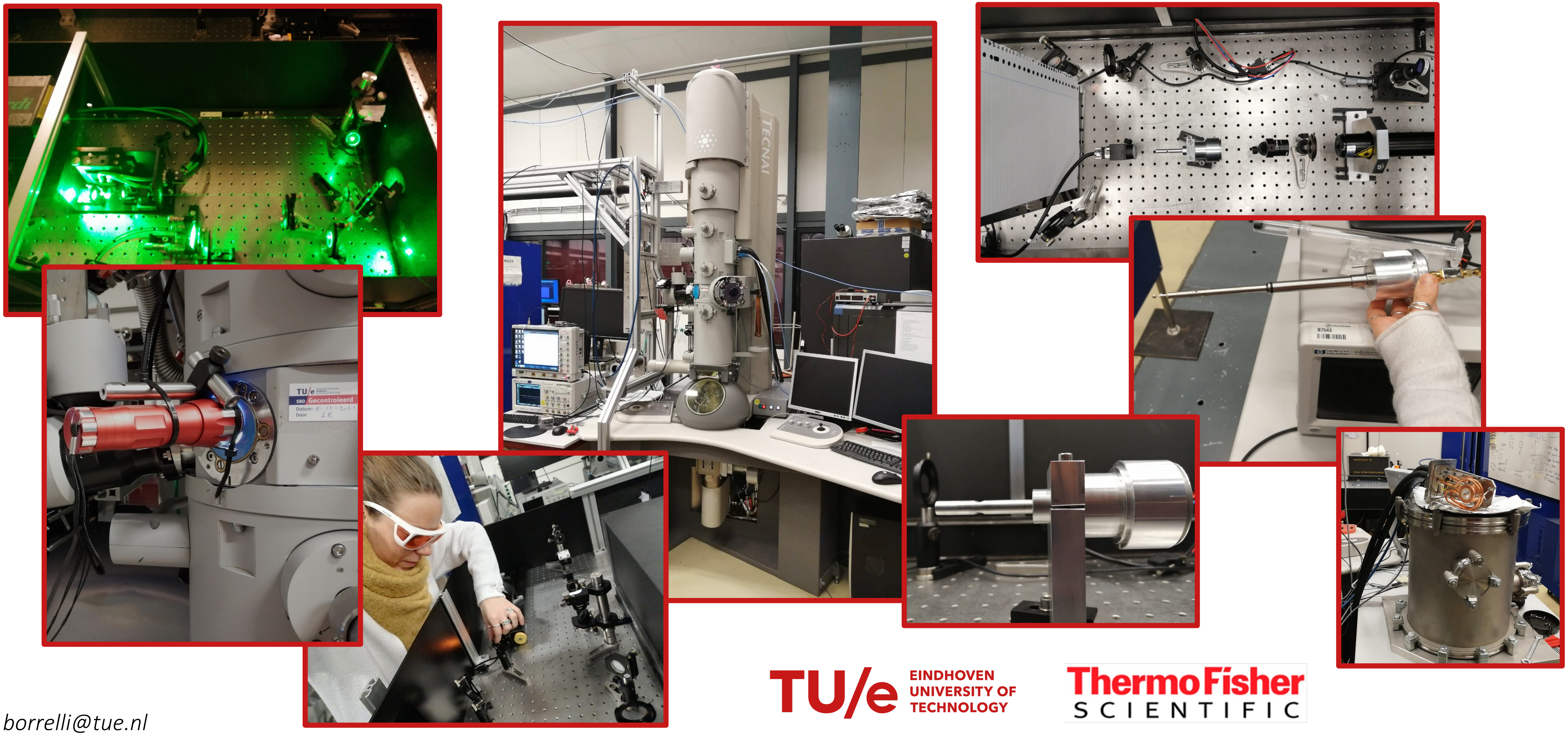
EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

Free-electrons manipulation with light in an RF-cavity-based Ultrafast Transmission Electron Microscope

Simona Borrelli

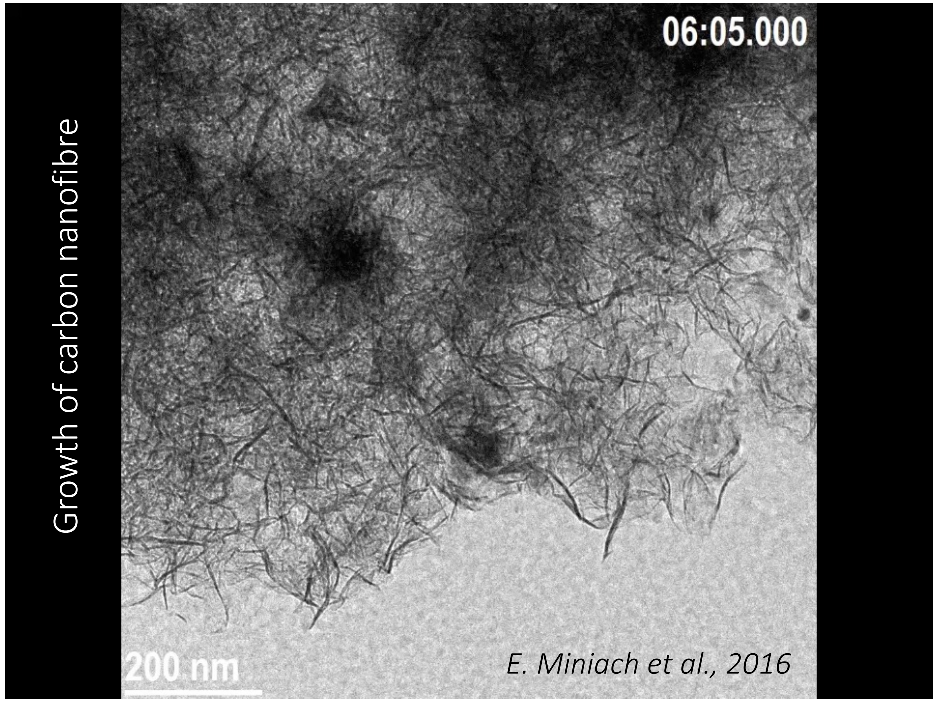
Ultrafast Transmission Electron Microscopy Technology

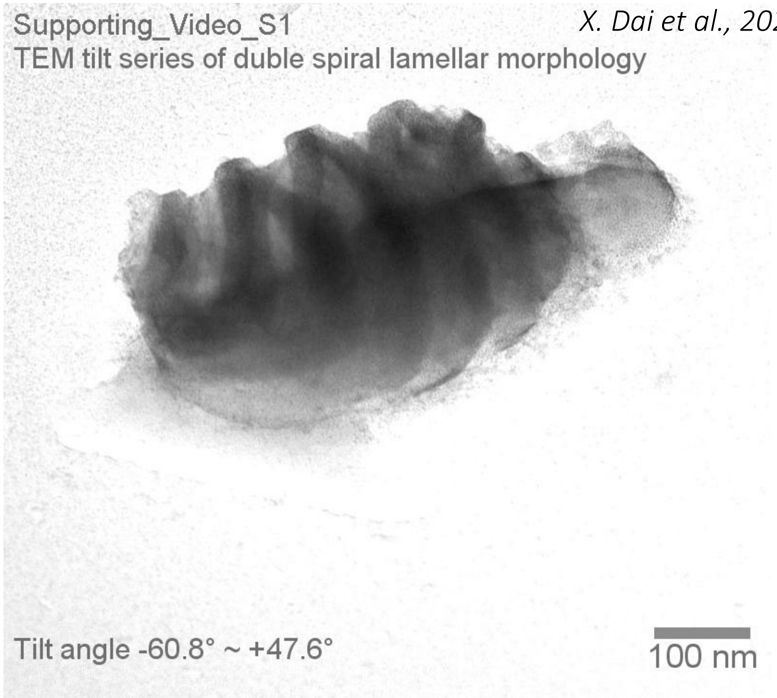


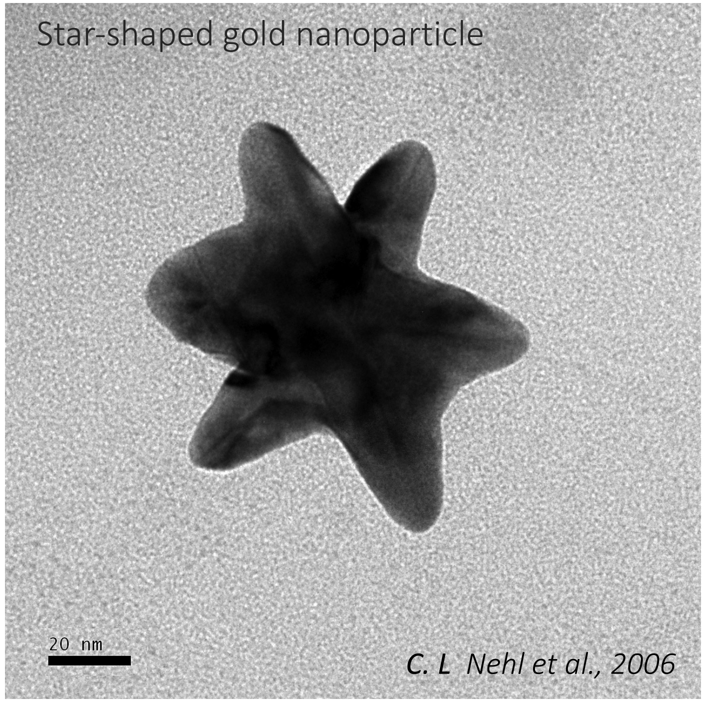
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

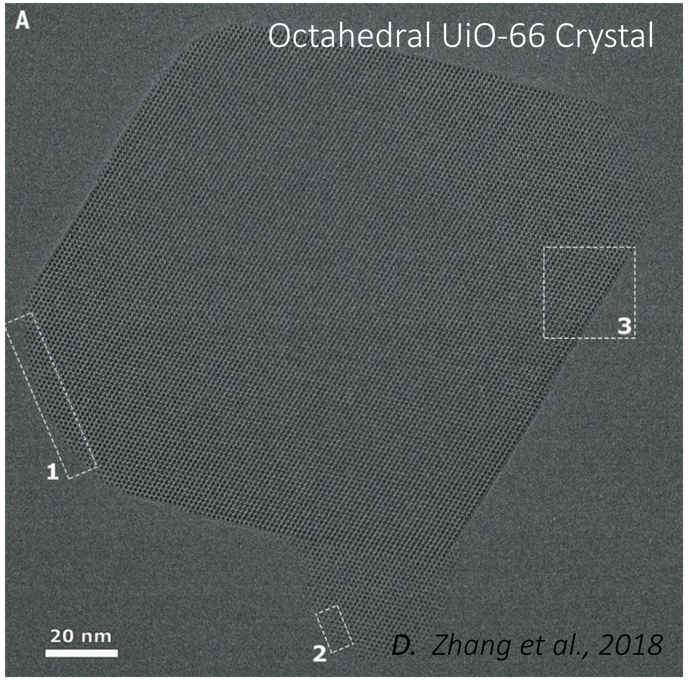
ThermoFisher SCIENTIFIC

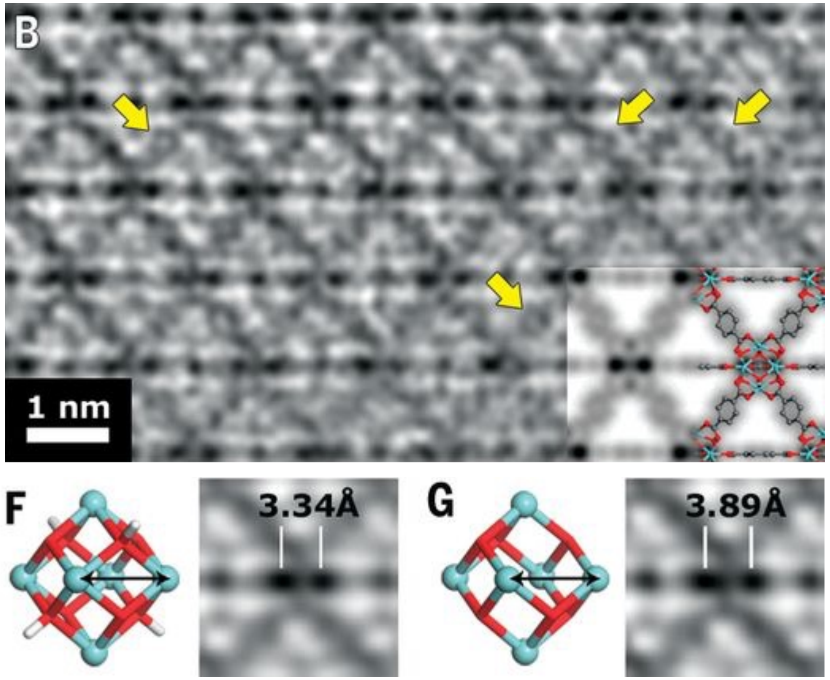
s.borrelli@tue.nl









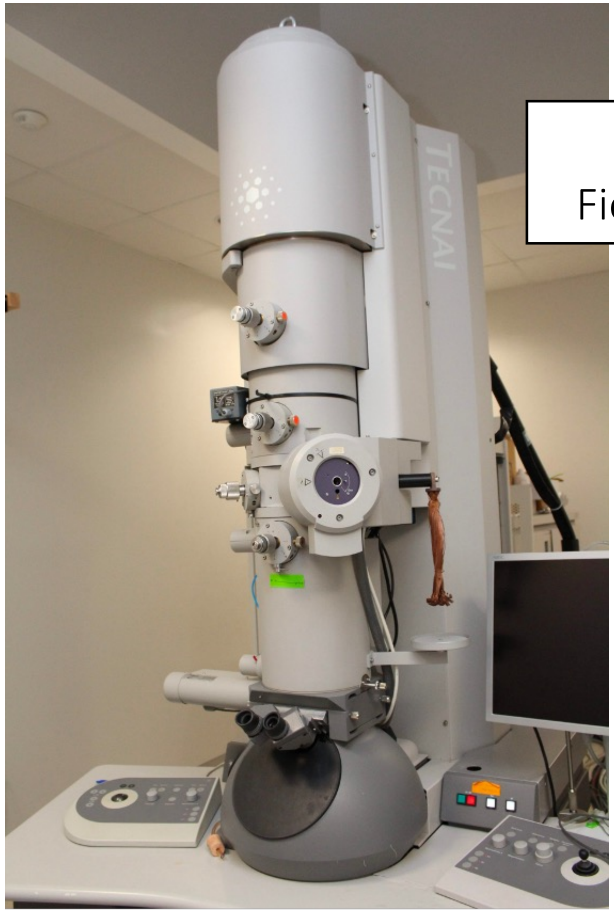


Ultrafast Transmission Electron Microscopy

s.borrelli@tue.nl

Ultrafast Transmission Electron Microscope

Continuous electron beam



Schottky
Field Emission Gun

Brightness

$$B_r = \frac{q_e}{m_e c^2} \frac{I}{4\,\pi^2\, \varepsilon_{n,x}\varepsilon_{n,y}} \sim 10^7 (\text{ A /m}^2 \text{ sr V})$$

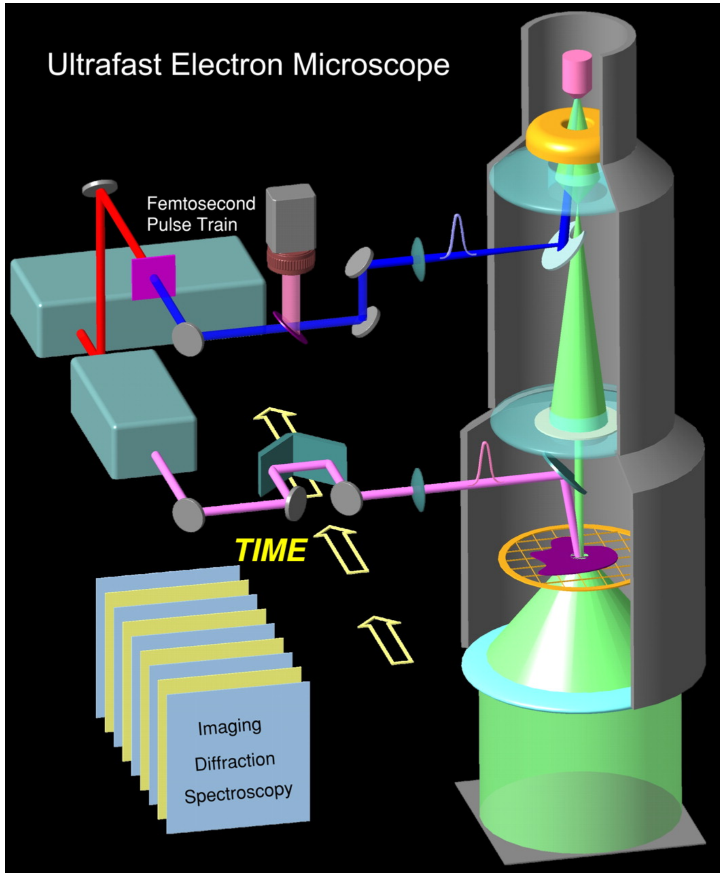
Beam coherence approaching the limit imposed by Heisenberg's uncertainty principle

Atomic spatial resolution

s.borrelli@tue.nl

Ultrafast Transmission Electron Microscope

Continuous electron beam



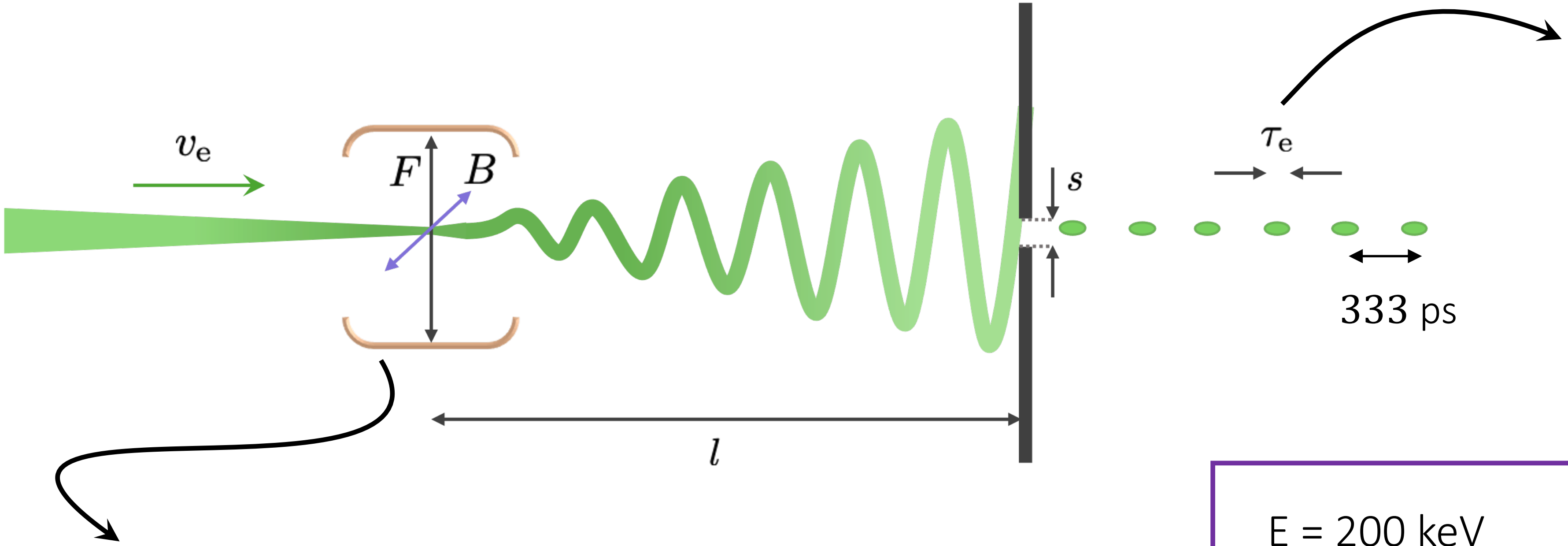
Lobastov et al., Proc. National Academy of Science, 2005, 7069-7073

Photoemitted pulsed electron beam

Atomic spatial and temporal resolution

s.borrelli@tue.nl

Pulse Generation by Beam Chopping



$$\tau_e \approx \frac{\gamma\, m_e\, s}{2\, l\, q_e B_0}$$

3 GHz RF-cavity in TM_{110} mode

E = 200 keV
B_0 = 3 mT
l = 10 cm
s = 10 µm

$\tau_e \sim 100$ fs
@ 3 GHz

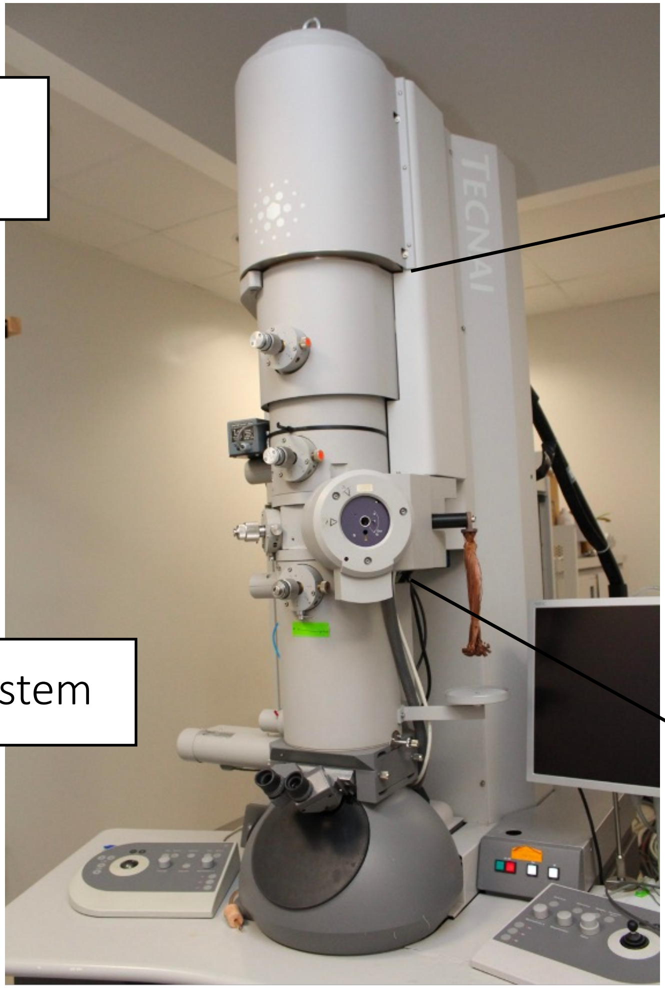
s.borrelli@tue.nl

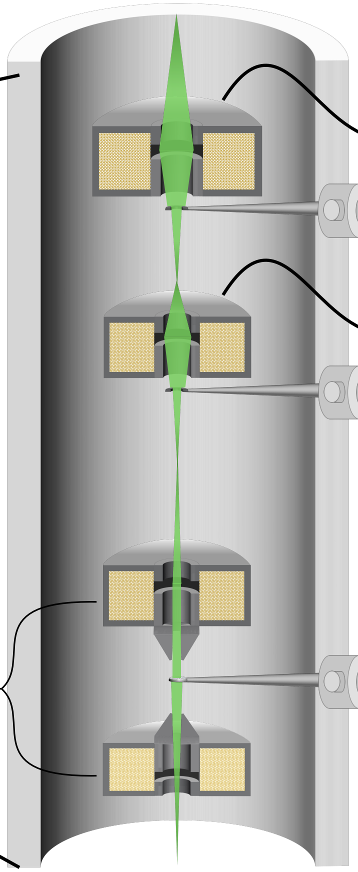
RF-Cavity-Based Ultrafast Transmission Electron Microscope

Schottky
Field Emission Gun

200 keV Tecnai TF20
Continuous electron beam

Projection System





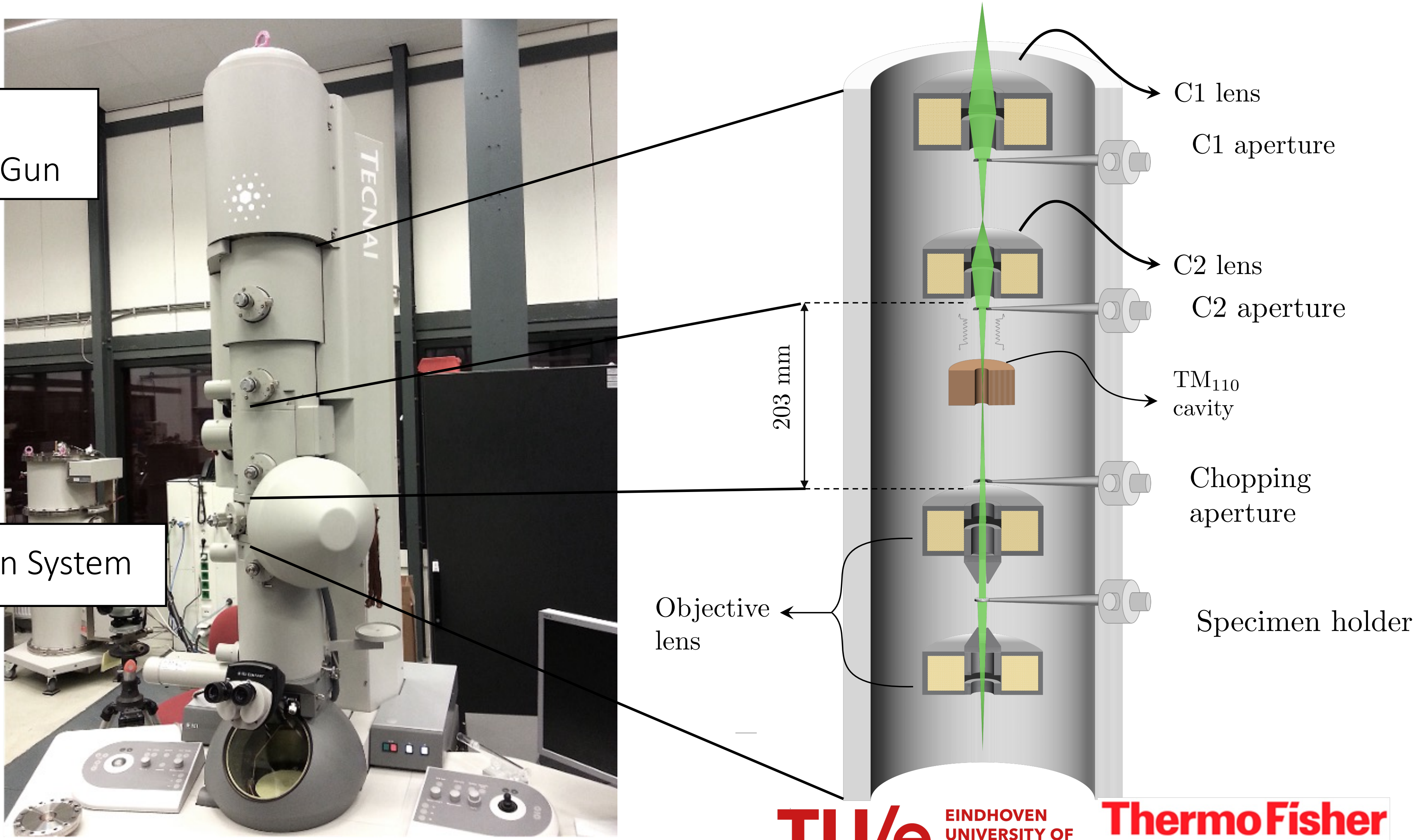
s.borrelli@tue.nl

RF-Cavity-Based Ultrafast Transmission Electron Microscope

Schottky
Field Emission Gun

200 keV Tecnai TF20
Pulsed electron beam

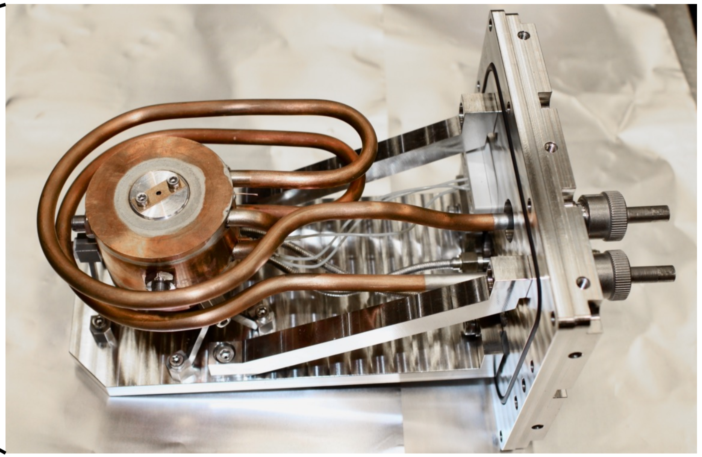
Projection System

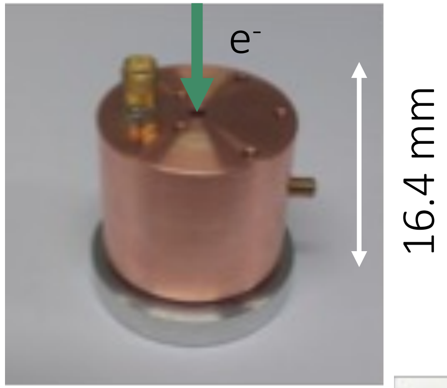


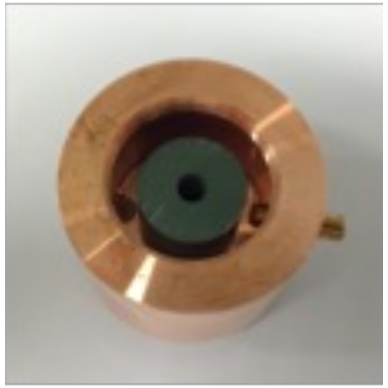
s.borrelli@tue.nl

TM$_{110}$ RF-Cavity in UTEM

Miniaturized TM$_{110}$ RF-cavity







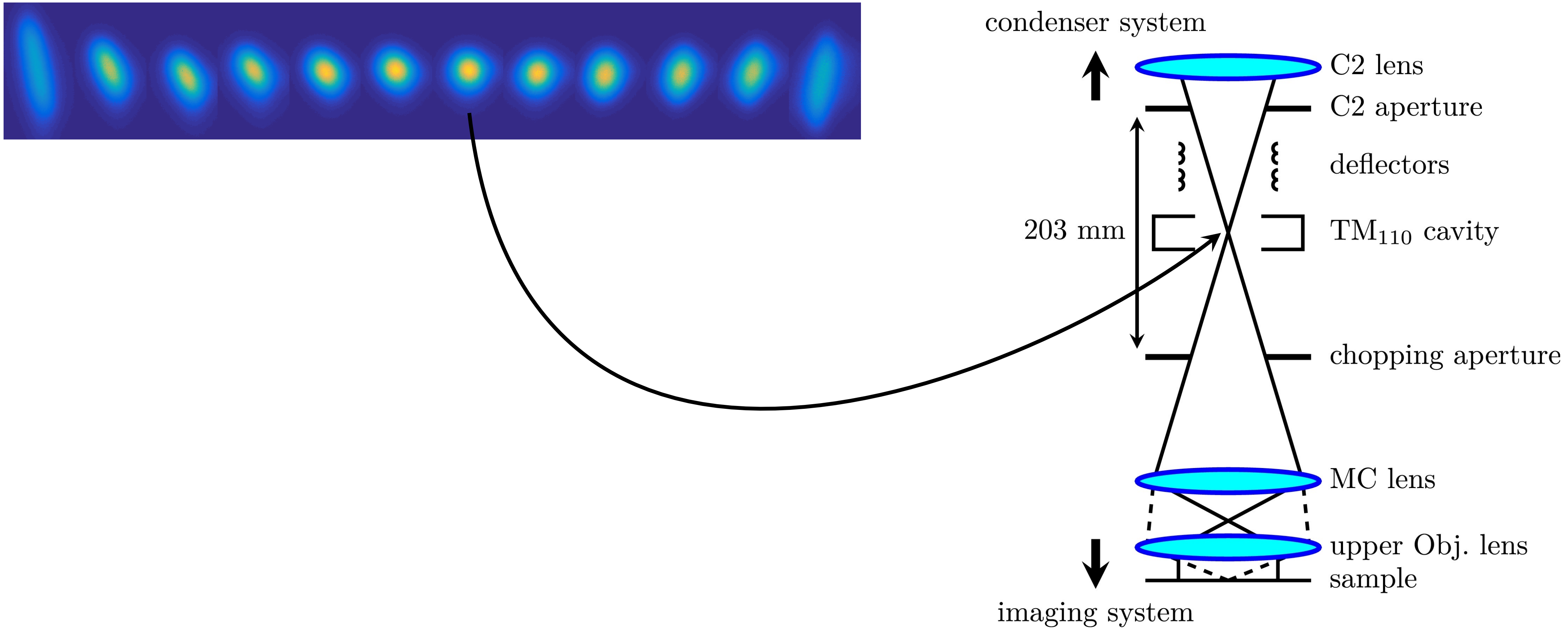
s.borrelli@tue.nl

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

ThermoFisher SCIENTIFIC

Conjugate Blanking Mode

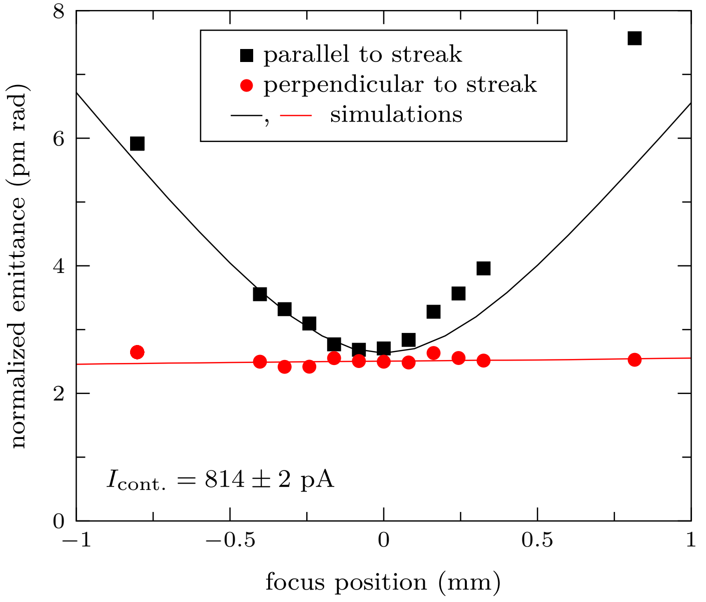
Pulsed beam on camera at different positions of the crossover in the cavity

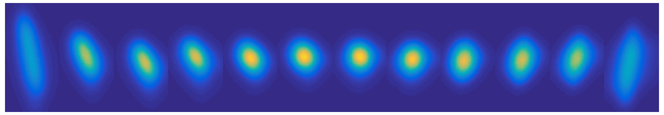


Verhoeven et al. , Ultramiscoscopy, 2018, 188, 85

s.borrelli@tue.nl

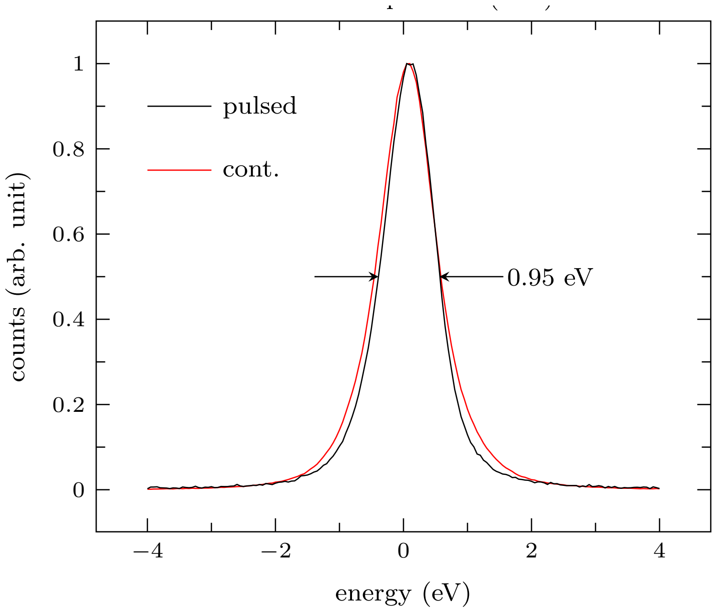
Conjugate Blanking Mode





Pulsed beam on camera at different positions of the crossover in the cavity

$\varepsilon_{n,y} = \varepsilon_{n,x}$ = (2.5 ± 0.2) pm rad



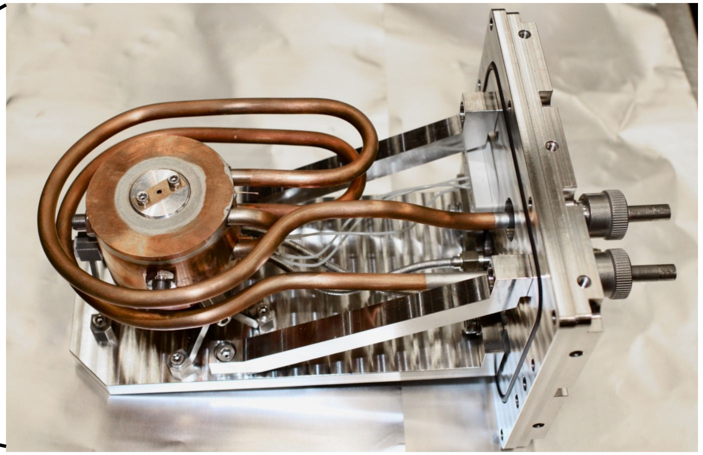
Peak brightness and beam quality of the FEG are conserved

	Schottky FEG	Cavity-based source
ΔE_{FWHM} (eV)	(0.9 ± 0.05)	(0.95 ± 0.05)
B_{rms} (A /m^2 sr V)	(7.5 ± 1) x 10^6	(7 ± 1) x 10^6

s.borrelli@tue.nl

Verhoeven et al. , Ultramiscoscopy, 2018, 188, 85

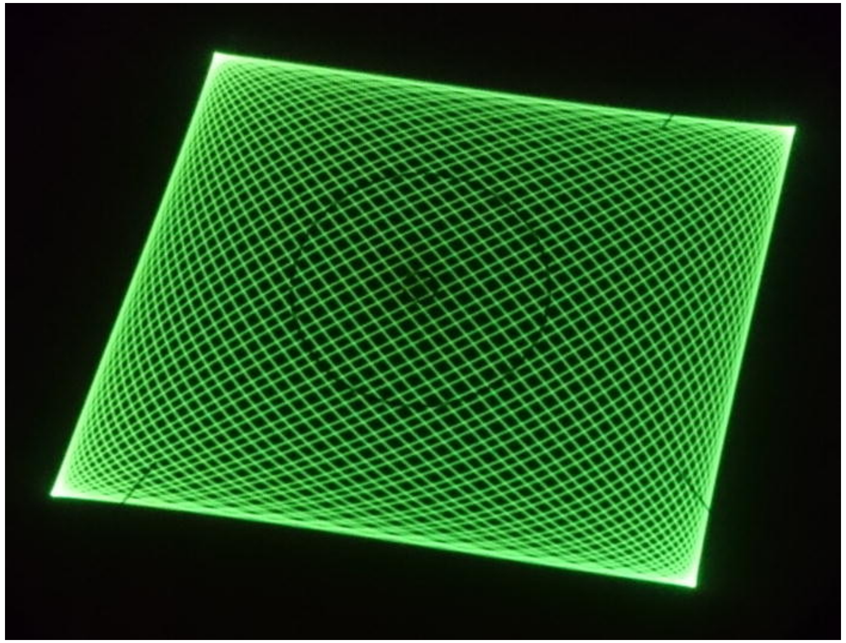
Dual mode TM_{110} Cavity for Ultrafast Electron Microscopy

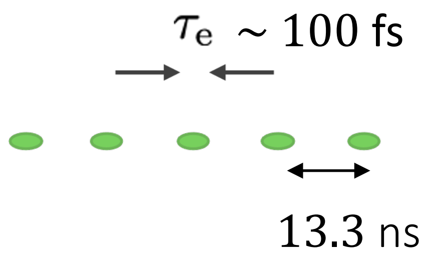


Two ortogonal modes @

$\nu_1 = 3.000$ GHz
$\nu_2 = 3.075$ GHz

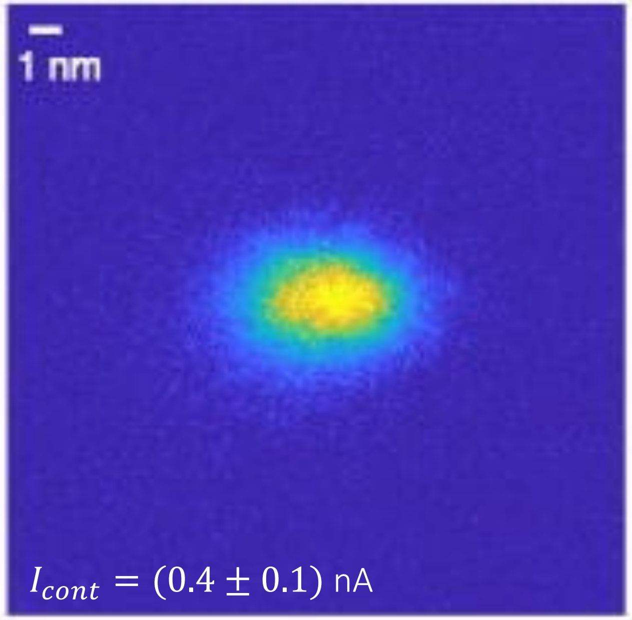
Lissajous patter traced @ 75 MHz



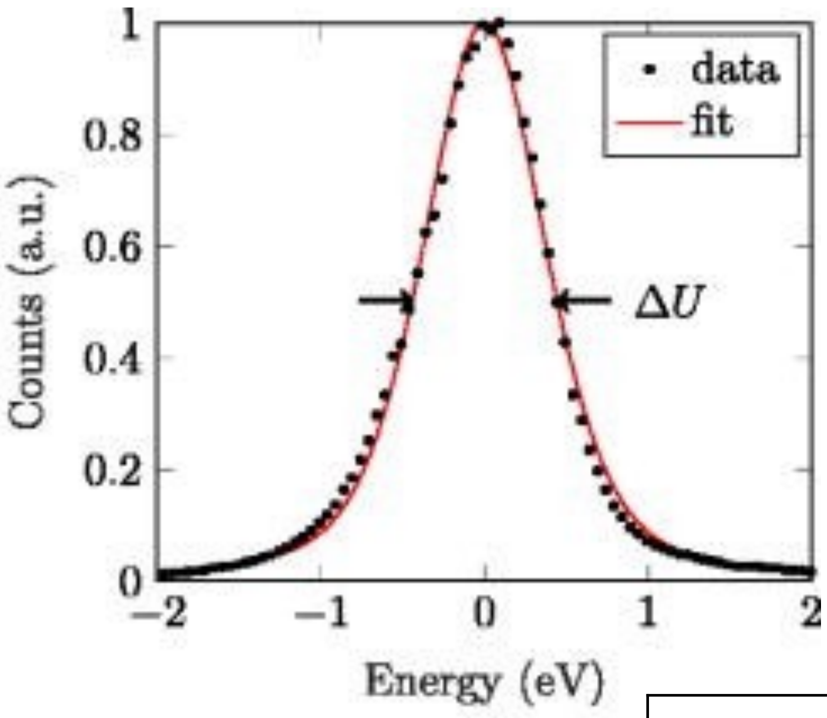


s.borrelli@tue.nl

Dual mode TM_{110} Cavity in Conjugate Blanking Mode



$\varepsilon_{n,x}$ (pm rad) = **(2.1 ± 0.2)**
$\varepsilon_{n,y}$ (pm rad) = **(1.3 ± 0.2)**



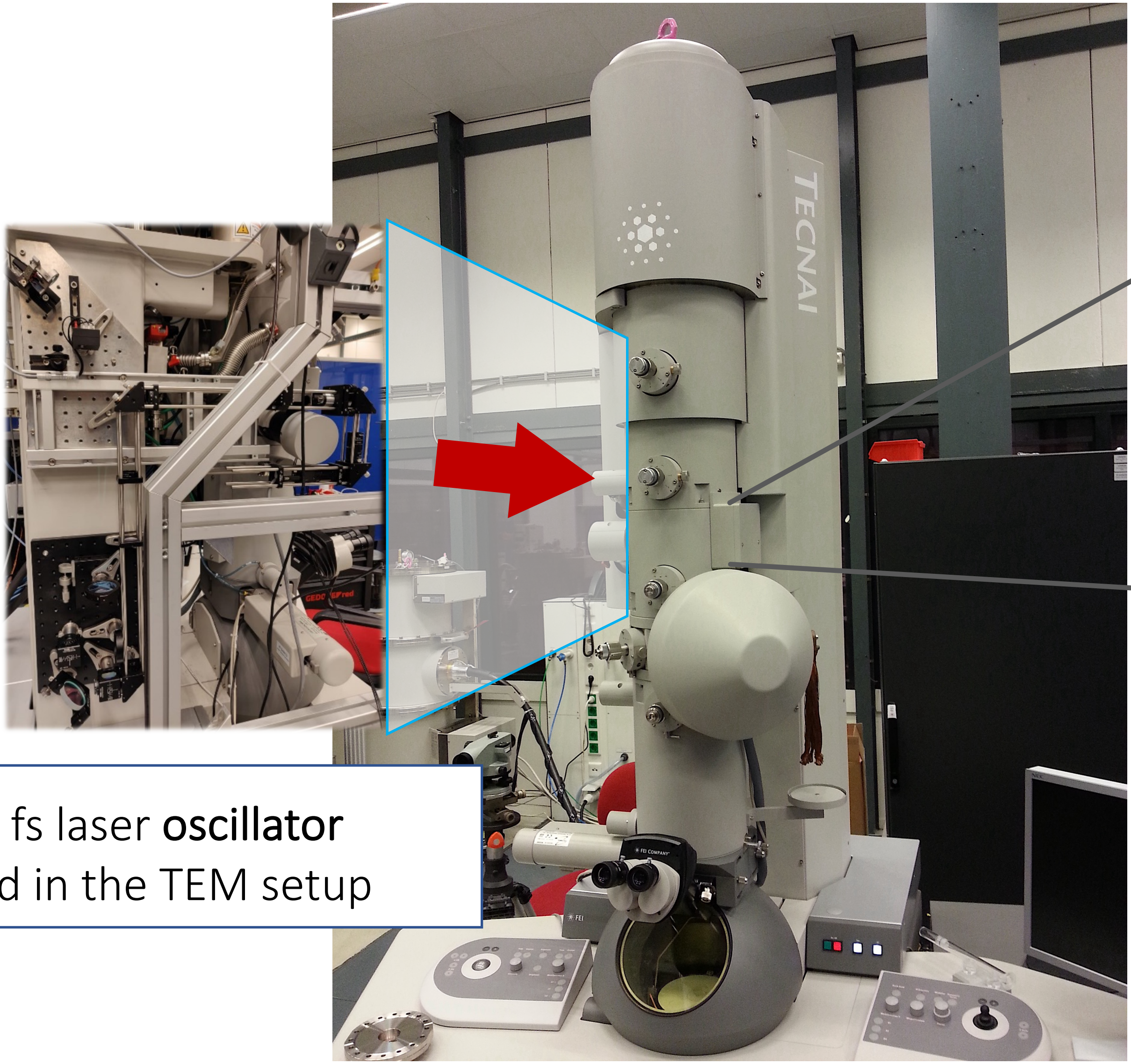
$\tau = (630 \pm 10)$ fs
@ Input Power (3.7 ± 0.1) W

	Schottky FEG	Cavity-based source
ΔE_{FWHM} (eV)	(0.9 ± 0.05)	(0.95 ± 0.05)
B_{rms} (A/m^2 sr V)	(7 ± 1) x 10^6	(7 ± 1) x 10^6

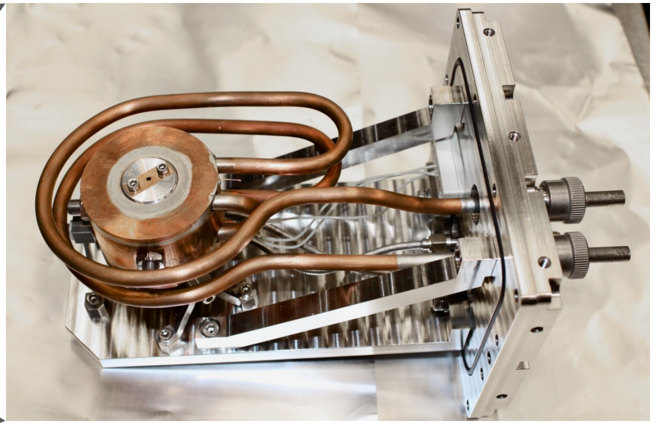
Van Rens et al. , Applied Physics Letters, 2018, 113.16: 163104

s.borrelli@tue.nl

RF-Cavity-Based UTEM



75 MHz fs laser **oscillator** integrated in the TEM setup



Dual mode TM_{110} cavity

Electron pulses @ 75 MHz rep rate synchronized to fs oscillator within < 100 fs

s.borrelli@tue.nl

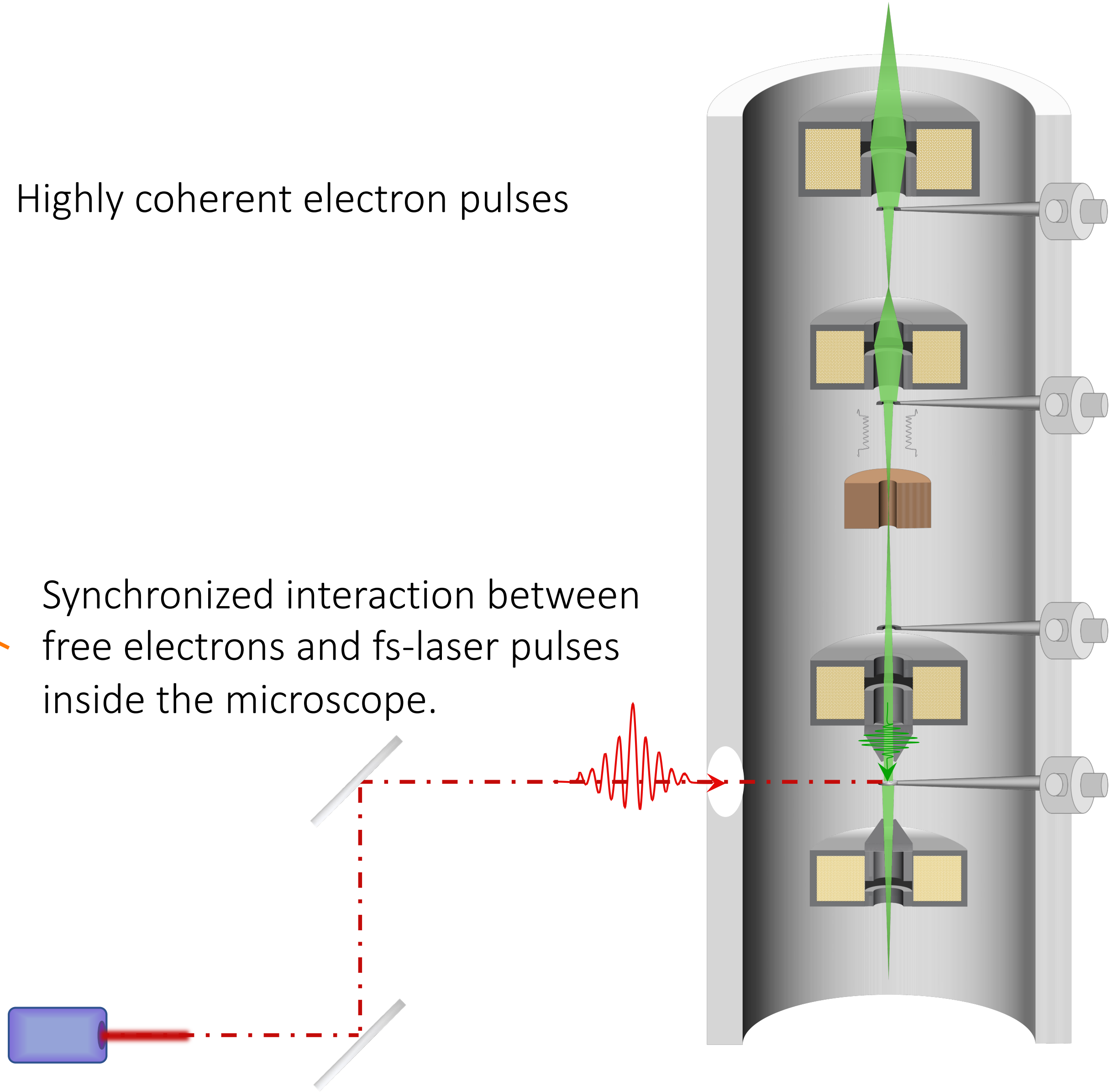
Coherent Manipulation of Electron Wavefunction with Light

Highly coherent electron pulses

Coherent manipulation and control of the electron's wavefunction with light

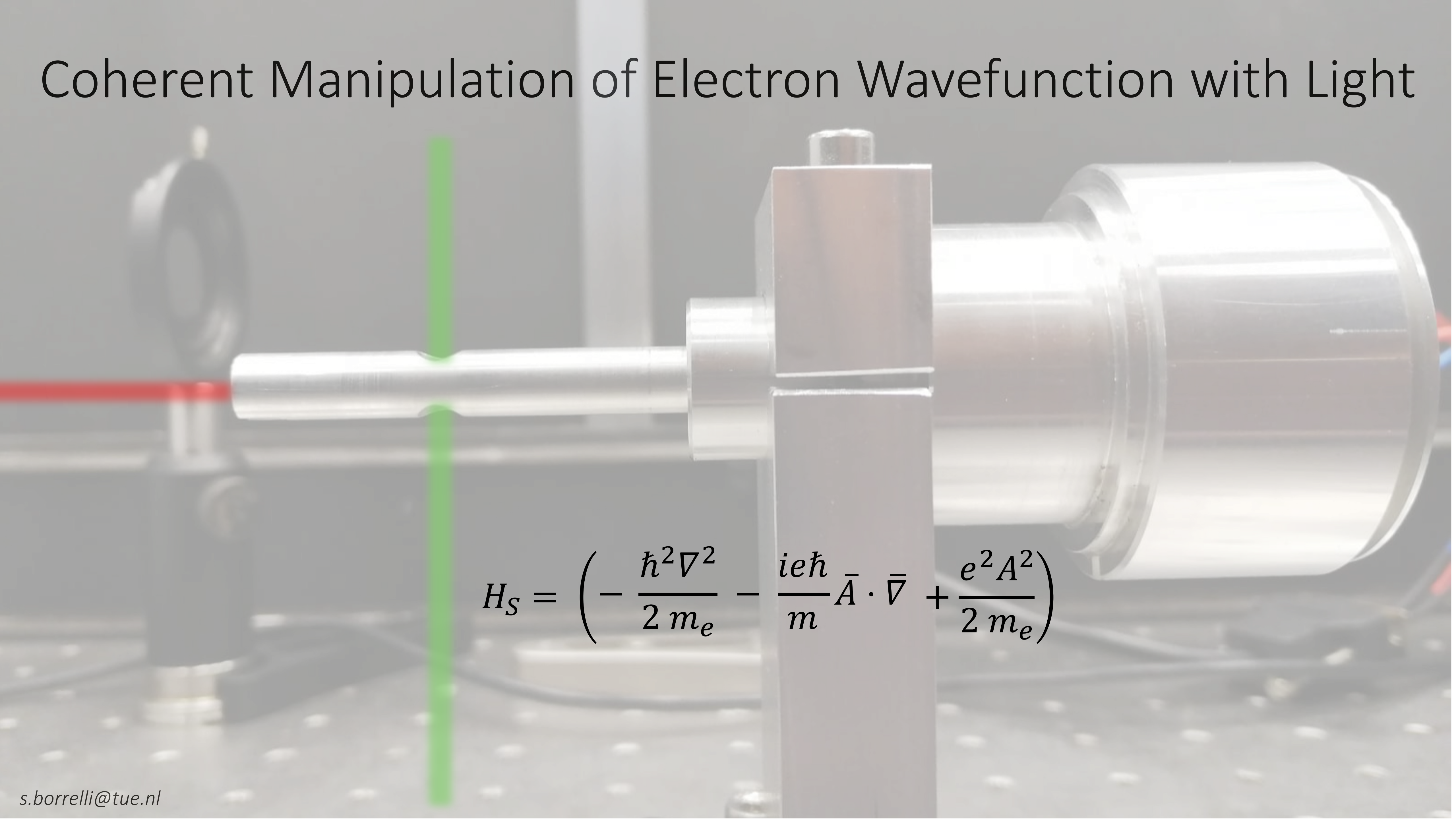
Synchronized interaction between free electrons and fs-laser pulses inside the microscope.

Establishing new free electron quantum optics based on the interaction of sub-ps electron pulses with the time-dependent electromagnetic fields of light.



s.borrelli@tue.nl

Coherent Manipulation of Electron Wavefunction with Light

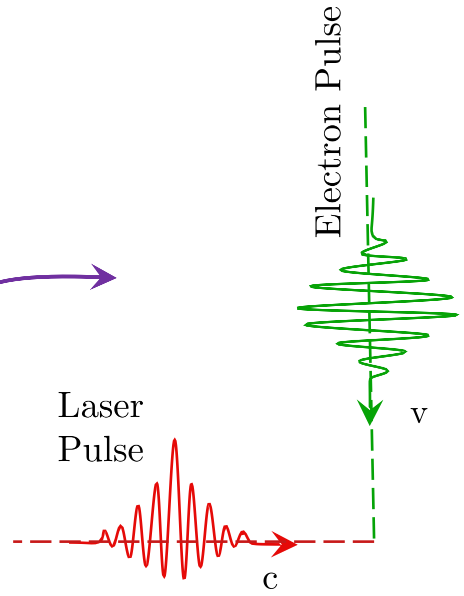


$$H_S = \left(- \frac{\hbar^2 \nabla^2}{2\, m_e} - \frac{ie\hbar}{m} \bar{A} \cdot \bar{\nabla} + \frac{e^2 A^2}{2\, m_e} \right)$$

s.borrelli@tue.nl

Coherent Manipulation of Electron Wavefunction with Light

Ponderomotive Phase Shaping

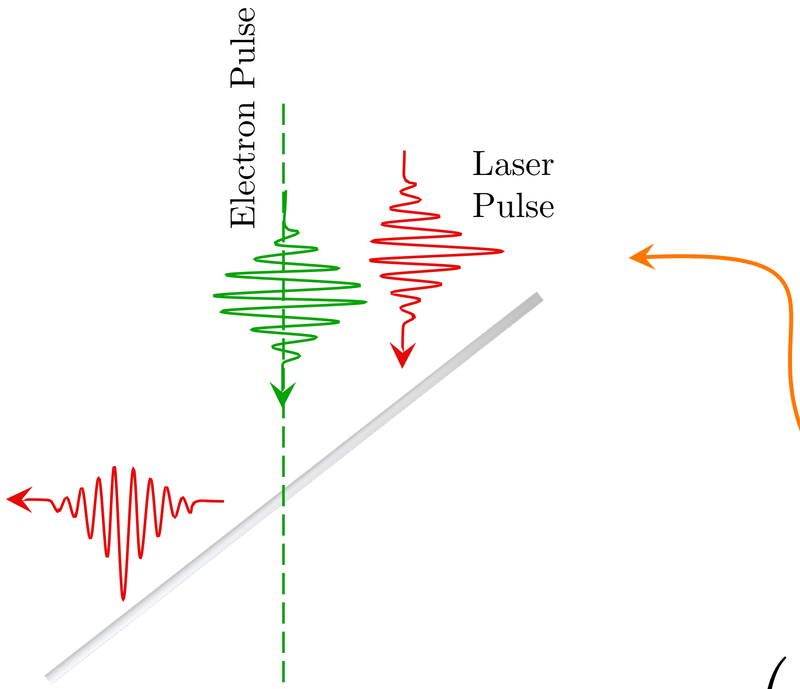


$$H_S = \left(-\frac{\hbar^2 \nabla^2}{2\, m_e} - \frac{ie\hbar}{m} \bar{A} \cdot \bar{\nabla} + \frac{e^2 A^2}{2\, m_e} \right)$$

s.borrelli@tue.nl

Coherent Manipulation of Electron Wavefunction with Light

Photon-Induced Near-Field Electron Microscopy

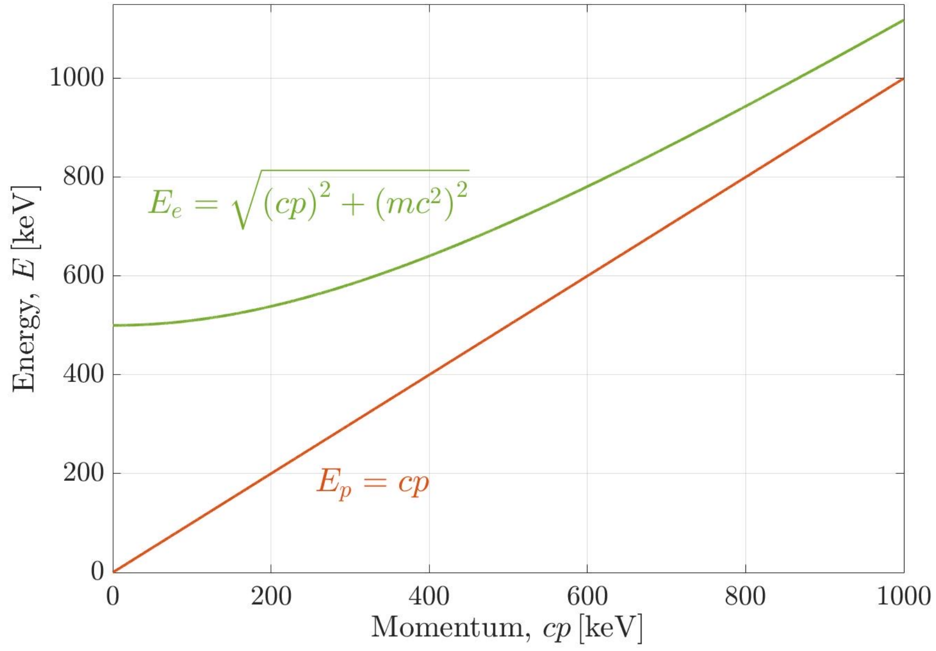


$$H_S = \left(-\frac{\hbar^2 \nabla^2}{2\, m_e} - \frac{ie\hbar}{m} \bar{A} \cdot \bar{\nabla} + \frac{e^2 A^2}{2\, m_e} \right)$$

s.borrelli@tue.nl

Photon-Induced Near-Field Electron Microscopy

$$H_S = \left(-\frac{\hbar^2 \nabla^2}{2\, m_e} - \frac{ie\hbar}{m} \bar{A} \cdot \bar{\nabla} + \frac{e^2 A^2}{2\, m_e} \right)$$

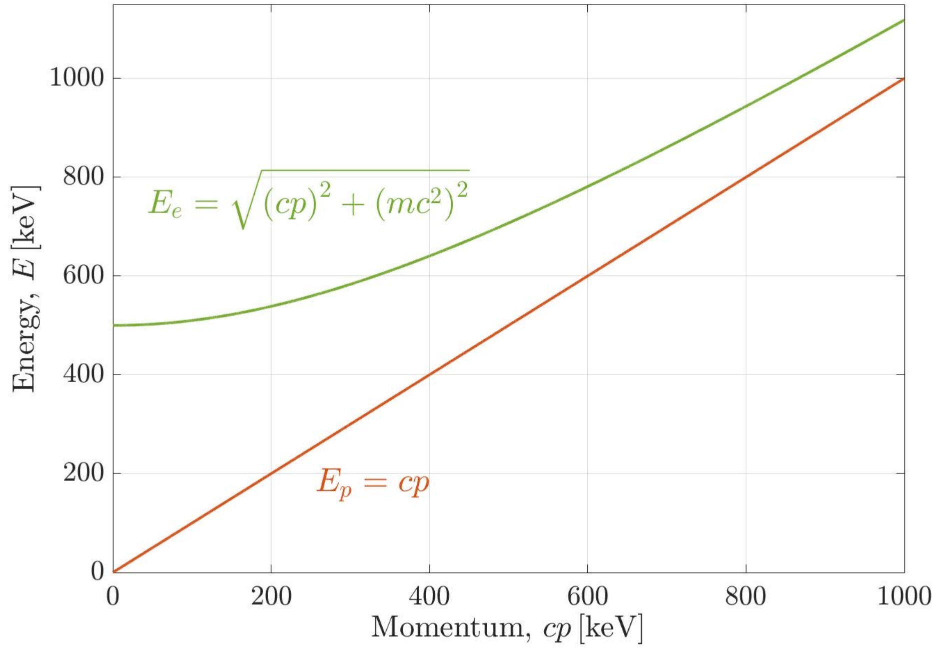


A free electron cannot absorb/emit a photon

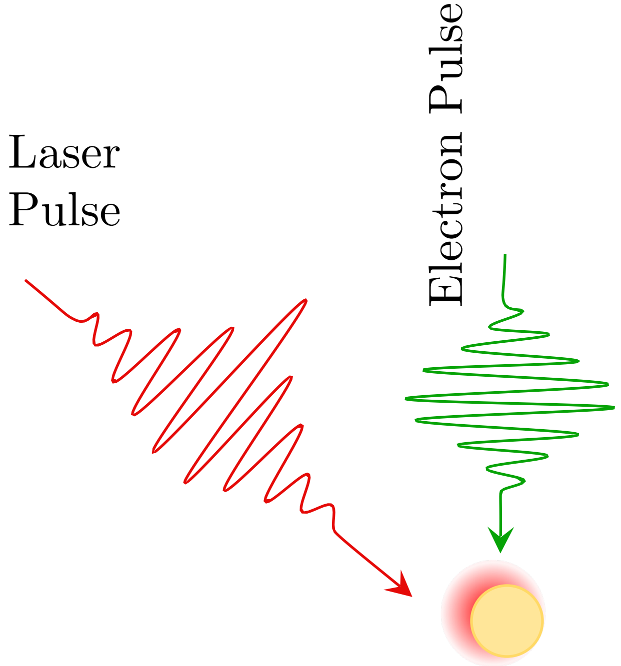
s.borrelli@tue.nl

Photon-Induced Near-Field Electron Microscopy

Dispersion relation is changed by the presence of matter



A free electron cannot absorb/emit a photon

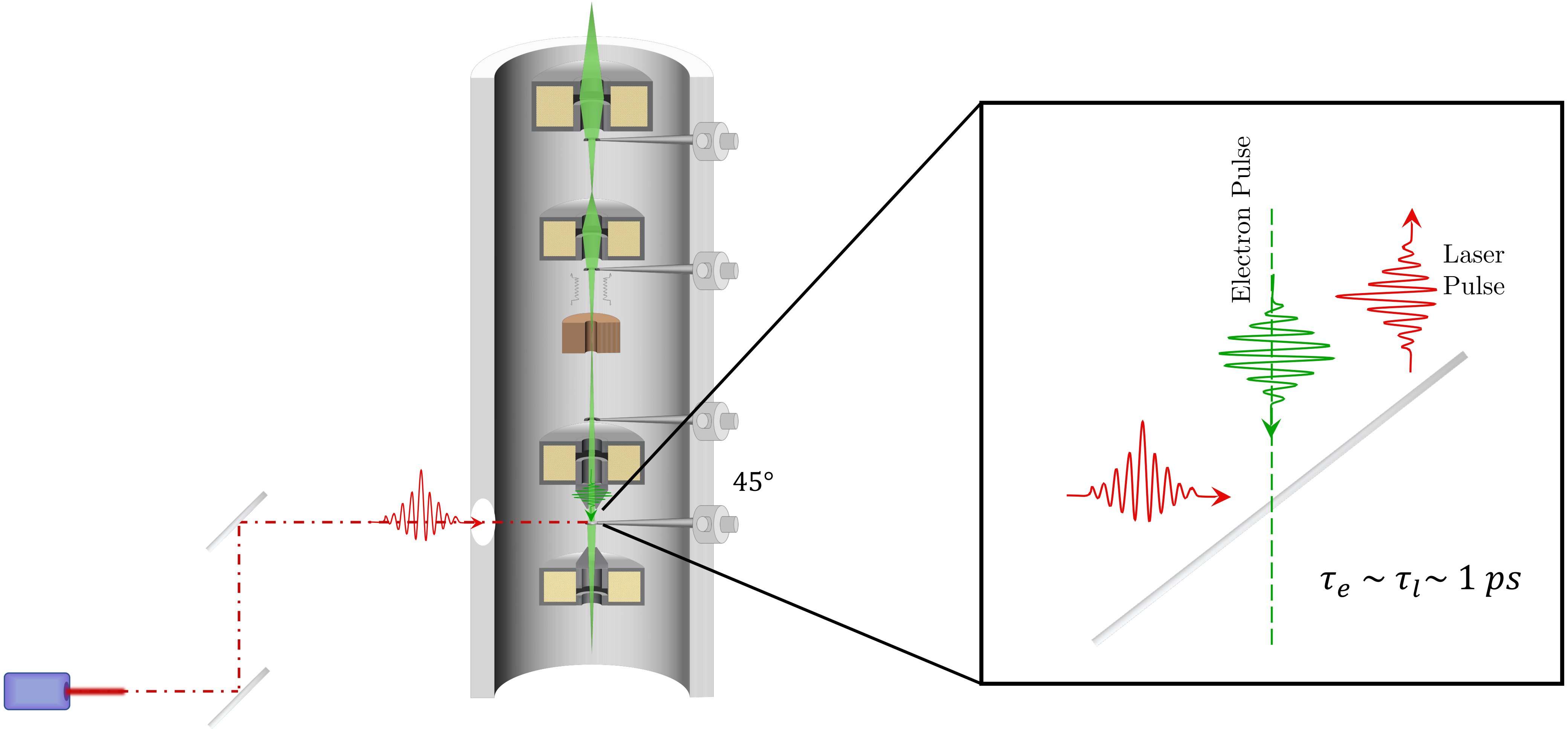


An electron can absorb/emit photons in the near-filed of the object

s.borrelli@tue.nl

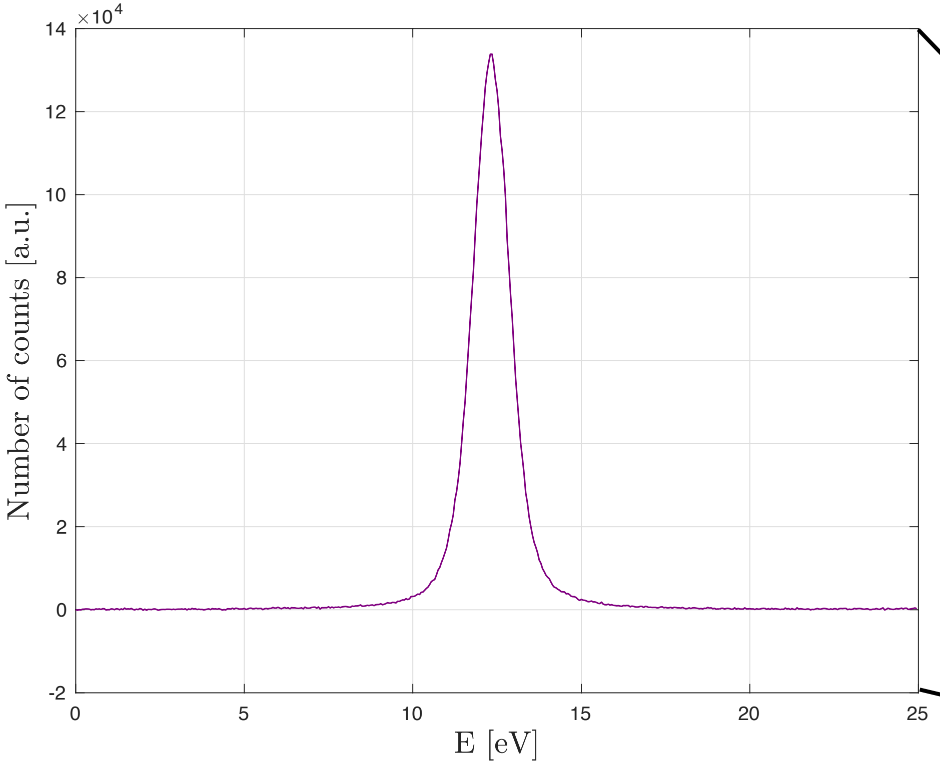
Photon-Induced Near-Field Electron Microscopy

A test-bed of coherent manipulation of electrons with light & Diagnostic Tool

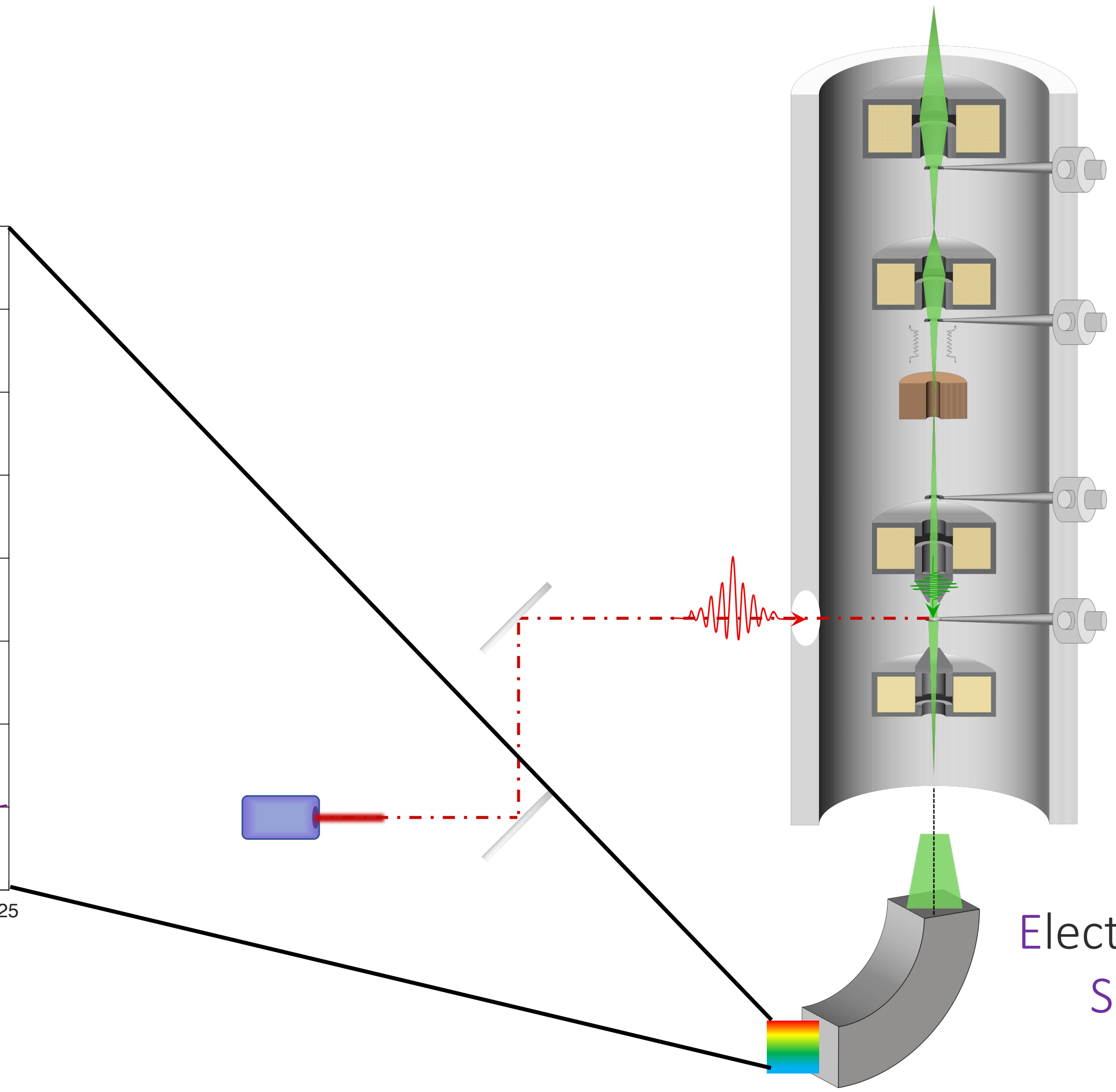


s.borrelli@tue.nl

Photon-Induced Near-Field Electron Microscopy



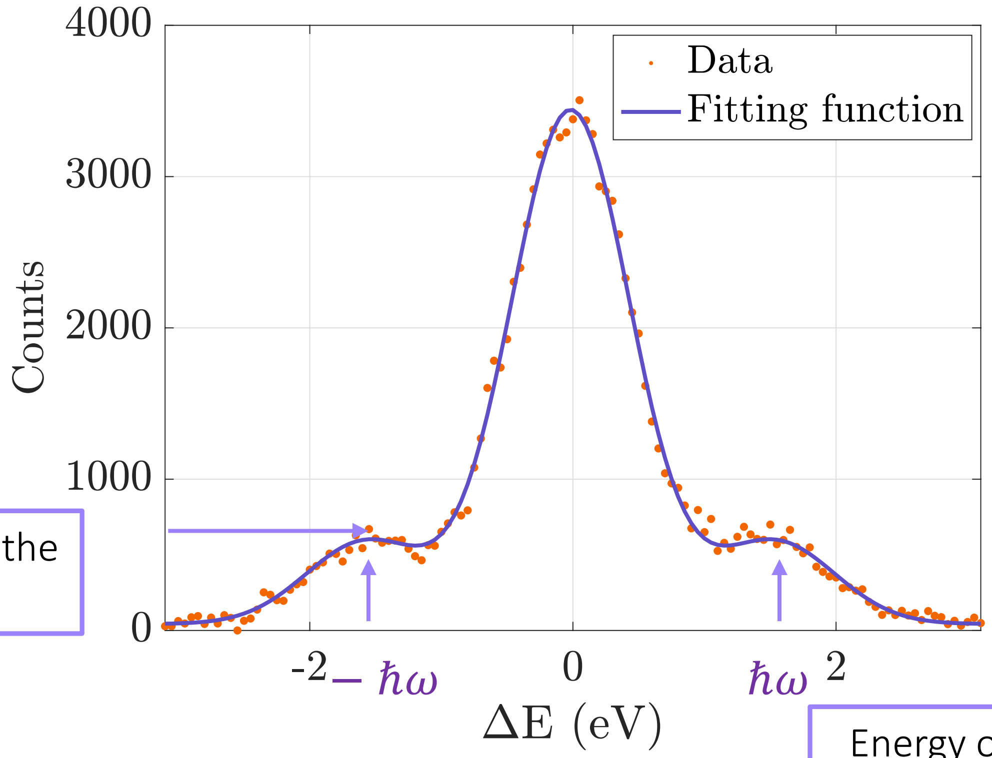
Zero-Loss peak



Electron Energy Loss Spectrometer

s.borrelli@tue.nl

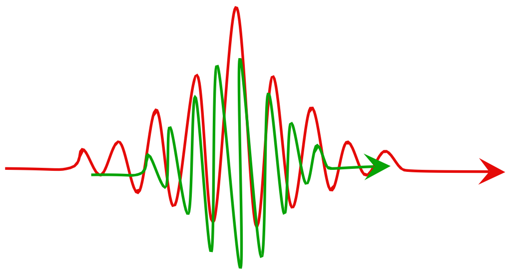
Photon-Induced Near-Field Electron Microscopy



Probability of the PINEM event

Energy of light-quanta emitted/absorbed

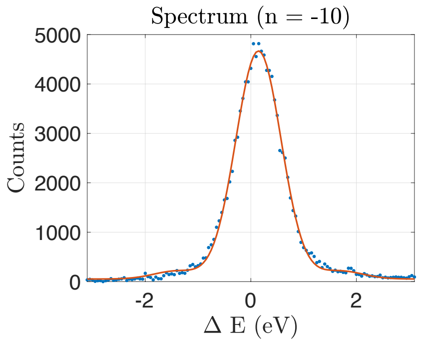
Space-time synchronization laser and electron pulses

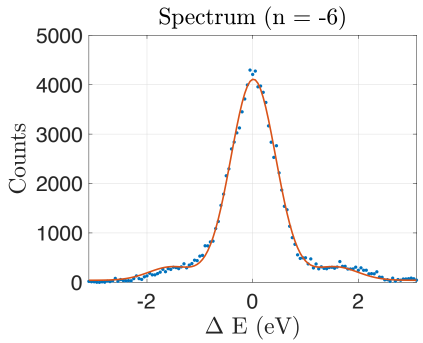


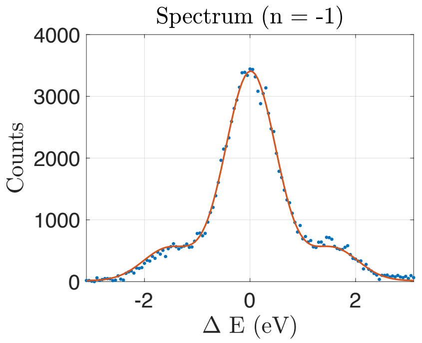
Spatial alignment < 20 μm
Temporal alignment < few-100 fs

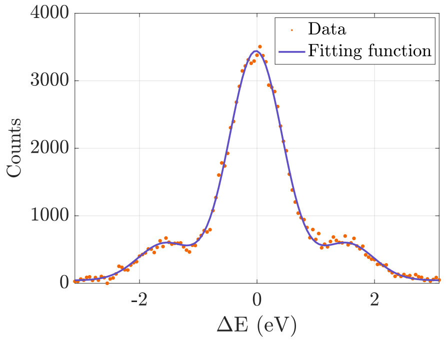
s.borrelli@tue.nl

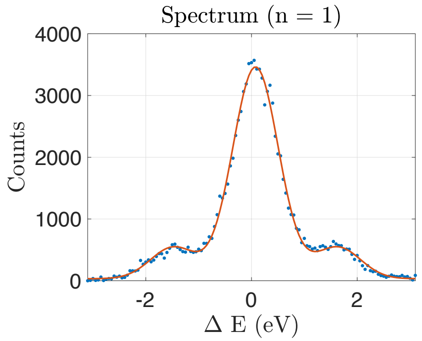
Photon-Induced Near-Field Electron Microscopy

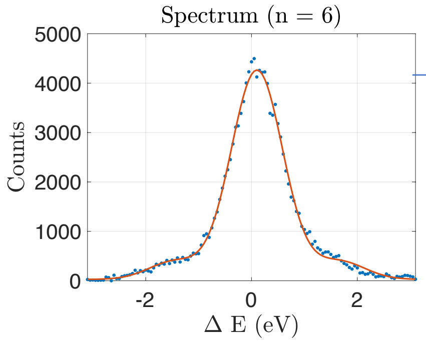


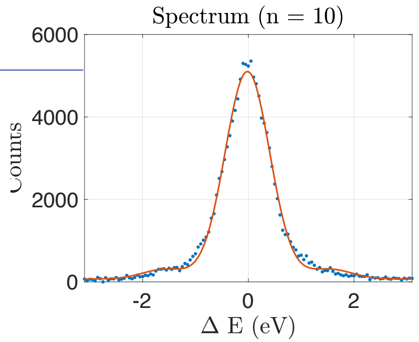










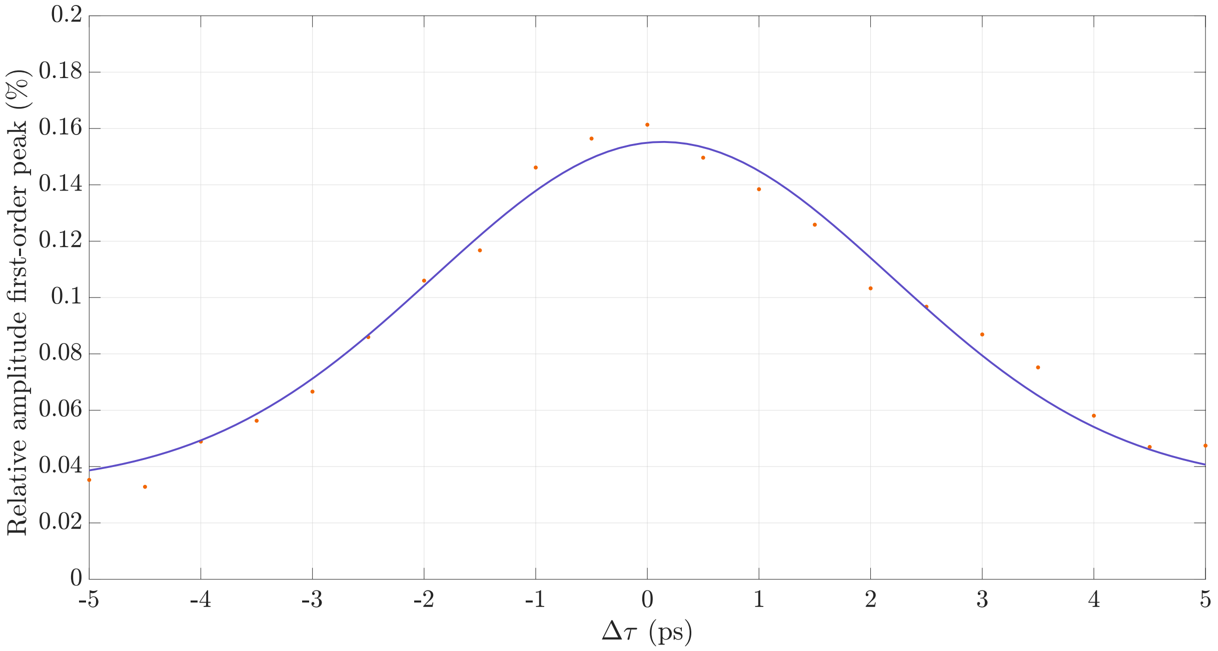


Time Delay between electron and laser pulses

s.borrelli@tue.nl

Photon-Induced Near-Field Electron Microscopy

Cross-correlation between laser and electron pulse lenght



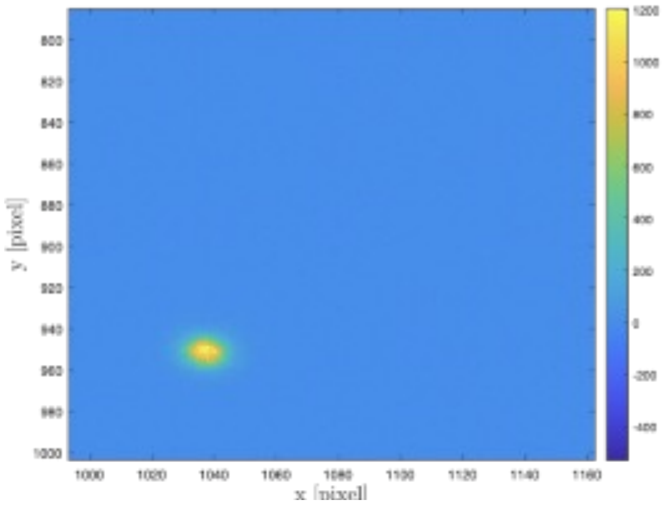
$$\tau = \sqrt{\tau_e^2 + \tau_l^2}$$

$\tau = 2.1$ ps

$\tau_l \sim 2$ ps

$\tau_e \sim 650$ fs

Preliminary

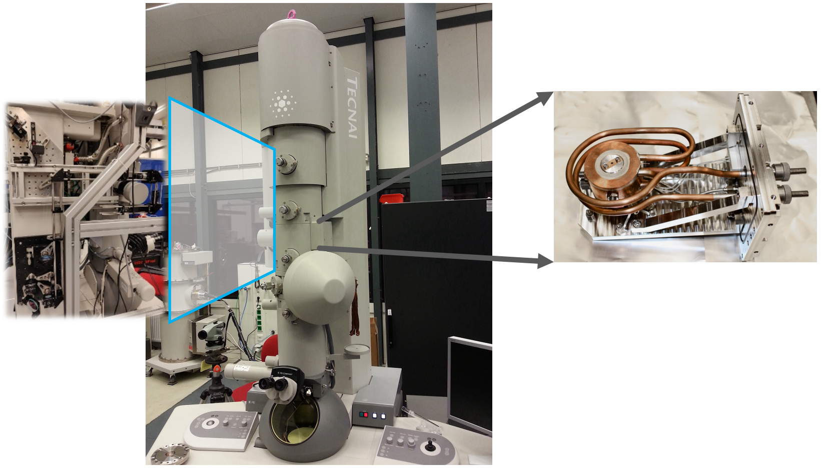


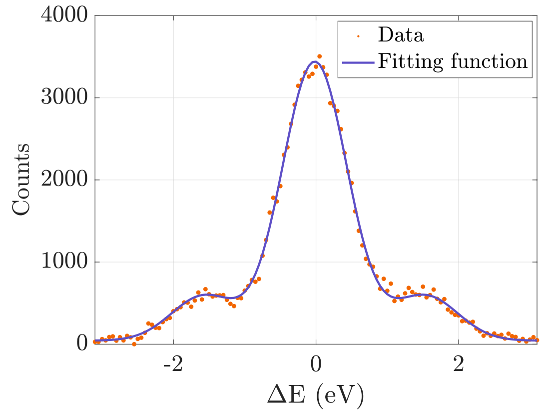
$$\tau_e = \frac{I_{pulse}}{I_{cont} * Rep\ Rate} \sim (630 \pm 10)\ \text{fs}$$

s.borrelli@tue.nl

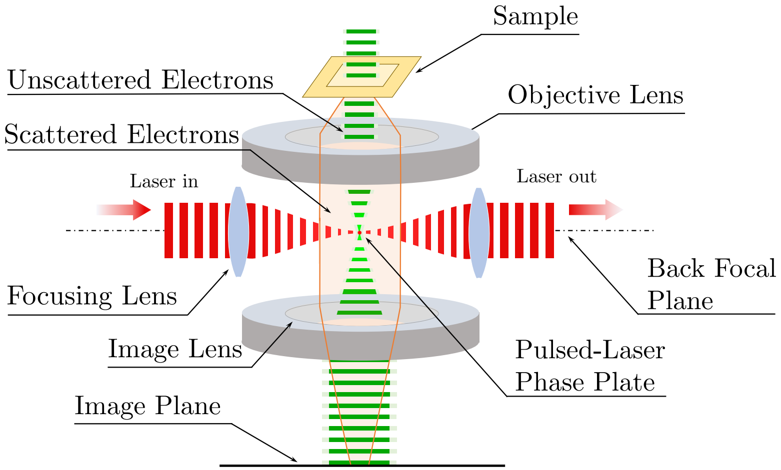
Wrap-up

- Pulse generation by beam chopping with miniaturized TM_{110} RF-cavity
- 100 fs pulses @ rep rate 3 GHz or 75 MHz
- Fast switching between continuous and pulsed mode operation
- High Brightness ($\sim 10^7$ A/m^2 sr V)) and energy spread (0.9 eV)
- fs-laser oscillator integrated into the microcope





- Photon-Induced Near-field Electron Microscopy for electron pulse length measurements

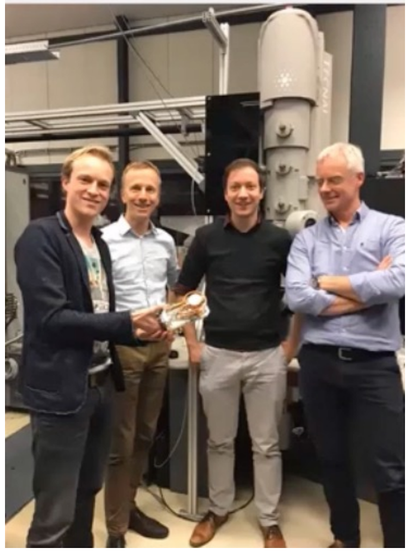


- Shaping of the electron wavefunction with fs laser pulses for Zernike phase contrast microscopy

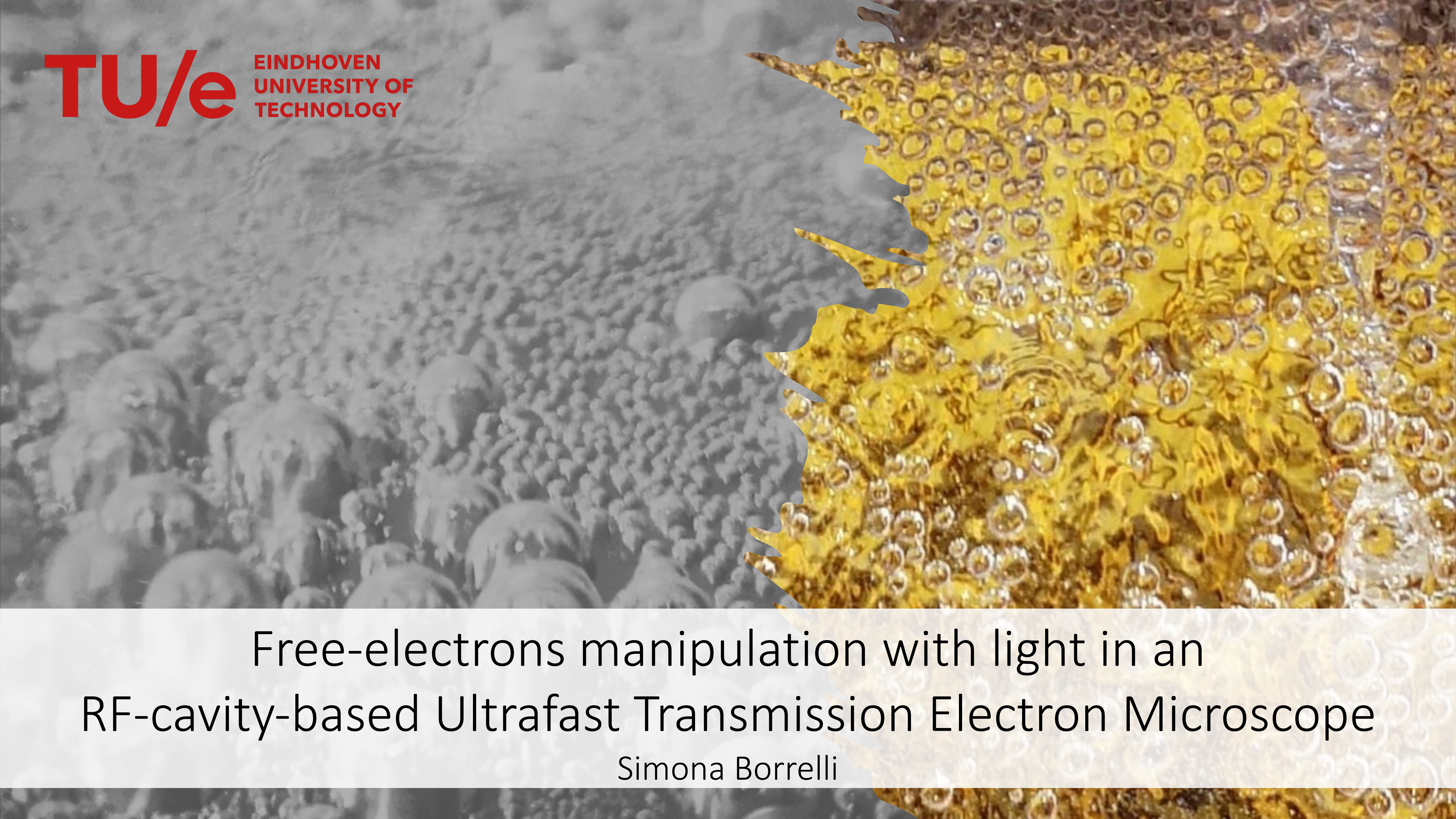
s.borrelli@tue.nl

CQT Coherence and Quantum Technology

Thank you!



TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY



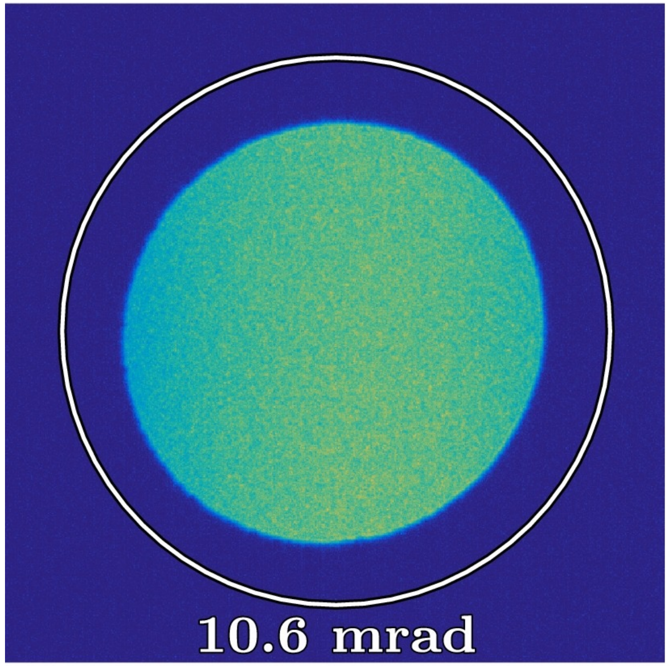
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Free-electrons manipulation with light in an RF-cavity-based Ultrafast Transmission Electron Microscope

Simona Borrelli

Backup slides

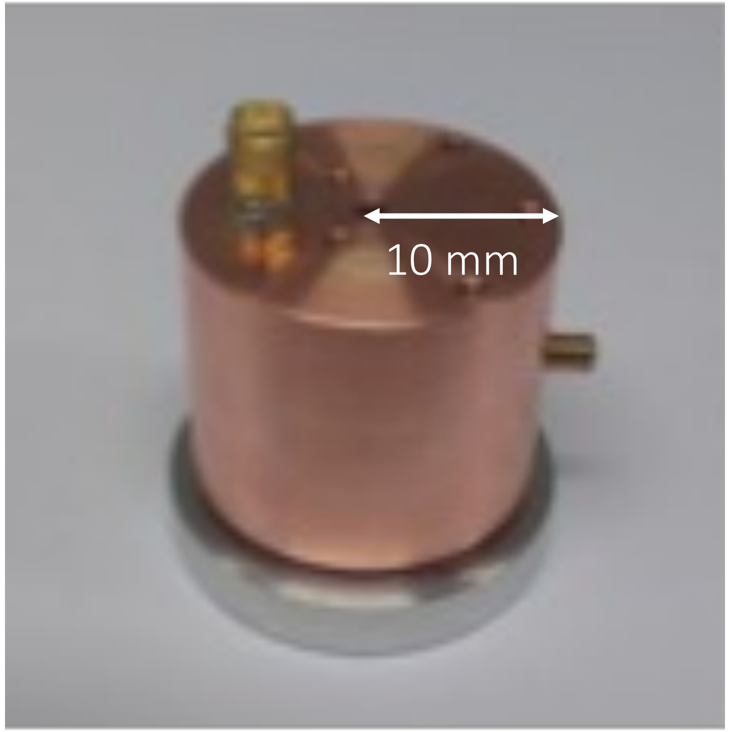
Anglular Distribution of the Pulsed beam – Single Mode



Angles calibrated using a known diffraction ring at 10.6 mrad from a typical cross grating sample.

The focusing angle is determined to be 8.74 mrad.

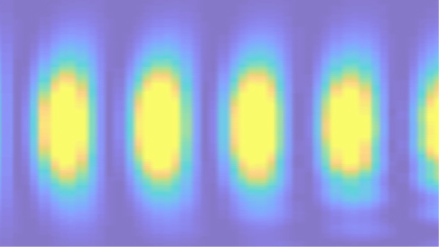
Cavity Radius



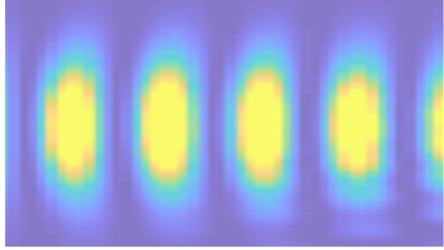
16.4 mm

$$a = \frac{X_{11}}{\sqrt{\varepsilon\mu}\,\omega_0}$$

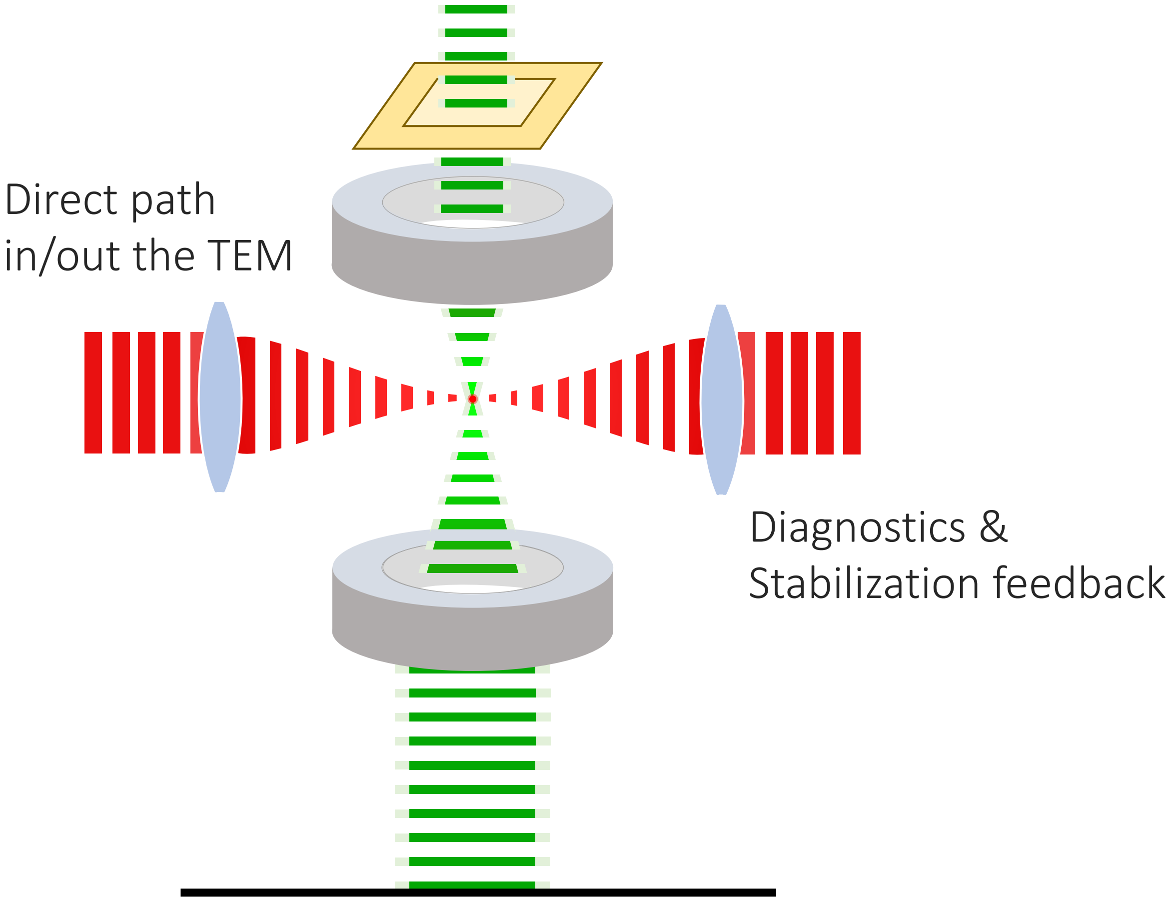
3 GHz in vacuum	a = 60.9 mm
3 GHz with ZrTO4	a = 10 mm



Pulsed-Laser-Based Zernike Phase Plate



Spatial Alignment and Diagnostics



Temporal Alignment