**PARIS DECEMBER 9-10 2005**

**École Nationale Supérieure de Techniques Avancées**

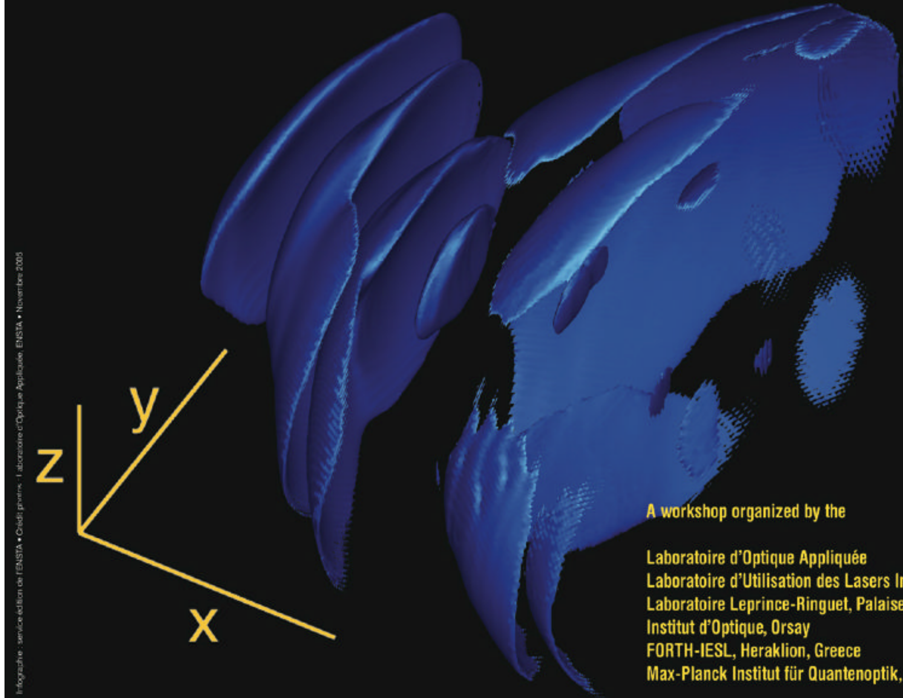
# SCIENTIFIC PROSPECTS FOR A EUROPEAN EXTREME LIGHT INFRASTRUCTURE

**SCIENTIFIC TOPICS**

- Attosecond and Exawatt lasers
- Attosecond EUV Physics
- Secondary beam sources of high energy photons, leptons, hadrons, ions
- Nuclear, Particle and High Energy Physics
- Astrophysics
- Cosmology, General Relativity
- Extradimensions Physics

**APPLICATIONS**

- Relativistic micro-electronics for compact accelerators
- Relativistic micro-photonics for compact synchrotron and XFEL
- Medical applications: radiation and hadron therapy
- New high peak and high average power drivers




A workshop organized by the

Laboratoire d'Optique Appliquée
Laboratoire d'Utilisation des Lasers Intenses
Laboratoire Leprince-Ringuet, Palaiseau
Institut d'Optique, Orsay
FORTH-IESL, Heraklion, Greece
Max-Planck Institut für Quantenoptik, Garching

Sponsored by

Infographie : service édition de l'ENSTA • Crédit photo : Laboratoire d'Optique Appliquée, ENSTA • Novembre 2005

# ESFRI

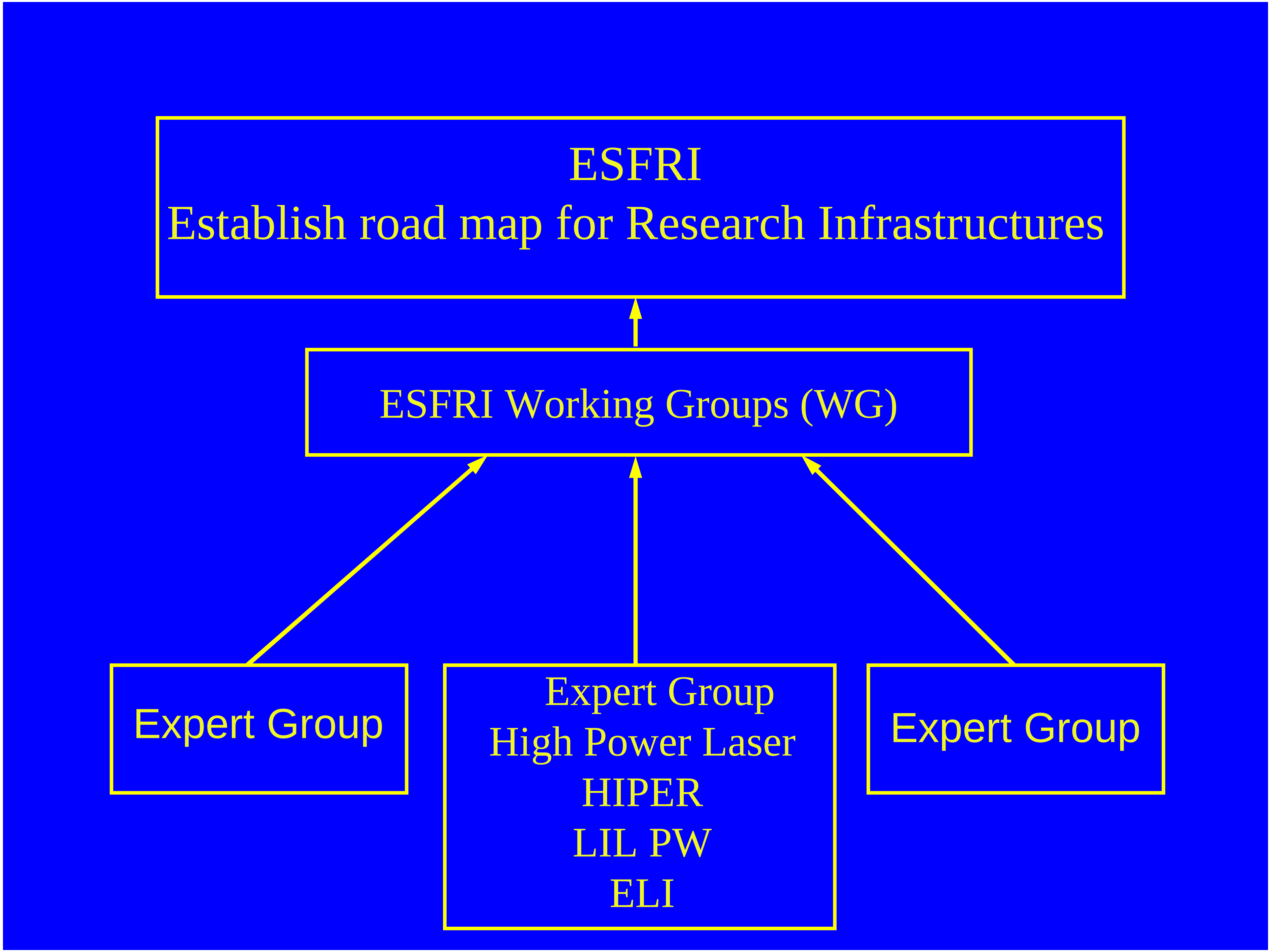
**The role of the European Strategy Forum on Research Infrastructures (ESFRI) is to support a coherent approach to policy-making on research infrastructures in Europe, and to act as an incubator for international negotiations about concrete initiatives. In particular, ESFRI is preparing a European Roadmap for new research infrastructures of pan-European interest.**

# ESFRI ROAD MAP

The ESFRI roadmap will identify needs of the European research communities for new or major upgrades of pan-European Research Infrastructure (RI), covering all scientific areas, regardless of possible localisation.

# European Roadmap for Research Infrastructures

With the appointment of the 15 Expert Groups, the process of creating Europe’s first ever Roadmap of large scale research facilities/research infrastructures has now been initiated. The ESFRI Roadmap will be instrumental in helping to identify those projects that are crucial for the scientific community in Europe. The first roadmap is to be published by early Autumn 2006.


ESFRI
Establish road map for Research Infrastructures
ESFRI Working Groups (WG)
Expert Group
Expert Group
High Power Laser
HIPER
LIL PW
ELI
Expert Group

# A Future European High Power Laser Facility

# HIPER

## CCLRC Rutherford Appleton Laboratory

An informal panel of scientists from seven EU countries was assembled at the behest of the CCLRC Rutherford Appleton Laboratory to consider the scientific case for a future high power laser facility within Europe.

The panel met three times between December 2004 and June 2005. This document presents the considered view of the panel that there is a strong case for a large-scale “fast ignition” laser of sufficient capability to make a significant contribution to the international pursuit of fusion energy, whilst supporting a broad base of high energy-density civilian research. A brief overview of the requirement for the laser is presented here.

# A MULTI-PW addition to the LIL laser in Bordeaux

- To carry out integrated fast-ignition experiments on LIL using its target implosion capability.

- To perform high-energy density experiments for matter under extreme conditions of interest to geophysics and astrophysics.

- To open the avenue that could lead to ultra-relativistic exawatt laser power by using the LIL as a pump beam, allowing exploring in the laboratory pressures, accelerations, magnetic fields, and nuclear processes that occur only in astrophysical objects.

# EXTREME LIGHT INFRASTRUCTURE (ELI)

Laboratoire d'Optique Appliquée
Laboratoire d' Utilisation des Lasers Intenses
Laboratoire Leprince-Ringuet
Institut d' Optique Theorique et Appliquée
FORTH-IESL, Heraklion, Greece
Max-Planck-Institut fuer Quantenoptik
VULRC Vilnius

ELI will be devoted to the investigation of fundamentally novel laser-matter interaction regimes in the ultra-relativistic regime.

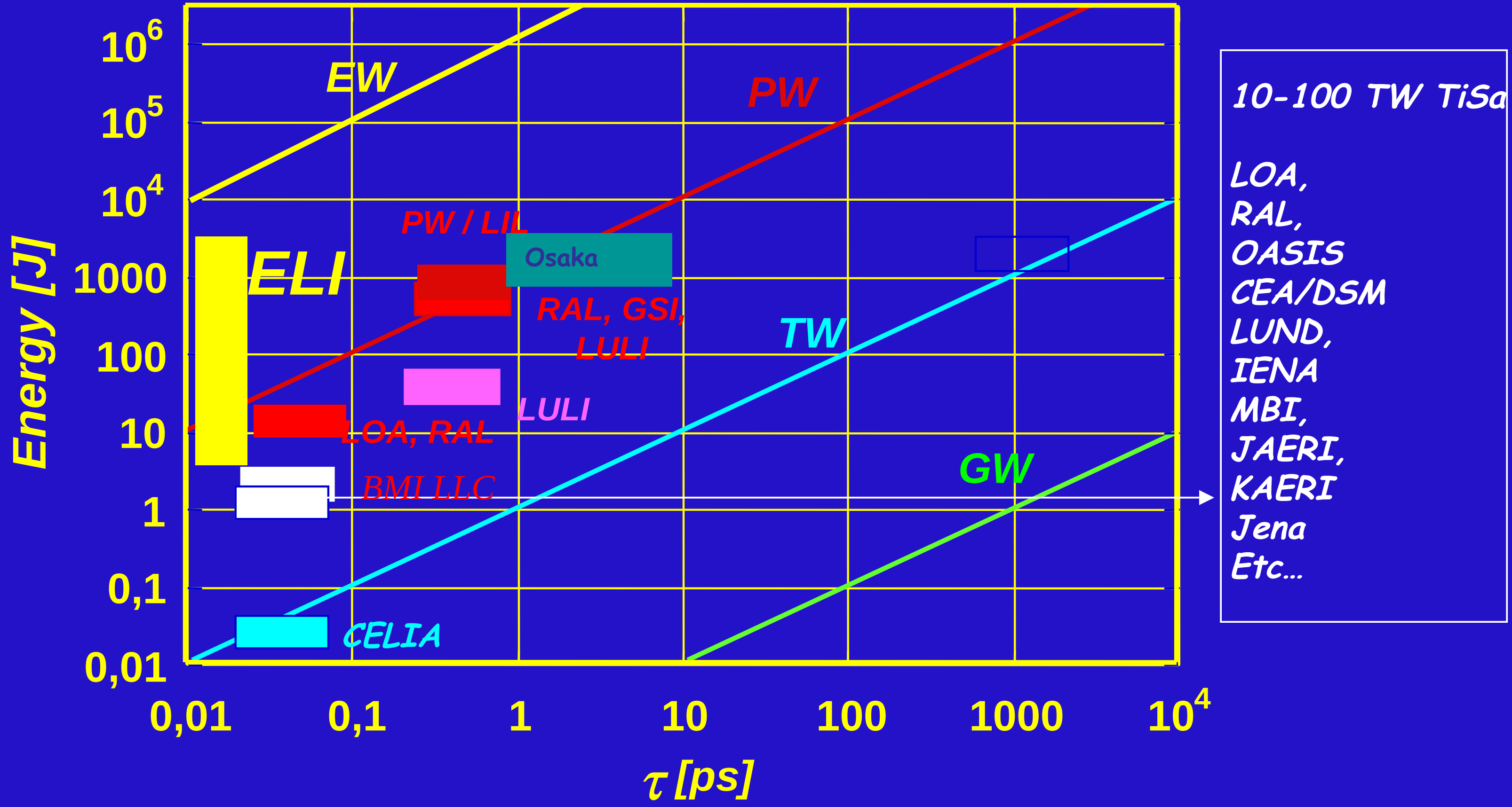
ELI will provide a new generation of compact accelerators delivering ultra short ($10^{-15}$-$10^{-18}$s) pulses of radiation from EUV to $\gamma$-ray and energetic particles beams for European scientists.

Eli will practice an aggressive technology transfer, education and training activities.

# Short Description of ELI

# Towards an Integrated Scientific Project for European Researcher : ELI

# Where do we stand ?



# ELI Objectives

The past 10-15 years has seen a new regime d' interaction: the regime of relativistic optics ($a_0$~1-10)

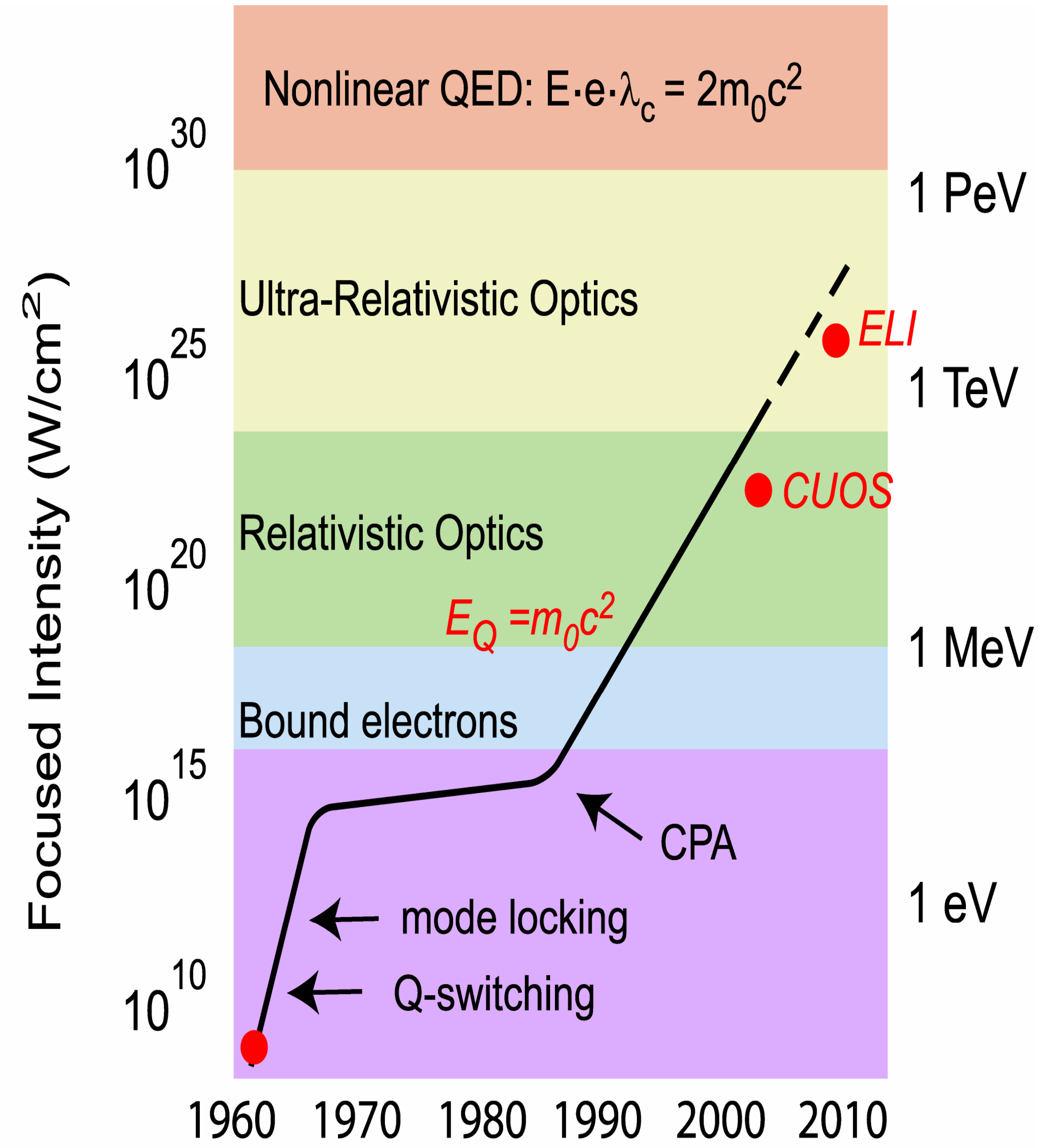
ELI will be a pluri-disciplinary scientific and Engineeringfacility.

The main scientific aim of ELI will be to investigate the ultra relativistic regime from $10<a_0<10^4$.

The very large $a_0$ required will be achieved by the shortness of the pulses and less by the energy.

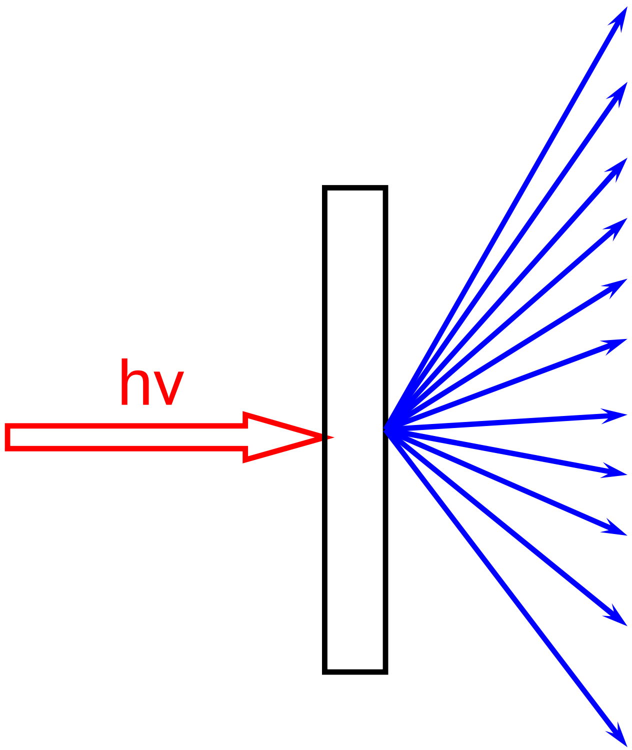
ELI rely on kHz front end and will evolve over the entire program 5-7 years towards an "Exawatt, 1/mn to 1Hz"

ELI will provide new beams of radiation, x, gamma, electron, proton, muon, neutrino



Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$
Ultra-Relativistic Optics
Relativistic Optics
Bound electrons
ELI
CUOS
$E_Q = m_0c^2$
CPA
mode locking
Q-switching
1 PeV
1 TeV
1 MeV
1 eV
Focused Intensity (W/cm²)
$10^{30}$
$10^{25}$
$10^{20}$
$10^{15}$
$10^{10}$
1960
1970
1980
1990
2000
2010

# *Nonlinear Optics (bound electron)*




Harmonic Generation *Franken 1961*

Sum and Difference Frequency Generation *Bass et al. 1962*

Optical Rectification *Bass et al 1962*

Parametric Generation and Amplification *Giordmaine et al. 1965*

Stimulated Raman Scattering *Woodbury and Ng 1962*

Stimulated Brillouin Scattering *Chiao et al.1964*

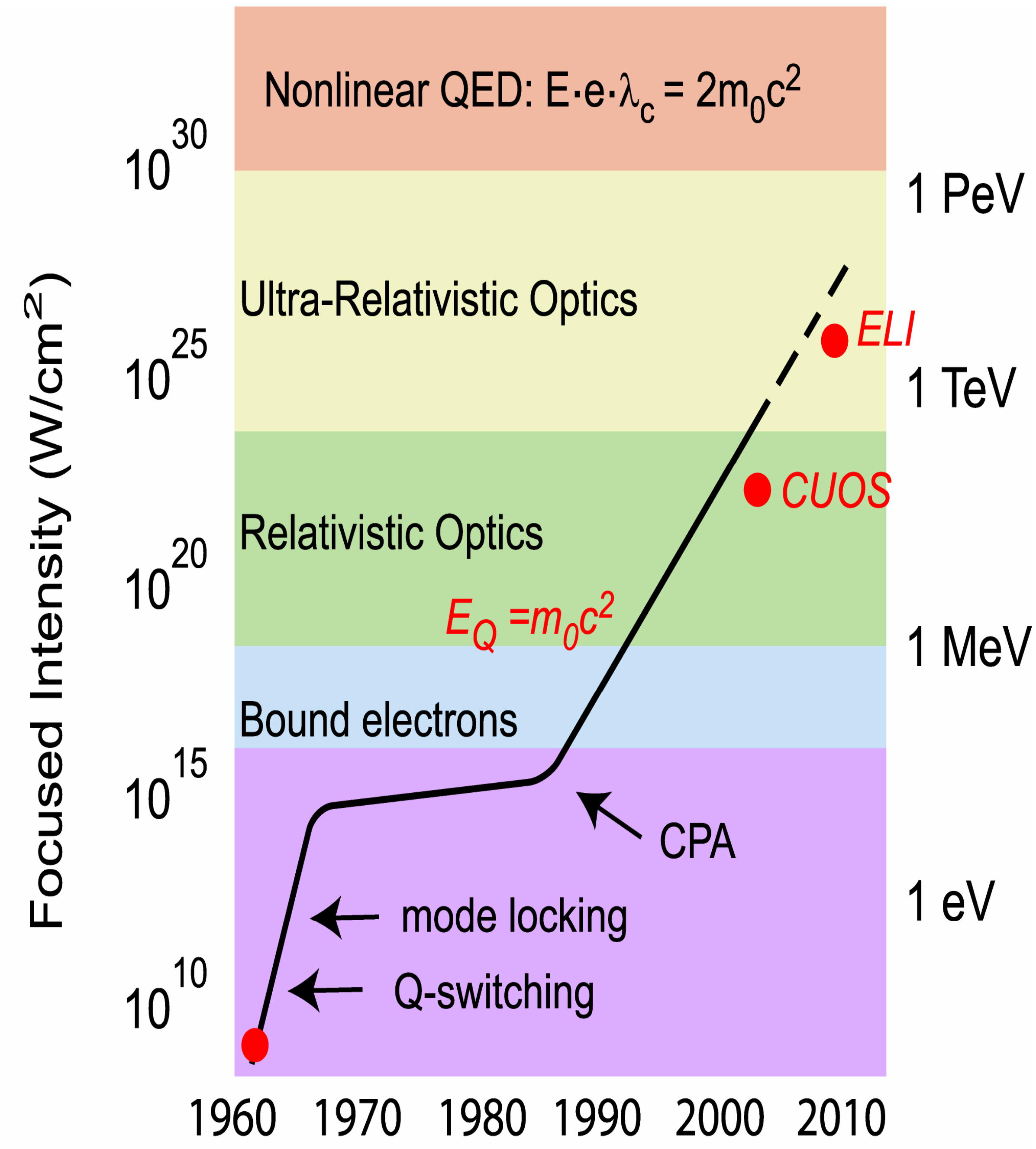
Two-Photon Absorption *Kaiser et al. 1961*

Four-wave Mixing *Maker and Terhune 1965*

Optical Kerr Effect Gires and Mayer *1964*

Multiphoton Ionization *Voronov and Delone 1965, G. Mainfray, P. Agostini, C. Manus, et al. 1967, N. Isenor and S. L. Chin 1969*

**High Harmonic Generation P. Agostini, A. L' Huillier, C. Manus, G. Mainfray 1989** → **Attosecond Generation**



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10^30
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10^15
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Focused Intensity (W/cm2)
1960
1970
1980
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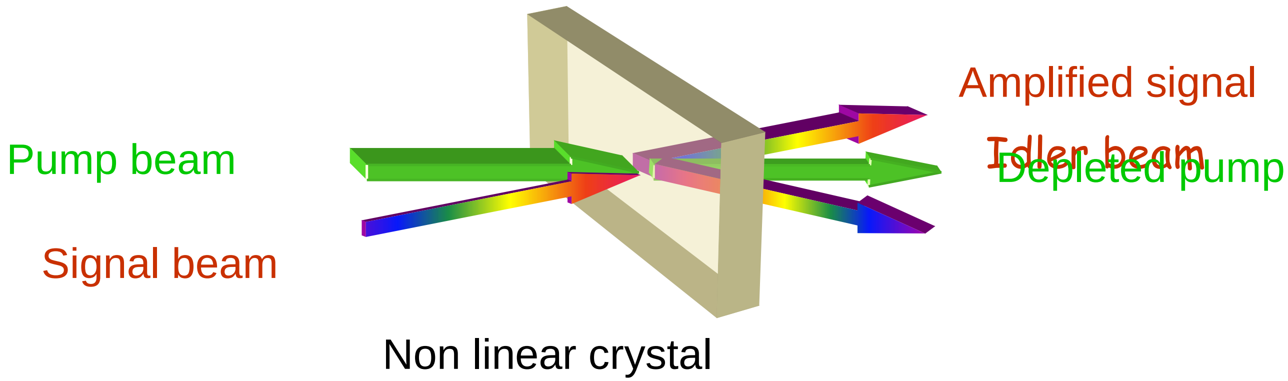
2000
2010

# Physics of parametric amplification



Special Laserlab Europe Session

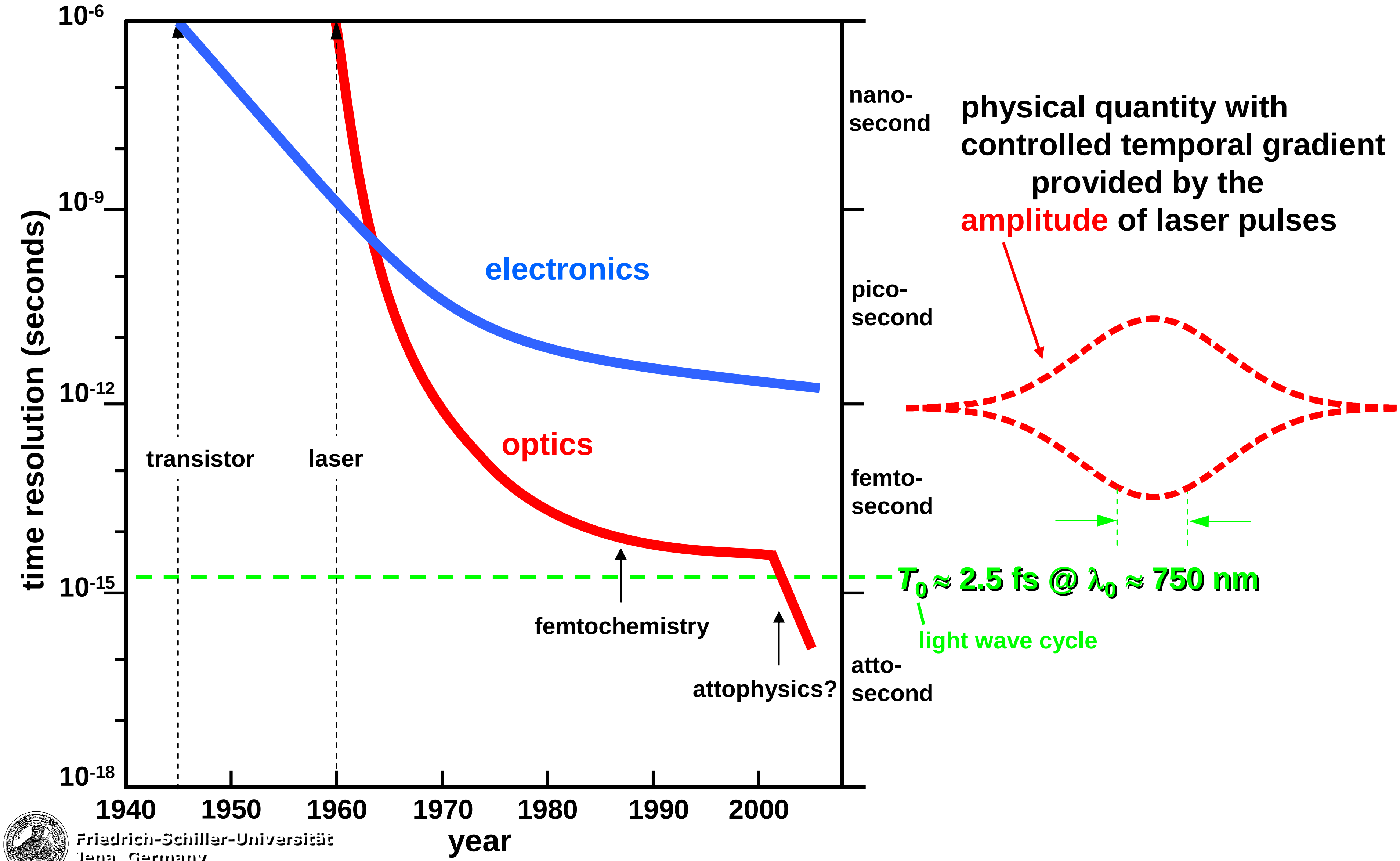
Overview and Latest Developments of OPCPA

by

A. Piskarksas

6:30 same Location

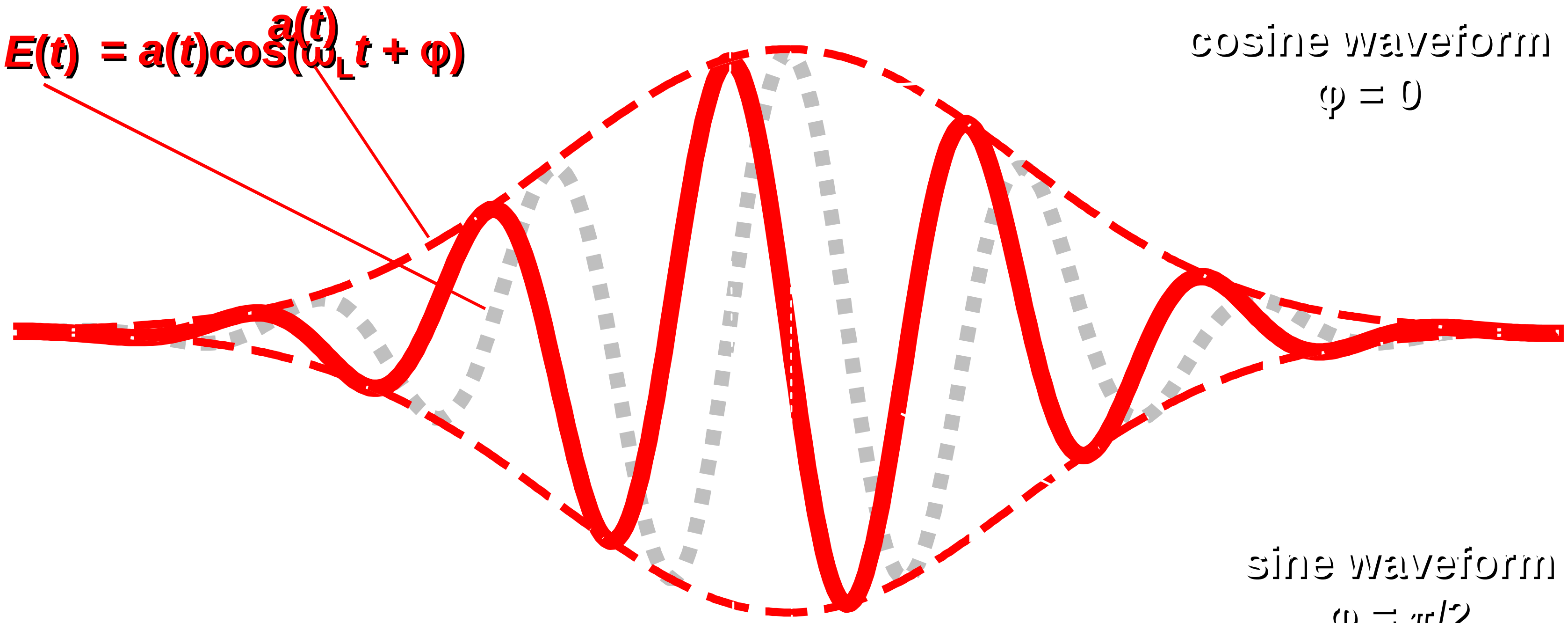
# evolution of ultrafast metrology




Friedrich-Schiller-Universität
Jena, Germany

# attosecond metrology: requires amplitude gradient within 1 femtosecond

# femtosecond technologies on *controlled* [illegible] of ultrashort laser pulses




$T_0 \approx 2.5$ fs

$T_0/4 \approx 625$ as (@ $\lambda_0 \approx 0.75$ µm)

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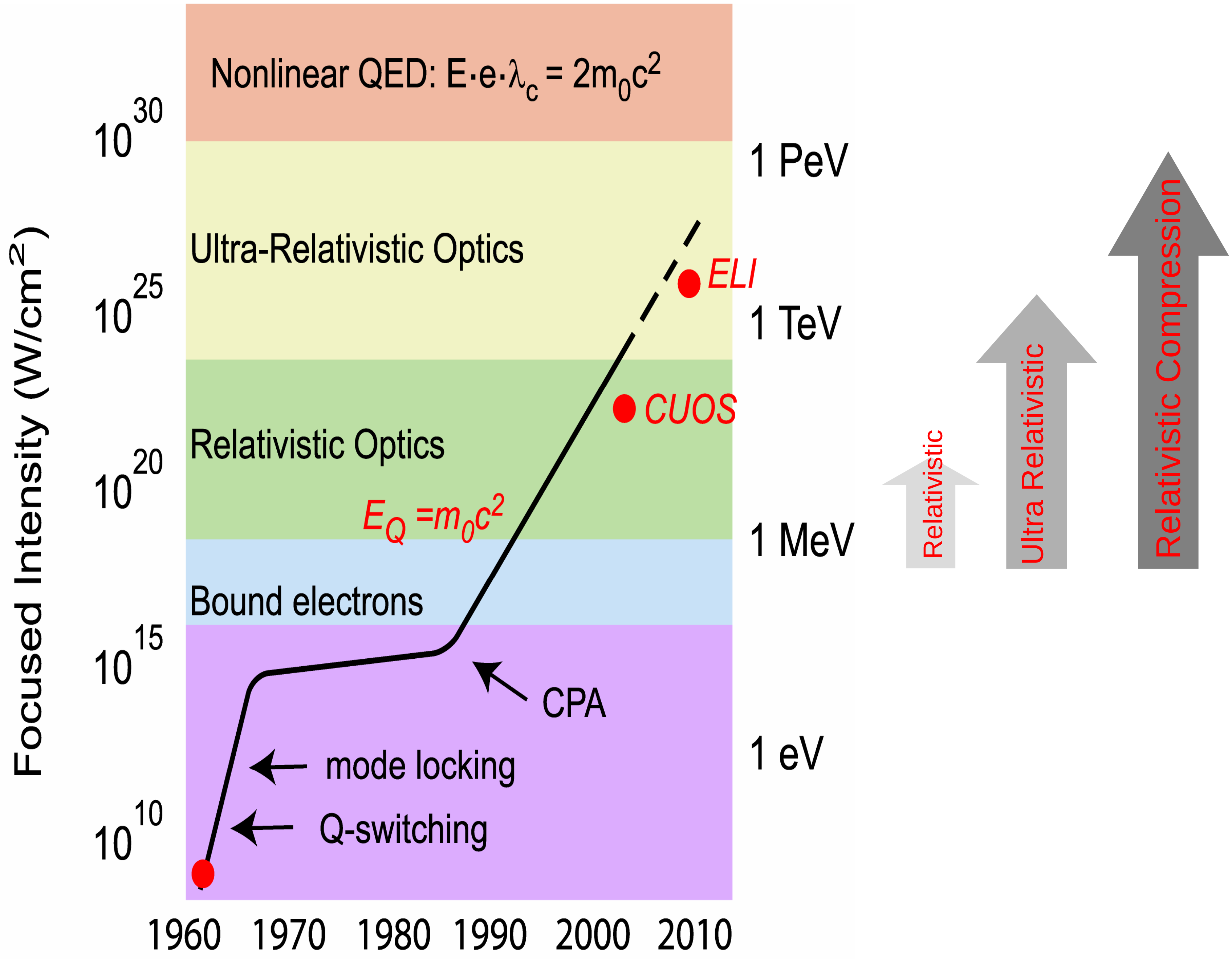
Jena, Germany



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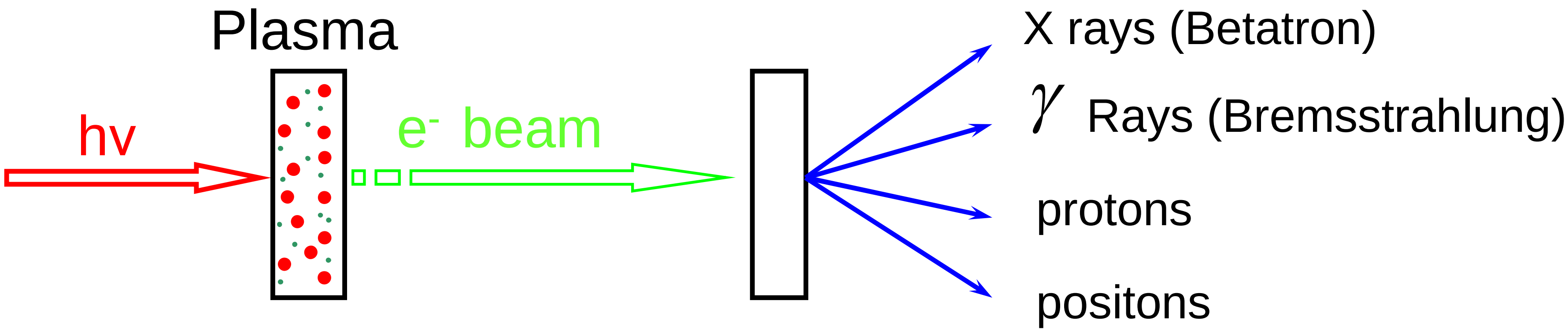
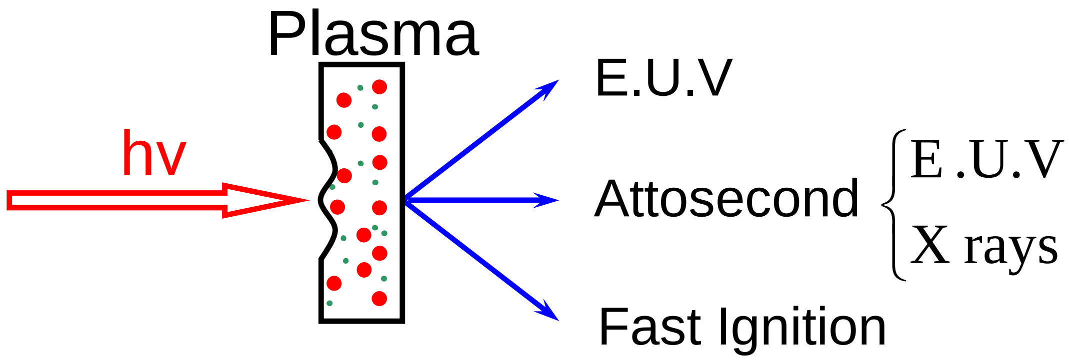
Focused Intensity (W/cm2)
1030
1025
1020
1015
1010
1960
1970
1980
1990
2000
2010
Relativistic
Ultra Relativistic
Relativistic Compression

# *Relativistic Optics*

## *Strong Motion of Matter*

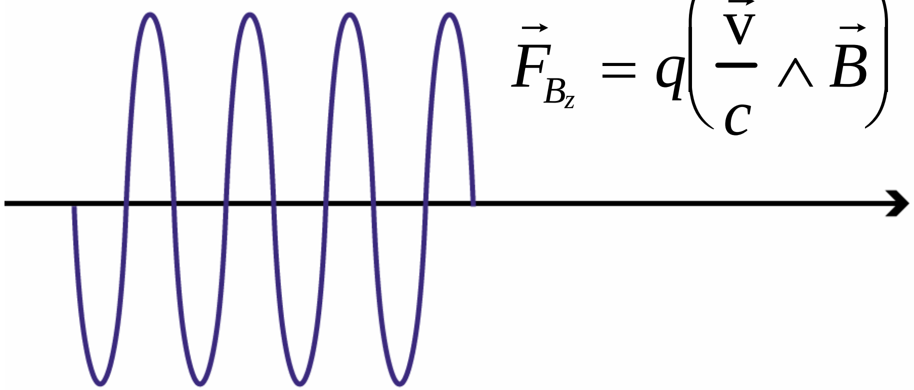



## *Large Laser Pressure*

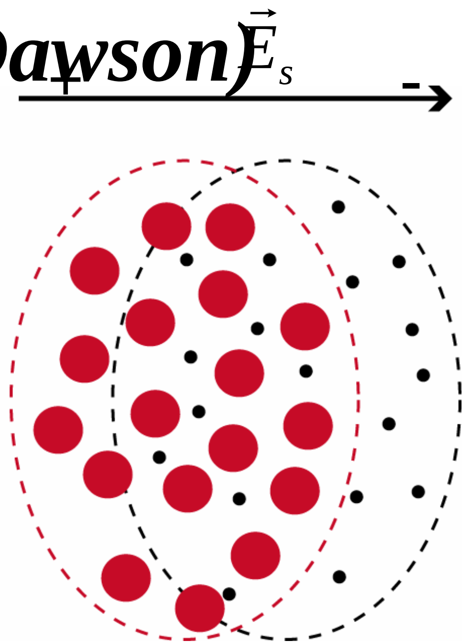


# *Relativistic Rectification*

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



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




1) $\vec{v} \wedge \vec{B}$ pushes the electrons.

2) The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough) $E_s = \frac{c\gamma m_o \omega_p}{e} = \sqrt{4\pi\gamma m_o c^2 n_e}$

3) The electrostatic field $E_s \approx E_L$

# Relativistic Rectification

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

$$E_L^2 = Z_0 * I_L$$

Medium Impedance ($Z_0$)

Laser Intensity ($I_L$)

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

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

# *Laser Acceleration:*

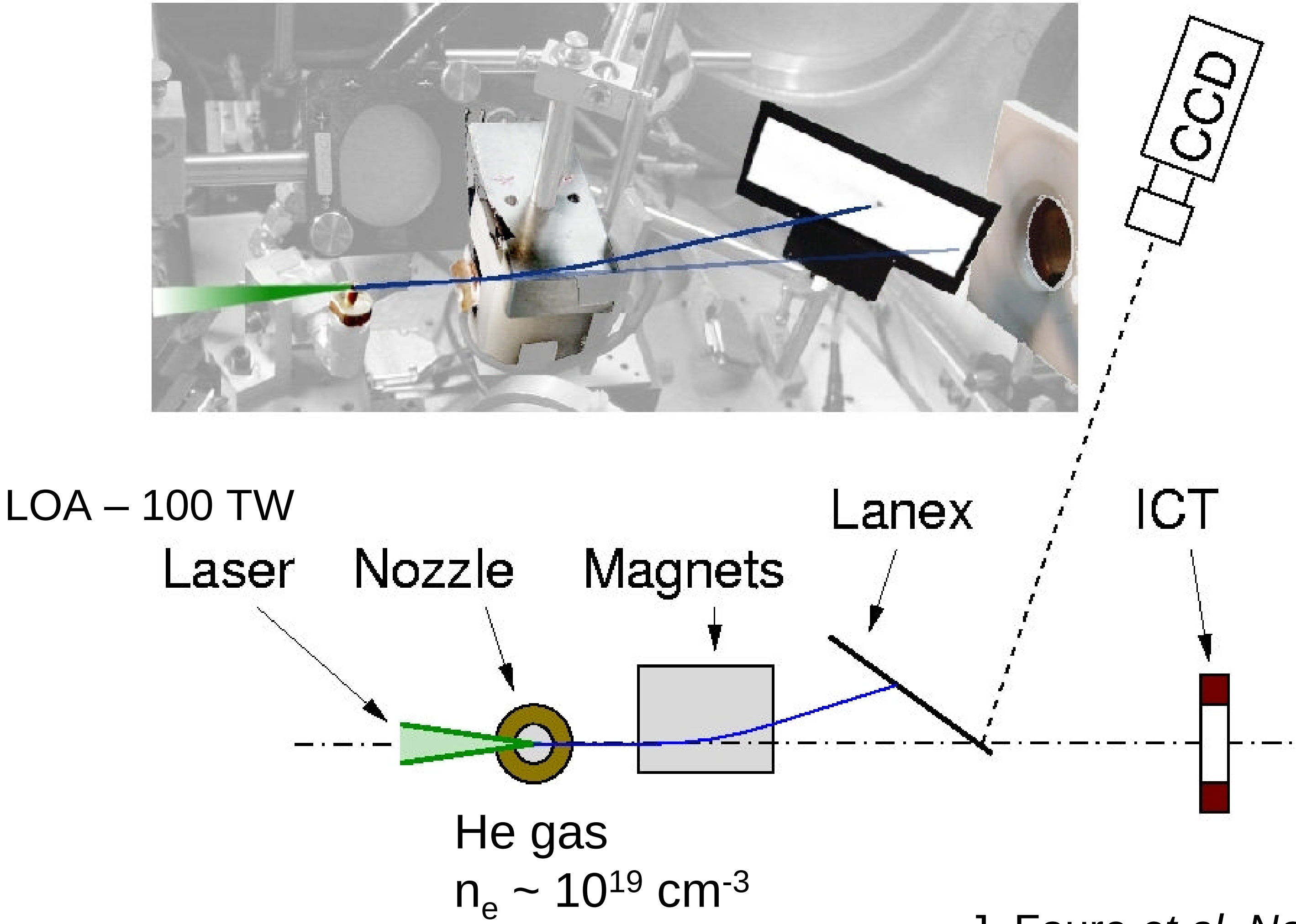
*At $10^{23}$W/cm$^2$ , E= 0.6PV/m, it is SLAC (50GeV, 3km long) on 10μm The size of the Fermi accelerator will only be one meter (PeV accelerator that will go around the globe, based on conventional technology).*

## *Relativistic Microelectronics*

# *The Dream Beam*

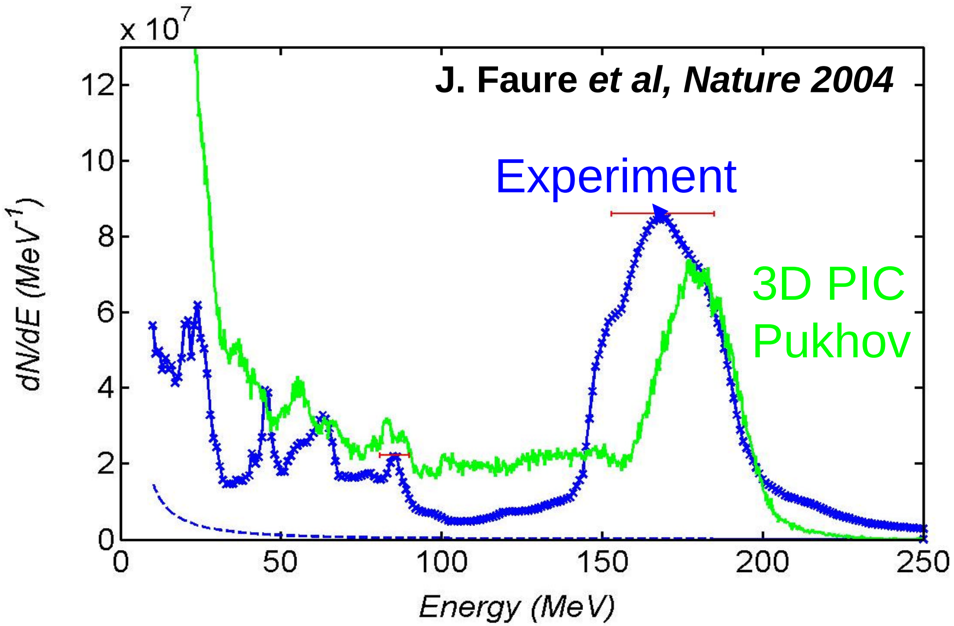

J. Faure et al., **C. Geddes et al., S. Mangles et al. ,**
**in Nature 30 septembre 2004**

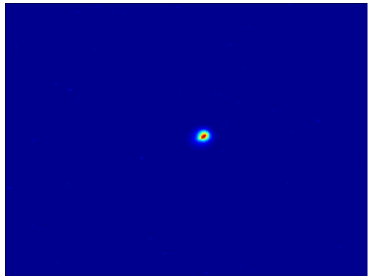
# Recent results on electrons acceleration - Setup



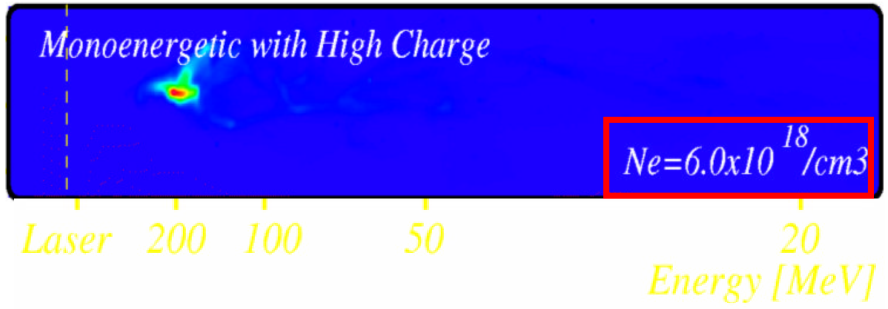

J. Faure *et al, Nature 2004*

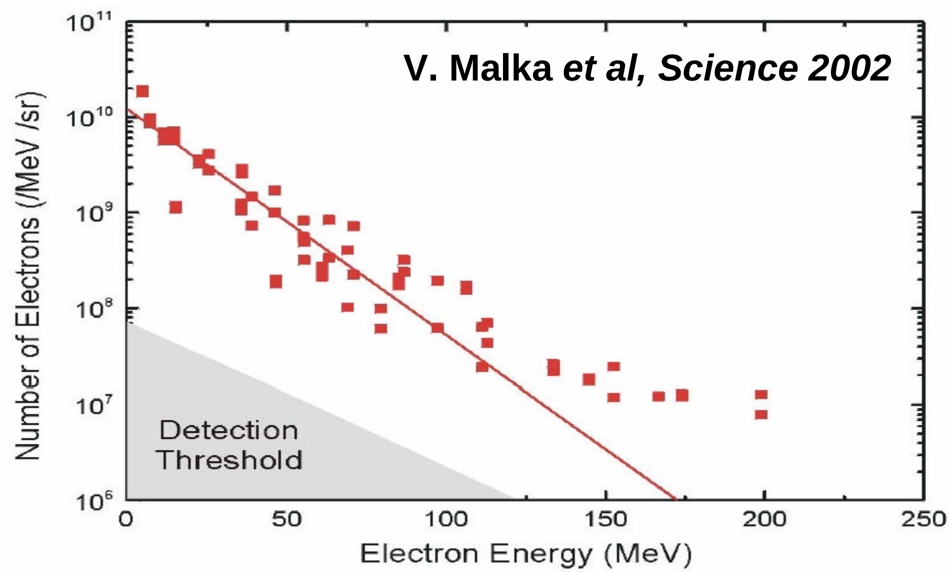
# Recent results on electrons acceleration

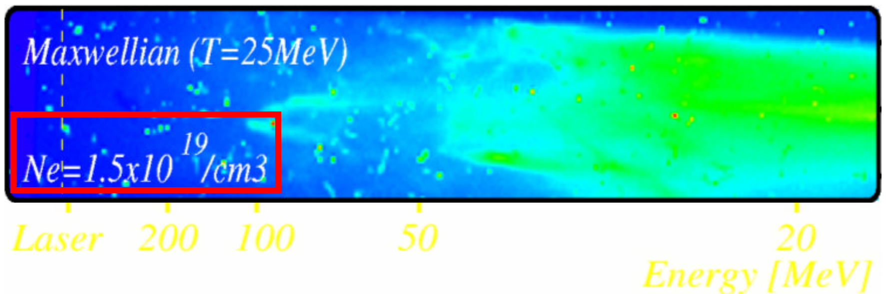


**Divergence**
**< 6 mrad**

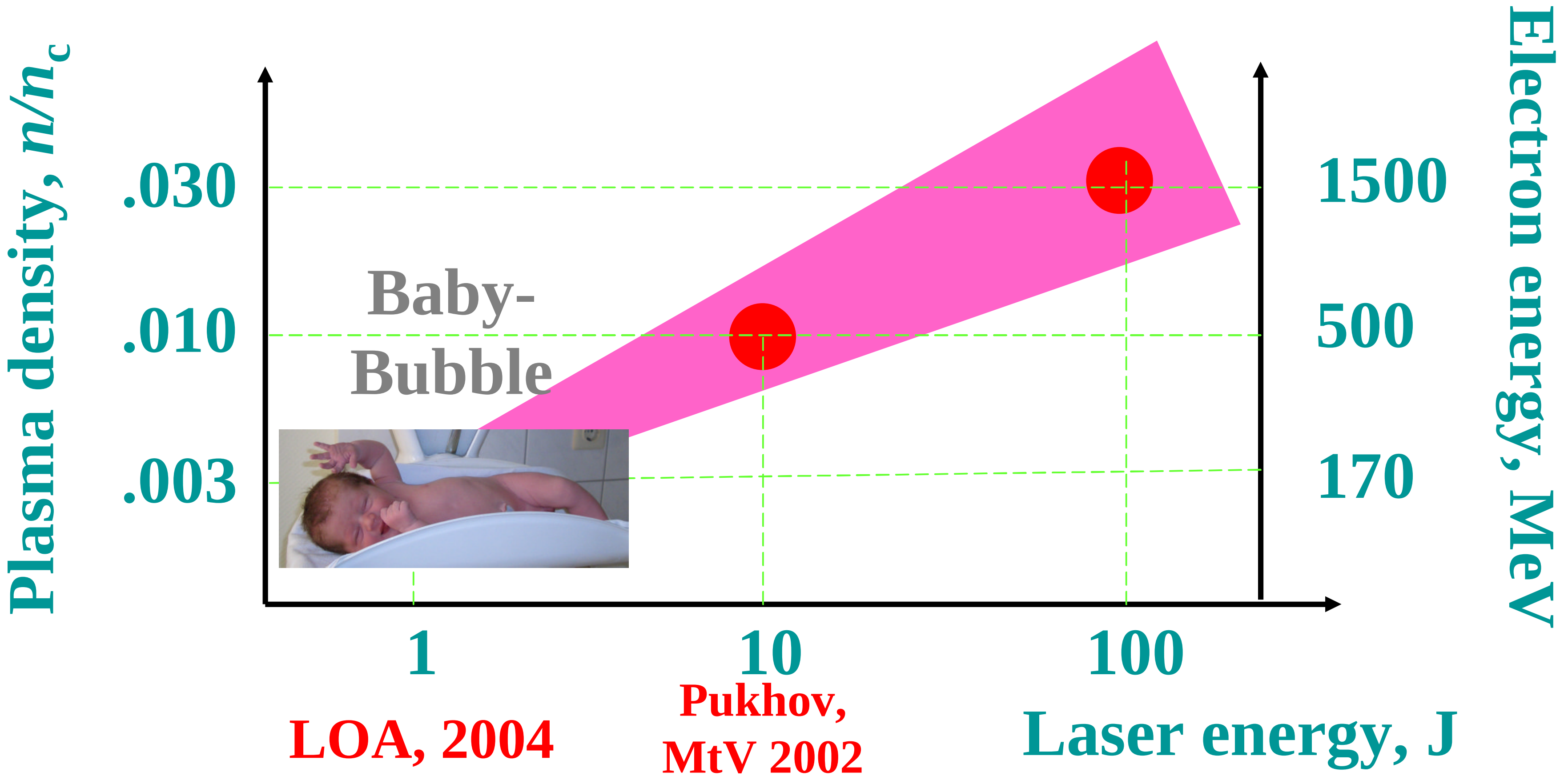


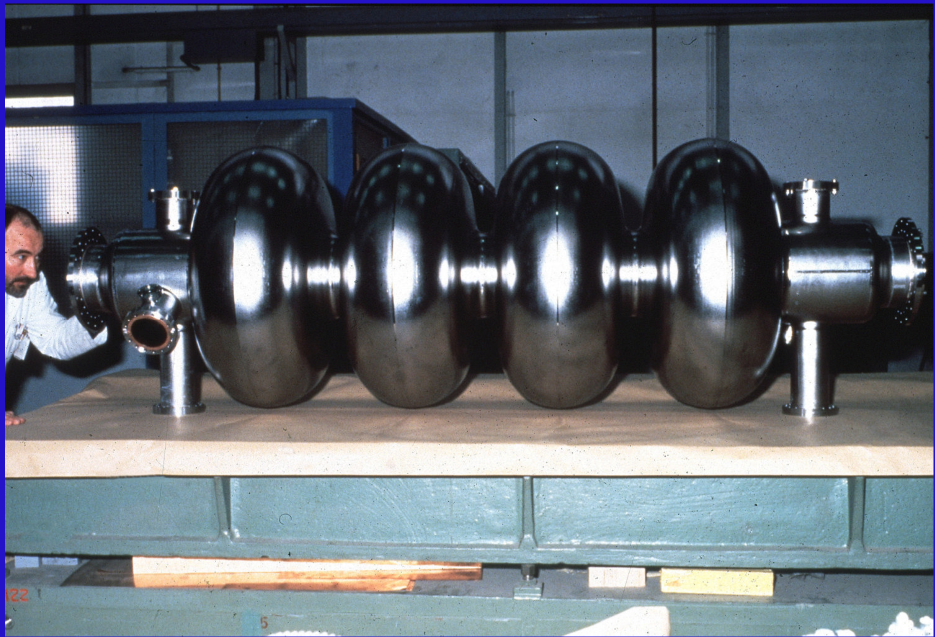



# The Bubble Family

## Fixing laser pulse duration to 30 fs

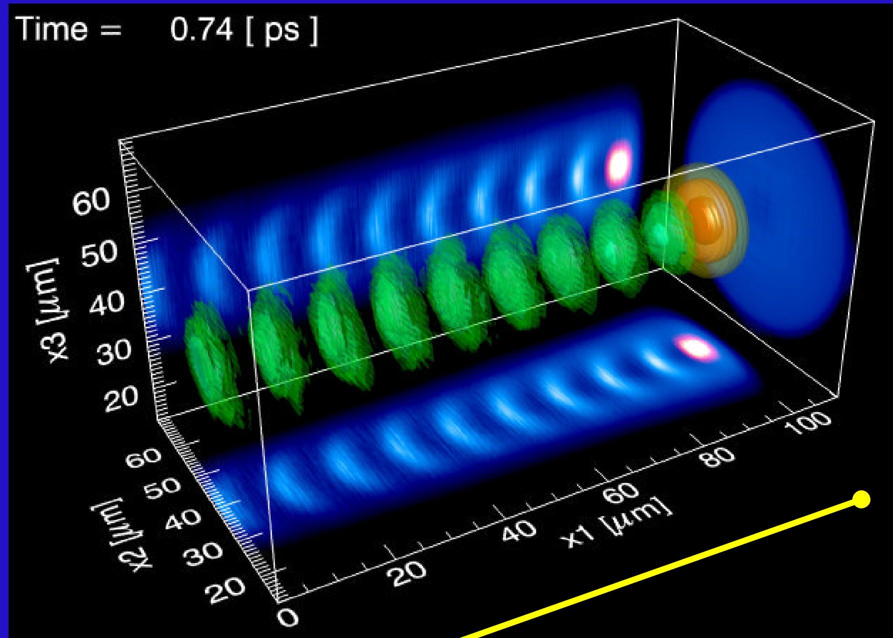


# Relativistics microelectronic devices



1 m

RF cavity

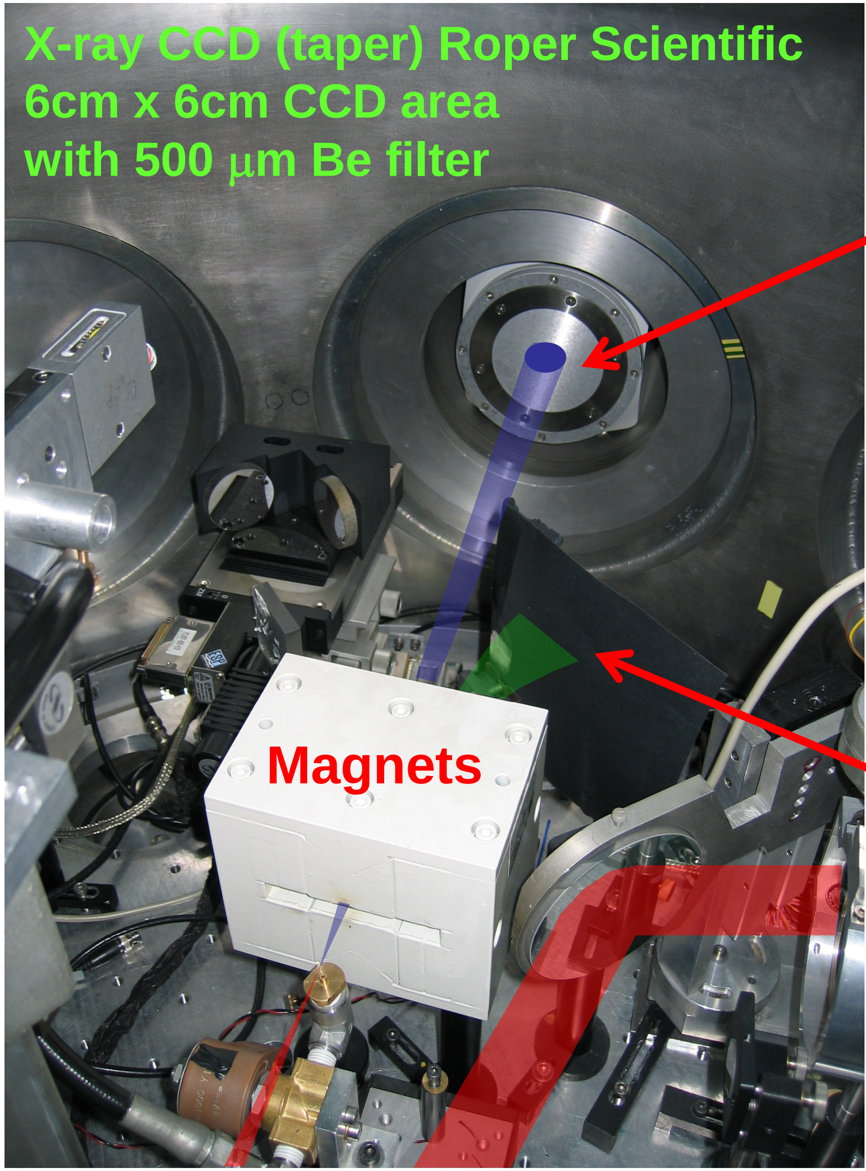


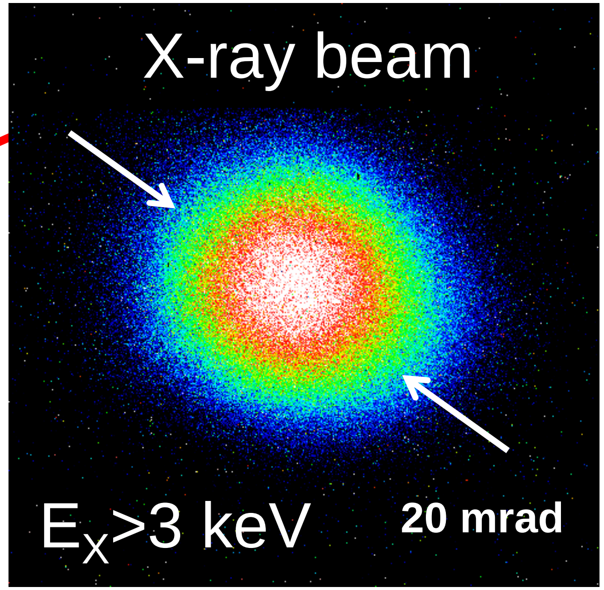

100 μm

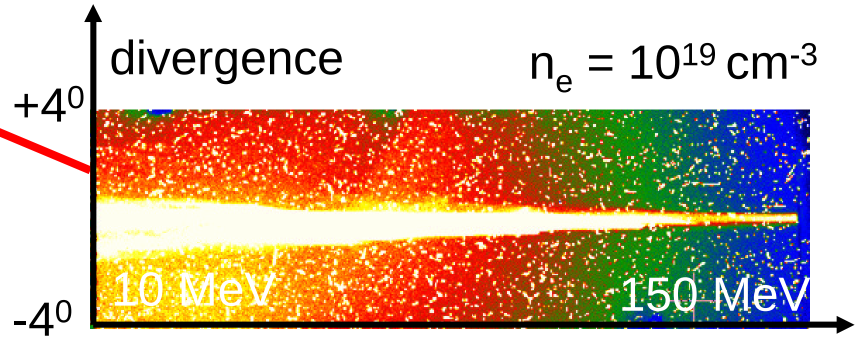
Plasma cavity

*Courtesy of W. Mori*

# Simultaneous measurements of X-ray and Electron Beams




Electron beam

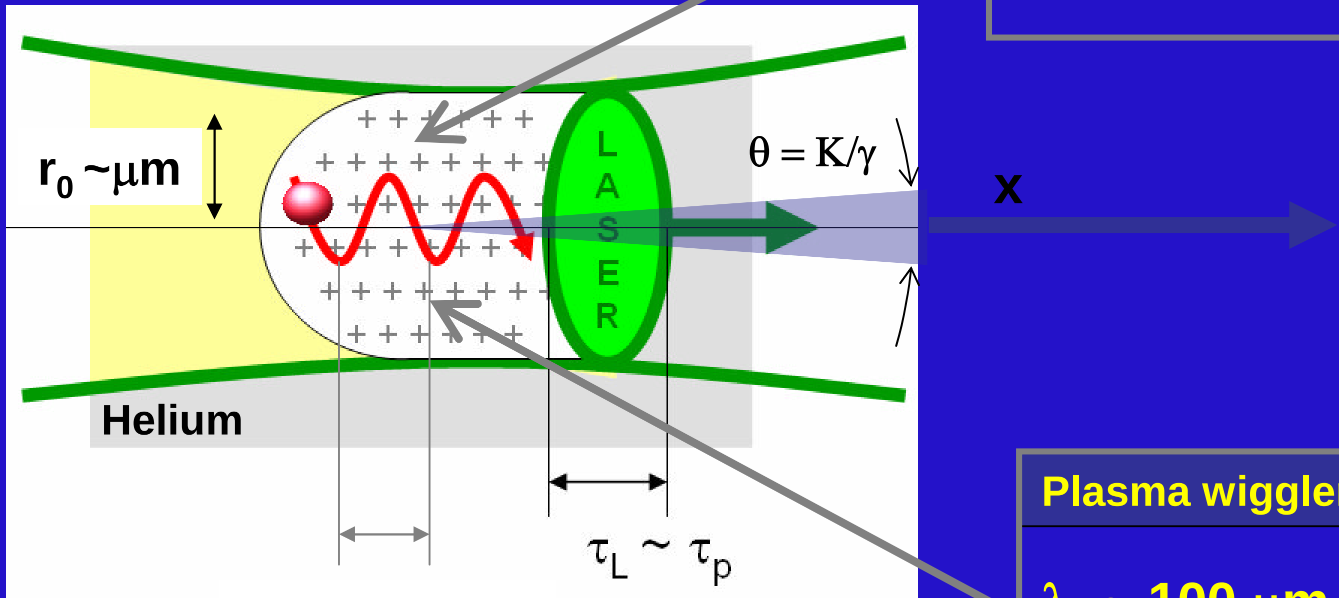
K. Ta Phuoc et al

# Principles of the Betatron radiation

**Plasma accelerator**

**Acceleration field**
**~ TeV / meter**

**$E_L \rightarrow$ 200 MeV**




**$\lambda_u$ ~ 100 µm**

Betatron oscillation

**X-ray beam:**
**$10^9$ ph/shot**
**20 mrad**
**femtosecond**

**Plasma wiggler**

**$\lambda_u$ ~ 100 µm**

***K* ~ 20>1,wiggler**

$K = \gamma k_b r_0$

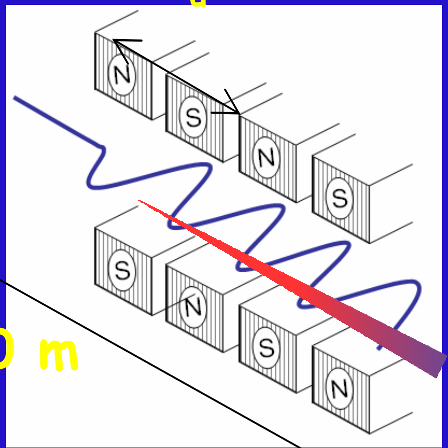
$K \sim \gamma r_0/\lambda_{bet.}$

# Laser based Synchrotron radiation

## Synchrotron

Accélérateur
E (GeV)

$l_u$ ~ cm

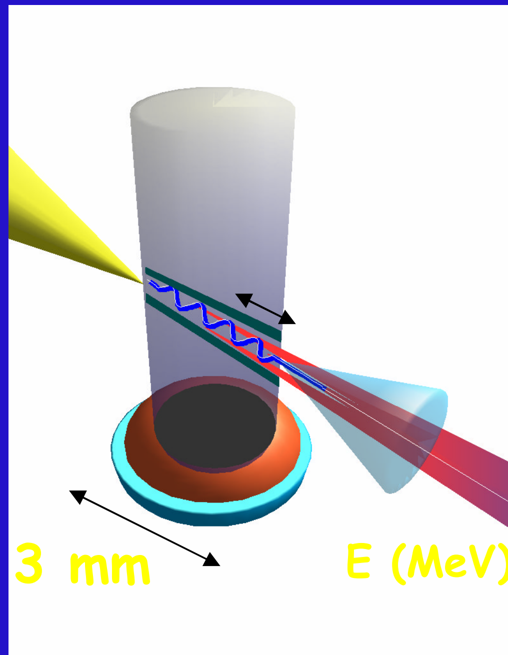



onduleur

100 m

## Laser based Synchrotron radiation

Laser



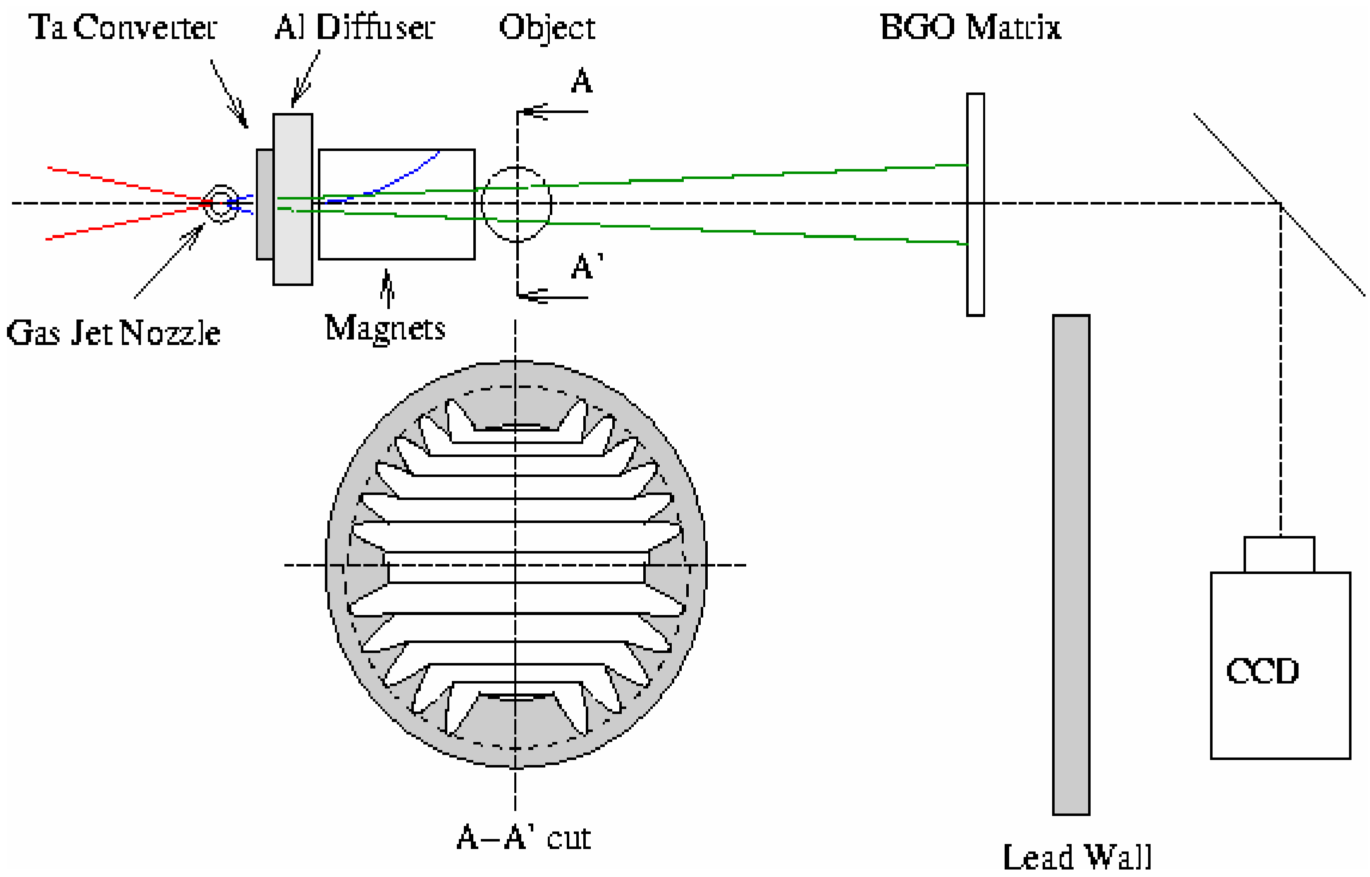

$l_u$ ~ 10-100 mm

Rayonnement X

$$\lambda \sim \lambda_u/\gamma^2$$

# Application: high resolution $\gamma$-radiography

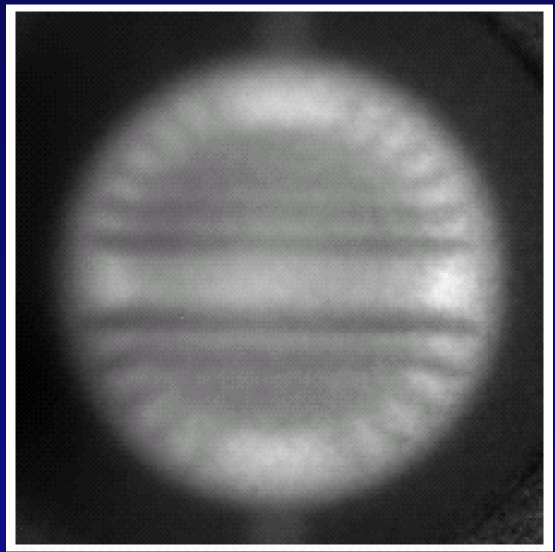
## Advantages: low divergence, point-like electron source



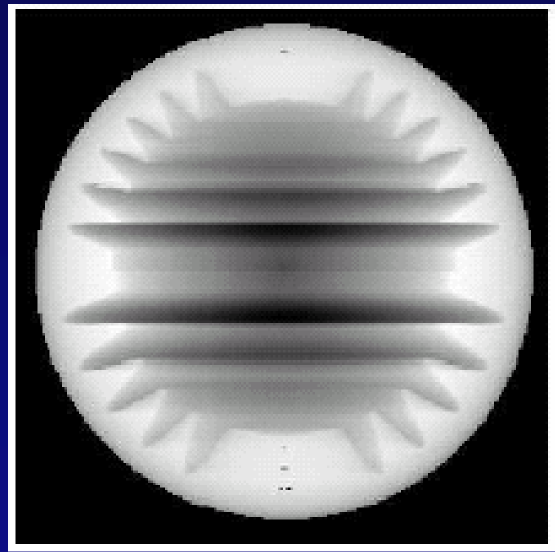

*In collaboration with L. Le-Dain, S. Darbon from CEA Mourainvilier and DAM*

# $\gamma$-radiography results

## Higher resolution: of the order of 400 $\mu$m



measured



calculated

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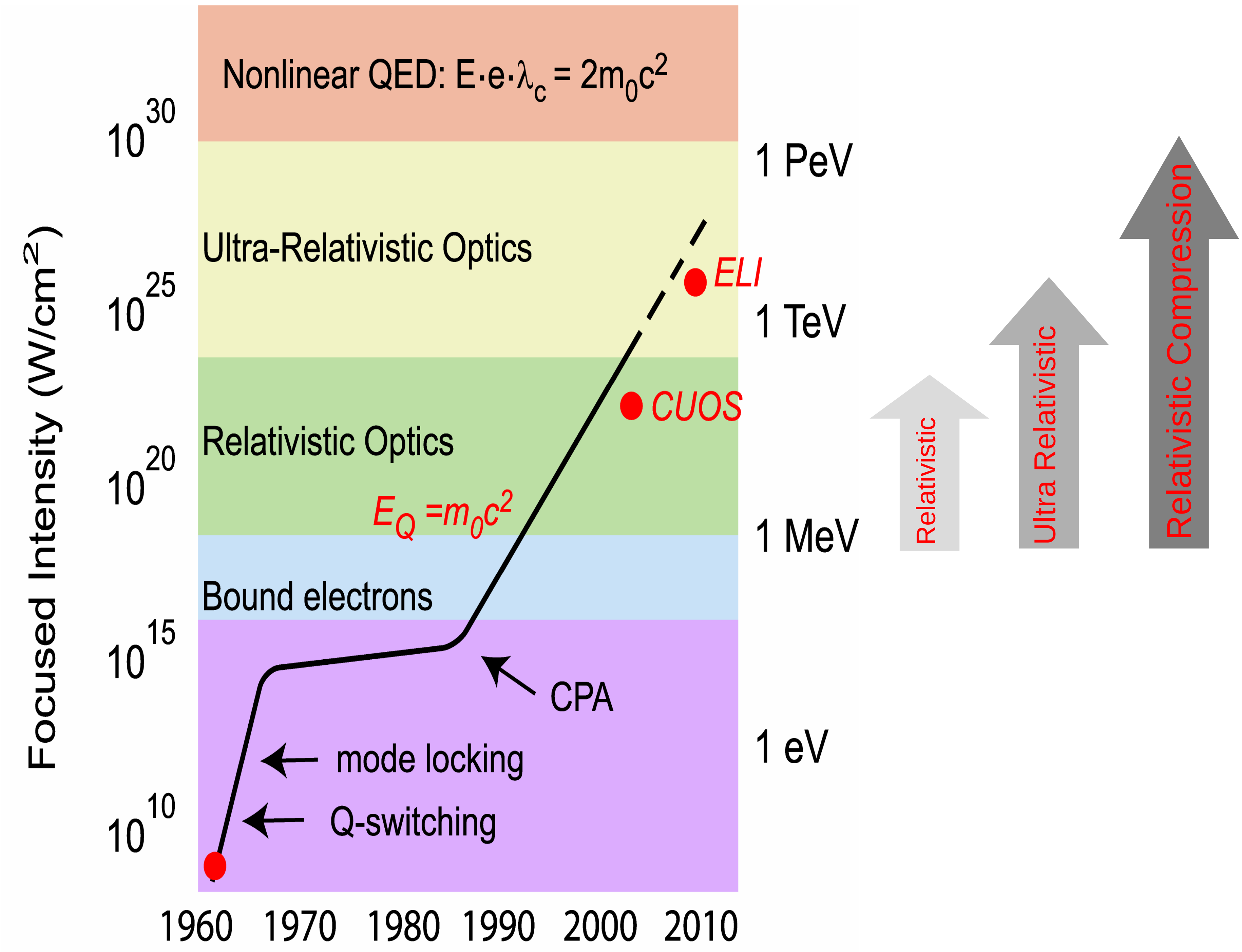

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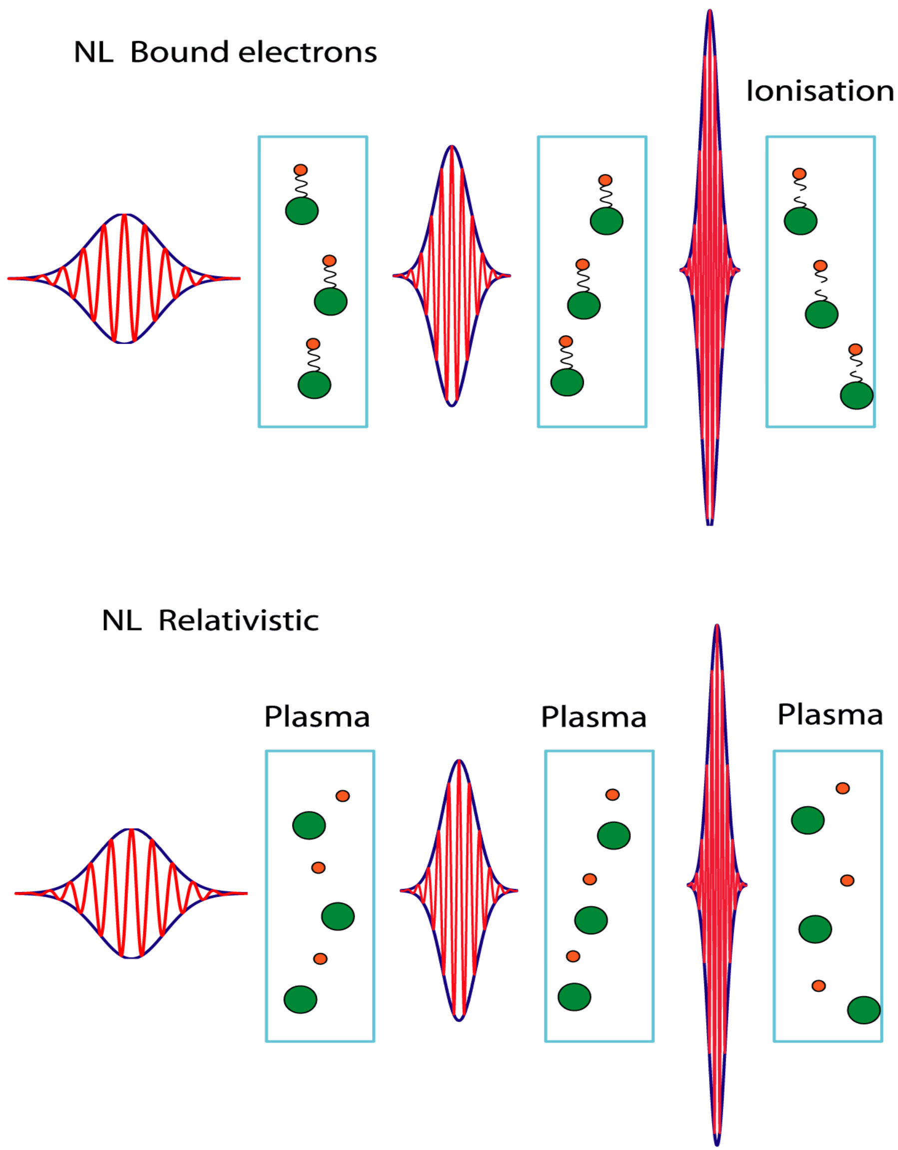
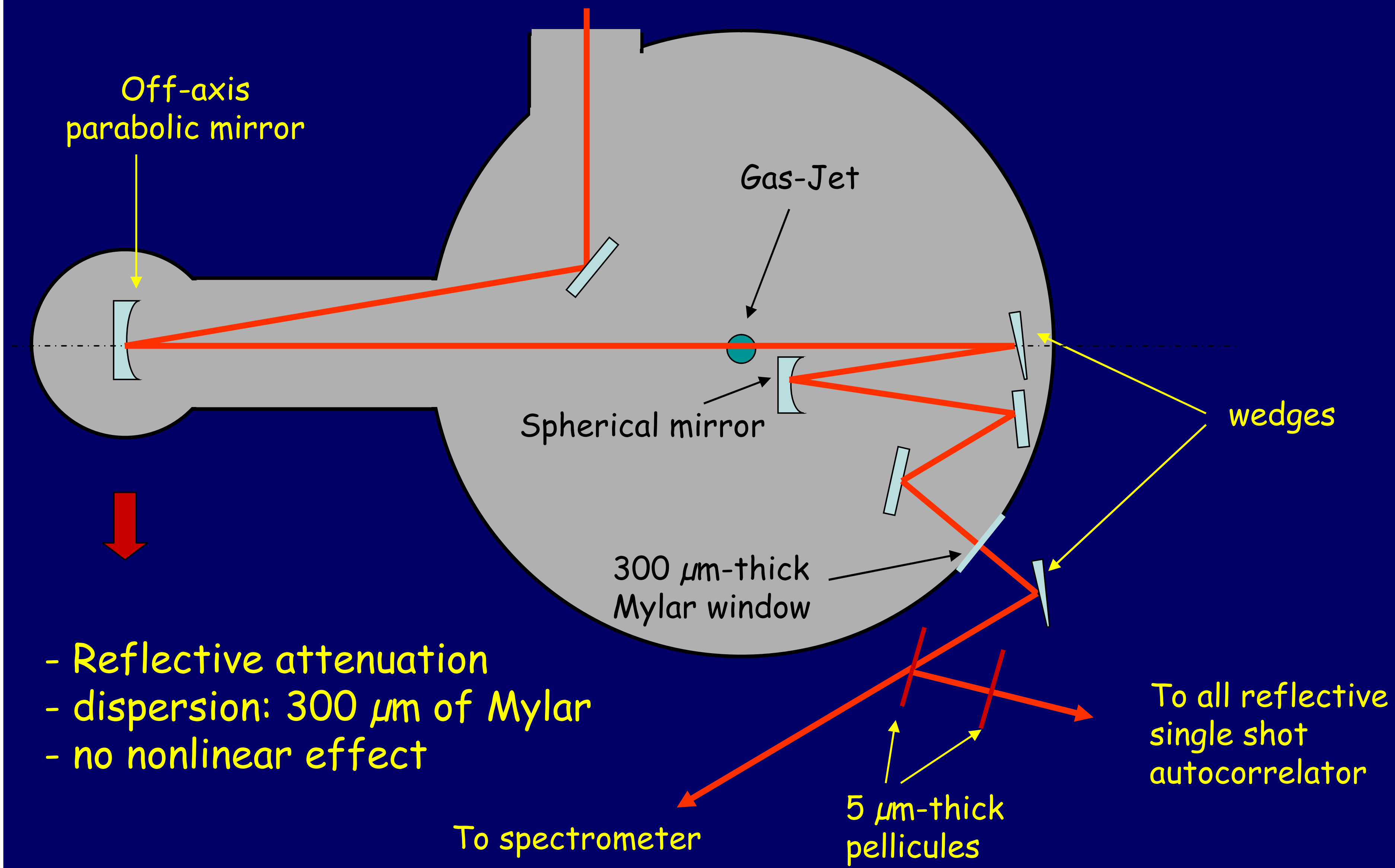
1 eV
Relativistic
Ultra Relativistic
Relativistic Compression

# The Pulse duration-Intensity Virtuous Cycle

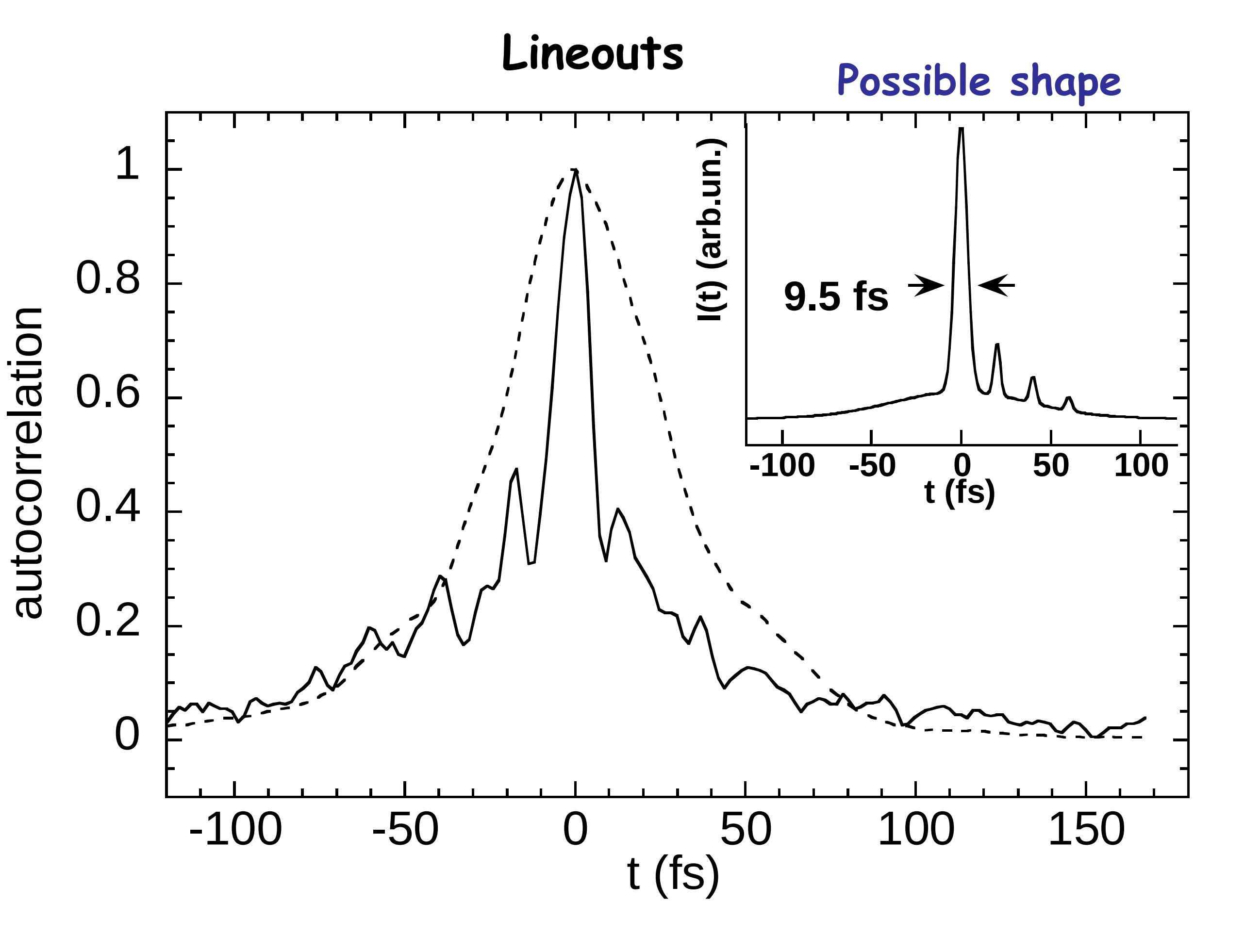


# Laser pulse self-compression: experiment




- Reflective attenuation
- dispersion: 300 μm of Mylar
- no nonlinear effect

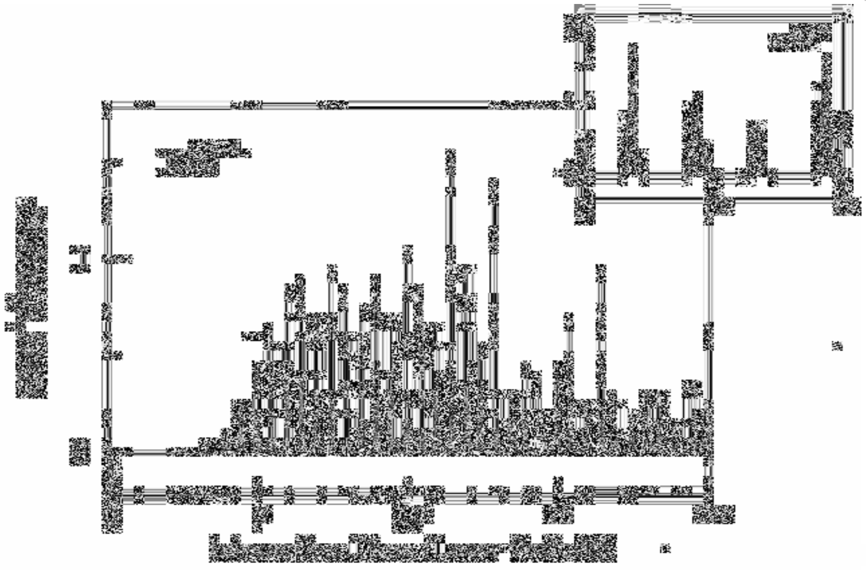
# Laser pulse autocorrelation



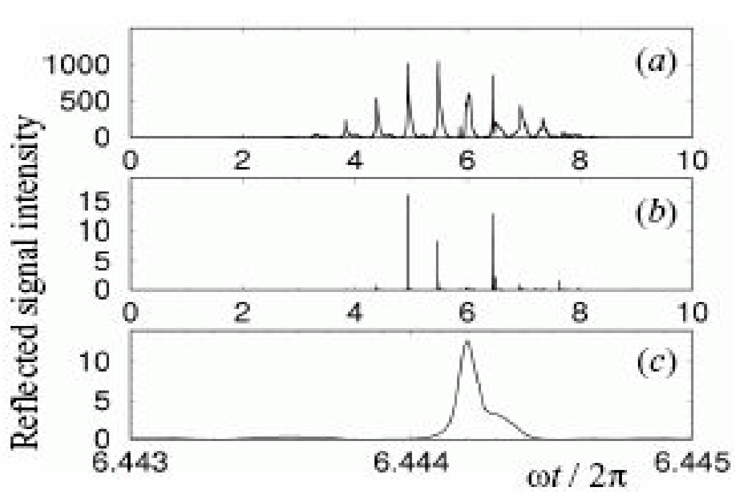

J. Faure *et al.*, accepted to *Phys. Rev. Lett.*

- sensitive to $c\tau/\lambda_p$
- duration depends on pulse shape (gaussian)
- Initial duration $\tau$ ~ 38+/-2 fs
- Final duration $\tau$ ~ 9.5+/-2 fs
- Energy efficiency ~ 20 %

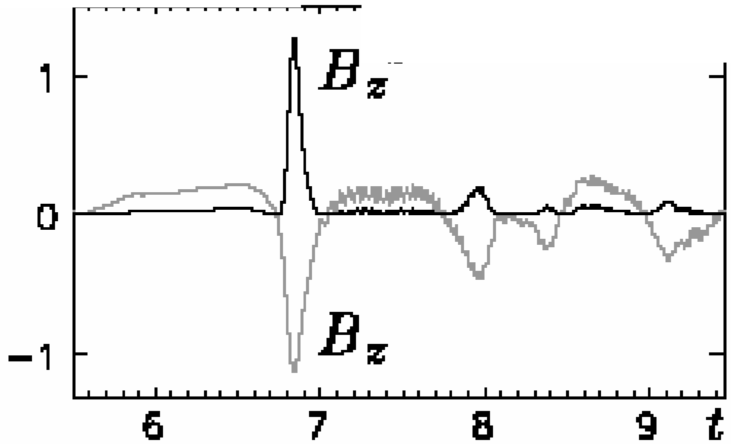
# HHG and Subfemtosecond Pulses from surfaces of dense plasmas



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



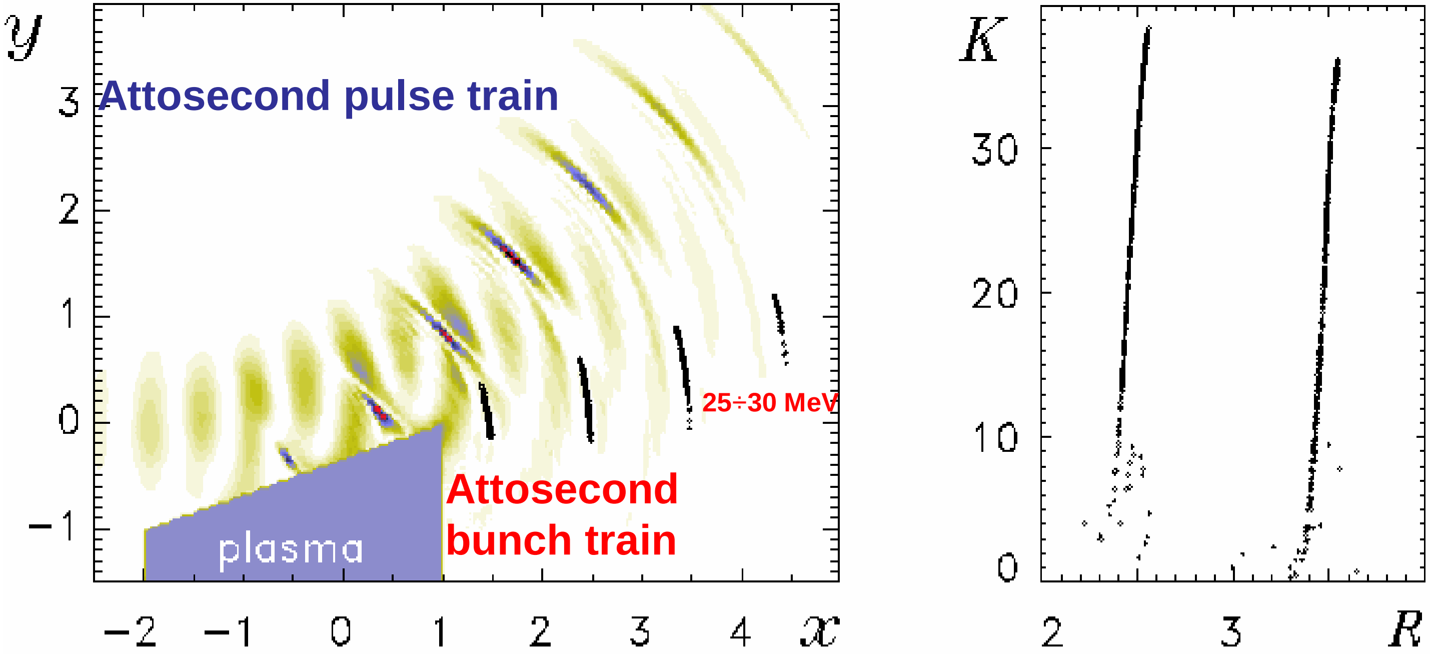

S. Gordienko et al PRL 93, 115002 (2004)




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

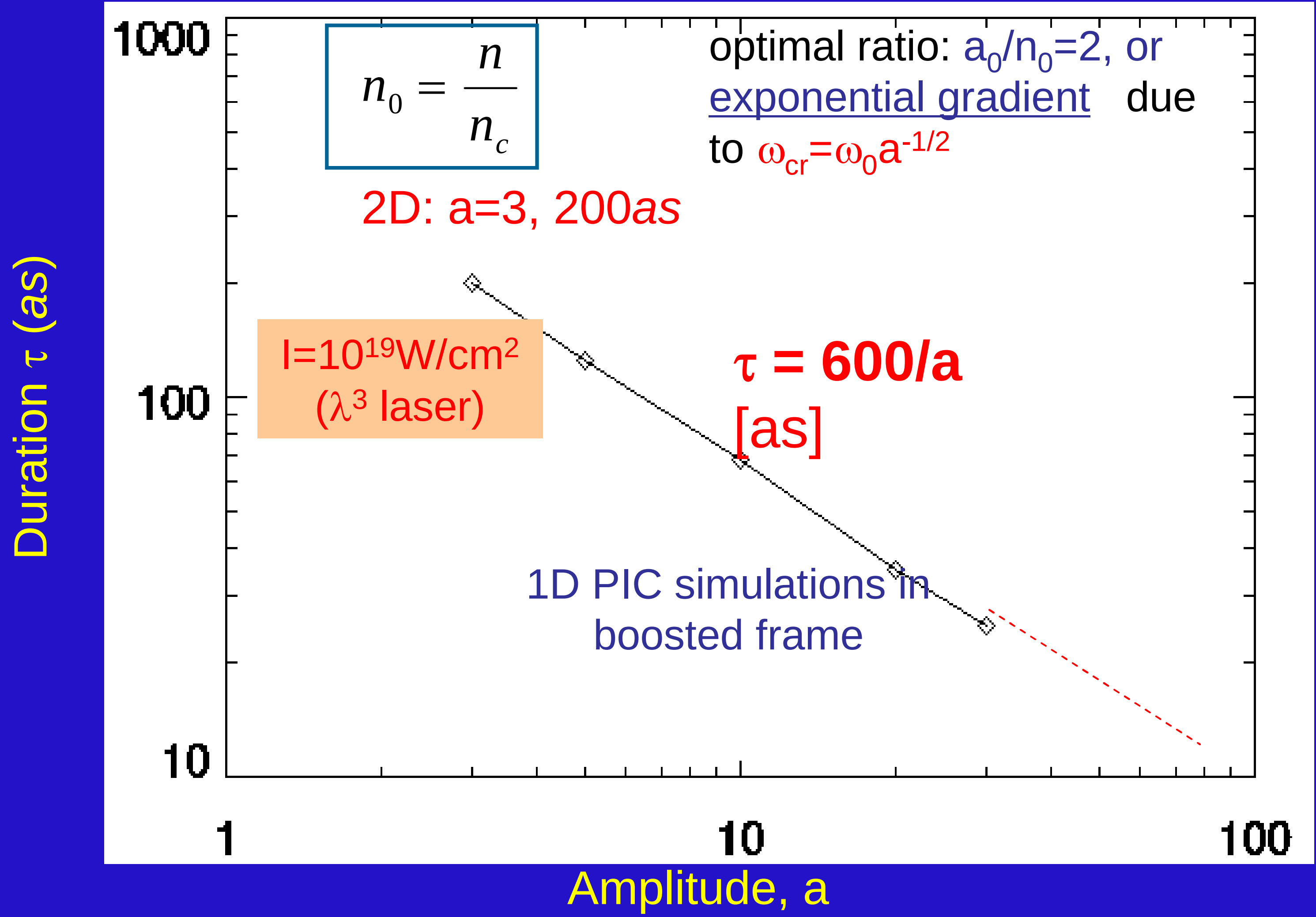
# Attosecond Electron Bunches

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



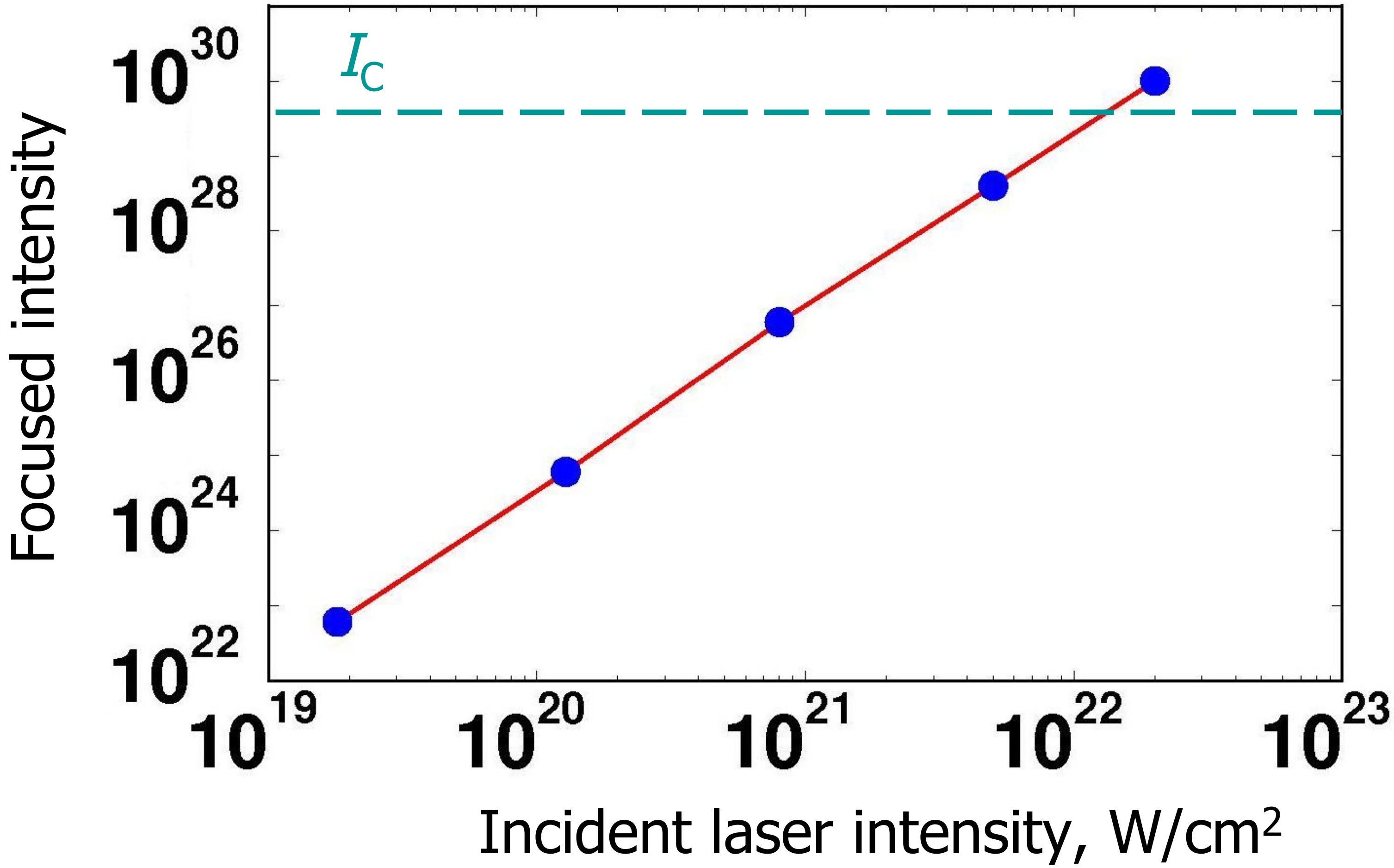

N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou, Attosecond Electron Bunches, *Phys. Rev. Lett.* **93**, 195003 (2004).

# Scalable Isolated Attosecond Pulses



# Scaling of the CHF intensity

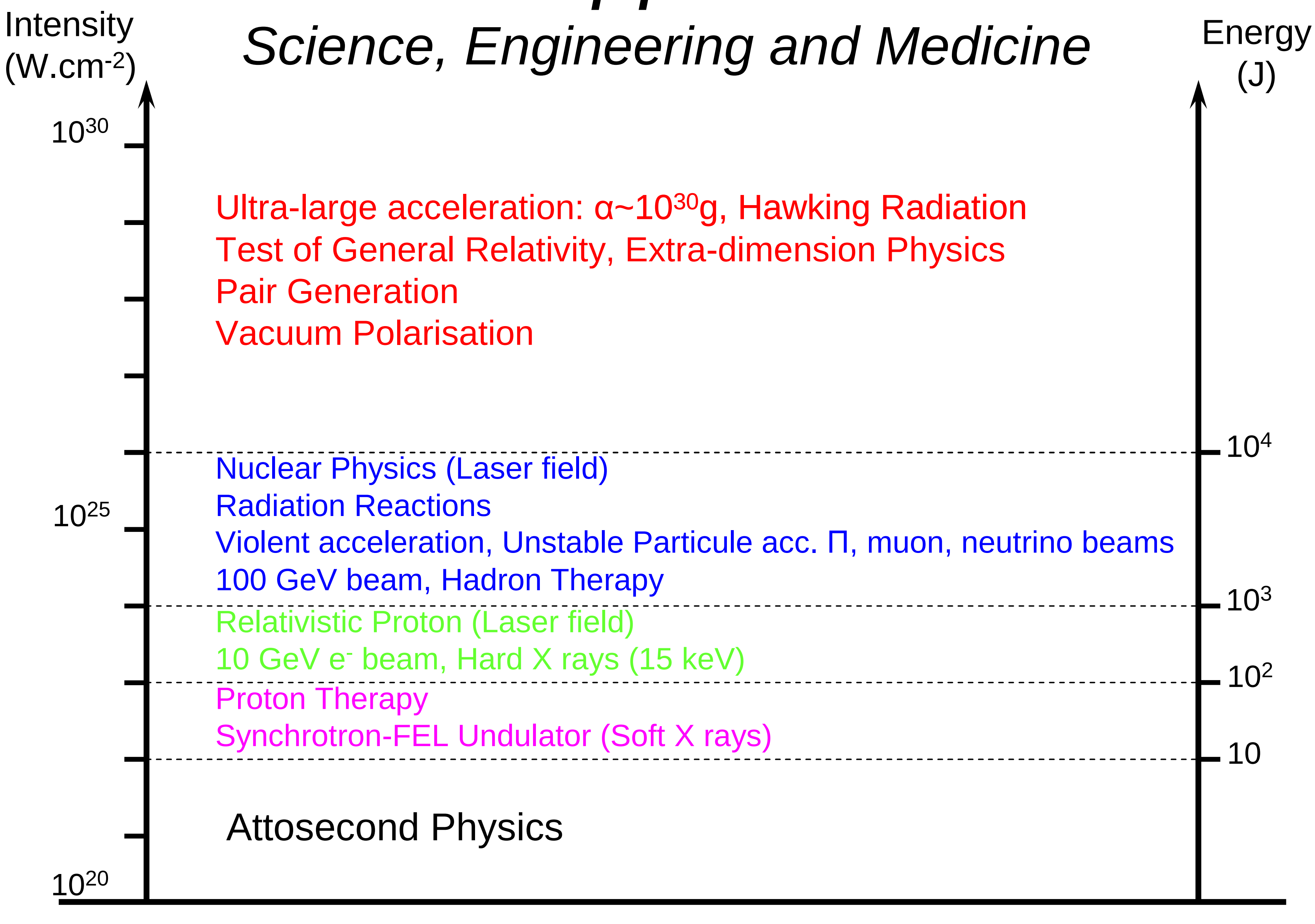
Gordienko, Pukhov, Shorokhov, Baeva, *Phys. Rev. Lett.* **94**, 103903 (2005)



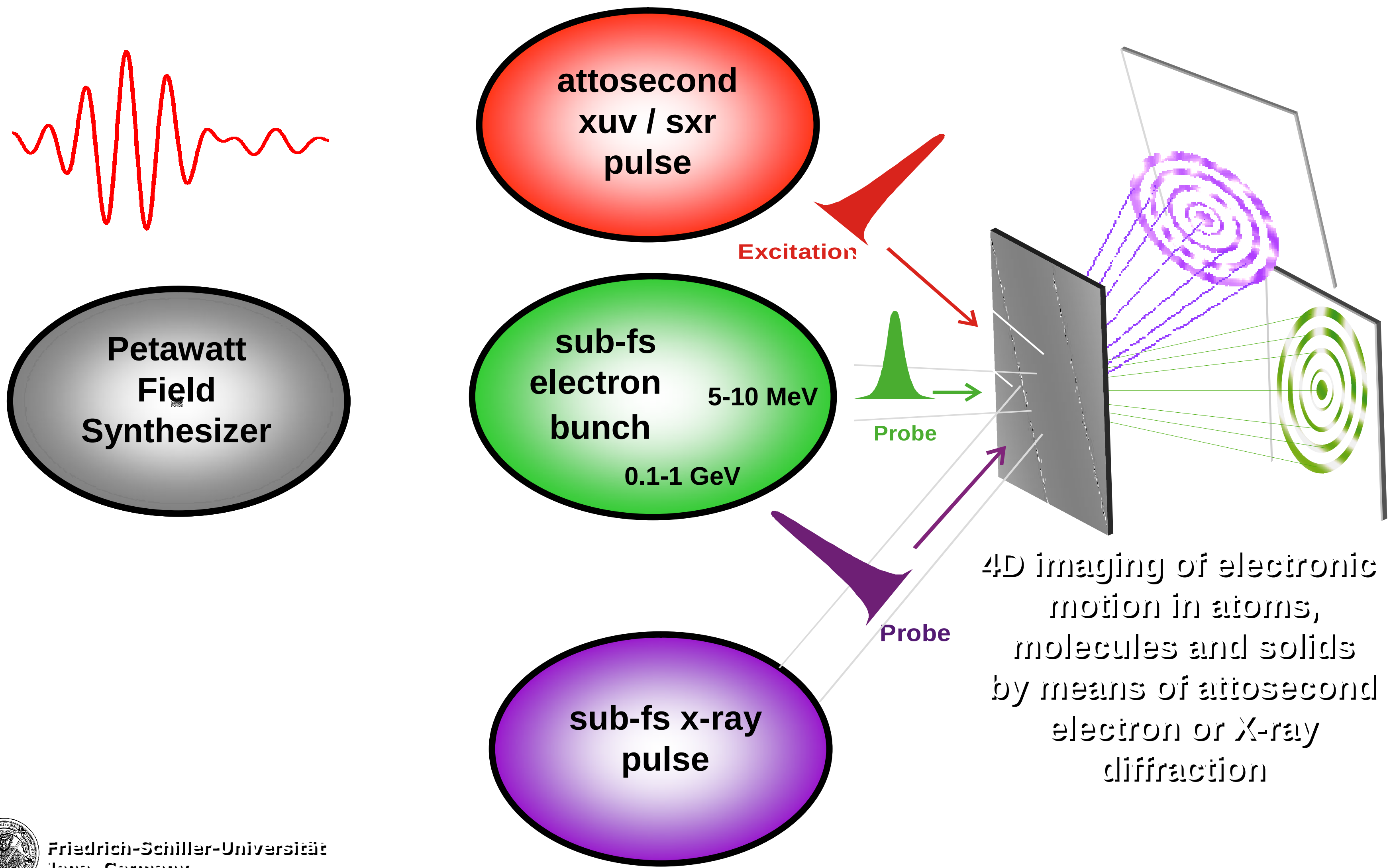
# Science case
# New areas to be opened

# *E.L.I Applications*

## *Science, Engineering and Medicine*

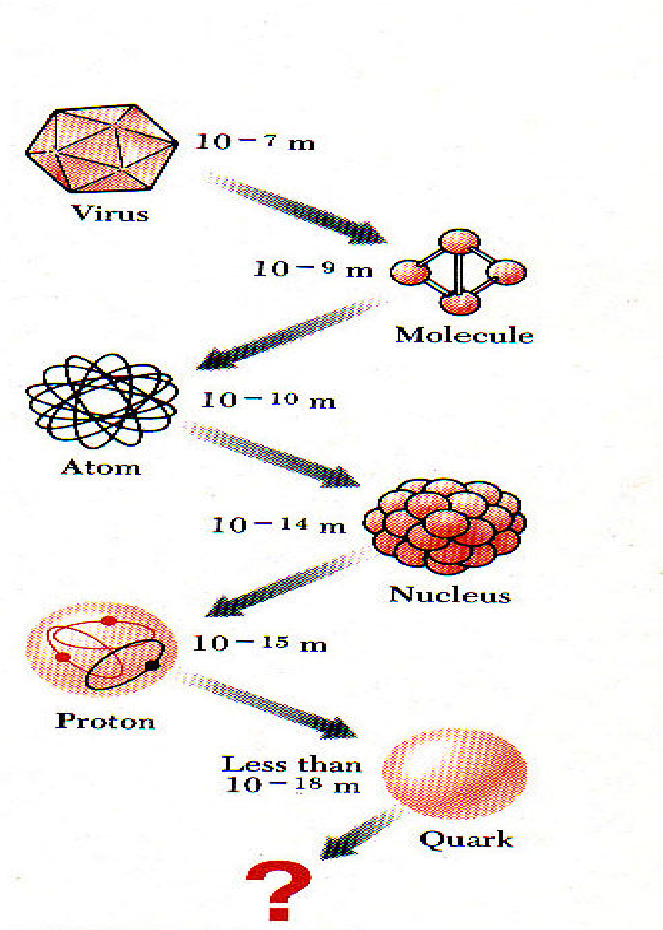


# control & 4D imaging of valence & core electrons with sub-atomic resolution



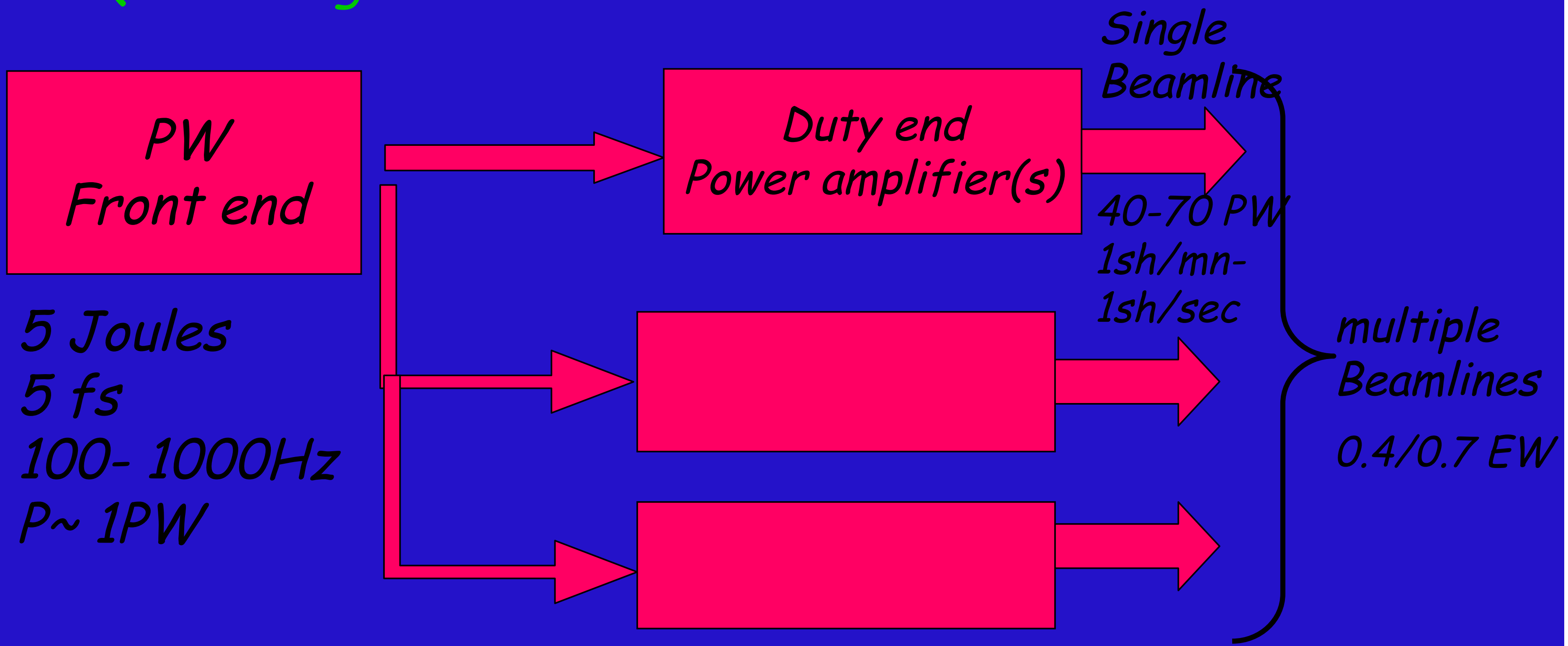

Friedrich-Schiller-Universität
Jena, Germany

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



# 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*

# Conclusion (Laser)

*Today it is realistic to design a single beam laser delivering 10 to 20 PW in 10/20fs at one shot per minute*

*By pushing everything to the limits on a single beam:*
*70 PW at 1 hertz ($10^{25}$ W/cm $^2$) is conceivable*
*( large improvements needed on pump lasers)*

*When combining 10 beams ( phase locked) ,*
*350 to 700 PW is acheivable leading to $10^{26}$ W/cm $^2$*

# Impact to society and New technologies for Industry

ELI will be the most sophisticated Optoelectronic Instrument ever built: High Energy(kJ), High Repetition Rate (Hz), Short Pulse(5-10fs), Phase front stabilized, and CPE stabilized.

Relativistic Engineering, with two new engineering disciplines:

a) Micro-electronic (lepton, hadron) Relativistic
b) Micro-photonics Relativistic

# Impact to society and new technologies for Industry

Science des matériaux: PALS, PIXE, Muon spectroscopy

Environment: Nuclear waste treatment

Medicine: Hadron therapy (proton hadron, muon)

Nuclear pharmacology

# Impact to society
# Education:

**<u>"ELI will offer an exceptional Education and Training Offering"</u>**

This laser-based facility dealing with :

1) the most sophisticated optoelectronic Grand Instrument (short pulse, ultra relativistic intensity, high average power average power, wavefront correction).

2) the exploration of a new physics regime and new engineering fields.

This program will conspire to provide an exceptional education and training offering

# Strategic Importance to ERA

Europe is a leader in Attosecond physics, EUV, X-ray generation, particle acceleration, the whole gamut. ELI will maintain its excellence and creativity in this field.

ELI is necessary to maintain the European scientific and technological Agenda at the highest level.

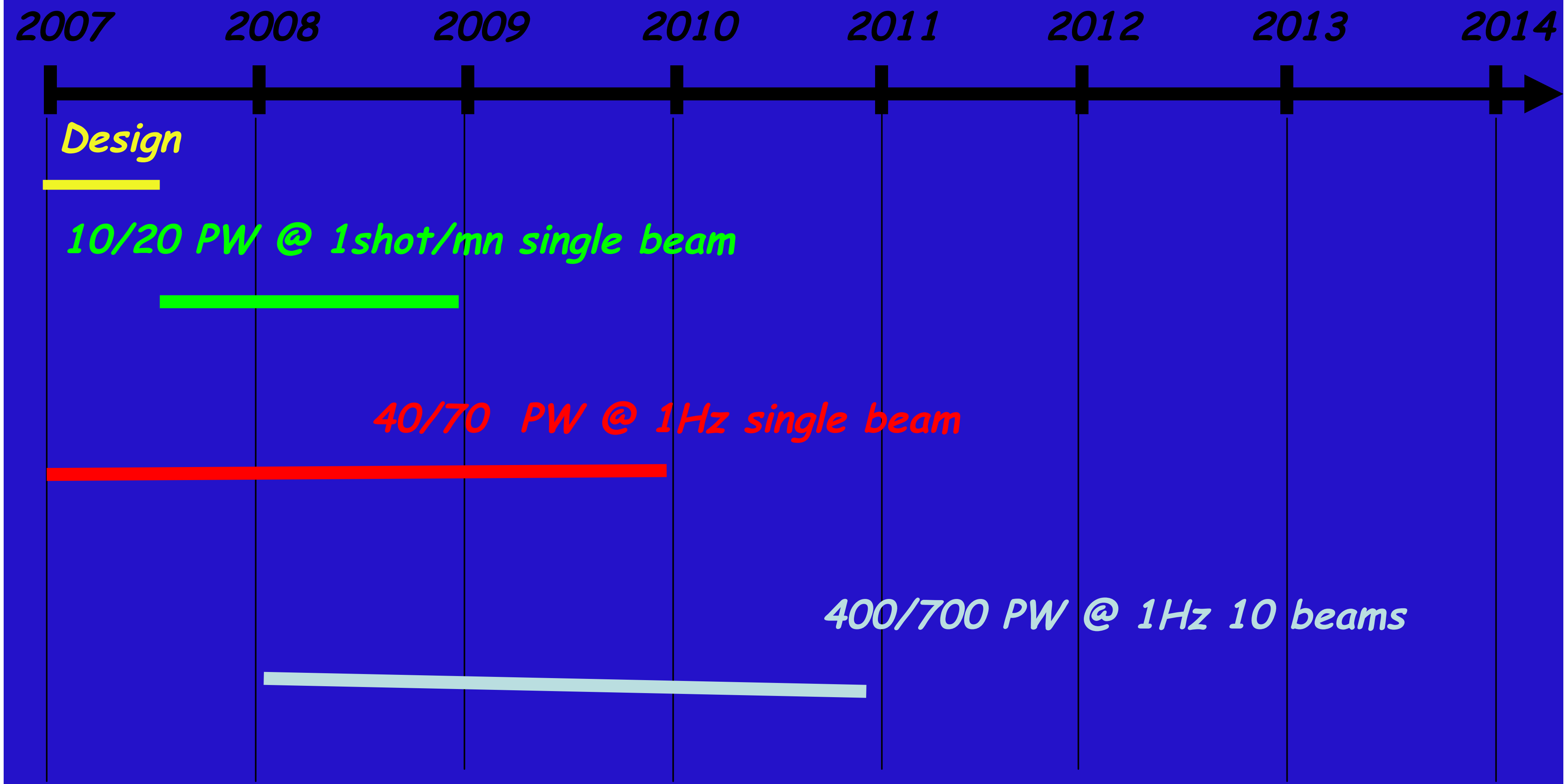
# Contribution from European Countries

ELI will aspire to attract the European talents to build this Ultrahigh Relativistics Scientific ad Engineering facility.

Participating countries in the ELI’s construction:

Germany Front End
Greece Diagnostics
France Back End
Lituania OPCPA

# Time line


2007
2008
2009
2010
2011
2012
2013
2014
Design
10/20 PW @ 1shot/mn single beam
40/70 PW @ 1Hz single beam
400/700 PW @ 1Hz 10 beams

# Estimated Budget

First step: Front end + 10/20 PW booster amplifier @ 1 shot/mn

| | |
|---|---|
| - Amplifying crystals + tools | 1M€ |
| - Gratings | 1M€ |
| - Pump lasers | 10M€ |
| - Front end | 10M€ |
| - Miscillaneous | 3M€ |
| | ---------------- |
| | **25M€** |

Second step Upgrade Single beam 40/70 PW @ 1 Hz

- Studies + Pump lasers + Phase locking Gratings **+ 30M€**

Third step 10 beams upgrade to 400/700 PW

- Pump lasers + coherent beam combining **+ 50 M€ ?**