Electron emission from sharp tungsten tips triggered by femtosecond laser pulses

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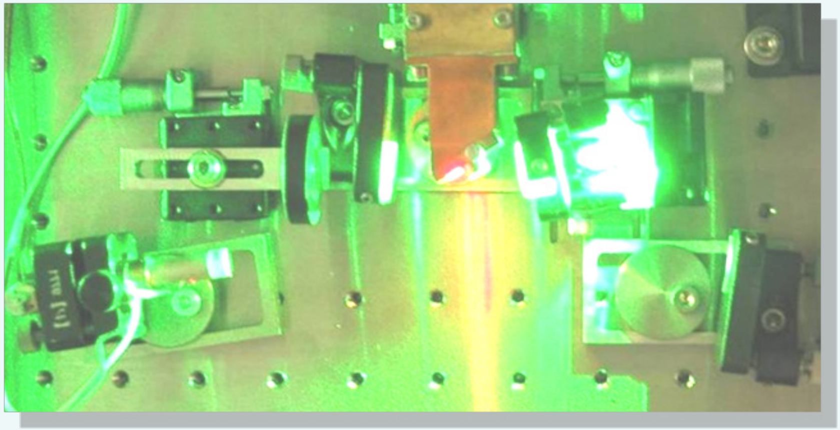
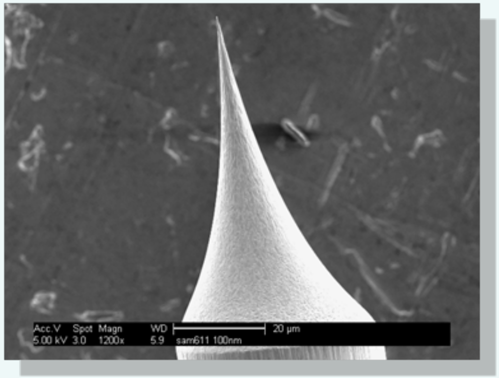


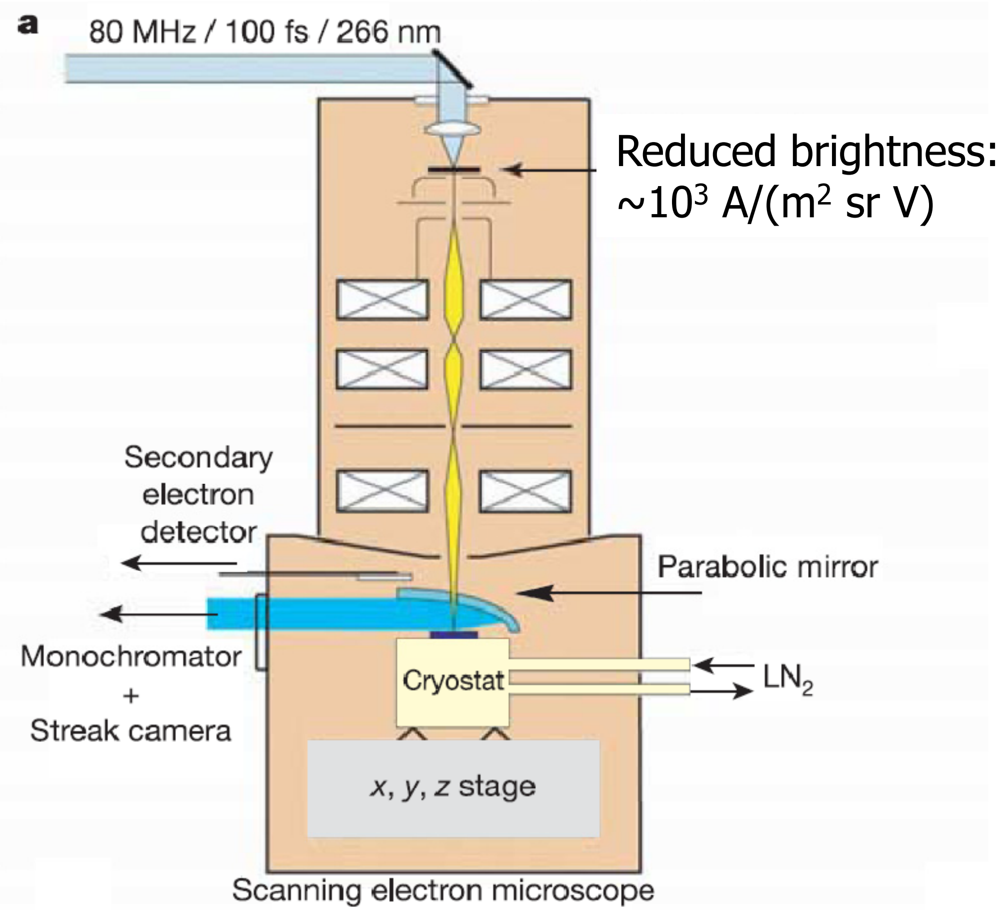
Femtosecond frequency comb:
- Control of optical electric field
- High peak electric field



Field emission tip:
brightest electron source

R. H. Siemann Memorial Symposium and ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders, SLAC, July 7-10, 2009

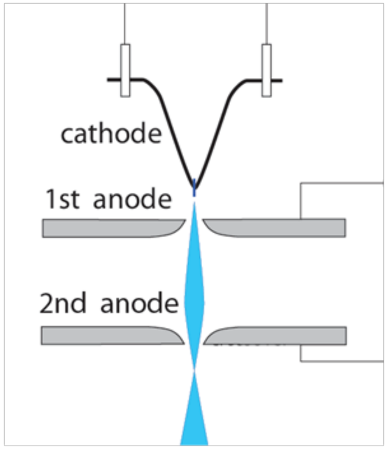
Ultrafast electron sources



Reduced brightness:
~10^3 A/(m^2 sr V)

M. Merano, S. Sonderegger et al., Nature 438, 479 (2005)

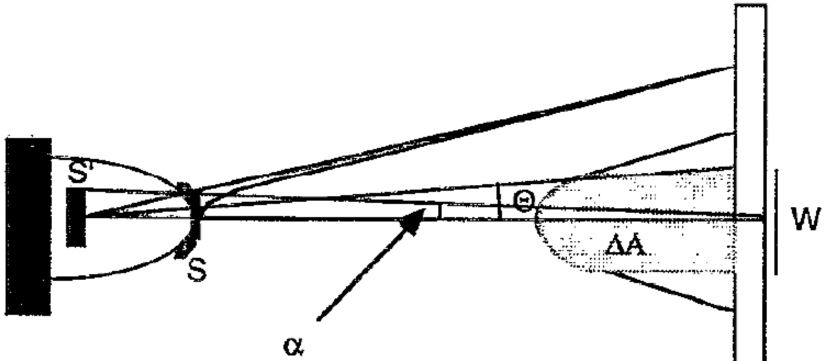
$$B_r = \frac{\mathrm{d}I}{\mathrm{d}\Omega}\frac{1}{U}\frac{1}{\pi r_v^2}$$



Field emission SEM
(high resolution SEM)

Reduced brightness with standard FE tip: > 10^8 A/(m^2 sr V)

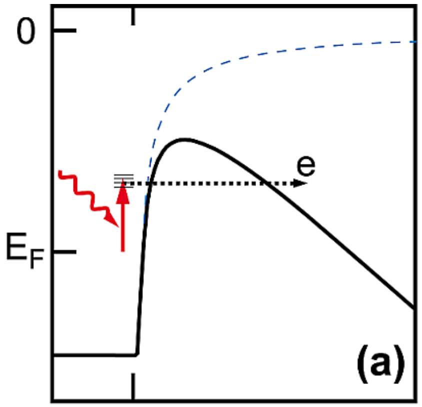
(Spence et al. 1994; Swanson, Schwindt 1997; De Jong, Bonard 2004; Kruit et al. 2006…)



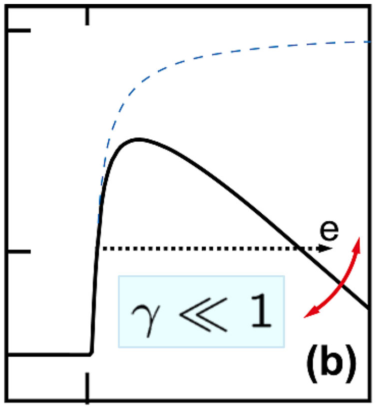
Qian et al., J. Appl. Phys. 1993

Light induced electron emission processes

Photo-assisted field emission

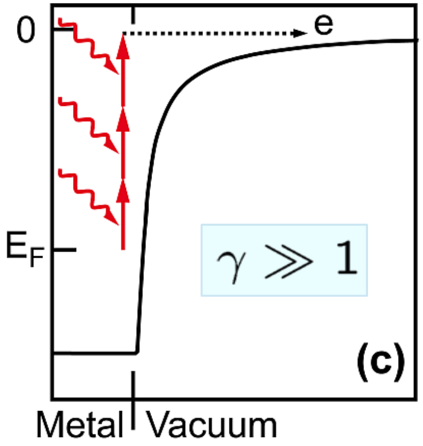


Optical field emission

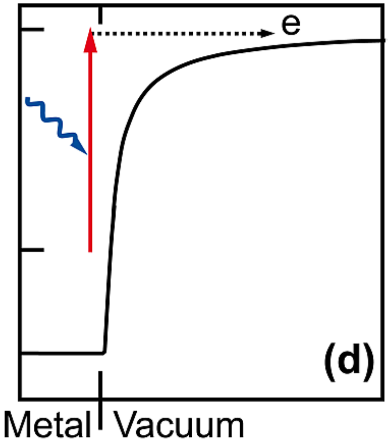


$$\gamma = \frac{\omega\sqrt{2m\Phi}}{eE}$$

Keldysh parameter



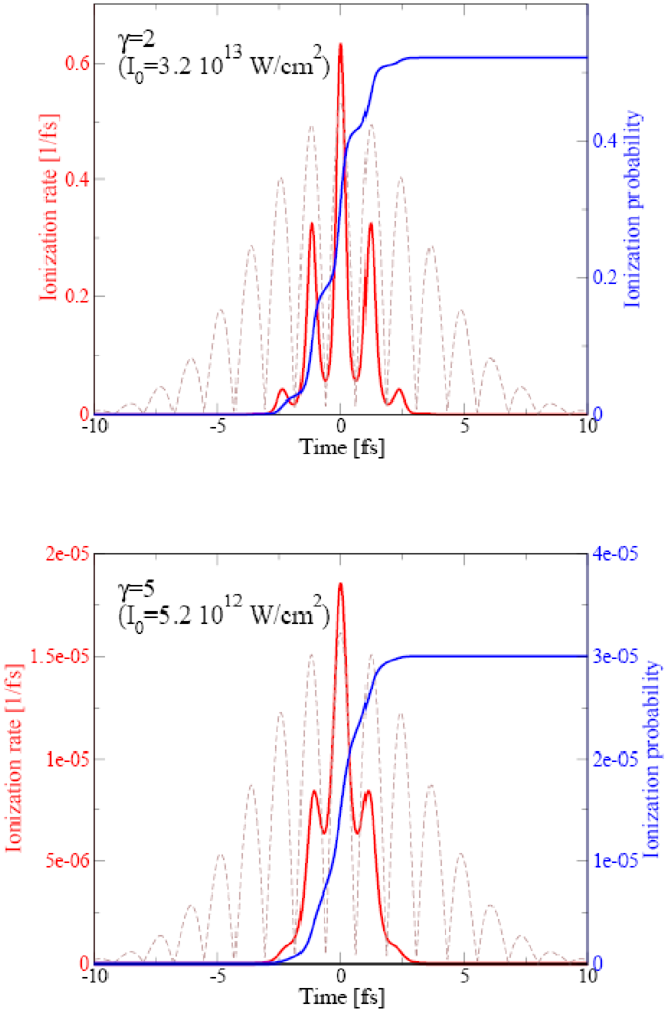
Multiphoton emission



Photoelectric effect

Thermally assisted emission: laser heating of the tip

Time-dependence in intermediate Keldysh regime



Suppl. Fig. 8: Strong-field ionization in the Yudin-Ivanov theory

(From Uiberacker at al.)

Yudin-Ivanov theory for tunnel ionization of atoms:

- No cycle averaging
- $\gamma \approx 1$: "non-adiabatic tunneling" (between extreme cases of multi-photon emission and quasi-static tunnel emission)

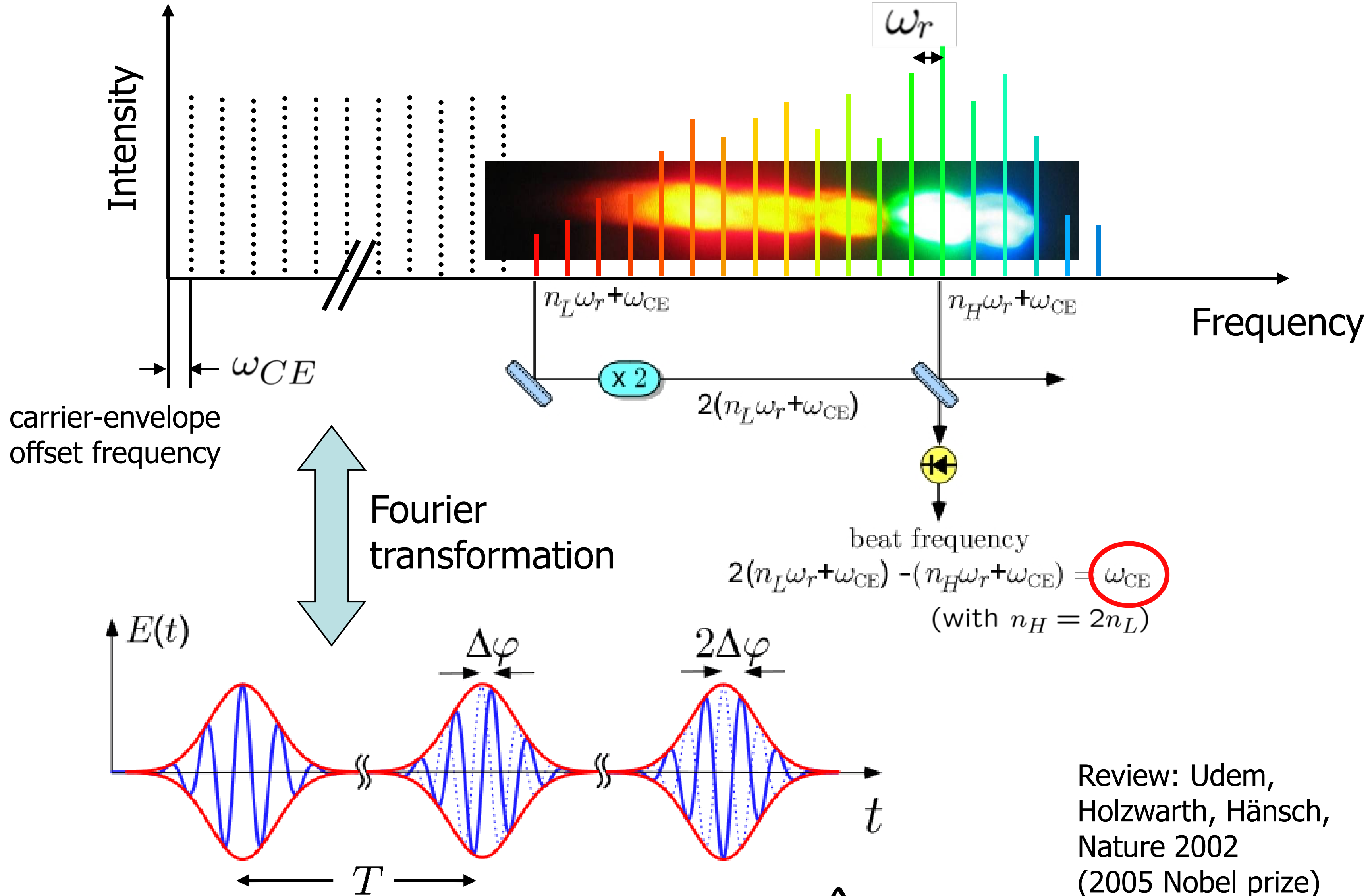
Theory:

- G. L. Yudin, M. Yu. Ivanov, Nonadiabatic tunnel ionization: Looking inside a laser cycle, PRA 2001

Experiments with atoms in gas phase:

- Uiberacker et al., Attosecond real-time observation of electron tunneling in atoms, Nature 2007
- Colosimo et al., Scaling strong field interactions towards the classical limit, Nat. Phys. 2008
- Eckle et al., Attosecond ionization and tunneling delay time measurements in Helium, Science 2008

Frequency comb: control of optical electric field



carrier-envelope offset frequency

Fourier transformation

beat frequency

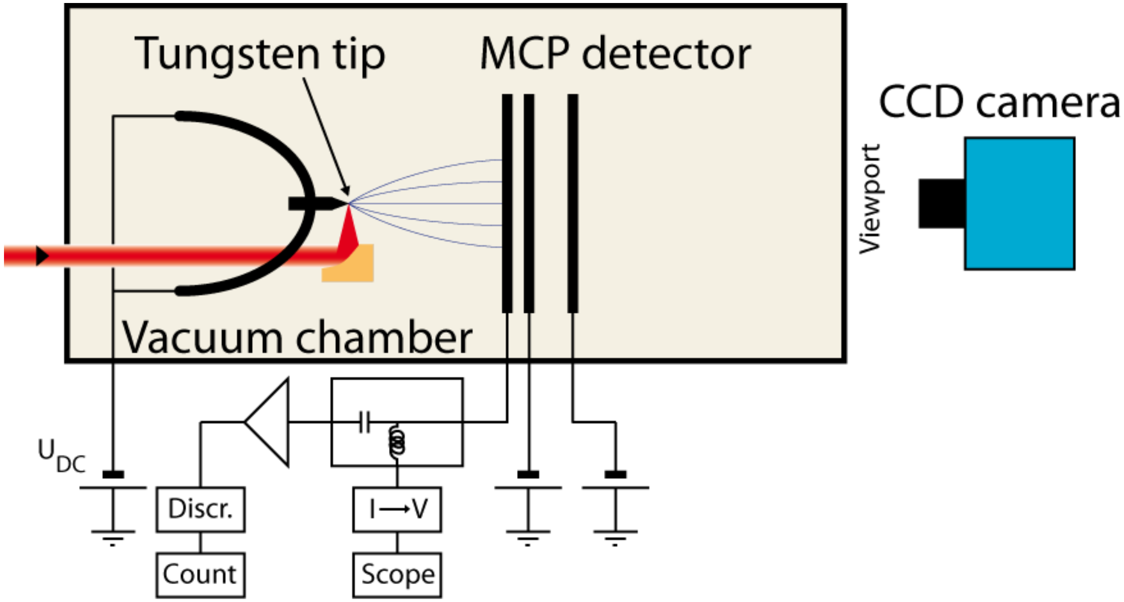
$2(n_L\omega_r+\omega_{CE})-(n_H\omega_r+\omega_{CE})=\omega_{CE}$

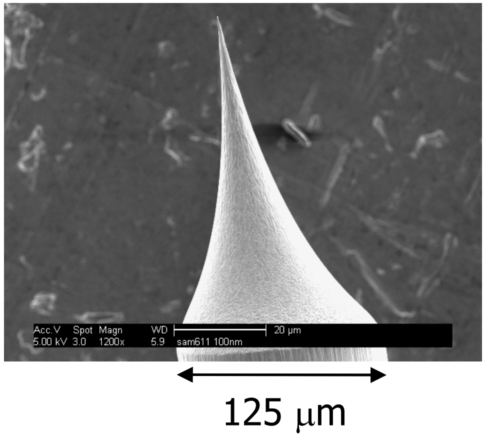
(with $n_H = 2n_L$)

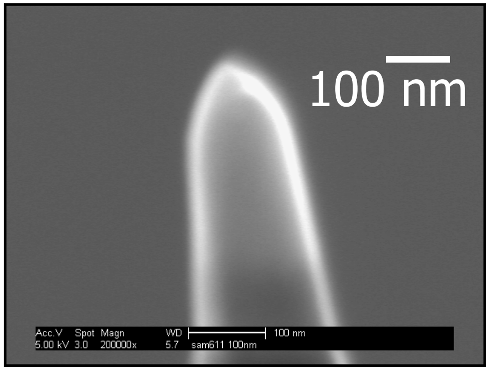
$$\omega_{CE} = 2\pi\frac{\Delta\varphi}{T}$$

Review: Udem, Holzwarth, Hänsch, Nature 2002 (2005 Nobel prize)

Experimental setup

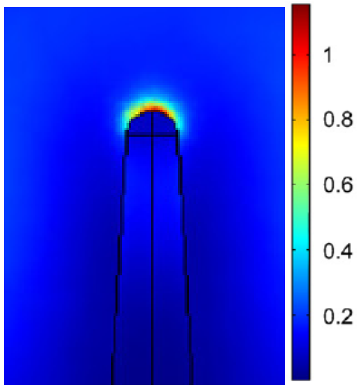






- Ti:Sa oscillator: ~780nm, 500mW, 6fs, 150MHz
- Spot radius on tip ~ 3 µm ($1/e^2$)

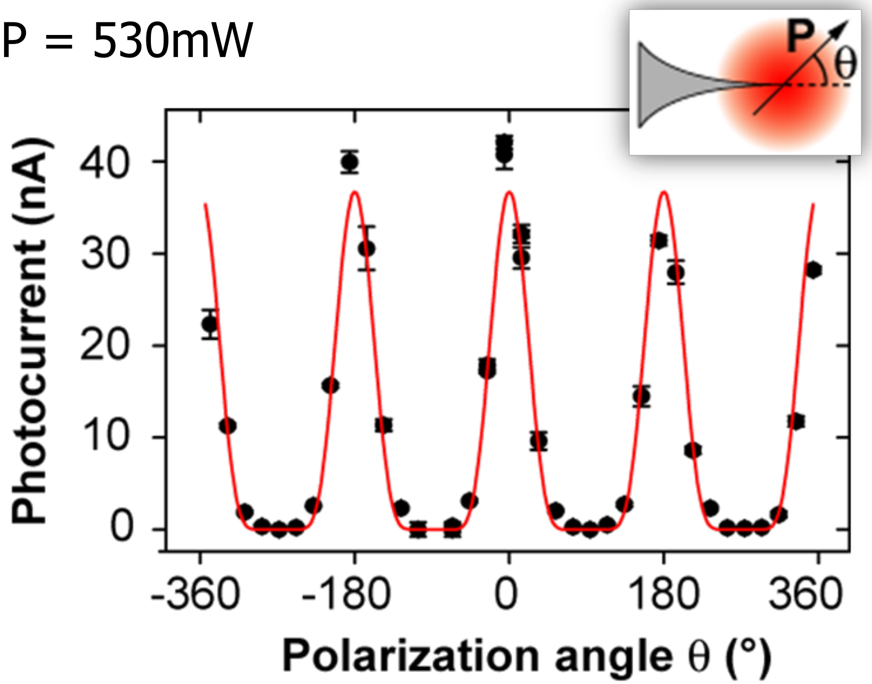
→ Peak elec. field up to 5GV/m w/o field enh.

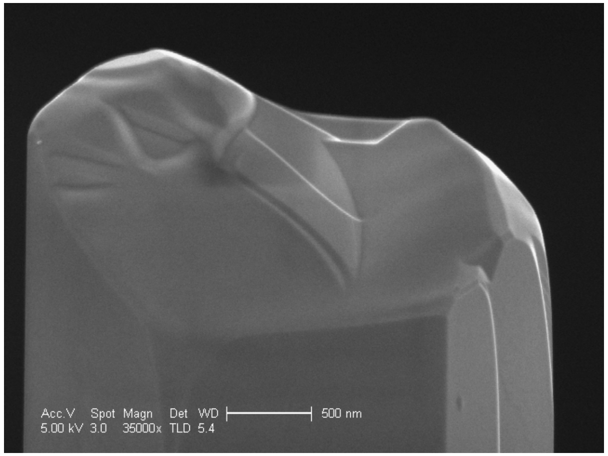


r=50 nm W tip,
780 nm light

Stub emitter instead of tip

P = 530mW





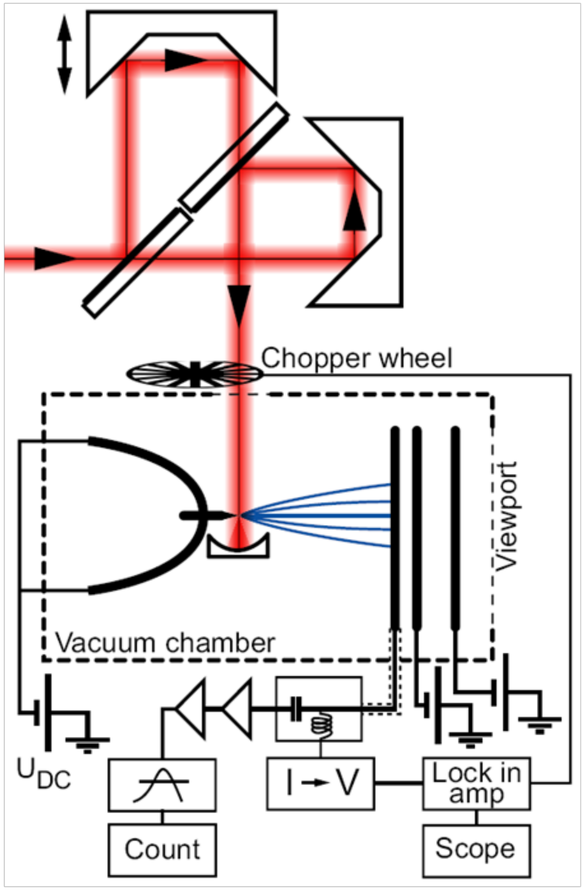
500nm

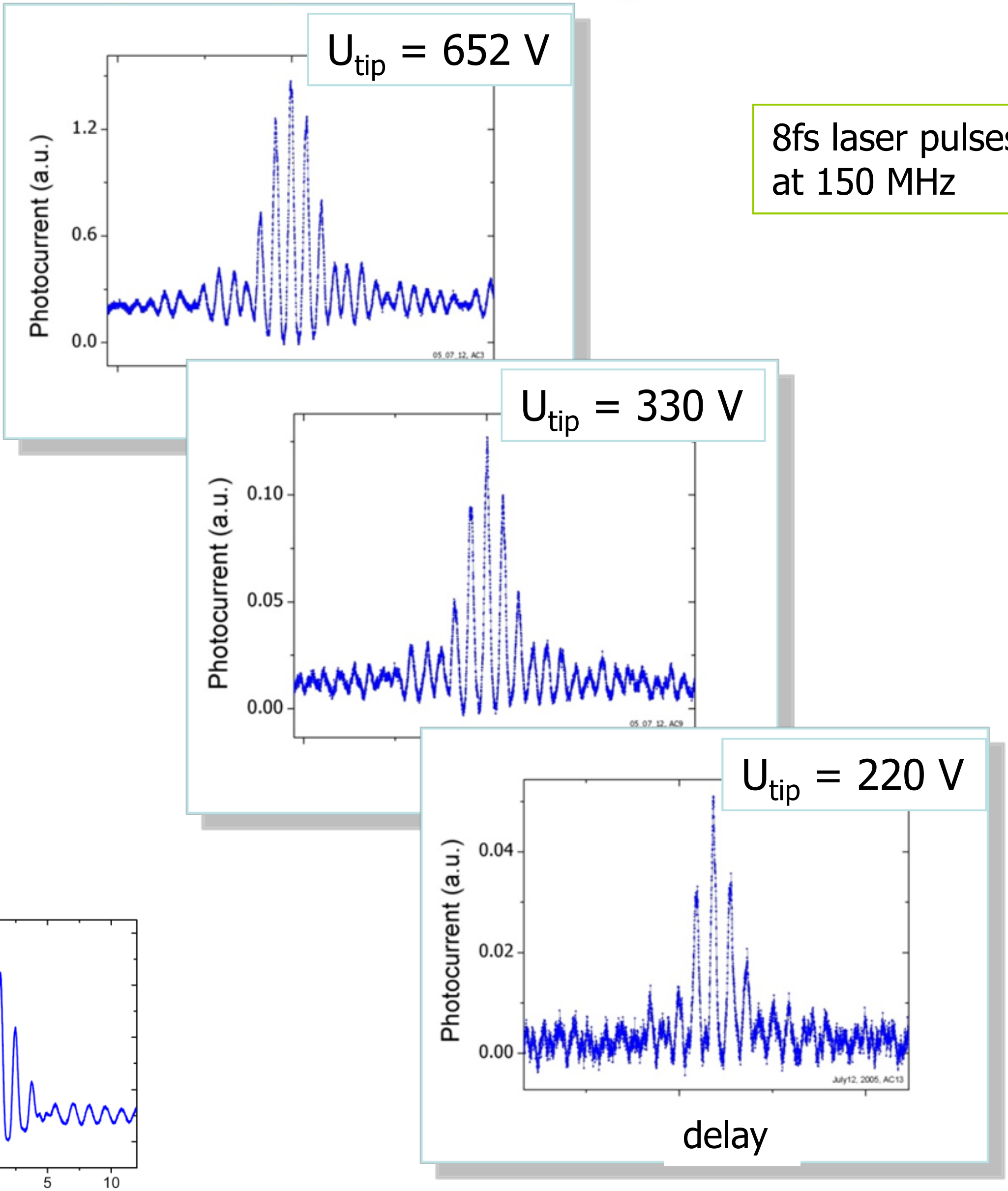
1 μm radius stub with sharp features (r~100nm → field enhancement)

60fs laser pulses at 1 GHz

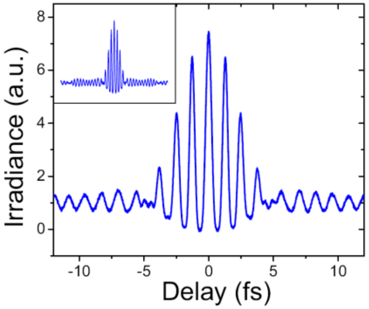
For $\theta=0$: 200 electrons per pulse (instantaneous current: 500μA).
If uniformly distributed over 65 fs and 1μm radius (worst case)
→ current density ~15 kA/cm^2
→ reduced brightness ~ $3\ 10^7$ A/(m^2 sr V)

Autocorrelator with tip as (non-linear) detector





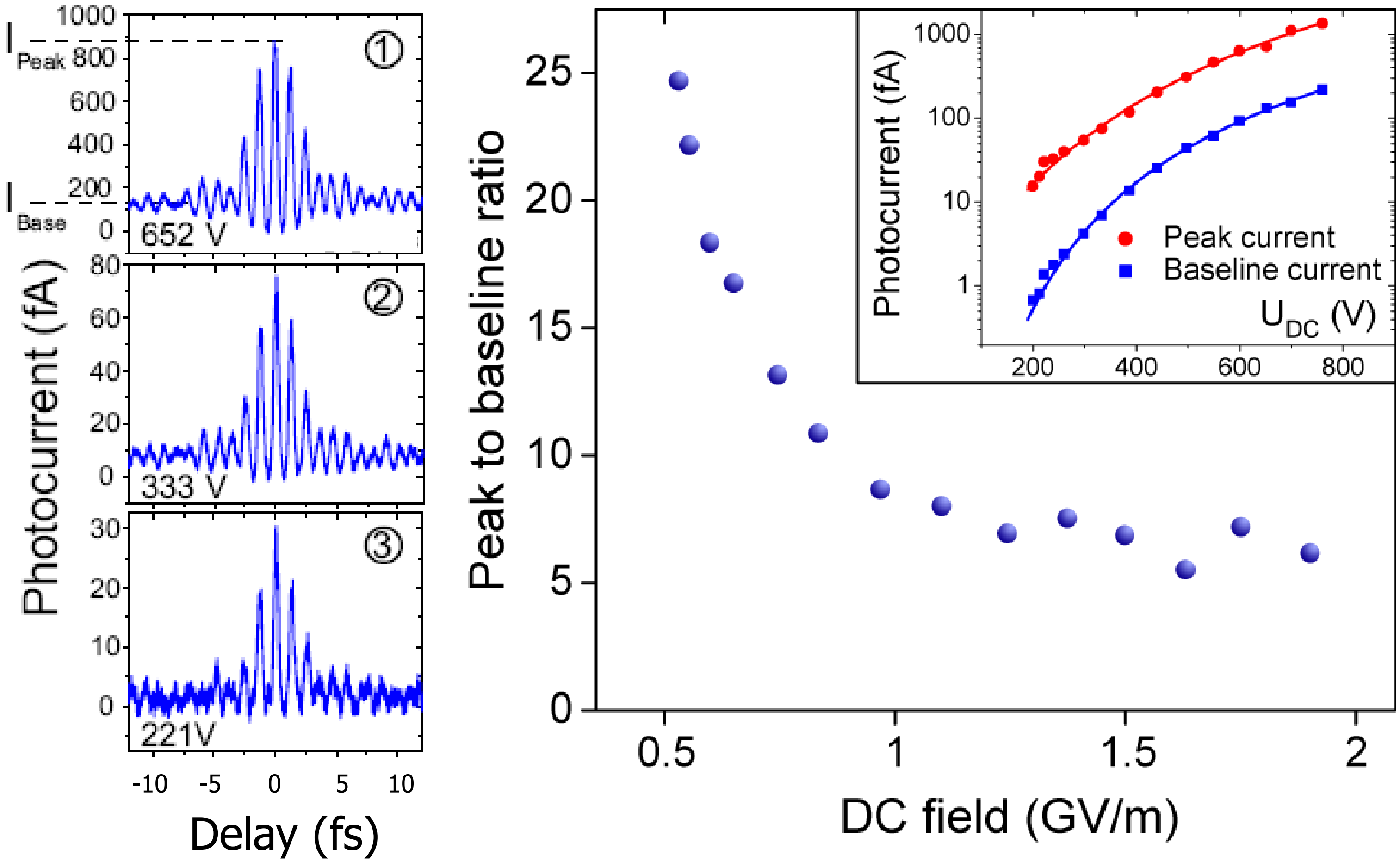
8fs laser pulses
at 150 MHz



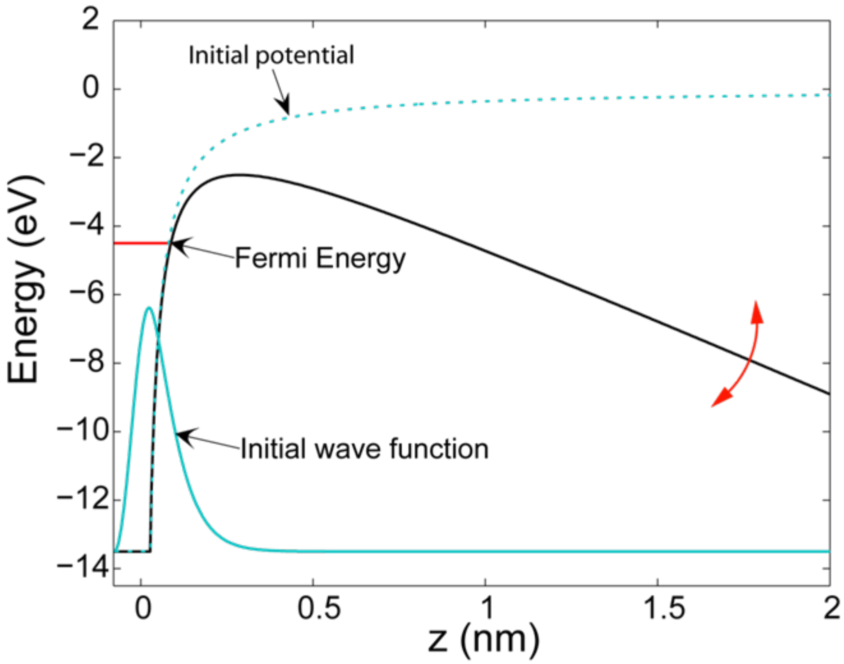
Optical 2nd harmonic
AC trace (thin crystal)

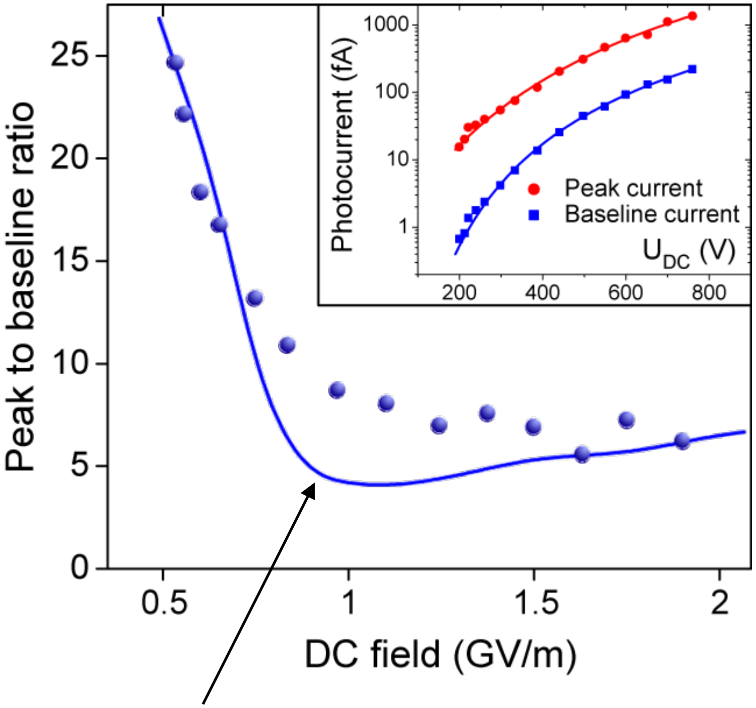
P. Hommelhoff, MPQ

Tunable non-linearity



Data and *model-independent* simulation





Model:

- Electron emission from surface state*
  → ground state wavefunction with kinetic energy = Fermi energy.
- Laser modulates barrier
- Integrate time-dep. Schrödinger eq.

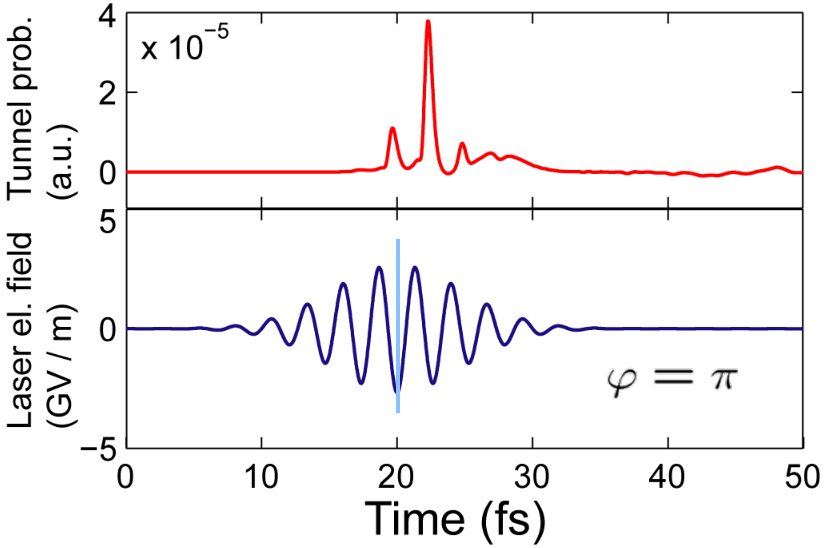
Simulation result with no adjustable parameters.

* T. Ohwaki, H. Ishida, A. Liebsch, PRB 68, 155422 (2003)

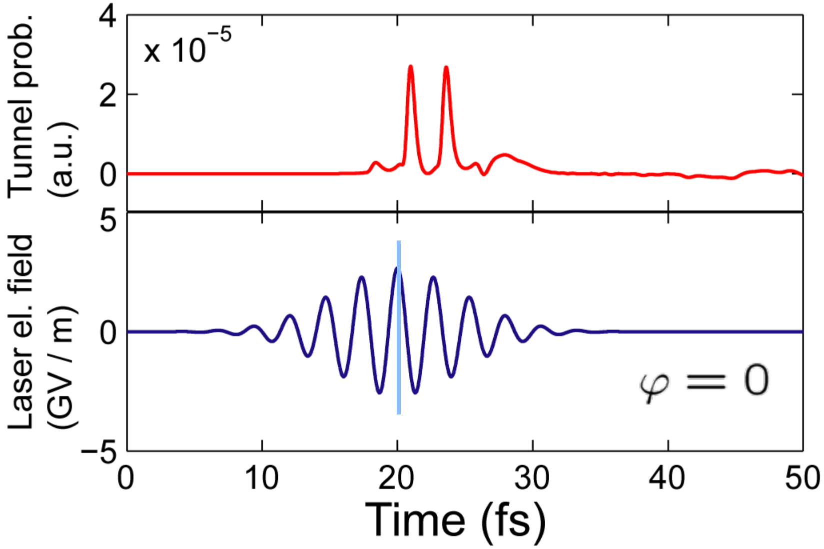
Simulation: time-dependent flux

Driving laser electric field:
8 fs pulse

Electron current:
A **single 700 as pulse**



Electron current:
Double pulse



- 700 attosecond emission duration
- Electric field driven
- Pulse shaping with CE dependence

P. Hommelhoff, C. Kealhofer, M. A. Kasevich, PRL 97, 247402 (2006)

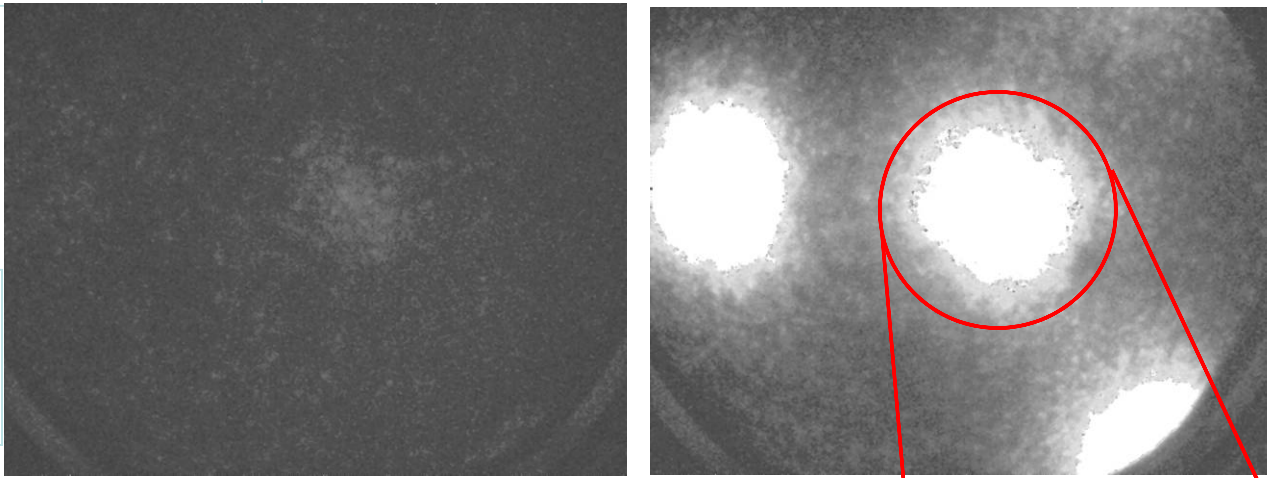
φ: carrier envelope phase (CE phase)

Atomic size emission area

30nm radius tip

without laser

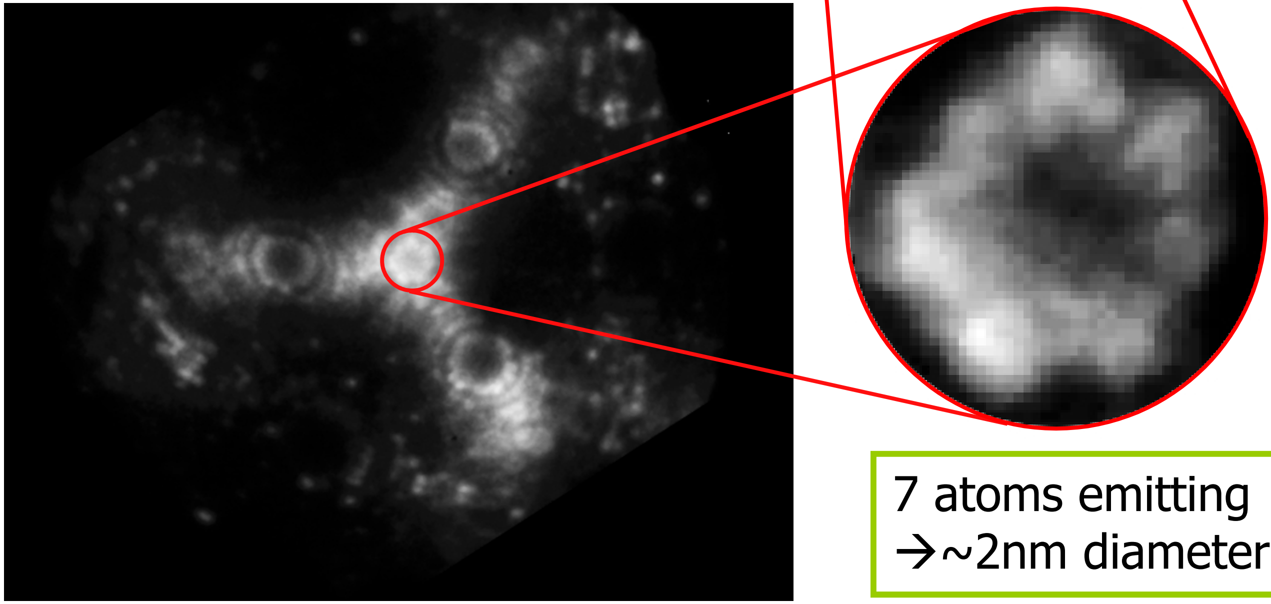
Field emission images



with laser

Up to 98(2)% photoelectrons (limited by dark count rate)

Field ion microscope image

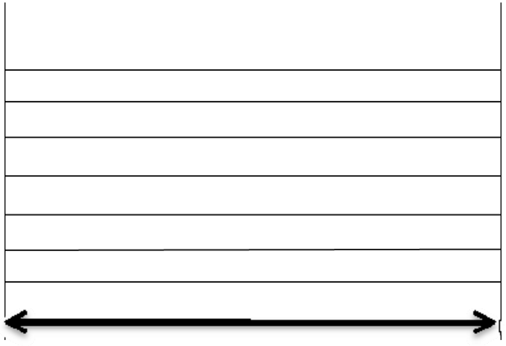


7 atoms emitting
→~2nm diameter area

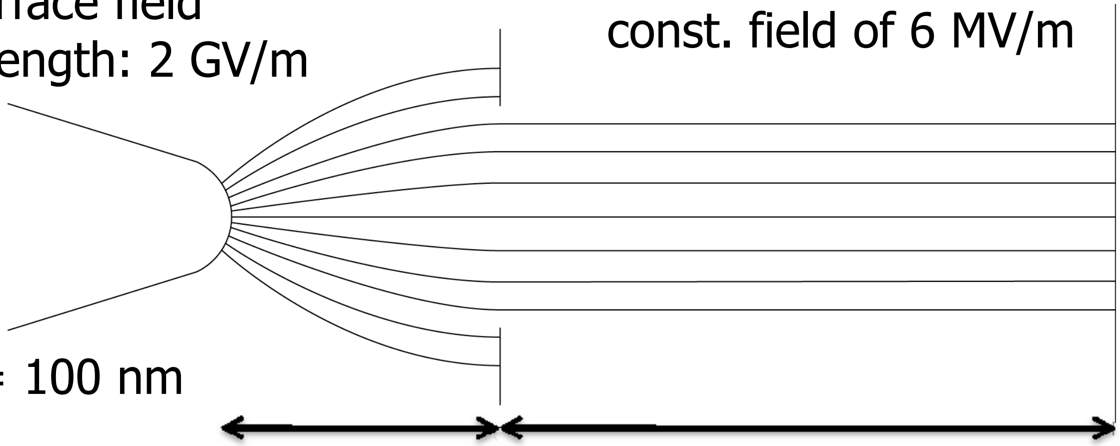
Kinematic pulse broadening during acceleration

Accelerate electron from 0 to 60 keV

Uniform acceleration:
const. field of 6 MV/m



1 cm



Surface field
strength: 2 GV/m

const. field of 6 MV/m

r = 100 nm

1.8 μm

~1 cm

Uncertainty relation

$$\Delta E \Delta t \geq h$$

$$\Delta E \geq \frac{4.1\,\mathrm{eV}}{1\,\mathrm{fs}} \Delta t$$

Initial energy jitter	**Timing jitter in uniform field**	**Timing jitter with tip**
6 eV (HL 0.7 fs)	950 fs	100 fs
0.5 eV	275 fs	~ 15 fs

No space charge yet!

8fs laser pulse
width included

Co-workers and collaborators

Markus Schenk
Michael Krüger
Johannes Hoffrogge
Hanno Kaupp
MPQ

Tomas Plettner
Robert Byer
Chris Sears (now MPQ)
Stanford University / SLAC

Catherine Kealhofer
Seth Foreman
Mark Kasevich
Anoush Aghajani-Talesh
Yvan Sortais
Stanford Physics and Applied Physics

Carbon nanotubes:
Sebastian Stapfner
Eva Weig
Khaled Karrai
Jörg Kotthaus
LMU CeNS

Conclusion

Prompt electron emission from atomic scale source demonstrated. 100 MHz… 1GHz. Few electrons per pulse so far from sharp tip.

✓ Sub-1 fs electron source; emission area diameter down to 2nm
✓ Laser electric field driven emission process

o Direct proof of previous point
o Go to larger pulse charge: limits?

Related work:
- PSI: ZrC tip
- PSI: Mo nanoarrays
- Philipps: FE from CNTs
- MBI: Au tips
- U Nebraska: W tips

❖ Brightness measurement of laser driven emission
❖ Variation of tip size: increase radius of curvature, increase (space charge limited?) current
❖ Join tip and dielectric structure: deflection, acceleration

Open questions / future R&D

- Longer wavelengths: 1.1, 1.5, 2um instead of 800nm helpful as
  - Keldysh parameter proportional to laser frequency
  - structure size / aperture size of dielectric accelerator relaxed
  - High power, high efficiency mode-locked (fiber) laser sources available

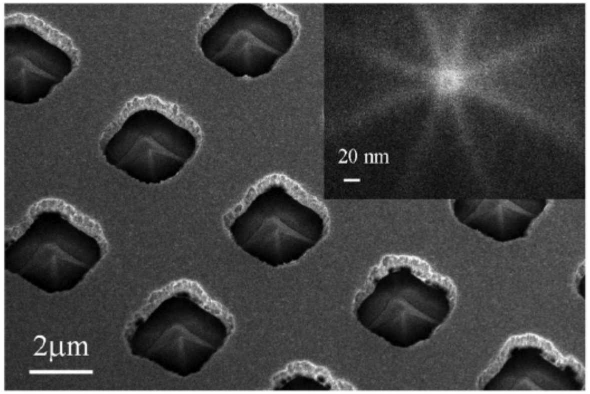
$$\gamma = \frac{\omega\sqrt{2m\Phi}}{eE}$$

- Explore tips:
  - larger tips: space charge issue relaxed, still high brightness, high stability
  - other tip materials: exploit field enhancement
  - explore Schottky effect for high brightness beams w/ photo-emission

- Measure brightness of *laser triggered* electrons

- Explore photo-electric effect with tunable Schottky barrier:
  High brightness , high quantum efficiency source?

- Arrays?



Tsujino et al.,
PSI group