Science and Techniques of Ultra-Fast Electron and Photon Sources ...

... the laser-driven approach

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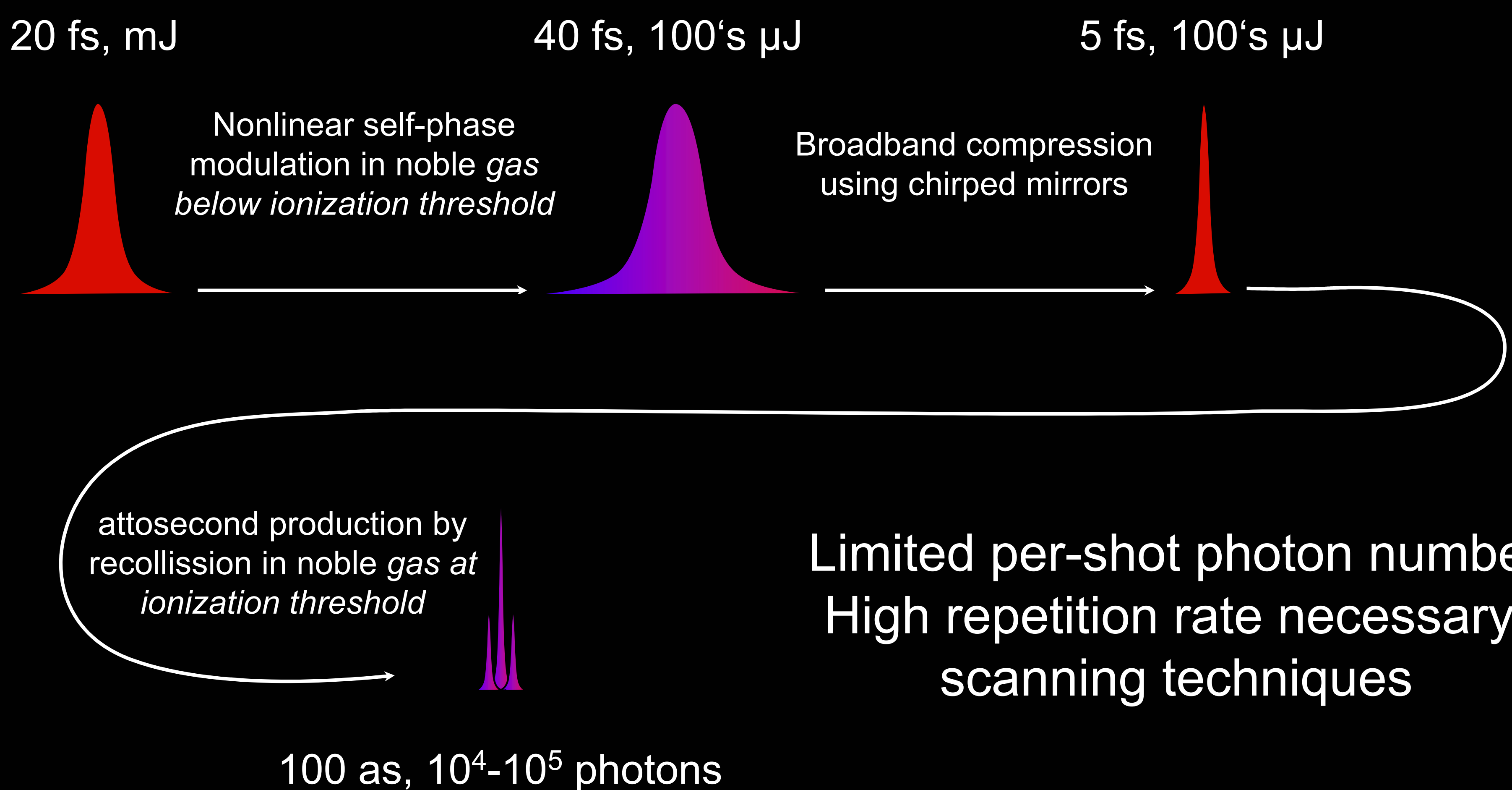
PAC 09, Vancouver, May 8, 2009

OUTLINE

- Attosecond sources - state of the art
- Detour - ultra-high intensity lasers
- New approaches to high-intensity few-femtosecond and attosecond sources

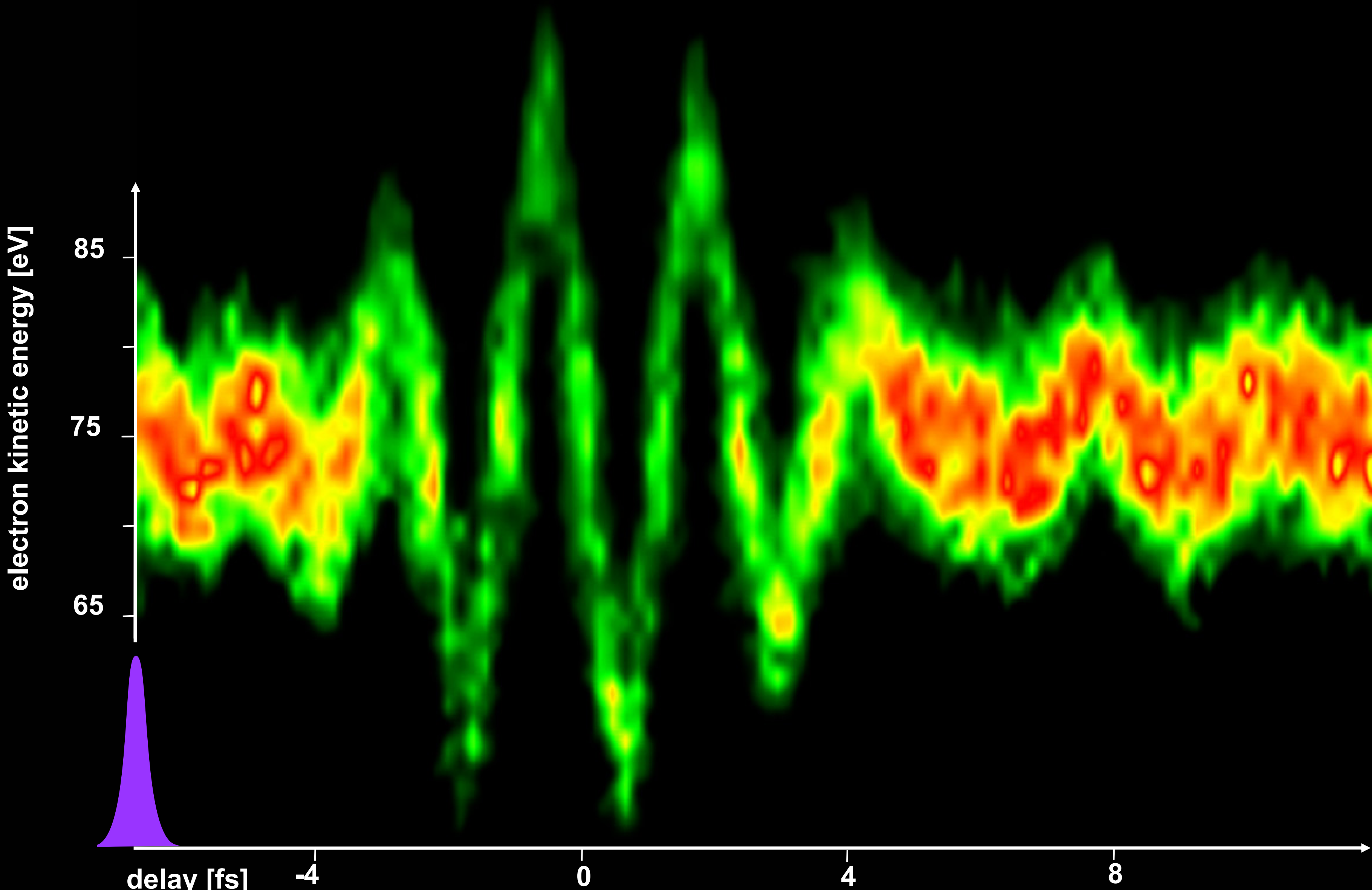
➡ relativistic high-harmonic generation
➡ ultrashort electron beams
➡ undulator and FEL radiation

Standard technology limits for XUV intensity



Limited per-shot photon number
High repetition rate necessary, scanning techniques

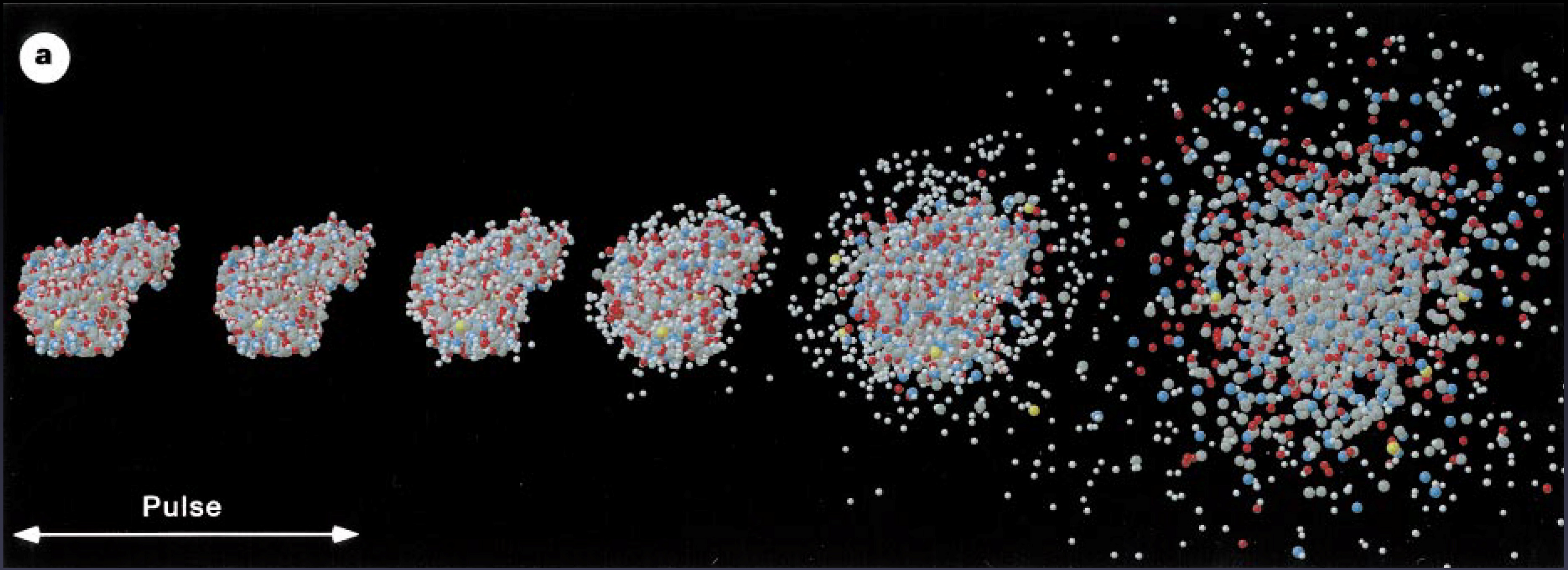
experimental evidence for the existence of a single sub-femtosecond xuv pulse and for the sampling of light waves in real time



E. Goulielmakis *et al*, *Science* ***305***, 1267 (2004)

Single Molecule imaging:Coulomb explosion of a protein molecule

Lysozyme with 137 structural waters



t =-2fs *t* =2fs *t* =5fs *t* =10fs *t* =20fs *t* =50fs

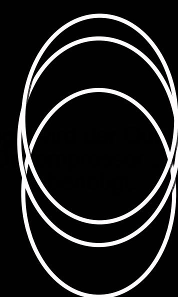
Freezing of atomic motion by short exposure time

↓

XFEL pulses with 10^{12} photons in <10 fs are highly desirable

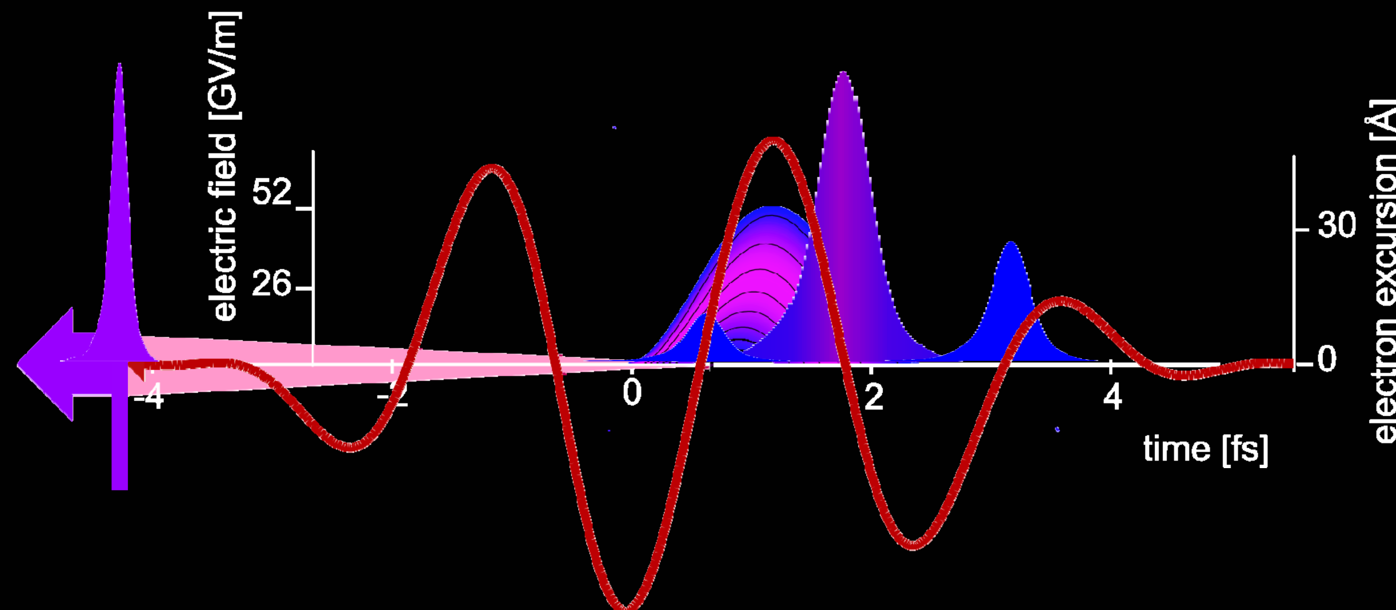
Neutze, R., Wouts, R., van der Spoel, D., Weckert, E. Hajdu, J., *Nature 406*, 752 (2000)

steering bound electrons with controlled light fields:
the birth of an attosecond pulse

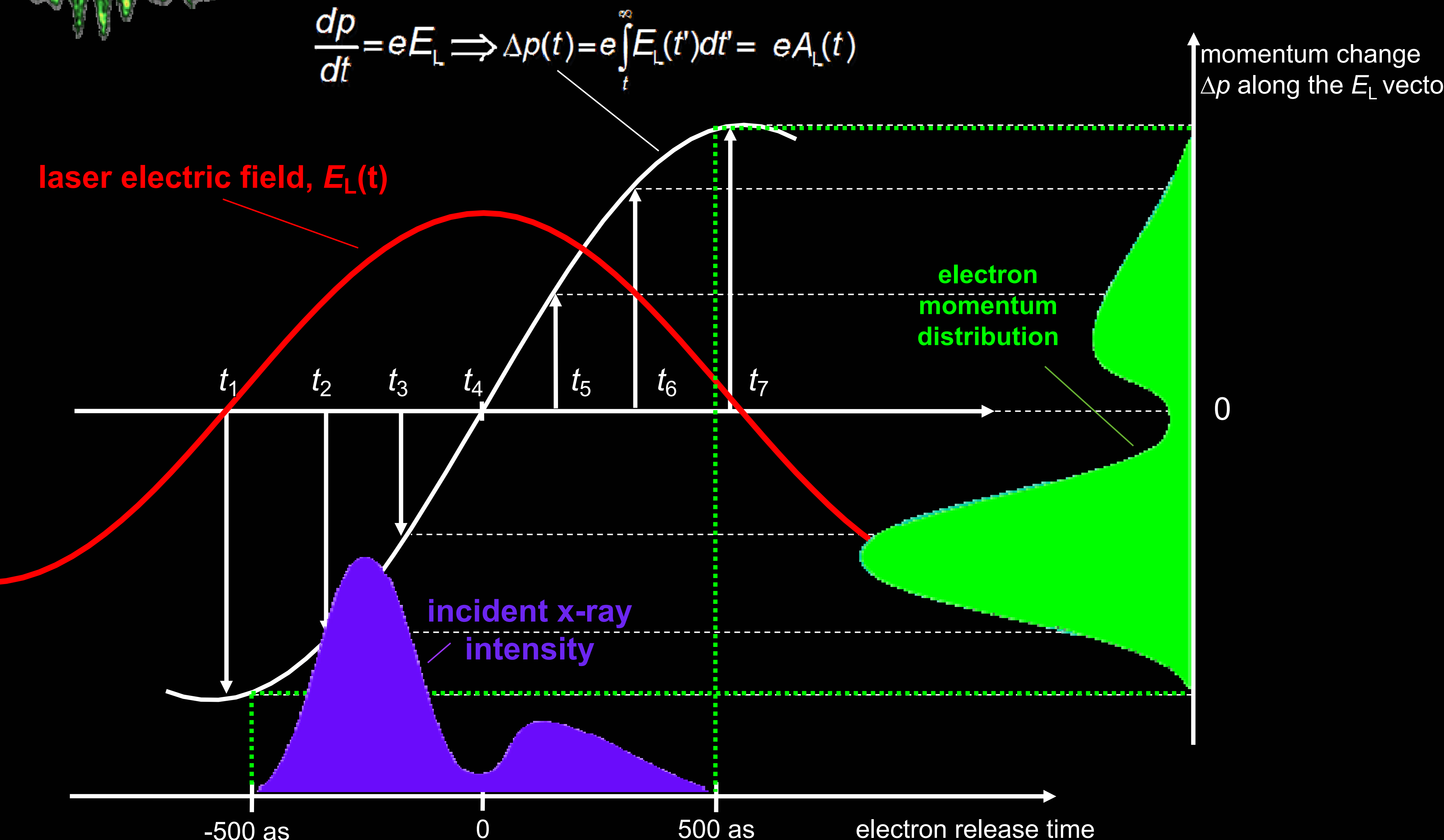


3D-solution of the Schrödinger equation for hydrogen: Armin Scrinzi
animation: Barbara Ferus, Matthias Uiberacker

electrons released and returning within the central wave cycle of a near-single-cycle light wave recollide with highest energy and produce an isolated sub-fs pulse at the highest photon energies emitted



steering freed electrons with controlled light fields: the measurement of an attosecond pulse

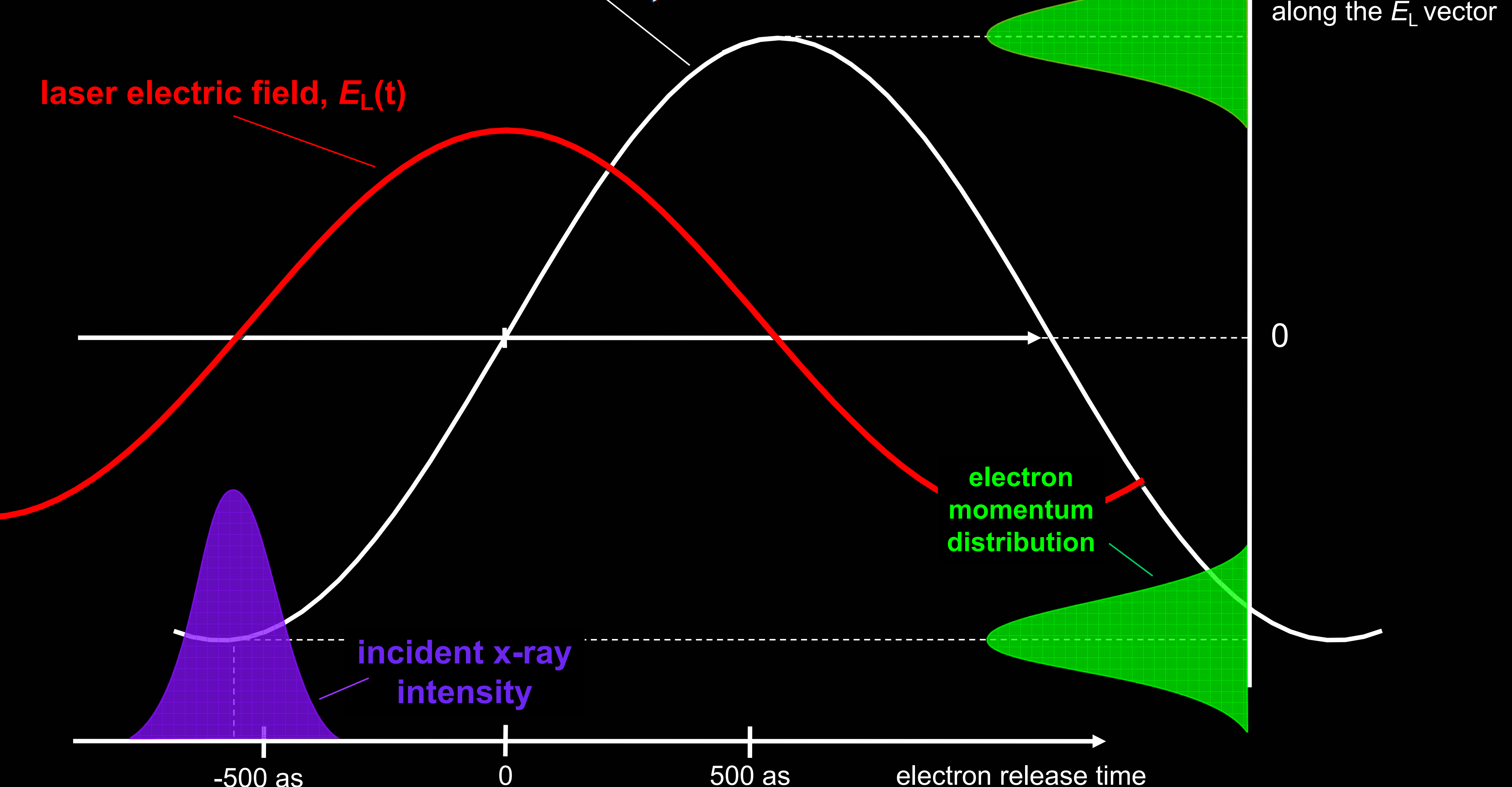


optical-field-driven streak camera

Drescher *et al*, *Science* ***291***, 1923 (2001)
J. Itatani *et al*, *PRL* ***88***, 173903 (2002)
M. Kitzler *et al*, *PRL* ***88***, 173904 (2002)

steering freed electrons with controlled light fields: the measurement of an attosecond pulse

$$\frac{dp}{dt}=eE_L \Longrightarrow \Delta p(t)=e\int_t^{\infty}E_L(t')dt'= eA_L(t)$$



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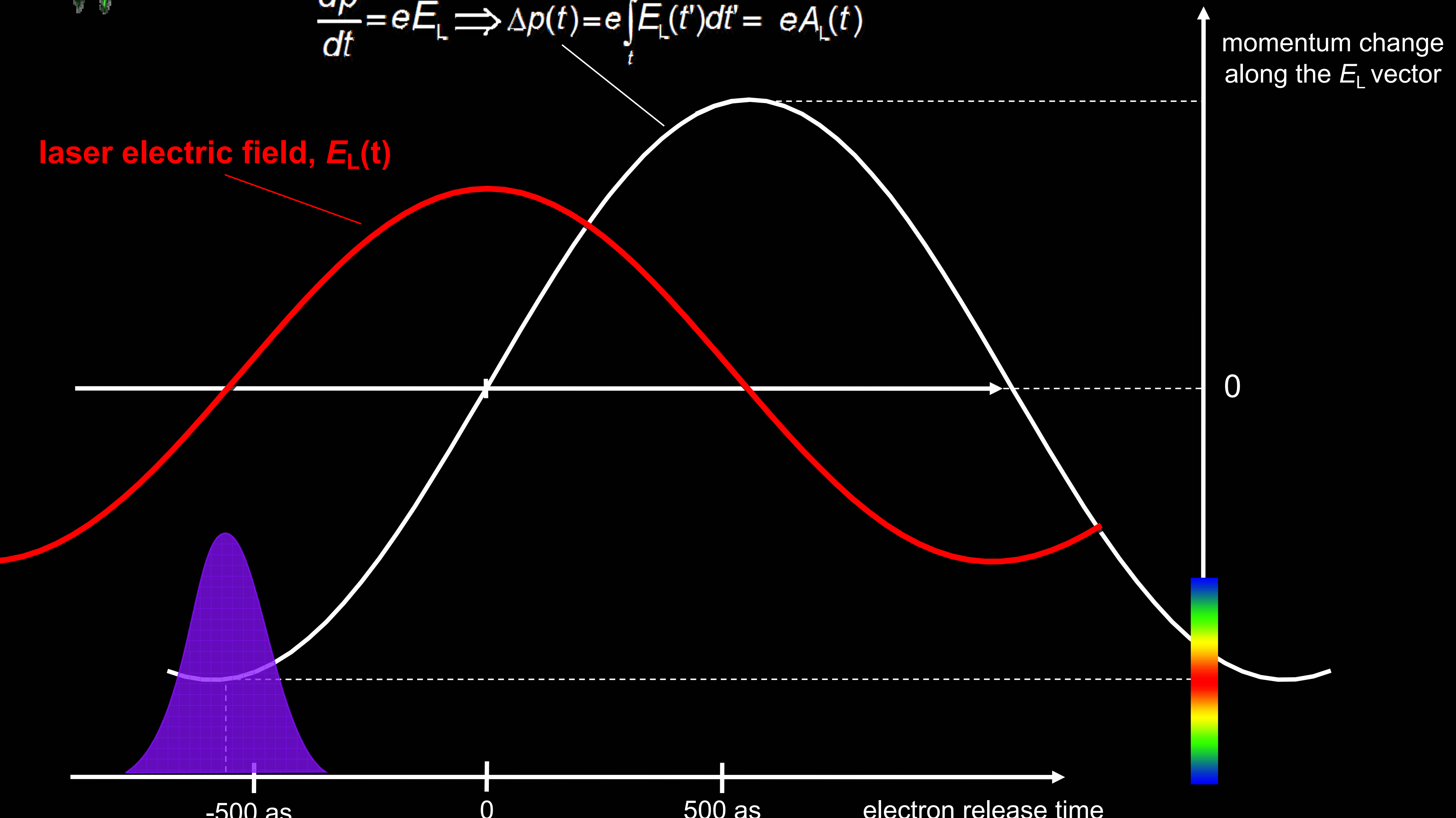

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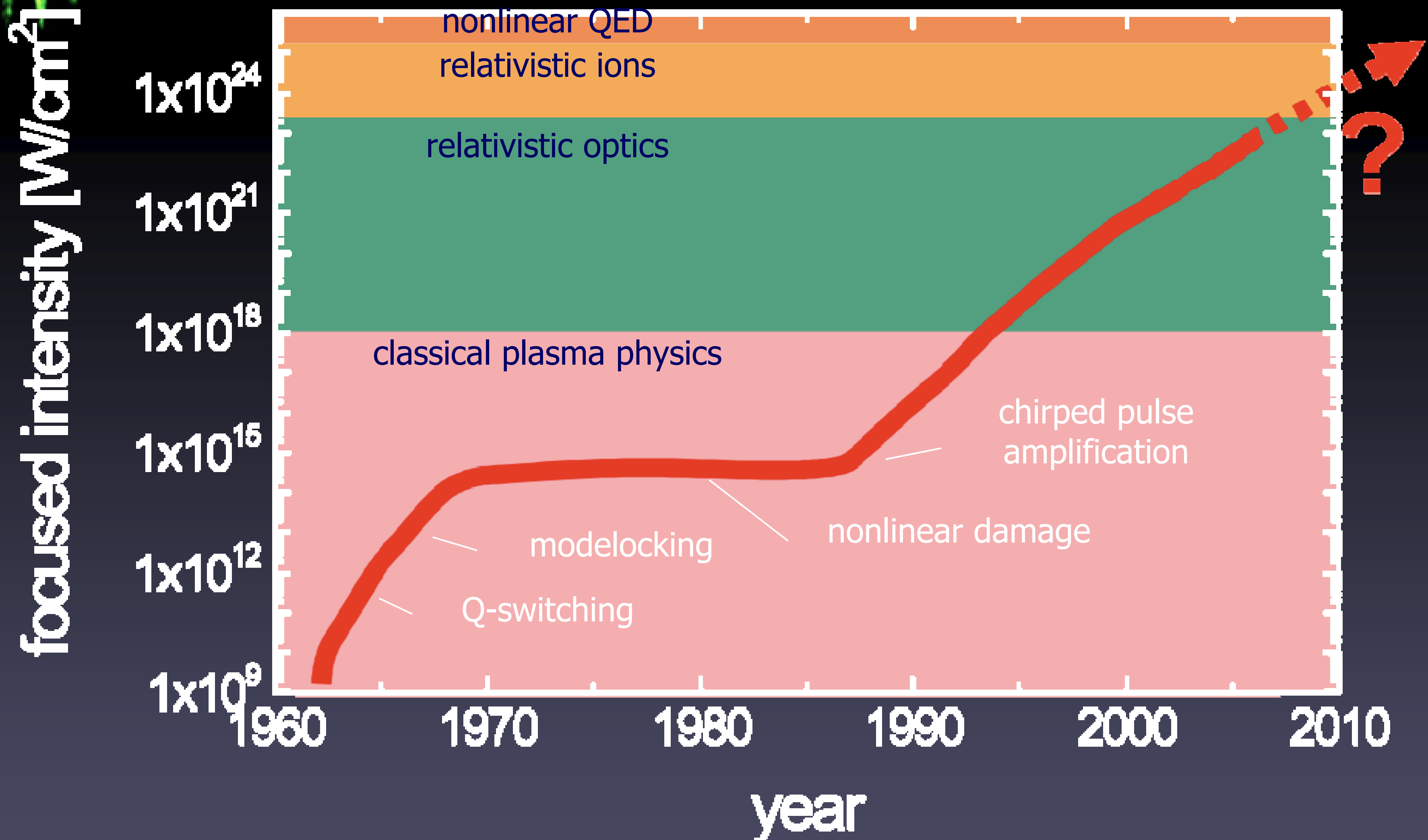
historical development of delivered laser intensities



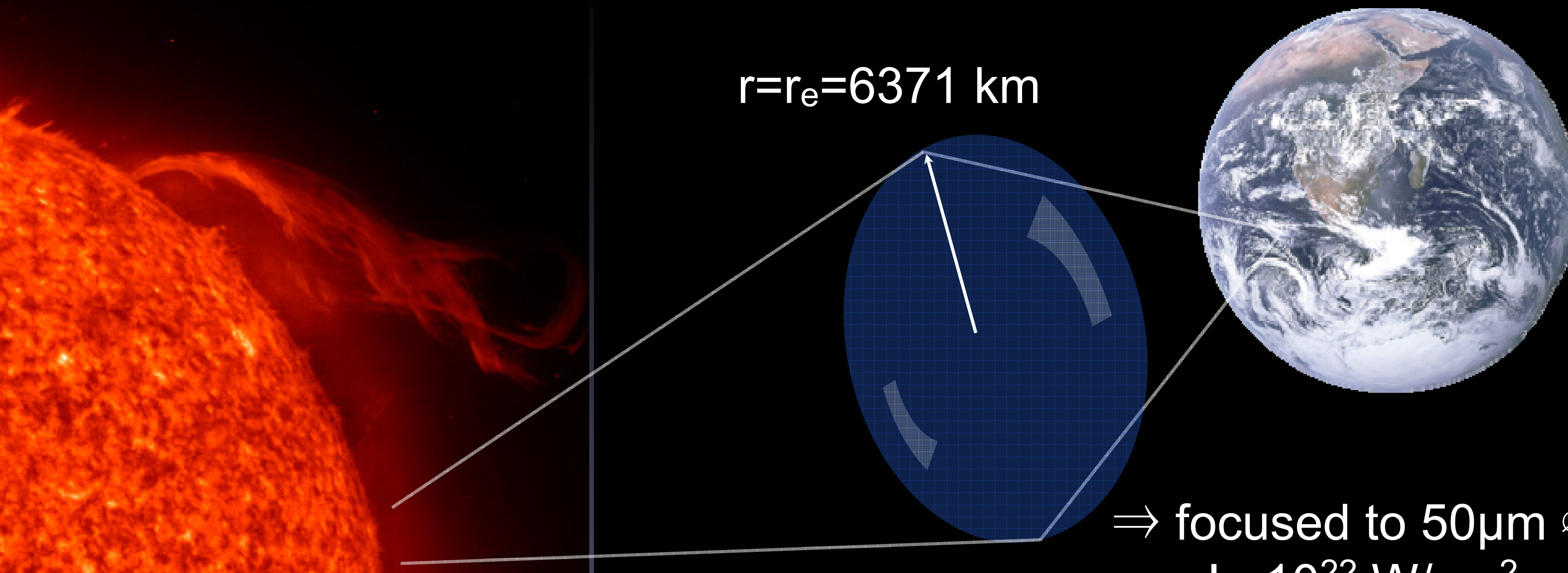
Necessary laser power:

Focusing to 3 µm x 3 µm: P = 1 PW for 10^{22} W/cm^2

How to generate 10^{22} W/cm^2

Images: NASA/Apollo 17
MPI f. Astronomie

solar constant:
1367 W/m^2



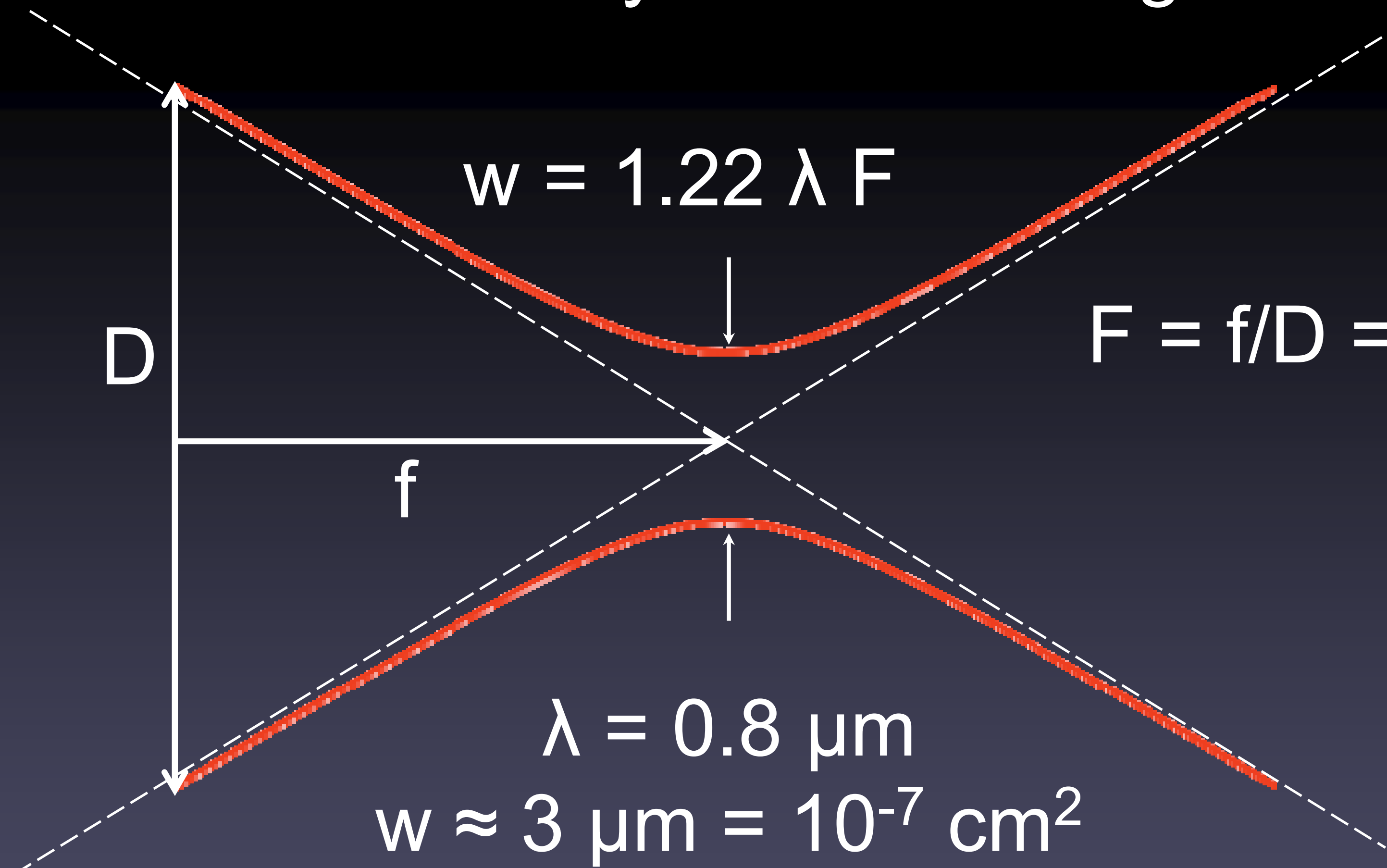
$\Rightarrow$ focused to 50μm ∅:
$I = 10^{22}$ W/cm^2

total radiation power hitting the earth: 1.7×10^{17} W

lens: focal length 17 mm, diameter=12700 km...

or: using lasers

focusability of coherent light:



$F = f/D = O(1..10)$

for 10^{22} W/cm^2 one needs 10^{15} W = 1PW!

1 PW?

picture: AP

10^6 x

Atomic power plant:
10^9 W

1 PW continuously is obviously hard to realize...

expensive

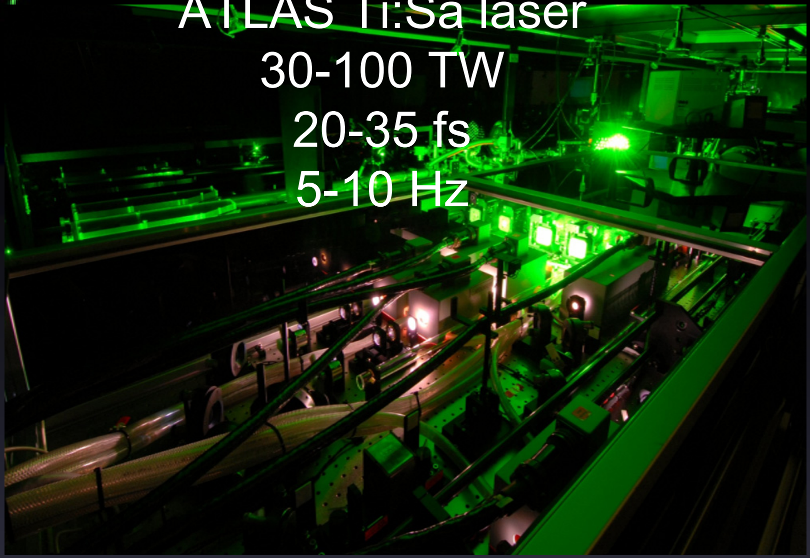
pulsed laser:

$$P = \frac{\Delta W}{\Delta t} = \frac{20J}{20fs} = 1PW$$

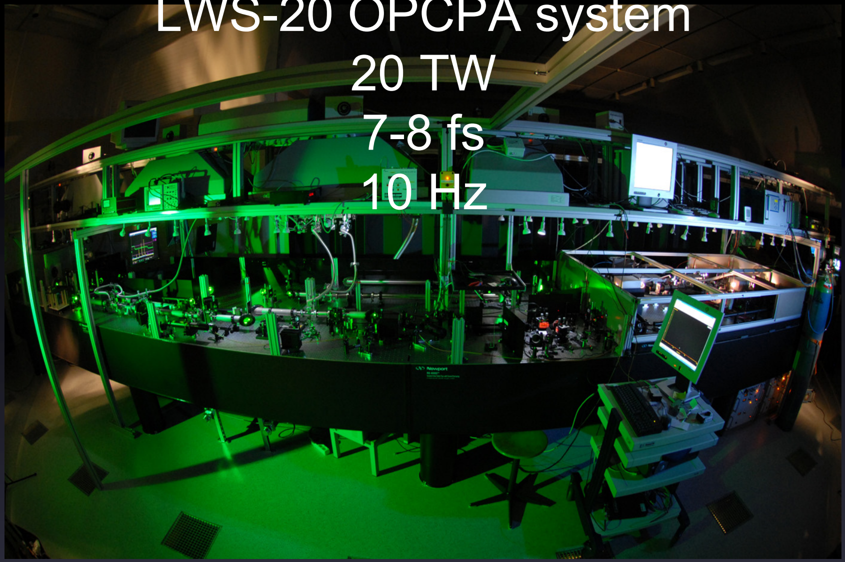
limited by laser material

Our Laser Suite

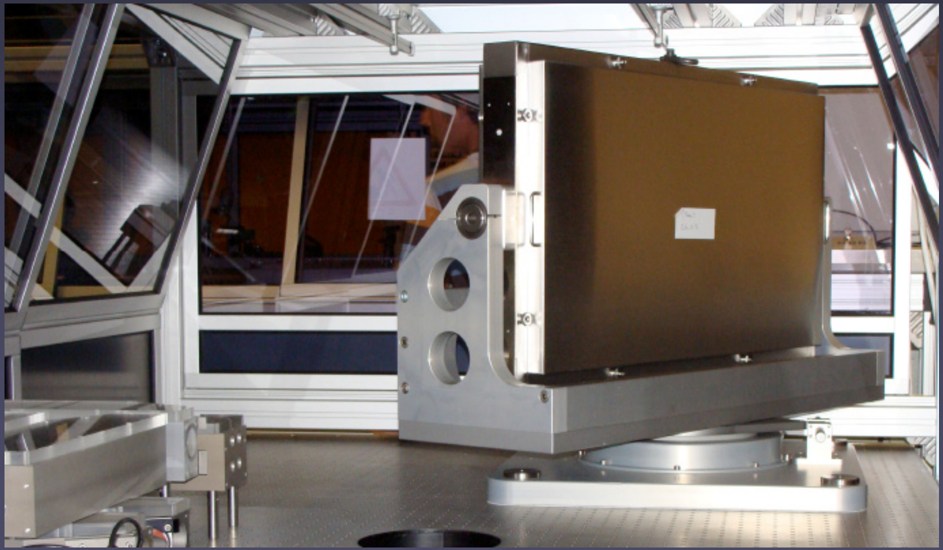
ATLAS Ti:Sa laser
30-100 TW
20-35 fs
5-10 Hz



LWS-20 OPCPA system
20 TW
7-8 fs
10 Hz



etawatt Field Synthesizer (PFS)
OPCPA system
5 fs, >500 TW
1-10 Hz



Strength of light fields

energy flux (Poynting vector) $\vec{S} = \epsilon_0 c^2 (\vec{E} \times \vec{B})$

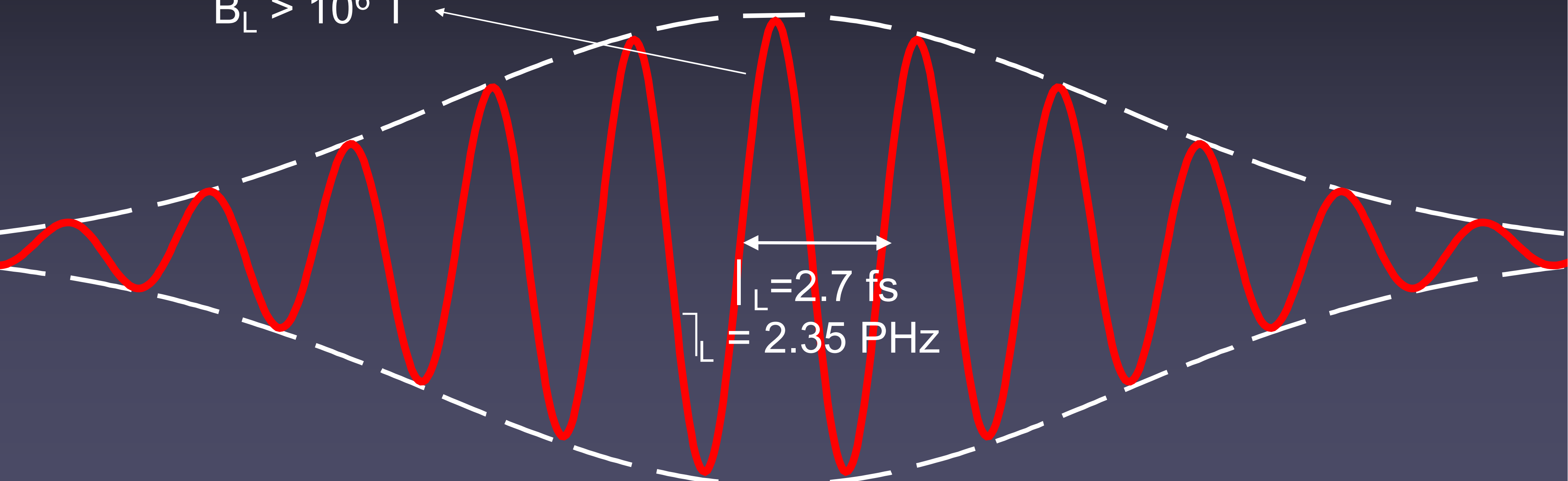
Intensity $I = \langle|\vec{S}|\rangle = \epsilon_0 c \langle|\vec{E}|^2\rangle = \frac{\epsilon_0 c}{2}|\vec{E}|^2$

$$I = 10^{22} W cm^{-1}, \lambda = 800nm \rightarrow |E| = 3 \times 10^{14} V m^{-1}$$

$$|B| = \frac{E}{c} = 1 \times 10^{6} T$$

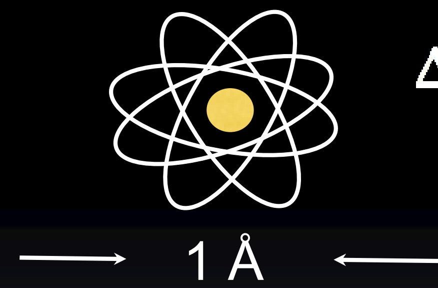
$E_L > 10^{14}$ V/m

$B_L > 10^{6}$ T



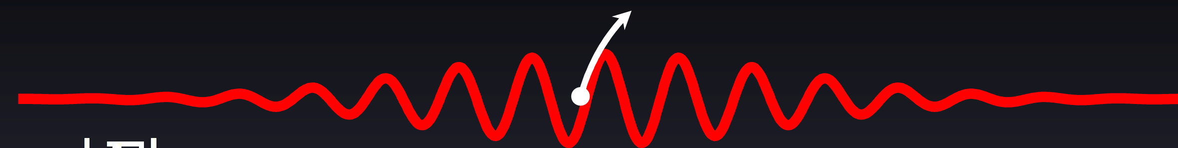
Interaction with matter

Potential difference across an atom:



$$\Delta\Phi = |E|dx \simeq 10^{14} V/m \cdot 10^{-10} m = $$
$$= 10^4 V \gg \text{atomic binding potential}$$

Matter is instantly ionized!



classical velocity of an electron after half a laser period

$$|v| = \frac{e}{m_e}\frac{|E|}{2}\frac{\tau}{2} = 1 \times 10^{10} ms^{-1} \gg c!$$

relativistic effects have to be taken into account when the energy gain in a half period equals its rest mass:

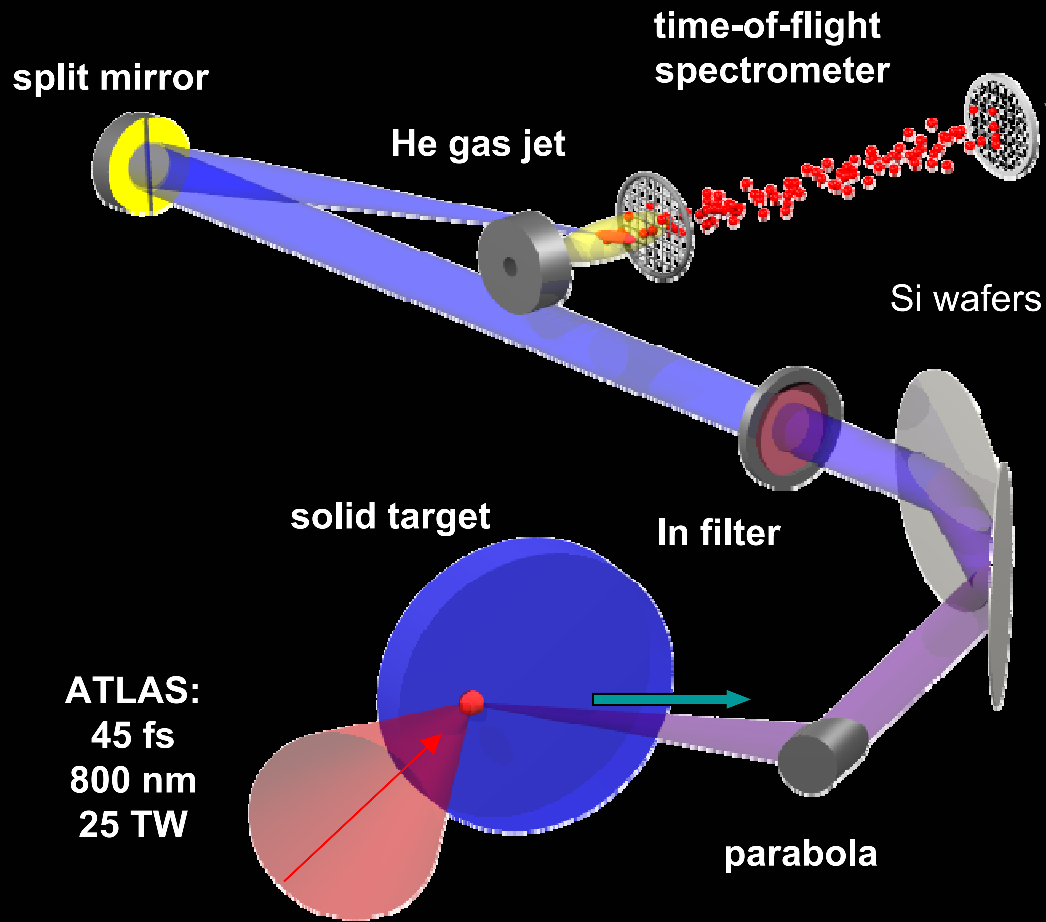
$$a_0 = \frac{e|\vec{E}|}{m_e \omega c} \simeq 8.5 \times 10^{-6}\sqrt{I}\lambda$$

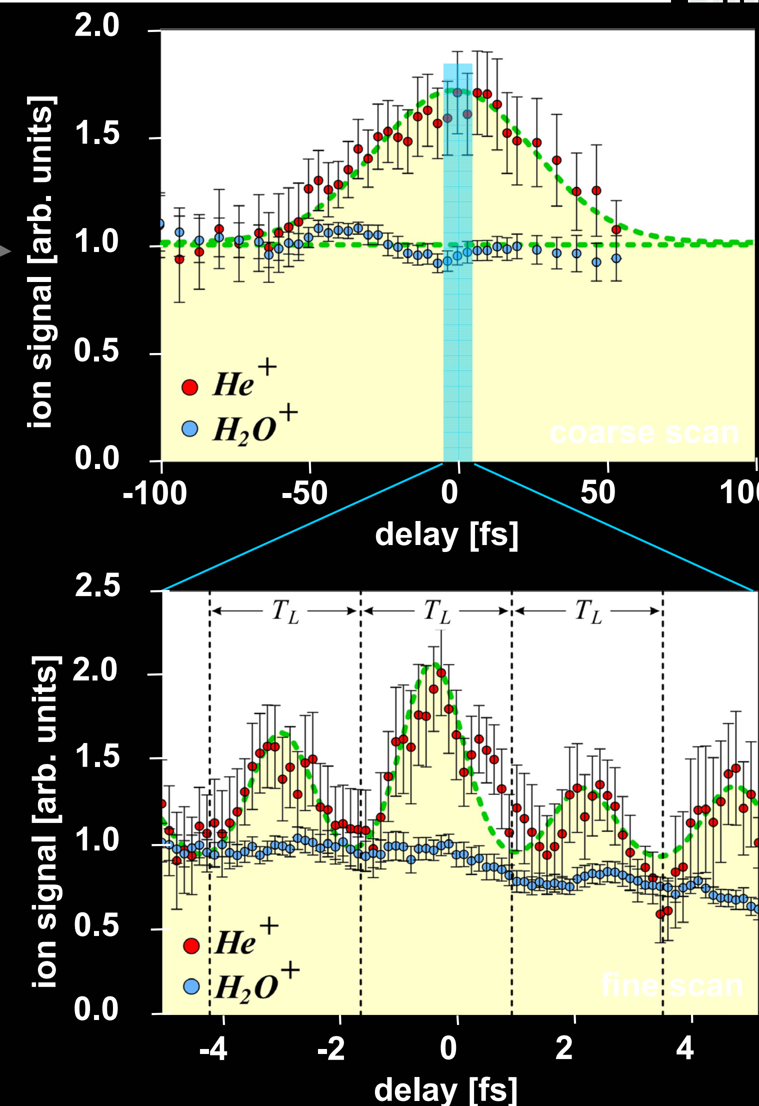
i.e. when dimensionless amplitude $a_0 \geq 1$, above 10^{18} W/cm^2 for 1μm light

Equation of motion for an electron in a plane, monochromatic light wave

$$m_e \frac{d}{dt}(\gamma\vec{v}) = -e(\vec{E} + \vec{v} \times \vec{B})$$
$$|\vec{B}| = \frac{|\vec{E}|}{c}$$

Attosecond autocorrelation of XUV pulse train by 2-photon ionization of helium



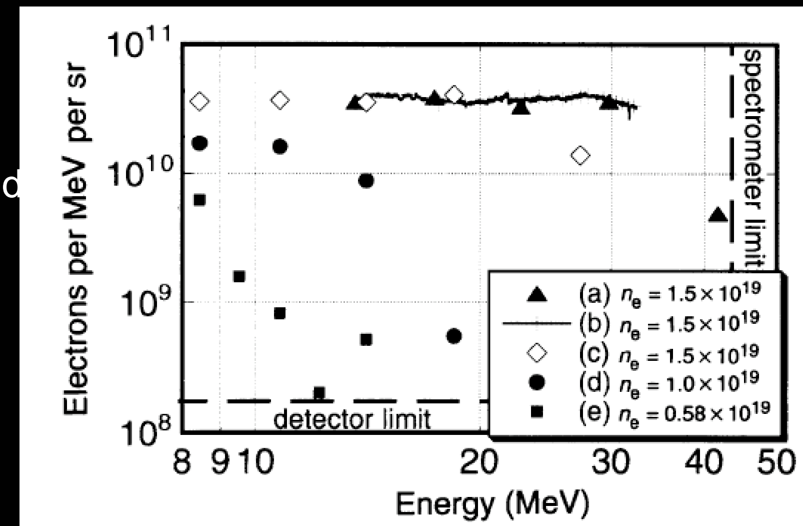


Y. Nomura, R. Hörlein, S. Rykovanov, Zs. Major, J. Osterhoff, S. Karsch, L. Veisz, G. D. Tsakiris
– in collaboration with D. Droomey, M. Zepf, P. Tzallas, D. Charalambidis

after a long, hard journey...

from long laser pulses....

A. Modena et al., Nature **377**, 606 (1995): (self-modulated wakefield

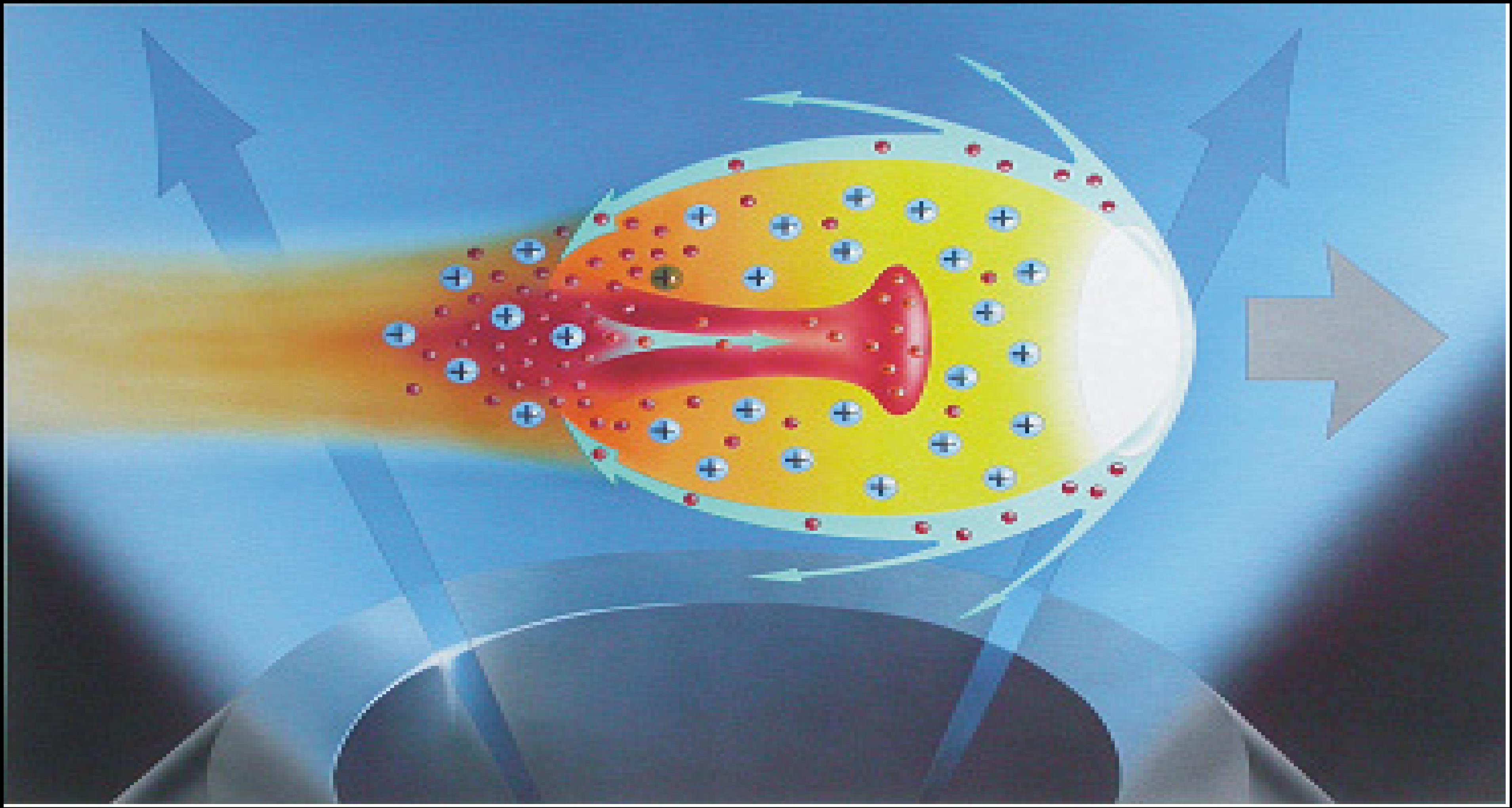


...to shorter ones...

Mangles et al., Geddes et al., Faure et al. Nature 2004

...where the laser pulses are much shorter than the plasma period

Basic mechanism



courtesy L. Veisz

Acceleration gradients scale as $n_e^{1/2}$ ⇒ higher density preferrable

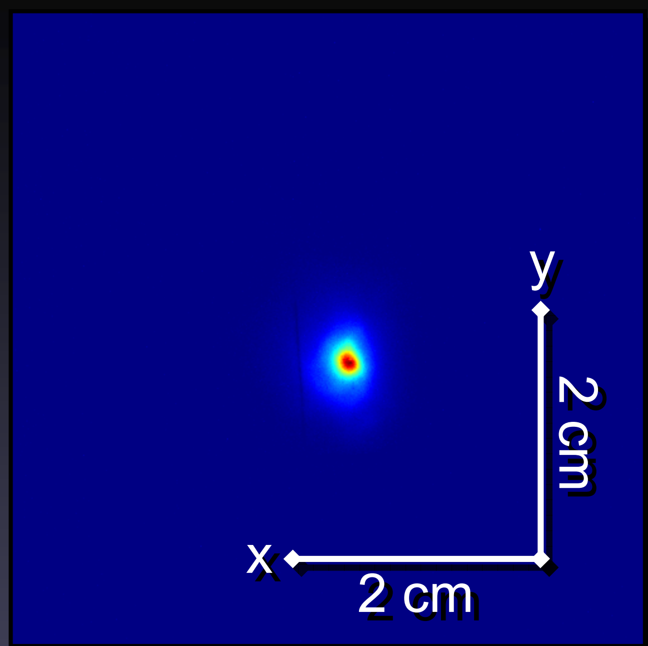
However:

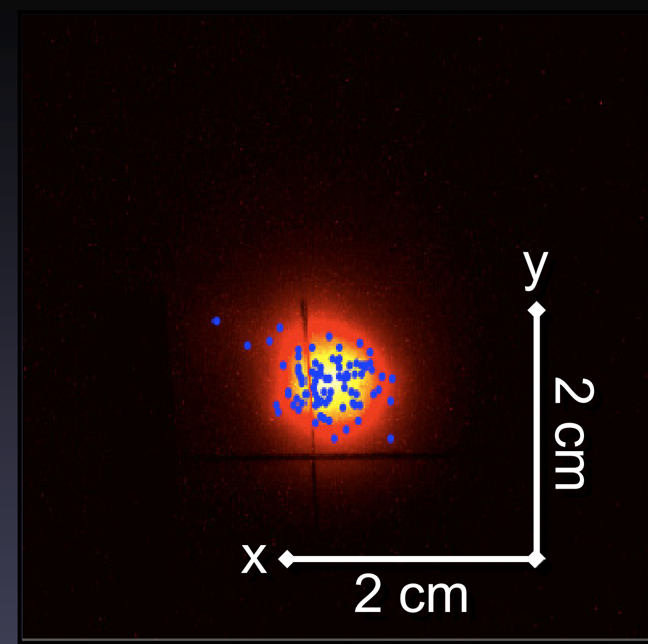
speed of light in plasma decreases for higher density ⇒ electrons and drive pulse dephase

Divergence, beam pointing stability

1.1 m behind electron source

Laser polarization axis





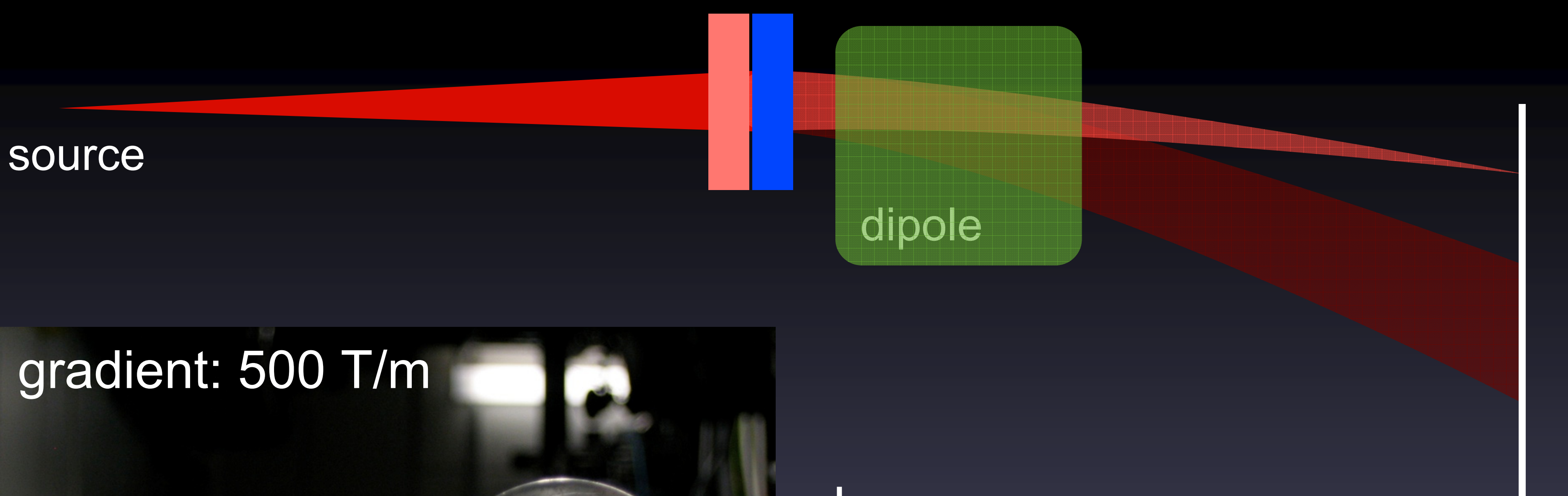
Single shots

Pointing stability in x-direction 2.2 mrad RMS
y-direction 1.4 mrad RMS

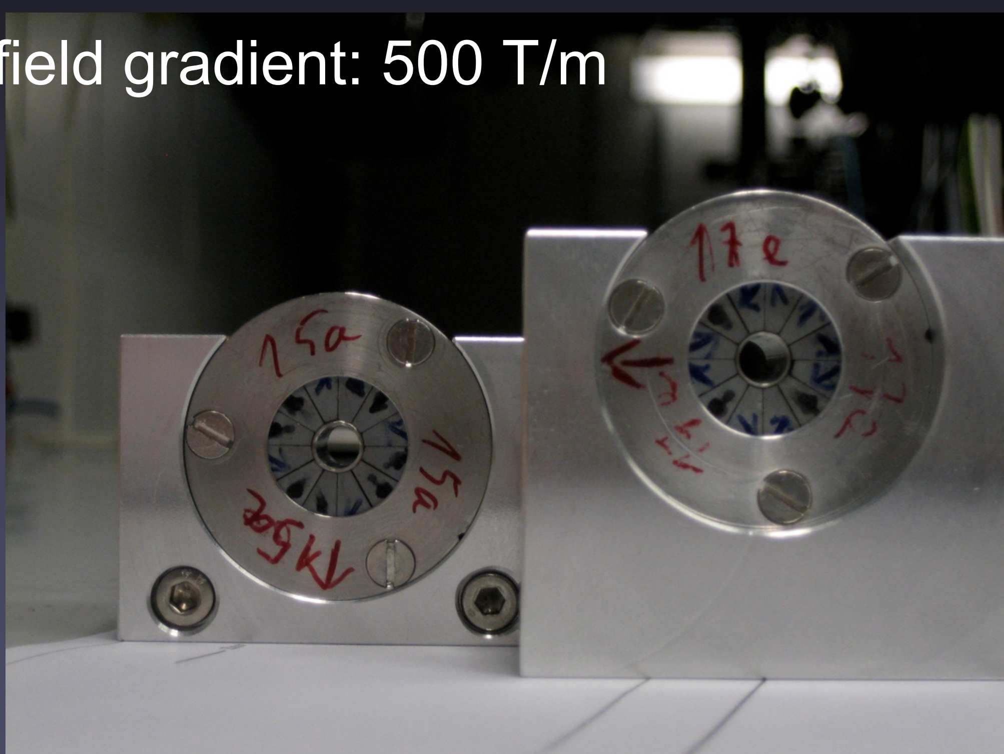
Summed shots

averaged over 100 shots

towards applications - beam transport: Focusing with mini-quadrupole lenses



field gradient: 500 T/m

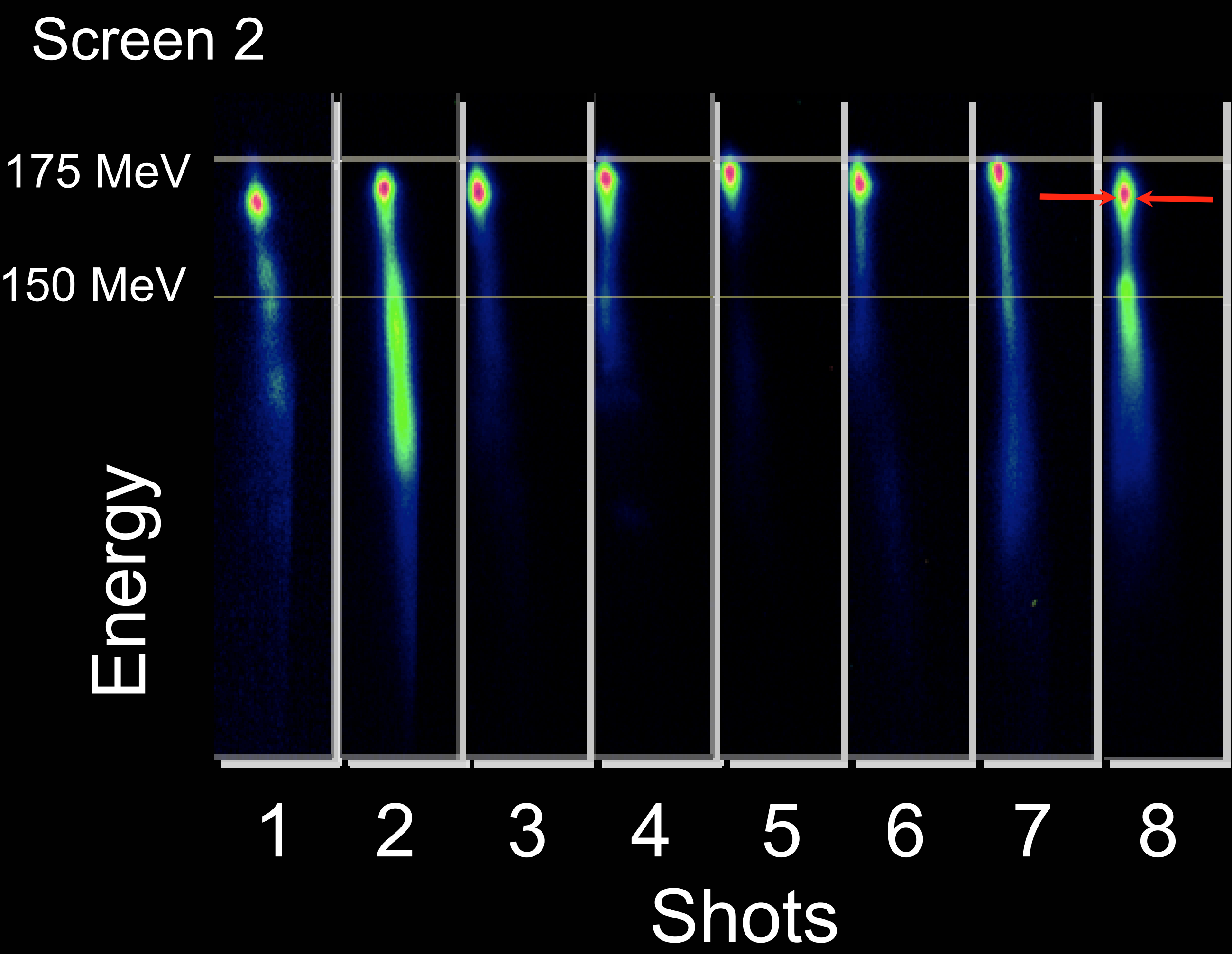


Lenses

- focus the beam
- improve spectrometer resolution
- strongly reduce pointing fluctuations

with F. Grüner, M. Fuchs, R. Weingartner, S. Becker, U.Schramm

Real energy spread



E ≈ 169.7 ± 2.0 MeV
1.1% peak energy fluctuation !

ΔE/E ≈ 1.76±0.26% RMS

→ Essential property for future table-top FEL operation

Source size image: provides emittance measurement, given the resolution can be improved

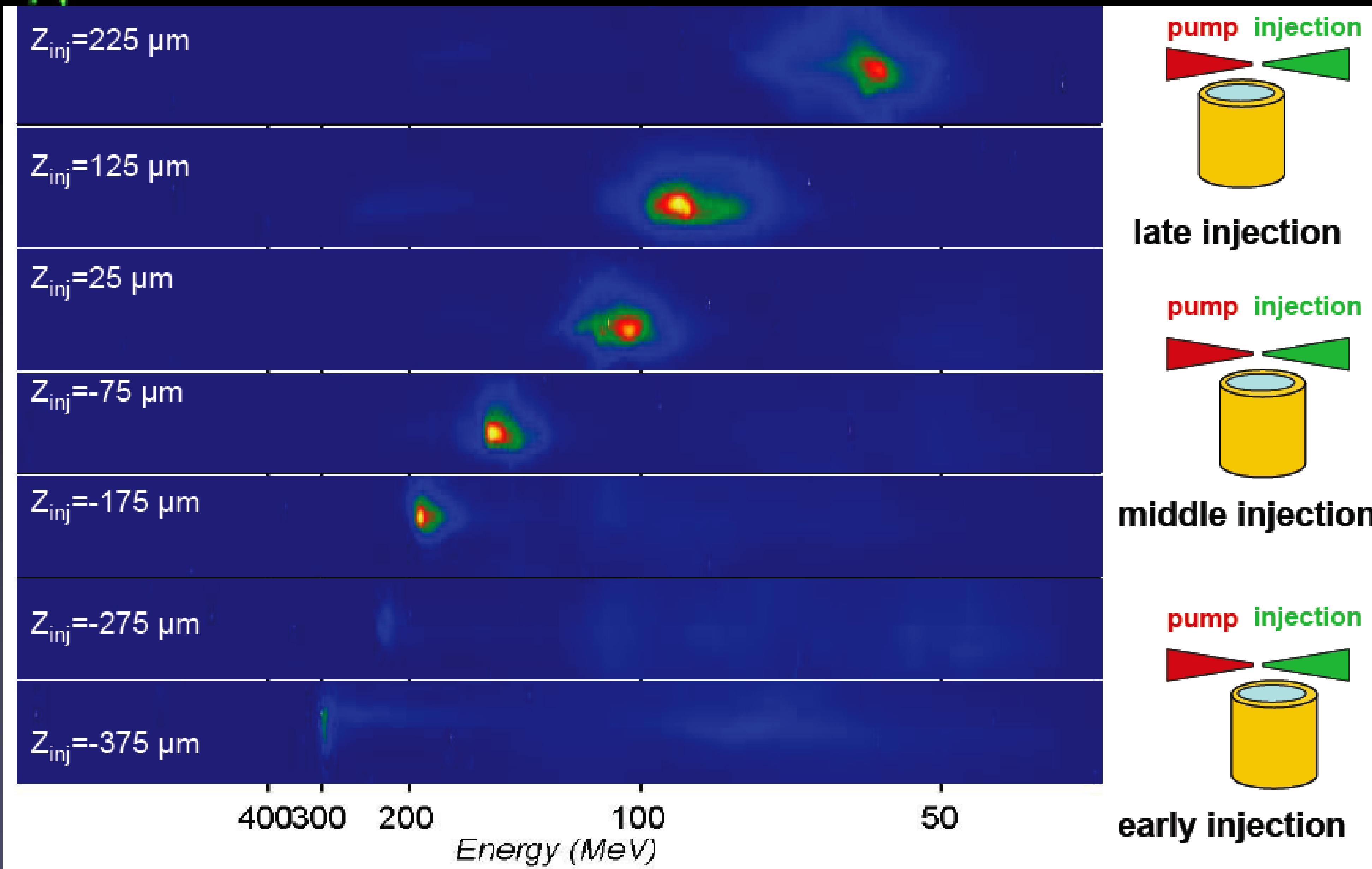
See also:

LOA: C. Rechatin et al., PRL 102, 164801 (2009): 3.1 % RMS spread

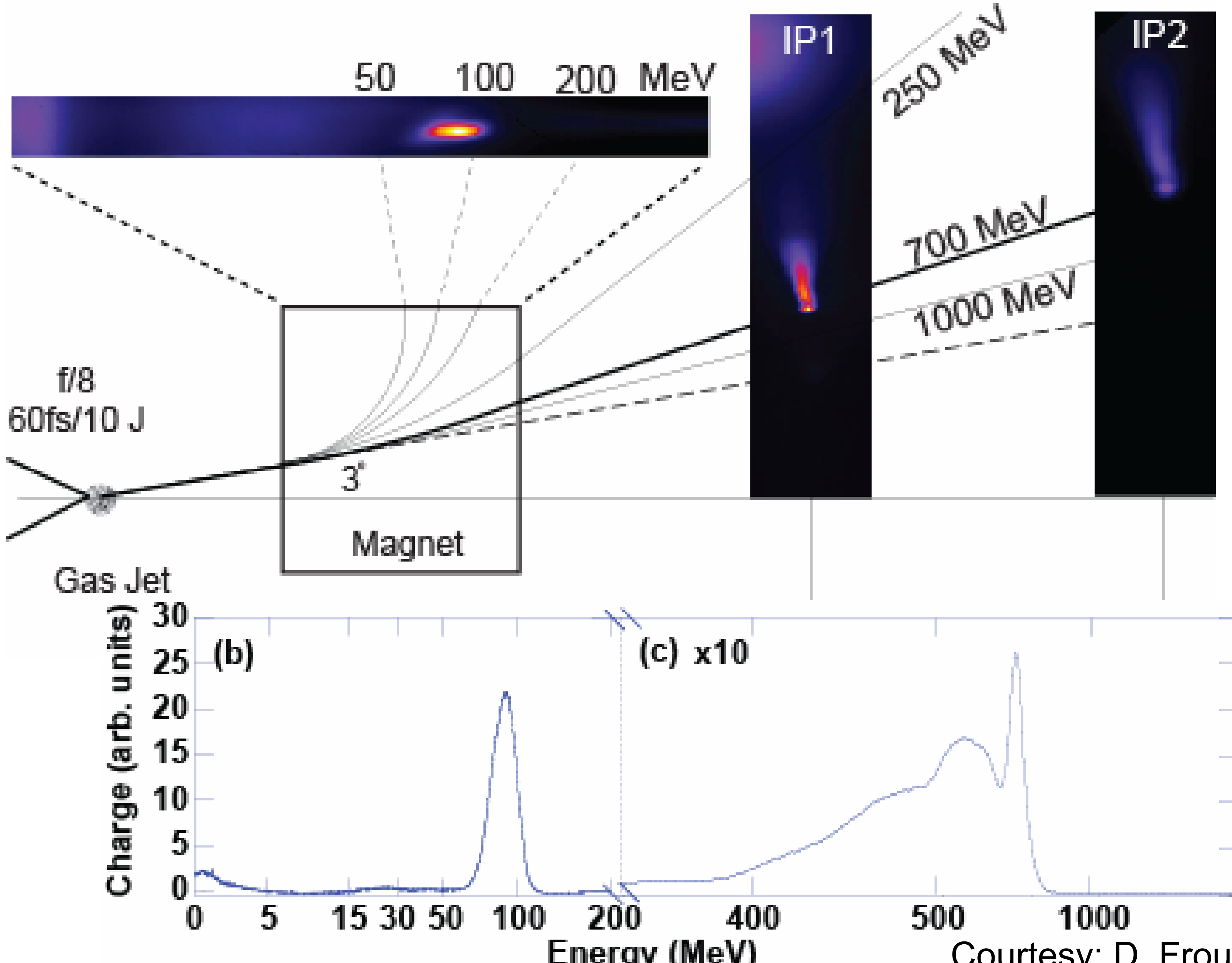
Nebraska: S. Banerjee et al., 0.8 % energy spread

Stability and control by external injection

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



A two-screen spectrometer unambiguously measures the energy and deflection of the electron beams

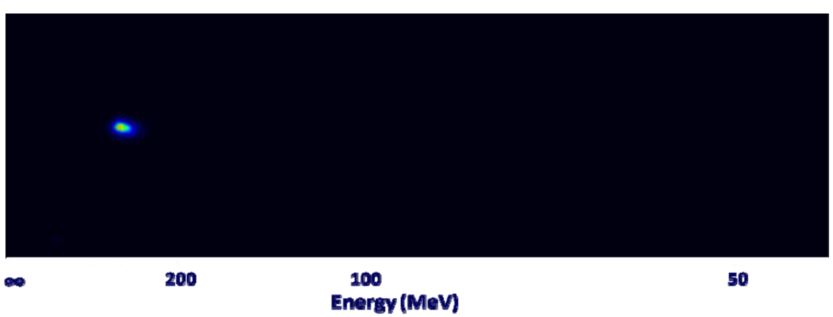


Courtesy: D. Froula, LLNL

Laser wakefield acceleration in the matched parameter regime University of Nebraska

- Guiding: only relativistic (no pre-formed channel)
- 1-10 mm He supersonic jet
- Laser parameters (intensity, pulse duration, focal spot-size) all matched with plasma

Laser Parameter	*Measurement*
Peak power	< 140 TW
Repetition rate	10 Hz
Central wavelength	805 nm
Pulse duration	< 30 fs
Pulse energy	3.5 J
Energy stability	0.8% rms
Strehl ratio	0.95
Pointing stability	3.5 μrad



Electron Beam	*Measurement*
Energy	50-600 MeV
ΔE/E	10%
Charge per bunch	100-600 pC
Divergence angle	2-5 mrad
Pointing & energy stability	1% (>30 shots)

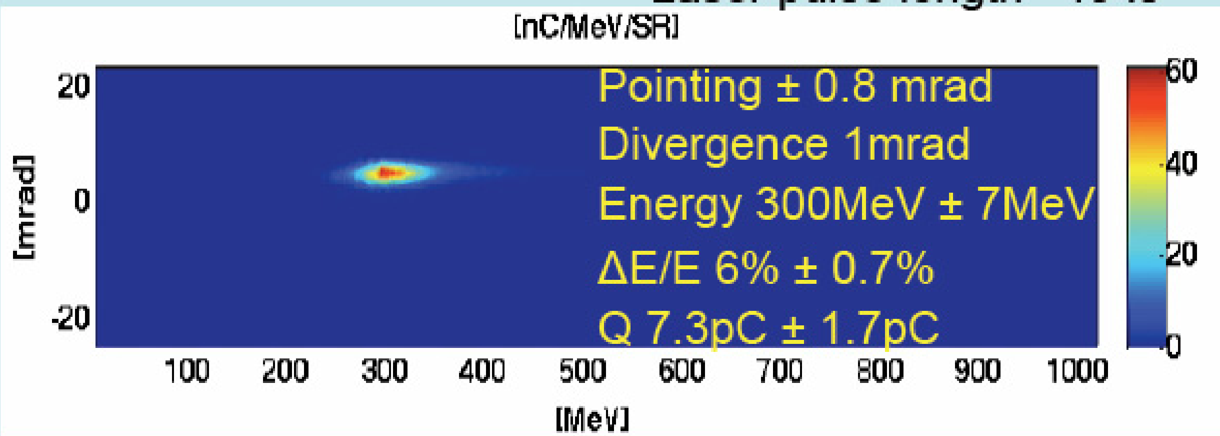
UNIVERSITY OF Nebraska Lincoln

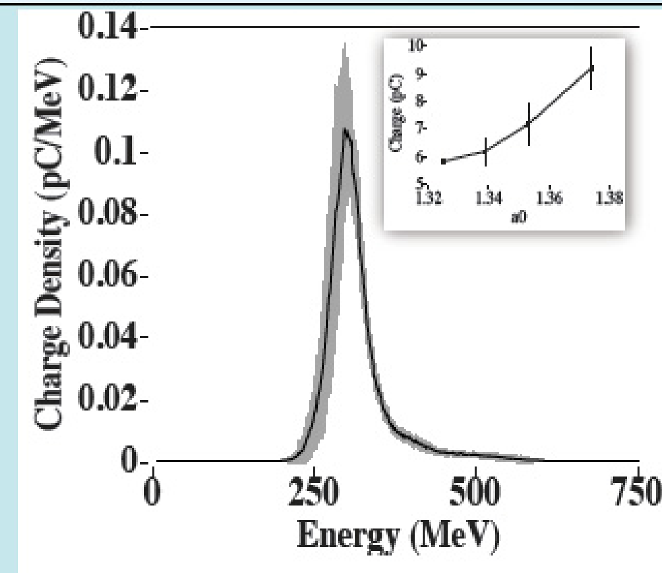
Courtesy: S. Banerjee, UNL

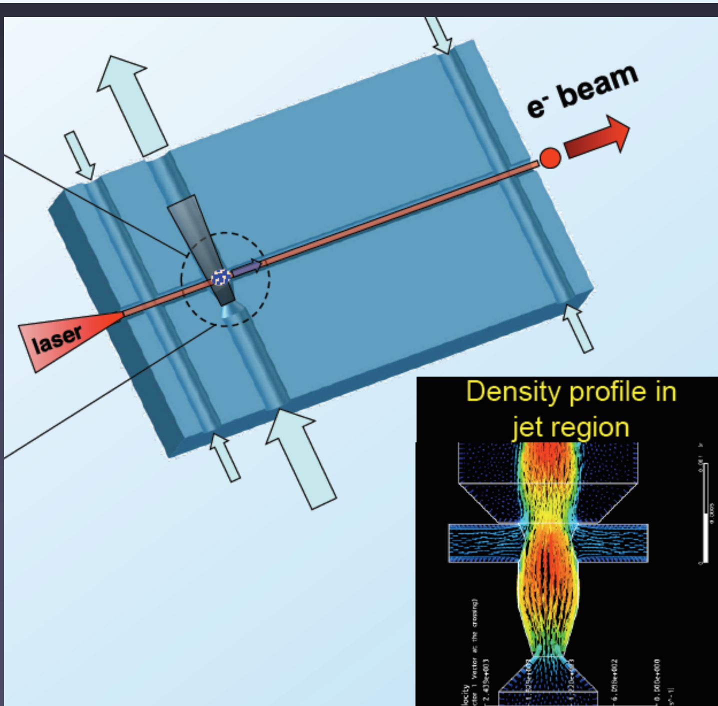
Jet Improves Beam Stability

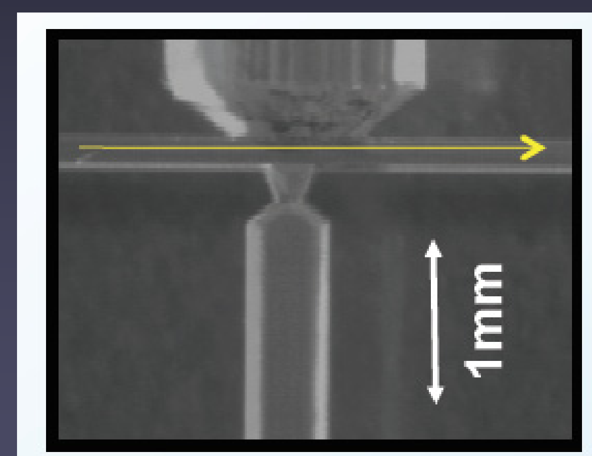
Stability with jet

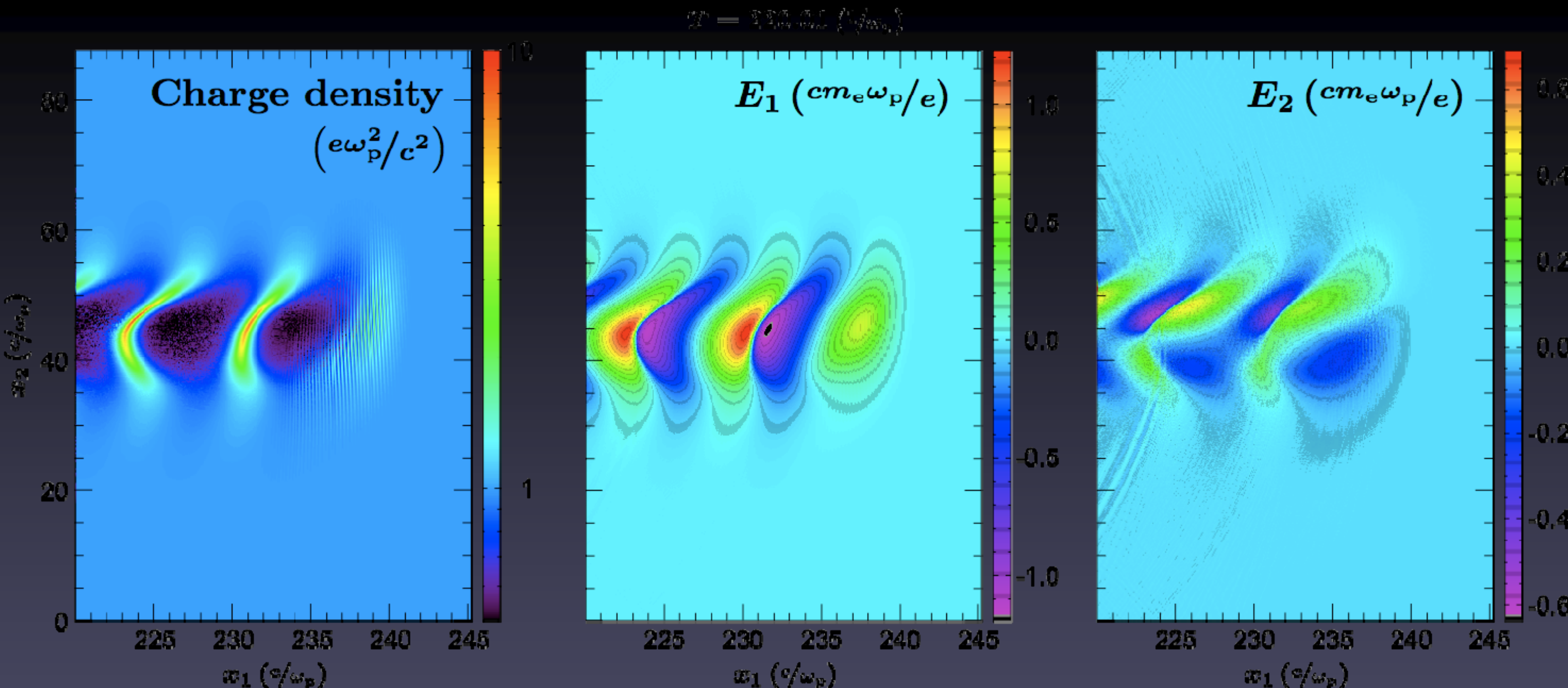
Input Parameters: P_{jet}≈145psi, $N_e \approx 2\times10^{18}\ cm^{-3}$, a_0≈1 (25TW), Laser pulse length≈ 45 fs









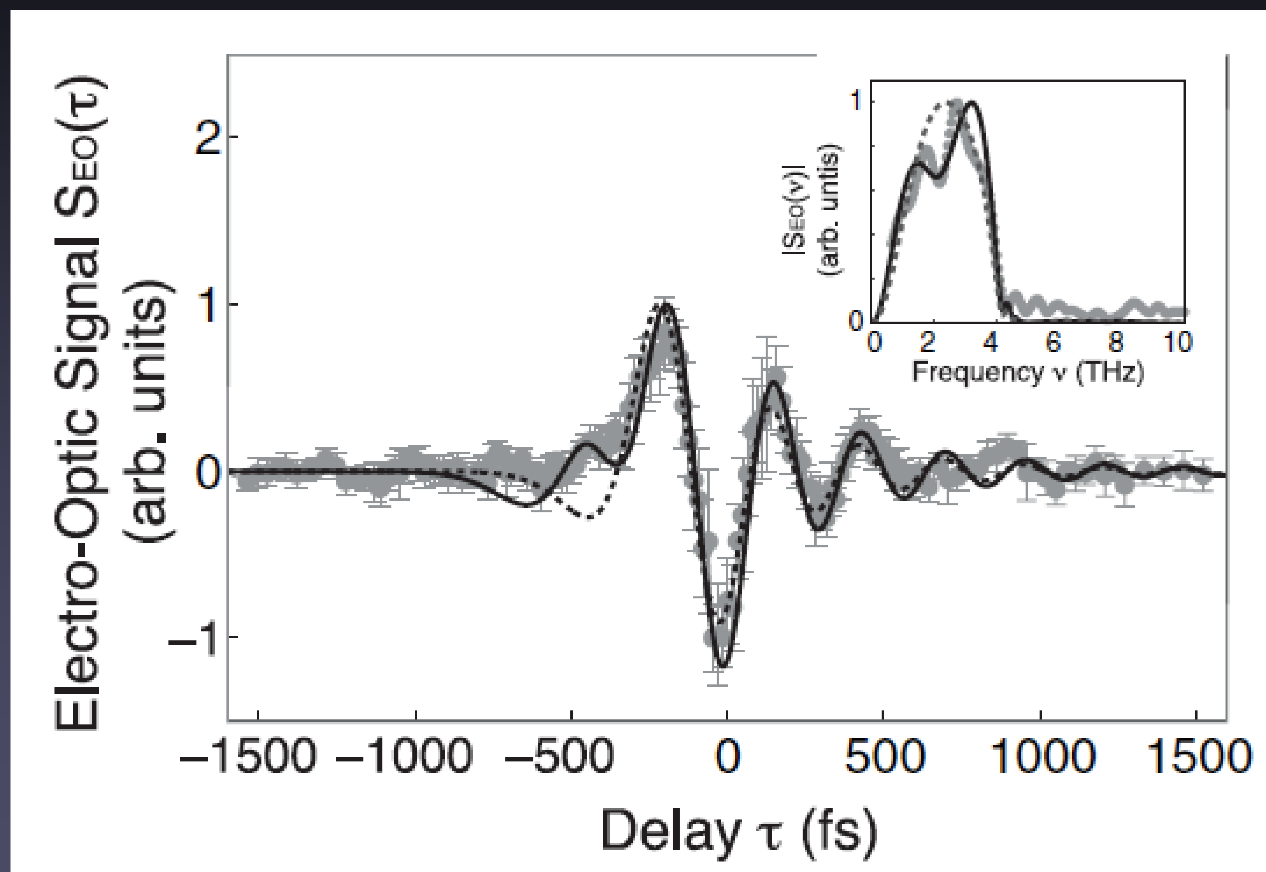


→ Pulse-front tilted beams drive asymmetric wakes

Pulse duration?

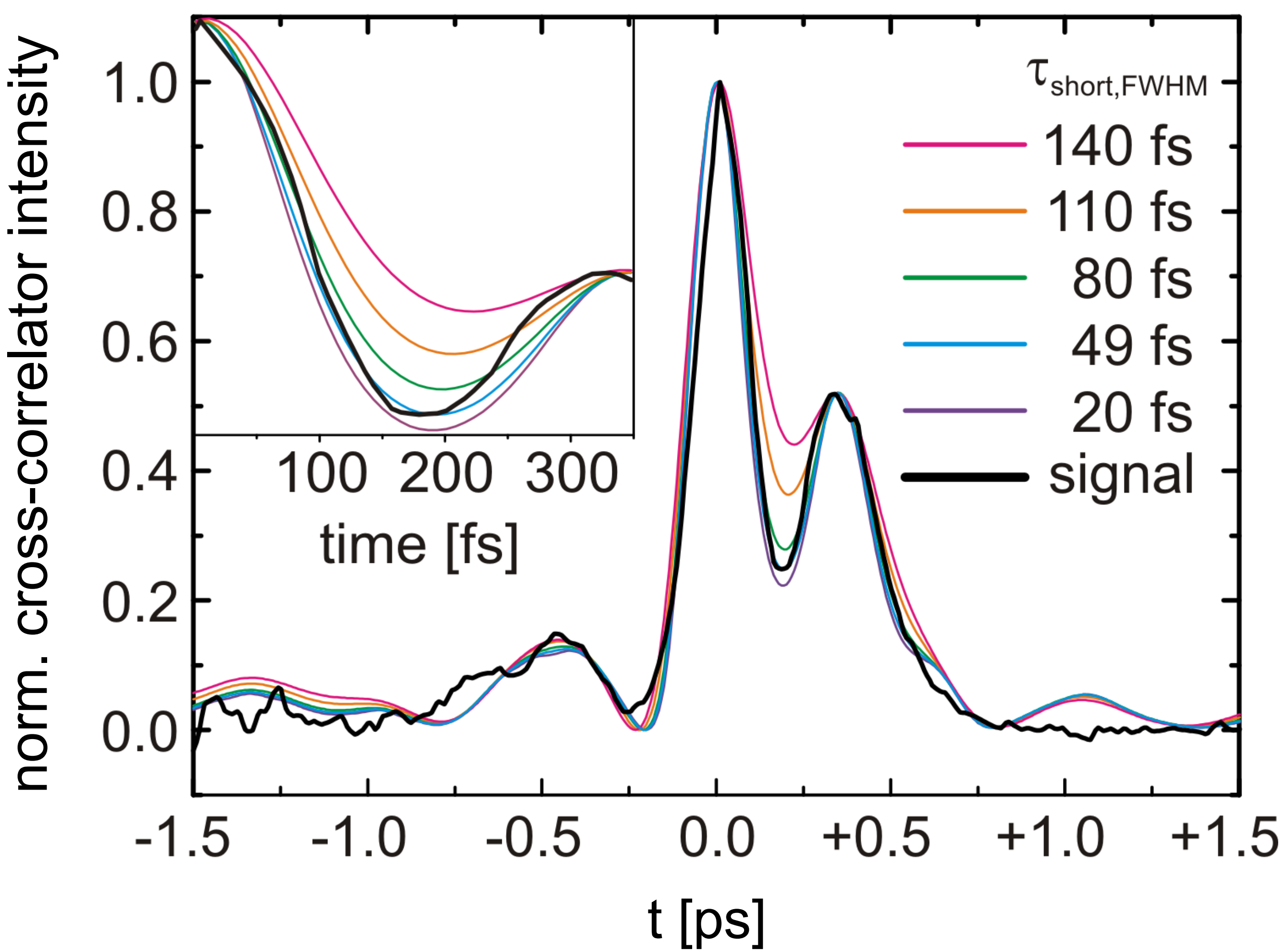
1st measurement:
Tilborg et al. PRL **96** 014801 (2006)

EO sampling, t < 50 fs RMS, limited by detection system resolution



Courtesy: A. Debus, FZD

Simulated vs. measured cross-correlator signal



- Delay between electron bunch distributions

  $\otimes | = 370 {}^{+\ 5}_{-10}$ fs

- Long bunch @ FWHM

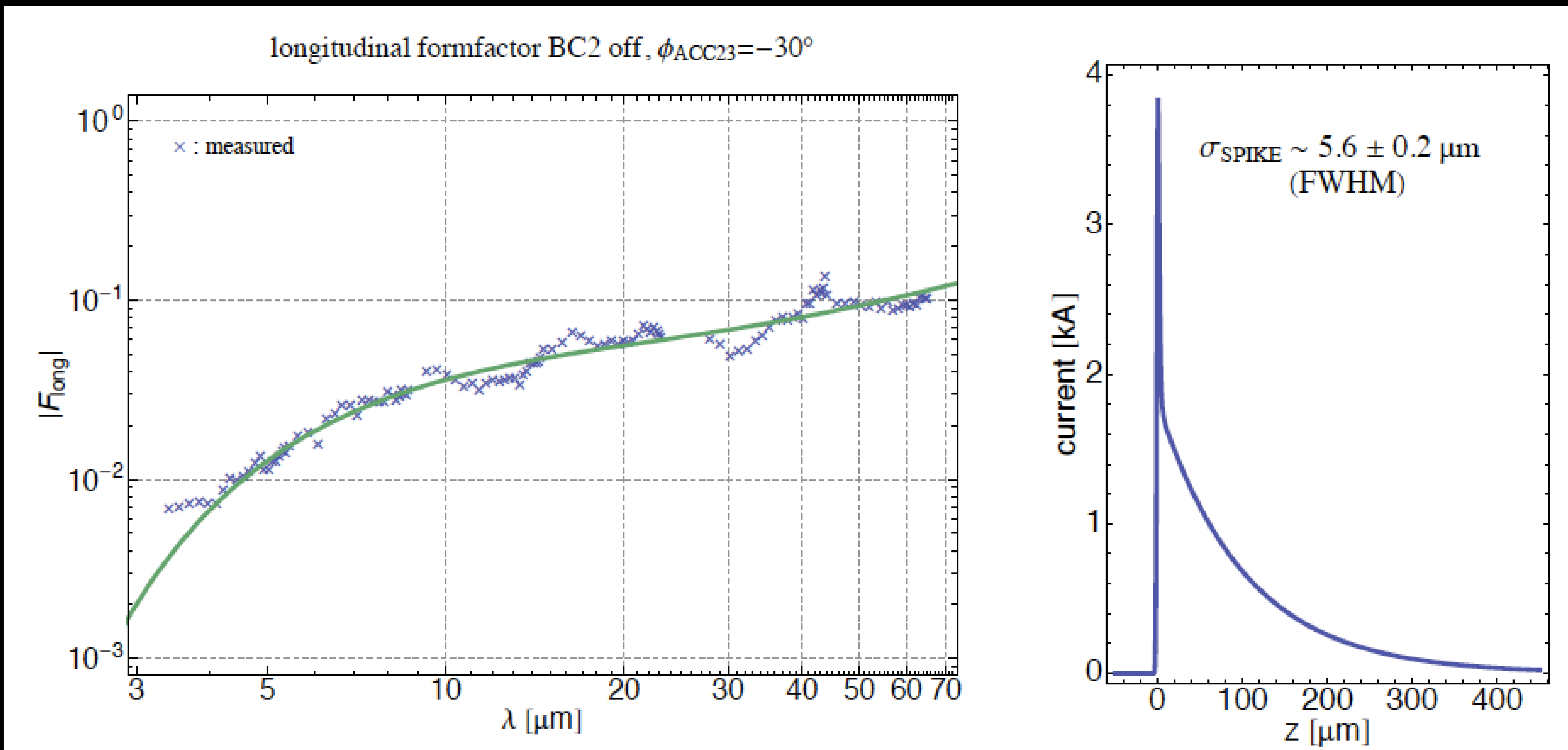
  $|_{long} = 650 \pm 25$ fs

- Short bunch @ FWHM

  $|_{short} = 49 {}^{+\ 8}_{-22}$ fs

- Laser probe distance from axis is compatible with

  $d_{off\text{-}axis} = 600 \pm 25$ µm

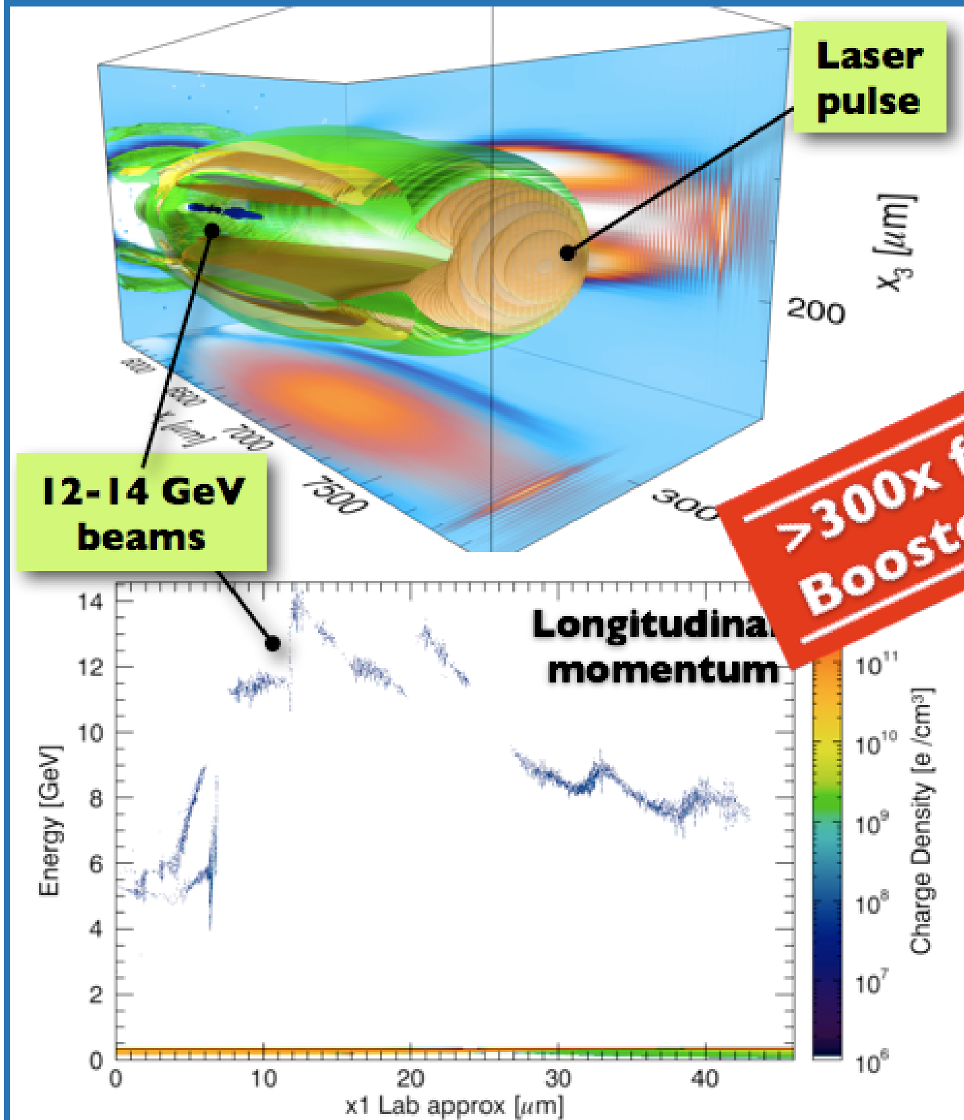


Courtesy: S. Wesch, DESY

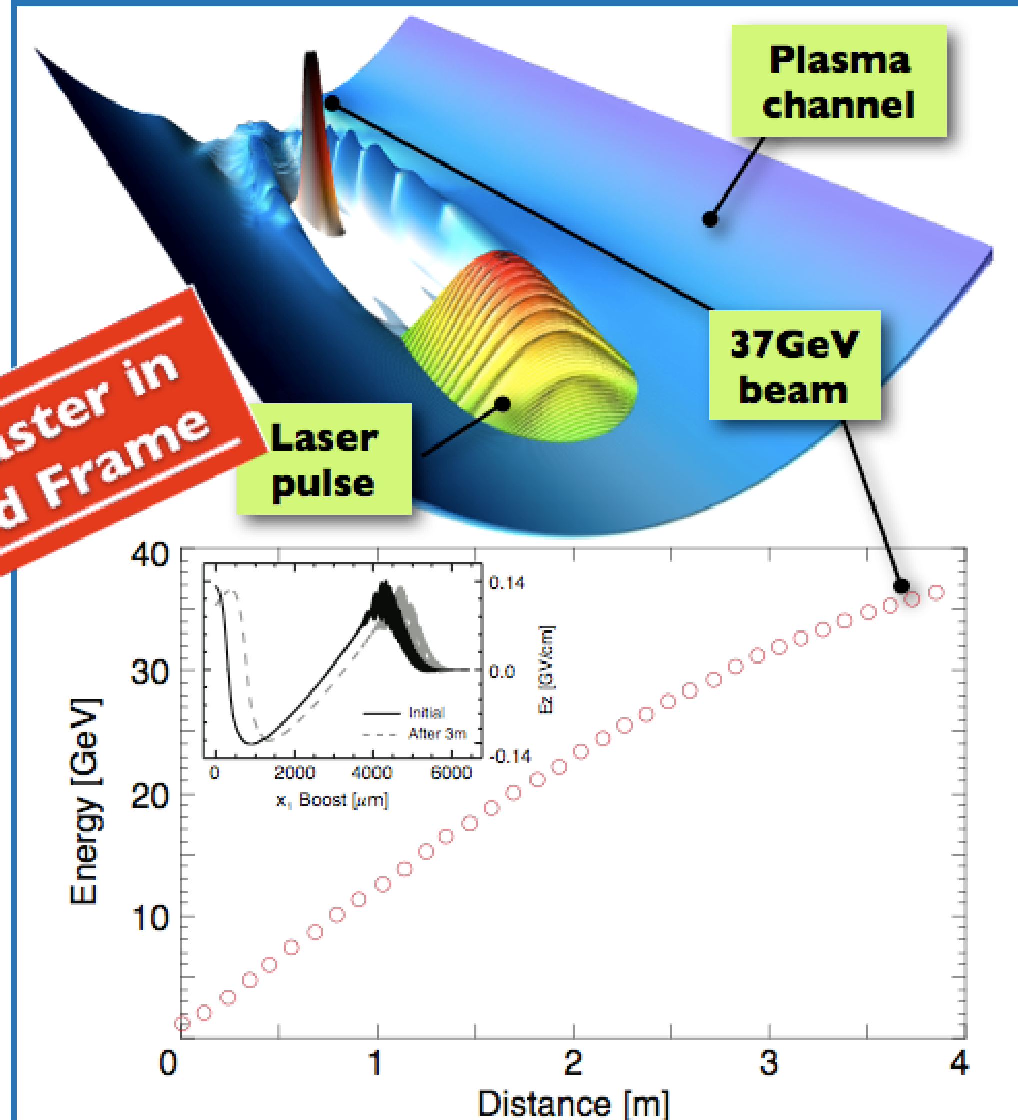
Full 3D ultra-fast boosted frame simulations for next generation lasers using OSIRIS

Courtesy: S.F. Martins, IST& UCLA

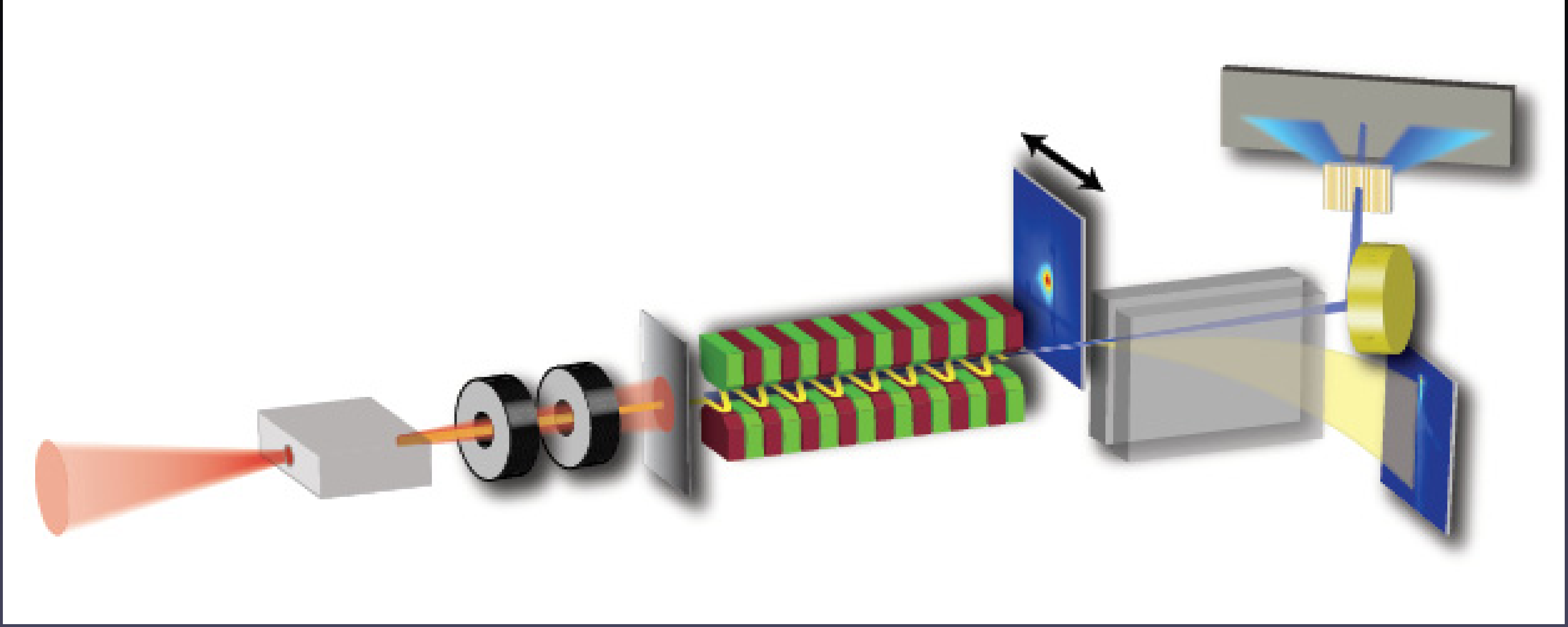
Self-injection: >10 GeV



External-injection: 37GeV & counting...

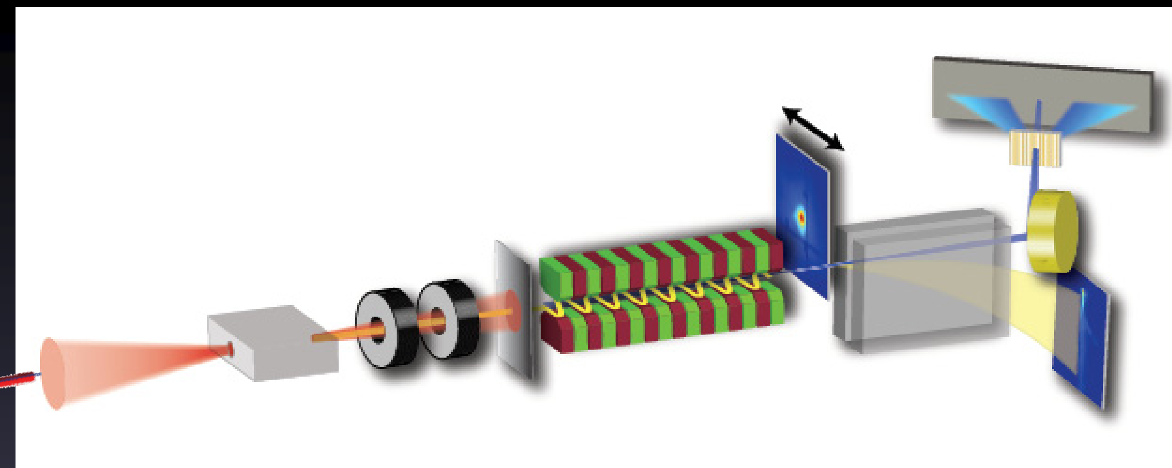


X-ray generation: Undulator radiation towards FEL

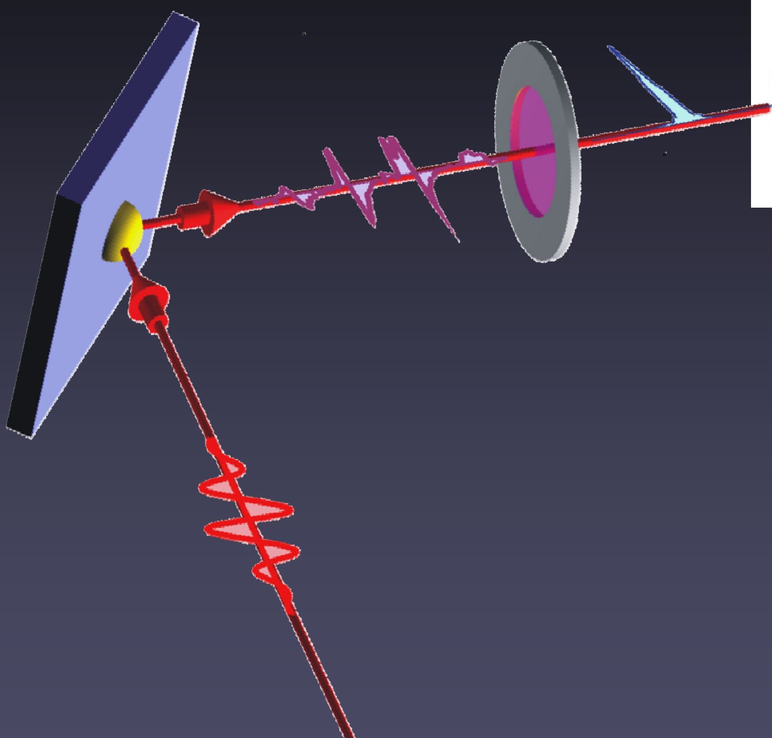


Future dreams:

Laser-driven FEL amplifier



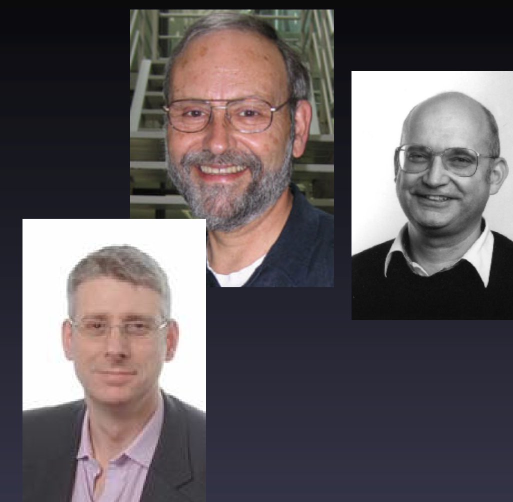
as-HHG seed



ultra-compact as-X-ray FEL

Coworkers

Main collaborators:



D.Habs group (LMU)
G. Tsakiris group (MPQ)
S.Hooker group (Oxford)
L.O'Silva group (Lisbon)
J. Hein (Jena)