# Extreme Light Infrastructure: Attosecond Physics to Relativistic and Ultra-Relativistic Optics

*Roumanian Institute of Atomic Physics*

*20/11/2008*

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# *Optics Horizon*

***This field does not seem to have natural limits, only horizon.***

# Two large Laser Infrastructures Have Been Selected to be on the ESFRI (European Strategic Forum on Research Infrastructures) Roadmap


"a - HIPER, civilian laser fusion research (using the fast ignition scheme ) and all applications of ultra high energy laser

"b - ELI, reaching highest intensities (Exawatt) and applications

**ELI has been the first Infrastructure launched by Brussels November 1st 2007**

*Why should we build an Extreme Light Infrastructure?*

# *Science* (1 july 2005)

## *"100 questions spanning the science…"*

- **1) Is ours the only universe?**
- **2) What drove cosmic inflation?**
- 3) **When and how did the first stars and galaxies form?**
- **4) Where do ultrahigh-energy cosmic rays come from?**
- **5) What powers quasars?**
- 6) **What is the nature of black holes?**
- **7) Why is there more matter than antimatter?**
- 8) **Does the proton decay?**
- **9)What is the nature of gravity?**
- **10) Why is time different from other dimensions?**
- 11) **Are there smaller building blocks than quarks?**
- **12) Are neutrinos their own antiparticles?**
- **13) Is there a unified theory explaining all correlated electron systems?**
- 14) **What is the most powerful laser researchers can build?** Theorists say an intense enough laser field would rip photons into electron-positron pairs, dousing the beam. But no one knows whether it's possible to reach that point.
- **15) Can researchers make a perfect optical lens?**
- **16) Is it possible to create magnetic semiconductors that work at room temperature?**

# Contents

- The Peak Power-Pulse Duration conjecture
- Relativistic Optics: A parallel with Bound Electron Nonlinear Optics
- Relativistic Rectification(wake-field) the key to High energy electron beam, proton beam, x-ray and $\gamma$-beams
- Source of attosecond photon and electron pulses
- Generation of Coherent x-ray by Coherent Thomson scattering
- A route to the critical (Schwinger)field
- Few examples of applications to High energy Physics

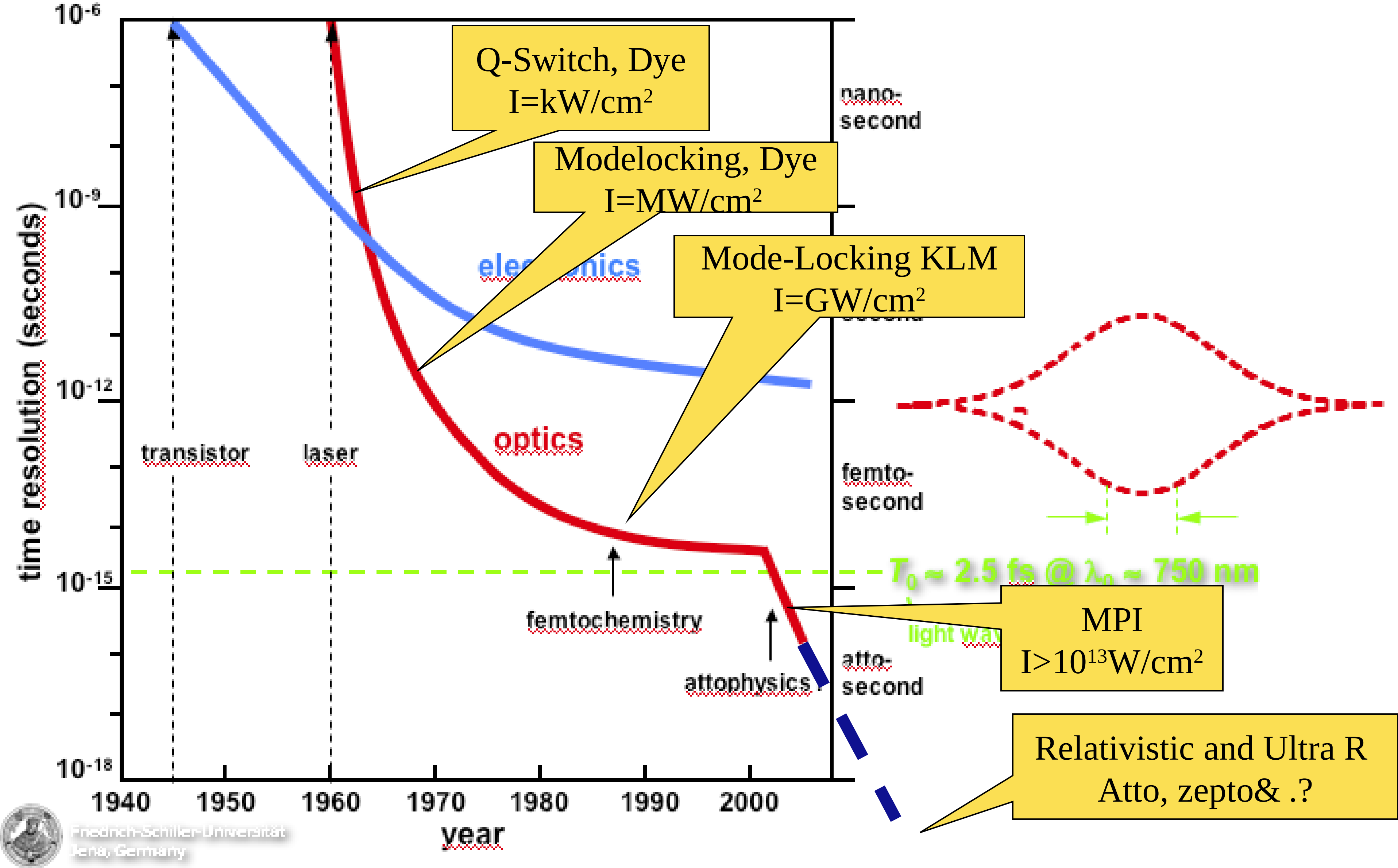
General Relativity, Hawking Radiation, Extradimensions.

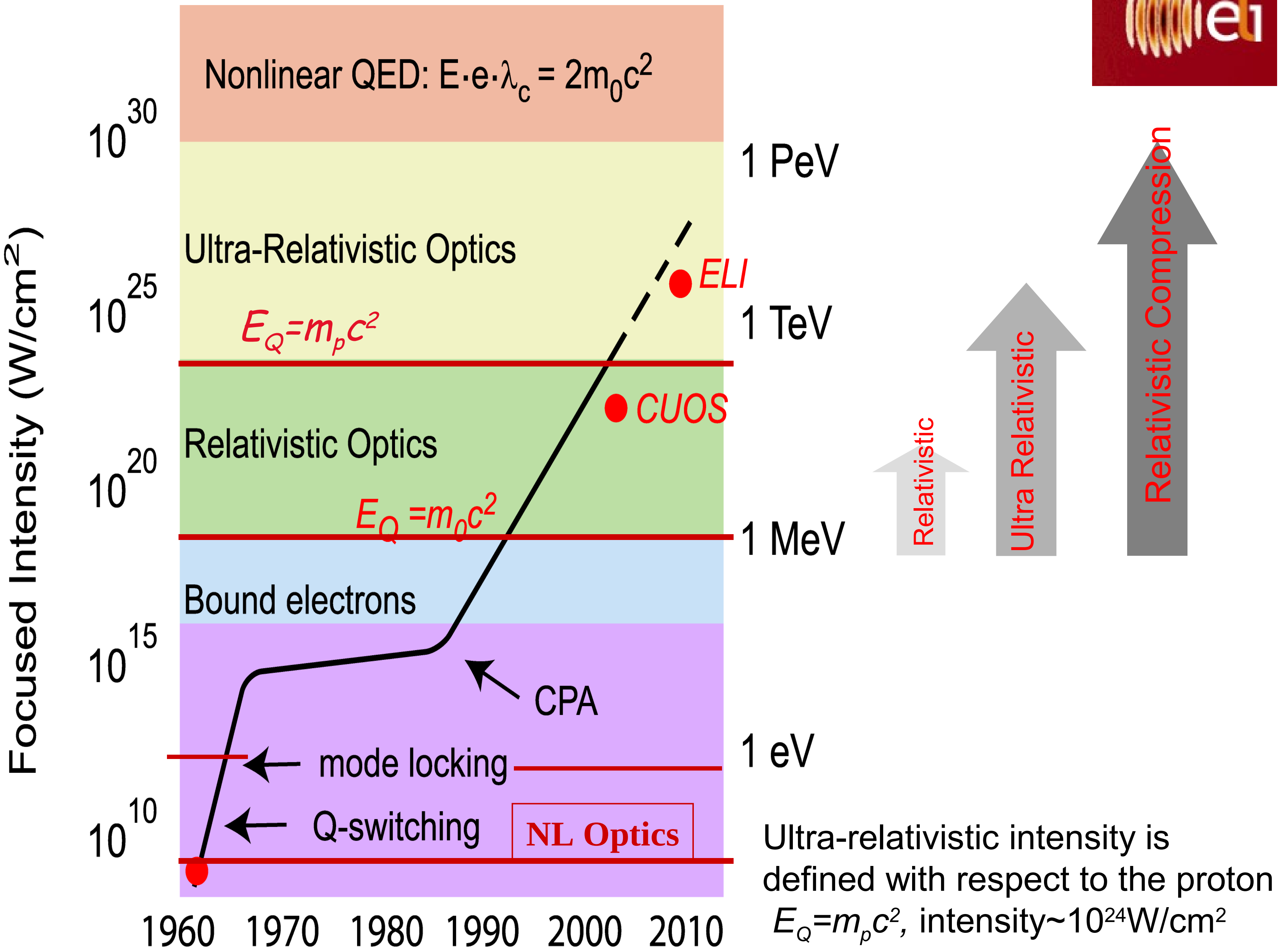
ELI(Extreme Light Infrastructure) An Exawatt laser Infrastructure on the Large Infrastructure Road Map of Europe

# Peak Power -Pulse Duration Conjecture

1) To get high peak power you must decrease the pulse duration.
2) To get short pulses you must increase the intensity

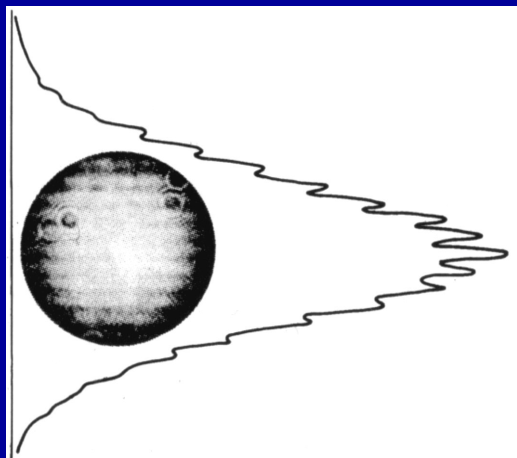
# Laser Pulse Duration vs. Intensity






Ultra-relativistic intensity is defined with respect to the proton $E_Q=m_pc^2$, intensity~$10^{24}$W/cm$^2$

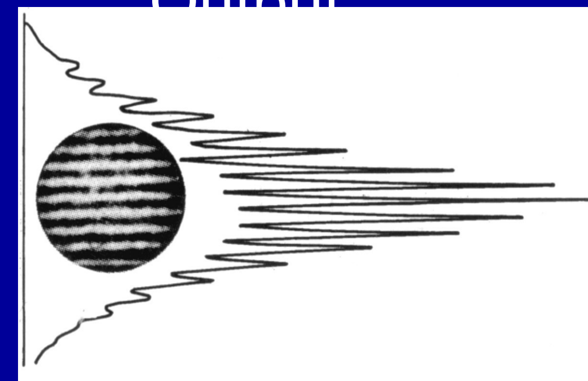
# Small-Scale Self-Focusing



Amplifier

$n = n_0 + n_2 I$

Output



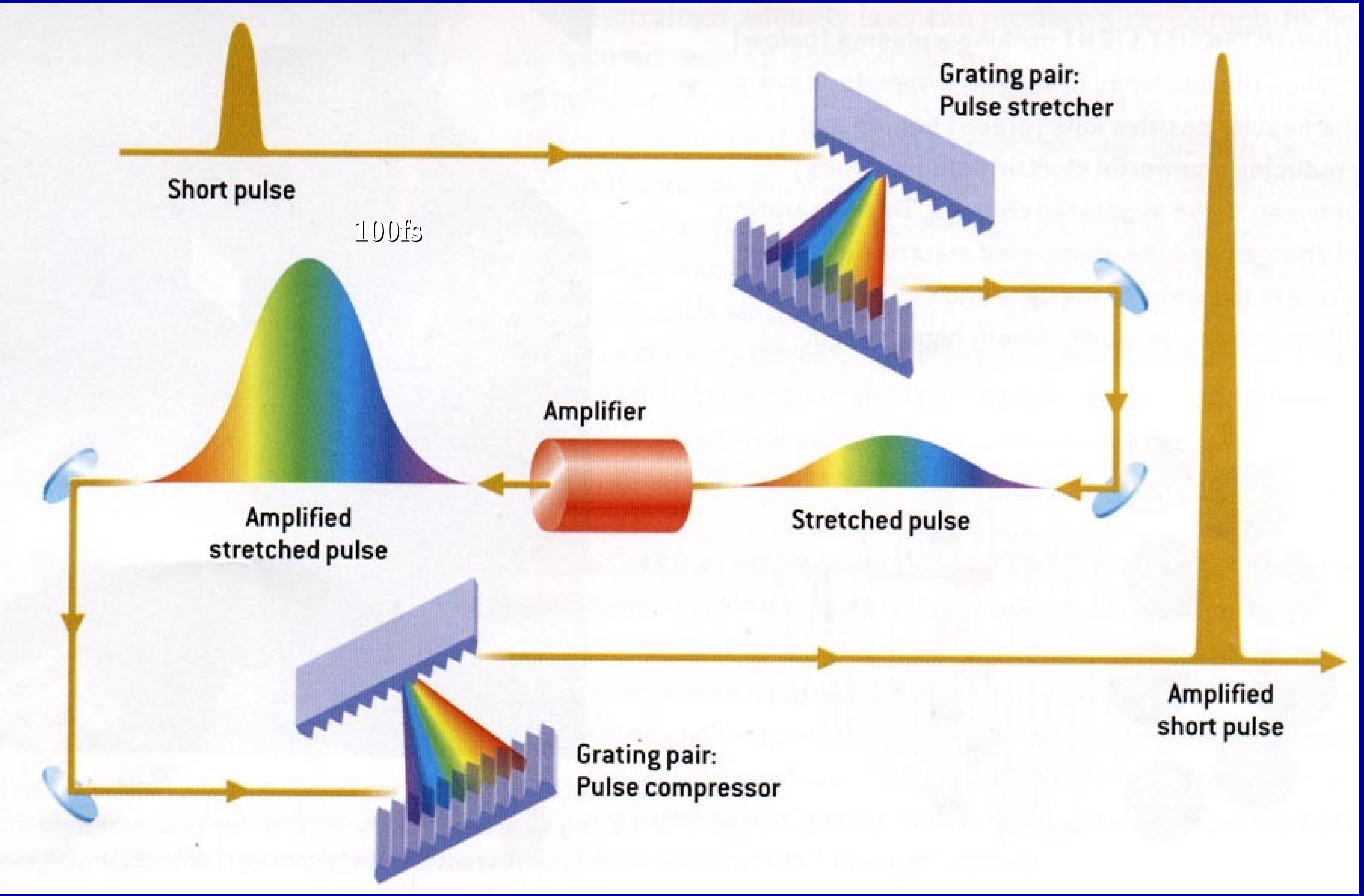
Instabilities grow with a maximum growth rate:

B-integral < 3 for good beam quality:

$$B = \frac{2p}{l} \int_0^L n_2 I(z) dz$$

# Chirped Pulse Amplification

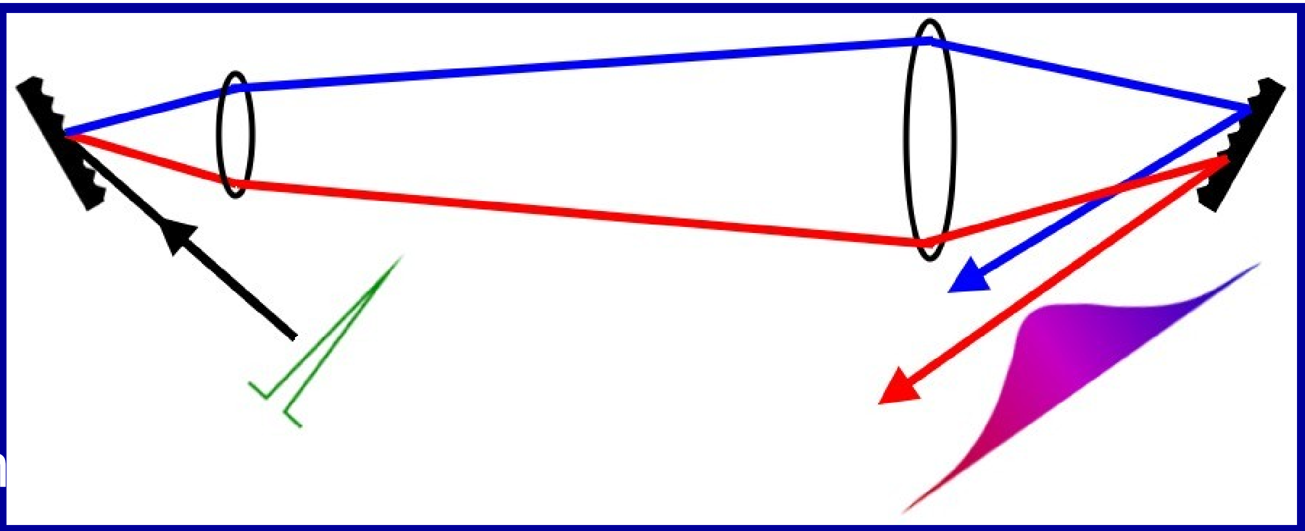
**D. Strickland and G. Mourou 1985**



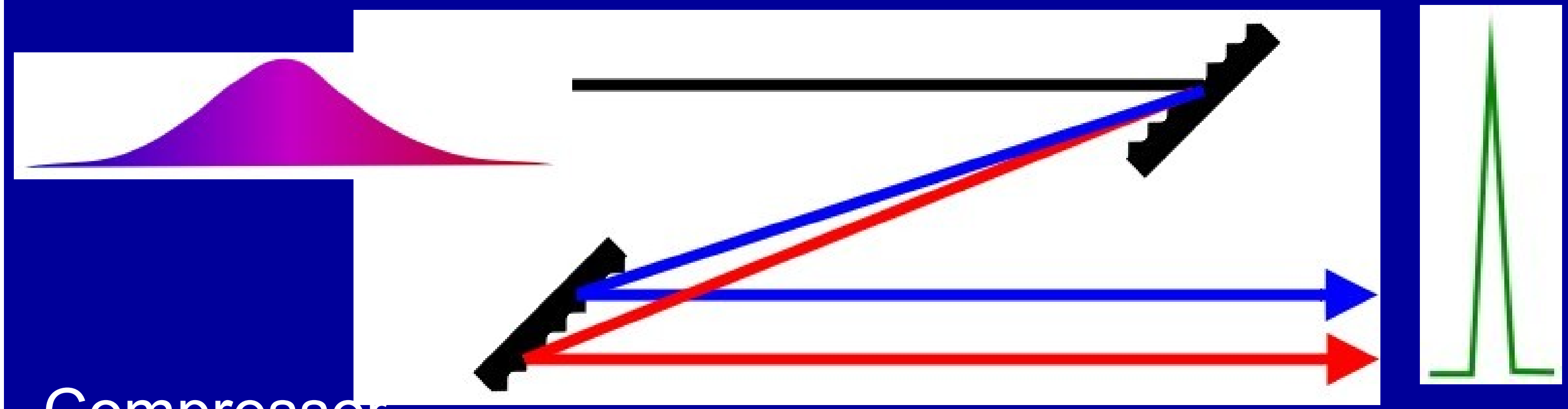
# Matched Stretcher-Compressor

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)

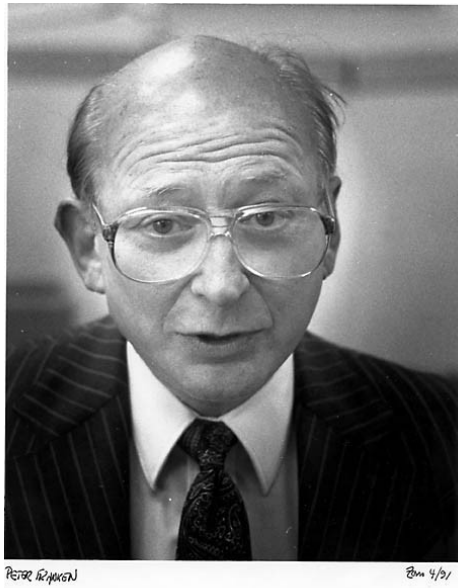


Stretch



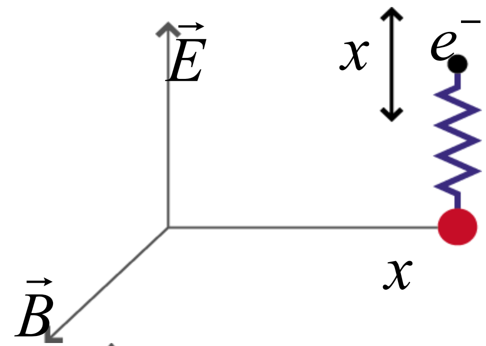
Compressor

# Bound Electron Nonlinear Optics

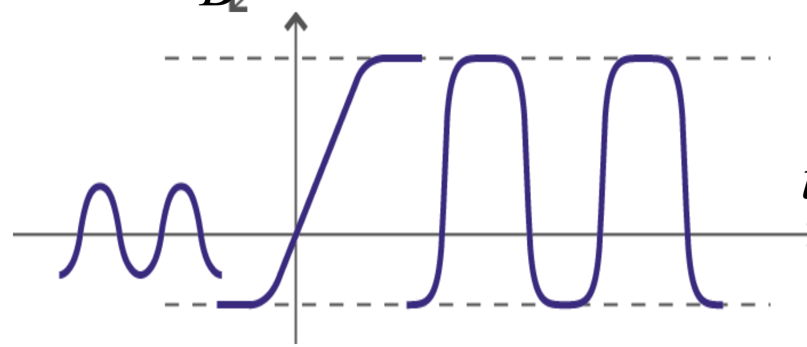


$$\vec{F} = q\vec{E} \qquad F \propto x$$

$v << c$




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




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

# Relativistic Optics

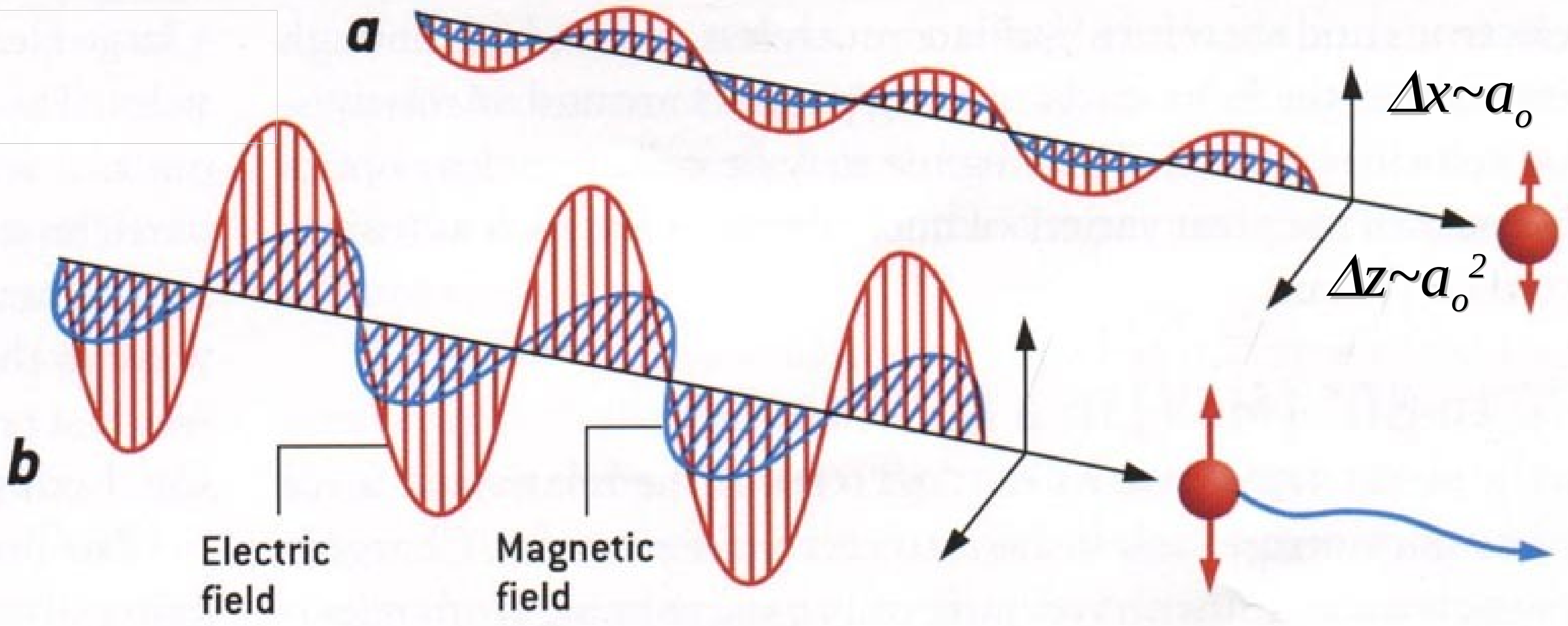
# *Relativistic Optics*

*a)Classical optics v<<c,*

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

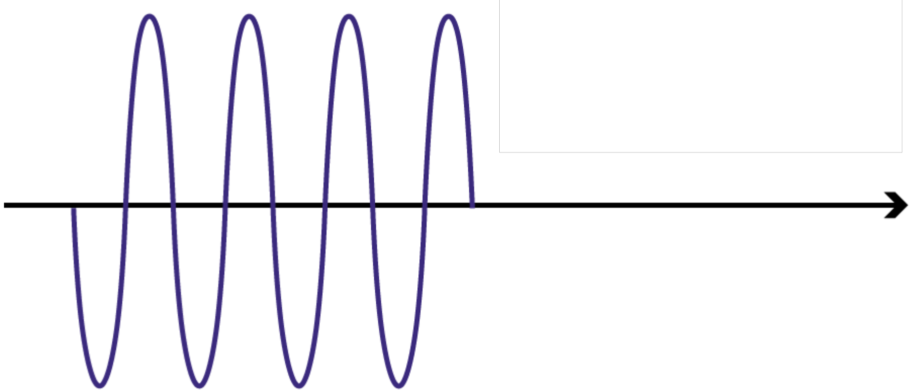
*b) Relativistic optics v~c*

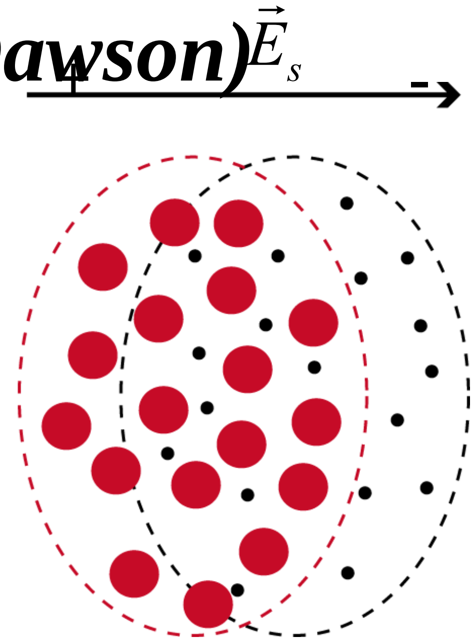
$a_0>>1,\ a_0<<a_0^2$



# *Relativistic Rectification*

## *(Wake-Field   Tajima, Dawson)*






1) pushes the electrons.

2) The charge separation generates an electrostatic longitudinal field.  (Tajima and Dawson: Wake Fields or Snow Plough)

3) The electrostatic field

# Relativistic Rectification

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

$$E_L^2 = Z_0 * I_L$$

Medium Impedance

Laser Intensity

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

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

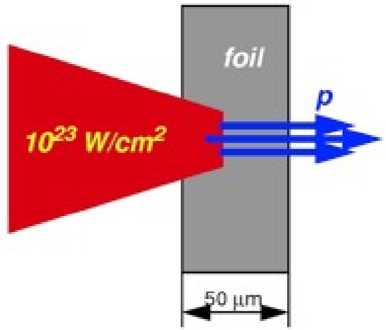
# *Laser Acceleration:*

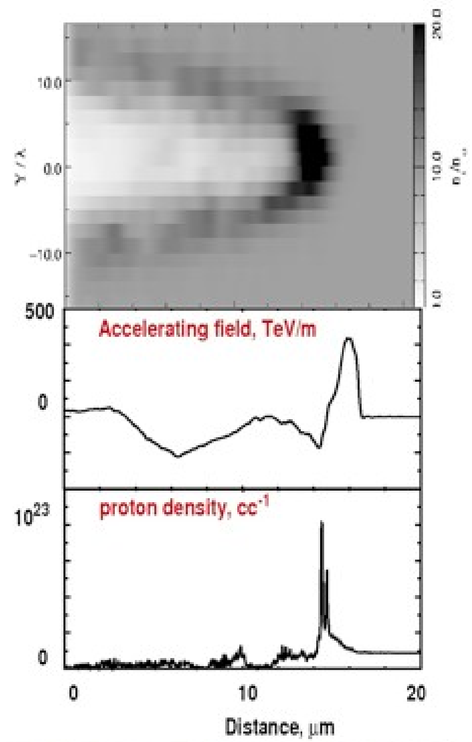
*At $10^{23}$W/cm$^2$ , E= 0.6PV/m, it is SLAC (50GeV, 3km long) on 10μm The size of the Fermi accelerator will only be one meter (PeV accelerator that will go around the globe, based on conventional technology).*

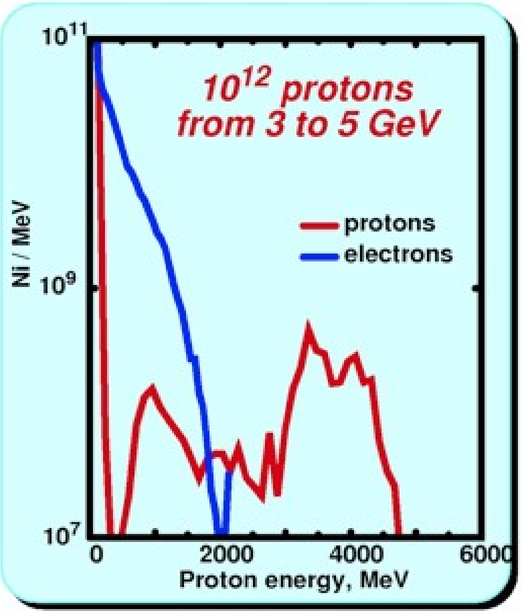
## *Relativistic Microelectronics*

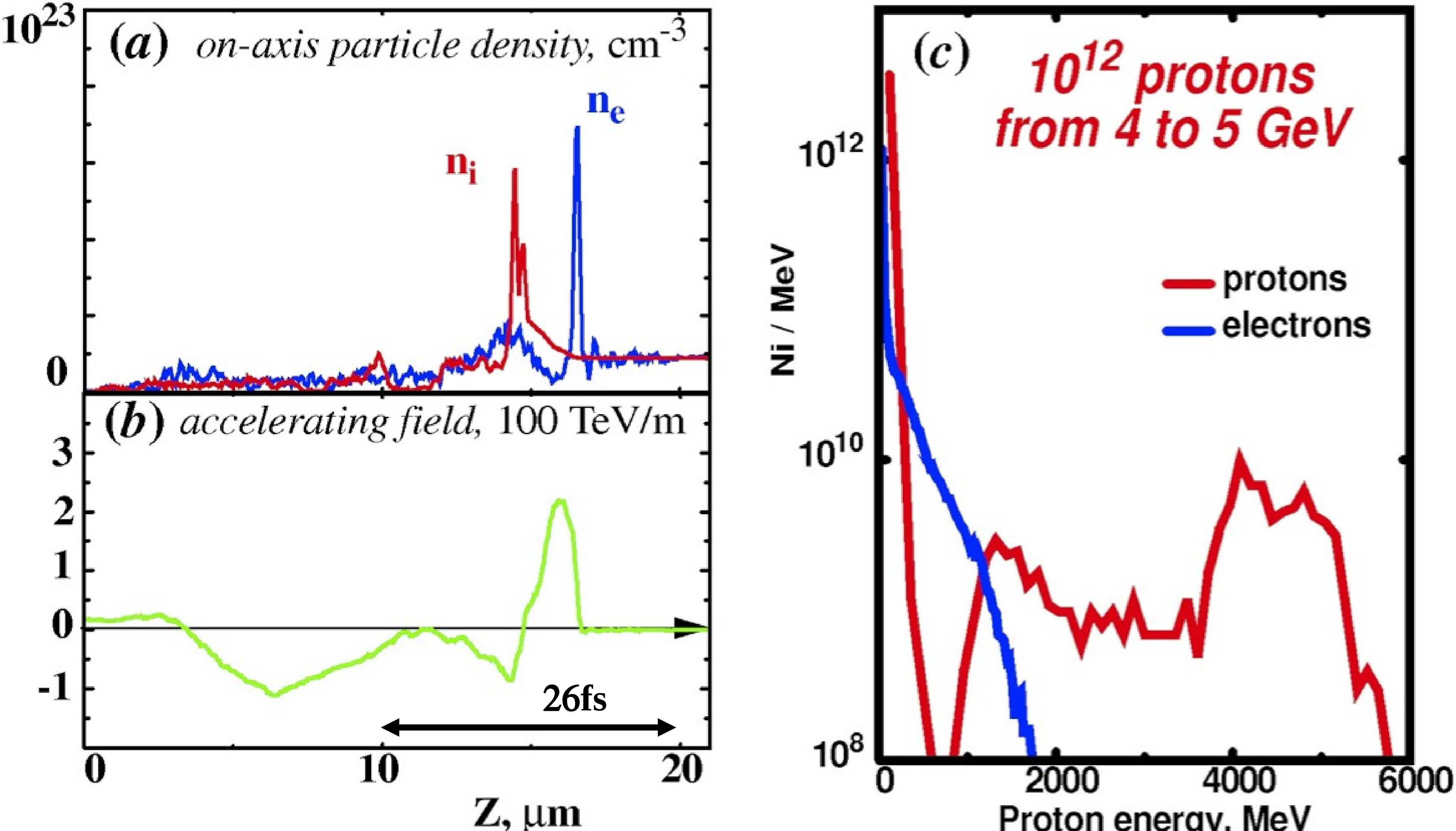
# 5 GeV proton bunch at solid state density

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





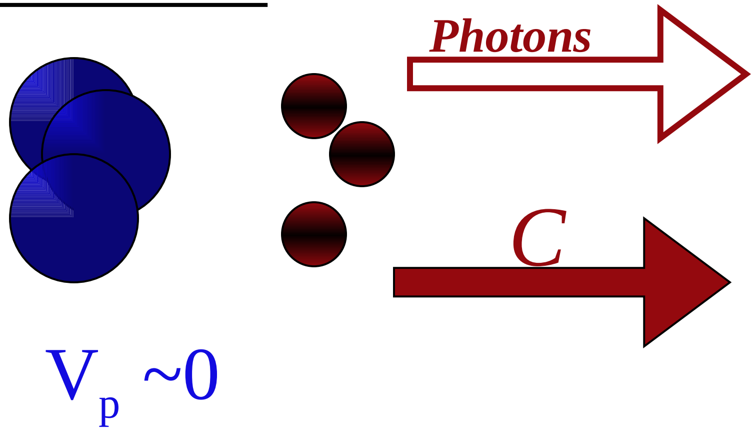
(a) on-axis particle density, cm-3
10^23
0
n_i
n_e
(b) accelerating field, 100 TeV/m
3
2
1
0
-1
26fs
0
10
20
Z, μm
(c)
10^12 protons from 4 to 5 GeV
Ni / MeV
10^12
10^10
10^8
protons
electrons
0
2000
4000
6000
Proton energy, MeV

# *The Dream Beam*


J. Faure et al., **C. Geddes et al., S. Mangles et al. ,**
**in Nature 30 septembre 2004**

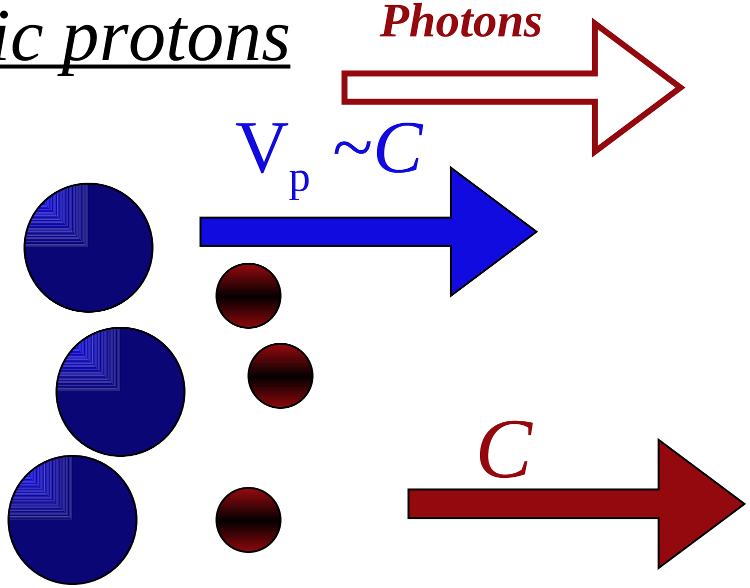
# Relativistic Protons

## *Non relativistic*



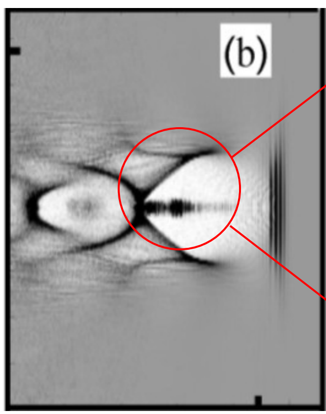

$$E_p \sim I^{1/2}$$

## *Relativistic protons*

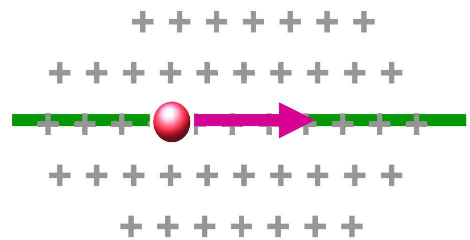


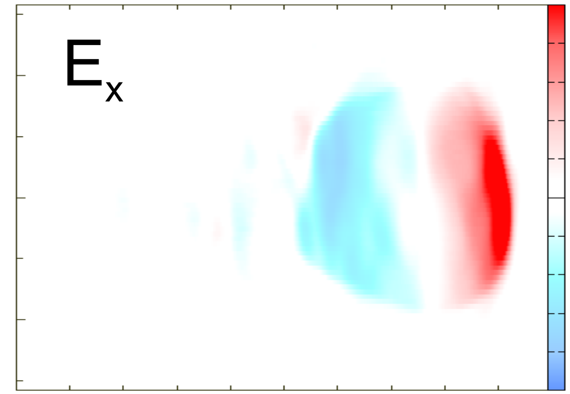

$$E_p \sim I$$

# The structure of the ion cavity



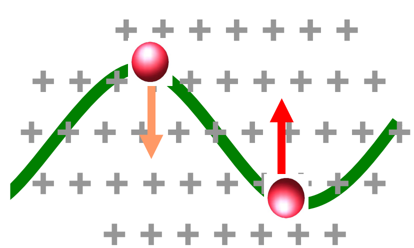

**Longitudinal acceleration**

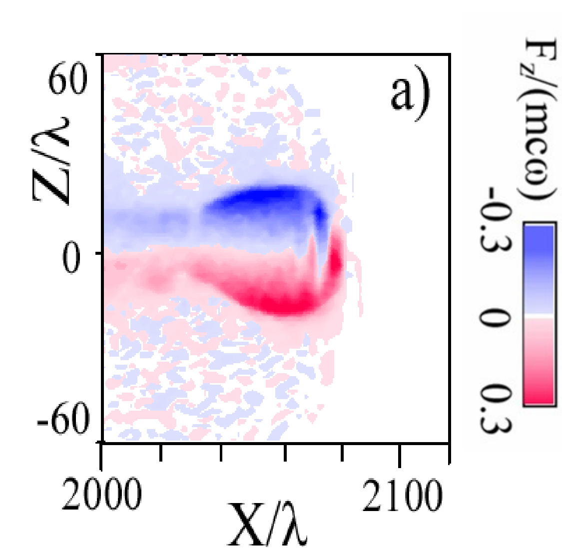





**Transverse oscillation: Betatron oscillation**

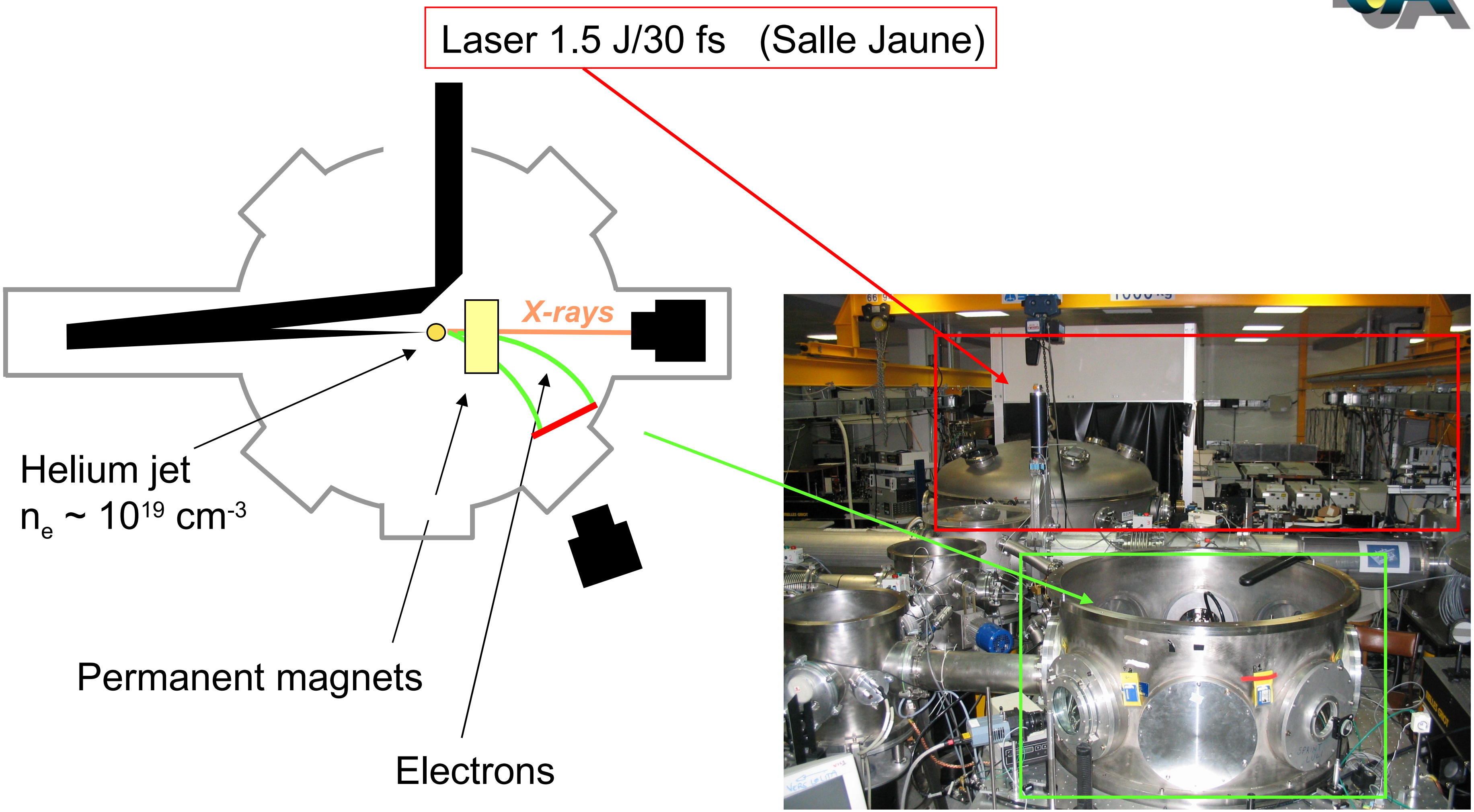
$F_{rap\perp}$



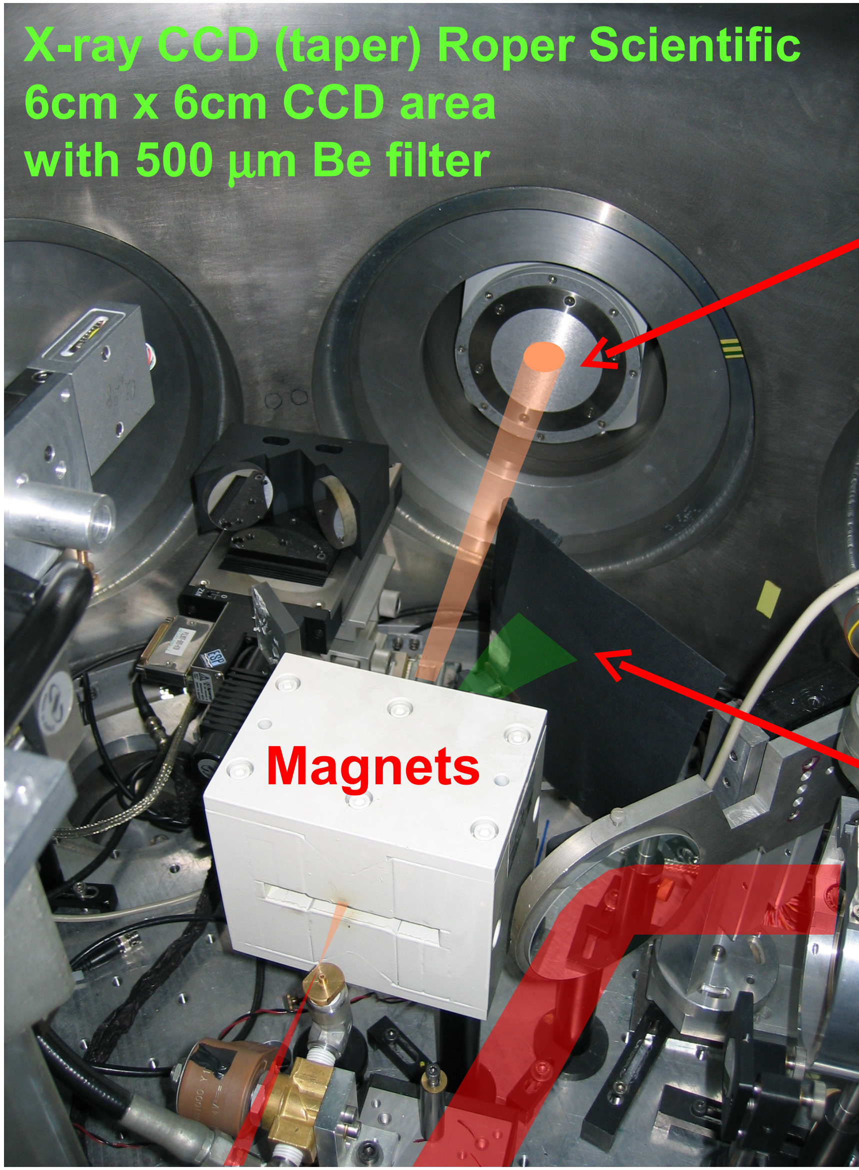


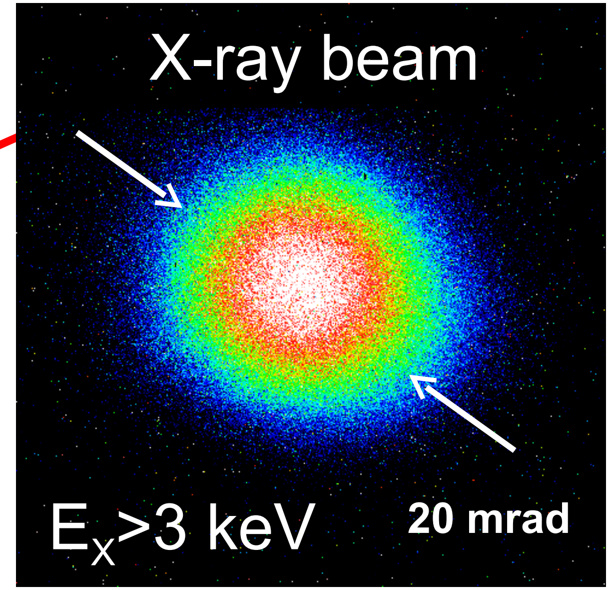
# Experiment Setup

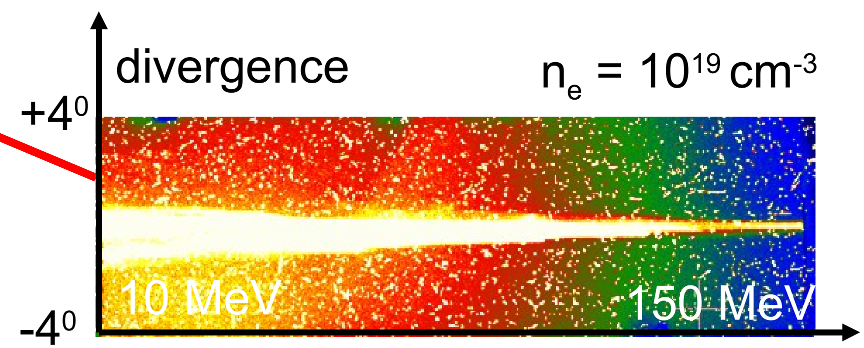
A. Rousse et al.



# Simultaneous measurements of X-ray and Electron Beams




Electron beam

K. Ta Phuoc et al

# *Attosecond Generation (photon)*

# *Attosecond by Bond electron Nonlinear Optics*

- P. Corkum, M. Ivanov and Burnett Sub.femtosecond Pulses Opt. Lett. 19, 1870 (1994)
- M. Hentschel *et al*. Nature 414, 509 (2001)
- A. Baltuslka *et al*. Nature 421, 6111 (2001)

*The technique relies on High harmonic Generation and not very efficient.*

*It is limited to nJ and not scalable to high energy.*

# HHG and Subfemtosecond Pulses from Surfaces of Overdense Plasmas

**S.V. Bulanov, Naumova N M and Pegoraro F, Phys. Plasmas 1 745(1994)**

**D. Von der linde et al Phys. Rev. A52 R 25, 1995**

**L. Plaja et al. JOSA B, 15, 1904 (1998)**

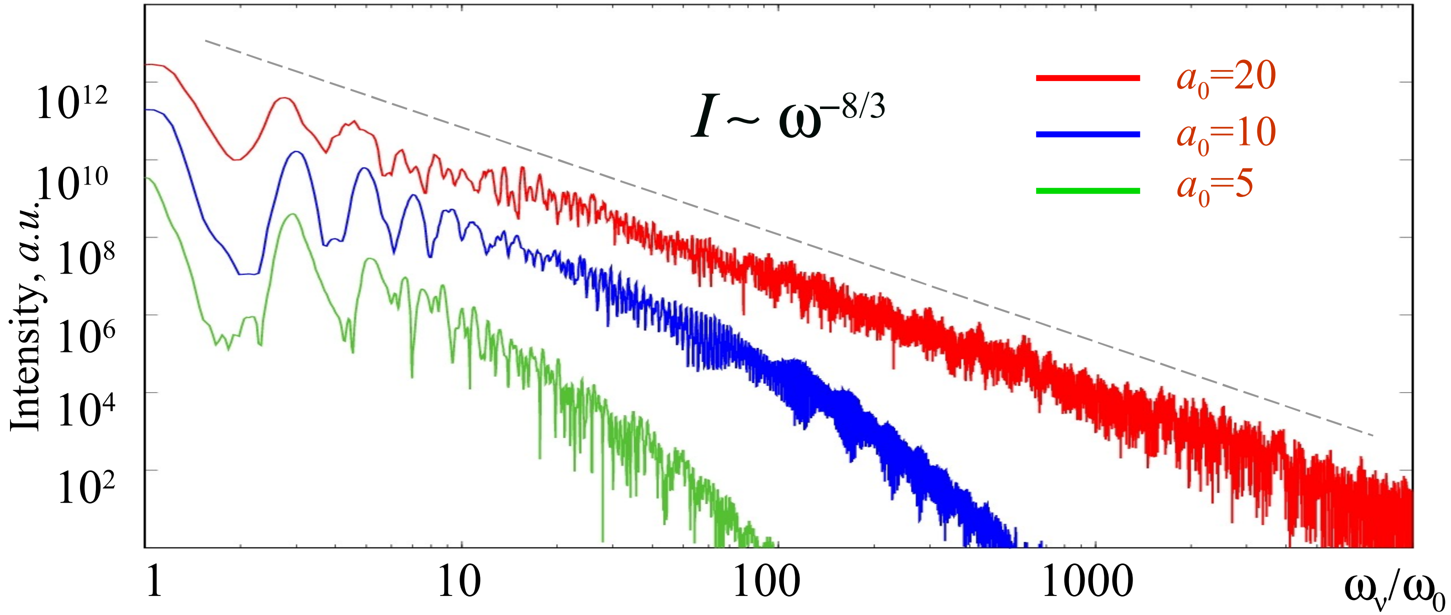
**S. Gordienko et al PRL 93, 115002 (2004)**

**N.M. Naumova et.al., PRL 92, 063902 (2004)**

**Tsakiris, G., *et al.*, New Journal of Physics, 8, 19 (2006)**

# 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!!!**

# VULCAN Experiment: Harmonics down to “Water Window”

B. DROMEY, M. ZEPF, et al., **NATURE** Physics, Vol. **2**, p. 456 (2006).

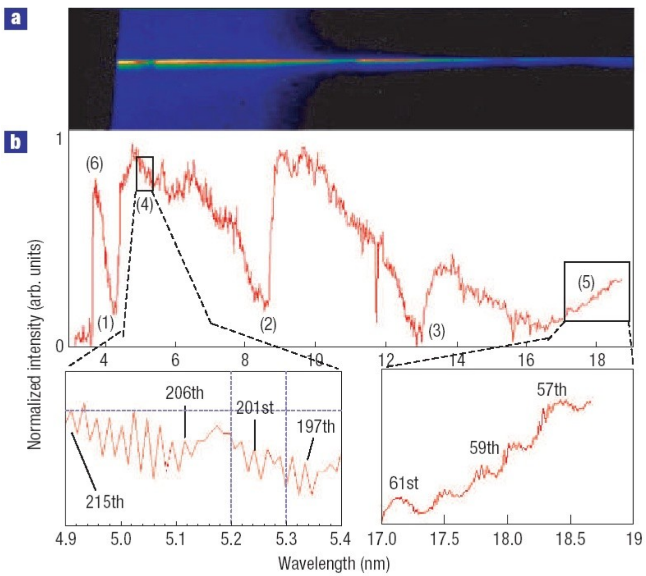
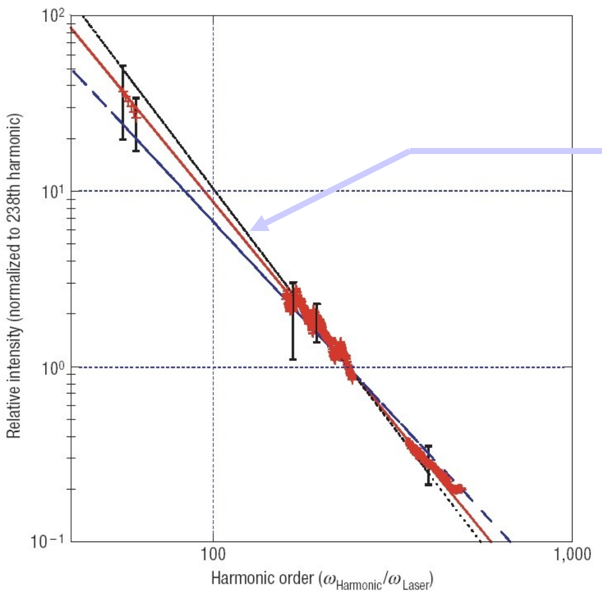



**Figure 3** **Unprocessed high harmonic spectrum recorded with the extreme-ultraviolet spectrometer. a**, Raw CCD image obtained with the double PM setup ($E = 70$ J on target, false colours). **b**, A lineout of **a**. Spectral features: (1) first-order carbon K-edge (4.36 nm), (2) second-order carbon K-edge, (3) third-order carbon K-edge, (4) region of resolved harmonics around 200th order




$I_n \sim n^{-2.5}$

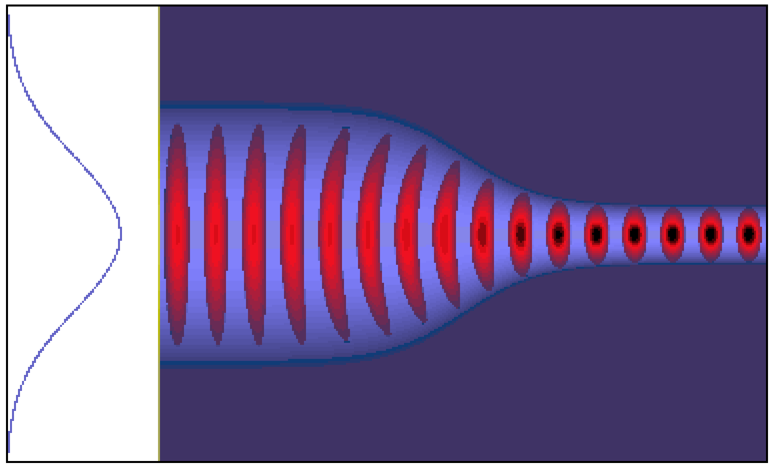
**Figure 4** **Relative intensity of harmonics normalized to the 238th harmonic (at the carbon K-edge).** The lines are fits to the data with the exponent $p$ as a fitting parameter such that $I(n)/I(238) = n^{-p}/238^{-p}$. The best fit (red line) corresponds to a value of $p = 2.5$ confirming harmonic production in the relativistic limit. The error

# Relativistic Self-focusing:

$$\varepsilon = 1 - \frac{w^2_p}{g_0 w^2} \quad \text{where} \quad g_0 = \sqrt{1 + |a_0|^2}$$

(a)

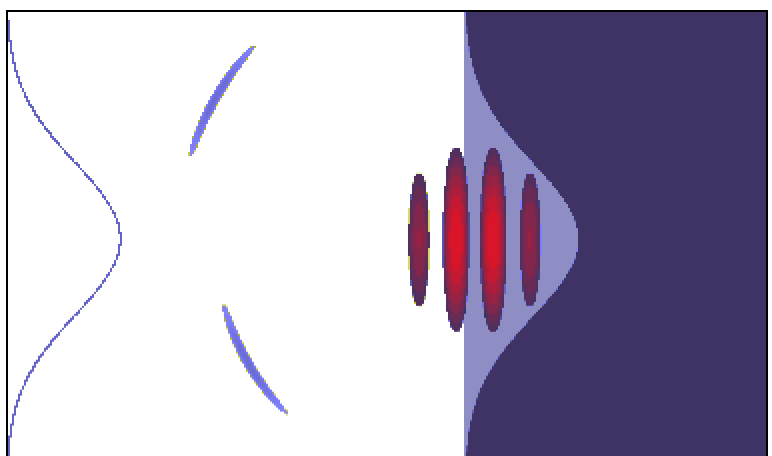
Refraction



A.G.Litvak (1969), C.Max, J.Arons, A.B.Langdon (1974)

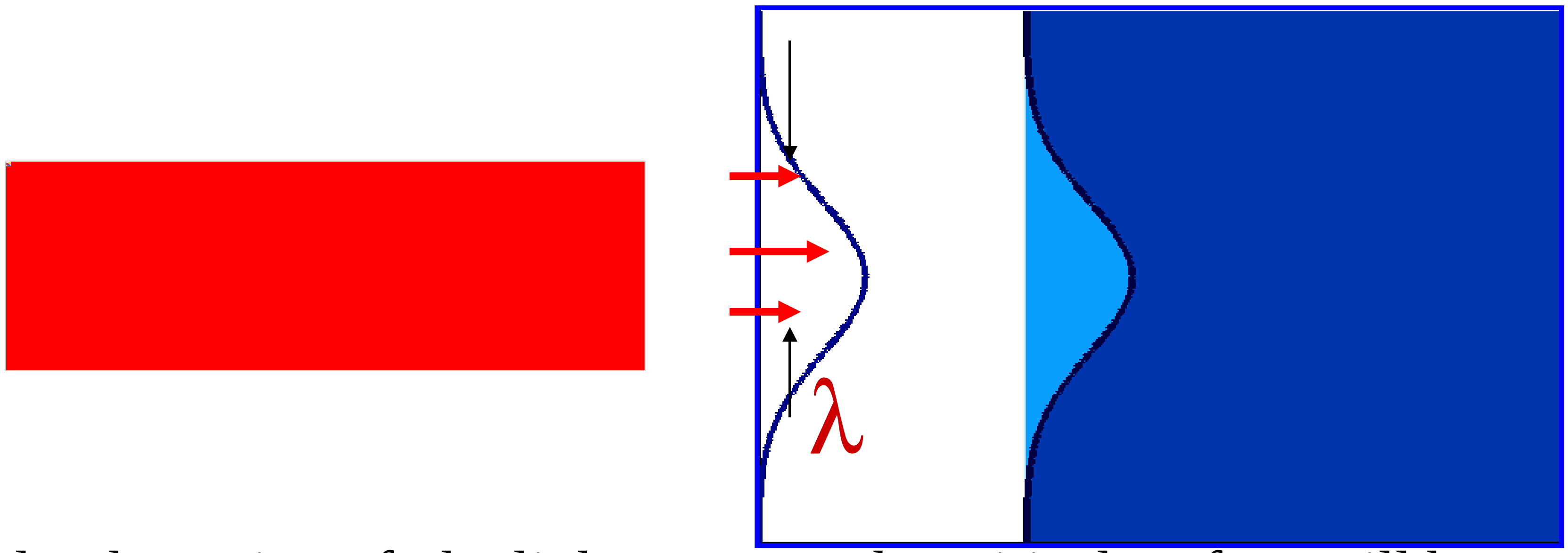
(b)

Reflection



?

# Single Mode Relativistic optics in Reflection

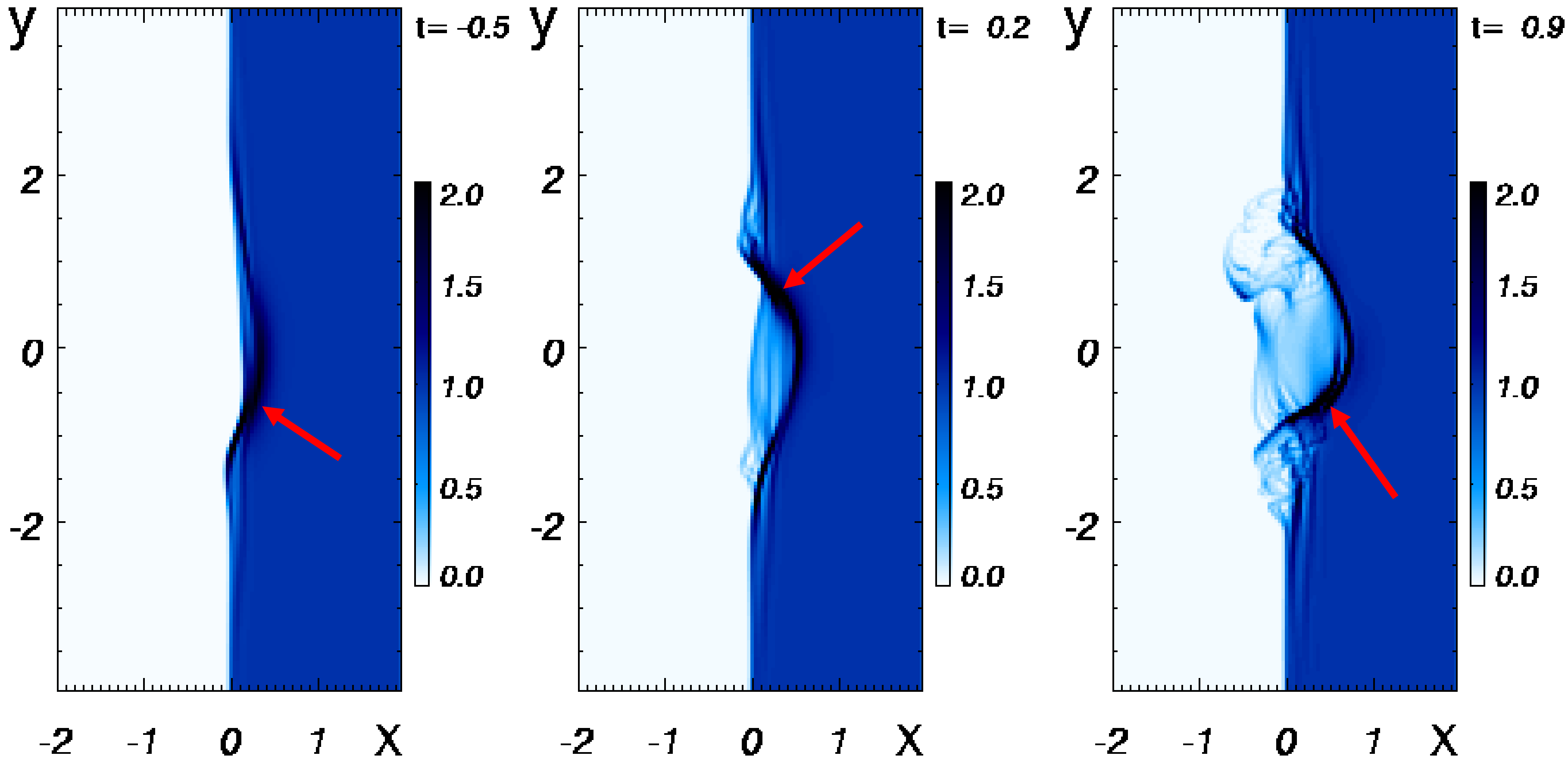



Under the action of the light pressure the critical surface will be pushed (curved) at relativistic speed at twice the laser frequency (ω).

If the laser is focused on 1$\lambda$, it will act as a perfect single mode mirror, leading to well behaved reflection and deflection.

The restoration force is a function of the plasma density

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



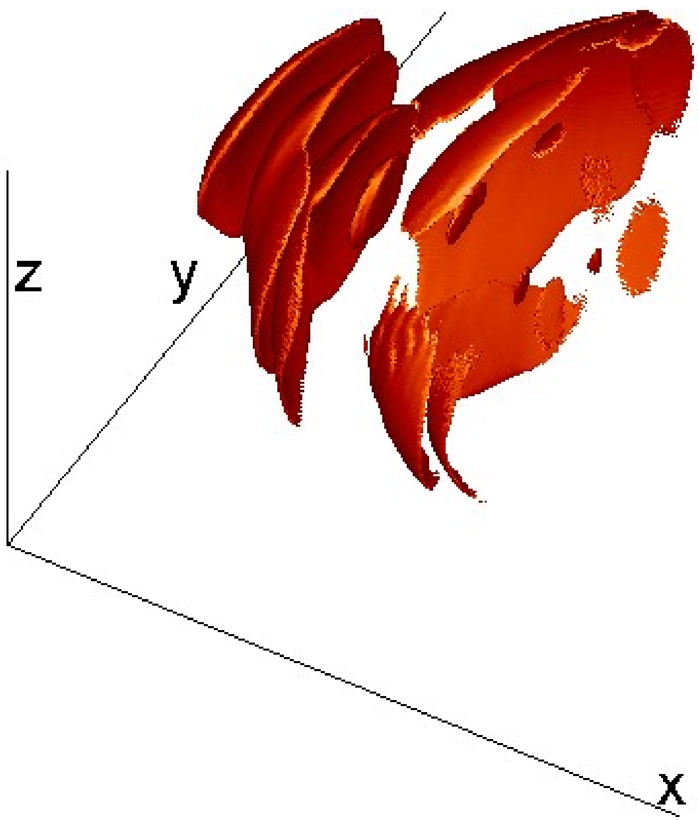

## Relativistic electrons create the Doppler compression

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

# 3-D PIC simulation

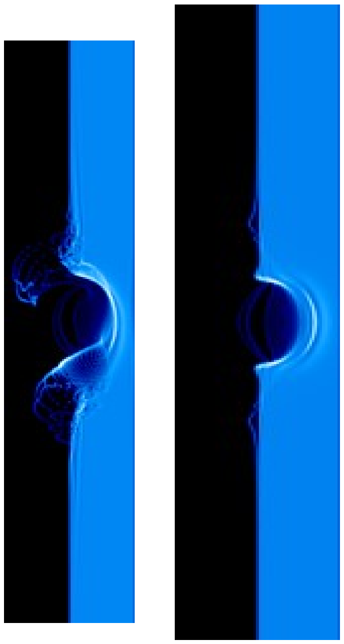
*Electromagnetic energy density*

*attosecond* pulse

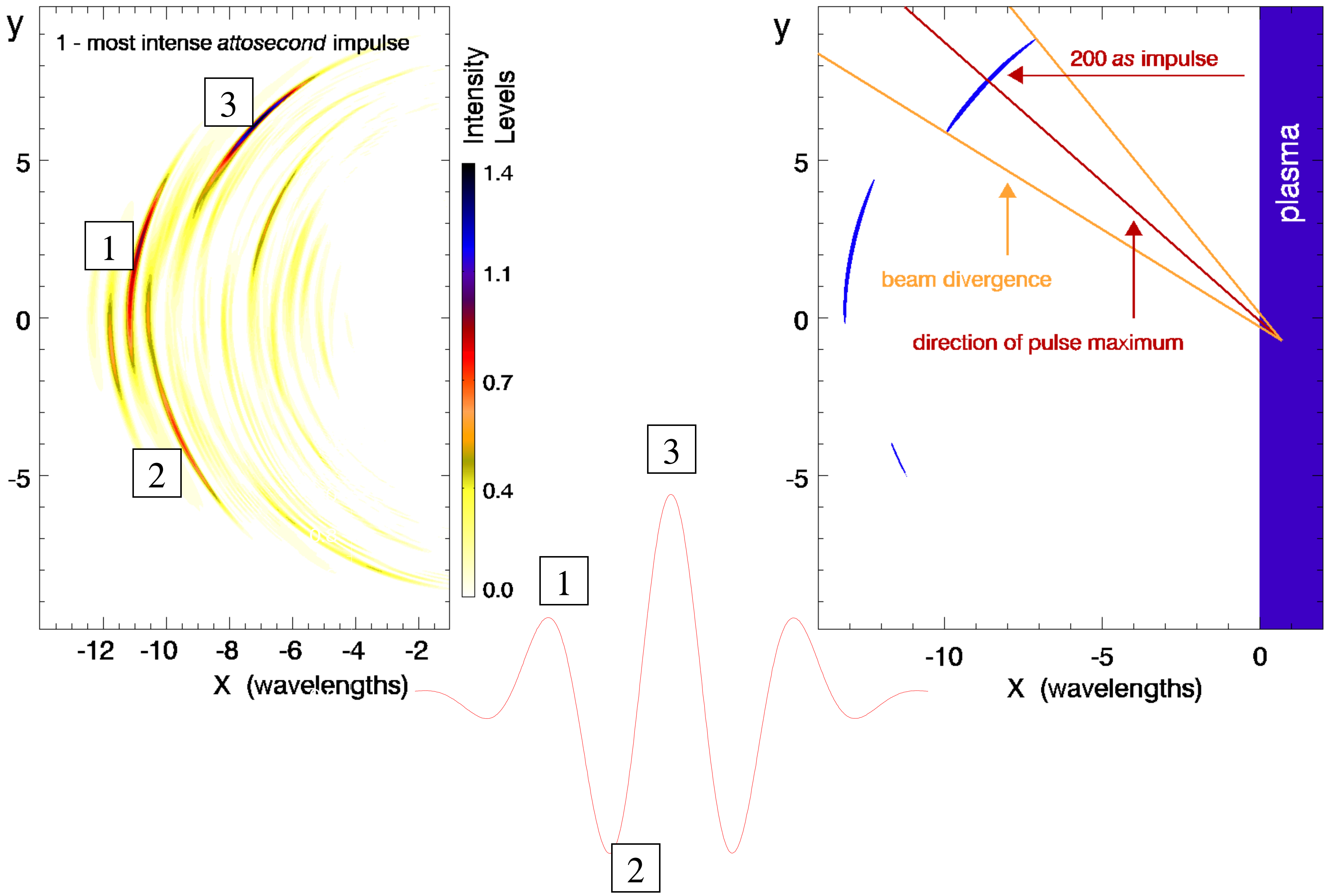



*Electron density*

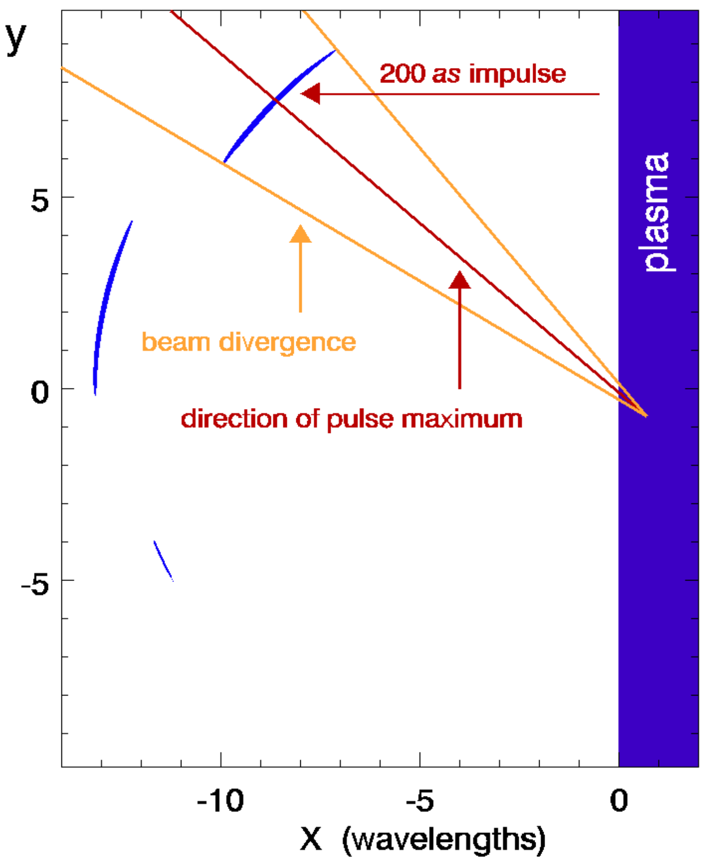
P-plane S-plane

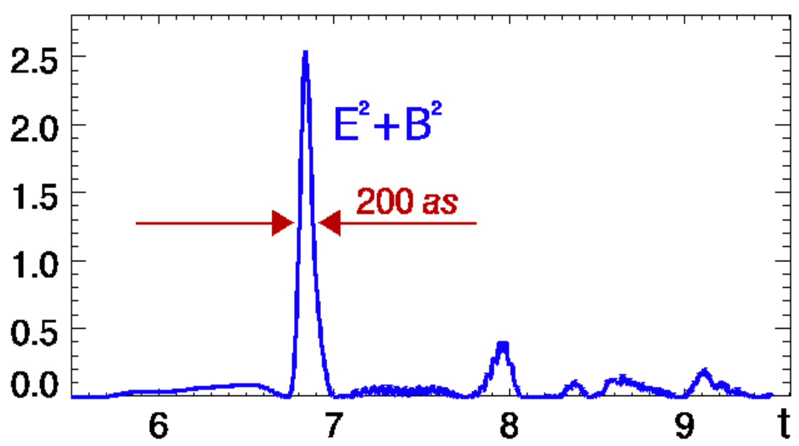


# 2-D PIC simulation

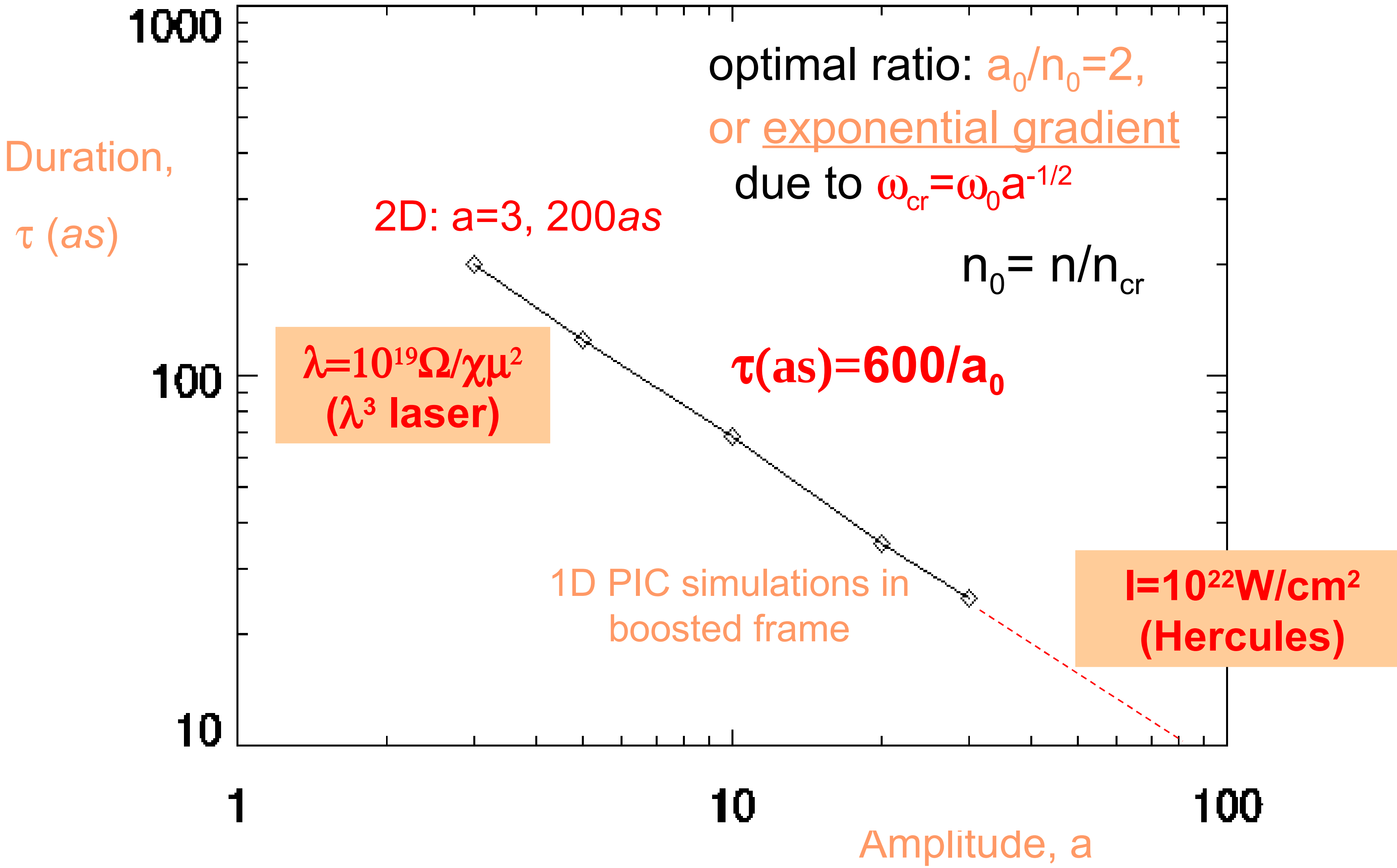


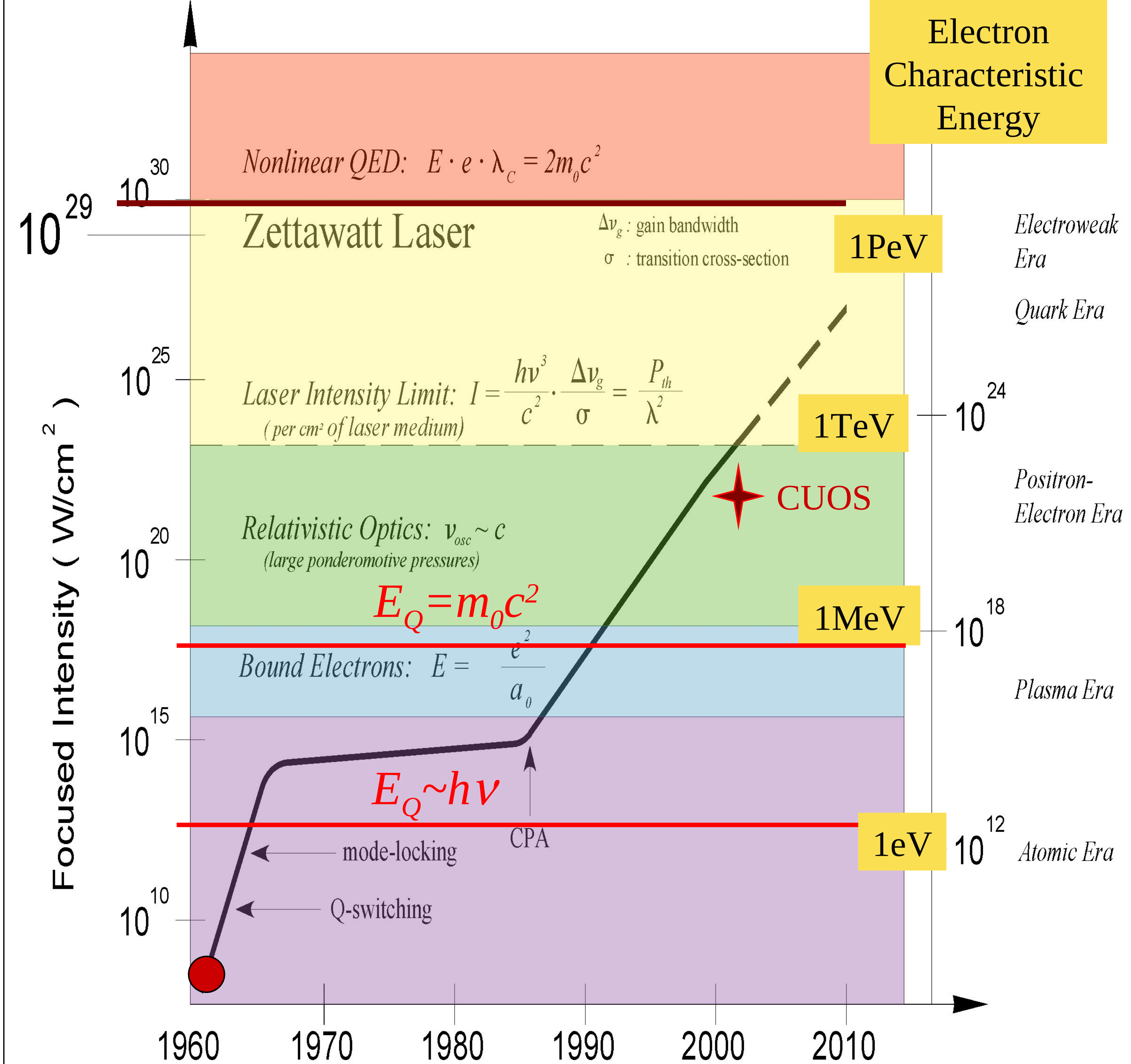
# 2-D PIC simulation



# Scalable Isolated Attosecond Pulses



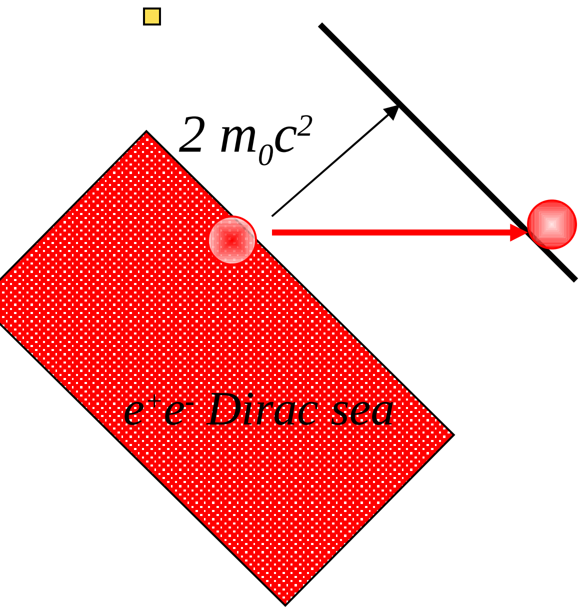


Electron Characteristic Energy
Nonlinear QED: E · e · λC = 2m0c2
Zettawatt Laser
Δνg : gain bandwidth
σ : transition cross-section
1PeV
Electroweak Era
Quark Era
Laser Intensity Limit: I = hν3/c2 · Δνg/σ = Pth/λ2
(per cm2 of laser medium)
1TeV
CUOS
Positron-Electron Era
Relativistic Optics: vosc ~ c
(large ponderomotive pressures)
EQ=m0c2
1MeV
Bound Electrons: E = e2/a0
Plasma Era
EQ~hν
CPA
mode-locking
Q-switching
1eV
Atomic Era
Focused Intensity ( W/cm2 )
1030
1029
1025
1020
1015
1010
1024
1018
1012
1960
1970
1980
1990
2000
2010

# Laser-Induced Nonlinear QED

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

## Vacuum can be considered like a dielectric




Schwinger Field

$E_s$=1.3 $10^{16}$ V/cm

Vacuum Tunneling

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

# Towards the Critical Field

For $I=10^{22} W/cm^2$  $a_0^2 = 10^4$

The pulse duration $\tau = 600 / a_0 \sim 6as$

The wavelength ~ $\lambda/1000$

The Focal volume decreases ~ $10^{-8}$

The Efficiency~ 10%

Intensity   $I=10^{22} W/cm^2 \longrightarrow I=10^{28} W/cm^2$

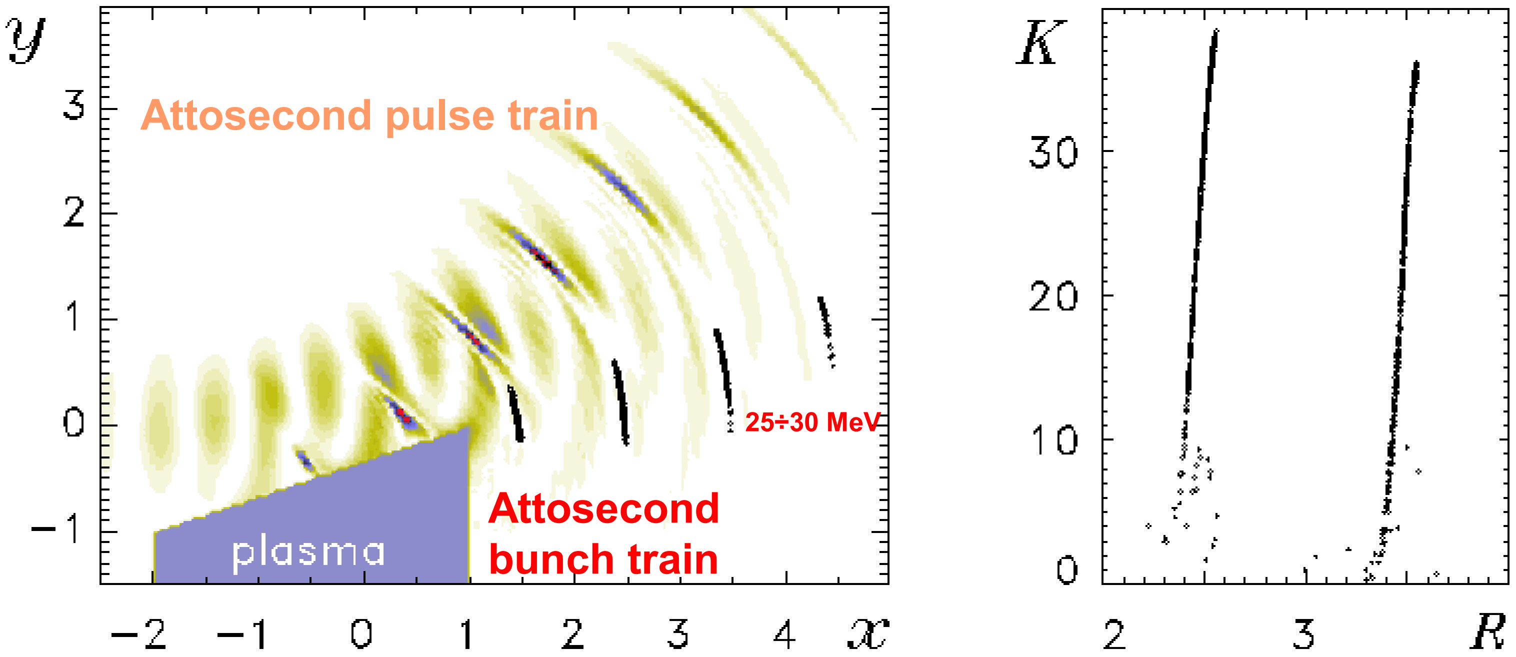
# Isolated Attosecond Pulse Generation by Relativistic Compression and Deflection in the $\lambda^3$

- Optimum use of the energy
- Provides pulse isolation
- Predicted to be efficient ($10^{-1}$-$10^{-2}$)
- Single mode and short pulse suppress the unstabilities, that is very good beam quality expected.
- It relies on relativistic plasma therefore scalable to  any pulse energy (kJ)
- The higher the intensity the shorter the pulse

# *Attosecond Generation (electron)*

# Attosecond Electron Bunches

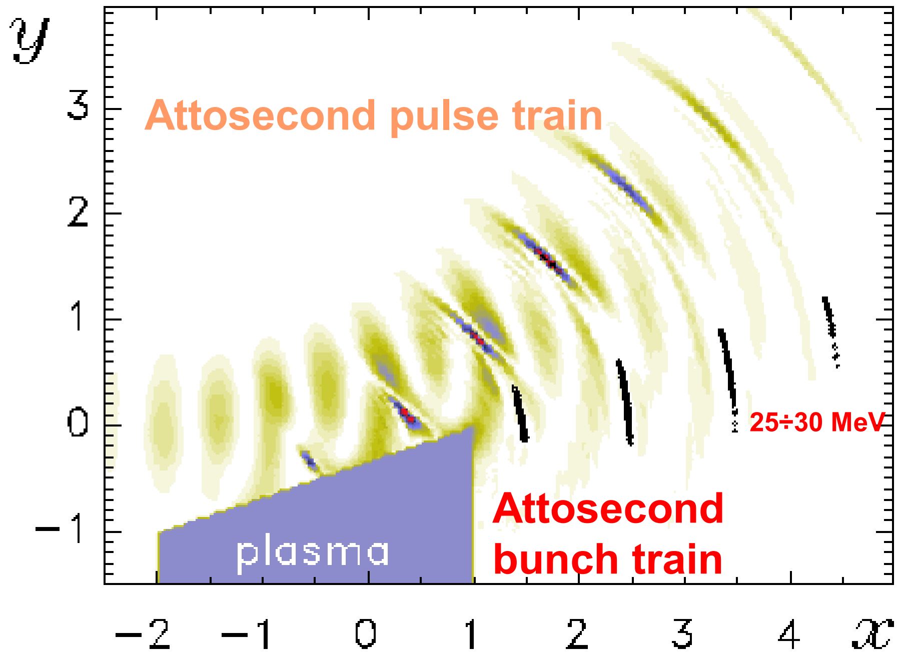
$a_0=10$, $\tau=15fs$, f/1, $n_0=25n_{cr}$

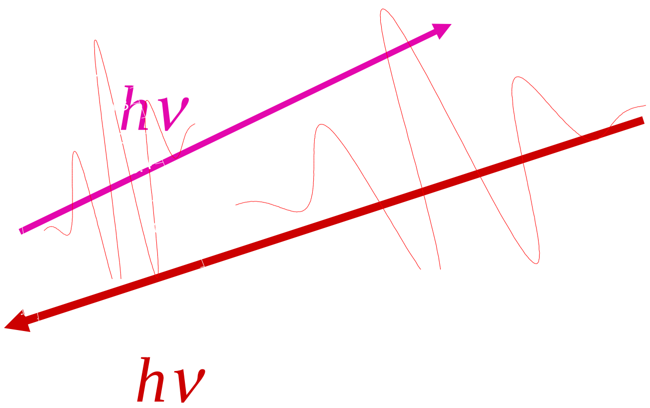



N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou, Attosecond Electron Bunches, *Phys. Rev. Lett.* **93**, 195003 (2004).

# Coherent Thomson Scattering

$a_0$=10, $\tau$=15fs, f/1, $n_0$=25$n_{cr}$

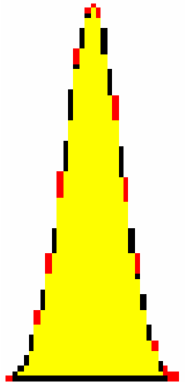



N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou, Attosecond Electron Bunches, *Phys. Rev. Lett.* **93**, 195003 (2004).

# 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 $\gamma$:
  $kd < \gamma^2( -0.125 \ln(\sigma_{Ch}/\sigma_T N^2) )^{1/2}$
- Attosecond bunches with width
  $d \sim 1/k\gamma^2 \sim (100 \text{ as}) \cdot c$



Bunch:

N particles with Gaussian distribution

$$\gamma_{photon} = \frac{l}{4g^2} \text{ for } g = 100$$

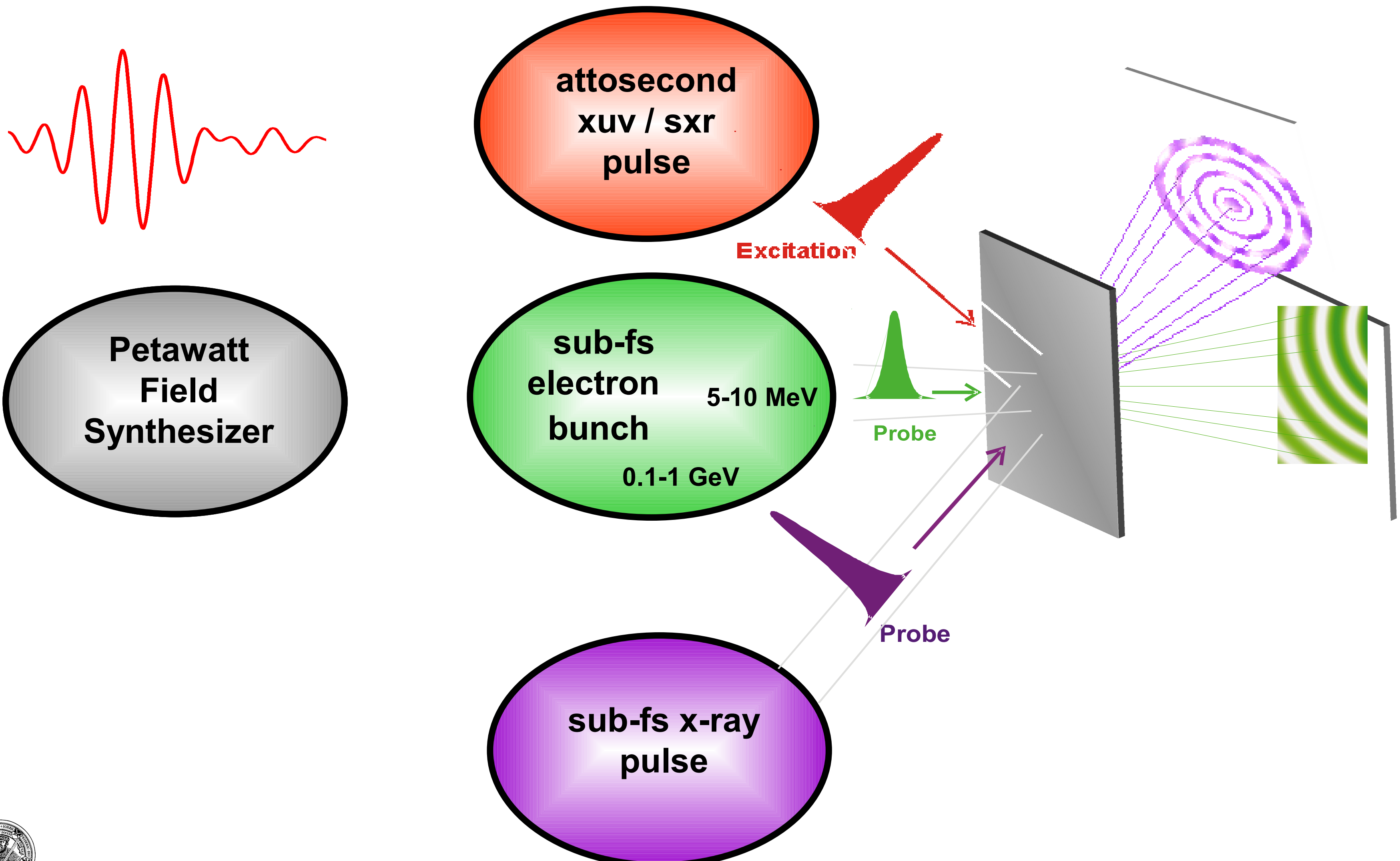
$$g_{\text{photon}} = 40 \text{ keV}$$

$$\text{For } g = 10^3 \text{ , } g_{\text{photon}} = 6MeV$$

η~1 efficiency

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

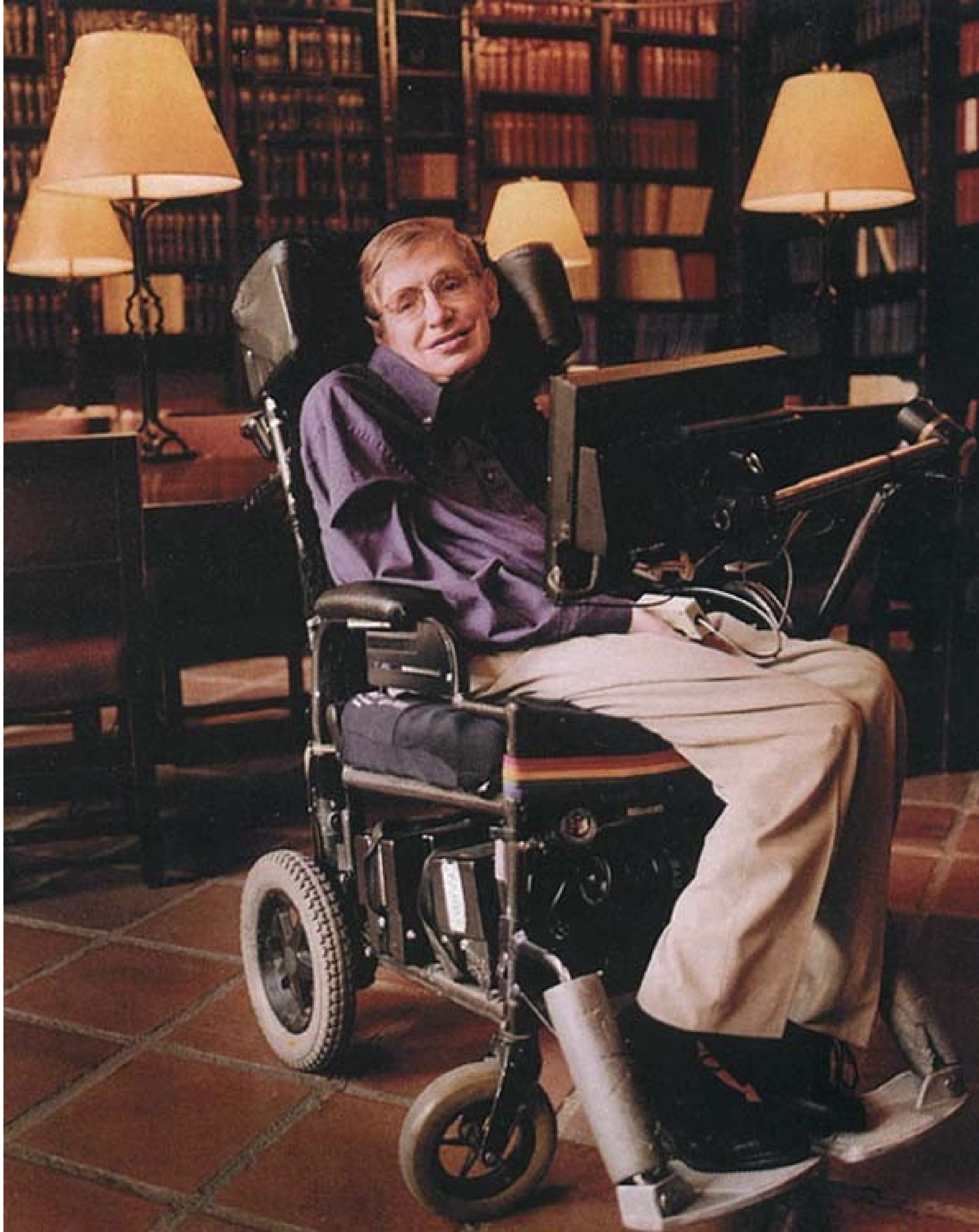
# Control & 4D imaging of valence & core electrons with sub-atomic resolution



*Ultra-high Intensity*

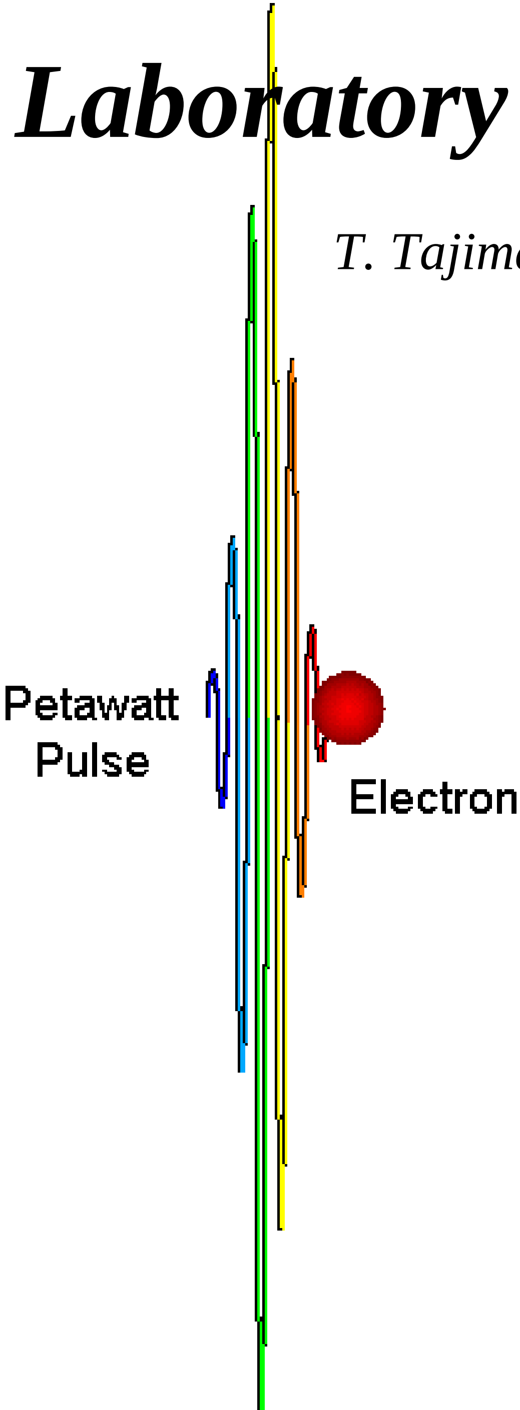
*General Relativity*

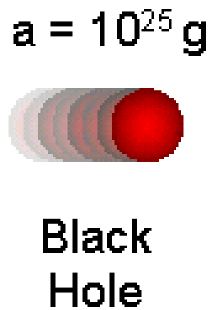
*and  Black Holes*



# *Laboratory Black Hole*

*T. Tajima and G. Mourou   Review of Modern Physics*




*Equivalent to be near a Black Hole of*

***Dimension?***

***Temperature?***

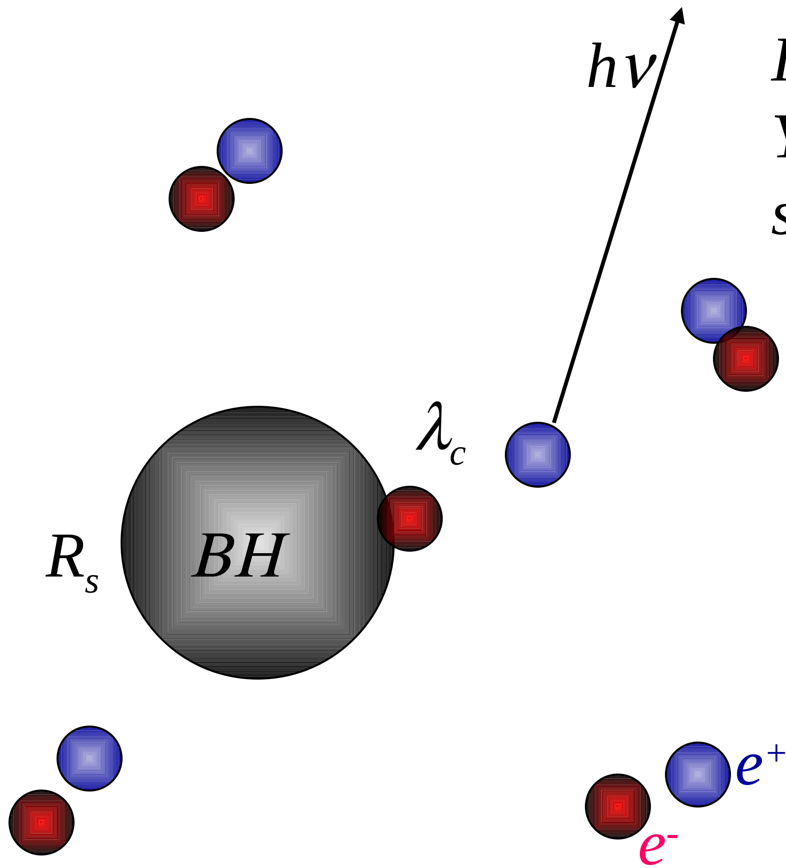
# Is Optics in General Relativity?

Using the gravitational shift near a black hole:

$$kT = \frac{h a_e}{2 p c}$$

As we increase $a_0$ the Swartzschild radius can become equal to the Compton wavelength.

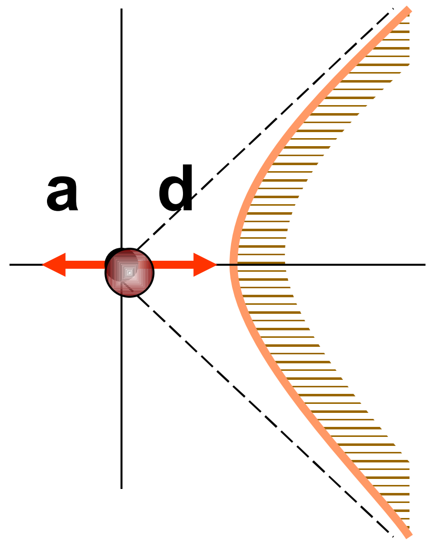
# Optics and General Relativity: Hawking Radiation



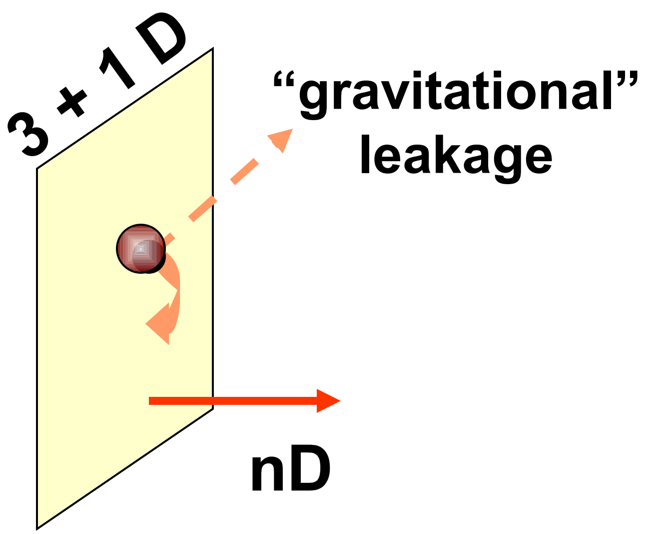

*In order to have Hawking radiation*
*You need the gravitational field*
*strong enough to break pairs*

# *Finite Horizon and extra-dimensions*

The distance to finite horizon is



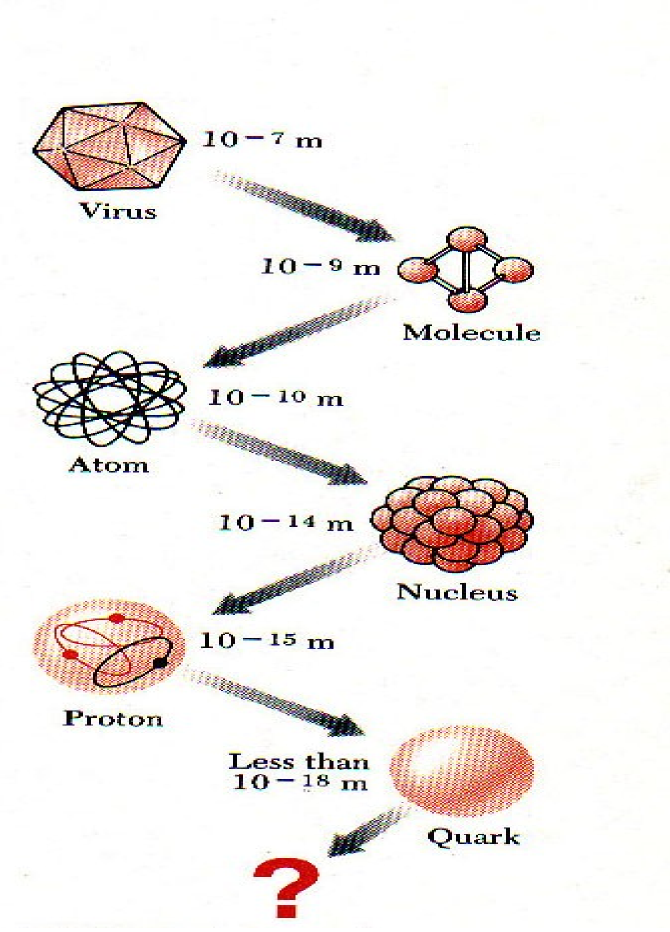

N. Arkani-Hamed et al. (1999)




Up to *n*=4 extra-dimensions could be tested.

T. Tajima phone # 81 90 34 96 64 21

# *Moving from the Atomic Structure to the Quark Structure of Matter*



# Conclusion

PeV

Cosmology

Astrophysics

High Energy Physics

Nuclear Physics

eV

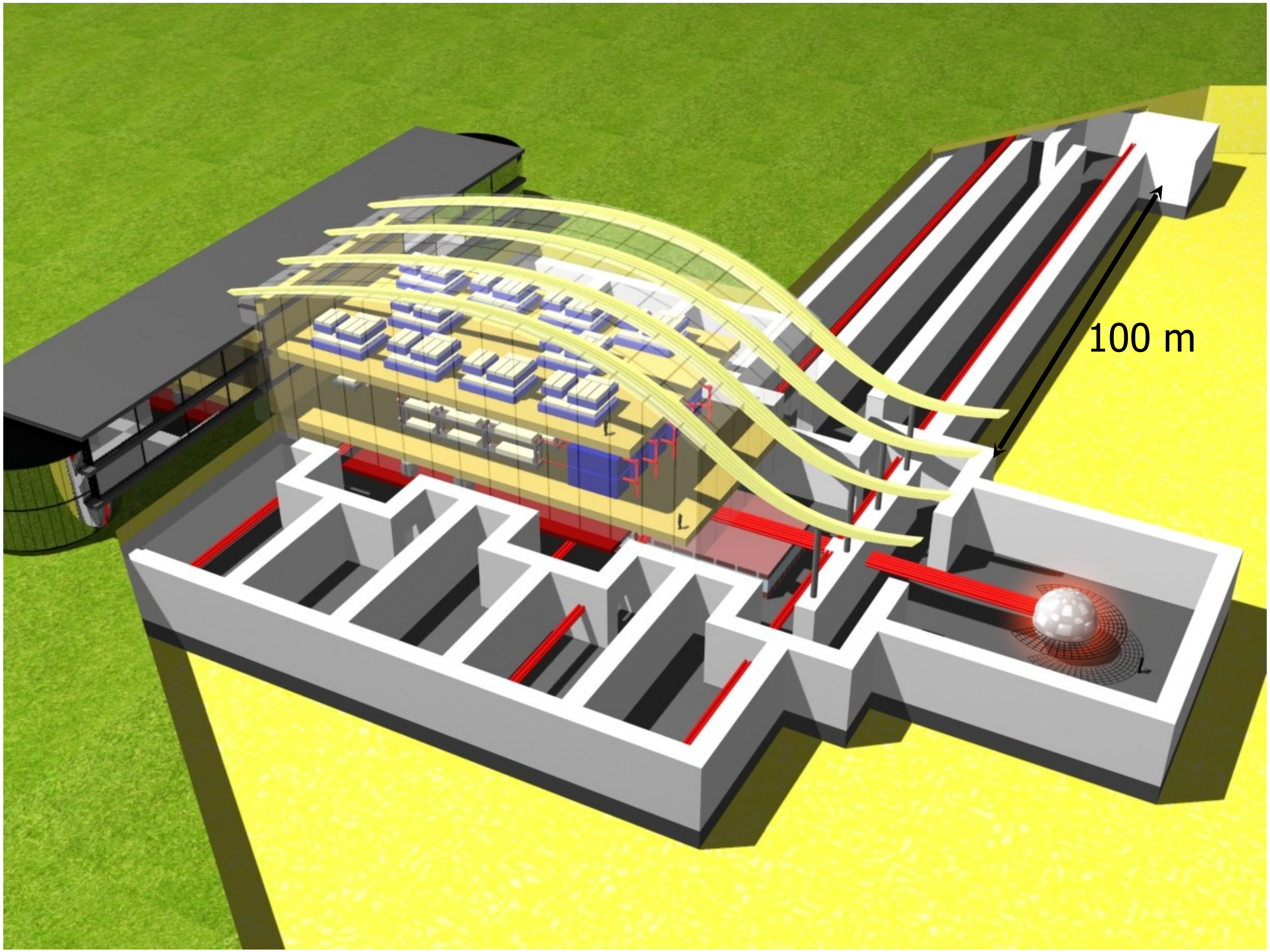
Atomic Physics

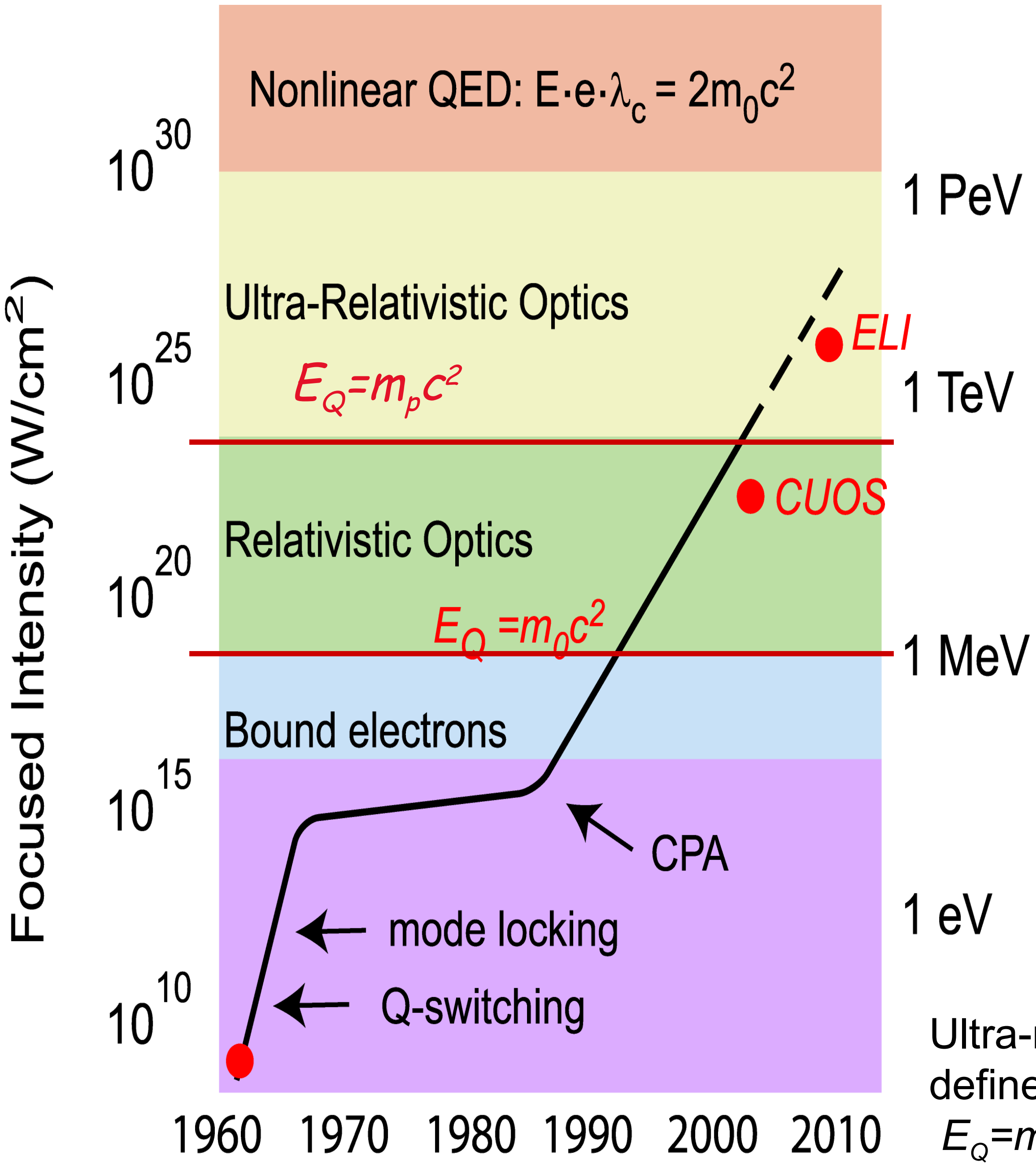
# Extreme Light Infrastructure
# ELI

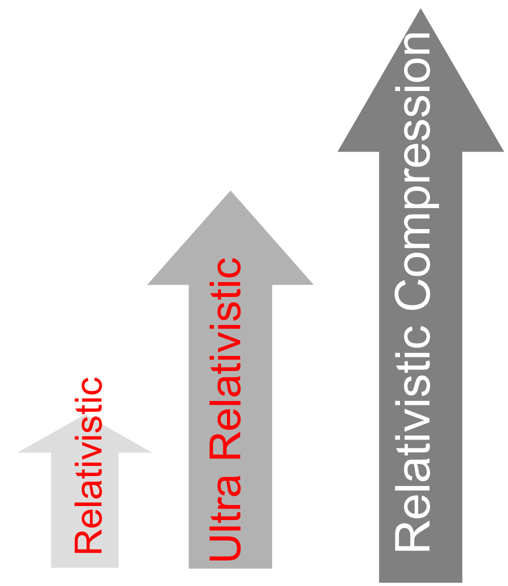
Extreme by its pulse duration
Extreme by its intensity
Extreme by the energy of its radiations and particules

## On the Map of the Very Large Scale European Infrastructures

ELI Proposal
http://loa.ensta.fr


100 m




Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity~$10^{24}$W/cm$^2$

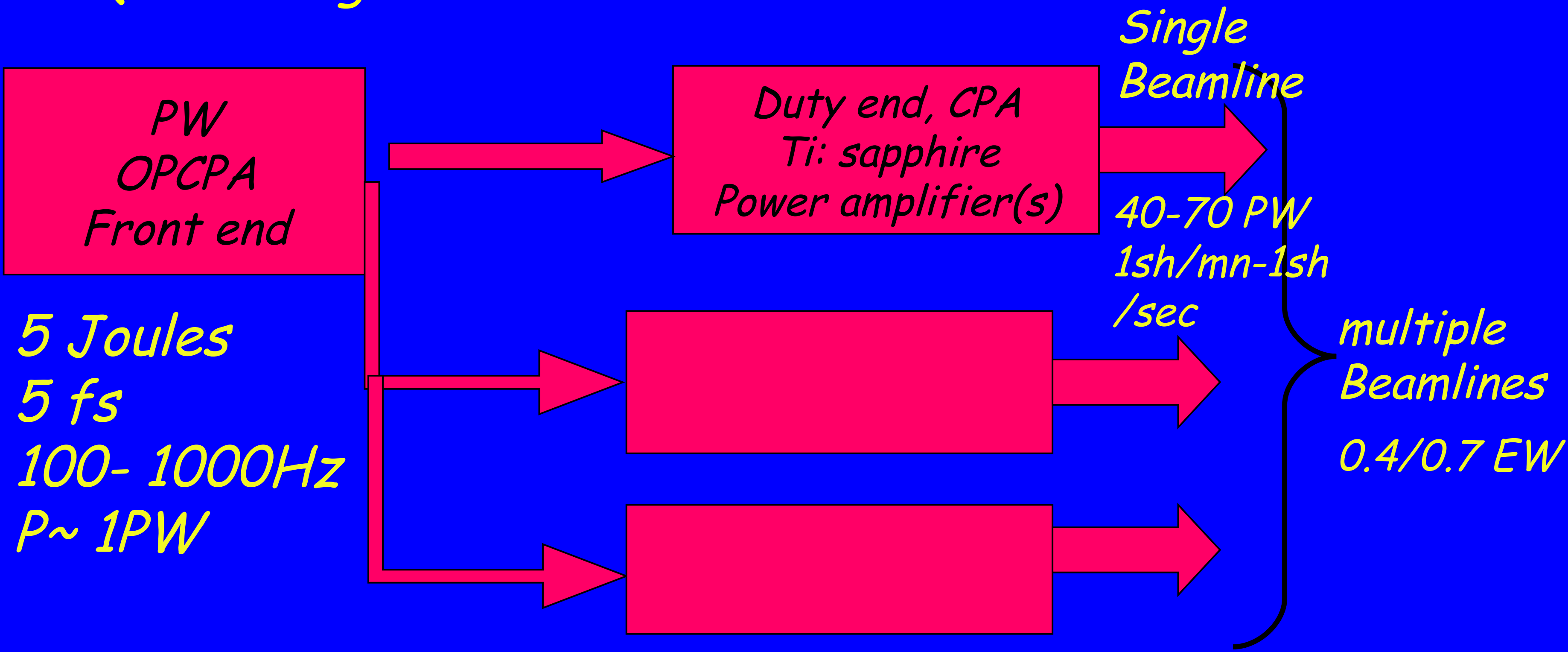
# ELI Scientific Program: Based on an Exawatt Class Laser

## Three Scientific Pillars

- Ultra high Field Science: access to the ultra-relativistic regime, ELI will afford new investigations in particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics and cosmology.
- Attosecond science: snap-shots in the attosecond scale of the electron dynamics in atoms, molecules, plasmas and solids.
- High Energy beam facility: ELI will provide ultra-short energetic particle (>10 GeV) and radiation (up to few MeV) beams produced from compact laser plasma accelerators.

# Exawatt laser scheme

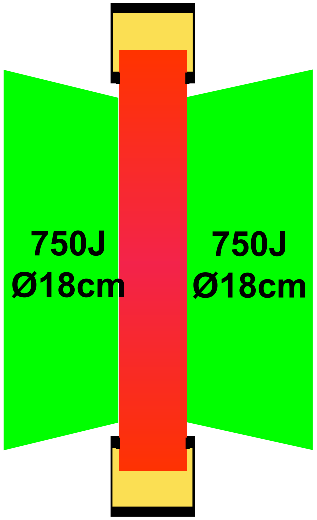
*MPQ Garching*



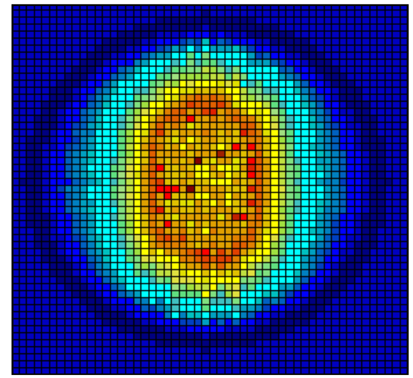

1 EW = 1000 PW = $10^{18}$ W ⇨ *10 KJ in 10fs*

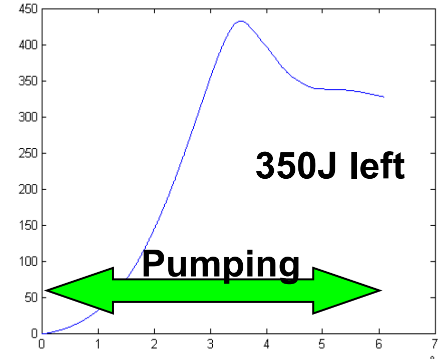
0.1 EW = 100 PW = $10^{17}$ W ⇨ *1 KJ in 10 fs*

# Pumping of a Ø20cm crystal




$[Ti^{3+}] = 1.2\ 10^{19}$ ions/cm$^3$

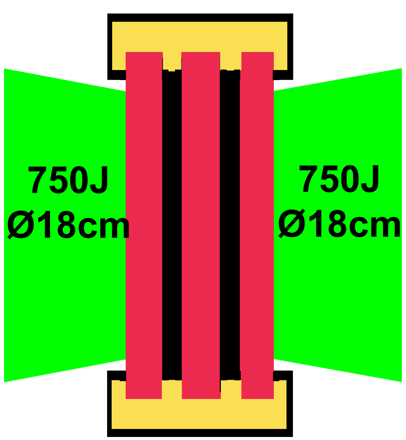




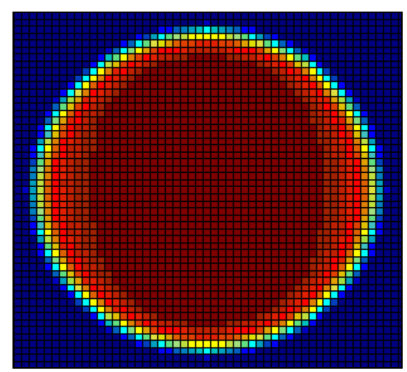

Gain profile after pumping

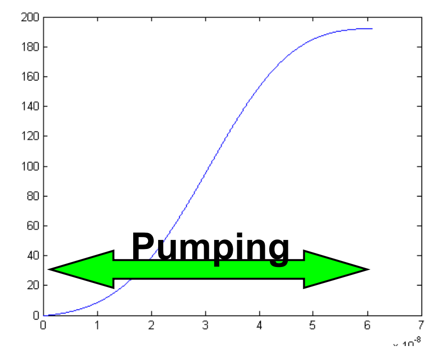
Population inversion versus time

# Stack of low absorbing disks




$[Ti^{3+}] = 6.6\ 10^{18}$ ions/cm$^3$






**NO parasitic effects in crystals**

# Participating Countries

- France
- Germany
- United-Kindom
- Spain
- Italy
- Greece
- Lithuania
- Austria
- Romania
- Bulgaria
- Hungary
- Belgium
- Poland
- Portugal

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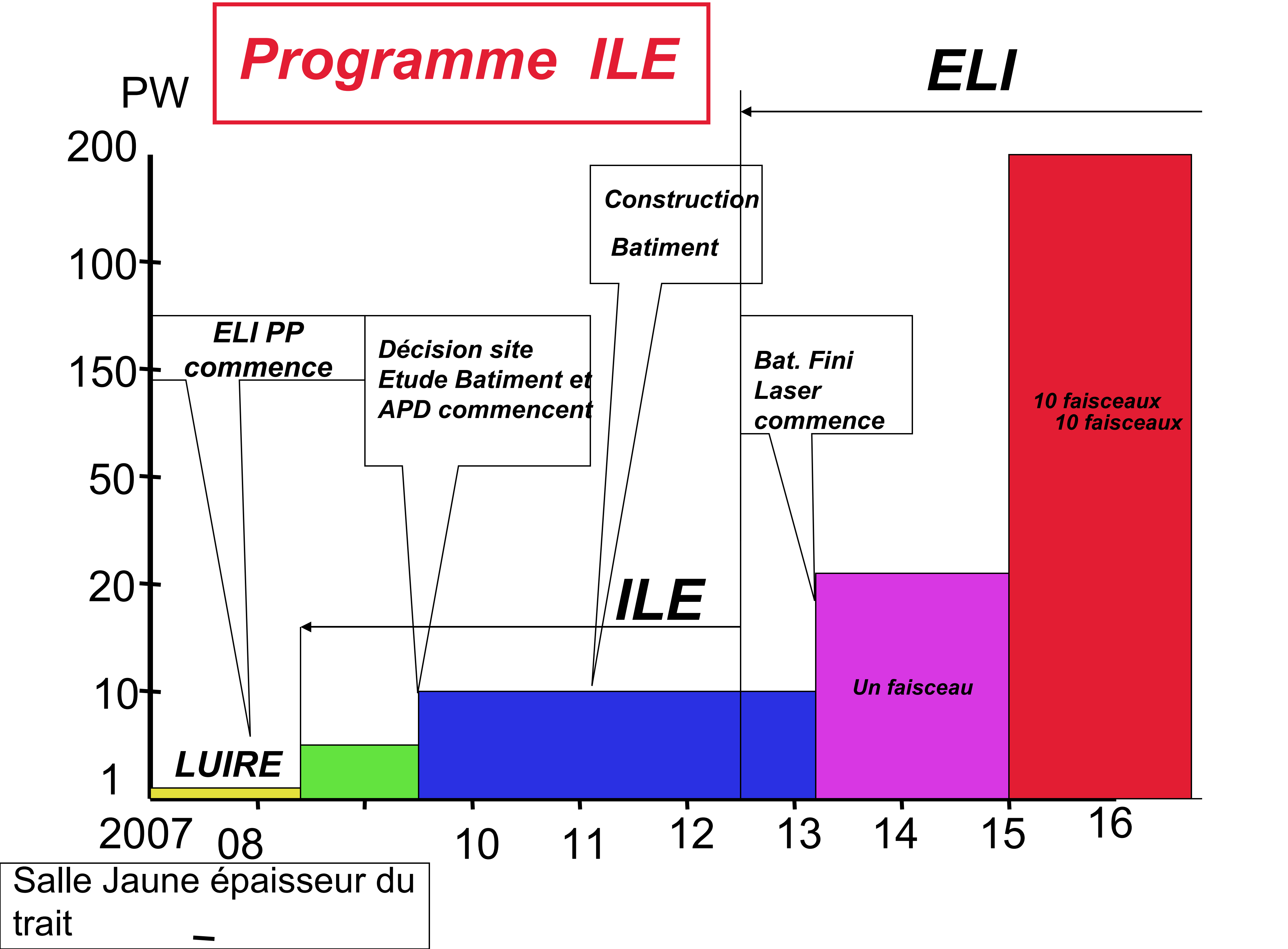
Programme ILE
ELI
PW
200
100
150
50
20
10
1
Construction
Batiment
ELI PP
commence
Décision site
Etude Batiment et
APD commencent
Bat. Fini
Laser
commence
10 faisceaux
10 faisceaux
ILE
Un faisceau
LUIRE
2007
08
10
11
12
13
14
15
16
Salle Jaune épaisseur du
trait

# *Thank you*

Become an ELI enthusiast

You can register @

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Eli@eli-laser.eu

*One of the big Chalenges*
*in Physics would be to built*
*A laser powerful enough to*
*breakdown vacuum.*

***Survey by Science 2005***

# Towards the Exawatt Laser: Relativistic and Ultra-Relativistic Optics

**Gérard A. MOUROU**

Laboratoire d Optique Appliquée LOA

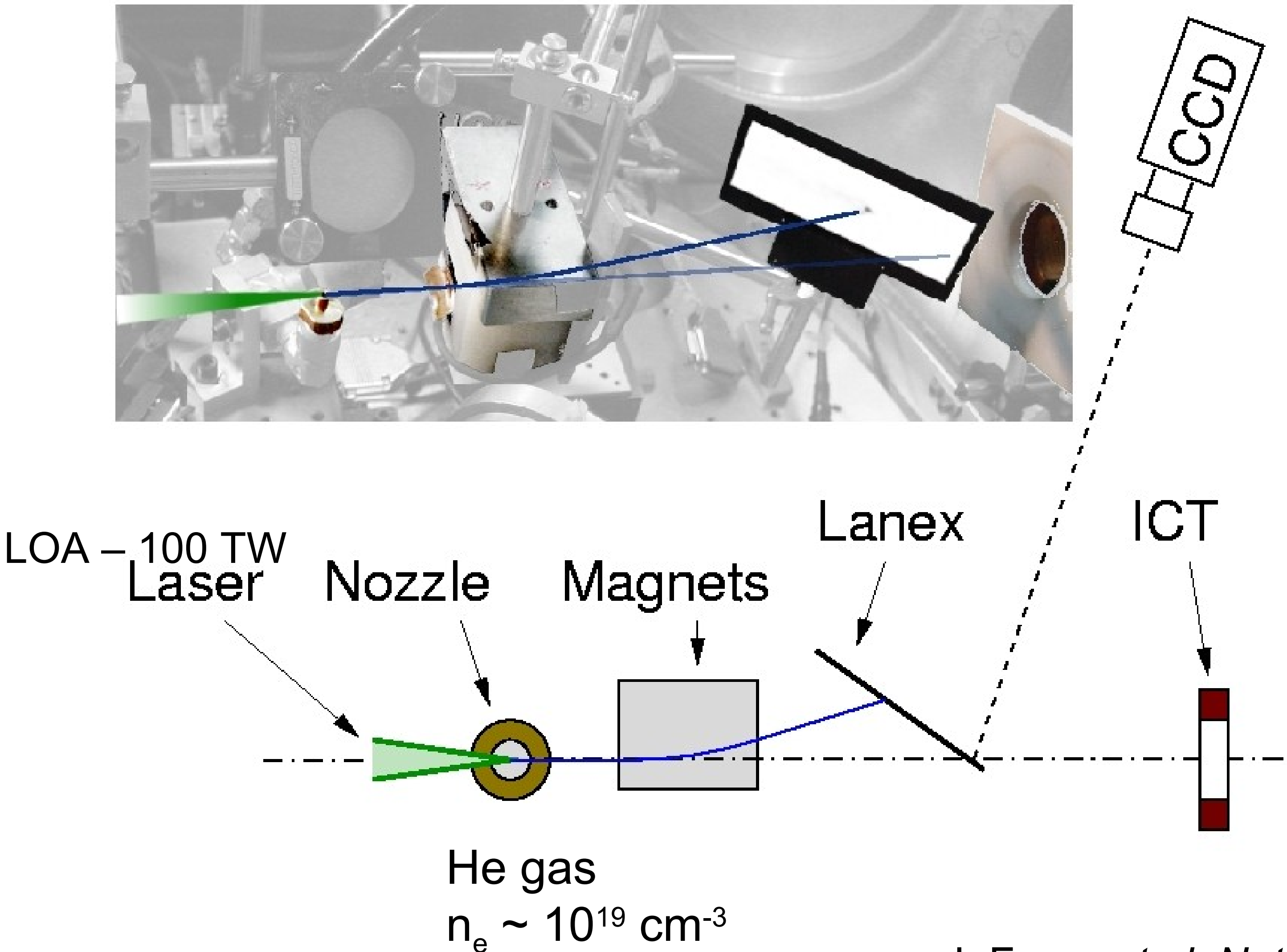
ENSTA Ecole Polytechnique CNRS

***PALAISEAU, France***

***gerard.mourou@ensta.fr***

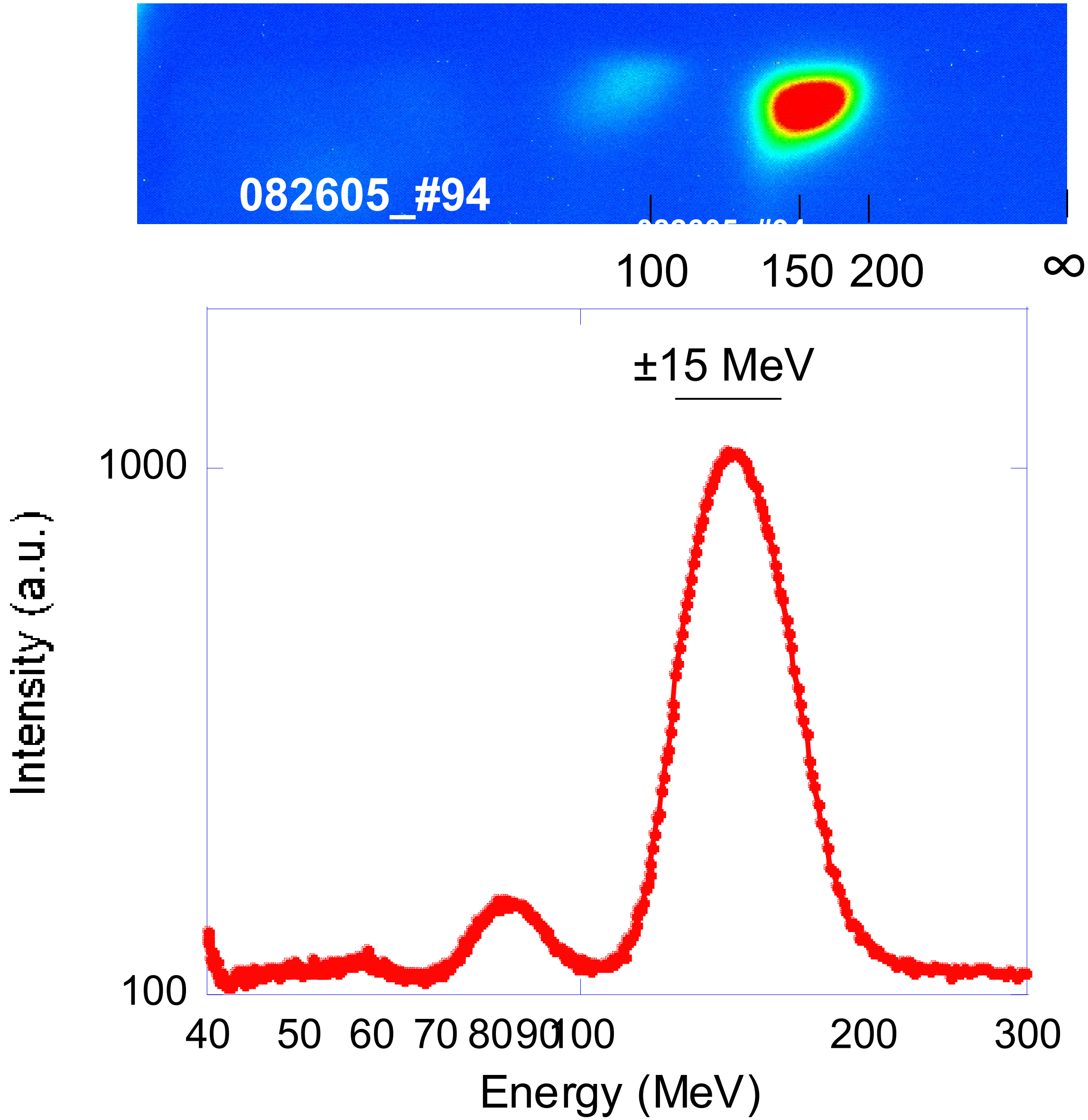
CLEO Europe 2007

# Recent results on electrons acceleration - Setup



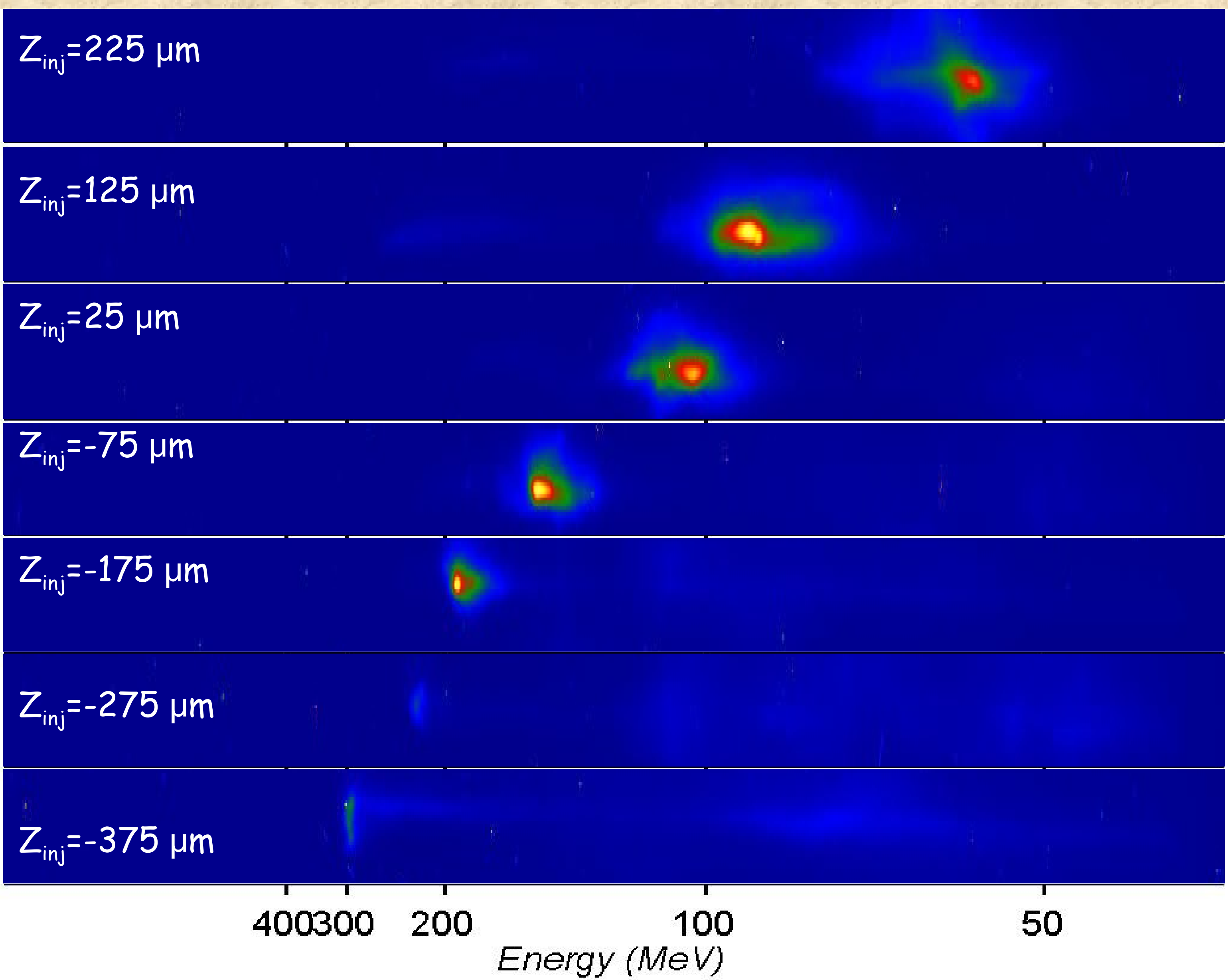

J. Faure *et al, Nature 2004*

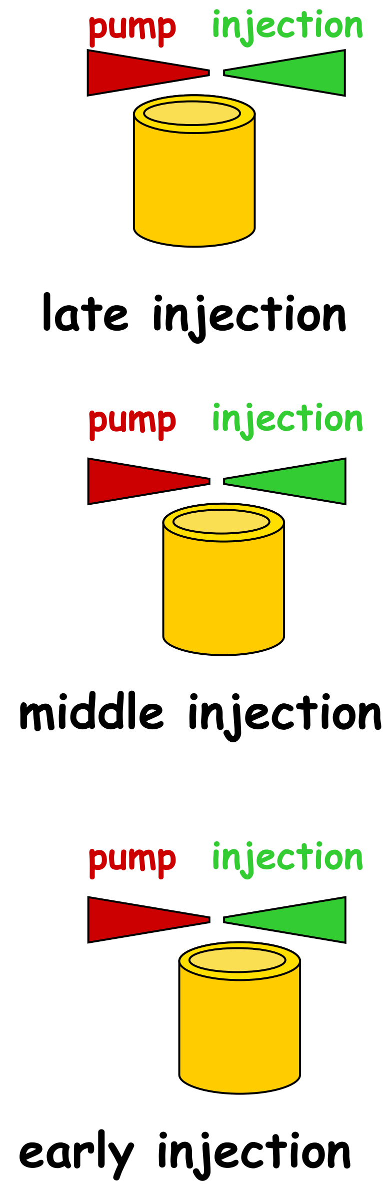
# Quasi-monochromatic beam with $E_{max}$=160 MeV at $n_e$=2.10$^{19}$ cm$^{-3}$



# Tunable monoenergetic bunches

V. Malka and J. Faure



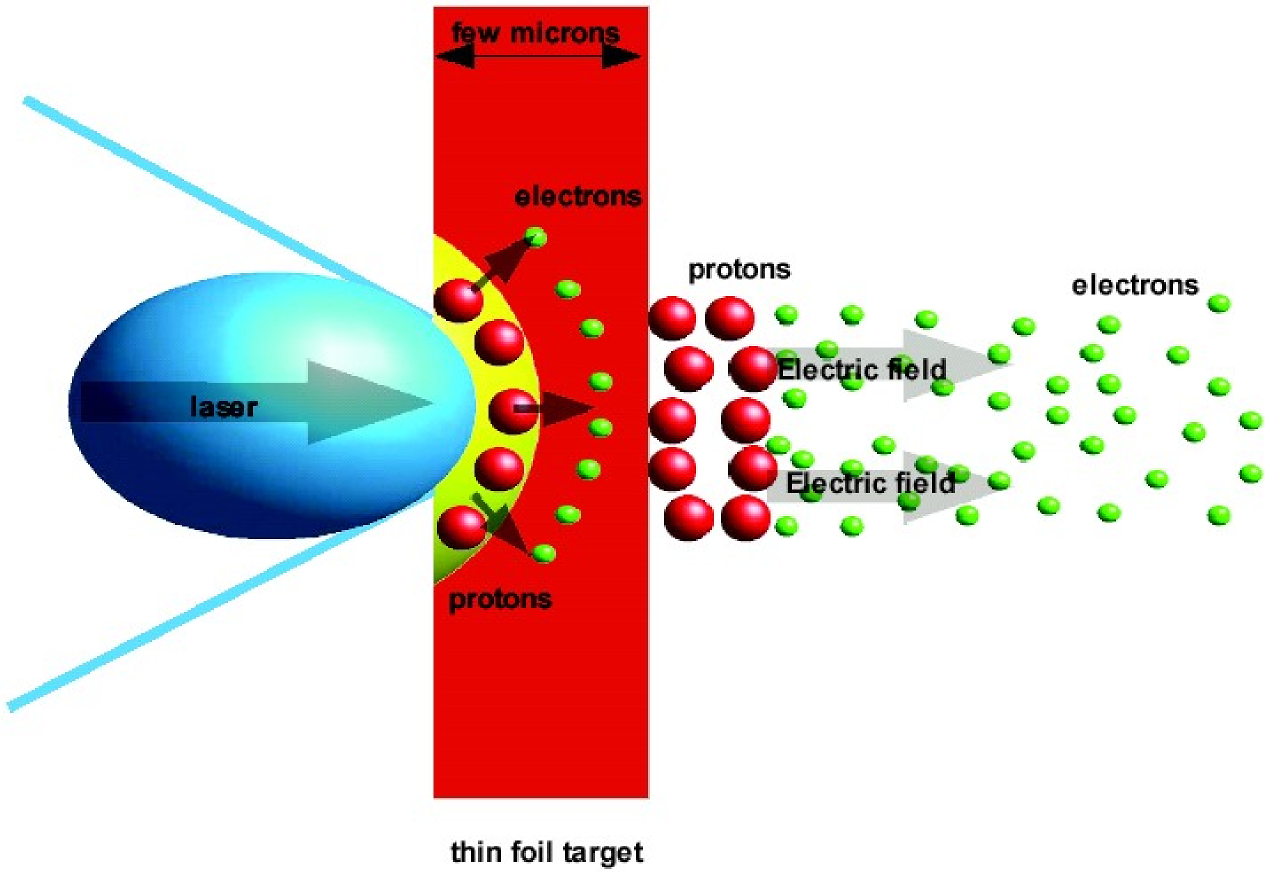
QuickTime[a] and a
Photo - JPEG decompressor
are needed to see this picture.

**T. Tajima and J. M. Dawson,**
**Laser electron accelerator,**
**Phys. Rev. Lett. 43, 267 (1979)**

Secondary effects of
electron acceleration:

# Proton Acceleration

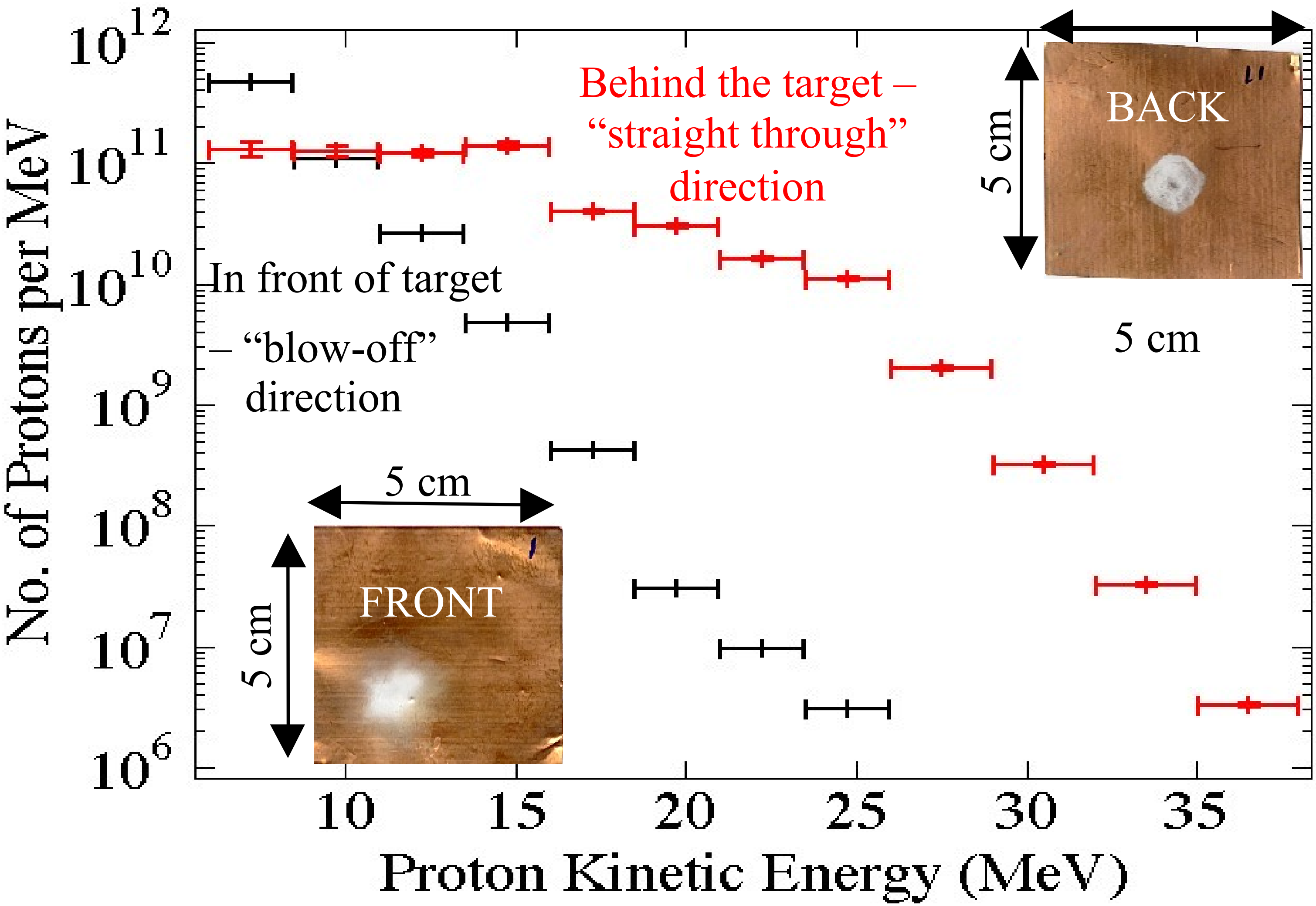
# Front and back acceleration mechanisms




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

# Large Laser results : Vulcan laser

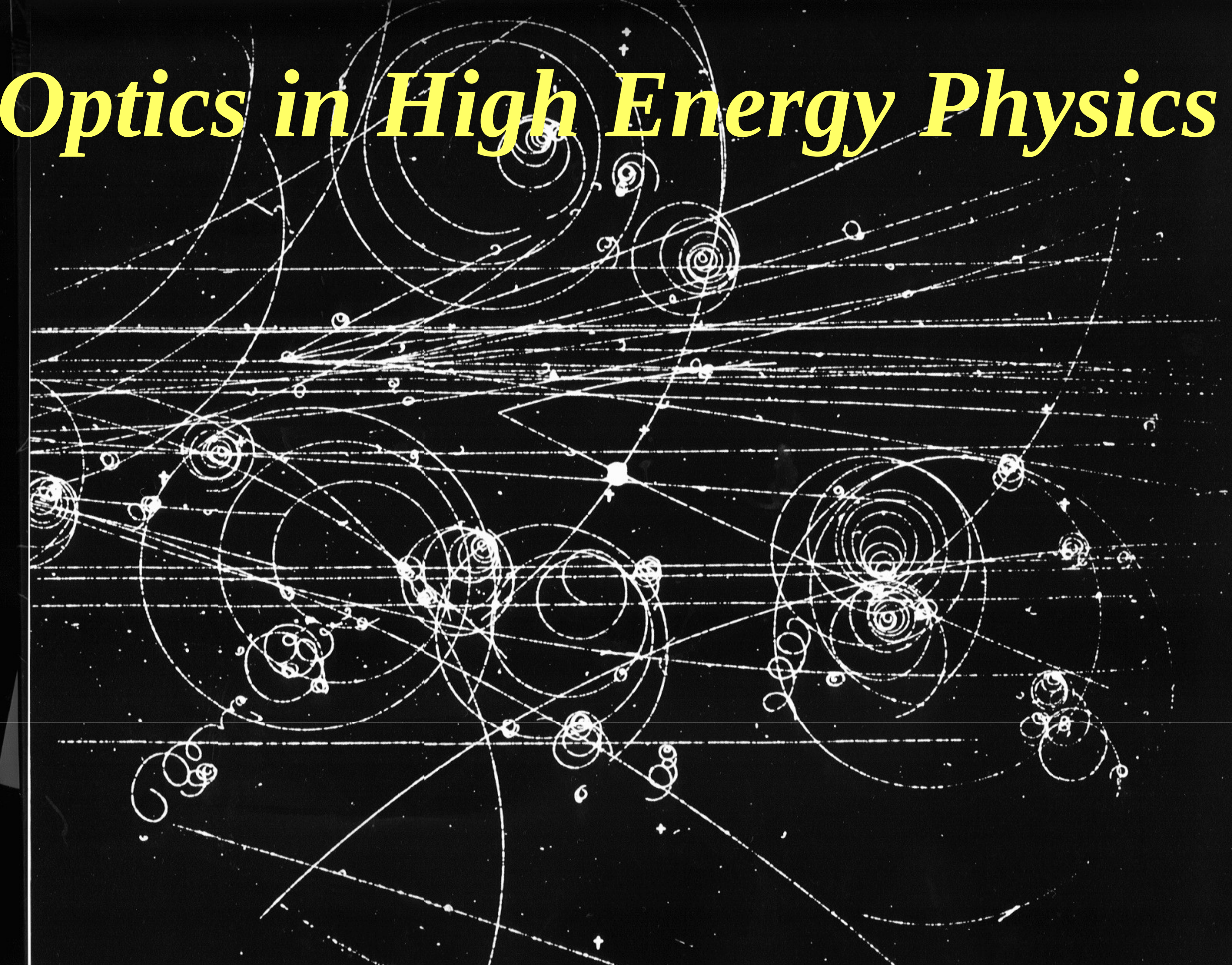
**50J:1ps & 1shot/20min.**



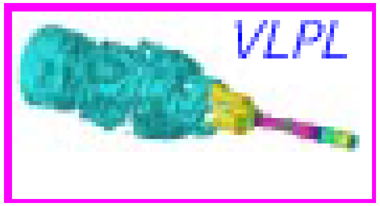
# Secondary effects of electron acceleration:

## X-rayBeam

# *Optics in High Energy Physics*

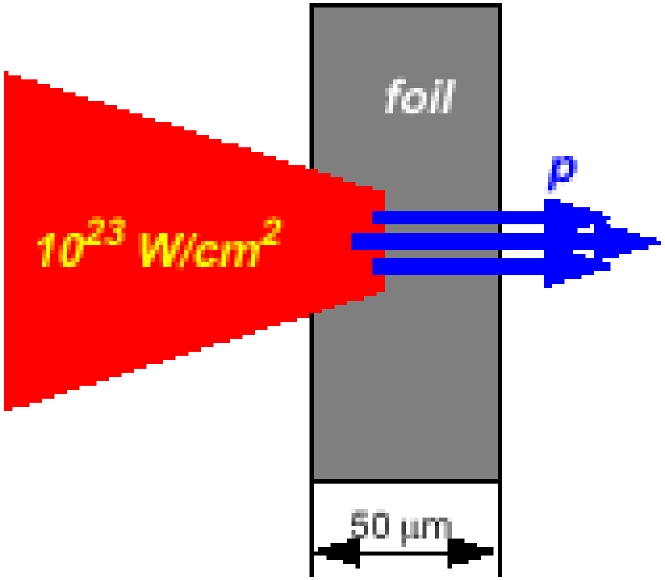


Virtual Laser Plasma Lab

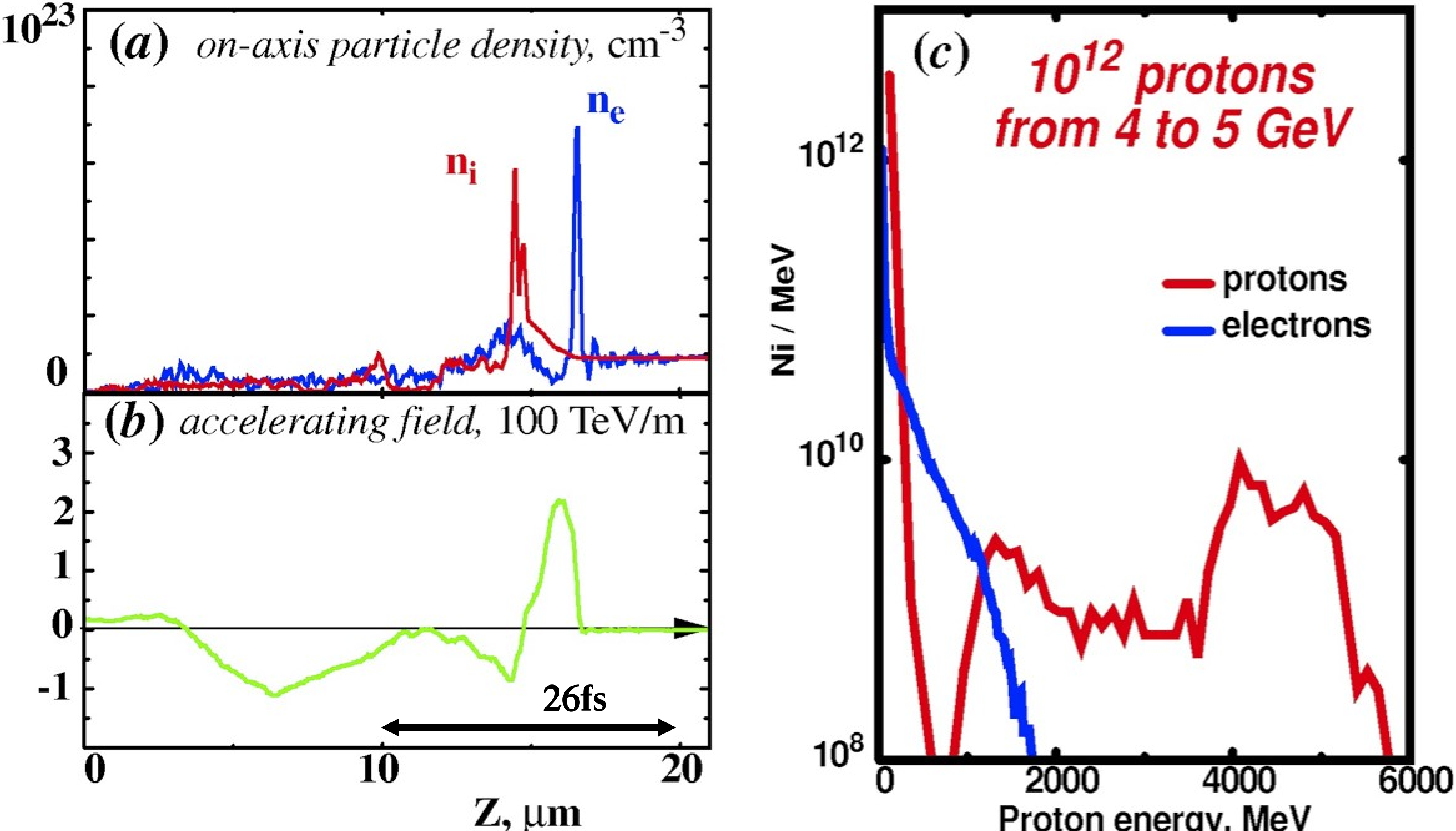



## 5 GeV proton bunch at solid state density

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



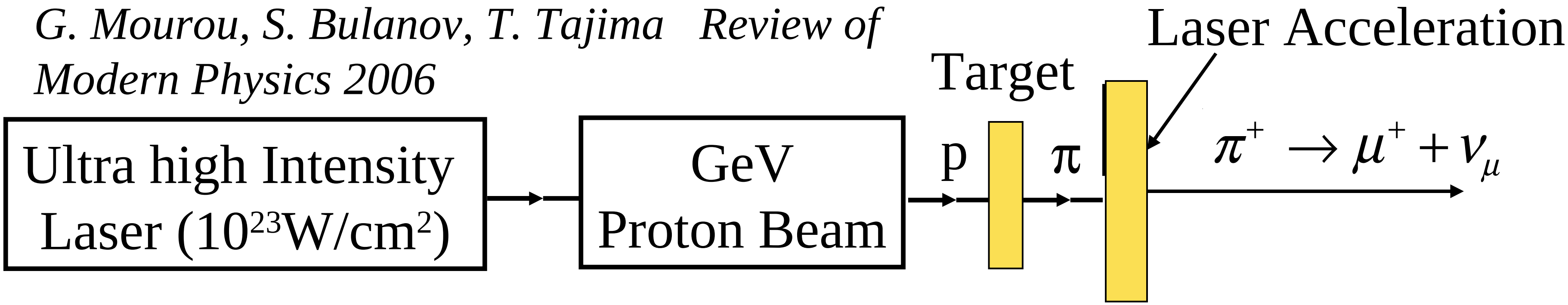

1 kJ, 15 fs long laser pulse focused down to 10 µm spot on a plasma with $n=10^{22}$ $cc^{-1}$



10^23
(a) on-axis particle density, cm-3
n_e
n_i
0
(b) accelerating field, 100 TeV/m
3
2
1
0
-1
26fs
0
10
20
Z, μm
(c)
10^12 protons
from 4 to 5 GeV
10^12
10^10
10^8
Ni / MeV
protons
electrons
0
2000
4000
6000
Proton energy, MeV

# *Unstable Particle Acceleration Muon and neutrino Beams*

*G. Mourou, S. Bulanov, T. Tajima Review of Modern Physics 2006*




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

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.