Ultrafast Dynamical Transmission Electron Microscopy

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Introduction

In the past decades, great effort has been made to improve the spatial resolution of Transmission Electron Microscopes (TEM). More recently, researchers have begun to focus on in-situ experiments for imaging a variety of dynamic processes inside the TEM. Many in-situ processes occur at very short time scales, often less than few microseconds. Studies on such processes are limited by the minimum acquisition time of the modern TEM cameras (~few millesconds) that miss salient details of the sample dynamics, e.g., defect processes, phase transformations, or nucleation phenomena. For these studies, a much higher temporal resolution is required and can be obtained using short pulse electron beams. Recent improvements in the quality of pulsed electron beams for TEM offer new opportunities for the study and understanding of sub-microsecond phenomena. The electron emission is correlated in time with the transient states in the TEM sample using pump-probe techniques which can have sub-ps temporal resolution using femtosecond laser illumination.

These pulsed electron imaging studies can be carried out in two different operating modes:

- **Single shot mode**, required for studying irreversible processes, using high intensity pulses with a sufficient number of electrons (>10^8 electrons) to capture single-shot images of transients states in the material on nanosecond to microsecond timescales.
- **Stroboscopic mode** allows imaging and spectroscopy of reversible processes with high spatial and energy resolution through the accumulation of millions of low intensity electrons pulses (1-100 electrons) at MHz repetition rates.

In this poster, the first results obtained with the Ultrafast Dynamical Transmission Electron Microscope (UDTEM) installed at the IPCMS Laboratory (Strasbourg, France) are shown.

Technique

Description of the UDTEM at Strasbourg operating in **Stroboscope Mode**.

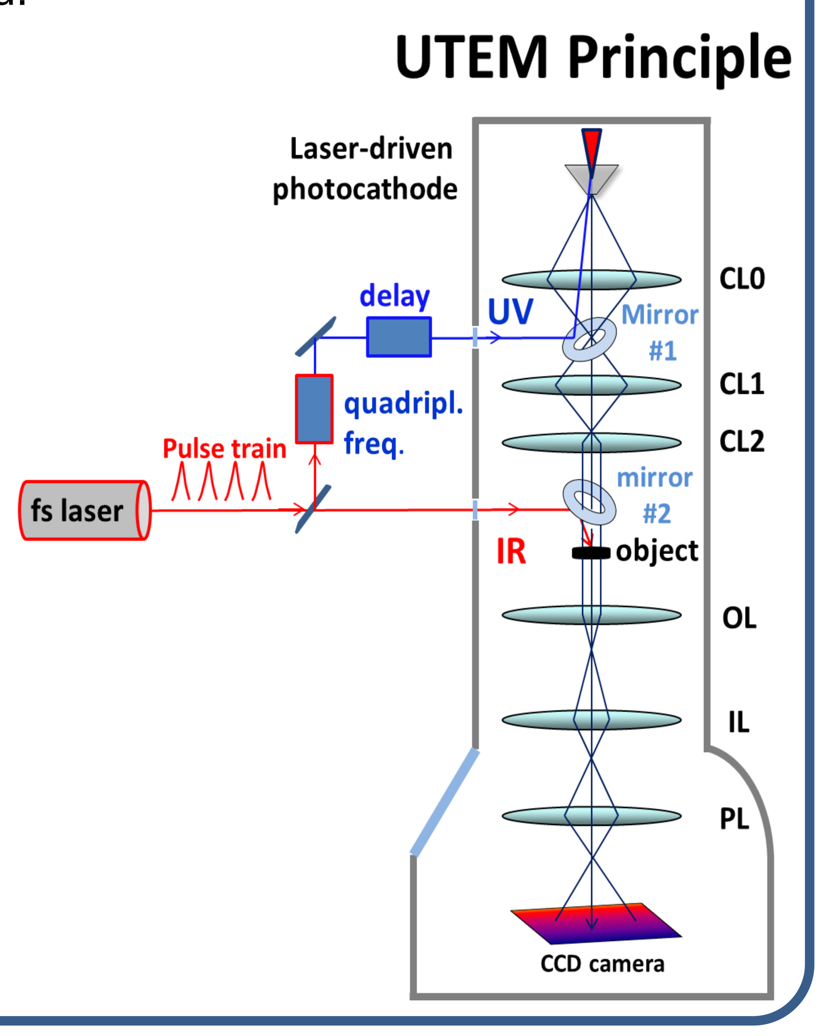
The femtosecond laser is split into ultraviolet (UV) and infrared (IR) beams. The UV pulse is aligned to the photocathode in the TEM gun and generates the electron bunch via photoemission. The high repetition rate of the laser (1 kHz - 2 MHz) generates a continuous train of pulses having 1-100 electrons per pulse that illuminates the TEM sample, allowing picosecond events to be recorded.

The infrared laser is focused on the specimen and excites the transient states in the material.

Both laser beams (UV and IR) are time-correlated on the sample with sub-ps resolution using a high-precision optical delay line.

The electron pulse illuminates the sample and probes the excited states in the sample at different, user-selected time delays between the IR pump and electron pulses. The repetition rate of the laser is set such that the sample relaxes to its ground state between pulses. Images and spectra are generated through the integration of millions of femtosecond pump-probe events.

The stroboscopic mode in the UDTEM works in the both imaging or diffraction modes and in Electron Energy Loss Spectroscopy (EELS).



Equipment

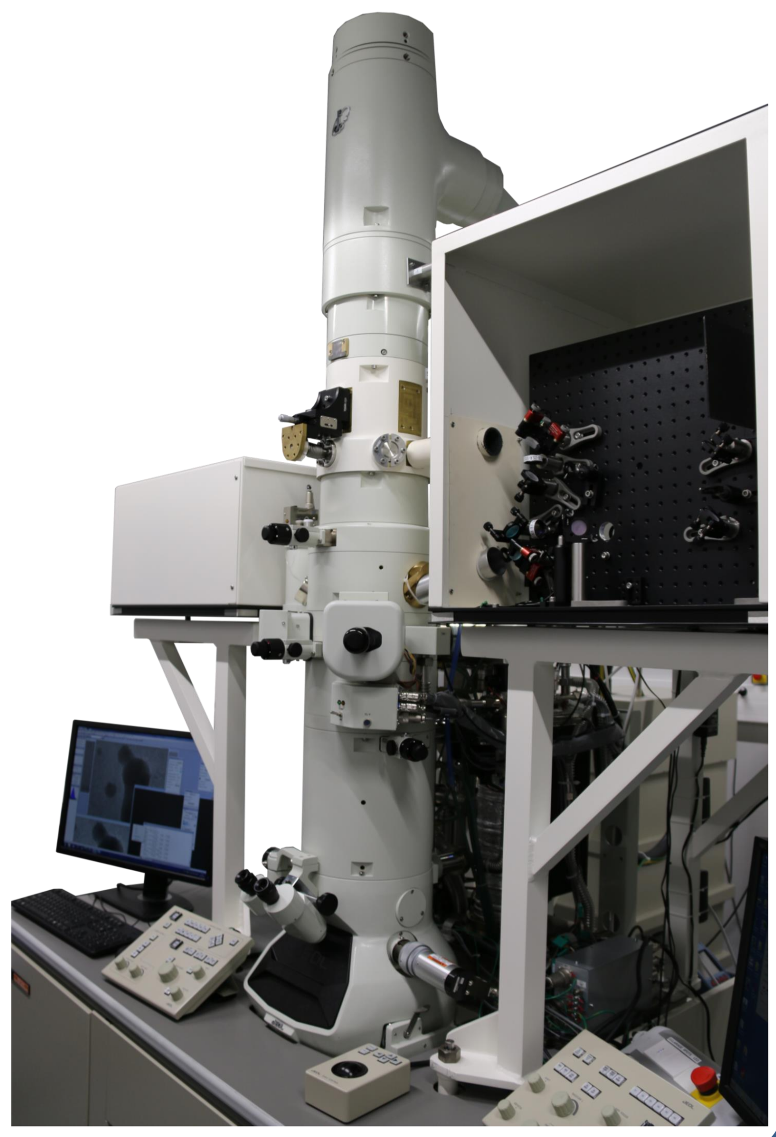
JEOL (Europe) SAS and IDES have collaborated for the development of the worlds first commercial UDTEM. This equipment is based on the JEOL JEM-2100 combined with IDES Laser Port system and optical benches composed of mirrors, lenses, and a delay line.

TEM gun and column has been modified and electron optical elements have been added for the integration of the laser:

- Addition of a brass drift section between the gun alignment coils and condenser optic that contains a laser port and a mirror.
- Integration of a new condenser lens for focusing the electron beam above the conventional condenser lens system.
- Use of an optimal cathode for pulsed photoemission.

The laser optical system has been designed and integrated around the TEM column. The optical bench is linked to the anti-vibration system of the microscope allowing a better mechanical stability during the experiments.

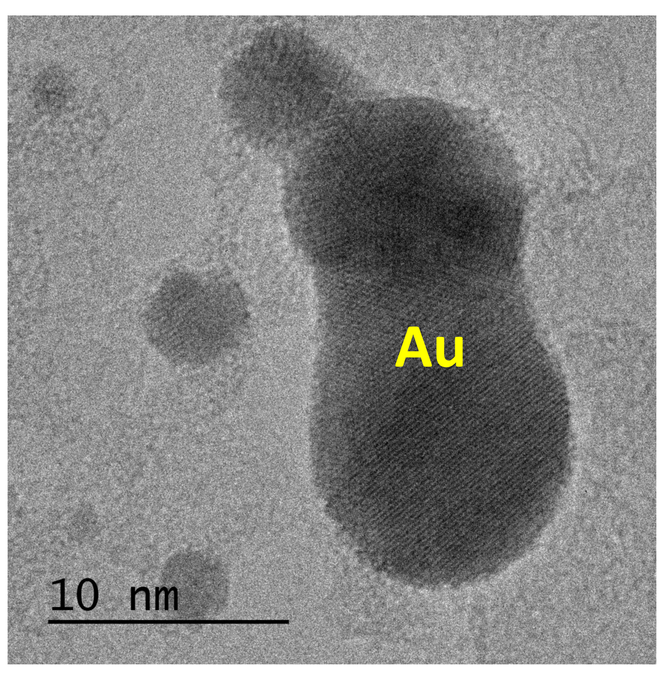
A post-column electron energy-loss spectrometer is installed for EELS experiments.



First resolution tests with UDTEM

Resolution in thermionic mode

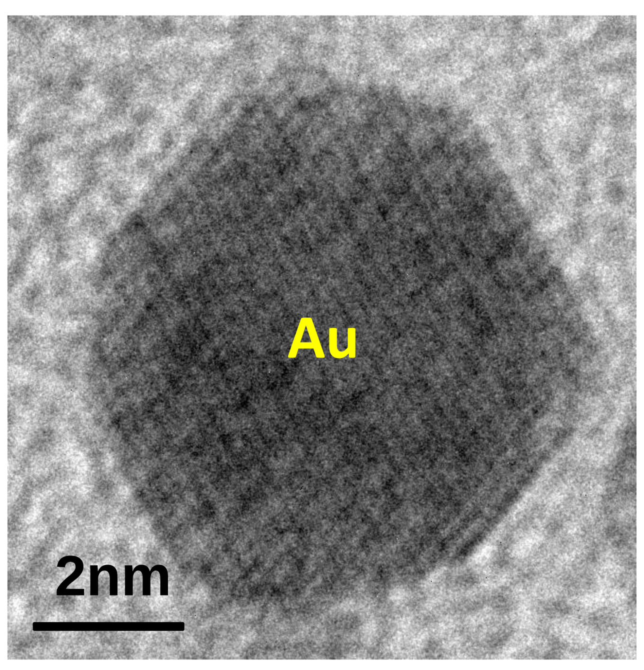
Ta disc cathode, heated
Sample: gold nanoparticles



Lattice image
resolution ~ 0.23nm

Resolution in photoelectron mode

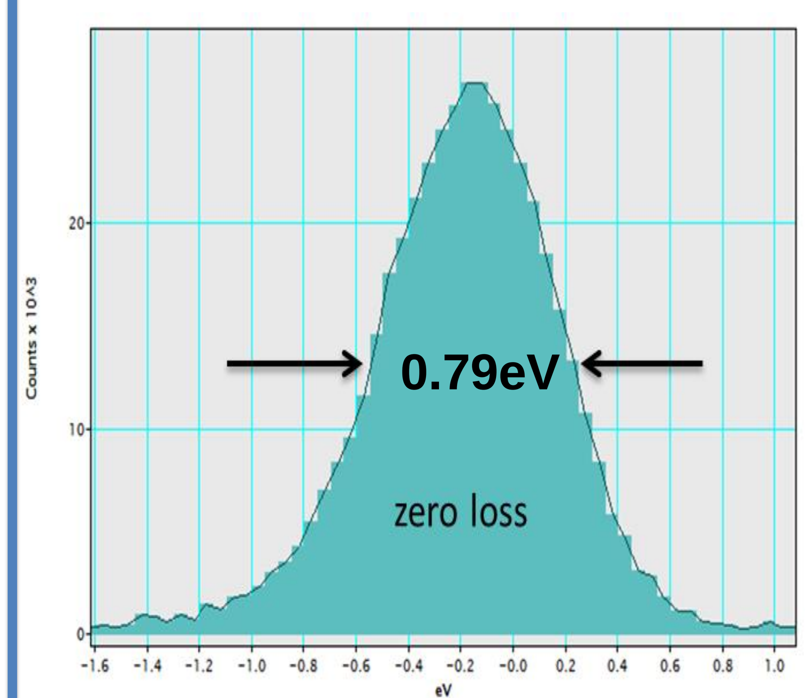
Laser repetition rate: 2 MHz
UV output power: 15 mW



Lattice image
resolution ~ 0.23nm

EELS resolution in photoelectron mode

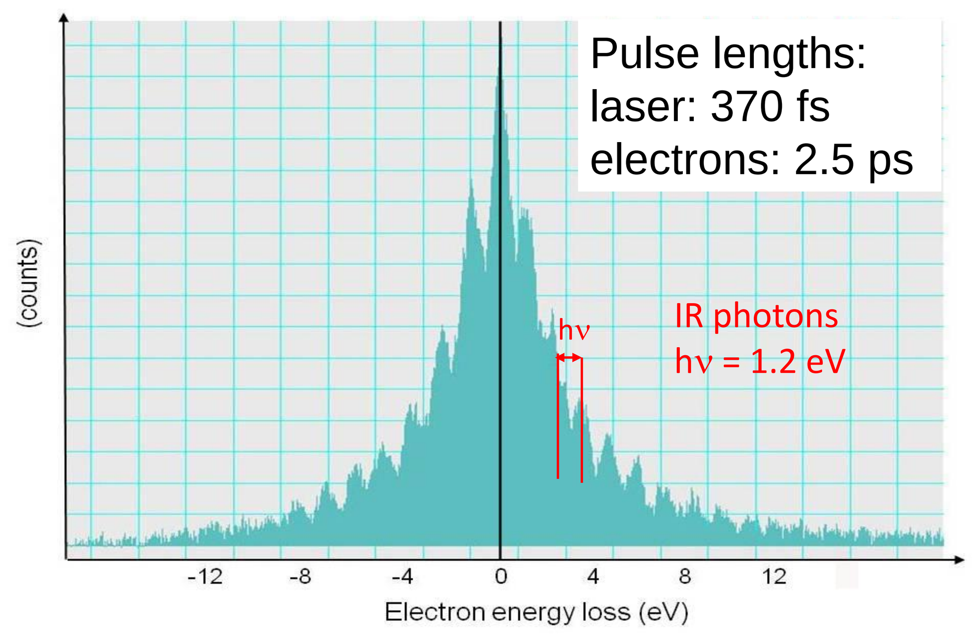
Laser repetition rate: 2 MHz
UV output power: 1 mW



Spread of zero loss
resolution ~ 0.79 eV

PINEM spectrum

Laser repetition rate: 500 kHz
UV output power: 8 µW



Photon-induced near-field electron microscopy
energy gain/loss by interaction with photon field

Conclusion

The world first commercial Ultrafast Dynamical Transmission Electron Microscope has been developed by JEOL (Europe) and IDES for the IPCMS laboratory in Strasbourg. The equipment and first tests are presented in this poster operating in stroboscopic mode. The thermionic and photoelectron mode results show comparable image resolution (0.23nm), while the energy resolution for EELS is much improved in the photoelectron mode. Using the novel capabilities of the UDTEM in stroboscopic mode, imaging at the nanoscale and Electron Energy Loss Spectroscopy (EELS) experiments can be linked to temporal resolution for the study of time resolved phenomena. These first results show the excellent integration and very high stability of the UDTEM systems.

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