Control and Pulsewidth-measurement of Laser Accelerated Electron Beams

Japan Atomic Energy Agency (JAEA)

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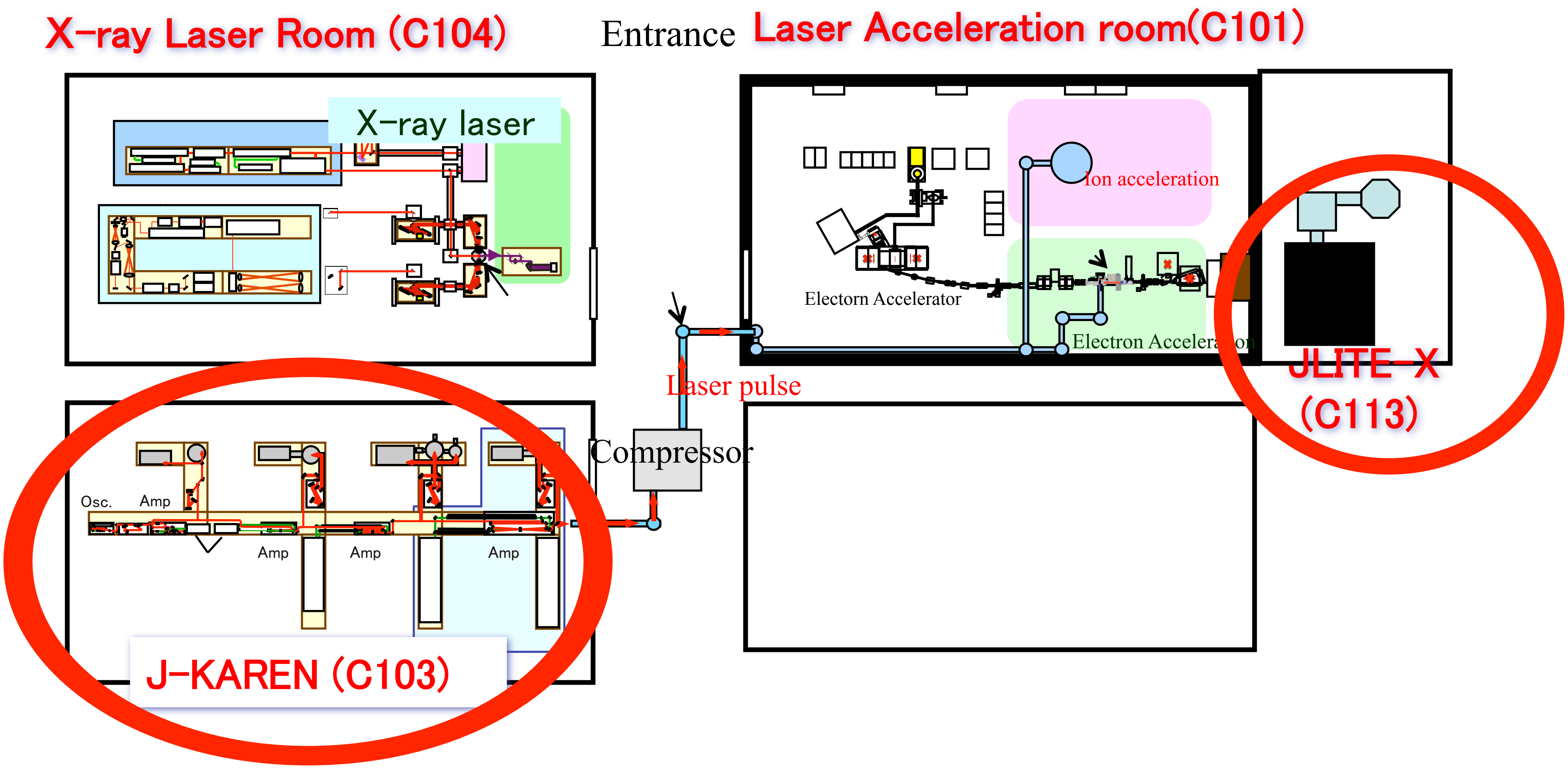
Outline

1. Introduction
   - Study of laser acceleration at JAEA
   - Laser Acceleration
   - Purpose of the study
2. Experimental setup
3. Experimental results
   - Direction control
   - Profile control
   - Observation of electron oscillation
4. Summary

Intense laser in JAEA



Intense laser in JAEA

Electron acceleration

- M.Mori, THPEC003, Stabilization of Laser Accelerated Electron Bunch by the Ionization-stage Control

Ion acceleration and applications

- M. Nishiuchi, MOPEA013, Laser-driven Proton Accelerator for Medical Application
- A.Yogo, MOPEA014, DNA Double-Strand Break Induction in A549 Cells with a Single-Bunch Beam of Laser-Accelerated Protons
- H.Sakaki, MOPEA015, Dose Calculation for Laser-driven Ion Accelerator
- A.Sagisaka, THPD039, Proton Generation Driven by a High Intensity Laser Using a Thin-foil Target

Microtron

- Y.Hayashi, MOPEA058, Measurement of the Parametric X-rays with the Rocking Curve Method

Simulation

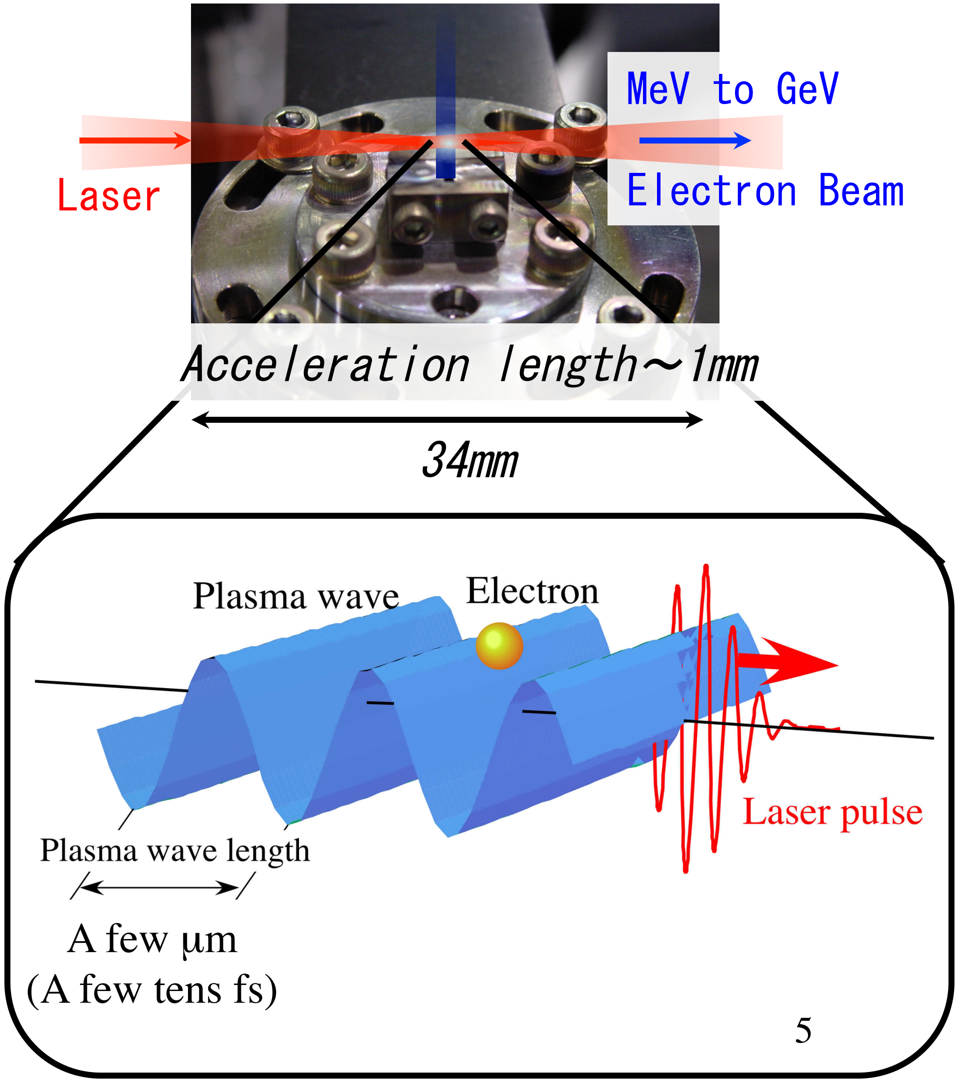
- T.Nakamura, MOPEA059, Laser Acceleration of Negative Ions by Coulomb Impolsion Mechanism
- T.Nakamura, TUPE027, Target Ionization Dynamics by Irradiation of X-ray Free-electron Laser Light

Laser acceleration

Laser Acceleration

1. Focused intense laser pulse produces a laser-plasma.
2. The laser pulse generates a plasma wake.
3. Electrons are accelerated by the plasma wake.

T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).



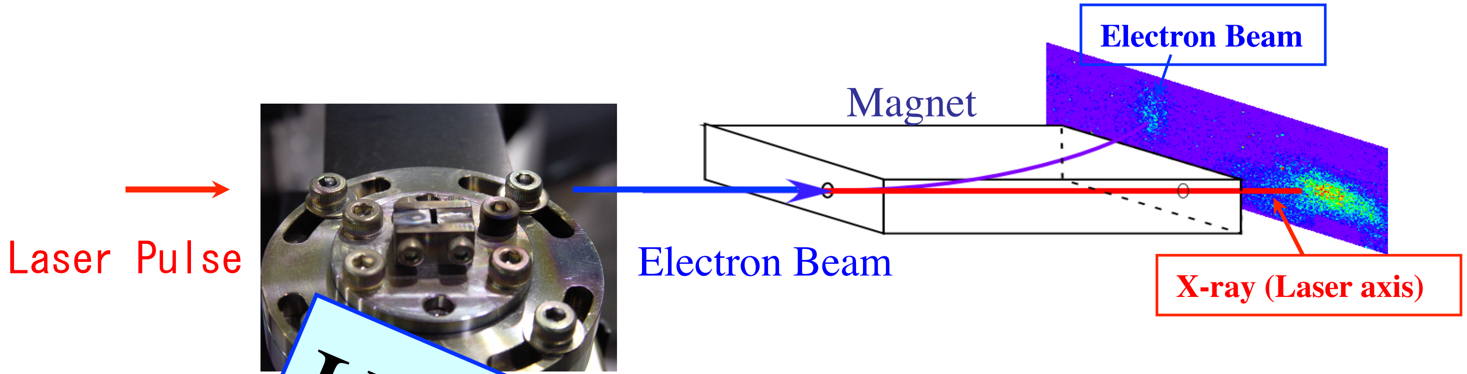
Electron Beam Generated by Laser Acceleration

- Low emittance
- Short pulse duration
- High energy (compact)

Application

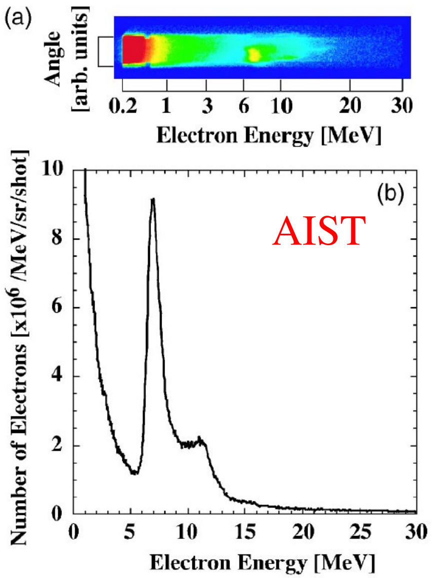
- Electron beam source for next generation accelerators.
- Femto-second pulse radiolysis
- Measurement of ultra-fast phenomena

High-quality electron beam generation

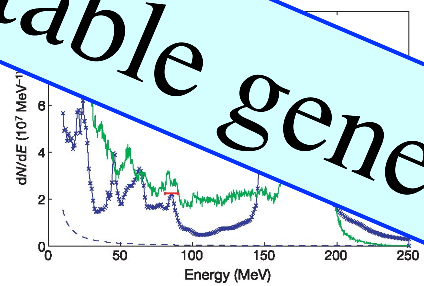


Quasi- [illegible] tron Beam Generation by one laser pulse

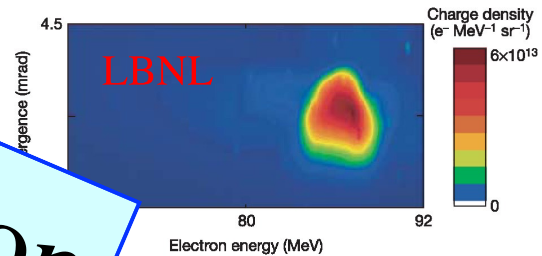
Unstable generation



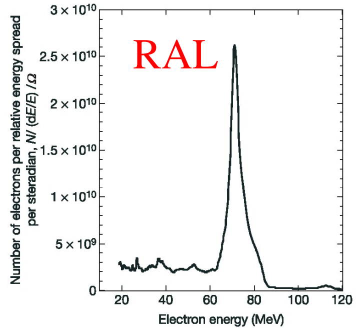
E. Miura, *et al.*, Appl. Phys. Lett., 86, 251501 (2005).



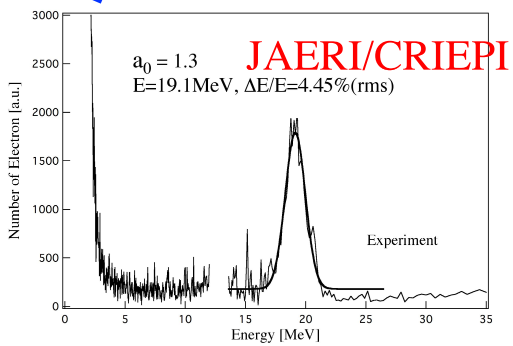
J. Faure, *et al.*, Nature 431, 541 (2004).



G. R. Geddes, *et al.*, Nature 431, 538 (2004).

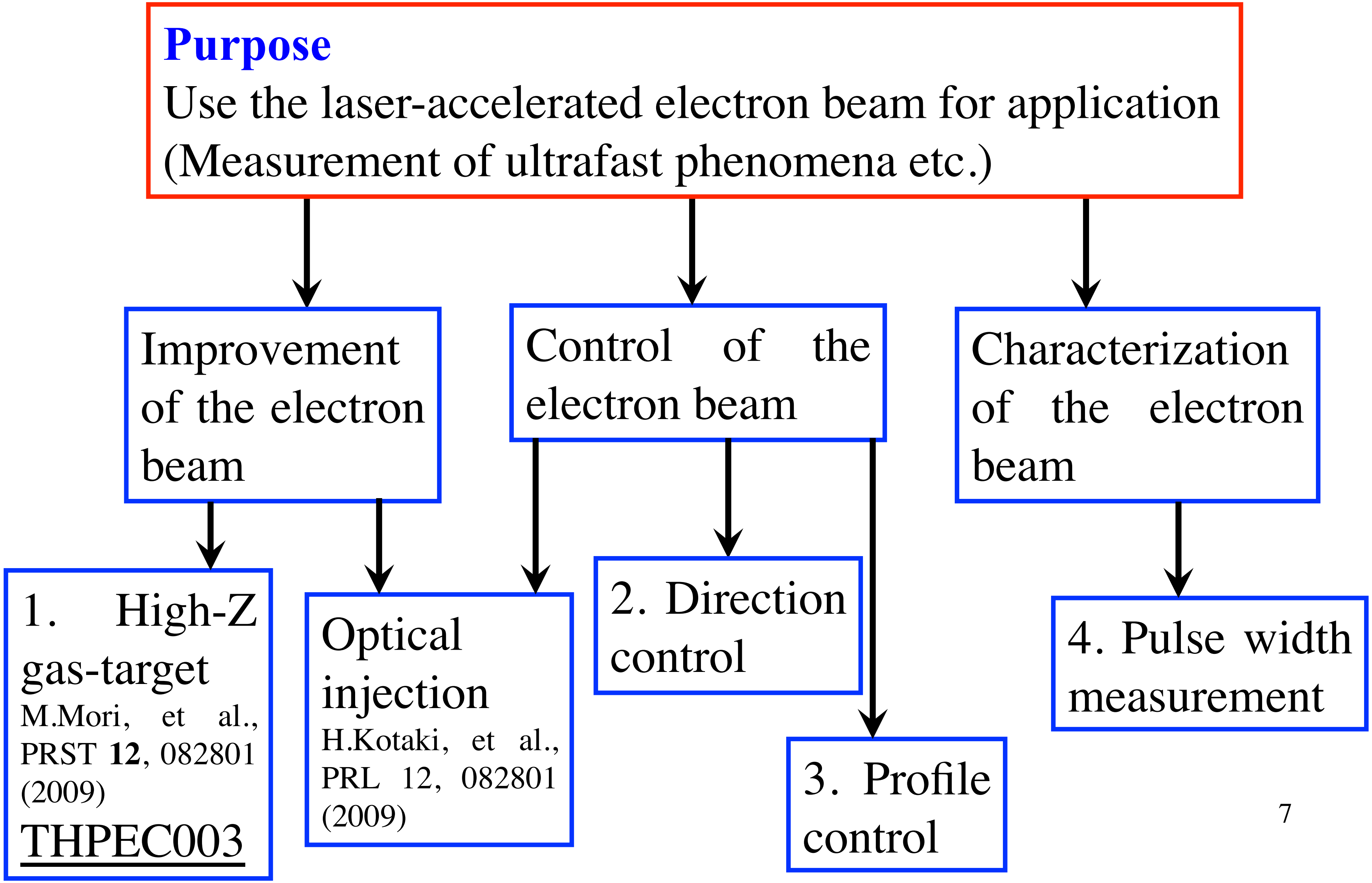


S. P. D. Mangles, *et al.*, Nature 431, 535 (2004).

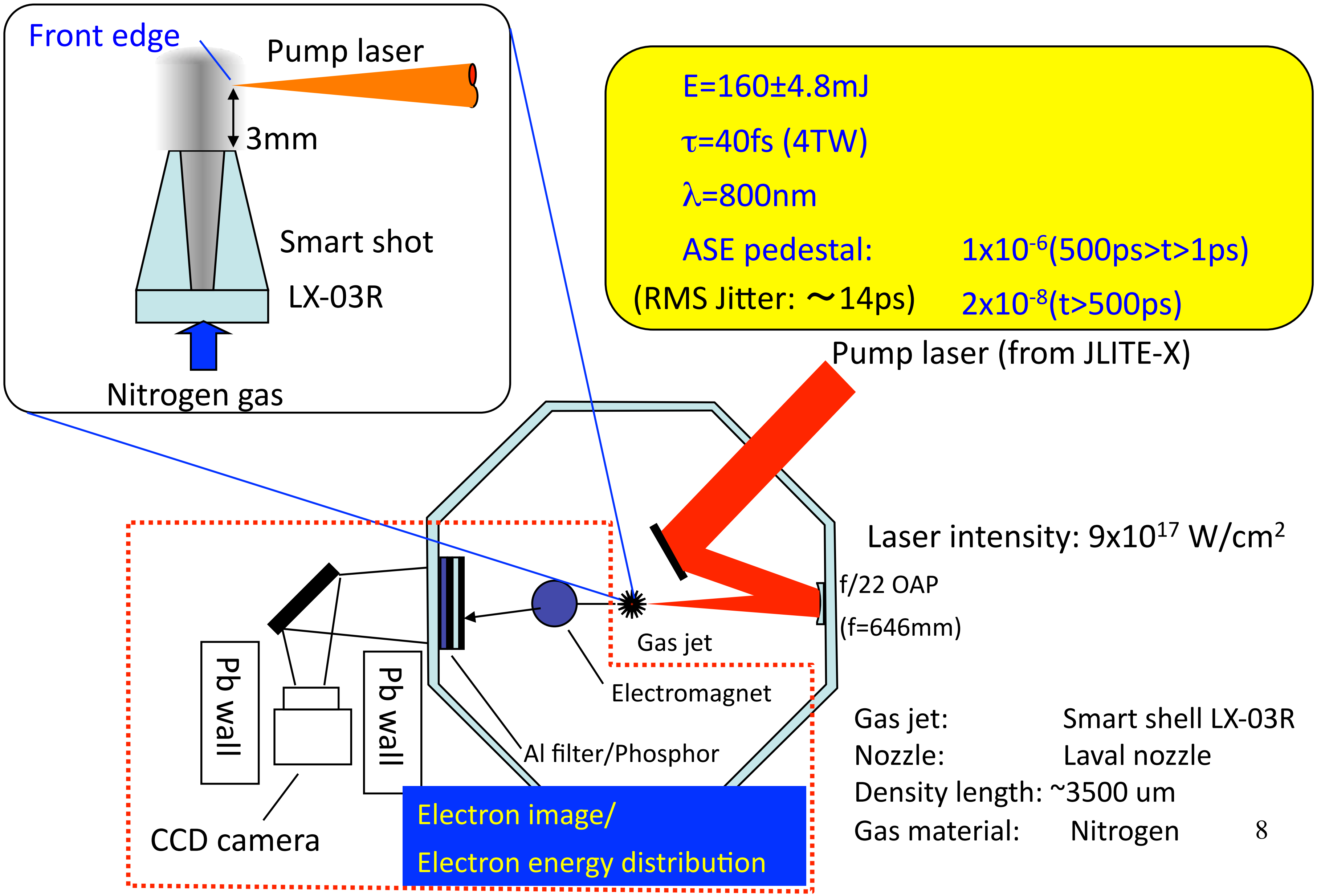


A. Yamazaki, *et al.*, Phys. Plasmas, 12, 093101 (2005).

Purpose of the study

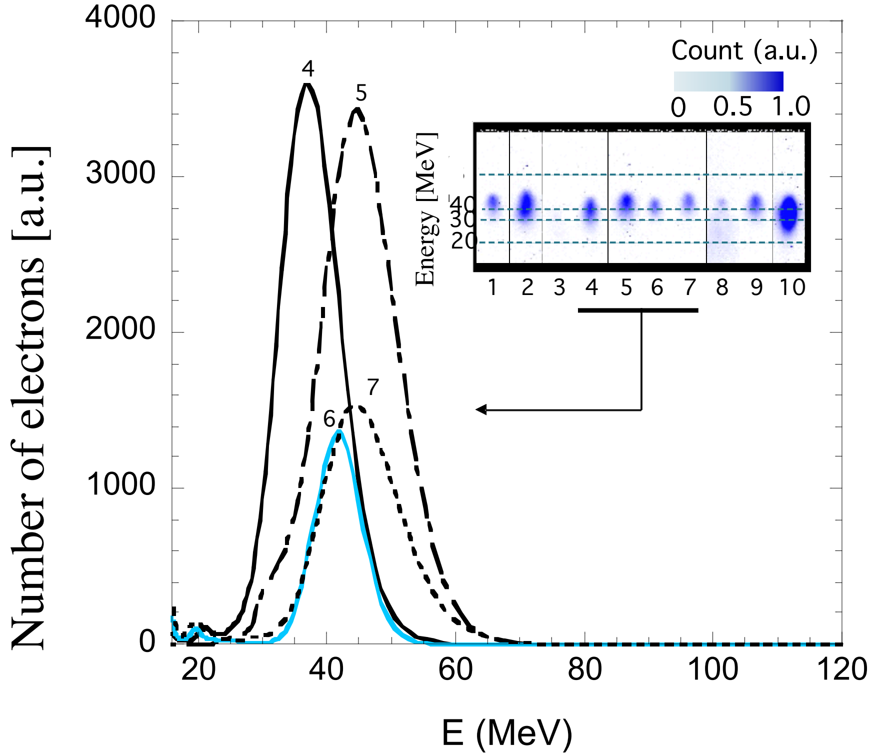


Setup for JLITE-X experiment

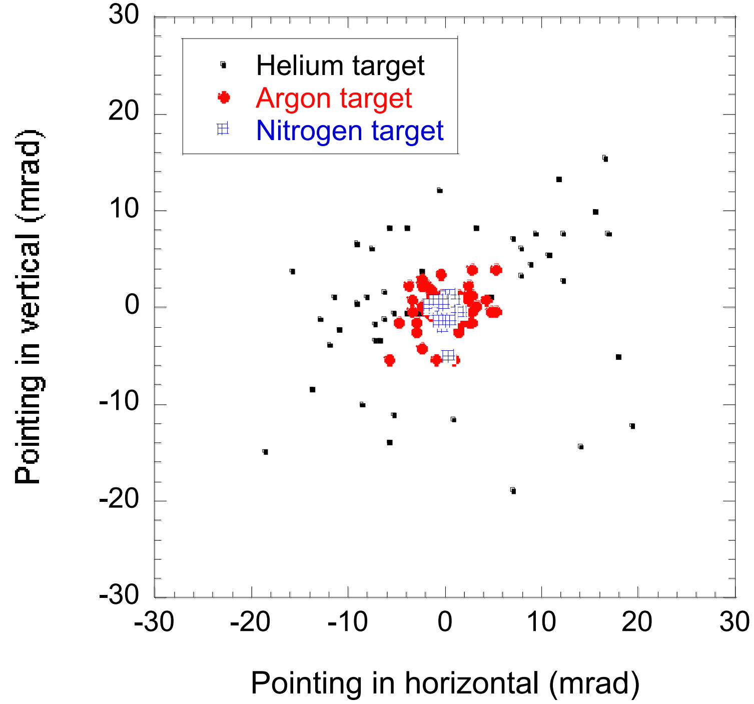


Gas jet: Smart shell LX-03R
Nozzle: Laval nozzle
Density length: ~3500 um
Gas material: Nitrogen

Laser accelerated electron beam



Energy distribution



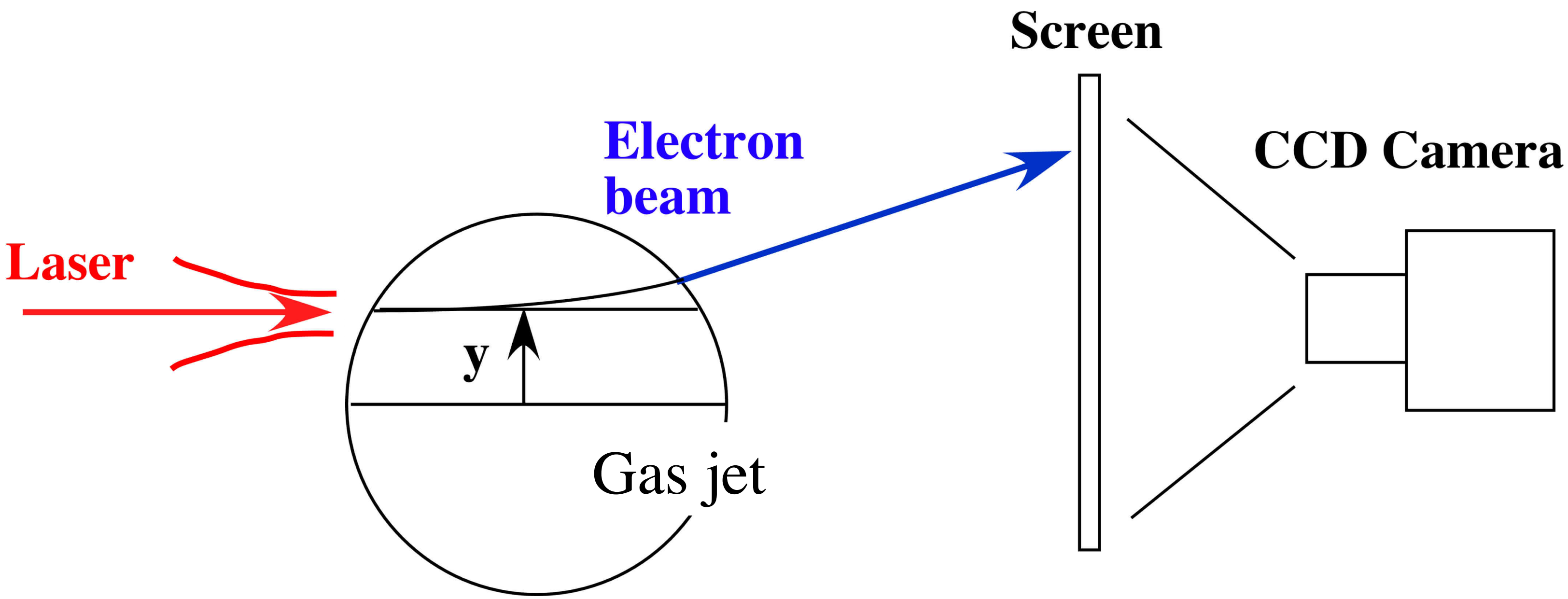
Pointing stability (1.7mrad)

Neutral gas density: ～$4x10^{18}$ cm^{-3}

We improved the stability of the electron beam divergence, pointing, and peak energy

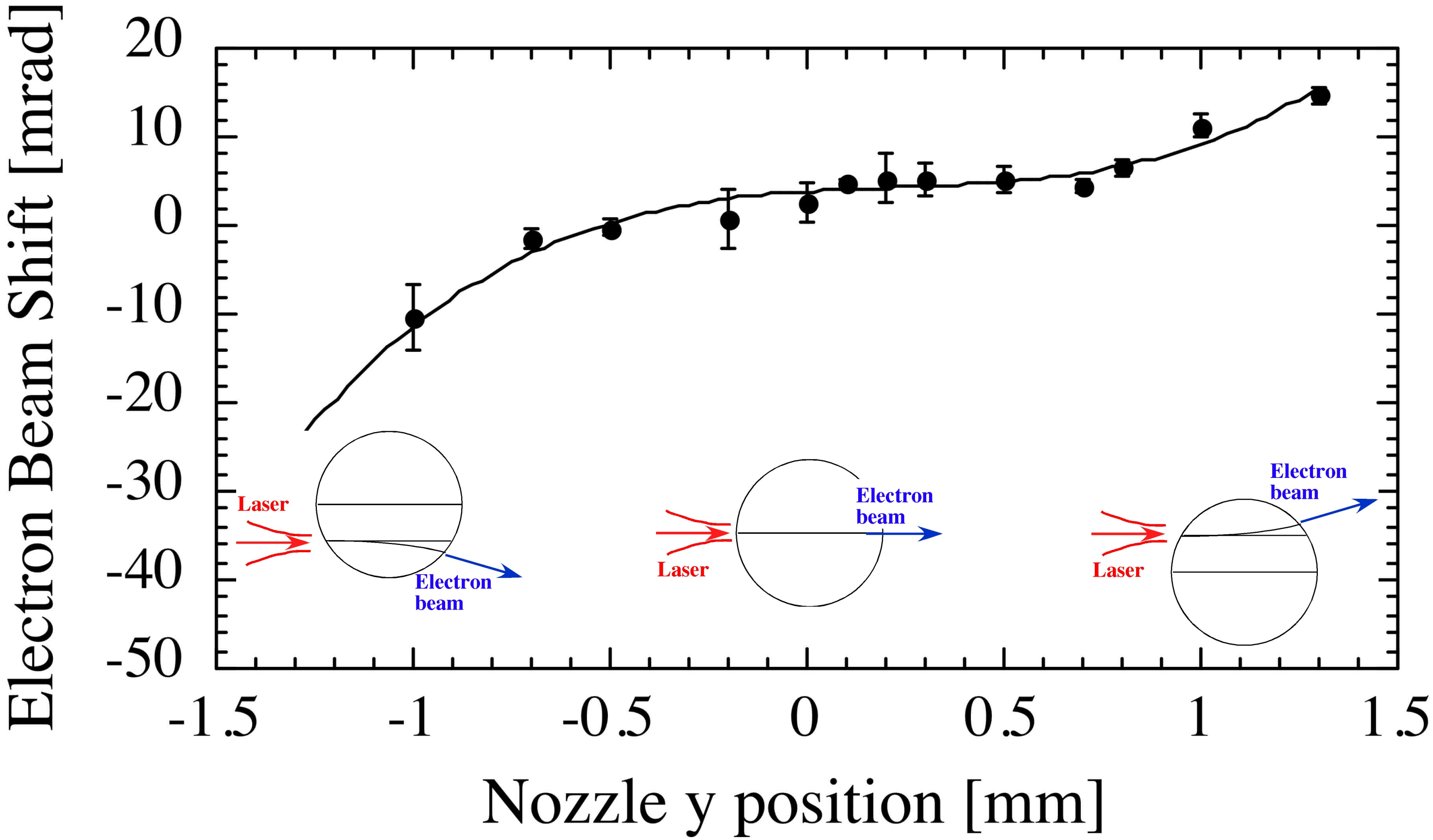
Initial direction control of the electron beam

Top view of the setup of the measurement of the electron beam direction



Initial direction control of the electron beam

Direction control of the laser accelerated electron beam



We can control the initial direction of the laser accelerated electron beam by changing the gas-jet position.

Profile control of the electron beam

Profiles of the laser accelerated electron beam

In order to manipulate the electron beam profile, we increase the plasma density. The plasma frequency is given by

$$\omega_p = \sqrt{4\pi n_e e^2 / m_e}\,.$$

Electric filed in laser pulse

P | Oblique | S | Oblique

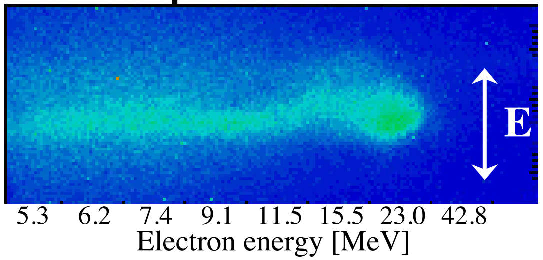
We can manipulate the profile of the laser accelerated electron beam by rotating the laser polarization.

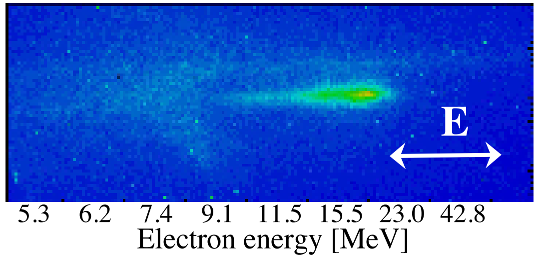
Similar result has been published in
S. P. D. Mangles, *et al*., PRL **96**, 215001 (2006)

Energy spectrum of laser-accelerated electron beams

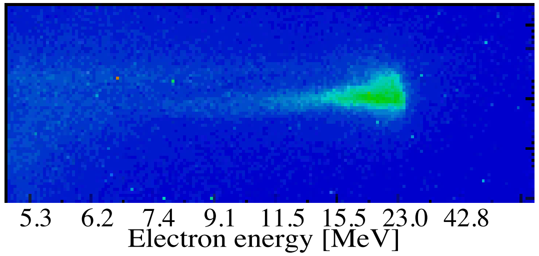
S polarization | P polarization

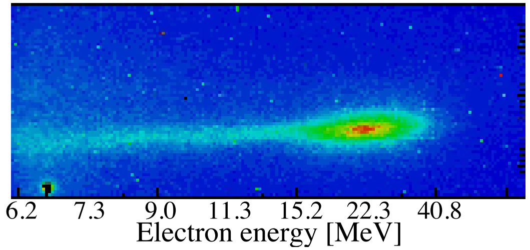
1.9×10^{19} cm^{-3}
(before dephasing)



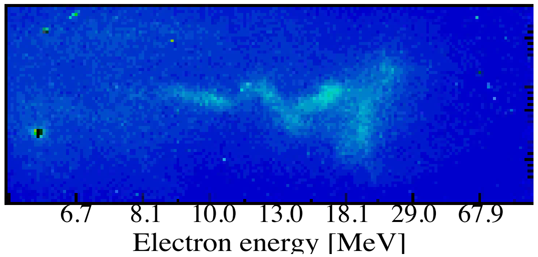


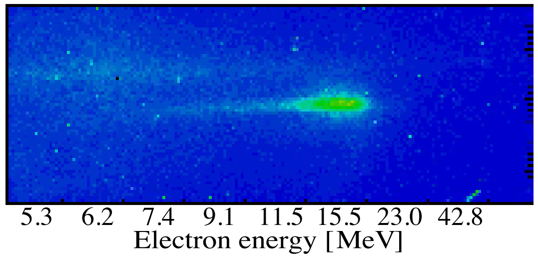
2.0×10^{19} cm^{-3}
(optimum)



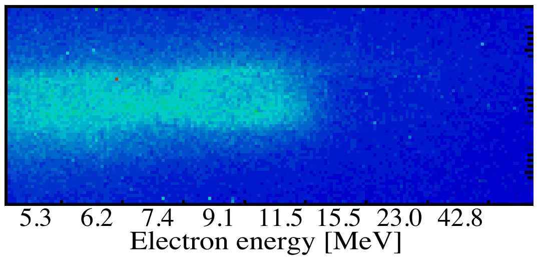


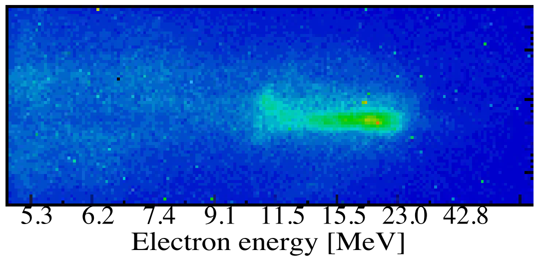
2.2×10^{19} cm^{-3}
(after dephasing)





2.4×10^{19} cm^{-3}
(after dephasing)

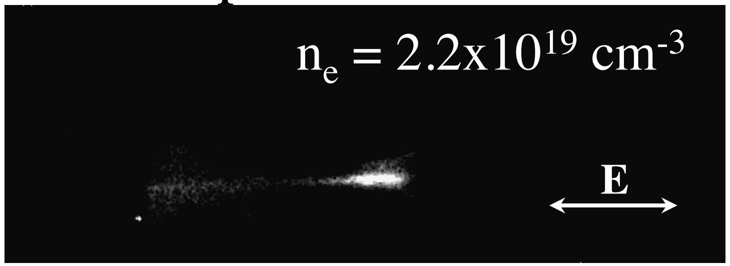




Typical images of the energy spectrum

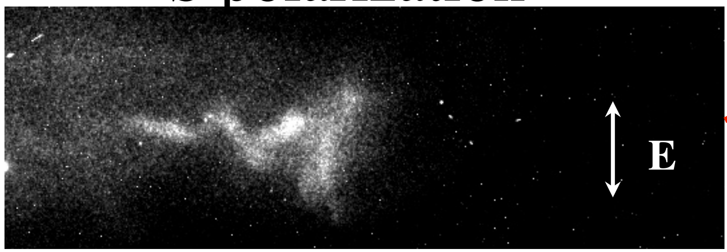
N_2 0.34MPa

P polarization

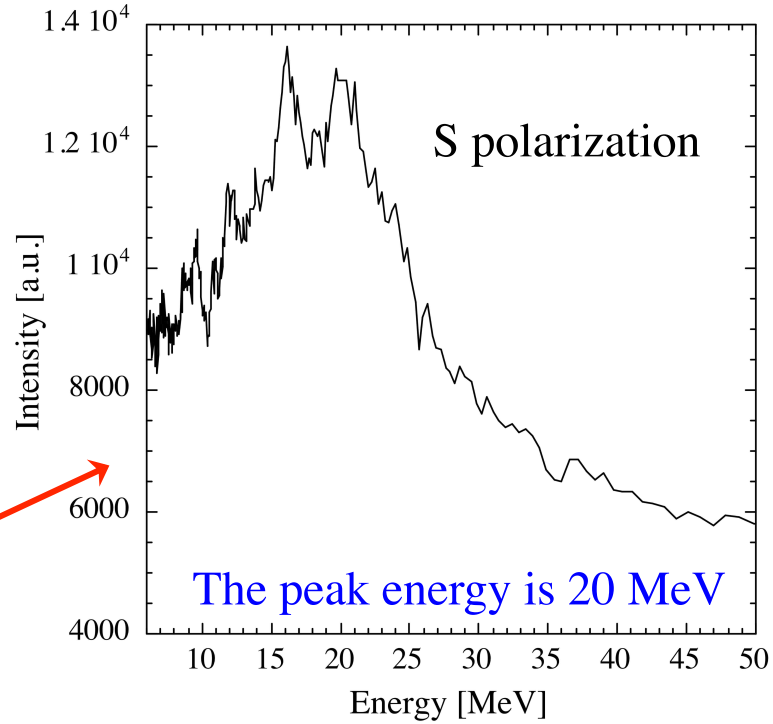


Energy

S polarization



Energy

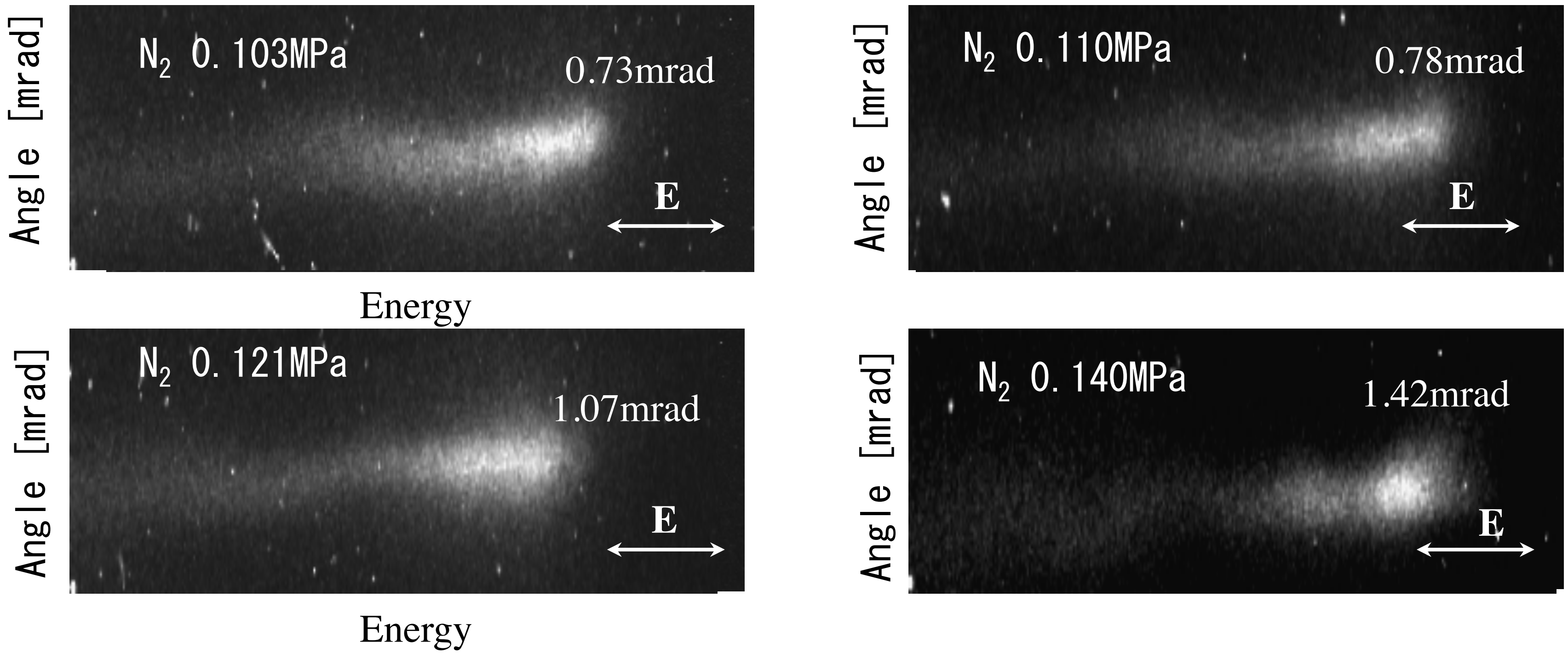


The oscillation depends on the laser polarization.

The pulsewidth (FWHM) of the electron beam is 1.5 period.

The oscillation is caused by the laser field or the plasma wave.

Electron oscillation for low plasma density



The oscillation is caused by the plasma wave

Y. Glinec, et al., Europhys. Lett. **81**, 64001 (2008), etc.

An angle of the oscillation is

$$\theta(\gamma) = -\frac{\theta_0}{\pi}\frac{(\gamma_0\beta_0)^{1/4}}{(\gamma\beta)^{3/4}}\sin\left[\frac{E_0}{E_z}\left(\sqrt{2\gamma\beta}-\sqrt{2\gamma_0\beta_0}\right)\right],$$

$\theta_0 = \pi\omega_p r_0/(2c)$,

$\gamma_0 = \omega_0/(\sqrt{3}\,\omega_p) = 4.86.$

From the equation, the amplitude is increased with ω_p

Good agreement with the experimental data

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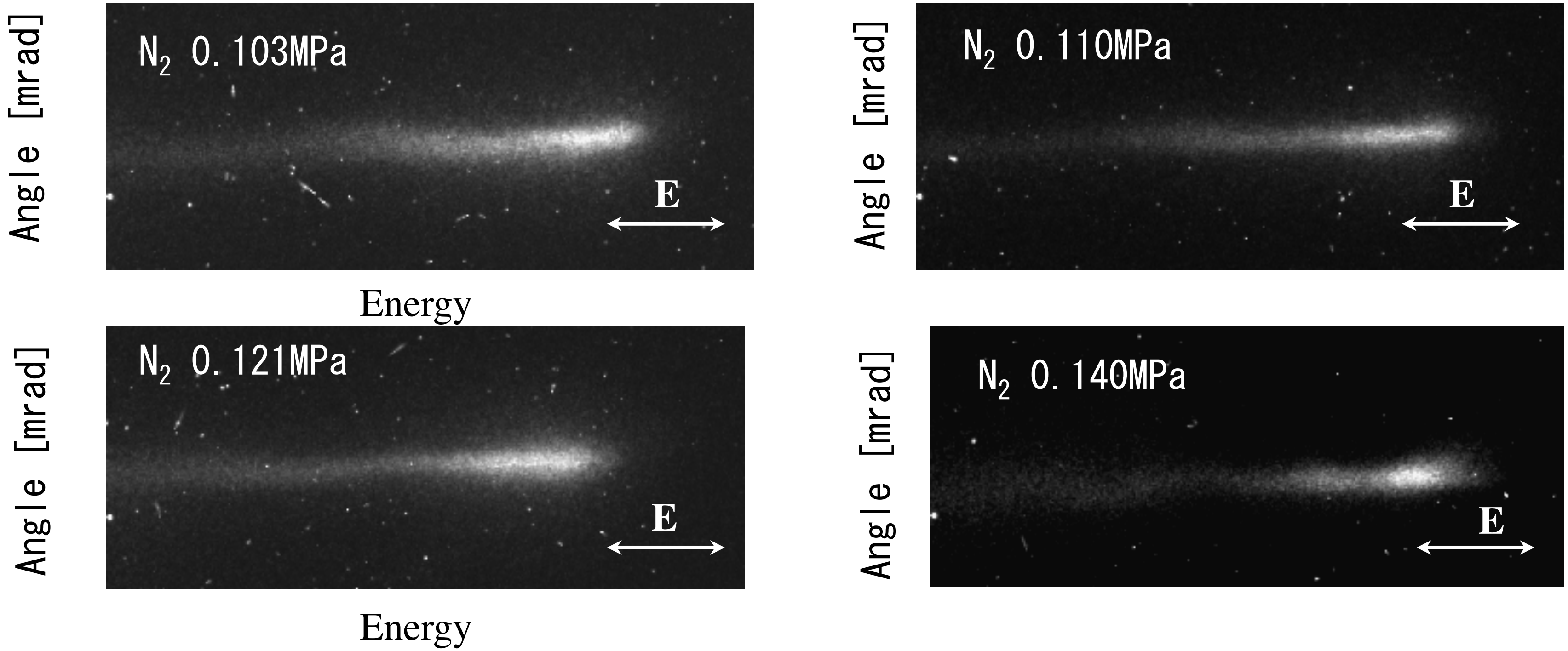

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Analysis 1

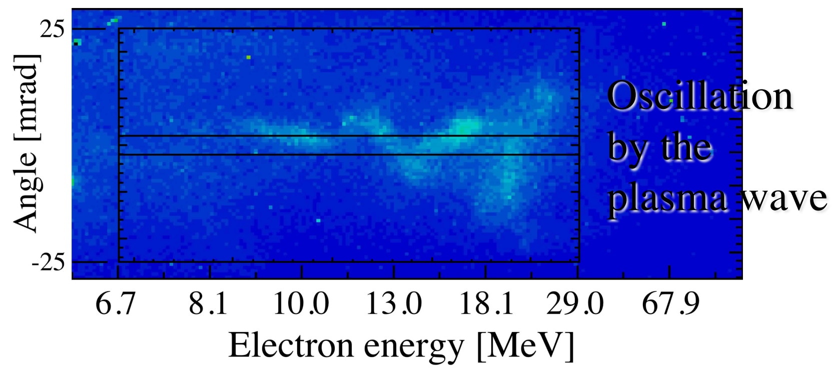
Y. Glinec, et al., Europhys. Lett. **81**, 64001 (2008), etc.

Assuming that the oscillation is caused by the plasma wave

1. The angle of the electron oscillation is

$$\theta(\gamma) = -\frac{\theta_0}{\pi}\frac{(\gamma_0\beta_0)^{1/4}}{(\gamma\beta)^{3/4}}\sin\left[\frac{E_0}{E_z}\left(\sqrt{2\gamma\beta}-\sqrt{2\gamma_0\beta_0}\right)\right].$$

The amplitude should be about 2mrad (contradiction).



2. When the laser pulse has P-polarization, we should be observed 2mrad of oscillation. However, we could not observe oscillation (contradiction).

Assuming that the oscillation is caused by the plasma wave

3. The electron oscillation frequency by the plasma wave is

$$\omega_\beta = \omega_p / \sqrt{2\gamma_0\beta_0} .$$

From this equation, the wavelength is λ_β = 20.8 [μm].

The oscillation has 1.5 periods. the electron pulsewidth, τ_{e_β}, is

$$\tau_{e\_\beta} = 20.8[\mu m] \times 1.5/c = 31.2[\mu m]/c,$$
$$= 104\ [fs].$$

The electron bunch length is 4.6 times longer than the plasma wavelength. When the electron bunch length is longer than the plasma wavelength, it is difficult to observe the oscillation in energy space.

There are contradictions.

Assuming that the oscillation is caused by the laser field

1. "oscillation frequency" = "laser frequency"

The electron beam has 1.5 oscillation.

The pulsewidth of the electron beam is

$$t_{e\_L} = 0.8[\mu m]\times 1.5/c = 1.2[\mu m]/c,$$
$$= 4\ [fs].$$

From the plasma density, the plasma wavelength is

$$\lambda_p = 6.73[\mu m].$$

The electron bunch length is **18**%of the plasma wavelength.

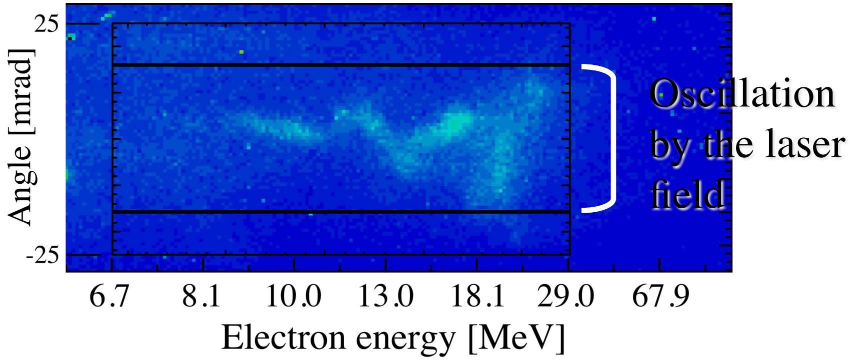
It is possible to observe the electron oscillation in energy space.

Analysis 4

Assuming that the oscillation is caused by the laser field

2. The angle of the oscillation is

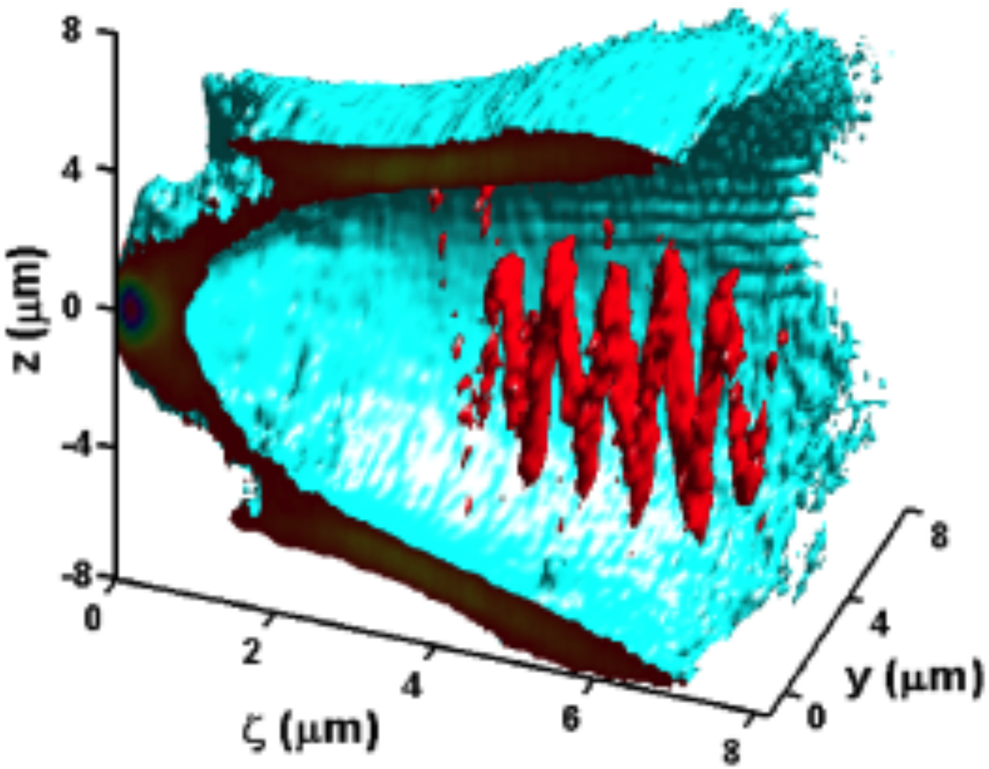
$$\theta_{las} = a_0/\gamma = 16 \text{ mrad}$$



3. When the laser pulse has P-polarization, it is difficult to observe the oscillation by the plasma wave due to the big oscillation by the laser field.

> If the electron oscillation is caused by the laser field, there is no contradict.

3D-PIC simulation



The electron oscillation is in the polarization plane with period the wavelength of the driver laser.

It was carried out using the VORPAL.

The figure is copied from
K. Nemeth, *et al*., PRL **100**, 095002 (2008)

Summary

1. We have succeeded in generating a stable laser-accelerated electron beam.

2. The electron beam direction was controlled by changing the gas-jet position.

3. The profile of the electron beam was manipulated by rotating the laser polarization.

4. 2 types of electron oscillation were observed in energy space.

5. From the oscillation, we thought that the pulsewidth of the electron beam was 4 fs.