Lumière Extrême
L' Optique Relativiste
et applications
EA 572 Part.1

Ecole Polytechnique

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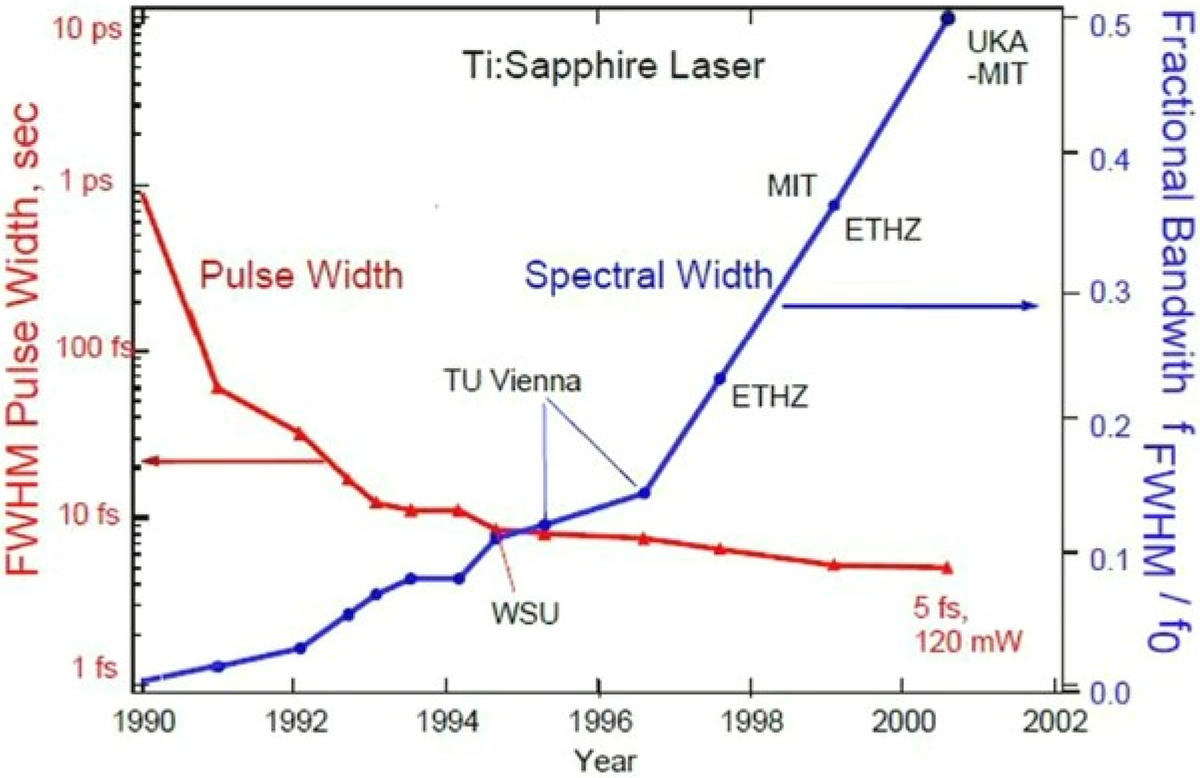
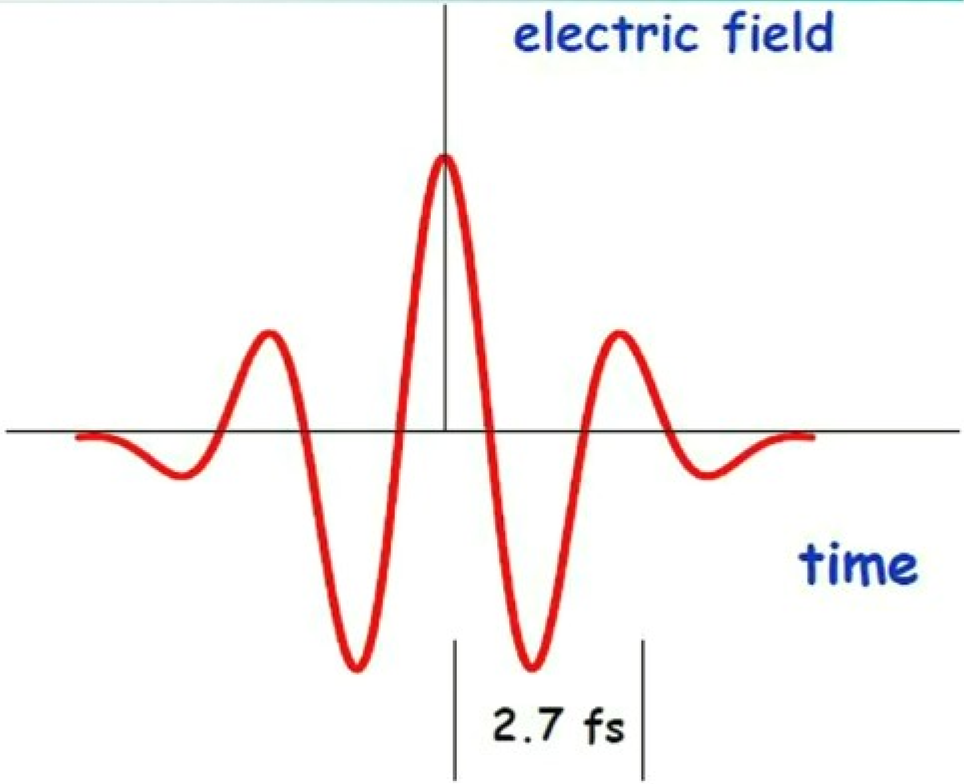
Durée des Impulsions depuis 1990

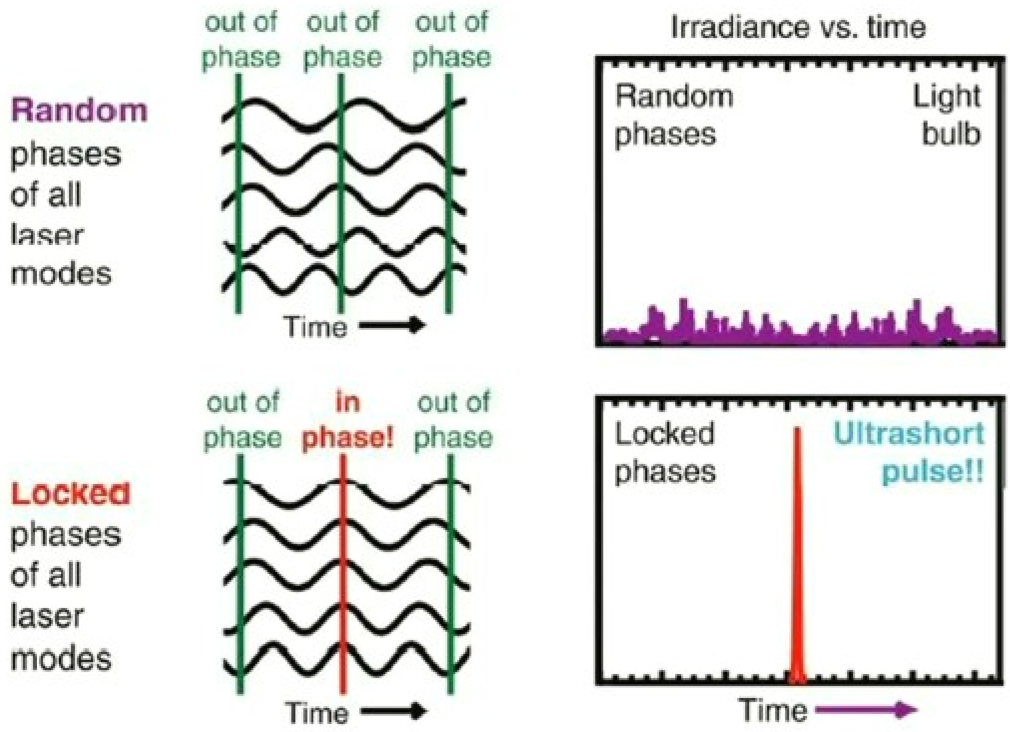


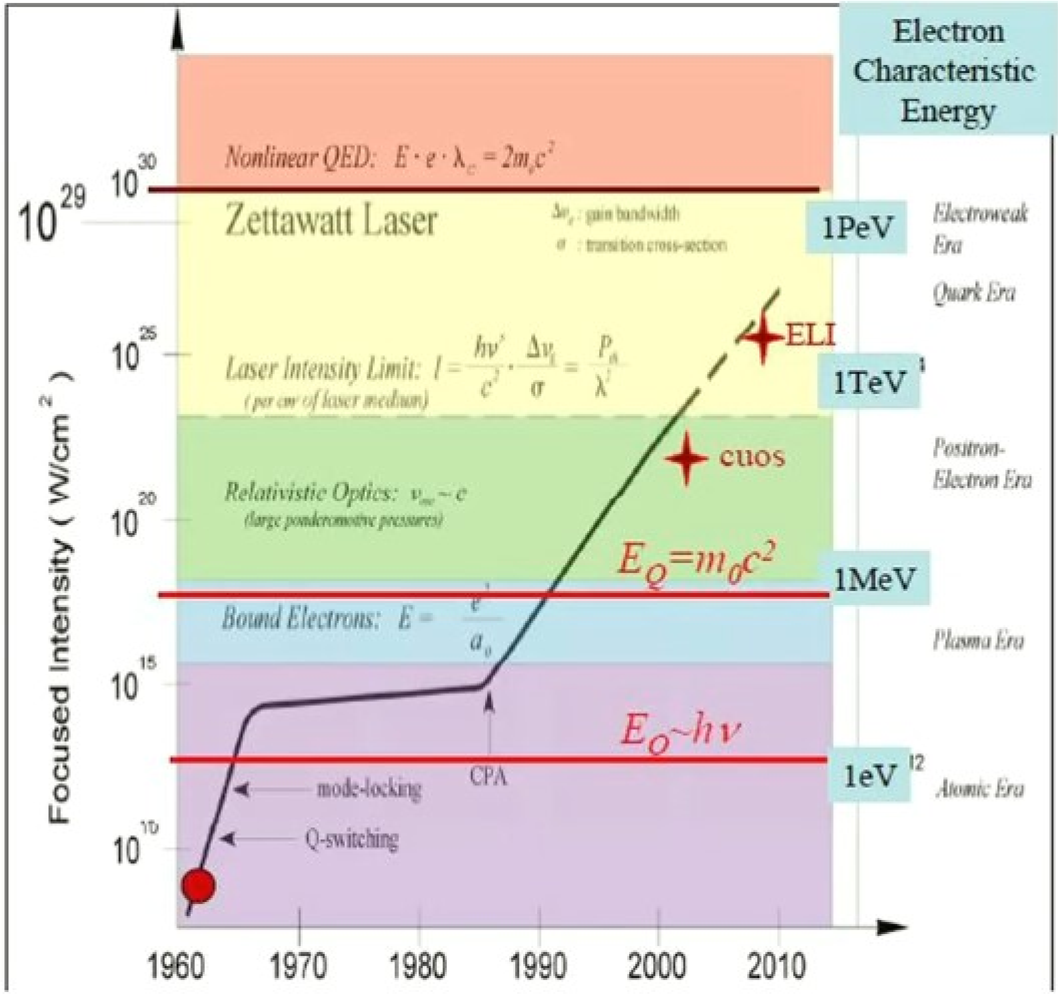
Shortest laser pulse today:
5 fs = 2 cycles of the electric field



Generating short pulses = “mode-locking”

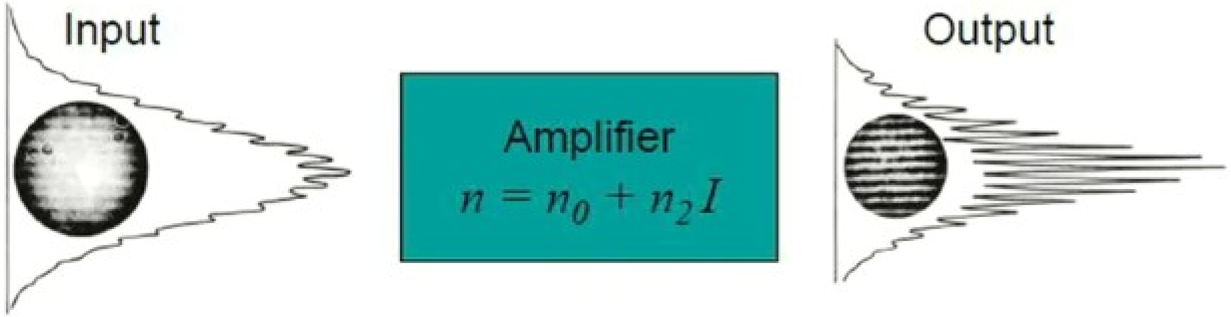
•Locking the phases of the laser modes yields an ultrashort pulse.





Electron Characteristic Energy
Nonlinear QED: $E \cdot e \cdot \lambda_C = 2m_ec^2$
Zettawatt Laser
$\Delta\nu_g$: gain bandwidth
σ : transition cross-section
Laser Intensity Limit: $I = \frac{h\nu'}{c^2} \cdot \frac{\Delta\nu_g}{\sigma} = \frac{P_{th}}{\lambda^2}$
(per cm² of laser medium)
Relativistic Optics: $v_{osc} \sim c$
(large ponderomotive pressures)
Bound Electrons: $E = \frac{e}{a_0}$
$E_Q = m_0c^2$
$E_Q \sim h\nu$
ELI
cuos
CPA
mode-locking
Q-switching
1PeV
1TeV
1MeV
1eV
Electroweak Era
Quark Era
Positron-Electron Era
Plasma Era
Atomic Era
Focused Intensity (W/cm²)
10^{29}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
1960
1970
1980
1990
2000
2010

Small-Scale Self-Focusing



Instabilities grow with a maximum growth rate:

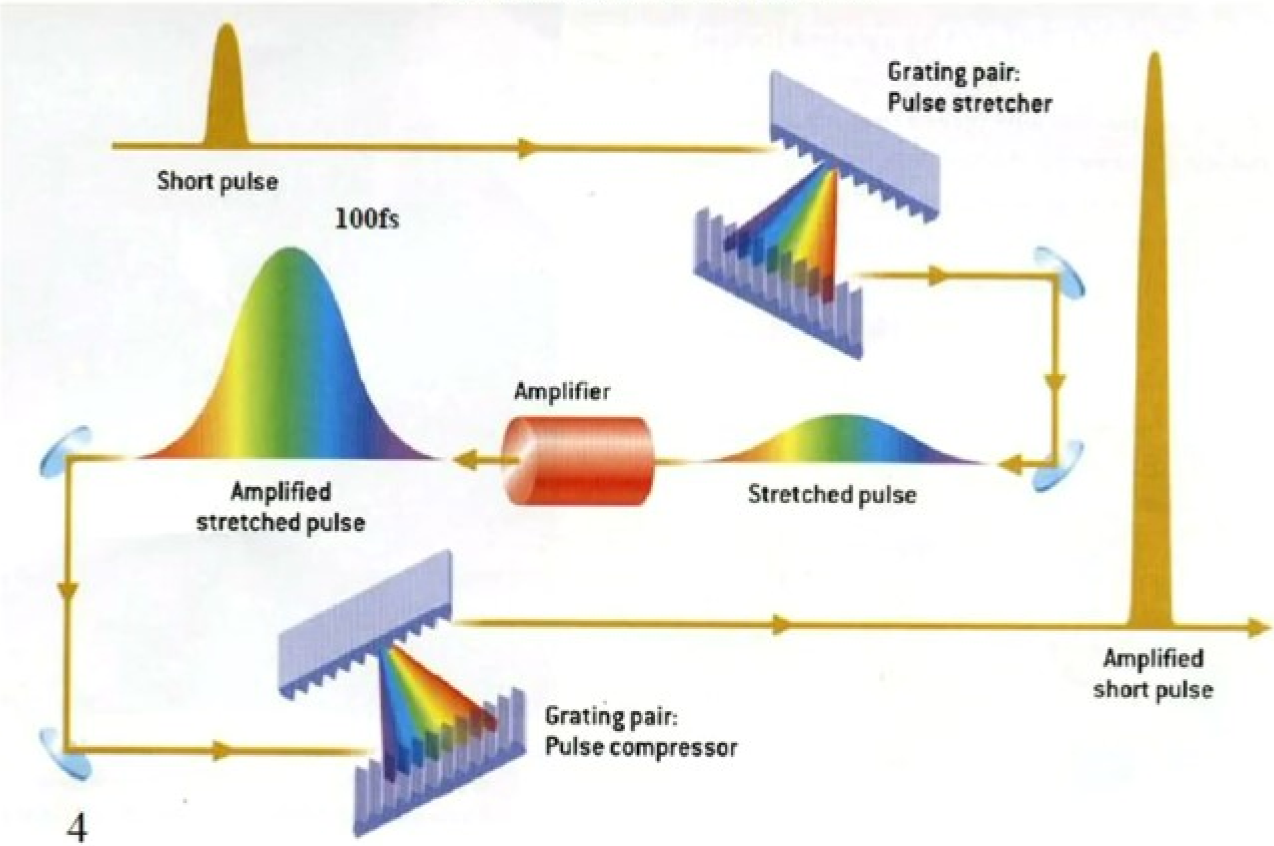
$$g_{\max} = \frac{2\pi}{\lambda}\left(\frac{n_2 I}{n_0}\right)$$

B-integral < 3 for good beam quality:

$$B = \frac{2\pi}{\lambda}\int_0^L n_2 I(z)\,dz$$

Chirped Pulse Amplification

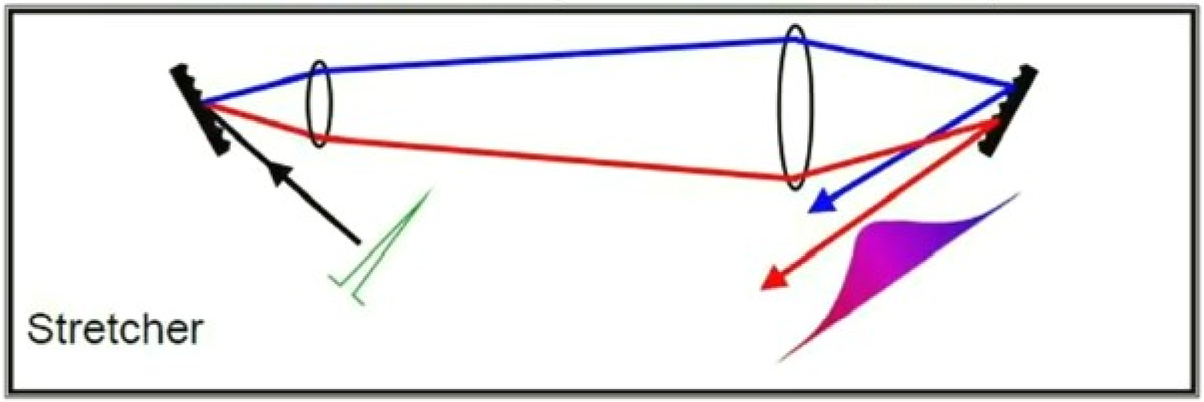
D. Strickland and G. Mourou 1985

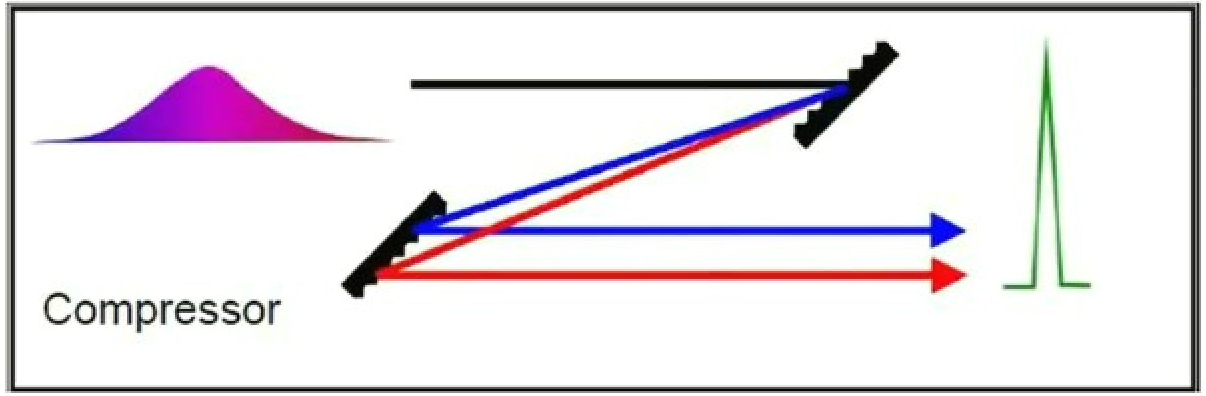


Matched Stretcher-Compressor

1000 Times Expansion/Compression of Optical Pulses for Chirped Pulse Amplification"

M. Pessot, P. Maine, and G. Mourou, *Optics Commun.* **62**, 419-421 (June 1987)

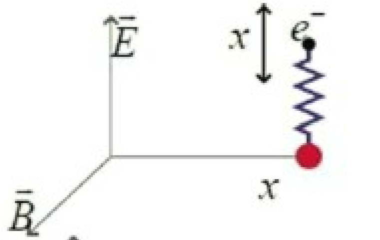




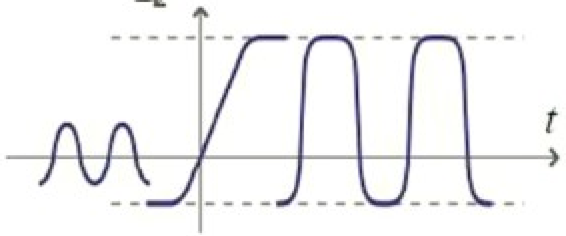
Bound Electron Nonlinear Optics

$\boxed{\vec{F} = q\vec{E}}$ $\quad F \not\propto x$

$v \ll c$

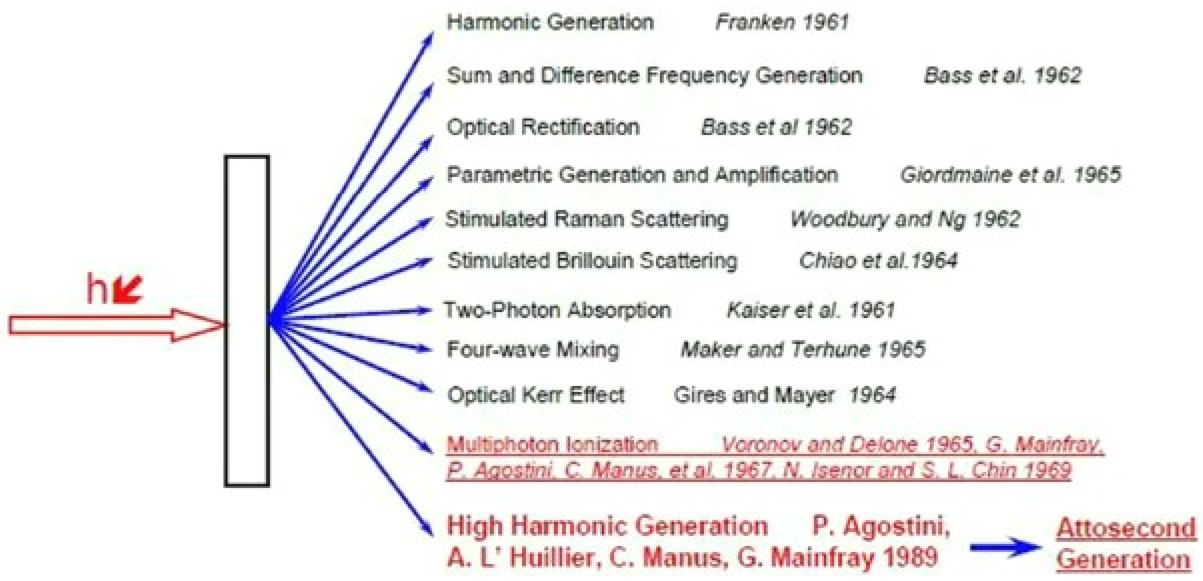


The field necessary corresponds to $h\nu/\lambda^3$



- *Harmonics*
- *Optical Rectification*
- *Self-focusing*

Nonlinear Optics *(bound electron)*



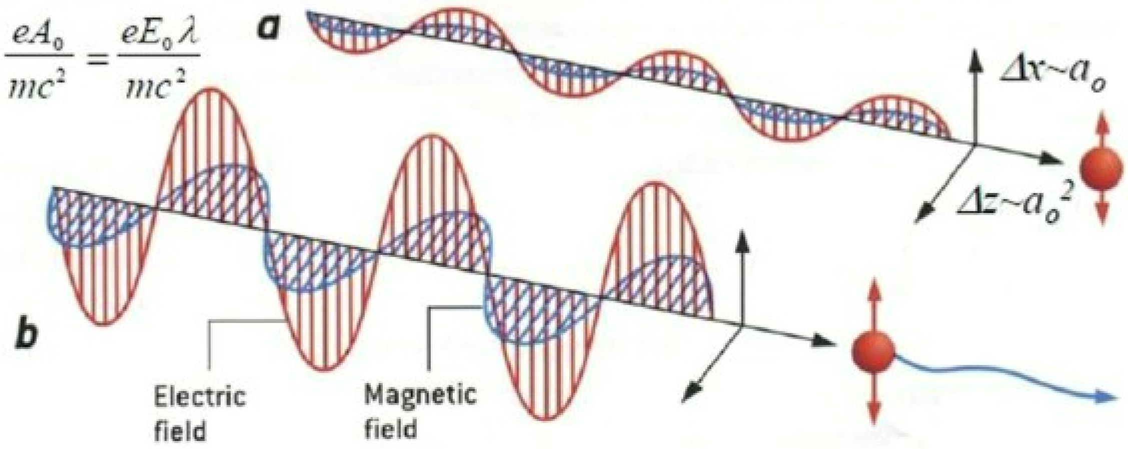
Relativistic Optics

$$\bar{F} = q\left(\bar{E} + \left(\frac{\bar{\mathrm{v}}}{c} \wedge \bar{B}\right)\right)$$

a) Classical optics v<<c, *b) Relativistic optics v~c*

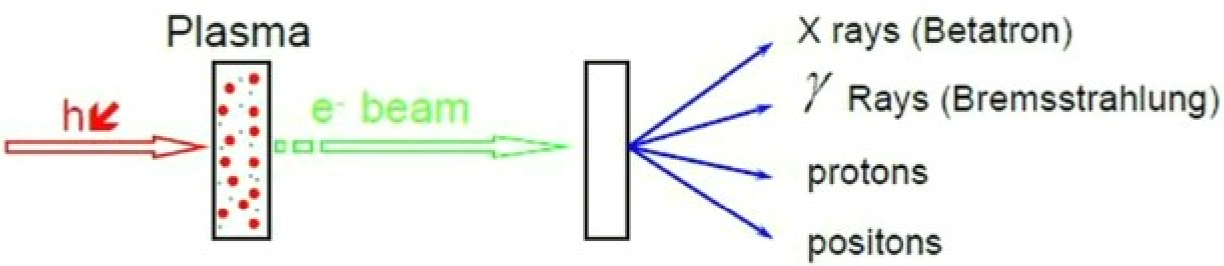
$a_0 << 1,\ a_0 >> a_0^2$ $a_0 >> 1,\ a_0 << a_0^2$

$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$

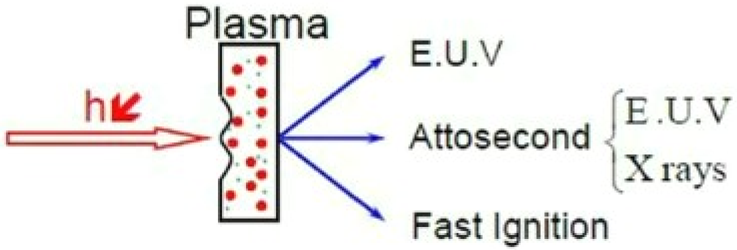


Relativistic Optics

Strong Motion of Matter



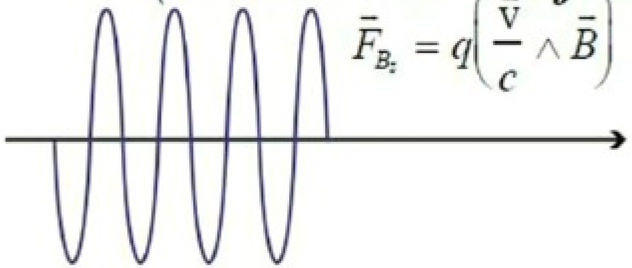
Large Laser Pressure

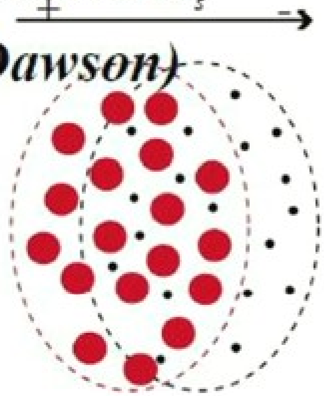


Relativistic Rectification

(Wake-Field Tajima, Dawson)

$$\bar{F}_{B_z} = q\left(\frac{\bar{\mathrm{v}}}{c} \wedge \bar{B}\right)$$





1) $\bar{\mathrm{v}} \wedge \bar{B}$ pushes the electrons.
2) The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough) $E_s = \dfrac{c\gamma m_o \omega_p}{e} = \sqrt{4\pi\gamma m_o c^2 n_e}$
3) The electrostatic field $E_s \approx E_L$

Relativistic Rectification

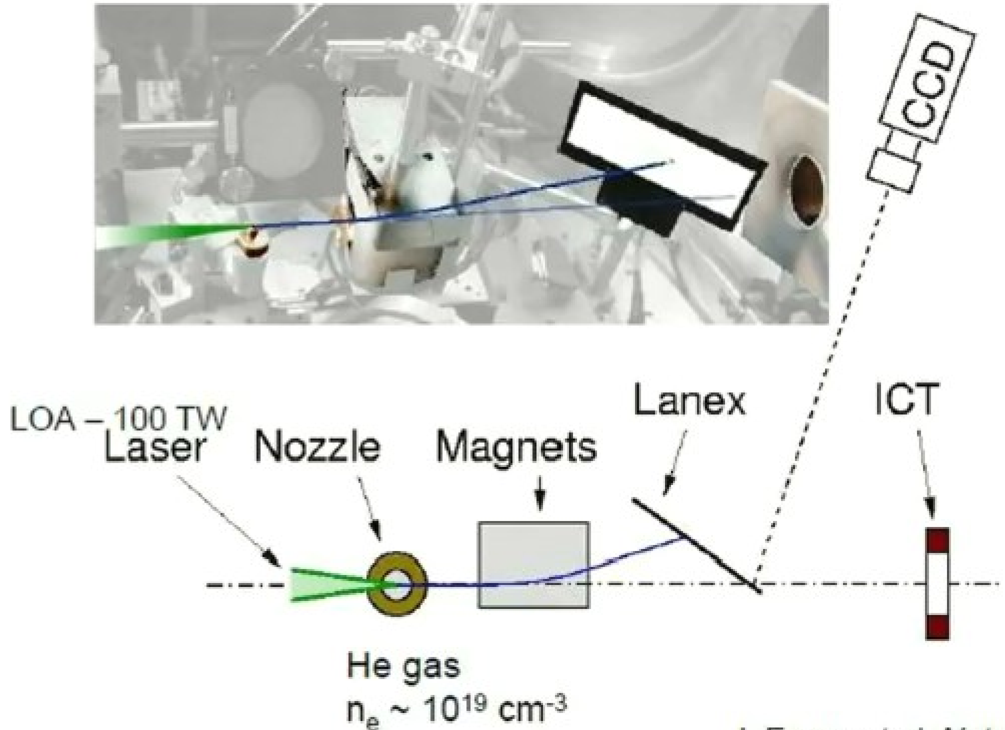
-***Ultrahigh Intensity Laser is associated with Extremely large E field.***

$$\boxed{E_L^2 = \underbrace{Z_0}_{\text{Medium Impedance}} * \underbrace{I_L}_{\text{Laser Intensity}}}$$

$I_L = 10^{18} W / cm^2$ $\qquad$ $E_L = 2 \quad TV / m$

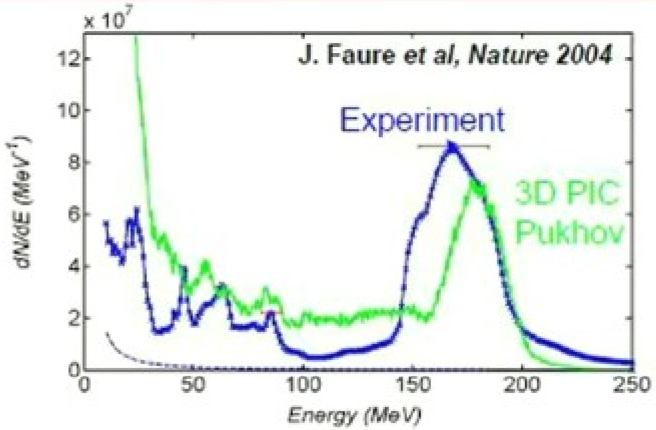
$I_L = 10^{23} W / cm^2$ $\qquad$ $E_L = .6\, PV / m \quad (0.6\, 10^{15} V / m)$

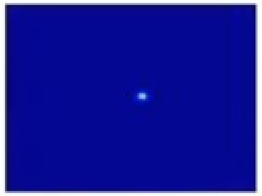
Recent results on electrons acceleration - Setup



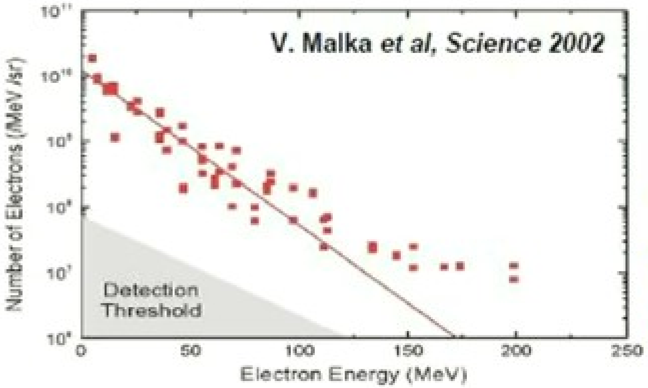
J. Faure *et al, Nature 2004*

Recent results on electrons acceleration

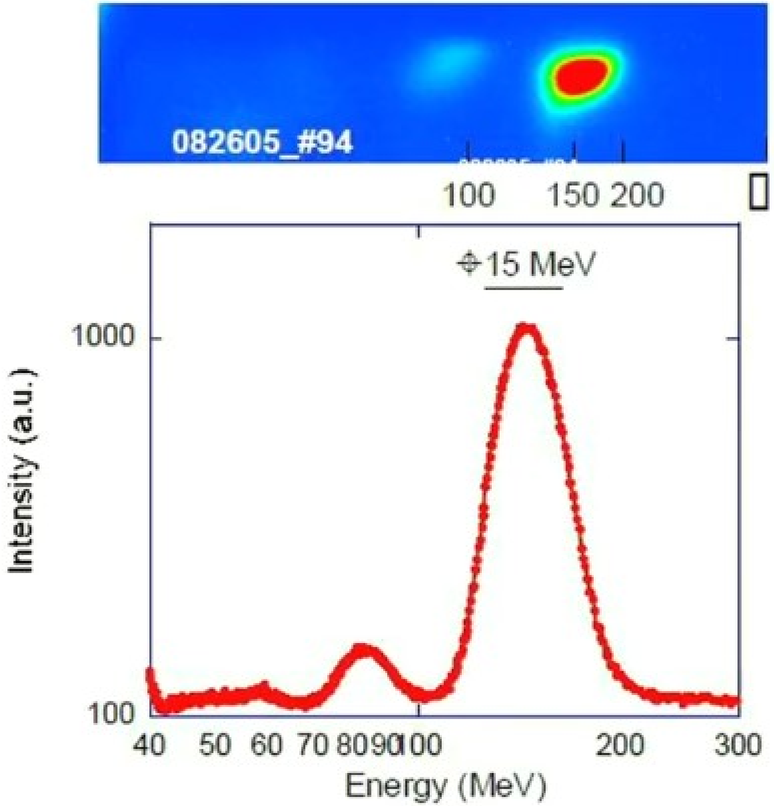




Divergence
< 6 mrad



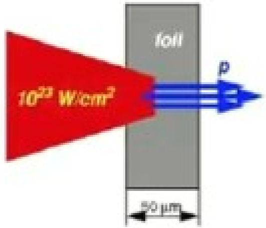
Quasi-monochromatic beam with E_{max}=160 MeV at n_e=2.10^{19} cm^{-3}

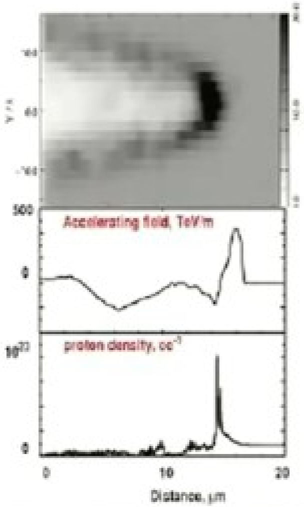


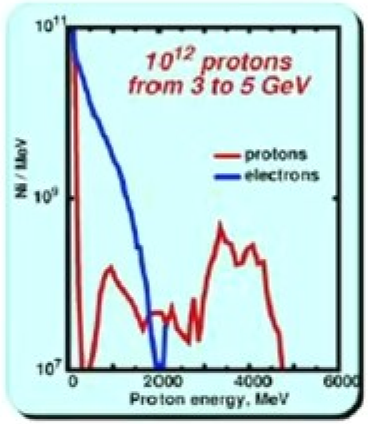
Virtual Laser Plasma Lab

5 GeV proton bunch at solid state density

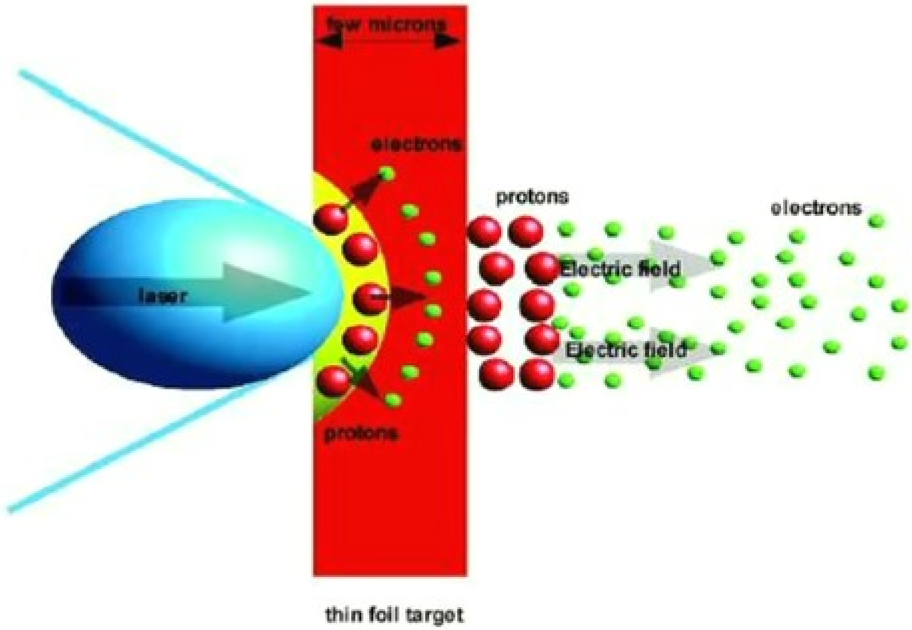
3d PIC simulations, A.Pukhov, Theorie, MPQ,







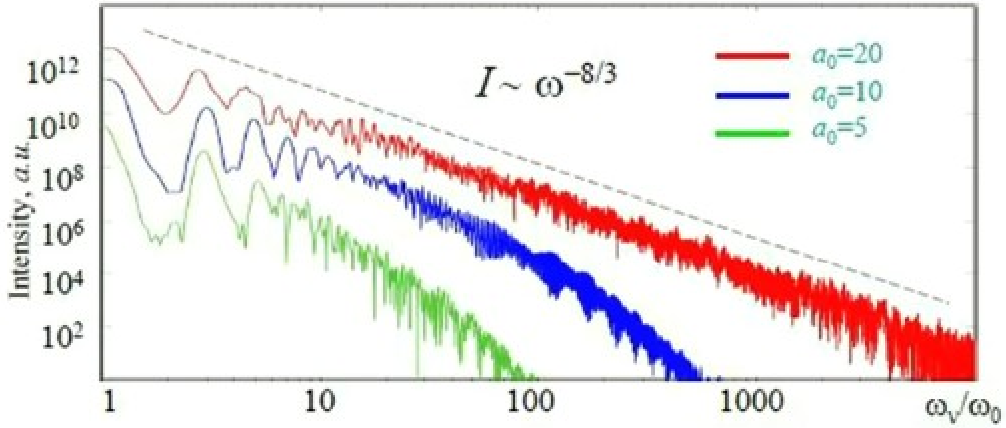
Front and back acceleration mechanisms



Peak energy scales as : $E_M \sim (I_L \lambda)^{1/2}$

Reflected radiation spectra: the slow power-law decay

1D simulation



Gordienko, et al., Phys. Rev. Lett. 2004

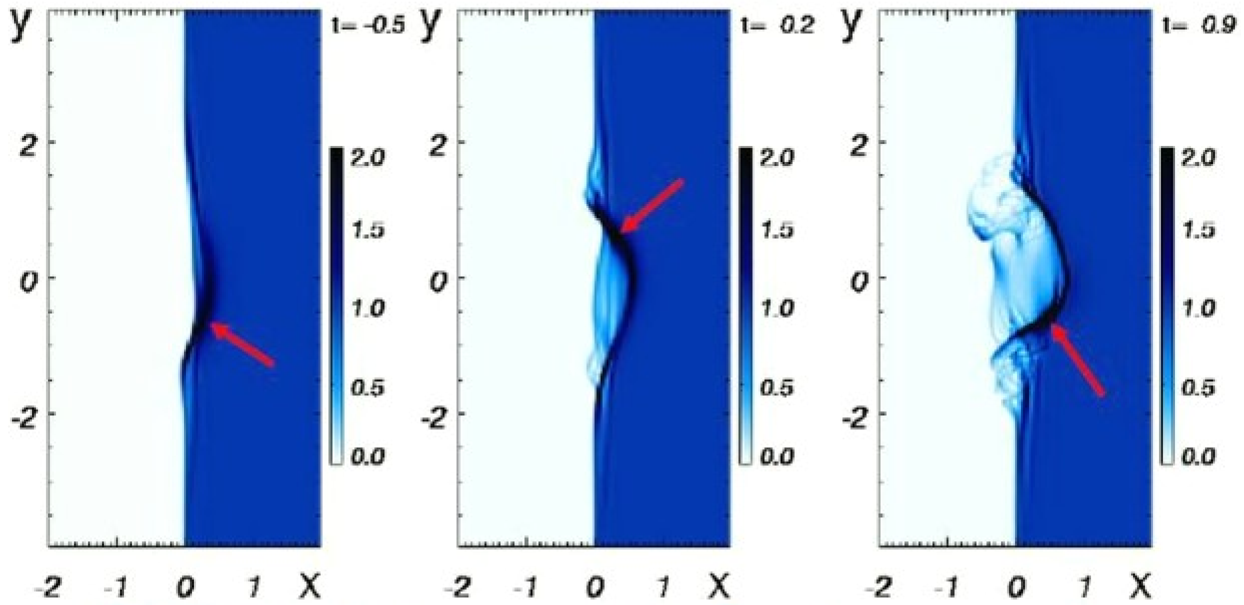
The Gaussian laser pulse $a=a_0\exp[-(t/\tau)^2]\cos\omega_0 t$ is incident onto an overdense plasma layer with $n=30n_c$.

The color lines correspond to laser amplitudes a_0=5,10,20.

The broken line marks the analytical scaling $I \sim \omega^{-8/3}$.

Possibility to produce zeptosecond pulses!!!

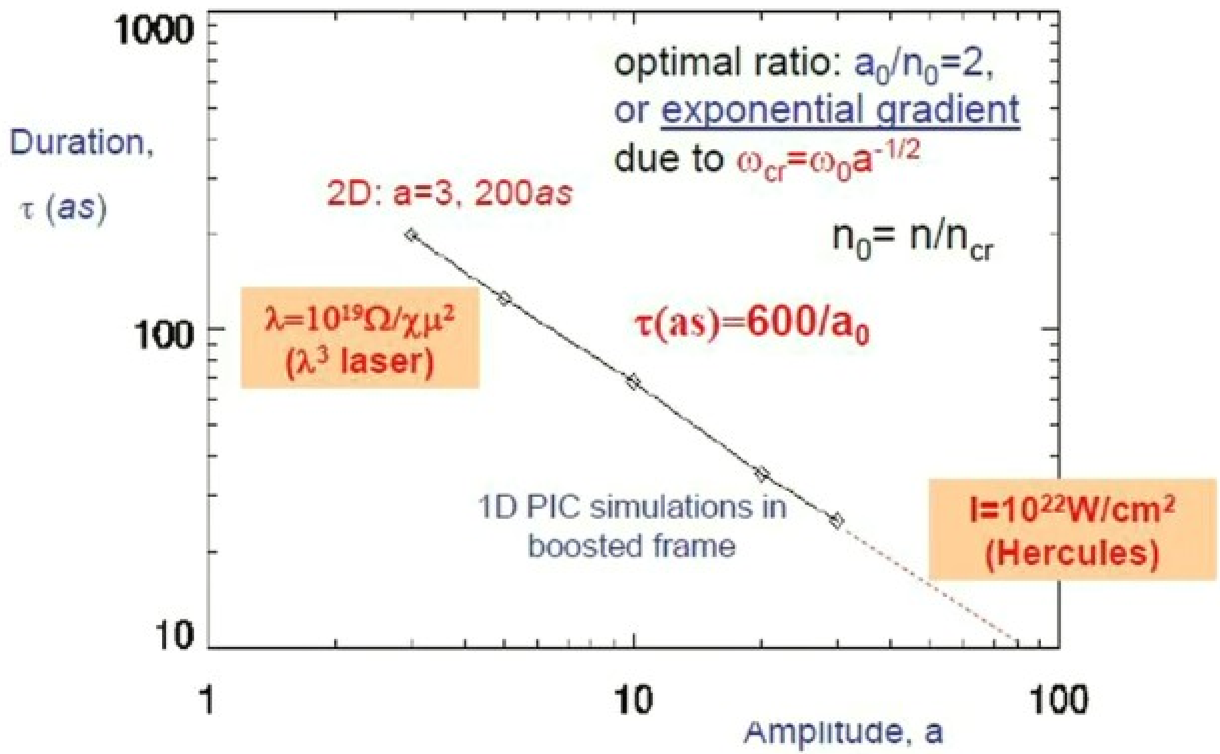
Moving plasma profile deflecting the isolated attosecond pulses at the instants of their generation



Relativistic electrons create the Doppler compression

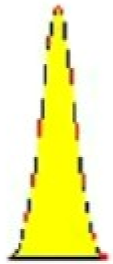
N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou, "Relativistic generation of isolated attosecond pulses in a λ^3 focal volume," *Phys. Rev. Lett.* **92**, 063902-1 (2004).

Scalable Isolated Attosecond Pulses



Electron bunches of ~100 *as* duration would produce backward CoherentThomson scattering efficiency

- Cross-section for the backward Thomson scattering:
  $\sim N+N(N-1)\exp(-2(k'd')^2)$
  depends on the factor in the exponent: $k'd'=kd(1+V/c)^2\gamma^2$.
- The resulting backward Thomson cross-section
  $\sigma_T N^2 \exp(-8(kd)^2\gamma^4) \sim 10^{-4} \exp(-8(kd)^2\gamma^4)$ cm^2
  is far above the channel cross-section $\sigma_{Ch}=10^{-8}$ cm^2
- Limitation for d and γ:
  $kd < \gamma^{-2}(-0.125 \ln(\sigma_{Ch}/\sigma_T N^2))^{1/2}$
- Attosecond bunches with width
  $d \sim 1/k\gamma^2 \sim (100 \text{ as}) \cdot c$



Bunch:

N particles with Gaussian distribution

η~1 efficiency

$$\gamma_{photon} = \frac{\lambda}{4\gamma^2} \text{ for } \gamma = 100$$

$$\gamma_{\text{photon}} = 40 \text{ keV}$$

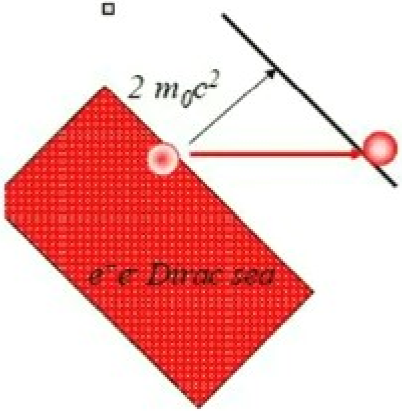
$$\text{For } \gamma = 10^3 \text{ , } \gamma_{\text{photon}} = 6MeV$$

N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou, Attosecond Electron Bunches, *Phys. Rev. Lett.* **93**, 195003 (2004).

Laser-Induced Nonlinear QED

E. Brezin and C. Itzykson Phys. Rev. D2 1191 (1970)

Vacuum can be considered like a dielectric



Schwinger Field $E_s = \dfrac{2m_0c^2}{e\bar{\lambda}_c}$ with $\bar{\lambda}_c = \dfrac{\hbar}{m_0c^2}$

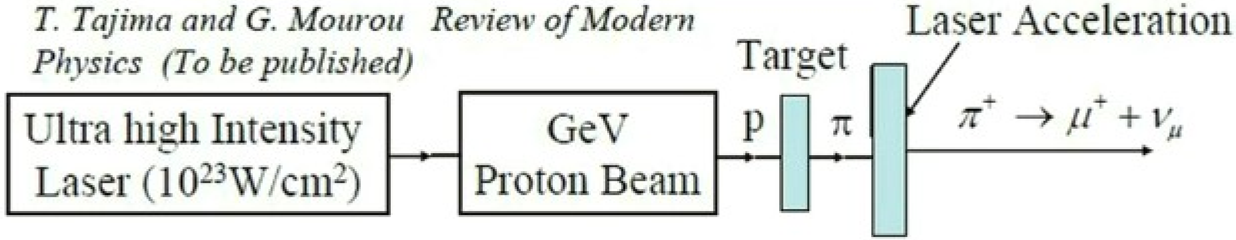
E_s=1.3 10^{16} V/cm

Vacuum Tunneling $W \propto \exp\left(-\dfrac{\pi E_s}{E}\right)$

$I_s=10^{30} W/cm^2$

Unstable Particle Acceleration Muon and neutrino Beams

T. Tajima and G. Mourou Review of Modern Physics (To be published)



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Pions have 20ns lifetime (6m). They can only be accelerated up to 100MeV during this time with conventional technology. Their mass is ~200MeV, to increase their lifetime 100times, to 2μs, we need to increase their energy by 100 to 20GeV. This can be achieved with laser technology over only 20μm.

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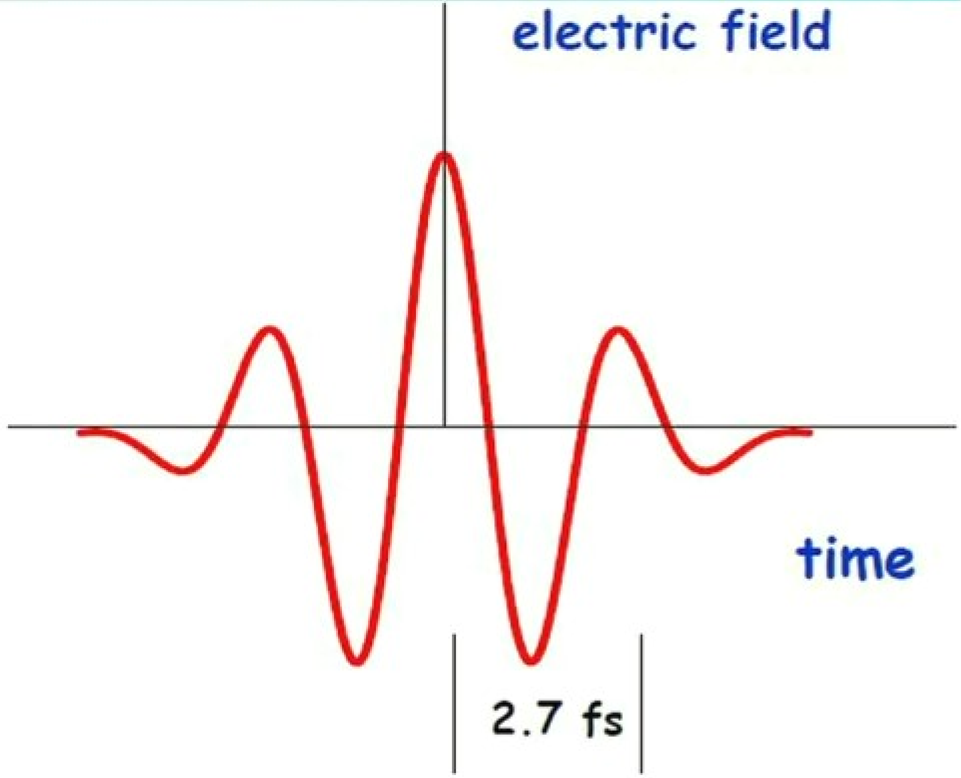
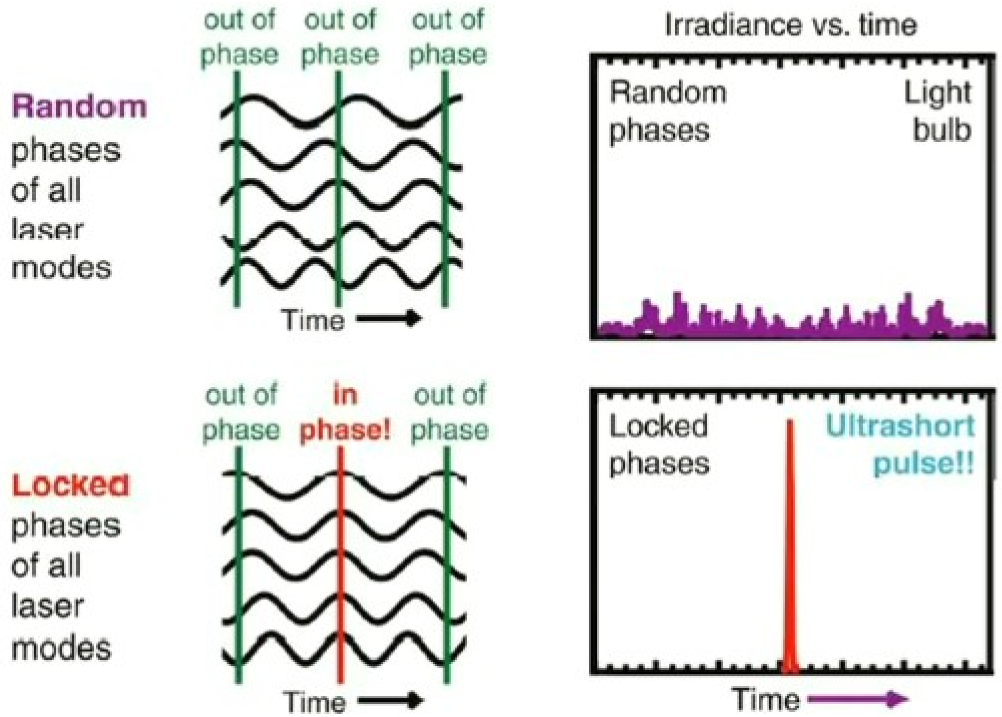
Shortest laser pulse today:
5 fs = 2 cycles of the electric field



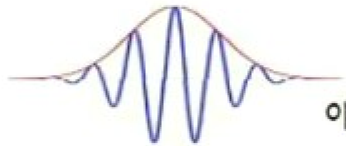
Generating short pulses = "mode-locking"

•Locking the phases of the laser modes yields an ultrashort pulse.



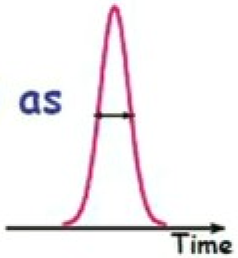
Can we make « attosecond » pulses?

5 fs @ 800 nm
$\Delta\omega$ = 1.5 ev

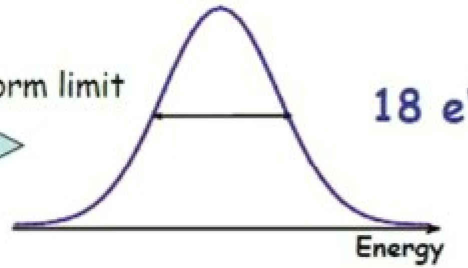


2 cycles at
optical frequencies

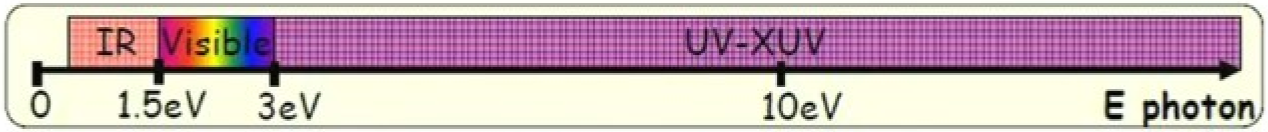
100 as



Fourier transform limit



18 eV

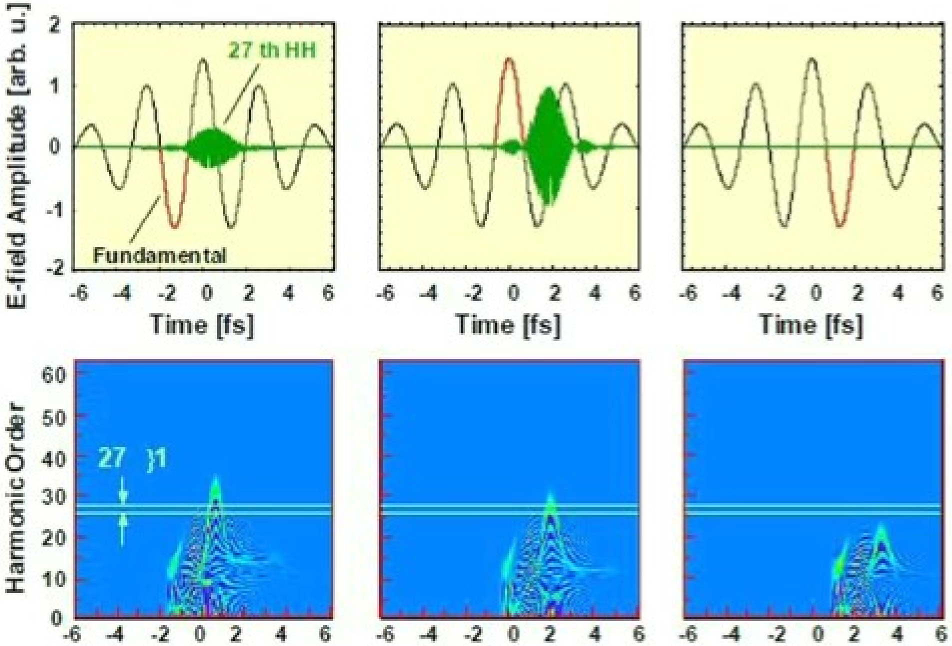


Need to go into the XUV…

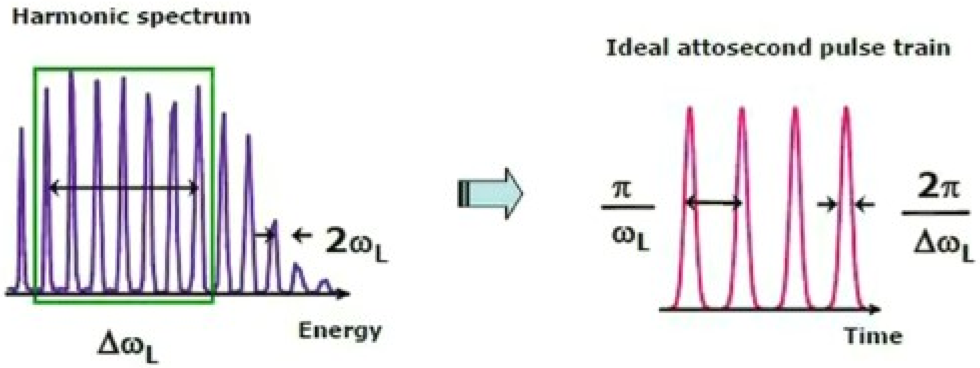
No lasers… go back to laser intensity

Higher Harmonic Generation During a Half Cycle of Driving Field

1.8 x10^{14} W/cm^2, 5.2 fs (FWHM), 785 nm in Ar



Harmonics: source of attosecond pulses



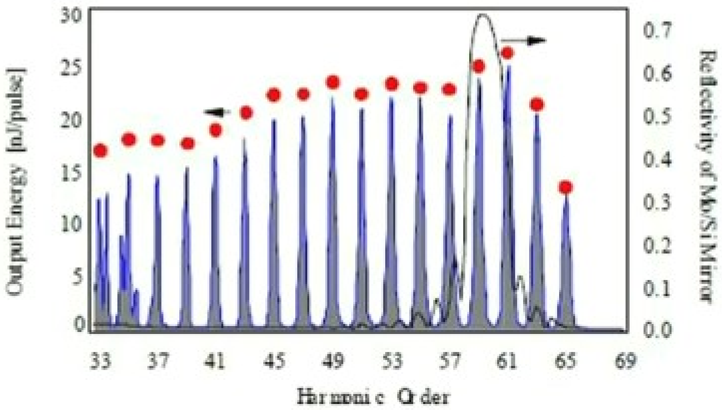
$$\boxed{\tau \approx \frac{T_0}{2N}}$$

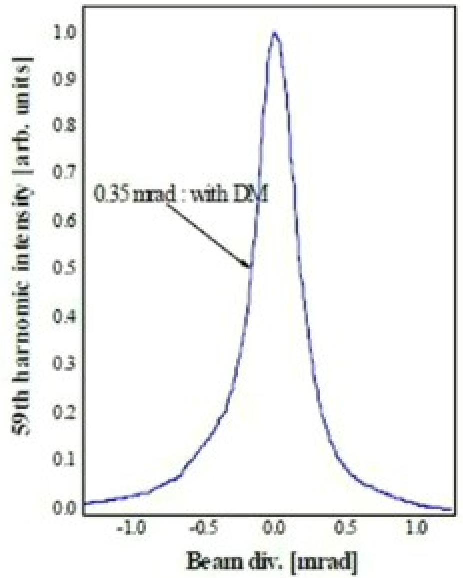
→ τ < 10 as with 300 phase-locked harmonics !

Harmonic output in Ne

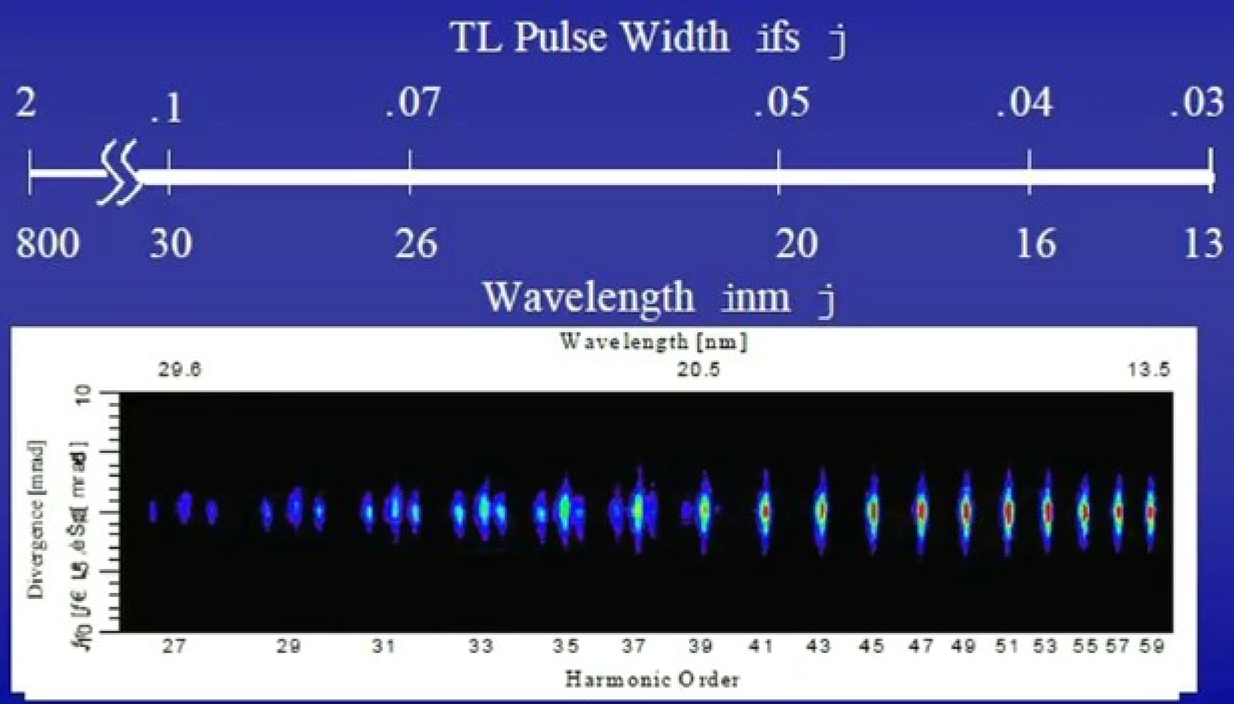
E = 51 mJ, ϕ = 21 mm
P_{Ne} = 9 Torr, L_{med} = 4 cm

13 nm harmonics with DM
Output energy : 50 nJ
C.E. : 1 x 10^{-6}





High-Order Harmonics in Ne

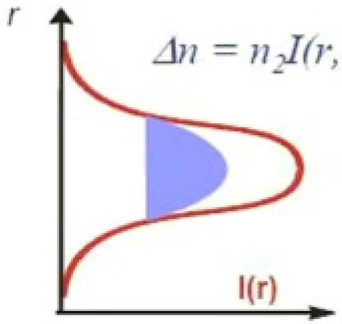


BASIC NON-LINEAR PROCESSES

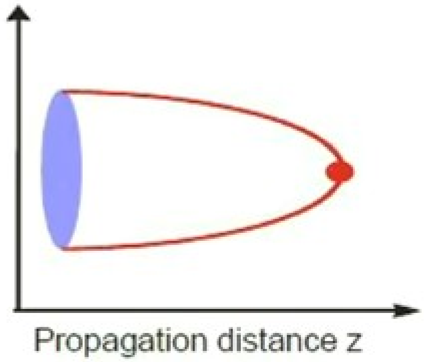
(1) Self-Focusing

Optical Kerr Effect : $n = n_0 + n_2 I(r,t)$

($n_2 = 3\ 10^{-19}\ cm^2/W$ in air)



Gaussian Profile



Catastrophic Collapse !!

BASIC NON-LINEAR PROCESSES

(2) Multi-Photon Ionization (MPI) and Plasma Defocusing

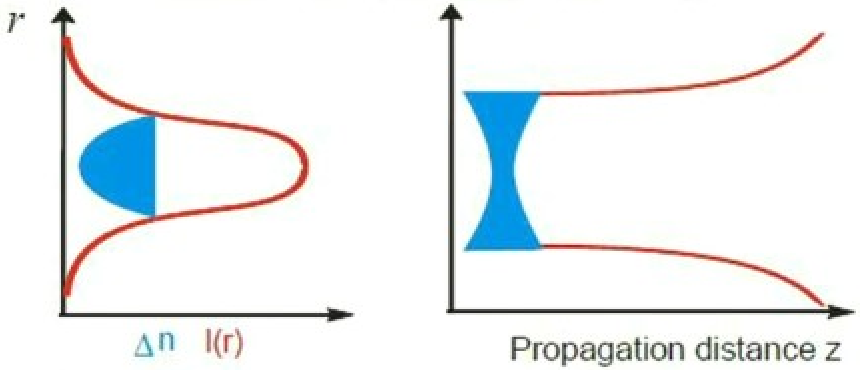
$$\text{MPI} \rightarrow \quad \Delta n = -\frac{\rho(I)}{\rho_c}$$

$\rho(I)$: electronic density ; $\rho_c = 2 * 10^{21} \text{cm}^{-3}$

With: $$\frac{\partial \rho}{\partial t} = \sigma |E|^{2\alpha} (N - \rho)$$

N : neutral density, σ:cross-section

α : # photons for MPI of N_2/O_2 =10 (800nm)



Negative Lens *Defocusing*