MeV Ultrafast Electron Diffraction and Microscopy Development at SJTU

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Outline

1. MeV UED/UEM project at SJTU
2. Current status of the UED/UEM project
   2.1 Conceptual Design
   2.2 Civil construction
   2.3 Commissioning UED/UEM test facility
   2.4 Improving beam brightness
   2.5 Development of high-field objective lens
3. Future plans
Accelerators for shaping the world
**Accelerator-based MeV UED/UEM at SJTU**

1. Femtosecond laser
2. High rep-rate rf source
3. High rep-rate rf gun
4. Advanced sample chamber
5. Superconducting solenoid
6. Advanced detection system

- First proposal to NSFC in 03/2011
- Project funded in 11/2013
- Construction: 2014 - 2018

<table>
<thead>
<tr>
<th>Mode</th>
<th>Diffraction</th>
<th>Microscopy</th>
<th>Rep-rate</th>
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<tbody>
<tr>
<td>State-of-the-art</td>
<td>~200 fs</td>
<td>10 ns/10 nm</td>
<td>~100</td>
</tr>
<tr>
<td>Goal</td>
<td>~50 fs</td>
<td>10 ps/10 nm</td>
<td>~1000</td>
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Strategic plan for a UED/UEN user facility

- Test critical technologies at the test facility
- Collaborate with national labs
- Let the users decide what they want
UED/UEM center at SJTU
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3. Future plans
Accelerator based UED

- **2011**
  - Gun
  - Buncher
  - Sample

- **2015**
  - Gun

- Emittance growth
- Energy spread growth
- Timing jitter

Bunch compression reduces bunch length and increases energy spread

Phase jitter leads to energy and timing jitter
Accelerator based UED

2011 gun

2015 buncher

- Emittance growth
- Energy spread growth
- Timing jitter

either degrade the sample or mask the structural dynamics. Here we show that a recently developed, ultrabright femtosecond electron source makes it possible to monitor the molecular motions in the organic salt \((\text{EDO-TTF})_2\text{PF}_6\) as it undergoes its photo-induced acting degrees of freedom. Here, we demonstrate that recent improvements in ultrafast electron diffraction (UED) instrumentation provide such a capability by exploring the nature of the semiconductor-to-metal transition in \(\text{VO}_2\) (8).

Miller’s group, Nature 2013

Siwick’s group, Science 2014

Achieved ~200 fs resolution and excellent S/N with rf compression

PRL 113 235502 (2014)
Accelerator based UEM

A representative design for 10 ps & 10 nm resolution

Formulation with accelerator terminology

- Imaging condition: $R_{12}=R_{34}=0$
- Chromatic aberration: $T_{126}$
- Spherical aberration: $U_{1222}$

$$T_{ijk} = \sum_{m=1}^{6} R_{im}^{(2)} T_{mjk}^{(1)} + \sum_{m,n=1}^{6} T_{imn}^{(2)} R_{mj}^{(1)} R_{nk}^{(1)}$$

Xiang et al., Nucl. Instru. Meth. A 759, 74 (2014); Li and Musumeci, PR Applied 2, 024003 (2014)
Conceptual design of the MeV UED/UEM facility

- **C-band cavity** used to remove beam quadratic energy chirp
  - Before and after C-band cavity
  - $\Delta E/E = 10^{-3}$

- **C-band cavity** used to imprint linear energy chirp for compression
  - Before and after C-band cavity
  - $\Delta E/E < 10^{-4}$

- **S-band gun**
- **C-band deflector**
- **C-band cavity**
- **S-band gun**
- **Solenoid lens**
- **Energy spectrometer**

At the sample
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Construction of a new experimental hall
Construction of a new experimental hall

Grounding system
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Commissioning the UED test facility

Photocathode rf gun based MeV UED test facility

High quality Al and Au diffraction pattern (Fu et al., Rev. Sci. Instru. 2014)
Finding time-zero with the perturbation from laser-induced plasma

First MeV UED pump-probe experiment in China (Zhu et al., CPL, 2014)
Initial test of a prototype MeV UEM

Simulation
Condenser-objective lens

Simulation
Condenser-objective lens

Resolution
keV TEM
Space charge

Temporal-spatial resolution (300 fs*3μm=10^{-18} s*m);
Shoot for 10^{-19} s*m with our user facility
Test of MHz MeV UED (PKU-SJTU collaboration)

- Beam energy: 3.4 MeV; Rep-rate: 81.25 MHz
- Beam current: up to ~1 mA (~10^{16} e/s)
- Permanent damage induced by 81.25 MHz beam;
- Forbidden peaks are observed;
- Likely due to heat-stress related distortion (surface bulging; 2.2 microsecond recovery time).
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1. Laser shaping to reduce emittance growth

Beam transverse phase space for various laser distribution (PRL 2004)

- 3 alpha-BBO crystals to produce 8 laser pulse trains
- Pulse separation < pulse width
- Nearly flat-top distribution

Improving beam brightness
Improving beam brightness

2. Corrugated structure to reduce beam energy spread

\[ \omega + 2\omega \]

- Requires one more rf station
- Requires accurate control of the phase
- Beam energy reduces by \(1/n^2\)

Quadratic chirp removal with an rf cavity

\[ W(z) = \frac{\pi^2}{16} \frac{Z_0 c}{\pi a^2} F e^{-k_0 z} \cos(kz) \]

Green function

E-beam wakefield
Improving beam brightness

2. Corrugated structure to reduce beam energy spread

ISS

0.6 mm
Improving beam brightness

2. Corrugated structure to reduce beam energy spread

Quadrupole wake cancellation

Fu et al., PRL 114, 114801 (2015)
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Development of high-field objective lens

1. Superconducting solenoids

\[ \frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v^2} \int B_z^2 \, dz \]

\[ C_c \sim C_s \sim f \]

A shielding lens with >7 T field provides \( f = 2 \) mm for a 1.5 MV TEM (Dietrich et al., 1967)

To be delivered to SJTU in 09/2015
Development of high-field objective lens

2. Room-temperature electromagnetic solenoids

\[
\frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v_z^2} \int B_z^2 \, dz
\]

\[C_c \sim C_s \sim f\]

High-field lens needed for MeV UEM

FeCoV

DT4

Magnetic field of the conventional solenoid

\[B_p = 2.1 \, \text{T when } J = 1.6 \, \text{A/mm}^2\]

Diameter: \(~75 \, \text{cm}\)
Height: \(~37 \, \text{cm}\)
Weight: \(~1 \, \text{ton}\)

To be delivered to SJTU in 12/2015
Development of high-field objective lens

3. Permanent magnet solenoid (PMS) and quadrupole (PMQ)

\[ \frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v^2} \int B_z^2 \, dz \]

\[ C_c \sim C_s \sim f \]

High-field lens needed for MeV UEM

- Russian quadruplet (FDFD)
- X/Y back focal planes coincide
- Movable with in-vacuum motors

PMQ to be delivered to SJTU in 06/2015
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Future plans

- Gatan K2 detector;
- A dedicated intense THz source for THz-pump UED-probe.
Thanks!
Everyone is welcome to use our UED/UEM facility.