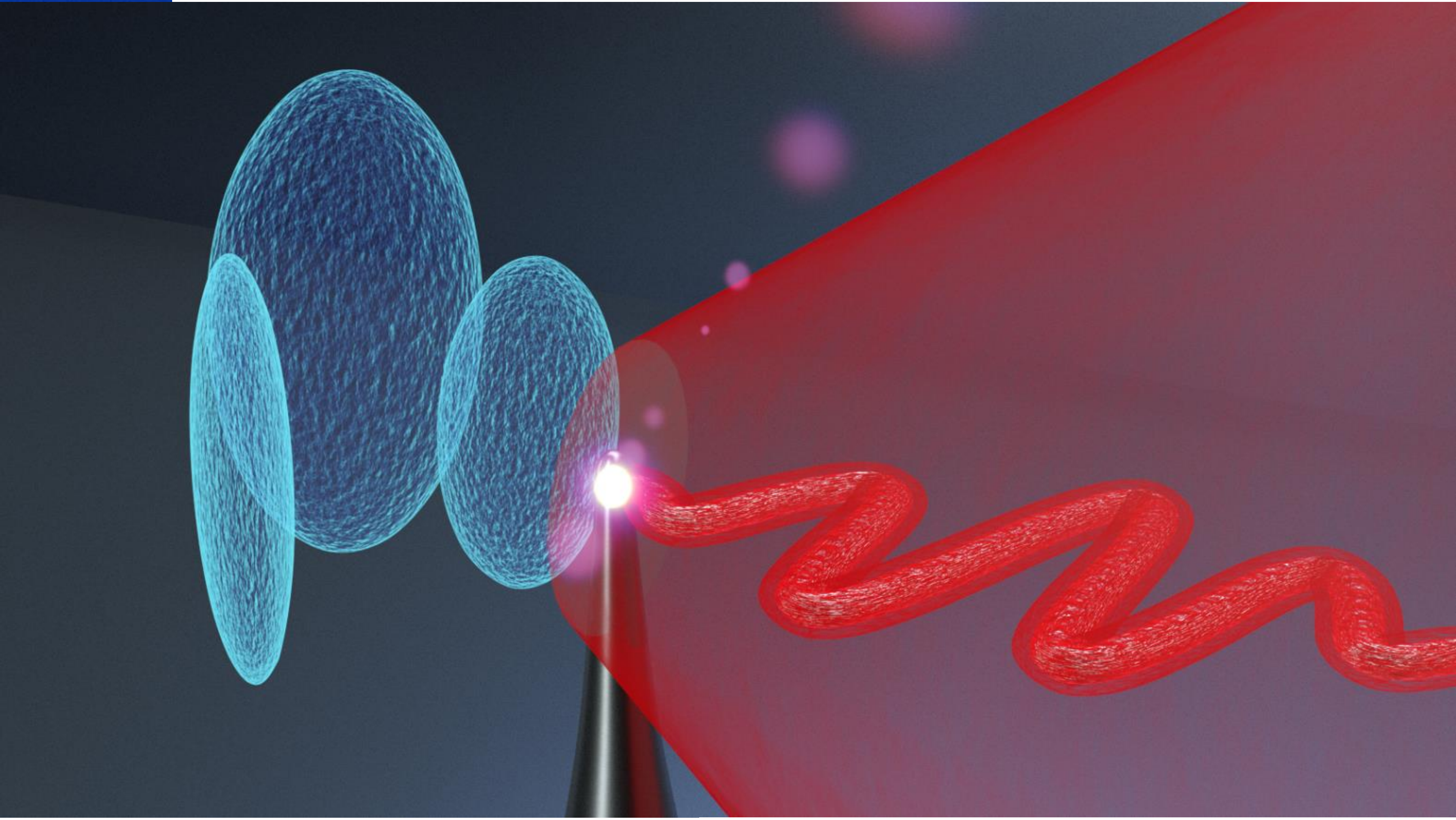
Relativistic Nanophotonics



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May 07 2019, LPAW 2019,
Split, Croatia

Outline

- Motivation
- Light Wave Synthesizer 20 – the laser
- Relativistic nanophotonics
  - Setup
  - Theoretical predictions
  - Results & interpretation
- Conclusions and outlook

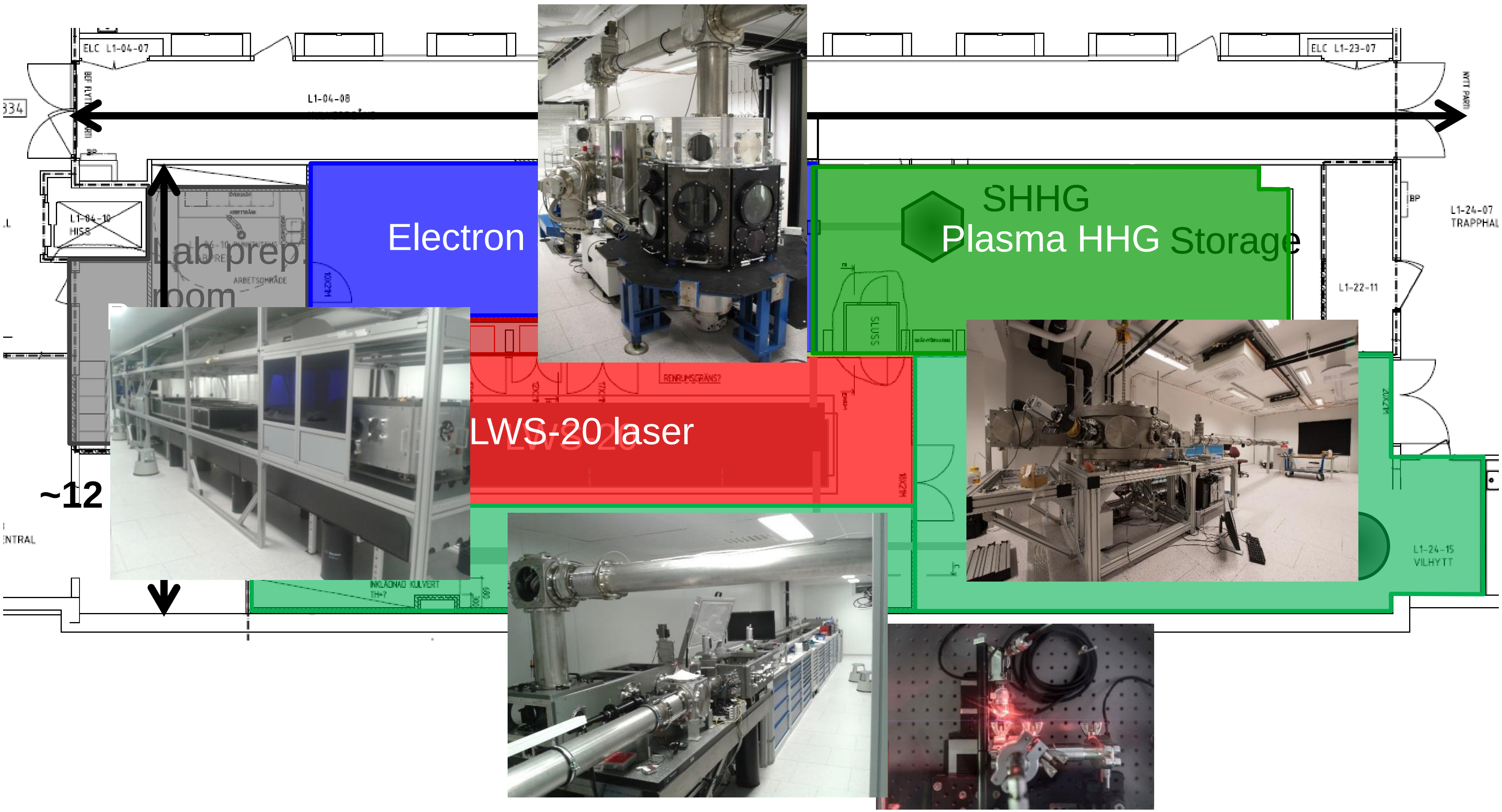
Umea University, REAL:
Relativistic Attosecond Physics Laboratory

2016 Move from Max-Planck Institute of Quantum Optics to Umea University

REAL is the northest high-intensity lab

Umea University, REAL:

Relativistic Attosecond Physics Laboratory

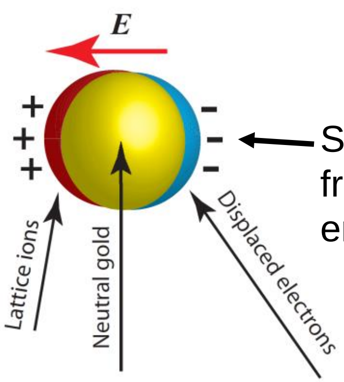


Nanophotonics

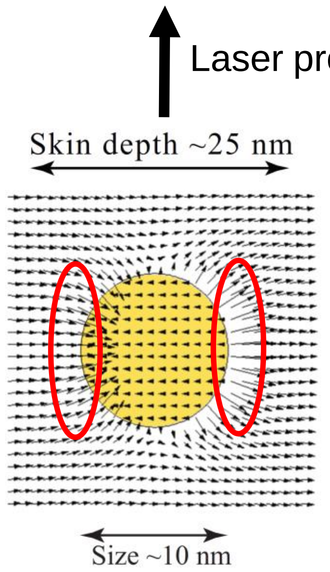
Nanophotonics: Interaction of nanometer, i.e. sub-wavelength, sized objects with light.

Two distinct features in this regime:

- Sub-wavelength focusing
- Field enhancement



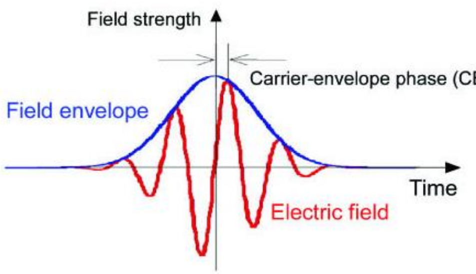
Strong electrostatic fields from charge separation enhance the laser field

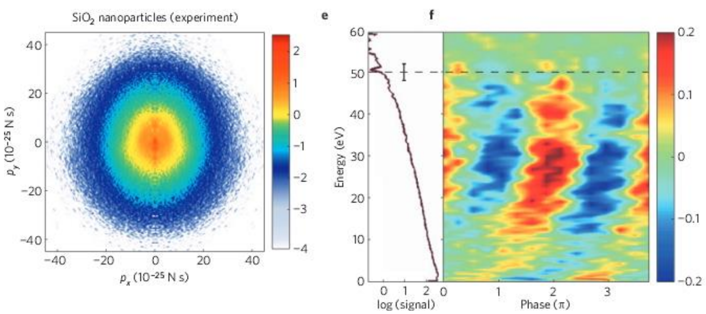


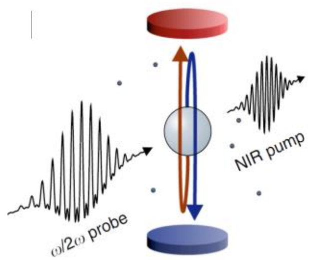
Size << wavelength

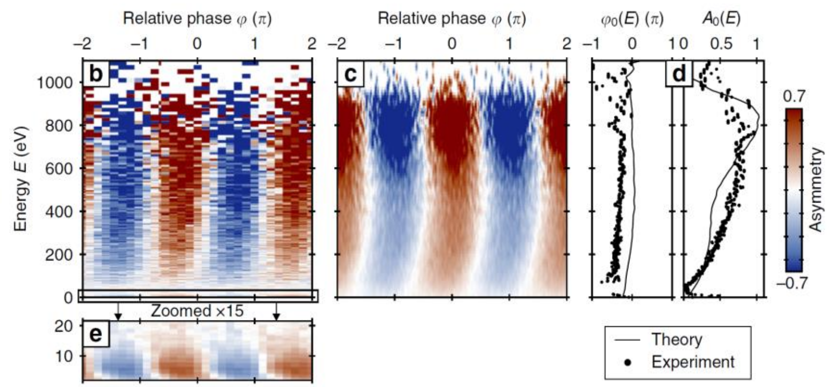
M. I. Stockman, *Opt. Express* **19**, 22029 (2011).

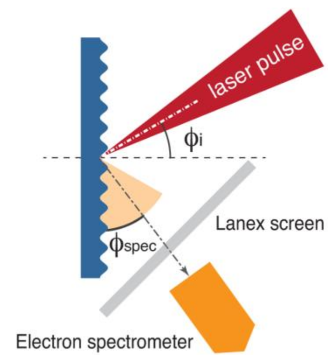
Motivation

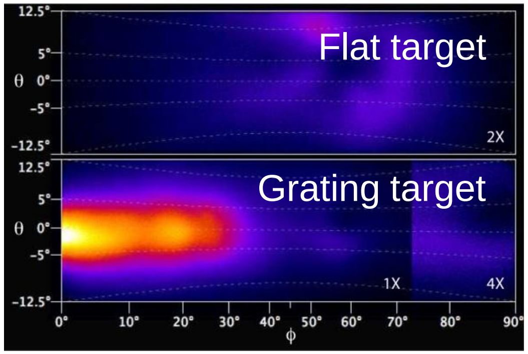












Motivation:

- o Attosecond few-MeV high charge electron source!
- o Nanophotonics at relativistic intensities
- o Attosecond control of matter with light

J. Passig et al, Nature Commun. 8, 1181 (2017)
L. Fedeli et al., PRL 116, 015001 (2016)
VLA: M. Thevenet et al., Nat. Phys. 12, 355–360 (2016)

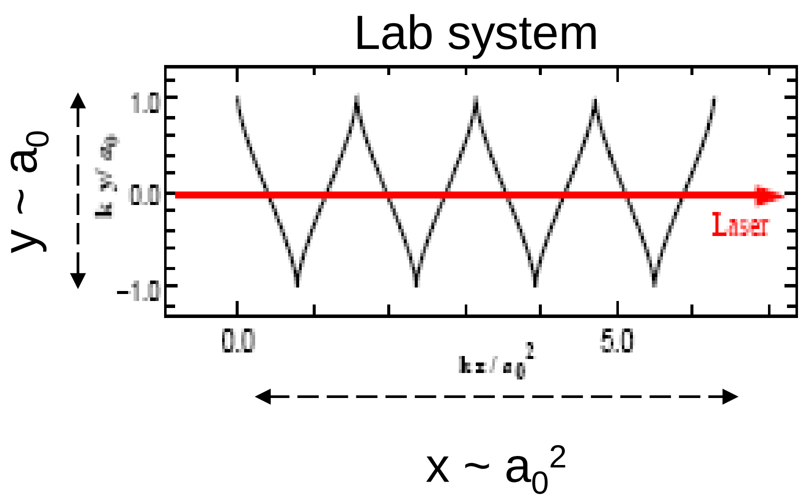
S. Zherebtsov et al, Nature Physics 7, 656 (2011)

Free electron in relativistic laser field

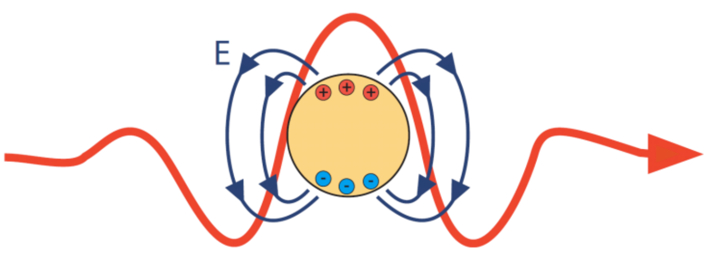
Amplitude of relativistic oscillation:

$ca_0/\omega = \lambda a_0/(2\pi)$ ~<u>0.8-0.9 μm </u>(λ=740 nm,a_0=8)

→ Microphotonics ?!?



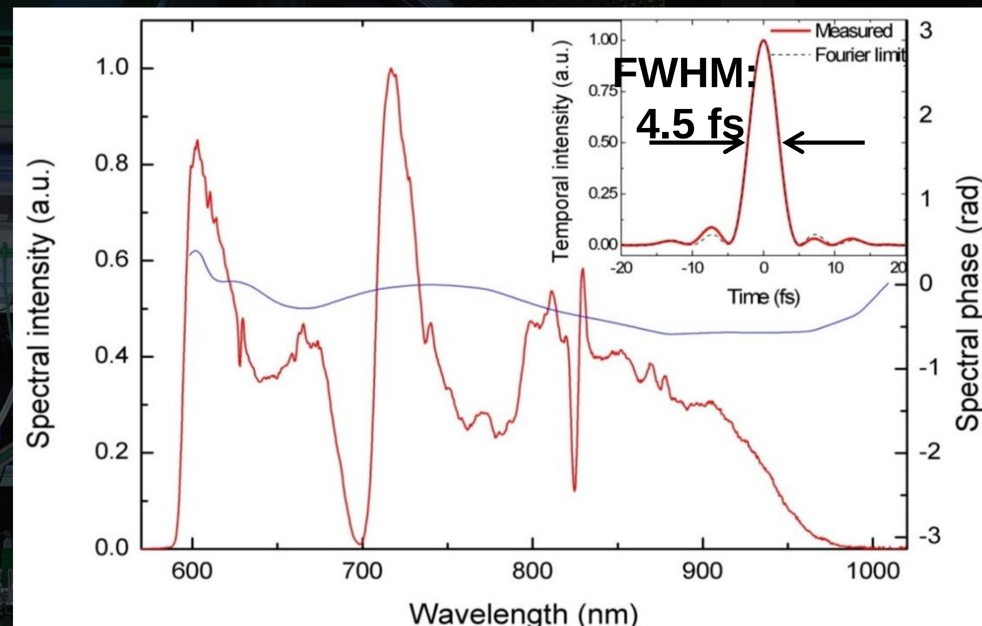
We have collective effects, which make the amplitude smaller !!!



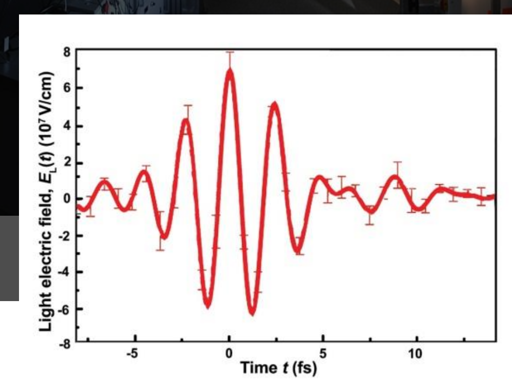
Light Wave Synthesizer 20 laser (optical parametric synthesizer)

Most intense few-cycle laser system in the world!

- **Spectrum: 580 – 1000 nm**
- **4.5 fs FWHM duration**
- **70-75 mJ energy**
- **16 TW peak power**
- **10 Hz rep. rate**
- **Focusable to 1.2 µm**
- **>10^{20} W/cm^2 intensity (a_0=6-7)**
- **Contrast >10^{16} for >20-30 ps and 10^7 at 2ps**

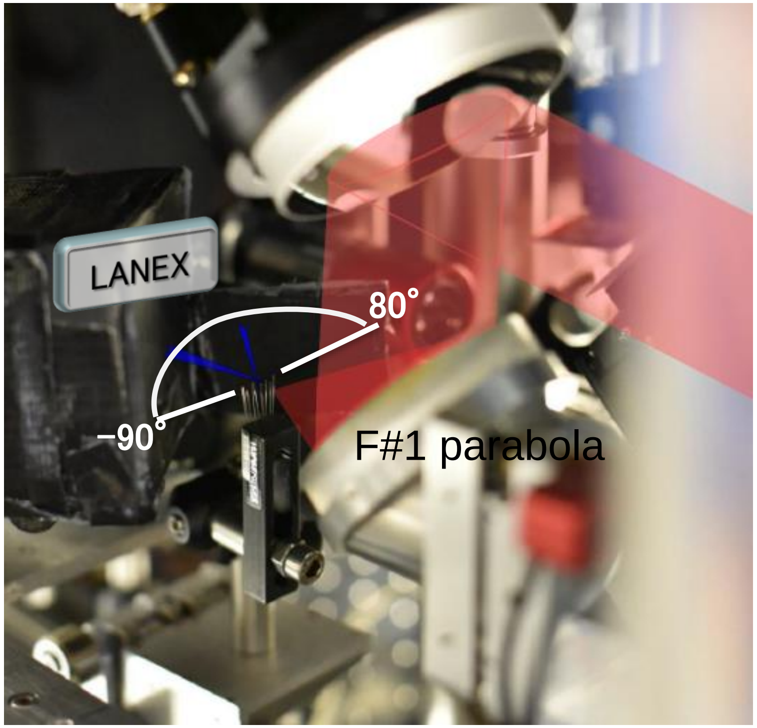


Next steps under preparation:
CEP stabilization and 100 TW upgrade



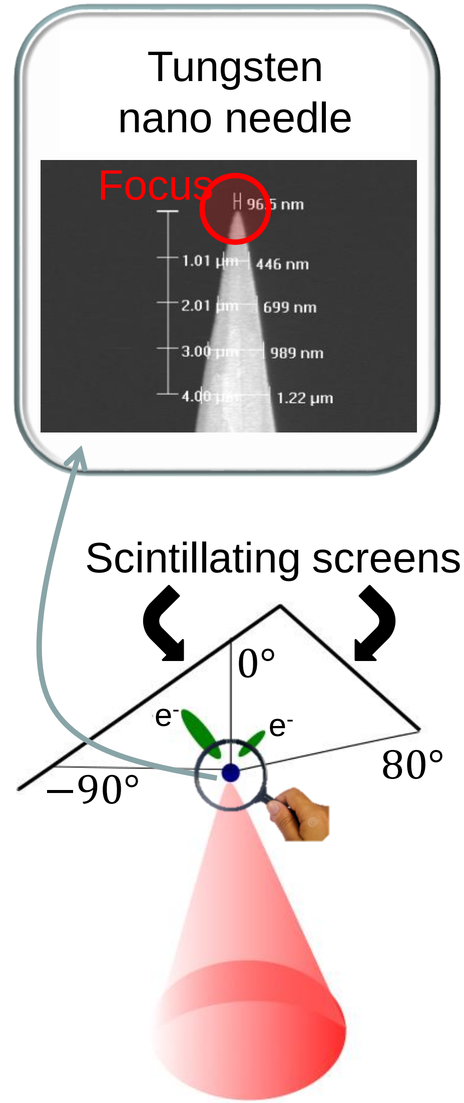
D. E. Rivas *et al.*, Sci. Rep. **7**, 5224 (2017)

Experimental setup



Tip radius
<50 nm

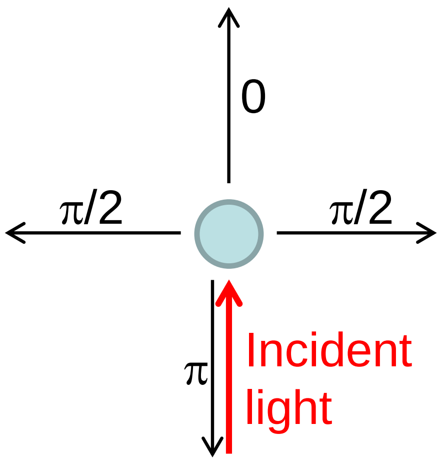
FWHM focus
size: 1.2 µm



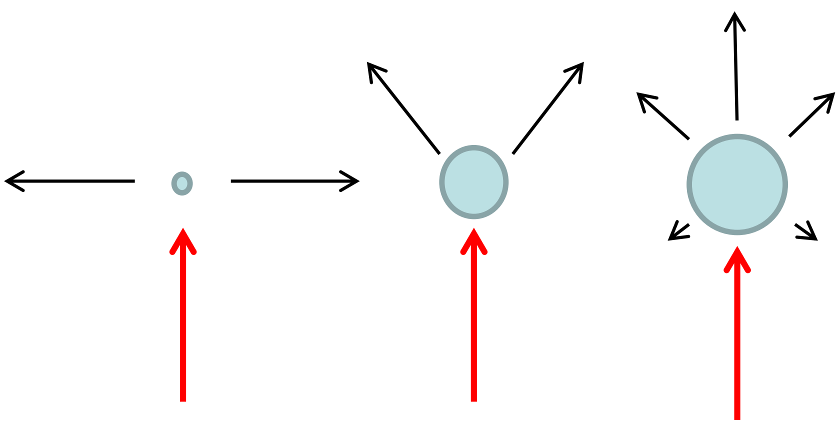
- ≈π screen for angular electron emission distribution
- Tungsten nano-needles with R<50 nm tip
- Sub-micron accuracy alignment for each needle
- Single-shot mini stereo CE phase meter
- Low-energy (<16 MeV) high-resolution spectrometer

Theoretical predictions 1

Mie theory (scattering on ~wavelength-sized conducting spheres)



Validity:
$a_0 \ll 1$
(low intensity)



R<<λ   R<λ   R~λ

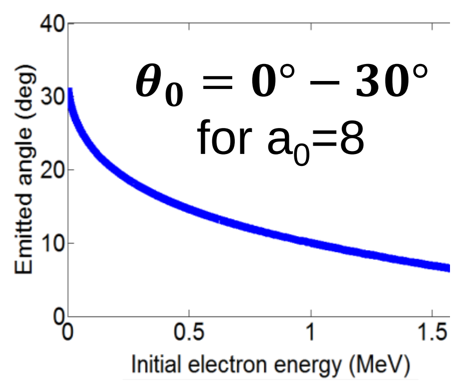
Relativistic regime:

Nonlinear ponderomotive scattering

Validity: $a_0 > 1$ (high intensity)

θ_0 = arctan sqrt[2/(γ-1)]

Electron initially at rest, γ: final electron energy



If electron is initially not at rest:
initial parameters: γ_0, β_0 parallel component

$$\theta_0 = \arctan \frac{\sqrt{\frac{2}{1+\beta_0}\left(\frac{\gamma}{\gamma_0} - 1\right)}}{\gamma - \gamma_0(1-\beta_0)}$$

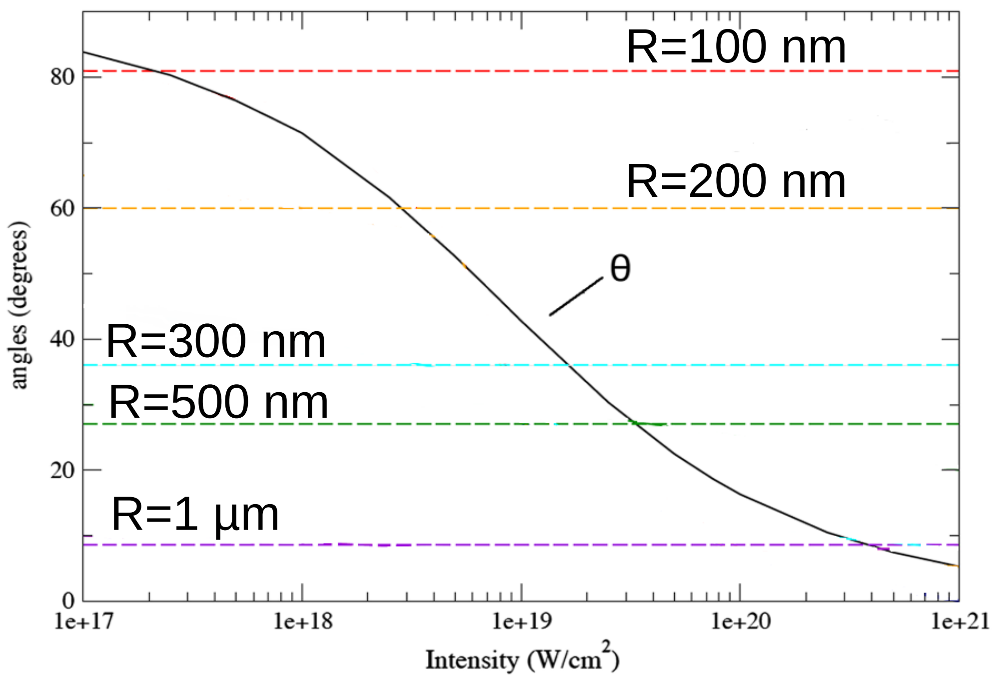
L. Di Lucchio et al, PRSTAB **18**, 023402 (2015), F. V. Hartemann et al. , Phys. Rev. E., **51,** 4833 (1995),

Theoretical predictions 2

Our parameters:

$$a_0 = 0.3 - 8$$

$$R \approx \sqrt{a_0}\delta = 10 - 30\ \text{nm}$$

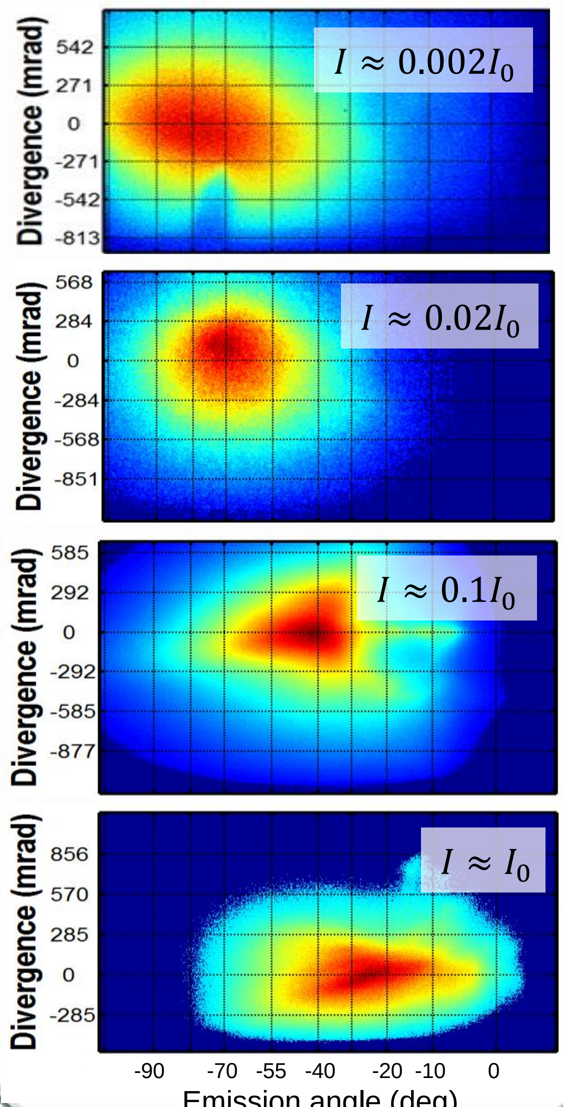


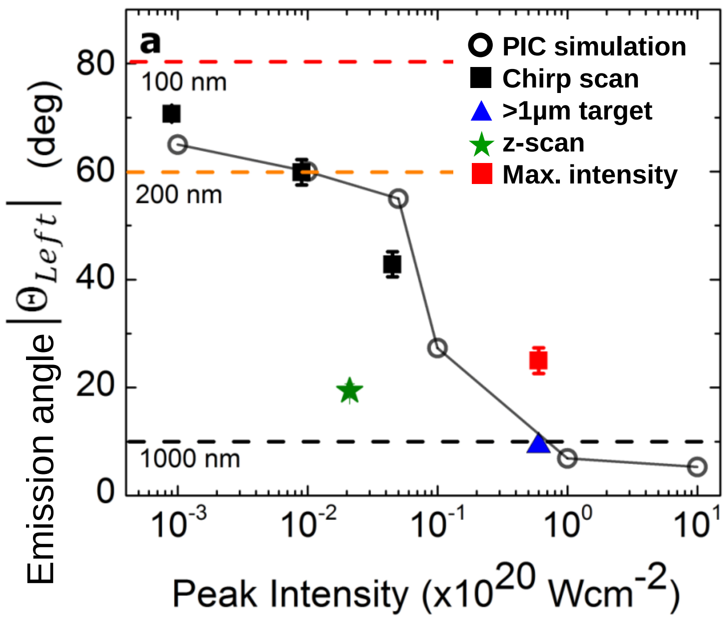
- Mie theory for lower intensities
- Nonlinear ponderomotive scattering bends electrons forward for small targets and high intensities

L. Di Lucchio et al, PRSTAB **18**, 023402 (2015)

Experimental results: Intensity dependent angular electron emission

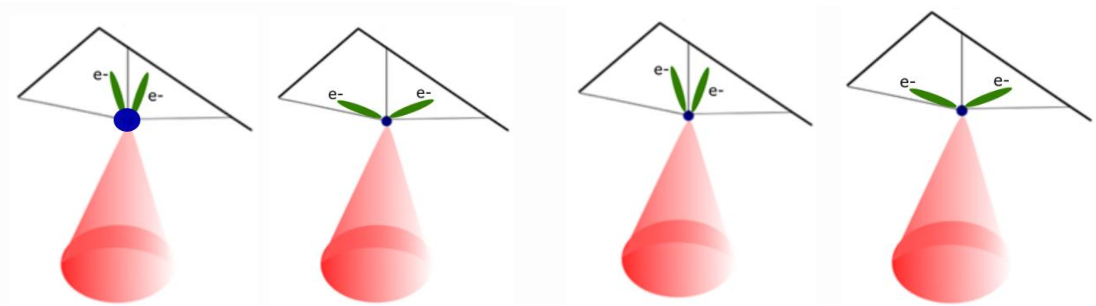
$\mathbf{I_0 \sim 10^{20} Wcm^{-2}}$





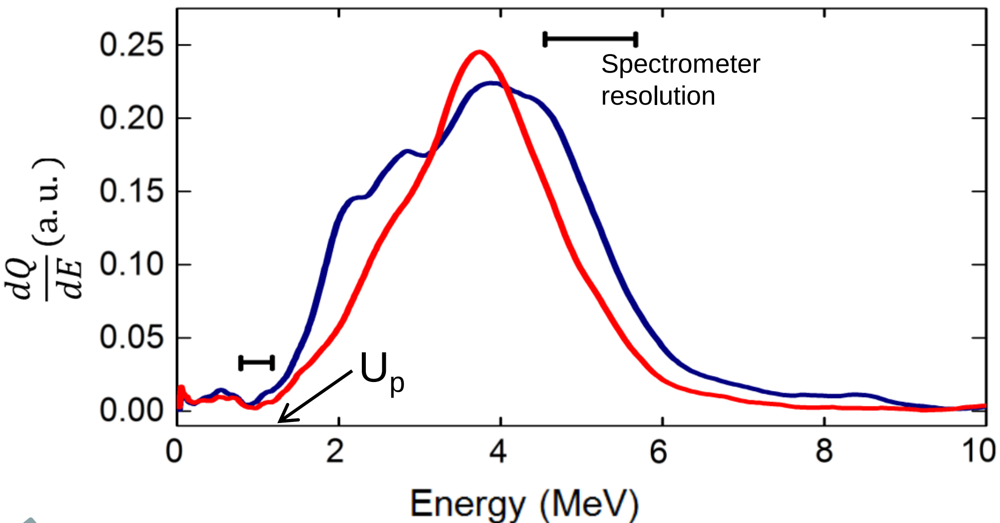
- At low intensities: Classical Mie scattering
- At high intensities: Nonlinear “pondermotive“ scattering

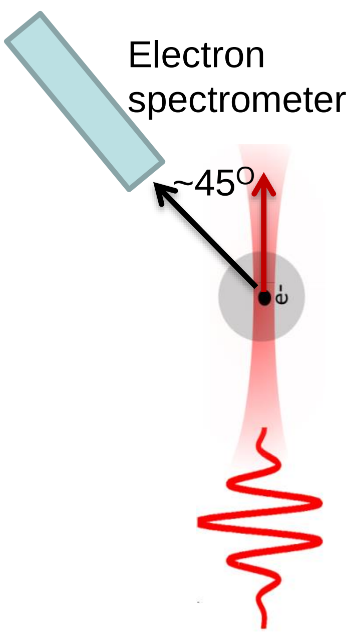
Classical Mie: size effect **Nonlinear “pond.” scattering:**



$\boldsymbol{R = 1000}$ **nm** $\boldsymbol{R = 200}$ **nm** $\boldsymbol{I \approx I_0}$ $\boldsymbol{I \approx 0.005 I_0}$

Experimental results: Electron spectrum and charge





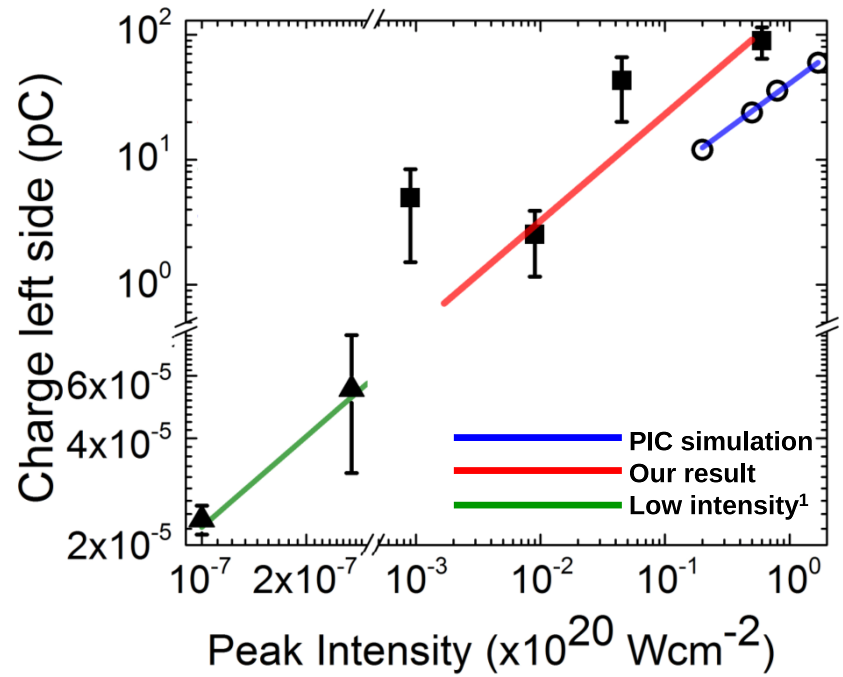
Ponderomotive potential

$$I = 6 \times 10^{19}\mathbf{Wcm^{-2}} \quad a_0 \approx 5$$

$$\gamma_L = \sqrt{1 + a_0^2/2}$$

$$U_p = mc^2(\gamma_L - 1) \approx 1.3\ \mathbf{MeV}$$

Electron energies much beyond U_p

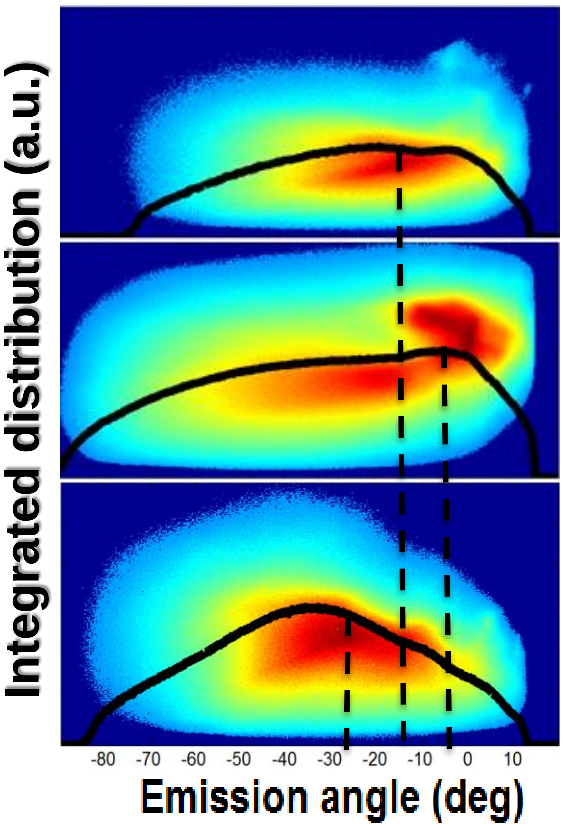


Charge vs. intensity is almost linear

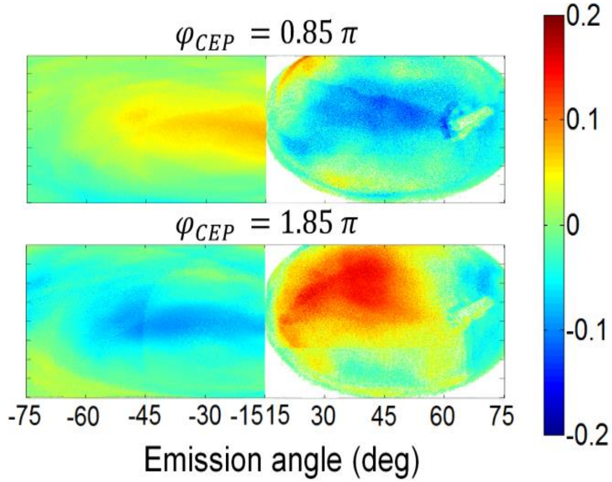
1: F. Süßmann et al, *Nat. Commun.* **6**, 7944 (2015)

Experimental results: Laser electric field dependence

Electron angular distribution under the same conditions

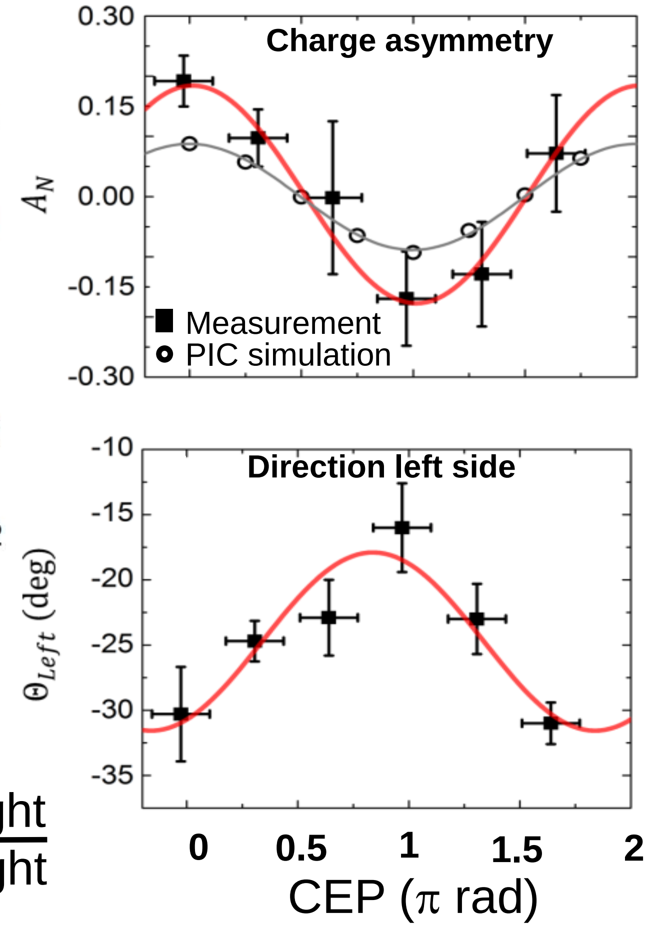


Electron angular distribution

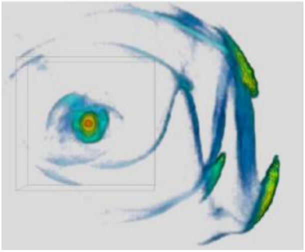


Charge asymmetry parameter:

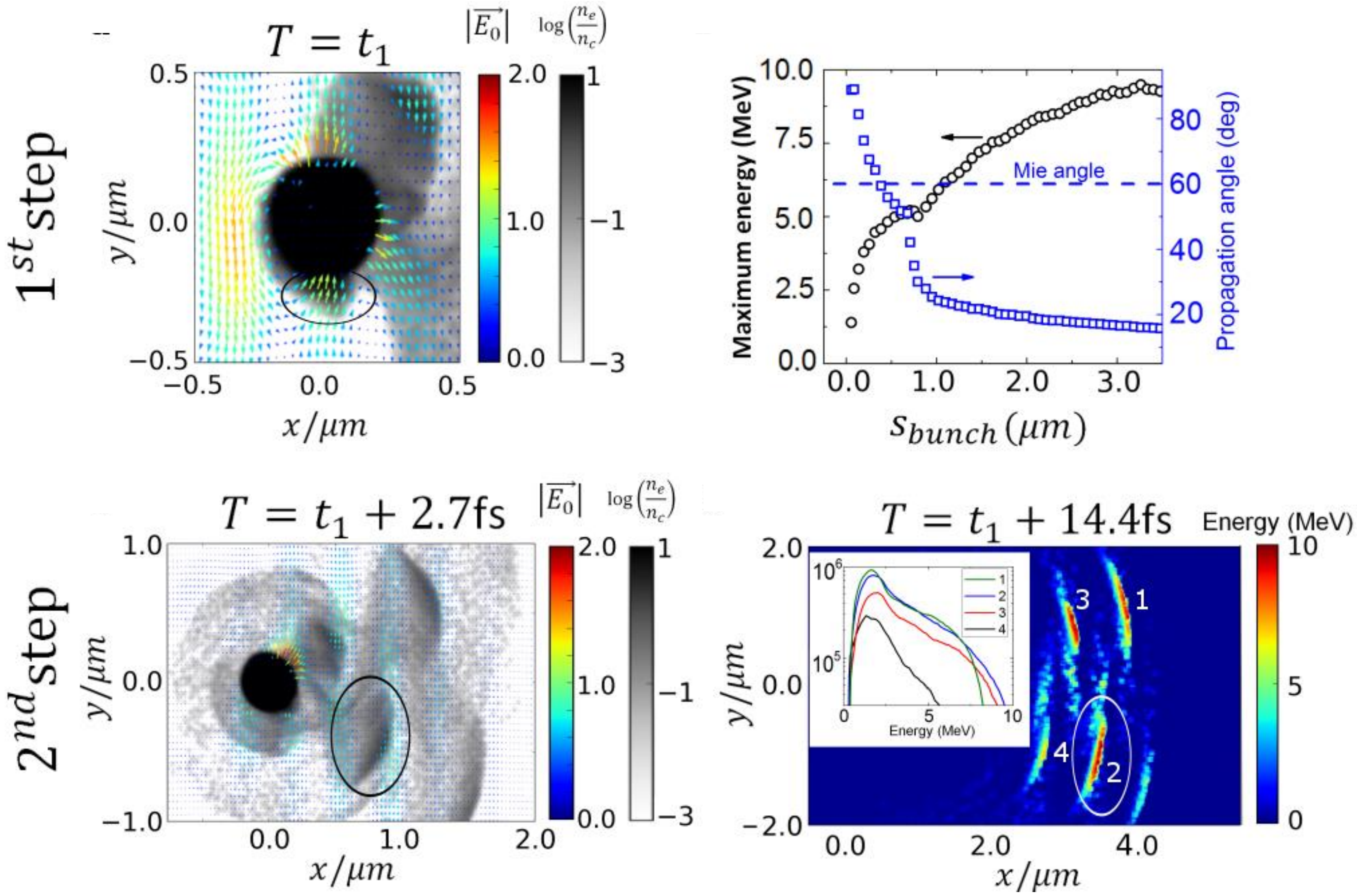
$$A_N = \frac{\text{Charge left} - \text{charge right}}{\text{Charge left} + \text{charge right}}$$



- **Electron propagation direction is controlled by the CEP**
- **Clear asymmetry in the electron yield as a function of the CEP**
- **CEP dependent relativistic nanophotonics**



PIC Simulations



- 2 steps: (1) nanophotonic electron emission (2) vacuum laser acceleration
- Sub-cycle regime (electrons do not oscillate in laser field, but run within a half-cycle)
- Electron properties: 10 MeV, 300 as, 40 pC

Accelerating fields

Accelerating field gradients in …

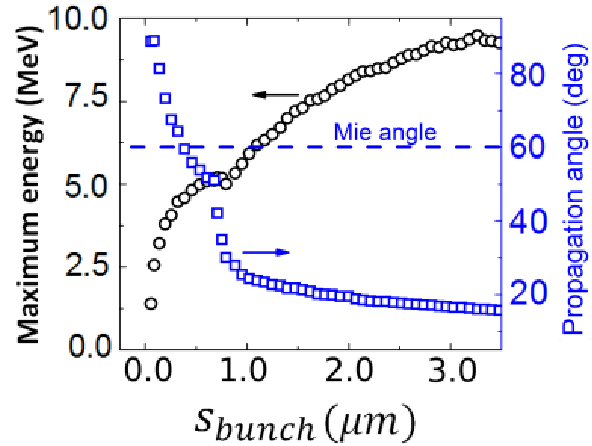
<u>PIC simulations:</u>

1. step (nanophotonic electron emission)

   5-10 TV/m

2. step (vacuum laser acceleration)

   2-3 TV/m

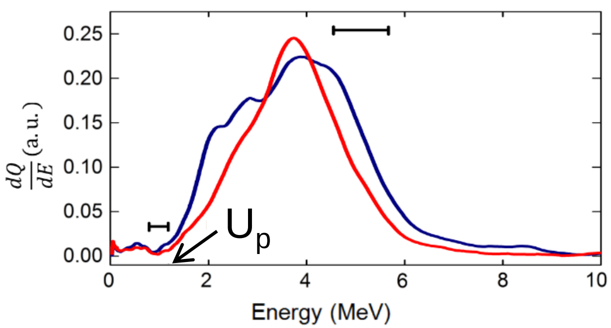


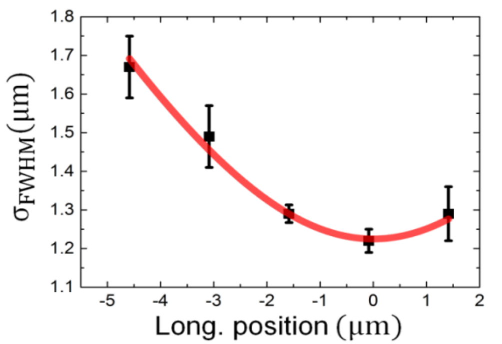
<u>Experiments:</u>

$E_{electron}/Z_{Rayleigh}$ =

9 MeV / 4.8 µm =

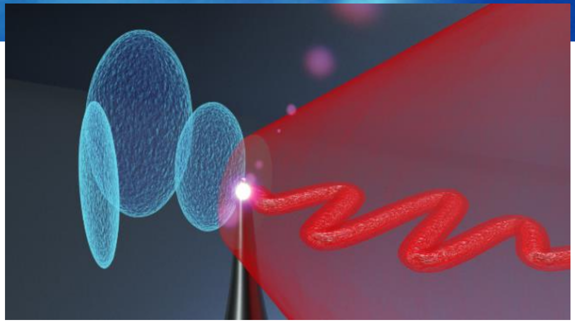
<u>2 TV/m</u>



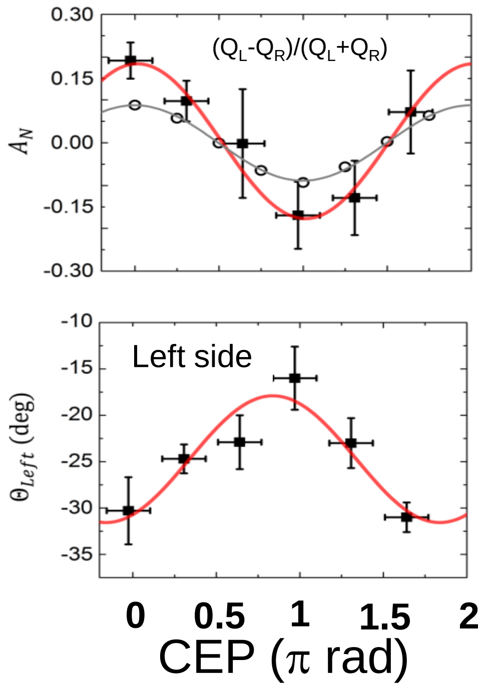


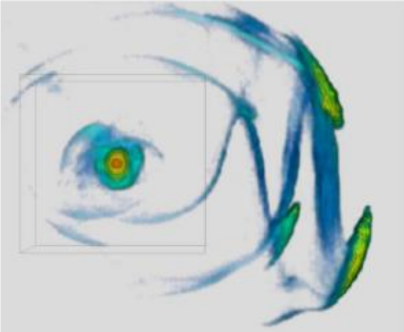
D. Cardenas et al, Sci. Rep. accepted (2019) www.nature.com/articles/s41598-019-43635-3 , link valid from 05.13.2019

Summary and outlook



- Nanophotonics is extended to the relativistic realm
- Sub-cycle electron acceleration
- First waveform control (CEP) in relativistic regime
- Hints for the highest accelerating gradients





Outlook:

- Thomson/Compton scattering to generate attosecond X-rays
- Relativistic electron bunches for FEL seeding or electron diffraction

D. Cardenas et al, Sci. Rep. accepted (2019) www.nature.com/articles/s41598-019-43635-3 , link valid from 05.13.2019

Former and new coworkers

Gas harmonics | **Relativistic plasma harmonics** | **Electron acceleration**






Bo

ardenas

Thank you for your attention!

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