MeV electron diffraction and microscopy in Osaka University

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Outline

1. Development of RF gun for UED/UEM
   Requirements / experimental results
2. RF gun based UED at Osaka Univ.
   MeV UED systems / measurements
3. RF gun based UEM at Osaka Univ.
   prototype of RF gun based UEM
   first electron image measurement
4. Conclusion
Photocathode RF gun for electron diffraction/microscopy in Osaka Univ.
What requirements for UEM?

The expected beam parameters:

- **Bunch length**: \(\leq 100\) fs
- **Beam energy**: 1–3 MeV
- **Emittance**: \(~0.1\) mm-mrad
- **Energy spread**: \(~10^{-4}\) (\(10^{-5}\) for challenge)
- **e- number**: \(10^7\)–\(8\) e\(^-\)s/bunch (1–10 pC) *with ultralow dark current*
New femtosecond RF gun

Developed under the collaboration with KEK

Improvements:

- remove two laser injection ports
- a new turner system
- new structure cavities
- a new insertion function of photocathode
  (The photocathode is removable)

The mode separation between $\pi$ mode and 0 mode is increased up to

$$f_\pi - f_0 = 8.5 \text{ MHz}.$$  

The Q value is increased up to 14,500.

(The cooling system and waveguide design are same as the BNL gun-IV.)
Transverse beam dynamics in RF gun

Experiment studies of femtosecond e- beam in RF gun
(exp. conditions: 100 fs UV laser, 30° gun phase, 3MeV)

For a copper cathode, the thermal emittance can be

\[ \varepsilon_{th} = \sigma_r \sqrt{\frac{E_{kin}}{m_0 c^2}} \approx 0.18 \text{mm} \cdot \text{mrad} \]

\[ E_{kin} = h\nu - \phi + \alpha \sqrt{\beta E_0} \sin \theta \approx 0.26 eV \]

Reducing laser spot size to 0.1mm,

\[ \varepsilon \sim 0.1 \text{mm} \cdot \text{mrad} \]
RF gun based MeV electron diffraction at Osaka Univ.

Electron energy: \(1 \sim 3\) MeV
Time resolution: 100 fs
RF gun based MeV UED at Osaka Univ.

use of electron optical lenses as like in electron microscopy

**RF gun**
- 1-5MW at 4 μs, 10 Hz
- 2856 MHz

**Solenoid**
- Φ 3.0 mm

**Sample**
- Area: 5x5 cm
- CsI (Tl) scintillator

**Probe 3ω**
- 257 nm, 90 fs, 1 kHz, 6 mW

**Pump 2ω**
- 385 nm, 90 fs, 10 Hz, < 40 mJ/cm²

**Area:**
- Φ 300, 350 μm

**EMCCD**

**Probe 3ω:**
- 3 MeV, 10 Hz
- 100 fs e-pulse
- 4.5 x 10⁷ e/pulse

**Si crystal**
- [1-10]

**Diffraction**
Picture of UED system at Osaka Univ.

use of electron optical lenses, therefore, compact.
Quality of MeV electron diffraction

Electron beam: 3 MeV, $8.9 \times 10^7 \text{e/cm}^2 / \text{pulse}$
Sample: 180 nm-thick single crystal Si

Intensity profile of 620 pattern

A high-quality MeV ED was observed!

- Beam convergence angle: 50 $\mu$rad
- Maximum scattering vector: $q_{\text{max}} > 1.56 \text{Å}^{-1}$
- Requirement of the e⁻ number: $10^6$ - $10^7$

Bragg law

\[
2d \sin \theta = n \lambda \quad \text{and} \quad \tan 2\alpha = \frac{D}{L}
\]

Power of the technique: static diffractions

- Single-shot measurement

- **Si**
  - Single crystal
  - Thickness: 180nm
  - e- energy: 3MeV

- **Au**
  - Single crystal
  - Thickness: 20nm
  - e- energy: 3MeV

- **Metal (Al)**
  - Polycrystal (100nm)
  - Large scattering vector

- **Insulator (Mica)**
  - Single crystal (~100s nm)
  - K(Fe,Mg)₃(AlSi₃O₁₀)(OH,F)₂
  - No charging effect

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Time-resolved measurement #2

Laser heating and melting dynamics of single crystal Au
RF gun based ultrafast electron microscopy

<table>
<thead>
<tr>
<th>Electron beam energy:</th>
<th>1~3 MeV</th>
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<td>Temporal resolution:</td>
<td>100 fs</td>
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<td>Spatial resolution:</td>
<td>10 nm</td>
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Concept of RF gun based UEM

RF gun

Solenoid

CL-1

CL-2

Specimen

50μm spot

50-fs laser

5μm spot

10μm spot

RF

aperture-1

Specimen

Objective lens

Intermediate lens

Projector lens

Image screen

(1024x1024 pixels)
Prototype of RF gun based MeV electron microscopy

Electron energy: 1~3 MeV
Bunch length: 100 fs
Emittance: < 0.1 mm-mrad
Energy spread: 10^{-4} (10^{-5} for challenge)
Charge: 10^7~10^8 e^-/pulse

Time resolution: 100 fs
Spatial resolution: 10 nm

Challenge!
Prototype of RF gun based MeV electron microscopy

The prototype was constructed at the end of Oct. 2012.
Detection of MeV electron images

The detection system was successfully used in UED measurement. (single-shot measurement with $10^5$ e·s/pulse)
MeV electron diffraction in UEM

MeV electron diffractions observed with 10 pulses and single-shot measurements

First exp. at Nov. 9, 2012

Sample: Au single crystal, ~15 nm
Electron charge: ~100 fC/pulse on the scintillator
MeV electron imaging in UEM

First exp. at Nov. 10, 2012

Electron beam (2 MeV)

Specimen

Objective
Lens

(Obj. Aper.)

BFP

Projector
lens

Final image screen

Sample: Au single crystal, ~15 nm
Electron charge: ~10 fC/pulse on the scintillator

Images of Au film

Exposure time: 2s

Exposure time: 60s

Observed images of Au film

Observation #1

Observation #2

x385

x650

x1200

38nm/pixel

10μm

38nm/pixel

10μm

19

x650

x1200
Magnifications & spatial resolution

- RF gun
- Solenoid lens
- Femtosecond electron beam
- CL-1
- CL-2
- Specimen
- Objective lens
- Intermediate lens
- Projector lens

**Cu grid (1000mesh)**

- 5.5 μm
- 25 μm
- 10 μm
- 5 μm

**Spatial resolution in future**
- 300 nm
- 10 nm
- <1 nm

**CL-1**

**CL-2**

**Objective lens**

**Spatial resolution**

- 75 nm/pixel
- 30 nm/pixel

**RF gun**

**Solenoid lens**

**Femtosecond electron beam**

**Cu grid (1000mesh)**

**RF gun**

**Solenoid lens**

**Femtosecond electron beam**

**CL-1**

**CL-2**

**Specimen**

**Objective lens**

**Intermediate lens**

**Projector lens**

**Spatial resolution in future**

- 300 nm
- 10 nm
- <1 nm
Next TEM: “Dream TEM”

**Weight:** 140t

**Photocathode**

**RF gun**

**15cm**

**10m**

**Compact High-voltage Transmission Electron Microscopy**

- **high-voltage TEM function** (nm or sub-nm, MeV)
- **time-resolved function** (femtosecond)

**Standard 3-MeV TEM at Osaka Univ.**

**Next TEM**
New science and technology using UEM

Imaging Technology
イメージング テクノロジー
Structural observation and imaging in "real space" with atomic-scale spatial resolution using high-energy electron beam.

Methods

Electron beam (1~3MeV)

Compact high-voltage electron microscopy (dream TEM)

MeV UEM

Ultrafast Observation
超高速現象の観察
Observations of fundamental dynamic processes in matter occurring on femtosecond time scales over atomic spatial dimensions.

Targets

Protein Structural Dynamics
タンパク質構造ダイナミクス

• Visualizations of protein structural dynamics using ultrafast electron diffraction and imaging technique.
• New technologies and applications in medical biology.

Making Molecular Movie
分子運動の可視化：- 新しい科学 -

• Observation of single molecule motion.
• Ultrafast chemical reactions.
• Discovery of transition states and reaction intermediates.

Nano-technology
ナノテクノロジー

• Photon-induced ultrafast dynamics of novel nano-scale materials.
• Creation of new functional materials and devices for nanotechnology.
Both RF gun based UED and UEM systems have been constructed at Osaka University. In UED, single-shot and time-resolved measurements have been succeeded. In UEM, the MeV electron imaging experiment was carried out. Both experiments suggest that RF gun is very useful for ultrafast MeV electron diffraction and is also expected to be used in ultrafast electron microscopy.

However, great efforts and many challenges are required:

- reduce further the emittance (<0.1 μm) and energy spread (10^{-5} or less),
- increase the beam brightness,
- improve the stabilities on the charge and energy,
- develop a detection of very electron with MeV energy region.