DE LA RECHERCHE À L'INDUSTRIE

CEA INVOLVEMENT IN FRENCH LASER SCIENCE

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PHYSICAL SCIENCE DIVISION

OUTLINE

Introduction: Laser science within the general objectives of the CEA

International context

The present involvement of CEA

- Matter at High Density Energy
- The Saclay laser-Matter Interaction Center (SLIC)
- R&D laser
- Physics at Ultra High Intensity
- Attophysics
- Physical chemistry

The future: The involvement in large projects

The objectives of CEA

The CEA is commissioned to “investigate the possibility of using atomic energy for any domain of **science, industry and defense**.”

Looking backward, we could say that CEA has also investigated the interest of laser in any domain of **science, industry and defense**.

Fundamental research

From multiphoton to attophysics and relativistic optics

Nuclear energy

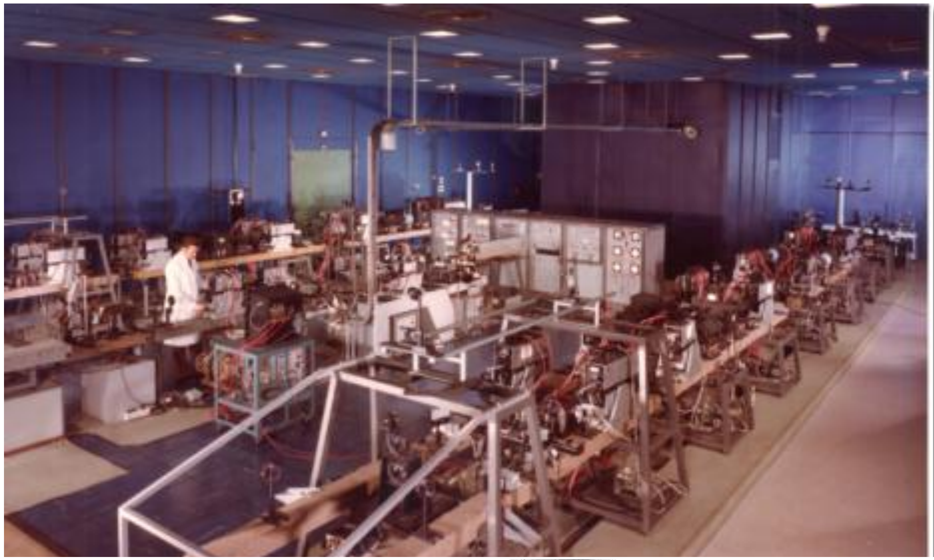
Silva program of isotopic separation

Fusion energy

From the early laser to the LMJ

A fast and spectacular success

Within a few years, huge, complex and performing systems were built



C6 laser, delivering up to 600 J

In 1968 the first fusion events are observed !

PHYSICAL REVIEW A VOLUME 1, NUMBER 3 MARCH

Nuclear Fusion Reactions in Solid-Deuterium Laser-Produced Plasma

F. Floux, D. Cognard, L-G. Denoeud, G. Piar, D. Parisot,
J. L. Bobin, F. Delobeau, and C. Fauquignon
Commissariat à L'Energie Atomique, Centre D'Etude de Limeil, 94 Limeil-Brevannes, France
(Received 23 September 1969)

When focusing a 4-GW, fast-rise-time, nsec-range laser onto a solid deuterium target, neutron production is observed. We give evidence for nuclear fusion reactions, measure the electronic temperature, and estimate the number of neutrons for each laser shot.

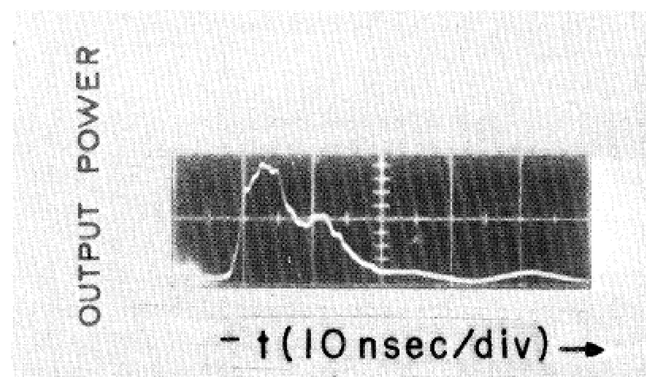


FIG. 1. Typical oscillogram of output laser pulse recorded on a Tektronix 519 oscilloscope. Signal is given by an ITT fast-rise-time photodiode.

Successive generations of lasers, more and more complex, more and more energetic

Rapid growth from table-top experiments to large facilities

P101

P102
1979

Octal
1979

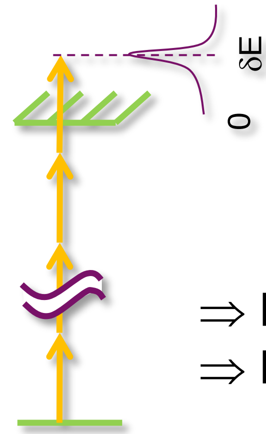
Phebus
20kJ
1985

Intense lasers for multiphoton investigation

- Investigate the variety of effects observed in integrated experiments
- Study the validity of the famous Keldysh theory

What is the response of an atom or a molecule when irradiated by a strong laser field ?

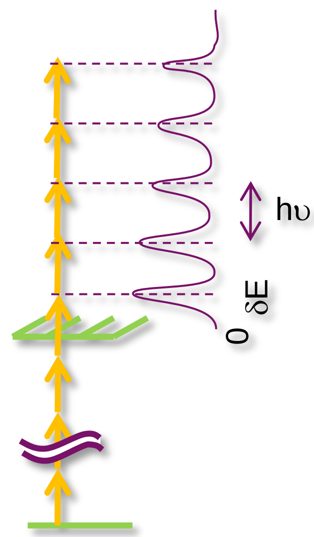
The laser intensity is so large (10^{13}-10^{15} W/cm^2) that an atom can absorb more photons than required for ionization



Photoelectron with excess energy δE

⇒ Multiphoton ionization
⇒ Free-free transition

1979 Above threshold ionization



Laser accordable de grande puissance, à impulsions ultra-courtes, conçu et réalisé à Saclay : outil de choix pour l'étude de l'interaction rayonnement-matière.

VOLUME 42, NUMBER 17 PHYSICAL REVIEW LETTERS 23 APRIL 1979

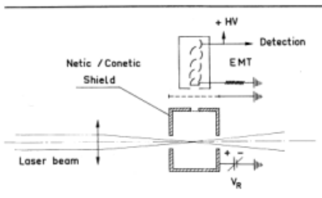


FIG. 2. Schematic of the experimental apparatus.

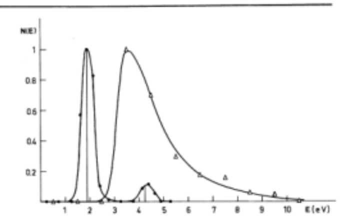


FIG. 3. Energy spectra of the emitted electrons for two photon energies: triangles, $\hbar\omega = 1.17$ eV, $I = 4\times10^{13}$

First observation of High Order Harmonics (Saclay 1988)

The famous « plateau » : conversion efficiency decreases very slowly with order)

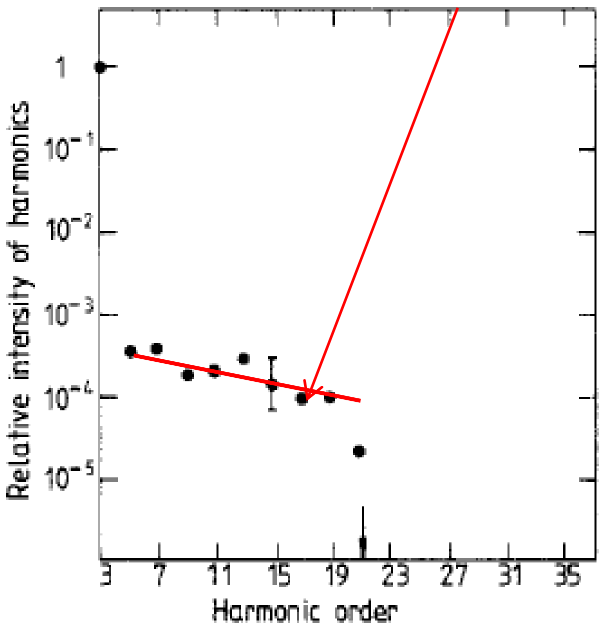
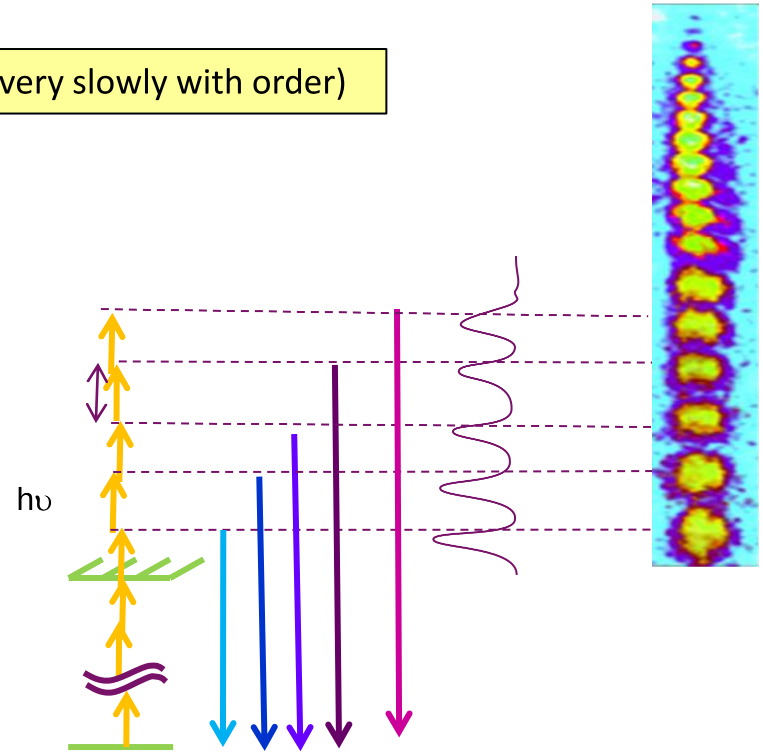


Figure 2. The relative intensity of the harmonics generated in Xe at a laser intensity of approximately 3×10^{13} W cm^{-2}. The typical error bar is shown for the 15th harmonic. The arrow indicates the highest harmonic order observed at 3×10^{13} W cm^{-2}.

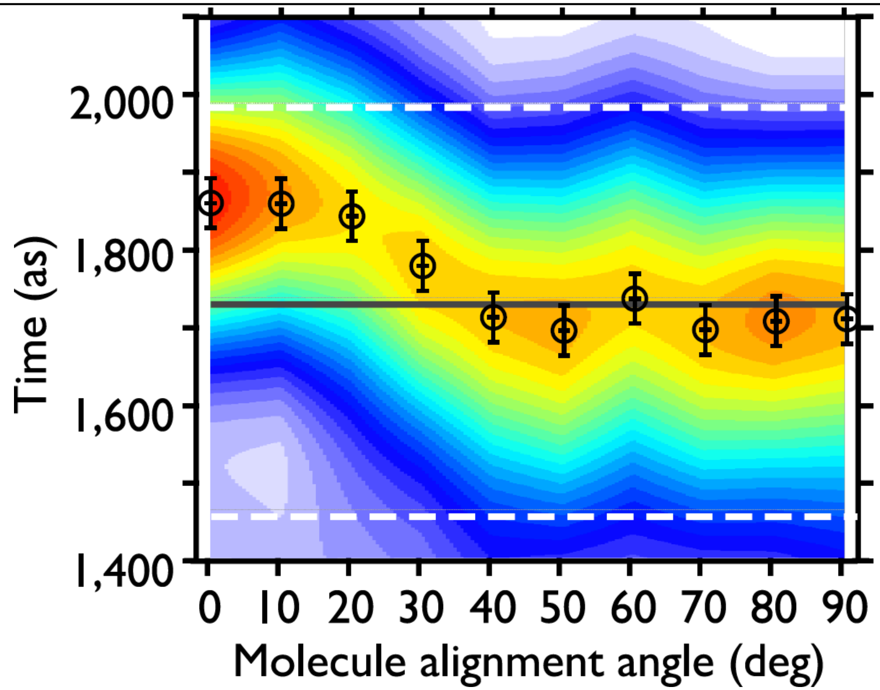


The harmonic generation

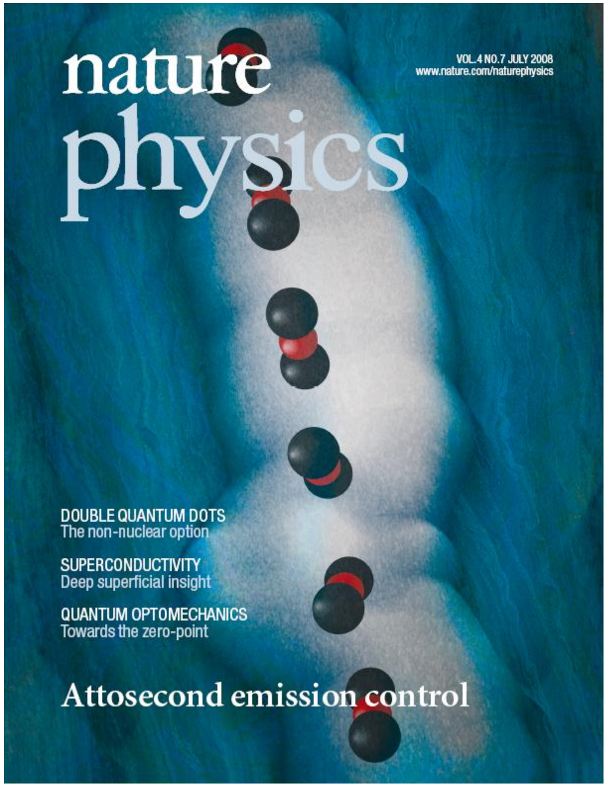
- provides unique ultra-short light in the XUV domain with unexpected efficiency (famous plateau)
- gives access to the dynamic response of matter highly excited by lasers

From High Order Harmonic to attophysics

HHG (High Harmonic Generation) in aligned linear molecules as a means to control the XUV attosecond emission



Reconstruction of one attosecond pulse in the train emitted by CO2 molecules, including H23 to H29 harmonic components, versus the alignment angle.



Nature Phys. 4, 545 (2008)

Towards the imaging of orbitals from HHG (tomographic reconstruction)

The CPA technique and the first TW lasers

1985 : CPA (Chirped Pulse Amplification) Technique by D. Strickland and G. Mourou

CPA opens route to UHI physics & exploration of new domains by increasing the laser intensity by a factor of $\mathbf{10^3}$

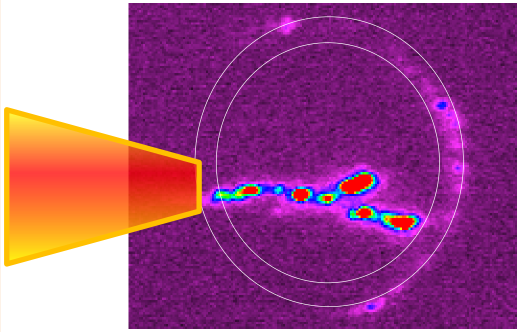
The Saclay group develops the first TW laser in Europe in 1989

Intensity of 10^{18} W/cm^2 reached on target

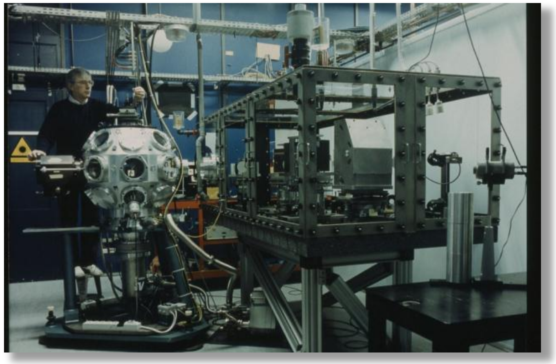
The matter is ionized to form a plasma and electrons are accelerated to velocity close to the speed of light

First demonstration of relativistic self-focusing

First evidence for relativistic self focusing : the plasma acts as a converging lens, increasing the light intensity by one order of magnitude, and generating multiple focii



Experimental evidence



→ Temporal Compression of laser P102 at Limeil in 1994 (80TW: world record)

⇒ Launched the Ultra High Intensity (UHI) activity

Relativistic Self-Focusing is now widely used for laser-plasma acceleration

OUTLINE

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International context: HDE and UHI

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The future: The involvement in large projects

INTERNATIONAL CONTEXT IN HIGH DENSITY ENERGY PHYSICS (HDE)

Context of strong competition in the world (USA, China, Japan, Korea) and Europe (France, Germany, UK, ...).

15 HDE facilities in the world

1/3 in Europe

2 MegaJoules Installations

NIF (USA) and LMJ (France)

INTERNATIONAL CONTEX IN ULTRA HIGH INTENSITY PHYSICS (UHI)

Context of strong competition in the world (USA, Canada, China, Korea) and Europe (France, Germany, UK, ...)

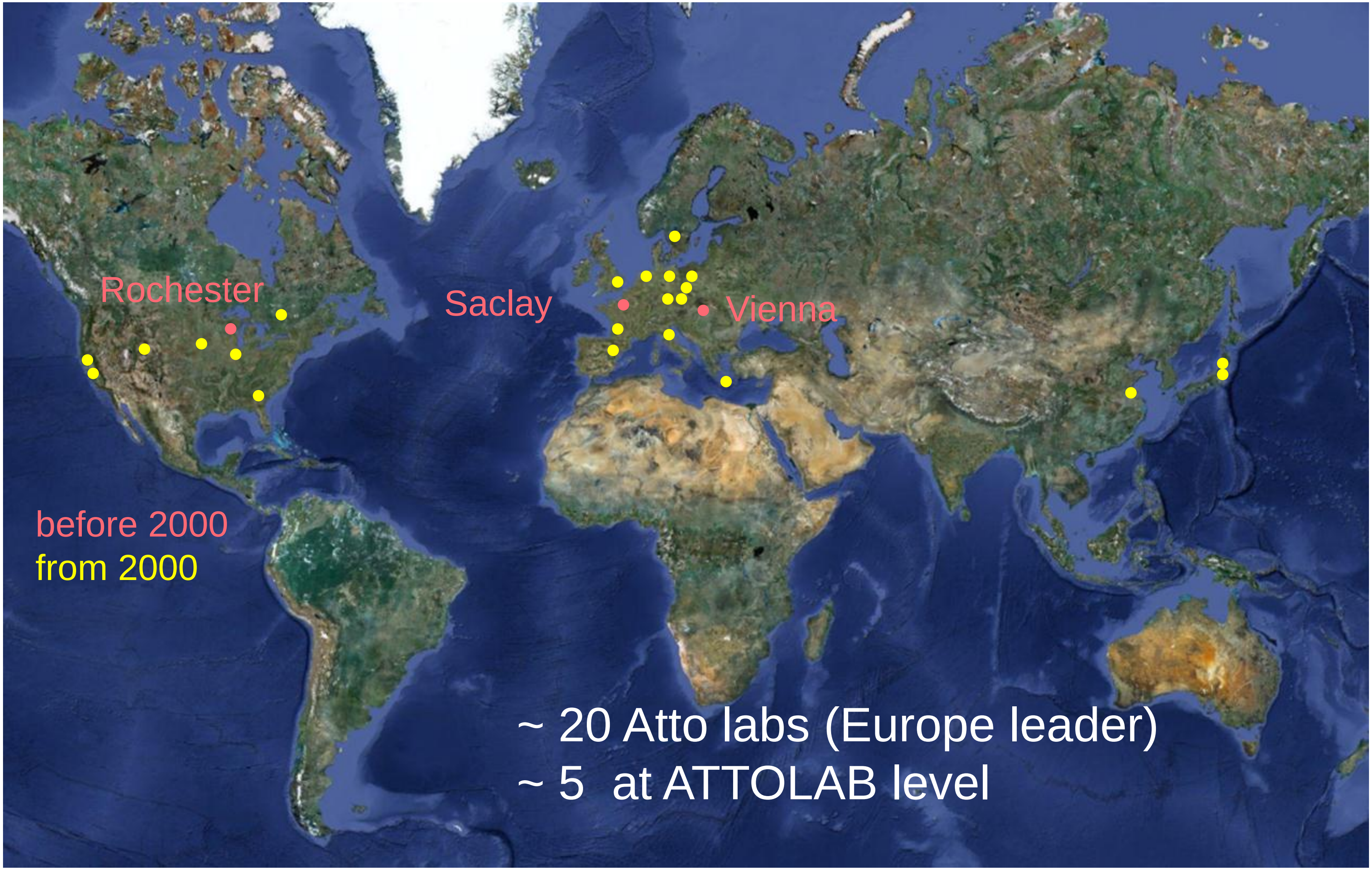
22 UHI facilities > 100TW in the world

2/3 in Europe

10 projects > 1PW

6 in Europe

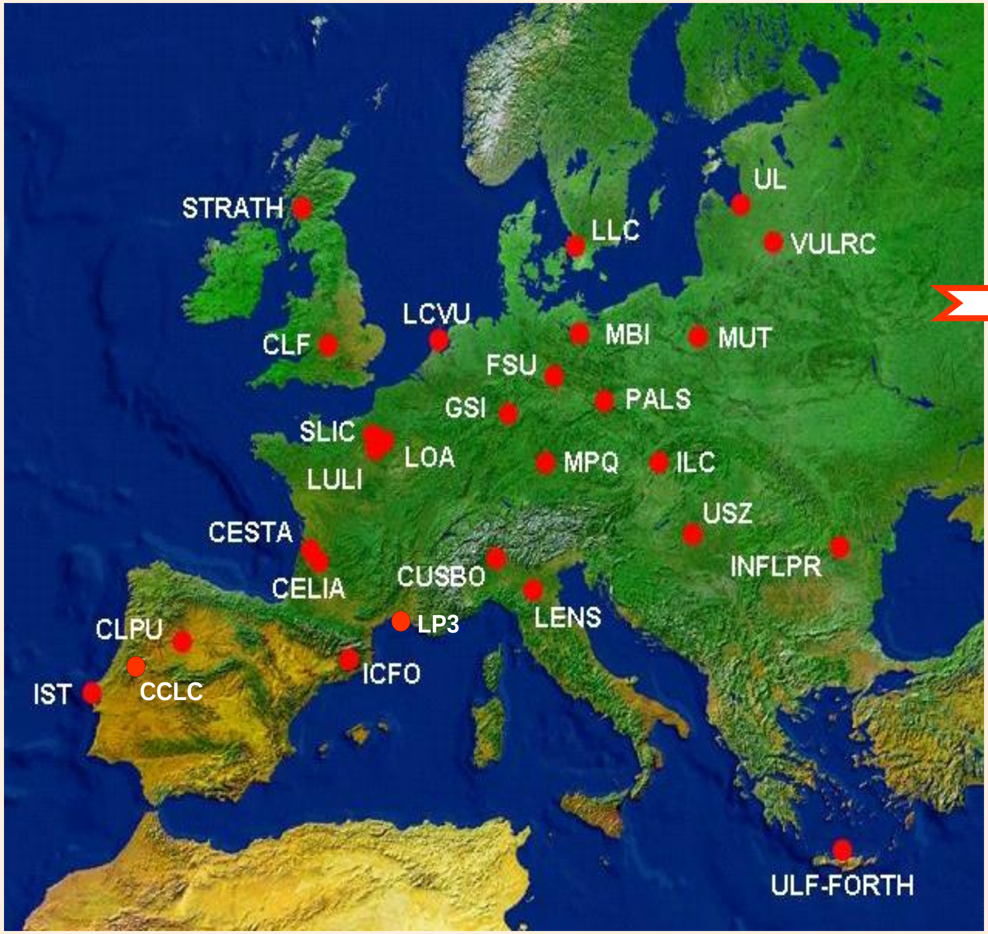
ATTOPHYSICS LABS WORLDWIDE



- before 2000
- from 2000

LASERLAB-III (2012-2015): THE INTEGRATED INITIATIVE OF EUROPEAN LASER RESEARCH INFRASTRUCTURES

Transnational Access to Laser Facilities, and Technological Joint Research Activities



Coordonator :

W. Sandner *(MBI – Berlin)*

New Claes Wahlström (Suède)

- 27 Partners
- 19 Member States

an I3 combining the majority of the largest European national labs in the area of laser-based inter-disciplinary research

 providing services to the user community more than 4000 access units

 developing for the next generation of UHI laser facilities

Romania : INFLPR National Point of Contact

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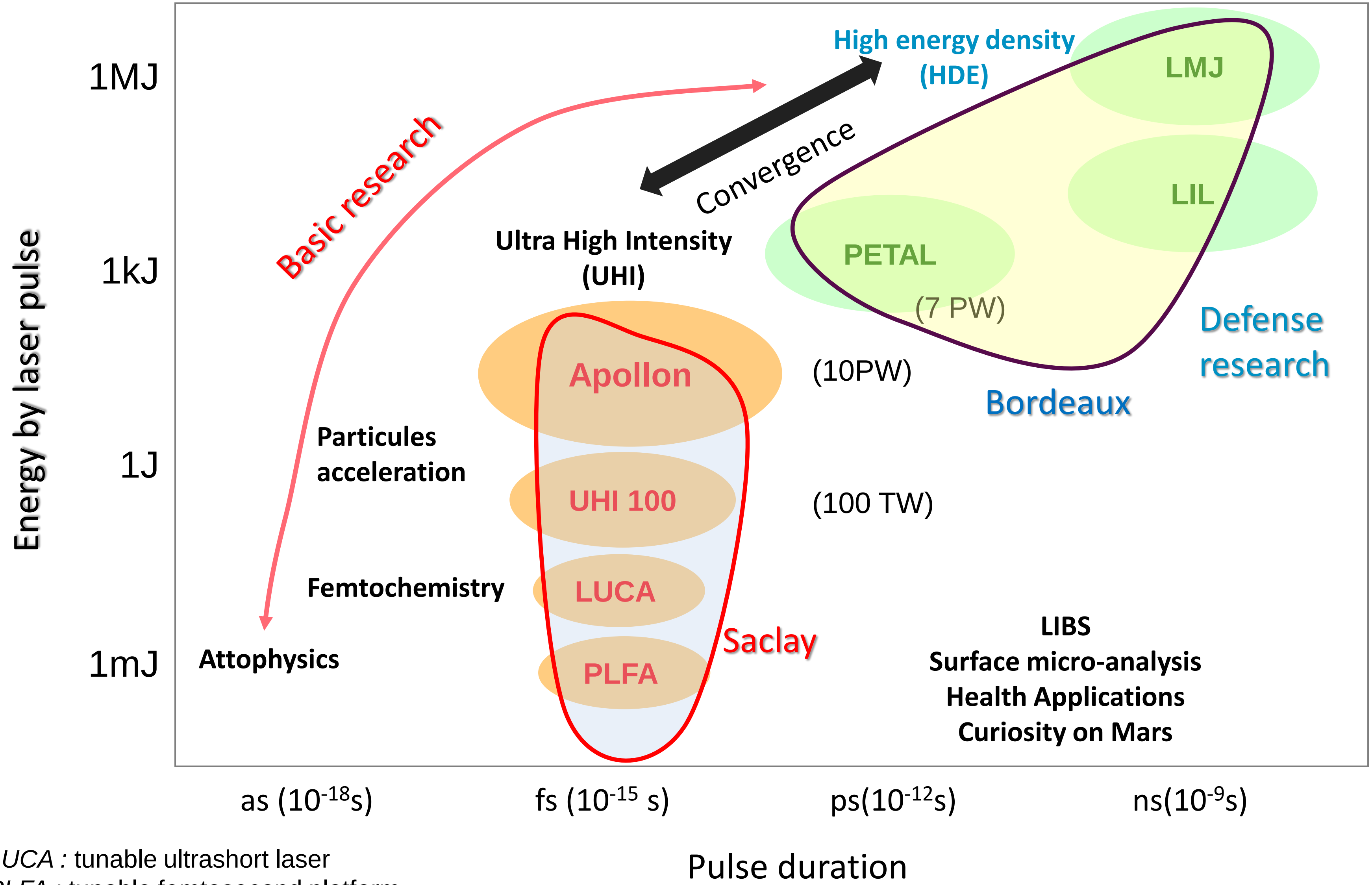
Laser-matter interaction domains and laser facilities



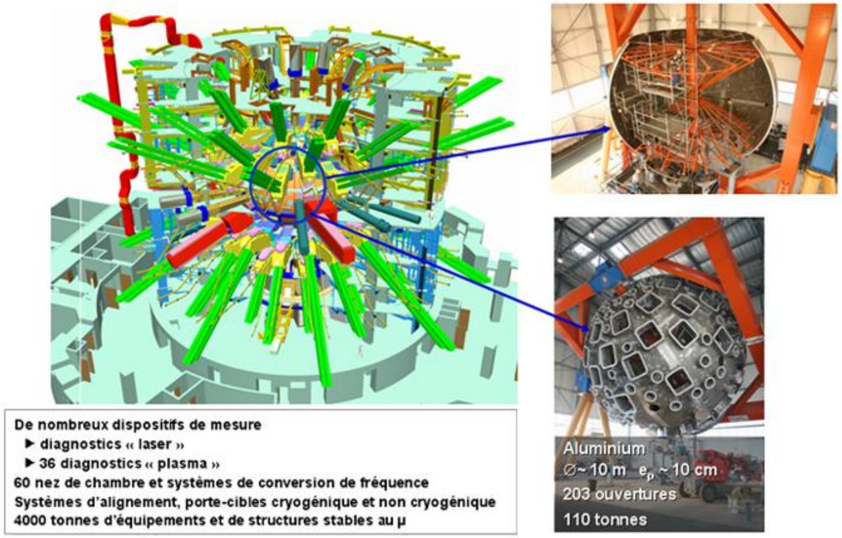
LUCA : tunable ultrashort laser
PLFA : tunable femtosecond platform
LIBS : Laser Induced Breakdown Spectroscopy

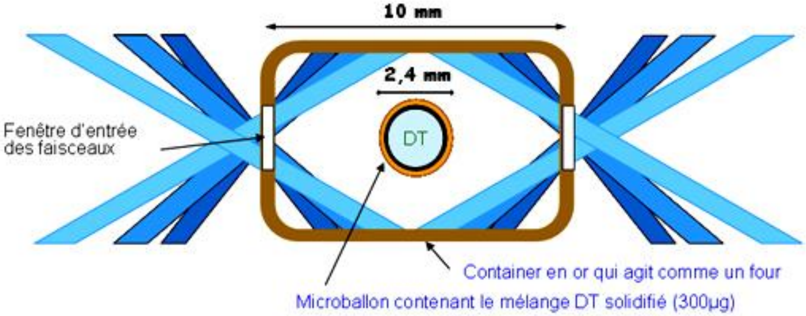
The MEGAJOULE LASER (LMJ) at Bordeaux

Inertial Confinement Fusion

Close collaboration with NIF

La chambre d'expériences

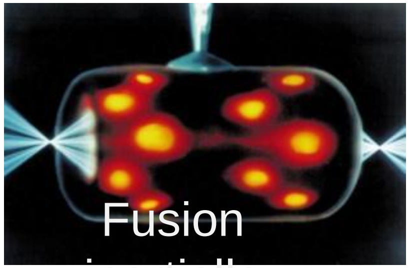




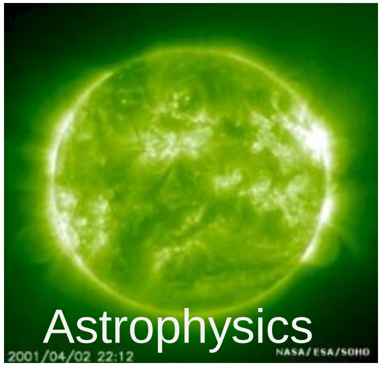
Matter at High Density Energy

Interaction with high energy density beams:

- Generation of hot and dense matter in T and P conditions
- Electronic and radiative properties of these dense plasmas
- Study in laboratory of energy production by thermonuclear fusion and astrophysics
  theory and experiments



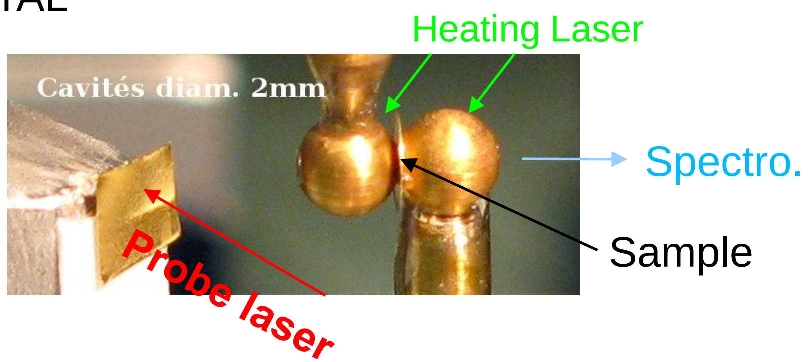
inertielle

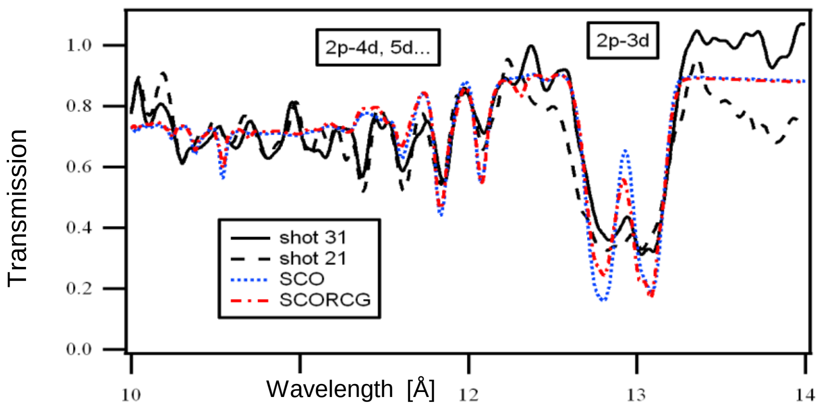


In strong link with the French Institute of Laser-Plasma (ILP) *: Large Collaborations with teams involved in Inertial Fusion and astrophysics within and without CEA (LULI, Meudon Observatory), etc.*

Matter at High Density Energy

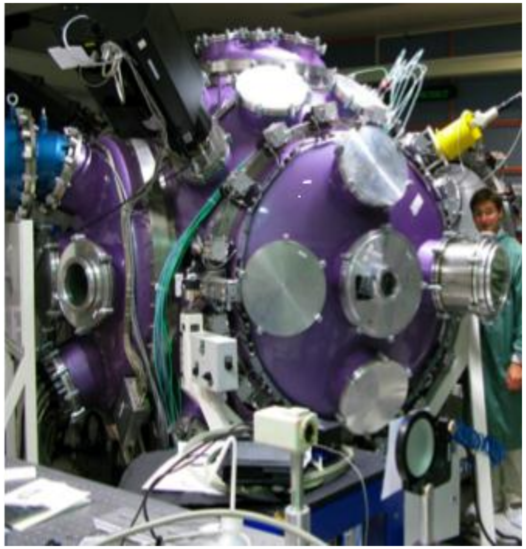
Experiments: two laser beams experiments : heating (ns) and probe (ps), using large laser facilities such as LULI2000, LIL, LMJ and PETAL





Experiment-theory comparison in the case of a Cu plasma (T~16 eV, rho~4mg/cm^3.)

2.4 m



LULI2000 experimental chamber

LIL experimental chamber

The Saclay UHI facility
(SLIC : Saclay Laser Interaction Center)

Ultrafast (<50fs), intense (TW-100TW) and high repetition rate (>10Hz) lasers

for studying ultra-fast dynamics & Laser-Matter interaction @ high and ultra-high intensity Physics & laser driven particle interaction

UHI100

Ultra high intensity

10 Hz – 25 fs - **100TW**

ultra-high contrast 10^{12}

LUCA

Many-users facility

20 Hz – 45 fs – 1 TW

5 experiments on line

PLFA

TW level @ kHz

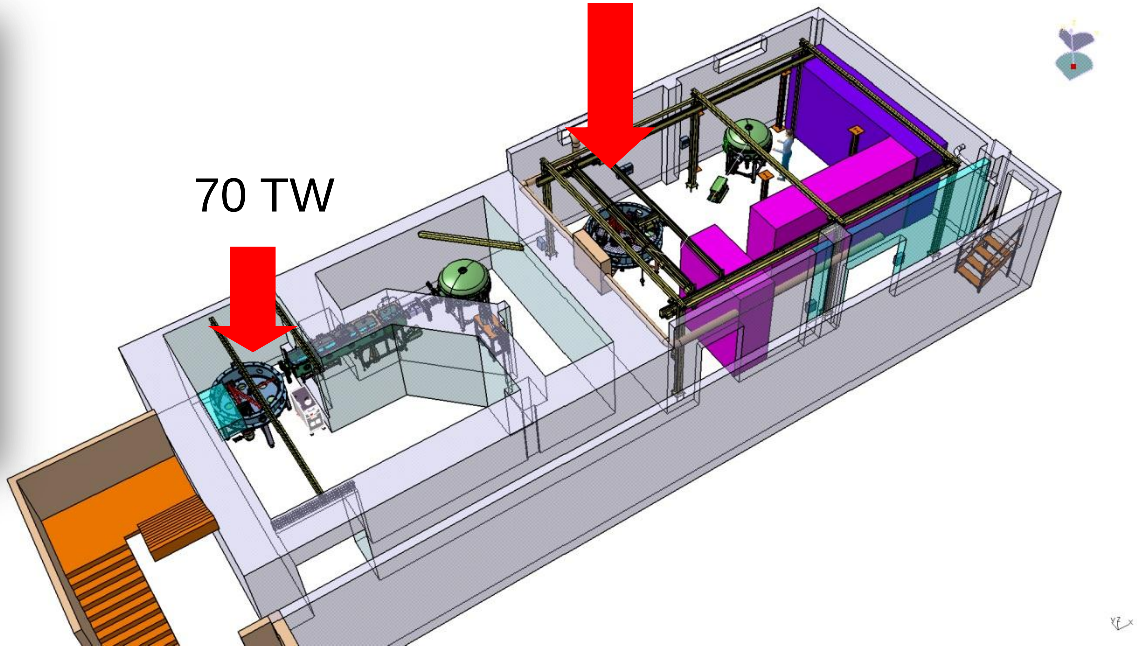
1kHz - 35 fs -0.4 TW

$\Rightarrow$ *Lasers operated by a dedicated team of 10 laser specialists*

$\Rightarrow$ **Total annual access : 700 experimental days** provided to ≈**55 scientists.**

SLIC facilities are based on **commercial lasers** that are **continuously upgraded internally** accordingly to the evolution of the users' needs **=> R&D** carried out by the SLIC team in close relationship with industry

Saclay UHI 100TW, 25 fs



Double Plasma Mirror
Deformable mirror under vacuum
+ many controls (laser and experiments) and associated diagnostics

Emphase on METROLOGY & LASER BEAM QUALITY

IMPULSE :
joint R&D laboratory CEA - Amplitude Technologies

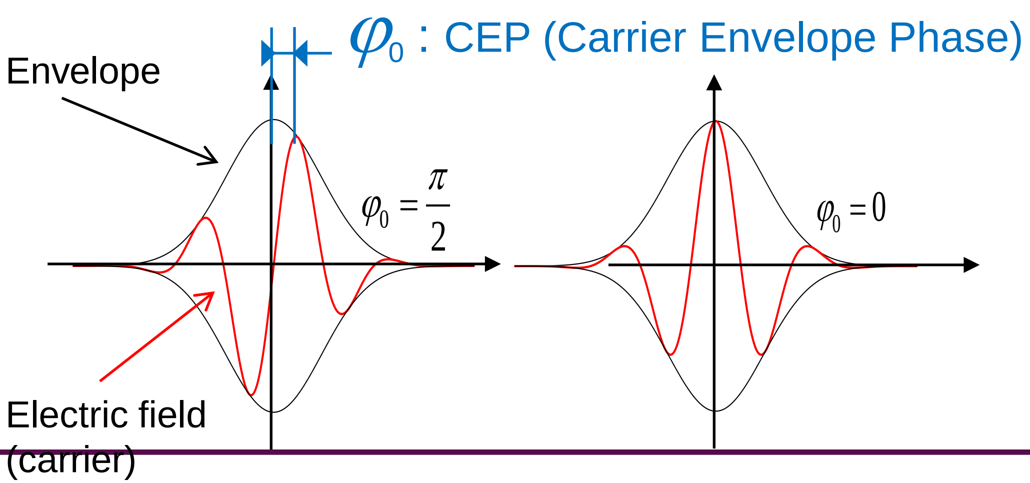
World market leader for Intense Femtosecond lasers

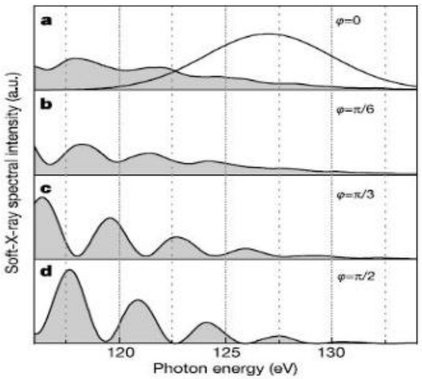
Location: Lisses (91) ZI Bois Chaland

Objective IMPULSE: to develop a prototype producing **CEP stabilized high energy** (>5mJ) pulses.

=> CEP stabilisation is often a prerequisite to use ultrafast pulses (sub 10fs) for research.

Ultrashort few cycle pulses with different CEP values …. may lead to different experimental results





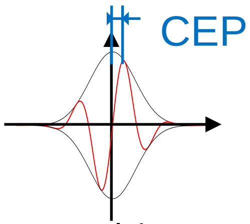
Spectra of UVX pulses produced by HHG

(Batulska et al., Nature, 2003)

Links with industry : prospectives

SLIC R&D is often carried out in close association with SMEs

R&D domains, motivation and industrial partners



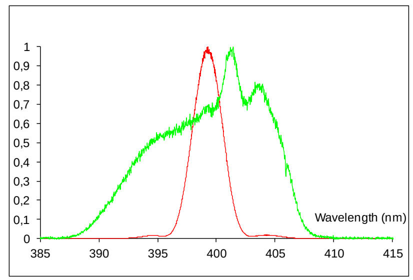
Impulsion ultrabrève

Stabilisation CEP

Produce intense sub-10fs pulses with identical temporal evolution of the electric field

Amplitude TECHNOLOGIES

FASTLITE ULTRAFAST SCIENTIFIC INSTRUMENTATION



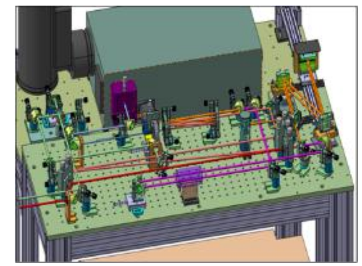
Second-harmonic spectrum : collinear vs achromatic

Non linear Optics

Produce ultra-short intense pulses at wavelengths different from 800nm (TiS)

CRISTAL LASER

FASTLITE ULTRAFAST SCIENTIFIC INSTRUMENTATION



SPIDER diagnostics for electric field reconstruction

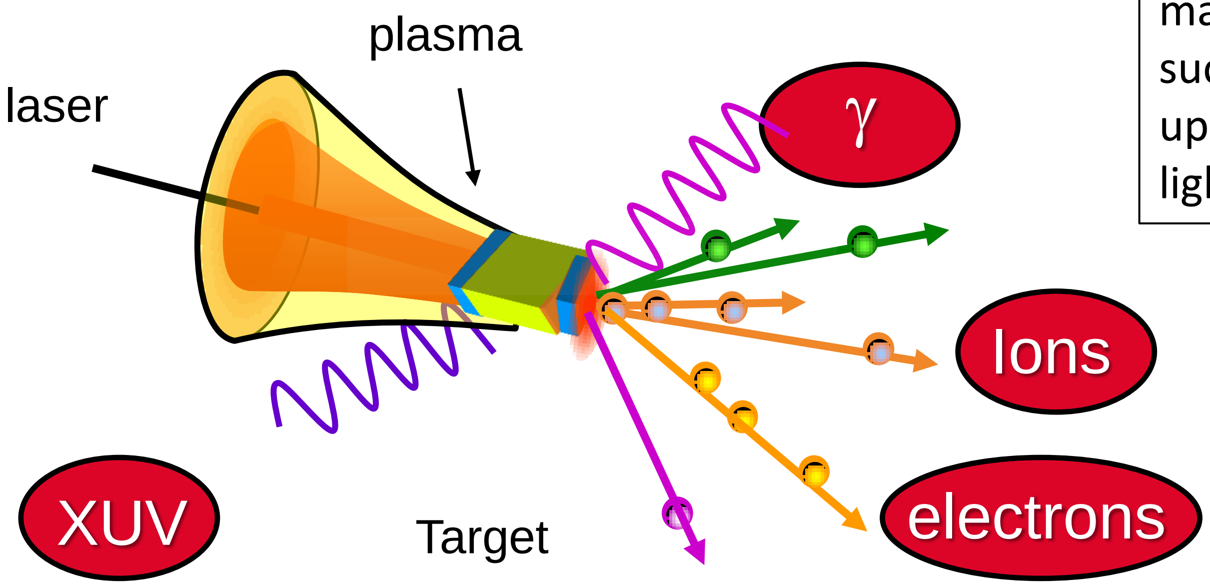
Ultrafast Diagnostics

Careful characterization of the temporal or spatio-temporal characteristics of the pulse

Amplitude TECHNOLOGIES

FASTLITE ULTRAFAST SCIENTIFIC INSTRUMENTATION

Ultra High Intensity physics



Study of the interaction of matter with ultra intense lasers such as particles are accelerated up to the vicinity of the speed of light within a few laser cycles

$\Rightarrow$ Coherent motion of matter

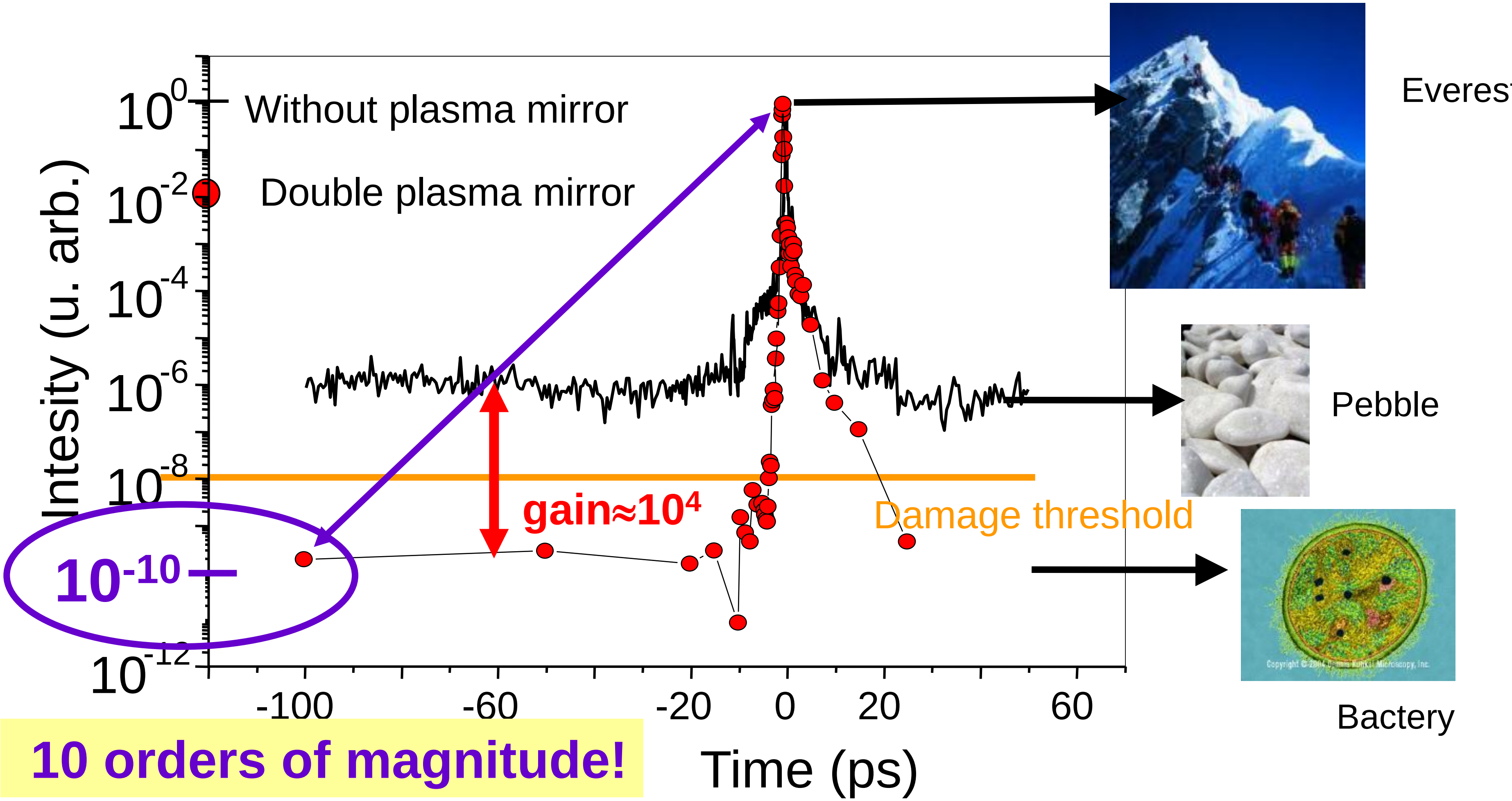
Particles and light emitted inherit the properties of incident laser (duration, beam quality…) and electrons are relativistic

« Relativistic optics »

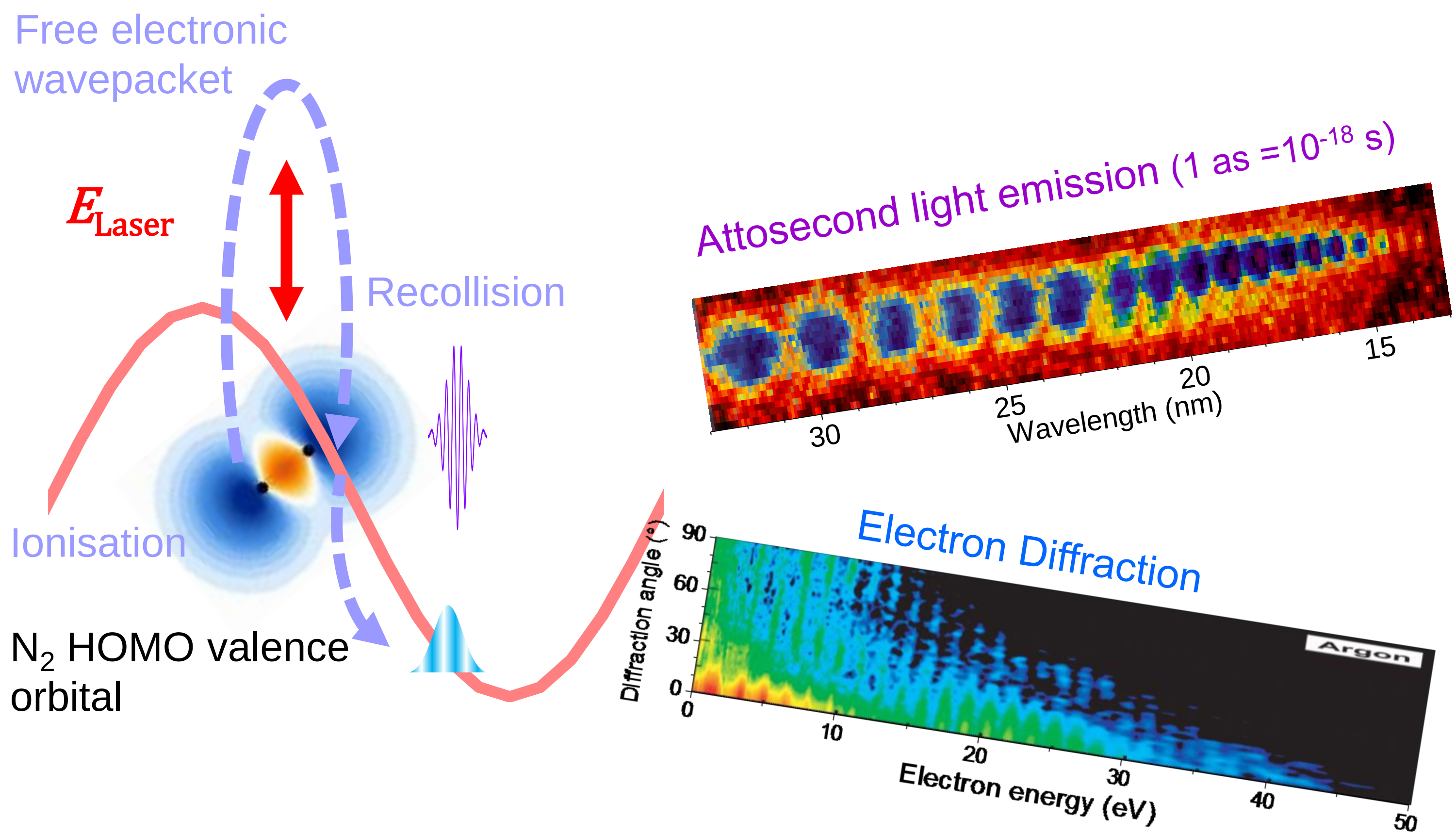
Application to health technologies (protontherapy)

High contrast is mandatory to control the way the energy is deposited to matter: development of PLASMA MIRRORS

PLASMA MIRROR: High contrast for interaction with cold and intact matter



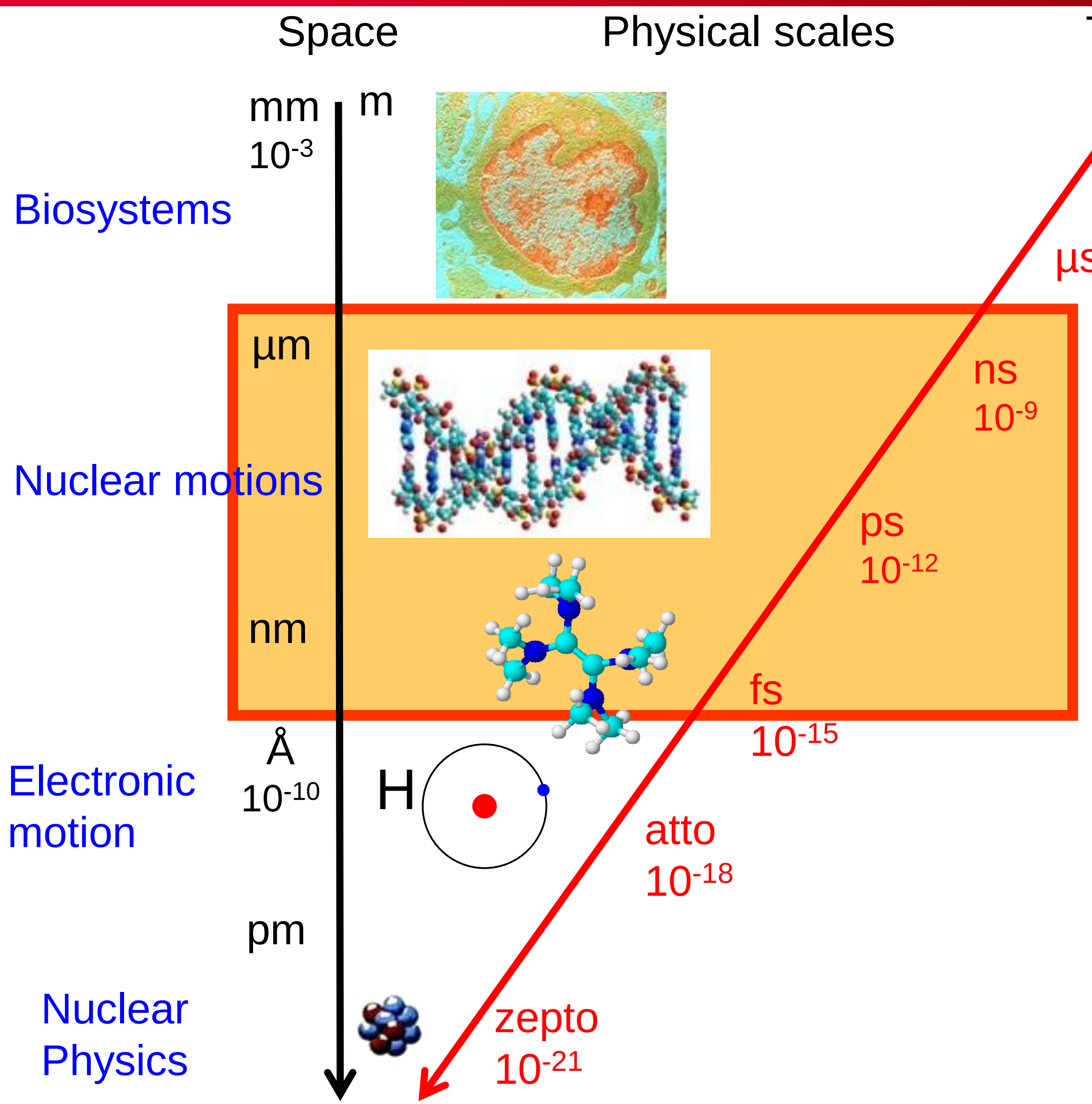
- Molecule strong field interaction as a probe:
- Non linear response in high intense field produces intense attosecond UV



Paul et al., Science 2001
Mairesse et al., Science 2001
Boutu et al., Nature Phys. 2008
Haessler et al., Nat. Phys. 6 (2010)

Capture electronic & nuclear motions at as-time & Å-space scales

CHEMICAL PHYSICS with LASERS



➢ At stakes:

Understanding
- Electronic and nuclear dynamics in complex systems

Charge transfer
Excitation transfer

- Relationship Structure vs. Dynamics

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TWO MAJOR EUROPEAN PROJECTS

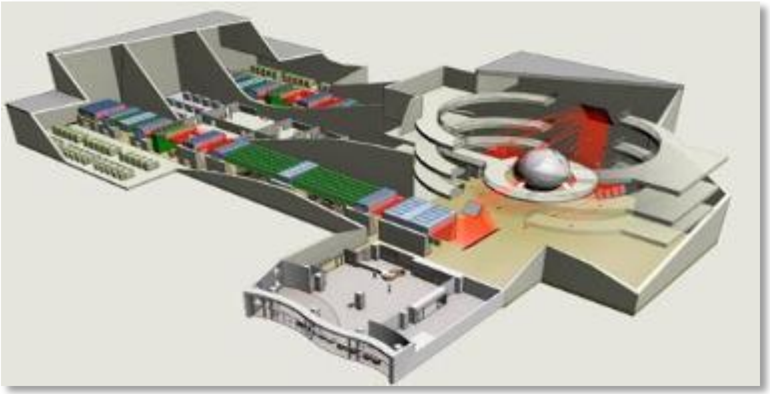
ELI : Extreme Light Infrastructure

3 complementary ELI facilities planned in

- Czech Republic : particles acceleration
- Hungary : ultra-fast dynamics
- Romania : ELI-Nuclear Physics

ELI-NP : two 10PW bricks + Gamma Beam + experimental halls

HiPER : demonstration of inertial fusion



200 kJ in 5ns + PW beams

- HIPER conditioned by the demo of the NIF ignition and the ability to rise in firing rate (LMJ / 7 with 10 shots / s!)
- Many technological barriers: cryogenics, targets, materials, ..

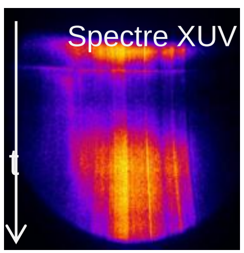
PETAL in the HiPER roadmap

<u>18/09/2012</u> : The ELI-NP Application for funding of the first phase of the project was Approved by the European Commission !

Congratulations from the French laser community !

THREE NEW FRENCH PROJECTS

Matter at High Energy Density (HDE):
pulses of very high energy (> 1 kJ) and long duration (ns)
Issues = confinement fusion and laser plasma laboratory study;



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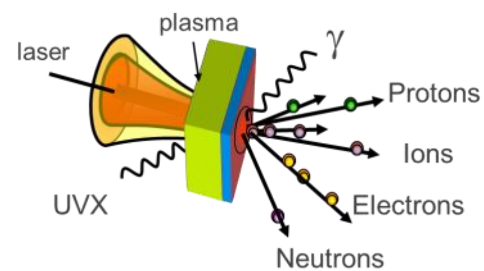
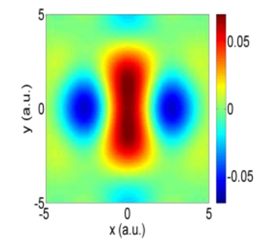
PETAL+

Matter under ultra-short pulses (fs-as)

Ultra-High Intensity Physics (UHI)

Attophysics (ATTO) ultra-fast dynamics





CILEX

ATTOLAB

National strategy for large laser facilities in the future:
HDE= BORDEAUX UHI: plateau de Saclay

PETAL+ : High Energy Density

PETAL+ compressor

© Agence Free Lens
Philippe Labeguerie

LMJ

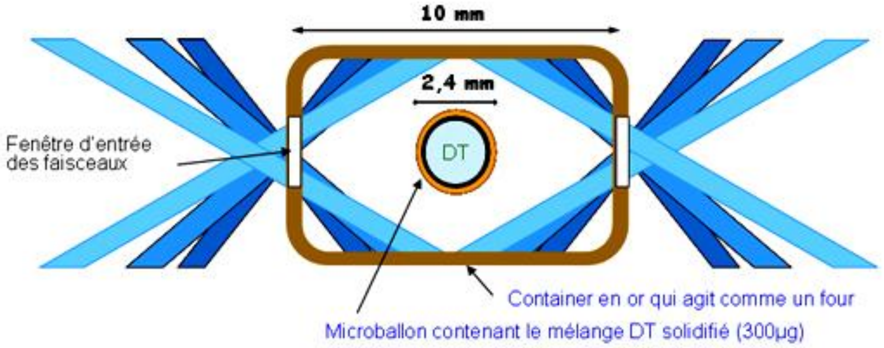
PETAL multi petawatt, 3,5kJ, 0 to 5ps

Coupled with LMJ
Inertial Confinement Fusion

Fundamental research program

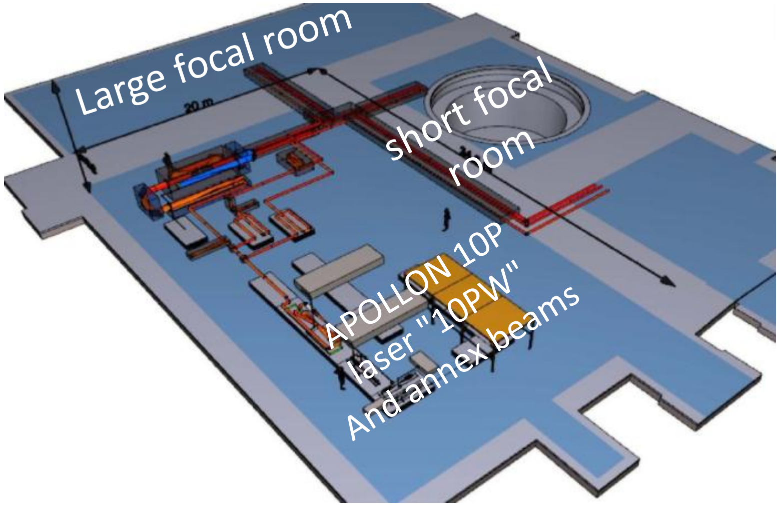
Dense matter equation of state

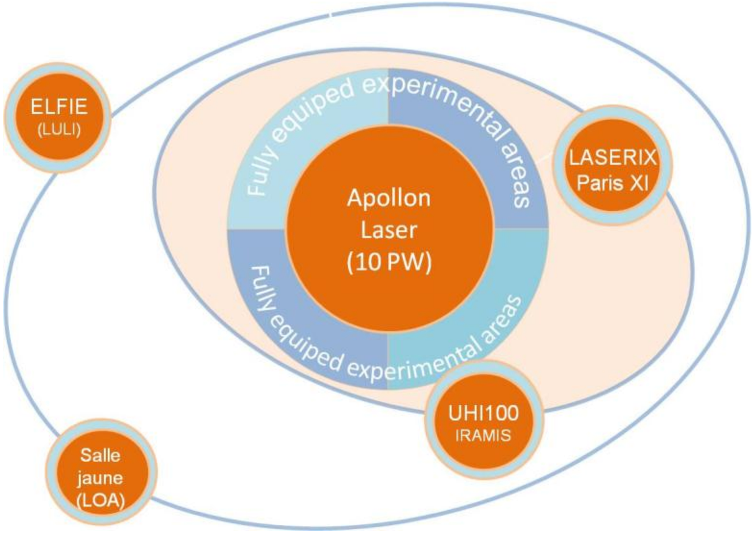
Laboratory astrophysics



CILEX - ApolloN

CILEX (Interdisciplinary Center for Extreme Light) includes
- the Apollon laser with 2 fully equipped experimental rooms
- 4 satellite lasers (versatile, high repetition rate) for staff training and experiment preparation





10^{18} 10^{20} 10^{22} 10^{24} I (W/cm^2)

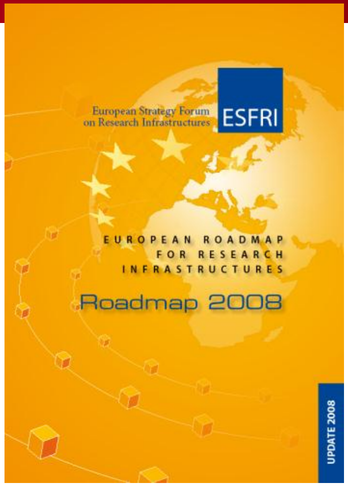
Relativistic Regime | Ultra-relativistic Regime

UHI100 **Apollon** ELI, IZEST ?

Experiments on particle acceleration and new generation X-rays and γ-rays

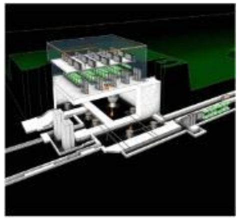
HISTORY OF CILEX-APOLLON GOES WITH ELI

2005: project of an Extreme Light Infrastructure (ELI) by G. Mourou



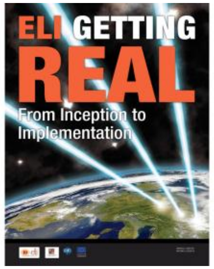
eli extreme light infrastructure

2007: ELI Enters Preparatory Phase and ESFRI roadmaps



2007: launching of APOLLON 10PW

2010: CILEX/APOLLON implemented at Saclay



2010: getting real!
ELI-BEAMLINES
ELI-NP
ELI-ALPS

2011

eli beamlines

2012

eli Nuclear Physics

2013?

ELI-ALPS

→ eli delivery consortium

Laser Apollon 10PW

Goal : 1 shot/min, Energy 150 J, Duration 15 fs, 10 PW, **10^{22} W/cm^2**

Team of 50 academic scientists and engineers involved in APOLLON

10 fs Oscillator / Stretching	Amplification	Compression	Transport to experiment
Institut d'Optique	loa		cea

- ☒ Laser architecture design
- ☒ R&D
- ☒ Laser chain integration issues
- ☐ First shot 2014

Relationship between CILEX-APOLLON and laser Industrials

- ☒ Close links with industrials for transferring the intellectual property
- ☒ Transformation of a cutting edge APOLLON in a commercial product

ATTOLAB

Interdisciplinary platform for ultra-fast dynamics

Atoms and molecules

electron/ion Spectroscopy

Laser beam femto (IR) / atto (XUV) 1 kHz
Laser beam femto / atto 10 kHz

XUV Optic

CeMOX facility

Condensed matter

Plasmas

Photoemission Spectroscopy

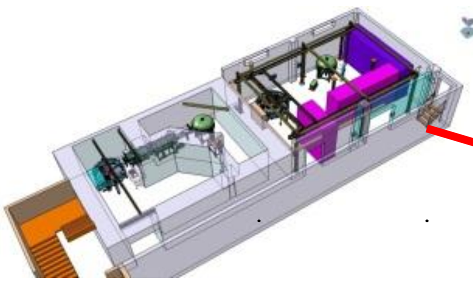
Laser beam femto / atto 1 kHz, High Energy

- Coherent Dynamics of electronic and nuclear wave packets in real time
- Pump-probe experiments with several atto / femto controlled pulses
- long term applications: light driven electronics and biochemistry

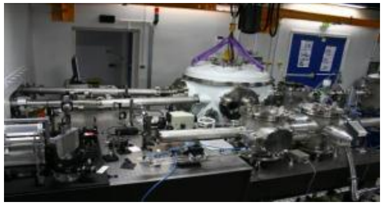
Plateau de Saclay : unique expertise in UHI laser Science

150 permanent staff; many students through University and “Grandes Ecoles”

UHI100 TW, 25 fs
CEA-Saclay



LPGP/LASERIX
University Paris Sud



Salle jaune 2x60 TW, 30 fs, LOA

ELFIE
LULI

Conclusion

- CEA has widely contributed during the last 40 years to the development of laser applications in the domain of fundamental science, industry and defense.

- Beyond UHI & HDE laser science, lasers have also invested all domains of activities within CEA, from particle physics, to biology and chemistry.

- The significant scientific results in this domain can be attributed to the special link existing between technological and fundamental research promoted within CEA