Time-Resolved (Ultrafast) Electron Microscopy

Thomas LaGrange, Ph.D.
Faculty Lecturer and Senior
Research Scientist

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thomas.lagrange@epfl.ch • www.epfl.ch• lumes.epfl.ch• +41 (0)21 6935861

Laboratory for Ultrafast Microscopy and Electron Scattering (LUMES)

Fabrizio Carbone

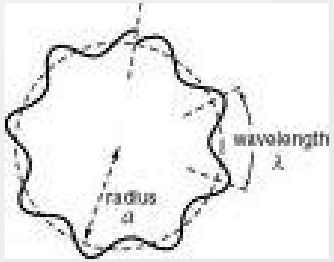
Funding sources

Outline

- Background
  - Transmission electron microscopy (TEM)
  - Motivation behing improving the temporal resolution of in-situ TEM
  - Brief history of the development of the Ultrafast TEM (UTEM)
- UTEM Technique
  - fs-Stroboscopic pump-probe approach
  - Space charge effects
  - Practical consideration when doing UTEM experiments
- UTEM experimental examples
  - Definitions of spatial and temporal coherence (coherent control)
  - Charge density waves, Phonons and Skyrmions
  - Light-electron interactions

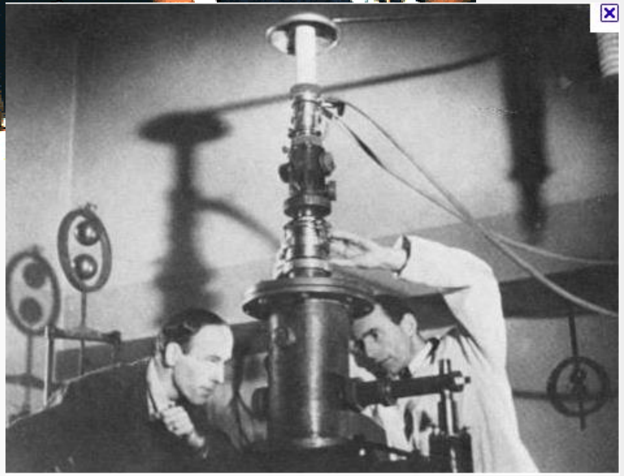
Electron wave-particle duality and the birth of the electron microscope

L. de Broglie (1923) postulates that $p=h/\lambda$ is valid for all particles λ wavelength of electrons (Nobel prize 1929)

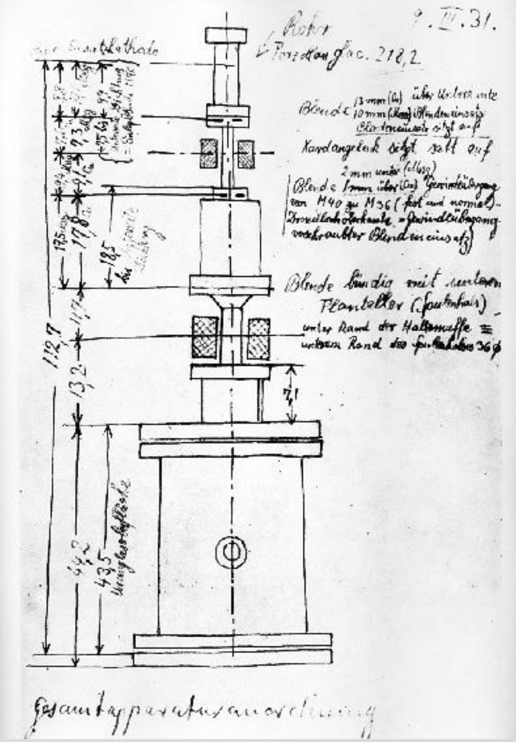


1986: E. Ruska Nobel Prize

E. Ruska: 1931



The resolution limit of the light microscope due to the length of the light wave which had been recognized 50 years before by Ernst Abbe and others could, because of lack of light, not be important at such magnifications. Knoll and I simply hoped for extremely low dimensions of the electrons. As engineers we did not know yet the thesis of the “material wave” of the French physicist de Broglie that had been put forward several years earlier (1925). Even physicists only reluctantly accepted this new thesis. When I first heard of it in summer 1931, I was very much disappointed that now even at the electron microscope the resolution should be limited again by a wavelength (of the "Materiestrahlung"). I was immediately heartened, though, when with the aid of the de Broglie equation I became satisfied that these waves must be around five orders of magnitude shorter in length than light waves. Thus, there was no reason to abandon the aim of electron microscopy surpassing the resolution of light microscopy.



Why do we use *electrons* as a probe?
High energy = short wavelengths= high spatial resolution

Electromagnetic radiation: $E = hc/\lambda$ so if $\lambda < 5$ nm, $E > 1$ keV

Electron wavelength according to de Broglie equation: $\lambda = \hbar/p$

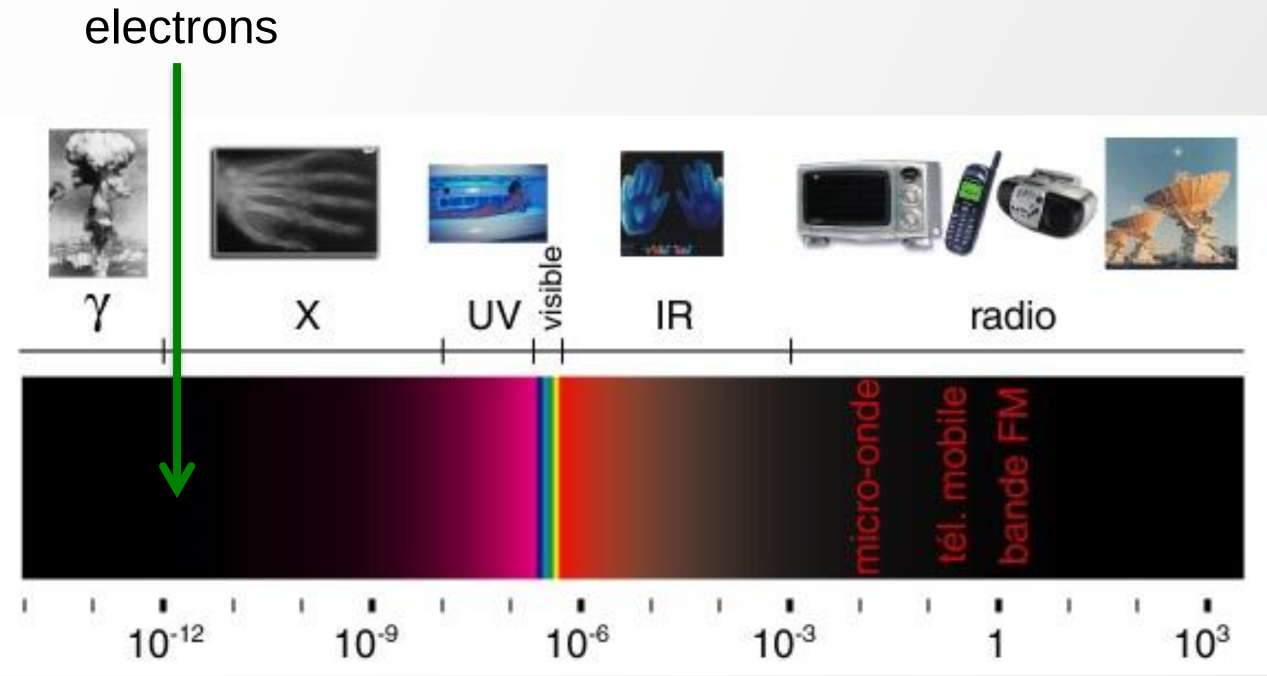
with $p = m_o v = (2 m_o e V)^{1/2}$

non relativistic (<50keV):

$$\lambda = \frac{h}{(2m_0 eV)^{1/2}}$$

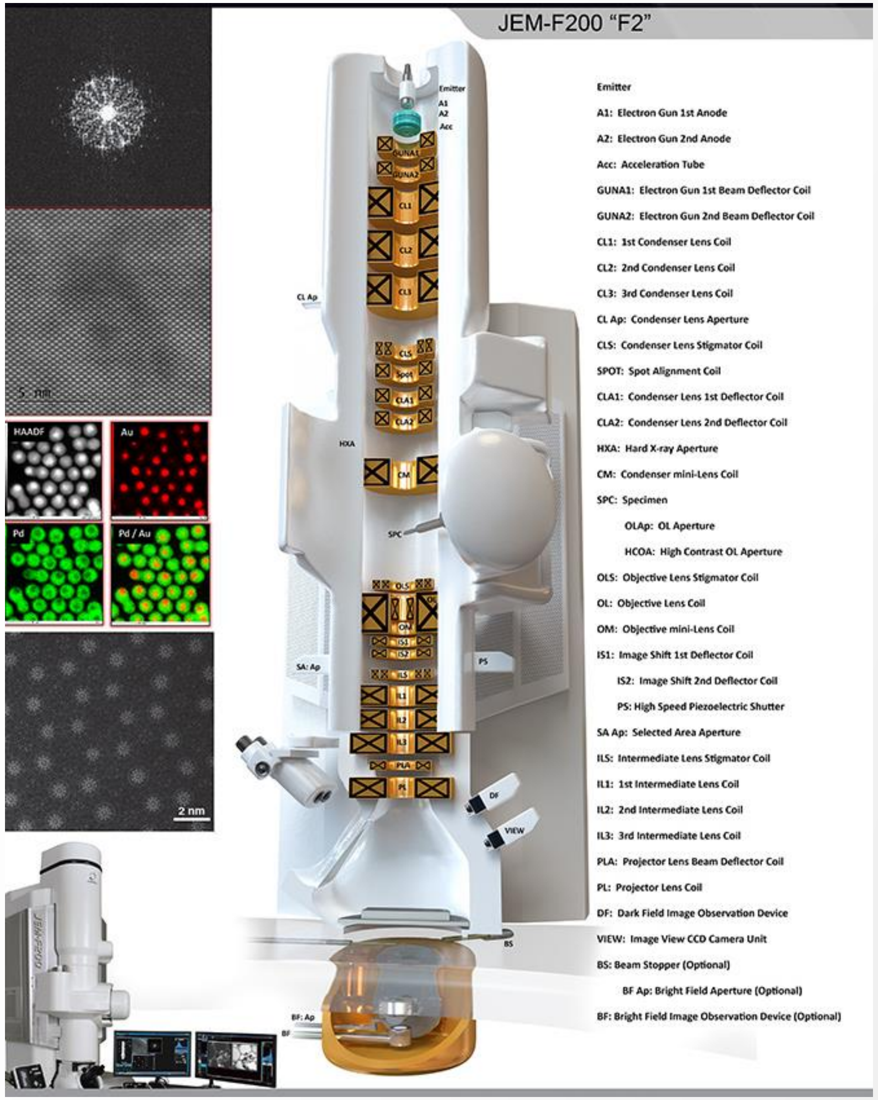
Relativistic correction (>50keV or >1% speed) :

$$\lambda = \frac{h}{\left[2m_0 eV\left(1+\frac{eV}{2m_0c^2}\right)\right]^{1/2}}$$



voltage [KV]	Nonrelativistic λ [pm]	Relativistic λ [pm]
1	38.79	0.03878
10	12.27	0.01221
80	4.34	0.00418
200	2.74	0.00251
300	0.00224	0.00197
1000	0.00123	0.00087

TEMs haves sets of electromagnetic and electrostatic lenses and deflector that allow to flexibly change between many different imaging modes

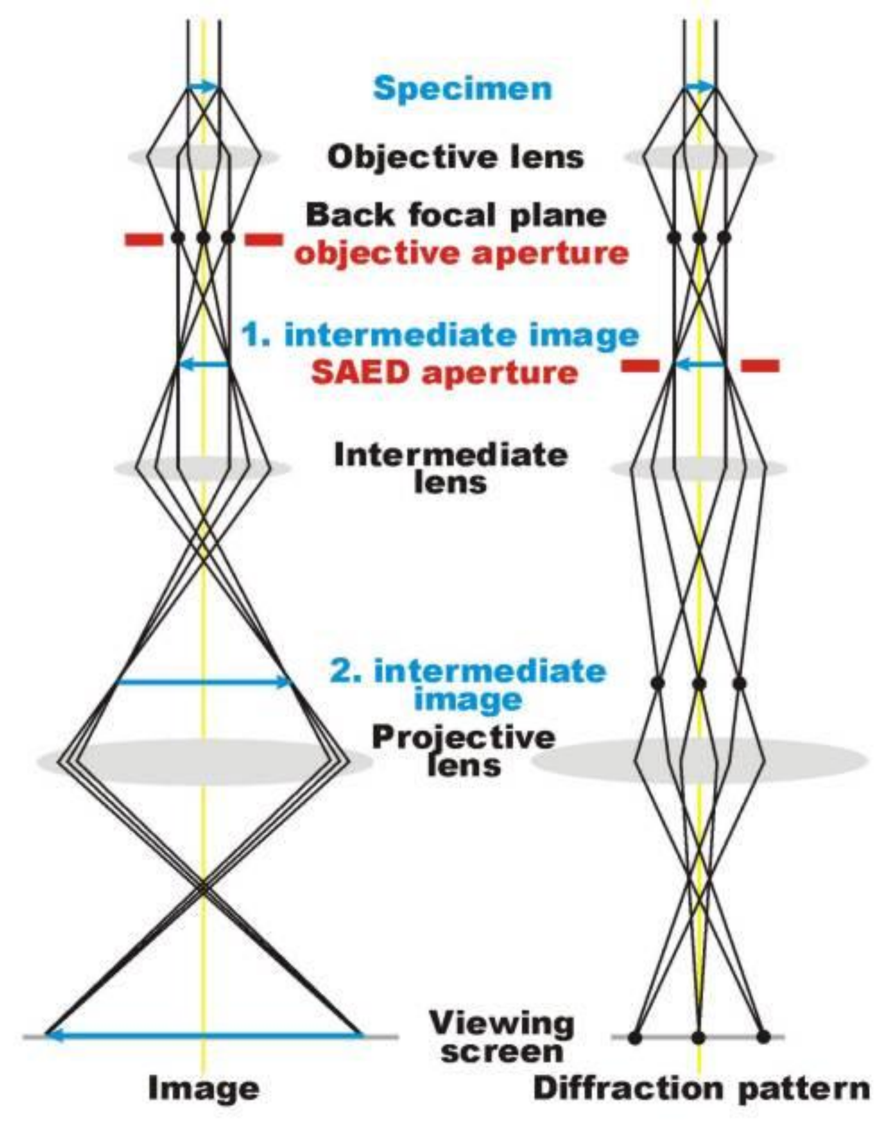


☐ Diffraction mode

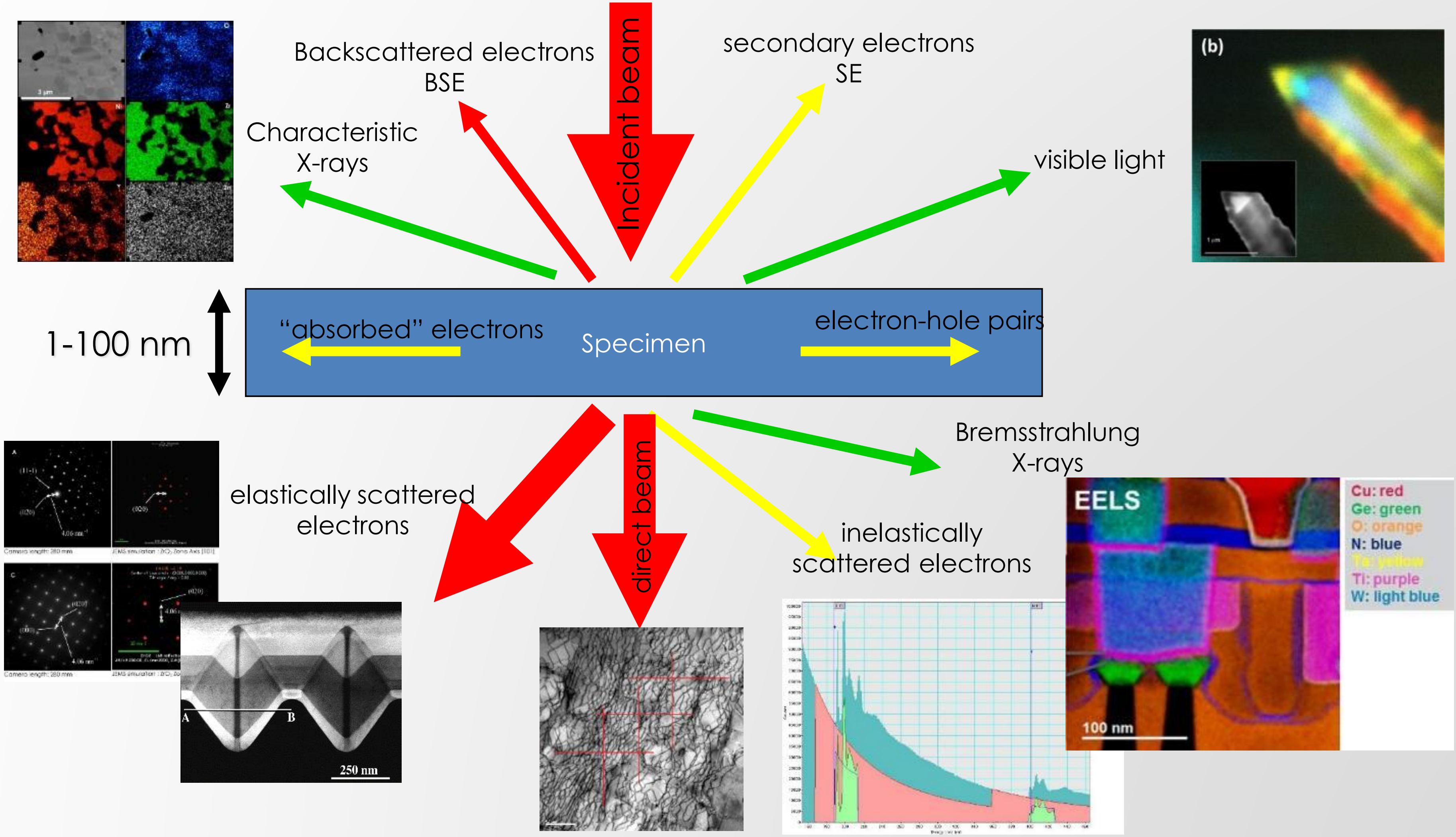
The intermediate and projector lens magnify and project the ***back focal plane (first diffraction pattern formed in the microscope)*** of the objective lens to the detector system

☐ Imaging mode

The intermediate and projector lens magnify and project ***the image plane*** of the objective lens to the detector system



Electron-matter interactions in a thin sample



Incident beam

Backscattered electrons
BSE

secondary electrons
SE

Characteristic
X-rays

visible light

1-100 nm

“absorbed” electrons

Specimen

electron-hole pairs

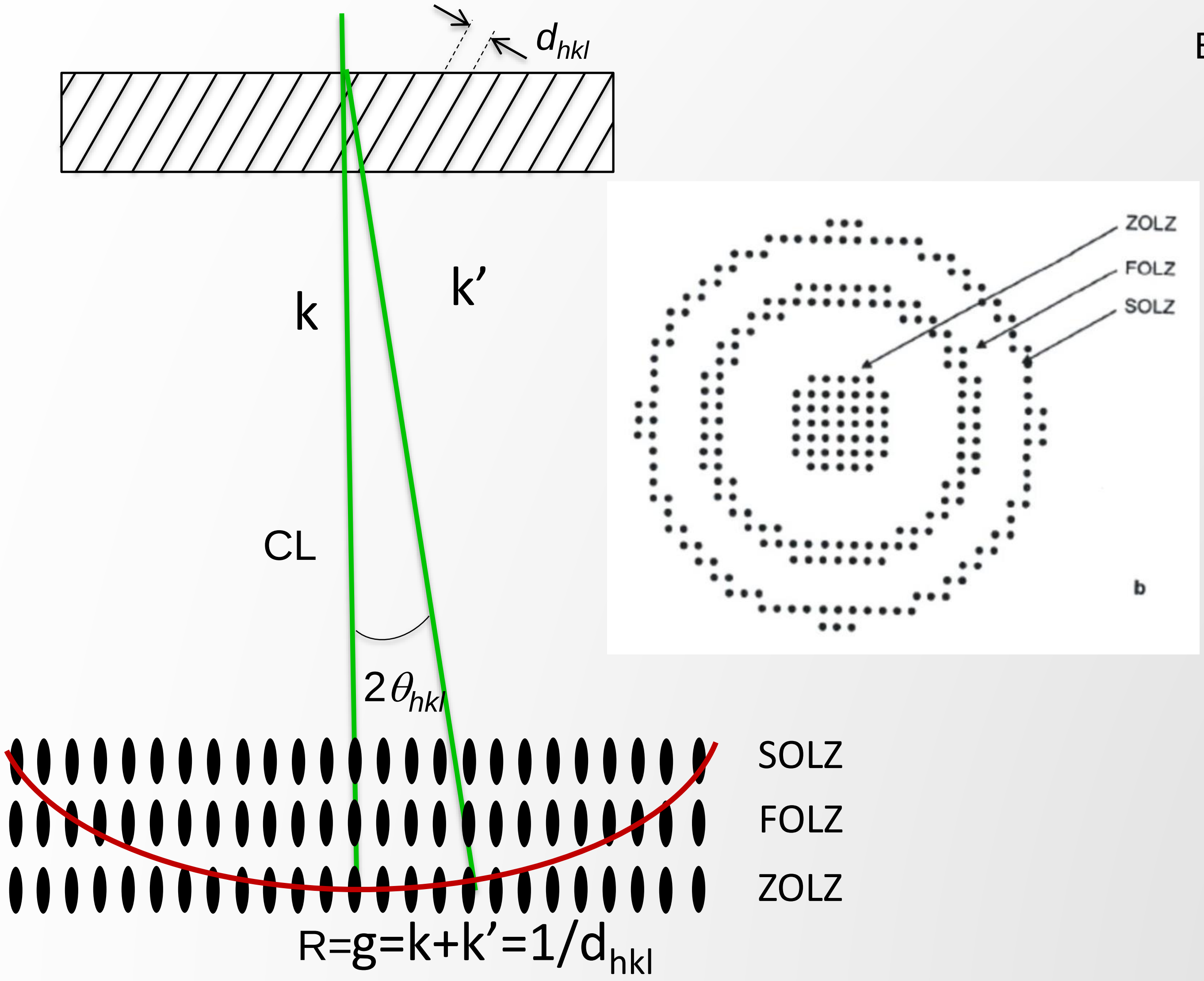
direct beam

elastically scattered
electrons

Bremsstrahlung
X-rays

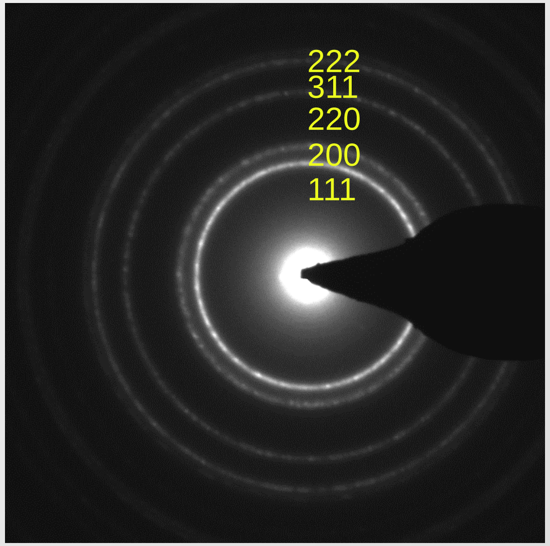
inelastically
scattered electrons

Transmission Electron Diffraction

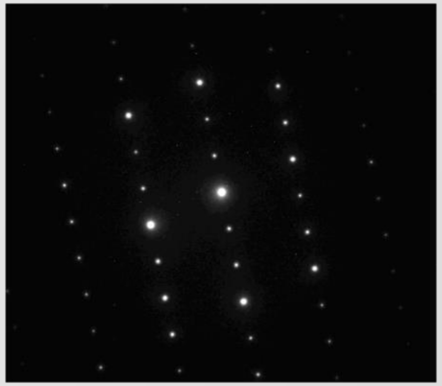


$$R=g=k+k'=1/d_{hkl}$$

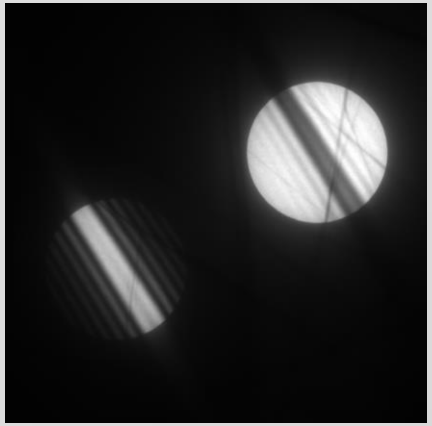
Bragg Diffraction Powder Pattern



Single Crystal Spot Pattern

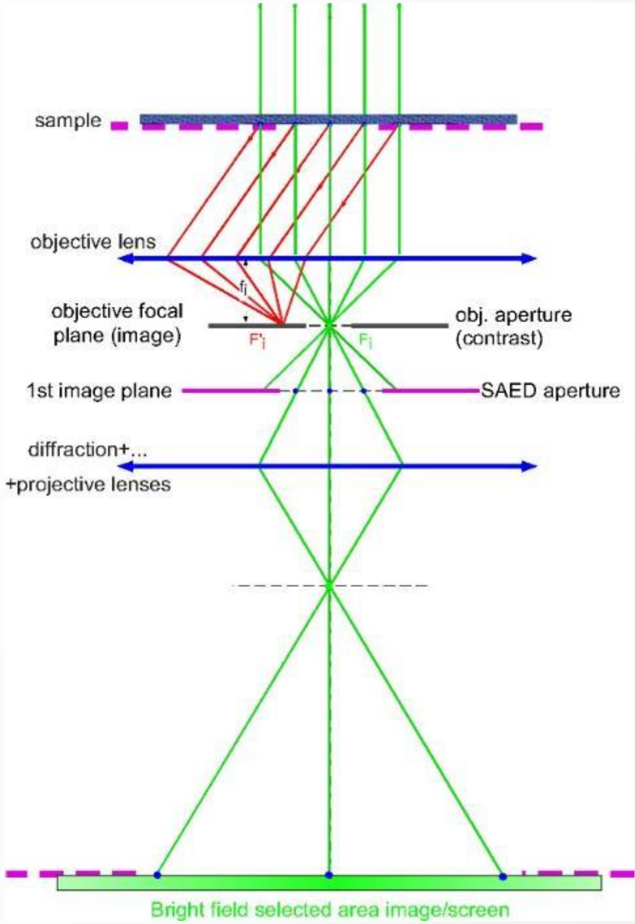


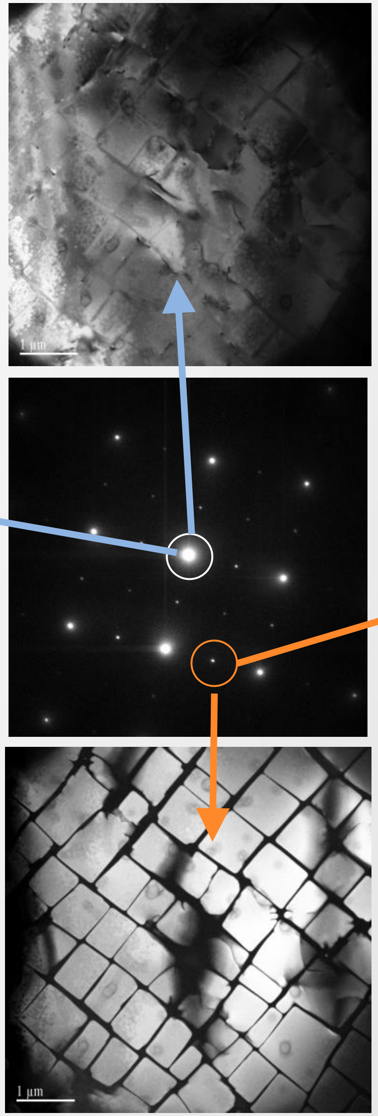
Convergent Beam Electron Diffraction



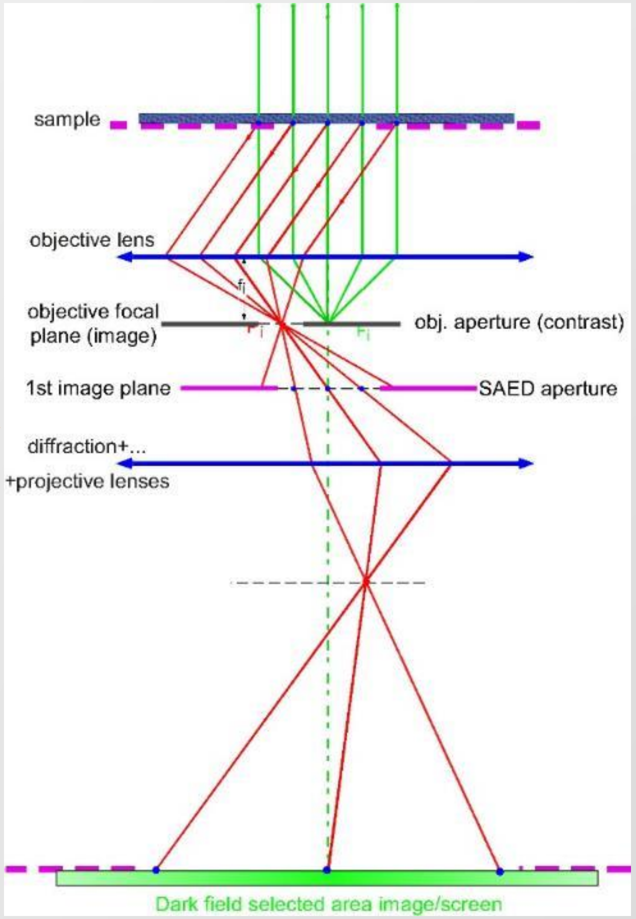
Imaging using Diffraction Contrast

Bright-field



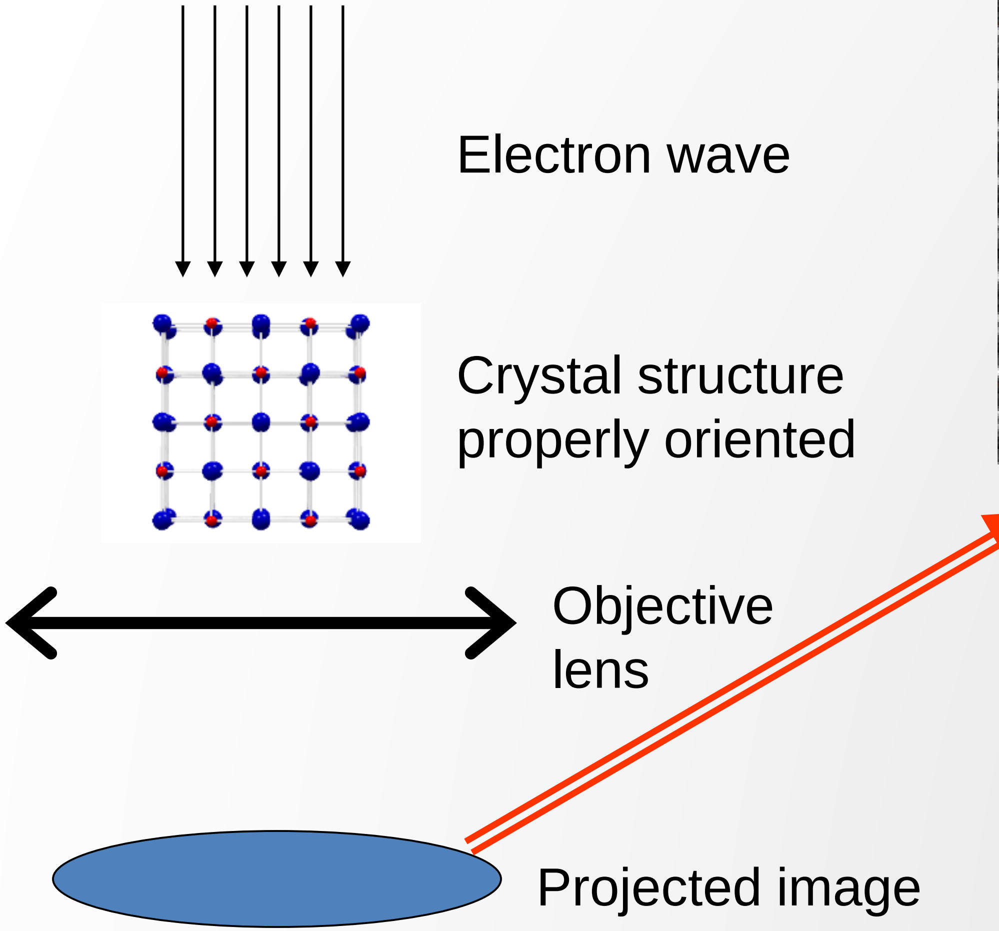


Dark-field



Phase Contrast Imaging: High Resolution Transmission Electron Microscopy (HRTEM)

Phase contrast for crystalline specimen



Parallel beam

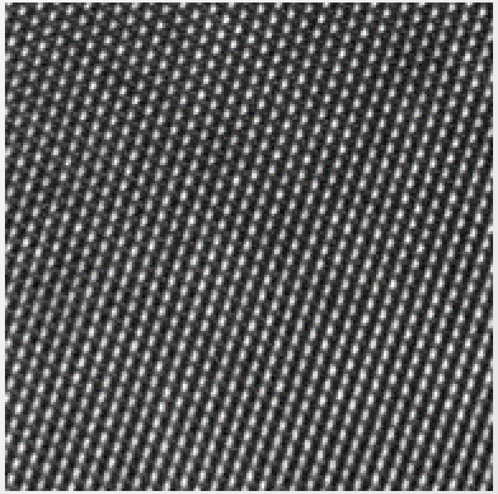
Electron wave

Crystal structure properly oriented

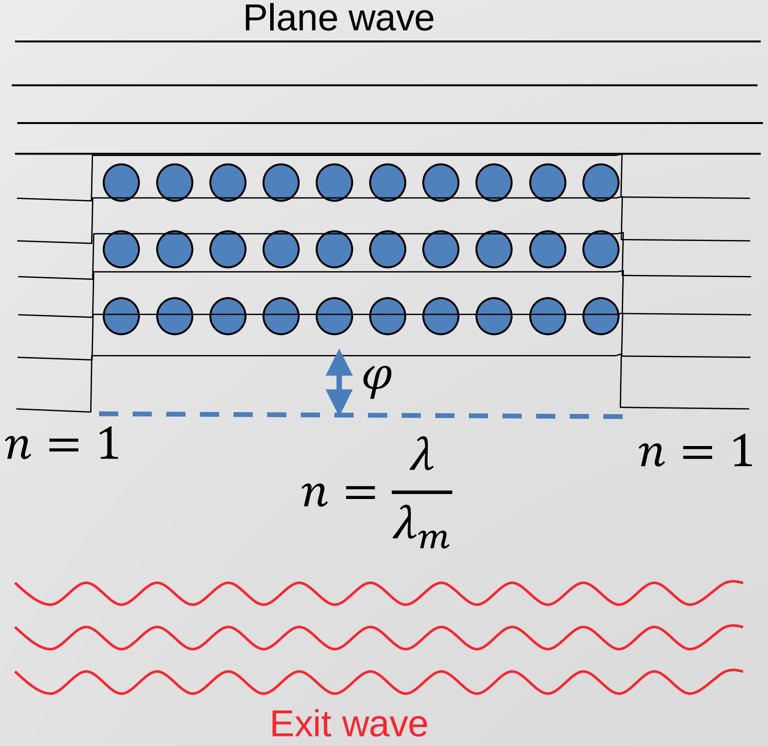
Objective lens

Projected image

Atomic resolved HRTEM image of Silicon



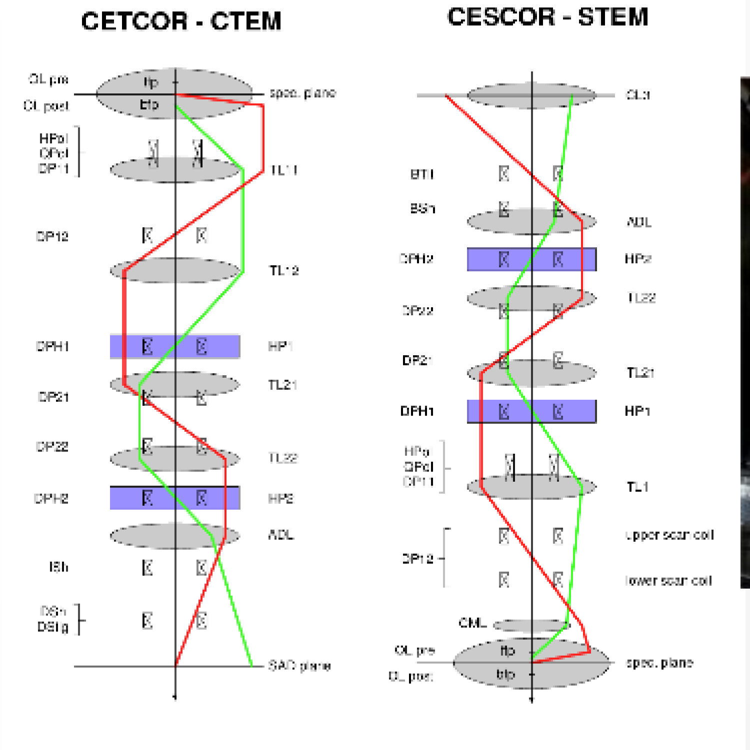
$$\Psi_i = \Psi_o \exp(2\pi i \vec{\boldsymbol{r}})$$

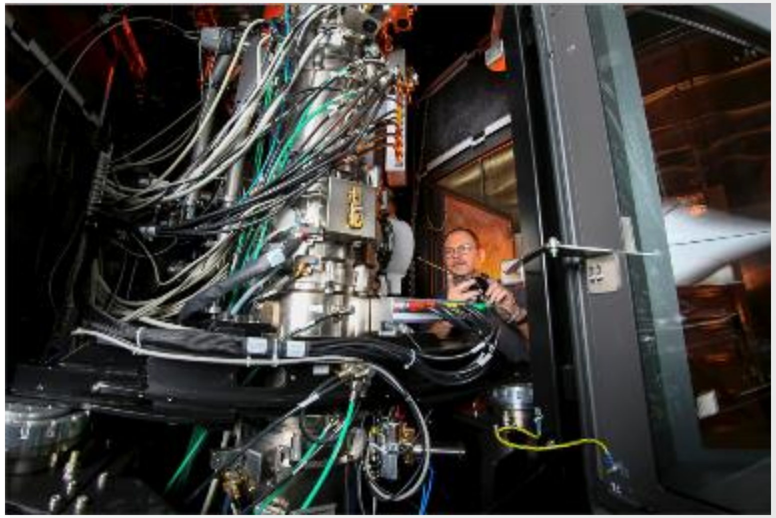


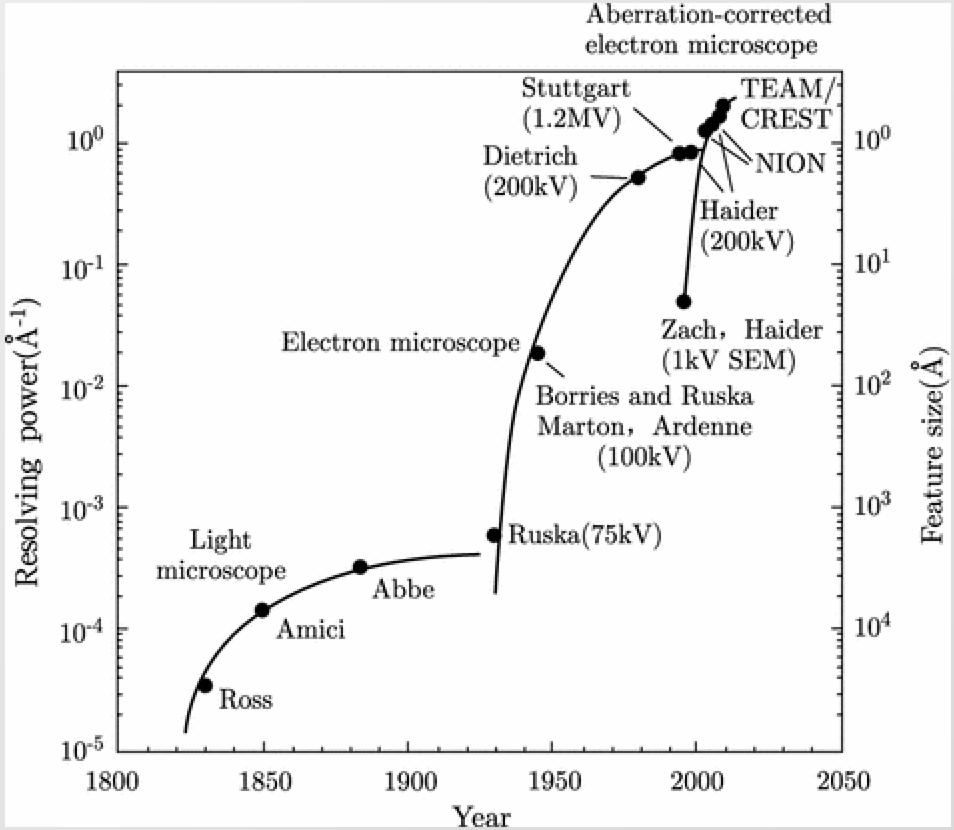
$$\Psi_{EW}(\vec{r}) = a(\vec{r})e^{i\varphi_s \vec{r}} \Longrightarrow \Psi_{obj}(\sigma_E, V_{proj}(\vec{r}))$$

Exit wave function in terms of weak phase object approximation (WPOA)

The advent Aberration correctors have pushed the boundaries of spatial resolution (spatial coherence)





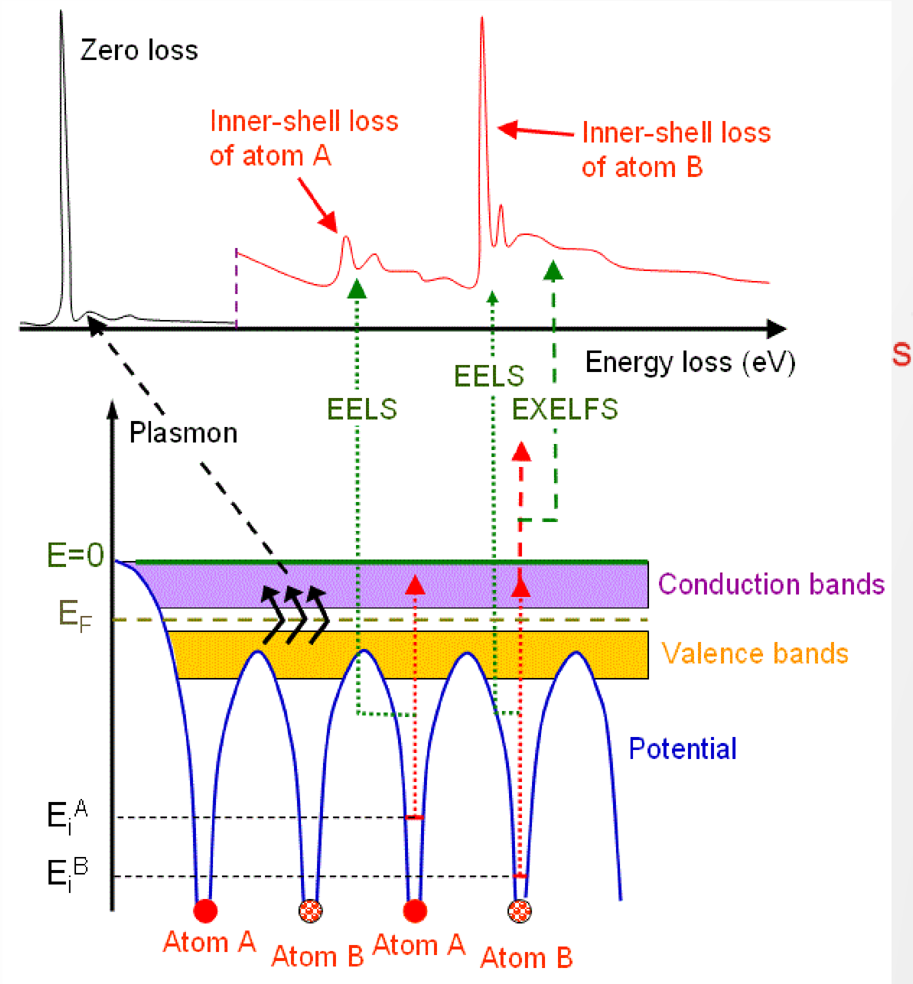


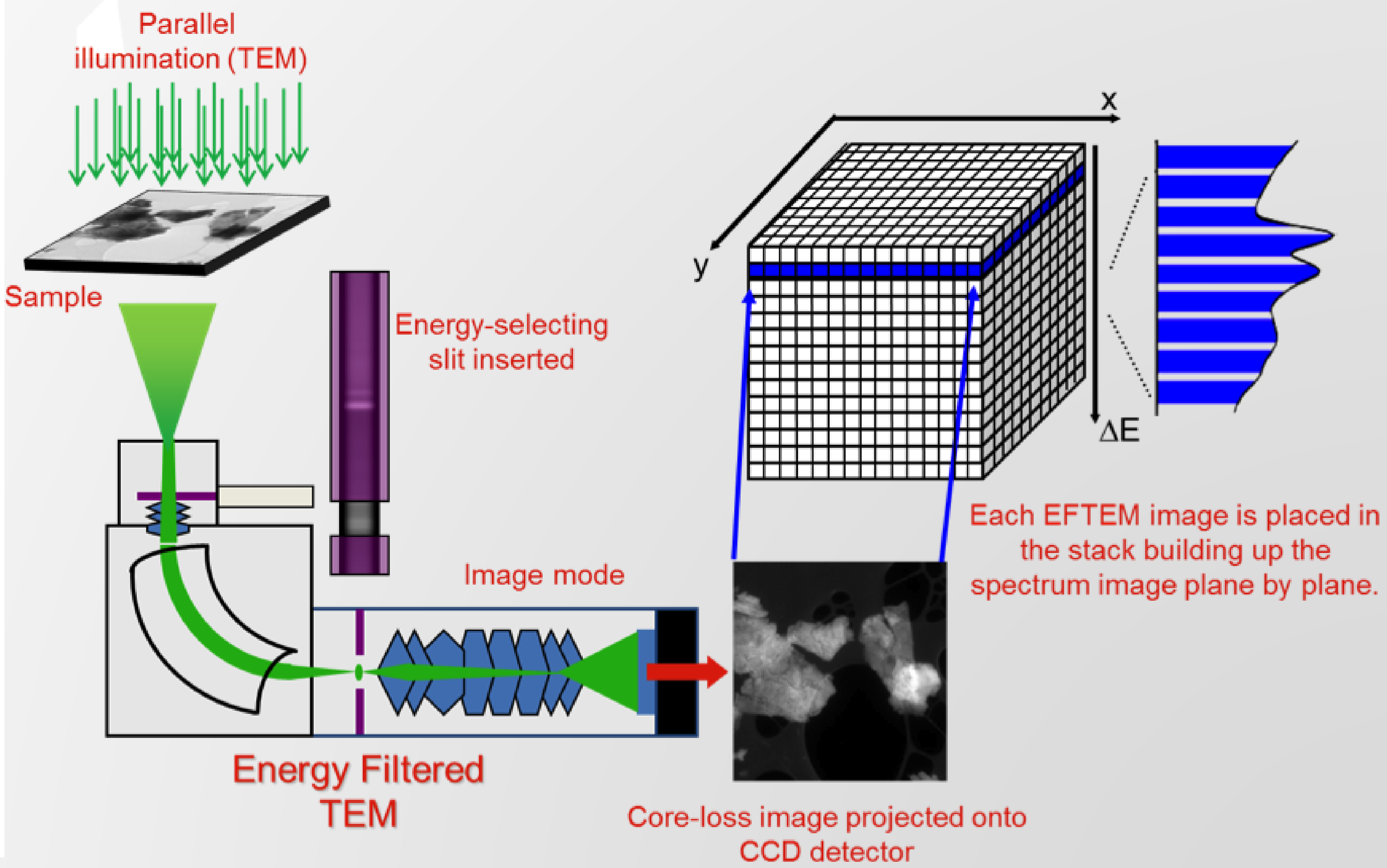
Uncorrected, resolution is ~100 X diffraction limit

Cs Correction, resolution is ~15 x diffraction limit

Electron Energy Loss Spectrocopy (EELS)

Energy filtered TEM with core loss electrons

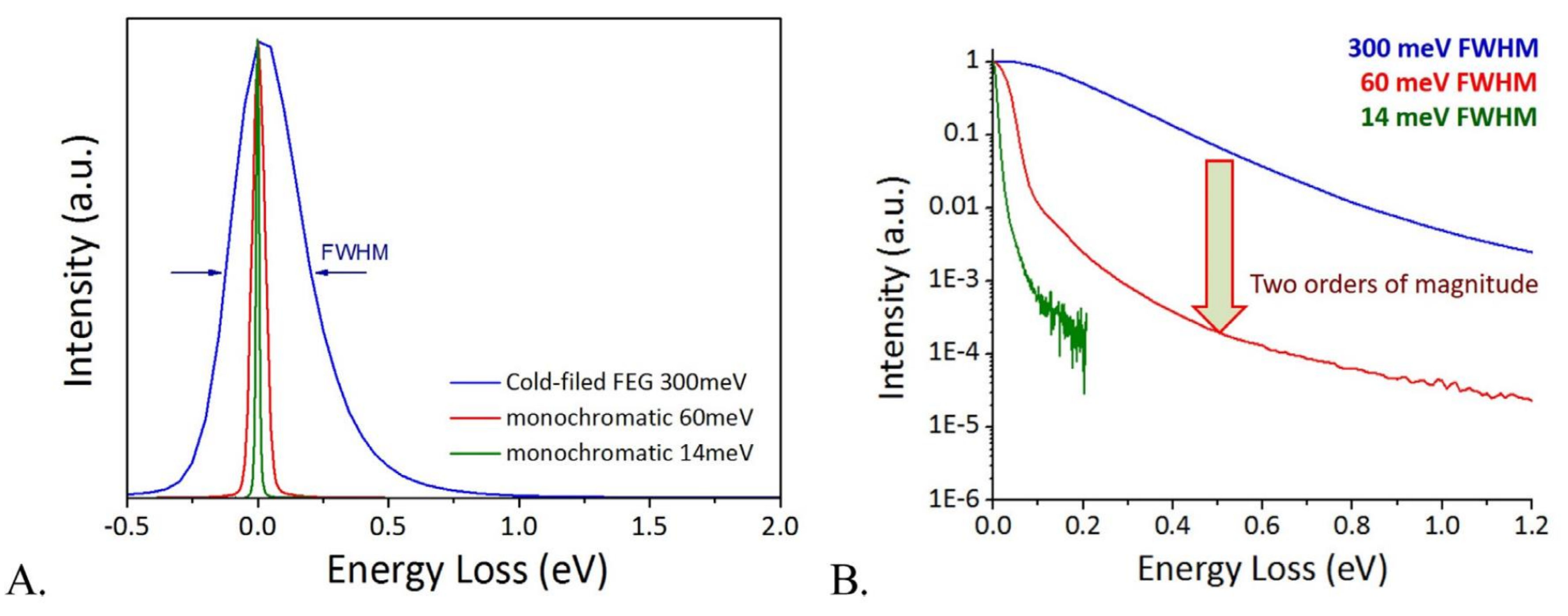




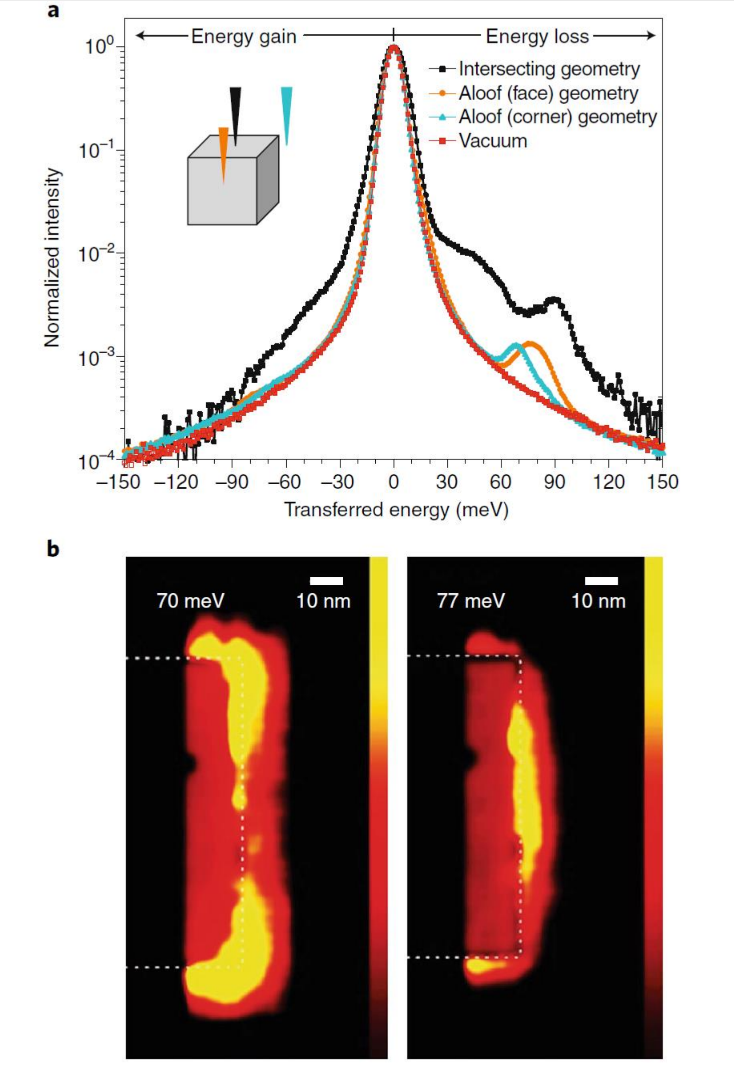
Each EFTEM image is placed in the stack building up the spectrum image plane by plane.

Core-loss image projected onto CCD detector

EELS technology has made great advancements in the past decade that local phonon modes can be probe on the sub-nanometer scale.



Maureen J. Lagos, Andreas Trügler, Ulrich Hohenester, and Philip E. Batson, Nature **543** (7646), 529 (2017).

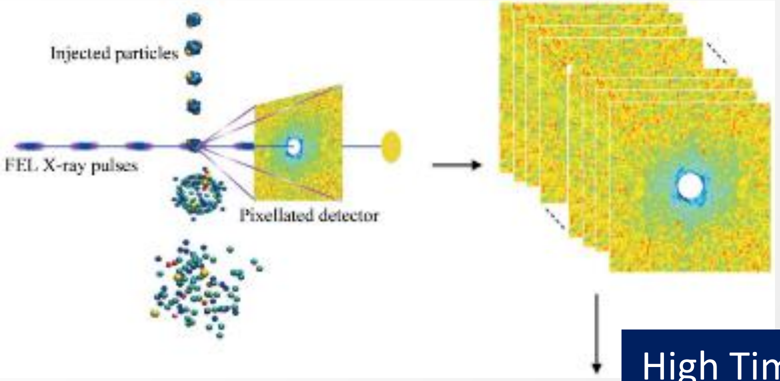


Modern TEM technology can combine high energy EELS and sub-nm STEM probes for nano-vibrational spectroscopy

Lagos, M. J., Trügler, A., Hohenester, U. & Batson, P. E. Mapping vibrational surface and bulk modes in a single nanocube. *Nature* **543**, 529–532 (2017).

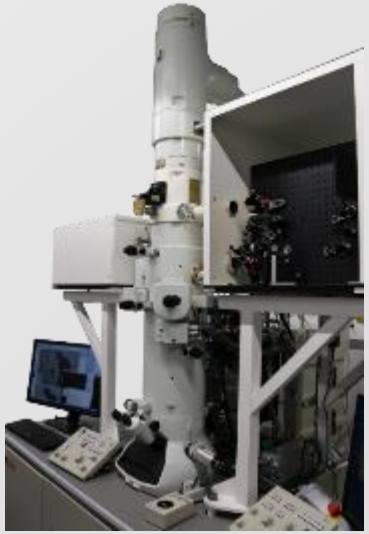
Development of ultrafast techniques are being pursed across many fields, e.g., physics, biology, materials science, chemistry, engineering…

Diffract before Destroy
Protein Structural Analysis



Bunch/Burst Modes at Synchrotron Sources

Ultrafast Electron Microscopy



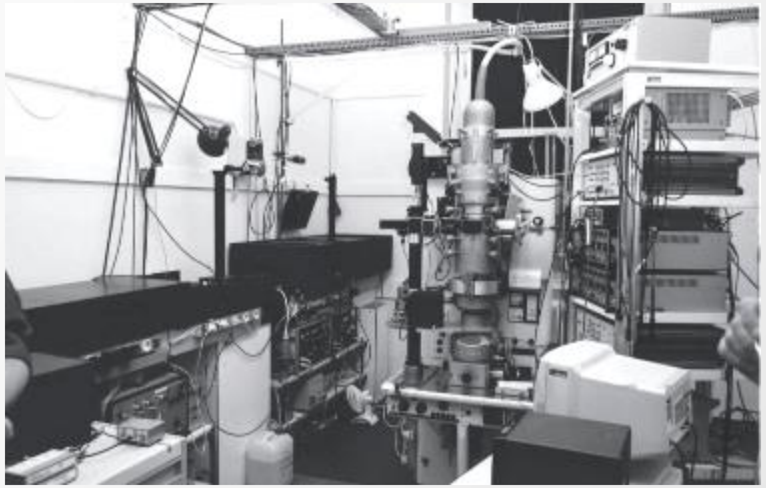
High Time Resolution allows you to observe unknown structures, transient states in matter, dynamics, and physics that cannot be captured with conventional techniques

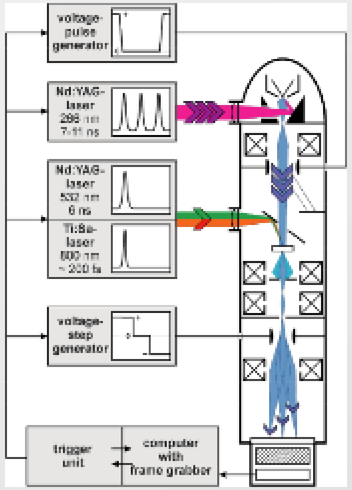
Free Electron (X-Ray) Lasers

Ultrafast Laser Spectroscopy

Ultrafast TEM grew out of developments in time-resolved electron microscopes that date back to the 1960's

Technical University of Berlin

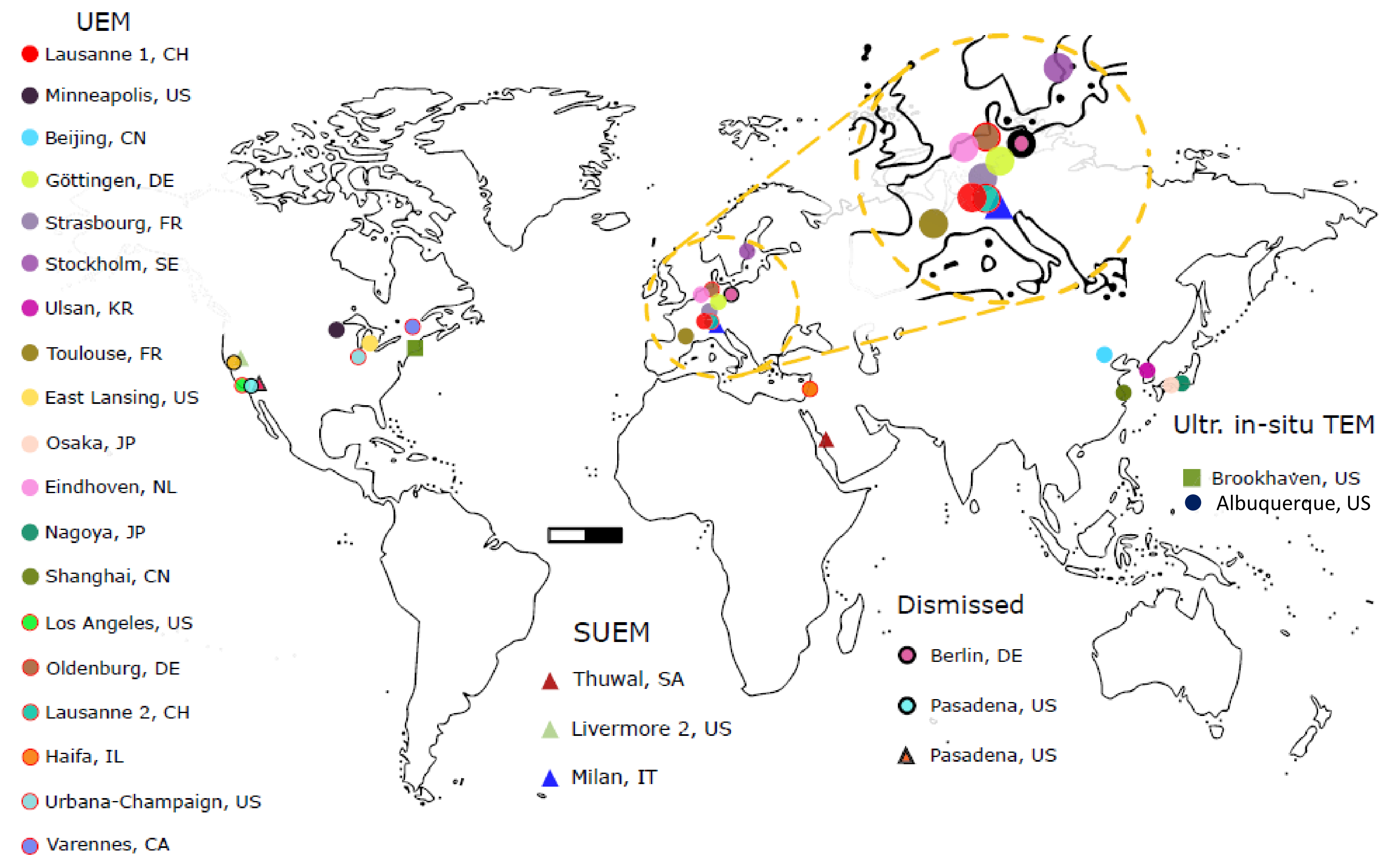




Lawrence Livermore National Lab

Caltech

There are growing number of UTEM installations worldwide

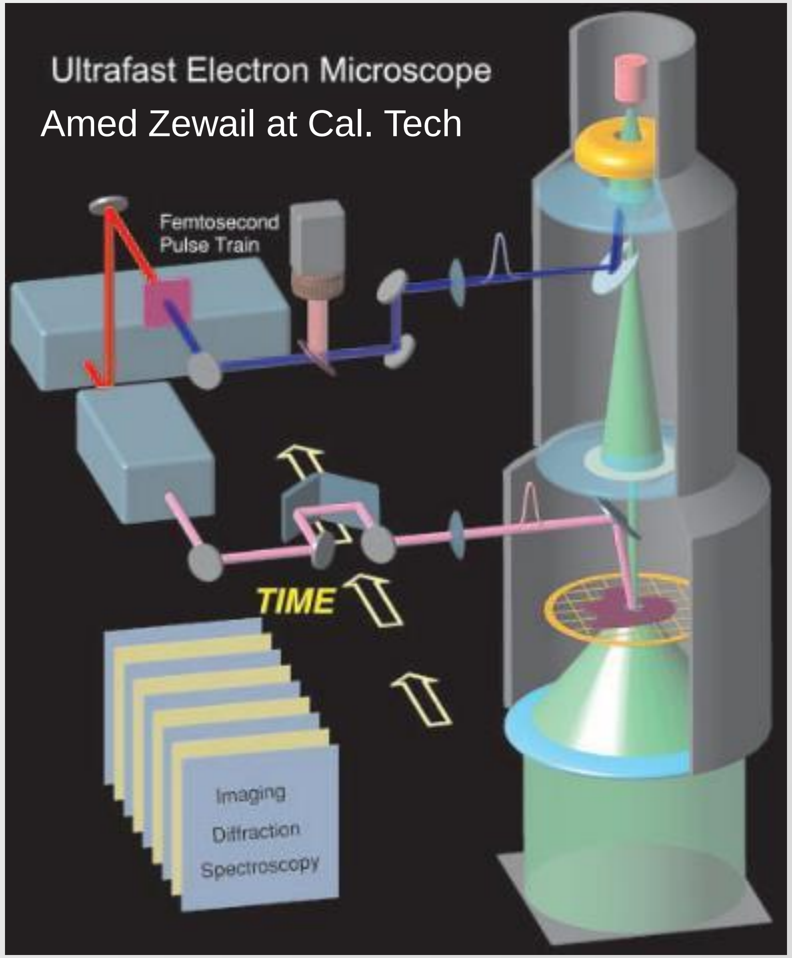


There are 2 laser based instrumentation approaches to Ultrafast Microscopy: Single-Shot and Stroboscopic

Single-Shot Method: one pump excitation to the sample and one electron pulse producing one image

Stroboscopic Method: integration of millions of pump excitations to the sample and electron pulses producing one image


LLNL Movie-Mode DTEM


Ultrafast Electron Microscope

Amed Zewail at Cal. Tech

Single-Shot method

- Probes irreversible processes
- Main challenges: limitations in resolution

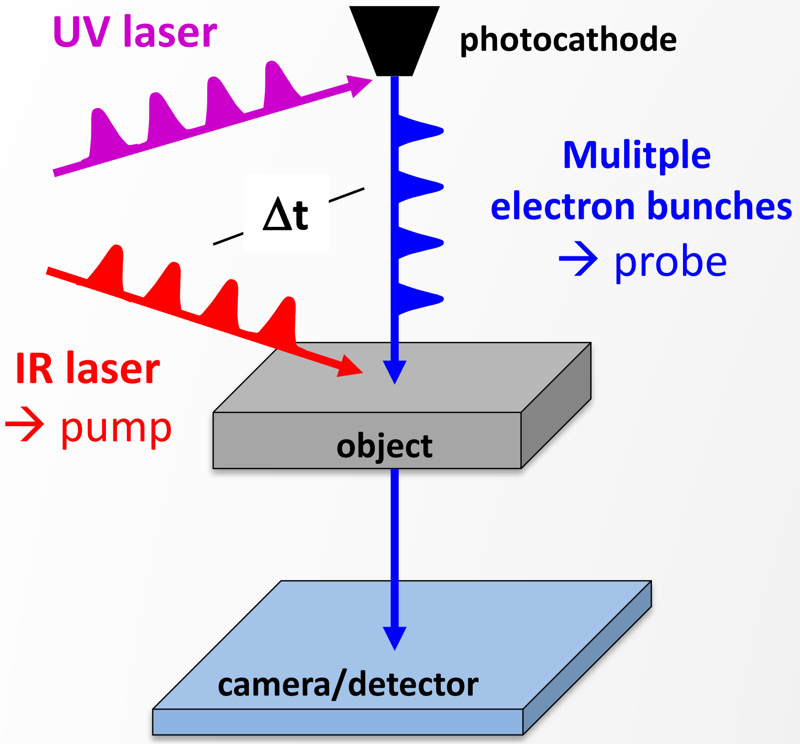
Stroboscopic method

- Can only probe highly reversible processes
- High spatial resolution
- Limited methods for sample excitation

fs-Ultrafast Electron Microscopy: Stroboscopic Technique

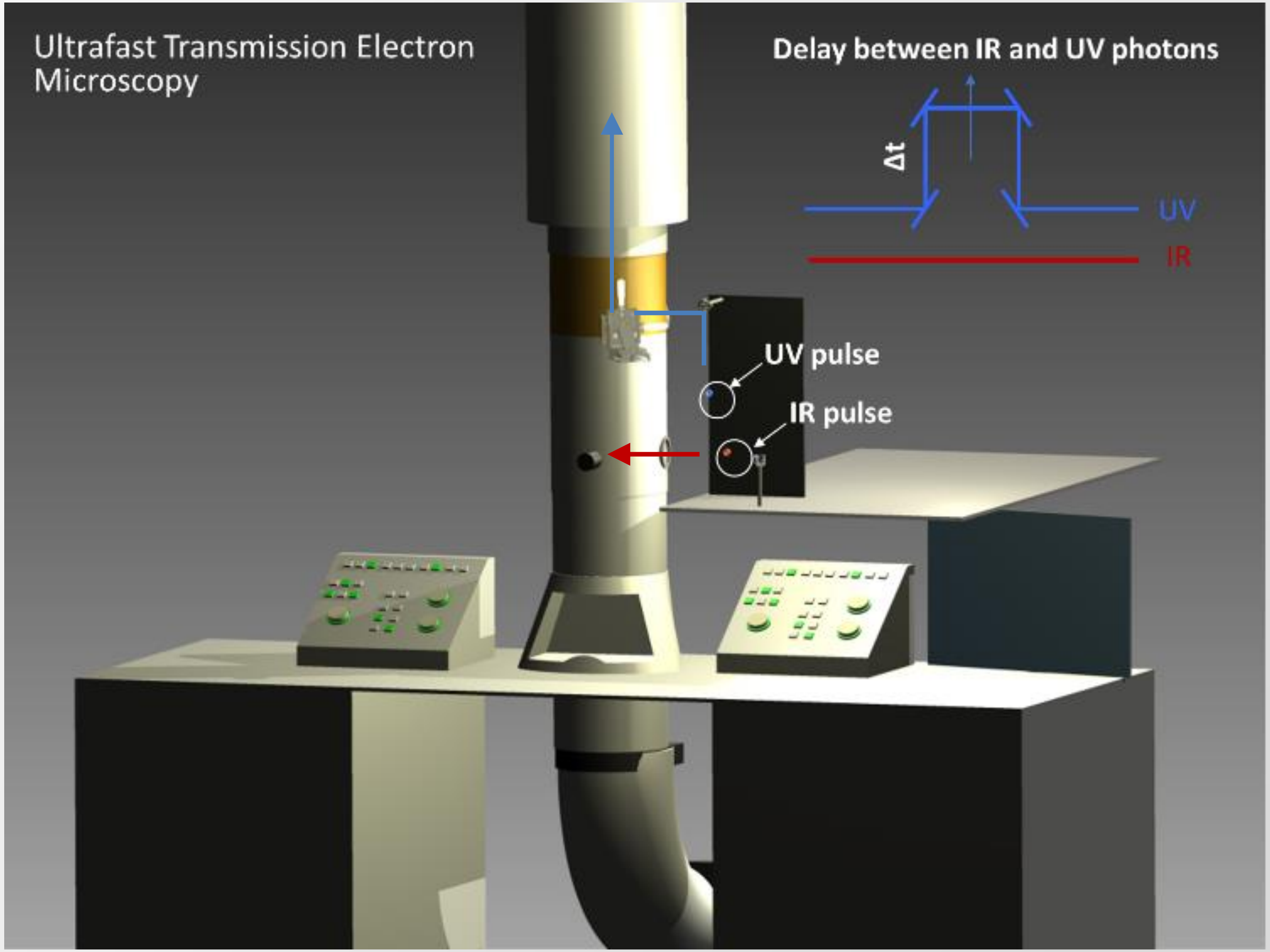
Stroboscopic

→ ***train* of weak pulses**



many pulses produce the image

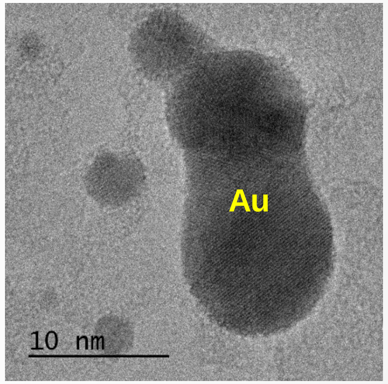
- ➢ for reversible transitions



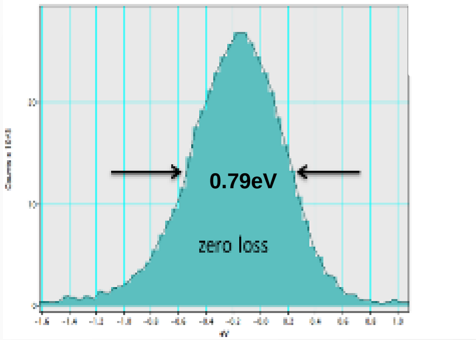
The Stroboscopic UTEM installed at IPCMS CNRS Strasbourg (Florian Banhart) achieves atomic resolution with a few ps electron pulses

Resolution in thermionic mode

Ta disc cathode, heated
Sample: gold nanoparticles



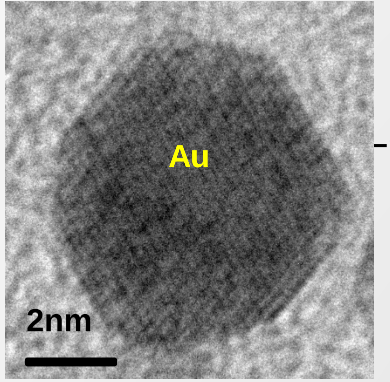
Laser repetition rate: 2 MHz
UV output power: 1 mW



Spread of zero loss resolution ~ 0.79 eV

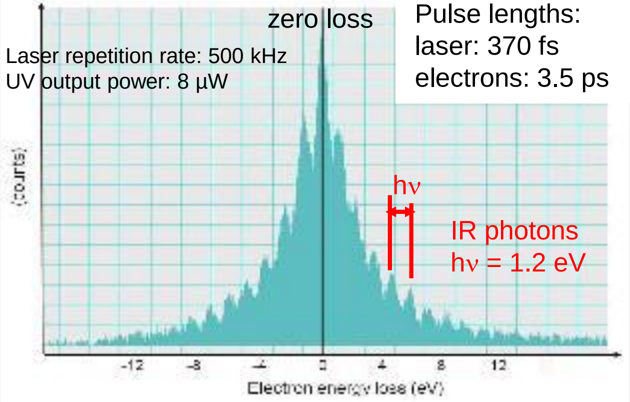
Resolution in photoelectron mode

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



Lattice image
resolution
~0.23nm

PINEM spectrum

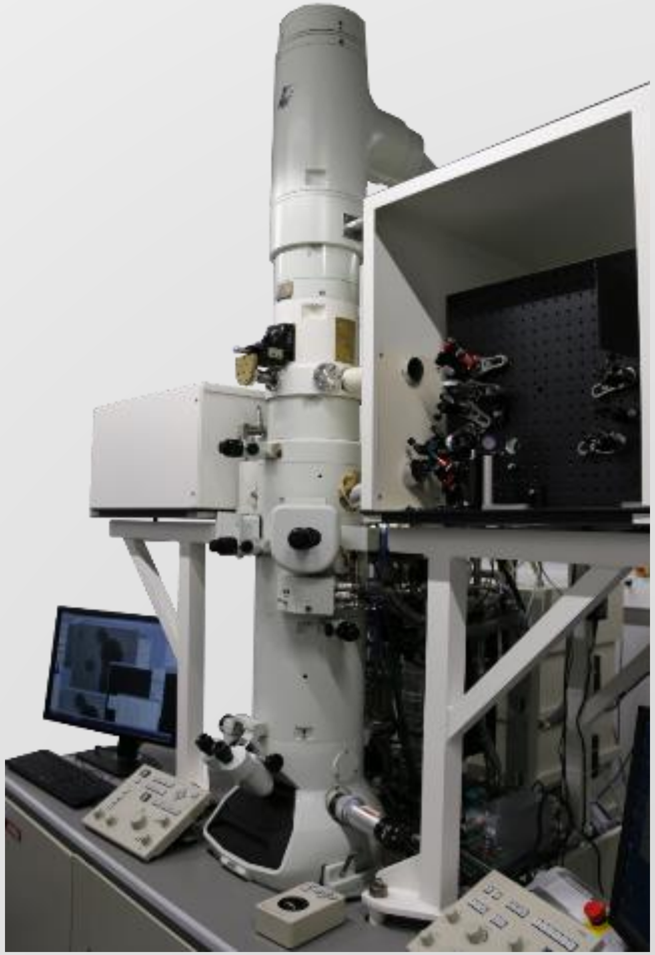


Laser repetition rate: 500 kHz
UV output power: 8 µW

Pulse lengths:
laser: 370 fs
electrons: 3.5 ps

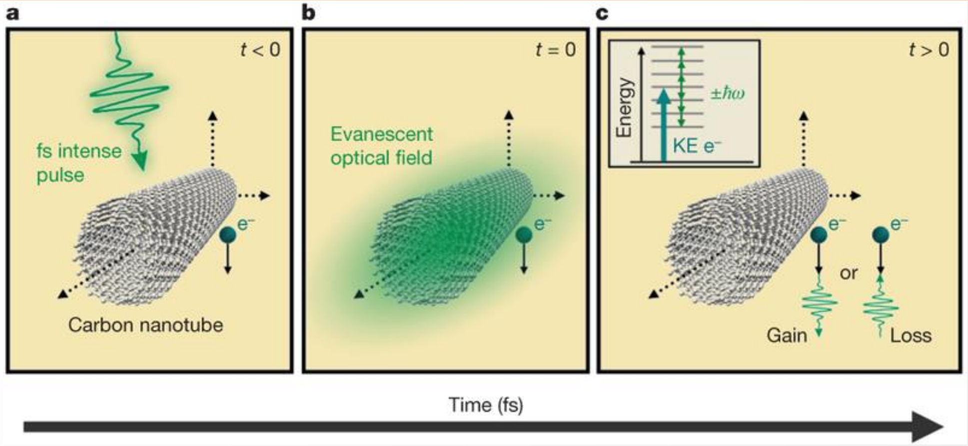
IR photons
hν = 1.2 eV

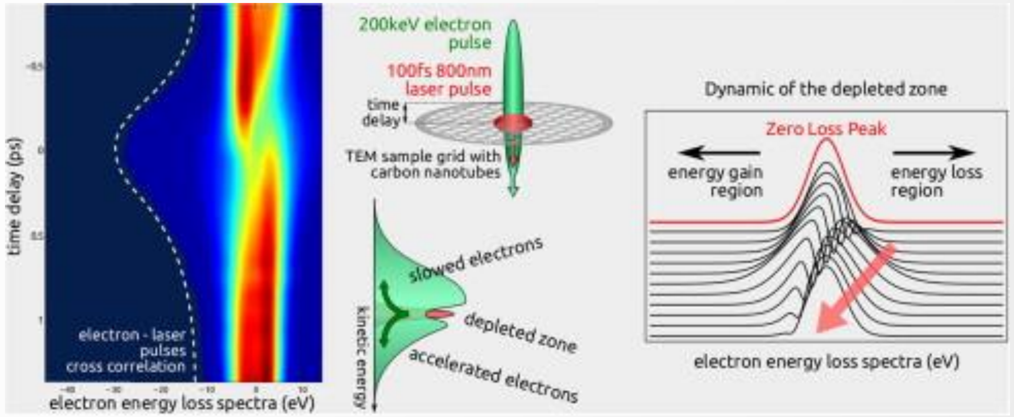
Photon-induced near-field electron microscopy energy gain/loss by interaction with photon field



K. Bücker, M. Picher, O. Crégut, T. LaGrange, B.W. Reed, S.T. Park, D.J. Masiel, F. Banhart, "Electron beam dynamics in an ultrafast transmission electron microscope with Wehnelt electrode, *Ultramicroscopy, Volume 171 (2016) pp.8-18*

Photon induced near-field electron microscopy (PINEM) can be used to study coherent photo-induced processes, such as plasmons





L. Piazza et al., *Chem Phys* **423**, 79 (2013).

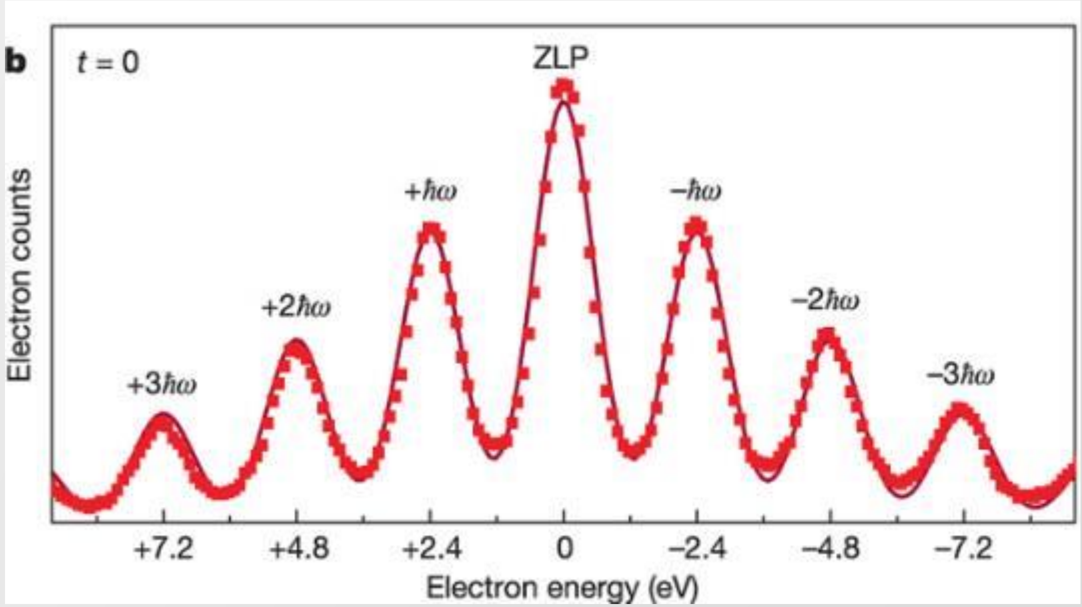
PINEM provides a means for determining “time zero” and temporal resolution of the electron bunch

Inelastically accelerated electrons

200 KeV + n•ħω

Inelastically decelerated electrons

200 KeV - n•ħω

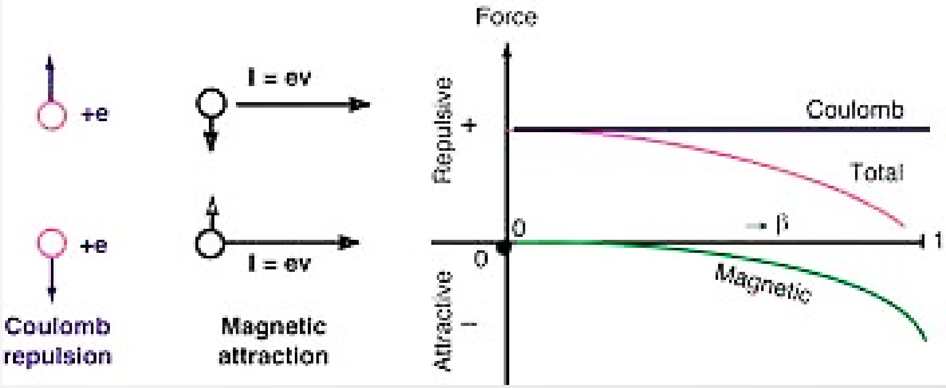


Brett Barwick, David J. Flannigan & Ahmed H. Zewail Nature 462, 902-906 (2009)

The major challenge for Ultrafast Electron Microscopy is using fermions as a probe!

EPFL

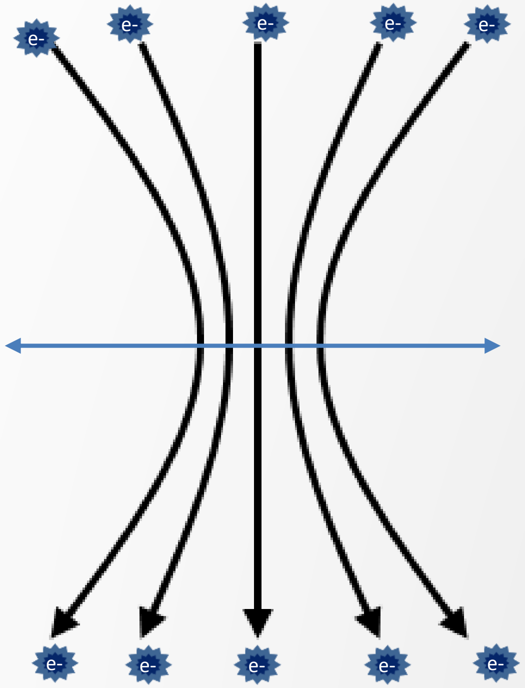
Coulomb interactions and replusion (electron-electron scattering) limit the temporal and spatial resolution of Ultrafast Electron Microscopy techniques!



Electron-Electron scatter events scramble the high-resolution information of the specimen encoded on the electron waves

With high electron currents, electron-electron interactions limit brightness and spatial resolution

Lateral Space Charge



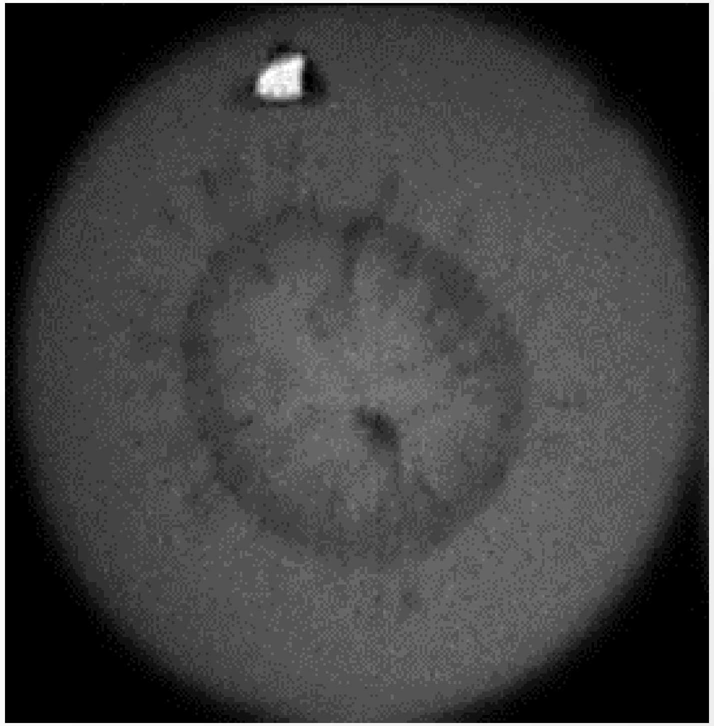
Virtual Lens crossover

Defocusing:

- **To first order, it's just a diverging lens**
- **Correction via readjustment of microscope alignment**
- **Higher orders create spherical aberration**

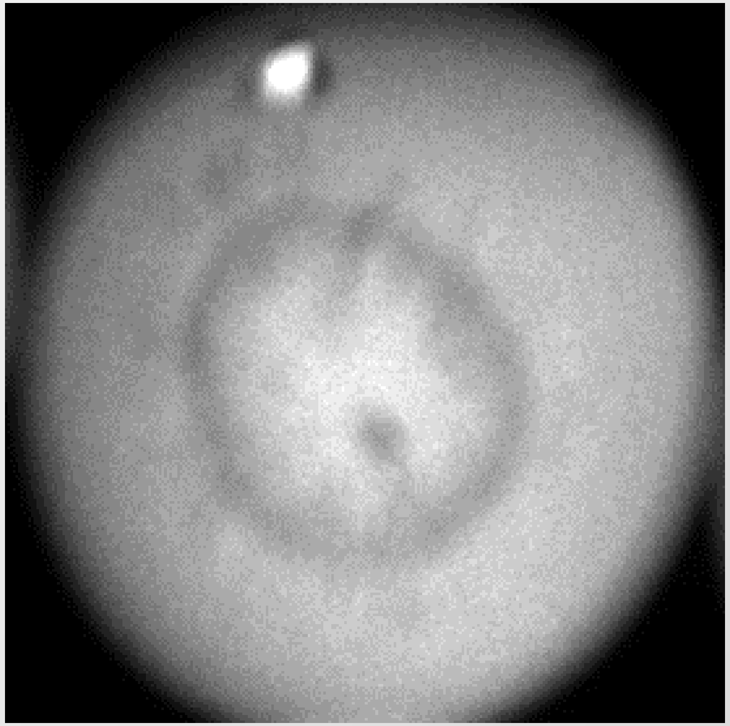
High Current electron pulses act as a “moving”, variable lens.

Focused image



5X more
electrons

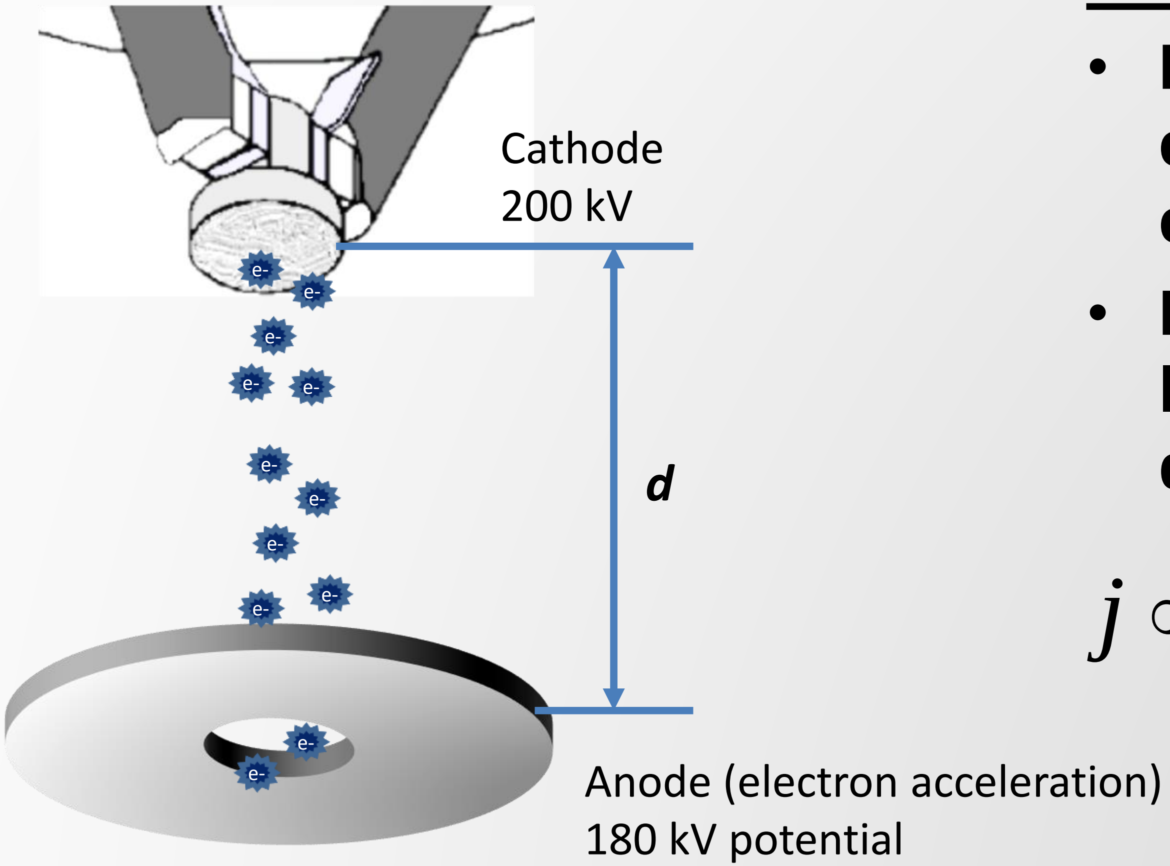
Defocused due to
Lateral Space Effects



Lateral Space Charge effects can be overcome easily in the TEM (*every lens in the microscope has a tunable focal length)* but these effects require that laser be stable and we work at Space Charge Limit

With high electron currents, electron-electron interactions limit brightness and spatial resolution

Longitudinal Space Charge

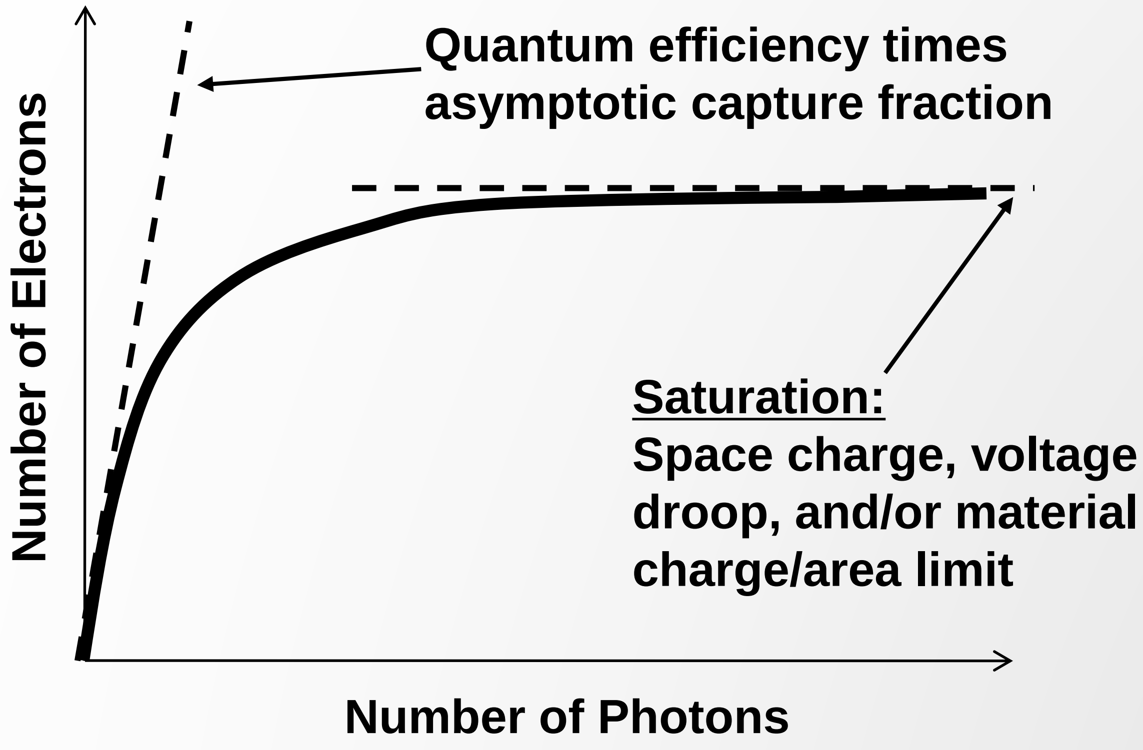


Child's Law:

- **Field from recent electrons retards emission**
- **Fundamentally limits current density (*j*):**

$$j \propto V^{3/2} / d^2$$

Electron yield saturates as the cathode laser energy increases

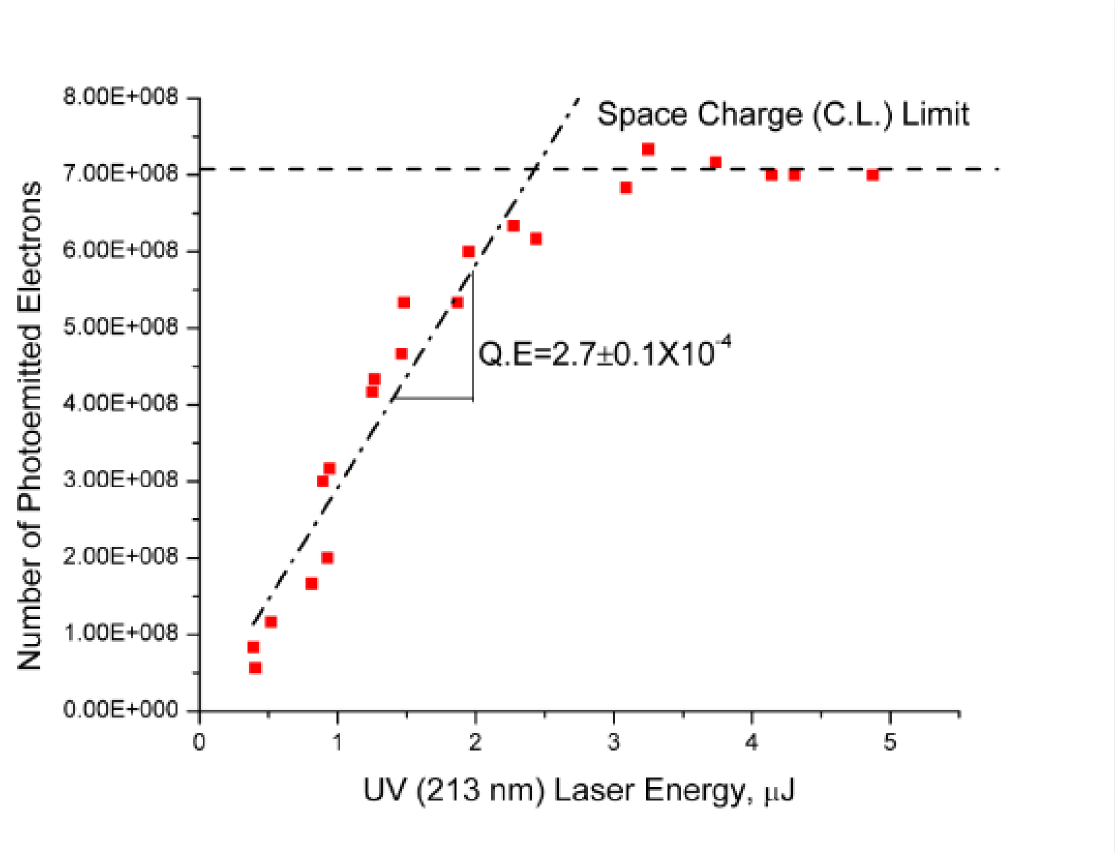


Quantum efficiency times asymptotic capture fraction

Saturation:
Space charge, voltage droop, and/or material charge/area limit

Number of Electrons

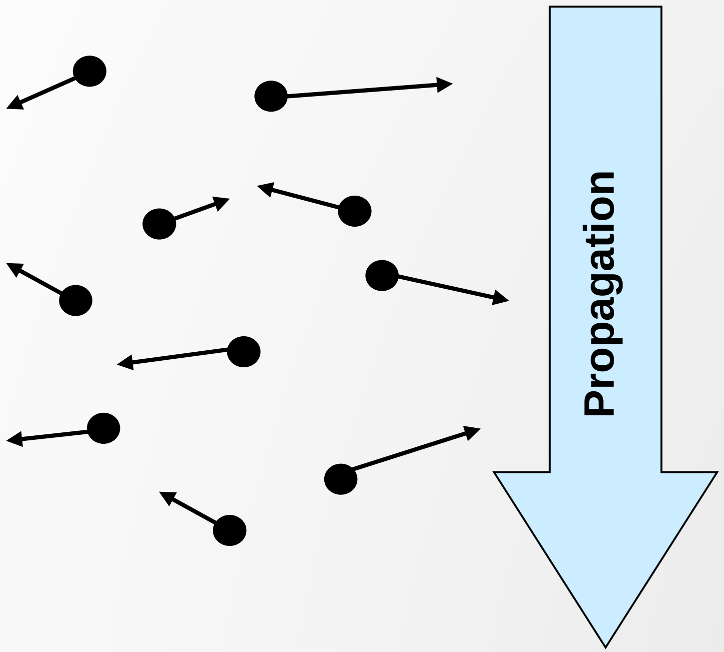
Number of Photons



The number of electrons per pulse is a function of the gun design. High spatial coherence (small emitting area) gives low signal. Larger signals are generated from large areas (low spatial coherence).

With high electron currents, electron-electron interactions limit brightness and spatial resolution

Longitudinal Inhomogeneous



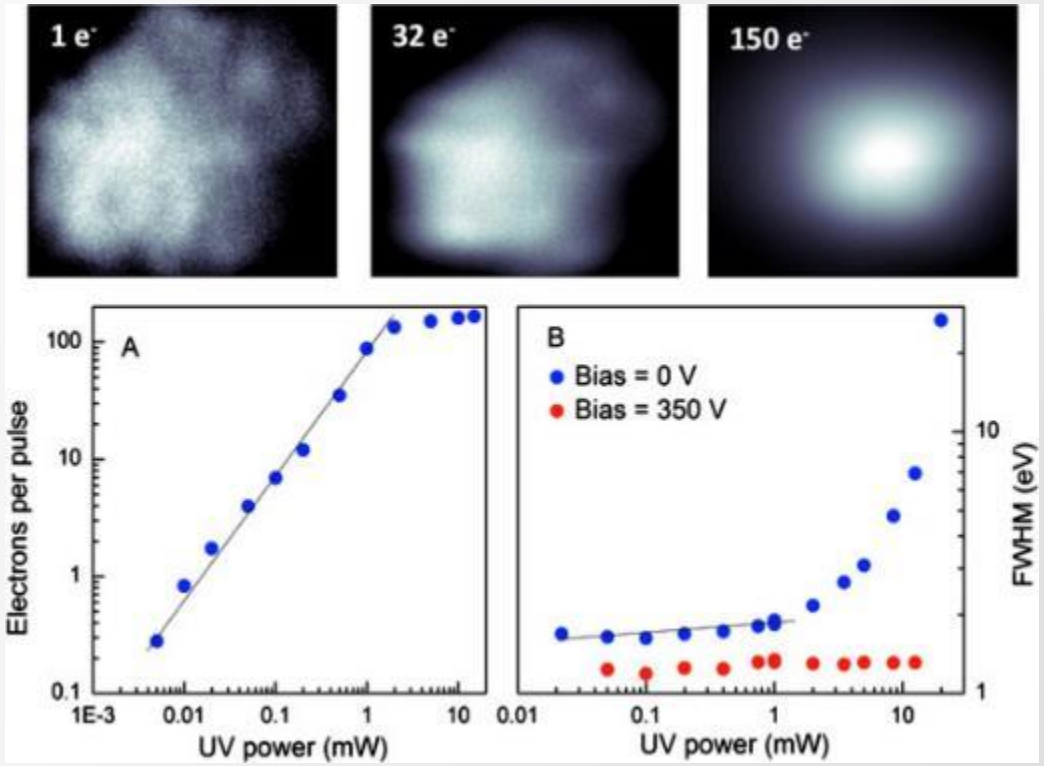
<u>Boersch Effect:</u>

- **Pulse viewed in rest frame**
- **Most velocity is lateral**
- **Equilibration increases ΔE**
- **Can create 1 kV energy spreads in high charge beams**
- **Cannot be corrected, only minimized**

Coulomb interactions increase bunch length and energy spread, that induce aberrations and greatly reduce temporal and spatial resolution

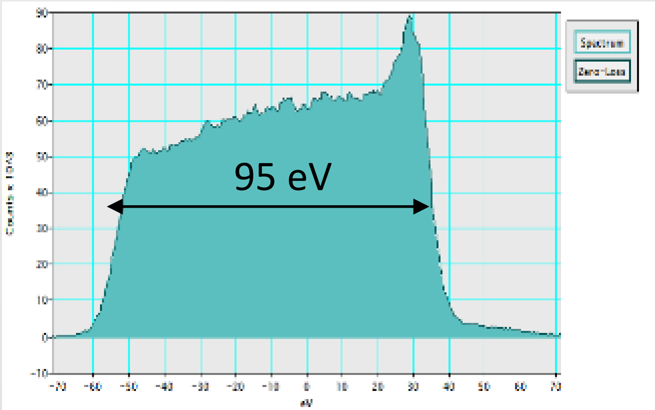
Operating with 10s of electrons per pulse causes

- ***Boersch effects*** reduce energy resolution
- ***Inhomogeneous and homogenous space-charge effects*** decrease spatial and temporal resolution
- ***Integration time and signal*** are traded-off with temporal resolution and coherence

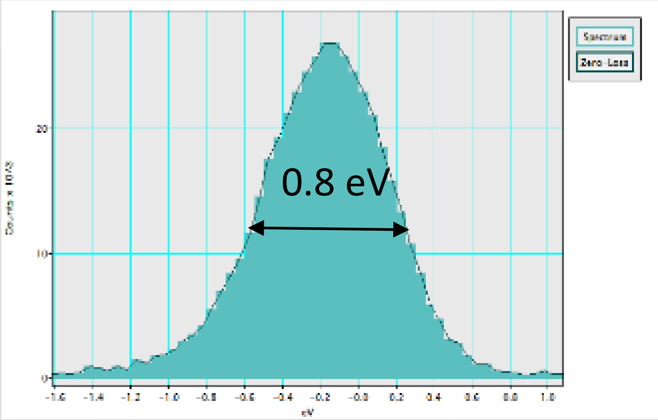


L. Piazza et al,*Chem Phys* **423**, 79 (2013).

Stroboscopic mode, 15 mW UV



Stroboscopic mode, 1 mW UV

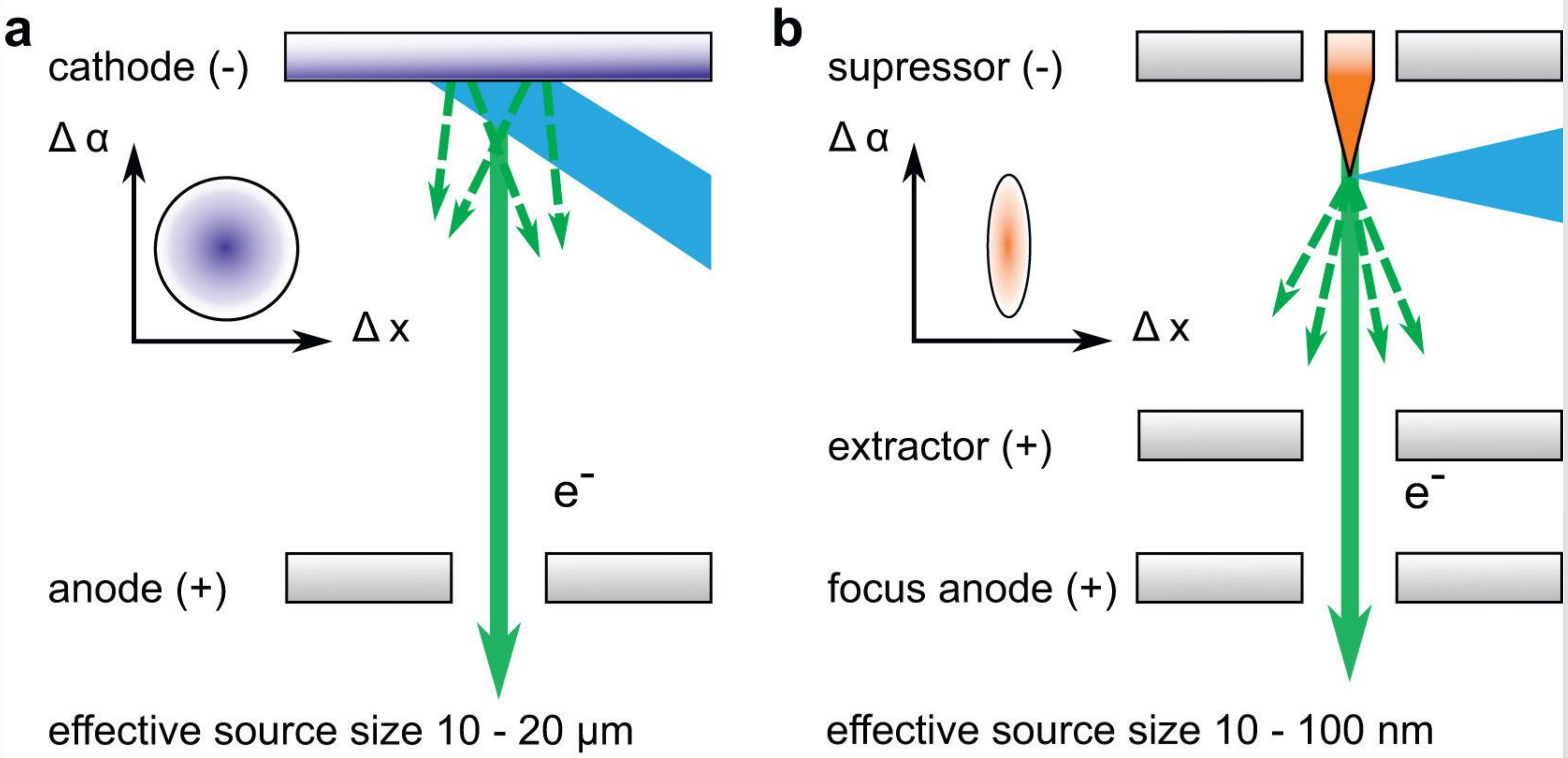


Unpublished data acquired on Strasbourg UTEM

Does FEG tip geometry provide better coherence?

“Flat” Thermionic TEM gun cathode

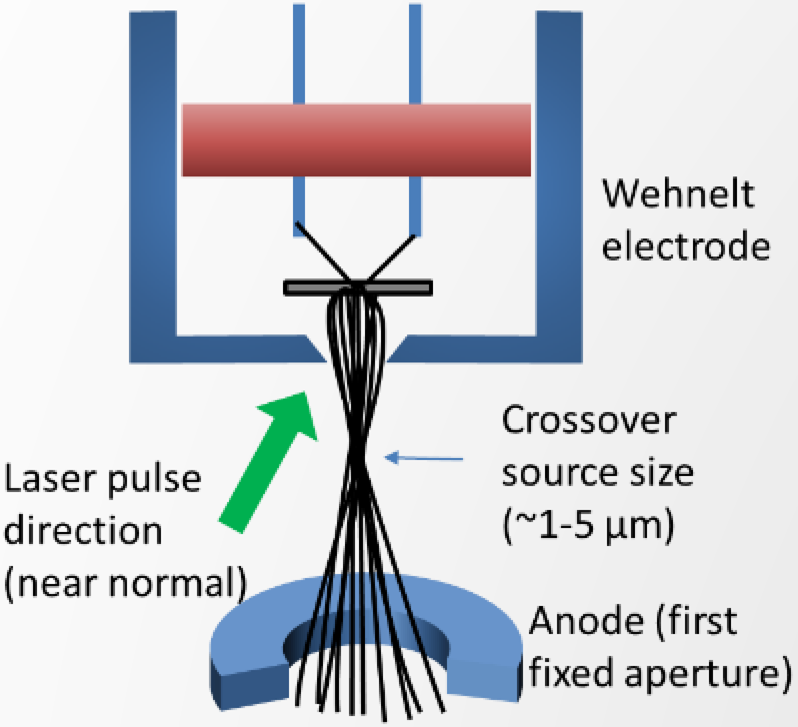
“Sharp” Field Emission Gun cathode

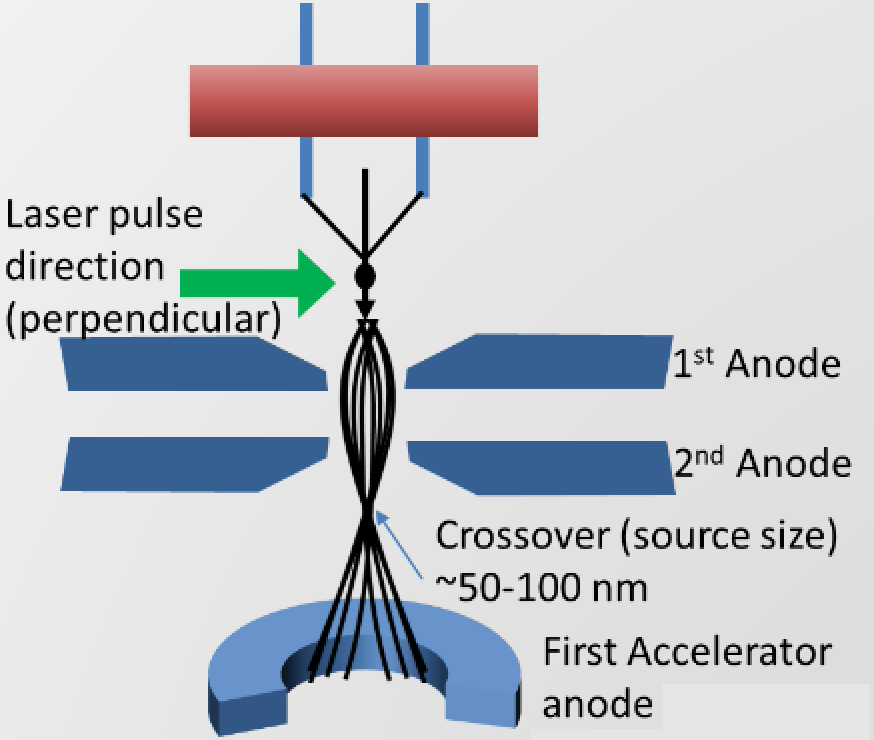


Armin Feist, Nora Bach, Nara Rubiano da Silva, Thomas Danz, Marcel Möller, Katharina E. Priebe, Till Domröse, J. Gregor Gatzmann, Stefan Rost, Jakob Schauss, Stefanie Strauch, Reiner Bormann, Murat Sivis, Sascha Schäfer, and Claus Ropers, Ultramicroscopy **176**, 63 (2017).

Flat (thermionic gun) vs. Sharp tip (FEG photogun) designs: Which is better?

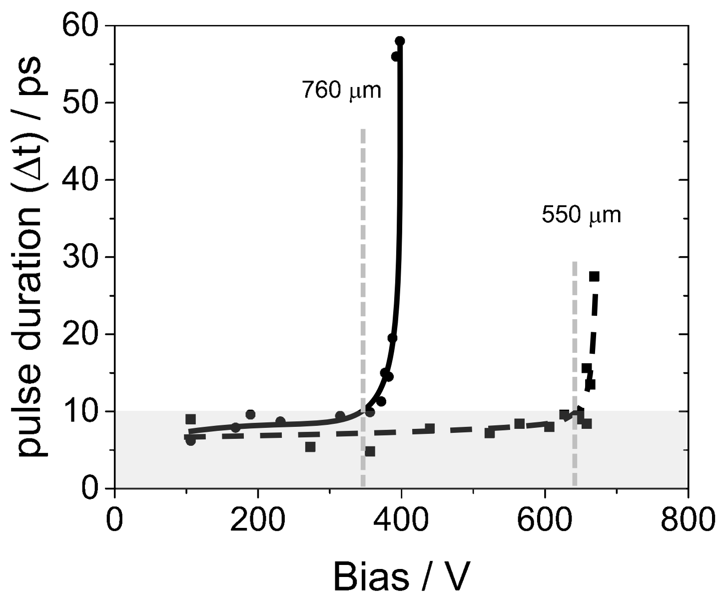
Each design trade-offs parameters:
Coherence and Temporal Resolution Vs. Signal and Average Brightness

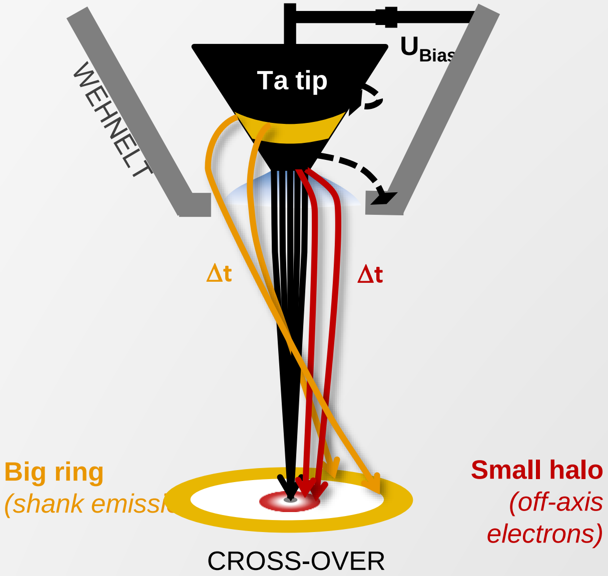


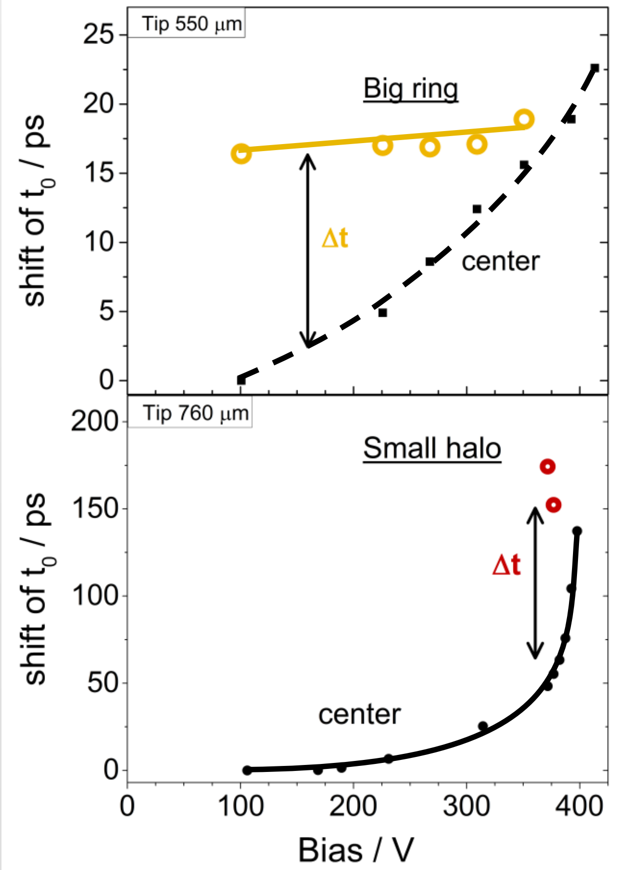


Space Charge Controls Brightness!
Both designs have similar photoelectron brightness

Flat photocathode temporal resolution characteristics



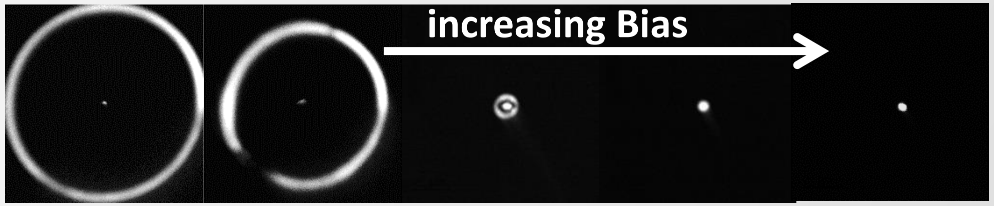




Space charge at the cathode

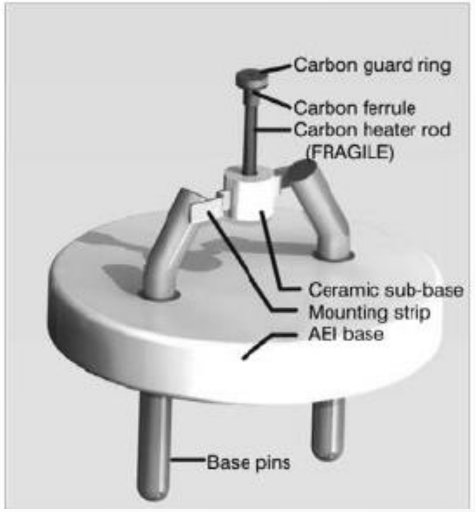
Boersch effect in the gun cross-over

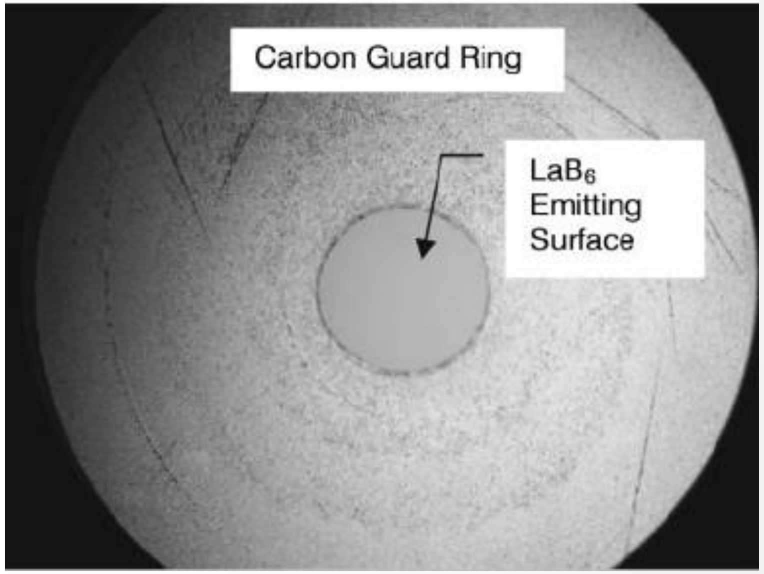
- XY-spread: **loss of coherence**
- Z-spread: **increase of pulse duration**
- High charge: **increase energy spread**
- High bias: **increases pulse duration and signal, but decreases in energy spread**



K. Bücker, M. Picher, O. Crégut, T. LaGrange, B.W. Reed, S.T. Park, D.J. Masiel, F. Banhart, “Electron beam dynamics in an ultrafast transmission electron microscope with Wehnelt electrode, *Ultramicroscopy, Volume 171 (2016) pp.8-18*

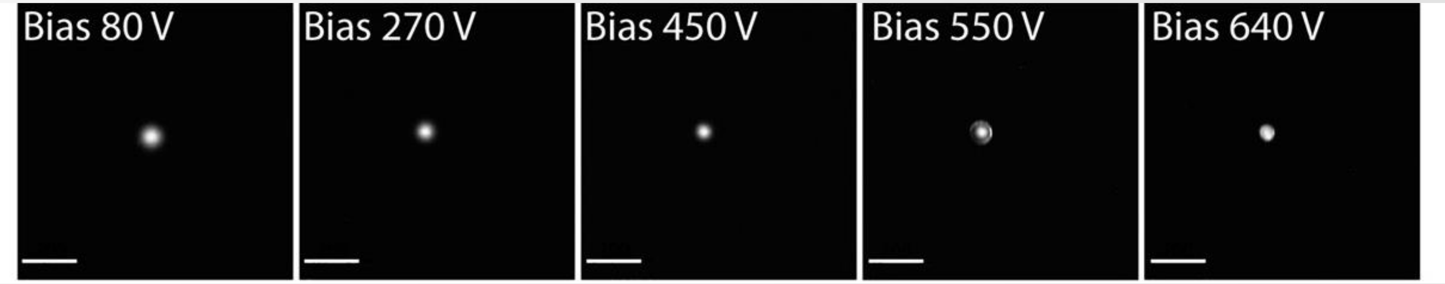
Guard Ring Cathodes limit the photoemission area (no shank electrons) providing high temporal resolution and moderate signal



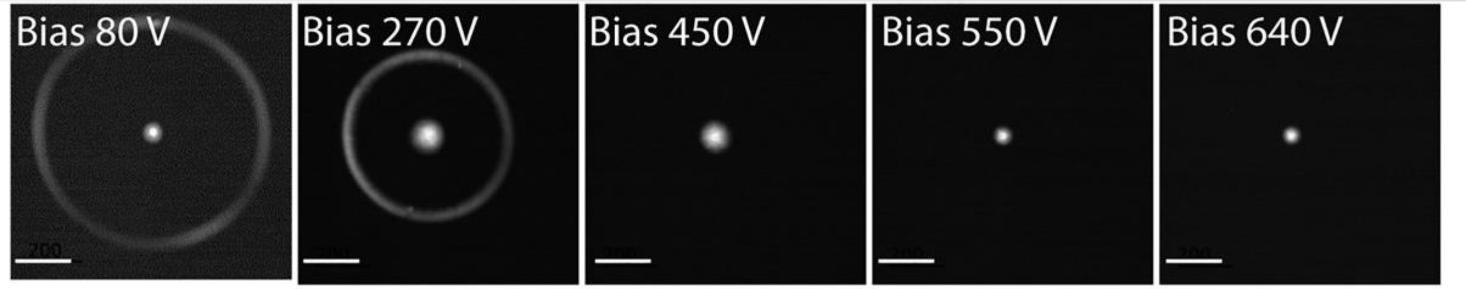


Improves coherence at high charge regime when operating at moderate bias voltages

LaB_6 Guard Ring Cathode



Standard Truncated LaB_6 filament

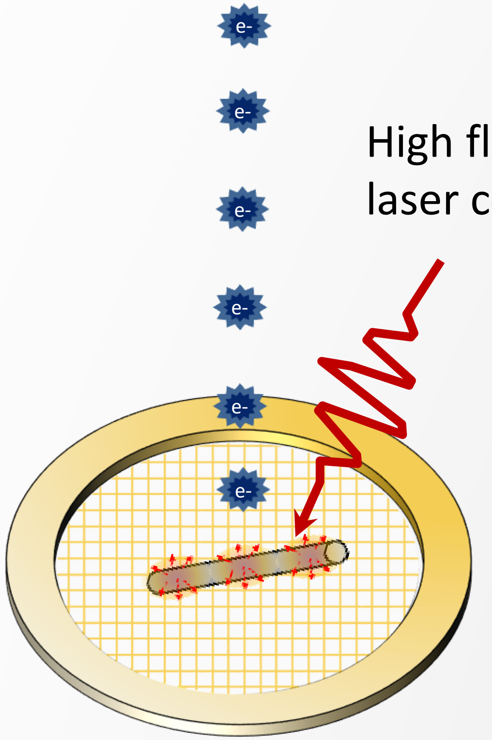


J. Shaozheng et al., “Influence of cathode geometry on electron dynamics in an ultrafast electron microscope, Structural Dynamics 4, 054303 (2017)

High-Fluence, femtosecond optical pump-probe are challenging

Practical Limitations of laser pumps in the UTEM approach

1. High power fs-lasers (>10 have limited repetition rates, <1 MHz
2. Samples need to sufficiently cool between pump pulses

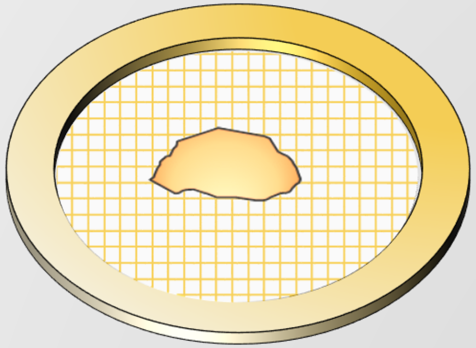


High fluence
laser conditions

Thin foil or nanostructures
on TEM carbon support grid

High-repetition rate can lead to

Melting and material modifications

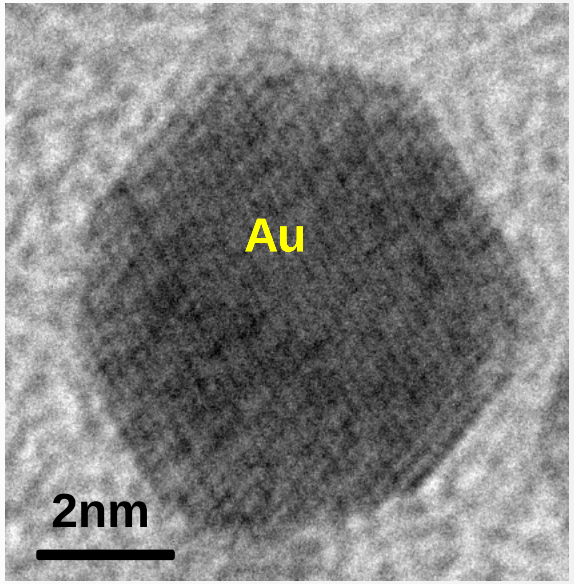


Nano-puddle on TEM
carbon support grid

In practice, imaging requires high signal, i.e., >1 e⁻/pulse, and thus Boersch effects are the limiting factor in the spatial resolution

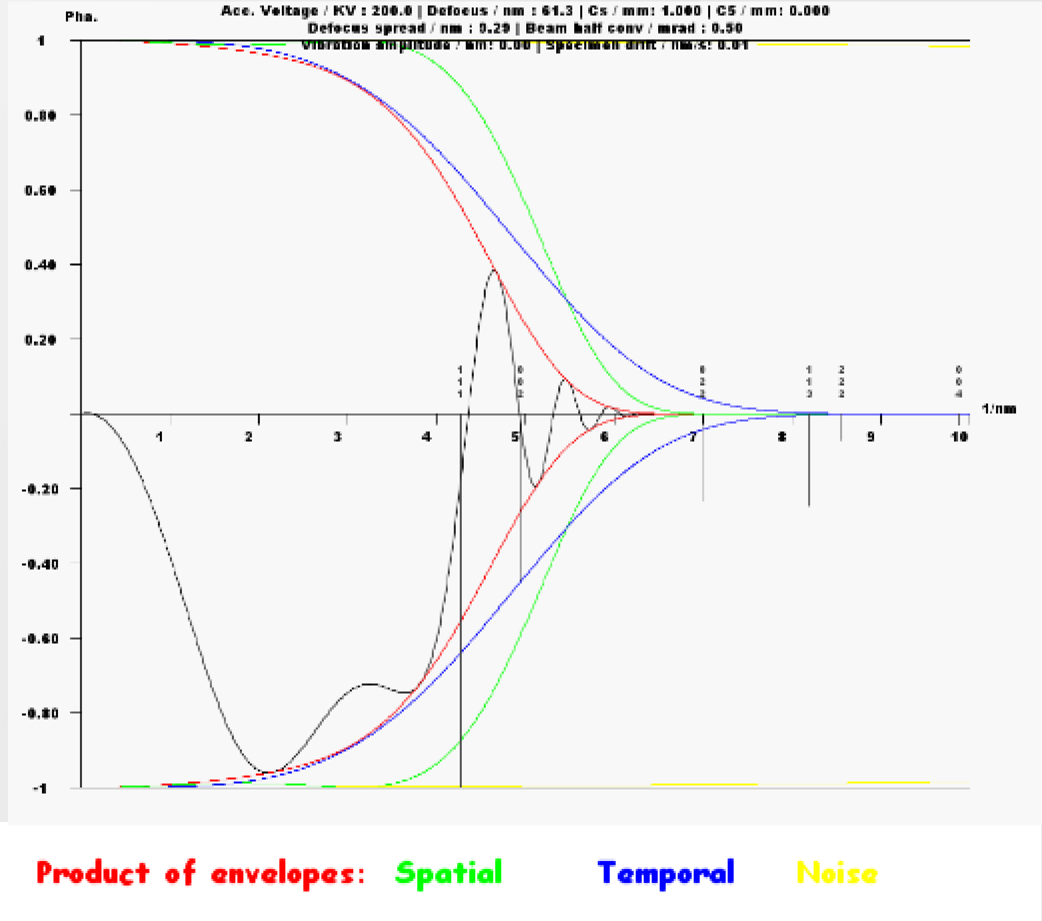
Resolution in photoelectron mode with Plate Cathode

- Laser repetition rate: 2 MHz
- Exposure time: 10s
- UV output power: 15 mW
- ***Electrons per pulse (@source): ~500***
- ***Total number of electrons: >10^9***
- Throughput:~1%
- Pulse duration at specimen: ~10ps



JEMS simulated CTF

Energy spread: 1.5 eV, sample drift: 0.2 nm/min,
Stability, Voltage: 2ppm/min, OL current: 1ppm/min, Field noise: <20 nT
JEOL 2100 HR pole piece: Cc 1.4mm and Cs 1.0mm



High resolution imaging is challenging with *single electron per pulse* operation in FEG due to inherently long exposure times

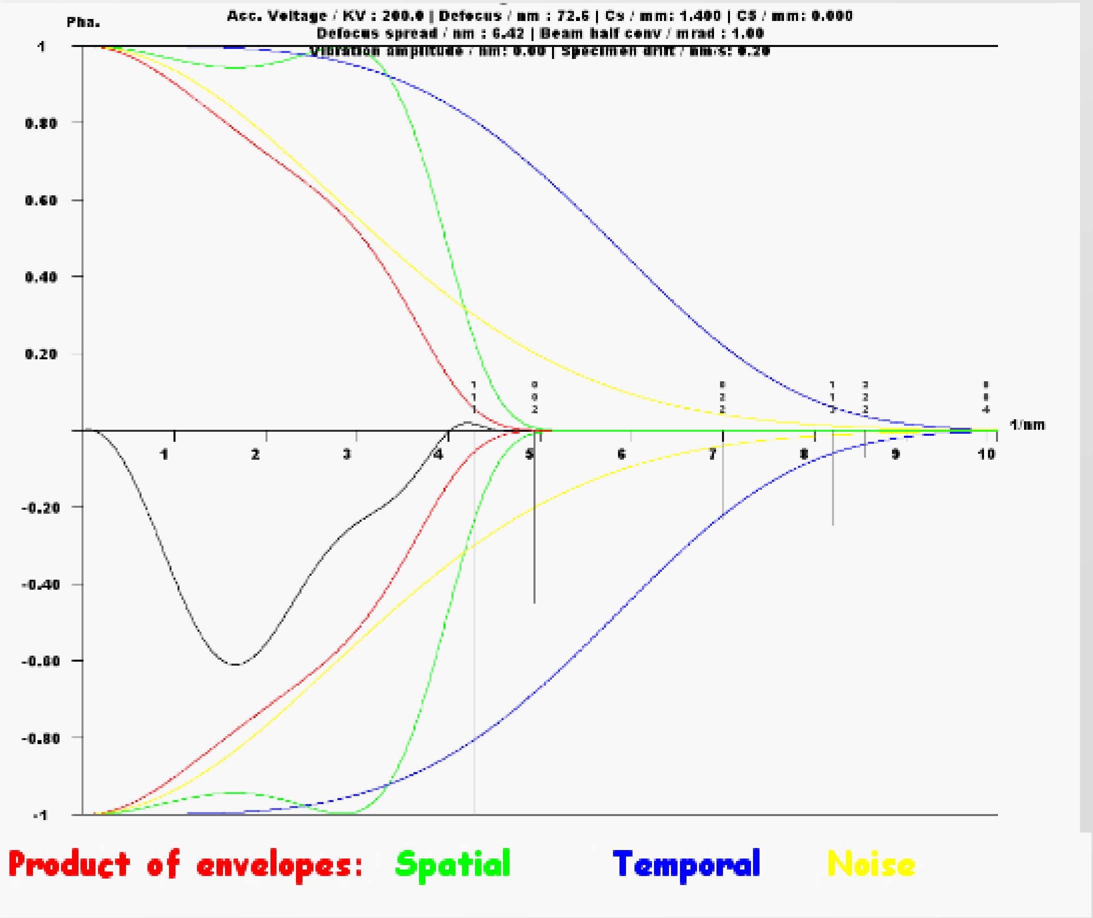
<u>Hypothetical conditions for 5 e$^-$/pulse operation of the FEG Sharp Tip</u>

- FEG photogun
- Laser rep rate: 2 MHz
- ΔE: 1 eV
- **Throughput: 10%**
- **5 electrons per pulse @ source**
- **Total electrons: >1x10^9**
- **Exposure time: 100 s**
- 10 ps pulses

Is sub-nm phase contrast imaging possible with exposure times >1 min?

Low Average Brightness and microscope instabilities prevent high spatial resolution imaging

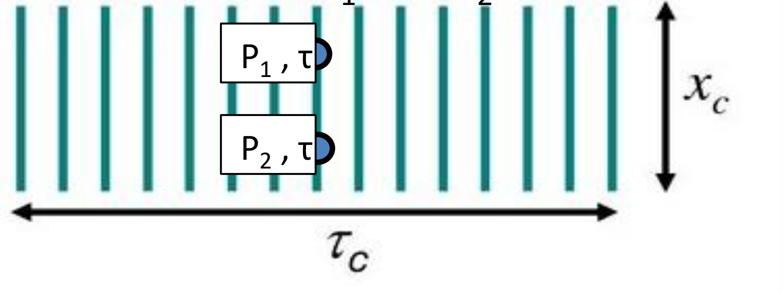
<u>JEMS simulated CTF for long exposure times, 100s</u>
JEOL 2100F HR pole piece: Cc 1.4mm and Cs 1.0mm
Energy spread: 1 eV, sample drift: ***0.2 nm/min!!***
Stability Voltage: <*1ppm/min* & OL current: 1ppm/min, noise: <10 nT



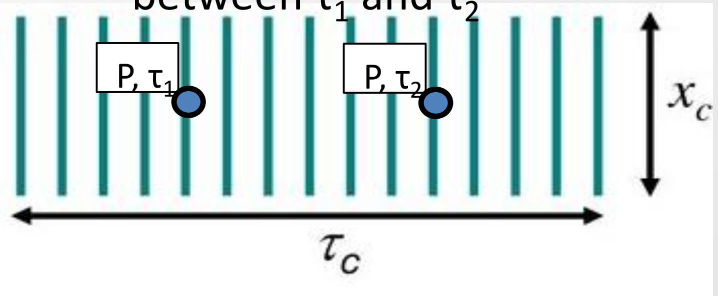
End of Part 1

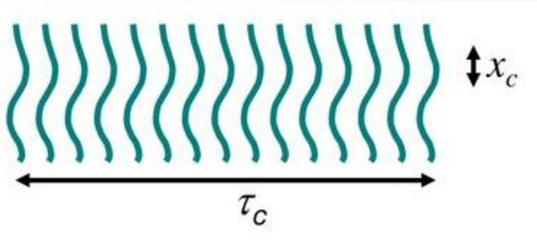
Part 2: UTEM experiments

Spatial coherence
Constant phase difference
between P_1 and P_2

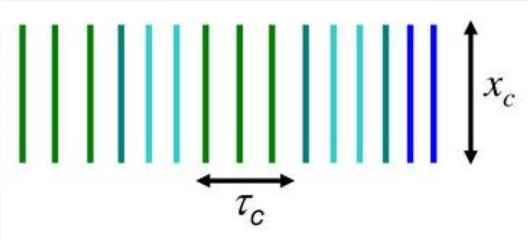


Temporal coherence
Constant phase at point P
between τ_1 and τ_2

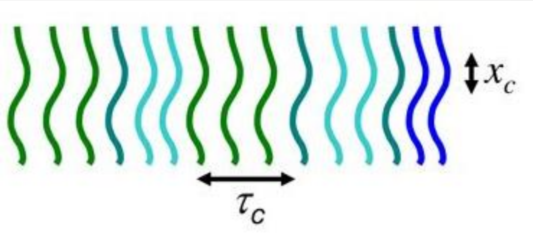




Temporal coherence
Spatial Incoherence
x_c = coherence length
$\tau_c = \infty$



Temporal Incoherence
Spatial coherence
τ_c = coherence time
$X_c = \infty$



Spatial *and* Temporal
Incoherence
x_c, τ_c

Laser sources

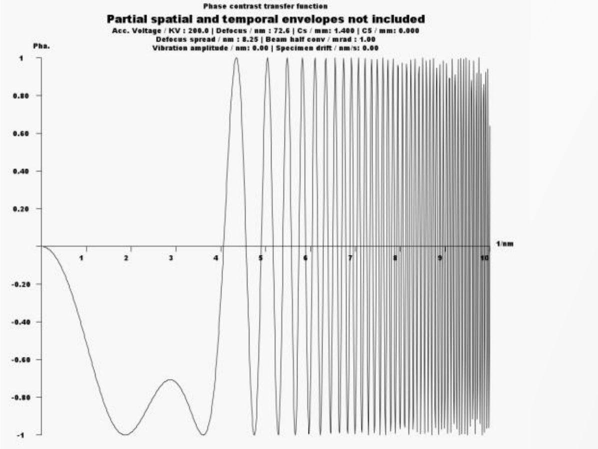
- Temporal coherence given by the inverse of the linewidth
- Excellent spatial coherence (depends on cavity and transport optics)

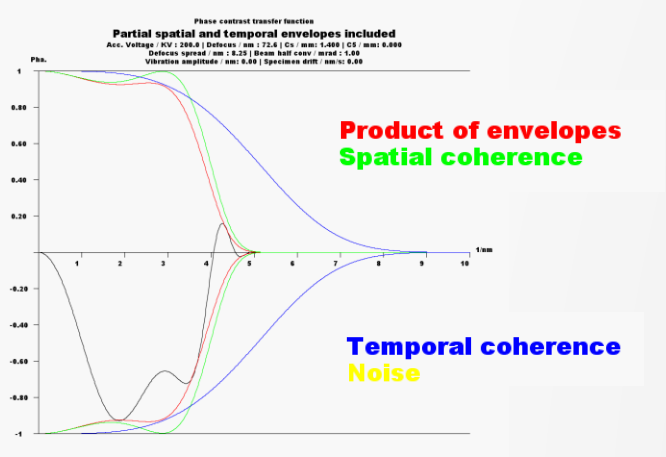
Pulsed electron sources

- Temporally incoherent on the femtosecond timescale
- Spatial coherence depends on the size of the source
- Space-charge degrades coherence

Spatial and temporal coherence

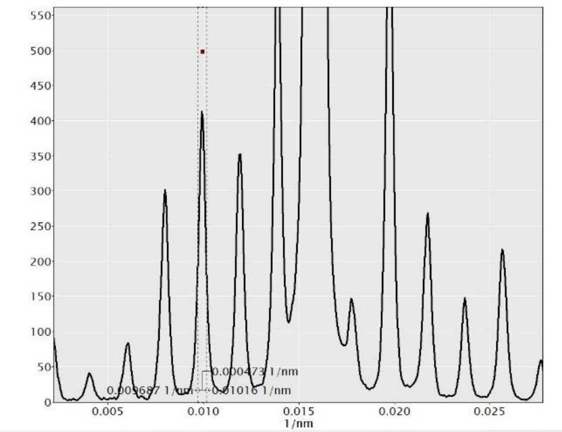
HRTEM phase contrast (spatial resolution)





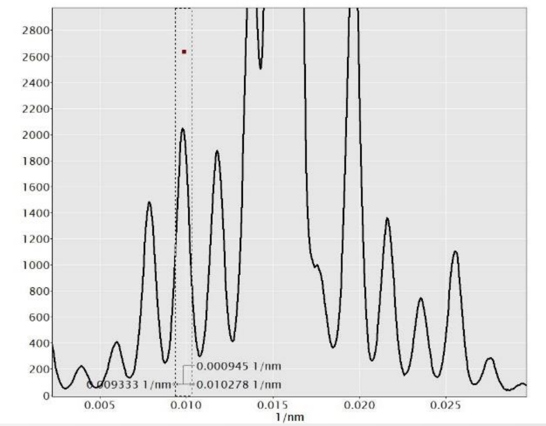
Effect of lens aberrations and source

Diffraction resolution Effect of transverse coherence



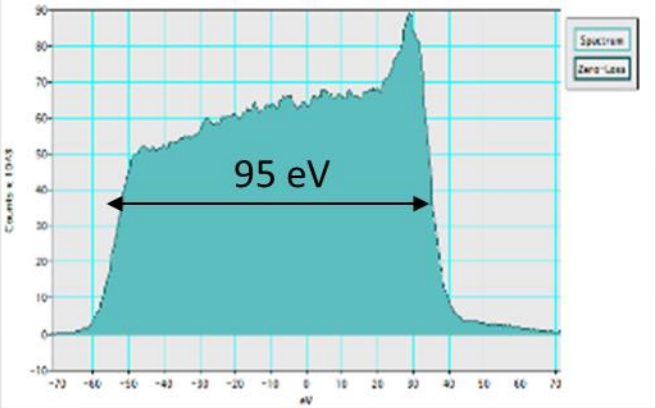
Source brightness is a fixed quantity

Small focused spot, small signal, but high coherence (900 nm)

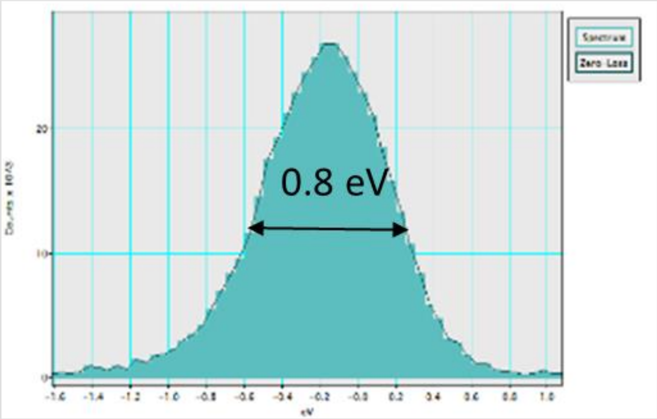


Large spot, 5x higher signal, but lower coherence (450 nm)

Effect of space-charge on energy resolution in fs-EELS

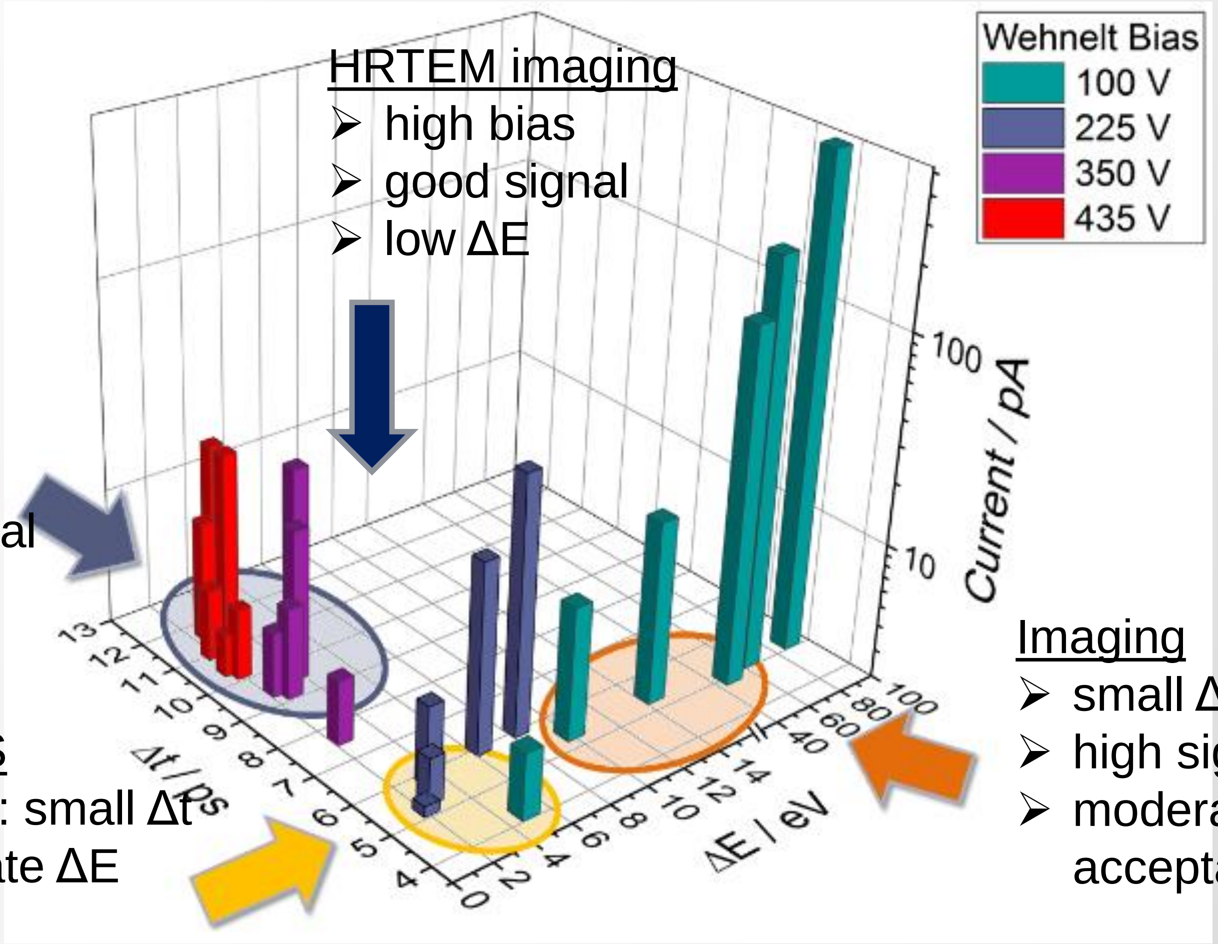


Effect of Boersch effects in the gun



There is a finite Electron Brightness, and trade-offs are made between signal, time resolution, temporal and spatial coherence

High temporal, spatial and energy resolution, as well as high signal are impossible to achieve all at once



HRTEM imaging
- high bias
- good signal
- low ΔE

HR EELS
- small ΔE
- high signal

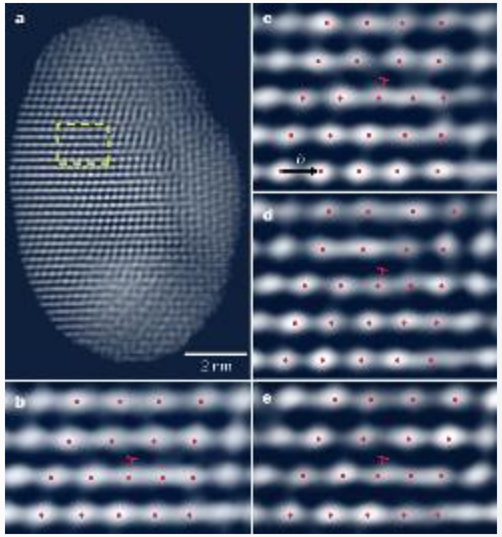
Ultrafast EELS
- central spot: small Δt and moderate ΔE
- weak signal

Imaging
- small Δt
- high signal
- moderate ΔE acceptable

K. Bücker et al, *Ultramicroscopy, Volume 171 (2016) pp.8-18*

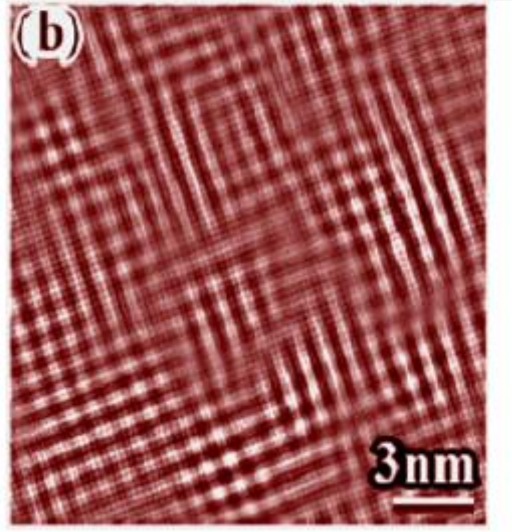
Applications of Ultrafast Transmission Electron microscopy in Condensed Matter Physics

Observing structure (lattice)



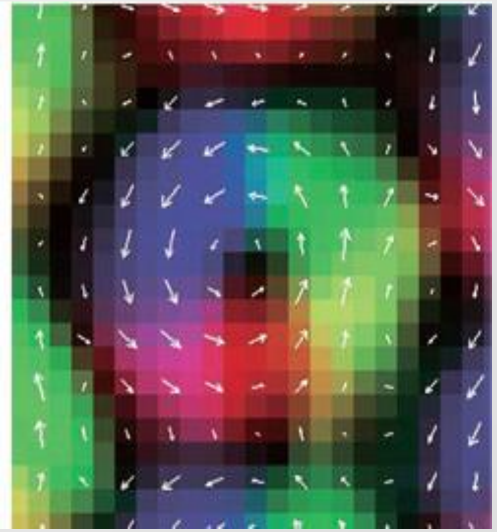
Nature 496 74 (2013)

Observing charges/orbitals



Tokunga et al., Nat. Mater. 5 (2006)

Observing spins

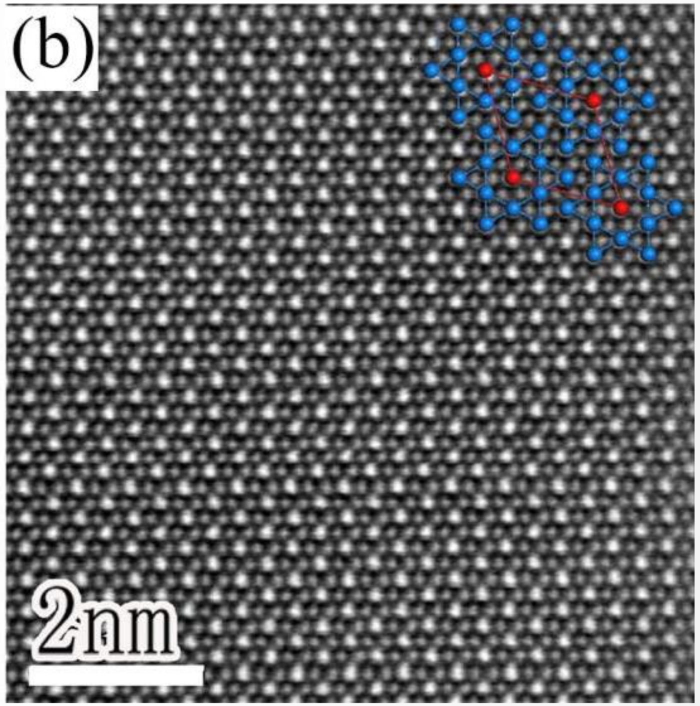


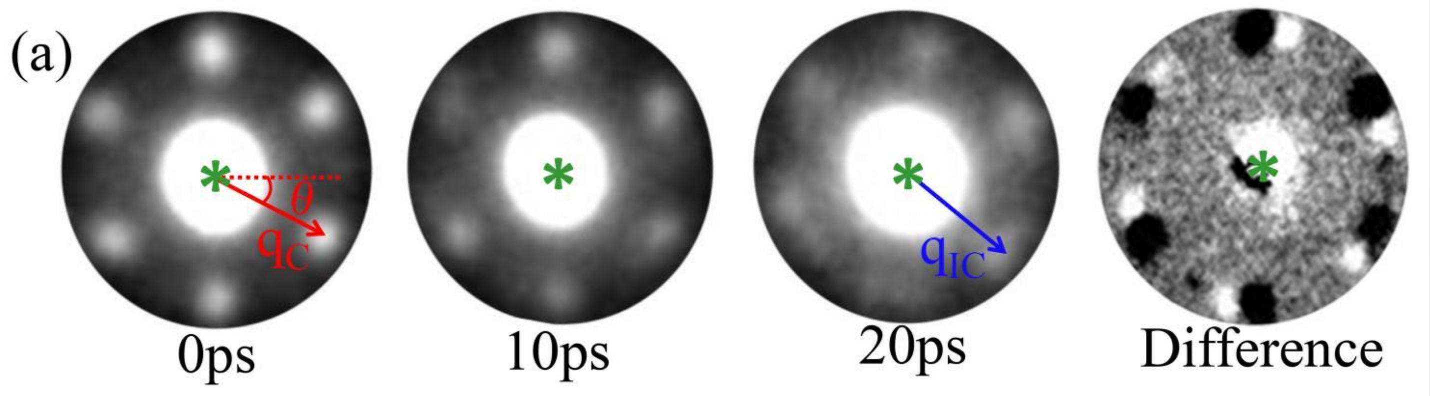
Seki et al, Science 336 (2012)

Textured ground states rule the physics of novel materials

W. Witczak--Krempa, et al., "Correlated Quantum Phenomena in the Strong Spin--Orbit Regime." Annual Review of Condensed Matter Physics, 5 57 (2014).

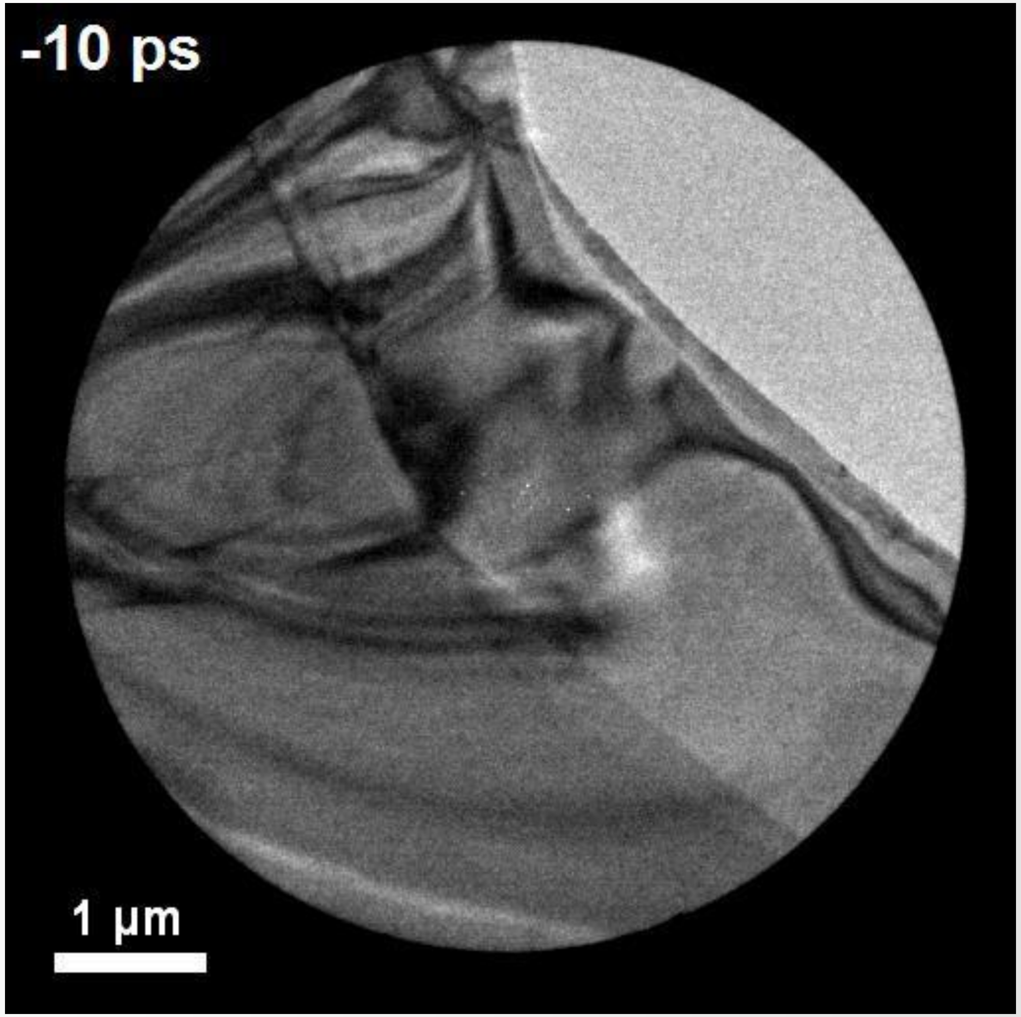
Eamples of UTEM science and applications: charge density waves





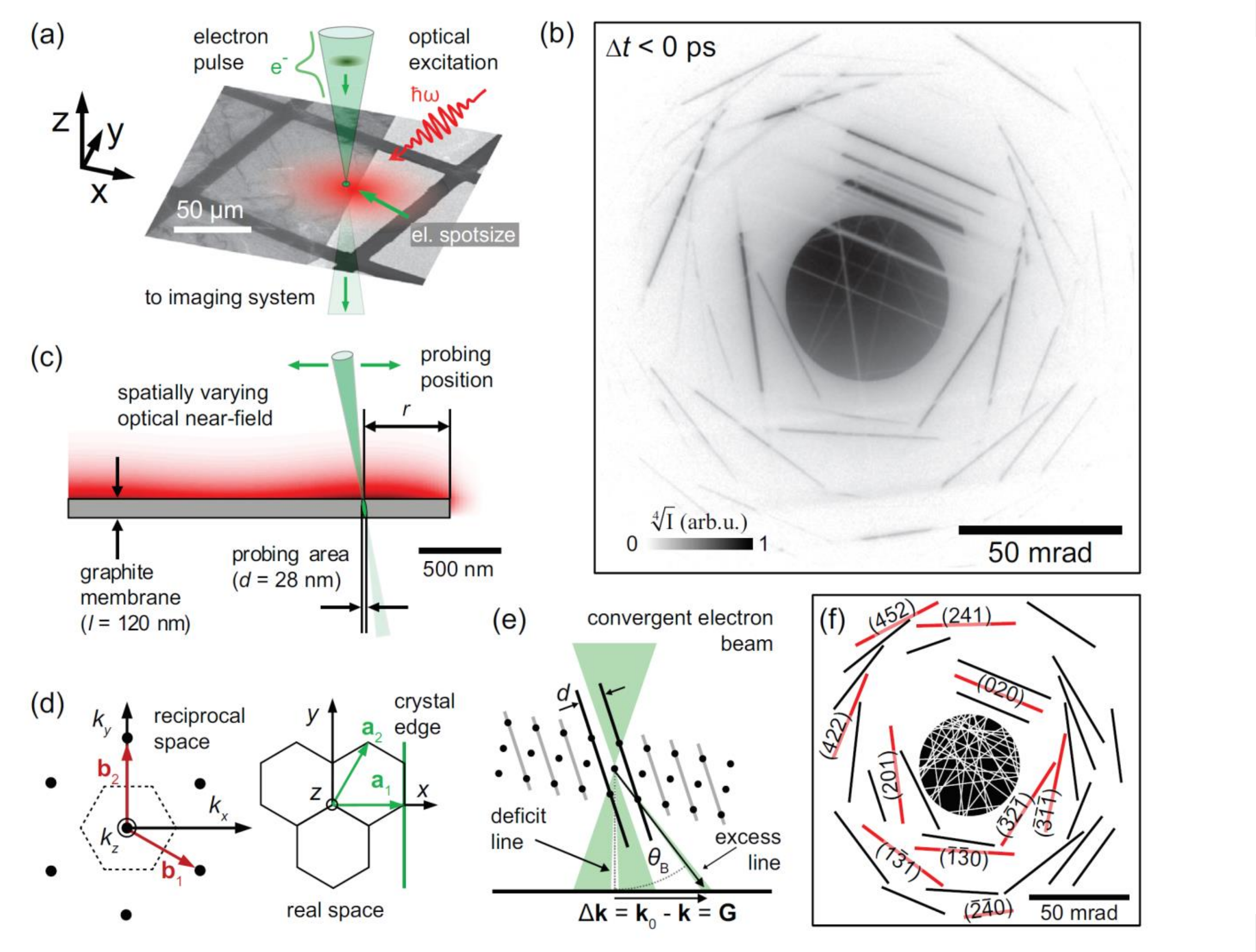
Sun et al., Phys. Rev. B 92 224303 (2015)

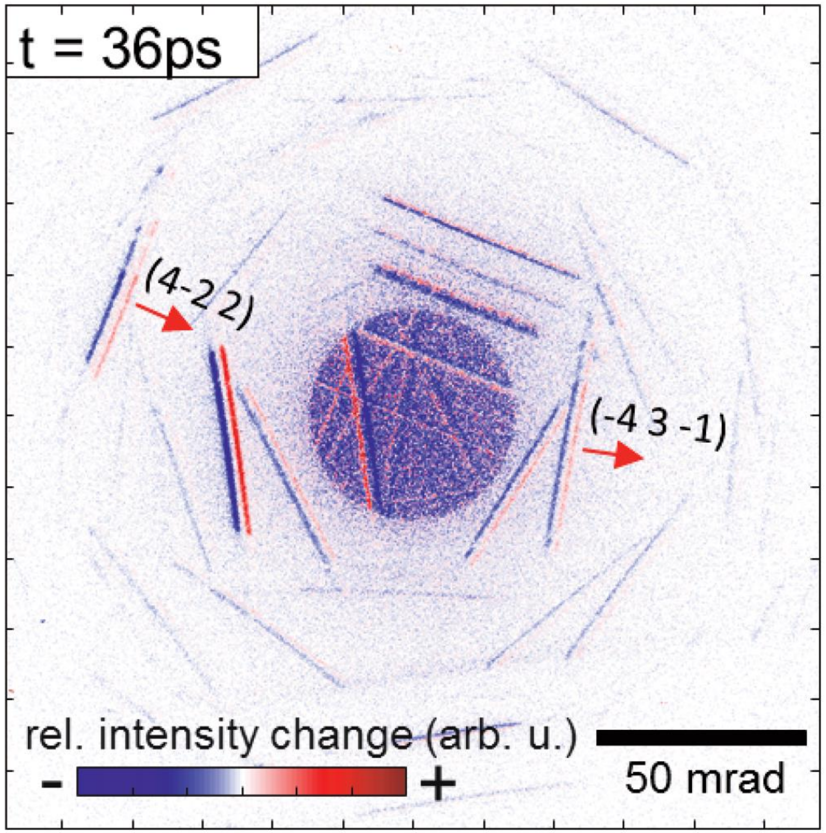
Applications of UTEM: lattice dynamics



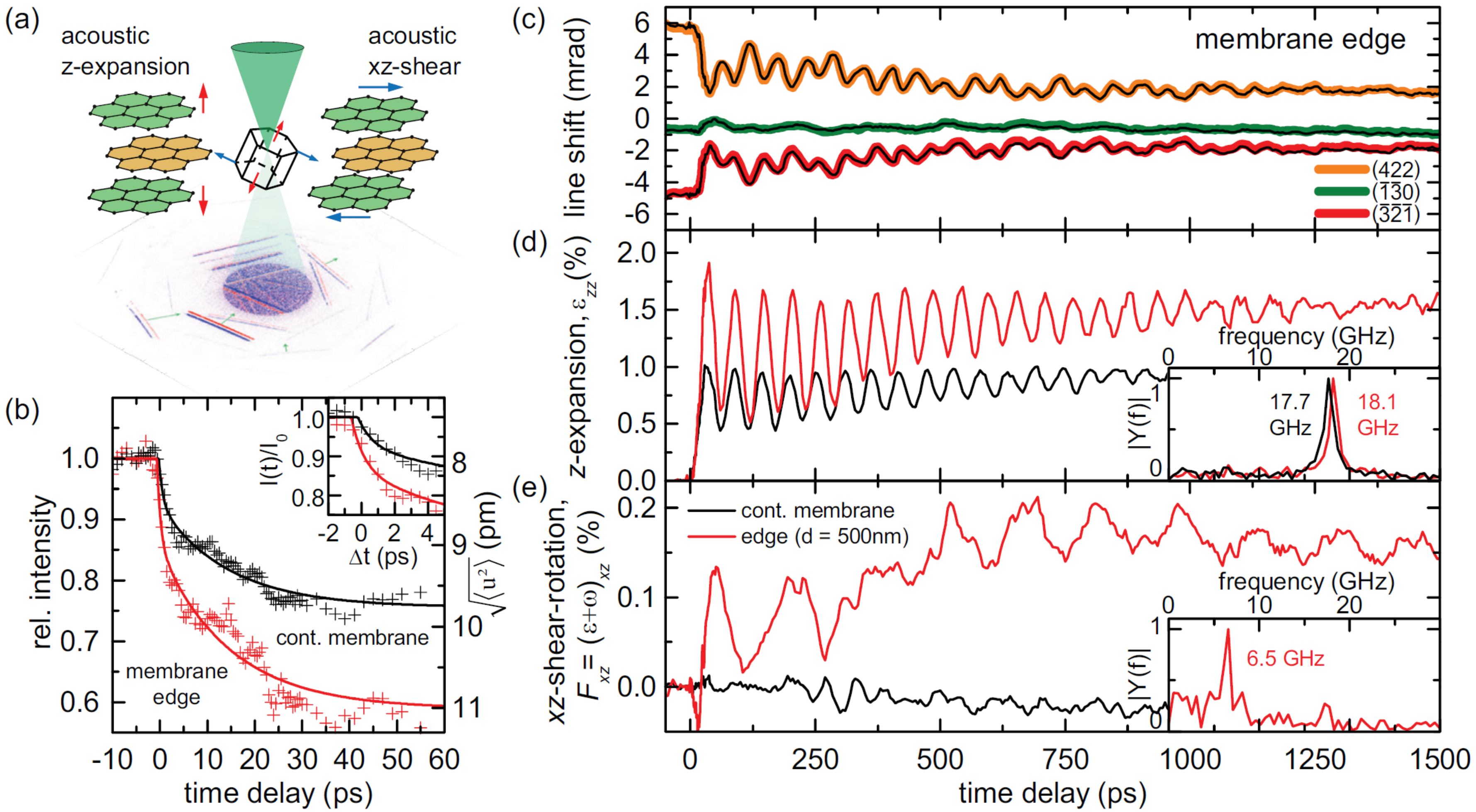
Cremons et al, Nat. Comm. 7, 11230 (2016)

Using Convergent Beam Electron Diffraction (CBED) for probing phonon modes

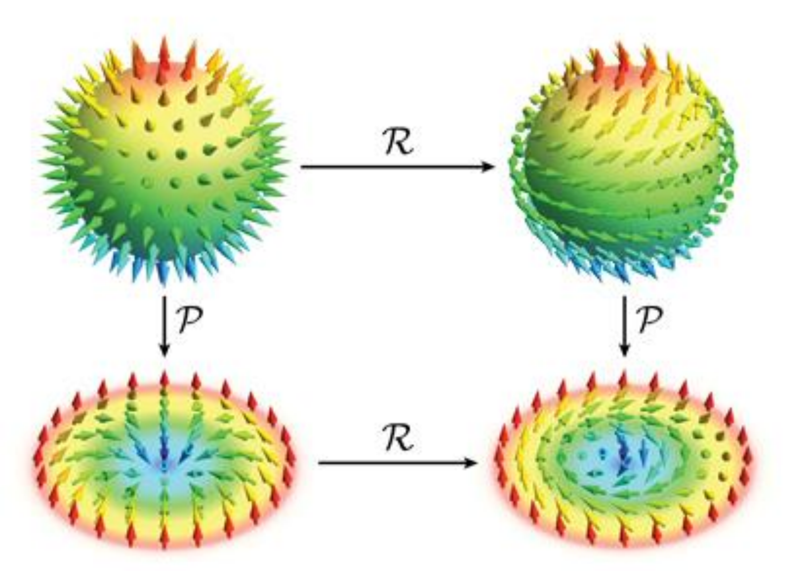




Mapping the excess line shifts give the vibrational harmonics of the system for breathing and in-plane shear modes



Skyrmions are nanometer sized topologically nontrivial defects



Néel skyrmion

Bloch skyrmion

Dzyaloshinskii-Moriya interaction
(DMI) favors canting of
neighboring spins

Bloch type
MnSi, FeCoSi, FeGe, Cu2OSeO3,
CoZnMn…

Néel type
Ferromagnet/heavy metal bilayers

Racetrack memory:

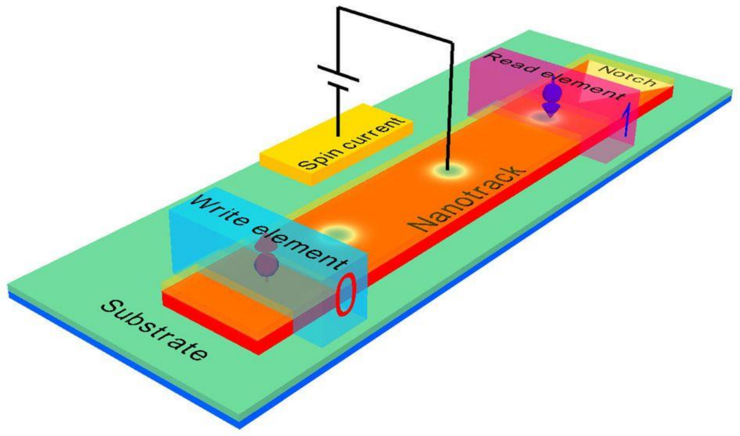


Image from Zhang et al. Sci Rep. **5** 7643 (2015)

The defined chirality of the spin configurations provides topological barrier (protection) that stabilizes the skyrmions

Ultrafast Cryo-Lorentz TEM TEAM in LUMES

Gabriele Berruto

Ivan Madan

Help with the experiments:

EPFL, ER-C Julich: Y. Murooka

EPFL: G. M. Vanacore

Sample preparation:

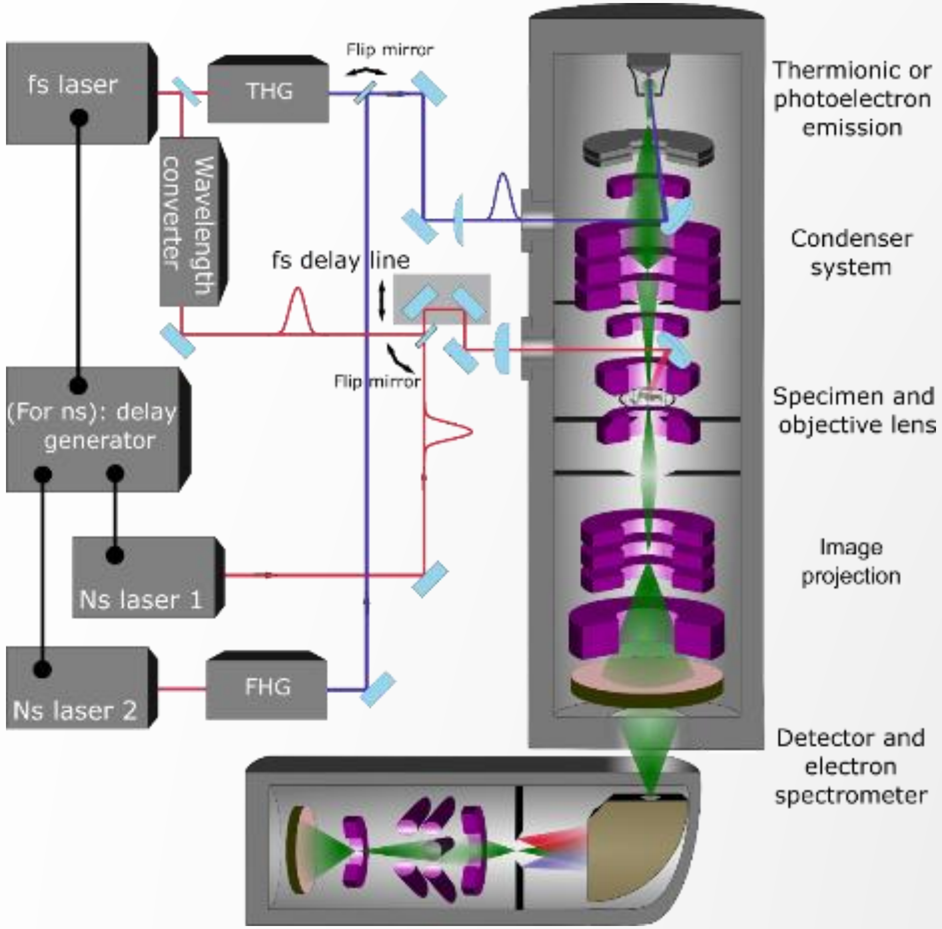
Uni Glasgow: R. Lamb, D. McGrouther

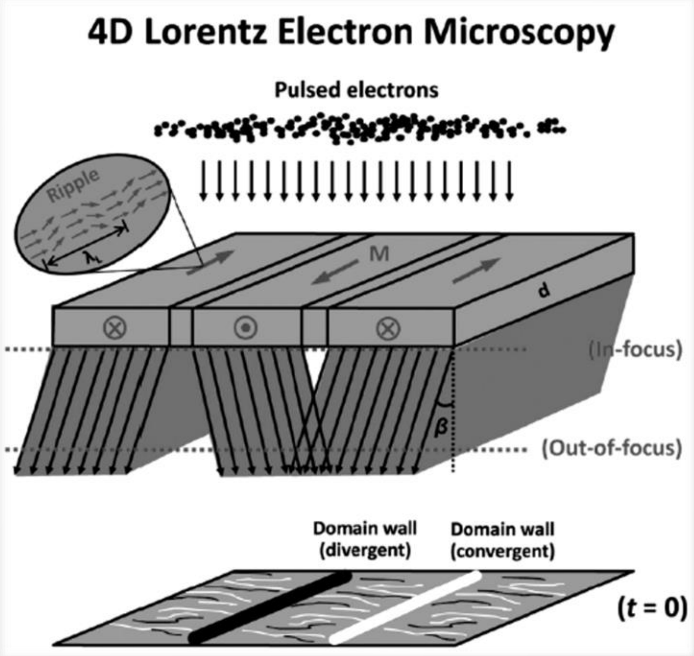
Uni Osaka: Y. Togawa

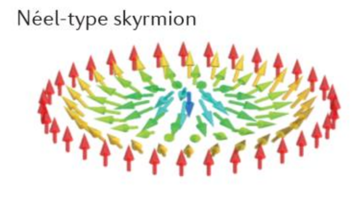
Funding:

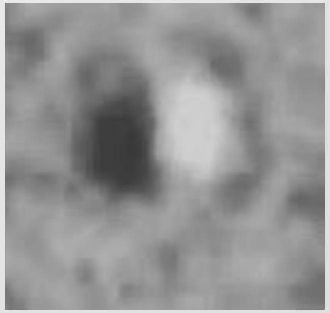
must NanoSkyrmionics FNSNF

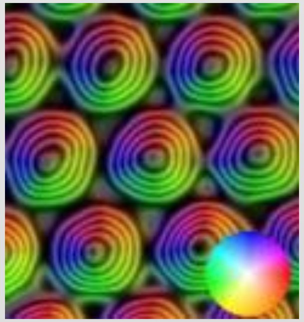
We use time-resolved *cryo*-Lorentz-transmission electron microscopy to characterize Skyrmion dynamics





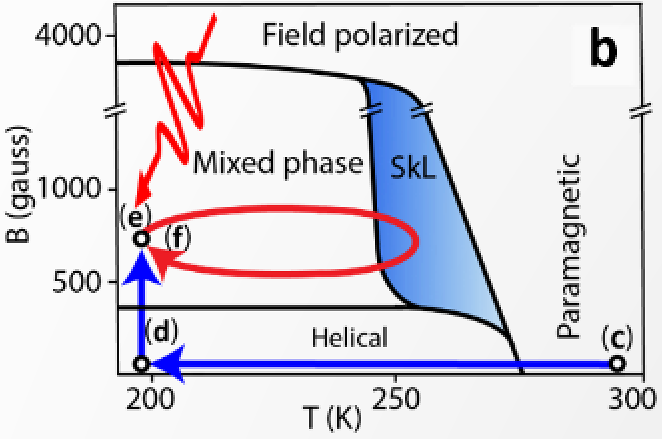




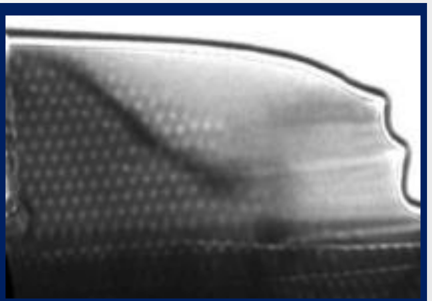


Manipulation of the magnetization texture using ultrafast laser pulses, and monitoring with high real space (nm) and time (ps) resolution

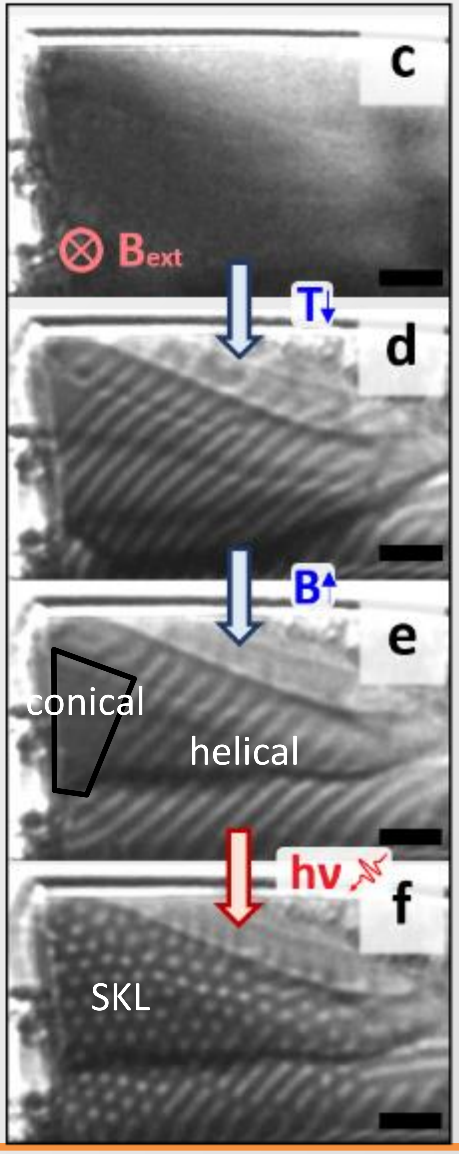
Writing and erasing of Skyrmions was studied using *ns*-stroboscopic pump-probe experiments in a cryo-Lorentz imaging mode



- Large and regular SkL upon adiabatic field cooling



- Skyrmions can be created by a single laser pulse
- Skyrmions erasing by magnetic field excitation, or by laser pulses with much higher fluence



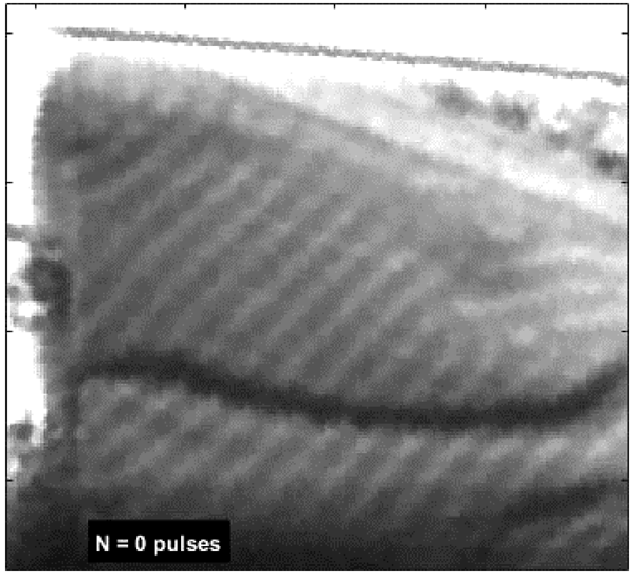
T= RT
$\vec{B}$= 0 G

T= 200 K
$\vec{B}$= 0 T

T= 200 K
$\vec{B}\sim$ 750 G

Write Skyrmions
using laser pulses
$\vec{B}\sim$ 750 G

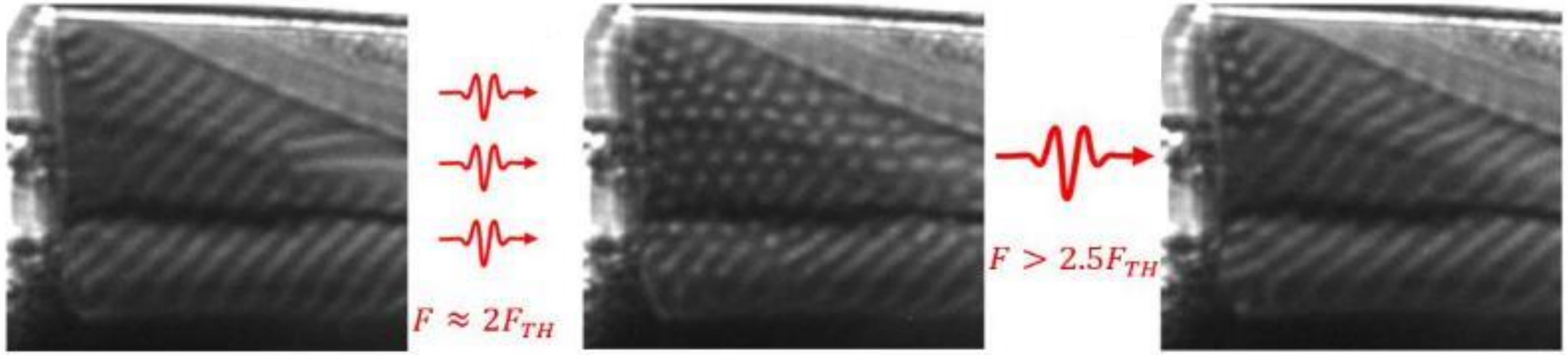
It is possible to "photocreate" skyrmions by irradiating the sample (in the helical phase) with multiple fs pulses



“Mixed” phase regime

Photocreated SkL

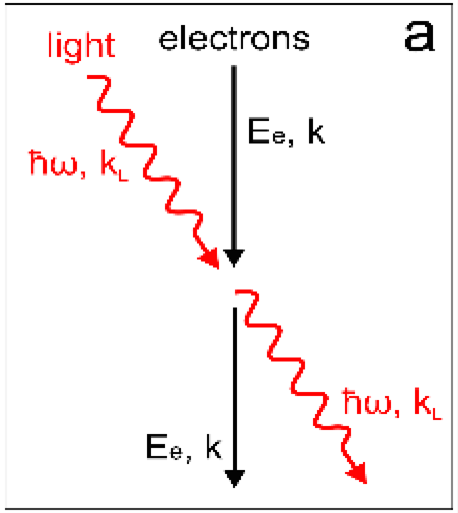
Photo-Erased SkL

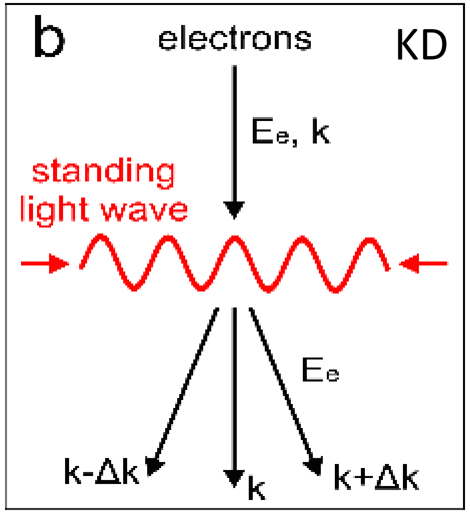


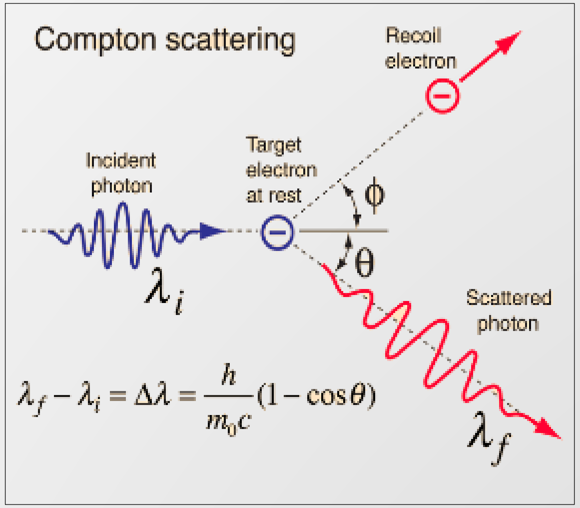
Skyrmions are created at the edges, gradually filling of the sample with skyrmions with multiple laser pulses

At a fluence of 2.5X above the threshold, skyrmions are mostly erased, i.e, they are annihilated, but a few of them reform during the cooling

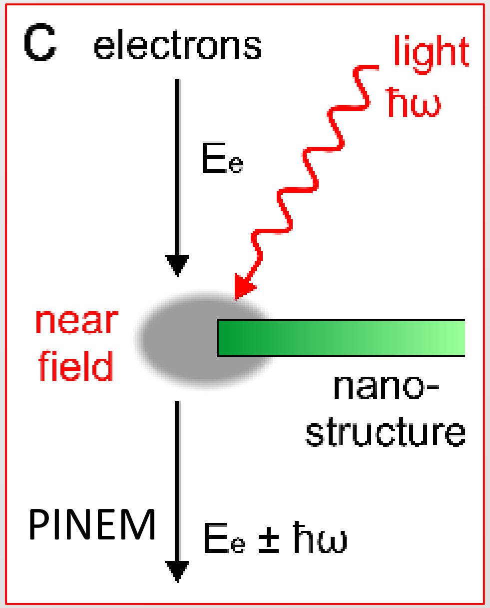
Example: Coherent control of Light-Electron interactions



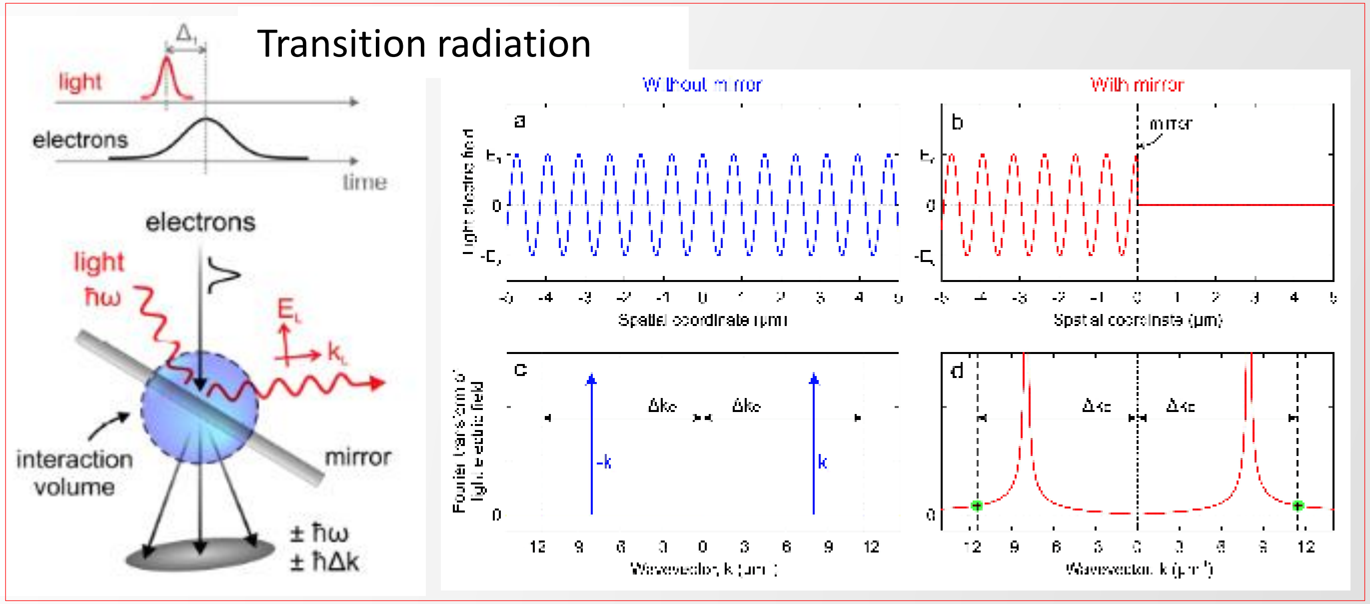




$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

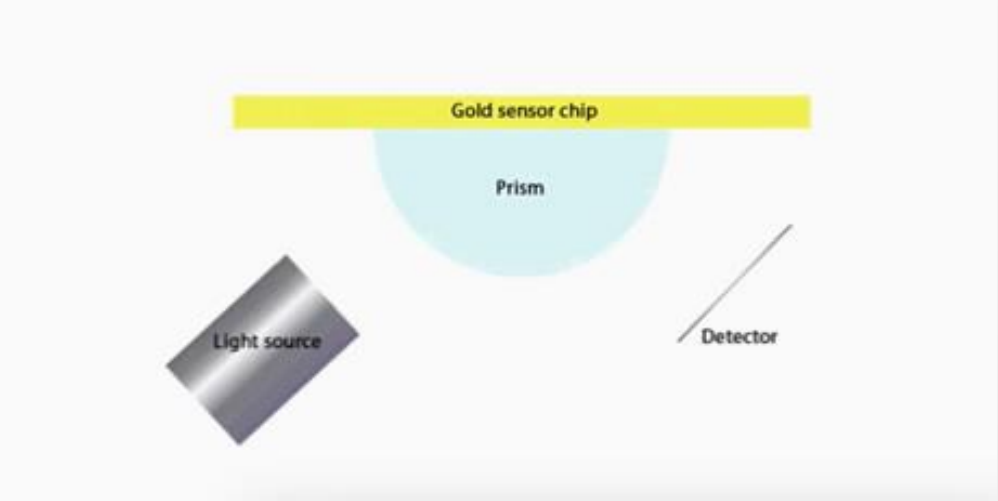


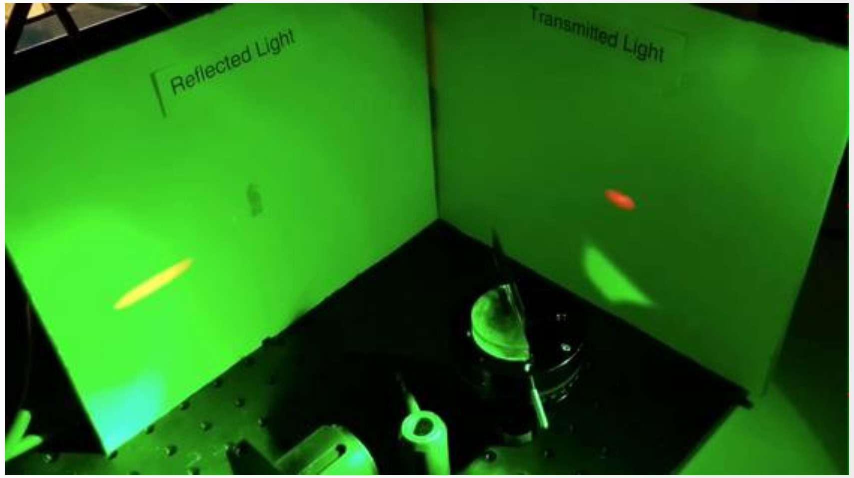
Transition radiation



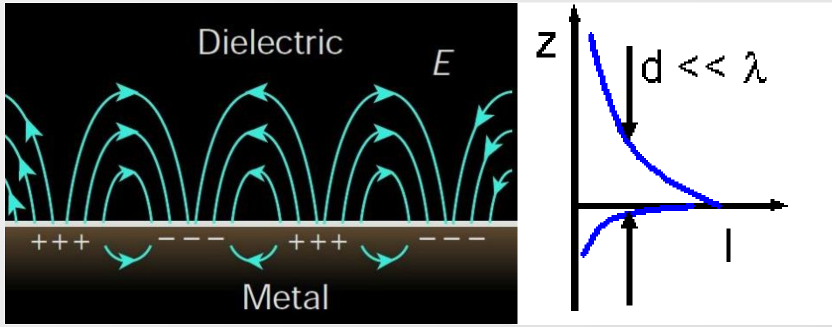
How can light and e^- interact?

Surface plasmons polaritons and plasma resonances

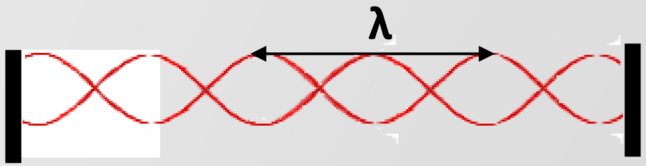




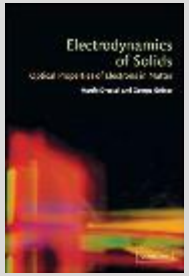
Surface plasmon:
Electrons-light coupled at an interface



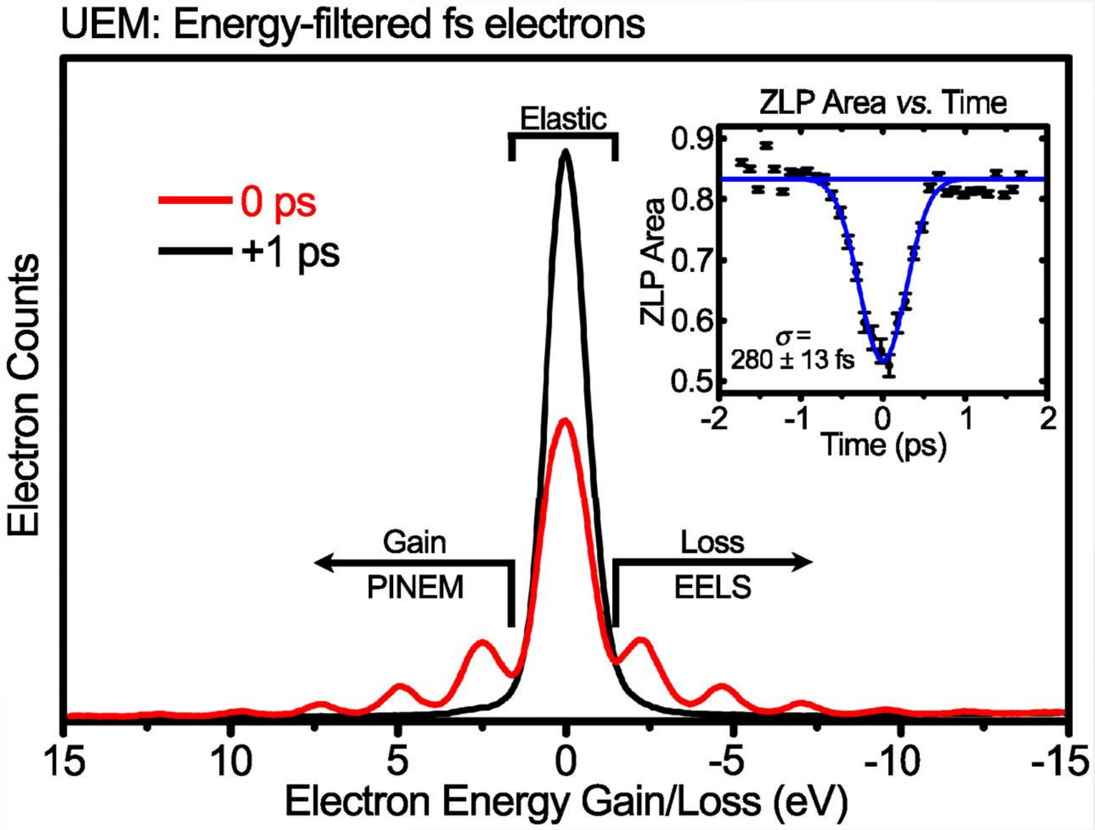
Plasma resonance



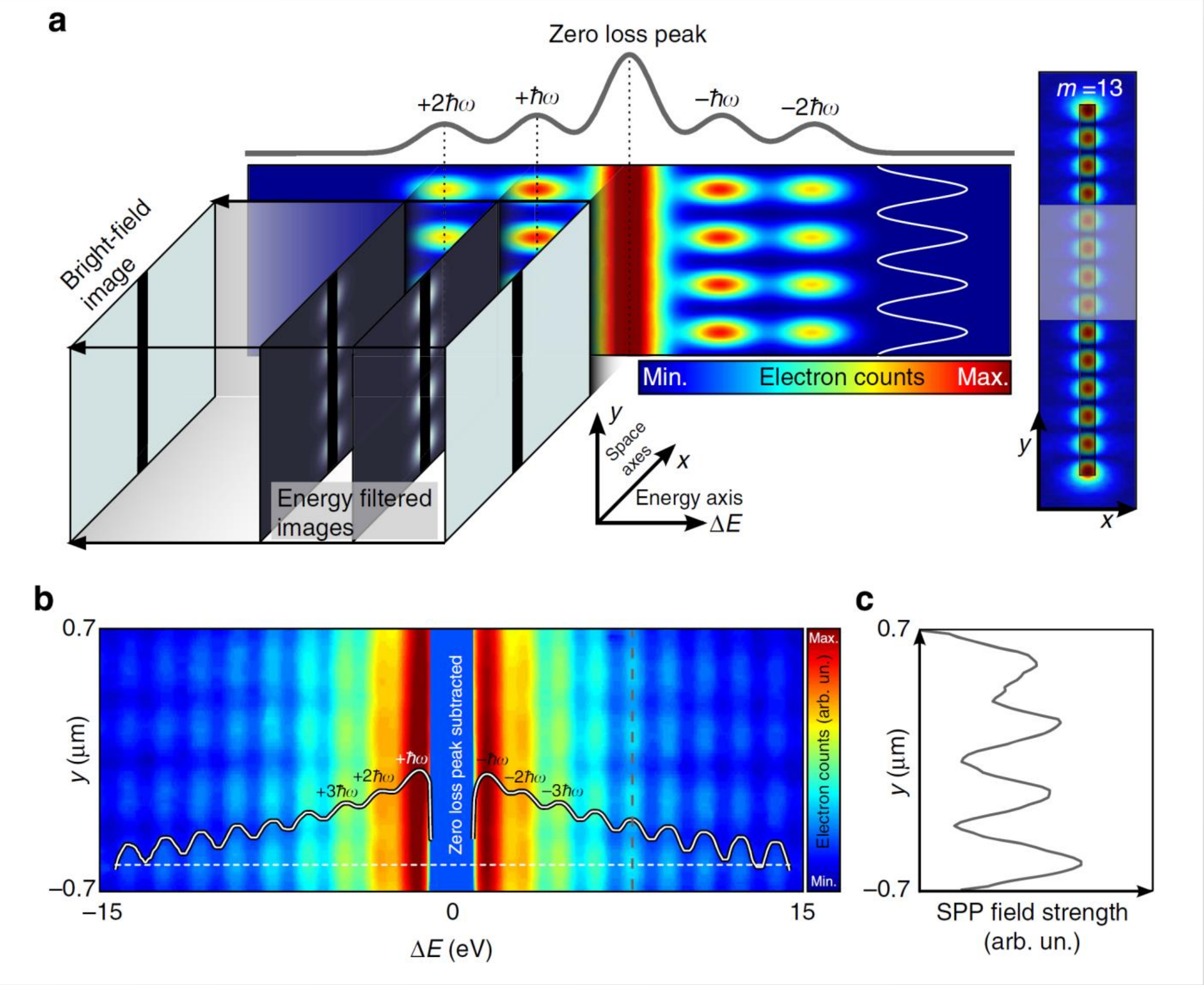
Suggested reading: Dressel, “Electrodynamics of solids”



Energy filtered TEM mapping in UTEM PINEM experiments

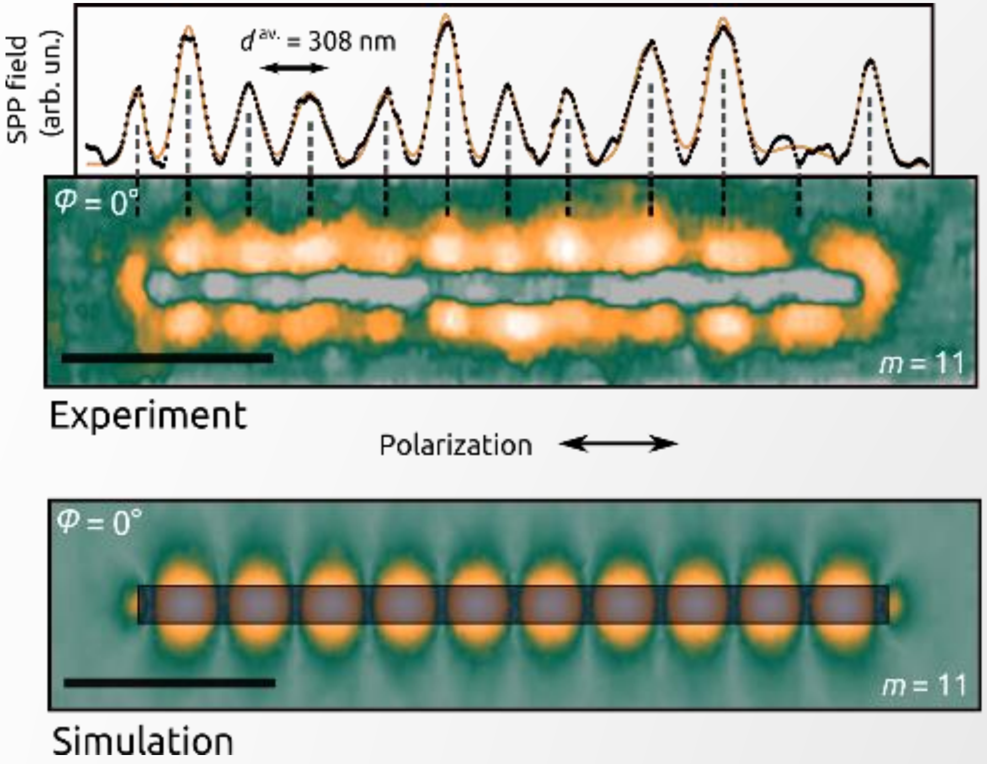


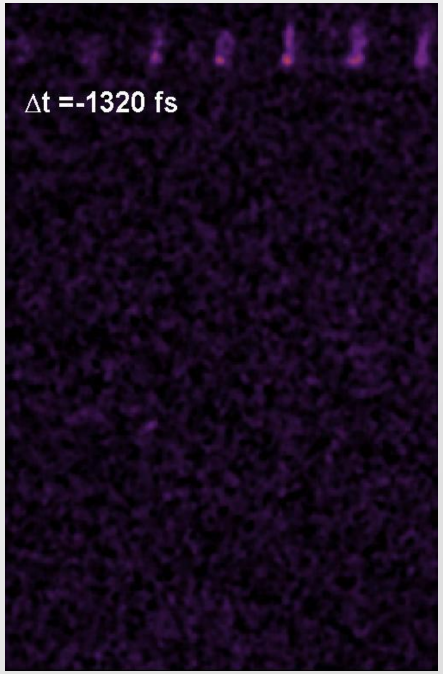
David J. Flannigan, Brett Barwick, and Ahmed H. Zewail, Proceedings of the National Academy of Sciences **107** (22), 9933 (2010).

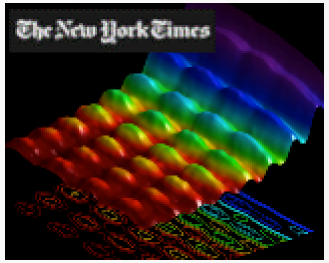


L. Piazza, T. T. A. Lummen, E. Quiñonez, Y. Murooka, B. W. Reed, B. Barwick, and F. Carbone, Nature Communications **6** (1), 6407 (2015).

Surface plasmons polaritons and plasma resonances





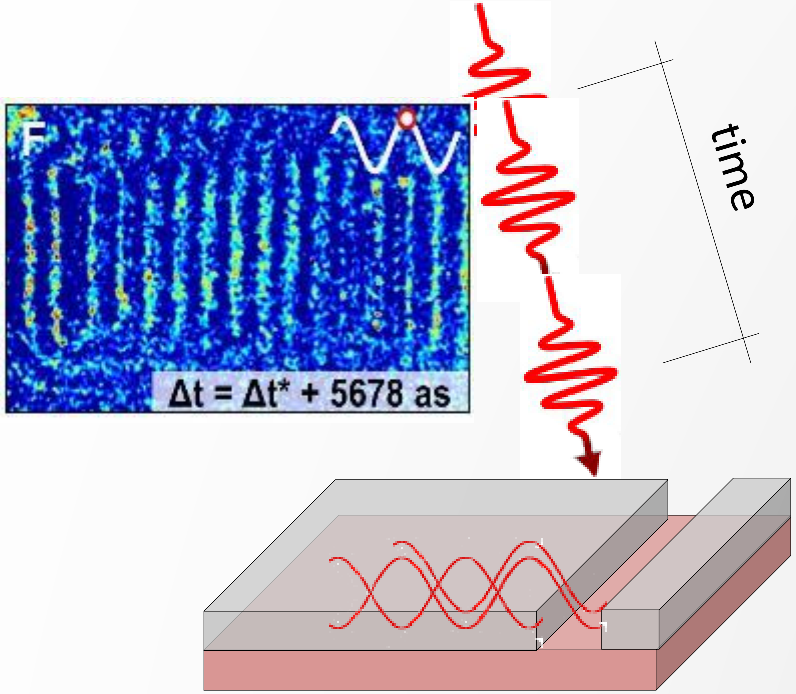


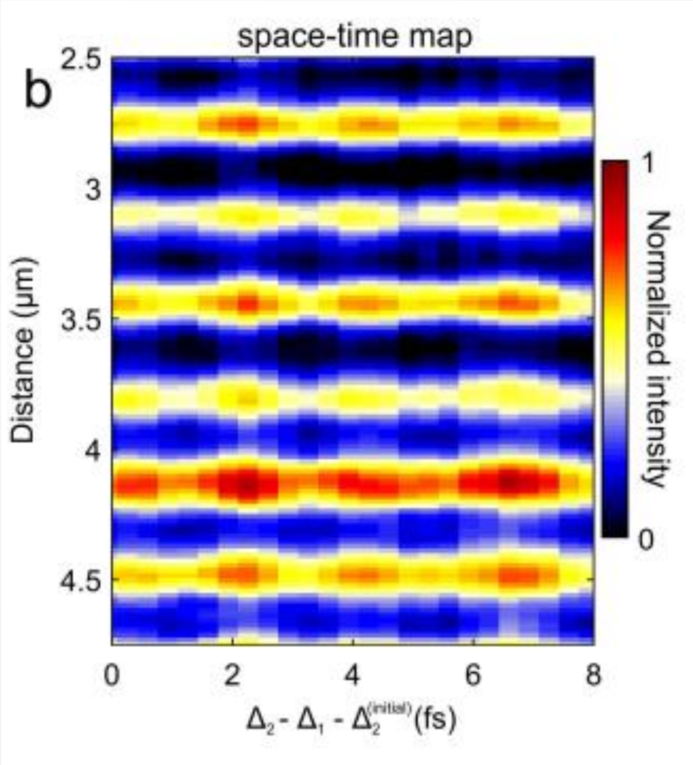
Piazza et al., **Nat. Comm.** 6 6407 (2015)

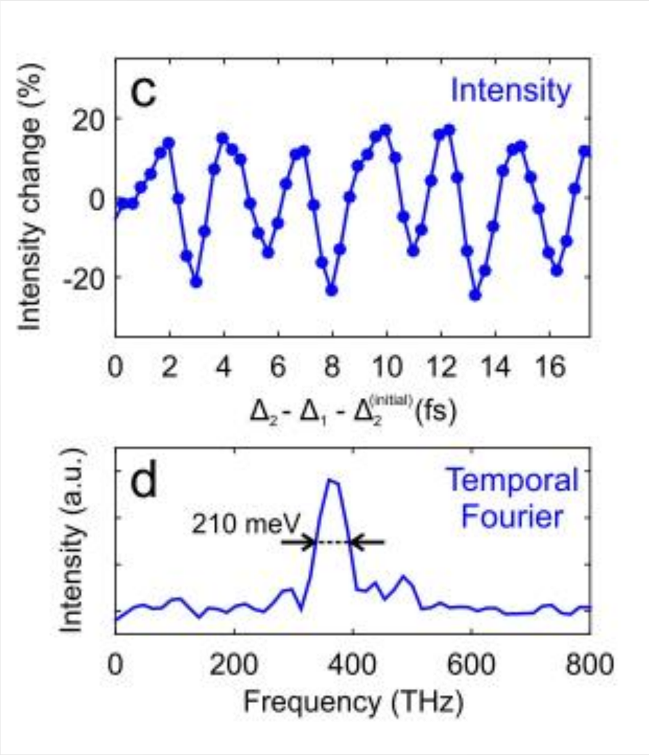
Most cited article in Nat Comm since 2015

Lummen et al., **Nat. Comm.** 7 13156 (2016)

Coherent control of plasma resonances

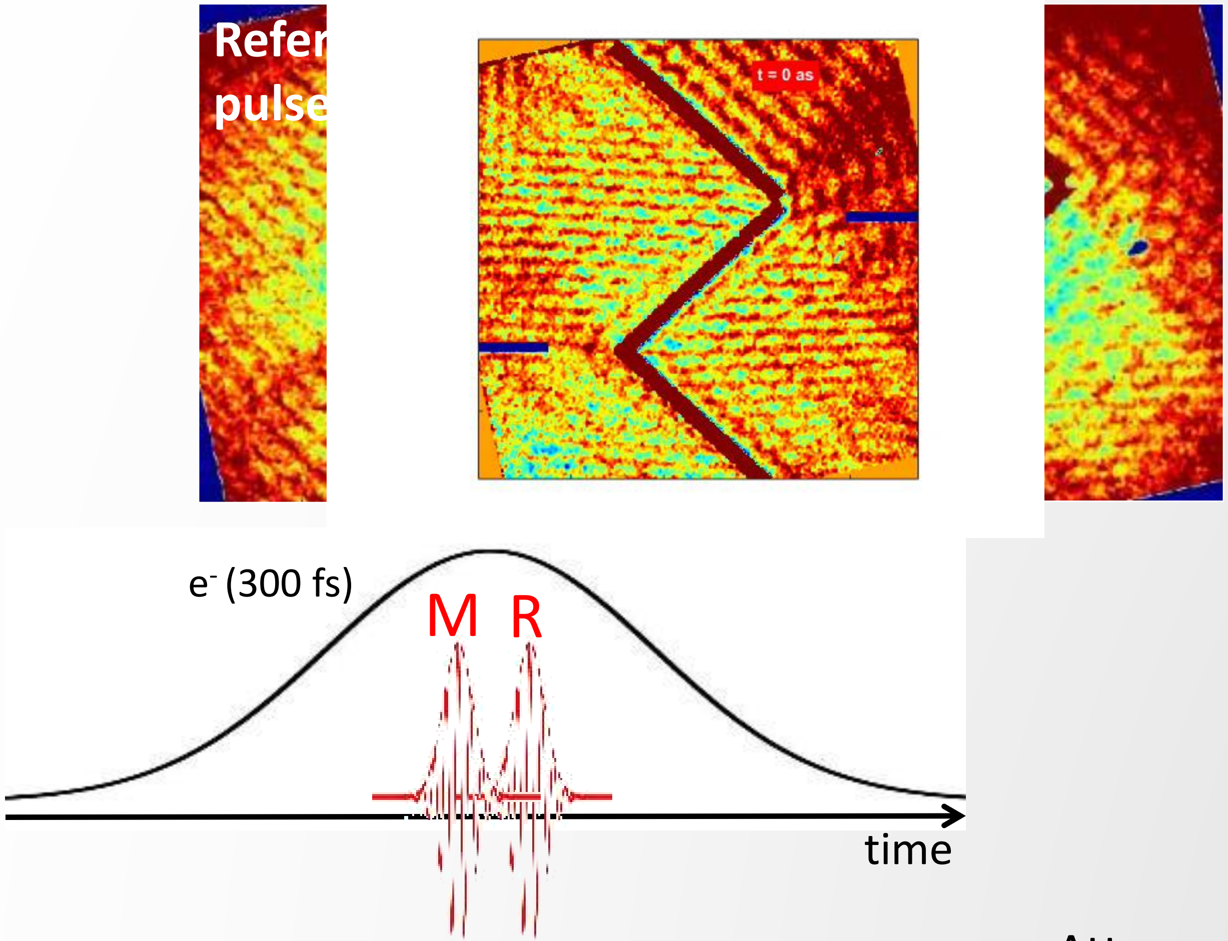


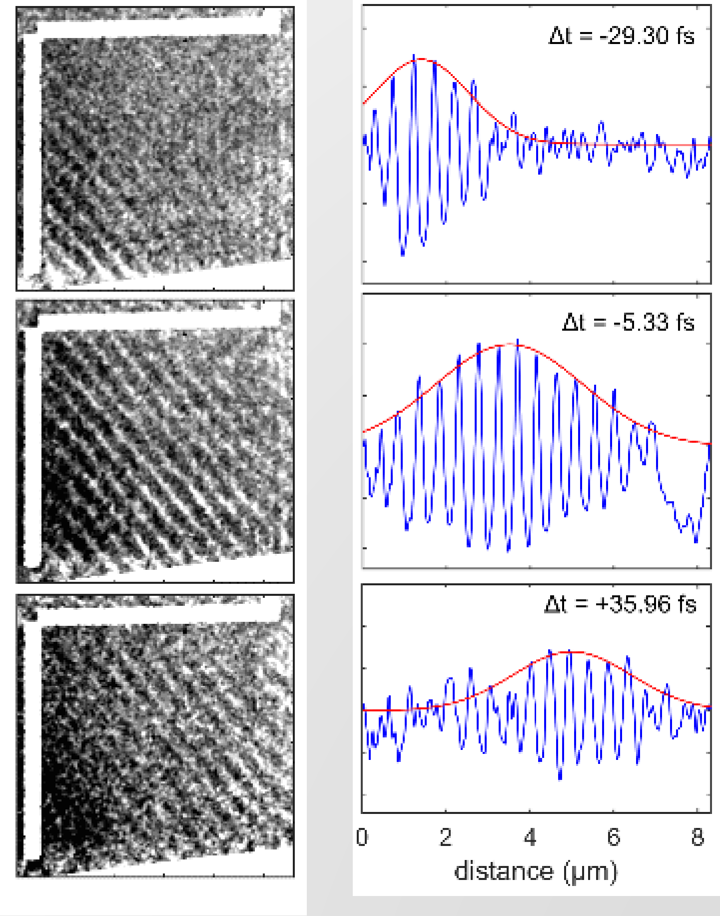




Vanacore, et al. **Nat. Comm** 9 2694 (2018)

Holography of plasma resonance

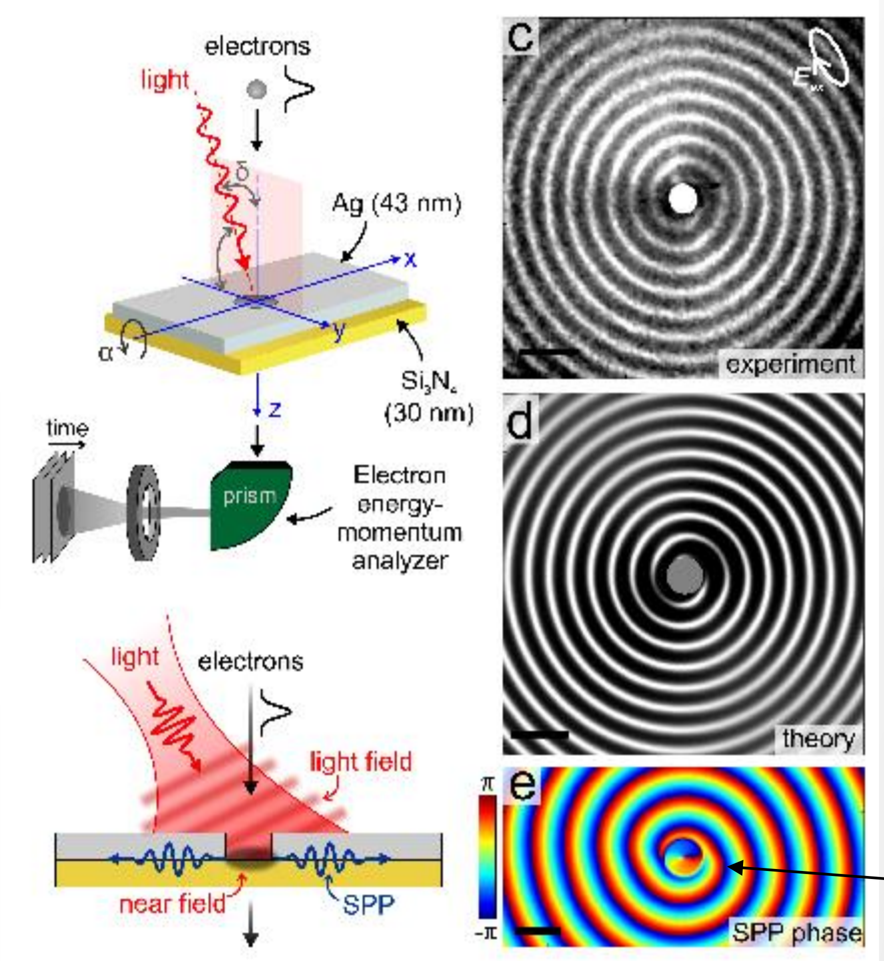




Madan et al, **Science Advances** 6 eaav8358 (2019)
News and Views article:
Ropers, **Nature** 571, 331 (2019)

- Attosecond mapping of plasmon propagation
- Direct measurement of group and phase velocity

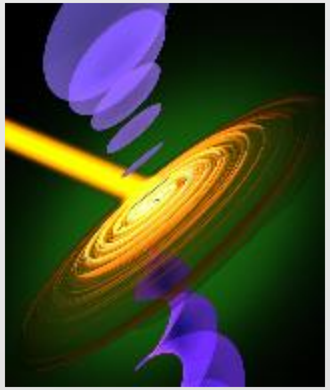
Coherent control of the transverse electron wavefunction



- Chiral SPP launched by elliptically polarized light

- Simulated Chiral SPP

- A chiral plasmonic field can impart a phase singularity onto the transverse component of an e^{-} wavefunction

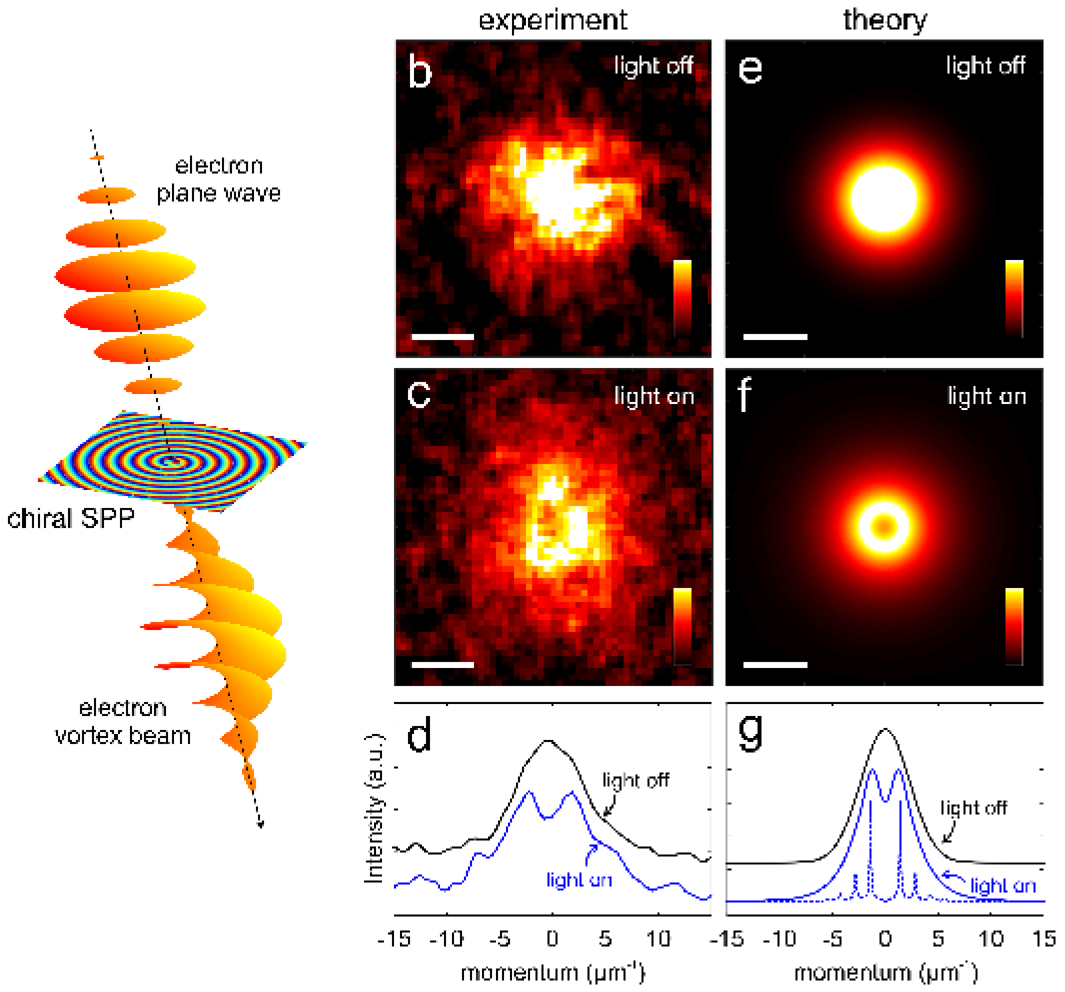


Vanacore et al., **Nature Materials** 18, 573 (2019)

New and Views article: Jun Yuan **Nature Materials** 18, 533 (2019)

https://www.youtube.com/watch?time_continue=5&v=TIJ-mlh2LSI&feature=emb_logo

Generation of electron vortex beams

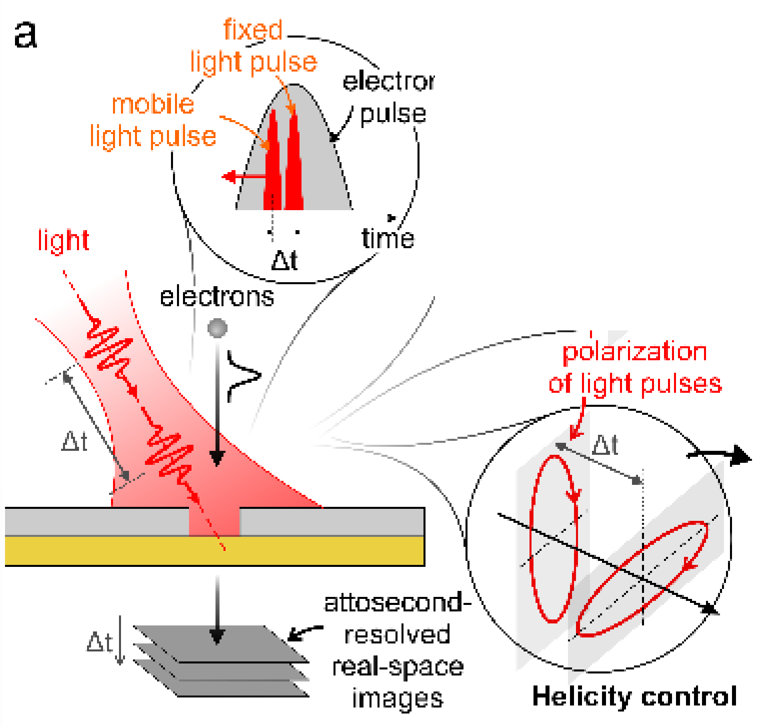


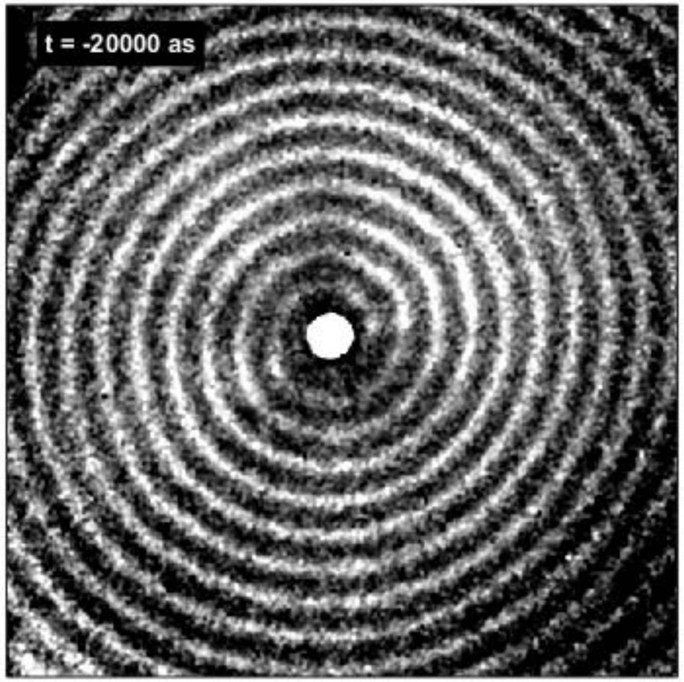
Vanacore et al., **Nature Materials** 18, 573 (2019)

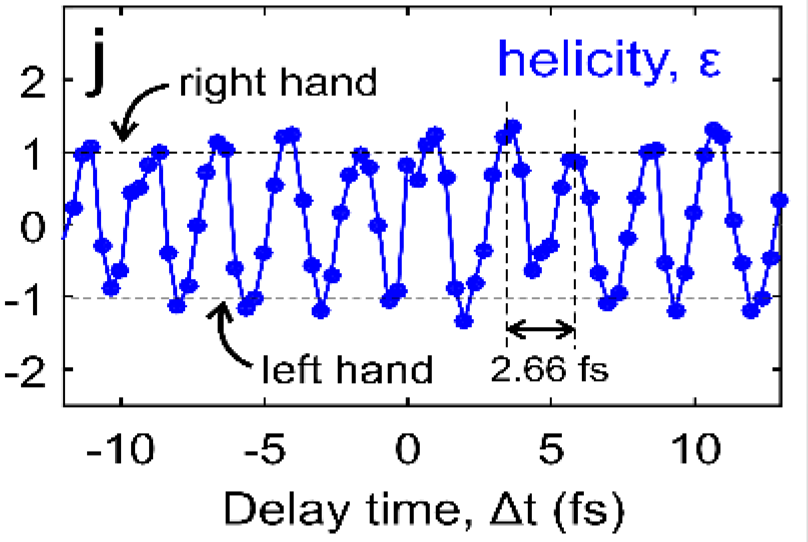
Electron wavefunction microscopy
in momentum space

High Dispersion Electron Diffraction (CL~80m)

Coherent control of vortex beams

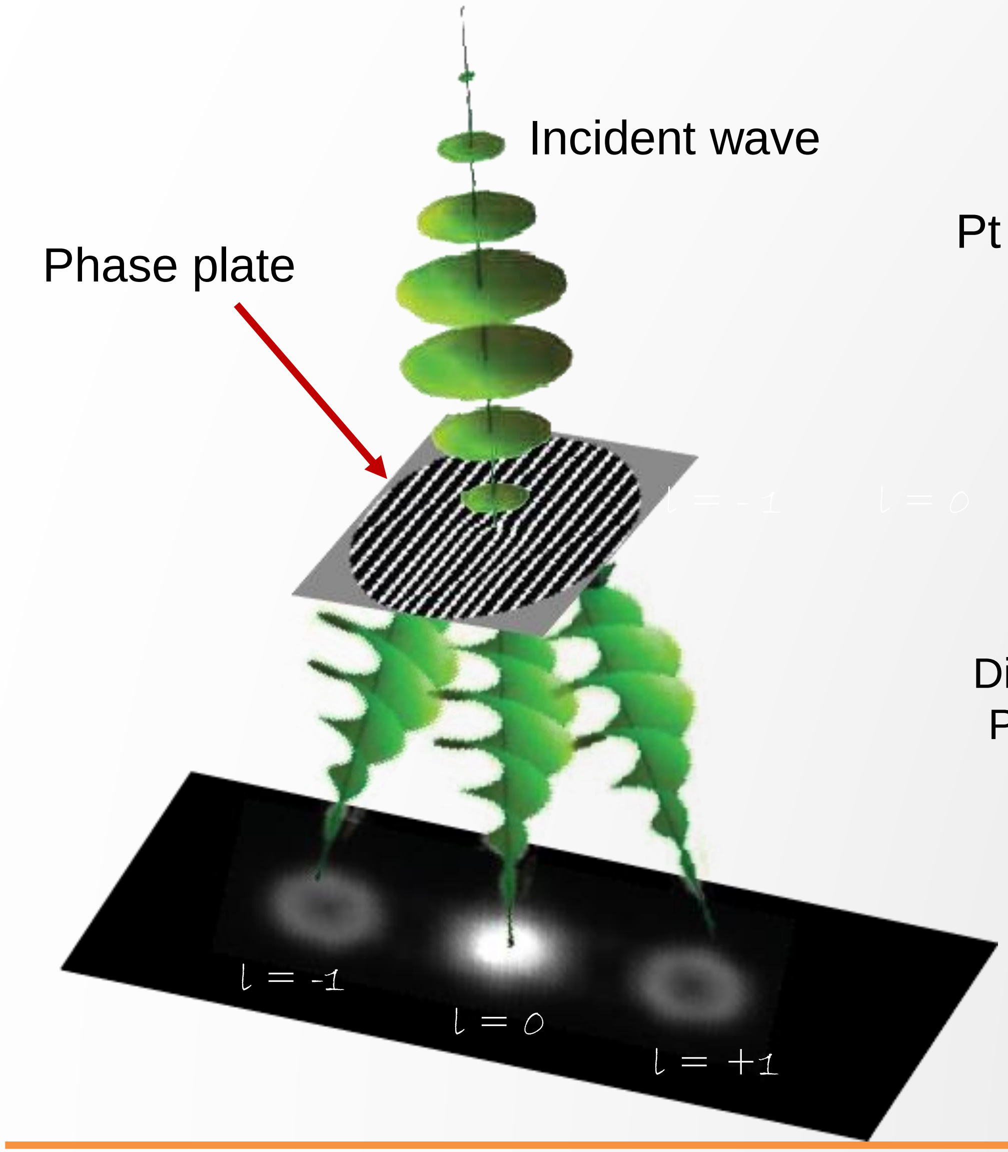






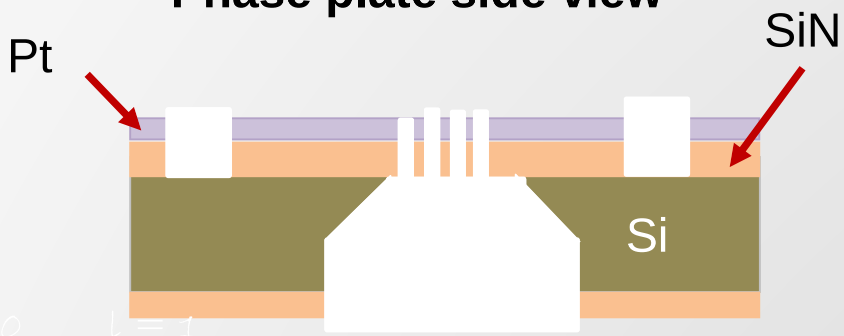
Three pulses experiment: attosecond control of the topological charge of an e$^-$ wavefunction between + 1 and - 1

Generating vortex electron beams with forked phase plates



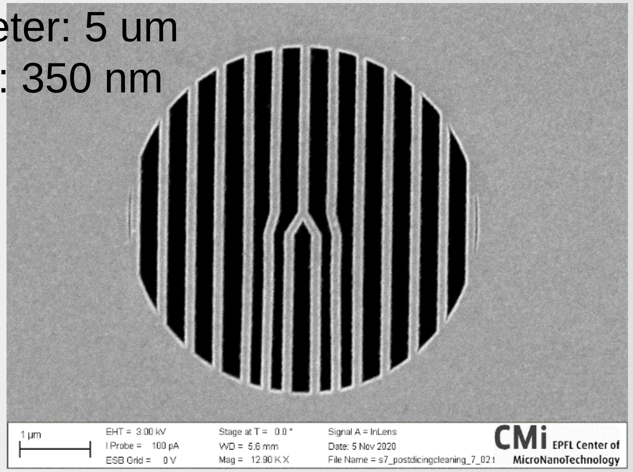
Nanofabrication

Phase plate side view



SEM image

Diameter: 5 um
Pitch: 350 nm



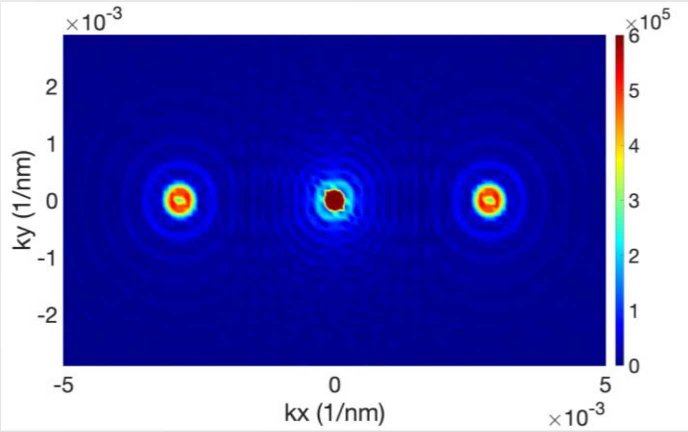
1 µm

EHT = 3.00 kV
I Probe = 100 pA
ESB Grid = 0 V

Stage at T = 0.0 °
WD = 5.6 mm
Mag = 12.90 K X

Signal A = InLens
Date: 5 Nov 2020
File Name = s7_postdicingcleaning_7_02.t

Simulations

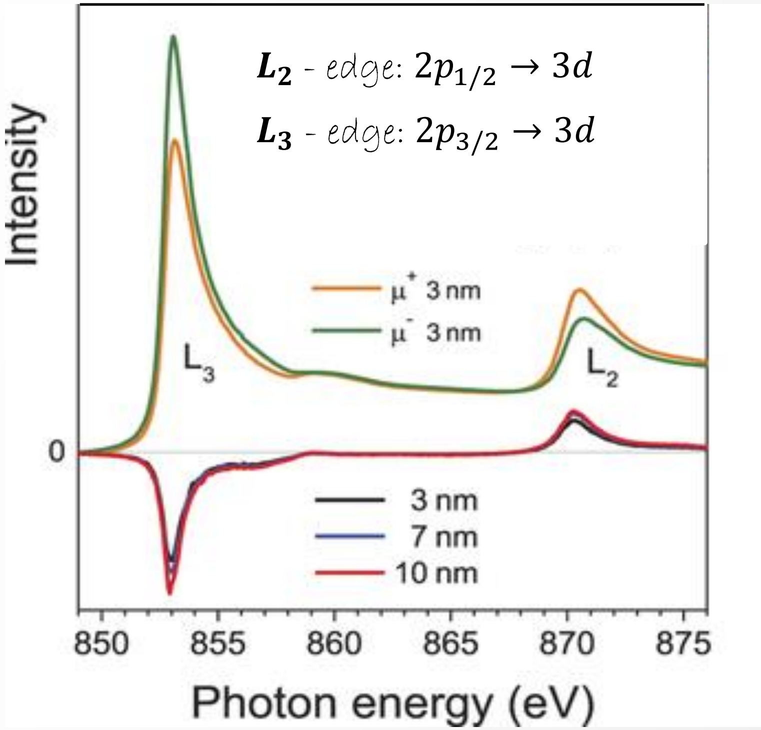


Experimental

Time-resolved Electron Magnetic Circular Dichroism (EMCD)

XMCD from literature (H. Shiozawa et al. Scientific Reports (2015))

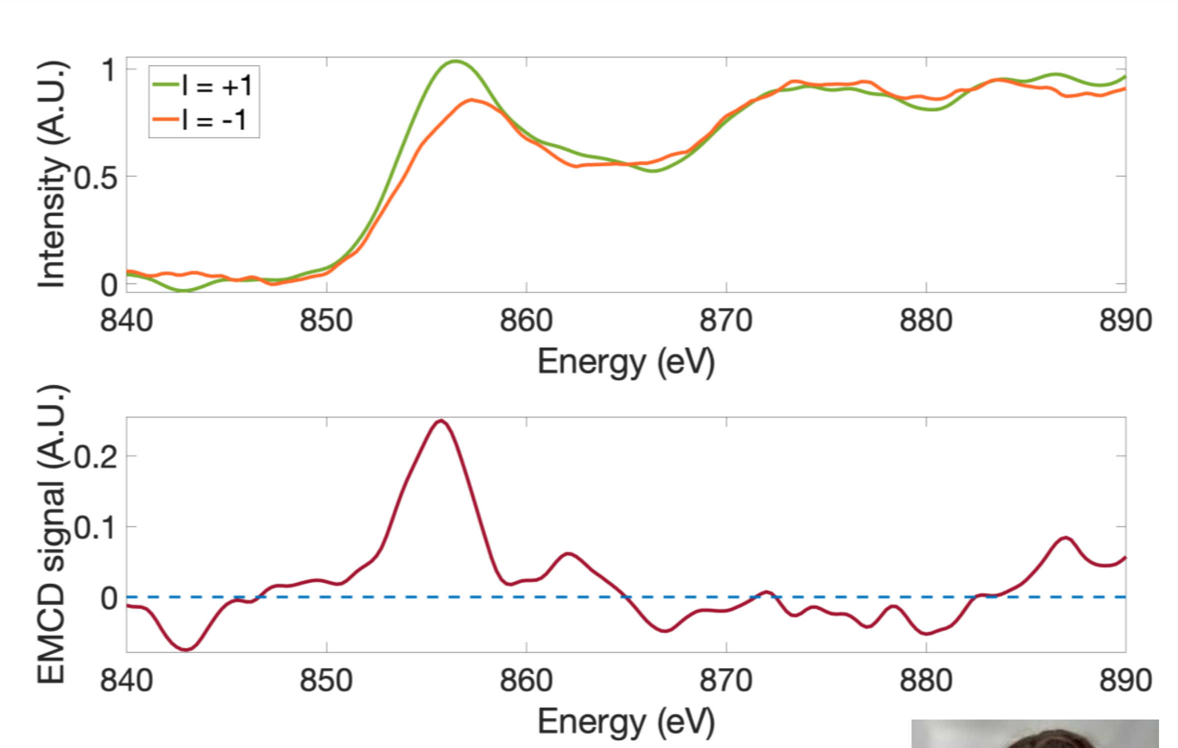
Mapping of spin polarized $2p_j \rightarrow 3d$ transitions in Ni



L_2 - edge: $2p_{1/2} \rightarrow 3d$

L_3 - edge: $2p_{3/2} \rightarrow 3d$

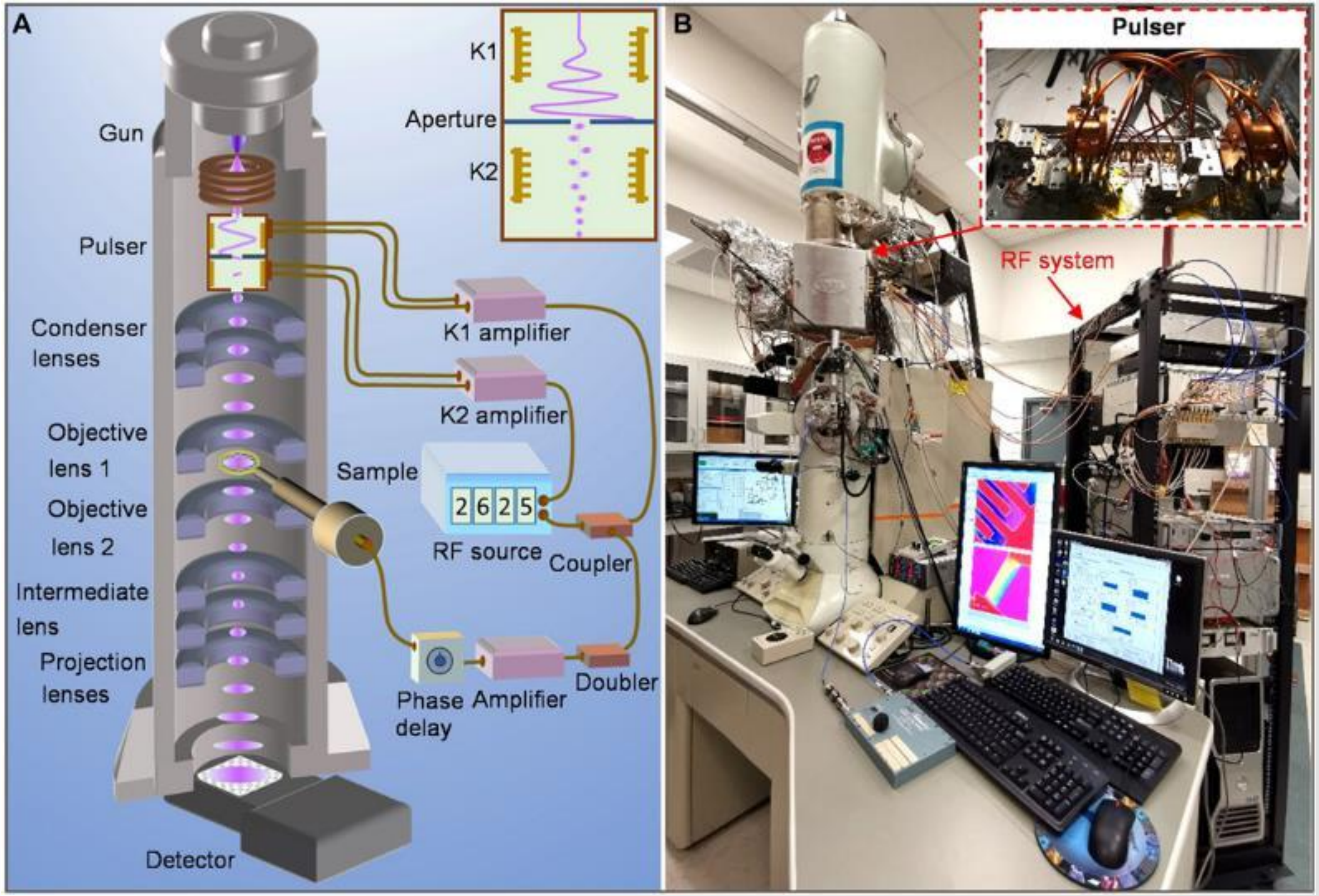
EMCD with phaseplates

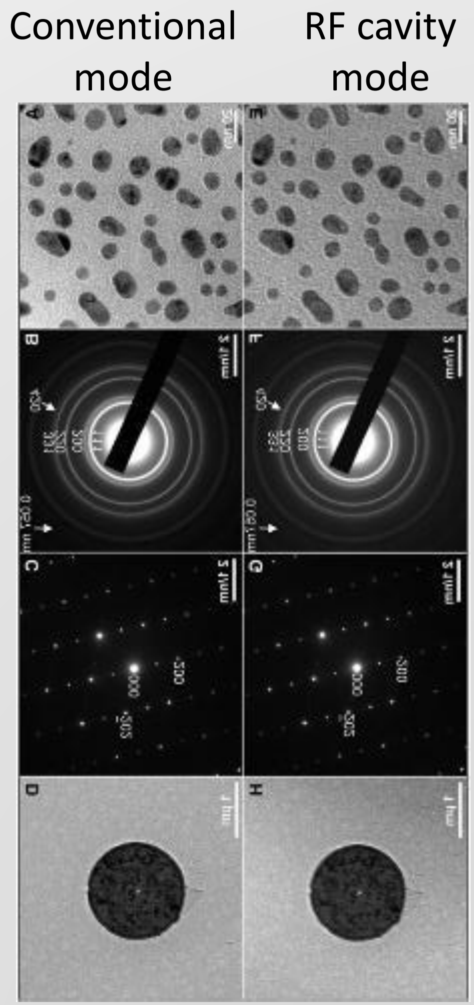


EMCD is based on the analysis of ionization edges in Electron Energy Loss Spectroscopy (EELS), allowing to quantitatively determine the spin and the orbital magnetic moments with atomic spatial resolution depth sensitivity

Veronica Lecesse

Laser free UTEM for magnetic imaging with ~10 ps resolution





Xuewen Fu et al. Sci Adv 2020

Thanks for your attention!