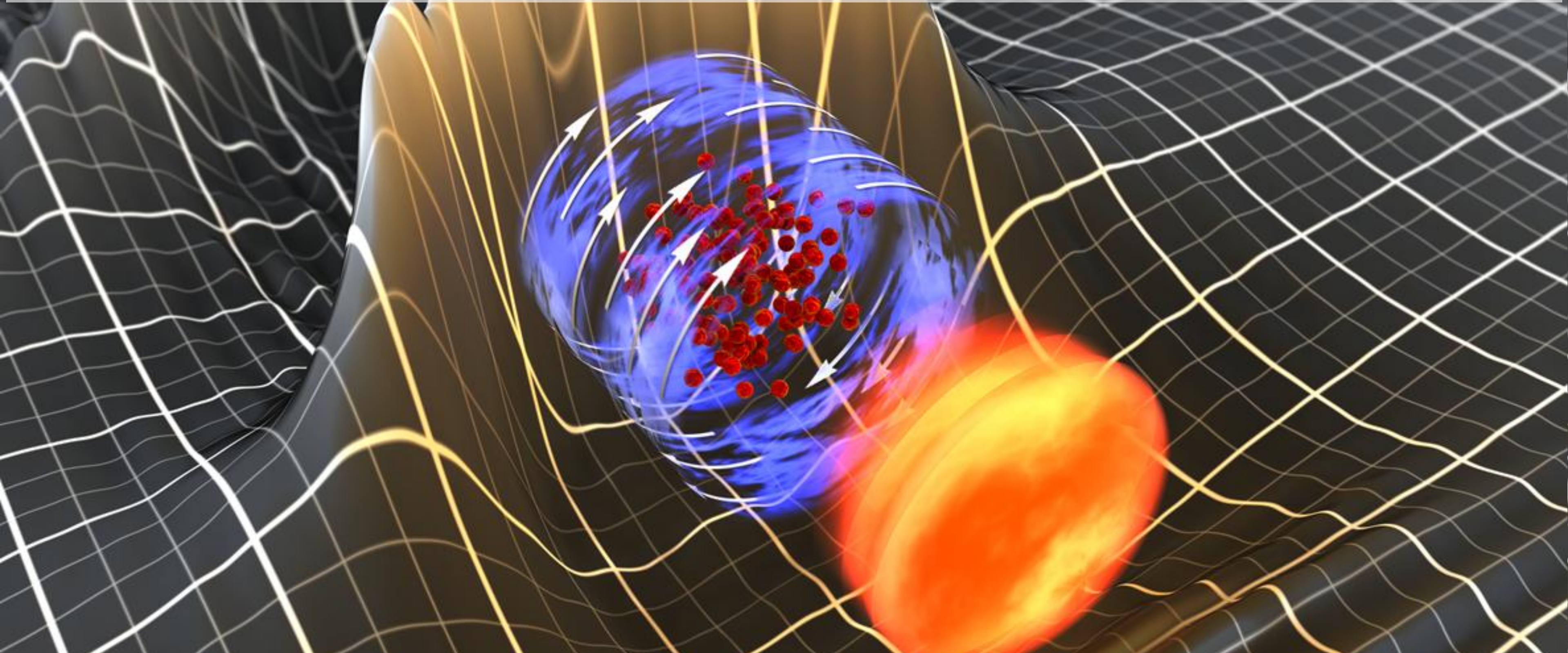
Few-cycle laser development and advanced control and characterization of laser-driven electron acceleration

Laszlo Veisz[1], Alexander Buck[1,2], Karl Schmid[1], Julia Mikhailova[1], Tai Dou[1], Chris Sears[1], Daniel Rivas[1], Johannes Wenz[1], Matthias Heigoldt[1], Konstantin Khrennikov[1], Benedikt Mayer[1], Raphael Tautz[1], Daniel Herrmann[1], Xun Gu[1], Gilad Marcus[1], Tibor Wittmann[1], Jiancai Xu[1], Maria Nicolai[3], Alexander Sävert[3], Stefan Karsch[1,2], Malte C. Kaluza[3,4], and Ferenc Krausz[1,2]



[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
[2] Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany
[3] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, 07743 Jena, Germany
[4] Helmholtz-Institute Jena, Helmholtzweg 4, 07743 Jena, Germany

October 21 2011 Berkeley, USA

Outline

1.) Motivation for optical parametric chirped pulse amplifier (OPCPA)

Light Wave Synthesizer 20 – an 8 fs OPCPA system and its chracteristics

Why and how to go to 5 fs pulse duration ?

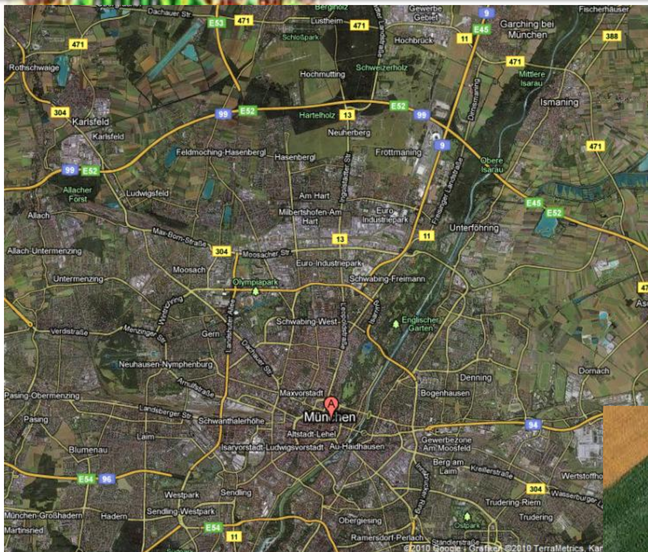
2.) Laser-driven electron acceleration

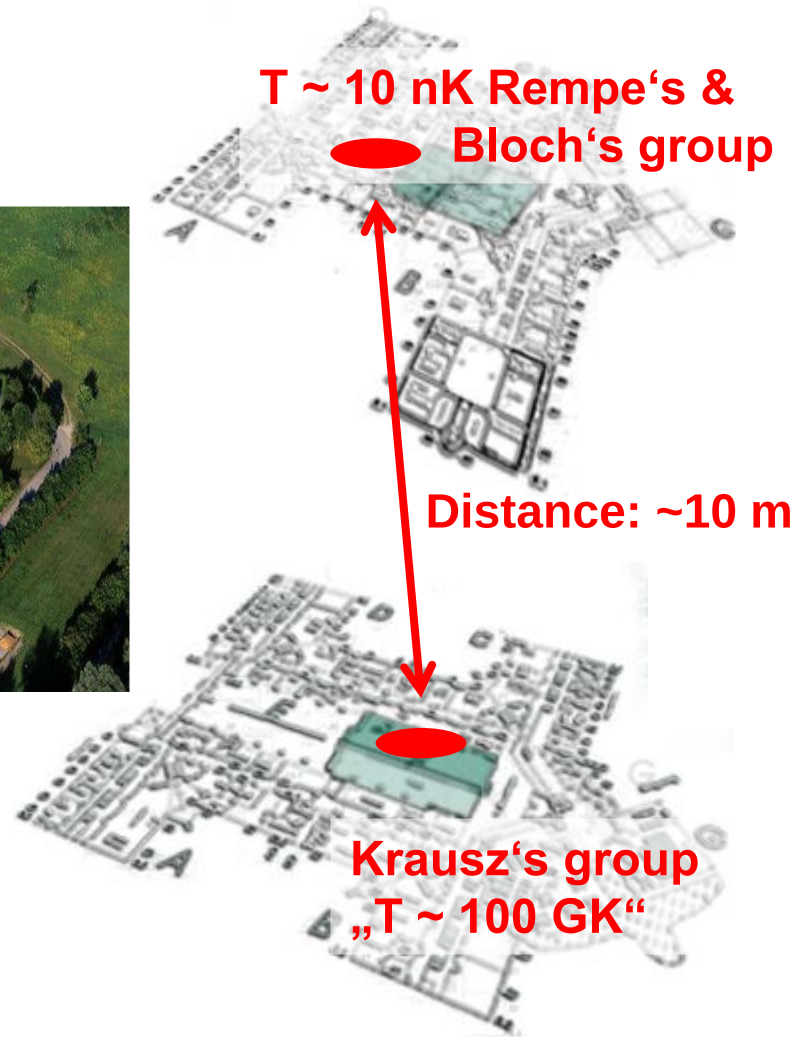
Shock front injection with LWS-20 (8 fs) and ATLAS (26 fs)

Electron bunch duration and direct temporal observation of laser wakefield acceleration

3.) Conclusions and outlook

Max Planck Institute of Quantum Optics Garching, Germany

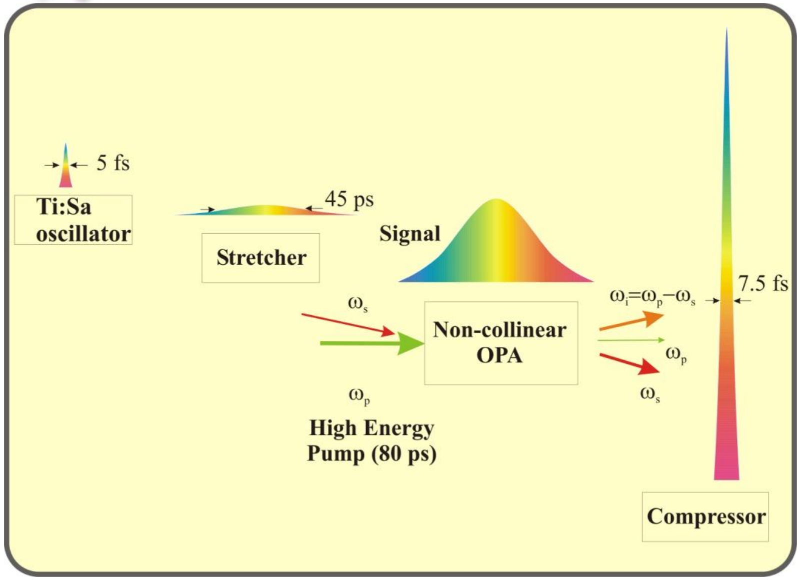


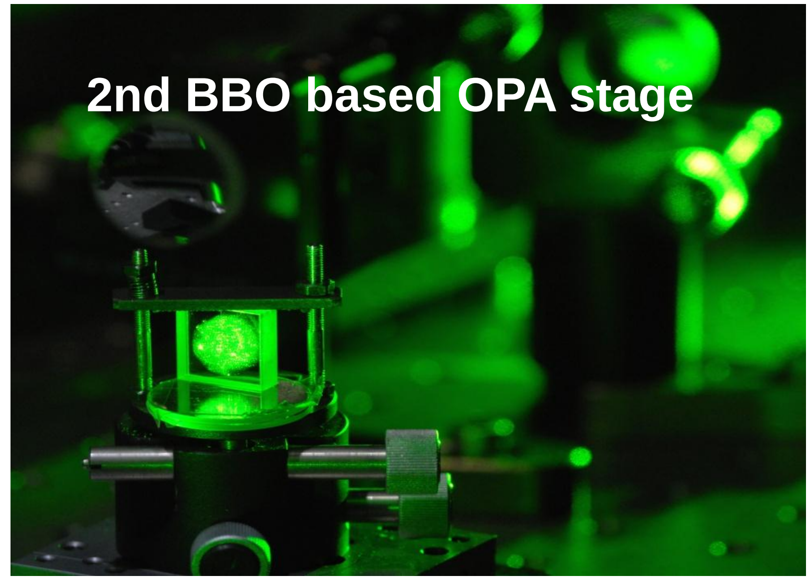


5 directors / groups
300 scientist

Investigations at different ends of the achievable temperature scale

Optical parametric chirped pulse amplification (OPCPA)





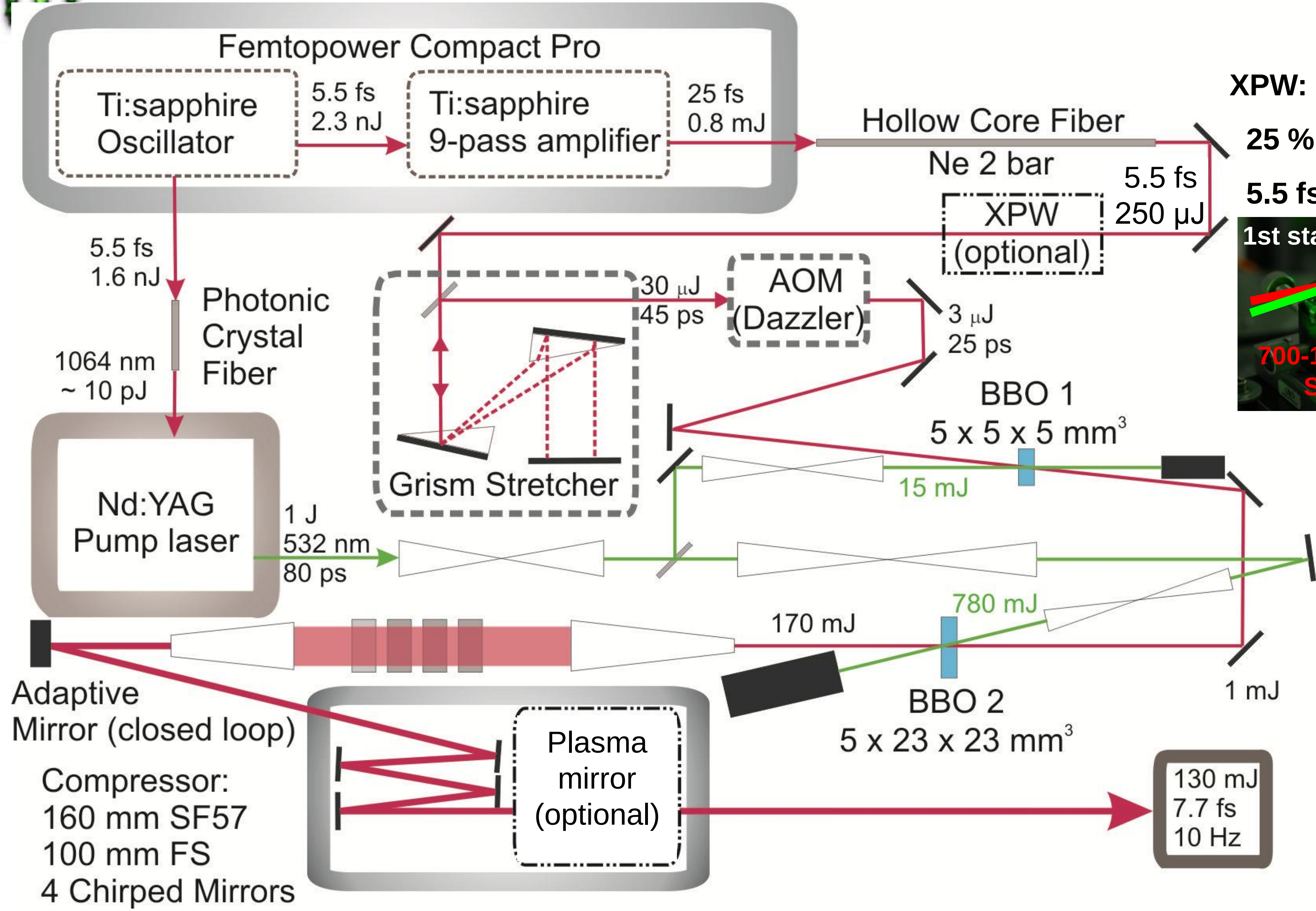
Advantages

- Broad gain bandwidth, supporting few-cycle pulses
- Huge single pass gain (~10^6)
- No thermal load in the amplifier crystals
- Good contrast achievable

Challenges

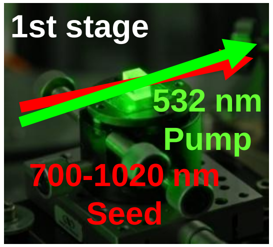
- Stretching and compression of huge spectral bandwidth
- Pump laser
- Synchronization of pump and seed
- Amplification of the optical parametric fluorescence (superfluorescence)
- Carrier envelope phase stabilization

LWS-20 OPCPA Setup



XPW:

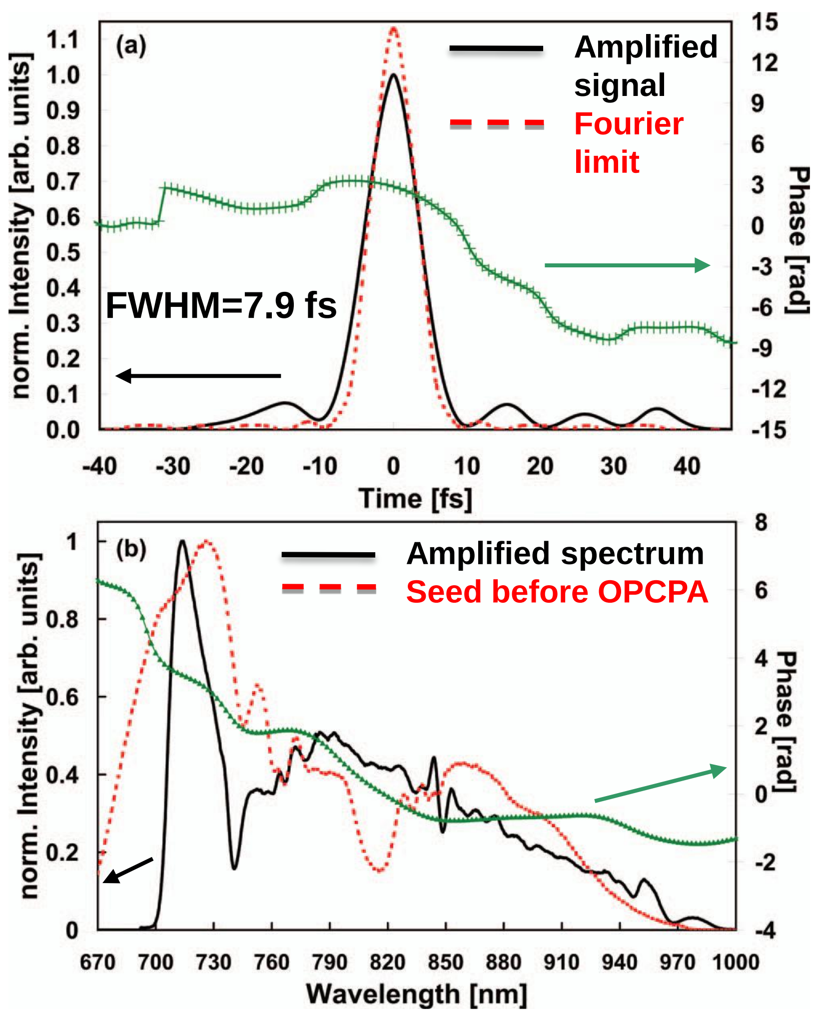
25 % eff with 5.5 fs pulses



LWS-20: D. Herrmann *et al.* Opt. Lett. 34, p. 2459 (2009)

LWS-20 pulse compression

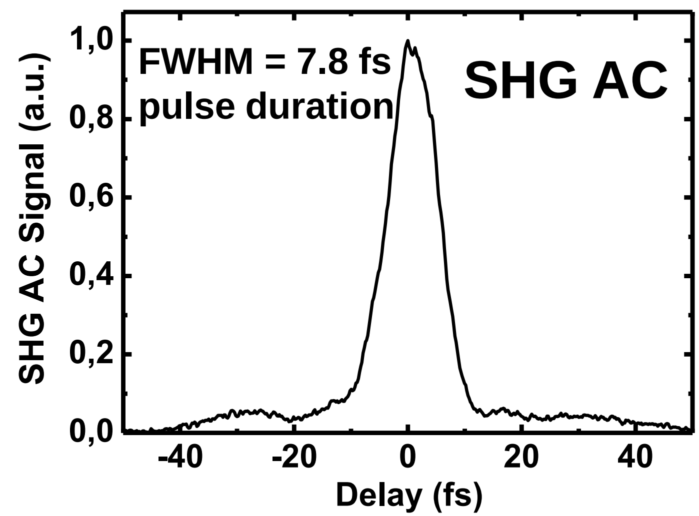
SHG FROG



LWS-20: D. Herrmann *et al.* Opt. Lett. 34, p. 2459 (2009)

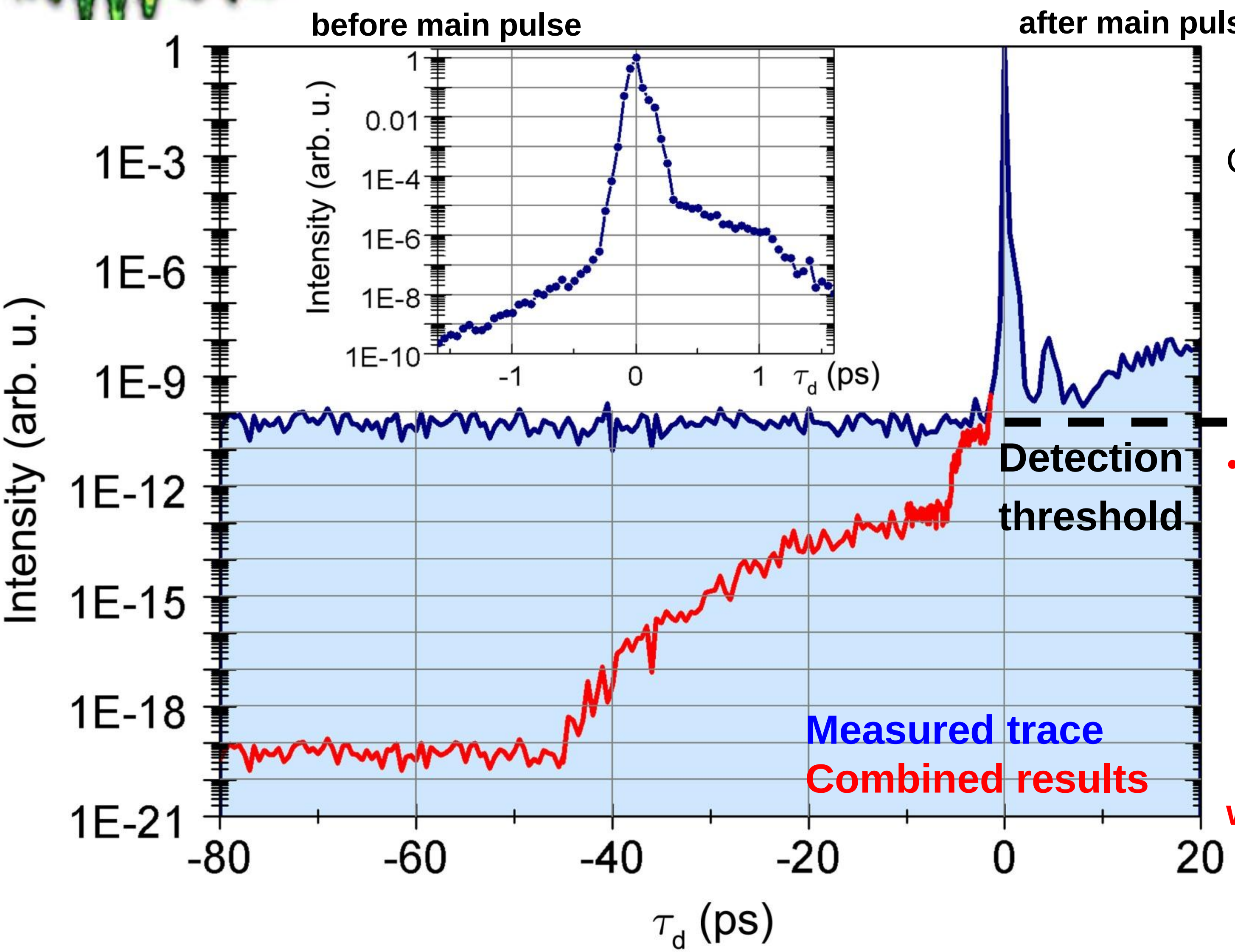
SHG AC & SHG-FROG results:

- Spectral components between 700-1000 nm
- Central wavelength 805 nm
- Duration (FWHM)= 8 fs, compressed within 5% of the Fourier limit
- Pulse duration stability: 3%
- >80% of the total energy is contained in the main pulse



<u>Conclusion:</u> 8 fs, 130 mJ,16 TW

LWS-20 contrast with cross-polarized wave generation (XPW) + Plasma mirror (PM)



Combining the enhancement factors and overestimating the optical parametric fluorescence (**$10^{10.5}$**).

- **contrast of LWS-20 + XPW + plasma mirror:**

$10^{-10.5}$ @ 2ps
10^{-13} @ 20ps
$<10^{-19}$ @ >45ps

with 8 fs duration !!!

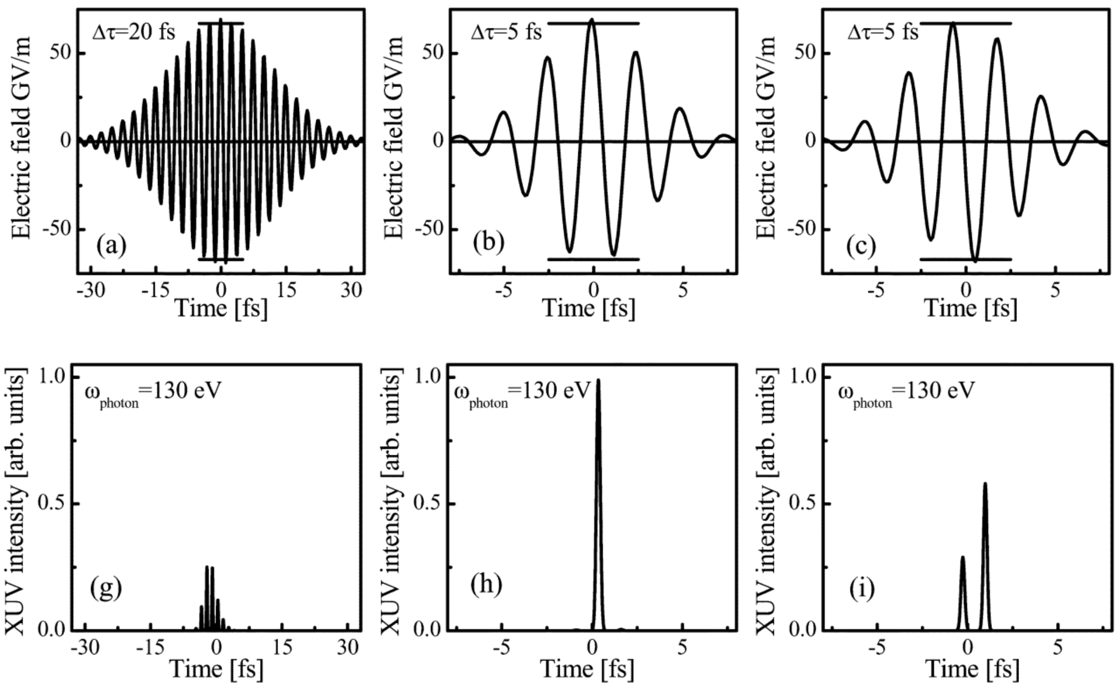
J. M. Mikhailova et al., Opt. Lett. **36**, 3145 (2011)

Why to go to 5 fs ?

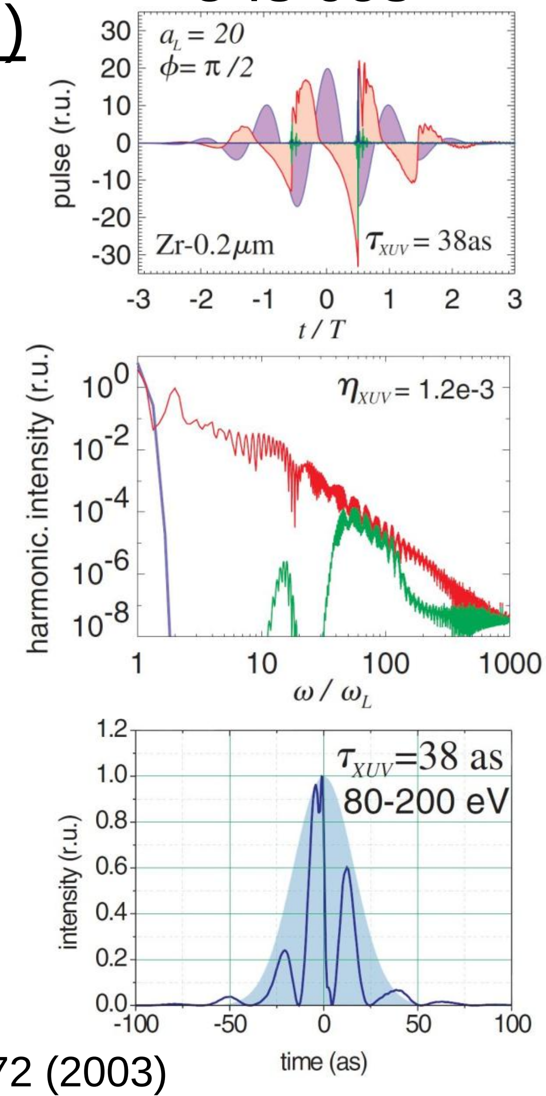
Generation of single attosecond pulses in gas and surface high harmonic generation (HHG)

Gas harmonics

20 fs | 5 fs cos | 5 fs sin



Surface HHG
5 fs cos

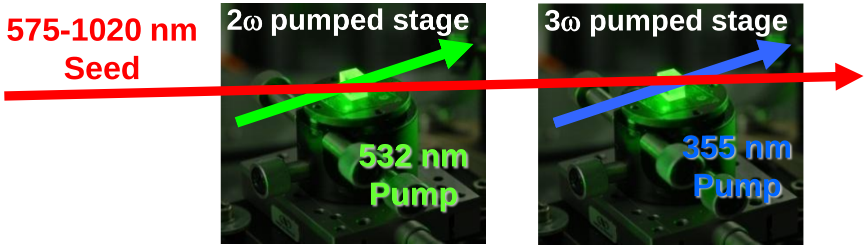


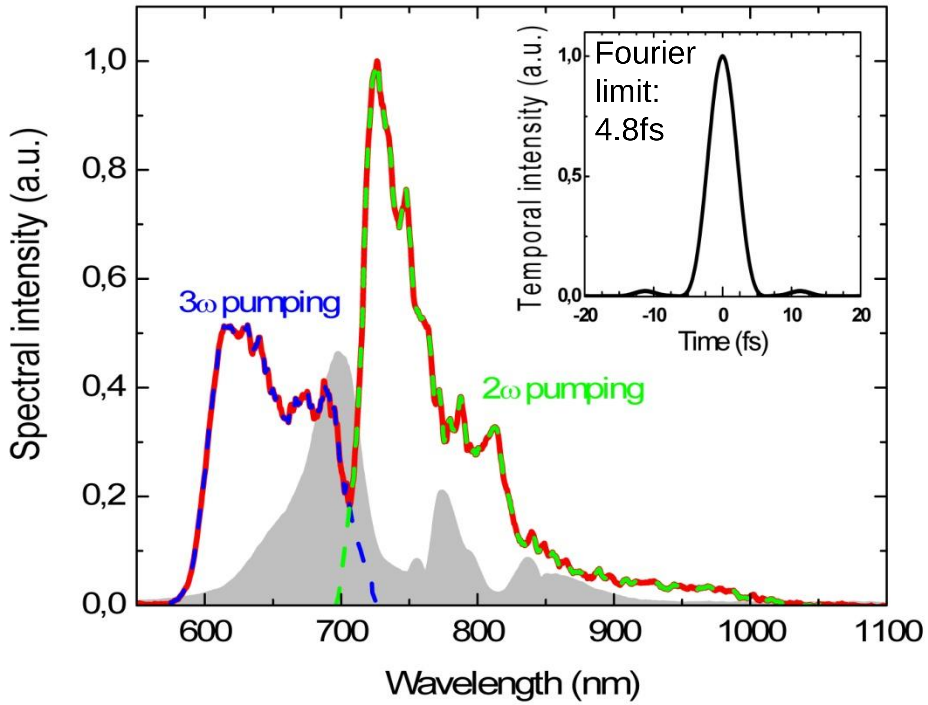
G. D. Tsakiris et al., New J. Phys. 8, 19 (2006)

A. Baltuska et al., IEEE J. of Sel. Top. in Quantum Electronics 9, 972 (2003)

How to generate 5 fs ?
Bandwidth increase

Two-colour pumping+ – with the **2ω** and **3ω** of the pump fundamental in two different NOPCPA stages



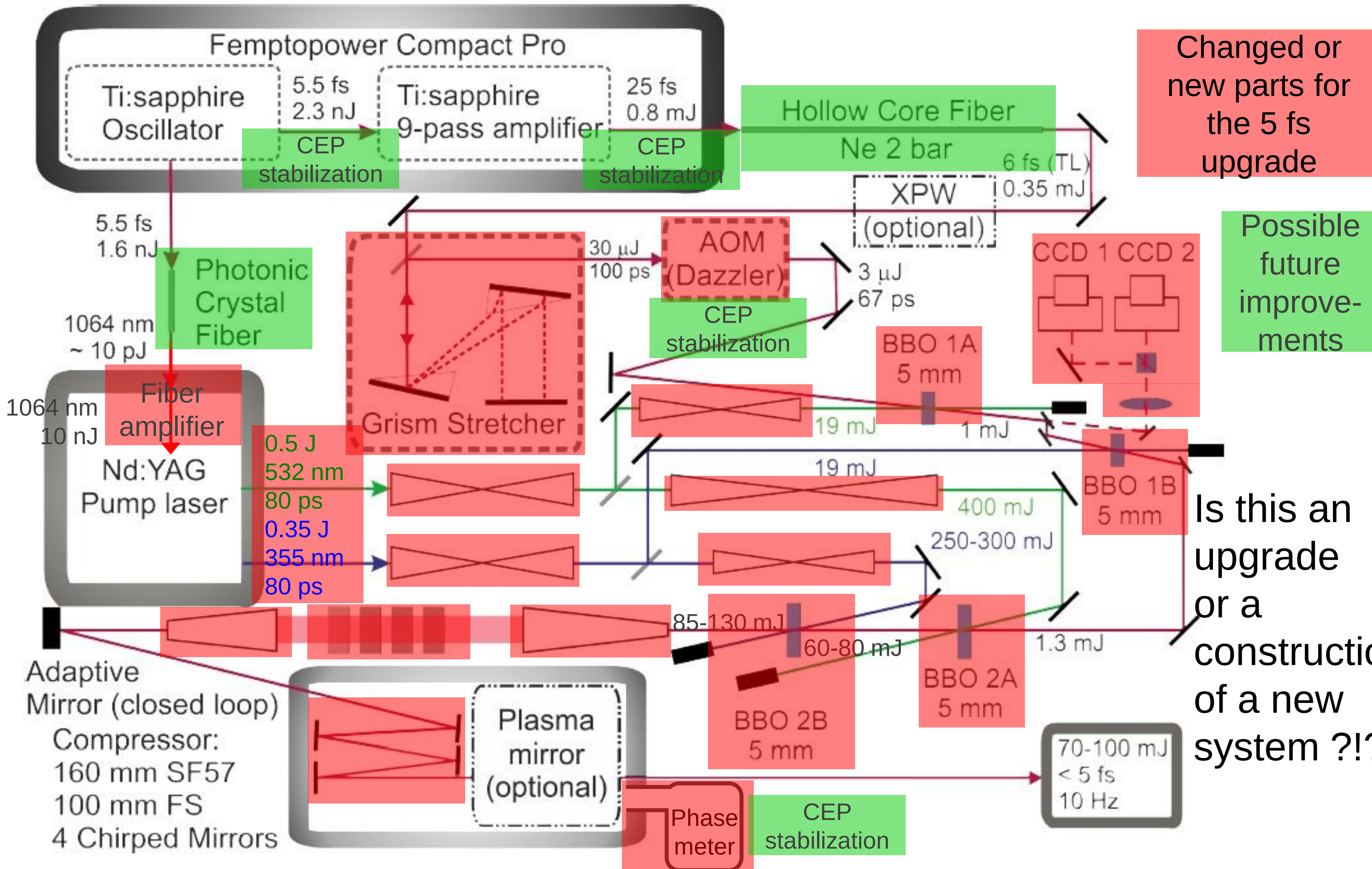


Advantages:

Even broader spectrum (575-1020 nm)
Even shorter (sub-two cycle) pulses (Fourier limit 4.8 fs)
Relative simple realization with the same pump laser

+ D. Herrmann *et al.*, *Opt. Exp.* **18**, p. 18752 (2010)

Setup for the 5 fs LWS-20



Is this an upgrade or a construction of a new system ?!?

www.attoworld.de

Further goals

www.attoworld.de

MPQ

LMU

Goals:

- Upgrade step I:
  Bandwidth increase to reach
  ~5 fs pulse duration

- Upgrade step II:
  Pump laser energy upgrade
  4 J (from 1J), 532 nm, 80 ps,
  10 Hz is delivered

Former status: LWS-20
130 mJ, 8 fs, 16 TW

Upgrade goal: LWS-100
500 mJ, 5 fs, 100 TW

- Single shot CEP-measurement / stabilization of the OPCPA system

Summary:

- LWS-20 upgrade is ongoing towards 100 mJ, 5 fs and excellent contrast

- Applications of LWS-20 are ready to start

Motivation for laser-plasma electron acceleration

www.attoworld.de

MPQ

LMU

Classical RF accelerators:

Maximal accelerating fields due to breakdown:

- $E_{max} \approx 100MV/m$
- many km long accelerators needed
- Expensive
- Longer pulse duration
- Timing jitter

SLAC

Alternative: Plasma-based Accelerators:

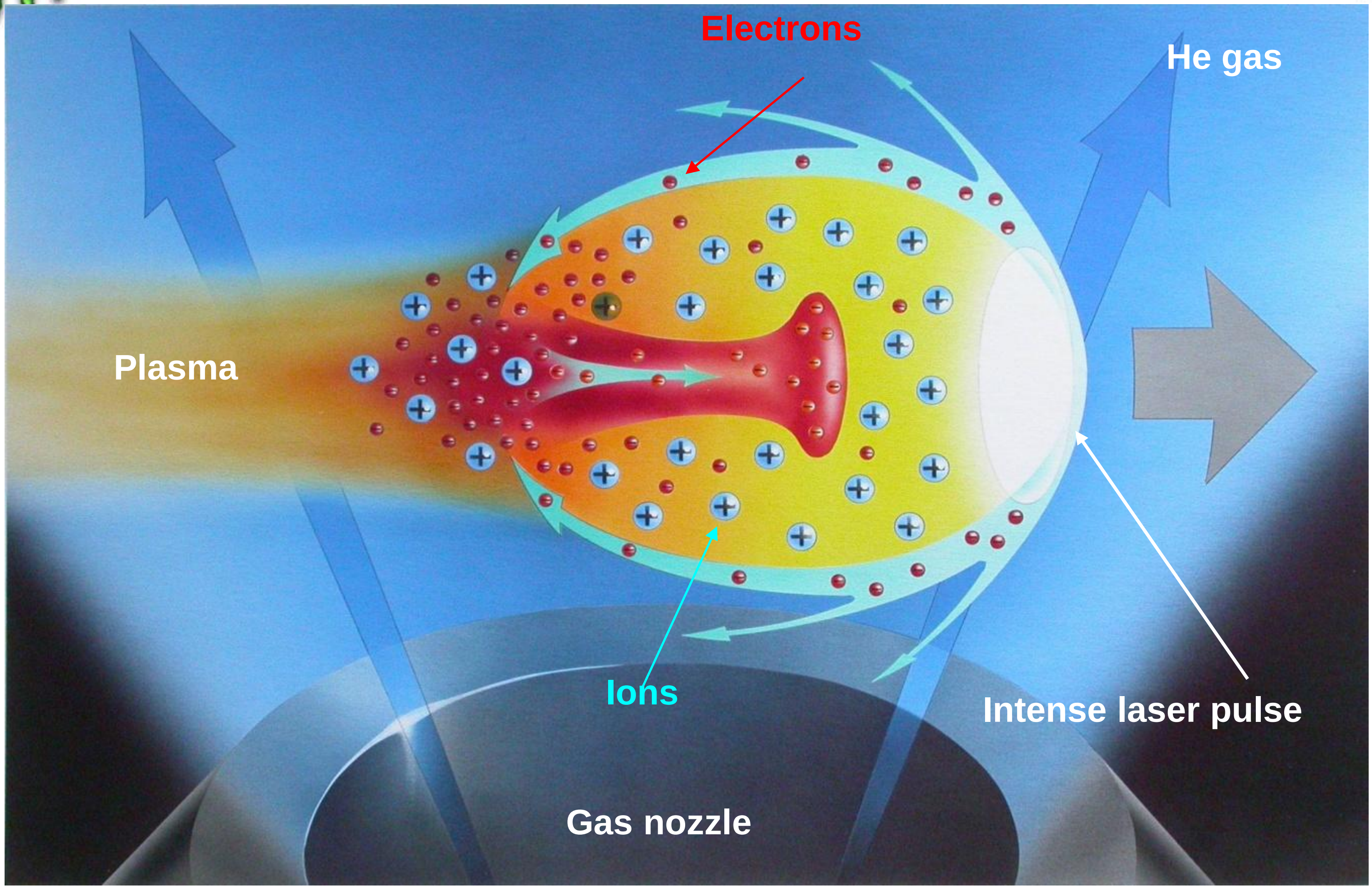
Already ionized acceleration medium → no breakdown

Sustainable fields:

- Possible fields: E=100GV/m - 1TV/m
  10^3 - 10^4 times higher
- Shorter acceleration distance
- Intrinsically short (few fs) pulses
- Intrinsically synchronized with laser pulse

Super-sonic Helium Gas Jet

Laser wakefield acceleration



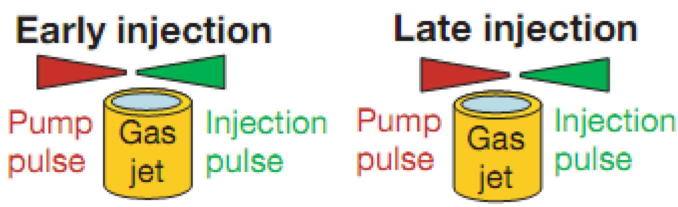
T. Tajima, et al. PRL **43**, 267 (1979)
A. Pukhov, et al. APB **74**, 355 (2002)

Injection Mechanisms

Common scheme: Separation of Trapping and Acceleration

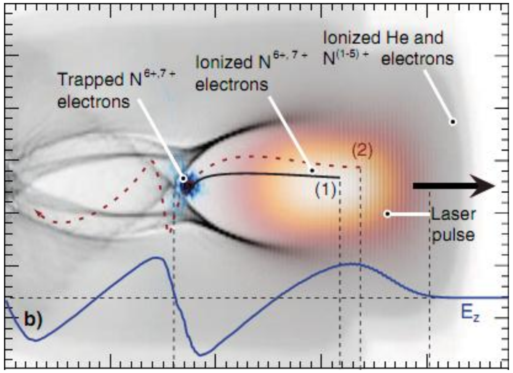
→ Inhibiting self-injection by lowering laser intensity and gas density

1. Colliding „Injection“ Pulse



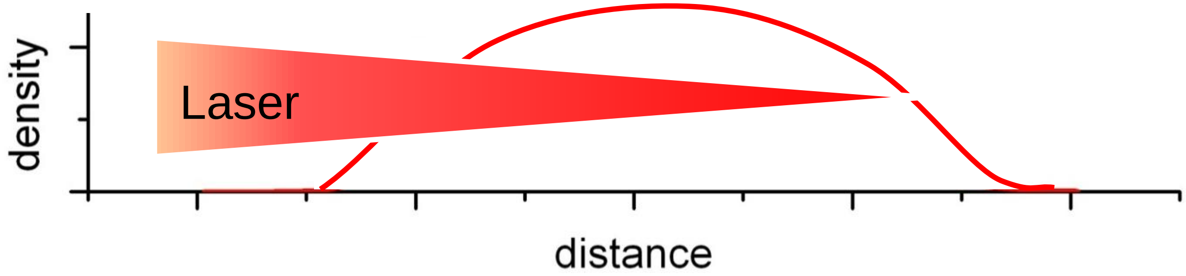
- J. Faure *et al.*, Nature **444**, 737 (2006).

2. Gas mixtures



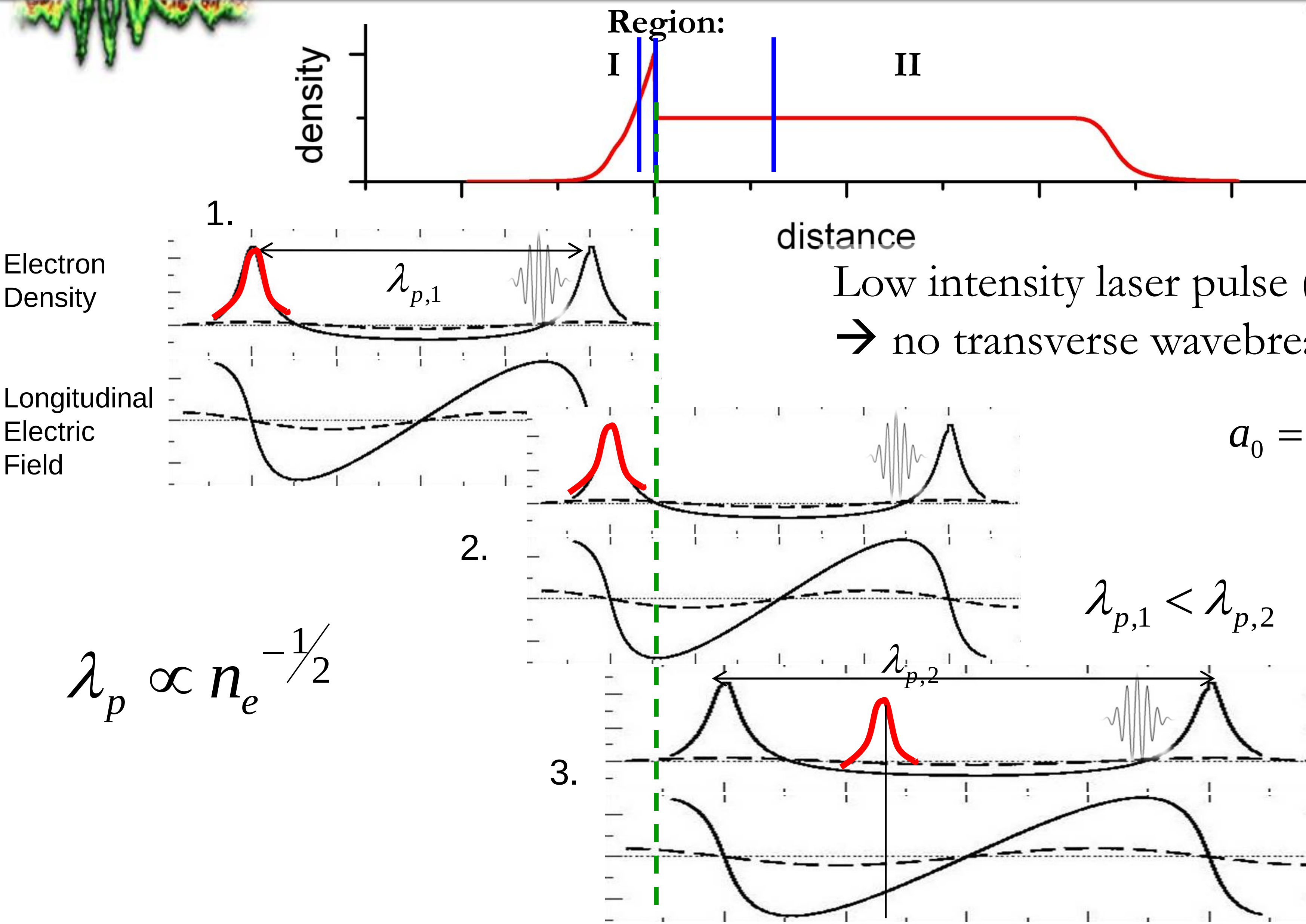
Pak *et al.*, PRL 104, 025003 (2010).

3. Downward density transition (down ramp)



C. G. R. Geddes et al., PRL **100,** 215004 (2008).

Injection at sharp density transition



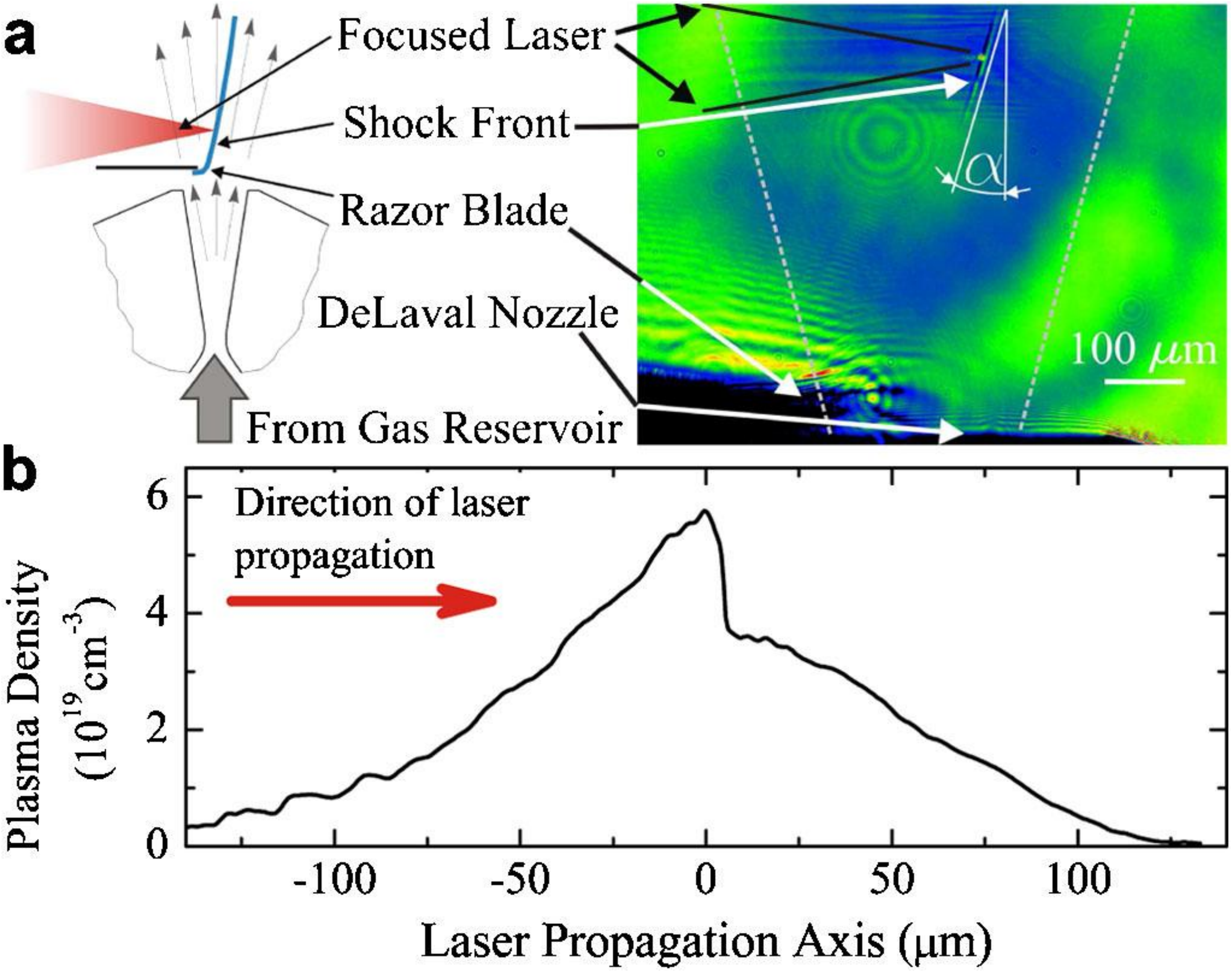
Low intensity laser pulse (a_0~1)
→ no transverse wavebreaking

$$a_0 = \frac{e|\vec{A}|}{m_e c}$$

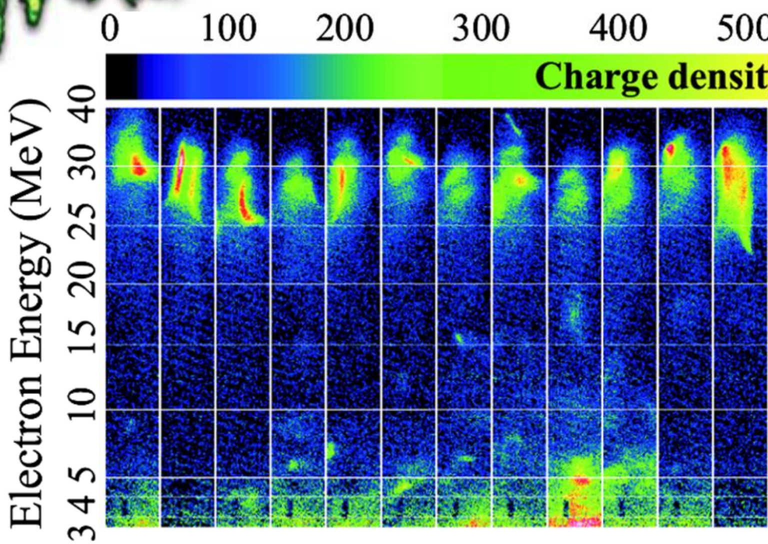
$$\lambda_{p,1} < \lambda_{p,2}$$

$$\lambda_p \propto n_e^{-1/2}$$

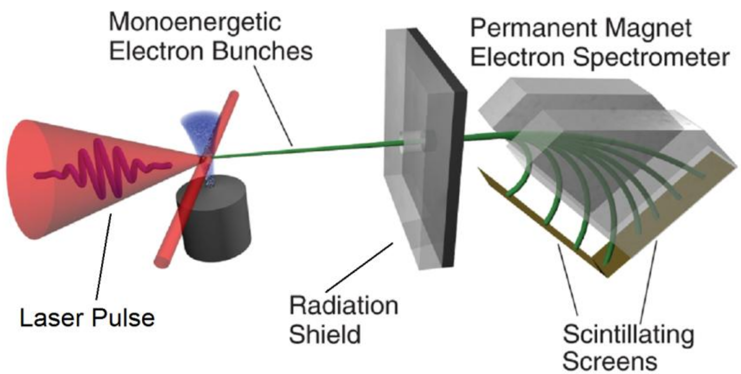
Density transition setup



Stabilized Injection with 8 fs pulses



(a) Self injection



		Best 10 %		Best 10 %
Peak energy (MeV)	26.0±7.4	(29.7±1.2)	23.3±3.2	(24.3±0.9)
Energy Spread (%)	12±9	(8±5)	9±7	(4.0±0.5)
Divergence (mrad)	10.9±3.6	(10.0±2.3)	8.9±3.2	(7.3±0.5)
Charge (pC)	3.7±3.0	(3.1±1.0)	3.3±2.1	(1.8±0.5)

- Injection stabilized
- Important beam parameters improved significantly

K. Schmid *et al.*, PRST-AB **13**, 091301 (2010).

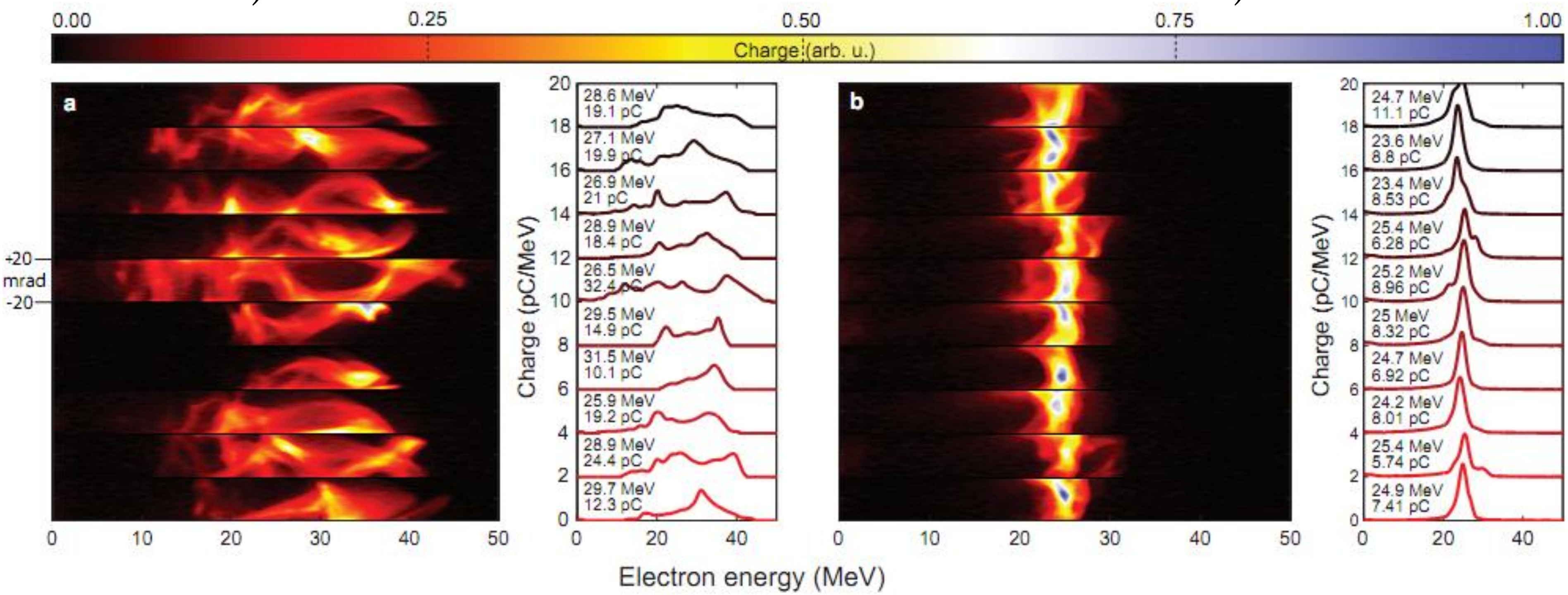
Application to Ti:Sa lasers

- Longer pulses (8 fs → 26 fs)
- More pulse energe (60 mJ → 1 J)
- Higher electron energies, more charge expected

Comparison of injection methods

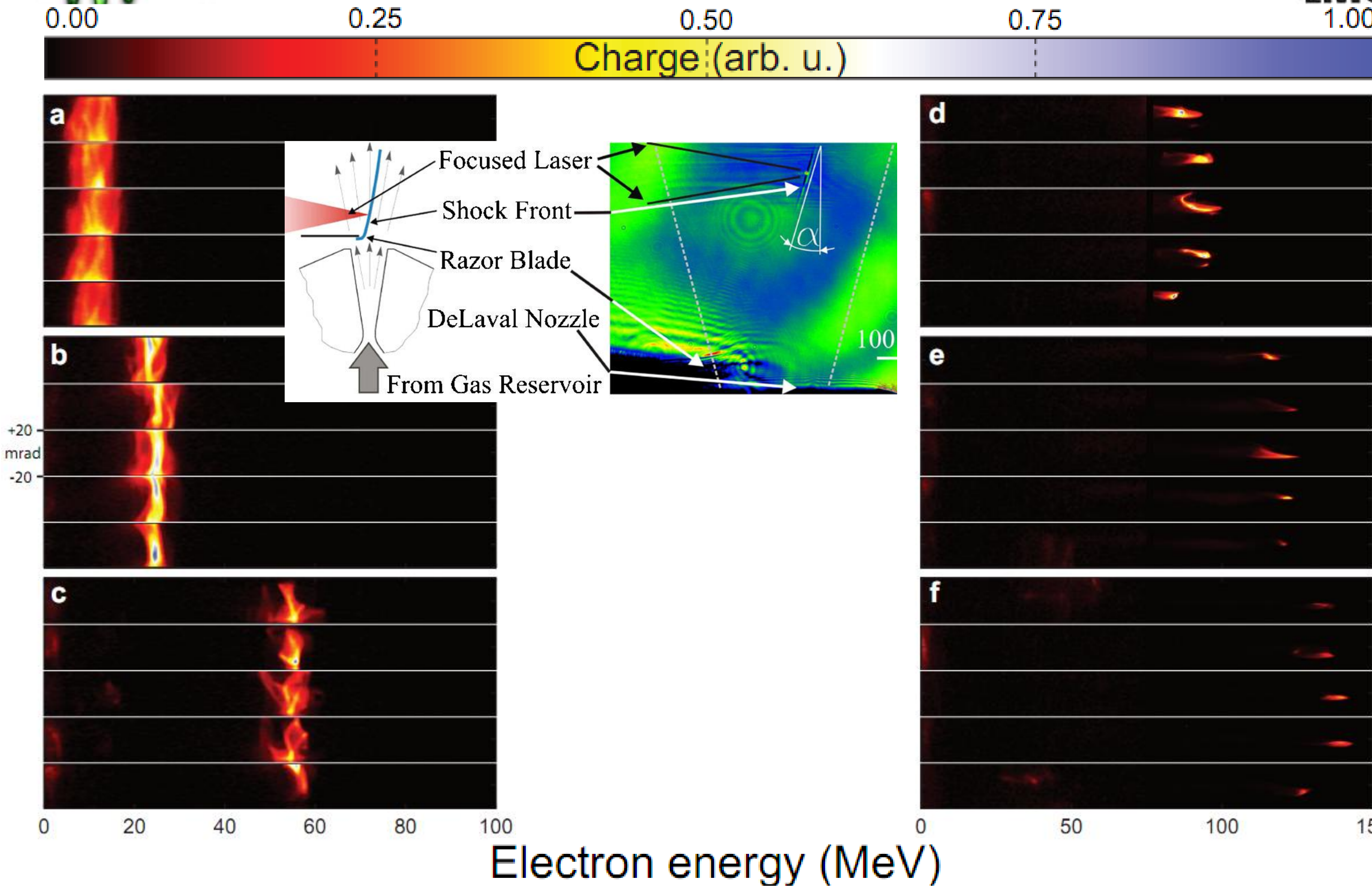
Self-injection

Controlled injection

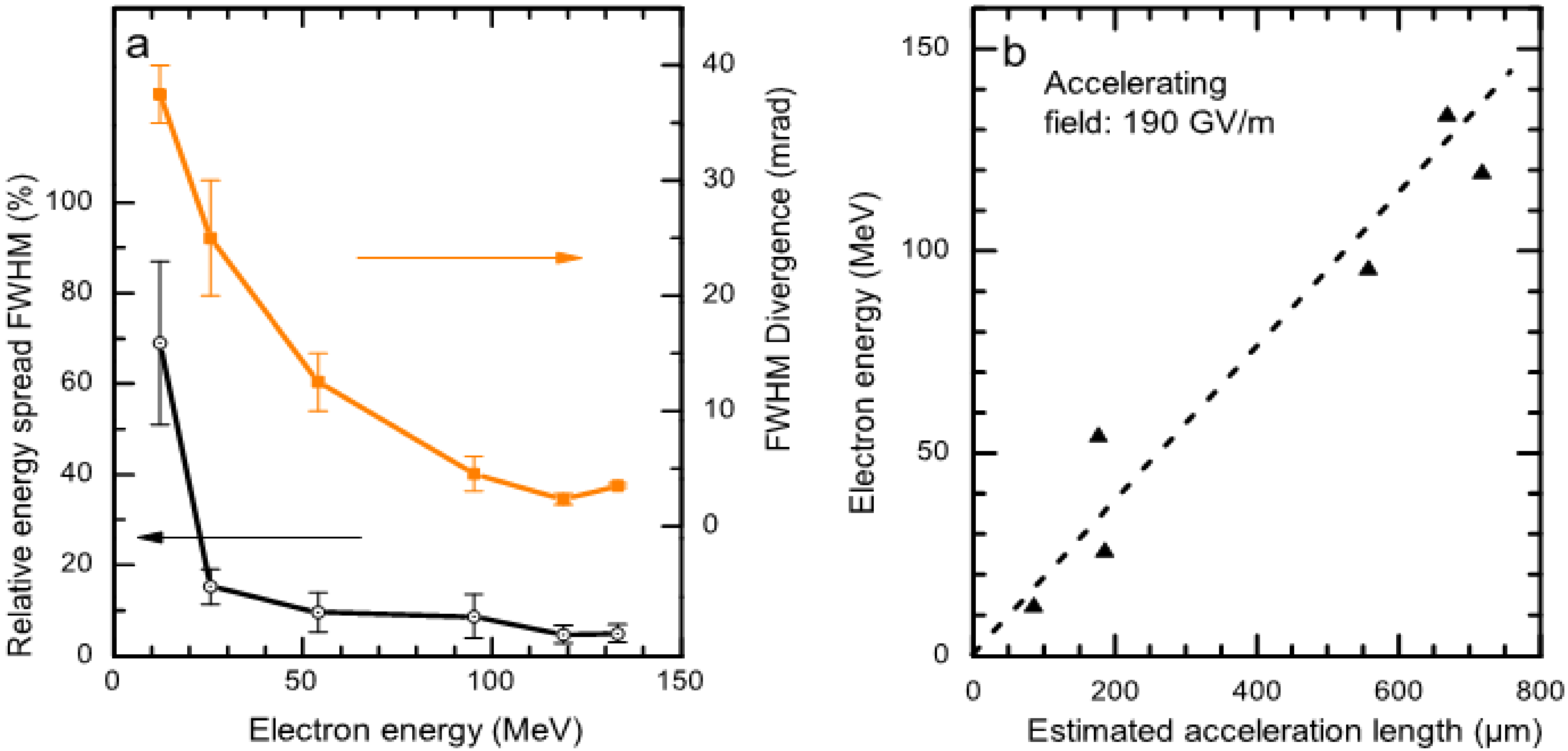


Parameter	Self-injection	Density transition injection
Electron energy (MeV)	28.3 ± 1.7	24.3 ± 0.70
Energy spread FWHM (MeV)	20.6 ± 6.7	3.07 ± 0.65
Charge (pC)	19.2 ± 2.0	8.0 ± 1.5
Divergence FWHM (mrad)	20 – 30	20 – 30
Electron density (cm^{-3})	$1.2 \cdot 10^{19}$	$0.6 \cdot 10^{19}$
Injection probability	93 %	99 %

Tunability of the electron energy



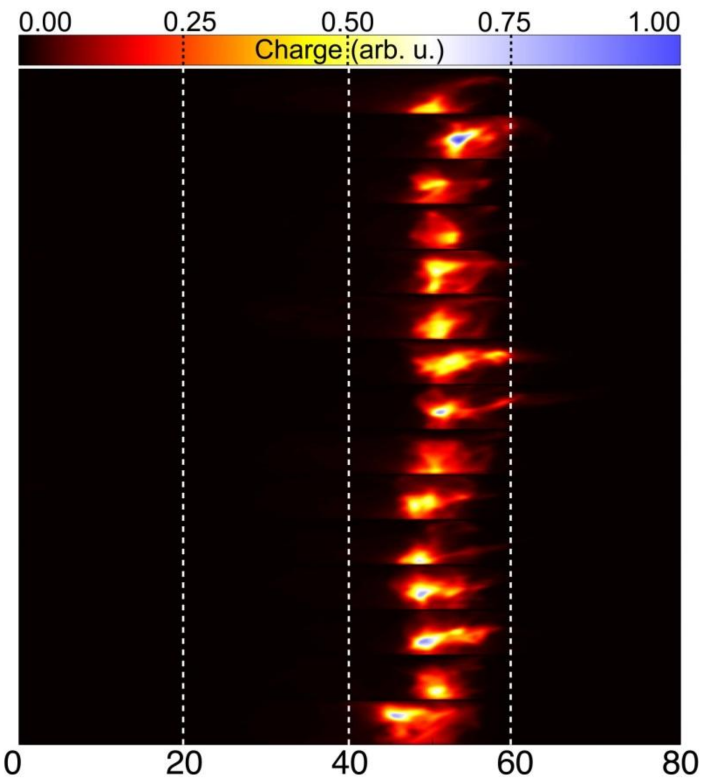
Electron beam properties

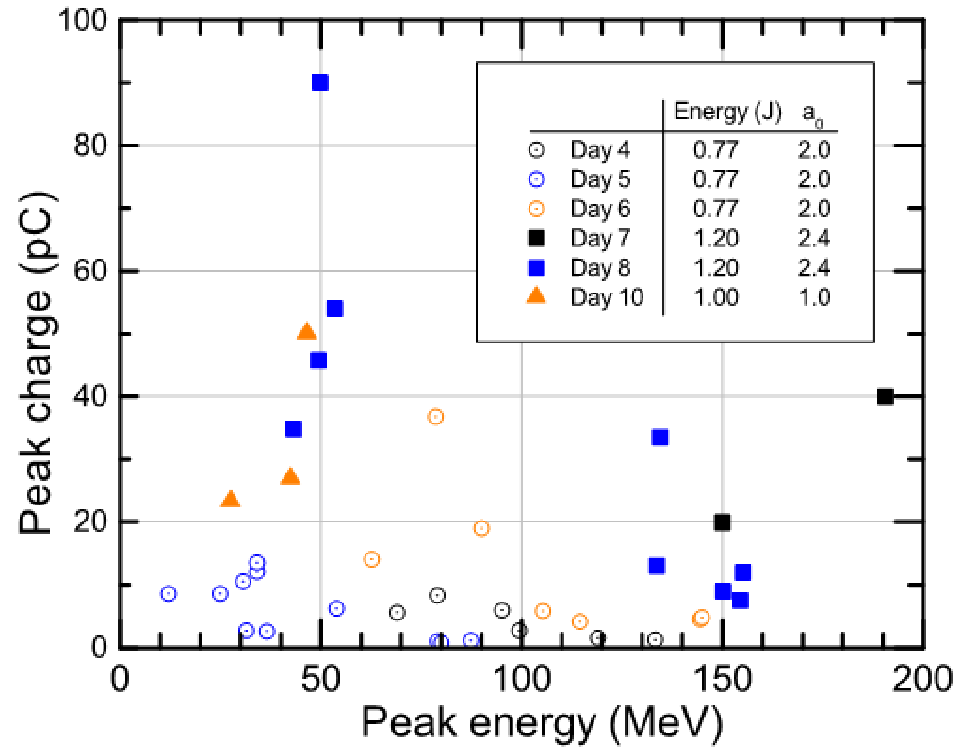


E_{peak} (MeV)	ΔE_{FWHM} (MeV)	$\Delta E/E$ (%)	Q (pC)	Divergence FWHM (mrad)	n_e (cm^{-3})	Nozzle (mm)
12.1 ± 1.3	8.3 ± 2.2	69 ± 18	8.5 ± 4.3	35-40	$2.5 \cdot 10^{18}$	1.0
25.6 ± 1.0	3.9 ± 1.0	15.2 ± 3.9	6.5 ± 2.5	20-30	$6.0 \cdot 10^{18}$	1.0
54.0 ± 1.3	5.2 ± 2.4	9.6 ± 4.4	6.2 ± 2.5	10-15	$5.0 \cdot 10^{18}$	1.0
95.3 ± 4.8	8.3 ± 4.7	8.7 ± 4.9	6.0 ± 3.8	3-6	$2.8 \cdot 10^{18}$	1.5
119.0 ± 4.8	5.6 ± 2.4	4.7 ± 2.0	1.5 ± 0.8	1.8-2.8	$2.7 \cdot 10^{18}$	1.5
133.3 ± 7.2	6.5 ± 2.7	4.9 ± 2.0	1.2 ± 1.0	3.3-3.7	$3.3 \cdot 10^{18}$	1.5

Increased energy and charge

After laser upgrade: 0.8 J → 1.2 J



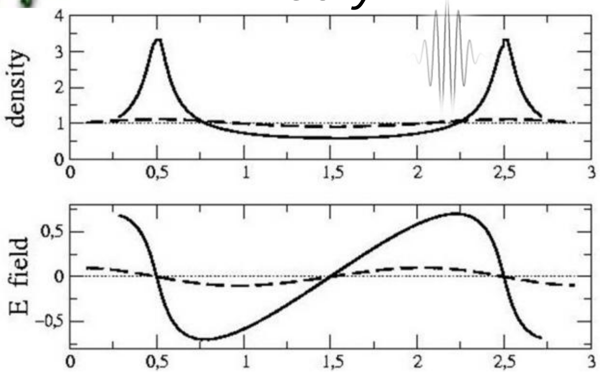


- Peak energy 49.8 +- 2.6 MeV
- Energy spread (FWHM) 10.6 +- 2.8 %
- Charge eval (1/e^2) 95 +- 30 pC

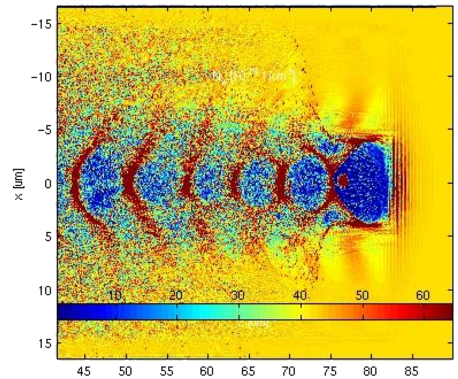
Application:
Thomson scattering
(50 keV photon energy range)

Temporal characterization of laser wakefield acceleration

Theory



(PIC) simulation

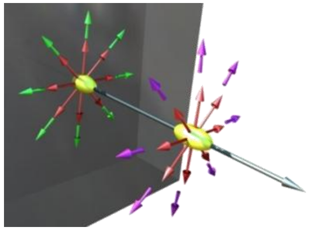


Experiment

?!?

Already measured:

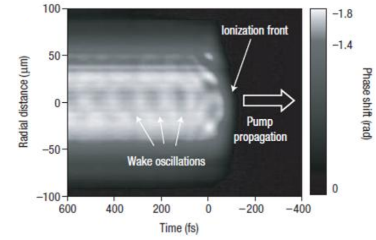
- ➢ Electron pulse duration
  - – Coherent transition radiation (CTR) → indirect
  - – THz, CTR X-correlation with light pulse → few-10-fs resol.



O. Lund *et al. Nature Phys.*, **7**, 219 (2011),
Debus, A. D. *et al. Phys. Rev. Lett.*, **104**, 084802 (2010).
W. P. Leemans *et al.*, Phys. Rev. Lett. **91**, 074802 (2003).
J. van Tilborg *et al.*, Phys. Rev. Lett. **96**, 014801 (2006).

- ➢ Plasma wave structure
  - – Frequency-domain holography → not time-resolved

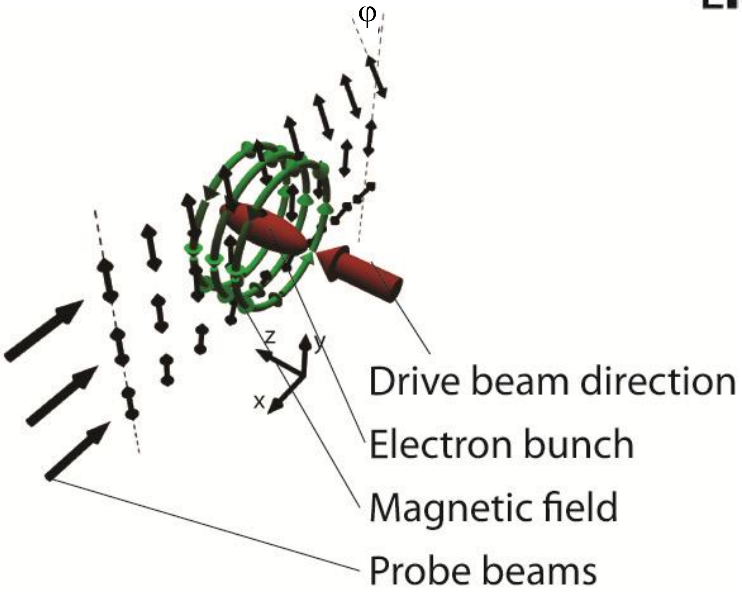
Matlis, N. H. *et al. Nature Phys.*, **2**,749 (2006).



- ➢ **Potentials of a single-shot, time-resolved technique:**
  - – Direct measurement and evolution of electron pulse duration
  - – Dynamical evolution of plasma wave amplitude (info about beamloading)
  - – Moment of wave breaking / electron injection

Faraday effect for LWFA

- Rotation of the laser polarization for linearly polarized probe pulse by the magnetic field
  - $\vec{k}_{\text{probe}} \parallel \vec{B}$
  - Medium: plasma
- Polarization rotation angle:



$$\varphi_{\text{rot}} = \frac{e}{2 m_e c n_c} \int_l n_e \vec{B}_\varphi \cdot d\vec{s}$$

→ Measure φ_{rot} and n_e to get B-field distribution!

Measurement of
- Location of the electron bunch
- Duration of the electron bunch (if resolution high enough)
- Magnetic field → charge

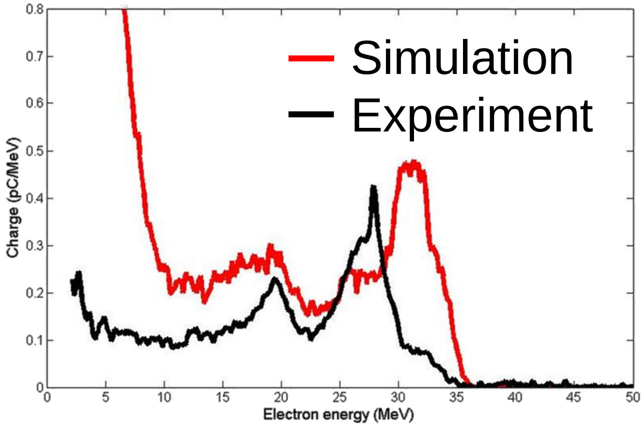
Particle-in-cell (PIC) simulations

Simulation parameters:

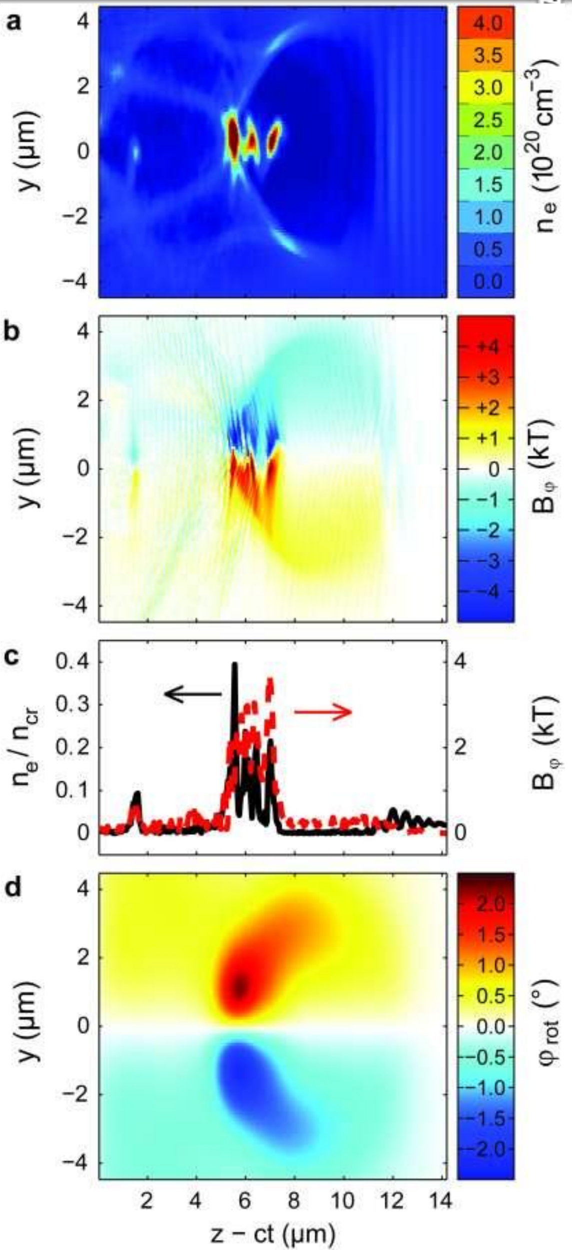
I_{peak}= 5.8 x 10^{18} W/cm^2
w_0 = 6.1 µm
n_0 = 3.5 x 10^{19} cm^{-3}
τ_{pulse} = 8.0 fs (FWHM)
Gas target: 300 µm He

- Magnetic field generated by displacement current is negligible

- Electron pulse length = magnetic field length



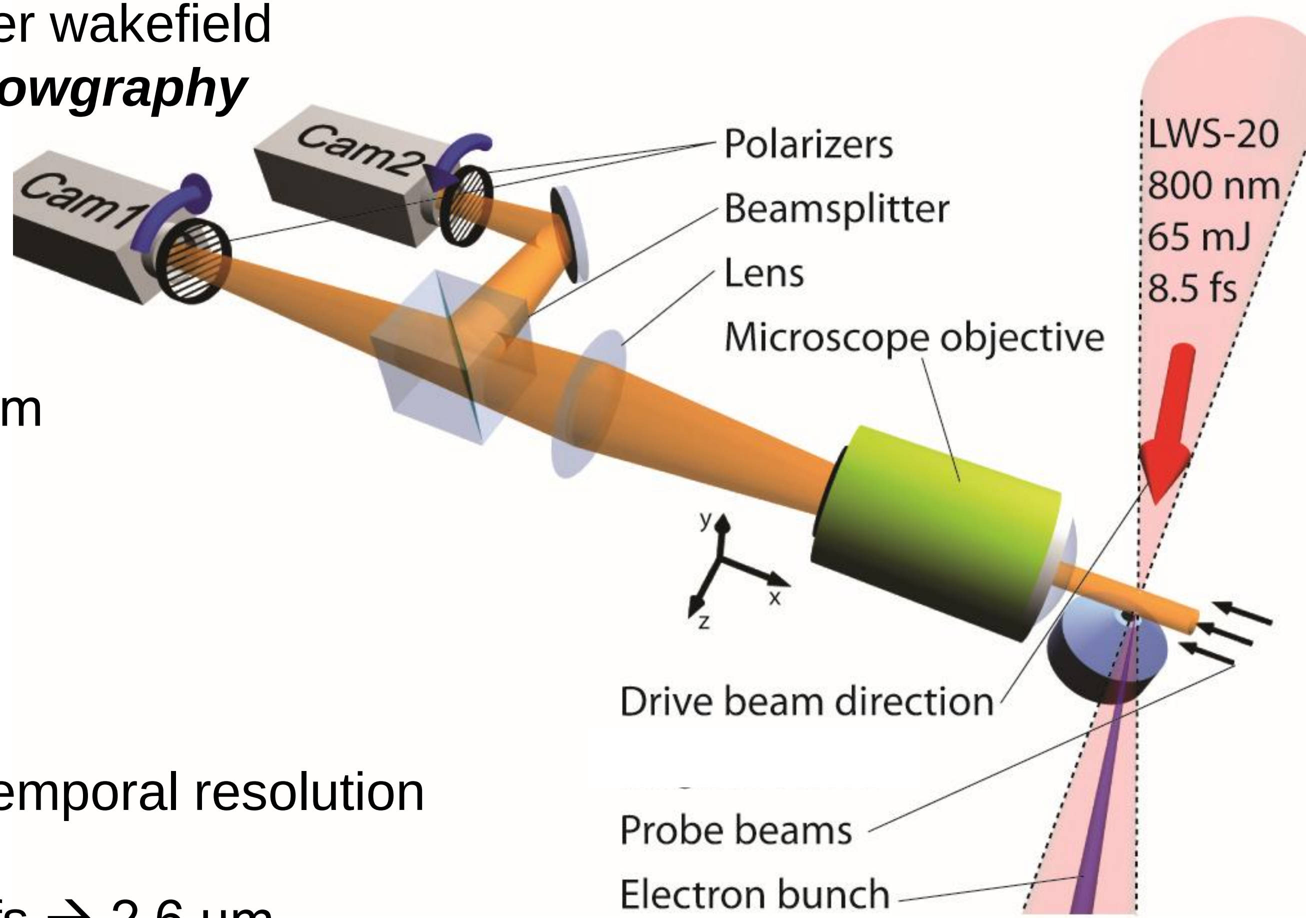
PIC:Code:
ILLUMINATION



M. Geissler *et al.*, *New J. Phys.* **8**,186 (2006).

Experimental setup

Visualization of the laser wakefield acceleration with ***shadowgraphy*** and ***polarimetry***



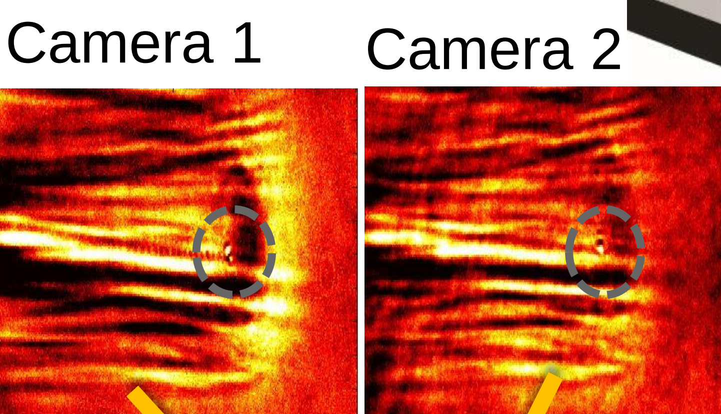
- Expected electron bunch duration:
  <10 fs → < 3 μm
- Plasma wavelength
  ~ 5-10 μm

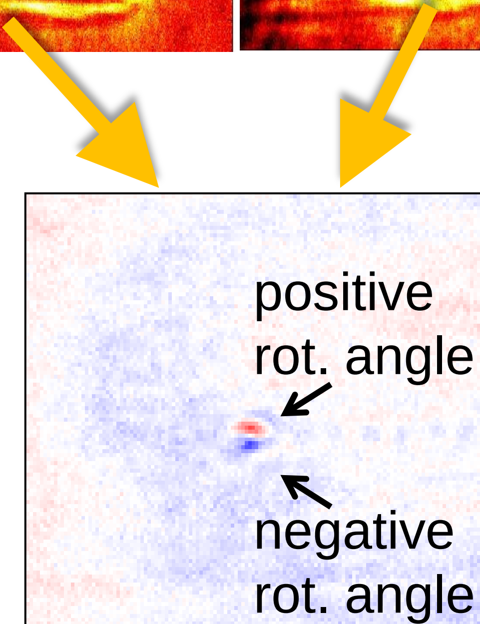
Requirements:

- Good spatial and temporal resolution
  - Spatial: 2 μm
  - Temporal: 8.5 fs → 2.6 μm

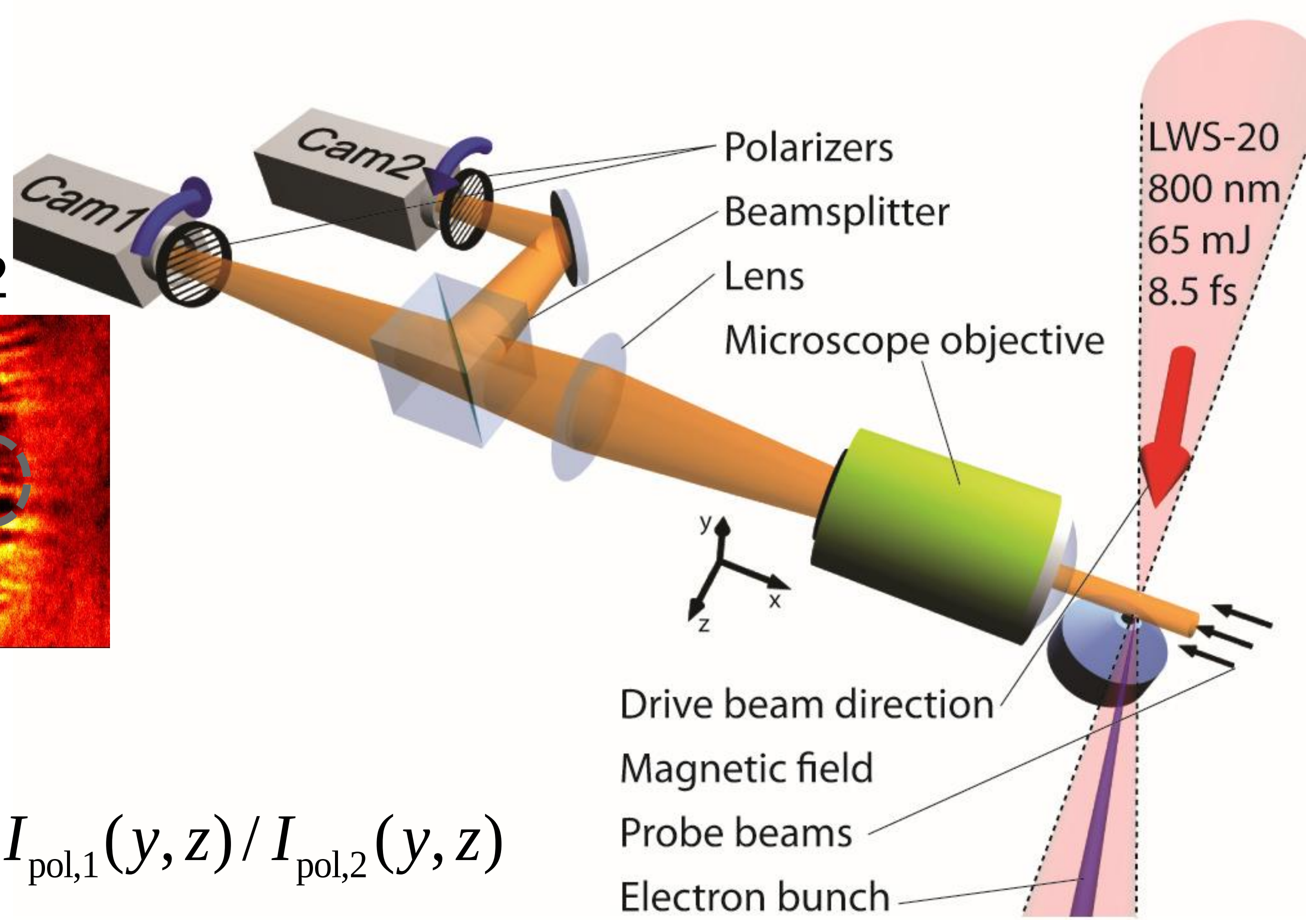
A. Buck *et al. Nature Phys.*, **7**, 543 (2011)

Polarimetry - Determination of the rotation angle





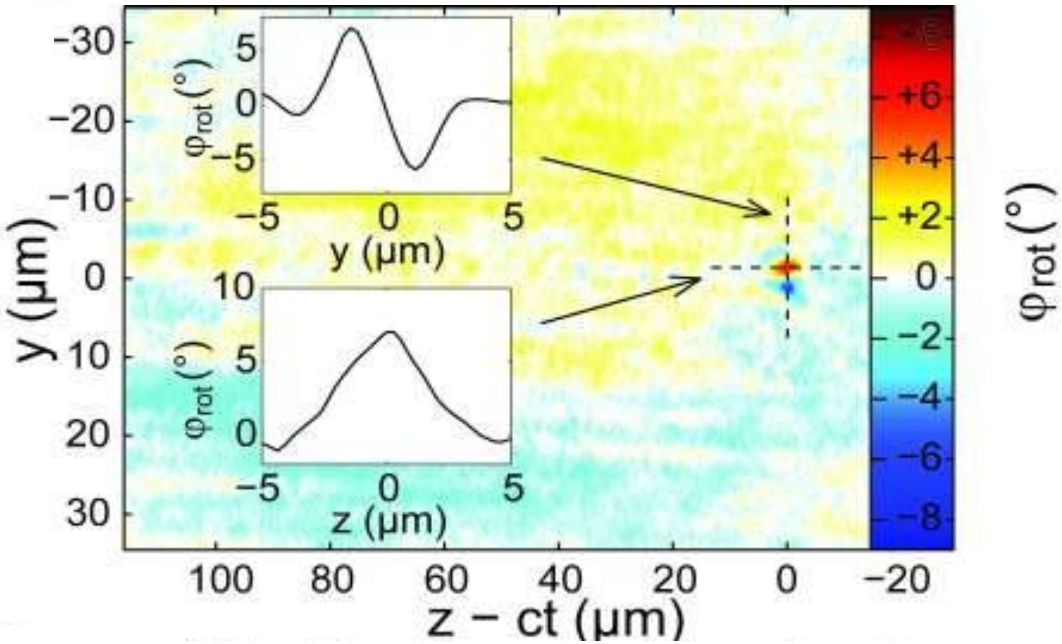
$$I_{\mathrm{pol},1}(y,z)\,/\,I_{\mathrm{pol},2}(y,z)$$



Advantage of detuned polarizers:
→ Correct background subs.
→ Sign of magnetic field

M. Kaluza *et al. Phys. Rev. Lett.*, **105**, 115002 (2011),
A. Buck *et al. Nature Phys.* **7**, 543 (2011)

Faraday Rotation Results



Deconvolution of the electron bunch duration

$\tau_{\mathrm{rot}} = \Delta_{\mathrm{rot}} / c \Rightarrow \tau_{\mathrm{bunch}}$

- τ_{probe}
- $\tau_{\mathrm{res}} = \Delta_{\mathrm{res}} / c$
- $\tau_{\mathrm{transv}} = \Delta_{\mathrm{transv}} / c$

Averaging over 85 shots:

$$\tau_{\mathrm{bunch}} = 5.8^{+1.9}_{-2.1}\,\mathrm{fs}$$

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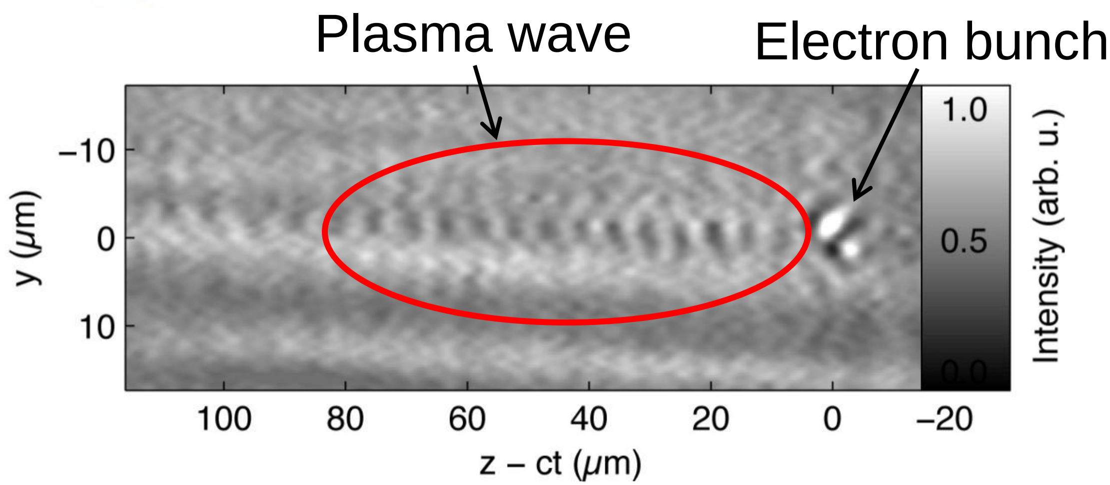
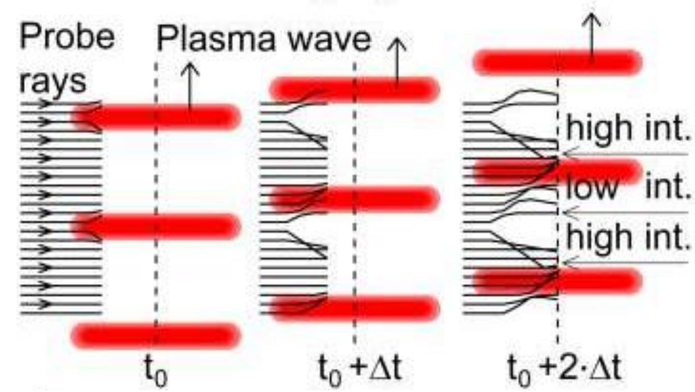
Shadowgraphy



Explanation:



Requirements to see plasma wave:
- Short probe pulse duration
- High-resolution and short depth-of-focus

Conclusions:

- Same period
- Modulation depth ~ plasma wave amplitude
- Pos. of max ~ accel. region

PIC Simulations
+ Ray-tracing

A. Buck *et al. Nature Phys.*, **7**, 543 (2011)

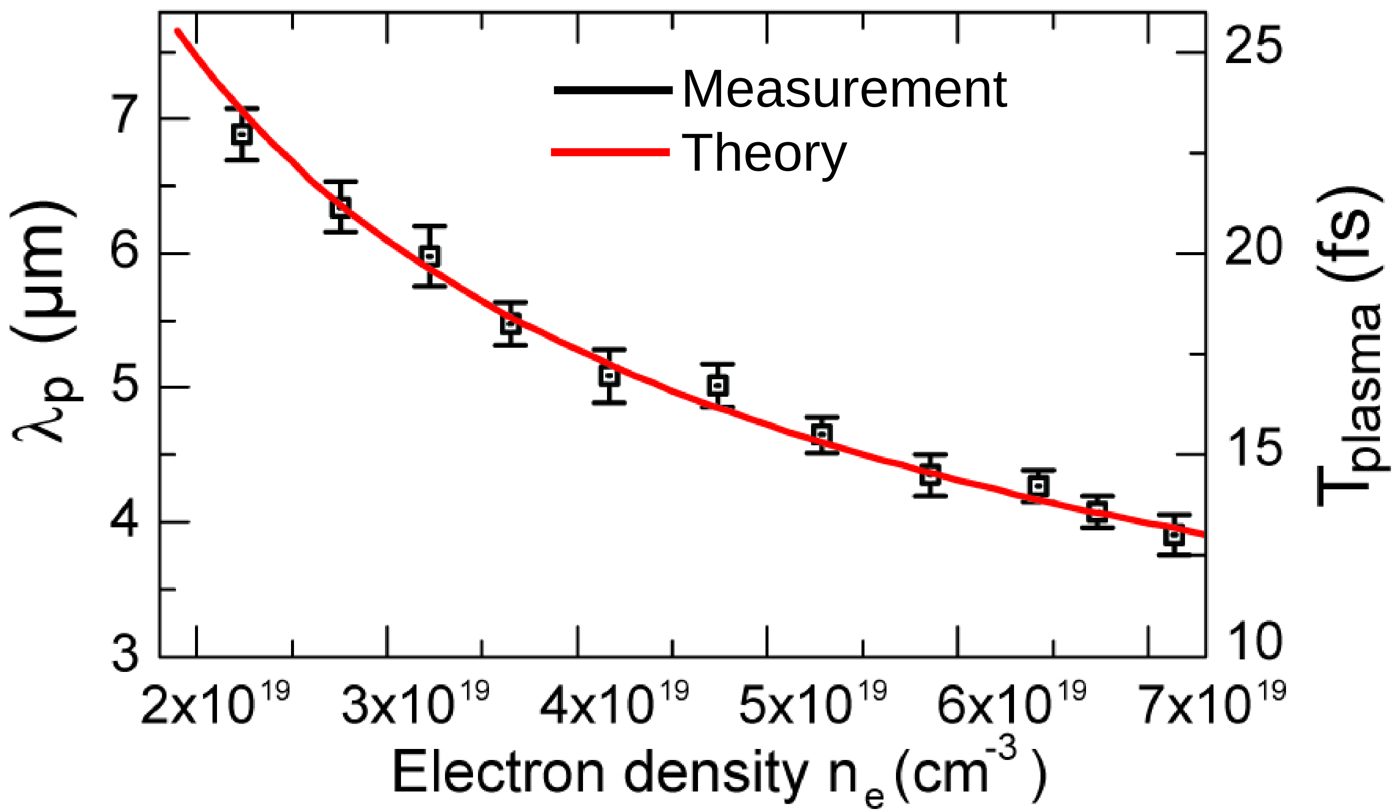
Plasma wavelength

$$T_{plasma} = 2\pi\sqrt{\frac{\varepsilon_0 m_e}{e^2 n_e}}$$

Good agreement with theory.

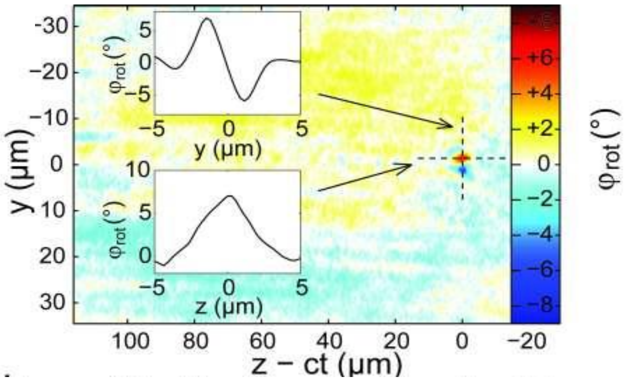
→ Another proof that modulation in fact originates from the plasma wave

→ No relativistic effects at a=1.67

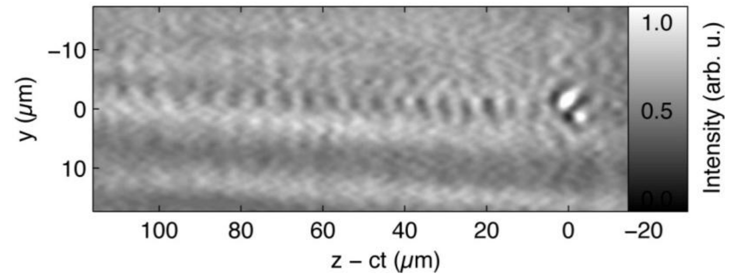


Characterization of the electron bunches + direct temporal observation of LWFA

Polarimetry
(Faraday rotation)



Shadowgraphy



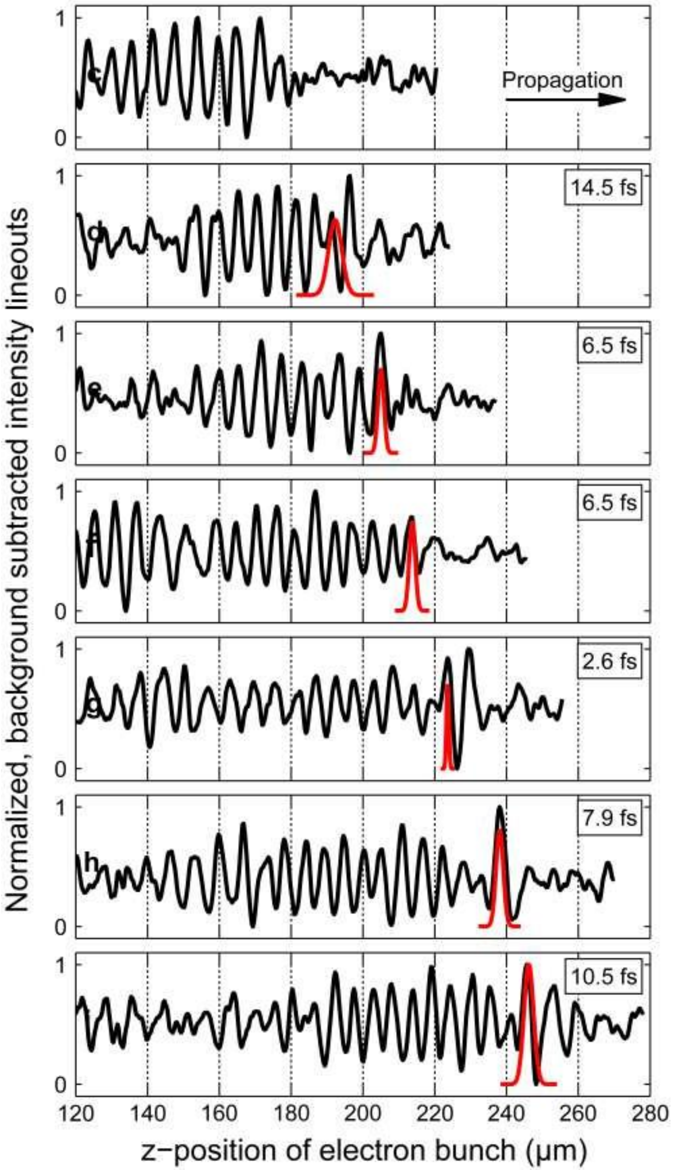
Direct observation of laser-driven electron acceleration with high spatio-temporal resolution

Plasma wave

Electron bunch

A. Buck *et al. Nature Phys.*, **7**, 543 (2011)

Results #1

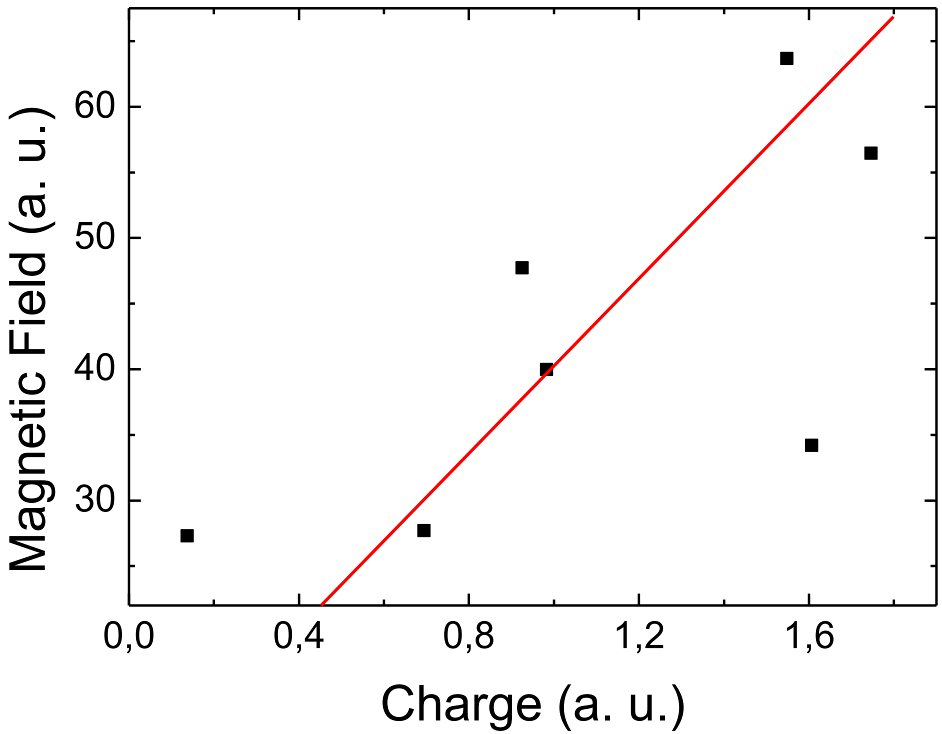


Real-time observation of electron bunch and plasma wave (by changing the delay between pump and probe pulse)

- Electron bunch sits in the first oscillation of the plasma wave
- Only one electron bunch visible
- Many plasma oscillations are visible
→No strong beamloading

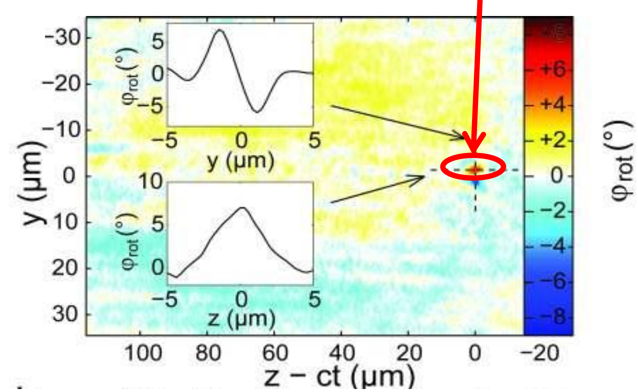
Signal vs. charge correlation and “LWFA movie“

Magnetic field (resolution corrected rotation angle) vs. charge in peak

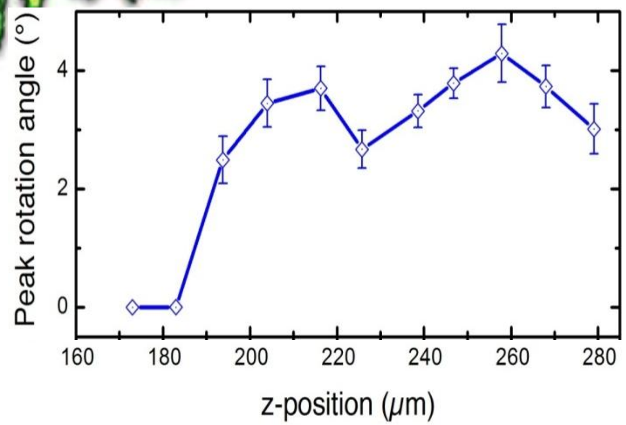


Only few shots were fully in spectrometer to determine charge correctly

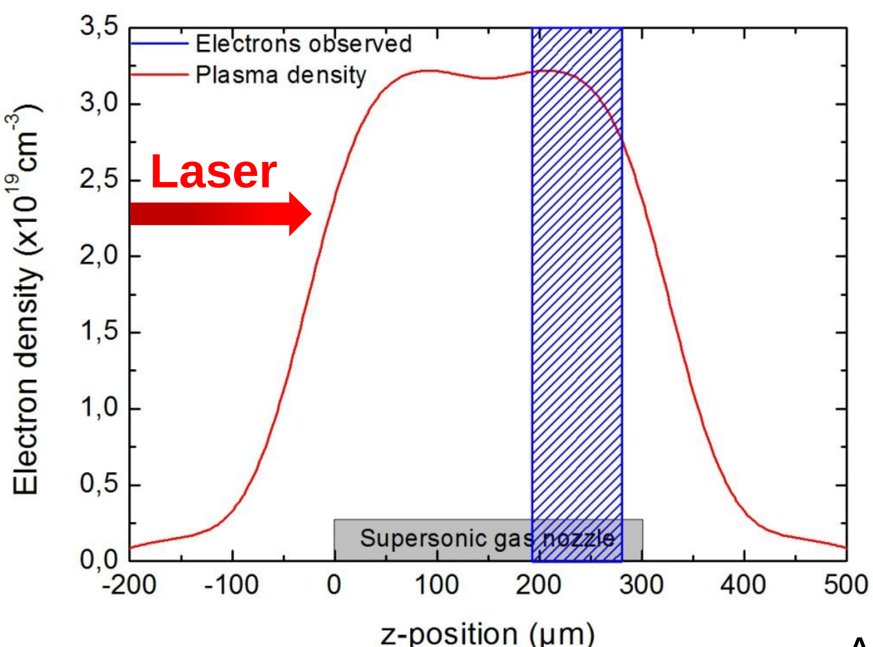
Magnetic field ~ area



Results #2

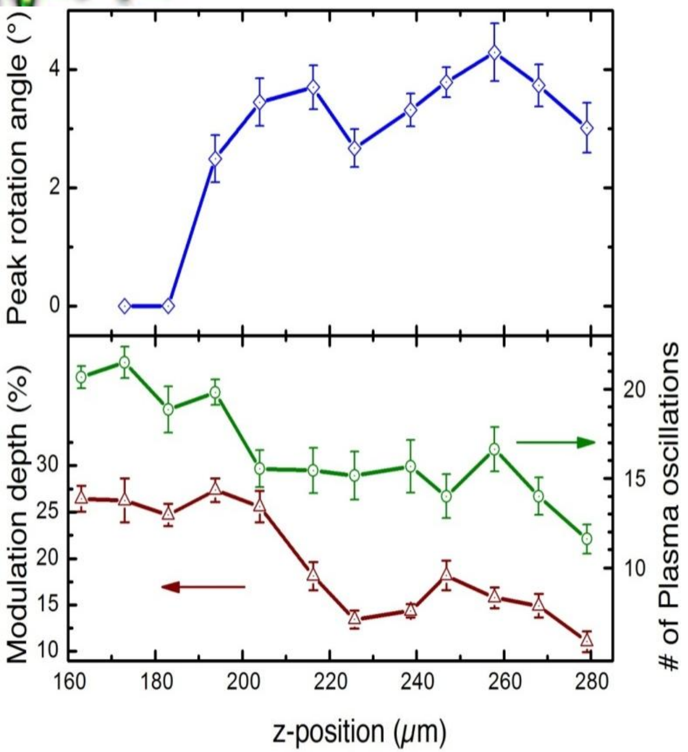


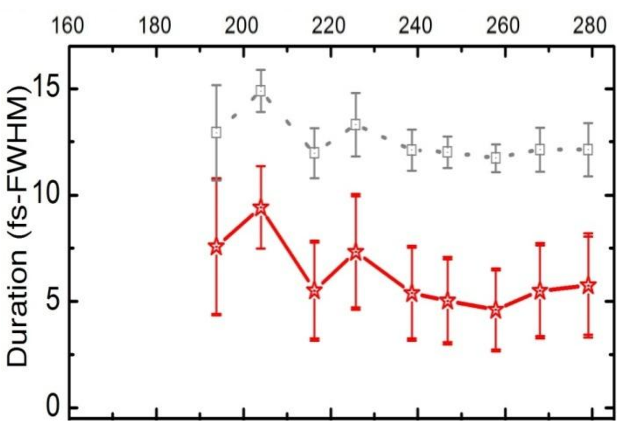
➢Signature of the electron bunch appears after ~200 μm of propagation
→ Injection point



All points in the plot are an average of 4-22 shots.

Results #2





➢Signature of the electron bunch appears after ~200 μm of propagation
→ Injection point

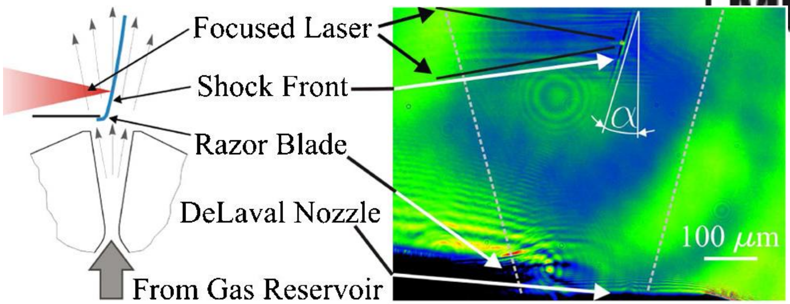
➢Simultaneous decrease of the number of visible plasma oscillations and the amplitude of the plasma wave
→Loading of electrons into the plasma wave

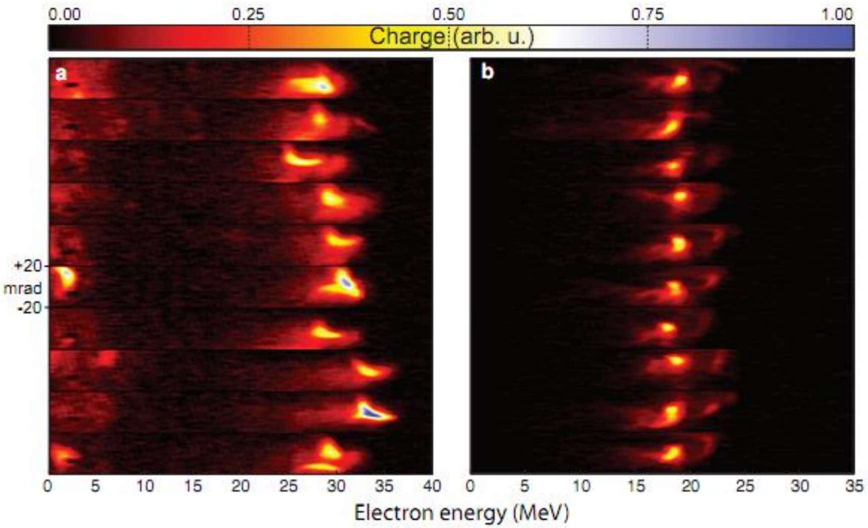
➢Constant rotation angle and bunch duration
→Loading of electrons only around 200 μm

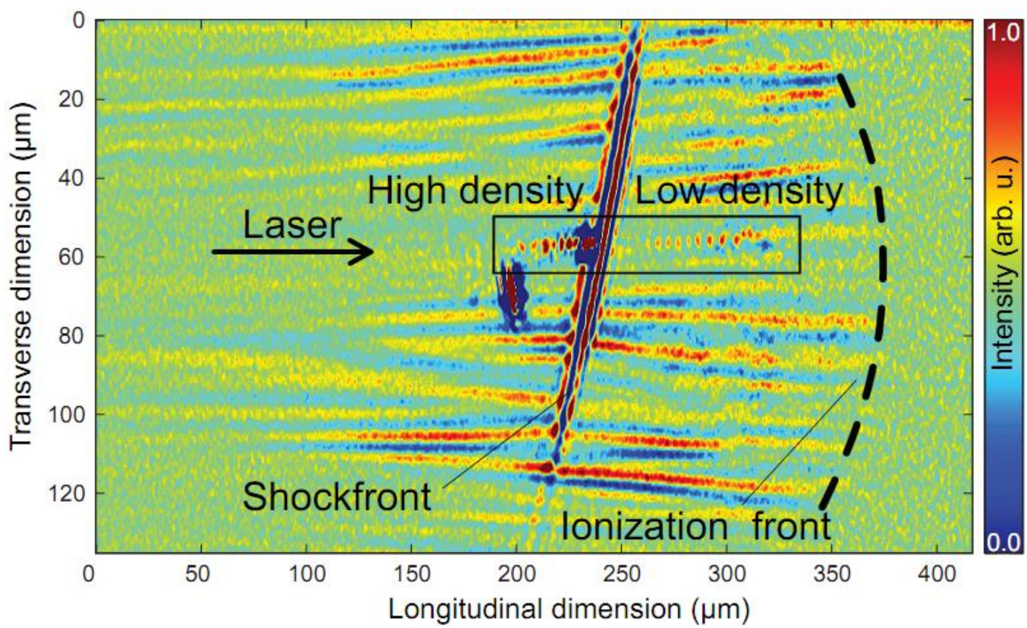
All points in the plots are an average of 4-22 shots.

Combination with controlled injection

Controlled injection
With LWS-20



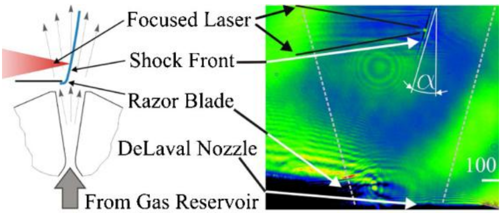




- Diagnostic applicable to other experiments
- Density jump at shockfront could be measured → 1.7 : 1
- Electron signal observed after shockfront with 6 fs duration

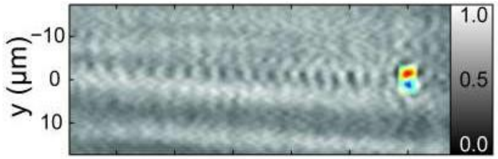
Conclusions and outlook

- Light Wave Synthesizer 20 is a unique tool for laser-plasma physics

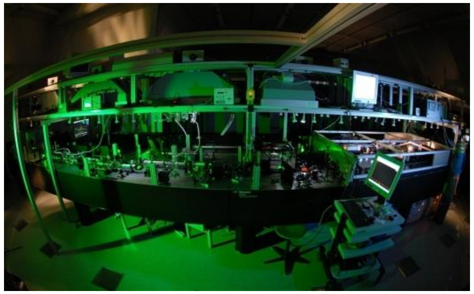


- Shock front injection stabilizes LWFA
- Real-time observation of laser wakefield acceleration (LWFA)

$$\tau_{\text{bunch}} = 5.8^{+1.9}_{-2.1}\,\text{fs}$$



Goals :



- LWS-20 upgrade to 5 fs 100 mJ later 500 mJ
- Geration of intense single attosecond pulses
- Stable few MeV electron bunch production
- Transition from LWFA to bubble / blow out regime

Thank you for your attention !

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