Diagnostics for SXFEL

- diagnostics specific for single pass FEL
- standard diagnostics tools for e-bunch measurement
- coherent radiation measurement of short bunches
- single-shot e-bunch measurement
- outlook---Prof. Yen-Chieh Huang

Bian Yu
2015/9/9

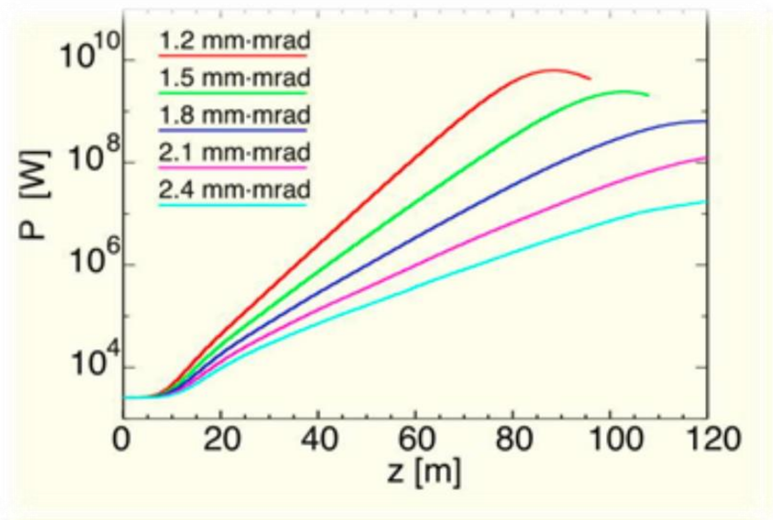
- no photon diagnostics
- personal perspective

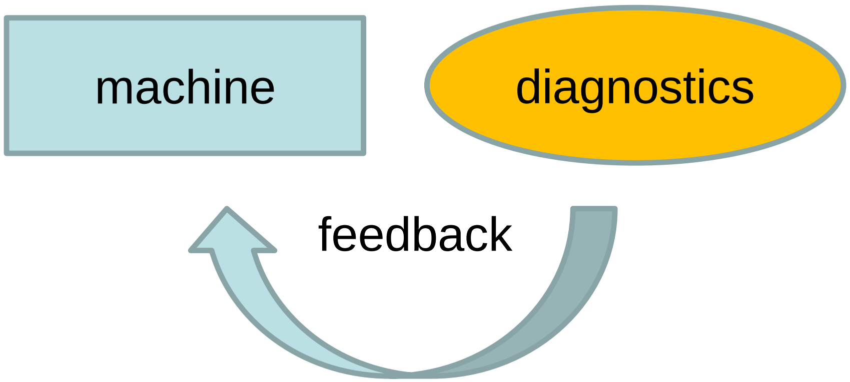
Diagnostics specific for single pass FEL

Main parameters of SXFEL＆SDUV		
Parameters	**SXFEL**	**SDUV**
Electron Energy	0.84 GeV	130MeV
Normalized emittance	< 2.5mm.mrad	< 6.0mm.mrad
Slice energy spread	< 0.02%	\
Peak current/ bunch length/charge	500 A /1ps/ 500pC	100A/100fs~3ps
Wavelength of laser seed	~265nm	1047nm/800nm
Scheme	HGHG	HGHG/EEHG
Cascading scheme	265-44-8.8nm；	\
FEL peak power	>100MW	~MW
FEL wavelength	8.8 nm	200~1200nm
FEL pulse length	100~150 fs (FWHM)	8ps/~130fs/~100fs

FEL pulse length and e-bunch length

Diagnostics specific for single pass FEL



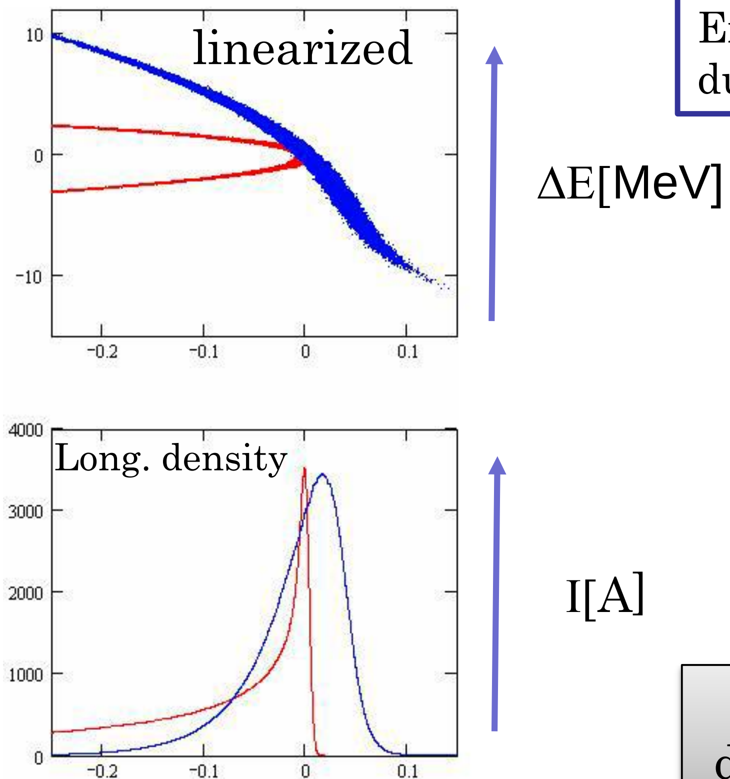


FEL power depends exponentially on beam parameters (peak current, emittance …)

Measure, control and stabilize beam parameters such that optimum FEL performance is achieved

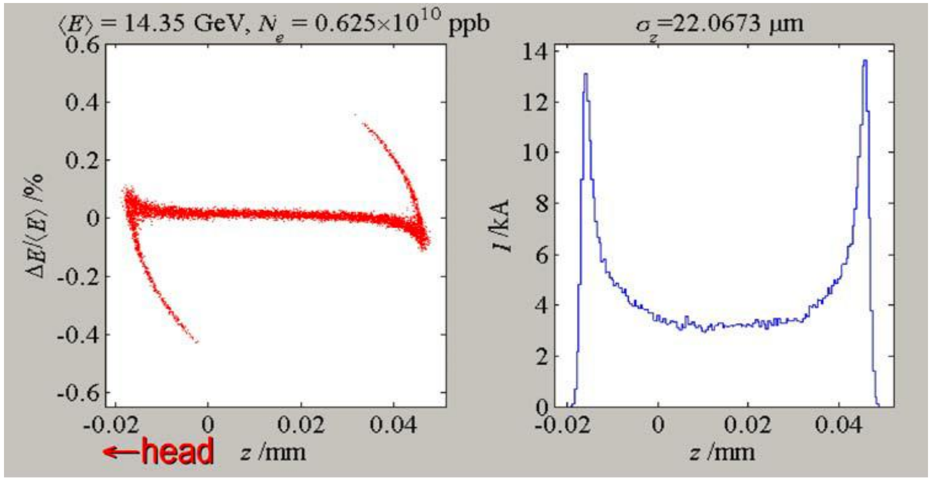
Diagnostics specific for single pass FEL

Bunch compression for high peak currents has non-linear components ⇨ complex phase space distributions



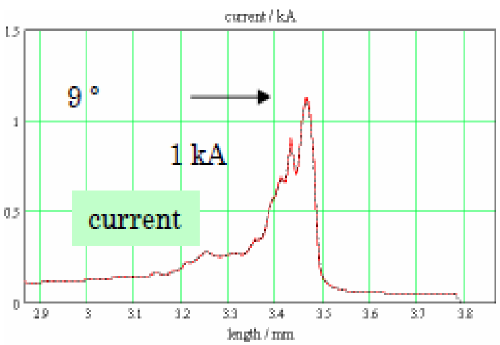
FLASH, XFEL

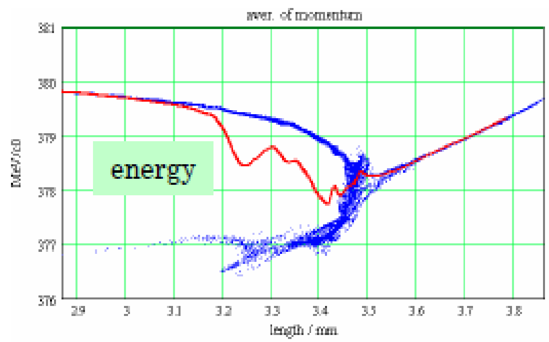
Expected long. bunch shape at LCLS, 'double horn' due to wake fields

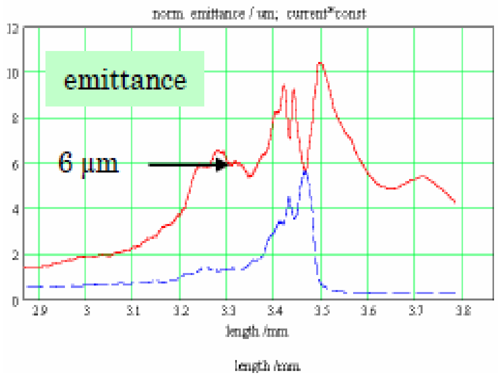


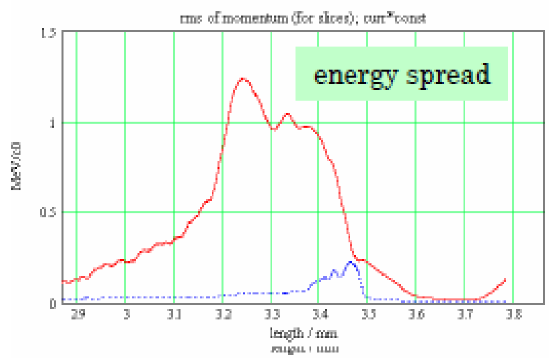
Only fraction of the total charge will 'lase', diagnostic has to be sensitive to this fraction

Diagnostics specific for single pass FEL









ideal diagnostics
- ultimate resolution
- comprehensive
- immediate feedback
- non-destructive

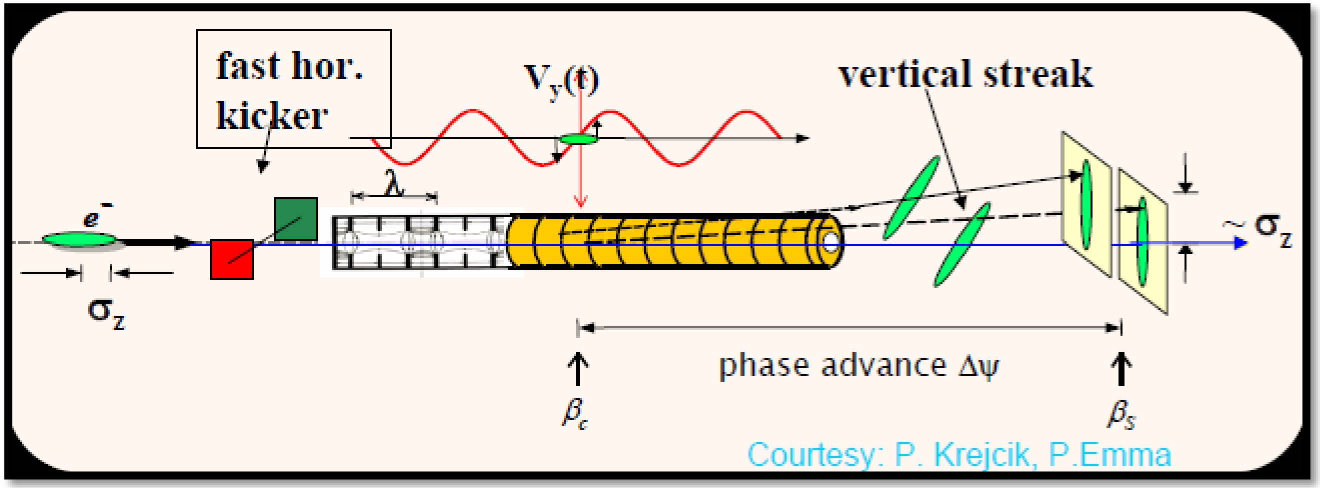
Projected parameters are of limited use !
Diagnostics has to reveal details of the bunch structure
slice emittance, bunch profile, slice energy spread, bunch position

Standard diagnostics tools for e-bunch measurement

Transverse deflecting cavities (TCAV)

•Adds z-position dependent transverse kick to bunch

•Phase advance to screen vertical streak of longitudinal bunch structure



- single bunch capable
- destructive (sacrifice 1 bunch)
- slow read out (imaging)

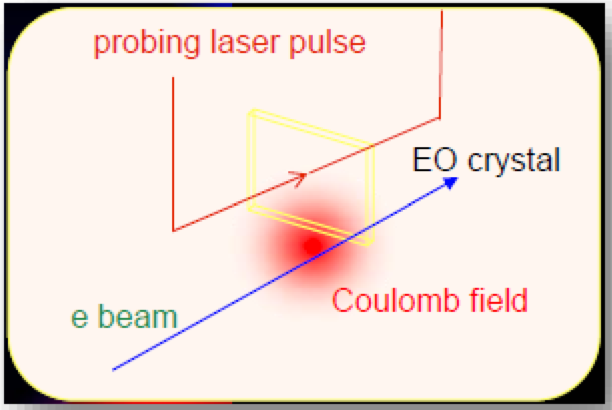
Typical Resolution: 20-50fs

Resolution depends on cavity power, beam energy and machine optics

Standard diagnostics tools for e-bunch measurement

Electro -Optic (EO) Techniques

Intra-beamline measurement of the bunch Coulomb field



•Field induced refractive index change
•Polarization-modulation of probing laser
•Temporal structure of Coulomb field impressed to ellipticity of optical pulse

- scanning techniques
- single-shot techniques

Limitations:
-high frequency cut-off due to finite distance to beam
-velocity mismatch of FIR and optical propagation in EO crystal
-phonon resonances of EO material

Standard diagnostics tools for e-bunch measurement

Make the electrons radiate coherently …

spectral energy density

source characteristics (CSR,CTR,CDR…)

$$\frac{dU}{d\omega} = CN^2 \left|F_{long}(\omega)\right|^2 T\left(\omega, \gamma, r_b, \theta, source\right)$$

$$F_{long}(\omega) = \int_{-\infty}^{\infty} \tilde{\rho}(t) \exp(-i\omega t) dt$$

normalized charge density

-integral intensity

⇨ compression factor, effective bunch length

-spectral resolved intensity

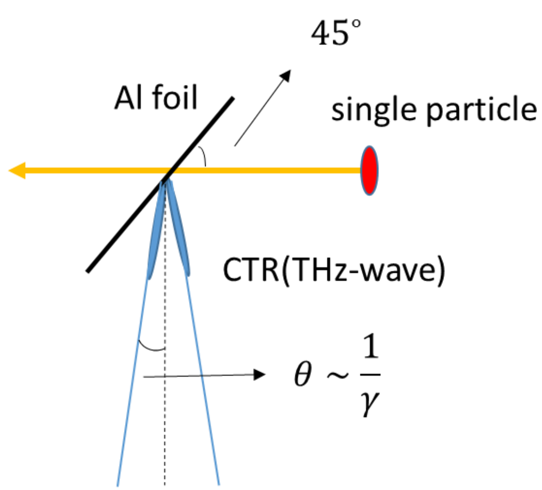
⇨ bunch structure, longitudinal beam profile

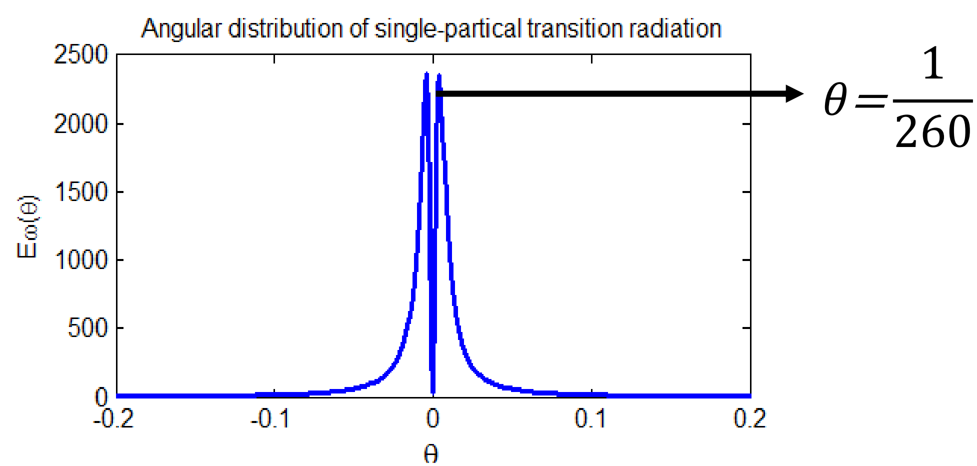
CTR measurement of short bunches----in frequency domain

Single-particle transition radiation (TR)

$$I_0(\omega)=\frac{d^2U_{1e}^{-}}{d\Omega dk}=\frac{r_e mc}{\pi^2}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\approx\frac{e^2}{\pi^2 c}\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}$$

Frequency independent → Ideal for analysis

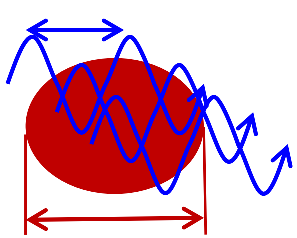




For SDUV, e-bunch energy is 130Mev.

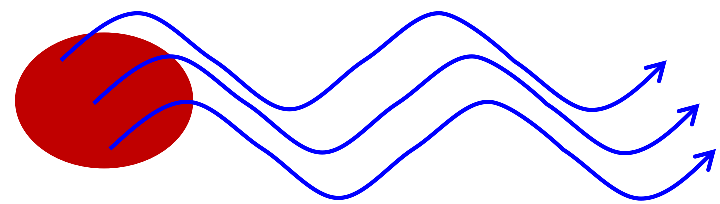
Coherent transition radiation(CTR) from e-bunch

Wavelength, λ_r



Bunch length, σ_z

Incoherent radiation $\lambda < \sigma, \; I \propto N$



Coherent radiation $\lambda > \sigma, \; I \propto N^2$

Far-field approximation:

$$I_{coherent}(\omega, \sigma_z) = I_0(\omega)\,[N + N(N-1)F_b(\omega, \sigma_z)]$$
$$\sim N^2 I_0(\omega) F_b(\omega, \sigma_z)$$

$I_{coherent}(\omega, \sigma_z)$: Power of coherent radiation
N: Number of particle in a bunch
$F_b(\omega, \sigma_z)$: Bunch form factor (BFF)
$I_0(\omega)$:Radiation emitted from an electron
σ_z : Bunch length

Bunch form factor :

$$F_b(\omega) = \left| f(\omega) \right|^2$$

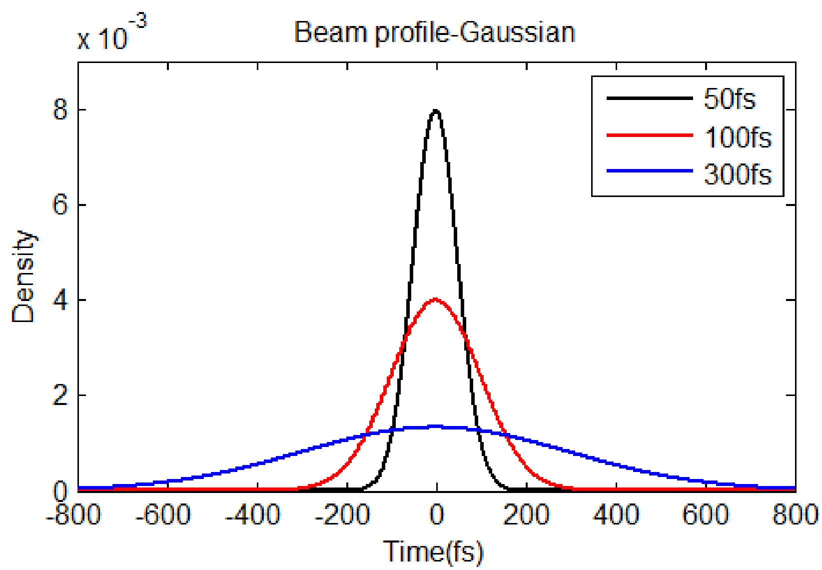
$$f(\omega) = \sum_{j=1}^{N} e^{i\omega t_j} \cong N \int_{-\infty}^{\infty} \rho(t) e^{i\omega t} dt$$

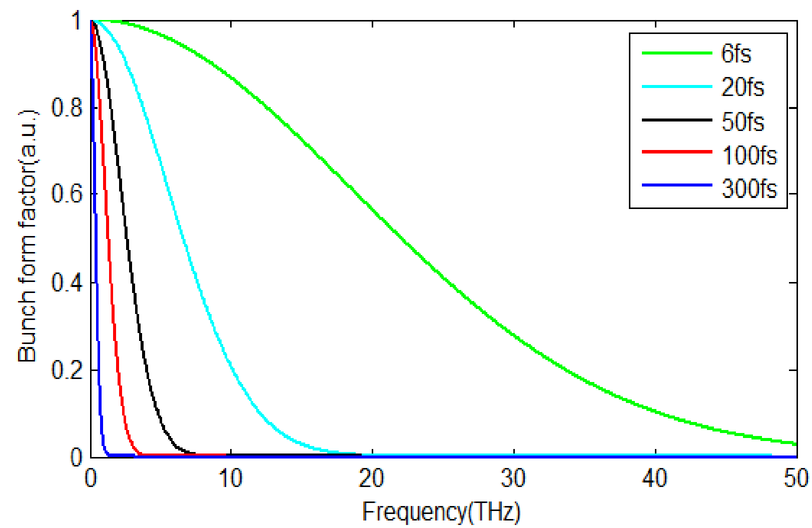
stack in same phase!

Coherent transition radiation(CTR) from e-bunch

For a gaussian beam the longitudinal beam profile is:

$$\rho(t) = \frac{1}{\sqrt{2\pi}\sigma}\exp(-t^2/2\sigma^2) \xrightarrow{\text{BFF}} F_b(\omega) = \exp(-\sigma^2\omega^2)$$



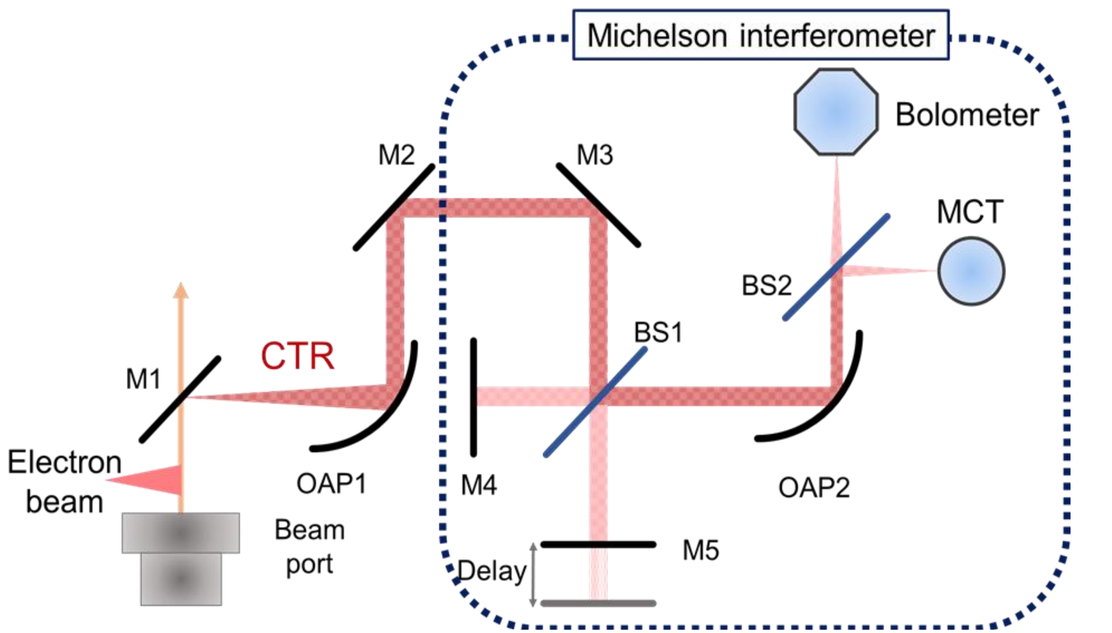


short e- bunch ⇔ radiation at higher frequency

Facility in Osaka University (<20fs)

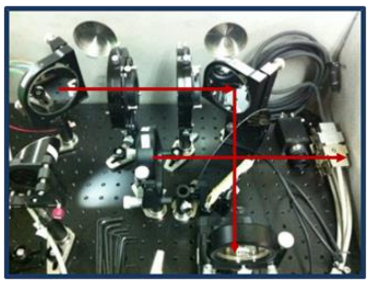
Bunch length measurement system（in a vacuum.）

M: mirror, OAP: off-axis parabolic mirror,
BS: beam splitter (high resistivity silicon or KBr), MCT: HgCdTe detector

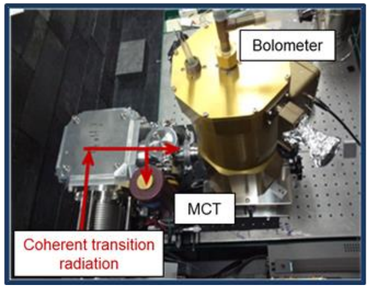


Pictures are from Professor Yang Jinfeng in Osaka University

Michelson interferometer



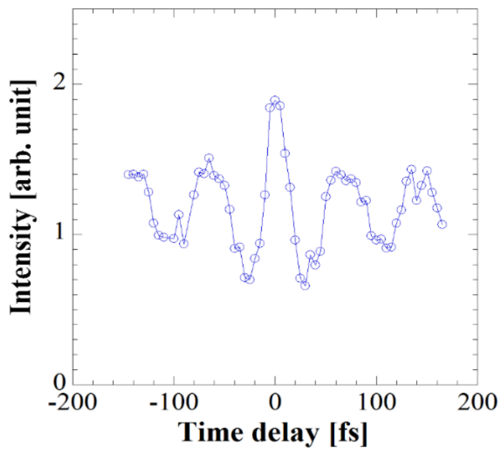
Infrared detectors



Two different infrared detectors are used!
(Bolometer: low-freq. radiation, MCT: higher freq. radiation)

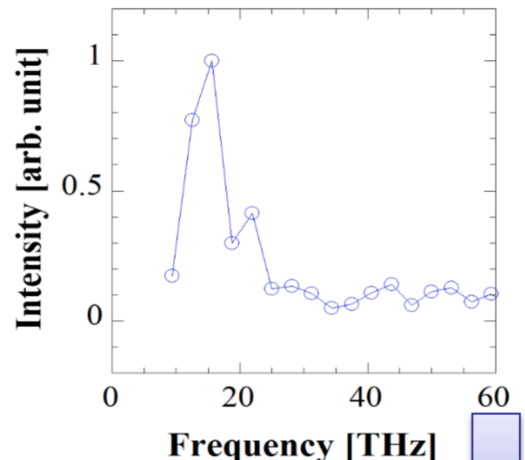
e-bunch length estimation

Exp. Interferogram data, $i_{eff}(t)$

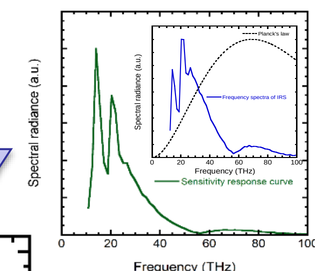


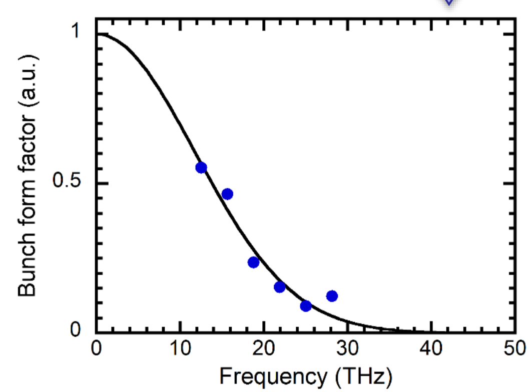
FT

Freq. spectrum, $I_{\text{eff}}(\omega)$

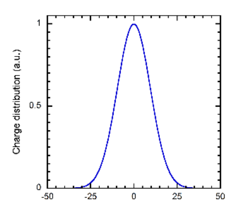


$S(\omega)$





assuming Gaussian distr.



σ= 8.9 fs

From Professor Yang Jinfeng in Osaka University

Longitudinal beam profile reconstruction

Using Kramers-Kronig (KK) transform

$$F_b(\omega) = I_{eff}(\omega) / S(\omega)$$

$$\phi(\omega_1) = -\frac{\omega_1}{\pi}\int_0^\infty \frac{\ln\left[F_b(\omega)/F_b(\omega_1)\right]}{\omega^2-\omega_1^2} d\omega$$

$$\rho(t) = \int_{-\infty}^{\infty} \sqrt{F_b(\omega)} \exp\left[-i\{\omega t - \phi(\omega)\}\right] d\omega$$

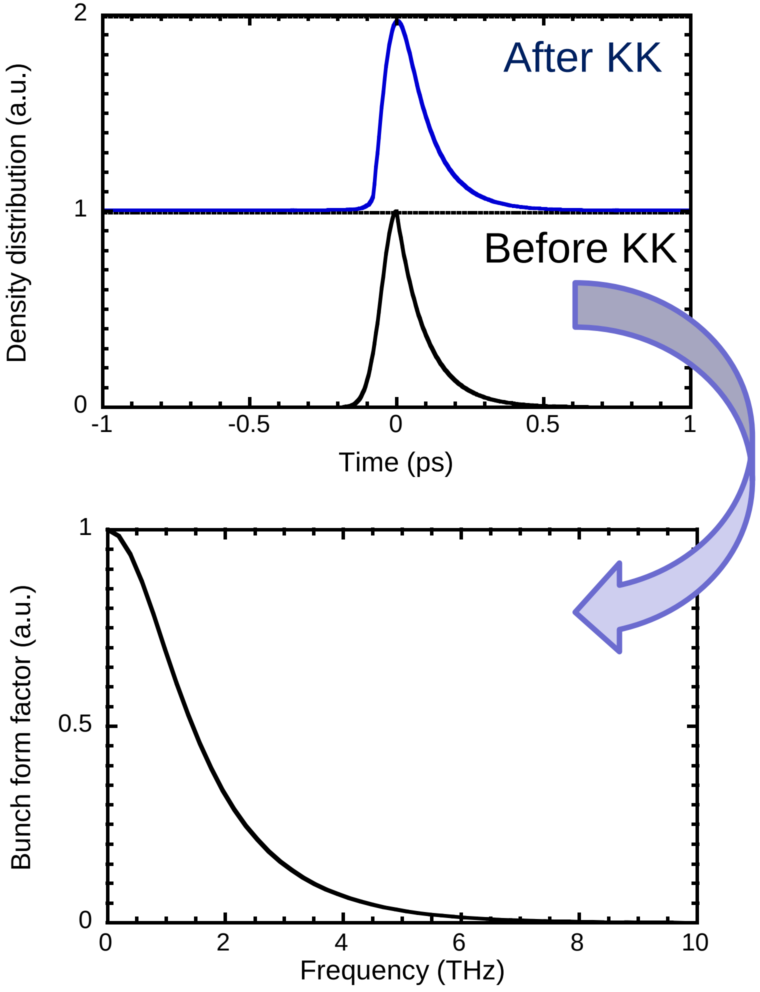
$\rho(t)$: Charge distribution

$\phi(\omega)$: Phase at each frequency

$I_{eff}(\omega)$: Effective frequency spectrum

$S(\omega)$: Sensitivity response function

$F_b(\omega)$: Bunch form factor



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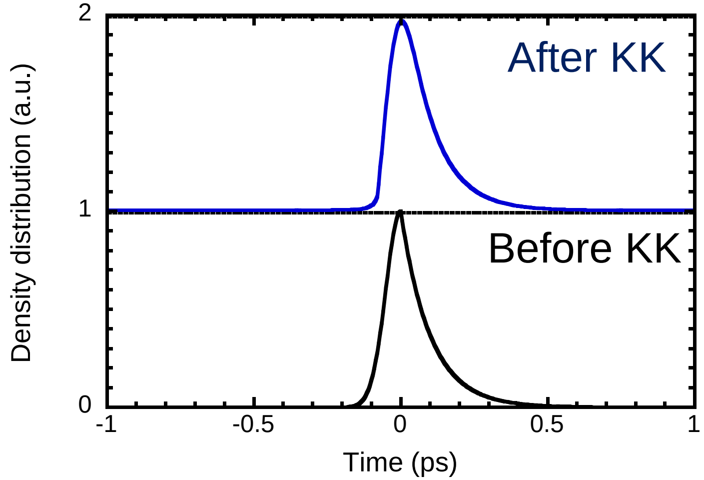

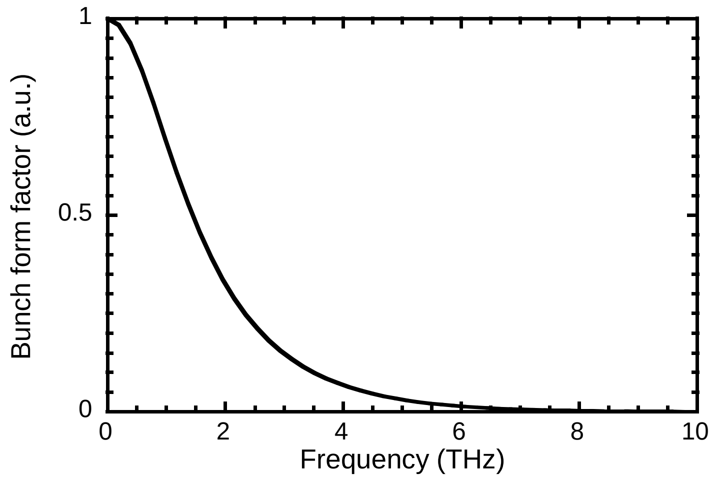

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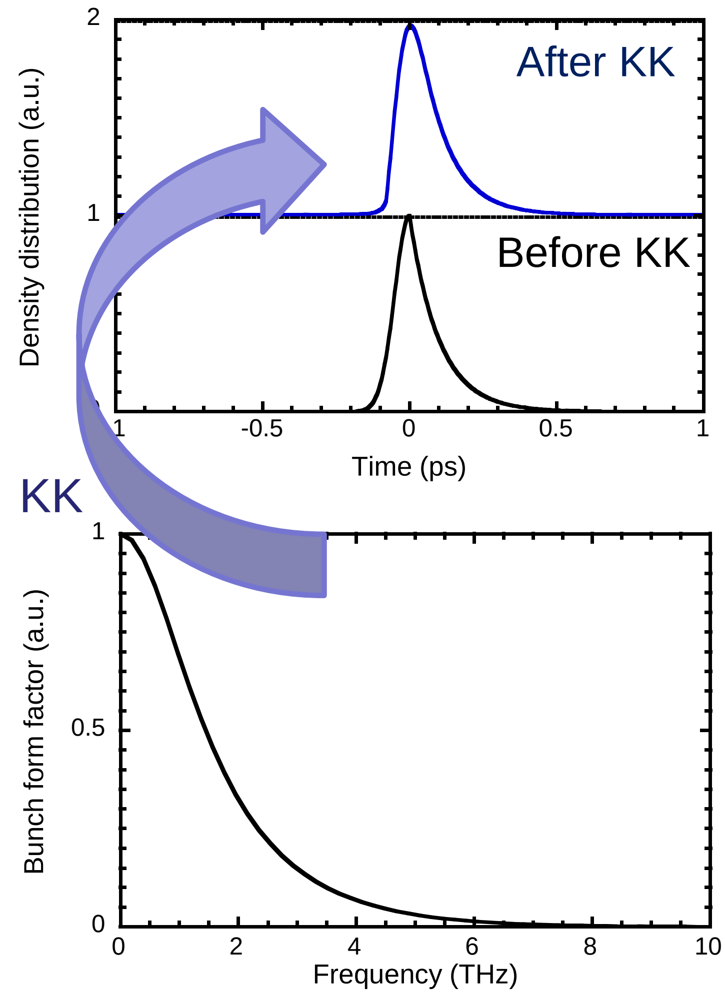
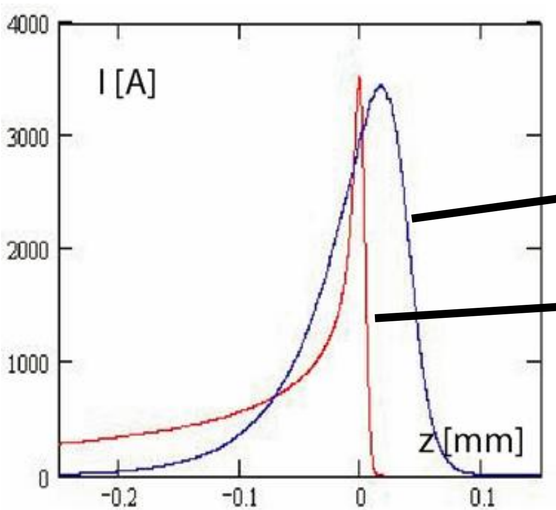
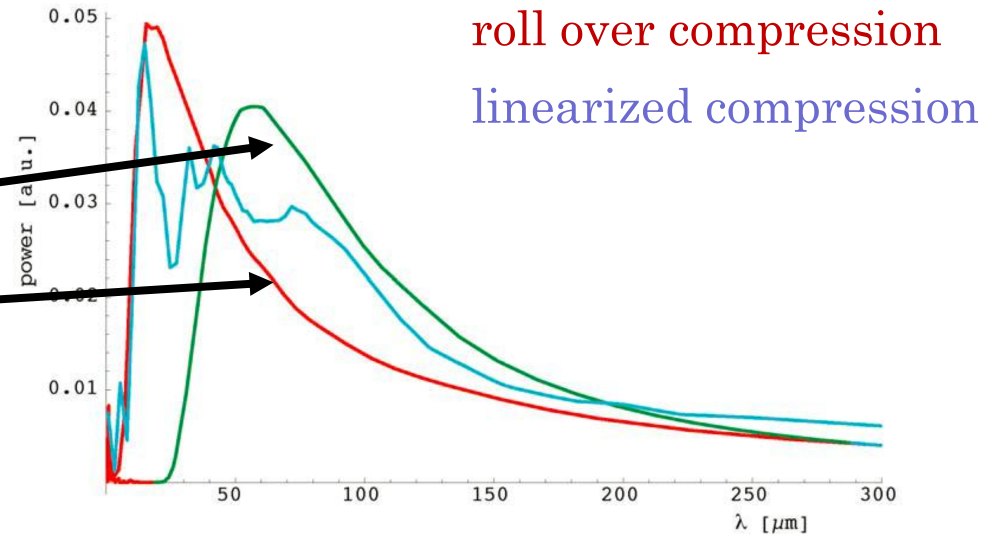


From Professor Yang Jinfeng in Osaka University

CSR measurement of short e-bunch





Depending on compression scheme
Coherent effects create spectral substructure
Micro-bunching can produce~ few μm coherent radiation

Technical implications
- diamond windows to accelerator vacuum
- no radiation transport in (humid) air
- broad wavelength range to cover, SINGLE SHOT

single-shot e-bunch measurement

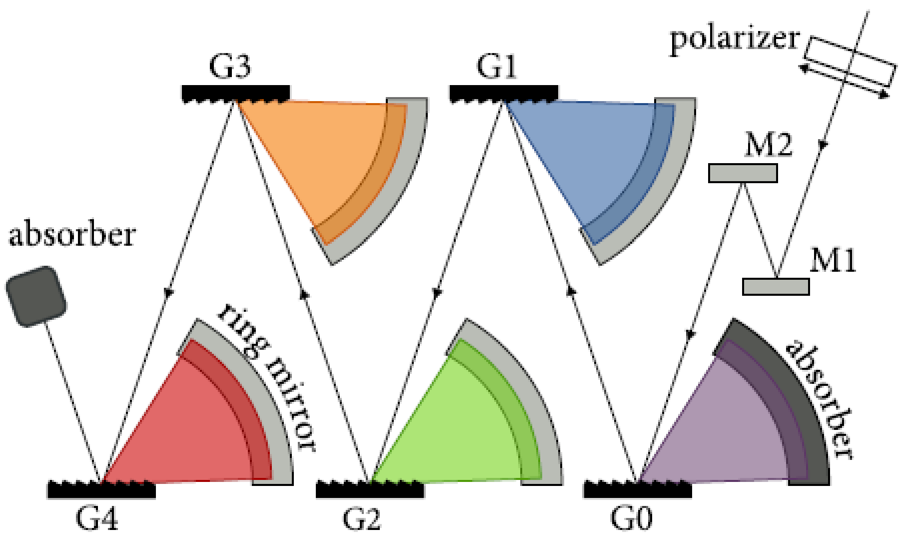
Classical：Michelson type interferometers

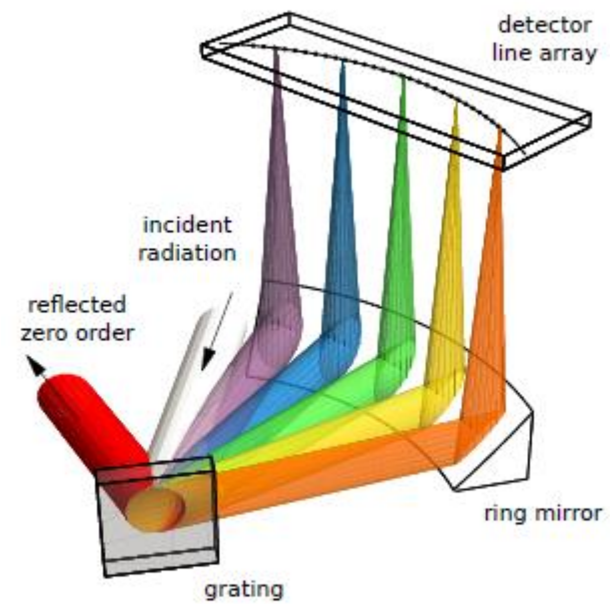
-scanning devices, no single shot

-complex unfolding procedure (autocorrelation function)

Single shot spectrometers:

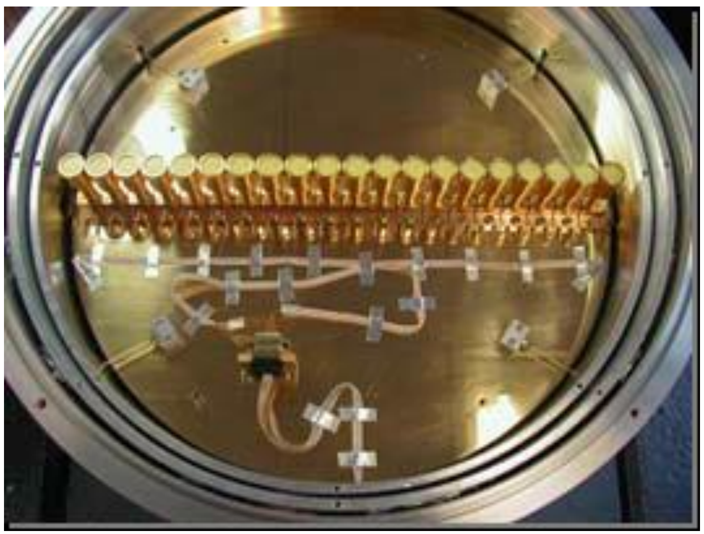
dispersive elements & multichannel detector





single-shot e-bunch measurement

Single shot multichannel detectors



+ commercial
+ fast
+ sensitive
-cryogenic device
-very expensive

Requirements：

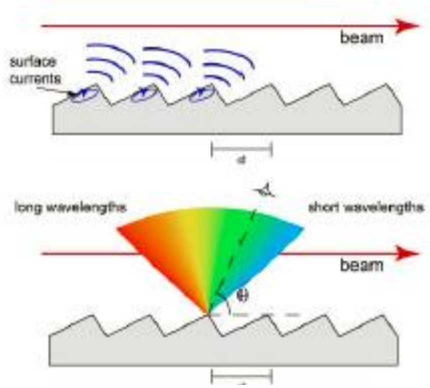
-fast, 200ns for XFEL bunch spacing
-uniform spectral response
-broadband (1 μm -1mm)

Pyro-electric line detector

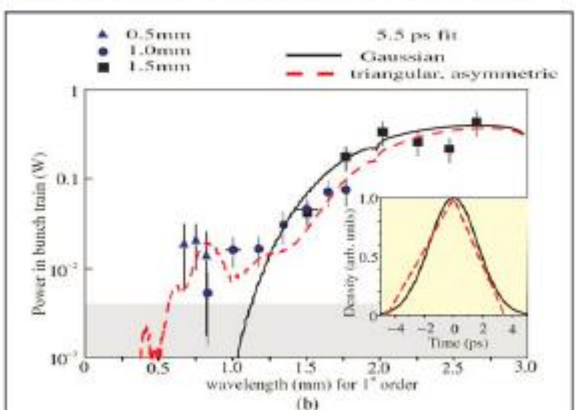
+ room temperature
+ sensitivity ~ 300 pJ

single-shot e-bunch measurement

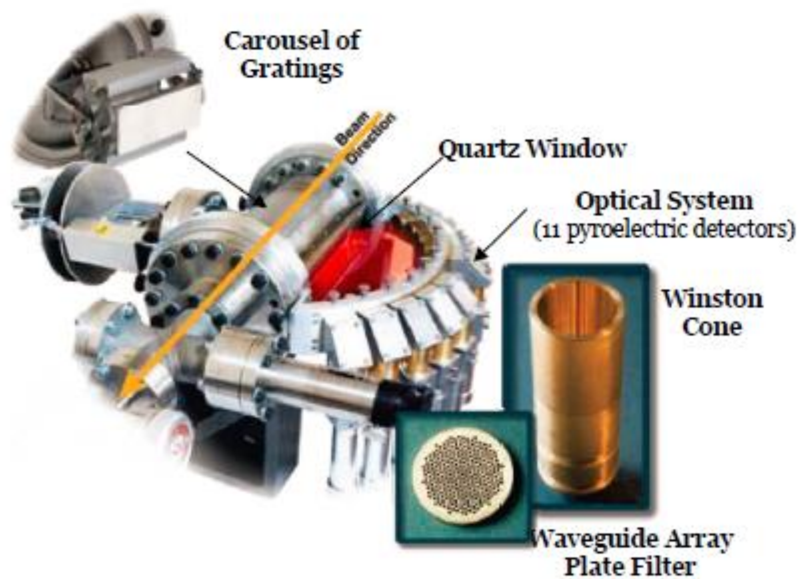
Smith-Purcell radiation measurements



Measurement at 45 MeV, FELIX



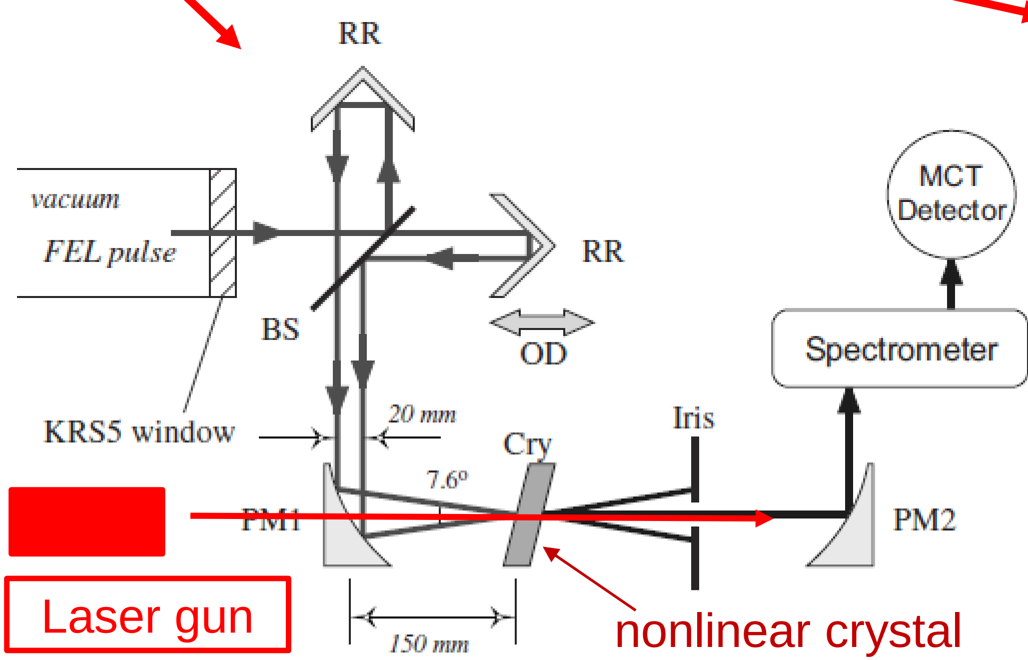
see PRST 9,092801 (2006)



Results of a run at 28.5 GeV from SLAC
are currently being analyzed.

outlook---Prof. Yen-Chieh Huang

'FROG' + Pyro-electric line detector +Reference Laser gun

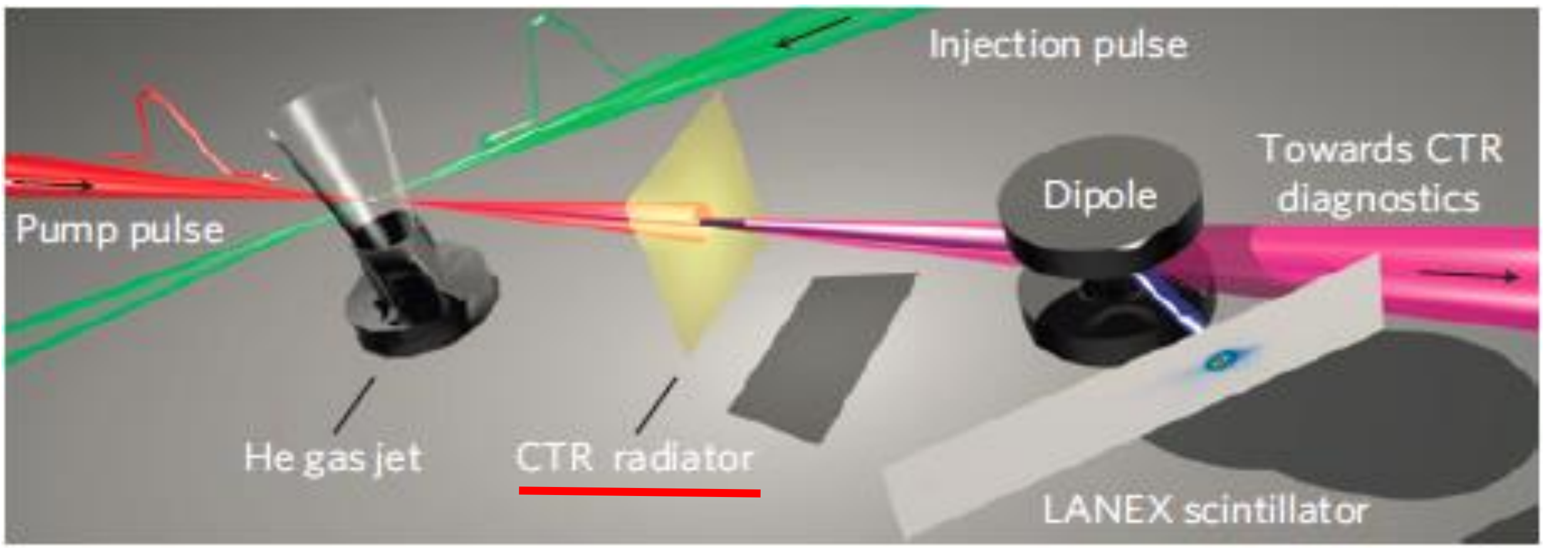


Advantages
- room-temperature
- inexpensive
- non-THz wave

A sketch of **Frequency-resolved optical gating system**

nature physics
LETTERS
PUBLISHED ONLINE: 9 JANUARY 2011 | DOI: 10.1038/NPHYS1872

Few femtosecond, few kiloampere electron bunch produced by a laser-plasma accelerator



Thank you for your attention !