ULTRA HIGH INTENSITY LASER-MATTER INTERACTION AT CEA - SACLAY

CEA / DSM / IRAMIS / SPAM / Physique à Haute Intensité

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Outline

- The laser UHI100: High Intensity @ Ultra High Contrast
- High order harmonic generation
- Electron acceleration
- Protons and ions acceleration
- Conclusion and perspectives
LASER
European Research Groups are encouraged to apply for access to SLIC Laboratory, member of the LASERLAB-EUROPE network.
SLIC
the Saclay Laser-matter Interaction Center

3 Main facilities

LUCA
• 1TW, 50 fs, 20 Hz
• Up to 6 lines, up to 4 users
• Femtochemistry, solid-state physics

PLFA
• 0.4TW, 32 fs, 1kHz
• High average flux, high shot-to-shot stability

UHI100
• 100TW, 25 fs, 10 Hz
• Contrast ratio = 10^8
• Ultra high intensity physics: I_{max} \approx 10^{20} W/cm^2
Increasing the contrast: the double plasma mirror device

- Pulse contrast: $10^{10}$
- Transmitted energy: 50%
- Maximum intensity: $6.10^{18}$ W/cm$^2$
- Focal spot size: $\varnothing = 8$ µm (FWHM)
- Polarization $p$

A. Lévy et al., Optics Letters 32, 310 (2007)
Improving the focal spot: the deformable mirror device

Best result (measured): \( I_{\text{max}} \approx 1.7 \times 10^{20} \text{ W/cm}^2 \)

FWHM = 3.5 \( \mu \text{m} \)  
FWHM = 2.8 \( \mu \text{m} \)
Experimental set-up

- Compressor
- Double plasma mirror
- Deformable mirror
- Interaction chamber
- Diagnostics
HHG
Motivations

- Understand the underlying physical mechanisms
- Radiation source: Intense ultrashort (fs to as) XUV pulses
Two different mechanisms of HHG on plasma mirrors

Relativistic Oscillating Mirror
Doppler effect

Coherent Wake Emission: light emission by collective plasma oscillations triggered by Brunel electrons

Experimental evidence: relativistic harmonics

ω_p, n=15

Plastic - $3 \times 10^{18}$ W/cm$^2$

Plastic - $8 \times 10^{18}$ W/cm$^2$

Control and measurement of the density gradient

**UHI100 laser**
25 fs - 2 J
CEA Saclay

Main pulse
HIGH CONTRAST
(double plasma mirror)

Few ps

Prepulse
$10^{16}$ W.cm$^{-2}$

$L \ll \lambda$

$n_e$

$400 \, n_c$

$n_c$

Plasma

Prepulse focal spot

Main pulse focal spot

S. Kahaly et al, PRL 110, 175001 (2013)
Control and measurement of the density gradient

FDI measurements of the gradient created by the prepulse

\[ \Delta \Phi (\text{rad}) \]

\[ \tau (\text{ps}) \]

\[ L/\lambda \]

\[ C_S = 37 \text{ (nm/ps)} \]

\[ I = 10^{18} \text{ W/cm}^2 \]

CWE to ROM transition

S. Kahaly et al, PRL 110, 175001 (2013)
Laser $a_L=8$, $L=\lambda_L/8$, $w_L=3\lambda$, $\tau=25\text{fs}$
Experiment vs model

Fully-analytical model of the plasma dynamical curvature, and its effect of the harmonic beam validated experimentally without any adjustable parameter

Divergence vs harmonic order

Divergence vs density gradient $L$

Attosecond lighthouses

**General principle**

- Few cycle pulses + spectral filtering
- Polarization gating (and extensions: DOG, GDOG)

\[ \frac{\theta_n}{\theta_L} \leq \frac{1}{\alpha p N_c} \]

- \( \theta_n \) = divergency of \( n\omega_L \) harmonic beam
- \( \theta_L \) = divergency of laser beam
- \( N_c \) = optical cycles in the driving-laser pulse
- \( p = \) attosecond pulses generated every laser optical cycle

**Benefits**

- Simple and universal (gases, plasmas)
- Collection of beams of single atto pulse
- Ultrafast metrology, including CEP changes

Footprint of the XUV beam in the far field

*Footprint of the XUV beam in the far field*

*Footprint of the XUV beam in the far field*

Single attosecond pulses from plasma mirrors at kHz rep rate

*Single attosecond pulses from plasma mirrors at kHz rep rate*

ELECTRON ACCELERATION
Laser-plasma accelerator for the generation of relativistic electrons

- Ponderomotive force pushes electrons away from high intensity regions
- Still ions space charge brings electrons back to their initial position
- $\omega_p^{-1} \approx \tau \Rightarrow$ large amplitude plasma wave in the wake of the laser pulse travelling @ $v_{ph} = v_g$ laser

$$E_{\text{max}}(\text{GV/m}) = 0.3 \times (\delta n_e/n_e)(\% \times n_e)^{1/2} \ (10^{17} \text{ cm}^{-3})$$

several 100’s of GV/m (several 10’s MV/m in conventional accelerators)

- Radiotherapy
- Femtosecond radiolysis
- XFEL
- Ultrashort and sub-mm $\gamma$-ray sources
- Fast ignitor
- Pump-probe experiments
Properties of electron bunches

The « Bubble regime »:

\[ a_0 = \frac{eE_L}{m_0 c \omega_L} = 0.85 \left( \frac{\lambda_L}{\mu m} \right) \left( \frac{I_L}{10^{18} \text{ W/cm}^2} \right)^{1/2} \]  >> 1

- radial dimension = longitudinal dimension < \lambda_p
- injection at c^{st}e phase
- \( a_0=(\omega_0/\omega_p)^{2/5} \) Laser pulse self-focusing
- \( k_p R = k_p w_0 = \sqrt{a_0} \) Bubble formation
- \( \tau c = 2 w_0 / 3 \)
- signature : monoenergetic spectra

1^{st} exp. obs. : Mangles et coll., Geddes et coll., Faure et coll., Nature 2004

Properties of electron beams:

- electrons of 100’s of MeV up to GeV
- low divergence (\sim mrad)
- short duration (<\tau_{laser})
- Charge : several nC
Towards higher energies….

To increase the electron energy:

- increase the laser energy (« blow out » regime at low $N_e$)
- use a wave guide (laser propagation length only limited by the length of the guide)

**Multi-stage LPA scheme**

1st step: 2-stage Laser Plasma Accelerator (LPA)

**ELISA**
**EL**ectron **I**njector for compact **S**taged high energy **A**ccelerator

Project: set up and study an electron source as an external injector into the accelerator stage
First step: 1 injector for 2nd stage LPA ELISA PROJECT

External injector: ionisation of a low Z gas doped with impurities for controlling the electron trapping

To be injected in a 2nd LPA stage
- duration (<10fs)
- emittance to be focused on ~10µm
- stability
- energy: monocinetic, several 10's of MeV

Originality:
- gas cell → stability
- ΔL → Vary the E
- différential pumping → reduce the density gradients at entrance/exit of the injector
- gas mixture (several % of impurities) → Electron trapping control
Ionisation injection

Idea: choose the impurities such as the ionisation happens at $I_{\text{max}}$ for optimising the electron injection and trapping into the plasma wave created in the rising edge of the laser pulse

- Experimental results

- Theory of ionization-induced trapping in laser-plasma accelerators

- Effect of the impurity percentage, of the medium length, etc … on the properties of the accelerated electron bunch

Research axis on LPA

- Generation of a reproducible, stable and controllable LPA as injector for 2-stage LPA  
  EquipeX CILEX on APOLLON-10P

  And also ....

- Harmonic generation in the laser propagation axis

- Spatio-temporal characterisation of the laser pulse \(\rightarrow\) pulse compression by propagation through the plasma
Laser driven ion acceleration: the TNSA mechanism
“…turning a light beam into a matter beam”

> 10 years of intense and ever-increasing research

- Short duration ~ ps
- Divergence ~ 10
- Laminarity
- Emittance ~ 0.002 π mm mrad
- Energy ~ dozens of MeV
- Flux ~ $10^{11-13}$ (E > 3 MeV)

S.C. Wilks et al., Phys. of Plasmas 8, 542 (2001)
Applications

Probing electric fields in plasma

L. Romagnani et al, PRL 95, 195001 (2005)

Probing dense plasmas


Isochoric heating


Medical isotopes production

McKenna et al. PRE 70, 036405 (2004)
10 millions more people affected each year
6 millions are treated by conventional radiotherapy
9% of them could be treated by proton therapy: only 0.1% actually are.

Proton beams have still a very low impact on overall tumor therapy
About 500 more proton therapy centers required to satisfy the need

- Cost of the installation: 80 to 140 M€ (~2.5 times a photon based center)
- Size of the installation: 1000 to 2000 m²

More affordable installations
- more clinical centers
- more treated patients
Applications: proton therapy – some numbers

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More affordable installations
   ↓
more clinical centers
   ↓
more treated patients

picture from the JAEA web site
The SAPHIR consortium on laser-driven protontherapy

**SAPHIR**: Source Accélérée de Protons par laser de Haute Intensité pour la Radiothérapie

(*Accelerated Proton Source by Ultra Intense Laser for Protontherapy*)

**Technical challenges**
- Getting more than 65 MeV pour eye treatment and 150-200 MeV for others.
- Proton energy spectrum fully managed and controlled
- Stability and reproducibility
- Applied dose

**Total budget (consolidated) : 20 M€**

Financial support
- OSEO: 6.25 M€
- Région Ile de France: 1 M€
Present main aims in laser-driven proton acceleration and related research paths

- Reducing the target thickness
- Reducing the target size
- Well controlled pre-plasma
- Engineered targets
- Simply increasing the laser power?

- RPA
- Engineered targets

- Laser-driven microlens
- Engineered targets

- Upstream study of main physical mechanisms in proton acceleration
- Setting scaling laws
- Exploration of new acceleration mechanisms
Proton emission under UHC conditions

- $E_{\text{max}}^{\text{FWD}} \approx E_{\text{max}}^{\text{BWD}}$
- $\theta^{\text{FWD}} \approx 0.7 \times \theta^{\text{BWD}}$
- Flux $^{\text{FWD}} \approx$ Flux $^{\text{BWD}}$
- Laminarity $^{\text{FWD}}$ and $^{\text{BWD}}$
- Emittance $^{\text{FWD}} \approx$ Emittance $^{\text{FWD}} \approx 0.1 \pi \times \text{mm} \times \text{mrad}$

Heating mechanism: Brunel effect

Quasi-symmetrical acceleration
TNSA model applies to both sides

Ultra thin targets @ ultra high contrast: an analytical model

- Self consistent solution of the Poisson equation for the electric field accelerating ions
- Adiabatic approximation for the hot electrons population
- Two ion sorts
- 1D analytical model

\[
\varepsilon_{\text{max},1,2} \approx \frac{3\pi Z_{1,2} e^2 (Z_2 n_{i2} \ell_{i2} \pm Z_1 n_{i1} \ell_{i1}) r_D e}{\sqrt{1 + (\ell_{i2}/r_D e)^2}} + \left( \frac{2\sqrt{2} T_0}{3^{3/4}} \right)^{3/2} + 4\pi e^2 Z_1 n_{i1} \ell_{i1} r_D e \right) \left( \frac{Z_{1,2}}{Z n_{i2}} \right) \left( \frac{Z n_{i2}}{1.0 \times 10^{23} \text{cm}^{-3}} \right) \right)^{-1/2}
\]

\[
\ell_{\text{opt}} \approx \lambda_L \frac{n_{\text{gr}}}{Z n_{i2}} \left( 5 + I_{18}^3 \left( \frac{t_L}{30 f s} \right)^{3/4} \right) \left( \frac{Z n_{i2}}{6 \times 10^{23} \text{cm}^{-3}} \right)^{-1/2}
\]

- Maximum protons and ions energy
- Optimal target thickness
- Protons and ions number

Lateral expansion of the fast electron cloud during the ion acceleration

Deviation of the traveling ions from the target normal

Analytical model for the divergence of fast ion beams

Experimental data

2D PIC simulations

First results with the UHI100 laser chain: ultra-thin foils & scaling law for bulk targets


100 MeV protons → 500 TW @ UHC

Engineered targets on UHI100: I - foam targets

Laserlab joint experiment: PHI - Politecnico di Milano (PI M. Passoni)

“Advanced” TNSA regime
multilayered targets: thin solid foil + low-density layer

Interest in “intermediate”, near critical conditions $n_e \sim n_c$

Scalings predicts more efficient absorption and fast electron generation

$$P = 32 \text{TW} \quad \tau = 25\text{fs} \quad w_0 = 3\mu\text{m} \quad U = 0.8\text{J} \quad l = 3.4 \times 10^{20}\text{W/cm}^2 \quad (a_0 = 10)$$

 exponential with a cut-off (like TNSA)

 thin foam ($l_f = 2\mu\text{m}, n_f = 2n_c$) \Rightarrow cut-off energy increased by a factor $\sim 2.5!$

 Sgattoni et al, PRE 85, 036405 (2012)

@NANOLAB POLIMI: Pulsed Laser Deposition
Nanostructured Carbon grown on aluminium
Engineered targets on UHI100: I - foam targets

High Contrast
Al 1,5 μm + foam ~ 10 μm

Low Contrast
Al 10 μm + foam ~ 23 μm

At HC and LC, FT similar to ST at maximum focalization / intensity
At low intensities, FT energies > ST energies
Engineered targets on UHI100:
I - foam targets

Comportement similaire pour des cibles simples et des cibles mousse si :
variation de l’intensité = variation de l’énergie ou de la durée de l’impulsion
Engineered targets on UHI100:
I - foam targets

2D-PIC simulations (ALaDyn)

Foam total ionization
$n_e = 2n_c$

Foam partial ionization
$n_e = 0.66n_c$

Underdense foam
considerable advantage
over ST (at low intensities)

M. Passoni et al., to be submitted
Engineered targets on UHI100: II - ‘μ-spheres’ targets

Laserlab joint experiment: CEA/IRAMIS, LULI, Czech Technical University, INO (PI A. Macchi)

2D3V relativistic EM (parallel) PIC code

Layer: 400 nm spheres
⇒ $E_{\text{max}}$ increase $>1.5$

Target: thin (μm thick) plastic foil (substrate) with a mono-layer of hexagonally-packed micrometer polystyrene spheres on its surface.

- 3 substrate thicknesses (900 nm, 20 μm and 40 μm)
- 2 polystyrene sphere sizes (471 nm or 940 nm)
- Proton $E_{\text{max}}$ as a function of incidence angle and pulse polarization


$D.$ Margarone et al., PRL, 109, 234801 (2012)
Engineered targets on UHI100: II - ‘µ-spheres’ targets

- Cut-off energy increase for thicker targets
- Not effective for large incidence angles
- Not effective for (too much?) thin substrates

V. Floquet et al., *Micro-sphere layered targets efficiency in laser driven proton acceleration*, submitted to APL
Engineered targets on UHI100: III - ‘grating’ targets

Laserlab joint experiment: CEA/IRAMIS, LULI, Czech Technical University, INO (PI A. Macchi)

- Solid foils with periodic surface modulation may allow resonant excitation of Surface Waves (SW)
- Previous investigations only at modest intensities $I \leq 10^{16} \text{ W/cm}^2$

$I=10^{19} \text{ W/cm}^2$

![SEM picture of engraved Mylar foils](image)

$\text{SW excitation Proton cut-off energy increase (~x 2 )}$

- 3 substrate thicknesses (800 nm, 20 μm and 40 μm)
- $2\lambda$ periodic engraving, 500 and 300 nm deep
- Proton $E_{\text{max}}$ as a function of incidence angle

M. Raynaud, Physics of Plasmas 14, 092702, (2007)
Détection des électrons, protons et rayonnement X sur ~ 330

Engineered targets on UHI100:
III - ‘grating’ targets

Porte cible + cible

filtre mylar Aluminisé

Amovible RCF ring

Impulsion laser
Motif réseau préservé lors de l’interaction (contraste laser $10^{12}$)

Direction d’émission principale des électrons: ~ $90^\circ$

Pas d’influence sur la direction d’émission des protons en face arrière
Engineered targets on UHI100:
III - ‘grating’ targets

Bas contraste => pas d’émission électrons (d)
Changement de l’angle d’incidence => shift angle émission électrons (e)
Engineered targets on UHI100:
III - ‘grating’ targets

No evidence of an optical emission close to the $3/2\ \omega$ wavelength.

- Bas contraste => pas d’émission électrons (d)
- Changement de l’angle d’incidence => shift angle émission électrons (e)
Engineered targets on UHI100: III - ‘grating’ targets

Grating target shows a clear maximum at resonance angle (30°)
For the same angle, reflected
Engineered targets on UHI100: III - ‘grating’ targets

Two different PIC configuration:
- Thin foil (0.8µm) + focused target (ALaDyn)
- Thick target (20 µm) + plane wave (EMI2D)

Grating vs. Plain target
- Increased absorption
- Higher proton energies
- «resonance» at 30°
CONCLUSION AND PERSPECTIVES
In a rich and stimulating scientific surrounding, CEA-Saclay offers a comprehensive panel of laser facilities, open to external researchers in the framework of the LASERLAB network

Thanks to the features of its high intensity laser chain, the PHI group carries on a pioneering research activity on laser-matter interaction in the UHC pulses domain

Pre-plasma free, UHC experiments are a nice benchmark for analytical models and/or numerical codes

« HHG »: fabien.quere@cea.fr
« ELECTRONS »: sandrine.dobosz@cea.fr
« PROTONS »: tiberio.ceccotti@cea.fr
General objective: a Research Centre on Intense Lasers, Plasmas and Applications, hosting the most powerful laser (APOLLON 10P, 10 PW, 15 fs, 150 J) and smaller scale facilities (ELFIE (LULI), UHI100 (IRAMIS), Salle Jaune (LOA), LaserX (Paris XI)) for pluridisciplinary programs and training of scientists and engineers

Operated as a user-facility

CILEX = APOLLON (20 M€) + SATELITTE FACILITIES + BUILDING REHABILITATION + EXPERIMENTAL SET-Up (20 M€)
A "laser and plasma labs" Campus on the « Plateau de Saclay »

Developing new instruments and an interdisciplinary centre CILEX will be devoted to address physics at unexplored power densities.
A "laser and plasma labs" Campus on the « Plateau de Saclay »

Developing new instruments and an interdisciplinary centre CILEX will be devoted to address physics at unexplored power densities
The ion beam line @ Apollon: tentative (almost definitive) set-up

1 Main beam 10PW
   +
1 synchronized energetic beam 1PW
   (15J/15fs/1shot per minute)
   +
1 probe beam few TW
   (150mJ to 1J/15fs/1shot per minute)

About 180 m², 2 experimental chambers, diagnostics, radio-shielding
GRAZIE PER L’ATTENZIONE