Development of a kHz laser-plasma accelerator for ultrafast electron diffraction

FemtoElec

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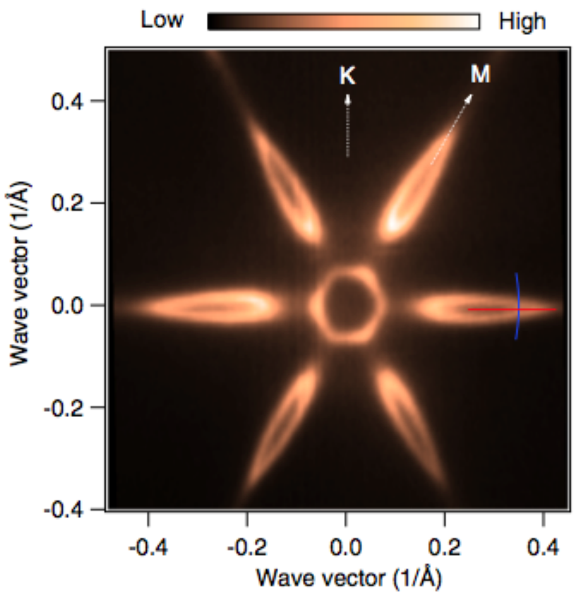
Motivations

Physics

- Ultrafast dynamics in condensed matter
- Dynamics of phase transitions
- Coupling of electronic, spin, lattice degrees of freedom

experimental techniques for microscopic understanding

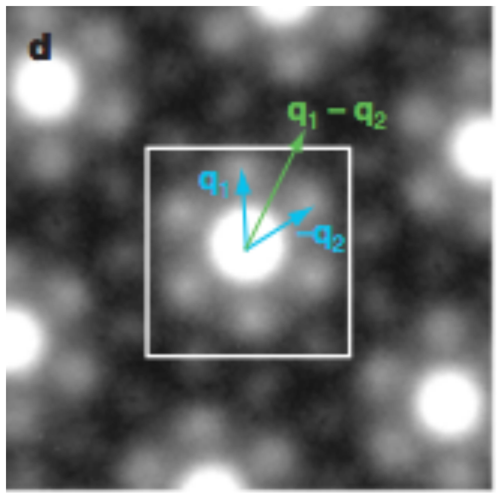
Electronic structure dynamics
→ photoemission



Bi

Lattice dynamics
→ diffraction

TaS_2



Electron sources for ultrafast diffraction

Compact and efficient - 10^5 gain in elastic scatt. cross section

Photocathode + static field: < 100 keV & < fC charge & > 300 fs

- Space charge limit — Sciaini and Miller, Rep. Prog. Phys. **74**, 096101(2011)
- Velocity dispersion

Photocathode + RF field: sub-100 fs & pC charge

- RF compression of 100 keV electrons - Van Oudheusden *et al.*, PRL **105**, 264801 (2010)
- RF MeV guns - Musumeci *et al.*, Appl. Phys. Lett. **97**, 063502 (2010)
- Synchronization and jitter: resolution > 100 fs

REQUIREMENTS

- time resolution < 10 fs*
- energy 50 keV – 5 MeV
- energy spread < few %
- charge fC – pC
- emittance < 0.1 mm.mrad
- rep rate > 100 Hz
- stability < few %

*Many phonon modes with period < 100 fs, (10 fs in graphene)

Why laser wakefield accelerators ?

Pros

- Few femtosecond duration*
- 100 keV/µm accelerating gradient
  - MeV electron bunches
  - Decreases space charge
- Accelerating structure is generated by the laser pulse
  - Perfect synchronization
  - No jitter in pump-probe experiment

Cons/ open questions

- Large energy spread: 1-10%
  - Chirped bunches, stretches in time
- Stability sufficient for UED ?
- Beam quality / coherence sufficient for UED ?
- Scaling of current system ?
  - From 100 MeV to MeV
  - From Hz to kHz
  - From J laser to mJ laser

* 1.5 fs rms, O. Lundh et al., Nat. Phys. 2011

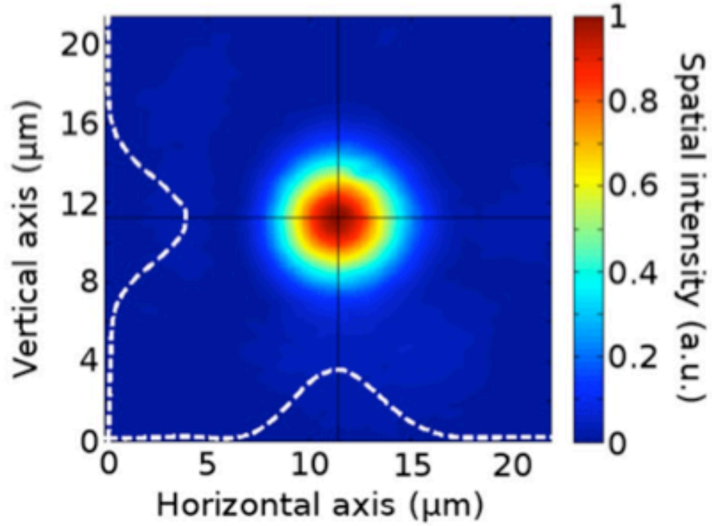
Scaling to MeV energies

$$a_0 > (\omega_0/\omega_p)^{2/5} \qquad k_p R = 2\sqrt{a_0} \qquad \tau c = 2R/3$$

	λ_0=0.8 μm	Scaling law 1 J	Demonstrated experiments 0.6 J	Scaling laws 5 mJ
LASER	W_0 (μm)	10	18	2.5
	τ (fs)	21	30	5.7
	Intensity (W/cm^2)	3×10^{19}	3×10^{18}	8×10^{18}
PLASMA	n_e (cm^{-3})	5×10^{18}	7×10^{18}	6.8×10^{19}
	$L_{ACCELERATION}$ (μm)	2000	1000	45
ELECTRON BEAM	E_{MAX}(MeV)	500	100-300	10
	Q_{MAX}(pC)	250	50-100	30

Lu *et al.*, PRSTAB **10**, 0613001 (2007)

Electron acceleration with kHz, 5 fs, mJ laser system



Chen *et al.*, Laser Physics **21**, 198 (2011)

Salle Noire laser:

duration 4-5 fs
focused down to 1.5 µm
I >10^{18} W/cm^2
< % rms fluctuations

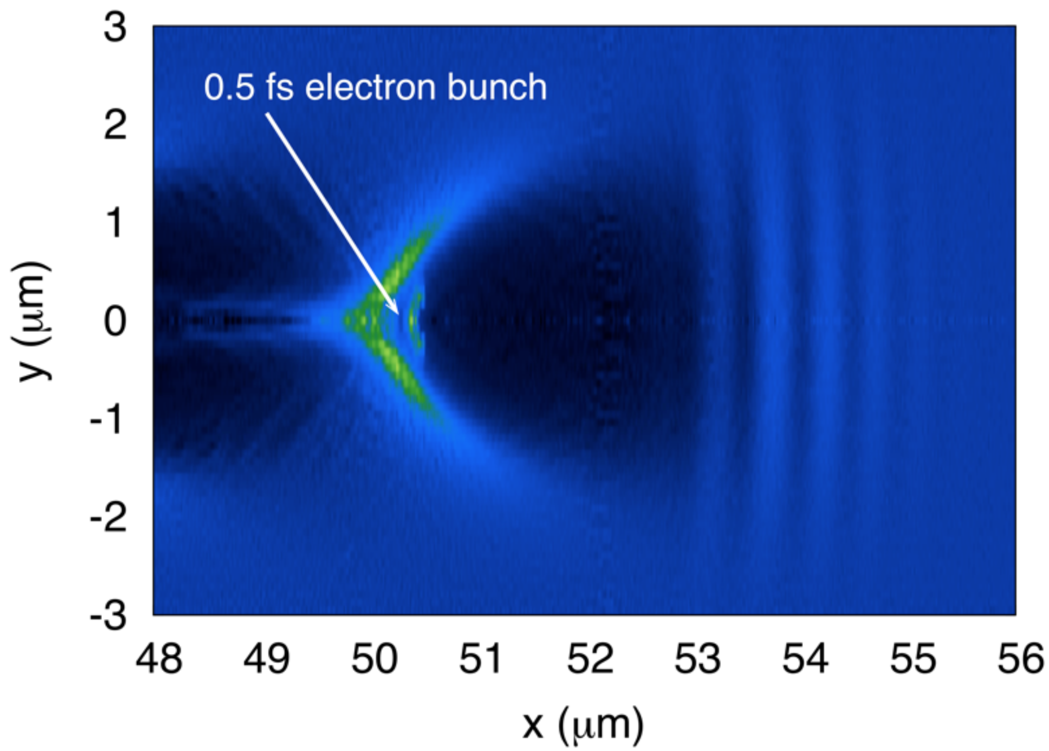
currently upgraded to 5 mJ

PIC simulations:

using experimental laser parameters
electronic density n_e=6-10×10^{19} cm^{-3}
explore self-injection / ionization induced injection

A. Lifschitz & V. Malka, NJP 14, 053045 (2012)

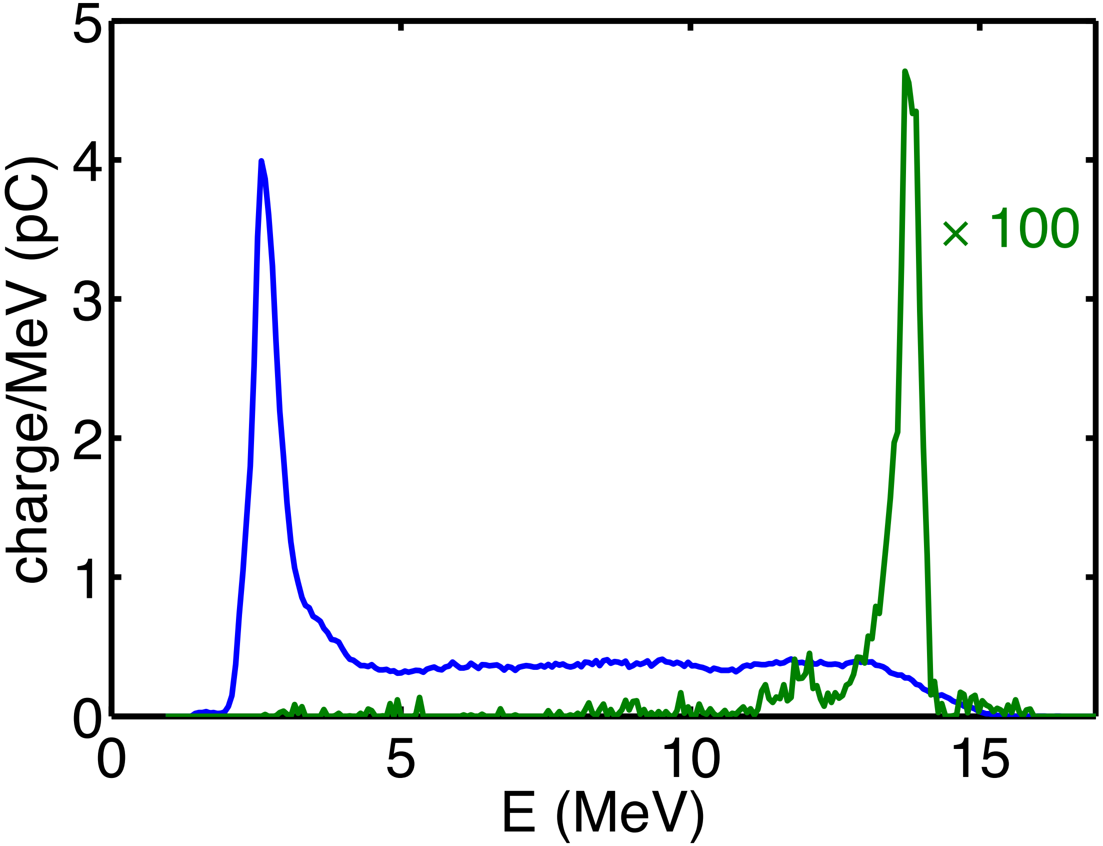
Results of PIC simulations (Calder-Circ)



Results of PIC simulations (Calder-Circ)

Lower quality beam:
self-injection
He plasma, $n_e = 10^{20}$ cm^{-3}
fs electron bunch
larger $\delta E/E$
few pC

Higher quality beam:
ionization induced injection
N_2 plasma, $n_e = 7\times10^{19}$ cm^{-3}
sub-fs electron bunch
$\delta E/E = 2.5$ %
50 fC



Experiments: first kHz laser-plasma accelerator

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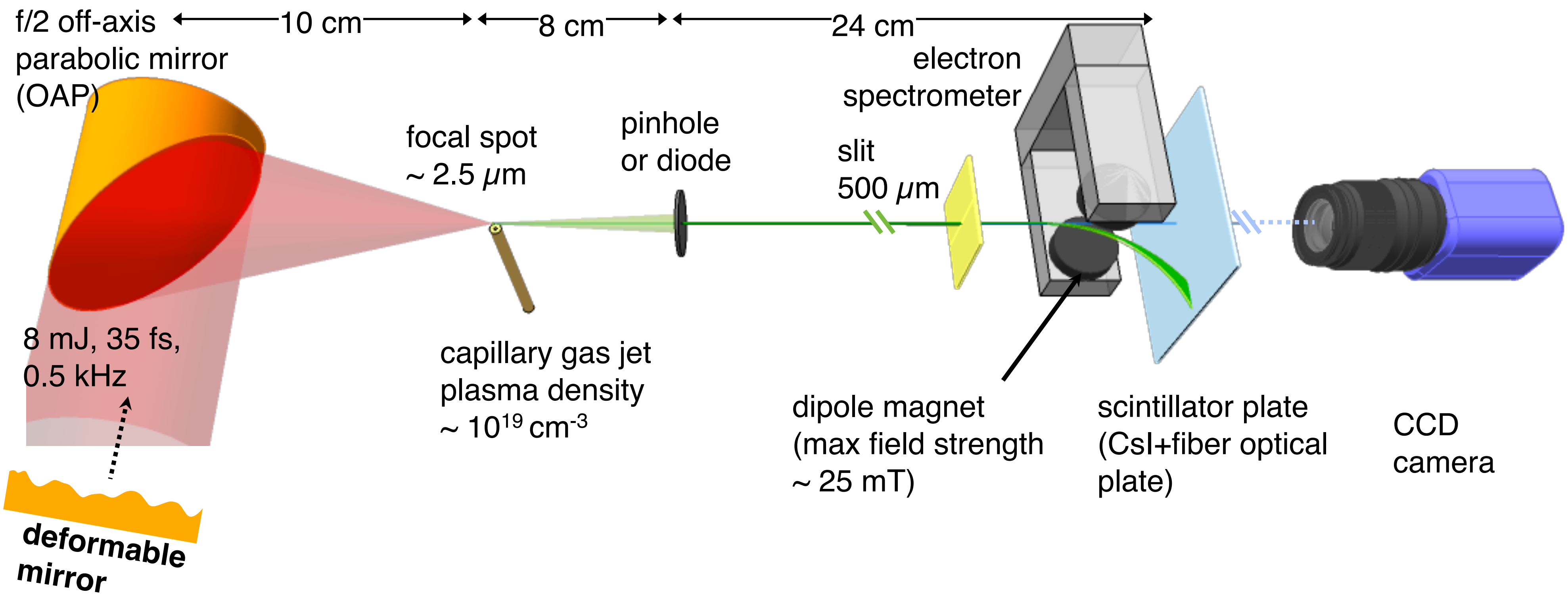
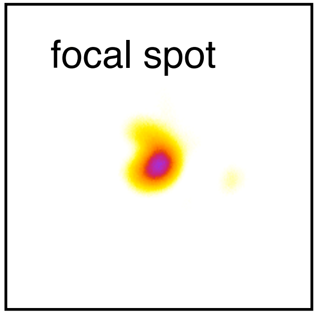
What we need: 5 fs, 2-5 mJ, kHz, n_e=5-10×10^{19} cm^{-3}

What we used: 35 fs, 8 mJ, kHz, n_e= 10^{19} cm^{-3}

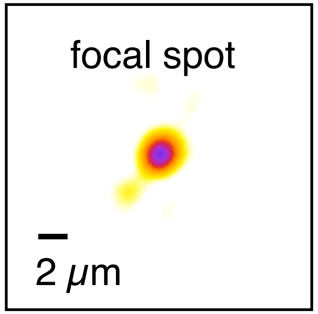


kHz beam: real time optimization

- Complex structures
- Stable ! (see later)
- e-beam is off-axis
- Sensitive to laser wavefront
- Can be optimized with deformable mirror

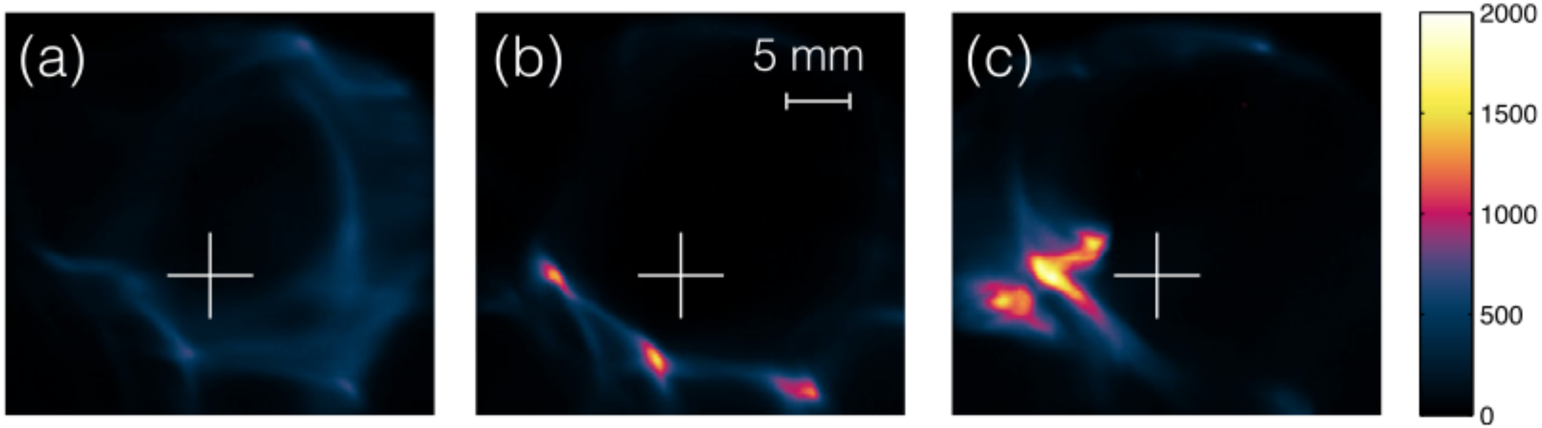


DM not active



Optimized spot

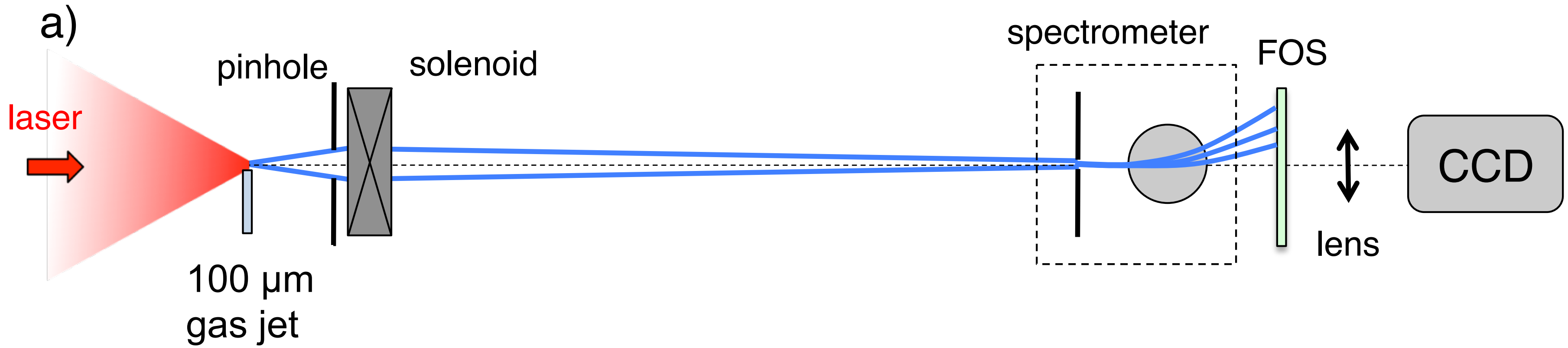
Optimized for electron signal

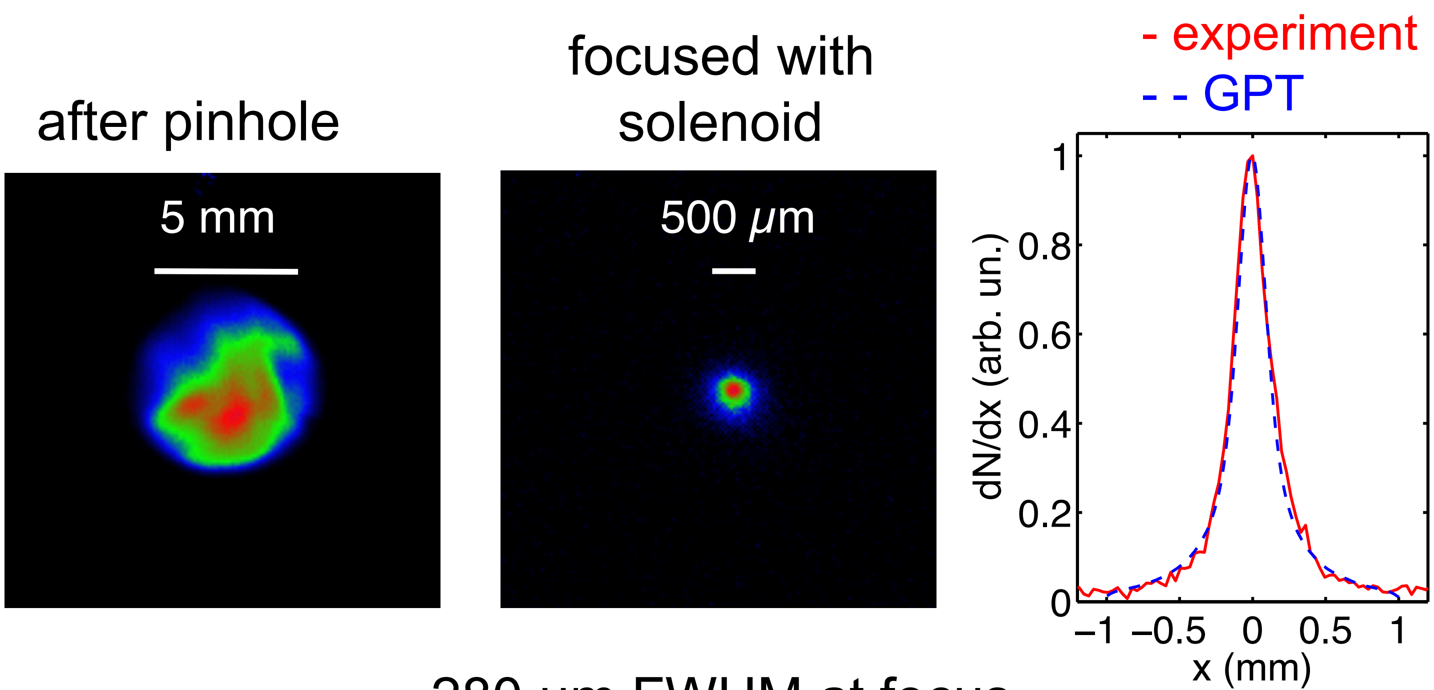


> 10 times more electrons !

Z. He et al., NJP **15** 05316 (2013)

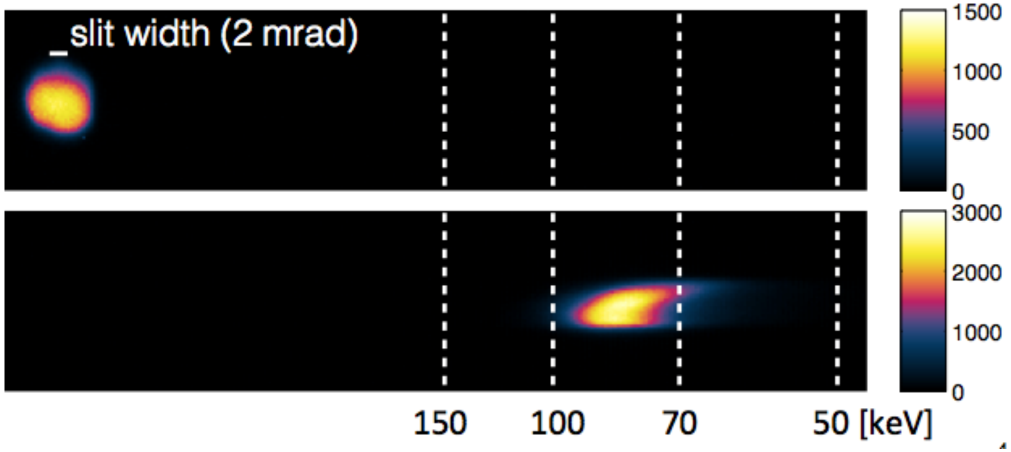
Beam manipulation with solenoid

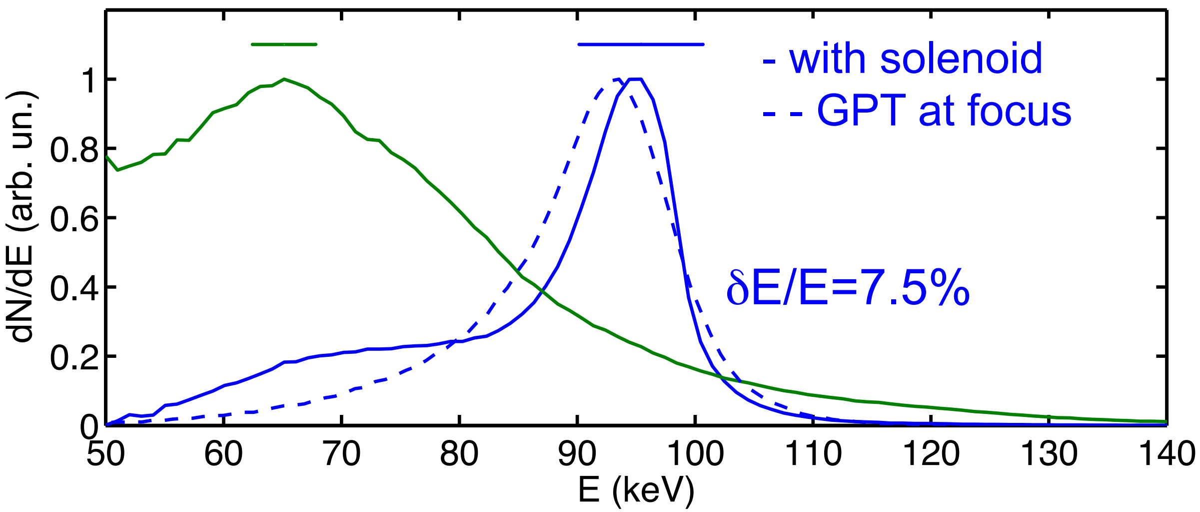




280 µm FWHM at focus

kHz electron beam: energy distribution





Stability study

- pointing < det. lim. (400 μrad)
- energy: 100 keV fluctuations < det. lim.
- charge 3 $\times 10^4$ el. (5 fC) +/- 7% RMS

Emittance obtained from GPT best fit to data

beam size: $\sigma_r = 15\ \mu m$

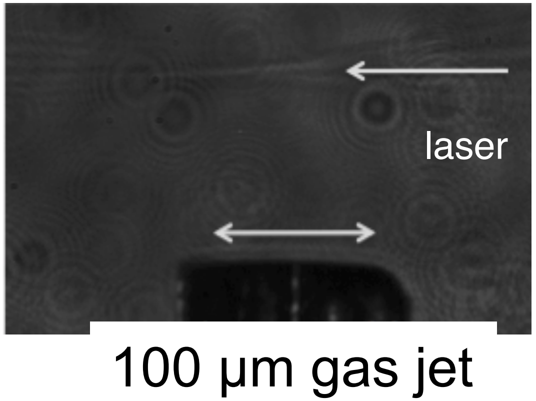
divergence: $\sigma_\theta = 5$ mrad

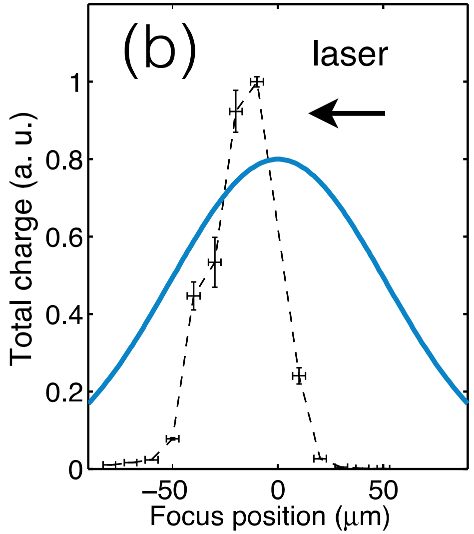
$\varepsilon_N = 2\times10^{-2}$ mm.mrad

Beam transverse coherence at focus: 5 nm

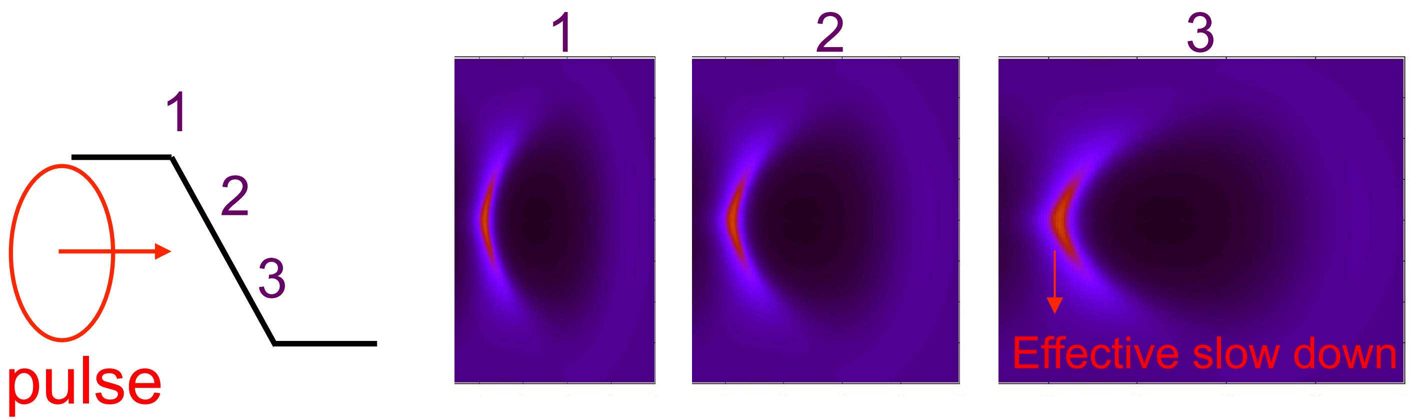
Z. He et al., Appl. Phys. Lett. 102, 064104 (2013)

Highest charge when focusing in density down ramp

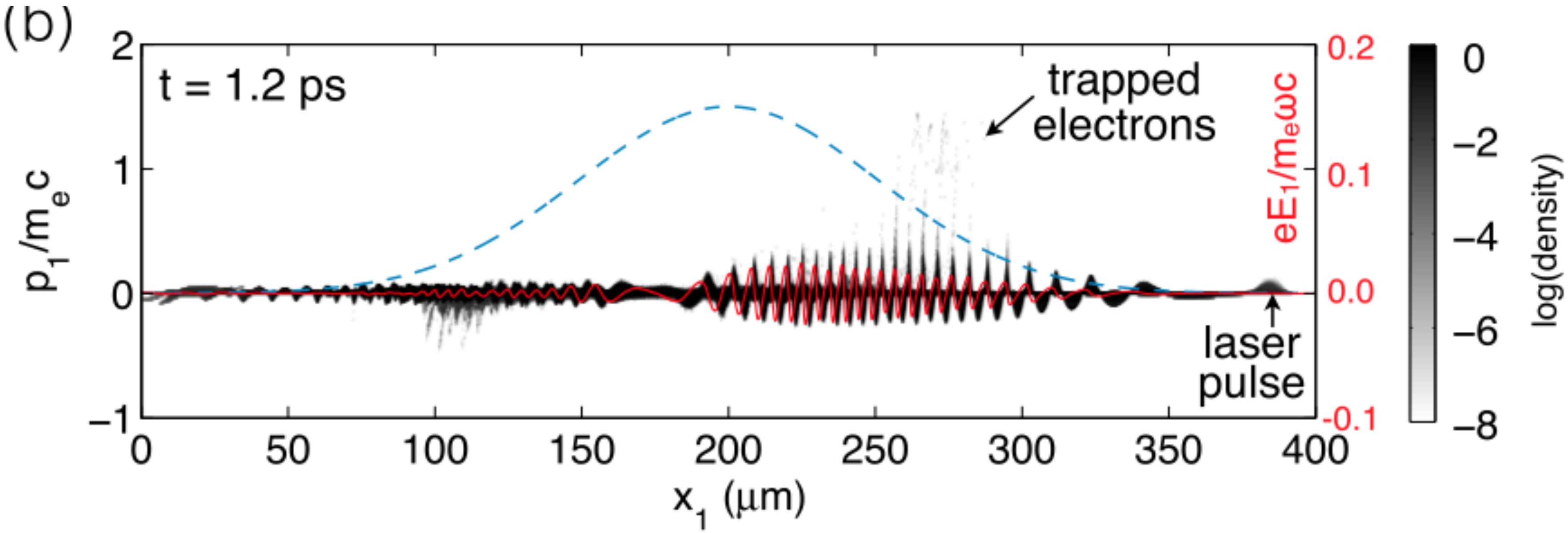




Injection in density down ramp ?



Injection in density down ramp: 2D PIC simulations



- trapping occurs 10 λ_p after laser pulse

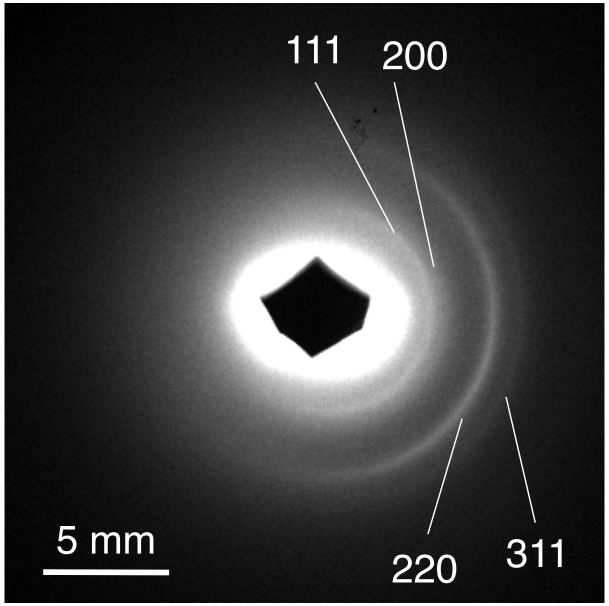
$$\frac{v_{ph}}{c} = \left(1 + \frac{\zeta}{k_p}\frac{dk_p}{dx}\right)^{-1}$$

- trapping in multiple buckets* (low charge, low beam loading)
- short accelerating length, small wake amplitude
  → small energy 100 keV

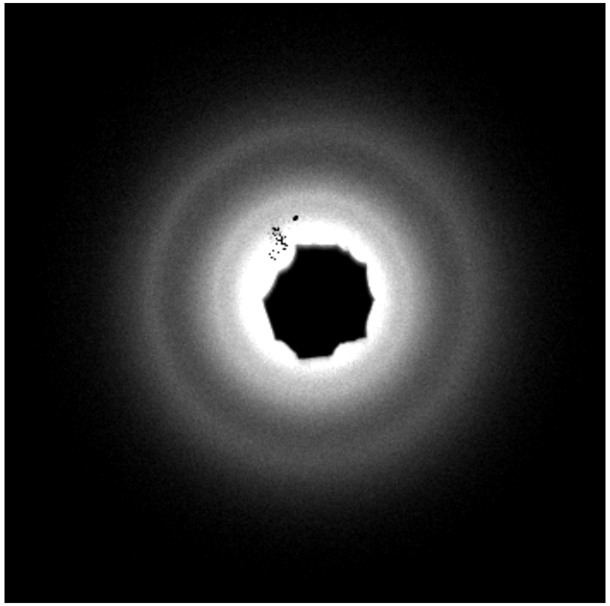
O. Lundh et al., Phys. Rev. Lett. 110, 065004 (2013)

First diffraction images on 10 nm Al foil

tilted solenoid +
spatial chirp in ebeam



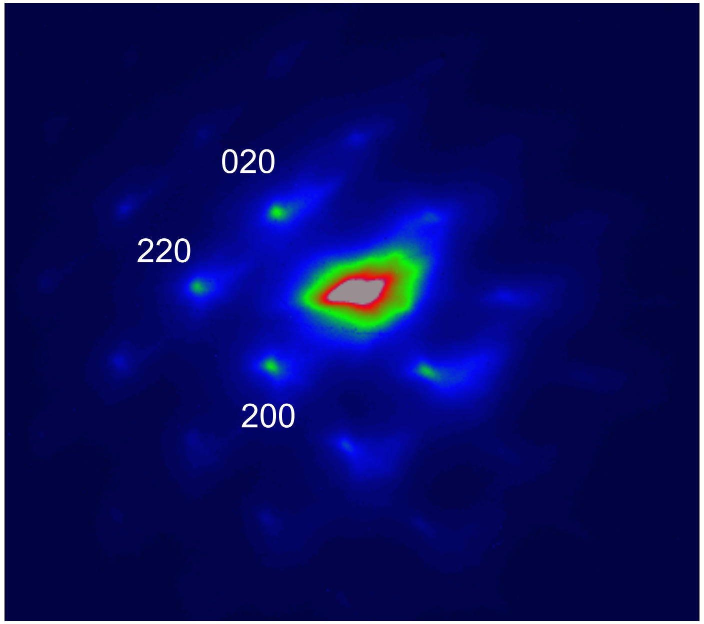
aligned solenoid
broader spectrum



Z. He et al., Appl. Phys. Lett. 102, 064104 (2013)

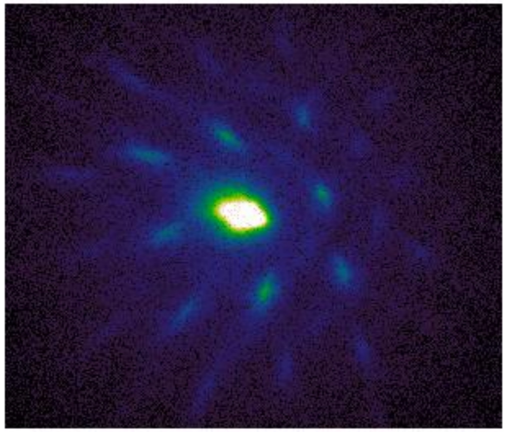
diffraction on single crystal gold

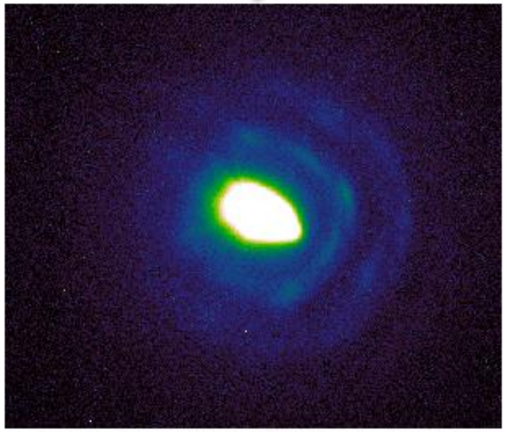
1 s integration



- Single shot images within reach (improve detection QE)
- Next step: time resolved study

Laser induced melting





Conclusions / perspectives

- ***First proof-of-principle experiment with mJ, kHz laser***
  - 100 keV energy level
  - not femtosecond
  - transverse coherence for diffraction patterns
  - clear / useable diffraction patterns
  - stability
- ***Perspectives: FEMTOELEC project***
  - Currently upgrading kHz laser system to 5 fs, 5 mJ
  - Currently buiding experiment (vacuum chambers …)
  - perform experiments with 5 fs laser pulses: MeV e-beams
  - Single fs bunches
  - Beam transport and manipulation
  - Ultrafast electron diffraction on samples

Opportunity to test practicality of plasma source for
A real & demanding scientific application

Collaborators

FemtoElec

Few-cycle 5 fs laser system:

PCO group at LOA:

R. Lopez-Martens, M. Bocoum, A. Jullien, J.-P. Rousseau, B. Mercier

Experiments: Electron source for UED:

APPLI group at LOA:

B. Beaurepaire, M. Thévenet, A. Vernier, G. Gallé, D. Boschetto

CUOS of University of Michigan:

Z. He, A. Thomas, J. Nees, K. Krushelnick

Simulations / theory

A. Lifschitz (LOA, France)

Beam transport

J. Luiten's group, Univ. Eindhoven

Samples …