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Advanced Accelerator Concepts Workshop
WG6 for Laser Plasma Acceleration

CTR Bunch Length Measurement of Monoenergetic and Maxwellian Electron Beams from Plasma Cathode

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Review of Ultrashort Electron Bunch Diagnosis

Mitsuru Uesaka (U.Tokyo)

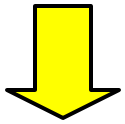
-Coherent Transition/Diffraction Radiation Methods (<50fs)
  Interferometer, Discrete Spectrum, Polychromator
  LBNL, DESY, U.Tokyo, Tohoku U. etc.
-Electro-Optical Methods(<50fs)
  DESY, SLAC, LBNL, BNL etc.
-RF Deflector (LOLA) (<50fs)
  SLAC, DESY
-50fs Streak Camera(near future?)
  Hamamatsu

Acknowledgement
Dr.W.Leemans, Dr.M.Hogan. Dr.S.Schreiber

Introduction

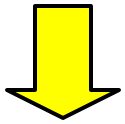
A laser plasma cathode is one of the most attractive ways to compact accelerators that can generate femtosecond electron bunches.

- Due to high electric fields (~100 GV/m) and high frequency (~100 THz) of plasma waves.
- ~10 fs bunch duration is possible according to simulation results[1].



Great Advantage of

- Time-resolved applications such as pulseradiolysis
- Femtosecond X-ray pulse generation by relativistic Thomson scattering



Measurement and evaluation of femtosecond electron bunches are required.

[1] T. Hosokai *et al*, Phys. Rev. E 67, 036407 (2003)

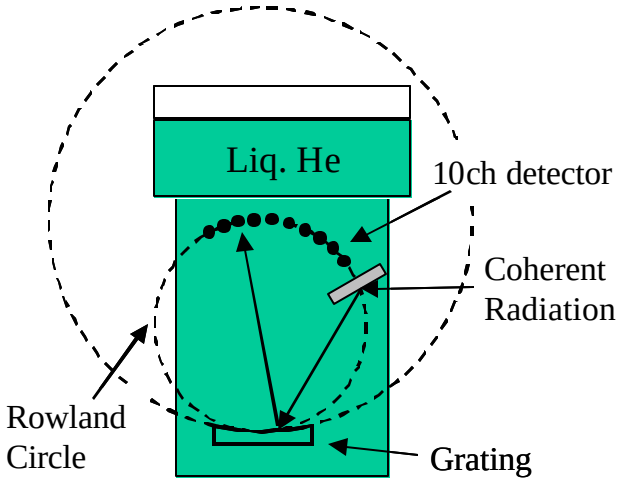
Measurement Methods of Femtosecond Electron Bunches

Methods	Radiation	Time resolution	Single-shot
Streak camera	Cherenkov radiation	200 fs	?
Michelson Interferometer [2]	Transition radiation	No limit	×
Electro-Optic method [3]	Transition radiation	No limit	?
Polychromator [2]	Transition radiation	No limit	?

[2] T. Watanabe et al, Nucl. Instr. and Meth. A 480, 315 (2002)
[3] J. van. Tilborg et al, Phys. Rev. Lett. 96, 014801 (2006)

Bunch duration measurement by spectrum measurement of coherent transition radiation (CTR)

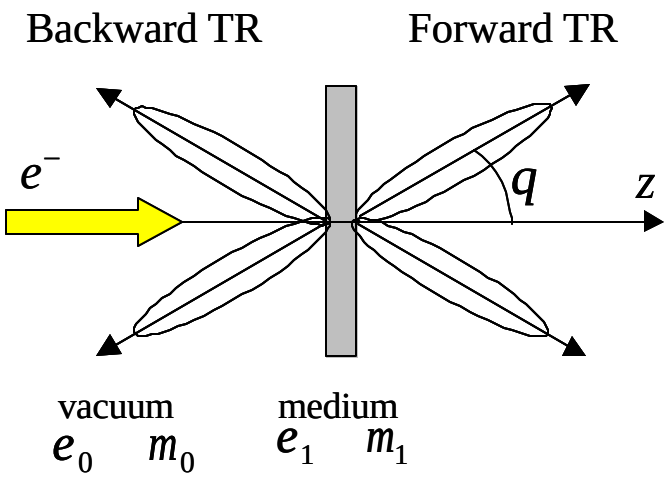
- Time-resolution is no limitation theoretically. (<100 fs in experiments?)
- Single-shot measurement is possible with 10-channel polychromator.



10ch polychromator

Coherent Transition Radiation (CTR)

TR from one electron

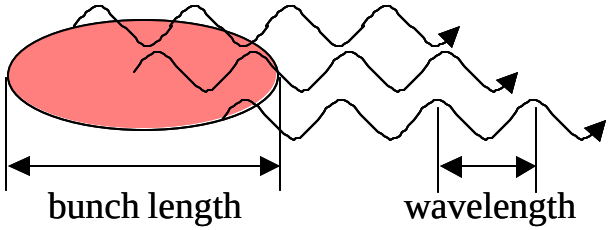


$$I_e(l) = \frac{ab^2 \sin^2 q}{p^2 l (1 - b^2 \cos^2 q)^2}$$

- l wavelength
- a fine structure constant
- q emission angle

TR from electron bunch

Incoherent (bunch length >> wavelength)



$$f(l) = 0$$

$$I_{total} \propto N$$

Coherent (bunch length << wavelength)

$$f(l) = 1$$

$$I_{total} \propto N^2$$

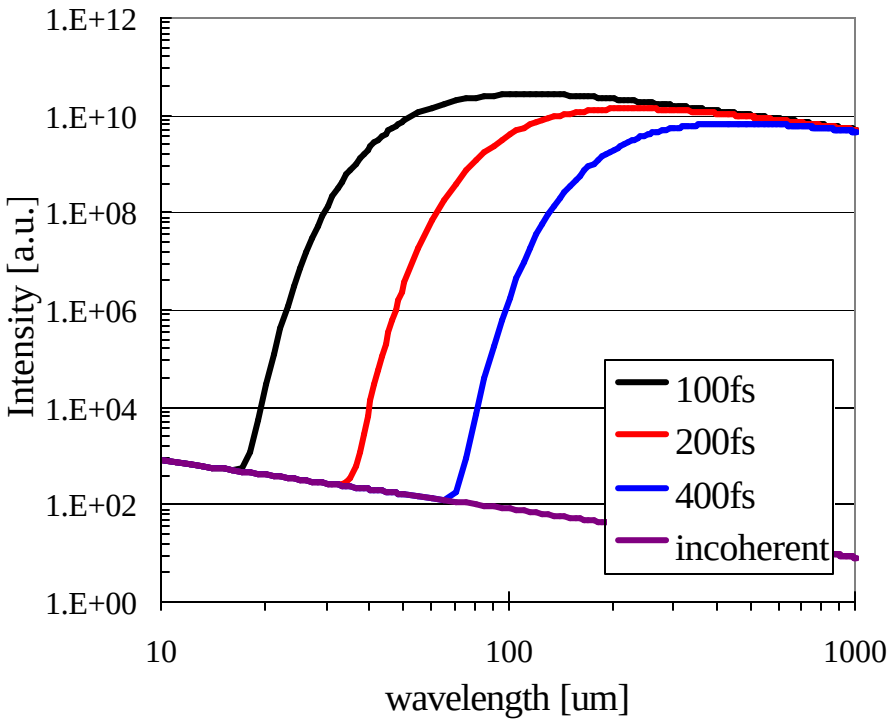
$$I_{total}(l) = \underline{NI_e(l)} + \underline{N(N-1) f(l) I_e(l)}$$

Incoherent factor — Coherent factor

- f bunch form factor
- N number of electrons in the electron bunch

Bunch form factor indicates *coherence of radiation.*

Bunch Duration Measurement



Theoretical spectrum of CTR

Bunch form factor is given by

- Fourier transform of the electron distribution function S(z) in theory

$$f(l) = \left| \int_{-\infty}^{\infty} S(z) \exp(\frac{i2pz}{l}) dz \right|^2$$

- Spectrum measurement of CTR in experiments

$$f(l) = \frac{I_{total}(l)}{N(N-1)I_e(l)}$$

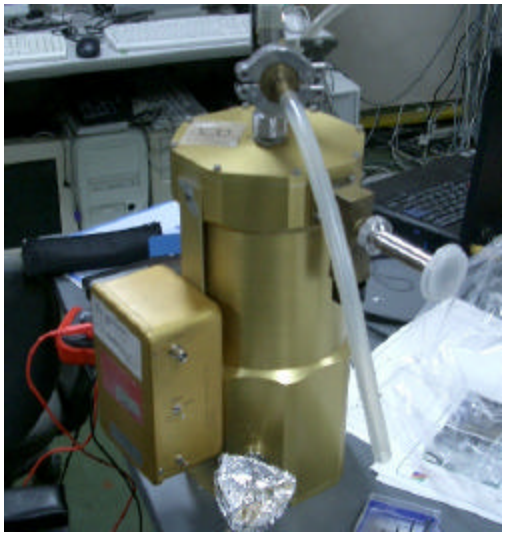
Bunch duration can be estimated by spectrum distribution of CTR.

Experimental Schedule

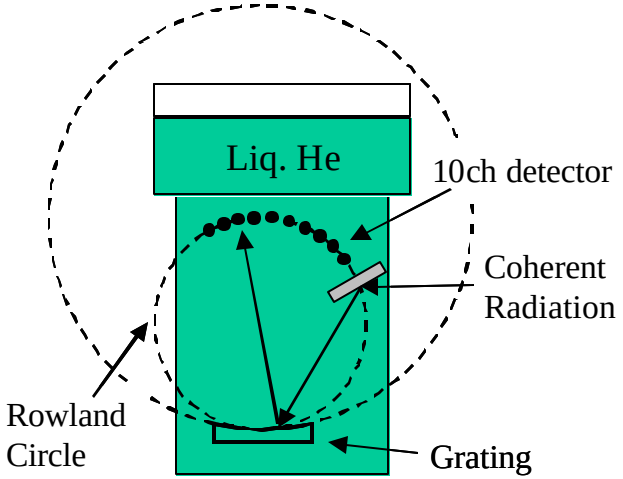
Bunch duration measurement

◆Multi-shots measurement with IR bolometer and different filters (high-pass filters and low-pass filters). ® *performed*

◆Single-shot measurement by 10-channel polychromator. ® *this July*



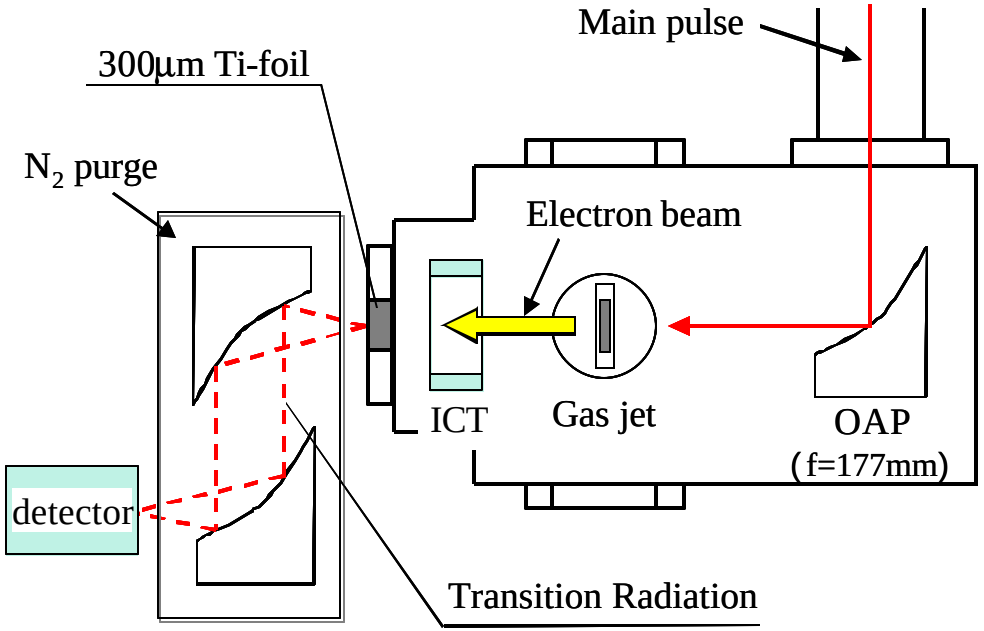
IR bolometer

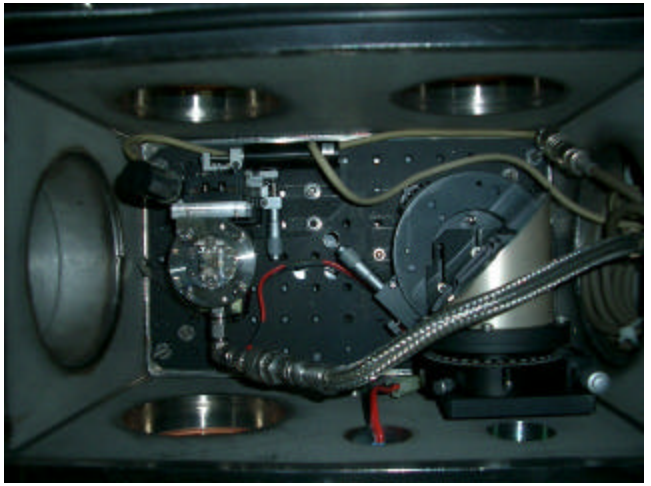


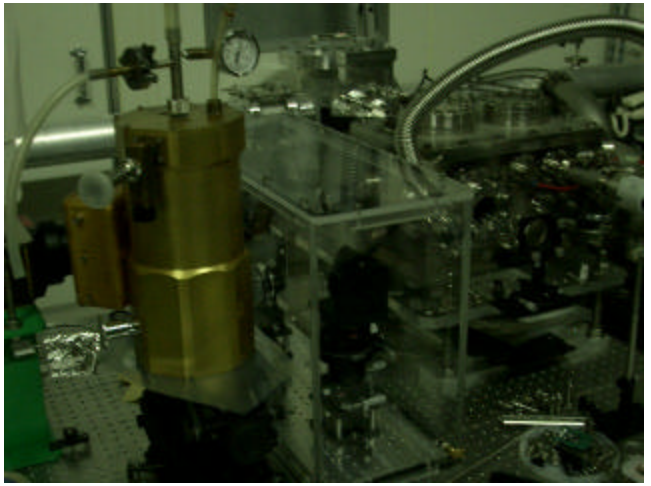
10ch polychromator

Experimental Setup

CTR emitted from 300um Ti-foil is detected with an IR bolometer.



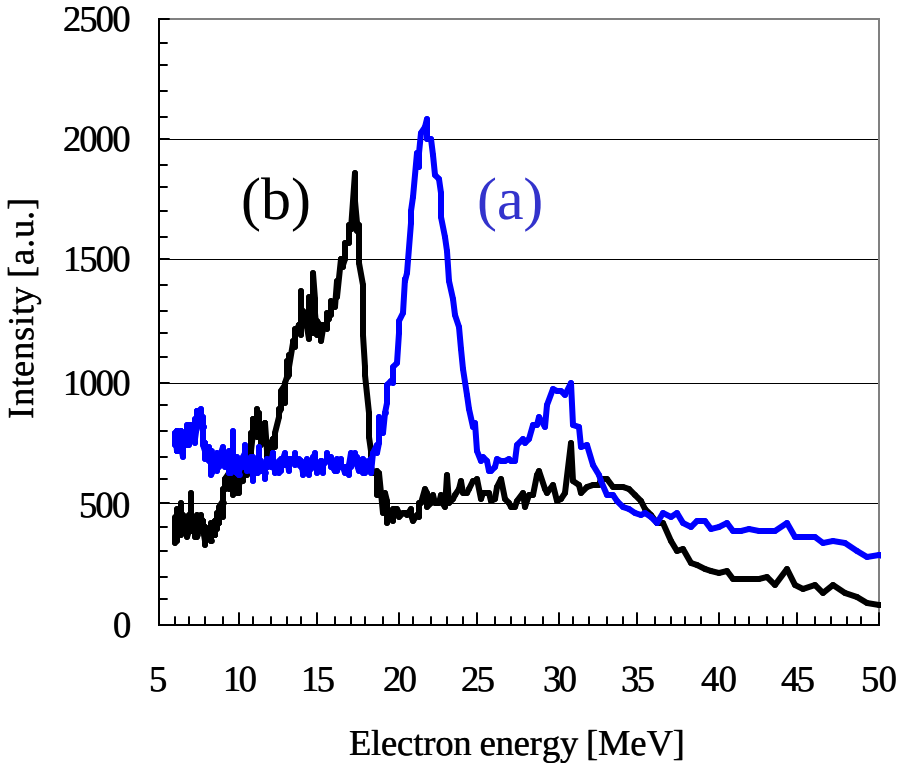


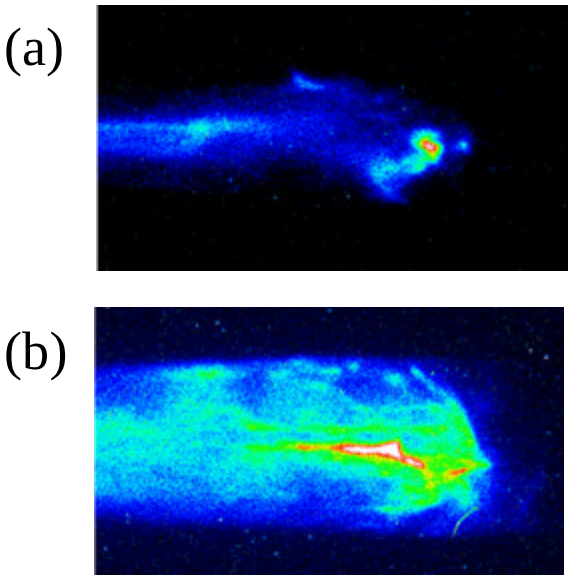


Experimental parameters

Peak power [TW]	10
Pulse duration [fs]	40
Spot size [μm]	6.0
Laser intensity [W/cm^2]	3.5x10^{19}
Electron density [/cm^3]	6.0x10^{19}

Electron Bunch Generation



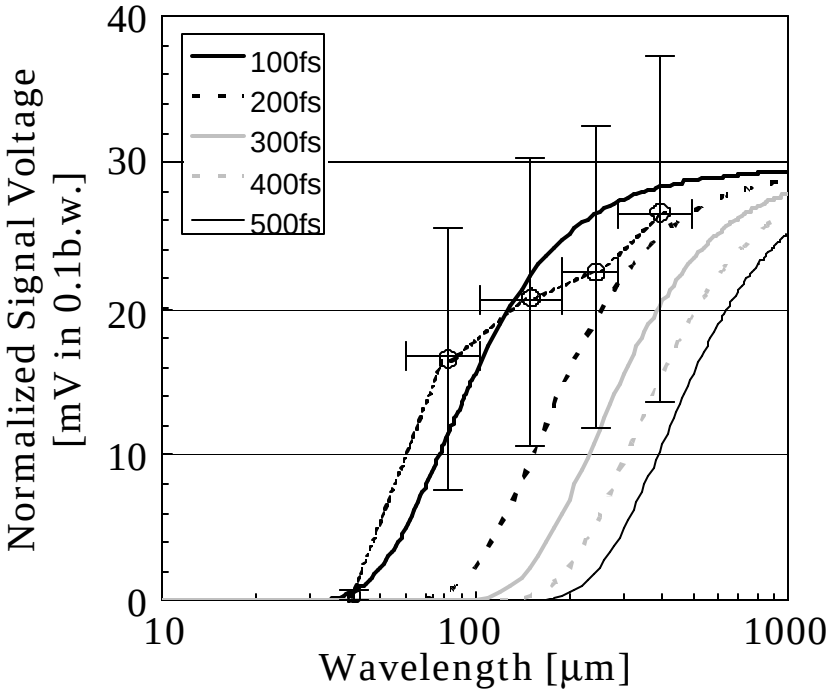


The quasi-monoenergetic electron bunch is obtained.

But, the peak energy and the energy spread change shot by shot due to shot-to-shot instability of laser and plasma parameters.

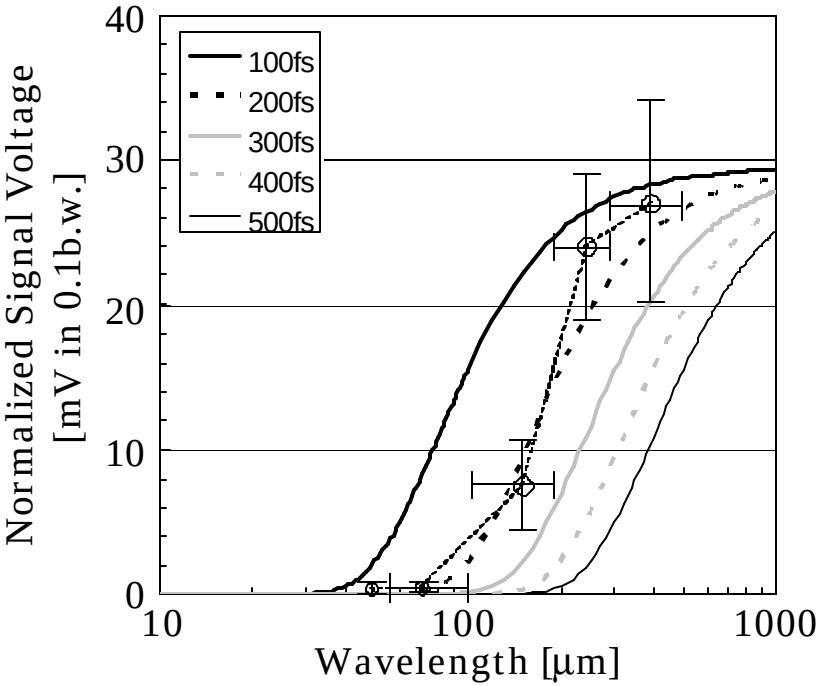
Spectrum Measurement of CTR

Experiments are carried out two times for *different beam parameters*.



High-monoenergetic case
(peak energy is around 20 MeV)

130±30 fs (FWHM)
@180 mm downstream from the gas jet

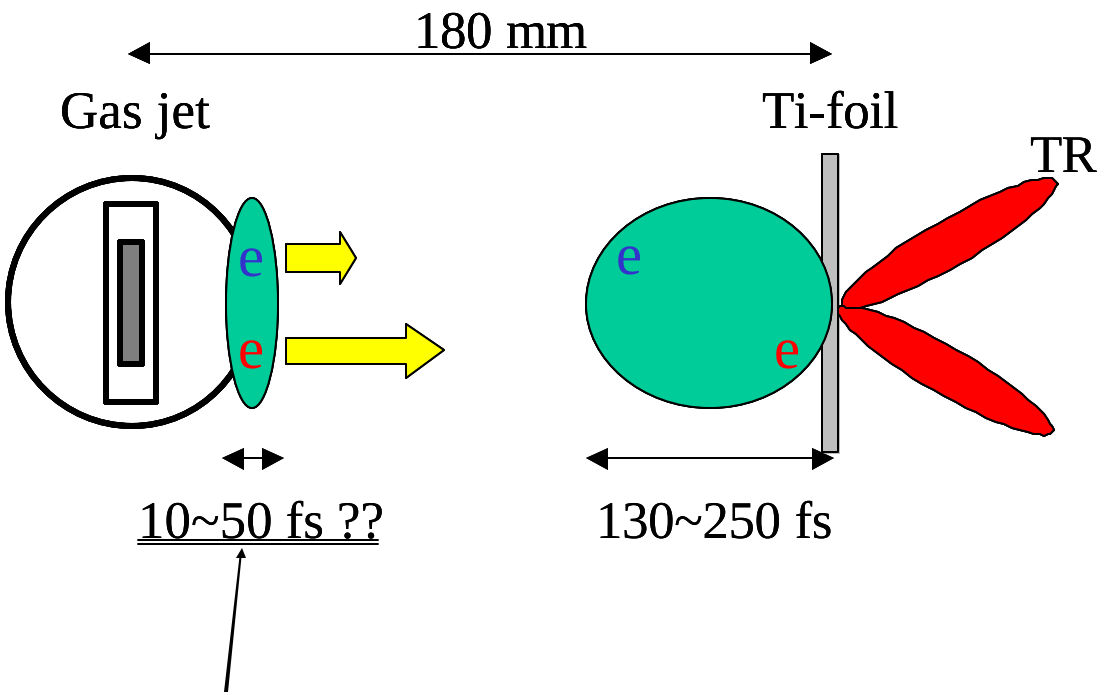


Low-monoenergetic case
(peak energy is around 4 MeV)

250±70 fs (FWHM)
@180 mm downstream from the gas jet

Bunch Elongation Effect

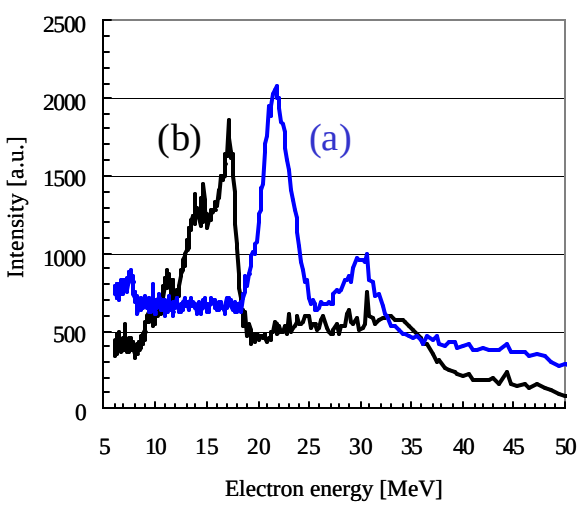
The energy spread of the electron bunches leads bunch elongation after 180 mm path from the gas jet to Ti-foil. The bunch elongation changes with the different energy spread.

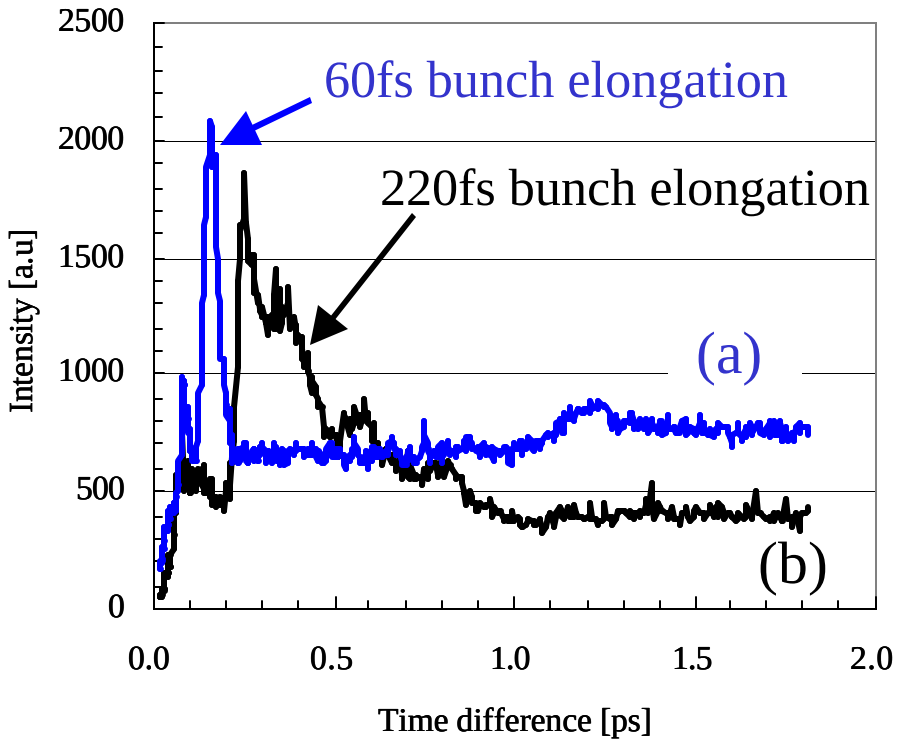


Initial bunch duration at the gas jet is expected to be 10~50fs. It is because plasma wavelength is 4.3 um (14.4 fs) at $n_e=6.0\times10^{19}cm^{-3}$

Evaluation of Bunch Elongation Effect

Bunch elongation effect is estimated on the assumption that initial bunch duration is zero at the gas jet.



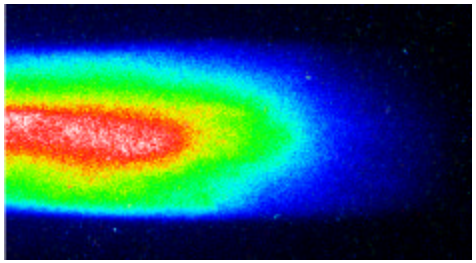


In high-monoenergetic case, the electron bunch duration are extended for 60~220 fs. As a results, the average bunch duration is determined to be 130 fs in the experiment. Initial duration at the gas jet is estimated to be <100 fs.

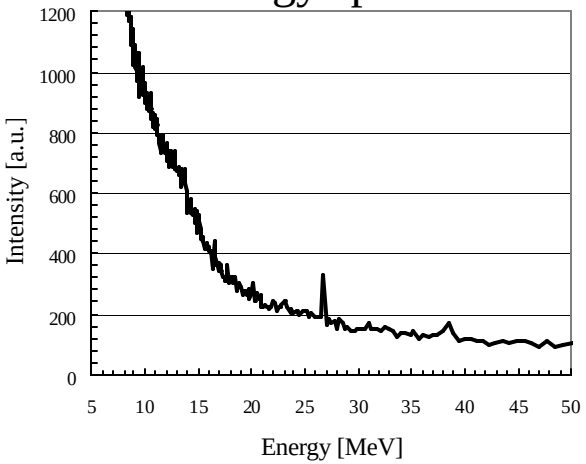
Examples of Bunch Shape @Ti-foil

Case 1: Maxwellian energy distribution

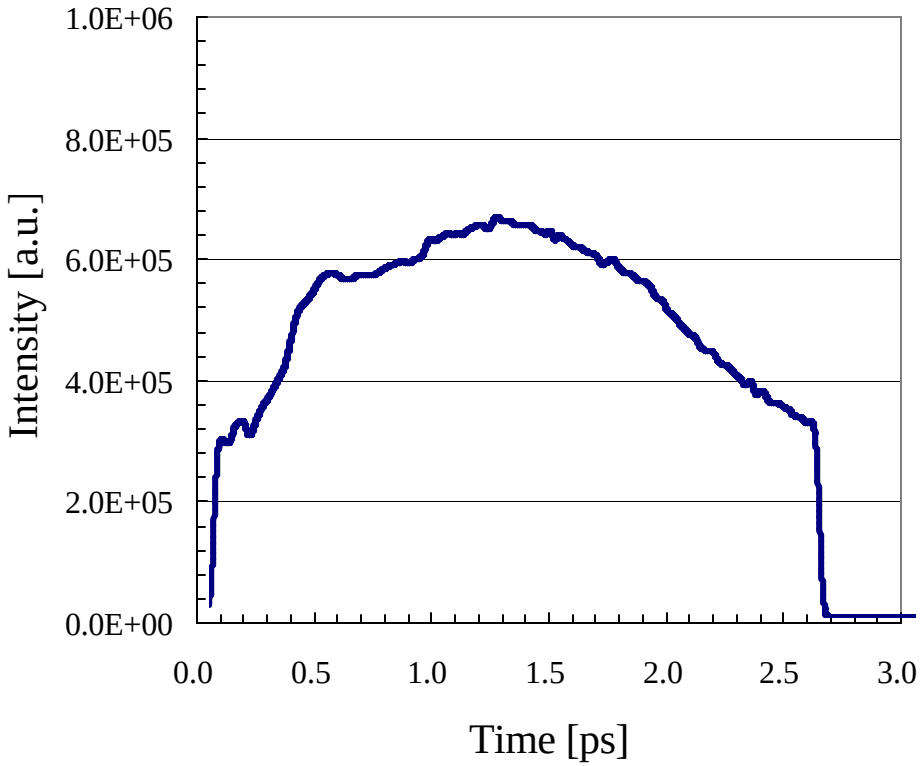
Assumed initial bunch duration: 30 fs, ΔE=10 keV, Δt=1 fs



Energy spectrum



Bunch shape @Ti-foil



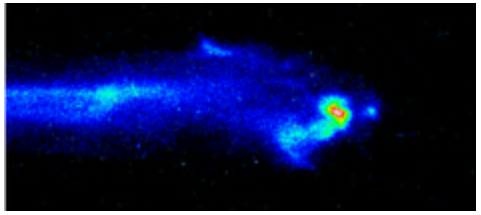
Bunch duration at Ti-foil is extended to be >2 ps.

Therefore, TR cannot be detected in this experiment if energy spectrum is Maxwellian.

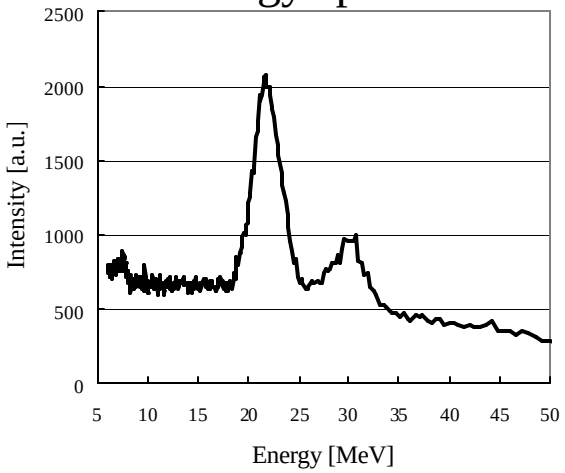
Examples of Bunch Shape @Ti-foil

Case 2: Quasi-monoenergetic energy distribution

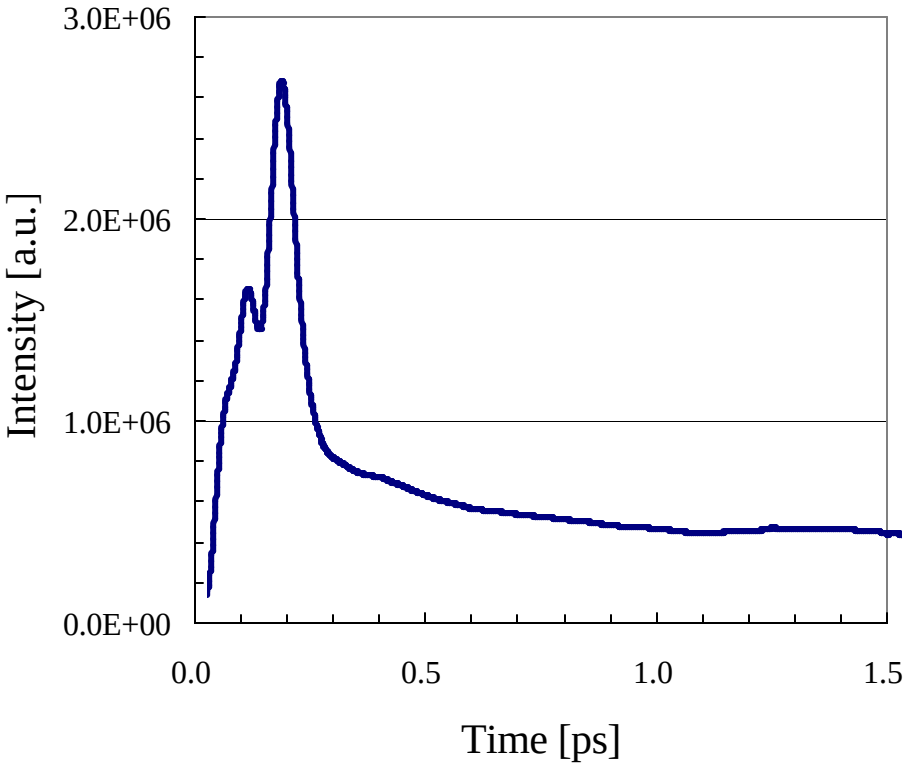
Assumed initial bunch duration: 30 fs, ΔE=10 keV, Δt=1 fs



Energy spectrum

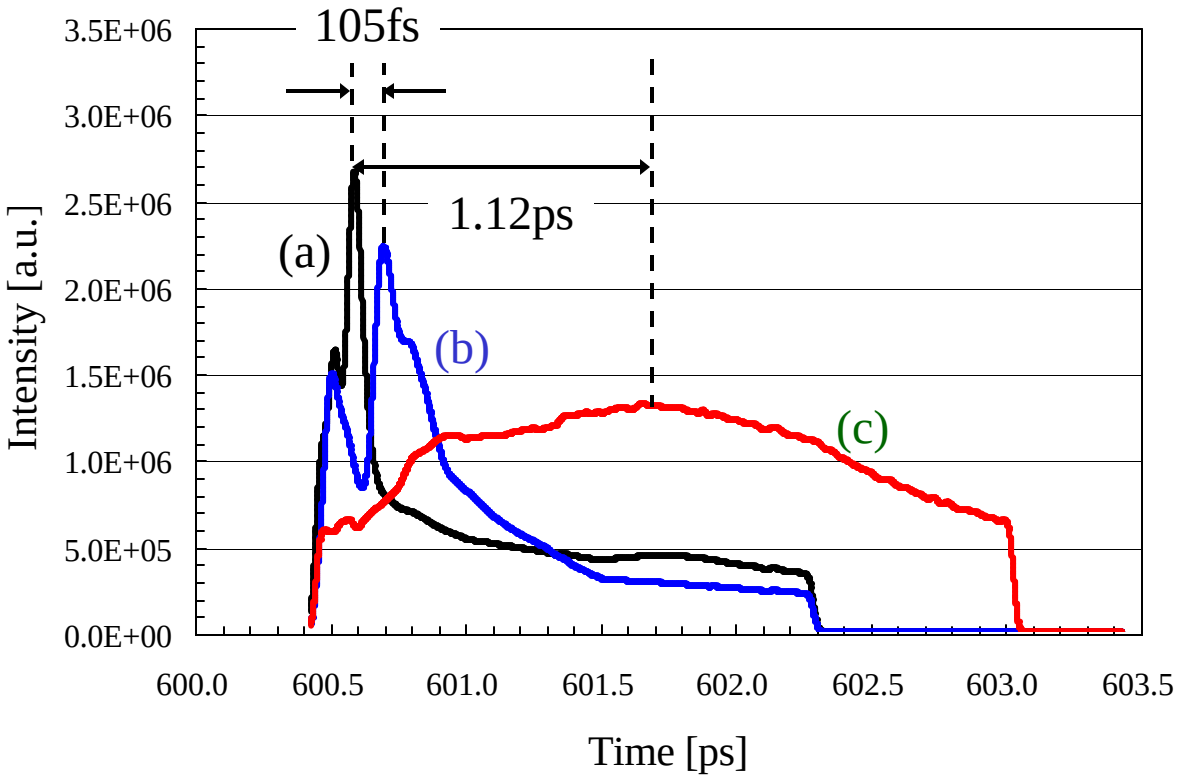


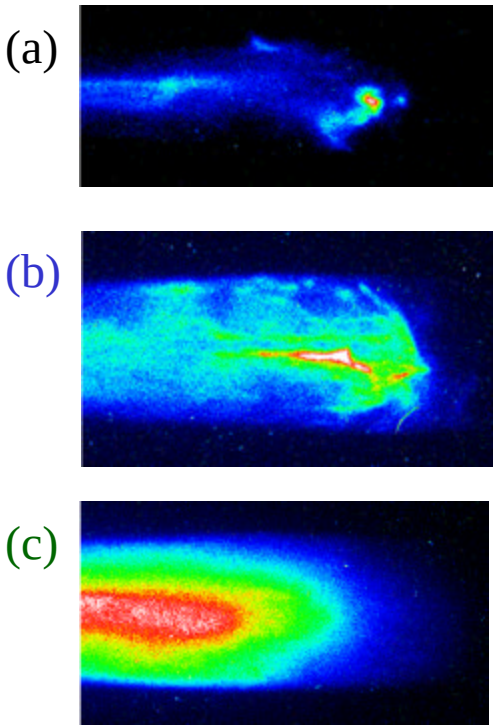
Bunch shape @Ti-foil



Bunch duration at Ti-foil is extended to be 95 fs.

Jitter in Laser Plasma Cathode

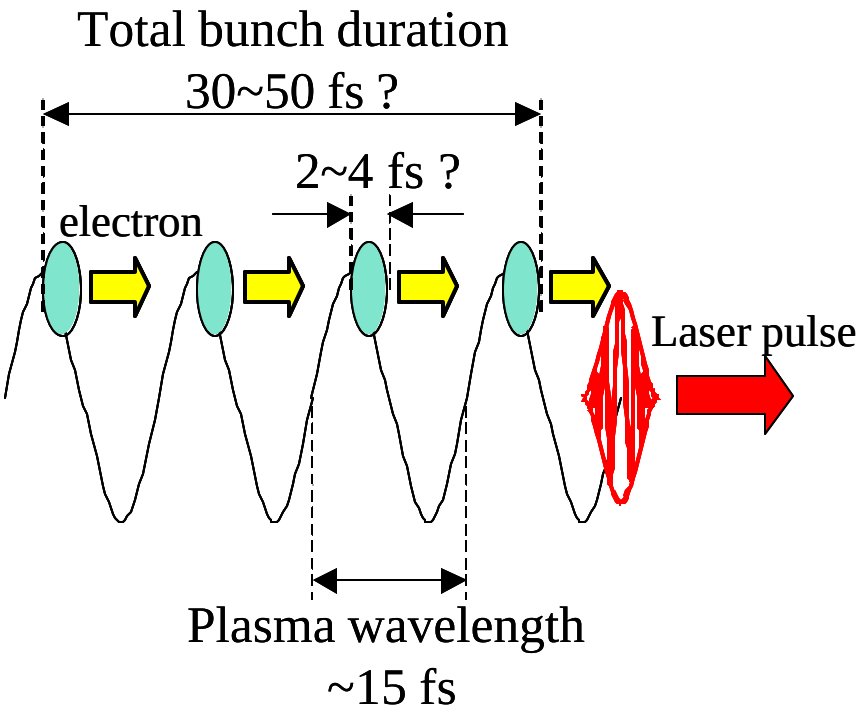


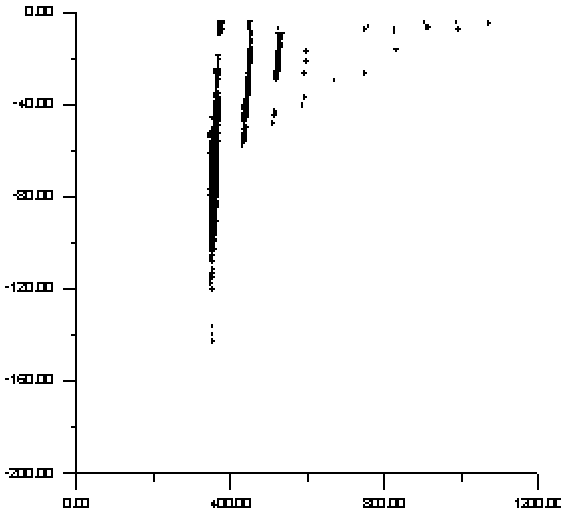


Energy spread leads jitter in laser plasma cathode.

- 105fs between quasi-monoenergetic cases.
- 1.12ps between quasi-monoenergetic case and Maxwellian case.

Initial Bunch Shape @plasma edge



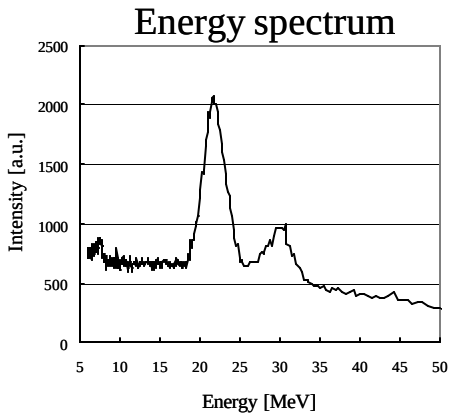


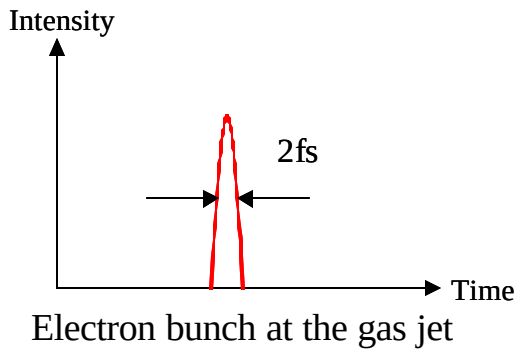
PIC simulation result
position vs. momentum

Generally, electron bunch is accelerated by few cycles of plasma waves in the laser plasma cathode. Therefore, electron bunch at plasma edge is composed of 2~4 fs bunches at intervals of ~15 fs, and total bunch duration is 30~50 fs.

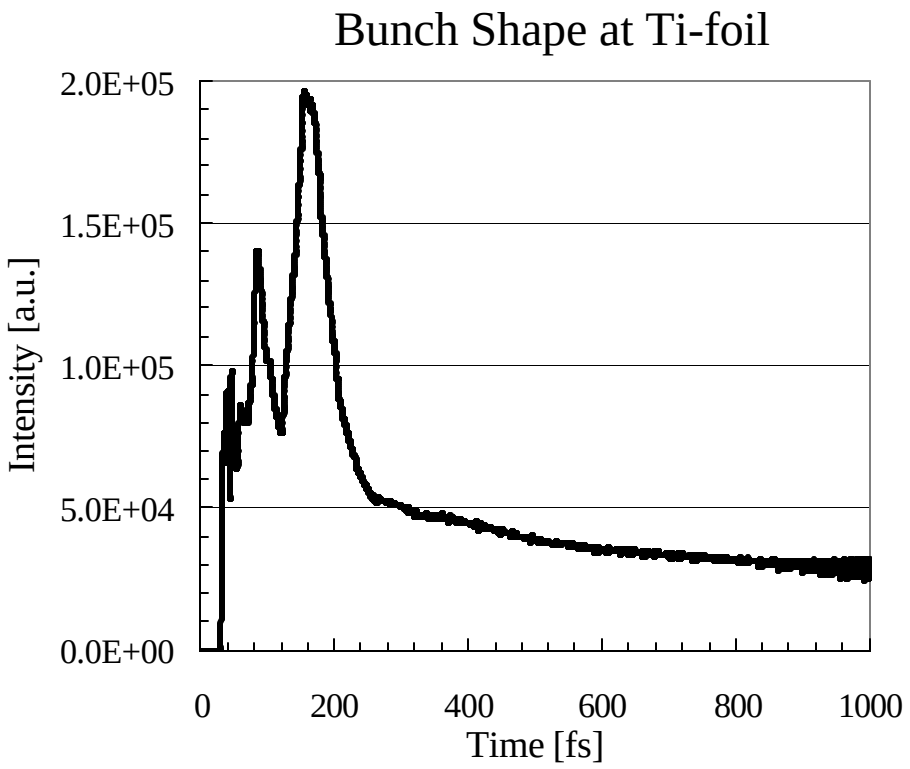
This characteristics can be seen in PIC simulation results.

Elongation Effect: 2fs single bunch



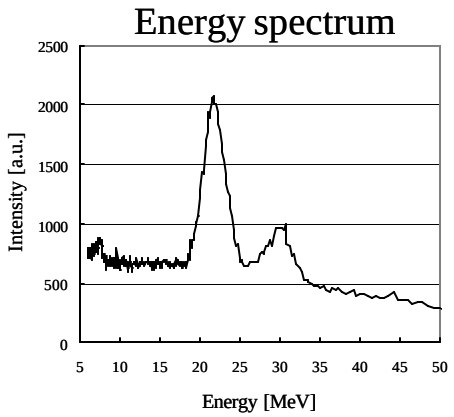


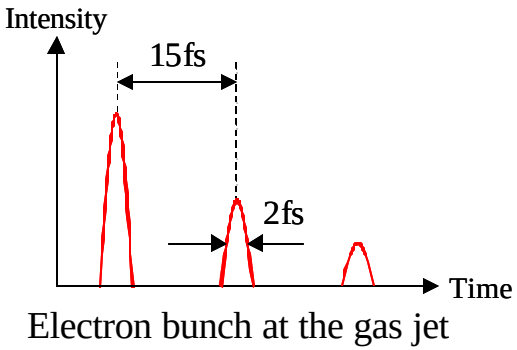
Electron bunch at the gas jet



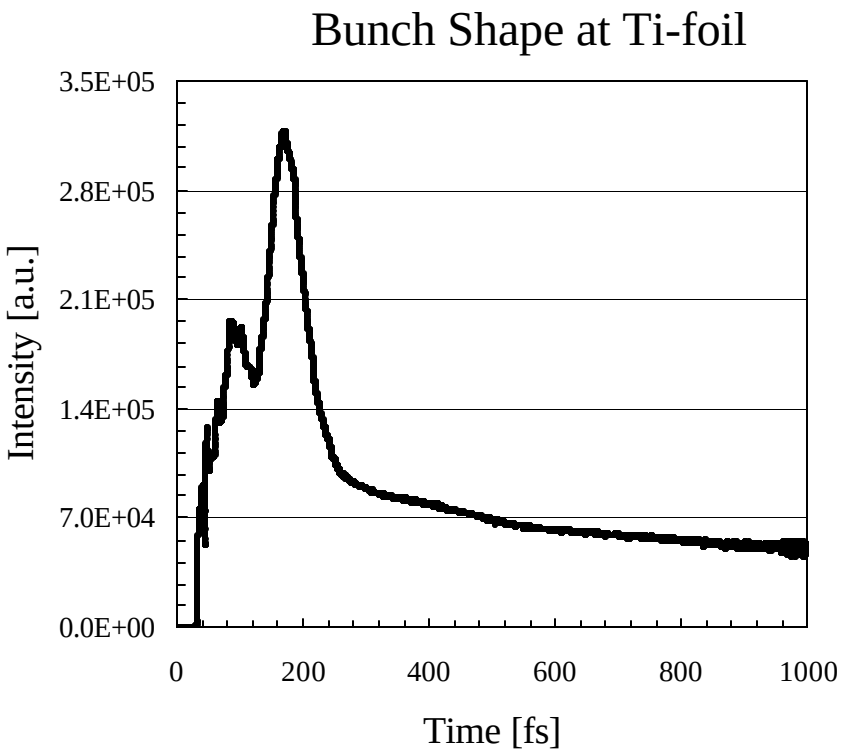
In the case of single bunch with bunch duration of 2 fs, bunch duration is extended to be 75fs.

Elongation Effect: multi bunch





Electron bunch at the gas jet



In the case of multi bunch composed of 2 fs bunches at intervals of 15 fs, bunch duration is extended to be 96 fs.

Conclusion and Future Work

- The bunch duration measurement of the electron bunch from laser plasma cathode by spectrum measurement of CTR has been performed.

- The bunch duration after 180 mm path is 130±30 fs in high-monoenergetic case and the initial bunch duration at the gas jet is estimated to be <100 fs due to evaluation of bunch elongation effect.

- A single-shot measurement with a 10-channel polychromator will be carried out this July.

Summary

-50-200 fs (FWHM) electron bunches were measured.

-CTR- and EO-techniques works effectively.

-Single-shot measurement with EO and THz started.

-Shot-to-shot fluctuation of energy spectrum gives bunch shape fluctuation and timing jitter respect to the laser pulse.

Subjects to be done

-Single-shot measurement of electron bunch shape coincided with energy spectrum acquisition is evitable.

-IF polychromator measurement has started at Univ. Tokyo.