Building An Ultrafast Photon-Induced Near-field Transmission Electron Microscope

Dr. Tom T.A. Lummen École Polytechnique Fédérale de Lausanne -- LUMES

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Collaborative Team

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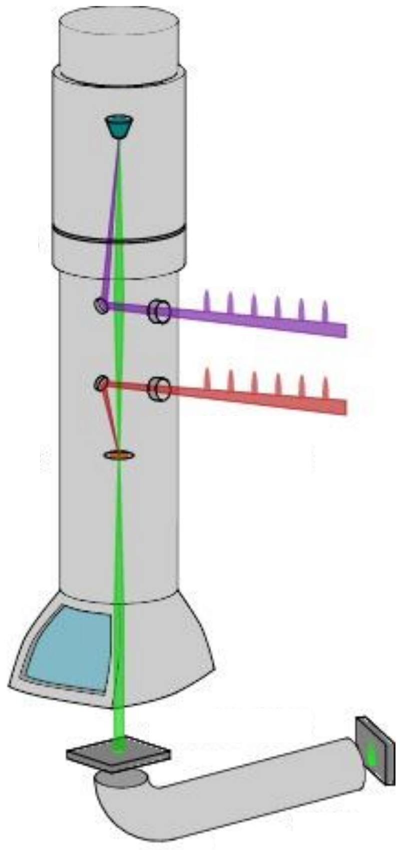
IDES INTEGRATED DYNAMIC ELECTRON SOLUTIONS

Dr. Dan Masiel

Outline

- Introduction & Motivation
  - ✓ Near-field imaging: Why & How?
- Concept
  - Photon-Induced Near-field Electron Microscopy (PINEM)
- Approach and Instrumentation
  - ✓ System choice and customization
  - ✓ Setup characteristics and specifications
- Results
  - ✓ PINEM on simple systems
  - ✓ Modeling of the evanescent field
- Outlook & Perspectives
  - ✓ *in-situ* PINEM
  - ✓ Take-home messages



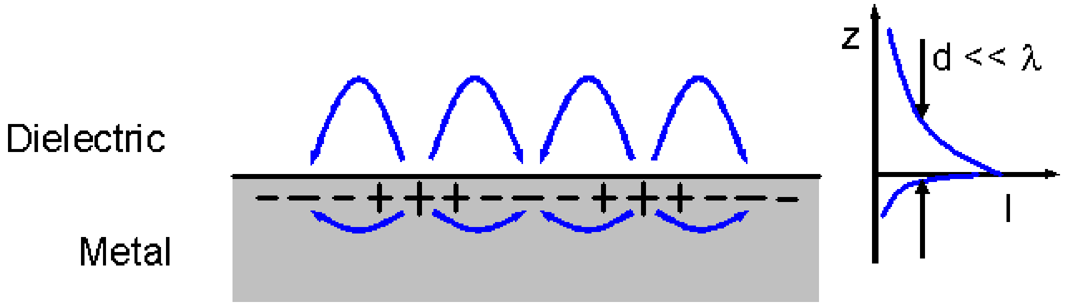
Introduction & Motivation

Integrated photonic and plasmonic circuitry:

- combine electronics and photonics
- advanced miniaturization and superior performance

The relevant scale demands the use of sub-wavelength confined light:

- Evanescent optical fields
- Surface plasmon polaritons
- No coupling to the far-field



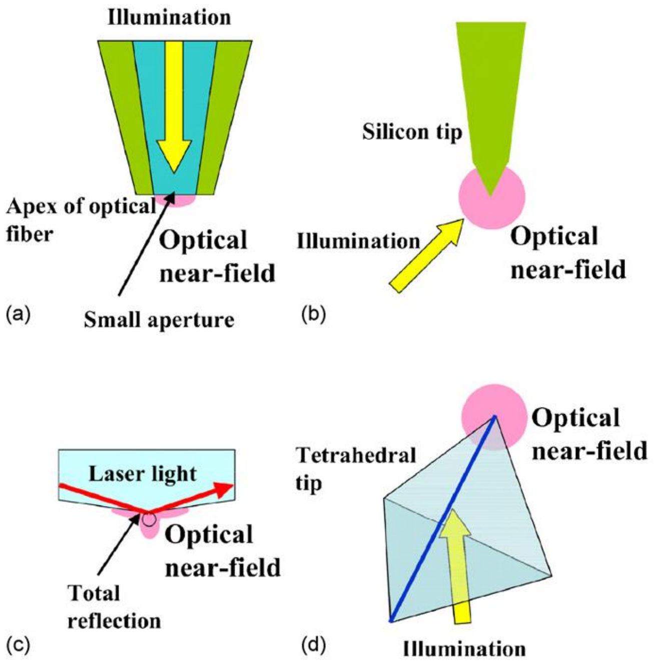
<u>Near-field Imaging is required</u>

Introduction & Motivation

Scanning Near-field Optical Microscopy (SNOM/NSOM)

D.W. Pohl *et al.*, *Applied Physics Letters* **44**, 651 (1984)

- Scanning probe microscopy
- Probe proximity to sample >> λ
- Different probe types



Y. Oshikane *et al.*, *Sci. and Technol. Adv. Mat.* **8**, 181 (2007)

Limitations

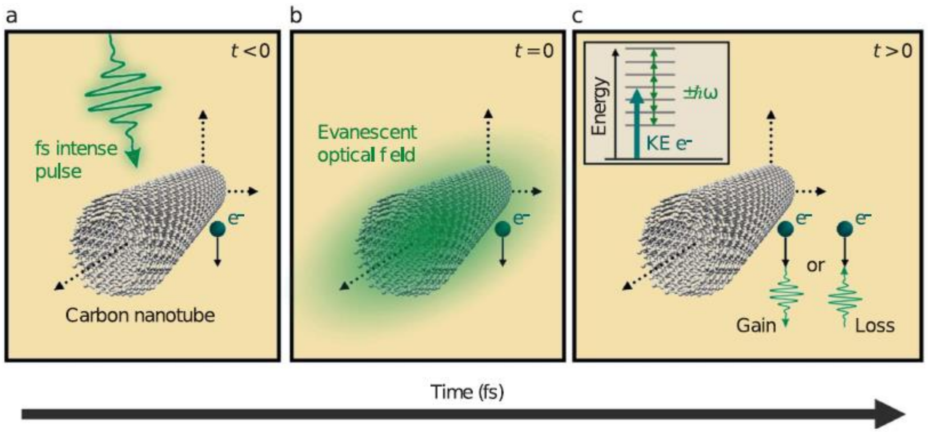
- spatial resolution (~20 nm)
- point-by-point probing
- long acquisition times
- time-resolution

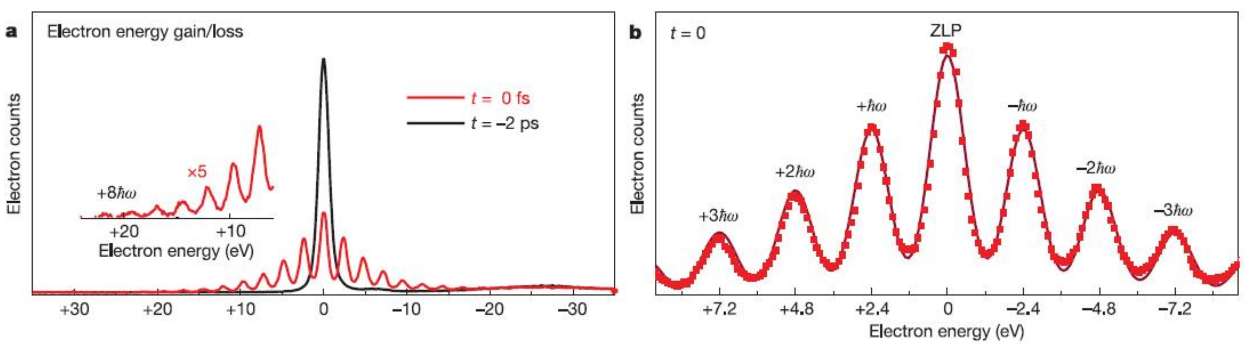
How to overcome these limitations?

Concept

Use electrons instead of photons to probe

- **Photon-Induced Near-field Electron Microscopy (PINEM)**





B. Barwick *et al.*, *Nature* **462**, 902 (2009)

Pump-probe TEM technique:

- fs optical pump
- fs electron probe

Energy exchange:

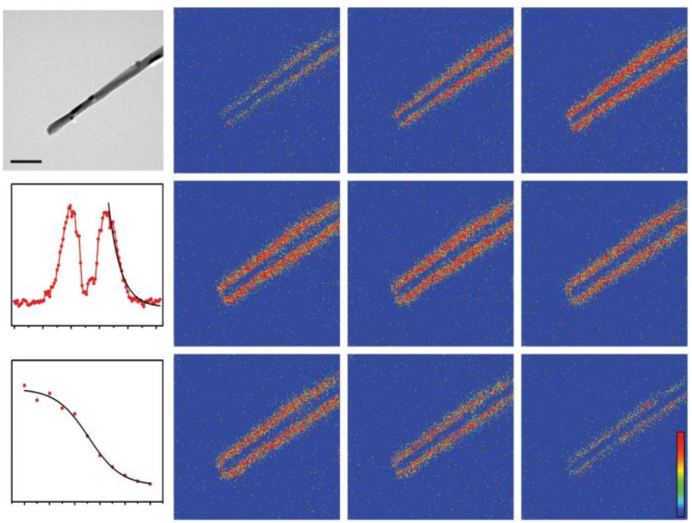
- electrons gain/lose photon energy quanta
- structure-mediated

Concept

Energy-filtering of electrons allows for direct visualization of the near-field

- Image using only inelastically scattered electrons

Carbon nanotubes



B. Barwick *et al.*, *Nature* **462**, 902 (2009)

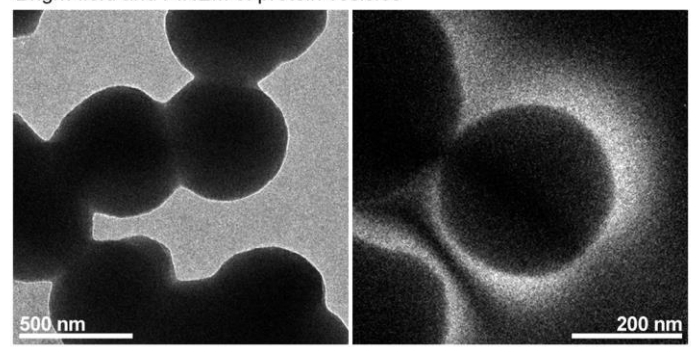
field-of-view technique

sub-nm spatial resolution

ultrafast time-resolution

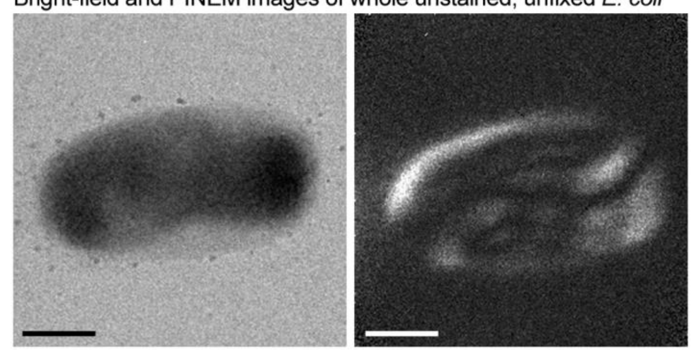
Protein Vesicles

Bright-field and PINEM of protein vesicles



E. Coli

Bright-field and PINEM images of whole unstained, unfixed *E. coli*



D. Flannigan *et al.*, *PNAS* **107**, 9933 (2010)

Approach & Instrumentation

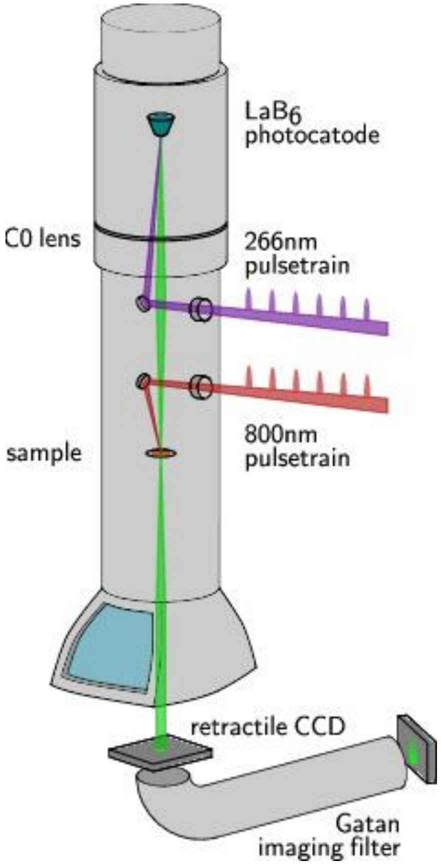
Until very recently, only one working ultrafast electron microscope in the world:

- **UEM system in laboratory of Prof. Ahmed Zewail (California Institute of Technology)**

EPFL – LUMES:
Build first working ultrafast electron microscope in Europe

Implementation: modified Transmission Electron Microscope

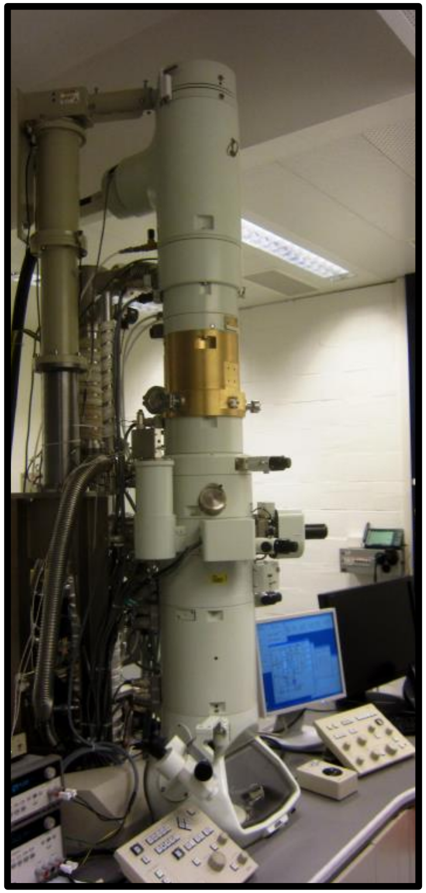
- **Optical port for specimen excitation (LLNL/IDES customization)**
- **Optical port for photo-electron generation (LLNL/IDES customization)**
- **Electron Energy Loss Spectrometer with energy filter for PINEM (GATAN Quantum GIF electron energy loss spectrometer)**

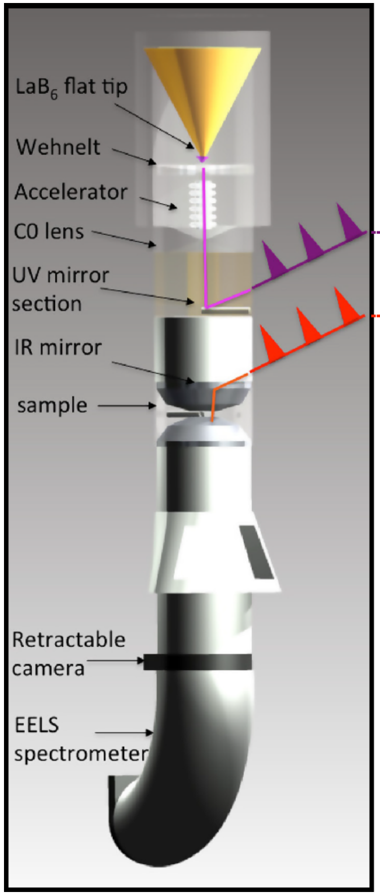


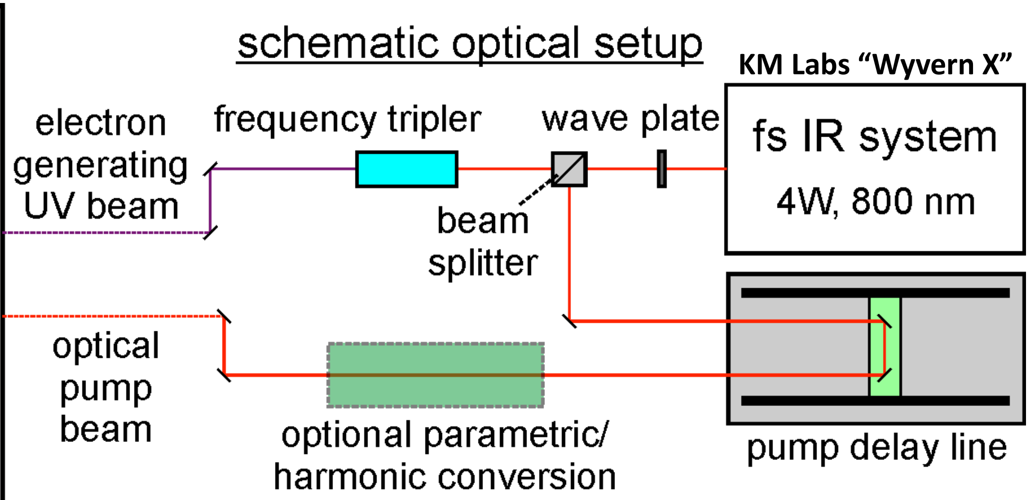
Approach & Instrumentation

- **Modified 200 keV Jeol JEM-2100**

- **Amplified Ti:sapphire laser system**







Additional elements:

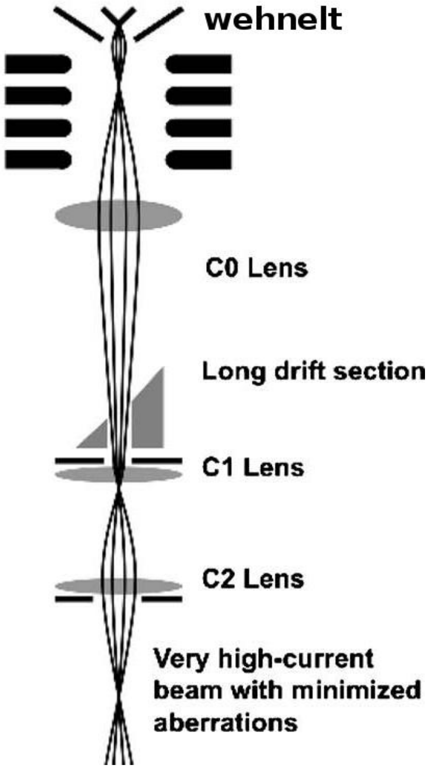
- **Wehnelt electrode**
- **"C0" extra electrostatic lens**

L. Piazza *et al.*, *Chemical Physics* **423**, 79 (2013)

Approach & Instrumentation

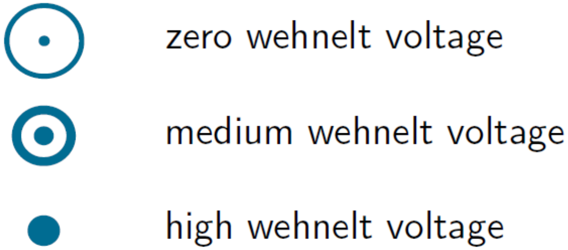
Optimal conditions for time-resolved experiments:

- (1) emit only few electrons from the tip
- (2) couple all of them down the column



(1) Wehnelt electrode:

- convergent electrostatic lens with static bias
- Used to tune electron emission from source



(2) C0 lens:

- Extra convergent magnetic lens (refurbished C1 lens)
- Couples majority of emitted electrons to imaging system
- Greatly improves brightness

Lawrence Livermore National Laboratory

IDES INTEGRATED DYNAMIC ELECTRON SOLUTIONS

Approach & Instrumentation

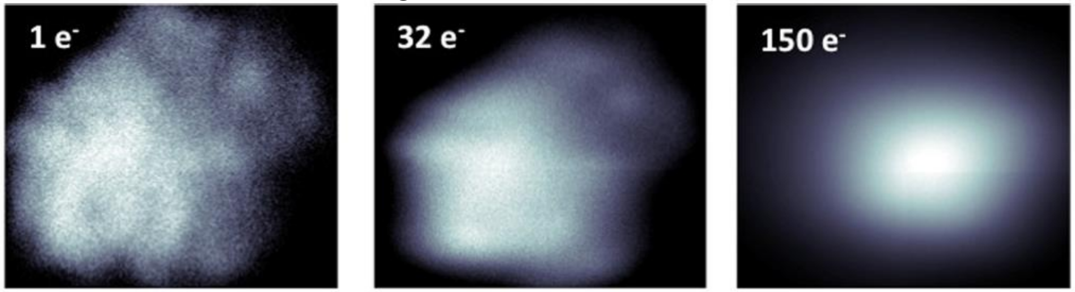
Depending on dynamic experiment:

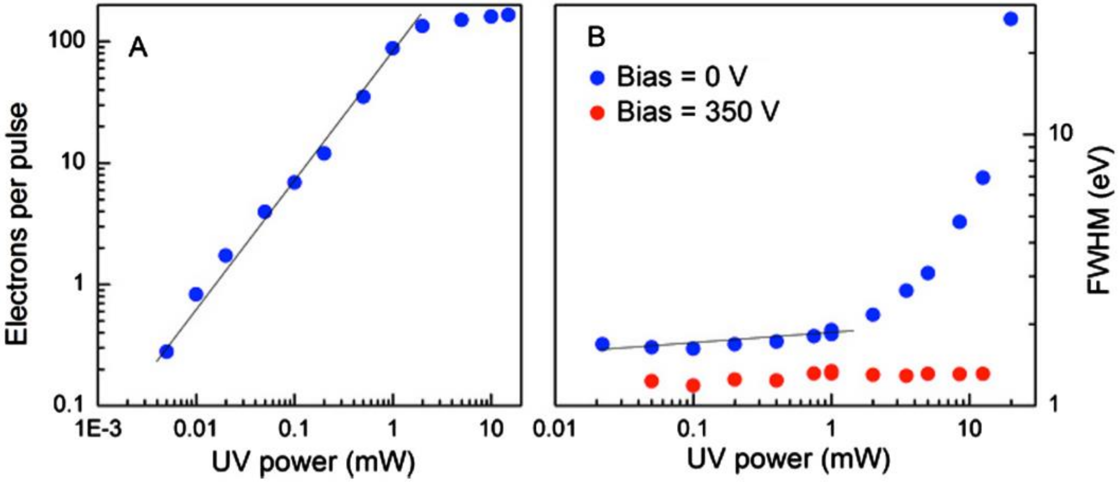
Quantities to optimize:
- Electron beam coherence (spatial resolution)
- Electron energy spread (energy resolution)
- Electron pulse duration (time resolution)
- Electron counts

Parameters to tune (trade-offs):
- Wehnelt bias
- Laser pulse duration
- UV fluence
- Integration time

Crucial control over
space charge effects

Images of the source





L. Piazza *et al.*, *Chemical Physics* **423**, 79 (2013)

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Crucial control over
space charge effects

Typically, the system can achieve:

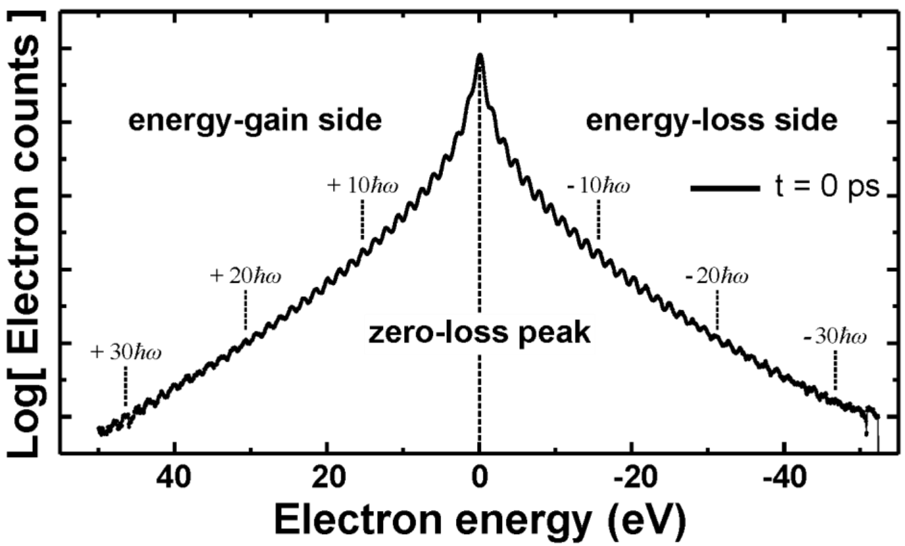
- Spatial resolution ≈ 1 nm
- Energy resolution ≈ 1 eV
- Time resolution ≈ 400 fs

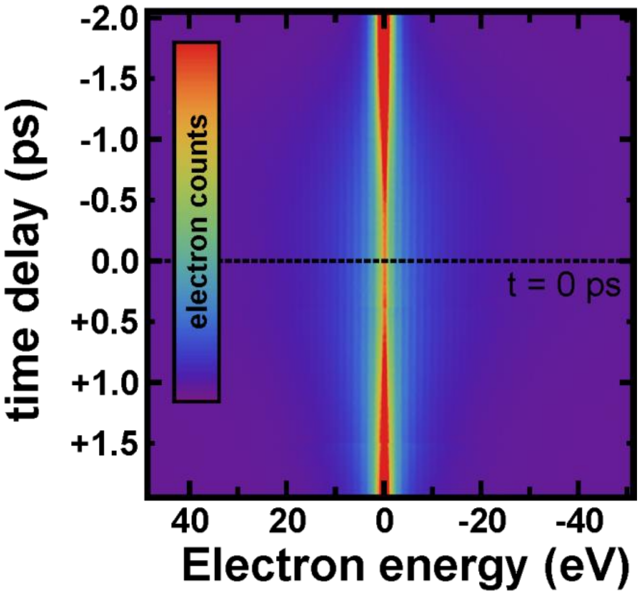
L. Piazza *et al.*, *Chemical Physics* **423**, 79 (2013)

Results

Time-resolved Electron Energy Loss Spectroscopy (EELS)

- Silver nanowires (≈100 nm diameter, ≈5 µm length)





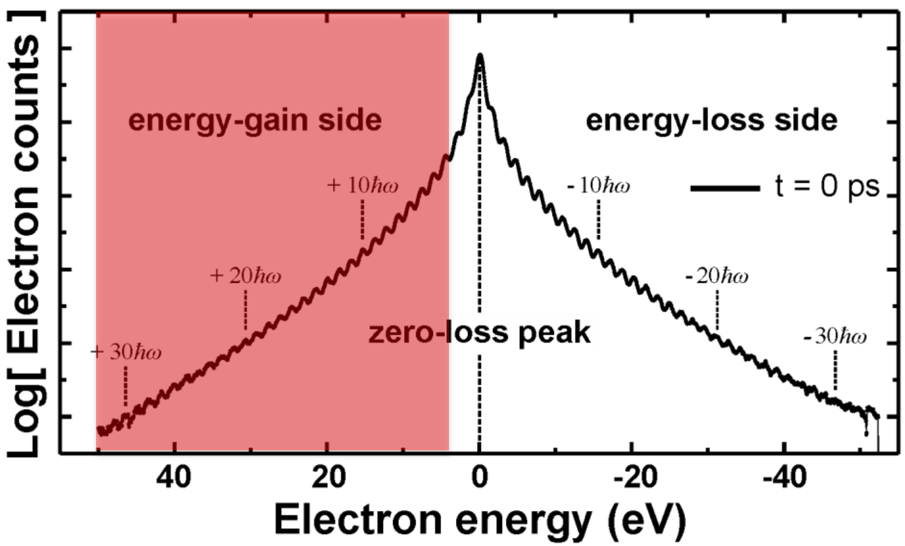
Energy exchange of over 30 photon quanta

Time-scan shows cross-correlation of electron and photon pulses

Results

Photon-Induced Near-field Electron Microscopy

- **Silver nanowires (≈100 nm diameter, ≈5 μm length)**



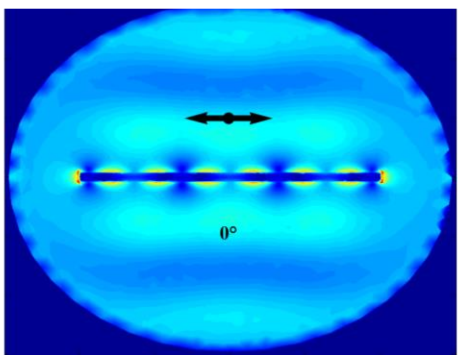
Energy filtered imaging

Silver wire, hanging off a TEM grid

Results

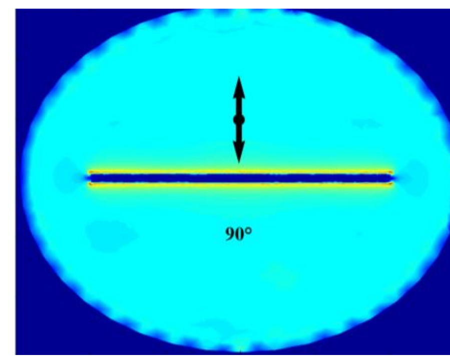
Polarization dependence of excitation pulse

Experimental data
Silver wire, suspended on a thin SiN film



Numerical Simulation
Silver wire, suspended in air

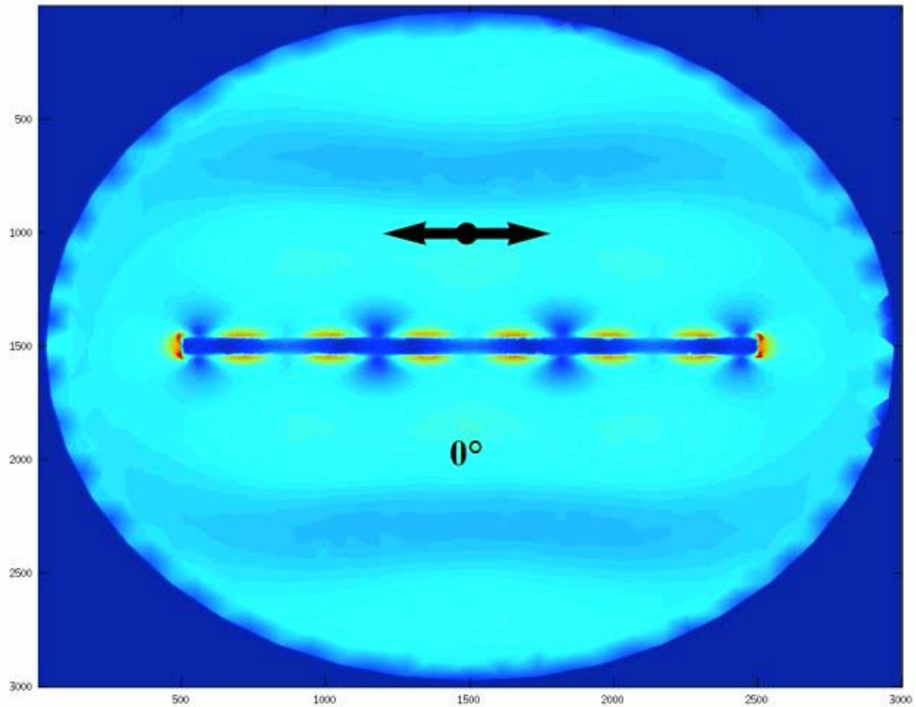
COMSOL Multiphysics® simulation



Excellent match between experiment and simulation

Results

Polarization dependence: numerical simulation



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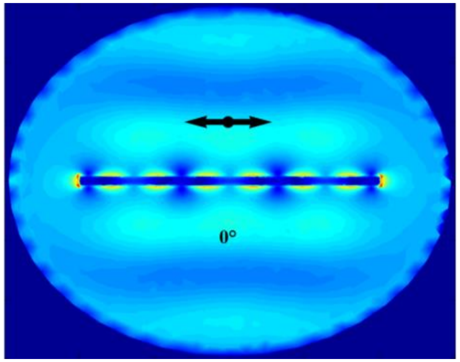
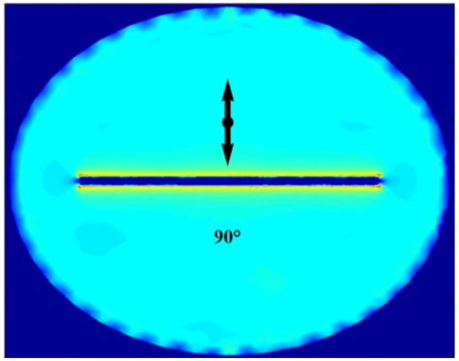




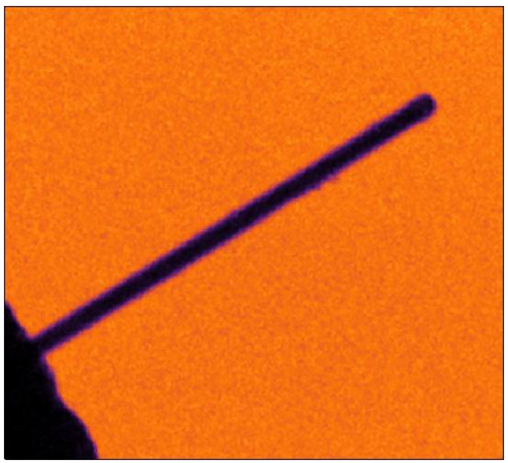
Continuous evolution of evanescent field with polarization

Results

PINEM: near-field interactions

Silver wire, hanging off a TEM grid

Conventional TEM Image



Corresponding PINEM Image

Zoomed-out PINEM Image

Interaction between nanowires influences the induced evanescent field

Outlook

PINEM: time-resolution

Conventional PINEM:

- Essentially a cross-correlation of the electron and optical pulses

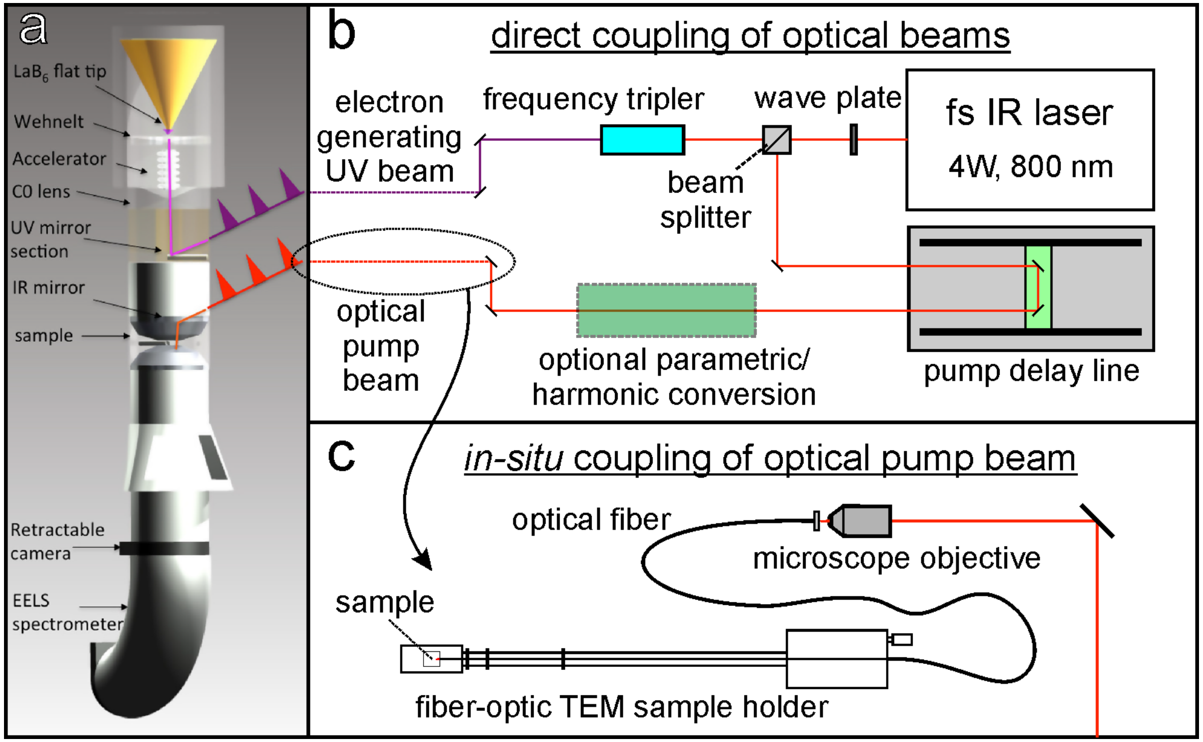
  - Pump pulse spot size >> imaged area → uniform excitation

Outlook

PINEM: time-resolution

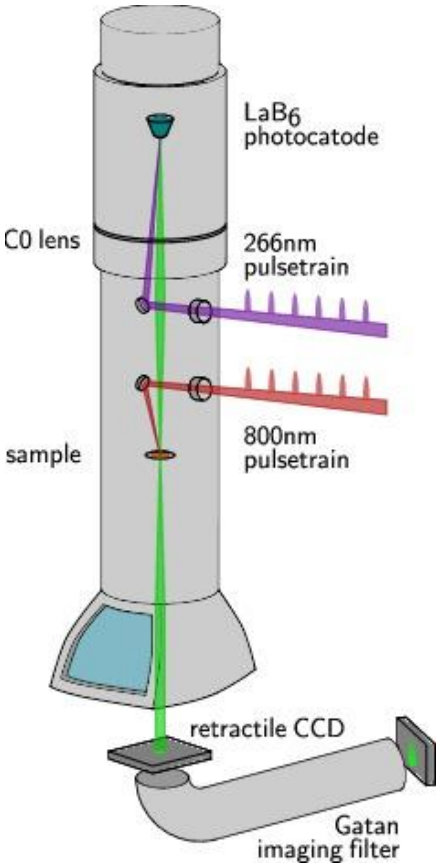
In-situ PINEM:

- *In-situ* coupling of optical pump beam
  - Focused spot size << imaged area → local excitation
- Time-resolved observation of traveling evanescent waves



Perspectives

- **First ultrafast electron microscope in Europe**
  (operational since early 2013)
- **Capable of time-resolved EELS and PINEM**
  (in addition TEM, diffraction and Lorentz TEM)
- **400 fs time resolution**
- **1 eV energy resolution**
- **Sub-nm spatial resolution**
- ***In-situ* PINEM in development**
- **Open to collaborations (science, samples, devices)**



Thank you!

Contact:

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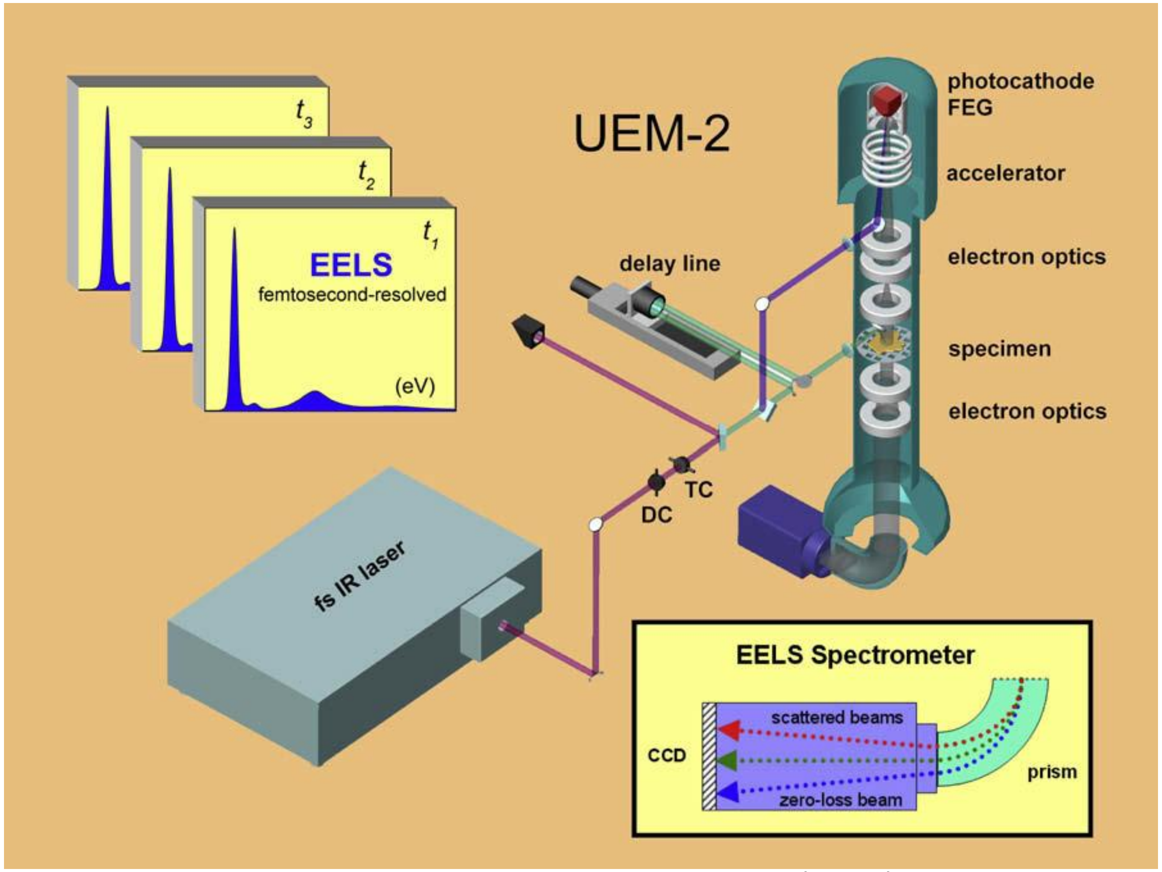
Approach & Instrumentation

- **Caltech UEM-2 system**

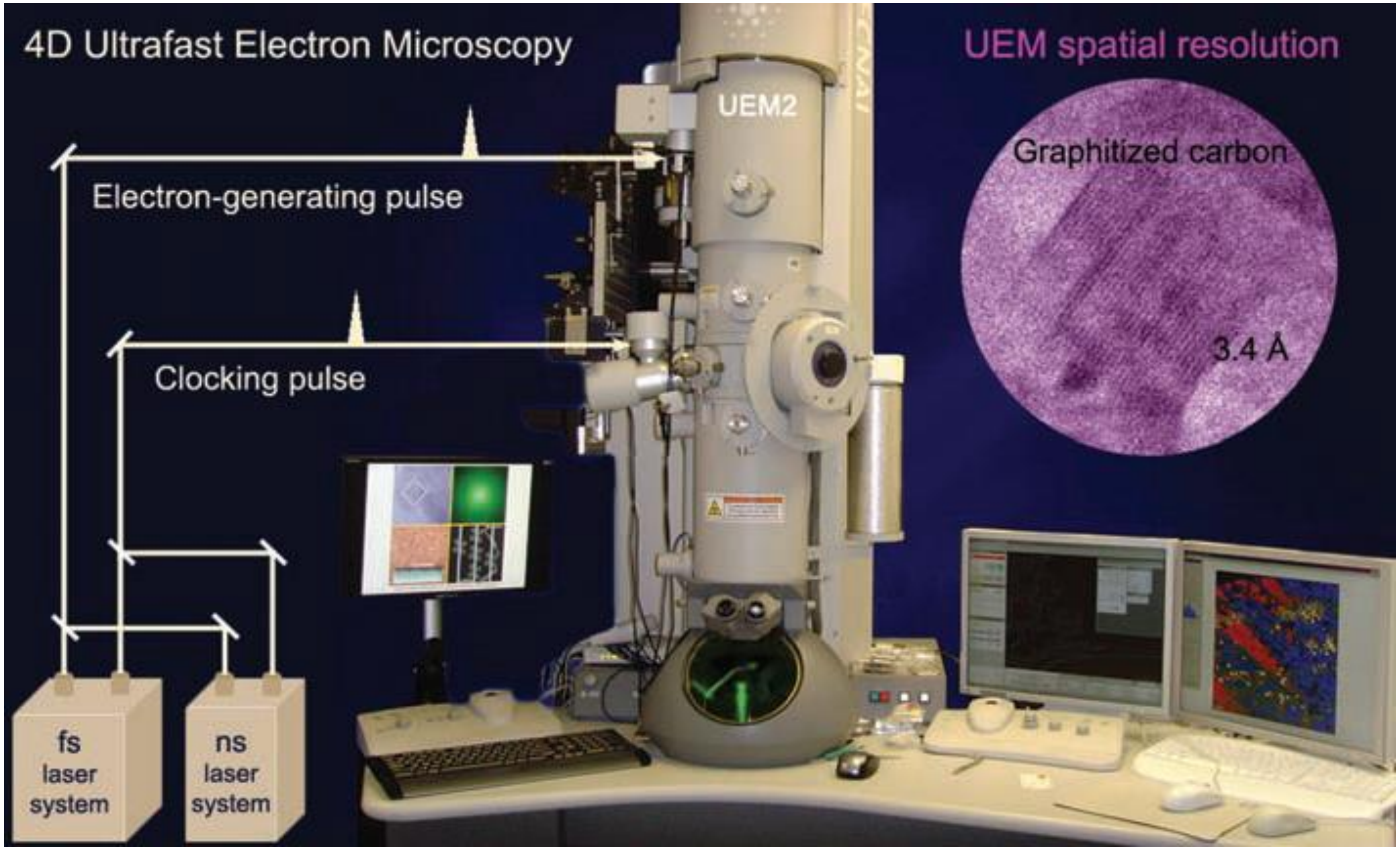
Ultrafast Electron Energy Loss Spectroscopy



F. Carbone *et al.*, *Chemical Physics Letters* **468**, 107 (2009)

Approach & Instrumentation

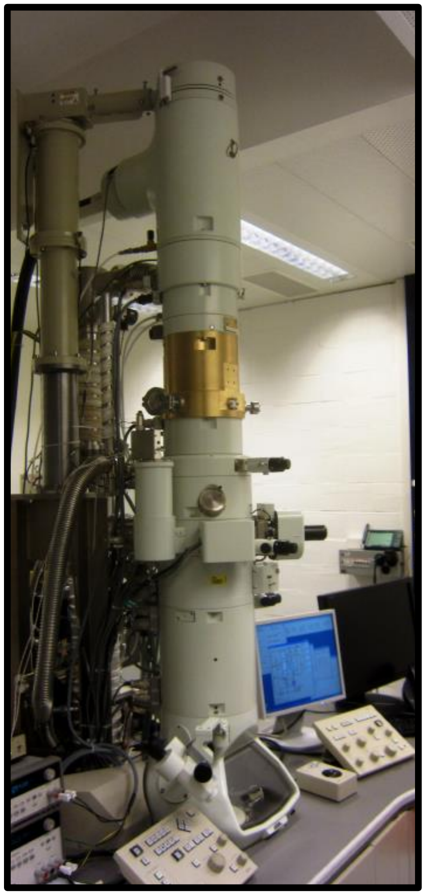
- **Caltech UEM-2 system**



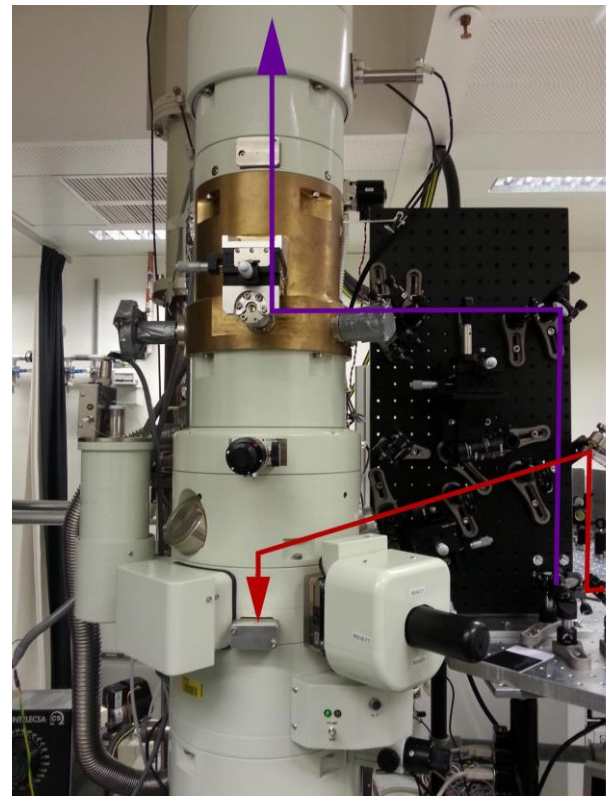
B. Barwick *et al.*, *Science* **332**, 1227 (2008)

Approach & Instrumentation

- **Modified Jeol JEM-2100**



Optical Coupling



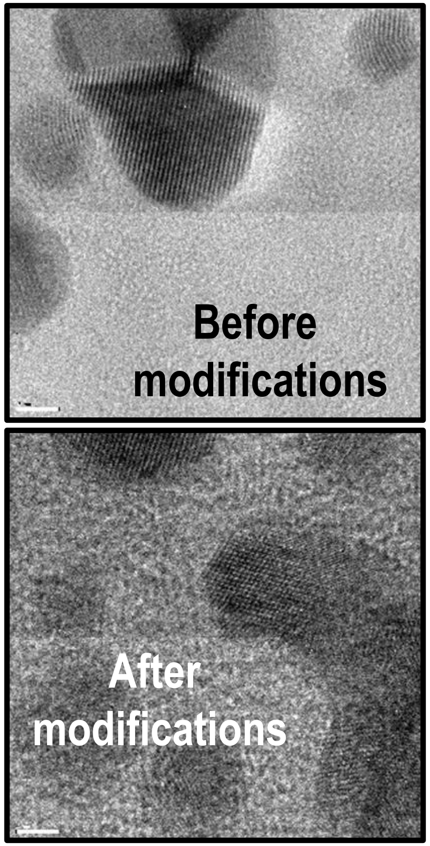
L. Piazza *et al.*, *Chemical Physics* **423**, 79 (2013)

Approach & Instrumentation

- Effect on static TEM

L. Piazza *et al.*, *Chemical Physics* **423**, 79 (2013)

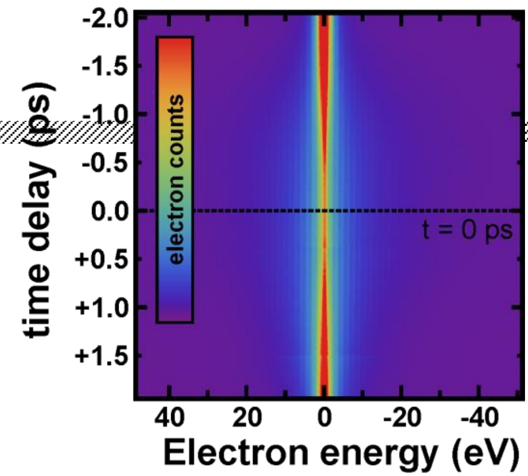
Spatial Resolution



Gold nanoparticles

- Slight blurring at image edge
- Lattice fringes observed
- Reasonable atomic resolution even after modifications

Approach & Instrumentation



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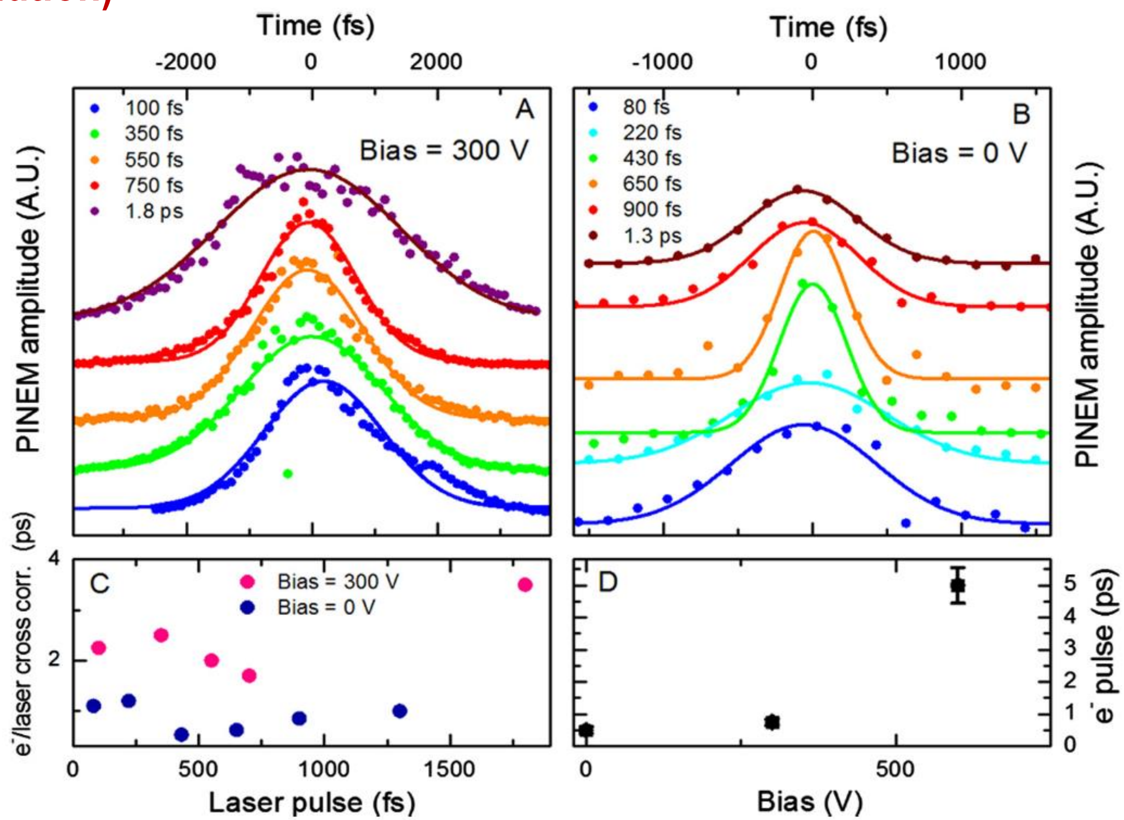
Crucial control over
space charge effects



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Results

Polarization dependence: numerical simulation

Numerical Simulation
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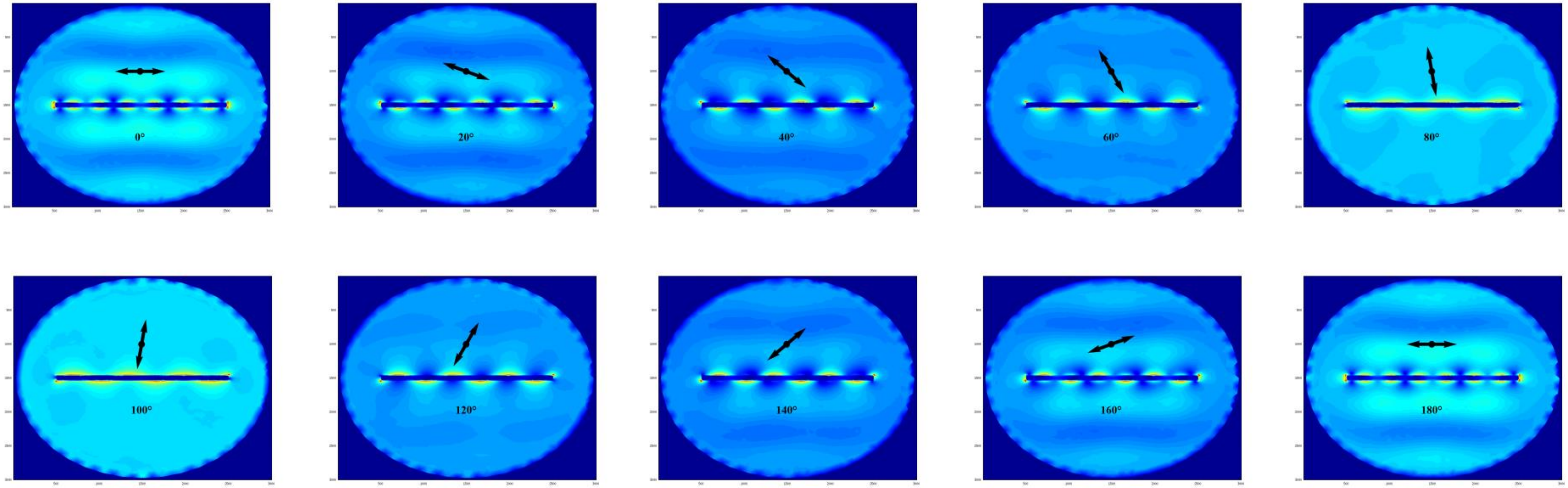

Continuous evolution of evanescent field with polarization