Paquets d'électrons femtoseconde accélérés par laser
Application à la dynamique structurale

Jérôme Faure
Laboratoire d'Optique Appliquée
Ecole Polytechnique, France

erc

FemtoElec

ÉCOLE POLYTECHNIQUE ParisTech

cnrs dépasser les frontières

UMR 7639

ENSTA ParisTech

http://loa.ensta.fr/

loa

Collaborators

Experiments: kHz laser-plasma source
D. Gustas, I. Gonzalez, N. Zaim, B. Beaurepaire
A. Vernier, G. Gallé, D. Guénot, A. Lifschitz

CUOS of University of Michigan:
Z. He, A. Thomas, J. Nees, K. Krushelnick

Laser system:
M. Bocoum, F. Böhle, A. Jullien, J.-P. Rousseau, R. Lopez-Martens

Beam transport
B. van der Geer, Univ. Eindhoven, Pulsar Physics

Sample preparation
S. Scott, M. Lagally, Univ. Wisconsin

Outline of the talk

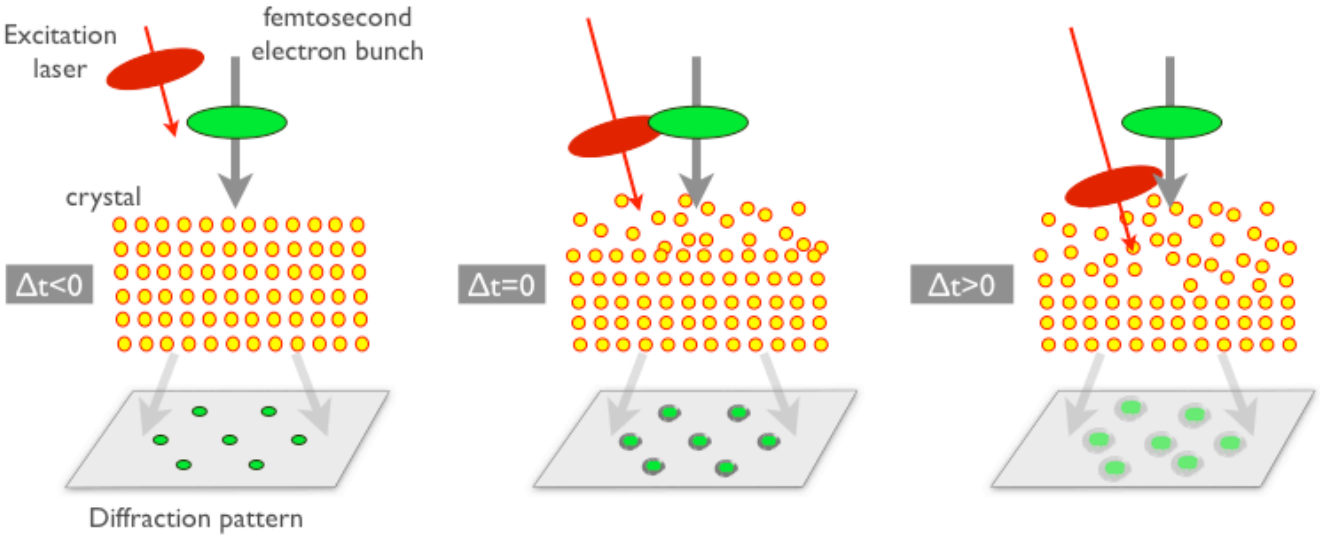
- Motivation / Introduction
- First laser-plasma accelerator at kHz and application to ultrafast electron diffraction
- First experiments with near-*single-cycle laser pulses*
  →Acceleration of ~ 5 MeV electrons at kHz

Motivations

- Study relativistic laser-plasma interaction

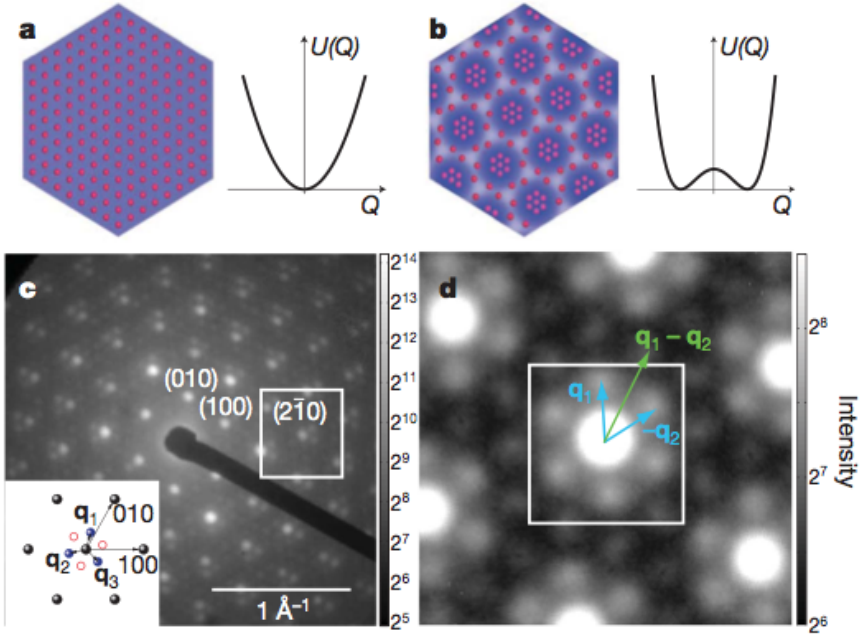
- Develop alternative technology for MeV femtosecond electron beams → Laser-plasma (wakefield) acceleration

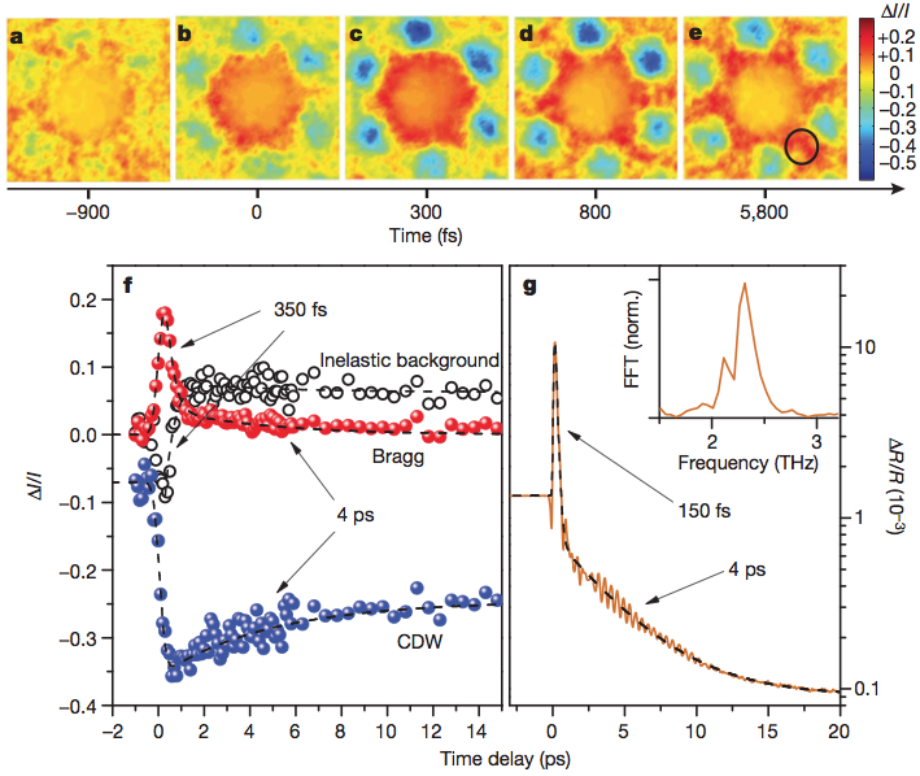
- Use electrons as a pump
  - Irradiation with femtosecond electrons, high charge
- Use electrons as a probe
  - Structural dynamics at the femtosecond level



Snapshots of cooperative atomic motions in the optical suppression of charge density waves

Maximilian Eichberger[1]*, Hanjo Schäfer[1]*, Marina Krumova[2], Markus Beyer[1], Jure Demsar[1,3], Helmuth Berger[4], Gustavo Moriena[5,6], Germán Sciaini[5,6]* & R. J. Dwayne Miller[5,6]



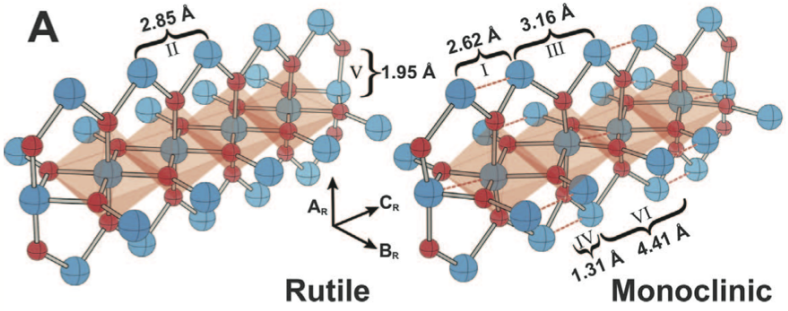


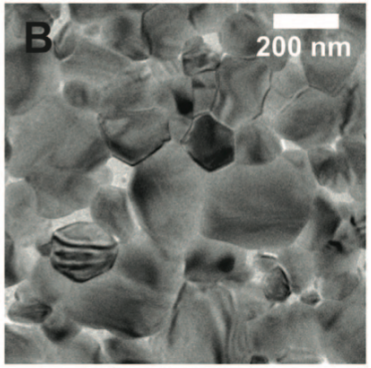
Electron diffraction on 1T-TaS_2, Eichberger et al., Nature 2010

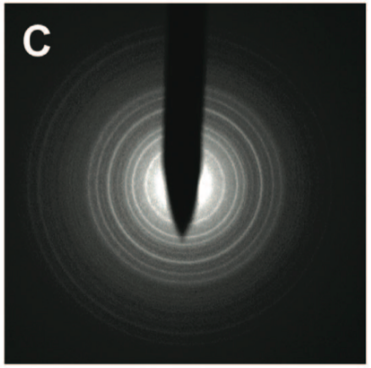
ULTRAFAST DYNAMICS

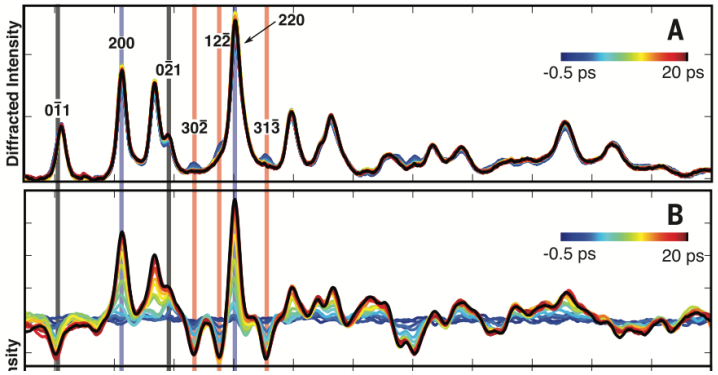
A photoinduced metal-like phase of monoclinic VO_2 revealed by ultrafast electron diffraction

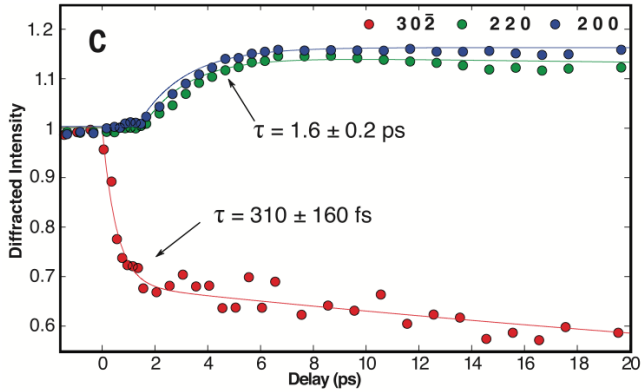
Vance R. Morrison,[1] Robert. P. Chatelain,[1] Kunal L. Tiwari,[1] Ali Hendaoui,[3] Andrew Bruhács,[2] Mohamed Chaker,[3] Bradley J. Siwick[1,2]*











Morrison et al., Science 2014

Electron sources for diffraction

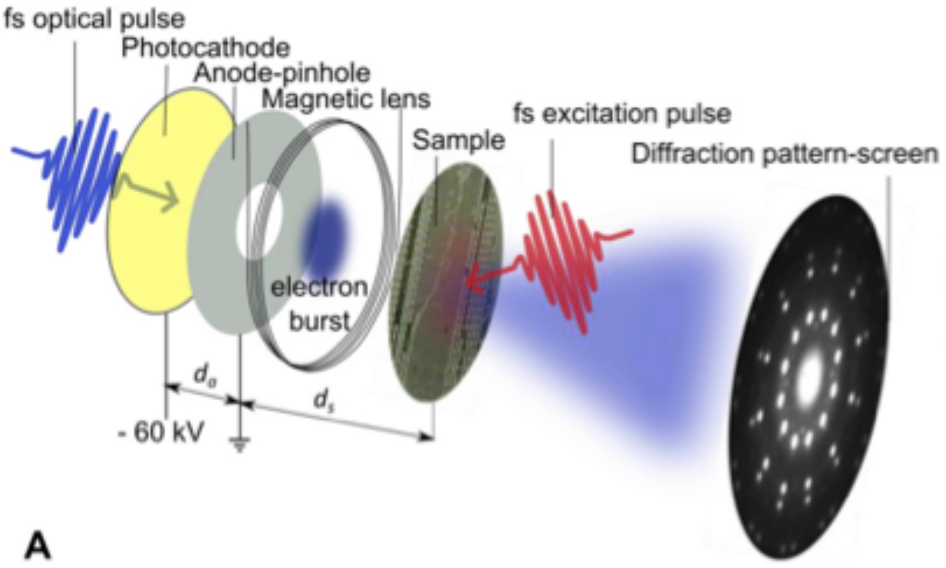
Compact and efficient - 10^5 gain in elastic scatt. cross section

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

Sciaini and Miller, Rep. Prog. Phys. **74**, 096101(2011)

Limited by space charge

Velocity dispersion



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

RF compression at 100 keV - Van Oudheusden *et al.*, PRL **105**, 264801 (2010)

RF guns at MeV - Musumeci *et al.*, Appl. Phys. Lett. (2010); Muro'oka *et al.*, Appl. Phys. Lett. (2011)

Synchronization and jitter: resolution > 100 fs

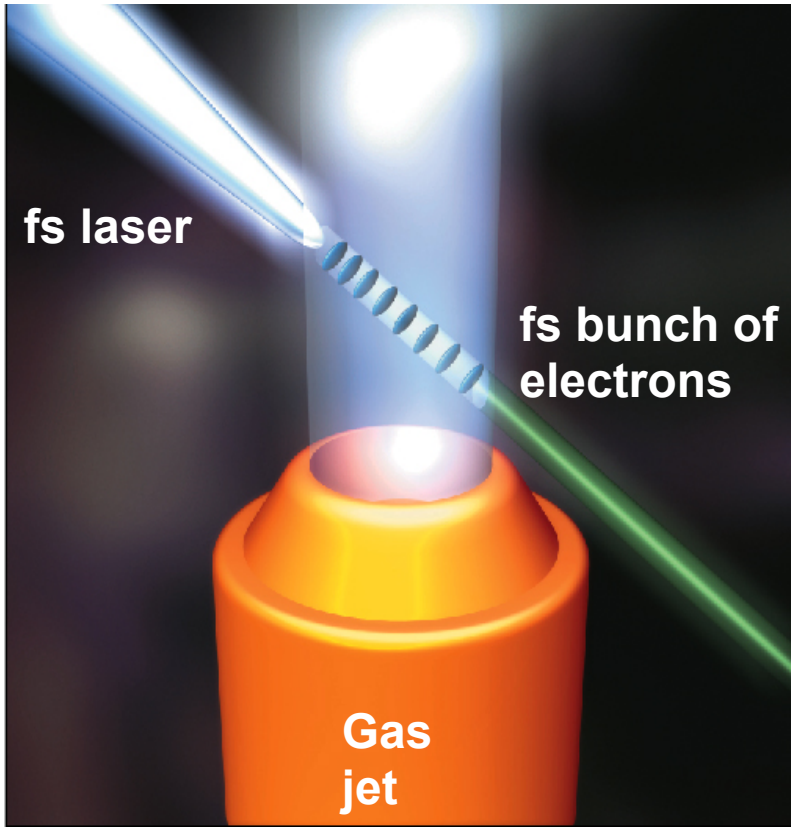
But many phonons with period < 100 fs, (graphene: 10 fs)

Parameters of ideal source

- 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 %

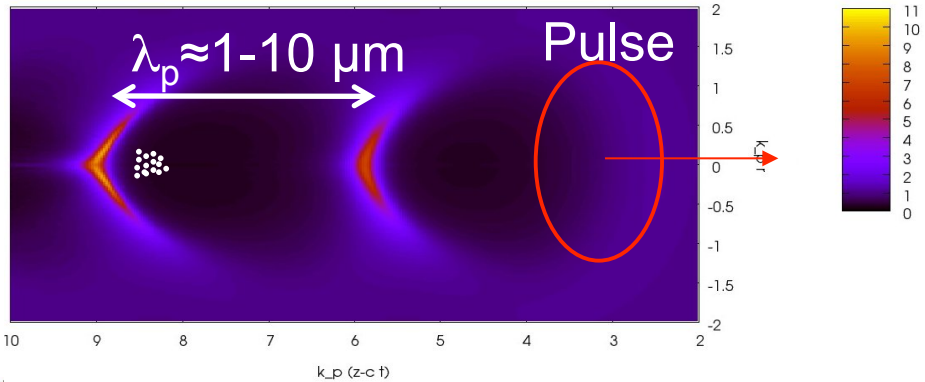
Using a laser-plasma accelerator



Relativistic intensity
10^{18} W/cm^2

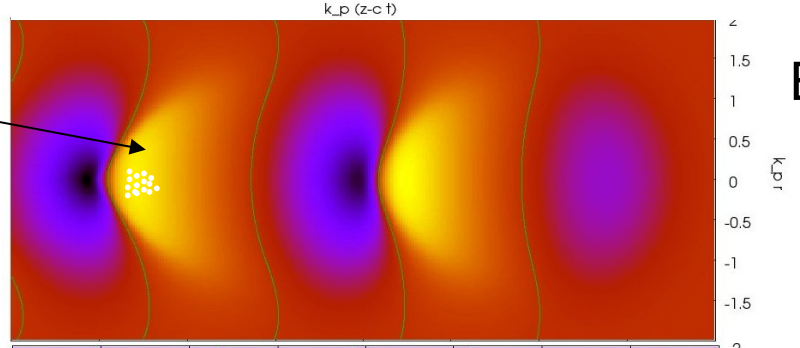
Short laser pulse
$c\tau \approx \lambda_p/2$

Accelerating electrons in wakefields

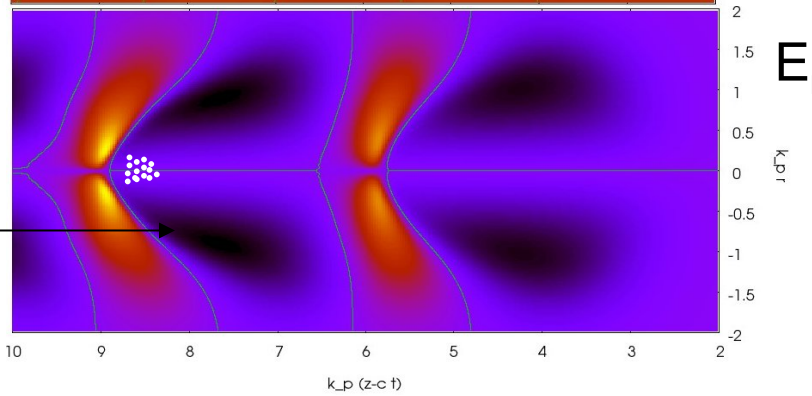


Electron density

accelerating



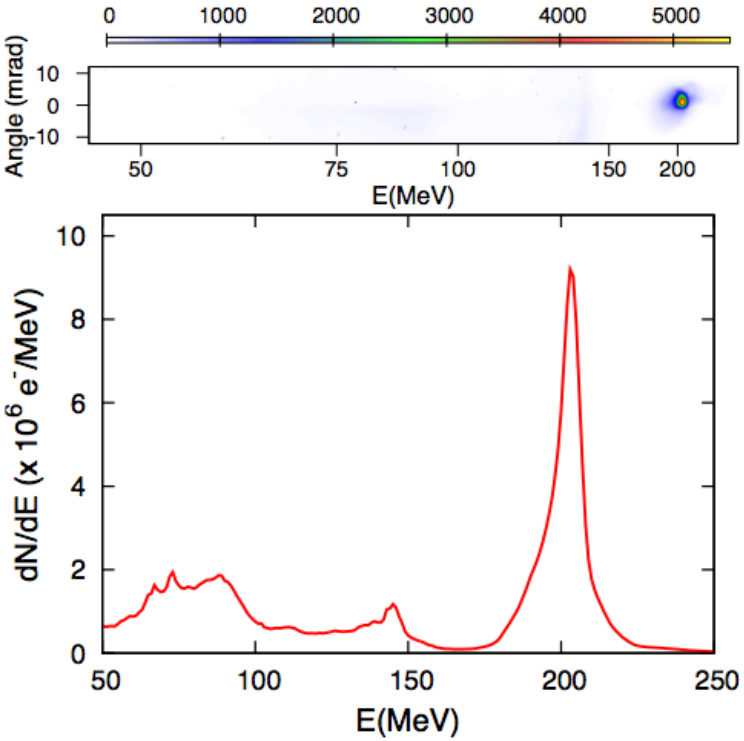
focusing



PROS

- Extreme fields
  1 MeV / 10 µm
  → Compact accelerator
  →Mitigates space charge
- fs bunches
  < $\lambda_p/4$
- no jitter

Laser-plasma accelerators: state of the art



Faure et al. Nature 2004
Mangles et al. Nature 2004
Geddes et al., Nature 2004
Faure et al, Nature 2006
Leemans et al., Nat. Phys. 2006
Rechatin et al, PRL**102**, 164801 2009
Leemans et al., PRL 2014

Laser:
1 J, 30 fs, 1 Hz

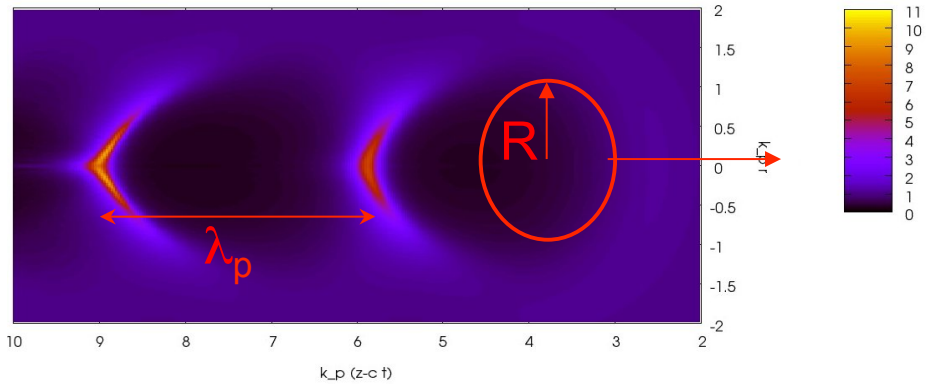
Electron beam:
collimated (few mrad)
100 MeV – 1 GeV (1-10 % spread)
1.5 fs rms duration (O. Lundh et al., Nat. Phys. 2011)

Our challenges

- Operate at kHz (with only <10 mJ)
- Accelerate electrons to few MeV
- High beam quality
- Stable source
- Sub-10 fs duration

Scaling laws: toward kHz lasers

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



Laser pulse has to be resonant with plasma wave: $R \approx \lambda_p/2$, $c\tau \approx \lambda_p/2$

Laser energy scaling $E_L \propto \tau^3 \propto \lambda_p^3$ Electron energy gain $\Delta E \propto \tau^2 \propto \lambda_p^2$

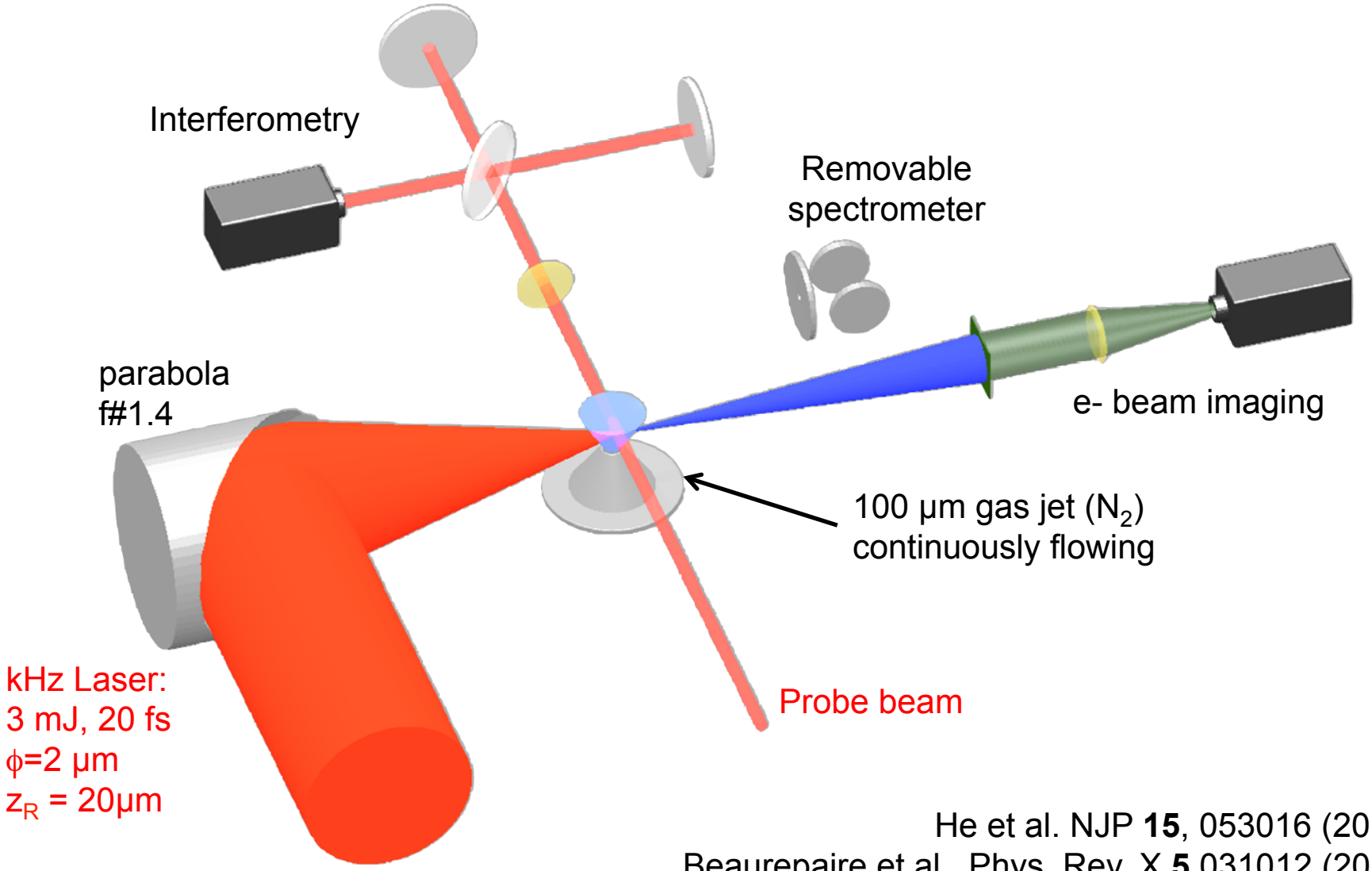
30 fs → 1 J → 100 MeV-1 GeV
3 fs → mJ → 1-10 MeV

Laser pulses of 5 fs, few mJ → possible @ kHz !

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

100 keV kHz laser-plasma accelerator (2013-15)

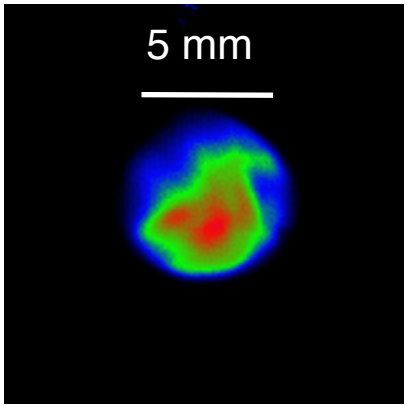
30 fs (too long !), 3 mJ, I=3×10^{18} W/cm^2, 1 kHz



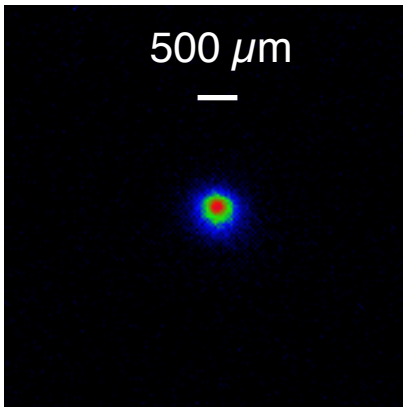
He et al. NJP **15**, 053016 (2013)
Beaurepaire et al., Phys. Rev. X **5** 031012 (2015)

kHz electron source @ 100 keV

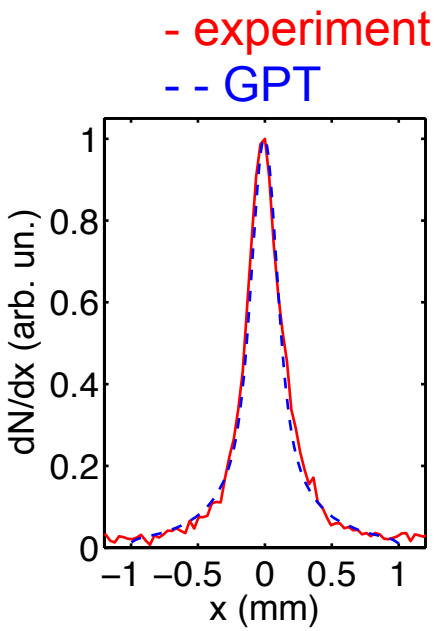
unfocused



focused

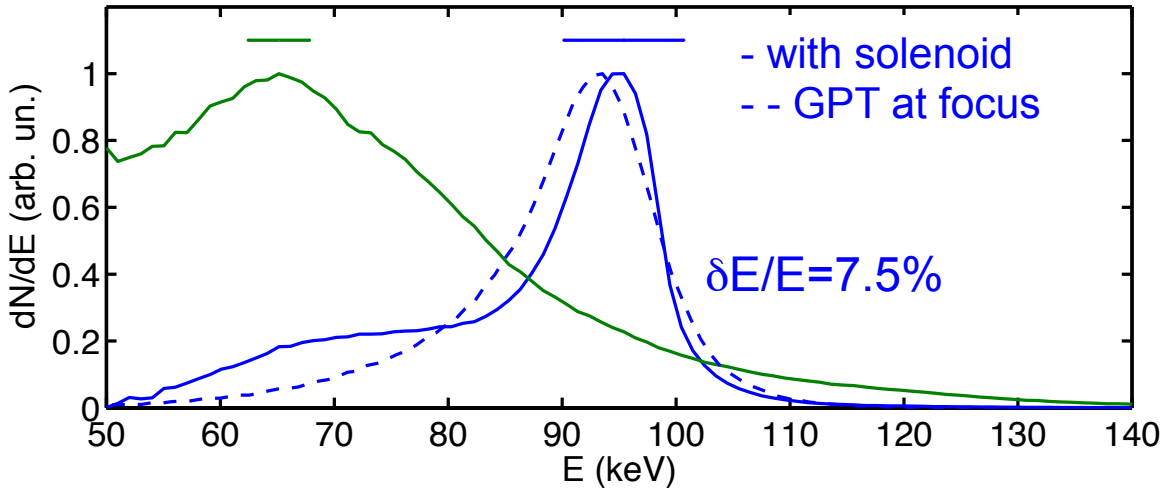


280 μm FWHM



Emittance from GPT best fit to data
$\varepsilon_N = 2\times10^{-2}$ mm.mrad

Coherence length
$L_{coh} = 5$ nm



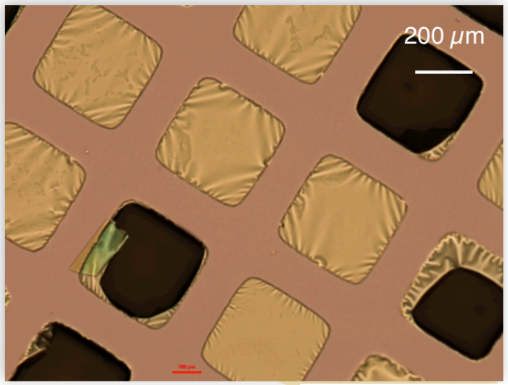
Stability at kHz:
pointing < 400 μrad
• energy: 100 keV, < det. lim.
• charge 5 fC +/- 7%

Z. He et al.,
APL **102**, 064104 (2013)

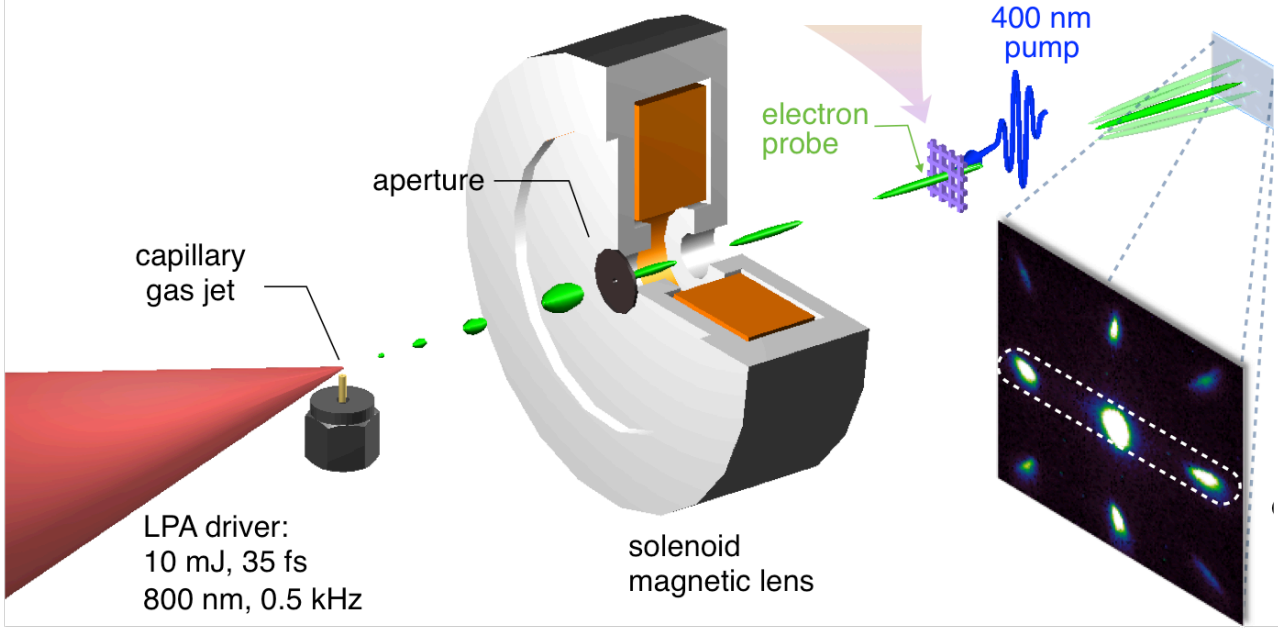
Set-up for electron diffraction experiment

MichiganEngineering

20 nm single crystal Gold



Z. He et al.,
APL **102**, 064104 (2013)

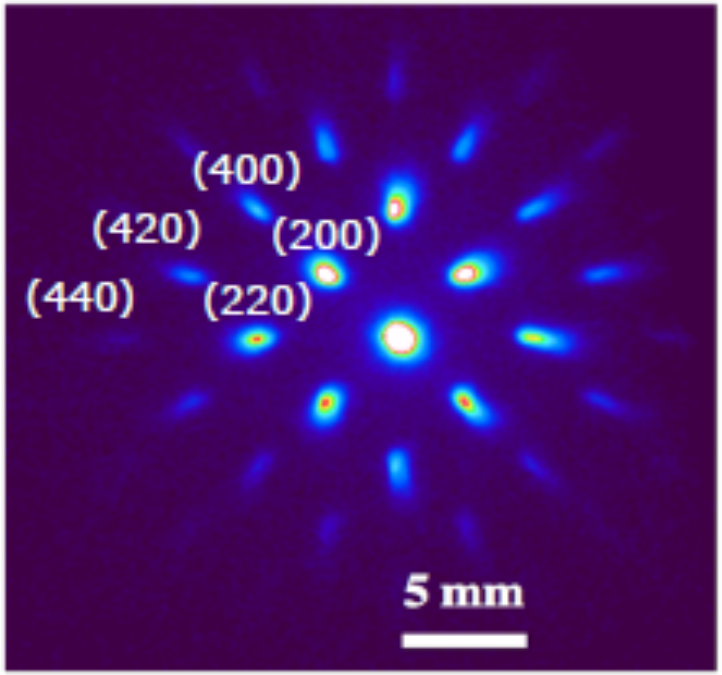


Phosphor screen
CsI(Tl)

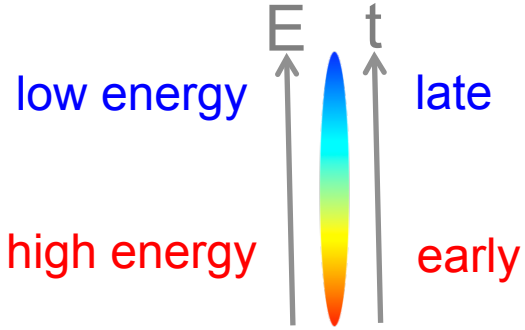
Diffraction pattern

Diffraction on single crystal Gold foil

laser-plasma source 95 keV



dE/E ≈ 10 % → « streaked » Bragg peaks

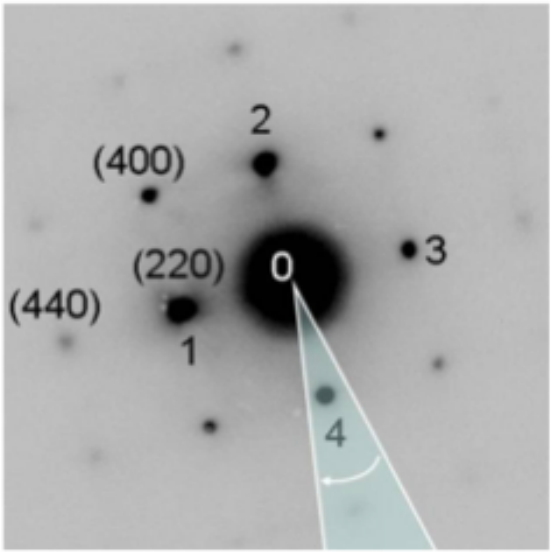


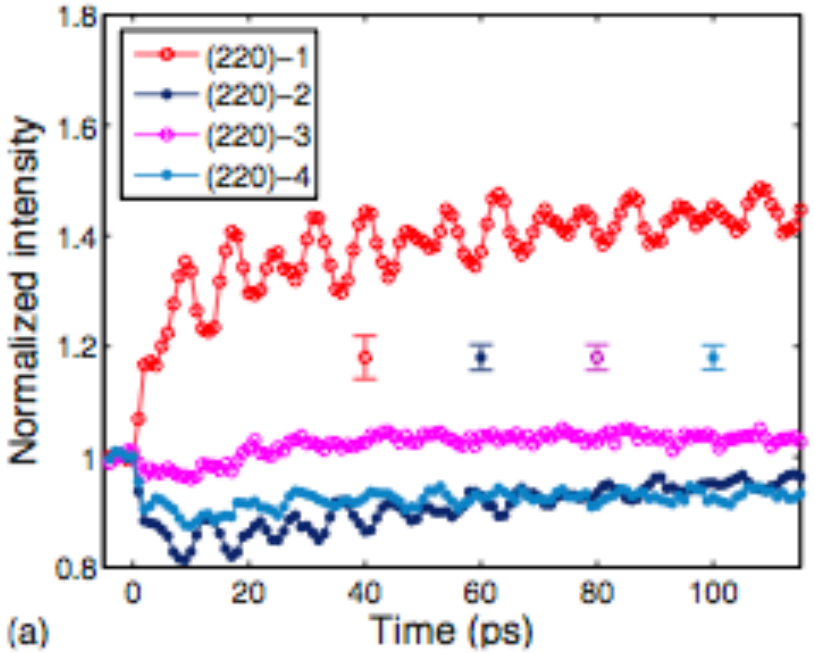
$$\sin\theta = \frac{n\lambda}{2d} \propto \frac{1}{\sqrt{E}}$$

→ **Temporal resolution along Bragg**

Why Silicon ?

Harb et al., Phys. Rev. B 79, 094301 (2009)





Perfect sample:

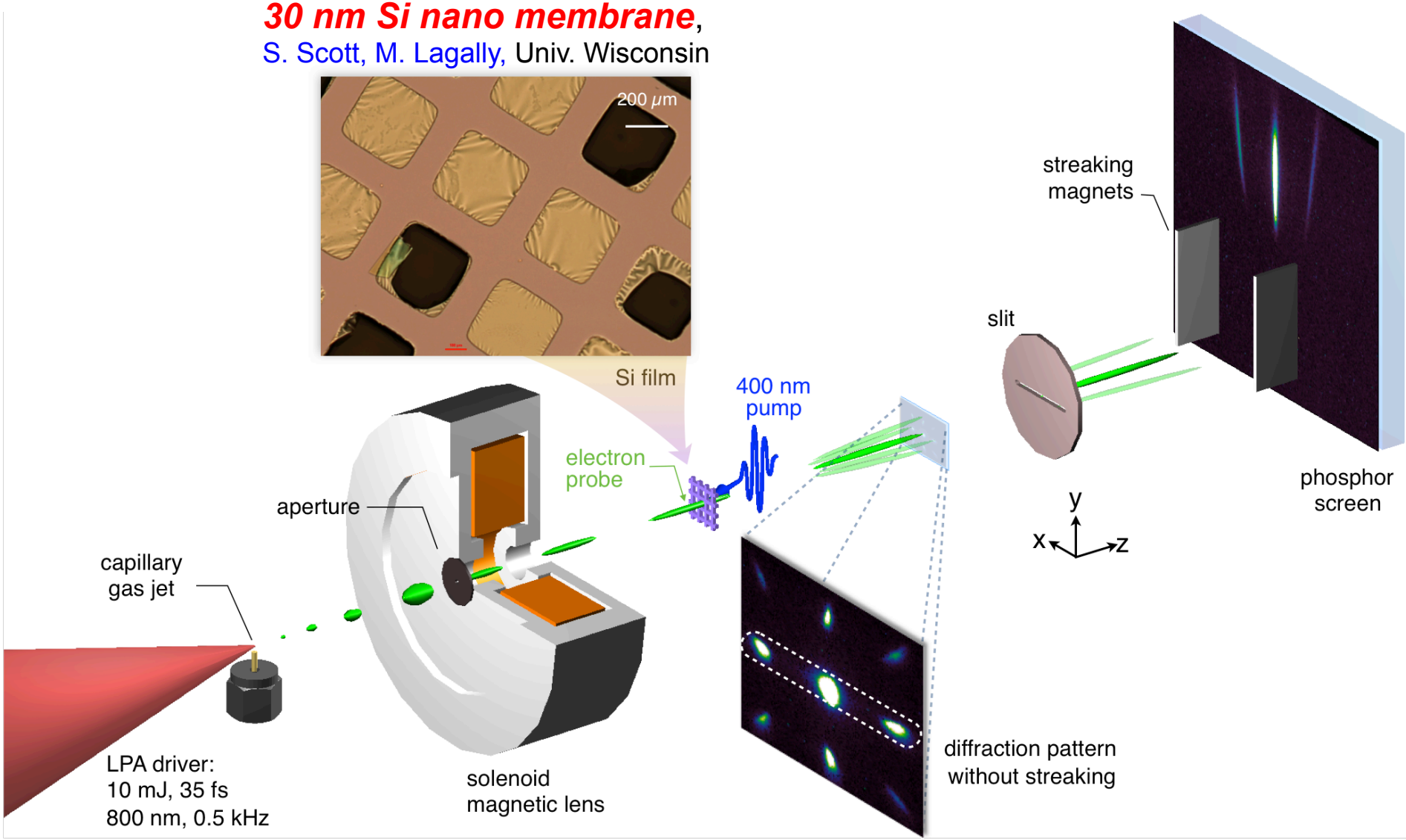
- Simple structure
- Available samples (30 nm on 100x100 μm^2)
- Extremely large photoinduced signal (what is it ?)

Time-resolved diffraction experiment on Si

→ streaking the Bragg peaks

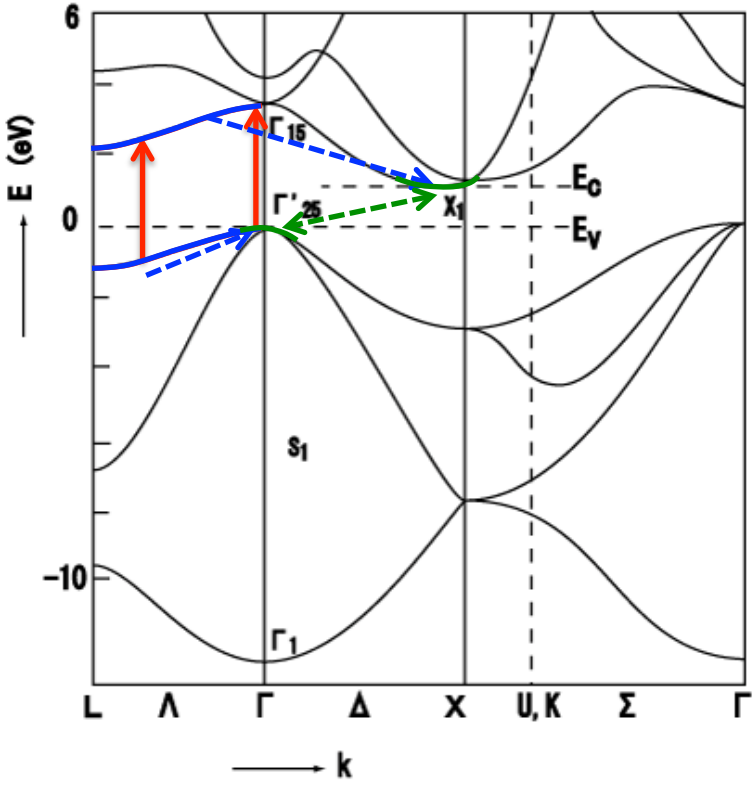
MichiganEngineering

30 nm Si nano membrane,
S. Scott, M. Lagally, Univ. Wisconsin



Expected scenario: lattice heating and Debye-Waller effect on Bragg peaks

Estimated absorbed fluence: F_{abs}=1.5 mJ/cm^2
Density of excited carriers: n_{exc}= 10^{21} cm^{-3} (0.5% of valence electrons)



- Direct photoexcitation @ 3 eV
- Electron thermalization **≈ 100 fs**

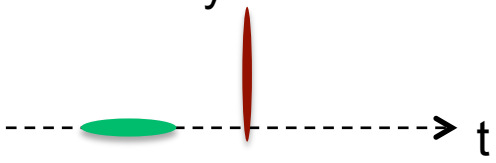
- Electron (hole) relaxation to bottom of conduction (valence) band **≈ ps**
  - Emission of phonons → lattice heating (70 %)
    ΔT=200 K

- Electron-hole pair recombination
  - Auger recombination **> 100 ps**
    (in principle ~2 ps, but screening effect)
  - Further heating of the lattice (30 %)
    ΔT=300 K

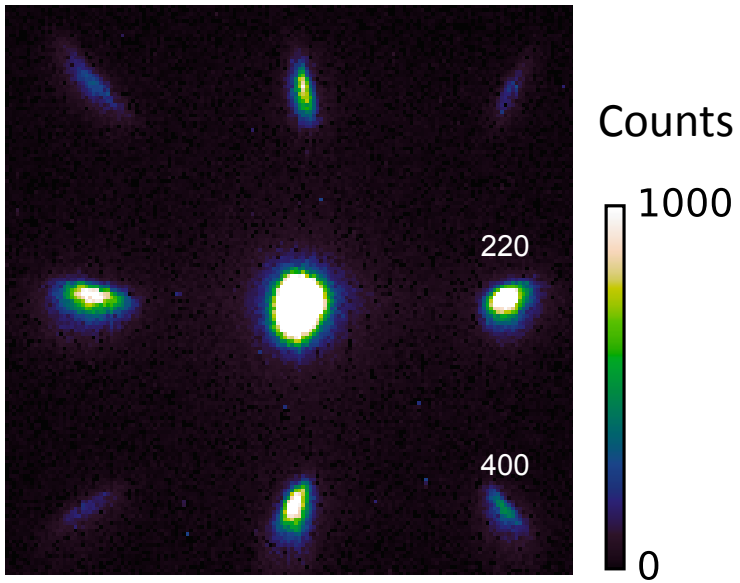
Effect of photo-excitation in Si

Estimated absorbed fluence: F=1.5 mJ/cm^2

Density of excited carriers: n_{exc}= 10^{21} cm^{-3} (0.5% of valence electrons)

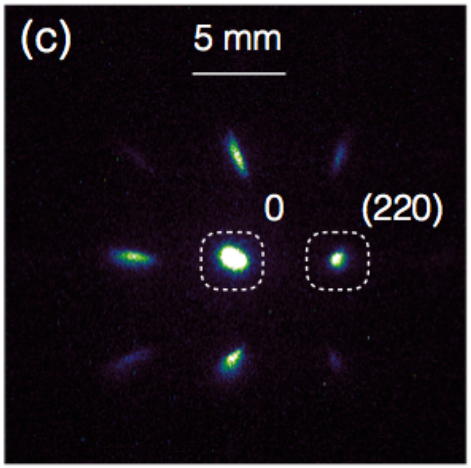


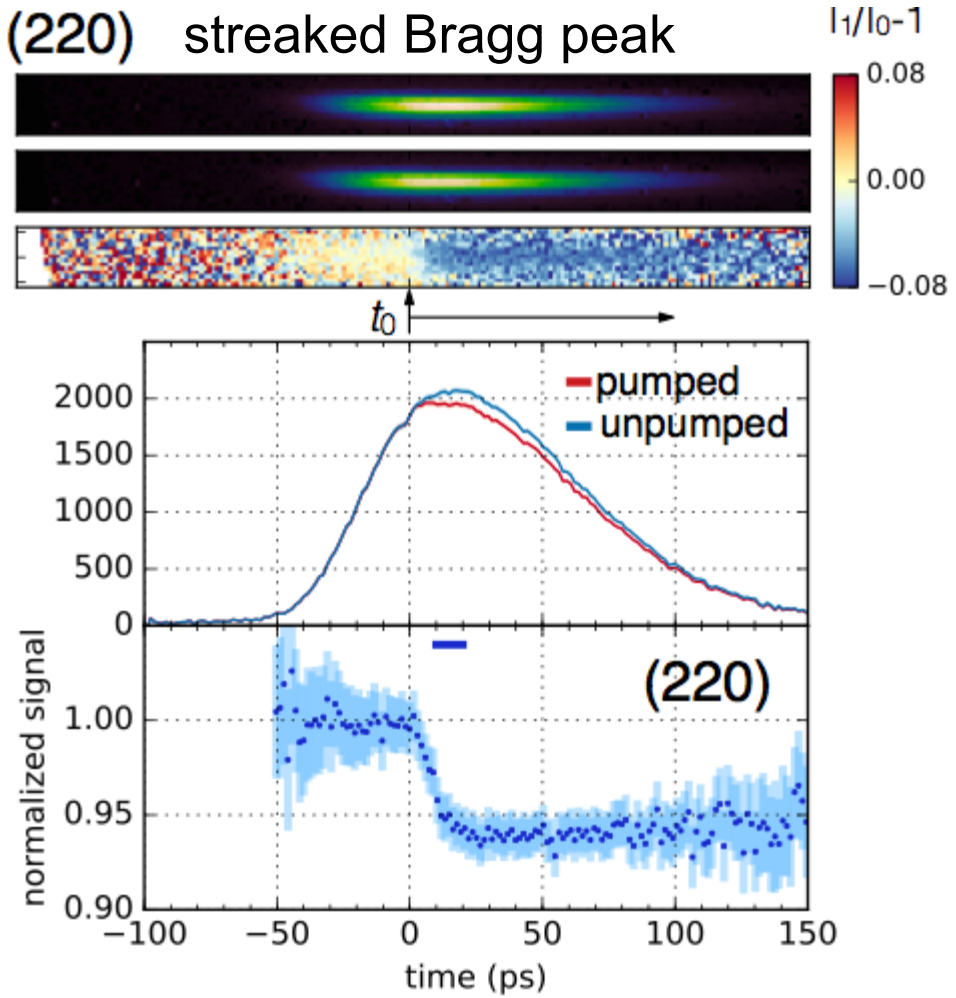
a unpumped, I_0



400 ms exposure

Streaking the Bragg peaks for time resolution





We observe:

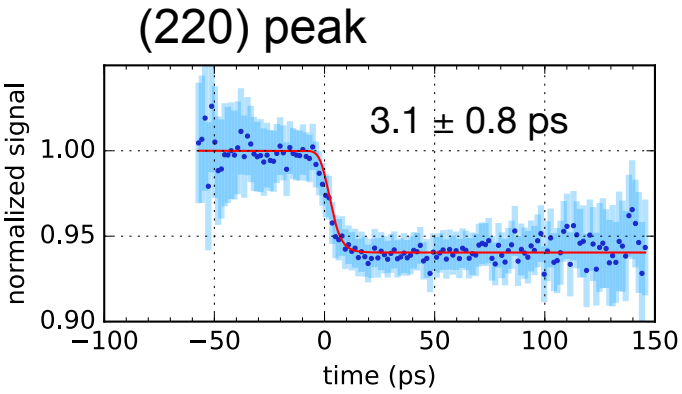
- A decrease of the 220 peak on ~ 3 ps time scale (el-phonon coupling)
- Long lived metastable state > 100 ps (hot Si)

Acquisition time: 10 min
(limited by charge fluctuations)

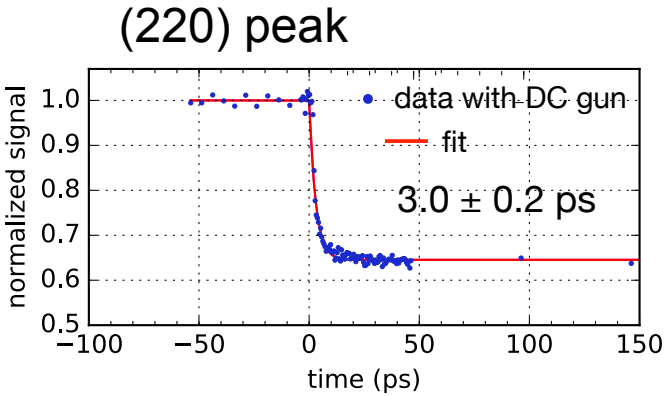
Z. He, B. Beaurepaire et al., Sci. Rep. **6**, 36224 (2016)

Comparison between plasma source (streaking) and DC gun (stroboscopic)

Laser-plasma electron source (100 keV)



DC electron gun (50 keV)



- Possible to retrieve picosecond dynamics
- kHz operation and source stability was key to the success of experiment
- Resolution is still > ps

→ Needs to improve by going to fs MeV electrons

→ laser-plasma source can resolve dynamics in Silicon

Z. He, B. Beaurepaire et al., Sci. Rep. **6**, 36224 (2016)

How to improve the resolution ?

$$\tau_{streak} = \frac{d}{v_z} \frac{m_e^2 c^4}{(E + m_e c^2)(E + 2m_e c^2)} \frac{\delta E}{E}\bigg|_{spectro}$$

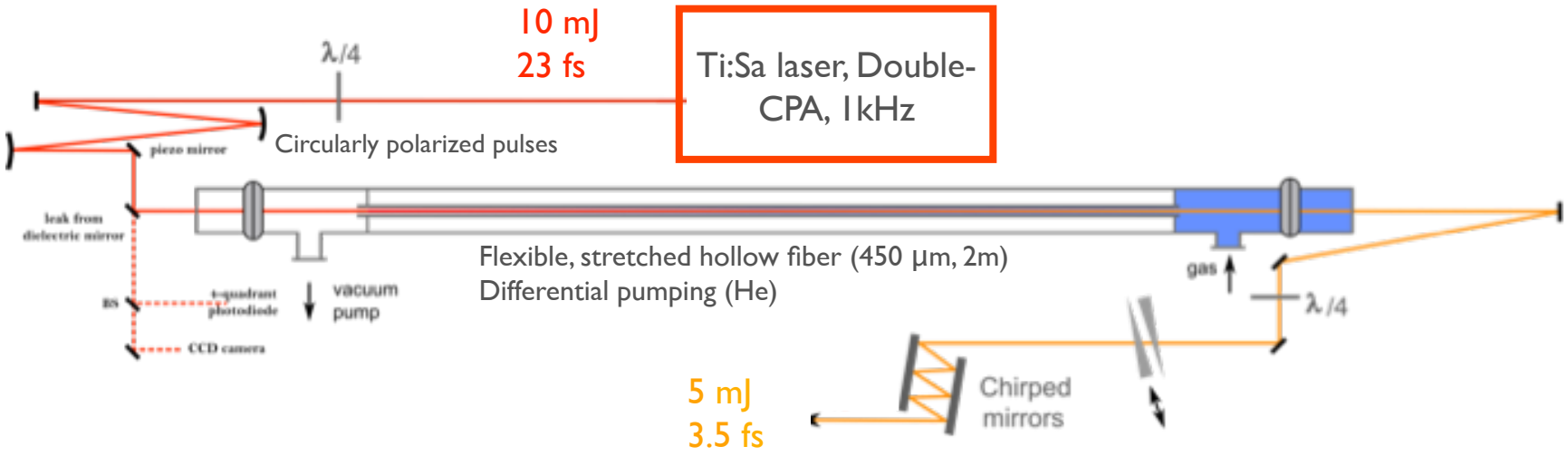
PROS	***CONS***
• Increase spectrometer resolution *δE/E*	• Lower signal
• Decrease distance to sample *d*	• Sample damage !
• Increase electron energy *E*	• challenging

To reach sub-10 fs resolution, we chose the challenging option
→ 5 MeV, few femtosecond bunches @ kHz

Laser: 5 mJ (2.5 mJ on target)
3.5 fs, kHz laser system

R. Lopez Martens' group:

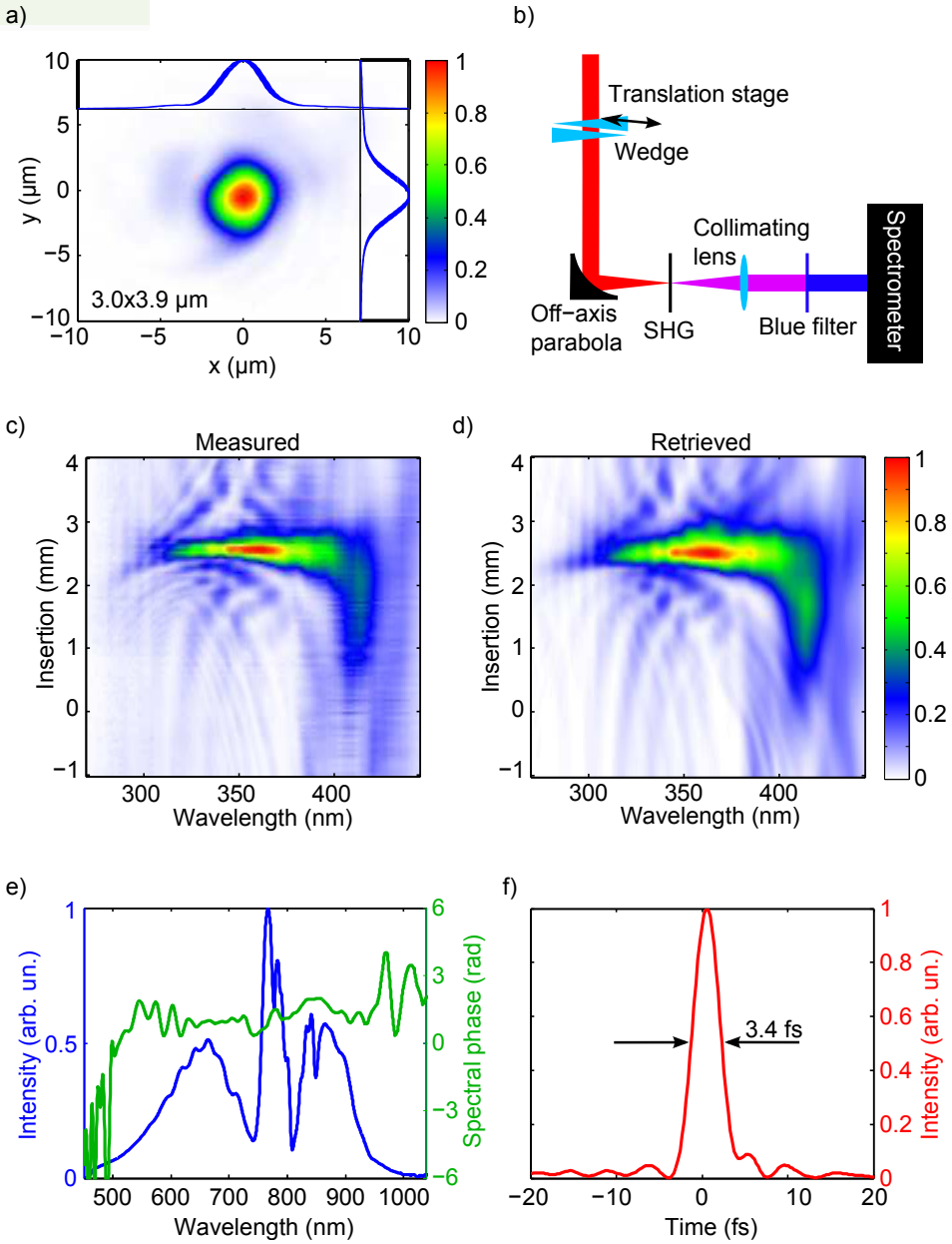
F. Böhle et al., Laser Physics Letters, 11, 095401 (2014)



From laser demonstration to implementation for experiments

→ One full year of development / debugging

Relativistic intensities with 2.5 mJ kHz laser



Full characterization in vacuum

- 3 μm spot FWHM
- D-scan measurement*
- 3.4 fs FWHM
- $I=3x10^{18}$ W/cm^2

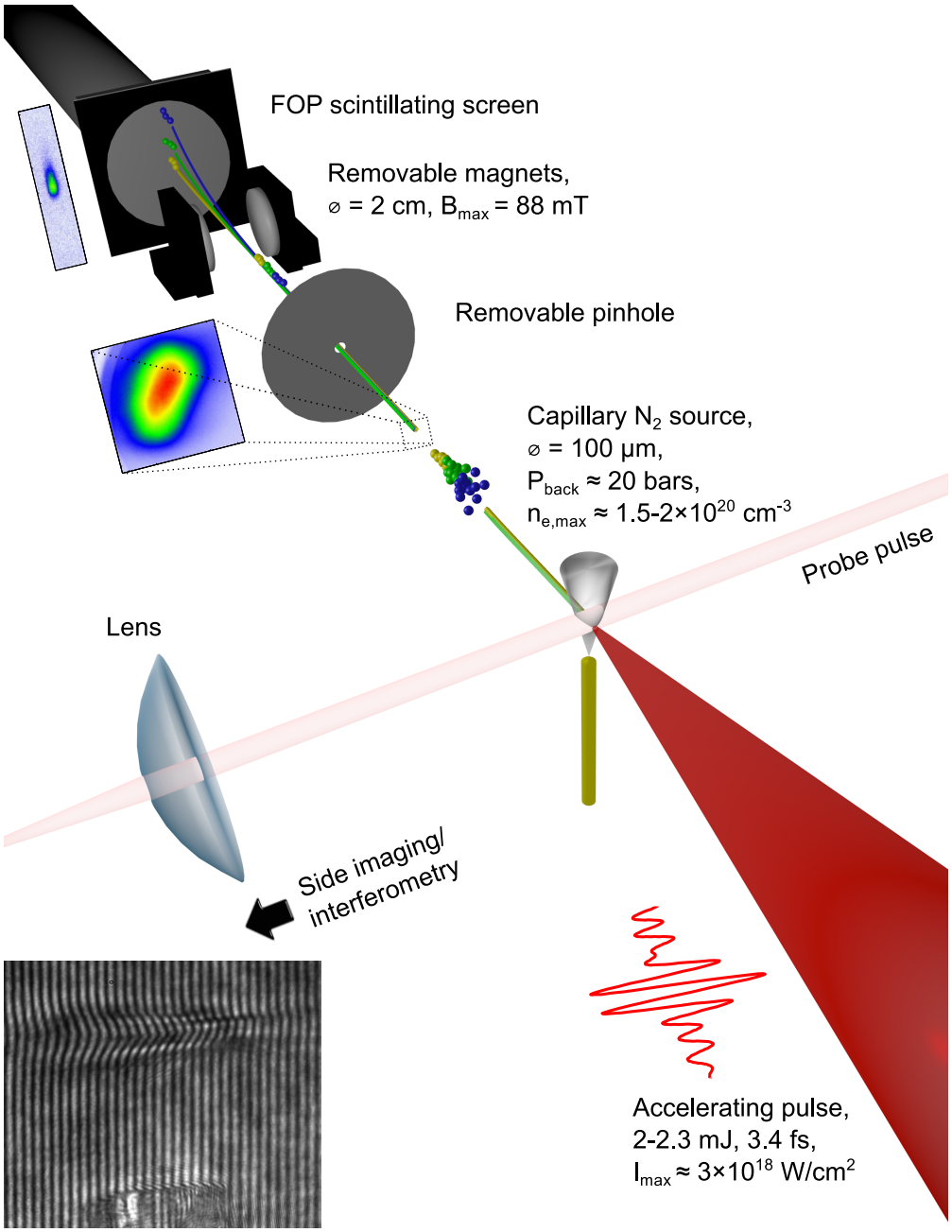
*Miranda, M. et al.
Opt. Express 20, 18732 (2012).

Experimental set-up

Work of D. Guénot, D. Gustas, A. Vernier

Gas target is a continuously flowing capillary N_2 gas jet

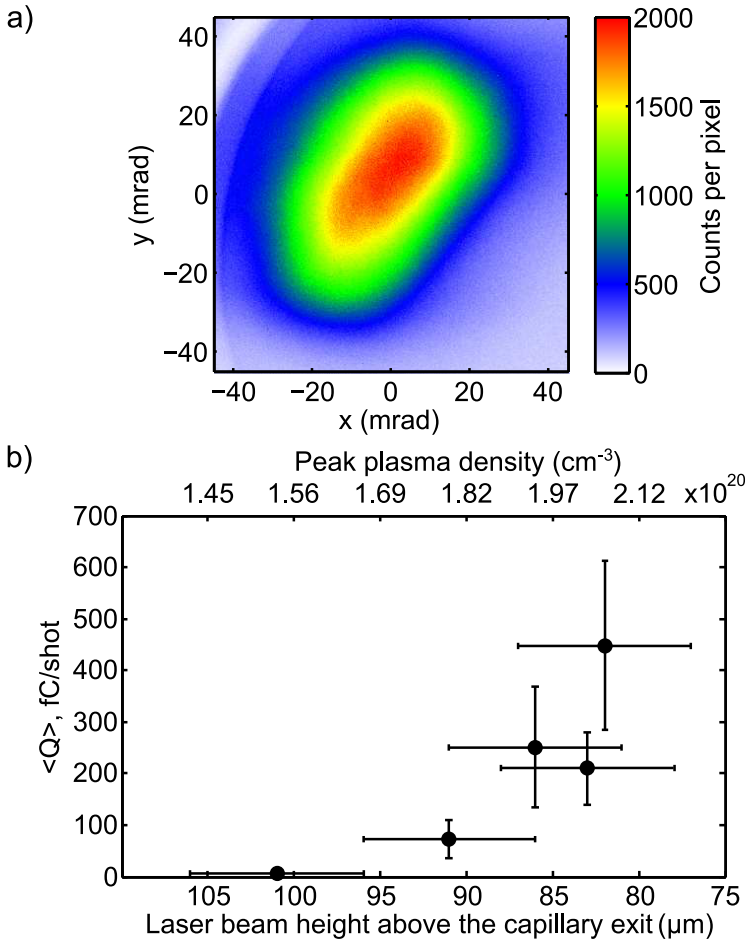
→ kHz operation
→ Pumping issues !



First MeV beams at kHz repetition rate

D. Guénot et al., accepted in Nature Photonics

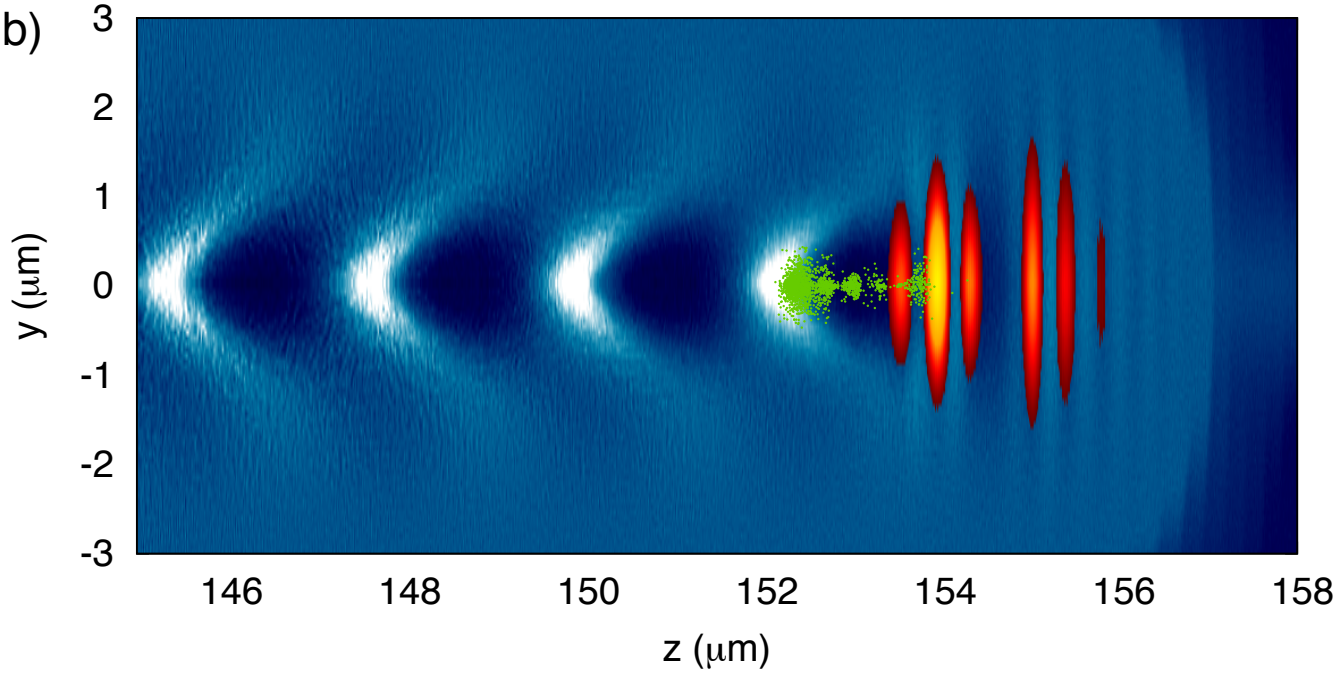
Divergence ~40 mrad



Charge ~0.5 pC/shot
up to 1 pC/shot

3D PIC simulations → 1 fs electron beams !

Trapped electrons in non linear wakefield



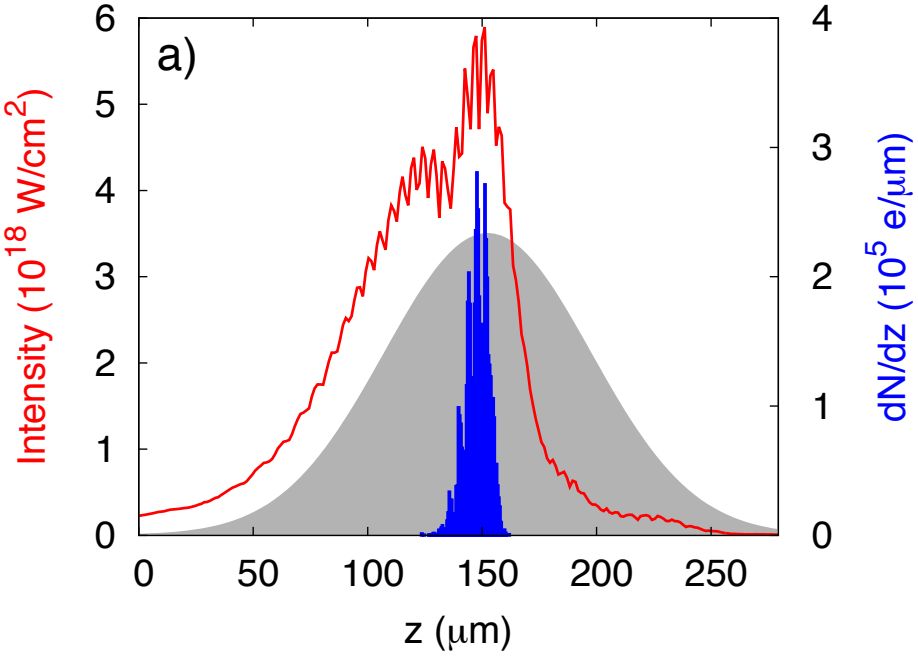
Simulation results at the jet exit:

5 MeV beams
400 fC of charge
20 mrad divergence
1 fs duration

3D PIC simulations reproduce the results

CALDER-Circ simulations performed using experimental Parameters and measured laser spectrum and phase

Evolution of intensity
Injected charge



slight self-focusing
accelerated electrons originate from ionization of N^{5+} to N^{6+}
very local injection at peak laser intensity

Conclusions:

- Operate at kHz (with < 10 mJ) ? ✓
- Accelerate electrons to few MeV ? ✓
- High beam quality ✓
- Stable source ✓…
- Demonstration of UED (ps resolution) ✓
- Sub-10 fs duration ?

- Optimize this source (different gases, jets, CEP…)
- Beam transport (select energy bin, recompress bunch)
- POTENTIAL APPLICATIONS
  - Sub-10 fs electron diffraction
  - Femtolysis of water / radio-biology…

Need for collaborations

Promote applications of our sources:

- Plasma source (5 MeV, pC, 1 fs ??)
- Conventional DC gun (300 fs, few fC, 50 keV)

- SAMPLES SAMPLES SAMPLES !!

  < 100 nm, 100x100 μm^2

- Irradiation applications, radiolysis…

Collaborators

Experiments: kHz laser-plasma source
D. Gustas, I. Gonzalez, N. Zaim, B. Beaurepaire
A. Vernier, G. Gallé, D. Guénot, A. Lifschitz

CUOS of University of Michigan:
Z. He, A. Thomas, J. Nees, K. Krushelnick

Laser system:
M. Bocoum, F. Böhle, A. Jullien, J.-P. Rousseau, R. Lopez-Martens

Beam transport
B. van der Geer, Univ. Eindhoven, Pulsar Physics

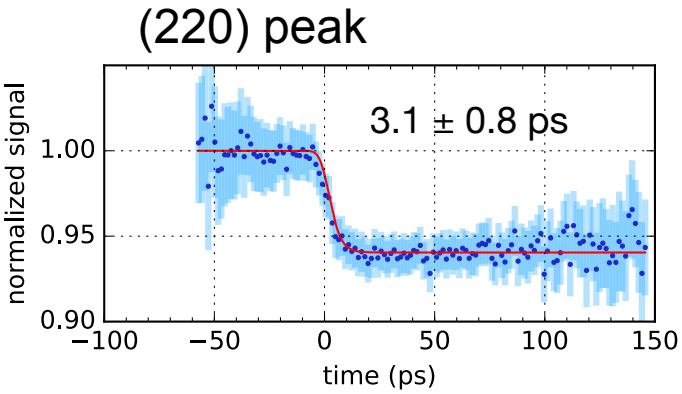
Sample preparation
S. Scott, M. Lagally, Univ. Wisconsin

Outline of the talk

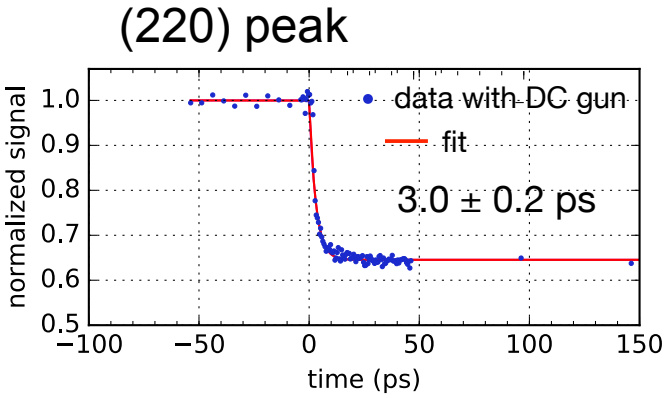
- Motivation / Introduction
- First laser-plasma accelerator at kHz and application to ultrafast electron diffraction
- First experiments with near-*single-cycle laser pulses*
  →Acceleration of ~ 5 MeV electrons at kHz
- Work in progress: ultrafast dynamics in Silicon, evidence of photo-induced dynamical diffraction effects

Comparison between plasma source (streaking) and DC gun (stroboscopic)

Laser-plasma electron source (100 keV): 30 nm sample



DC electron gun (50 keV): 78 nm sample



- Similar dynamics
- Much larger signals on 78 nm sample

→ Use conventional DC gun to explore the physics

Z. He, B. Beaurepaire et al., Sci. Rep. **6**, 36224 (2016)

Collaborators

Experiments: kHz laser-plasma source
B. Beaurepaire, D. Gustas
A. Vernier, G. Gallé, D. Guénot, A. Lifschitz

CUOS of University of Michigan:
Z. He, A. Thomas, J. Nees, K. Krushelnick

Laser system:
M. Bocoum, F. Böhle, A. Jullien, J.-P. Rousseau, R. Lopez-Martens

Beam transport
B. van der Geer, Univ. Eindhoven

Sample preparation
S. Scott, M. Lagally, Univ. Wisconsin