

Development of MeV Ultrafast Electron Scattering Instruments at SLAC National Accelerator Laboratory

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Recent years have witnessed rapid development of ultrafast electron and x-ray scattering instruments, aimed at enabling the studies of structural dynamics on the fundamental time and length scales [1, 2]. Ultrafast electron diffraction (UED) and microscopy (UEM) using a few mega-electron volts (MeV) electron beams is a promising new R&D area which has the potential to open many opportunities for groundbreaking science [3-7].

Electrons and x-rays are complementary tools to study material structures. While x-rays primarily interact with electrons in matter, electrons are sensitive to both electrons and nuclei. Compared with hard x-ray, a few MeV electrons have 10^5 times larger scattering cross sections, 10^3 times shorter wavelength, and 10^3 times less radiation damage per elastic scattering [8]. The strong interaction with matter makes electrons the ideal choice to capture information from nanoscale or smaller samples, particularly monolayer and gas phase samples. Electrons are also charged particles and can be easily focused by electromagnetic lenses to form high spatial resolution real-space images.

MeV UED and UEM can achieve much higher spatio-temporal resolution compared to their keV counterpart at 100-300 keV energies. State-of-the-art MeV electron sources have one order of magnitude higher field gradient, thus the generated electron beams have much higher brightness. Moreover, space charge effects, the essential limit to the machine performance, between the source and sample, are dramatically suppressed by 10^2 - 10^3 times following the $\beta^2\gamma^3$ scaling, where γ is the Lorentz factor and β is the normalized speed.

To exploit the synergy and complementarity with the Linac Coherent Light Sources (LCLS), SLAC National Accelerator Laboratory recently launched a UED/UEM Initiative aiming at developing the world's leading ultrafast electron scattering instruments. A MeV UED setup has recently been built, commissioned, and brought into full operation at SLAC's Accelerator Structure Test Area (ASTA). The platform, as shown in Fig. 1, consists of a complete photocathode RF gun system, including a LCLS-type S-band photocathode RF gun, a 5 mJ femtosecond Ti:Sapphire laser, the laser-RF synchronization system, a high power modulator and an S-band klystron. This system tremendously benefits from many common key technologies developed for LCLS. The setup is now serving an active ultrafast science program and supports R&D on future UED/UEM instruments and accelerators.

The UED machine has already generated exciting science results: The machine provided very high SNR and stable intensity in the diffraction patterns, which enabled us to study the lattice dynamics and diffuse scattering of Bismuth polycrystalline samples at high precision. It sparked more interest in this

extensively studied, but yet not fully understood system. As another example, we've observed ultrafast lattice dynamics in FePt nano-cluster thin films following laser excitation. The samples consist of 5-10 nm size FePt grains and are currently being developed for the next generation magnetic data storage media. The laser induced ultrafast electron and spin dynamics is currently being actively investigated using soft x-rays at the LCLS. While x-ray holography at LCLS will enable direct imaging of magnetic switching, the current UED and future UEM instruments open up complementary studies of the currently inaccessible lattice dynamics on comparable nanometer length scales.

The next milestone of machine develop will be performing gas phase MeV UED experiment. MeV electrons travel at a speed very close to that of the pump laser, thus the velocity mismatch issue, which is a major constrain for keV UED, is essentially eliminated with MeV beams. For example, for 100 keV electrons, to keep the velocity mismatch below 100 fs the gas target needs to be 40 μm or thinner, while a few mm thick gas sample can be used for 2.5 MeV electrons. We will also upgrade the machine repetition rate from 120 Hz to 360 Hz to minimize the data accumulation time.

There are several other exciting targets in the Roadmap of UED/UEM development: (1) to improve the temporal resolution from 100 fs to <20 fs level to study fast chemical processes; (2) to improve the probe size in diffraction mode from a few hundred μm to sub- μm , which greatly eases the sample fabrication processes; (3) to develop single-shot UEM revealing real-space images with ps-nm spatio-temporal resolution.

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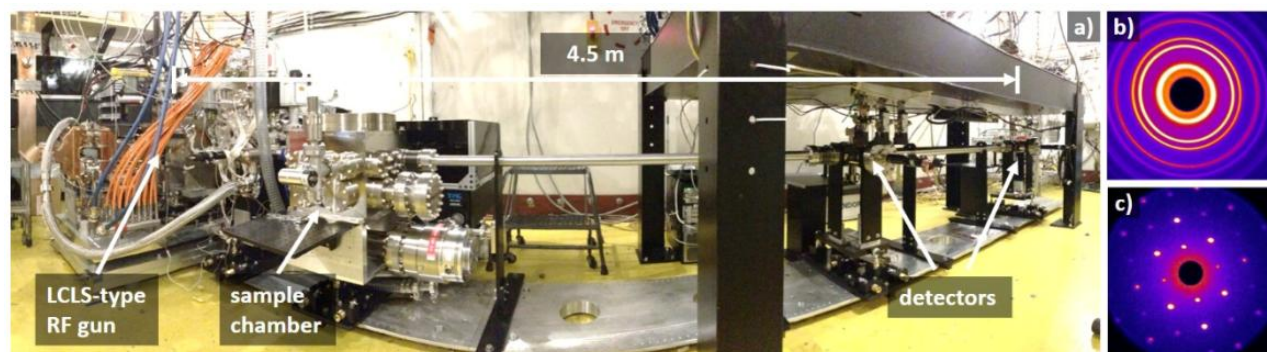


Figure 1. (a) The MeV UED beamline at SLAC's ASTA. Diffraction patterns of two recently studied system: (b) Bismuth and (c) FePt.