MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK
GARCHING

Laser Electron Acceleration and Atto-second Streak Camera

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Outline

I. Electron Acceleration

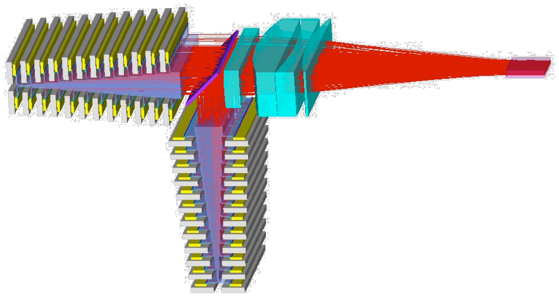
- Laser Development
- Electron Acceleration
    - Bubble Acceleration
    - Capillary Acceleration
- Table-Top XFEL
- Requirements on Detector

II. Atto-second Measurements

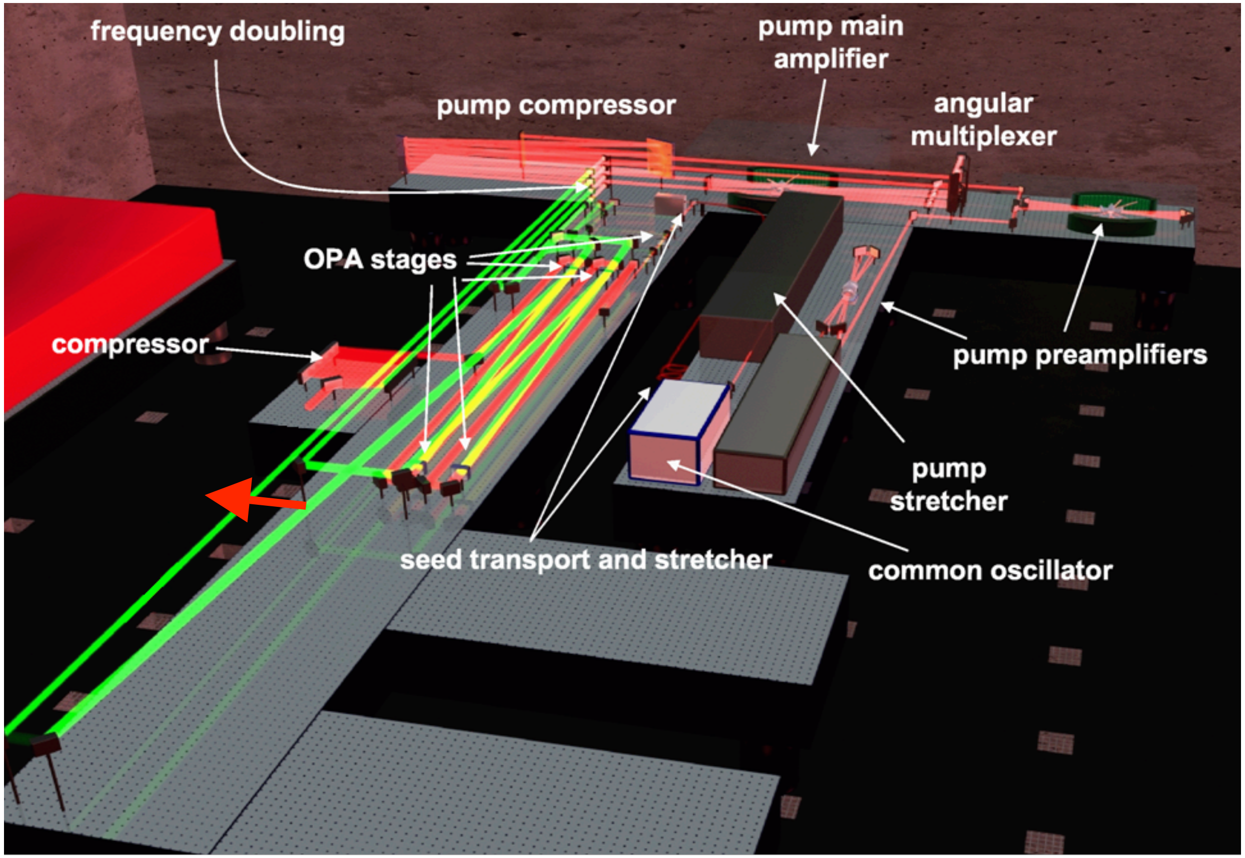
- Atto-second Pulses
- Atto-second Streak Camera

Pushing the frontiers of X-ray and high-field science: Petawatt Field Synthesizer (PFS)

primary pump source:



laser diode stack: 54% from socket to laser light



aim (PFS): τ < 5 fs
P > 0.5 PW
λ = 1.2 μm
f = 10 Hz

vision (ELI): τ < 10 fs
P > 500 PW
λ = 0.8 μm
f = 0.03 Hz

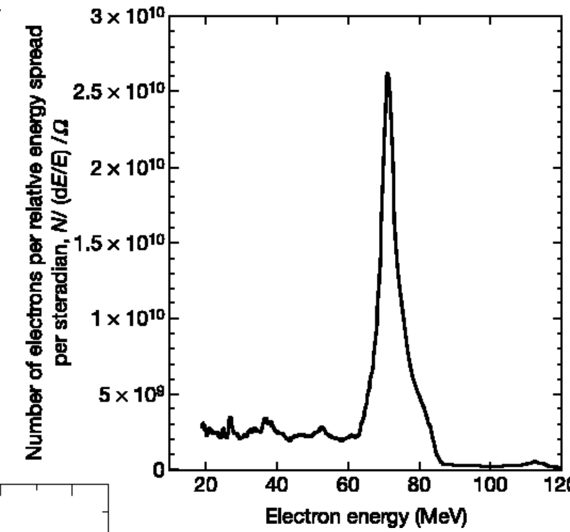
* funded by the Max Planck Society

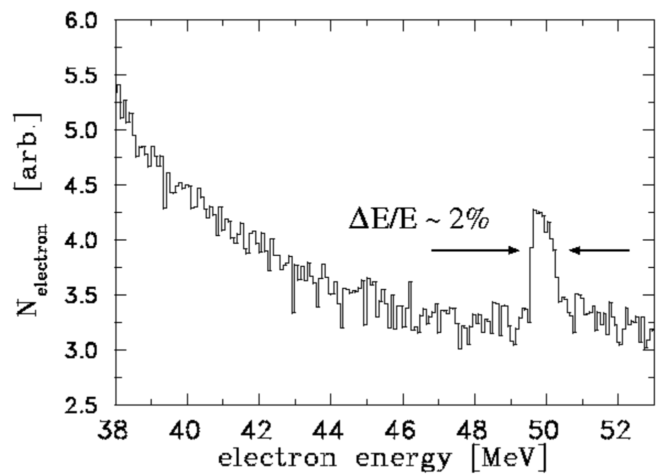
Quasi-monochromatic electron beams

nature, Nov. 2004

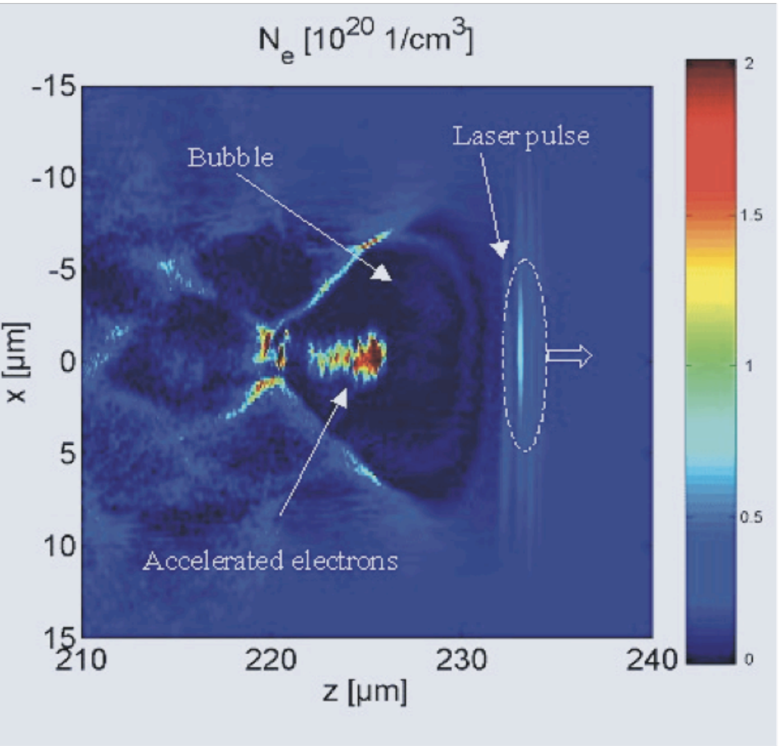
quasi-monochromatic electron beams:

- 50–200 MeV, very good longitudinal and transverse emittance
- 10 fs bunches with density
- 10^6 * classical density





Bubble acceleration of electrons in plasma



Theory: A. Pukhov, J. Meyer-ter-Vehn
Appl. Phys. B 74 (2002) 355

- laser ionized gas target as it moves
- laser generates a plasma wave
- for high enough laser energy: wave breaks
- just a single "bubble" survives
- electrons are pushed sidewards and are scattered into the bubble
- electrons are accelerated by the positive ion background (strong fields: TV/m)
- stable bubble moving through plasma with v^l_{gr}

$$E_e = 0.65\, m_e c^2 \sqrt{\frac{P_L}{8.5\,\mathrm{GW}}} \cdot \frac{c\tau}{\lambda}$$

$$N_e = \frac{1.8\,\lambda}{2\pi r_e} \sqrt{\frac{P_L}{8.5\,\mathrm{GW}}}$$

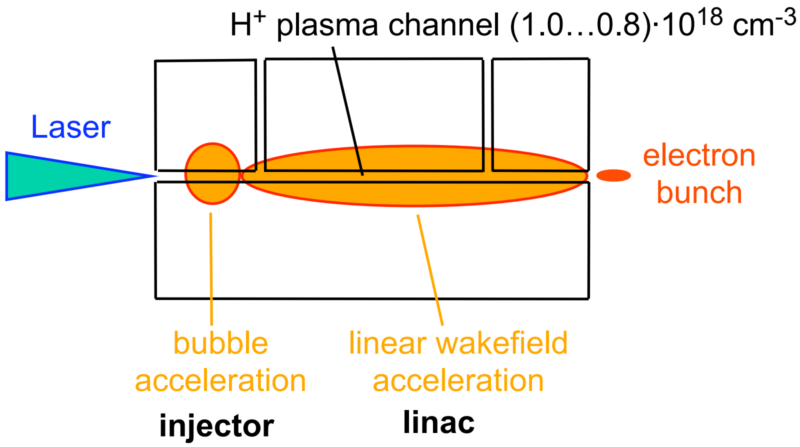
$$L_{\mathrm{acc}} = 0.7 \cdot \frac{c\tau}{\lambda} Z_R$$

Result unexpected for published laser pulses:
Self focusing, self shortening

A. Pukhov &
S. Gordienko
Phil. Trans. R. Soc. A 364 (2006) 623

Laser capillary acceleration I

- 300 μm gas filled channel
- parabolic electron density generated by other pulse
- guiding of the laser beam beyond Rayleigh length



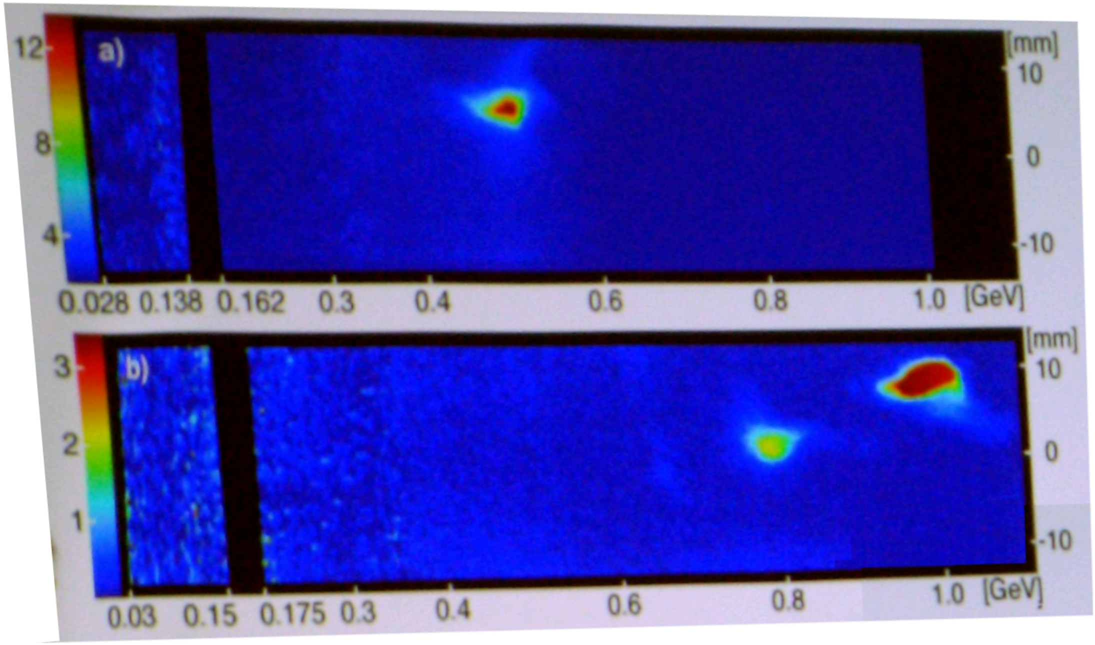
- bubble acceleration, nonlinear wave breaking injection of electrons
- linear wave breaking acceleration in plasma channel mode guiding of laser

linear wake-field acceleration:

- laser with larger beam size accelerates electrons further without additional electron capture
- acceleration without increase in energy spread

PFS bubble injection: 1 nC

Laser capillary acceleration II

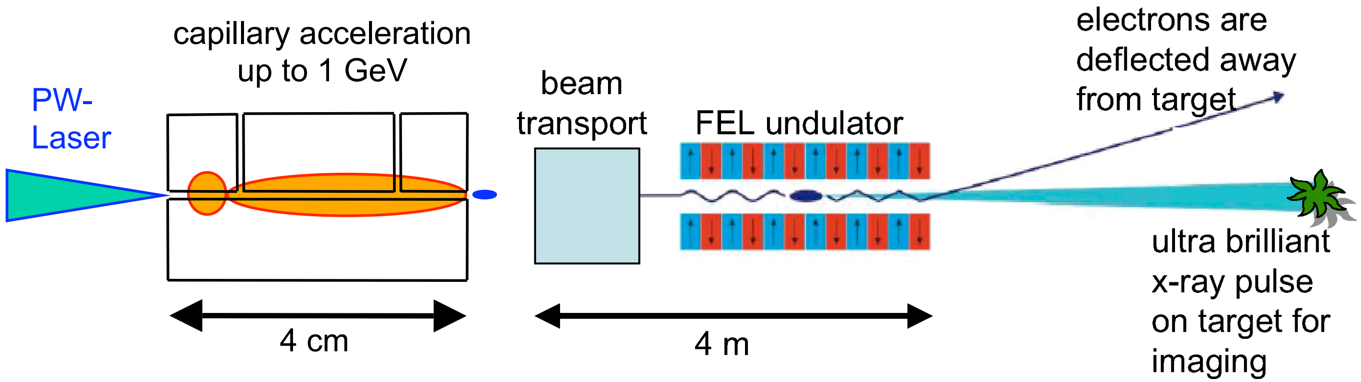


C. Geddes et al. (Berkeley)
40 TW, 40 fs

up to 1.2 GeV, 200 pC,
$\Delta E/E < 2.5\%$, prob. 0.2%
probably $\epsilon_n = 1\pi$ mm mrad
$\Delta\theta < 1.6$ mrad

No focusing behind spectrometer!

Table-top X-FEL



compact laser accelerator: with $I \sim 100\,\mathrm{kA}$ in $10\,\mathrm{fs}$

bubble + capillary: $N_e \propto \sqrt{P_L} \quad \rightarrow \quad 1\,\mathrm{nC}$

transport: beam expansion but current preserved; linear chirp

$$\frac{\sigma_\gamma}{\gamma} < \varrho \quad = \quad \text{Pierce parameter} \qquad \varrho = \frac{1}{\gamma}\left[\frac{I}{I_n}\left(\frac{\lambda_u A_u}{2\pi\sigma_x}\right)^2\right]^{1/3} \quad = \quad \text{large}$$

compact FEL: for $\lambda = 25\,\mathrm{nm}$ length $= 3\,\mathrm{m}$

$$L_{\mathrm{gain}} \propto \frac{\lambda_u}{\varrho} \quad ; \qquad P_{\mathrm{sat}} \propto (I \cdot \lambda_u)^{4/3}$$

$\rightarrow$ λ_u smaller $\rightarrow$ γ smaller

quantum fluctuations $\propto \gamma^4$ $\rightarrow$ larger photon energies

$\rightarrow$ nuclear applications

Table-top X-FEL

Comparison	DESY X-FEL vs.	TT-XFEL	Test
Electron beam energy:	17 GeV	0.9 GeV	100-130 MeV
Accelerator length:	3.3 km	4 cm	~ 1 mm
Undulator length:	201 m	3 m	0.5 m
Emission wavelength:	0.8 Å	2.5 Å	25-40 nm
Peak brilliance:	10^{34}	10^{32}	10^{29} $\frac{\text{photons}}{\text{s mm}^2\text{ mrad}^2\text{ 0.1\% BW}}$
Photons per bunch:	10^{12}	10^{12}	10^{12}
Repetition rate	56 kHz	10 Hz (PFS) 1 kHz (ELI)	10 Hz

We have 20 x smaller electron beam energy and reduced requirements on beam quality

→ Maximum Energy $E_{\gamma max}$ limited by quantum fluctuations:

$$E_{\gamma max}(\text{DESY}) \approx 15\text{ keV} \Leftrightarrow E_{\gamma max}(\text{TT-XFEL}) \approx 10\text{ MeV}$$

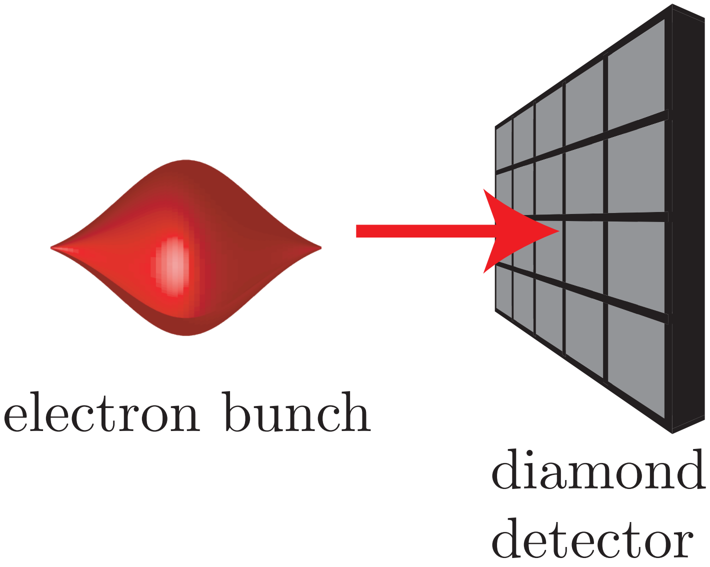
Diagnostics of Electron Bunch with Diamond Detector

online detection of the electron bunches:

- detector constantly in the beam without influencing it
- spatial distribution of charge (also change after refocussing)
- number of electrons

bunch parameters:

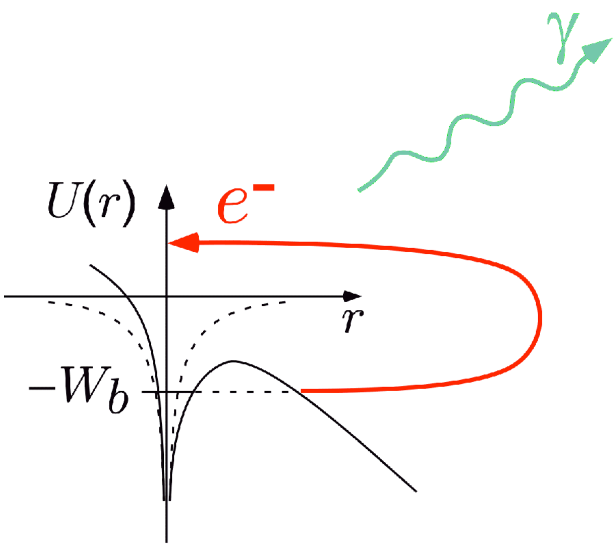
- 50 fs
- 10^9 electrons
- 50 MeV - 1 GeV
- up to 10 Hz repetition rate



demand on diamond detector:

- radiation hard
- good spatial resolution
- must have to cope with 10^9 electrons

Attosecond Pulses

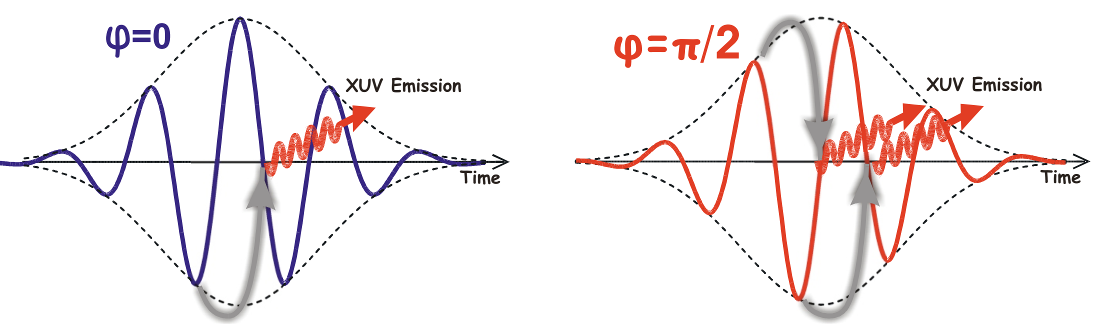


first generate atto-second pulse:

- few cycle (fs) wave deforms atom potential
- electron can tunnel through potential
- field of light wave accelerates electron away and back to vicinity of ion
- electron has gained high energy
- recombines with ion
- emits xuv photon

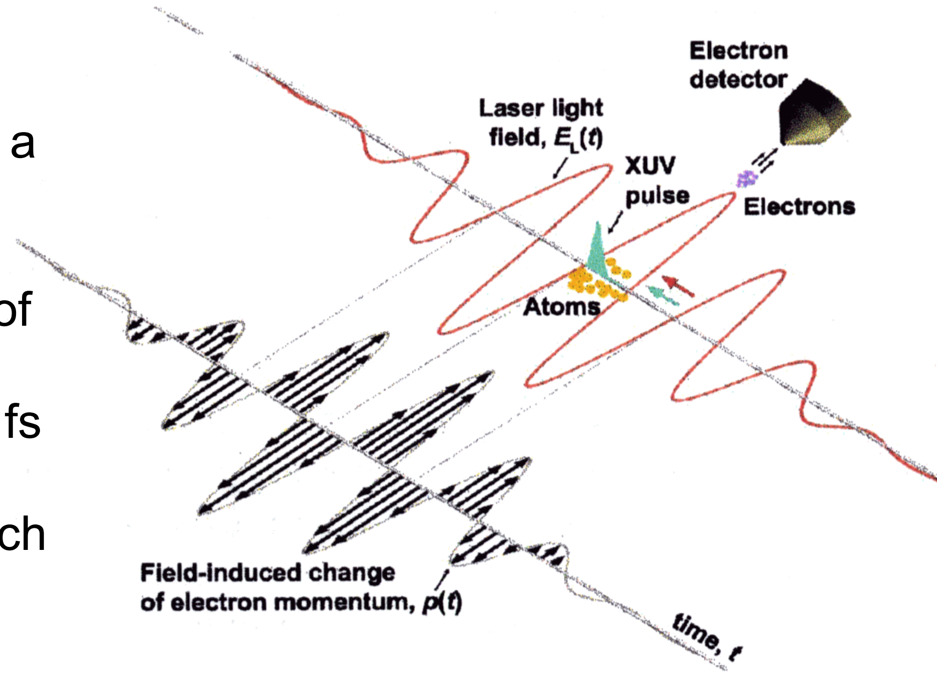
for a single atto-second burst:

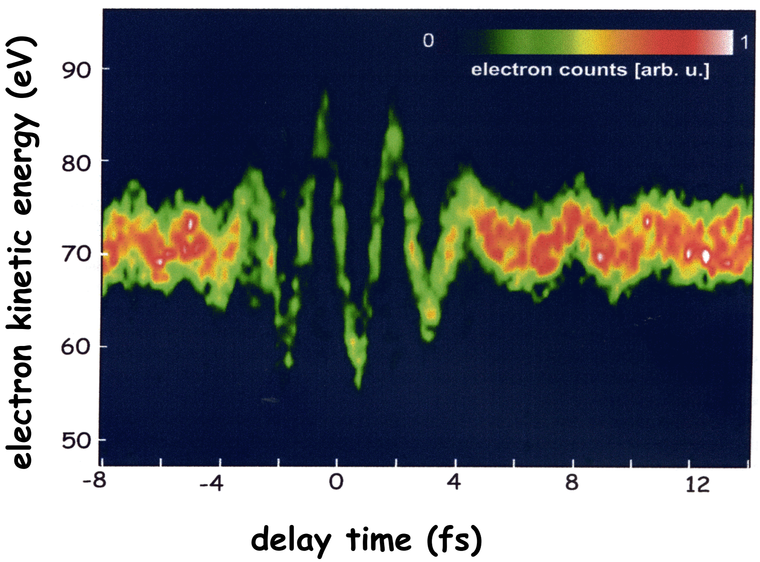
- max. envelope - max. field amplitude
- only one single half-cycle exceeds threshold
- highest energy obtainable



Atto-second Streak Camera

streak camera:
- precisely superimpose few-cycle pulse with XUV-as pulse with a variable delay in a gas target
- XUV pulse ionized atoms,
- imprints its temporal structure to a bunch of photoelectrons
- electrons are asymmetrically deflected by fs pulse (like ultra-fast oscilloscope)
- detector spatially resolves asymmetry which is directly associated with the pulse length

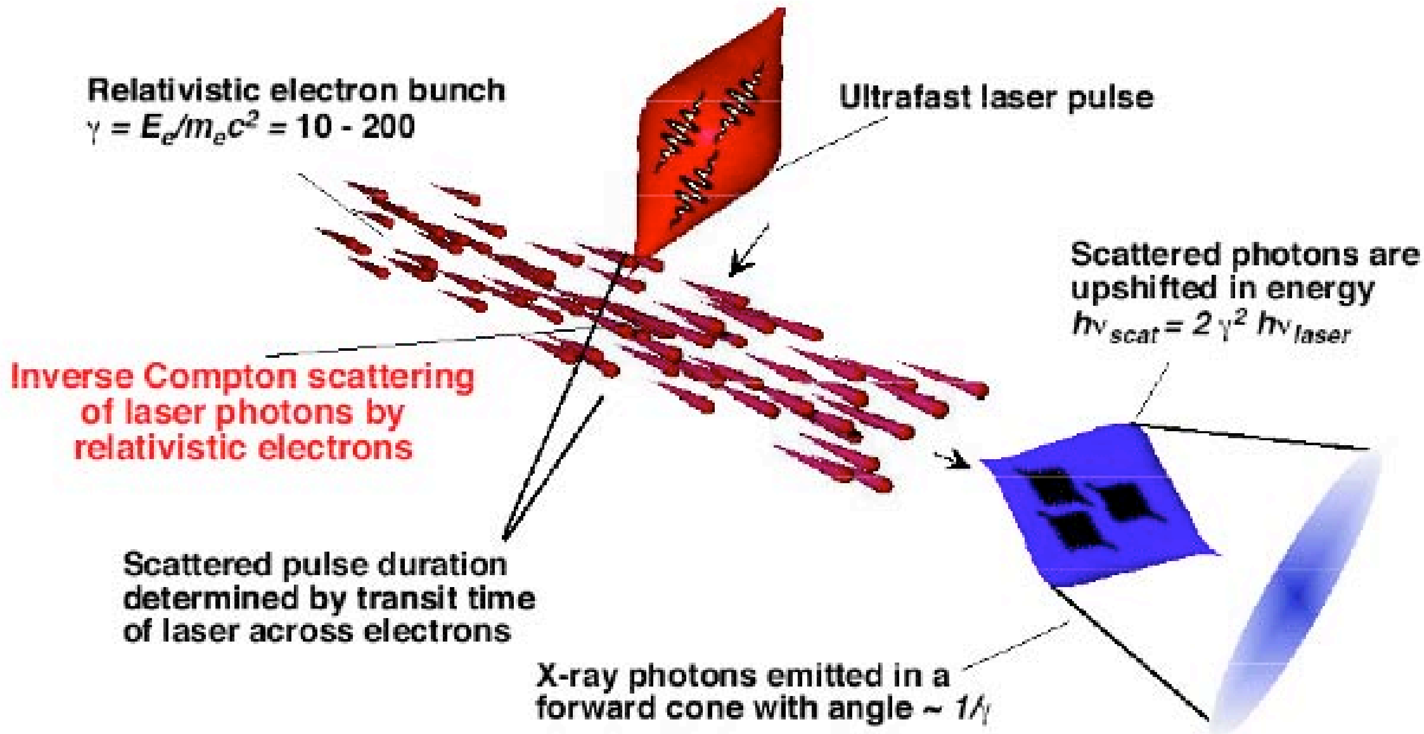




can also measure the electric field of fs pulse:
- change of electron momentum proportional to vector field of laser pulse
- measure electron kinetic energy
- change delay of the two pulses

-> scan electric field

measuring of the electron bunch length: inverse Compton scattering



Thank you for your attention!