Ultrafast electron sources based on plasmas produced by intense femtosecond laser pulses

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Ultrafast pulse (< several 100fs) and high energy (several 10 keV - 1 MeV) are key characteristics of short pulse laser photocathode electron guns.

Acceleration is achieved by an external field. The UV laser pulse is used to stimulate the photocathode, releasing electrons. An electron pulse is generated, which is then accelerated by the external field. The electron pulse is extended by the space charge effect.

Total charge = 100 fC (6.2 × 10⁵ electrons)
Acceleration field = 50 kV / 5 mm (10 MV/m)
Photocathode space width = 50 µm (FWHM, Gaussian)
Initial pulse duration = 50 fs (FWHM, Gaussian)

For instance, to get 500 fs:
Charge/pulse < fC (several 1000 ele.)
--- 10~1000 pulses for one image
Electron energy < 50 keV
--- sample property or thickness is limited.

Research aim is single shot UED

Conventional UED is not available for irreversible processes!
We are proposing the single shot UED using the combination of high-energy electron pulses accelerated by intense femtosecond lasers with their self-compression.

Plasma electrons accelerated with intense femtosecond lasers

- **Short pulse** < several 100fs
- **High energy** 100keV~1MeV
- **High-density flux** > 10^6/pulse
Maximum electron energy is given by the oscillation motion in the electromagnetic field

\[
\frac{T_h}{\text{keV}} \approx mc^2(\gamma - 1)
\]

\[
\approx mc^2 \left\{ \left( 1 + \frac{p_{\text{os}}^2}{m^2c^2} \right)^{1/2} - 1 \right\}
\]

\[
\approx 511 \left\{ 1 + 0.73 \left( \frac{I_L}{10^{18} \text{ W/cm}^2} \right) \left( \frac{\lambda_L}{\mu\text{m}} \right)^2 \right\}^{1/2} - 1
\]
We are proposing the single shot UED using the combination of high-energy electron pulses accelerated by intense femtosecond lasers with their self-compression.

**Short pulse** <several 100fs  
**High energy** 100keV～1MeV  
**High-density flux** >10⁶/pulse

**Plasma electrons accelerated with intense femtosecond lasers**

- **E-field**
- **Laser Pulse**
- **Plasma**
- **Normal E-field**
- **Plasma**

>10¹⁸W/cm²

Pulse electron source as short as laser pulse  
Direct acceleration in plasmas by intense optical field (accelerator is unnecessary)  
Laser plasma interaction at high density region

Small influence of space charge effect  
Broad electron velocity distribution

Acceleration in ultimately short duration and short length

Suitable to self pulse compression

This scheme can reduce space charge effect rather much.

High density electron flux

Phase rotator

Sample position
UED configuration using laser accelerated electron pulses and their self-compression

**Pulse generation**

- Laser beam
- Top view: Off-axis parabolic mirror, Beam for electron source drive, Slower electrons, Faster electrons

**Pulse compression**

- Diffraction
- Side view: Collimation lens, Dipole magnets, Quadrupole magnets, Aperture, "A", 63mT, Energy slit, Compression point

**Diffraction**

- Phosphor Screen, EMCCD Camera

*View on arrow "A"*
For the present work

Since Sep. 2012

800nm
130-150fs
<1J
<10Hz
<10^{19} \text{W/cm}^2

800nm
35fs
<500\text{mJ}
<5Hz
<10^{20} \text{W/cm}^2

Laser used for the experiment of Single-shot UED with laser plasma electron

Optics Express 16(19), 14875-14881 (2008)

“0.3% energy stability, 100-millijoule-class, Ti:sapphire chirped-pulse eight-pass amplification system”

S. Tokita, M. Hashida, S. Masuno, S. Namba, and S. Sakabe
Foil target rotator and auto-corrector of target surface movement

Target foil (Polyethylene ~10\(\mu\)m\(^t\)) stretched over an membrane rim

Laser irradiation position

Correction of the target

drive the target stage

PC : position memorization and driver control

position sensor laser

Foil target

rotational transfer

Intense short pulse laser

\(~10^{18}\)W/cm\(^2\)

\begin{figure}
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\includegraphics[width=\textwidth]{figure.png}
\caption{Diagram showing the Foil target rotator and auto-corrector of target surface movement.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{graph.png}
\caption{Graph showing displacement vs. angle with and without compensation.}
\end{figure}
UED configuration

using laser accelerated electron pulses and their self-compression

Pulse generation

Pulse compression

Diffraction

V-shape configuration enables the achromatic bending by simple and compact magnets.

A residual chromatic aberration is corrected by two quadrupole magnets.

The use of permanent magnets realizes high-stable compression and compact design.
Self-compression of electron pulse generated from laser plasma

Polyethylene foil target  Dipole magnets  Quadrupole magnets  Screen with CCD camera

Laser
Electron beam intensity profiles in the present UED system

Beam divergence: <2 mrad
Charge in a pulse: 6 fC (37,000 electrons)

Achromatic beam transport is successful.
Even by single shot a clear diffraction image was successfully obtained.
From the gold grid spacing ($a=0.407\text{nm}$) the electron energy can be reduced to 356keV.

This is the first demonstration of single-shot electron diffraction using a compressed sub-MeV laser plasma electron beam.
Measurement of electron pulse duration by scattering by Ponderomotive force driven by intense femtosecond laser pulses.

The electron beam is focused to 70µm in diameter by a lens to make its density high enough to be scattered much more by crossed high-intensity laser beam.
The part of electron beam is scattered by a laser pulse.

-215 fs

Removed line

Scattered electrons
Electrons scattered by a laser pulse

\[ S(\tau) = \int |Y| D_\tau (X,Y) \, dX \, dY \]

\[ = \frac{T}{m_e} \int |F_y(x - ct, y, z + vt)| \, dt \, dx \, dy \, dz \]


\( S(\tau) \) is corresponds to a cross-correlation trace between the laser and electron pulse.

Electron energy: \(~356\) keV
Estimated pulse duration: less than 300 fs
(FWHM, assuming Gaussian pulse)

The first demonstration of the compression of electrons produced / accelerated by a laser pulse

Research aim of UED with laser plasma electrons

The first demonstration of electron diffraction by a single pulse using laser plasma electrons


The first success of pulse compression of laser accelerated electron pulses


Photo-cathode and RF cavity
T. van Oudheusden, et al.,

Electron energy ~ several 100 keV
Strategy for single shot UED with laser plasma electrons

- **Number of electrons in a pulse**
  - $10^0$ to $10^8$

- **Electron bunch (pulse) duration**
  - $10p$ to $1f$

- **Electron energy**
  - ~several 100keV

- **Improvement of electron numbers**
  - Optimization of laser foil interactions to develop high flux source

- **Improvement of self compression**
  - Optimization of laser foil interactions to generate low emittance electron pulse

- **Image mode**
  - Real images

- **Diffraction mode**
  - Diffraction patterns

- **Present research aim**

- **Shorten laser pulse**

- **Photo cathode + accelerator 200keV**
- How the number of electrons can be increased.

- How we can confirm the duration of the original electron pulse just when it is emitted from the target surface.
To develop laser plasma electron sources, more detailed study of intense femtosecond laser interaction with plasma is necessary.

Angular distribution of electrons emitted from a foil target.

Aluminum foil emits much more electrons than a polyethylene foil.

The detailed processes of electron generation must be investigated. It may be due to the pre-plasma produced by a pre-pulse.

Directional electron emission has been obtained from a metal fine wire

- As the wire length is increased, the angular divergence decreases (65 mrad at L = 30 mm), and the beam intensity increases.
- It is expected that the beam intensity can be increased two orders of magnitude compared to that of the planar target.

Energy spectrum of electrons emitted from a wire target

- Relatively broad in 200-400keV
- Longer wire shifts the center energy to higher and the intensity higher

$7 \times 10^{11}$ electrons/sr @ $L=30\text{cm}$

More than 30 times for foil targets
● How the number of electrons can be increased.

● How we can confirm the duration of the original electron pulse just when it is emitted from the target surface.
Two equivalent electron pulses are generated on a foil target by two laser pulses. Two electron pulses are influenced with (deflected by) each other. The deflection can be on the source image relayed through an electron lens.

Estimation of electron pulse duration with the simulation by GPT code

Two electron sources

General Particle Tracer code*

Interaction near the target and movement in lens optics for the screen.

Two laser pulses

Experiments

Deflections

Emission distribution: isotropic
Temperature: 60 [keV]
Total charge of electrons: 6 [nC]
Electron pulse durations: 200, 410, 540, and 690 [fs]
Time-delay of two electron pulses: 0 ~ 1.5 [ps]

The duration of the electron pulse is as short as that of the laser pulse.


*http://www.pulsar.nl/gpt
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<th>Future expectation</th>
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<td><strong>Number of electrons</strong></td>
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Plasmas produced by intense lasers are “SPRING(fountain)” of radiations such as electrons, ions, x-rays, higher harmonics, THz, and so on.

These are perfectly synchronized with the probe (electron) beams, and therefore available to the pump beam.

“No jitter”
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Recent Related Publications :


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Thank you for your kind attention

We welcome you to visit our laboratory in Kyoto University.