June 25, 2004
Advanced Accelerator Concepts Workshop 2004

Femtosecond Beam Sources and Applications

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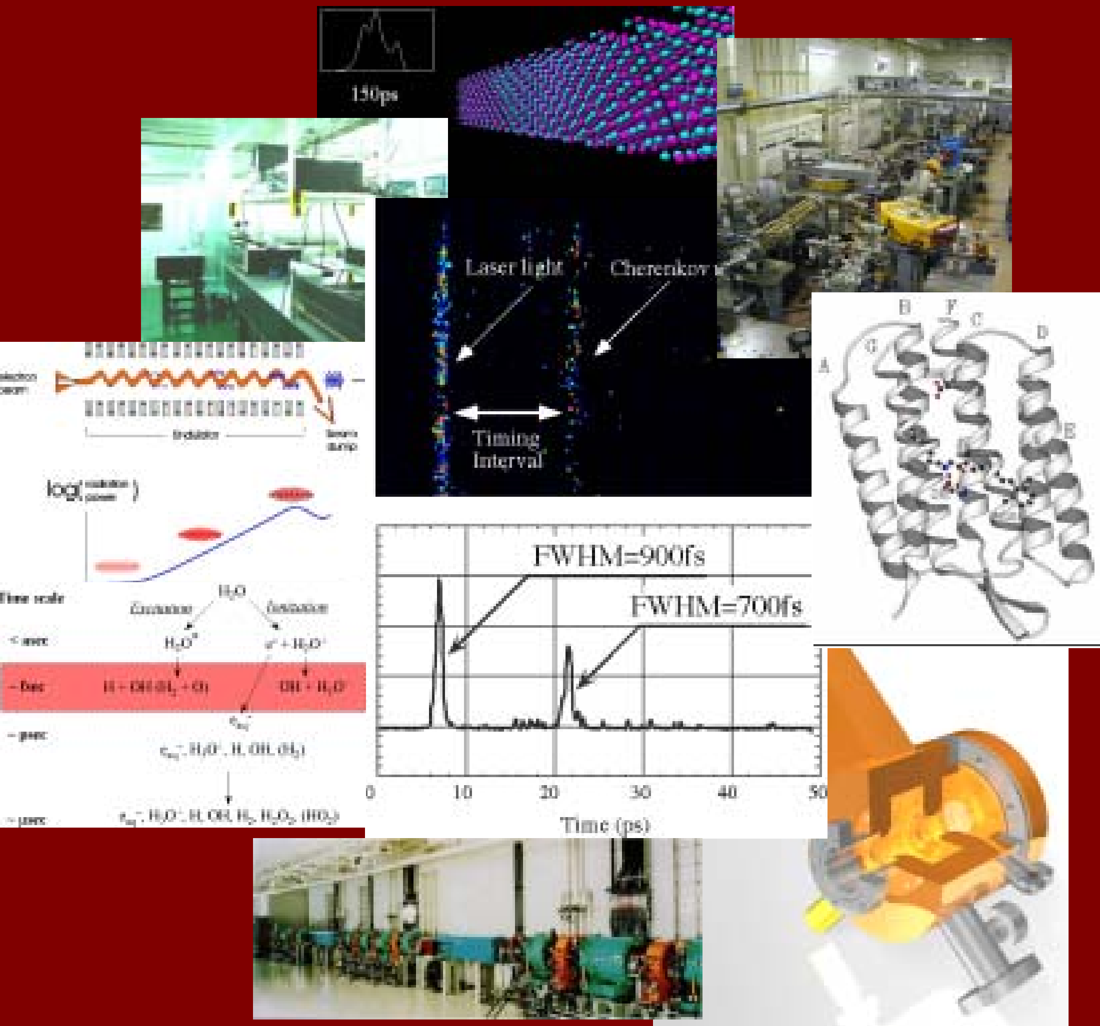
Femtosecond Beam Science



Chapter 1 Introduction

Chapter 2 Femtosecond Beam Generation
2.1 Femtosecond TW Laser
2.2 Linear Accelerator
2.3 Synchrotron
2.4 Laser Plasma Acceleration
2.5 Thomson/Compton Scattering
2.6 Slicing
2.7 X-FEL
2.8 Energy Recovery Linac

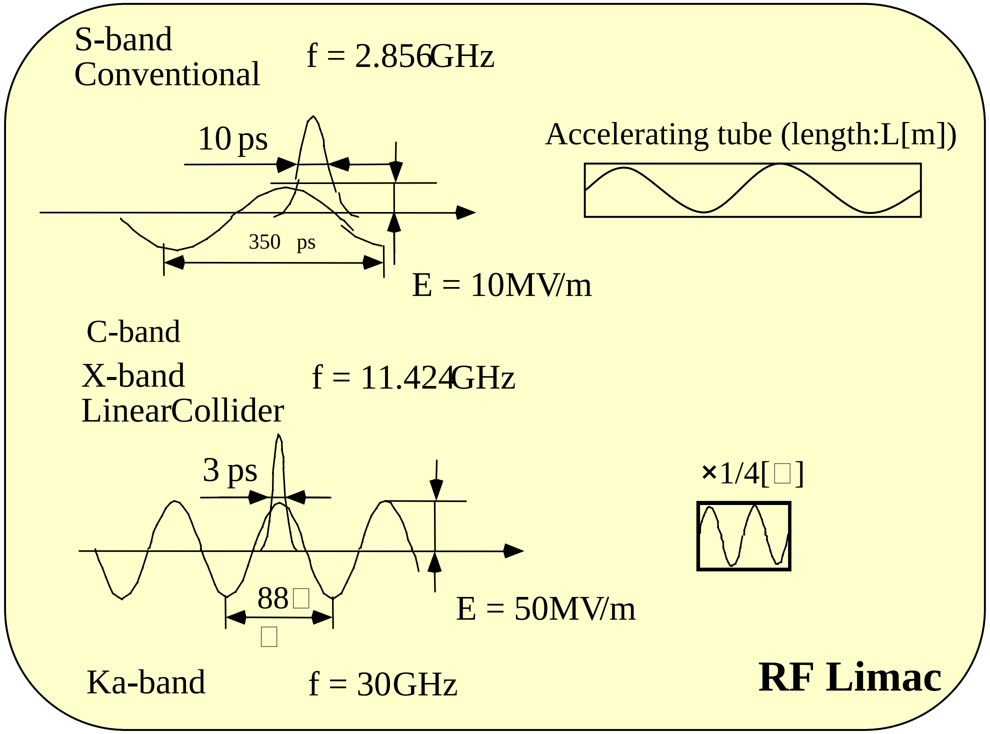
Chapter 3 Diagnosis and Synchronization
3.1 Pulse Shape Diagnosis
3.2 Synchronization

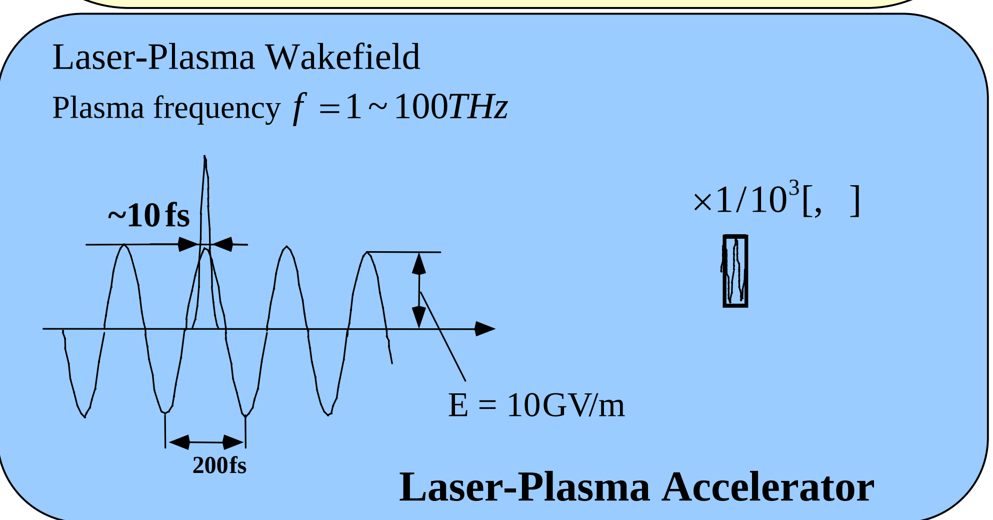
Chapter 4 Application
4.1 Radiation Chemistry
4.2 Time-resolved X-ray Diffraction
4.3 Protein Dynamics
4.4 Probing Molecules and Clusters
in Intense Laser Feilds
4.5 Molecular Dynamics Simulation

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

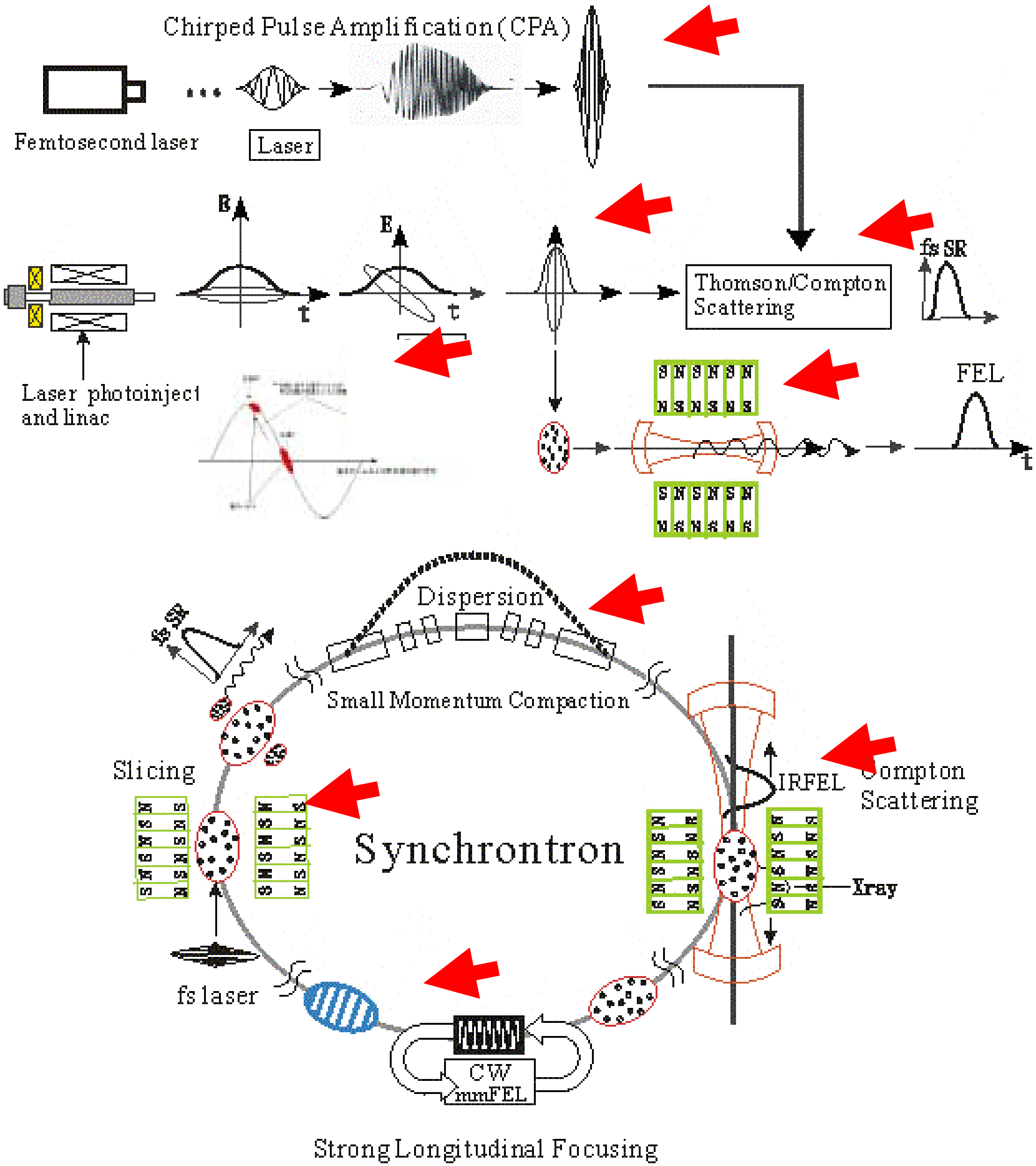
↓

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

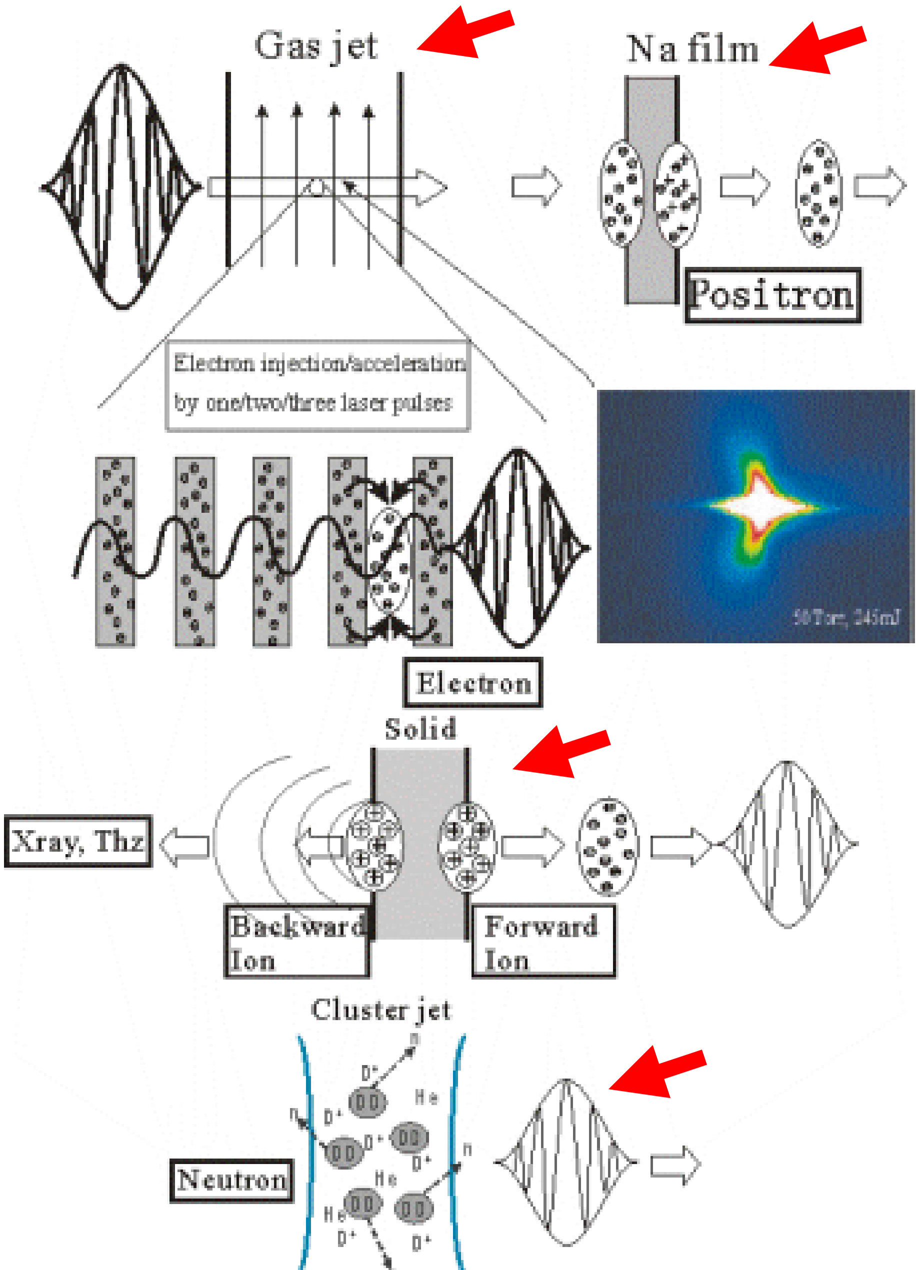
in Undulator Field

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

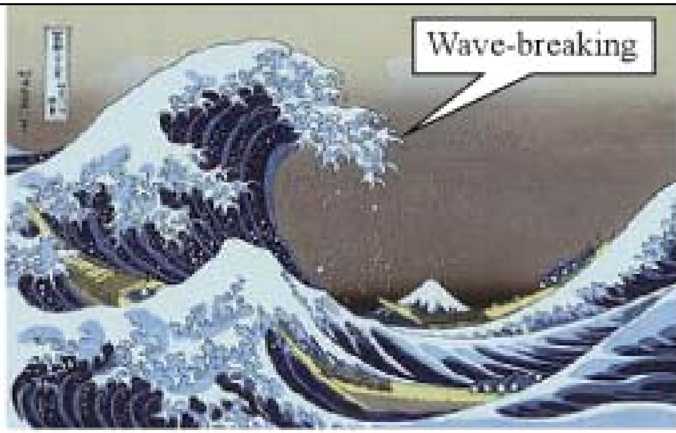
Ion

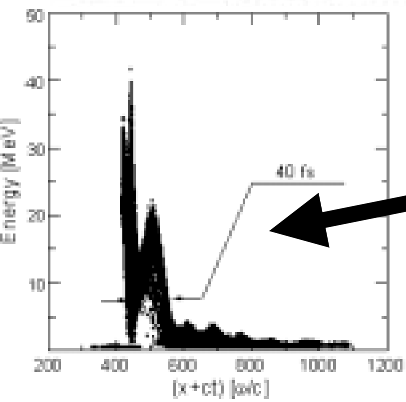
□**Film Target**

Neutron

□**Deutrium Cluster Jet**

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

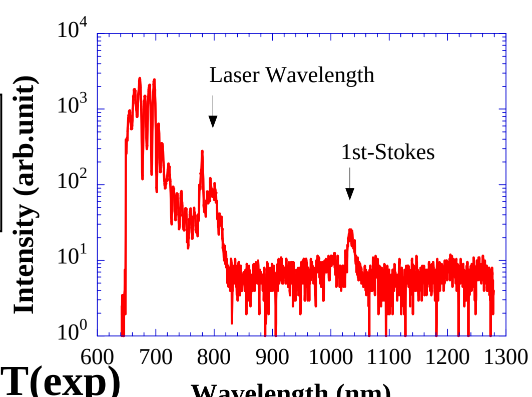




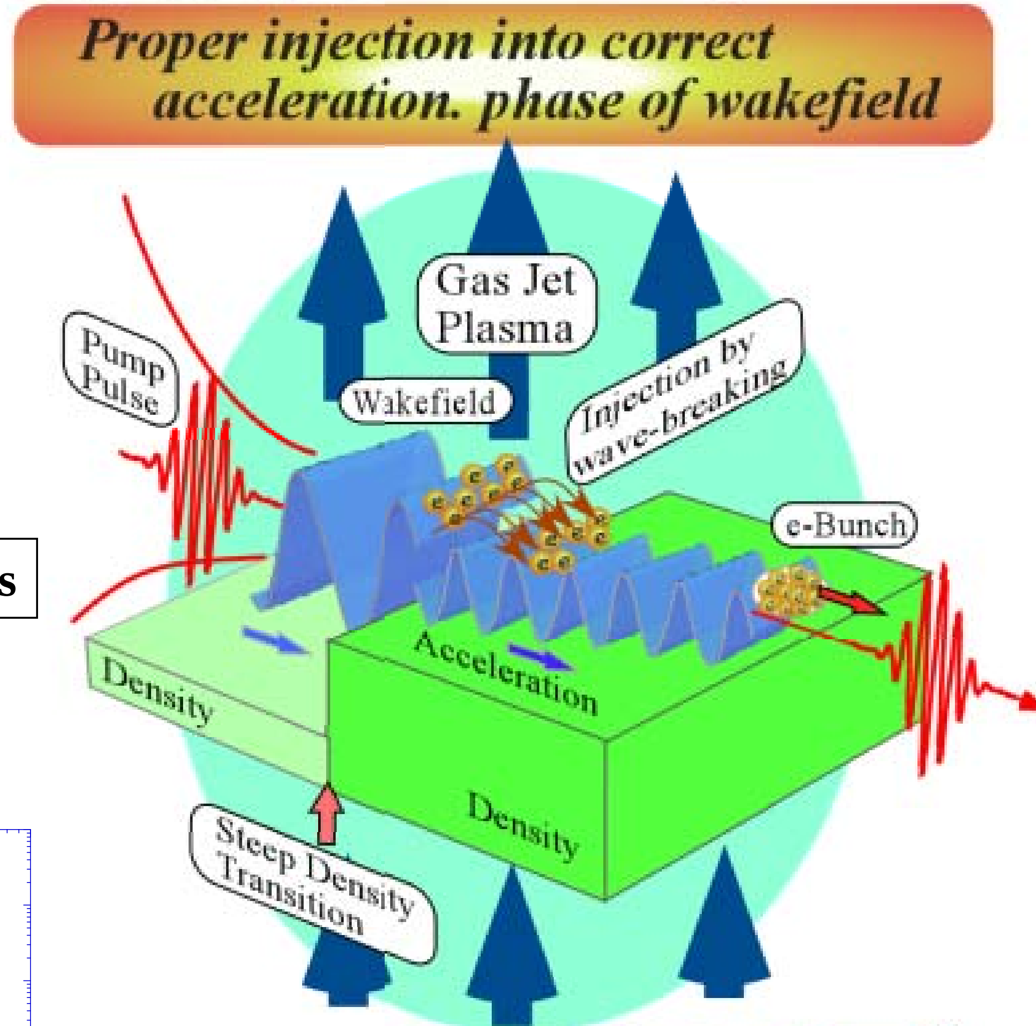
Tens femtoseconds

U.Tokyo(cal)

Quasi-monochromatic

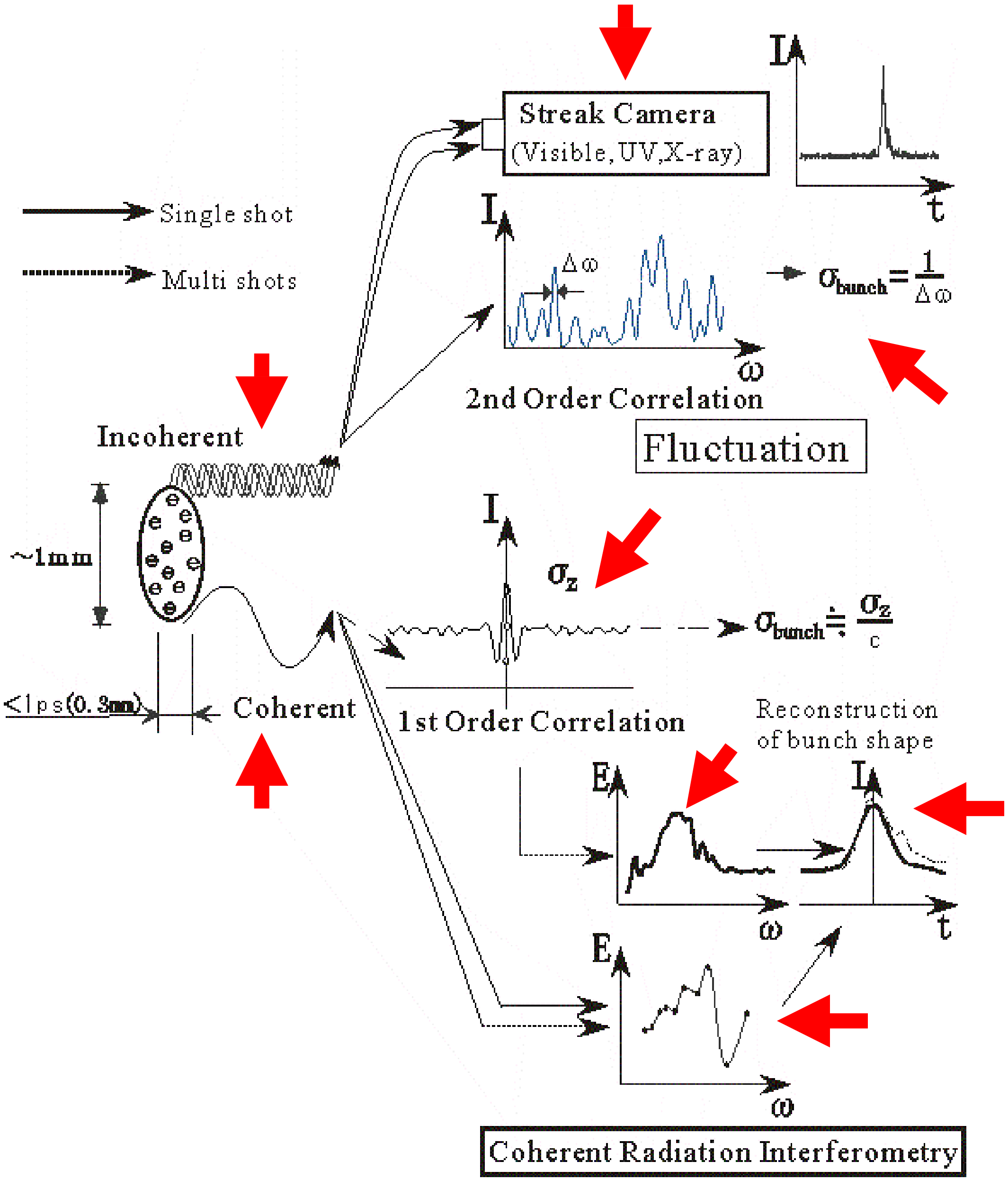


AIST(exp)



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 t_k probability variable N number of electron

1st order spectrum correlation function

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

$\langle \ \dots \ \rangle$ 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

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

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 $\quad t_k$ probability variable $\quad N$ 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

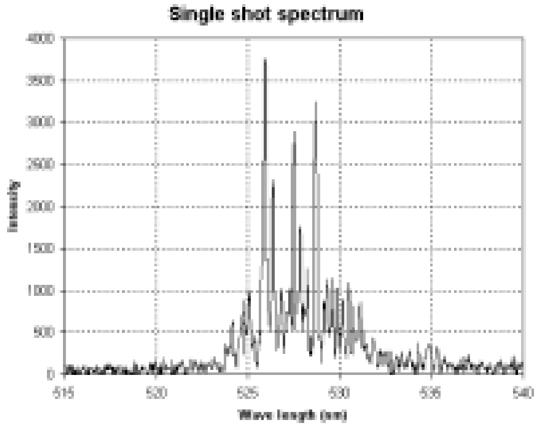
$$C_{meas} = \frac{\langle I(\omega_i) I(\omega_{i+n}) \rangle}{\langle I(\omega_i)^2 \rangle} = \frac{\left\langle |E(\omega)|^2 |E(\omega')|^2 \right\rangle}{\left\langle |E(\omega)|^4 \right\rangle}$$

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

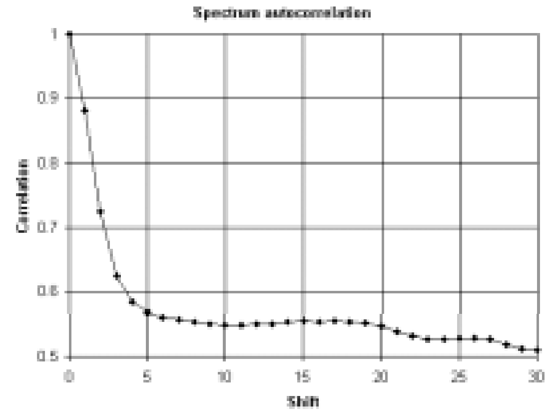
Bunch form factor

* 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 $\sigma_t \sim 1/2\delta\omega$

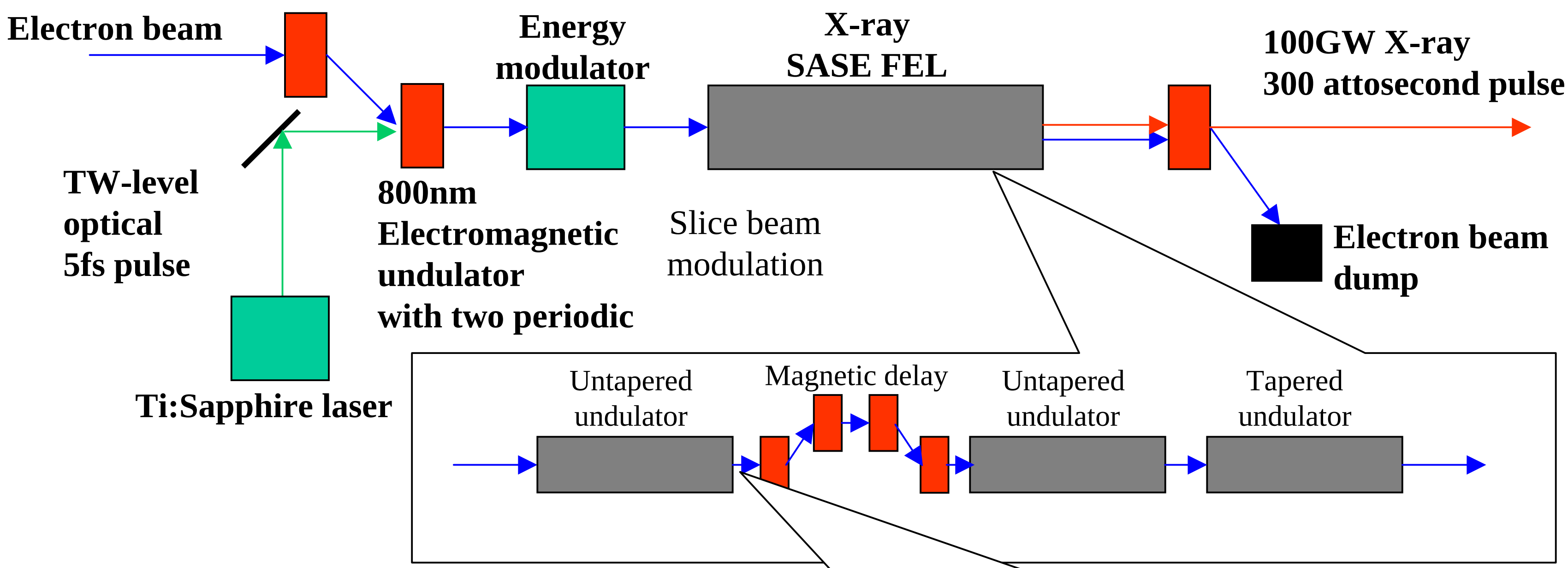
↓

Pulse width ~ 4.5 ps (FWHM)

Sajaev et al., EPAC2000

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

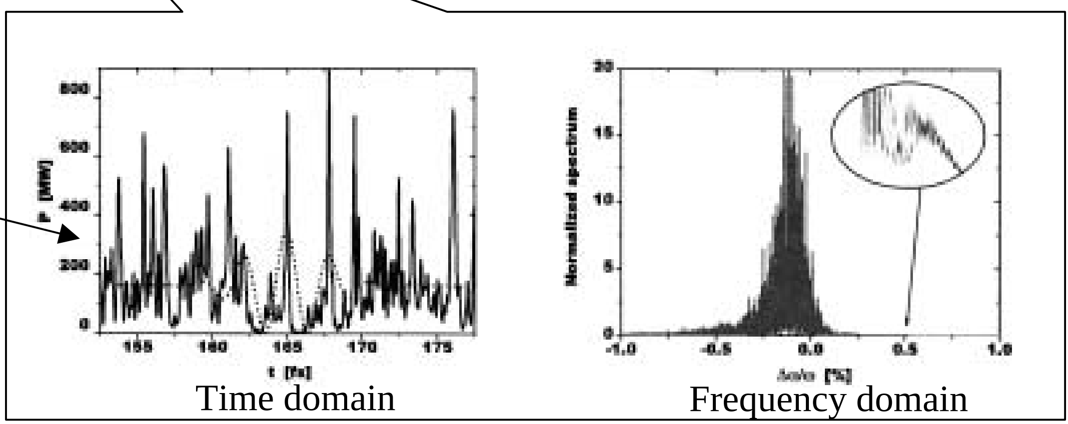
Saldin, Schneidmiller and Yurkov.DESY)



Slice beam modulation is clearly seen

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

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

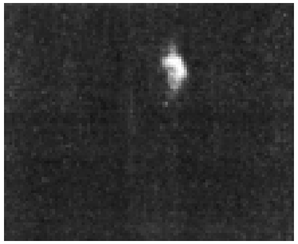


Temporal and spectral evolution of the radiation pulse along the undulator

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

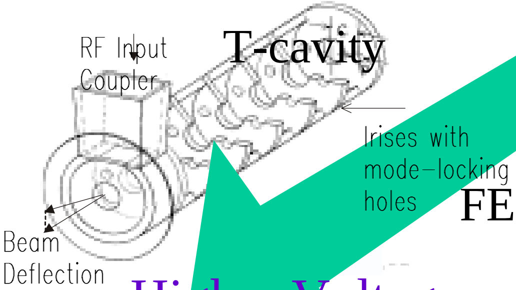
FESCA200 (Hamamatsu Photonics)

15 kV/1.6mm

Resolution: ~200 fs

Sweep velocity on the Phosphor

10mm/20ps (5×10^8 m/s)



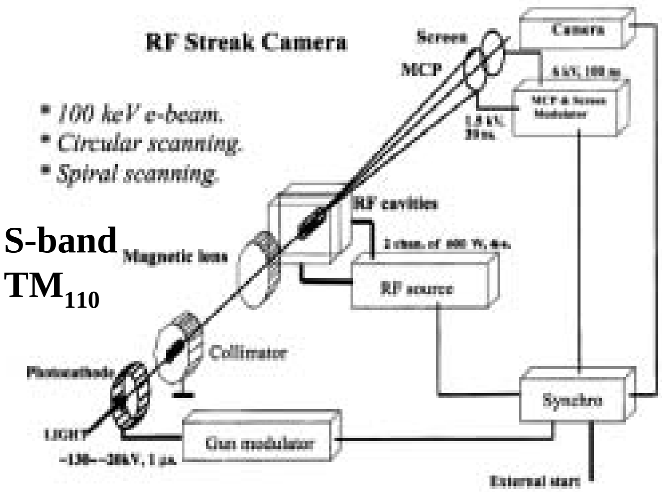
Higher Voltage

to suppress

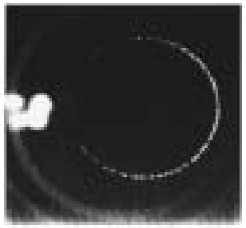
space charge force

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)

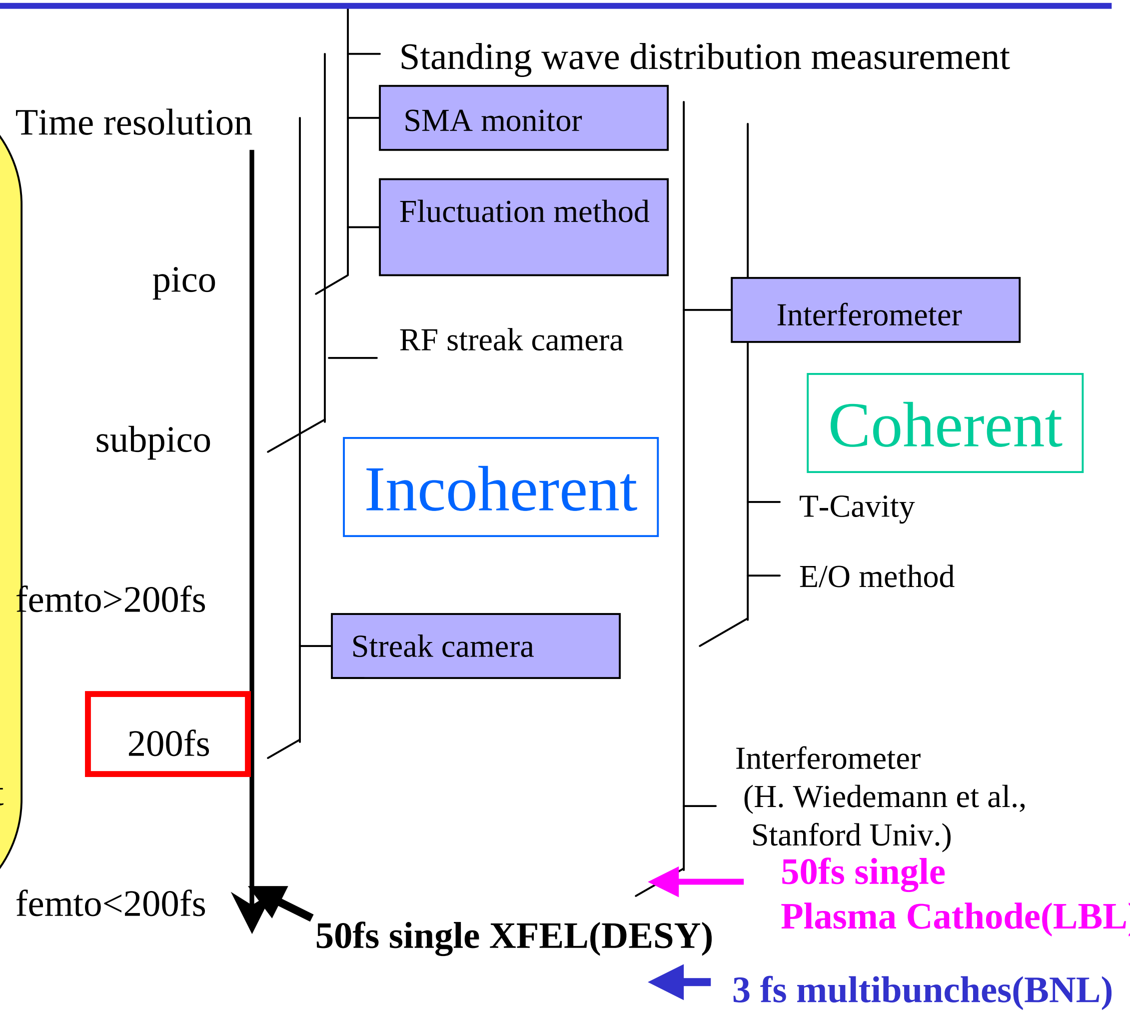
Methodology and Resolution of Pulse Length Measurement

□ 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



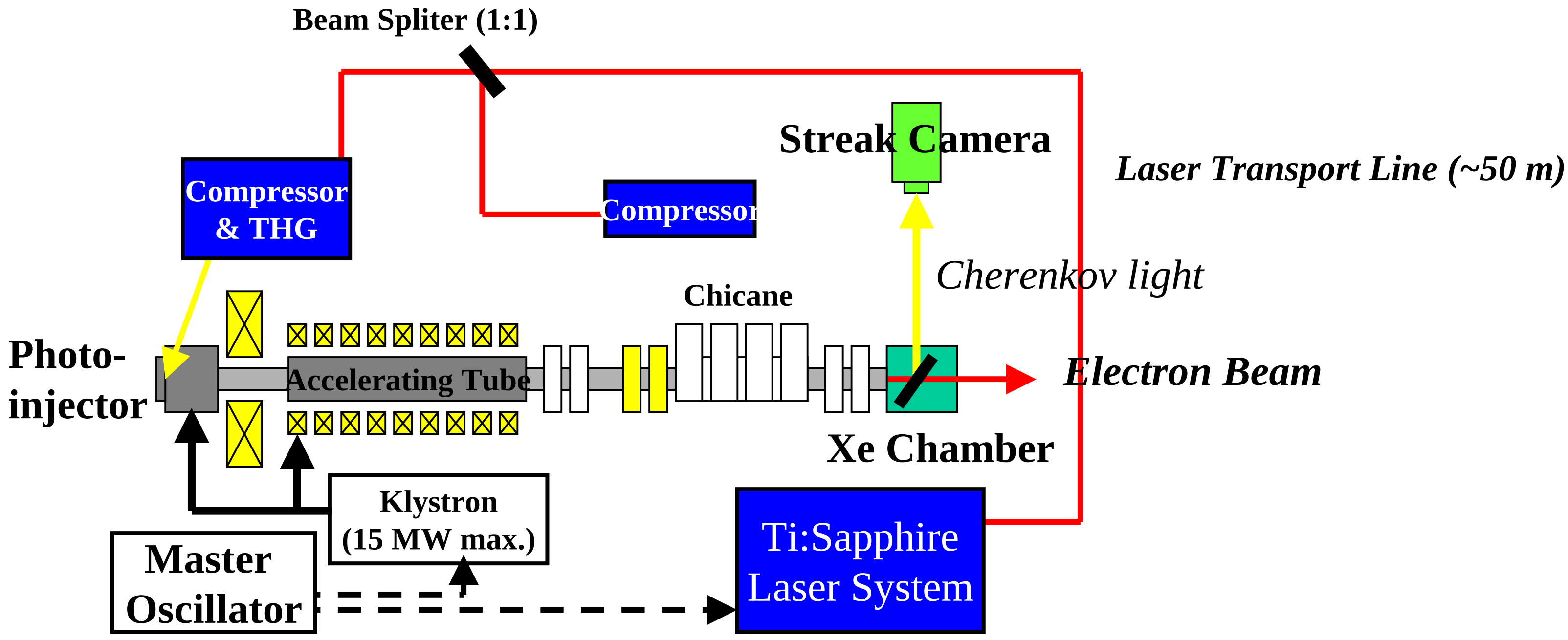
○ Radiation techniques
□- Streak camera
□- Interferometer
□- Fluctuation method

Suitable!!

Experiment of 10fs electron pulse generation from plasma cathode

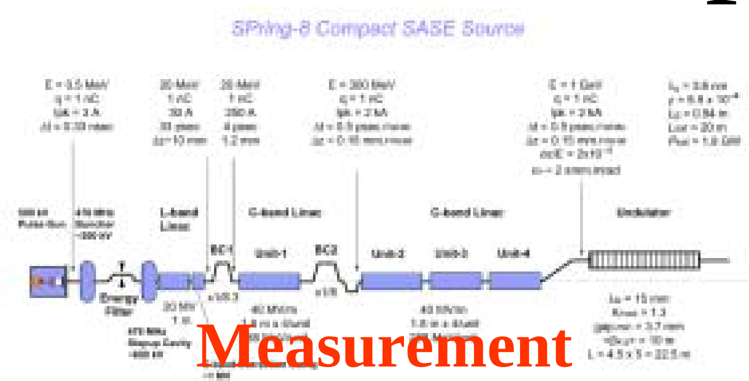
Size of Measurement System

Past/Present



Future

Advanced Measurement Concepts Workshop 2040???



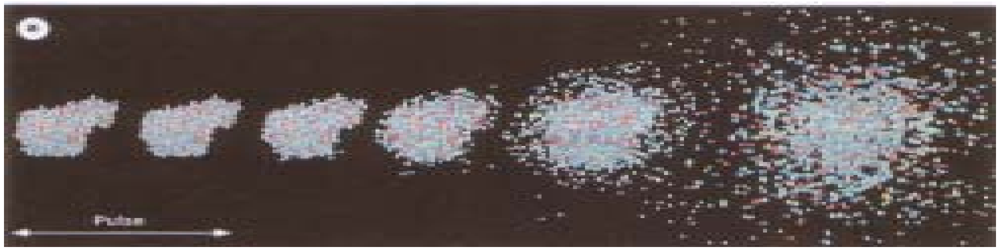
Applications

Single Shot Imaging

Intense Beam by Large System

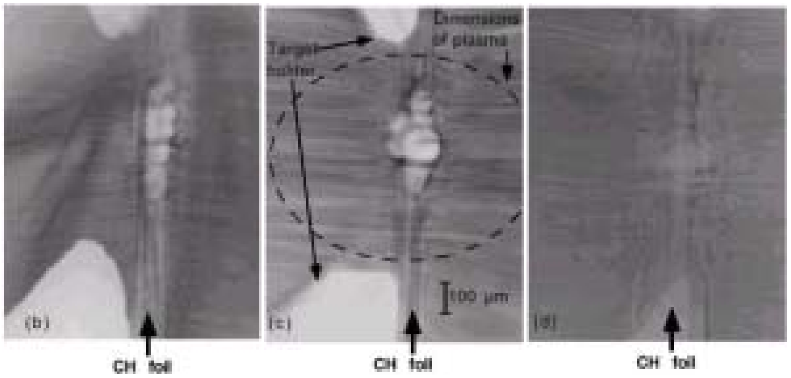
In-situ observation at any time

Irreversible process



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

Simulation of single shot imaging of protein by X-FEL



Laser Ablation Process by 7.5 MeV Laser Plasma Ions

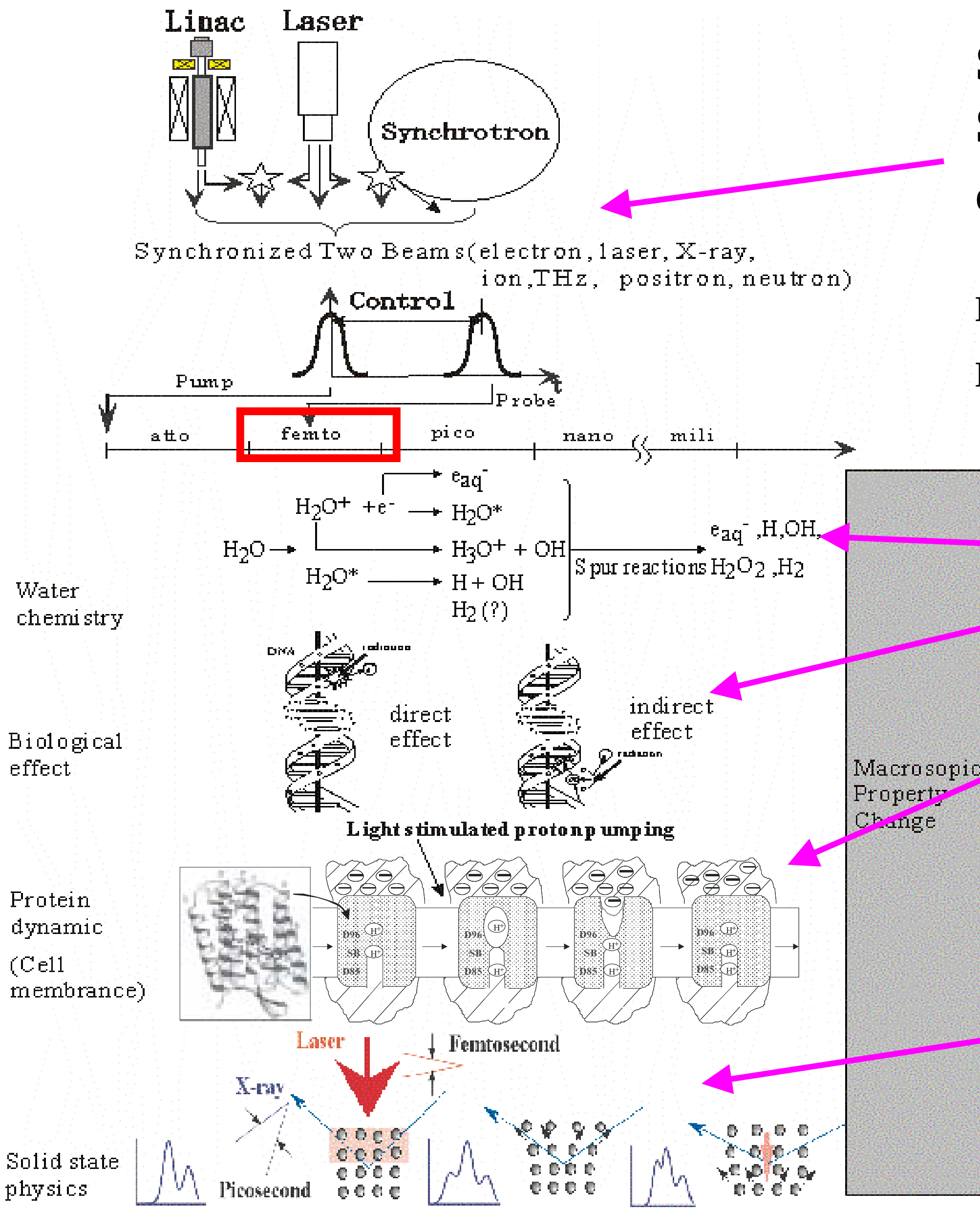
M. Borghesi, et al., Phys. Rev. Lett. 88, 135002 (2002).

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

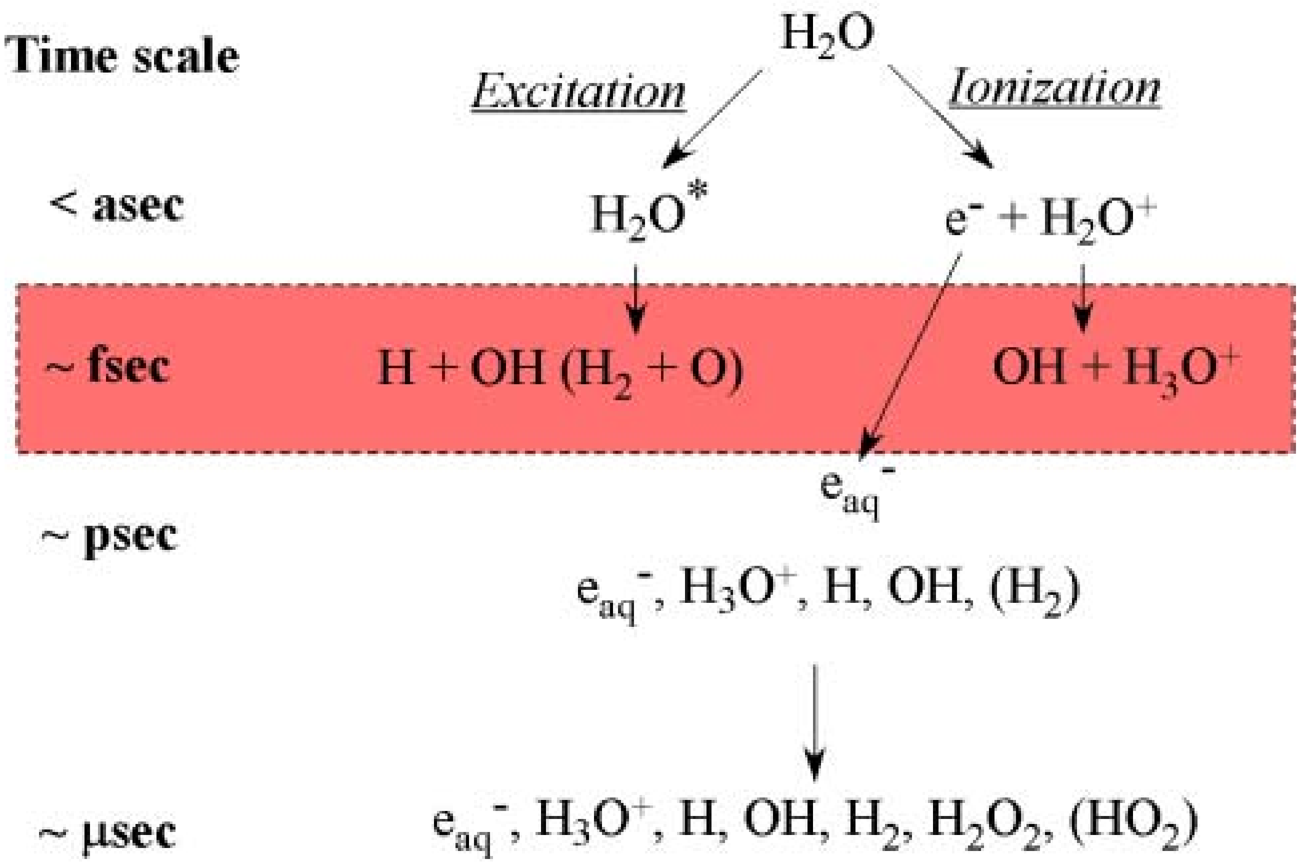
Dynamics of Phonon

>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 !

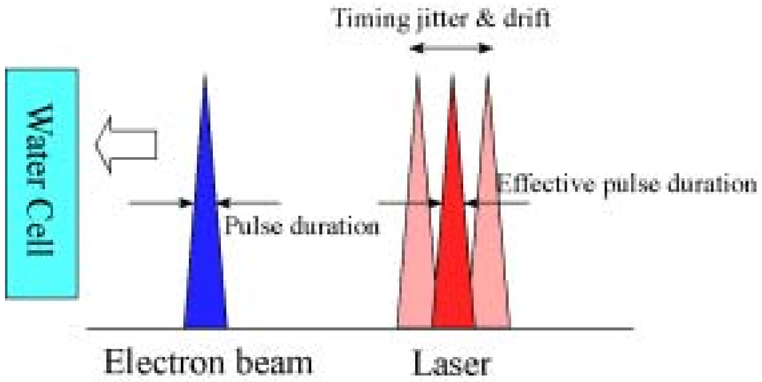
Hot Water Chemistry in Nuclear Reactor
to avoid Stress Corrosion Cracking
in 1970-1990.

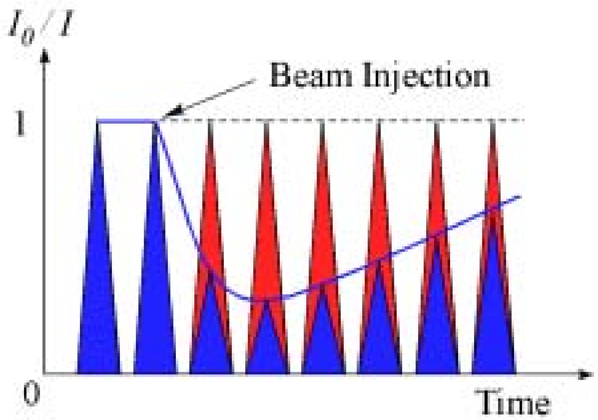
→

Supercritical Water Chemistry
For Compact Nuclear Reactor
and Environmental Science

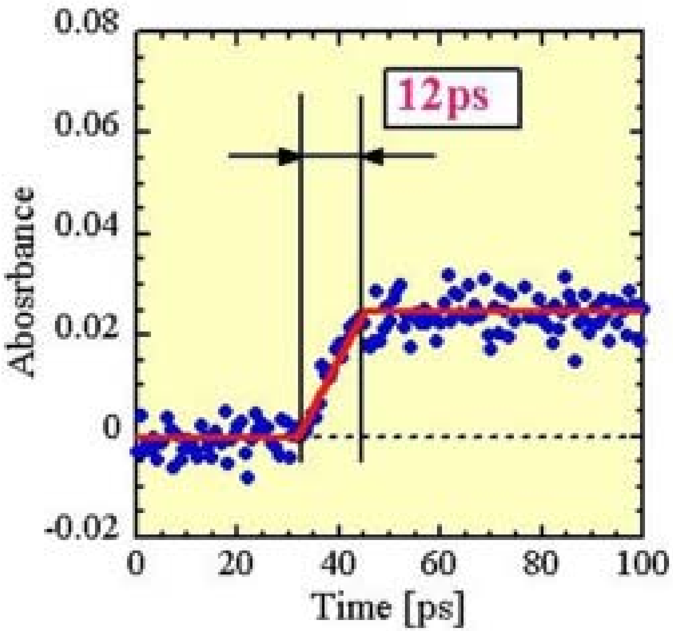
Radiation Chemistry

Pulse radiolysis method





Chemical reaction of water

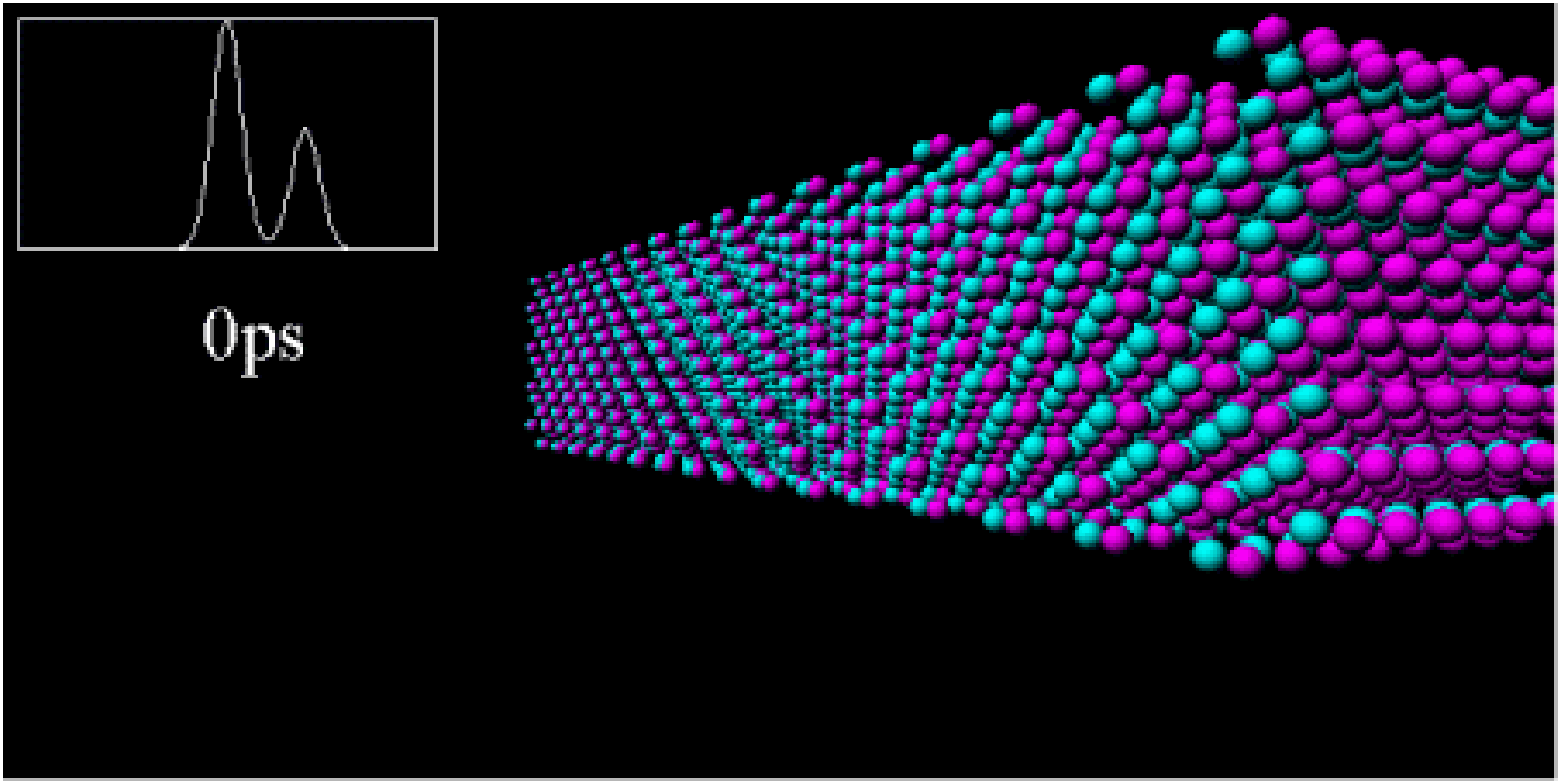


Systematic time-resolution is 12 psec !

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

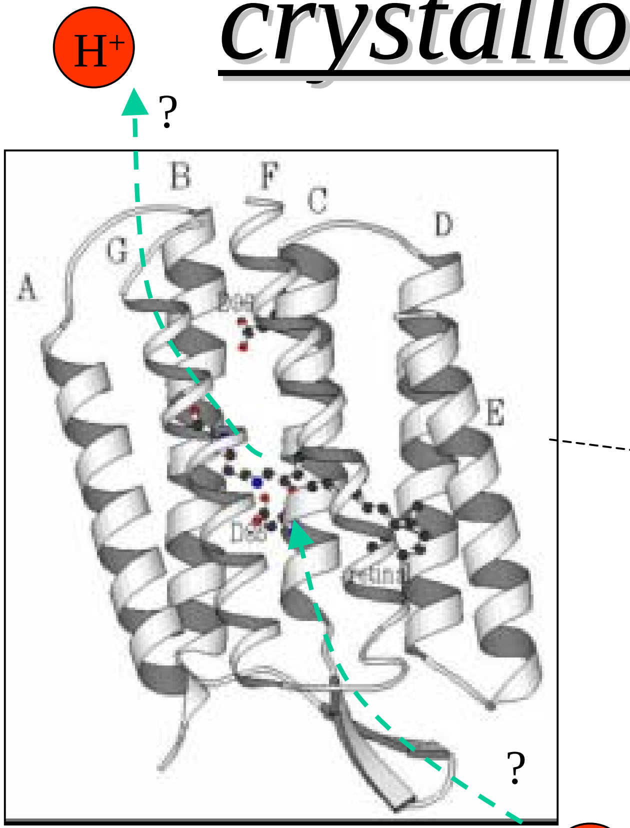
4D Microscopy of GaAs Lattice Dynamics

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

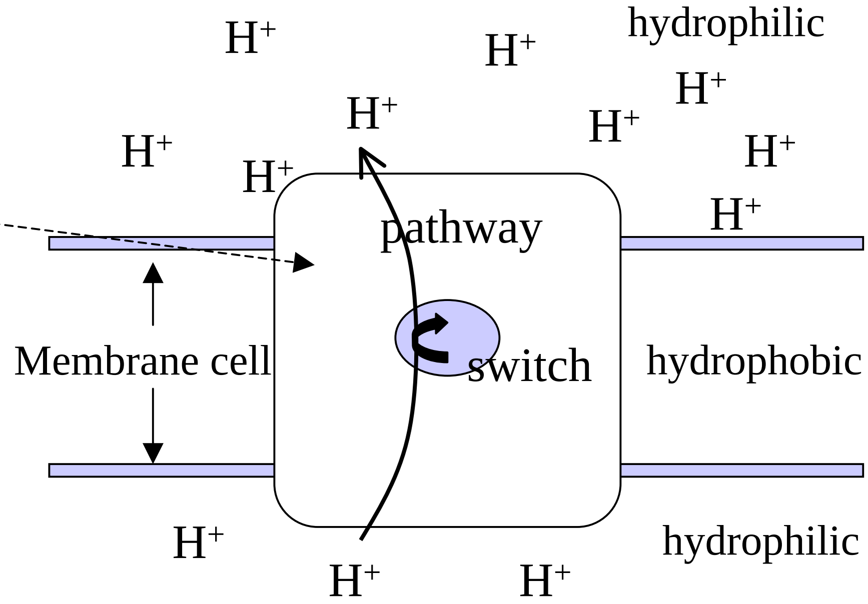


Related Refs. Rischel, C. et al., Nature(1997)
Rose-Petrick, C. et al., Nature(1999)
Hironaka, Y. et al., Jpn.J.Appl.Phys.(1999)

Time-resolved X-ray crystallography of photoactive-proteins



Bacteriorhodpsin



Proton pump

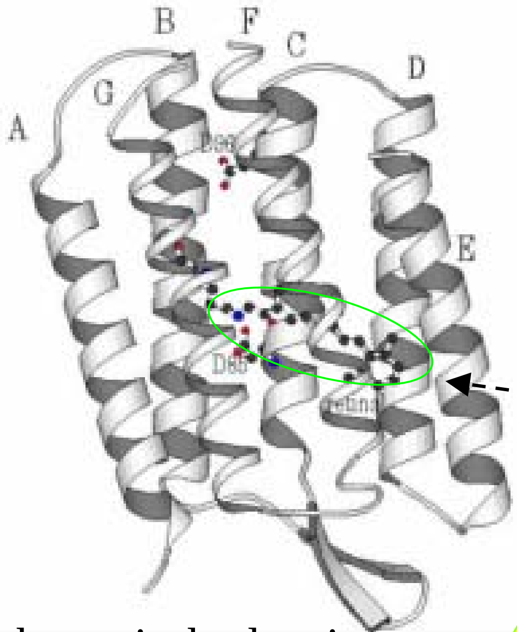
Membrane protein exists in the cell of extremely halophilic bacteria.

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



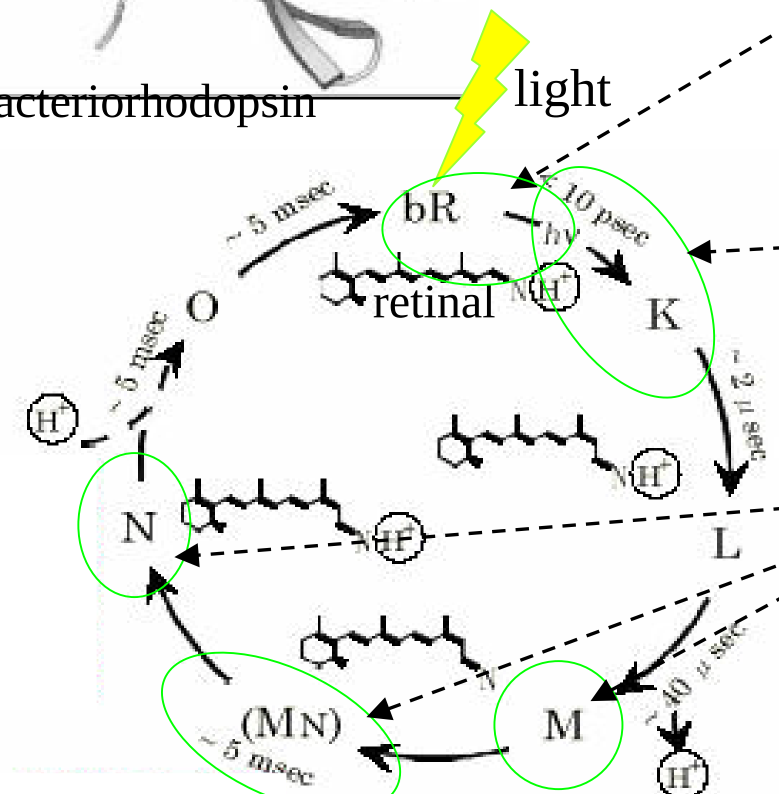
bacteriorhodopsin

Local structural change

Time scale ; fs ~ ps

Exam. fs(~5fs) pulse laser

T.Kobayashi et al,NATURE,2001



photocycle

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

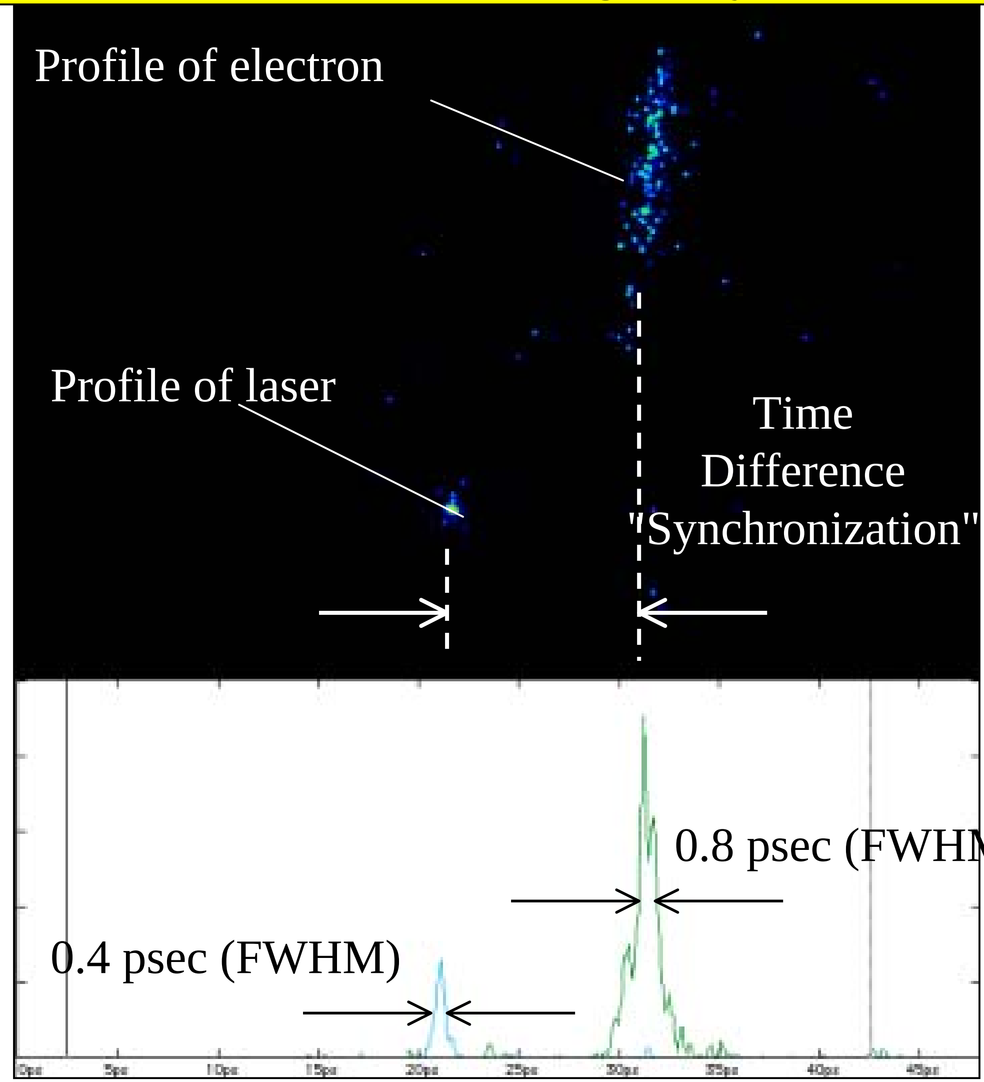
Synchronization

Accelerator

vs

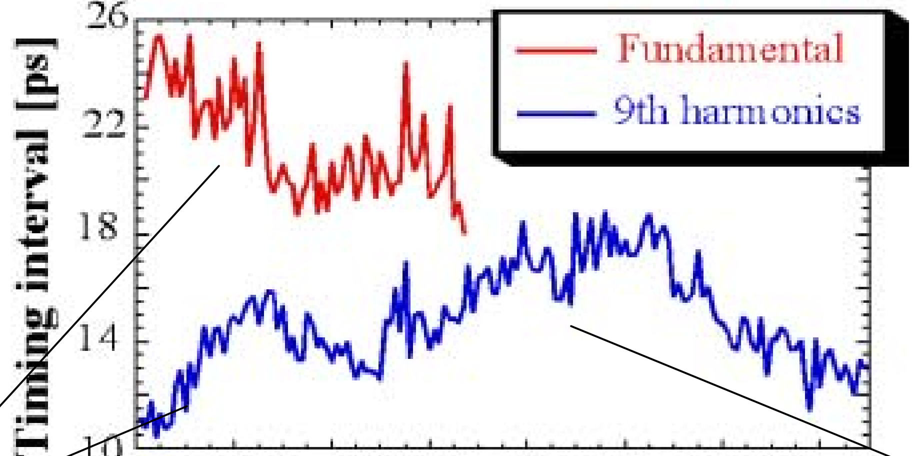
Laser

Femtosecond Streak Camera Image of Synchronization



Timing Jitter and Drift

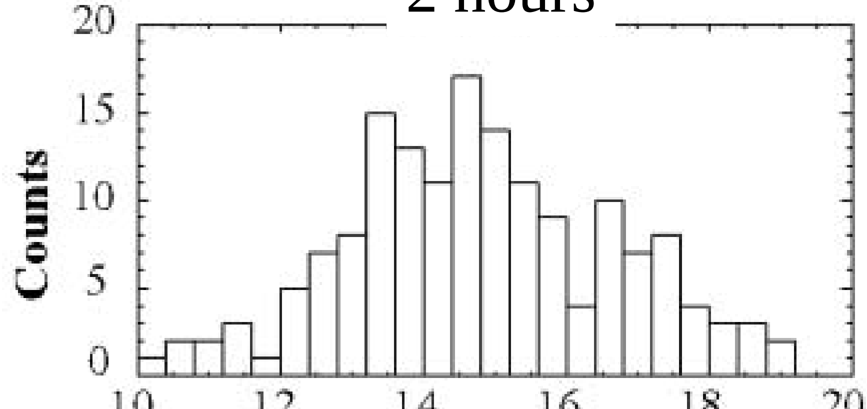
Timing interval between RF and laser



Timing drift of long term was left.

Timing jitter was suppressed.

2 hours

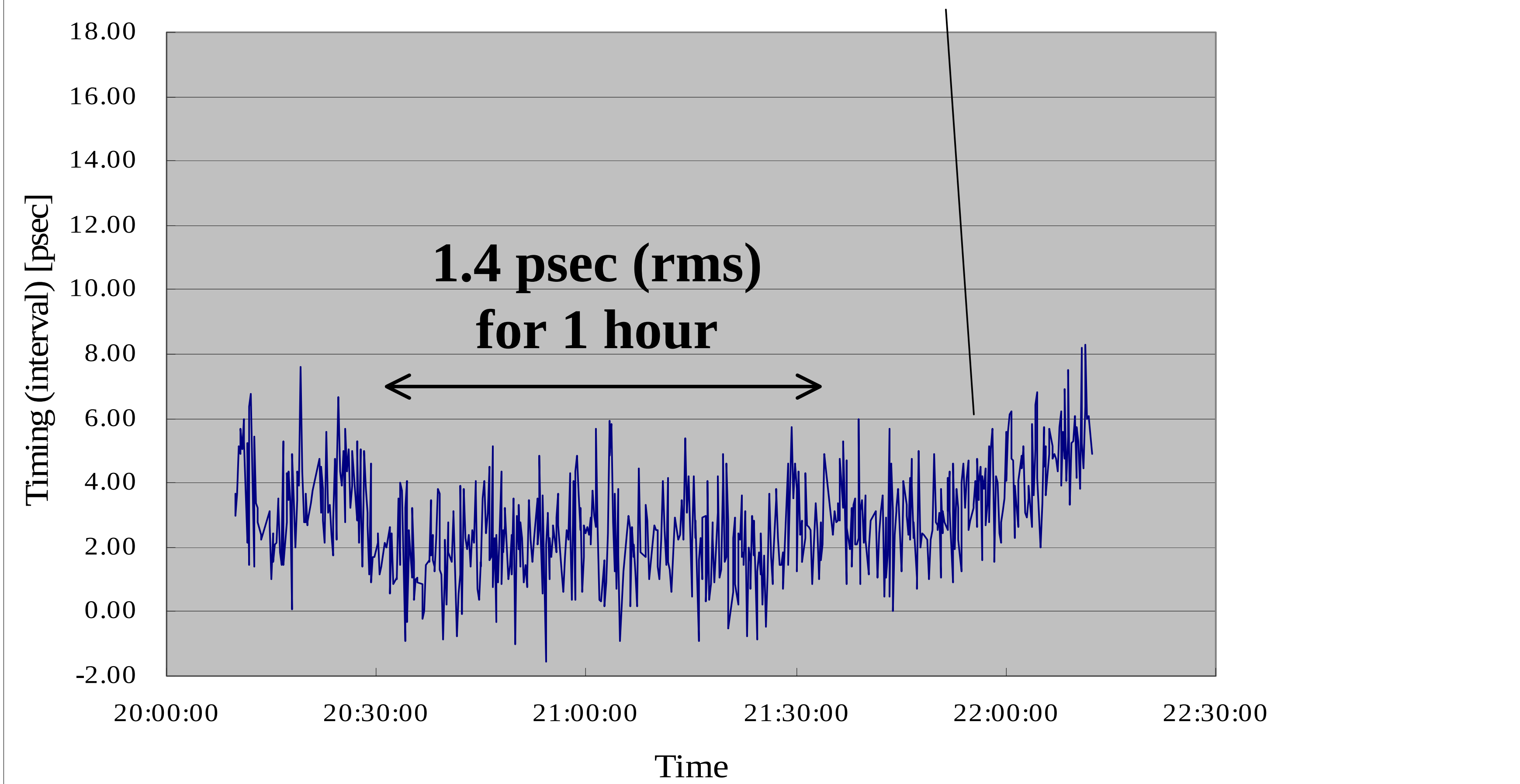


The phase-lock of higher harmonics suppresses the timing jitter, but the timing drift was remained.

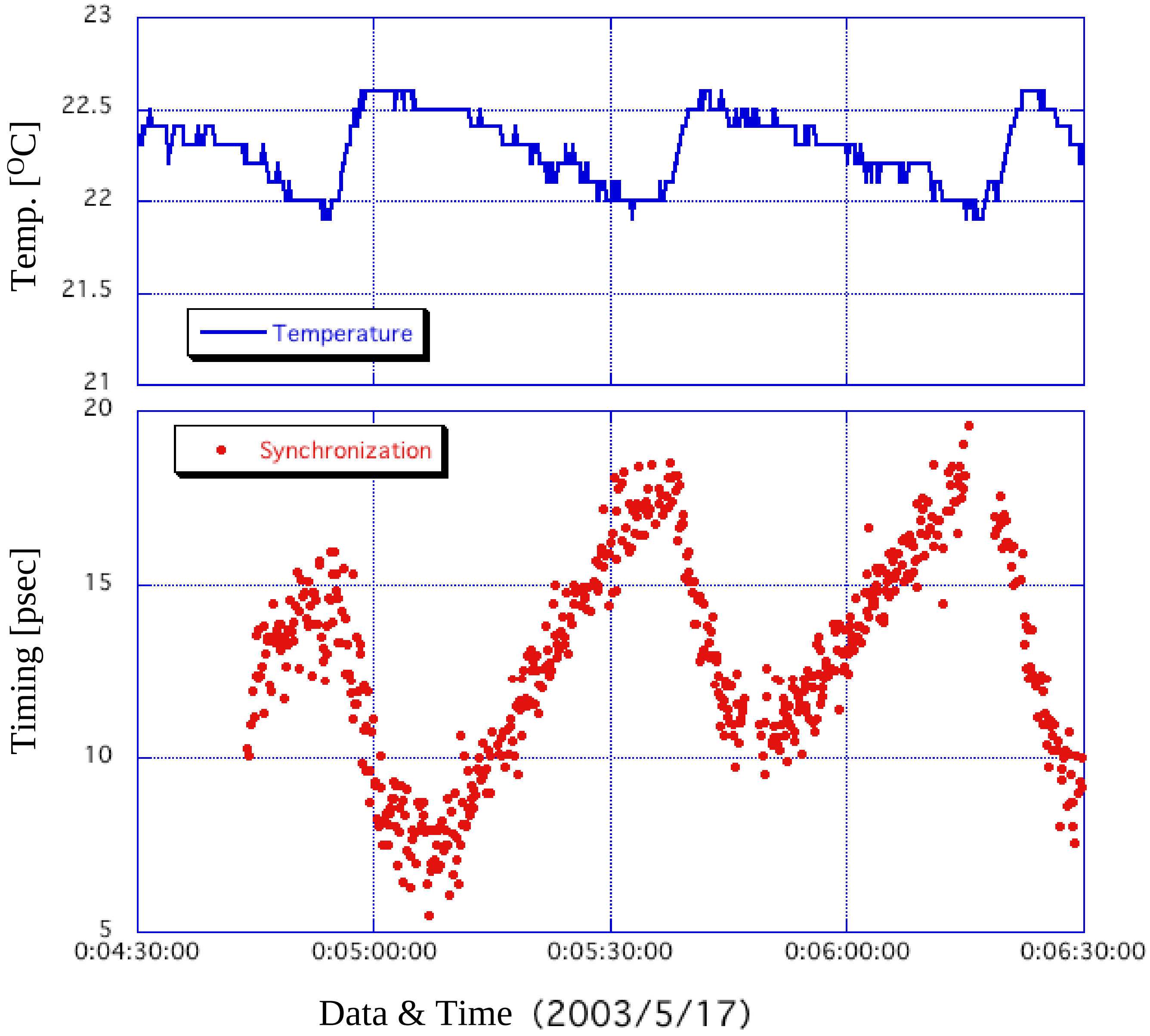
Stable Synchronization

~ Result of transport line improvement~

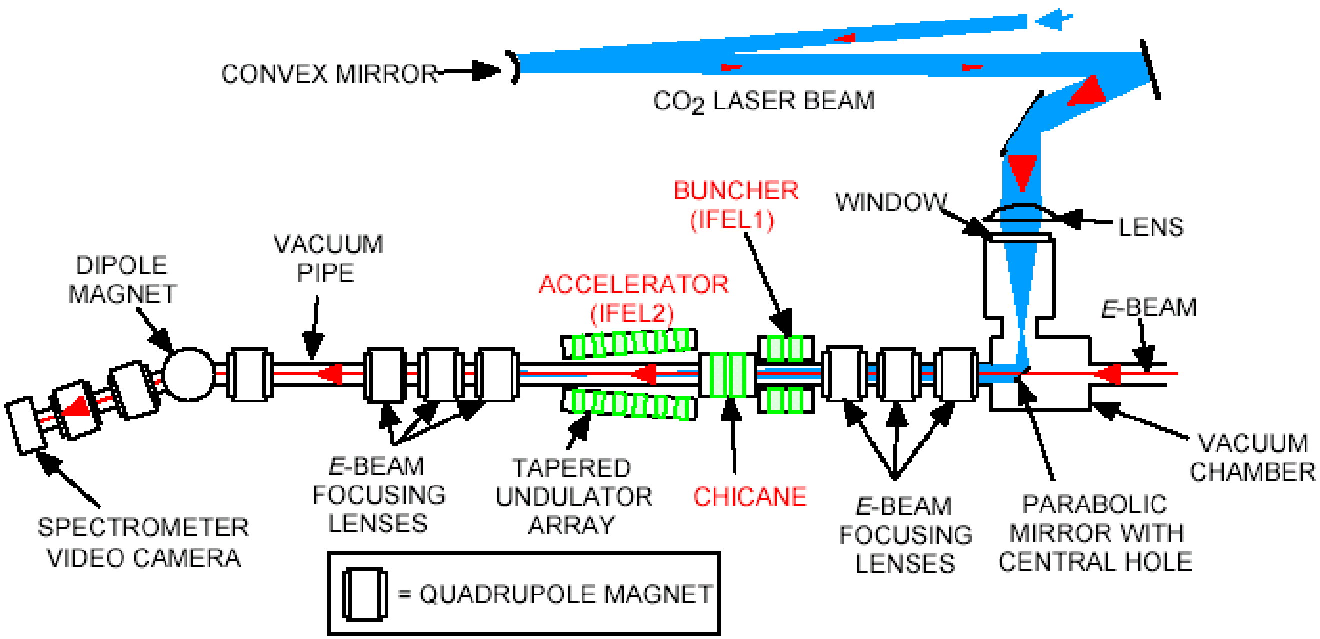
The pressure effect due to evacuated transport line was suppressed.
The expansion and contraction effect due to temperature was left.

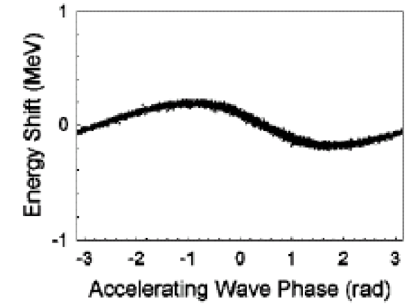


Correlation between Laser-room temperature and Synchronization

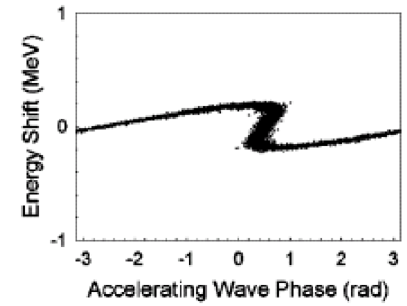


Laser Seeded Staged Accelerator

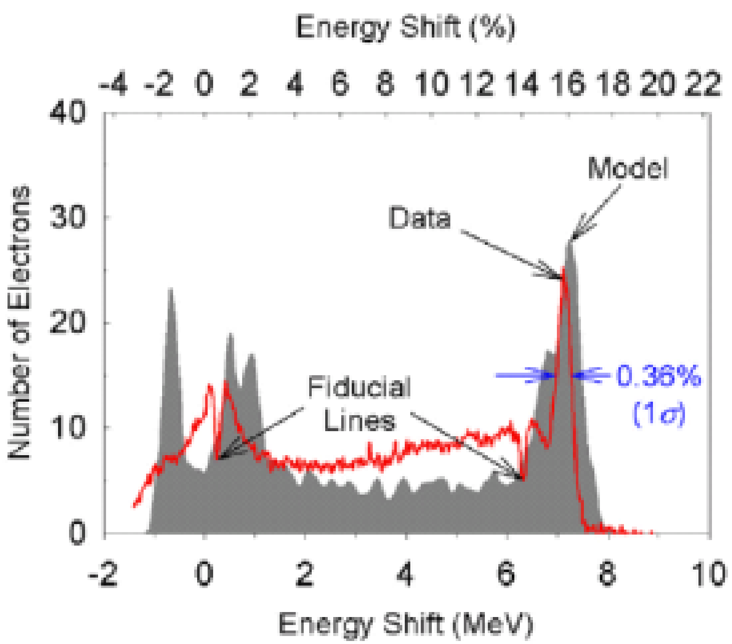




Modulation (IFEL1)



Compression (Chicane)



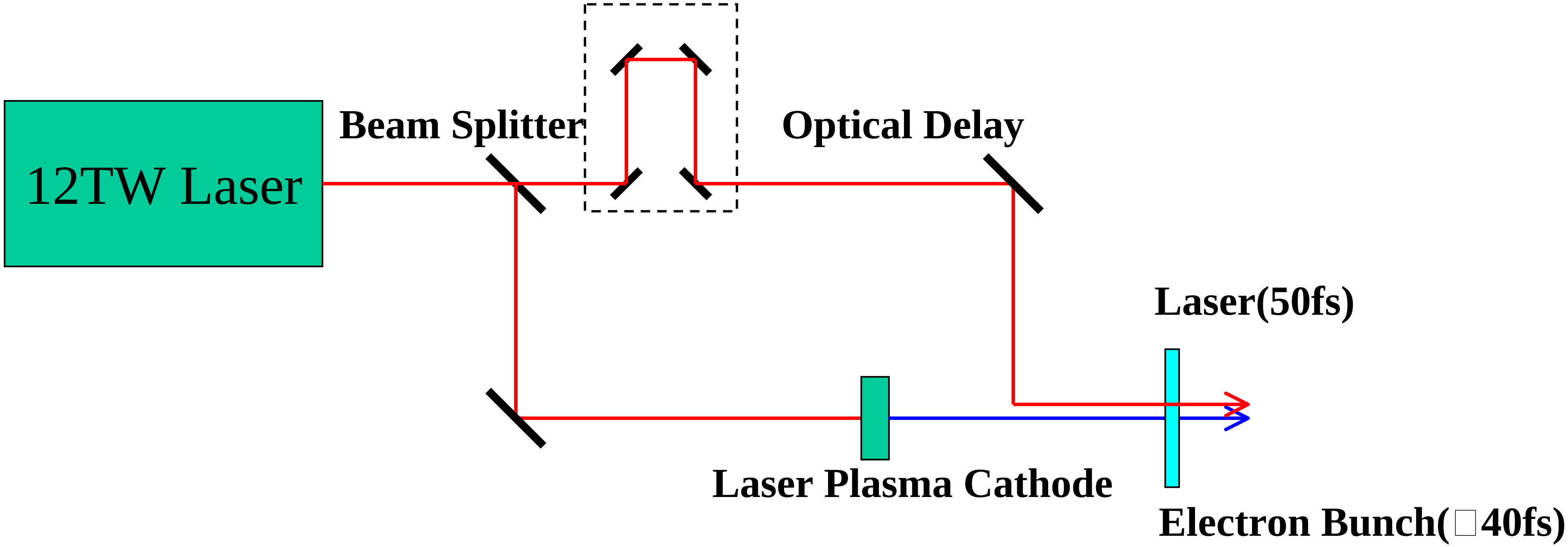
Bunching and synchronization with the seeded laser phase

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!

Pump-and-probe Experiment Using Plasma Cathode at University of Tokyo

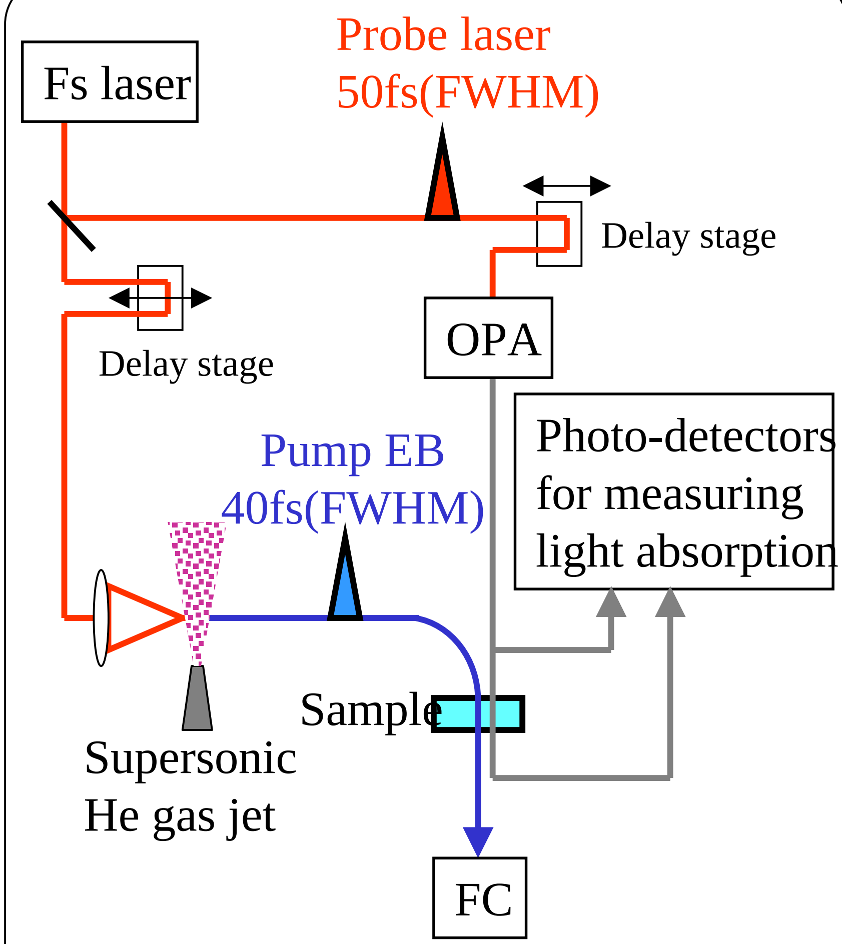


Fig. Schematic diagram of pump-probe experiment using plasma cathode

Dominant factors for time resolution

- EB for pump : 40fs(FWHM)
- Laser for probe : 50fs(FWHM)
- Timing jitter : ~0fs
- Desynchronization in sample : ~1ps/mm

Current problems to be solved

- Electron beam
  - Energy spread : 100% → <10%
  - Charge : <1nC → >2nC
  - Stability of charge : 100% → <1%

Development of the system

Subject : radiolysis of liquids

- Direct observation of radiation-induced physico-chemical processes within 1ps (Vibrational&rotational relaxation, intramolecul reactions, geminate ion recombination etc.)

World trend of the generation and measurement of ultra-short pulse

DESY-TESLA-TTL

SASE-FEL :σ=~40fs by fluctuation method using undulator radiation.

But could not measure by FESCA200.

Thomas Jefferson Lab

IRFEL : Generate 2WTHz light with σ=300fs electron bunch.

BNL-STELL

IFEL : σ=3fs by the spectrum of the coherent radiation spectrum

Acceleration of Energy sift of 9MeV and σ=1.2%.

BNL,DESY,LBNL,UTNL

Verification of velocity bunching (CTR & FESCA) and generate the sub-ps electron bunch.

LBNL

Measurement of coherent radiation at boundary of two beam collision plasma cathode.

Osaka Univ,

Femtosecond pulse radiolysis by RF gun + Linac.

UTNL

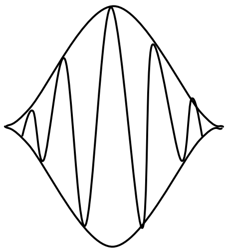
Measurement of 40fs electron bunch from self-injection type plasma cathode by the spectrum of coherent radiation.

Suggestion of attosecond streak camera.

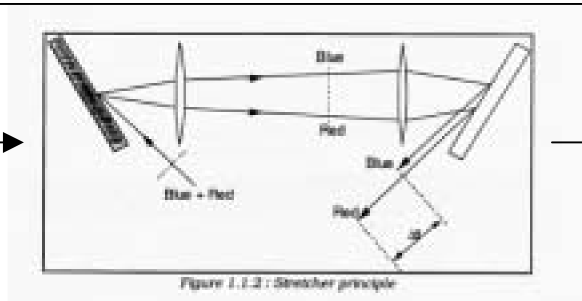
How to Form
Femtosecond Electron Bunch

1. Magnetic bunch compression (relativistic, small R_{56}) and velocity bunching(non-relativistic)
2. Control of momentum compaction factor
3. Collision of femtosecond laser and picosecond electron bunch
4. FEL and IFEL
5. Laser Plasma Cathode

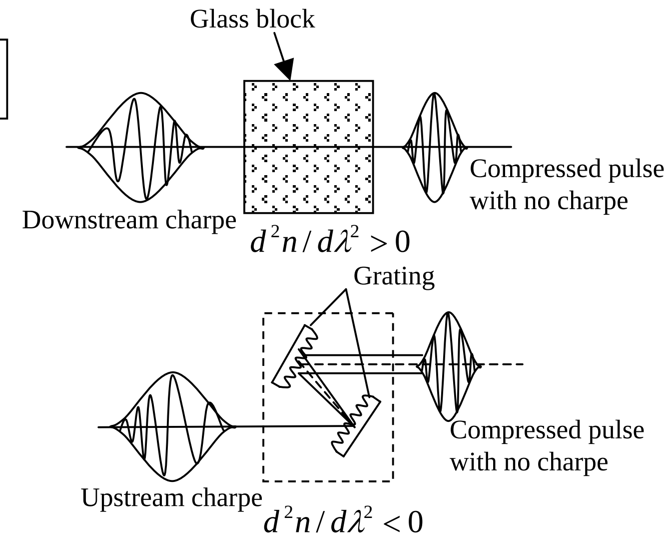
Charped pulse compression of femtosecond laser



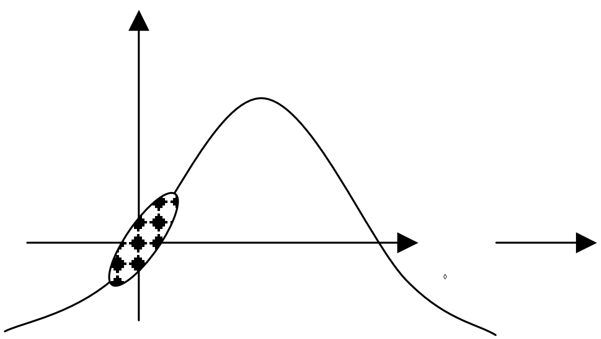
Light pulse with no charpe

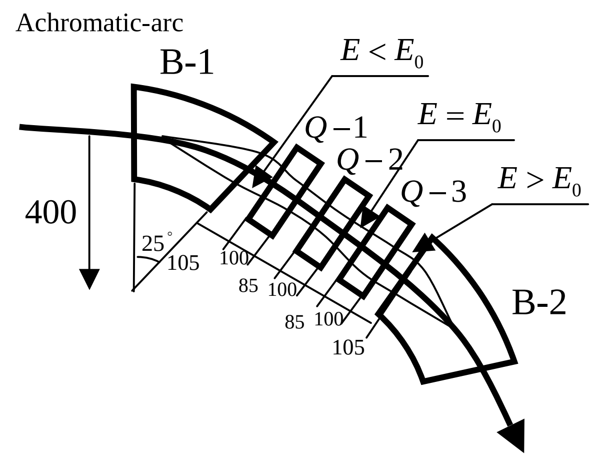


Stretcher

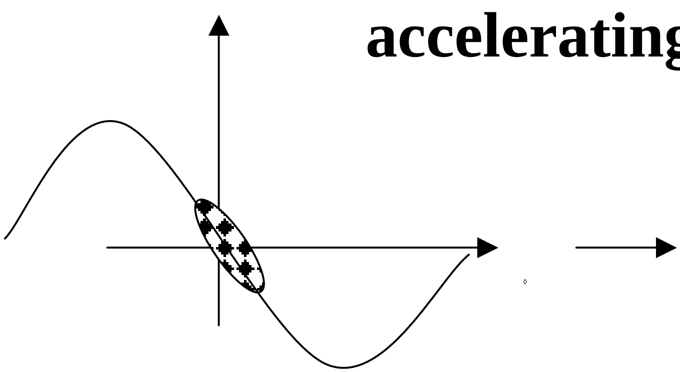


Magnetic pulse compression of electron beam

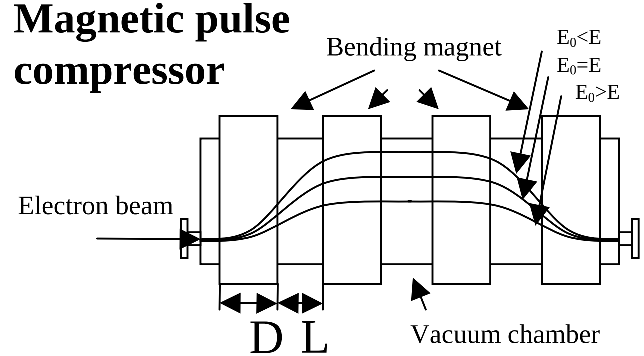




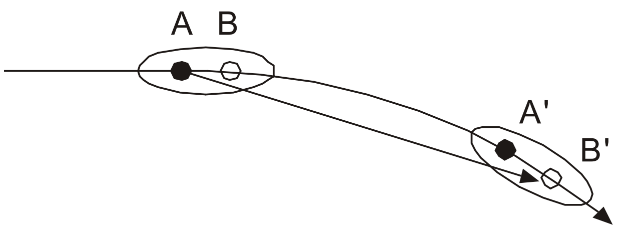
Energy variation at accelerating tube



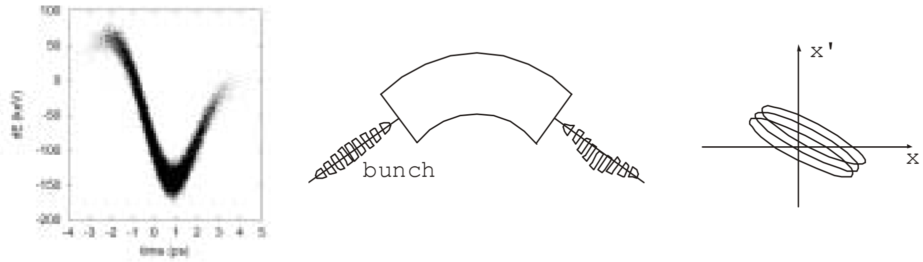
Magnetic pulse compressor



Emittance growth by Coherent Synchrotron Radiation (CSR)



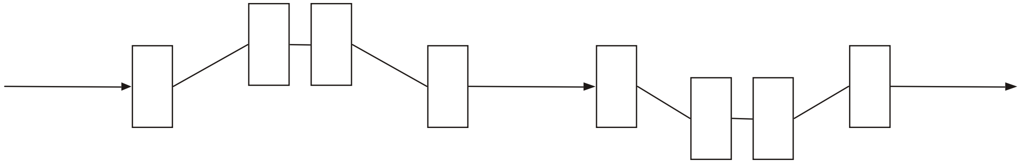
The self-interaction in electron bunch by the curved course. The radiation from the electron bunch rear affects other electrons of the bunch front part.



.left. Energy dispersion by CSR.
(middle) variation of the bunch form by CSR.
.right. Emittance growth by CSR kick.

Emittance is growth by the CSR in the magnetic pulse compressor

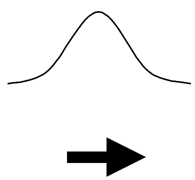
To deduce the emittance growth by the CSR effect
Tandem type bunch compressor



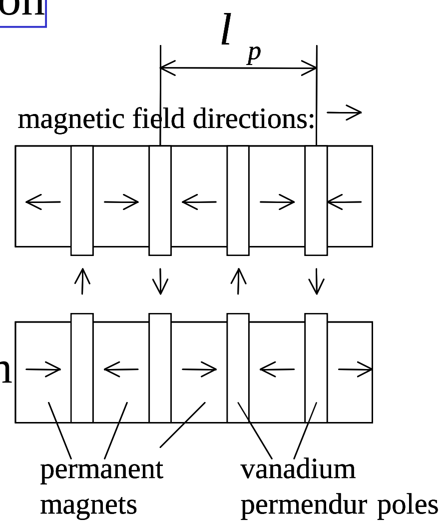
Compton scattering X-ray source
as the miniature version of undulator radiation.

Undulator radiation

Long pulse



Electron beam



$$\lambda = \frac{\lambda_p}{\gamma}$$

Doppler shift

$$\lambda_r = \frac{\lambda_p}{\gamma^2 (1 + \beta \cos\theta)}$$

$$\approx \frac{\lambda_p}{2\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

$K = \gamma\theta$ $\quad E = \gamma mc^2$

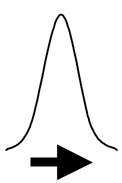
$\lambda_p \approx 10mm$ $\quad mc^2 = 0.511 MeV$

$\gamma \approx 10^4 (5 GeV)$

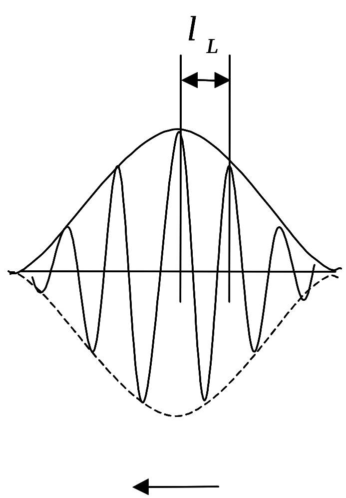
$\lambda_r \le 1$ (X)

Inversed Compton scattering

Short pulse



Electron beam



Femtosecond laser

$$\lambda_r = \frac{\lambda_L}{2\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

$\lambda_L \approx 1\mu m$

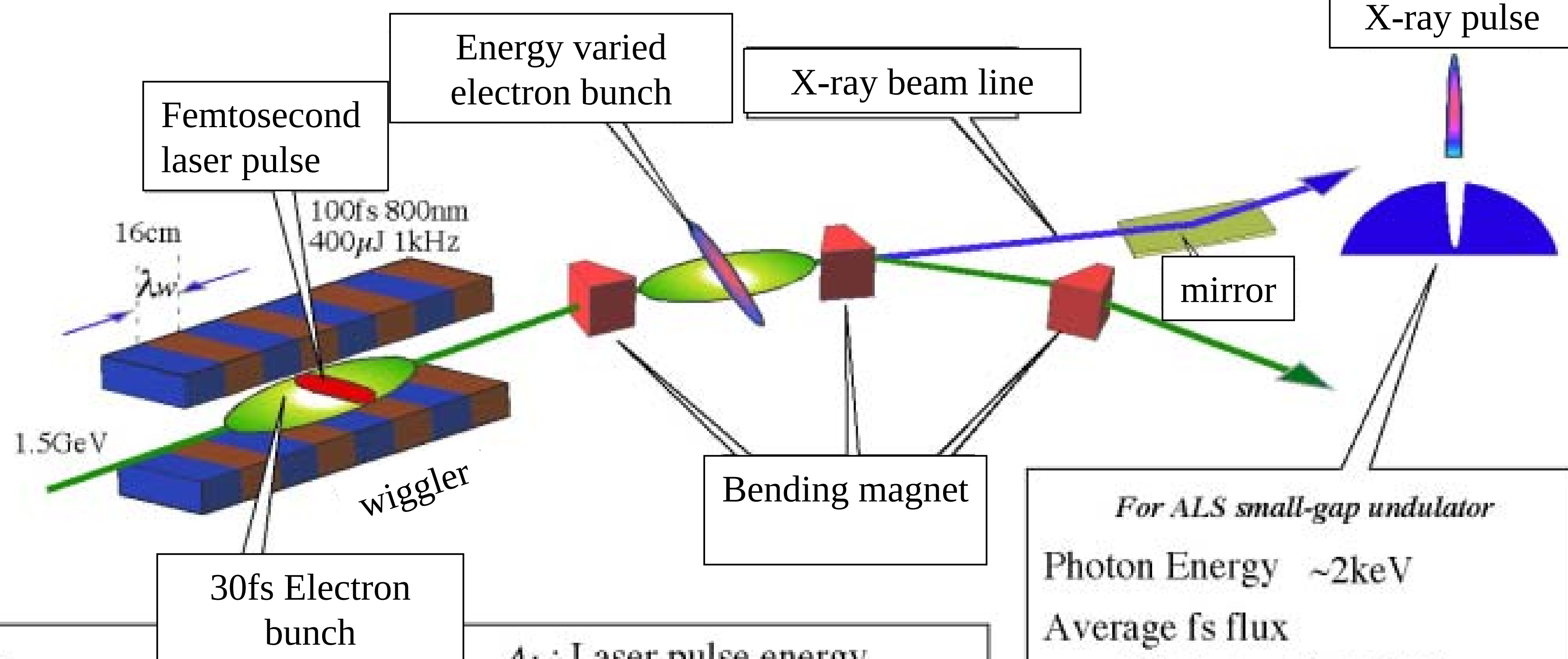
$\gamma \le 10^2 (50 MeV)$

$\lambda_r \le 1$ (X-ray)

Generation of fs pulses by energy-modulation of an ultrashort slice of e-bunch

Report @ALS(Advanced Light Source) storage ring

"Generation of Femtosecond Pulses of Synchrotron Radiation"
R.W.Schoenlein, et.al, Science **287**, 2237 (2000)



Electron energy modulation

$$\Delta E \cong 2\left(A_L A_W \frac{M_W}{\sqrt{2M_L}}\eta_{emit}\right)^{1/2}\cos\Phi$$

A_L : Laser pulse energy
A_W : Energy spontaneously radiated by a single passing through wigglar
M_W: Number of wigglar periods
M_L : Laser pulse length
η_{emit}: Emission cofficient ~ 0.7

For ALS small-gap undulator

Photon Energy ~2keV

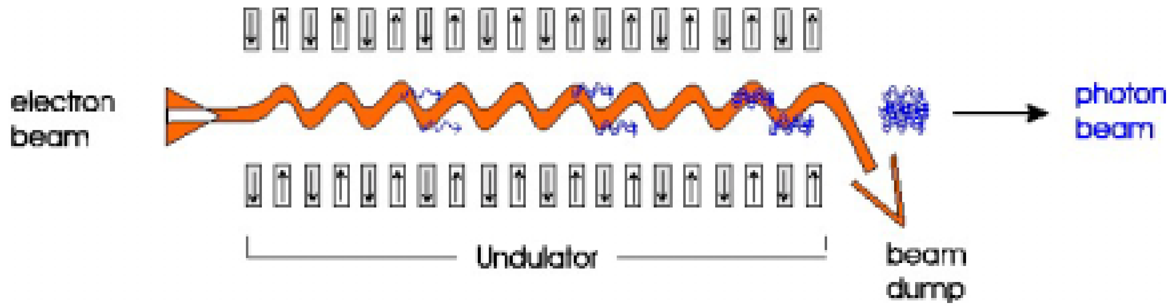
Average fs flux
~10^7photons/0.1%BW

Average brightness
~10^{11}photons s^{-1} $mrad^{-2}mm^{-2}$ /0.1%BW

X-FEL (X-ray Free Electron Laser)

Next generation light source !

High quality beam
from laser photocathode
RF gun is required.

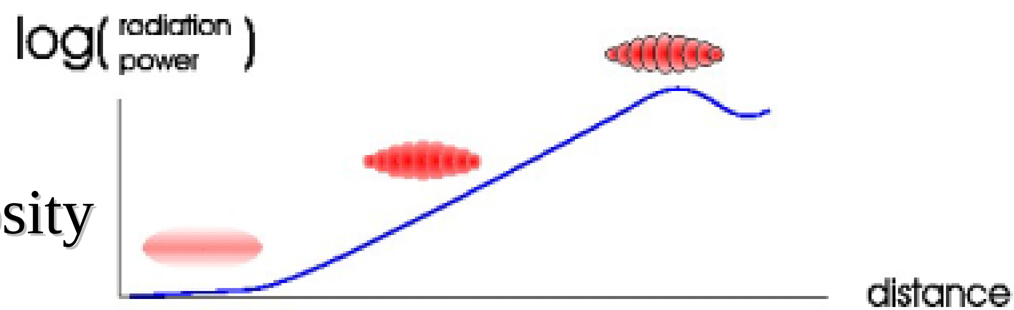


Feature

□Ultra short X-ray pulse

(100 femtosecond pulse)

□High intensity & High luminosity



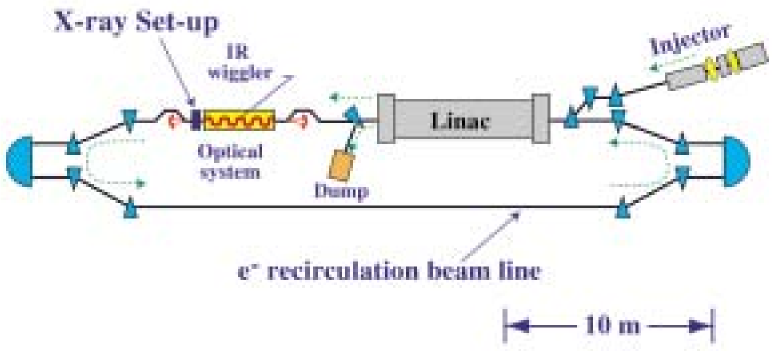
Applications

□Structural dynamic analysis. □Microanalysis.

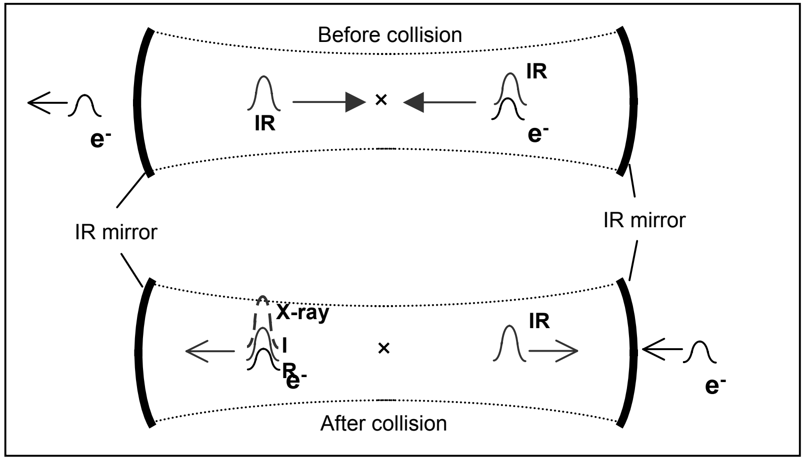
□Precise surface analysis.

(photoelectron spectroscopy, light-electron holography)

Thomson scattering in resonant cavity (Jefferson Laboratory)

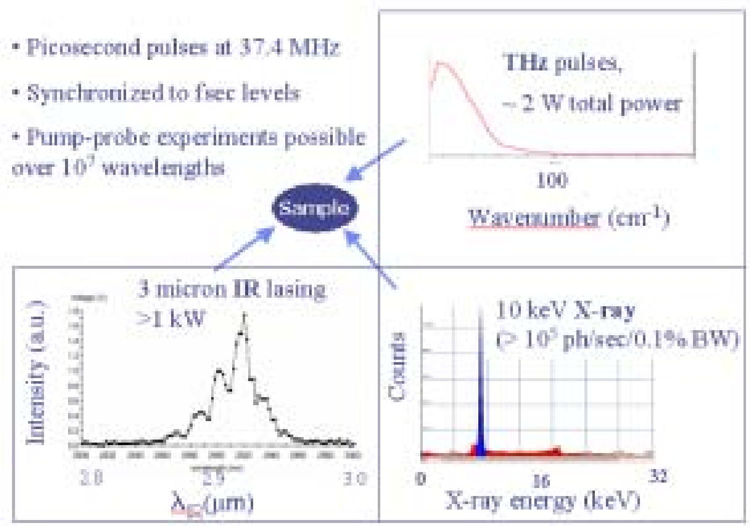


Injector..10 MeV electron bunch
.↓
Linac..25 ~ 48 MeV
.↓
Undulator..infrared light
.↓
Energy recovery..decelerated to10 MeV
.↓
Dump



Resonant cavity for infrared light

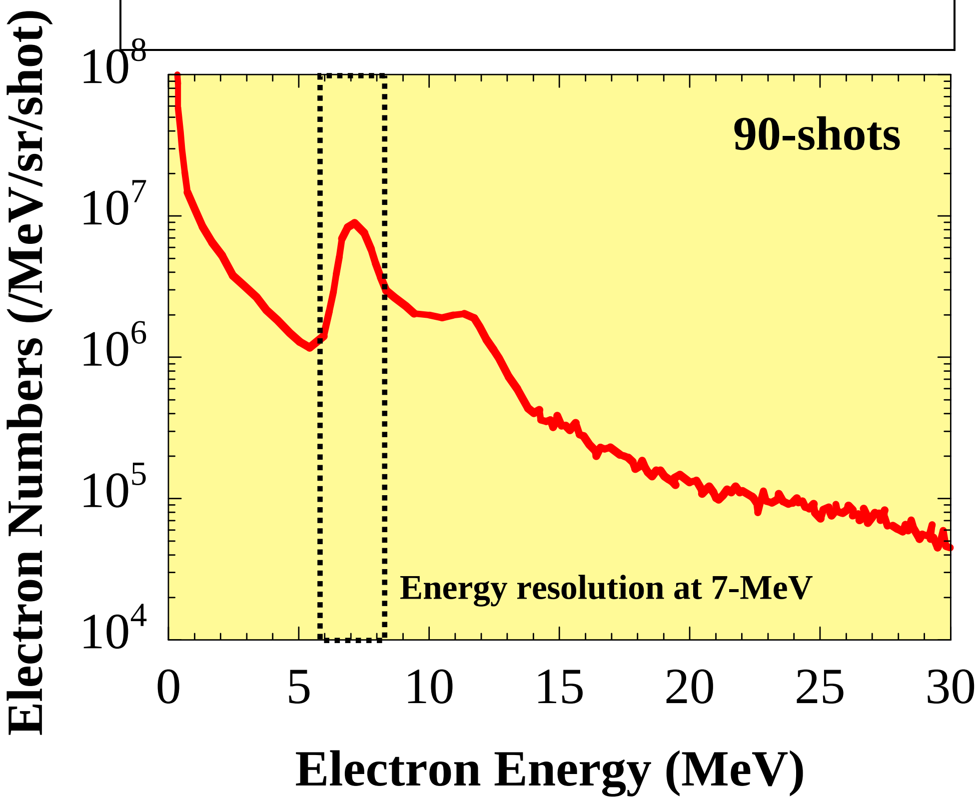
.infrared light...electron beam
..→.X-ray due to Thomson scattering
.....Pulse width of X-ray
......= pulse width of electron bunch . 300 fs



X-ray...infrared light...THz light
→.Femtosecond science by pump & probe

Electron Energy Spectrum including quasi-monoenergetic beam

Monoenergetic beam was emitted in an narrow divergence angle.

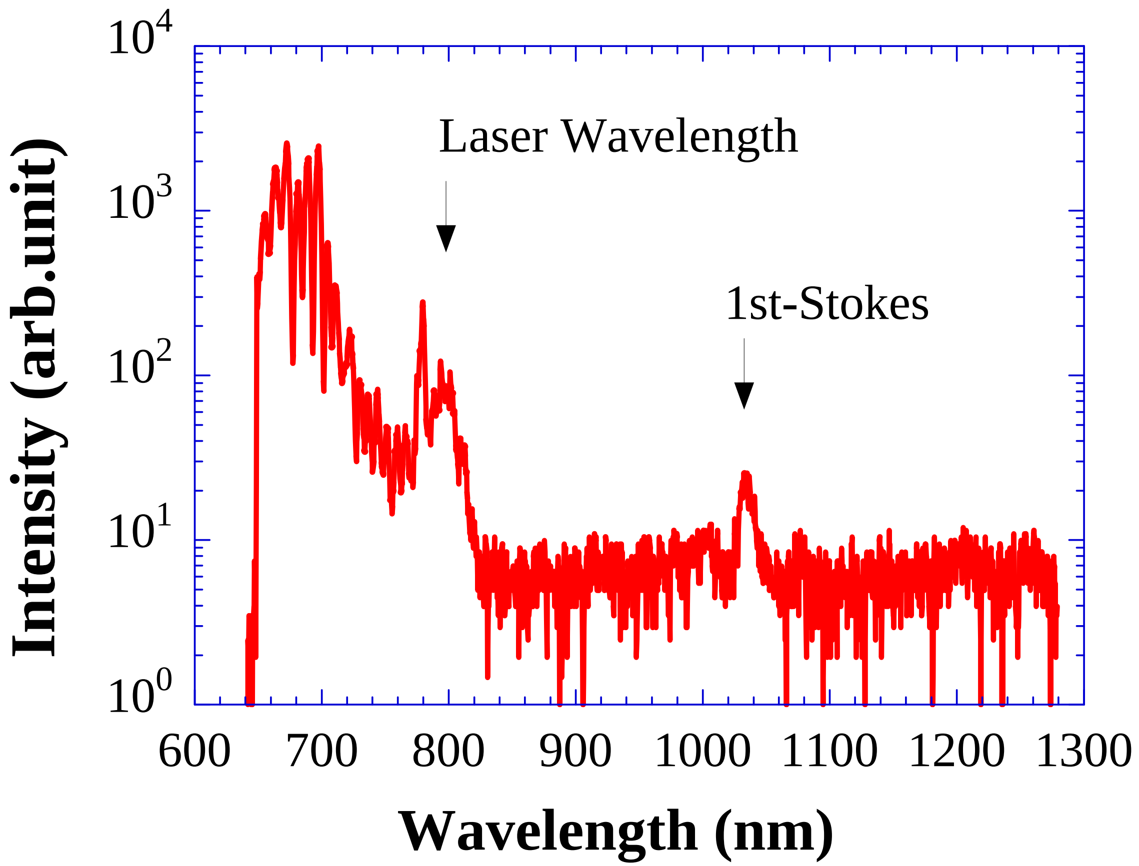


Energy spread of the monoenergetic beam was limited by the resolution of the spectrometer.

Raman Satellite in Forward Scattering Spectrum

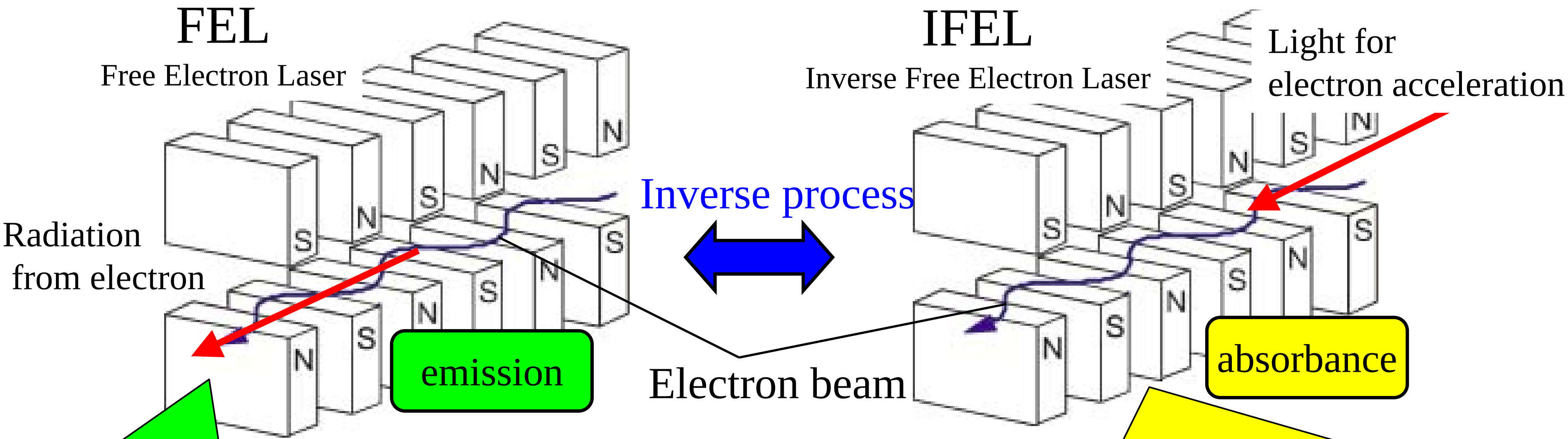
Raman Satellite in Forward Scattering Spectrum

AIST



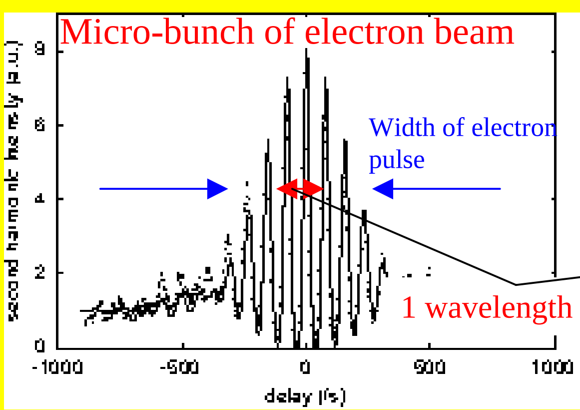
Acceleration of the quasi-monoenergetic beam closely correlated with the excitation of the plasma wave.

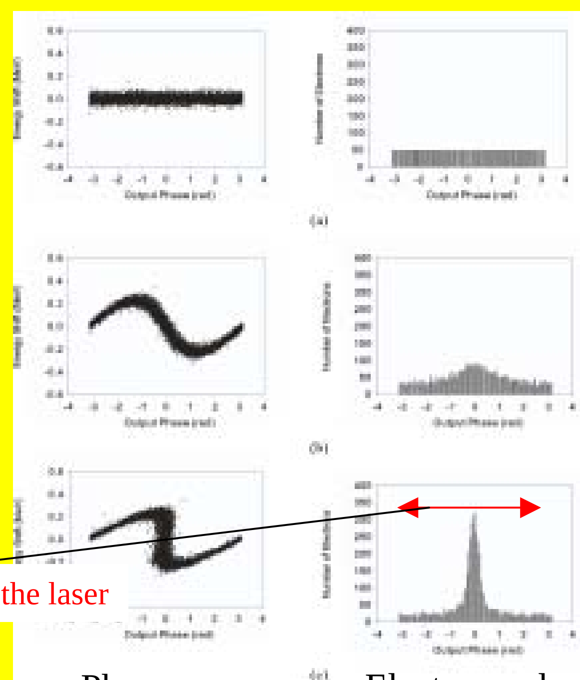
Ultra-short pulse generation at IFEL at BNL-ATF



A part of electronic energy is changed into light.

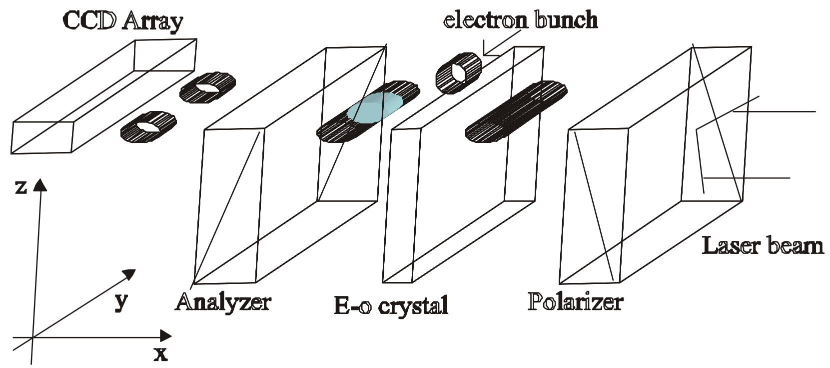
Due to the electric field of laser, acceleration and compression are occurred. Then the light is changed into electron energy.





Scheme of bunch compression
.3 fs

Electron bunch length measurement using E-O crystal



Schematically experimental setup.
Inject the linear polarized laser to the E-O crystal to probe the double refraction excited by the electron bunch.

Electron beam injection → Excite the double refraction at E-O crystal.

→ Rotate the polarization of injection laser. → Observe the distribution of transmission laser

→ Evaluate the bunch form

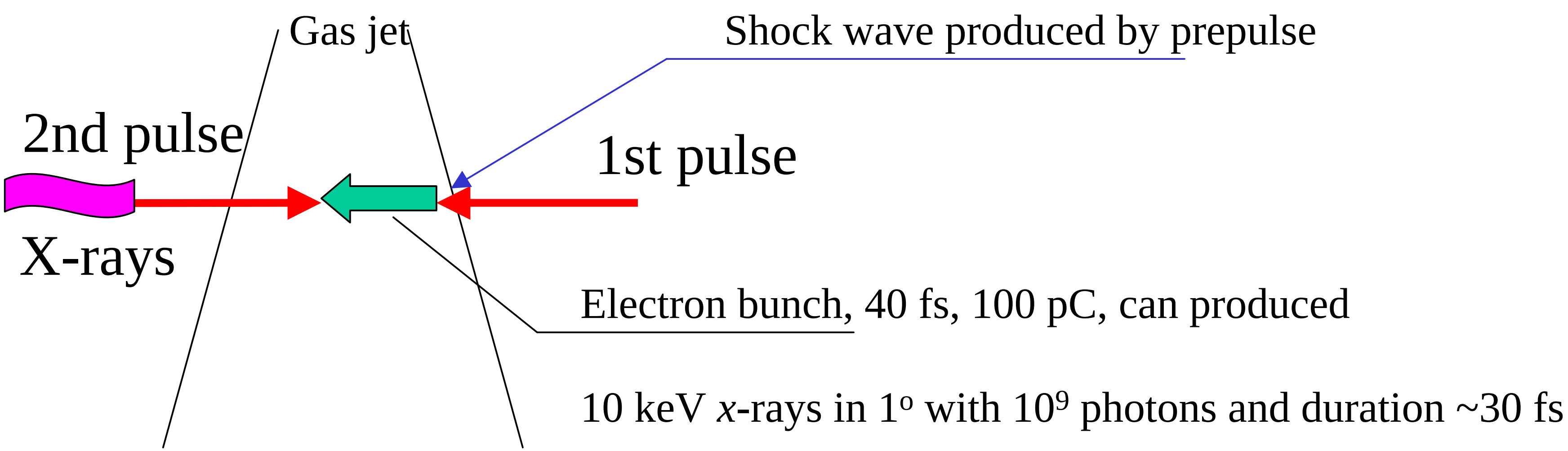
All Optical Thompson scattering

M. Uesaka *et al.*, Proceedings of PAC2003

Moving through the laser pulse, a relativistic electron transforms the laser light to X-rays.
The total number of photons produced by the electron is

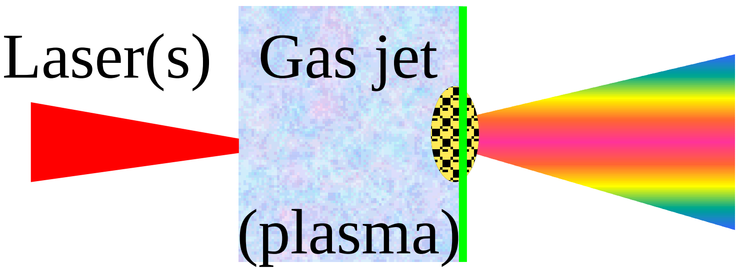
$$dn/dt=\sigma I/h\omega \longrightarrow n=\sigma W/h\omega$$

$\sigma\sim\pi r_e^2=\pi e^4/(mc^2)^2$, I the pulse intensity, W the energy density
For the laser pulse with total energy 1 J, $\lambda\sim1$ μm, and focus spot ~10 μm -W=1 MJ/cm^2 that gives $n\sim2\text{-}3$



LOA
LBNL

T.R. from plasma-vacuum boundary



- laser (800nm)
- laser (blue shifted)
- laser (scattered)
- transition radiation (plasma-vacuum)

Information of 40fs

Coherent: ~THz

Incoherent ~optical

Fluctuational interferometry[*3, 4]

[*3] M. S. Zolotorev and G. V. Stupakov, SLAC-PUB-7132, 1996

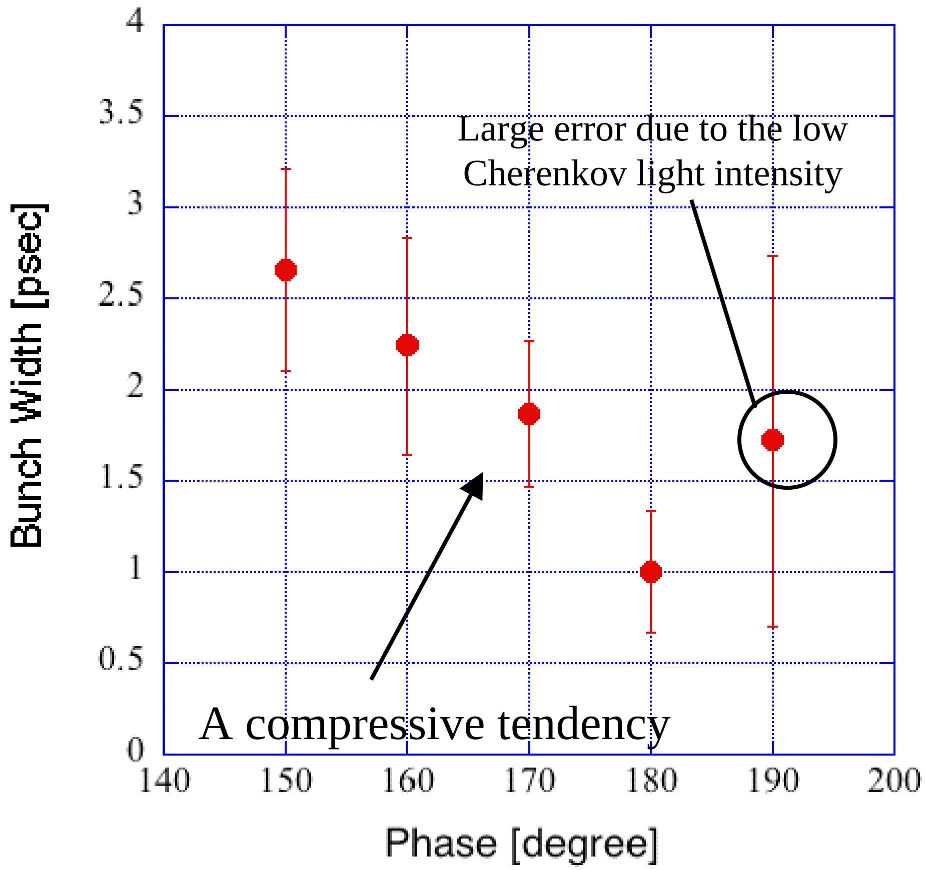
[*4] P. Catravas, W. P. Leemans et al., Physical Review Letters **82**, 5261 (1999)

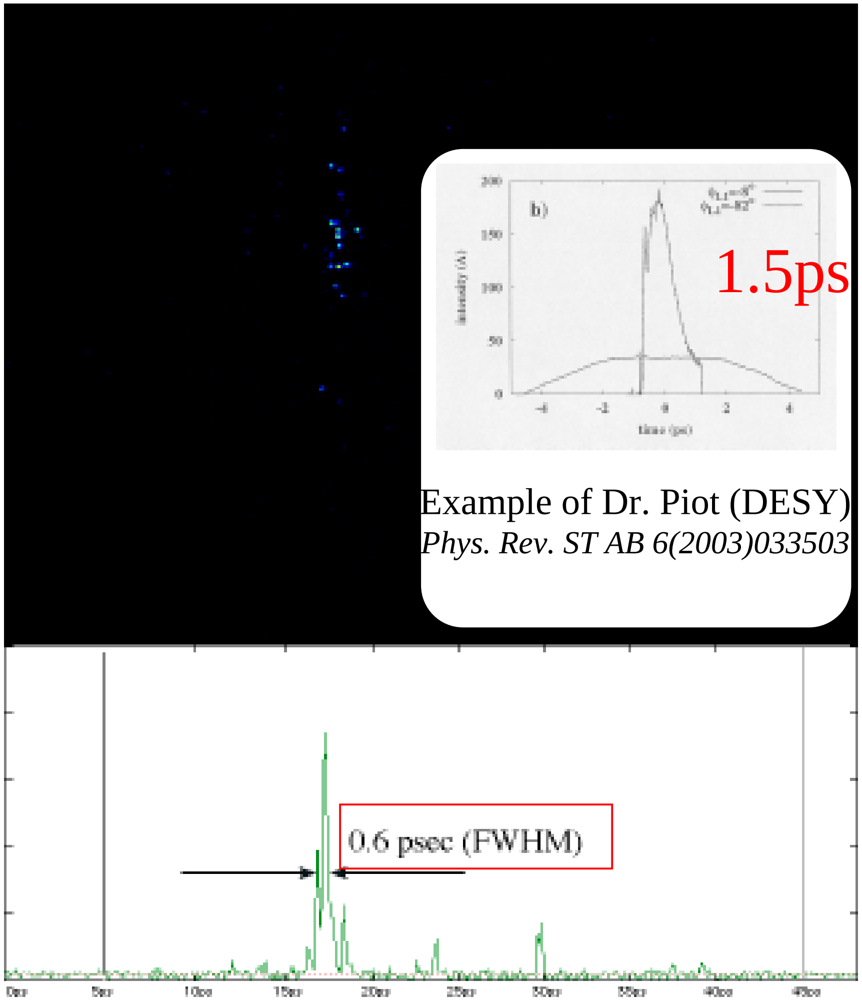
Pulse compression by velocity bunching

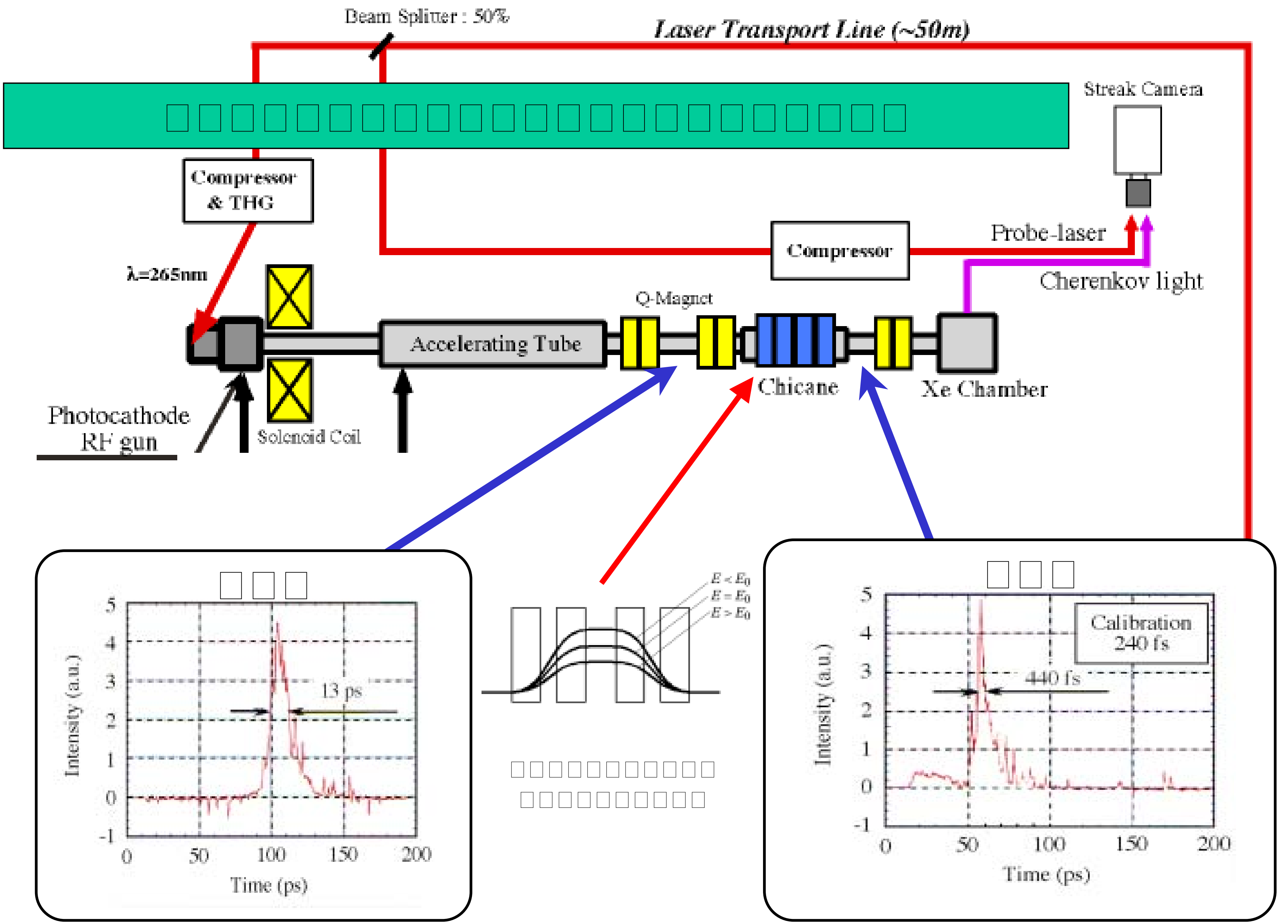
Variation of the bunch width for different accelerating phases

Bunch width is measured by the FESCA with a cherenkov right from Xe gas.

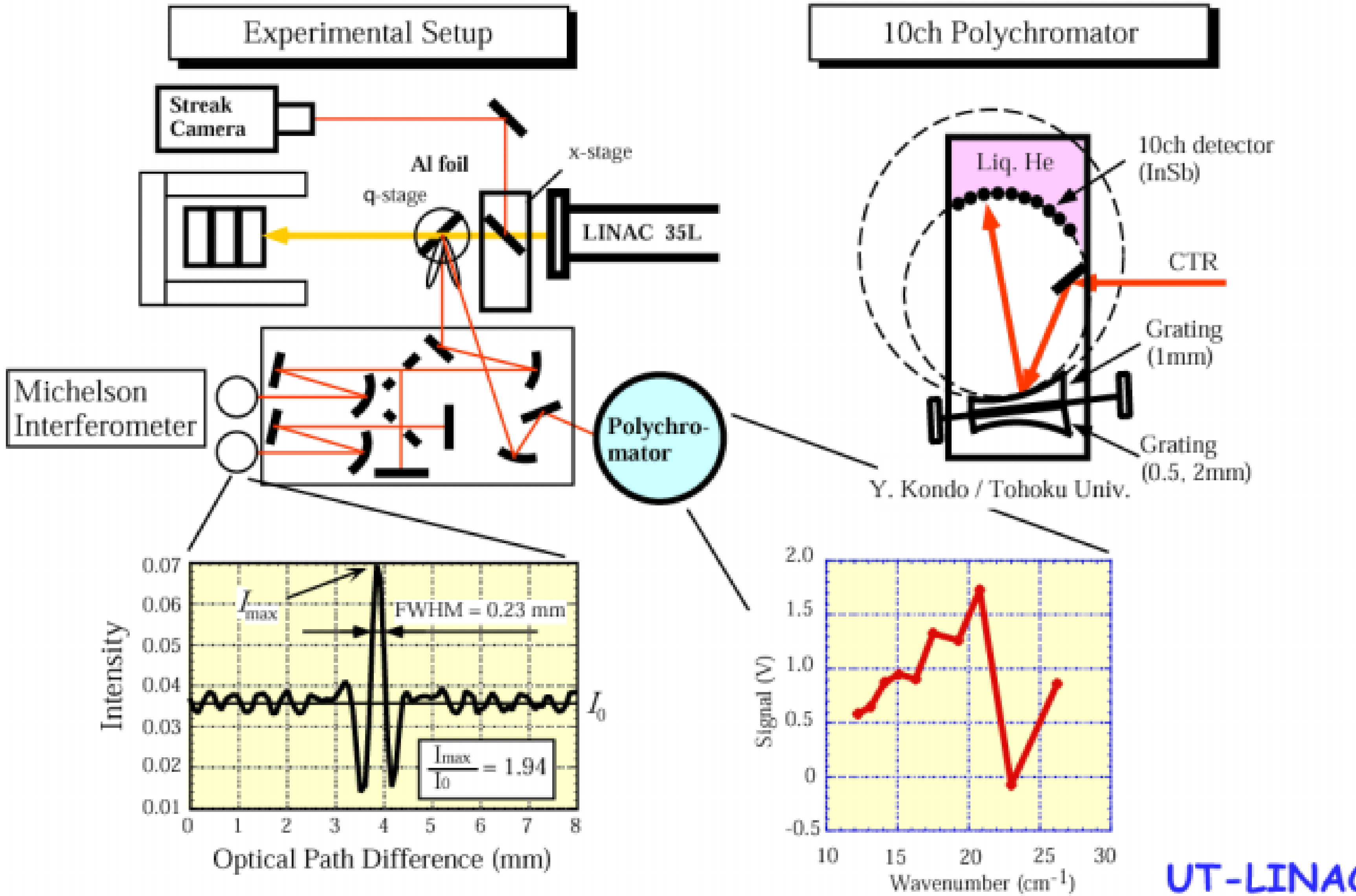
Average (FWHM) of 30 shots and variance.





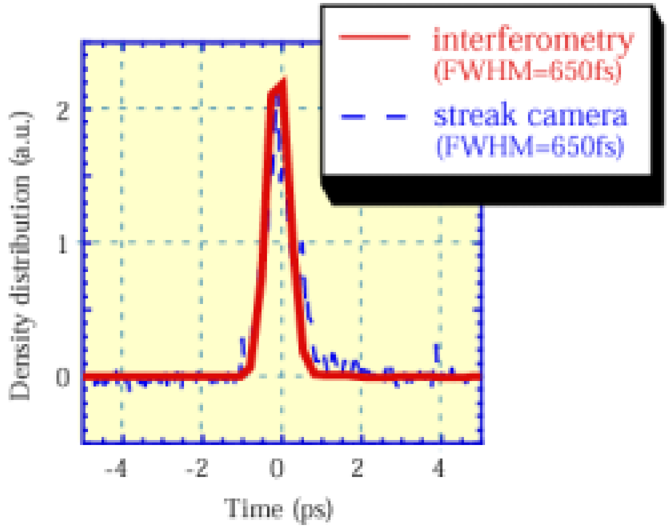

Beam Splitter : 50%
Laser Transport Line (~50m)
Streak Camera
Compressor & THG
Compressor
Probe-laser
Cherenkov light
λ=265nm
Q-Magnet
Accelerating Tube
Chicane
Xe Chamber
Photocathode RF gun
Solenoid Coil
13 ps
Intensity (a.u.)
Time (ps)
E < E0
E = E0
E > E0
Calibration 240 fs
440 fs
Intensity (a.u.)
Time (ps)

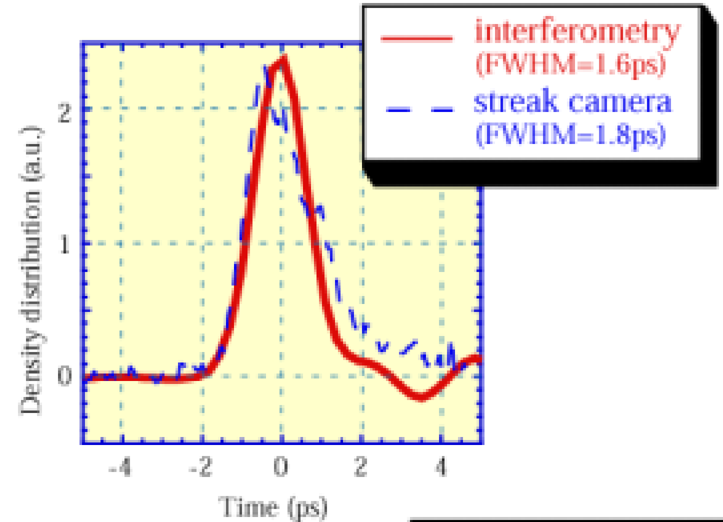
Measurement using coherent radiation

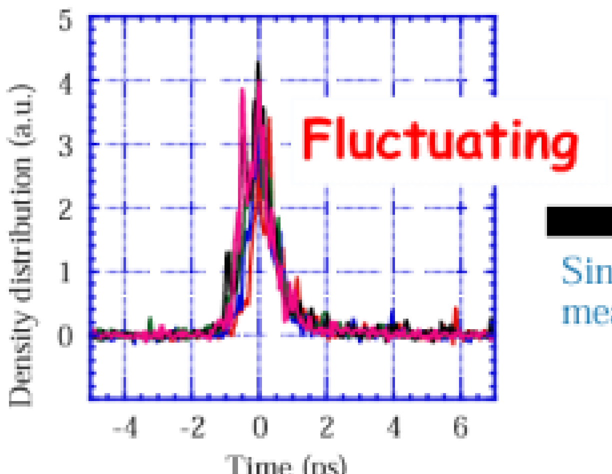


UT-LINAC

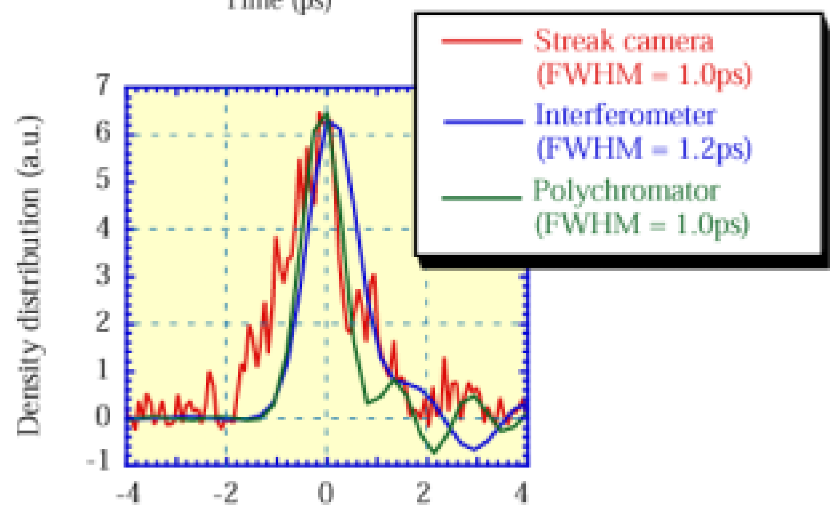
Bunch distribution from interferogram







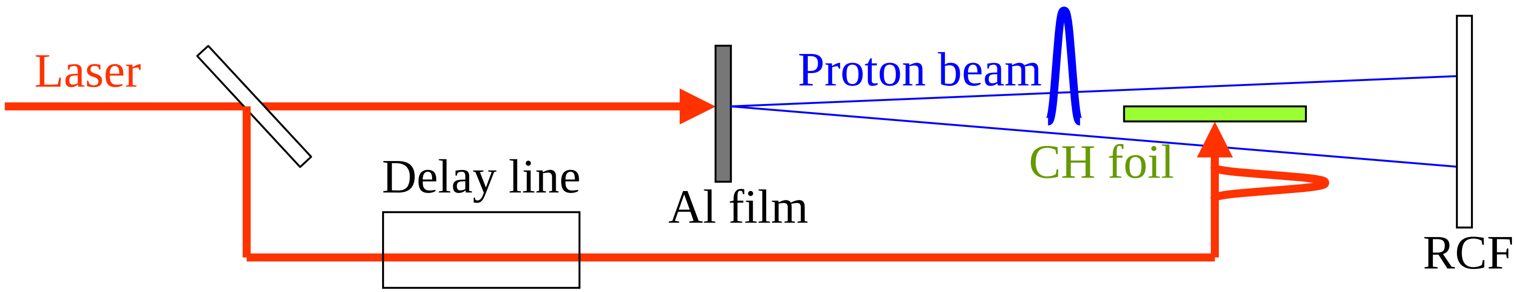
Single-shot measurement

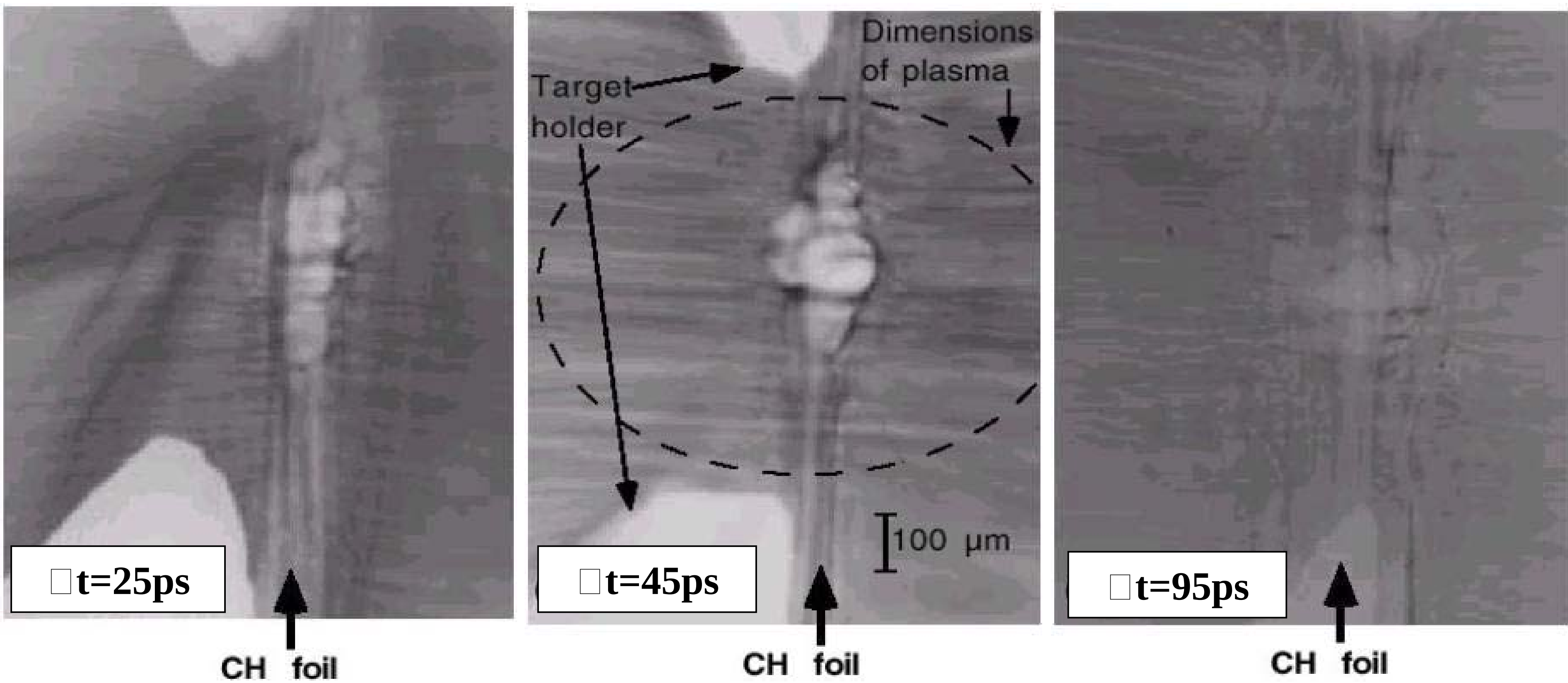


Good agreement within 20% error could be obtained, but,,,

UT-LINAC

Visualization of irreversible process by single-shot imaging



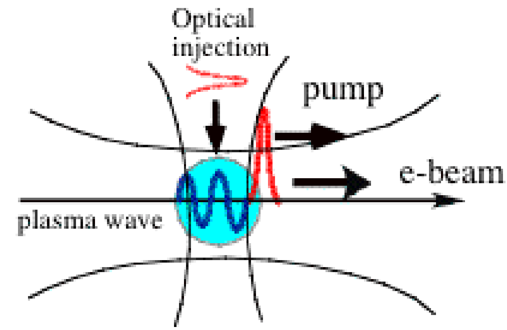


M. Borghesi, et al., Phys. Rev. Lett. 88, 135002 (2002).

Optical Injection Methods

- Ponderomotive injection from single pulse
  - Injection pulse intersects wake from pump at 90^0
  - Ponderomotive force injects electrons
    - Umstadater et al., PRL 96
    - Hemker et al., PRE 98

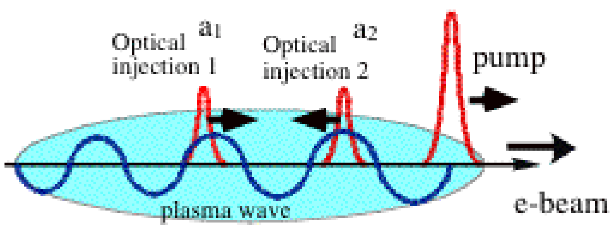
$$F_z \propto \nabla a_1^2 \propto a_1^2 / r_1$$



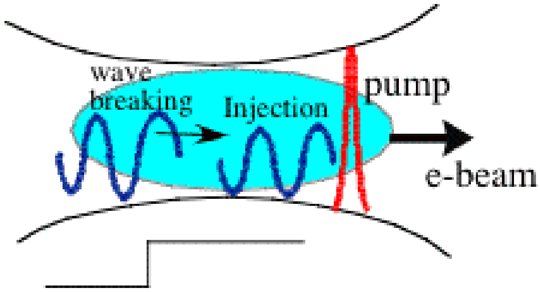
- Beat wave injection from colliding pulses
  - Two counterpropagating injection pulses collide
  - Injection from beat wave with slow phase velocity
    - Esarey et al., PRL 97
    - Schroeder et al., PRE 99

$$F_z \propto \nabla a_1 a_2 \propto a_1 a_2 / \lambda_0$$

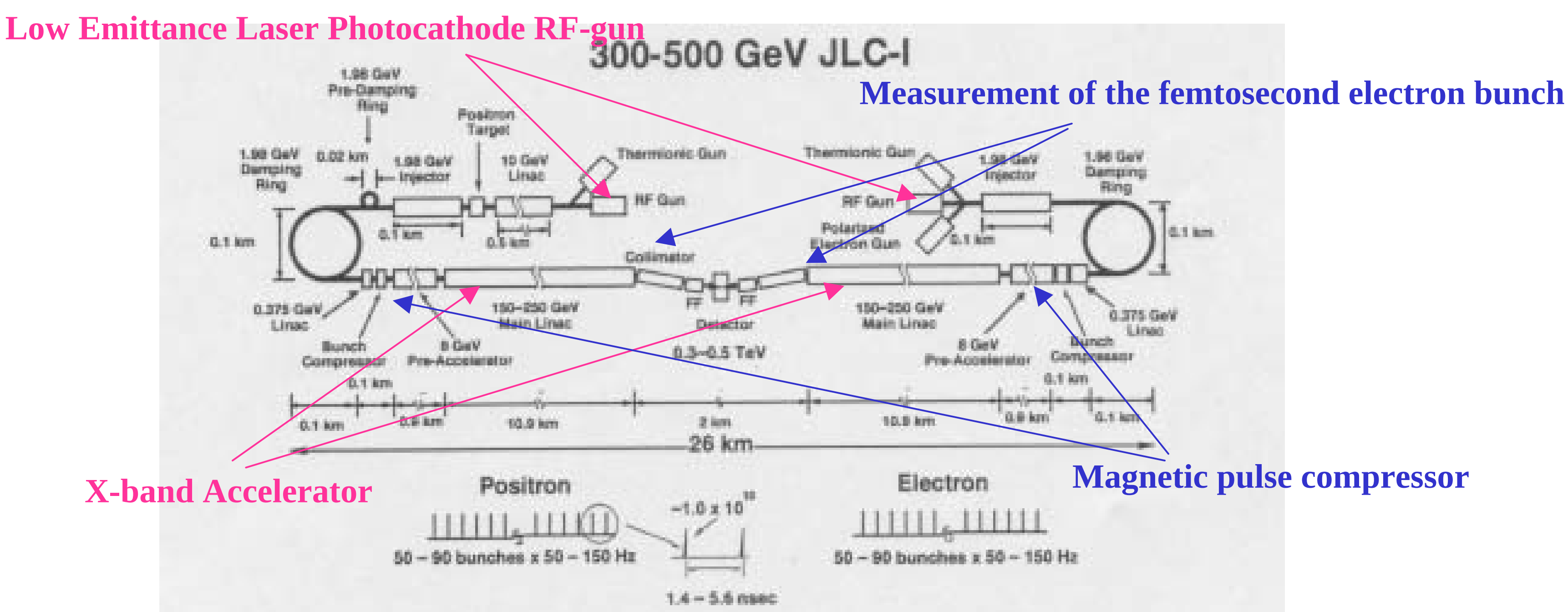
$$v_{ph} \approx \Delta\omega / \Delta k \approx \Delta\omega / 2k_0 << c$$



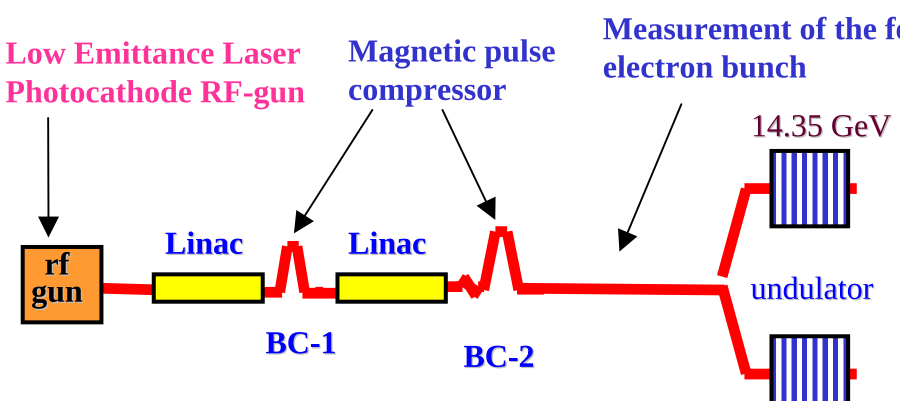
- Downward density transitions
  - Wake phase velocity decreases on down ramp
  - Wavebreaking induced some distance behind pump
    - Bulanov et al., PRE 98
    - Suk et al., PRL 01



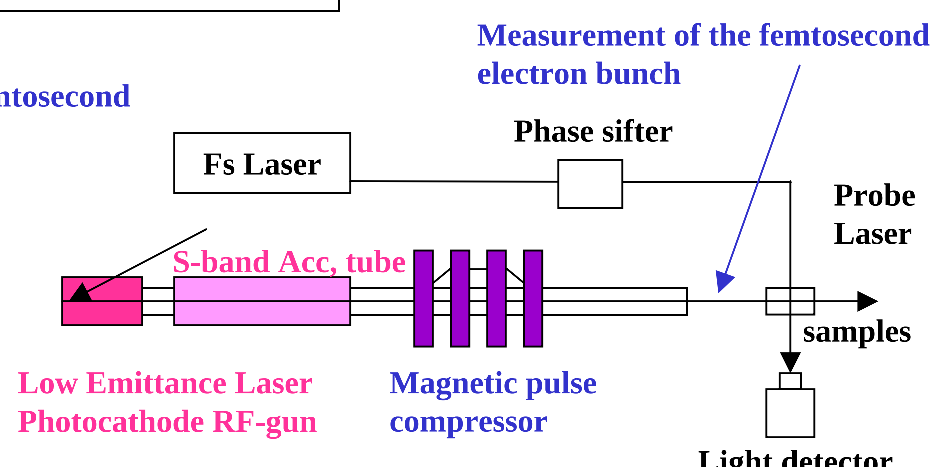
Common component of the advanced accelerators



Linear Collider – Higgs boson search



4th generation light source – X-ray FEL



Femtosecond Linac for radiation chemistry