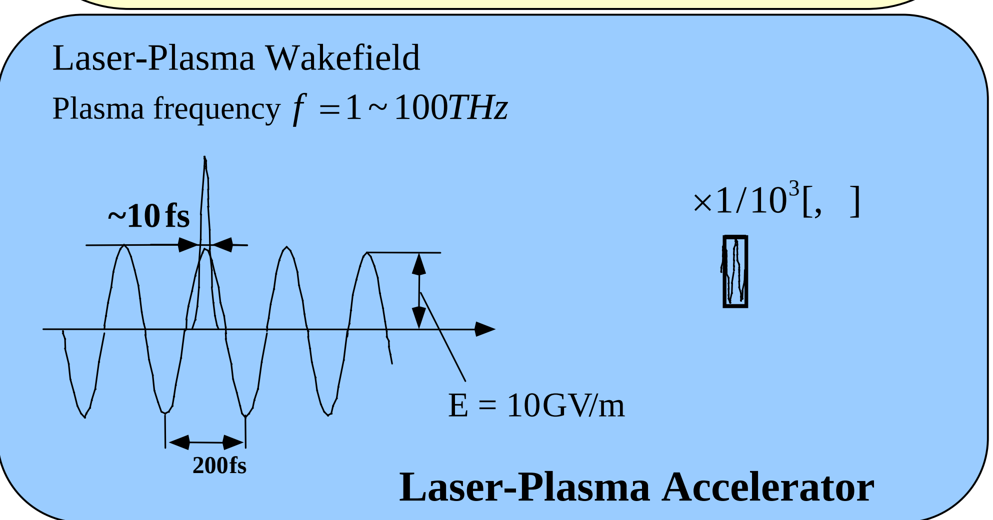


Mitsuru Uesaka(Eds.)
University of Tokyo

Imperial College Press/World Scientific

Short Bunch Generation and Downsizing of Accelerator





T (Kinetic Energy)

= E (Electric field) x L (length)

J (Input RF power) = E^2V(volume of accelerating tube)

f (RF Frequency) $\propto V^{-n}$

T : fixed

J : fixed

shorter L

↓

larger E

↓

smaller V

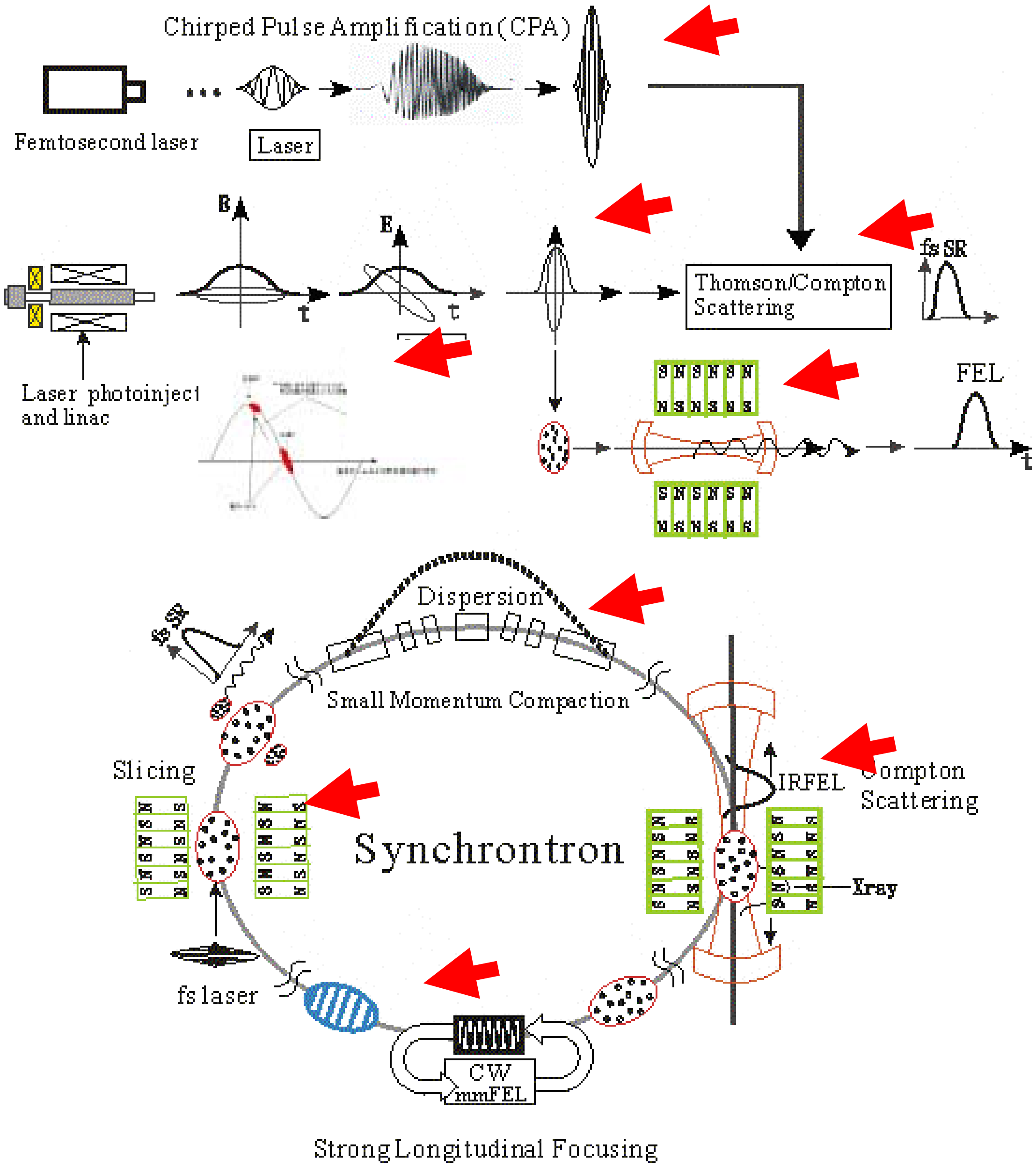
↓

higher f (shorter RF wavelength)

↓

Short pulse generation

Femtosecond Beam Generation at Laser, Linac and Synchrotron



Laser

□CPA(Chirped Pulse Compression)

Linac

□Magnetic Pulse Compression □□□ (relativistic, control of R_{56}) □□□

Velocity Bunching(nonrelativistic)

FEL, IFEL(multibunches)

Thomson/Compton Scattering

Synchrotron

□$z=R_{56}\delta$, $R_{56} \longrightarrow 0$ (isochronous)

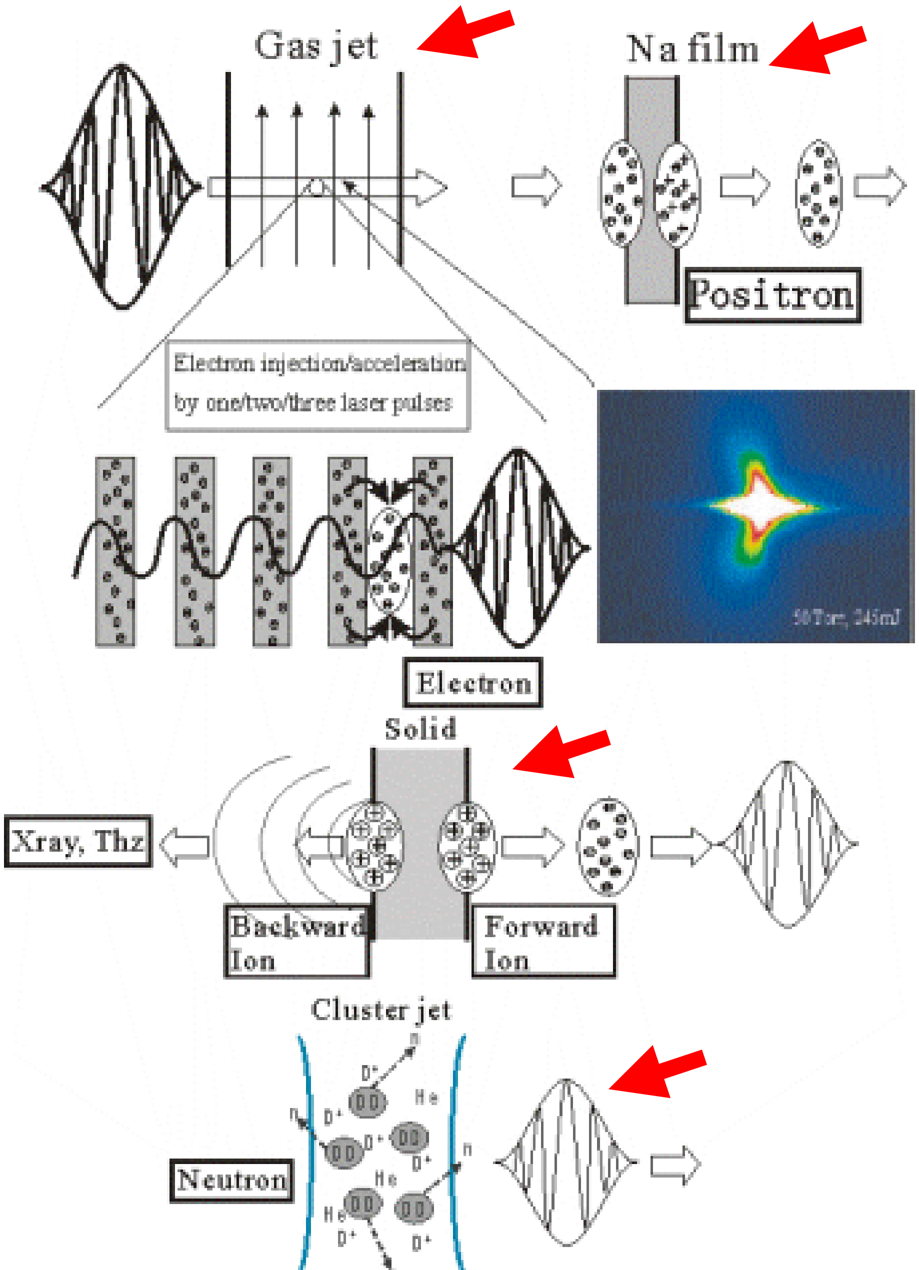
□□**Electron-laser Interaction in Undulator Field**

FEL, IFEL

Slicing

Strong Longitudinal Focusing

Ultrashort Beam Generation by Laser Plasma Acceleration



Electron

□**Gas jet**

Wake field Acceleration

Positron

□**Irradiation of Na film by**

Accelerated Electrons

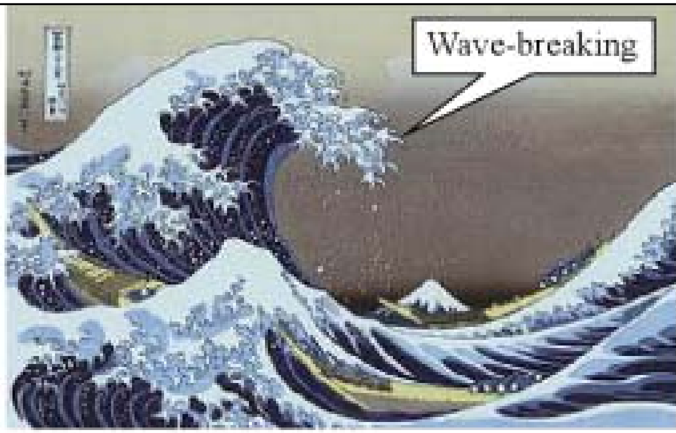
Ion

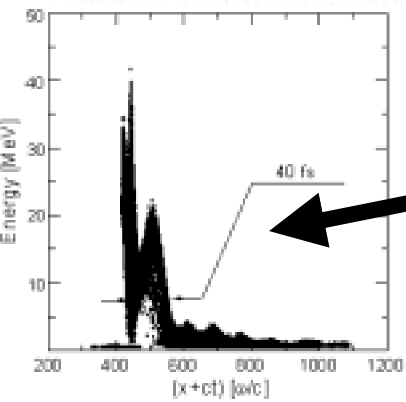
□**Film Target**

Neutron

□**Deutrium Cluster Jet**

Tens Femtosecond or Quasi-Monochromatic Electron Single Bunch by Laser Plasma Cathode (RAL, LBNL, LOA, AIST, U.Tokyo at AAC2004)

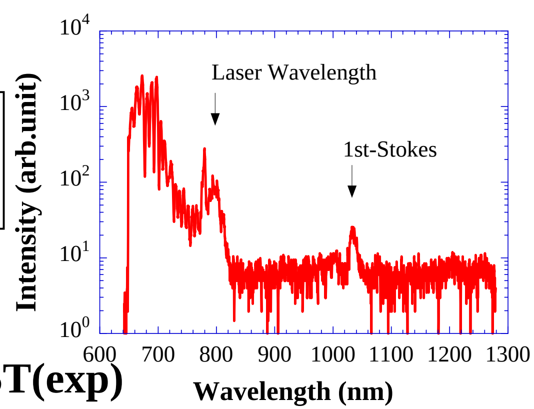




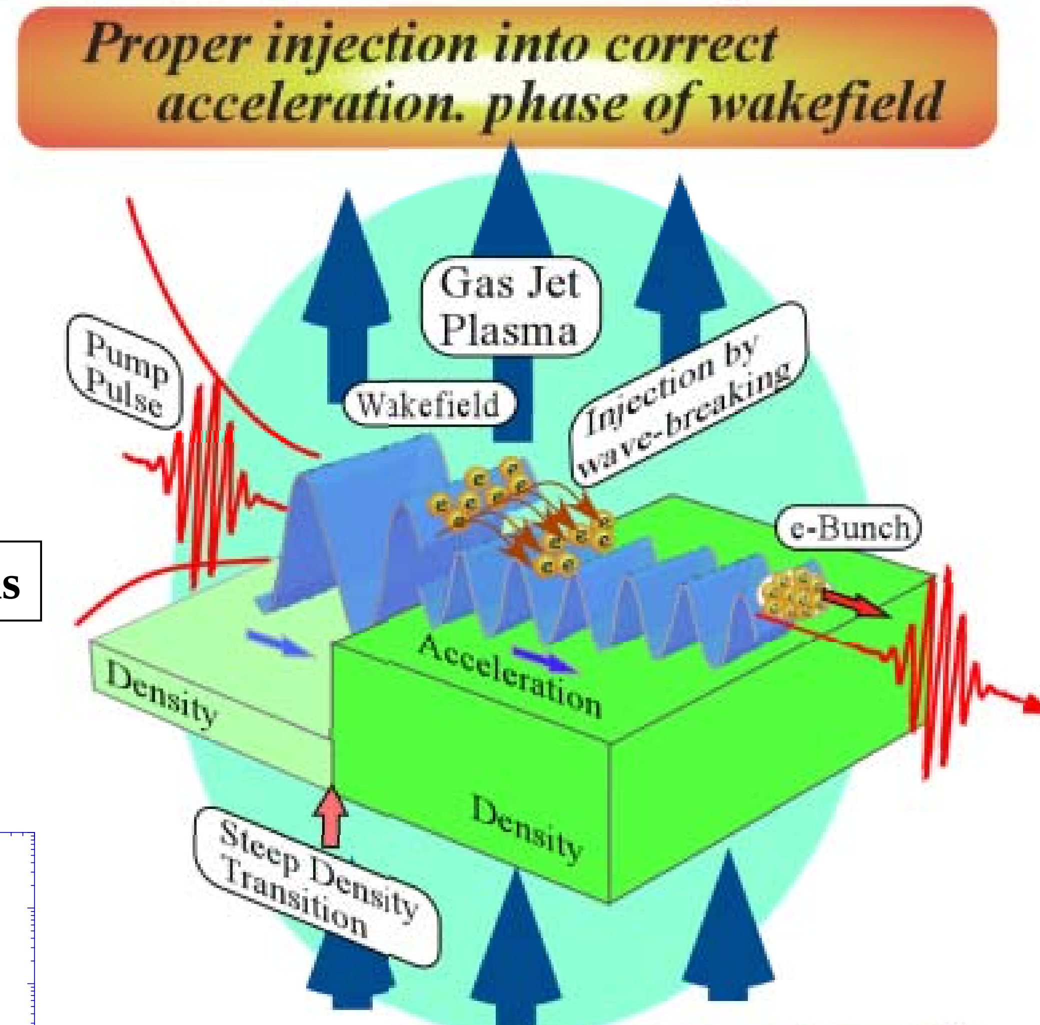
Tens femtoseconds

U.Tokyo(cal)

Quasi-monochromatic

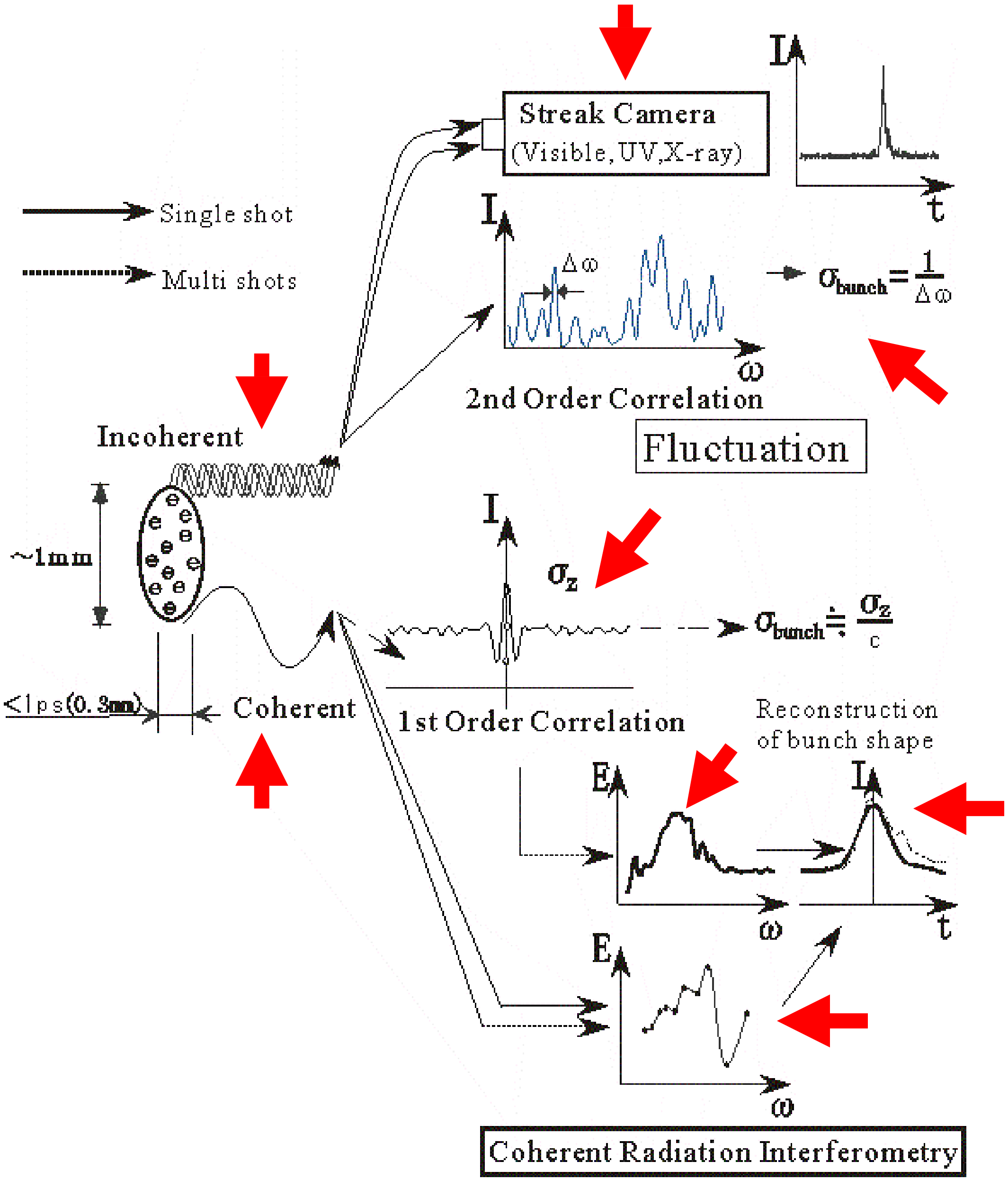


AIST(exp)



Reference : S.V.Bulanov, et al, Phys.Rev.E. 58, R5257

Femtosecond Electron Bunch Diagnostics



Incoherent Radiation

Streak Camera

Fluctuation Method□

2nd Order Correlation

□□□□□↓

□□**Bunch Form Factor**

□□□□□↓

□□□**Bunch Shape**

Coherent Radiation

1st Order Correlation

or

□**Single-shot Acquisition of Spectrum**

□□□□□□↓

□□□**Bunch Form Factor**

□□□□□□↓

□□□□**Bunch Shape**

Theory of Electron Bunch Shape Evaluation by Coherent/Incoherent Radiation

T.Watanabe(BNL-ATF/U,Tokyo)

Radiation electric field
From electron pulse

$$E(\omega) = e(\omega)\sum_{k=1}^{N}\exp(i\omega t_k)$$

$e(w)$ radiation electric field from 1electron $\quad t_k$ probability variable $\quad N$ number of electron

1st order spectrum correlation function

$$\langle E(\omega)E^*(\omega')\rangle = e(\omega)e^*(\omega')\left\langle \sum_{k=1}^{N}\sum_{l=1}^{N}\exp(i\omega t_k - i\omega' t_l)\right\rangle$$

$\langle \ldots \rangle$ shot average

$$= e(\omega)e^*(\omega')\{\underline{\underline{NF(\Delta\omega)}} + \underline{\underline{N(N-1)F(\omega)F^*(\omega')}}\} \quad , \Delta\omega = \omega - \omega'$$

Incoherent factor

Coherent factor

$$\left(\langle \exp(iwt_k)\rangle = \int_{-\infty}^{\infty} \underline{\underline{F(t_k)}}\exp(iwt_k)dt_k = F(w), \quad |F(w)|^2 = \underline{\underline{f(w)}} \right)$$

Pulse distribution function

Bunch form factor

$$= |e(\omega)|^2 N\{1+(N-1)f(\omega)\}$$ Coherent radiation $(\omega = \omega')$

$$= e(\omega)e^*(\omega')NF(\Delta\omega)$$ Incoherent radiation

Radiation electric field From electron pulse $E(\omega) = e(\omega)\sum_{k=1}^{N}\exp(i\omega t_k)$

$e(\omega)$ radiation electric field from 1electron t_k probability variable N number of electron

2nd order spectrum correlation function

$$\left\langle |E(\omega)|^2 |E(\omega')|^2 \right\rangle = e(\omega)e^*(\omega)e(\omega')e^*(\omega')\left\langle \sum_{k=1}^{N}\sum_{l=1}^{N}\sum_{m=1}^{N}\sum_{n=1}^{N}\exp[i\omega(t_k - t_l) + i\omega'(t_m - t_n)]\right\rangle$$

$$= |e(\omega)|^2 |e(\omega')|^2 N^2 \left(1 + |F(\Delta\omega)|^2\right)$$

$$= |e(\omega)|^2 |e(\omega')|^2 N^2 (1 + f(\Delta\omega))$$

Example spectrum correlation by P.Catravas

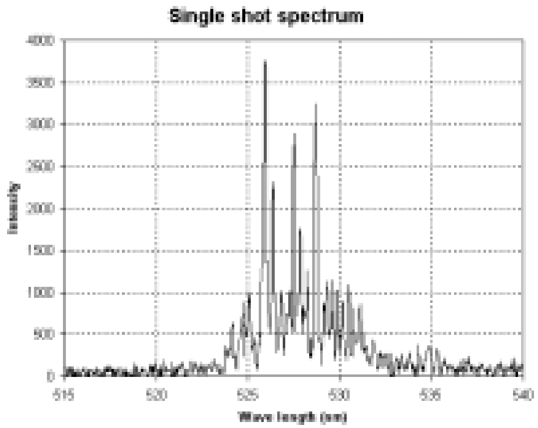
$$C_{meas} = \frac{\langle I(\omega_i)I(\omega_{i+n})\rangle}{\langle I(\omega_i)^2\rangle} = \frac{\left\langle |E(\omega)|^2 |E(\omega')|^2 \right\rangle}{\left\langle |E(\omega)|^4 \right\rangle}$$

$$\Rightarrow \quad C_{meas} = \frac{I_0(\omega')\{1 + f(\Delta\omega)\}}{2I_0(\omega)}$$

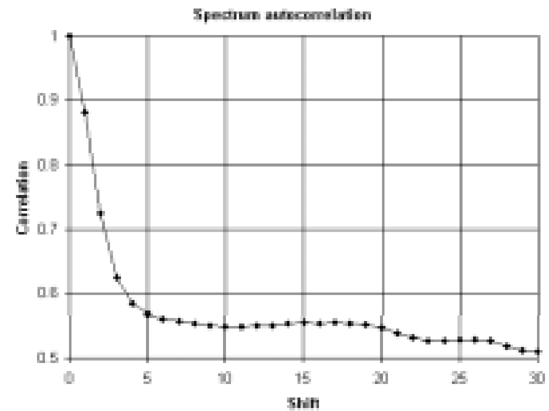
Bunch form factor

* P. Catravas, et al., Phys. Rev. Lett. 82 (1999) 5261.

Bunch Length Measurement by Fluctuation Method(ANL)



Example of the single-shot spectrum



Autocorrelation of the spectrum
Horizontal axis : pixel size of the CCD
(1pix= 2.4×10^{11} rad/s)

Measure the spectrum of the incoherent radiation

↓

The width of the spike is corresponds to the pulse width $\sigma_t \sim 1/2\delta\omega$

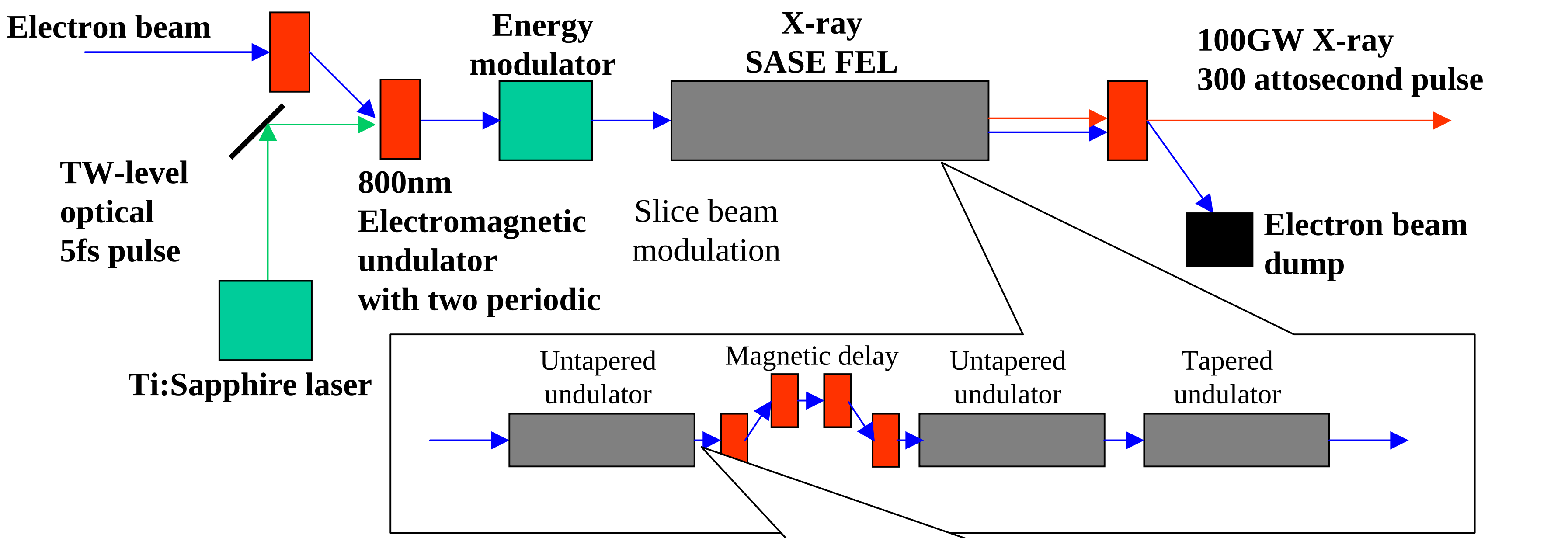
↓

Pulse width ~ 4.5 ps FWHM

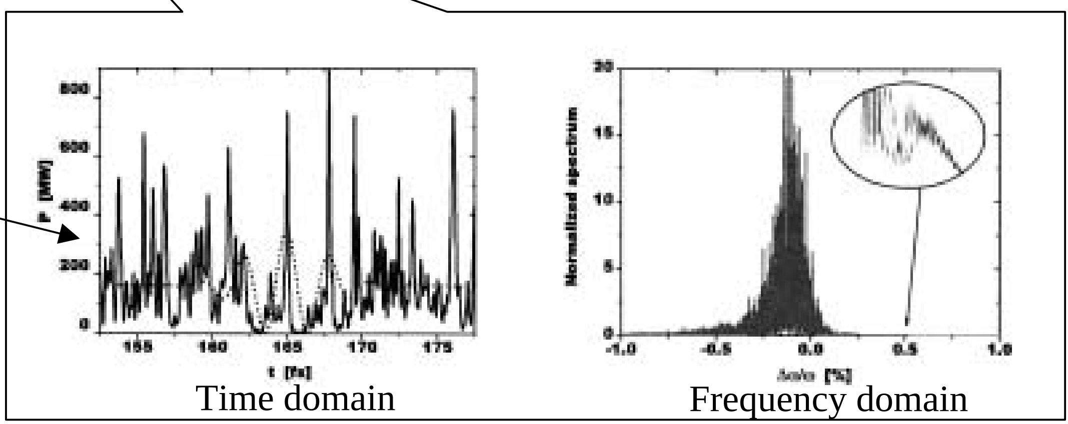
Sajaev et al., EPAC2000

Femtosecond electron bunch measurement by fluctuation method at DESY-TESLA-TTL

Saldin, Schneidmiller and Yurkov DESY)



Slice beam modulation is clearly seen



Frequency detuning of the spike corresponding to time (slice pulse length)

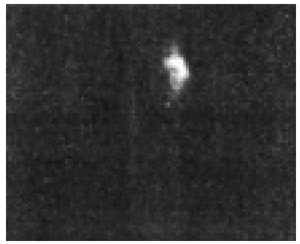
$$t = 30 \quad 50\text{fs}$$

Temporal and spectral evolution of the radiation pulse along the undulator

Past / Present /Future of Streak Measurement

•Space charge effects limit the time resolution.

Low Accel. Voltage



High Accel. Voltage

B.E.Carlsten et al., Micro bunches workshop (1995) p21

C4575-01

(Hamamatsu Photonics)

10 kV/1.6mm

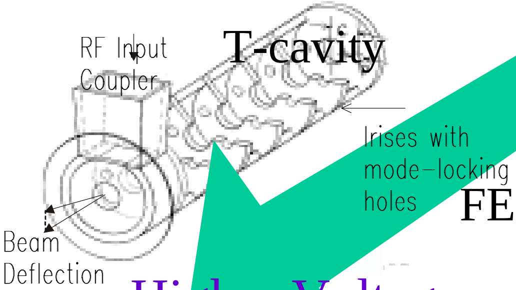
Resolution: ~ ps

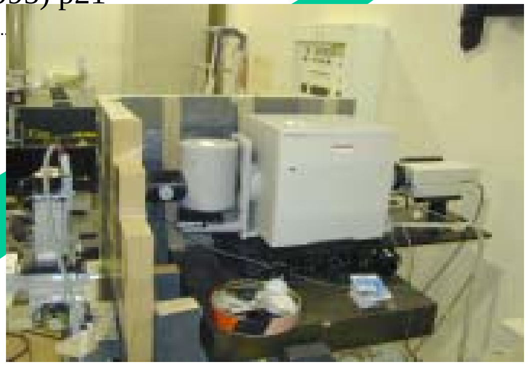
Sweep velocity on the Phosphor

28mm/0.1ns (2.8×10^8 m/s)

Accelerator Voltage: High

Time resolution: Low





FESCA200 (Hamamatsu Photonics)

15 kV/1.6mm

Resolution: ~200 fs

Sweep velocity on the Phosphor

10mm/20ps (5×10^8 m/s)

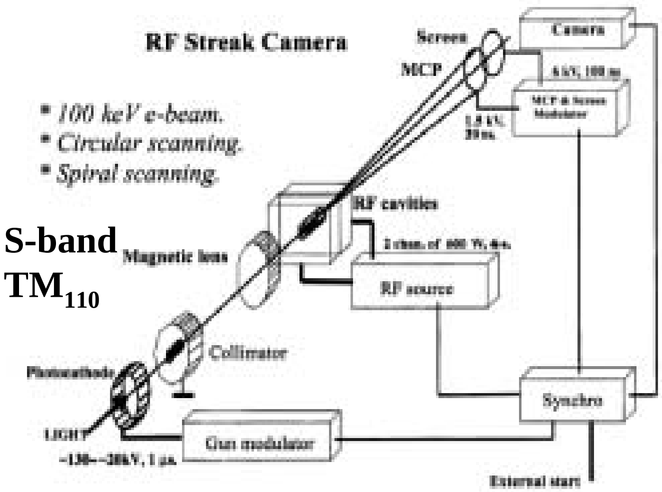
Higher Voltage

to suppress

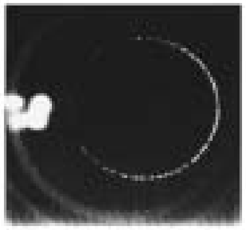
space charge force

S-band

TM_{110}



Radio Frequency based streak camera.



A.V. Aleksandrov et al.
RSI 70 (1999) 2622.
P.Bak et al.,
Laser Part. Beam 19(2001) 105.

Under development

50 fs resoluted Camera and Attosecond Streak Camera
(Hamamatsu Photonics/ U. Tokyo)

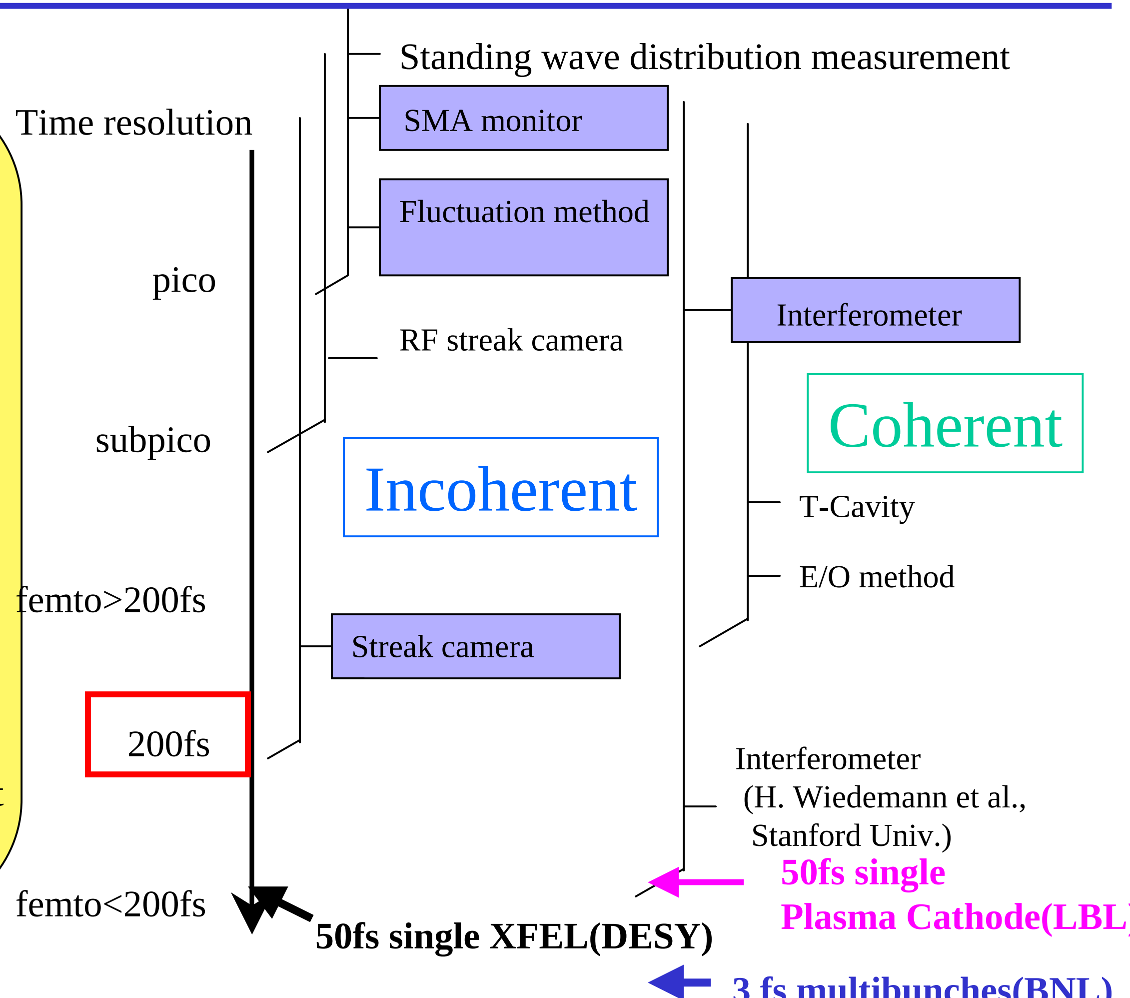
Methodology and Resolution of Pulse Length Measurement

□ Bunch length measurement method

○ Radiation techniques
□- Streak camera
□- Interferometer
□- Fluctuation method

○ RF techniques
□- Zero-Phasing method
□- RF streak camera
□- T-Cavity

○ Electric field of electron techniques
- SMA monitor
□- Standing wave distribution measurement
□- E/O method



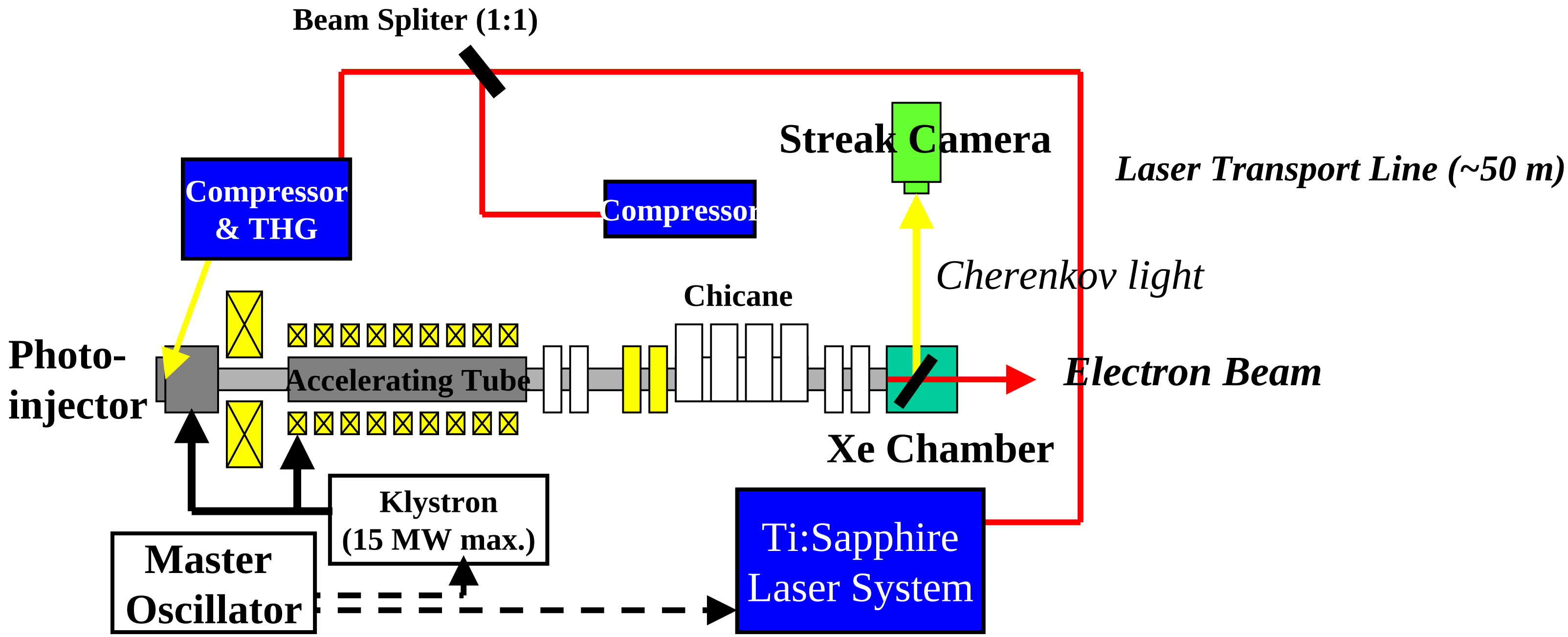
○ Radiation techniques
□- Streak camera
□- Interferometer
□- Fluctuation method

Suitable!!

Experiment of 10fs electron pulse generation from plasma cathode

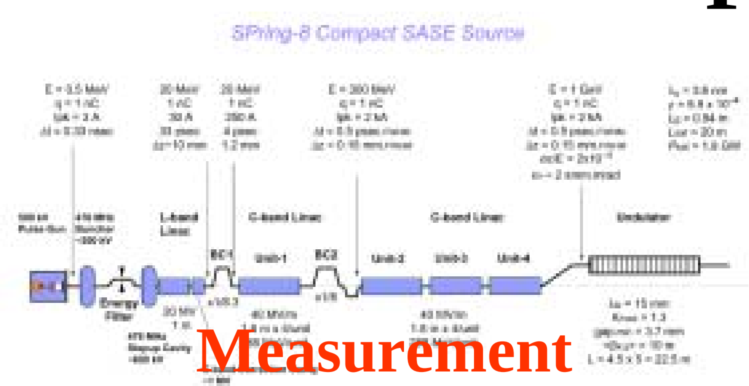
Size of Measurement System

Past/Present



Future

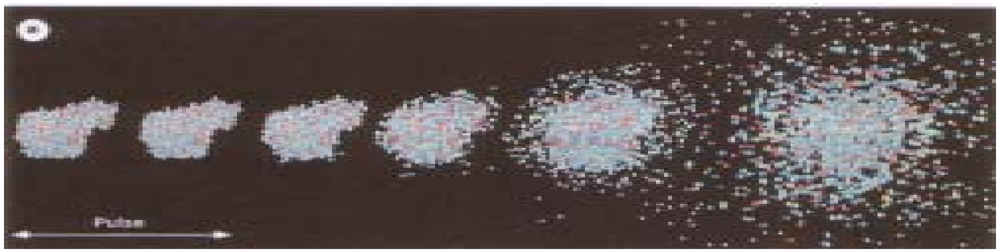
Advanced Measurement Concepts Workshop 2040???



Applications

Single Shot Imaging

In-situ observation at any time

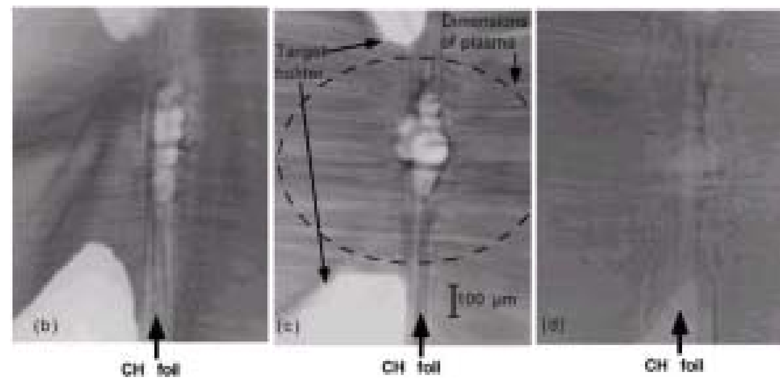


-2fs 2fs 5f 10fs 20fs 50fs

Simulation of single shot imaging of protein by X-FEL

Intense Beam by Large System

Irreversible process



Laser Ablation Process by 7.5 MeV Laser Plasma Ions

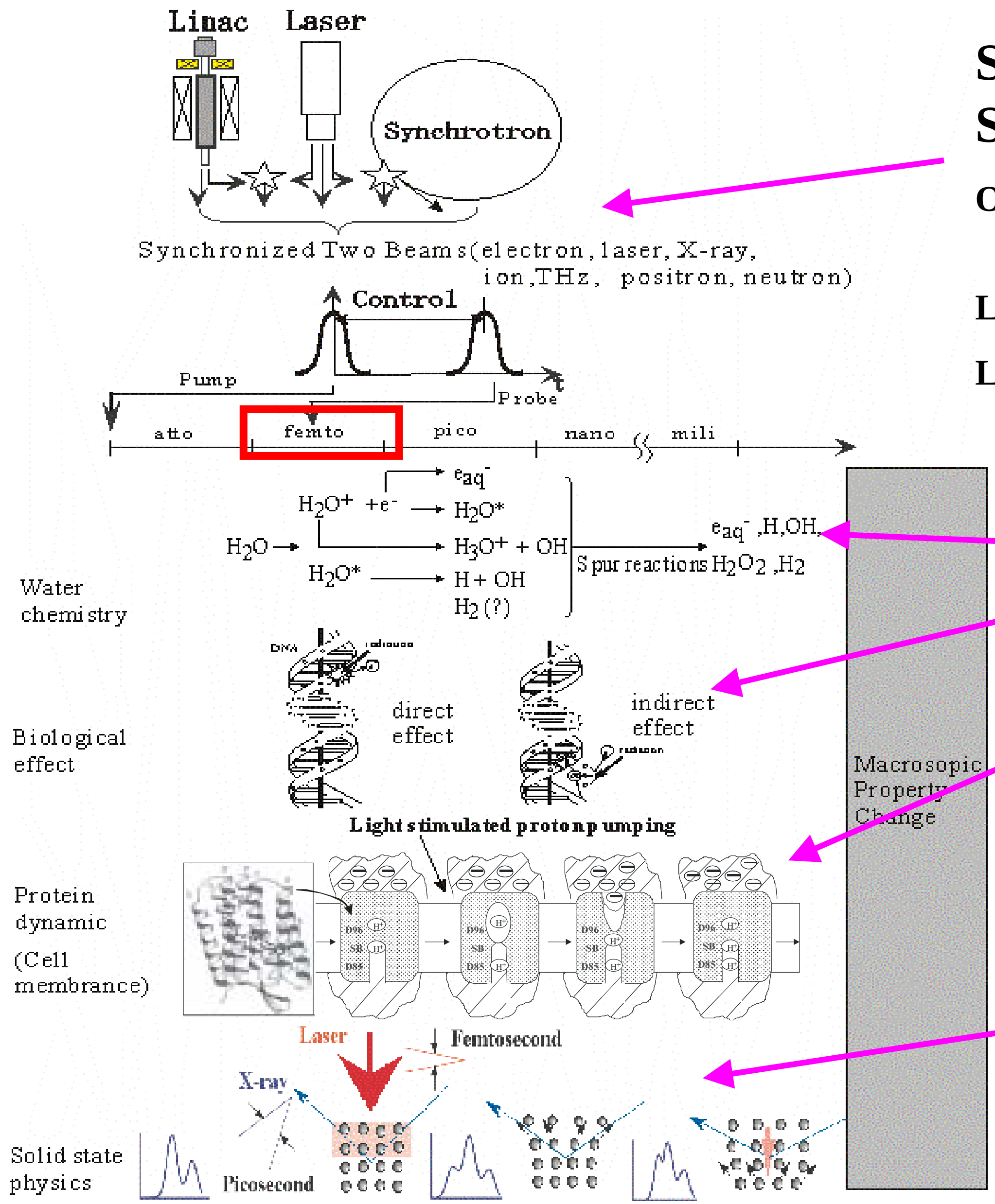
M. Borghesi, et al., Phys. Rev. Lett. 88, 135002 (2002).

Pump-and-probe analysis

Reversible process

Available by Beam Sources of Moderate Intensity and Size

Femtosecond Pump –and-Probe Analysis



Synchronization of Laser, Linac and Synchrotron

Only Laser : Complete synchronization with beam splitter

Laser vs Linac : 300fs (a few min,), 1ps (a few hour))

Laser vs synchrotron : a few ps

Radiation Chemistry

Liquids : ps order & fs order (under way)

Biological effect : μs order (not yet)

Dynamics of Protein

fs : laser (under way)

μs : SR (under way)

ps - ns : not yet

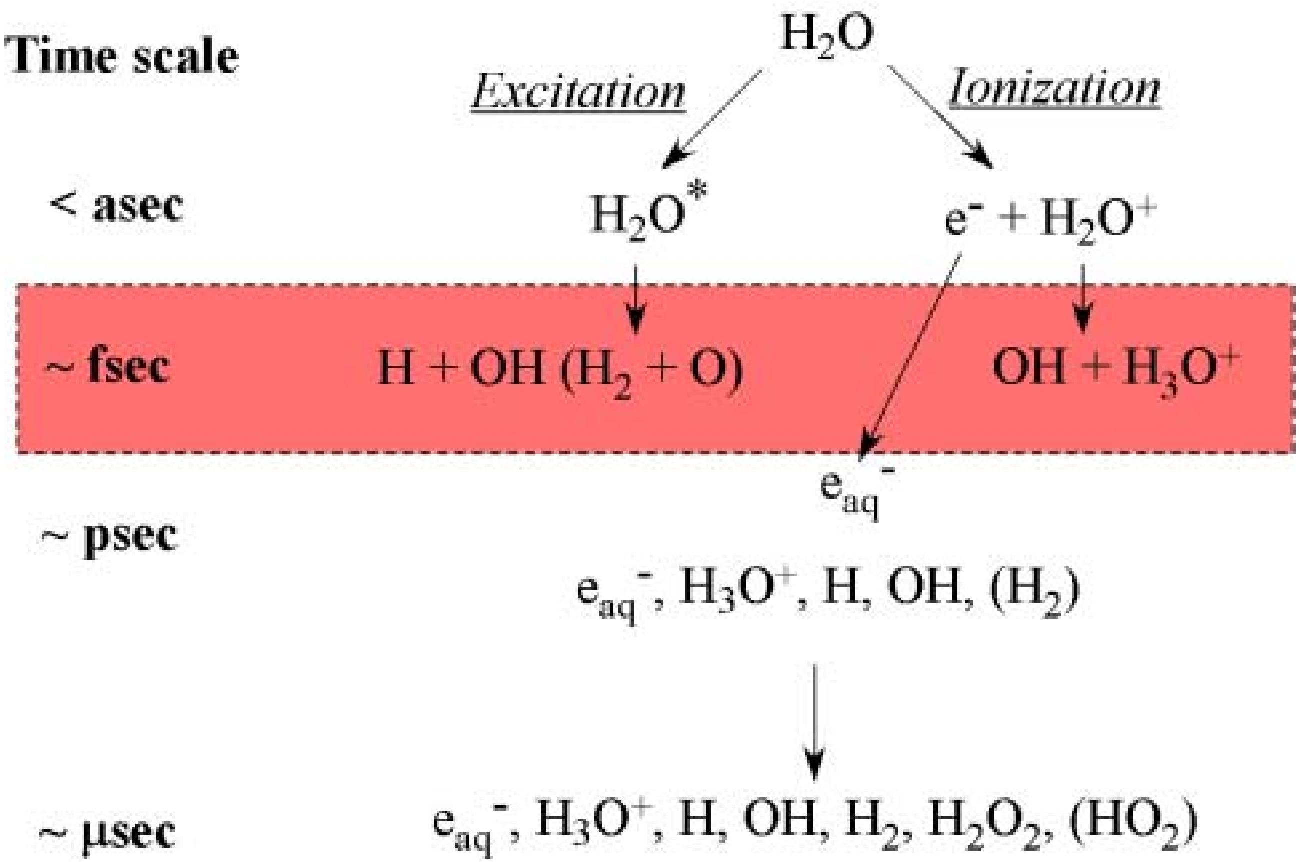
Dynamics of Phonon

>50ps : Laser-plasma Cu Kα X-ray (done)

<50ps : not yet

Chemical Reaction of Water

U.Tokyo, Osaka U., ANL, BNL, U.Pari-Sud, Waseda U, etc.



Final target !

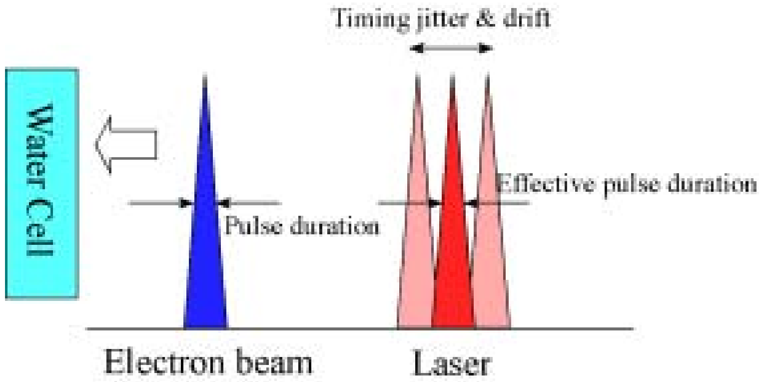
Hot Water Chemistry in Nuclear Reactor
to avoid Stress Corrosion Cracking
in 1970-1990.

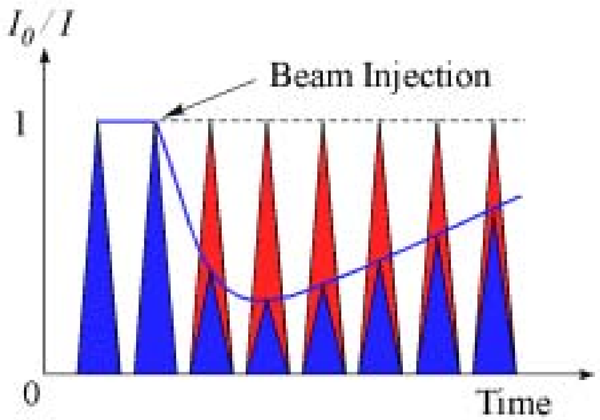
→

Supercritical Water Chemistry
For Compact Nuclear Reactor
and Environmental Science

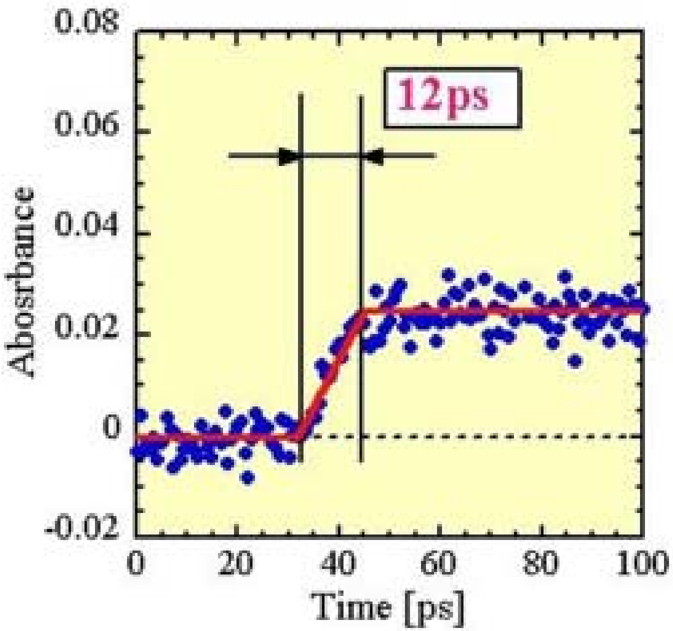
Radiation Chemistry

Pulse radiolysis method





Chemical reaction of water

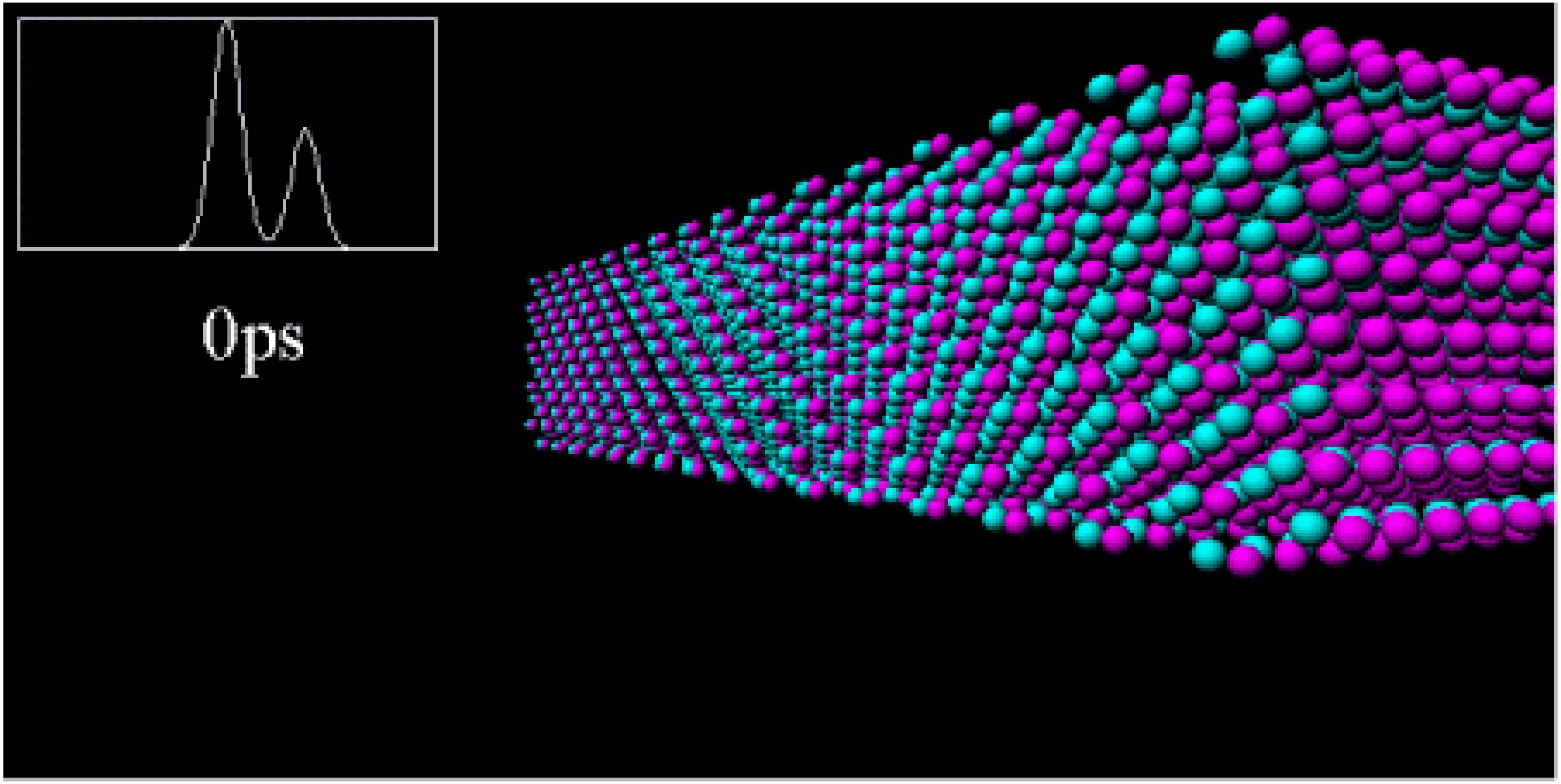


Systematic time-resolution is 12 psec !

Workshop on Ultrafast Accelerators for Radiation Chemistry in BNL on June 26, 27 chaired by Dr.J.Wishart

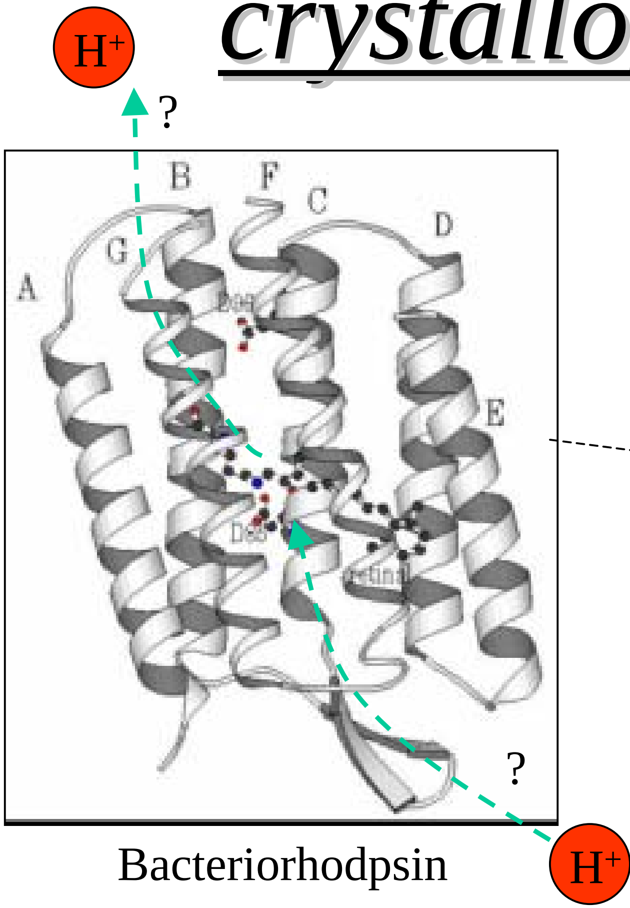
4D Microscopy of GaAs Lattice Dynamics

Kinoshita, K. et al., Laser Part. Beams 19(2001)

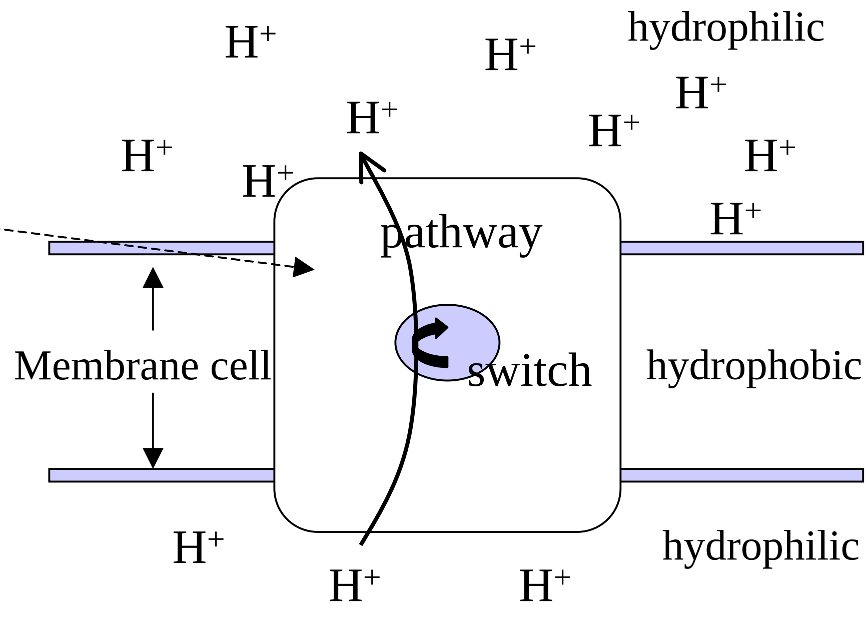


Related Refs. Rischel, C. et al., Nature(1997)
Rose-Petrick, C. et al., Nature(1999)
Hironaka, Y. et al., Jpn.J.Appl.Phys.(1999)

Time-resolved X-ray crystallography of photoactive-proteins



Bacteriorhodpsin



Proton pump

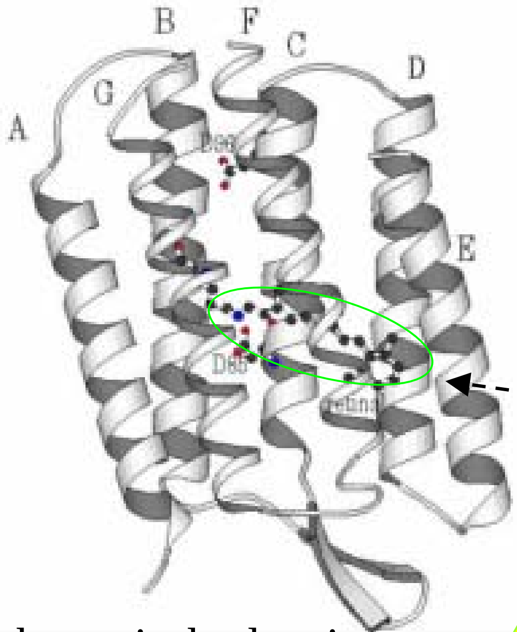
Membrane protein exists in the cell of extremely halophilic bacteria.

It has a function of a proton pump.

The bacteria live using pumped charge.

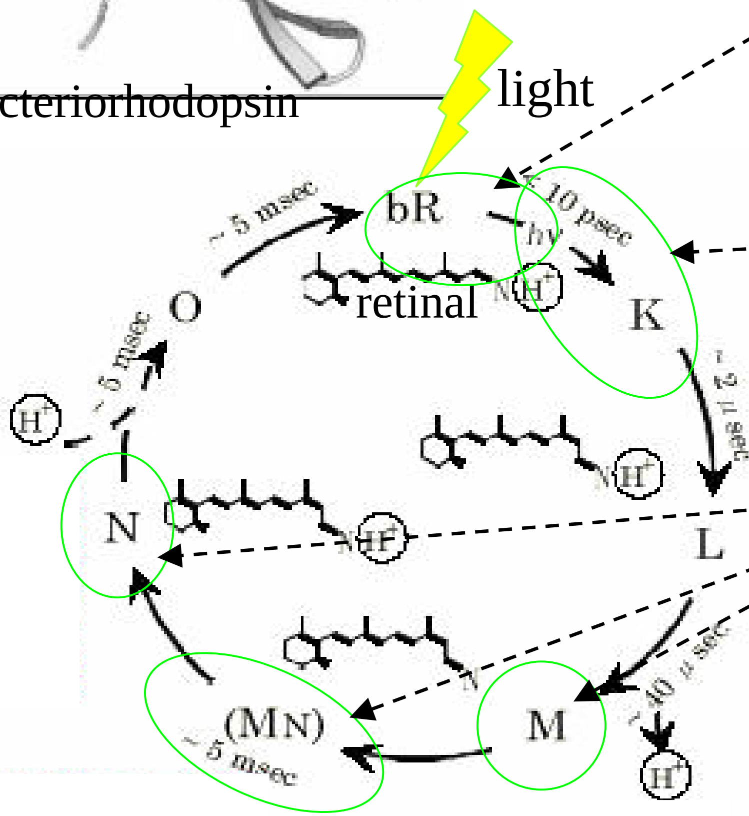
Example; make up ATP(Adenosine TriPhosphate)

Time-resolved X-ray crystallography of photoactive-proteins



bacteriorhodopsin

light



photocycle

Local structural change

Time scale ; fs ~ ps

Exam. fs(~5fs) pulse laser

T.Kobayashi et al,NATURE,2001

Our aim by laser plasma X-ray source.

Time scale ; <10ps

Total structural change

Time scale ; μs ~ ms

Exam. Third generation synchrotron radiation light source

Toshihiko Oka.et,al PANS,2000

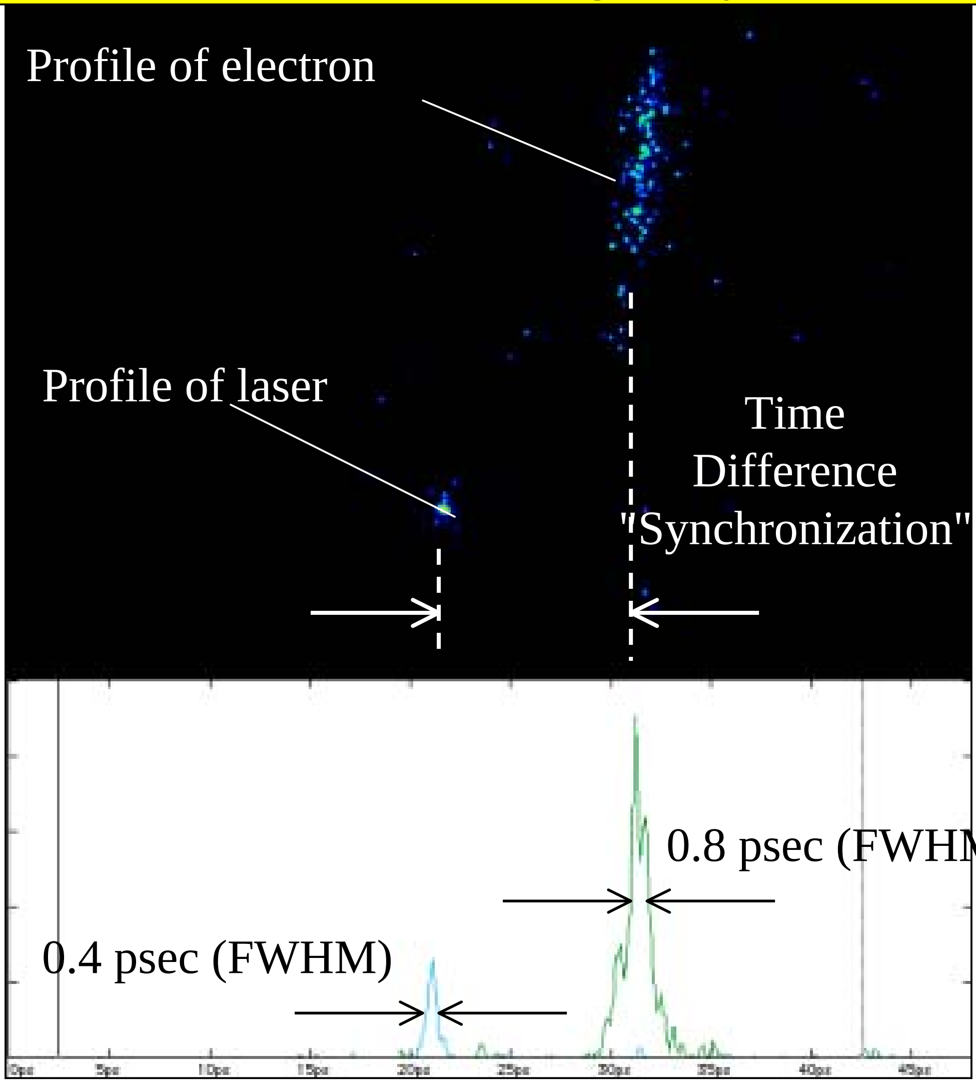
Synchronization

Accelerator

vs

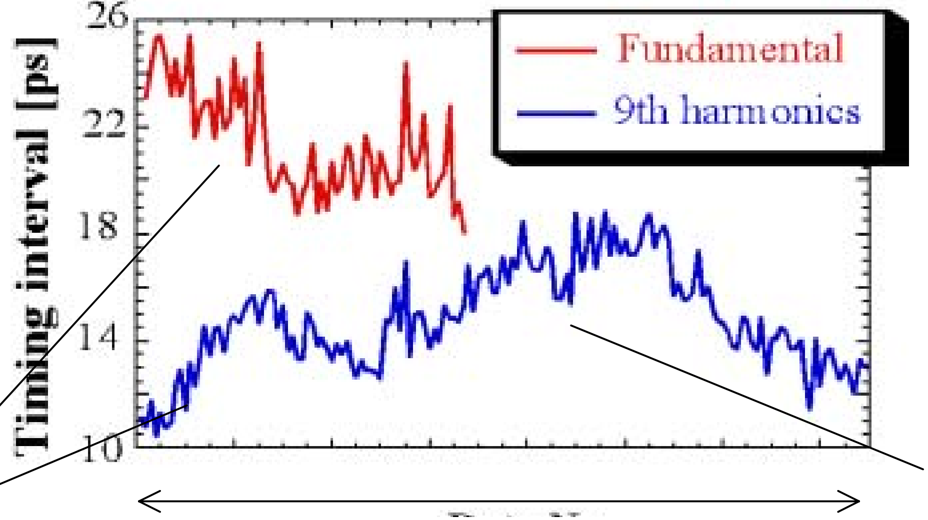
Laser

Femtosecond Streak Camera Image of Synchronization



Timing Jitter and Drift

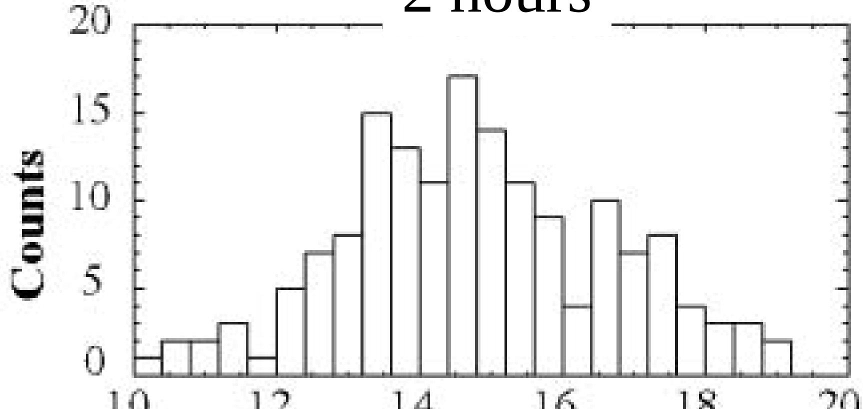
Timing interval between RF and laser



Timing jitter was suppressed.

Timing drift of long term was left.

2 hours

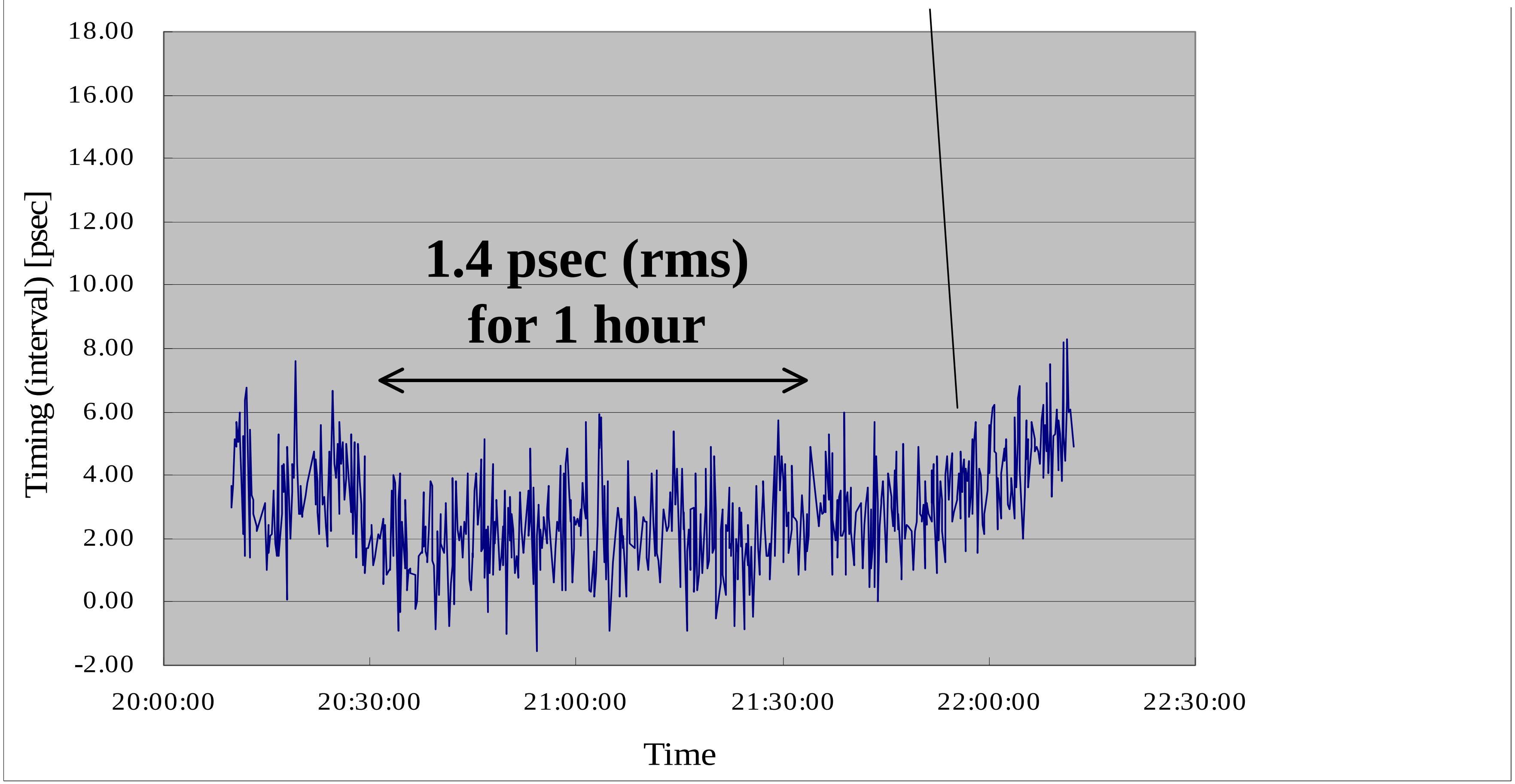


The phase-lock of higher harmonics suppresses the timing jitter, but the timing drift was remained.

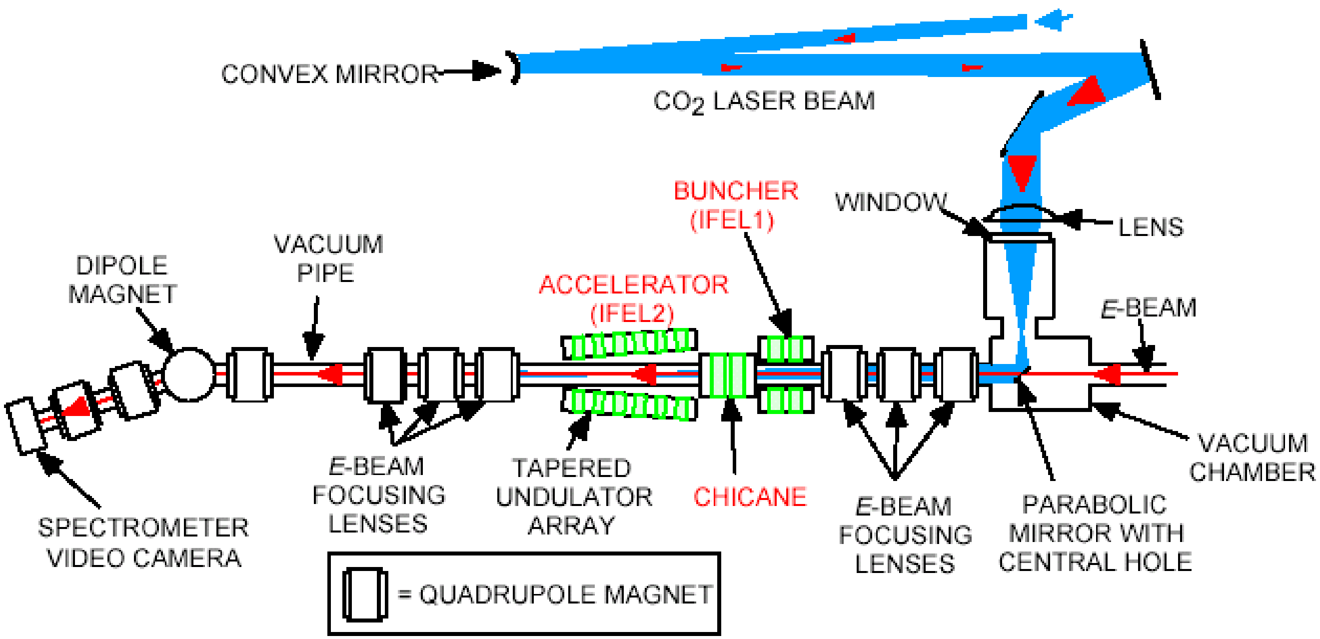
Stable Synchronization

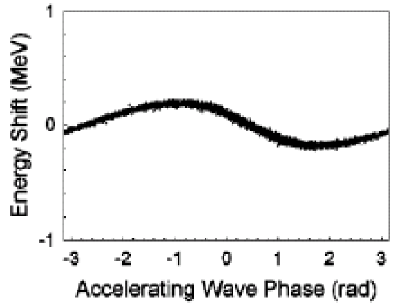
~ Result of transport line improvement~

The pressure effect due to evacuated transport line was suppressed.
The expansion and contraction effect due to temperature was left.

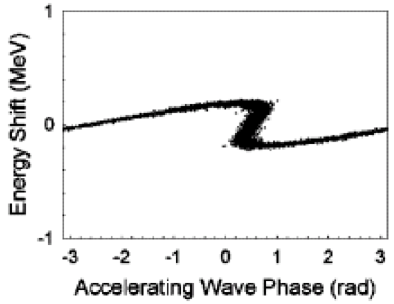


Laser Seeded Staged Accelerator

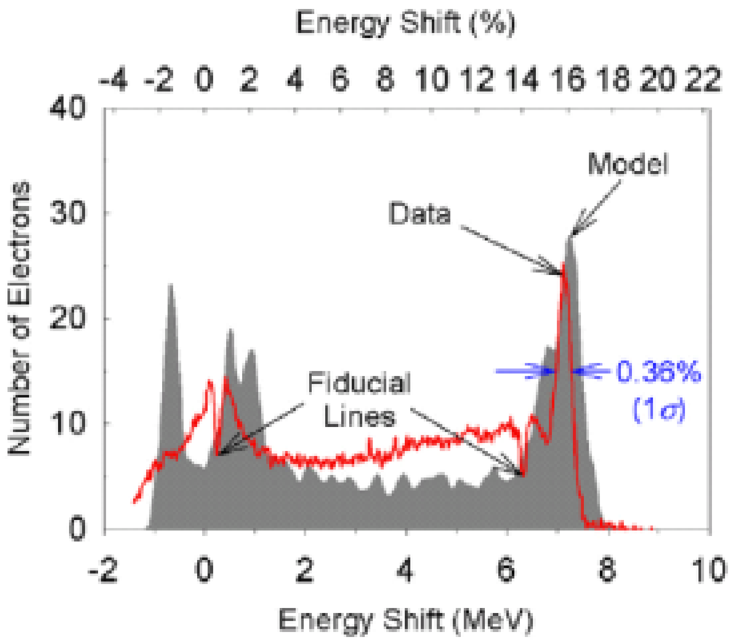




Modulation (IFEL1)



Compression (Chicane)



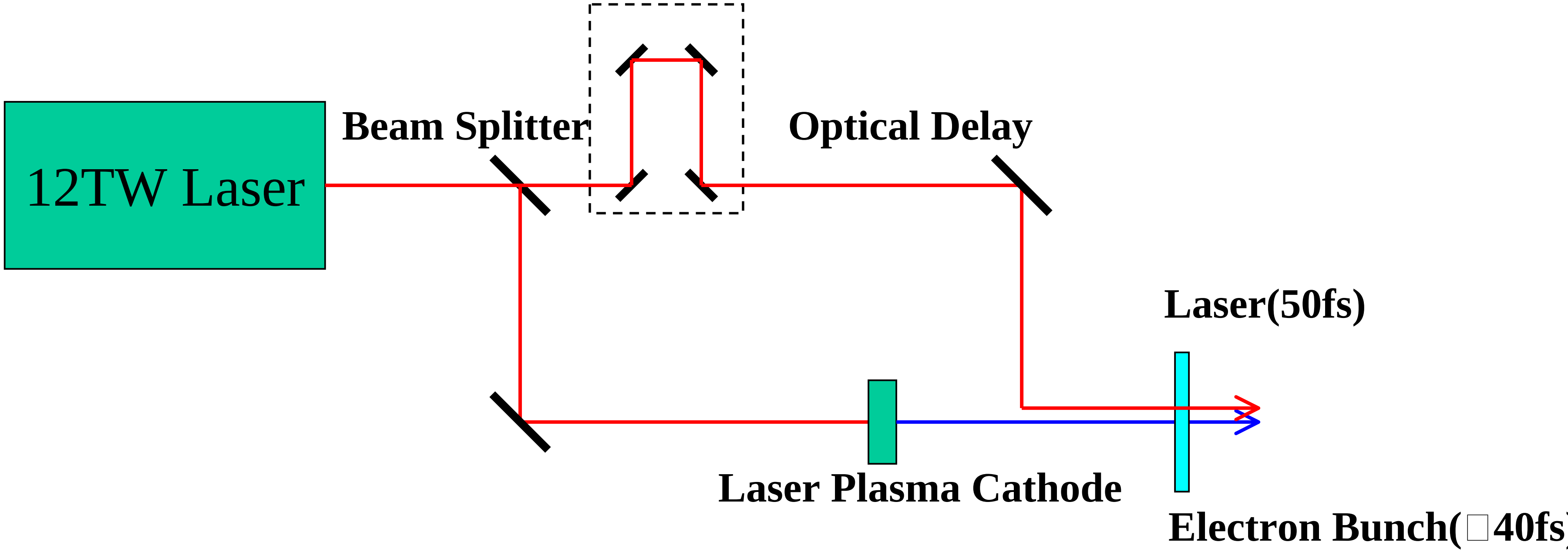
Bunching and synchronization with the seeded laser phase

To be injected to the next acceleration phase

W. D. Kimura et al., PRL 92 (5): Art. No. 054801

Big Advantage of Laser Plasma Accelerator for Pump-and-probe analysis

- Synchronization is perfectly passive without any electronics.
- No timing jitter and drift between laser and secondary beam.
- Femtosecond time-resolved analysis is surely available
- after the bean quality and stability are upgraded.



Summary of Synchronization

1. Laser vs Accelerator Synchronization System via Electronics

Picoseconds time-resolution

2. Laser Seeded Staged Accelerator

Femtoseconds time-resolution

Available for multibunches

3. Laser Plasma Accelerator

Beam Splitter enables even Attoseconds time-resolution

After Stable and reliable beam generation and diagnosis are established

Summary

1. Advanced Accelerator is Femtosecond Beam Source.

2. Its application is to visualize Ultrafast Microscopic Dynamics.

3. Laser-Accelerator synchronization systems are already applicable for Picosecond Time-resolved Analysis.

4. Laser Plasma Accelerator has a big potential to realize Femtosecond Beam Pump-and-probe Analysis.

5. Precise Synchronization/analysis is finally a battle with Environments.

Thank you!