DE LA RECHERCHE À L'INDUSTRIE

ULTRA HIGH INTENSITY LASER-MATTER INTERACTION AT CEA - SACLAY

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

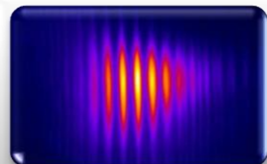
Tiberio Ceccotti

INFN FRASCATI, 16 MAI 2013

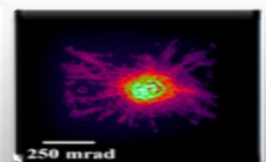
www.cea.fr

Outline

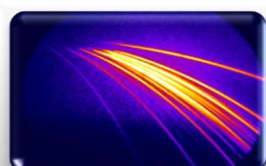
The laser UHI100 : High Intensity @ Ultra High Contrast



High order harmonic generation



Electron acceleration



Protons and ions acceleration

Conclusion and perspectives

LASER

SLIC
the Saclay Laser-matter Interaction Center

3 Main facilities

LUCA

- 1TW, 50 fs, 20Hz
- 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

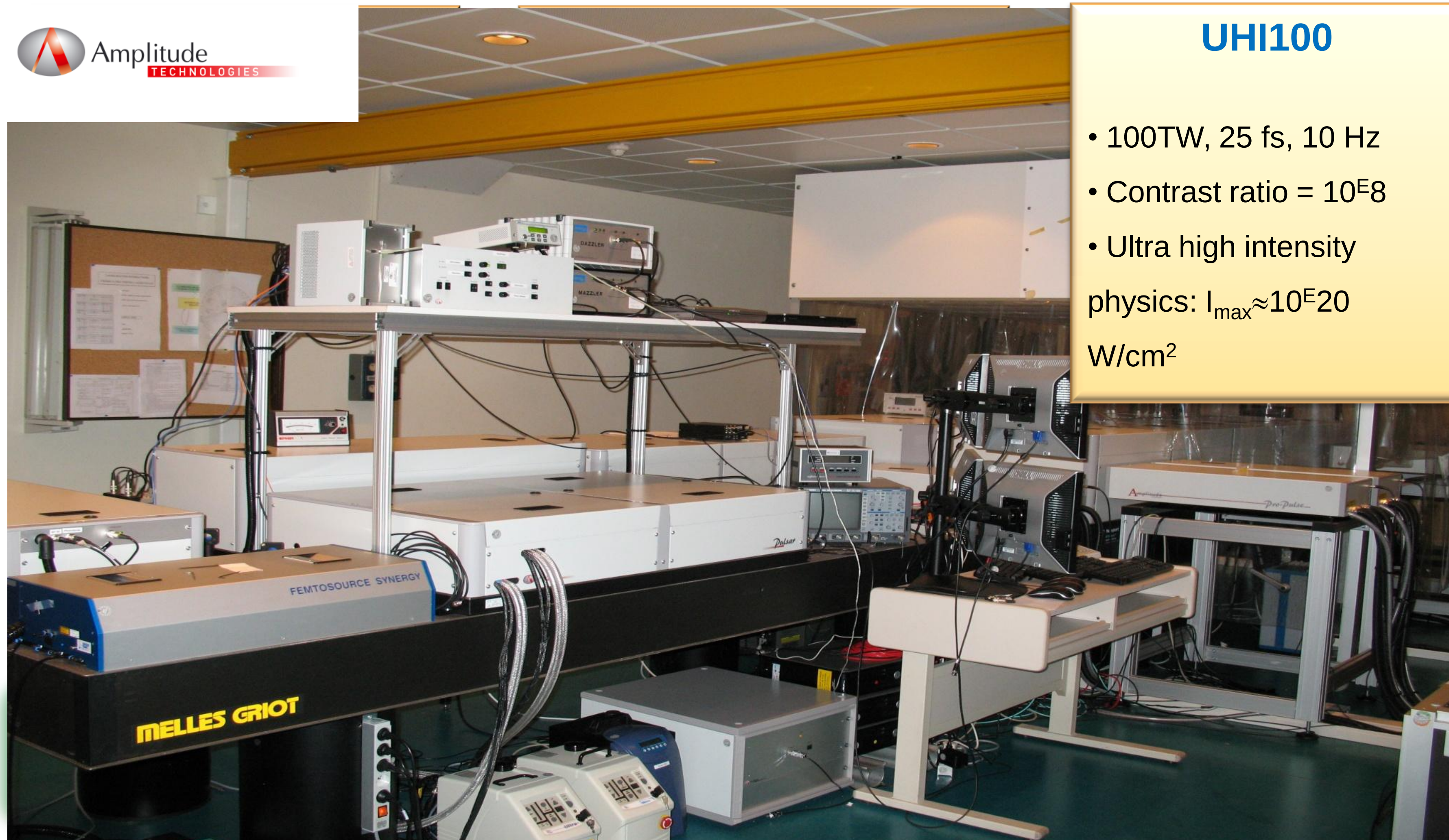
UHI100

- 100TW, 25 fs, 10 Hz
- Contrast ratio = $10^{E}8$
- Ultra high intensity physics: $I_{max} \approx 10^{E}20$ W/cm^2

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

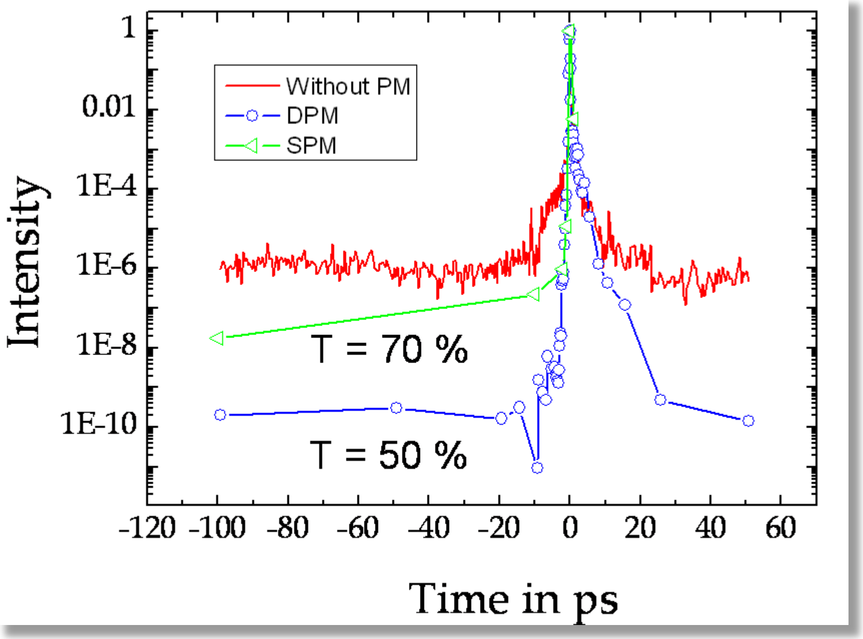
3 Main facilities

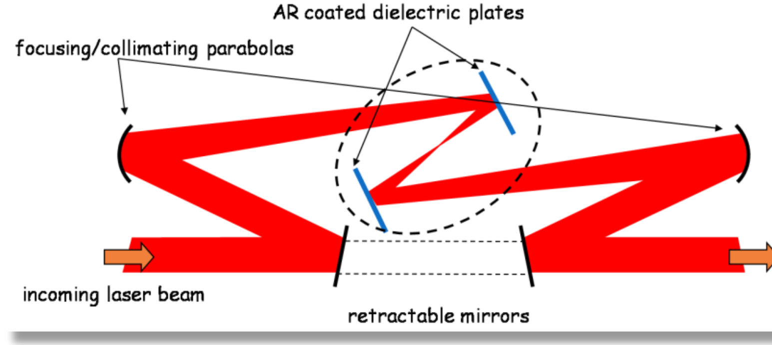


UHI100

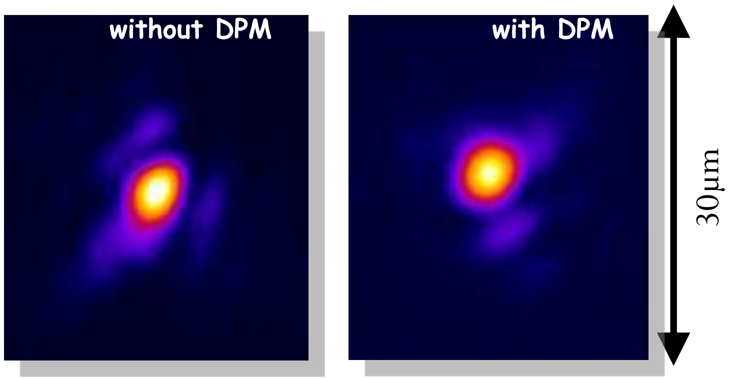
- 100TW, 25 fs, 10 Hz
- Contrast ratio = $10^{E}8$
- Ultra high intensity physics: $I_{max} \approx 10^{E}20$ W/cm^2

Increasing the contrast: the double plasma mirror device





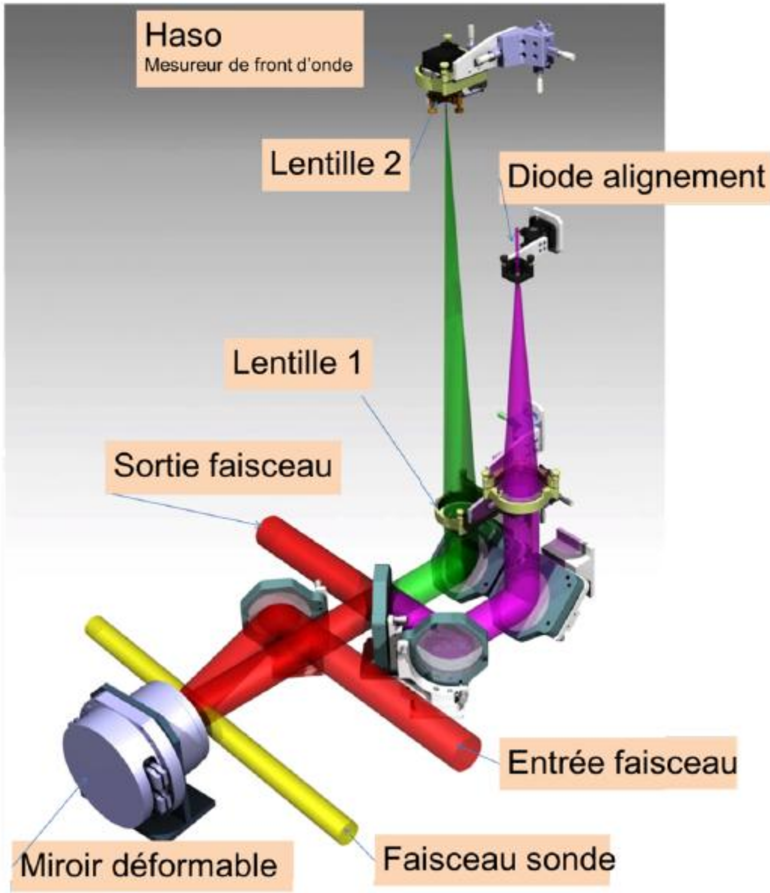
focal spot

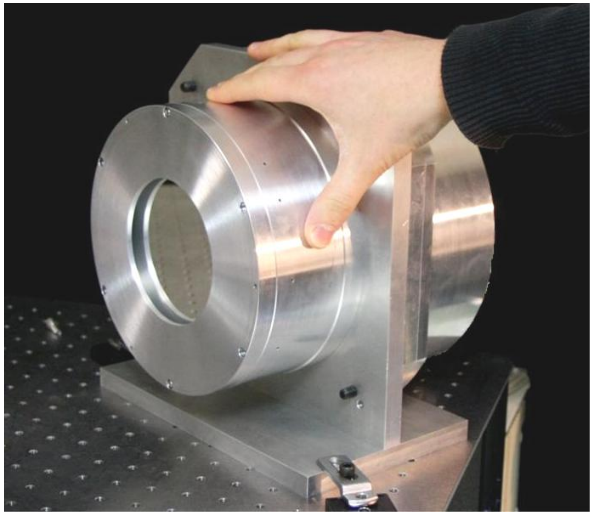


- Pulse contrast : 10^{10}
- Transmitted energy: 50%
- Maximum intensity : 6.10^{18} W/cm^2
- Focal spot size : Ø = 8 µm (FWHM)
- Polarization *p*

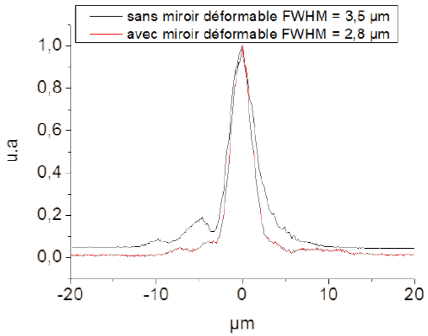
A. Lévy et al., Optics Letters ***32****, 310 (2007)*
C. Thaury et al., Nature physics, ***3****, 424 (2007)*
G. Doumy et al., Phys. Rev. E, (2004)

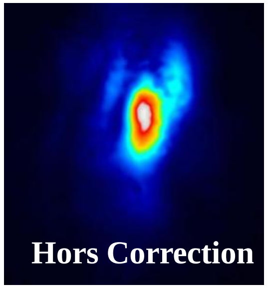
Improving the focal spot: the deformable mirror device



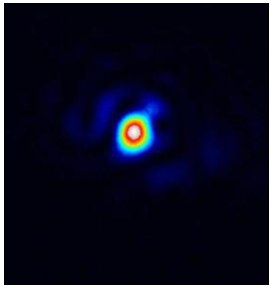


Best result (measured): $I_{max} \approx 1.7\ 10^{20}$ W/cm^2



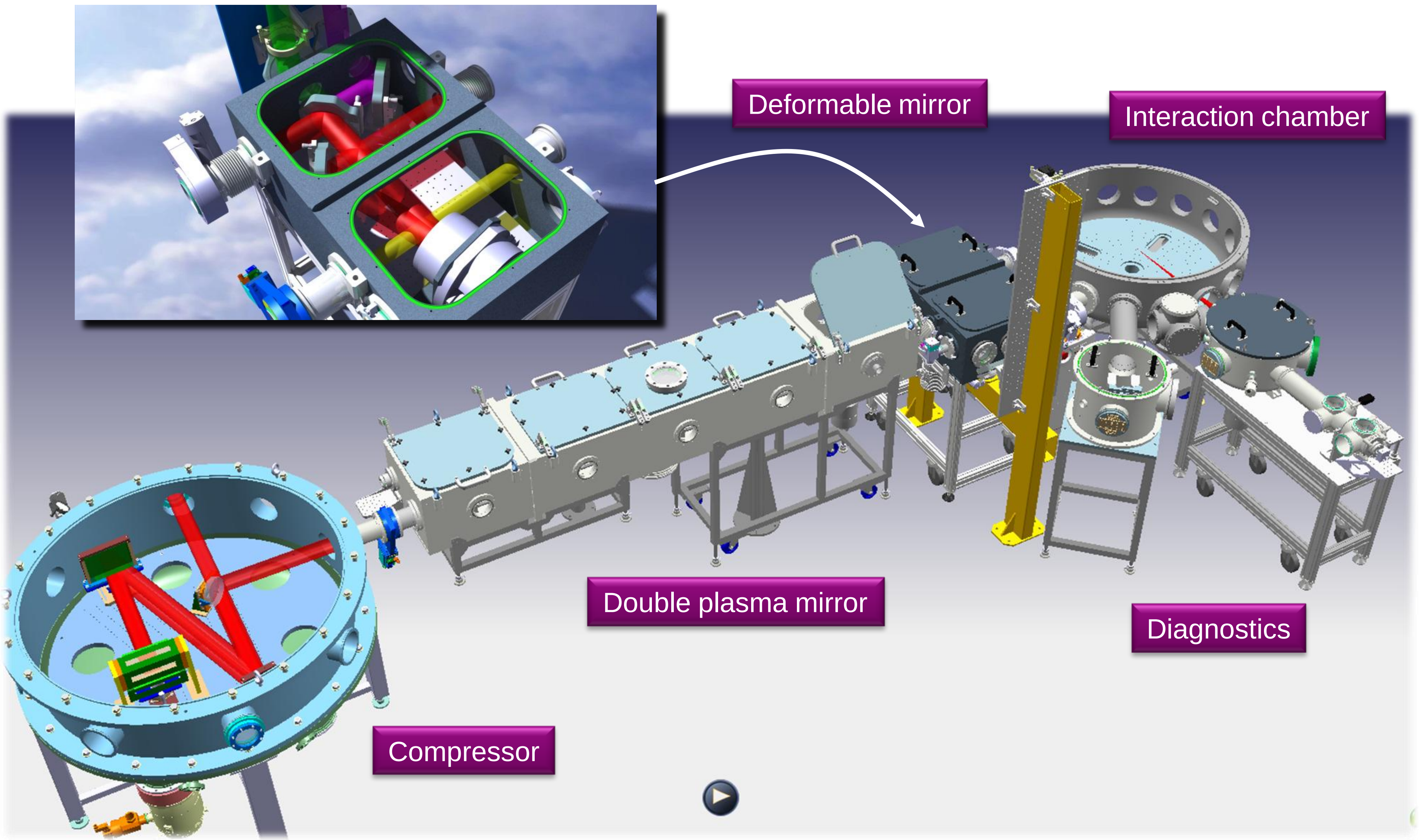


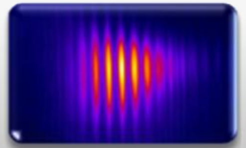
FWHM = 3.5 µm



FWHM = 2.8 µm

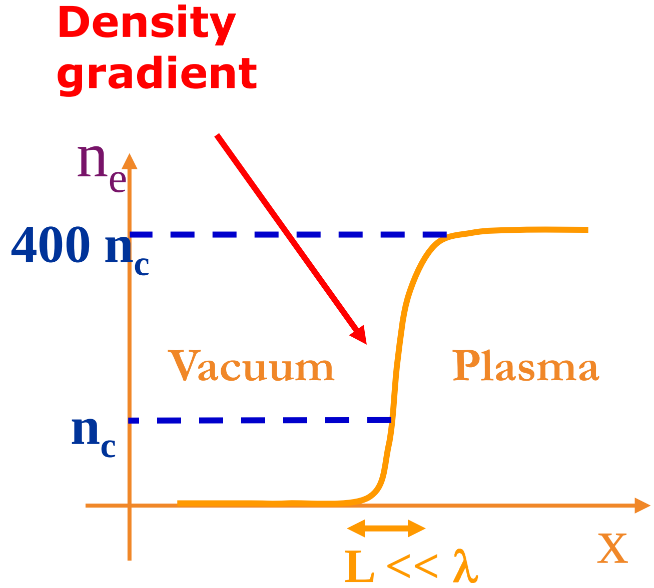
Experimental set-up

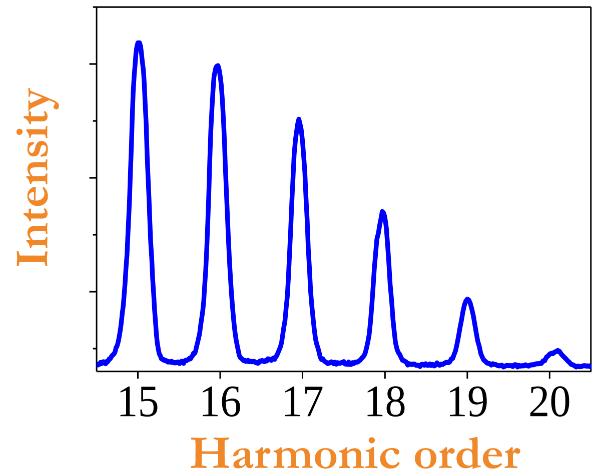


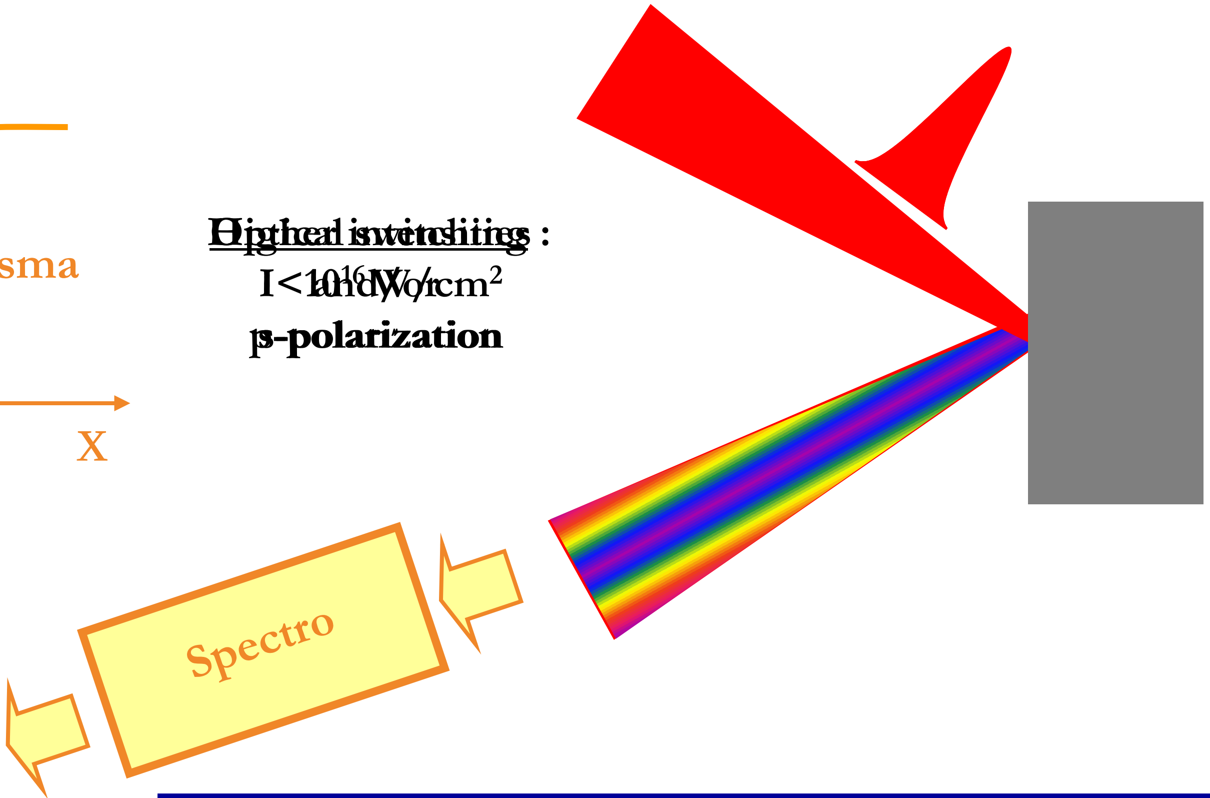


HHG

High order harmonic from solid targets







Motivations

-Understand the underlying physical mechanisms

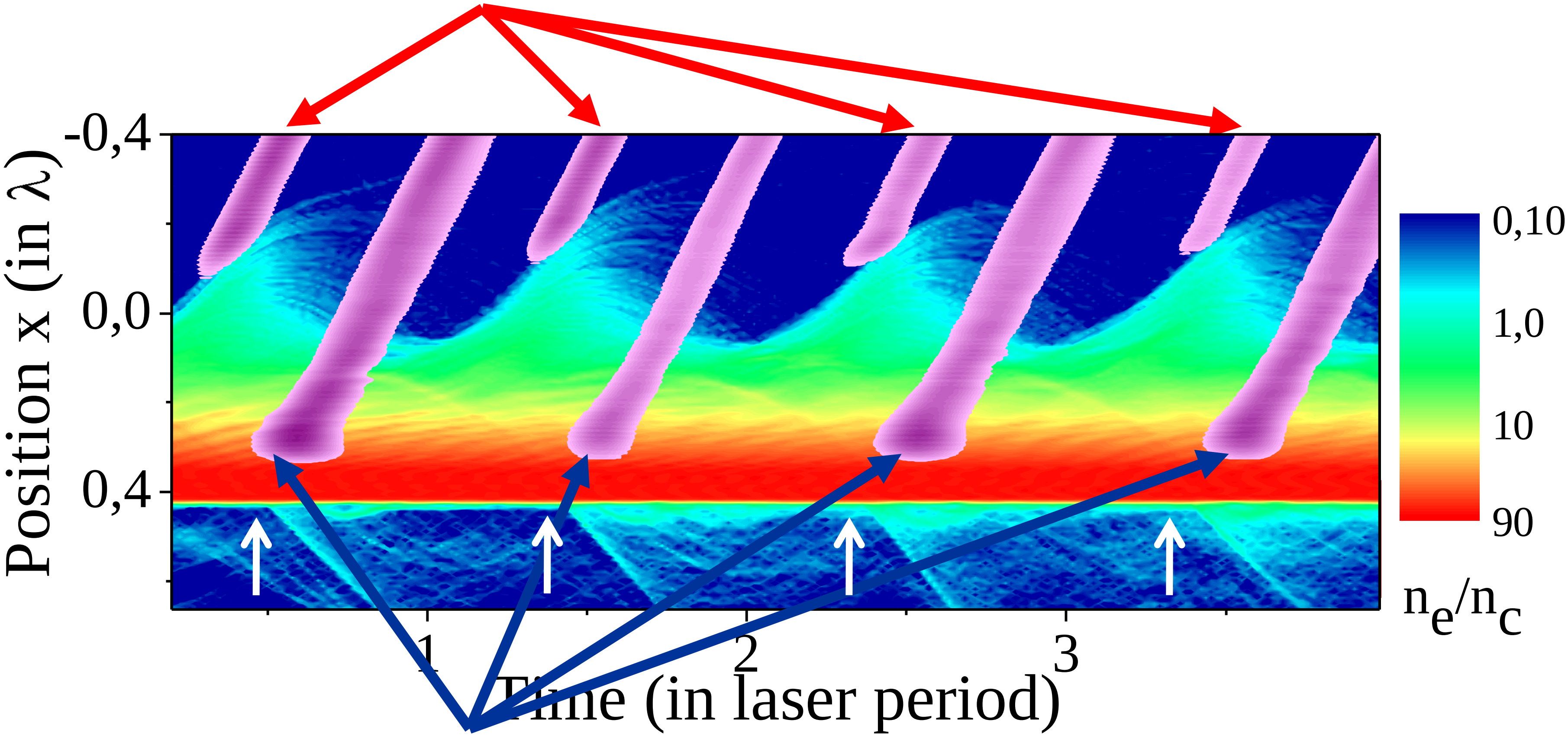
-Radiation source :

Intense ultrashort (fs to as) XUV pulses

Two different mechanisms of HHG on plasma mirrors

Relativistic Oscillating Mirror

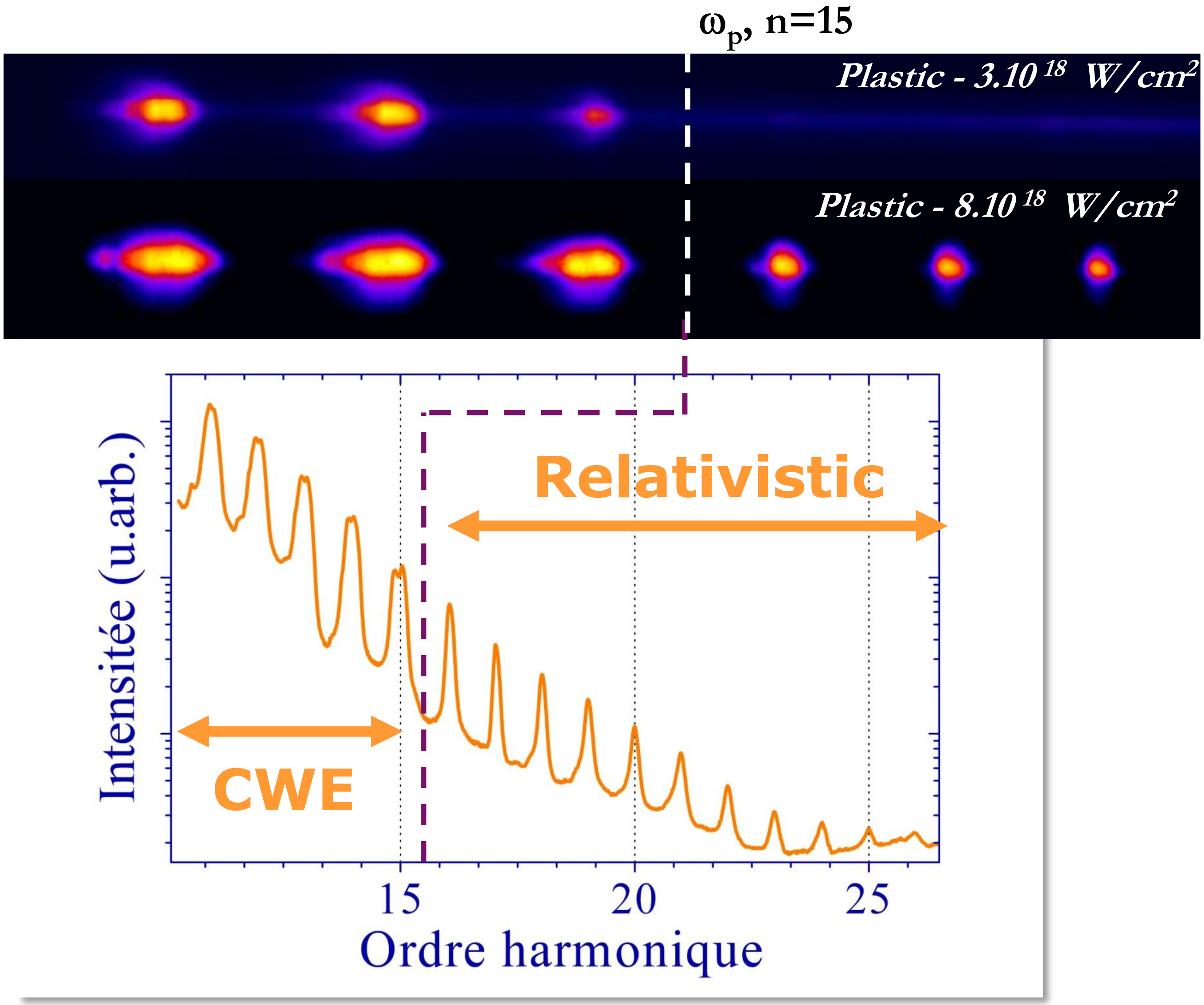
Doppler effect



<u>Coherent Wake Emission</u> : light emission by collective plasma oscillations trigered by Brunel electrons

F. Quéré et al, Phys. Rev. Lett. 96, 125004 (2006)

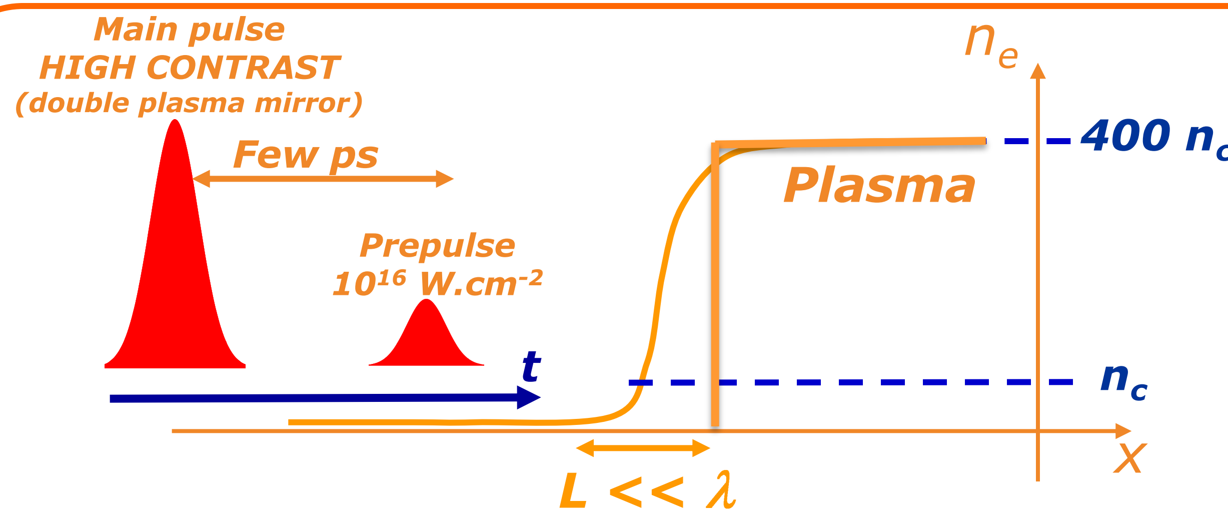
Experimental evidence : relativistic harmonics



C. Thaury et al, Nature Physics **3**, 424 (2007)

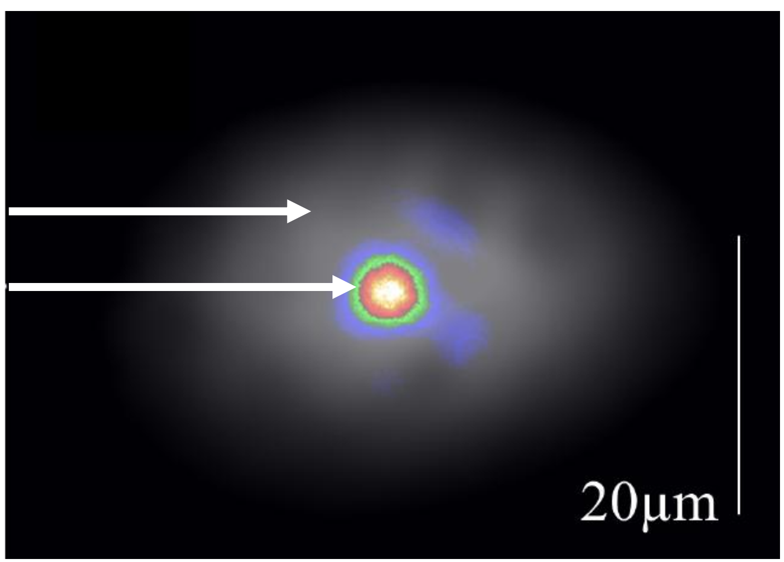
Control and measurement of the density gradient

UHI100 laser
25 fs- 2 J
CEA Saclay



Prepulse focal spot

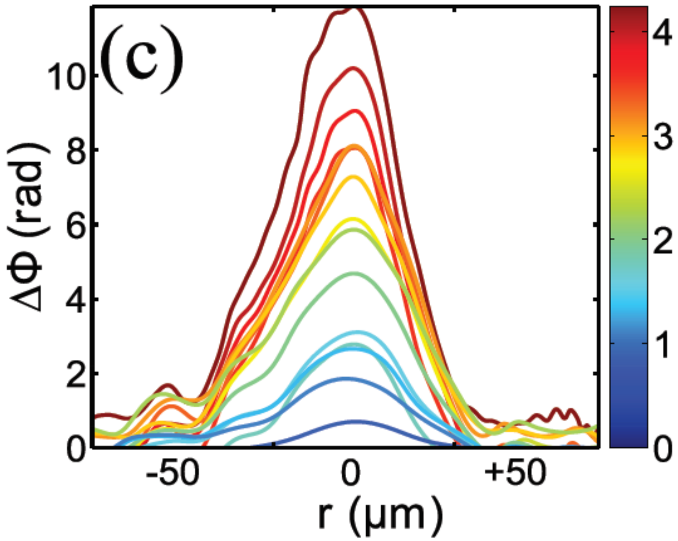
Main pulse focal spot

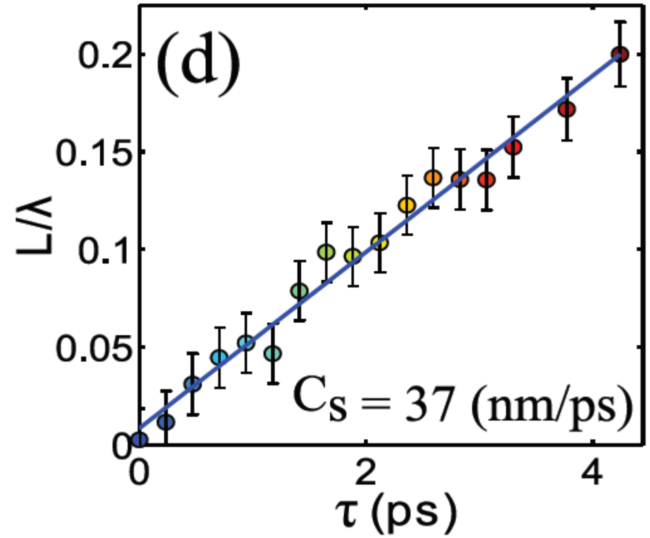


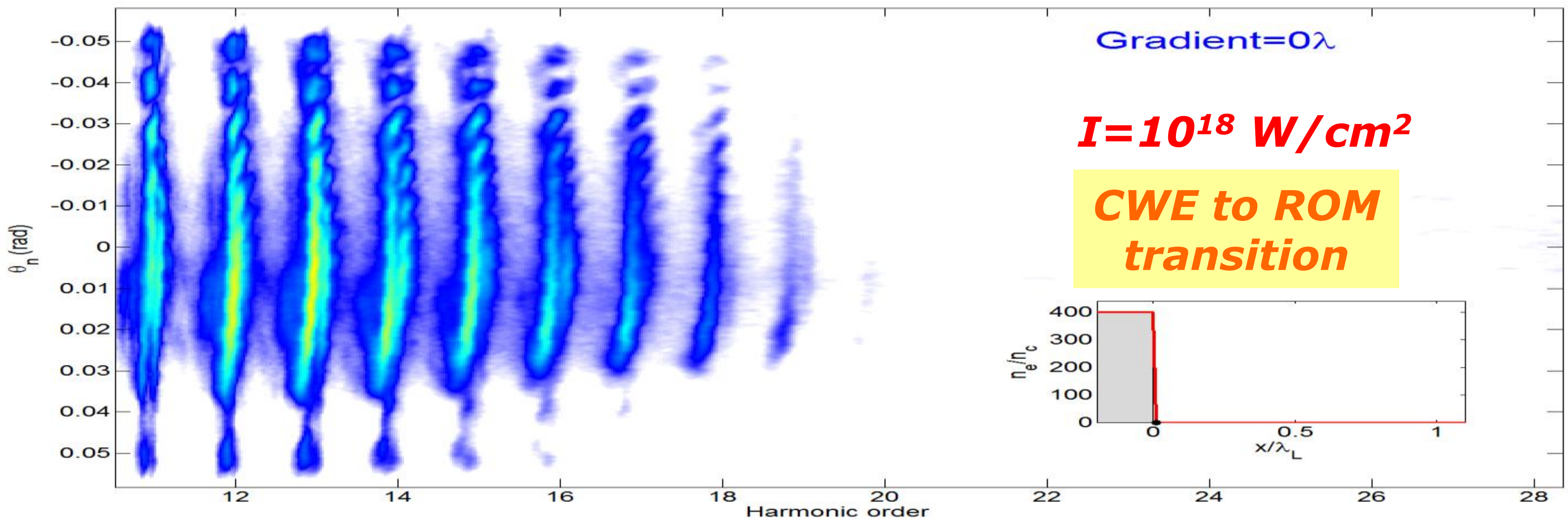
*S. Kahaly et al, PRL **110**, 175001 (2013)*

Control and measurement of the density gradient

FDI measurements of the gradient created by the prepulse

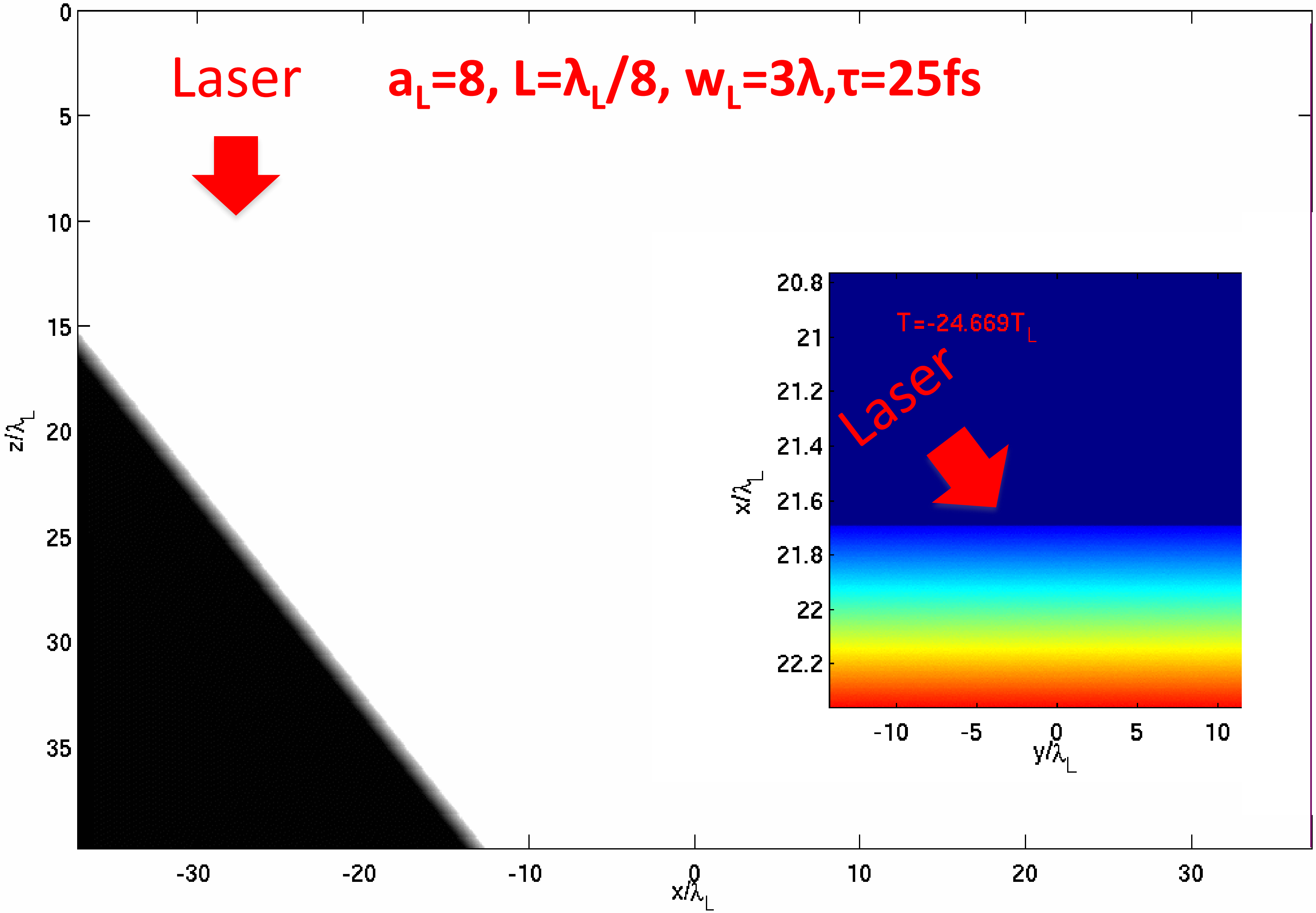






S. Kahaly et al, PRL ***110****, 175001 (2013)*

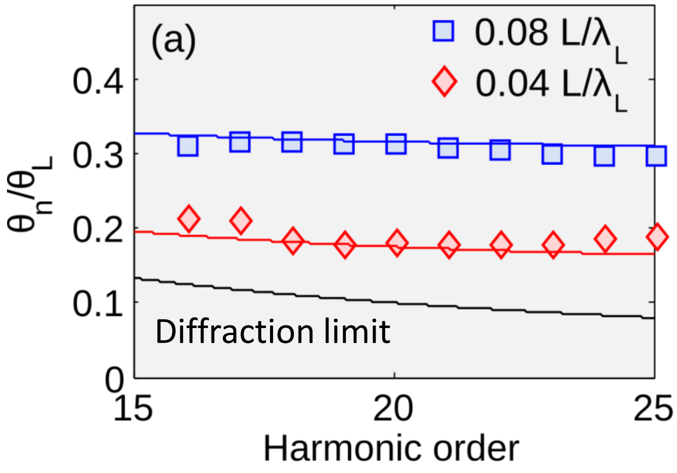
Focusing by laser-induced plasma mirror curvature



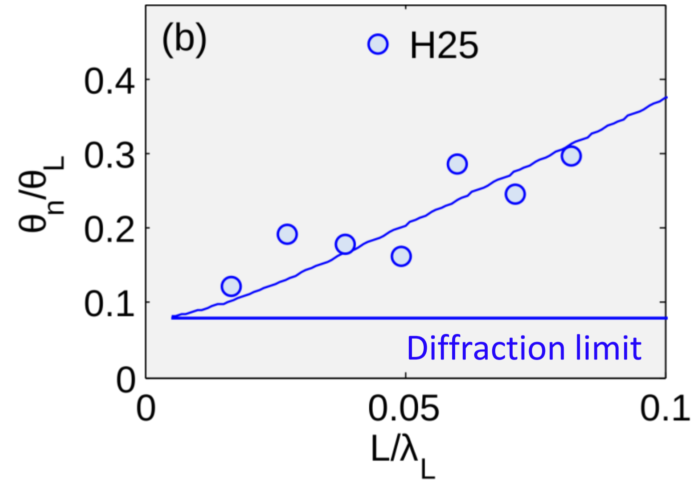
Experiment vs model

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



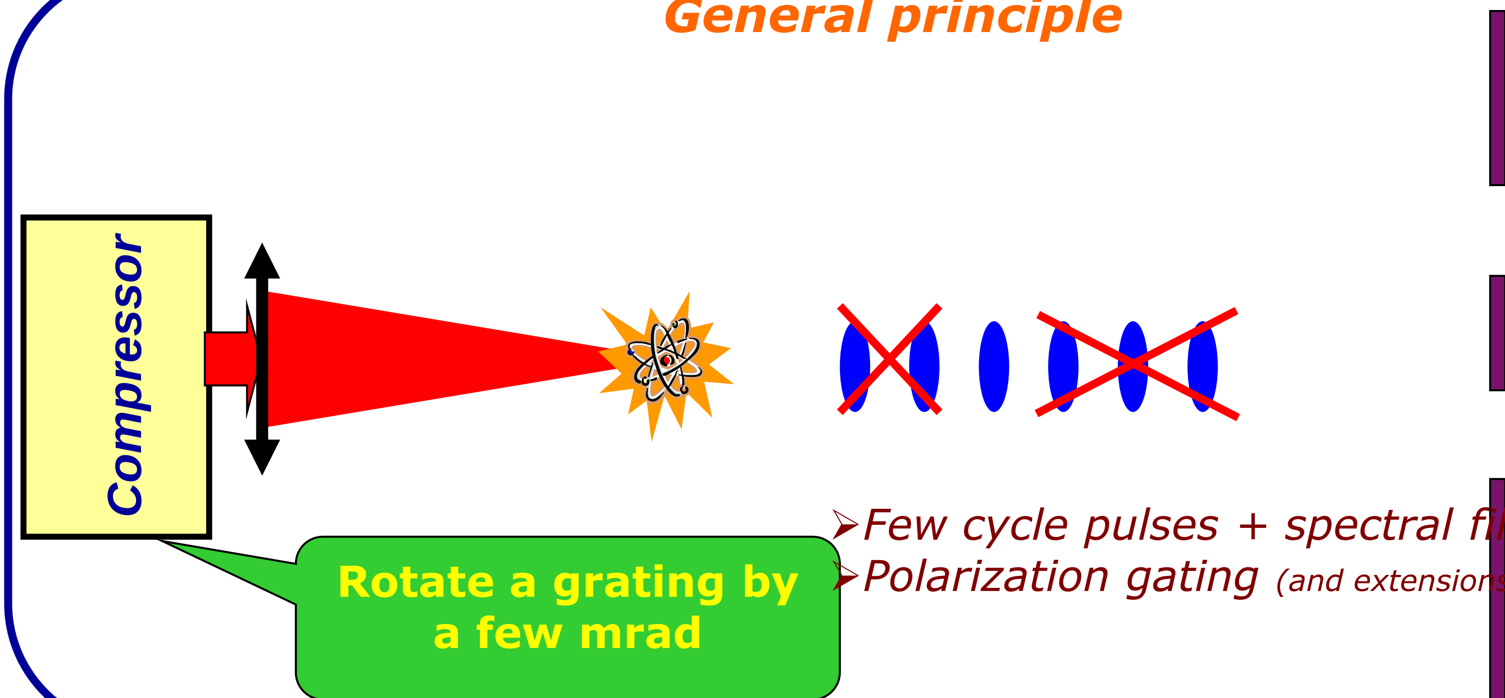
Divergence vs density gradient L



H. Vincenti et al, submitted (2013)

Attosecond lighthouses

General principle



$$\theta_n / \theta_L \leq 1/\alpha p N_c$$

θ_n = divergency of $n\omega_L$ harmonic beam
θ_L = divergency of laser beam
N_c = optical cycles in the driving-laser pulse
p = attosecond pulses generated every laser optical cycle

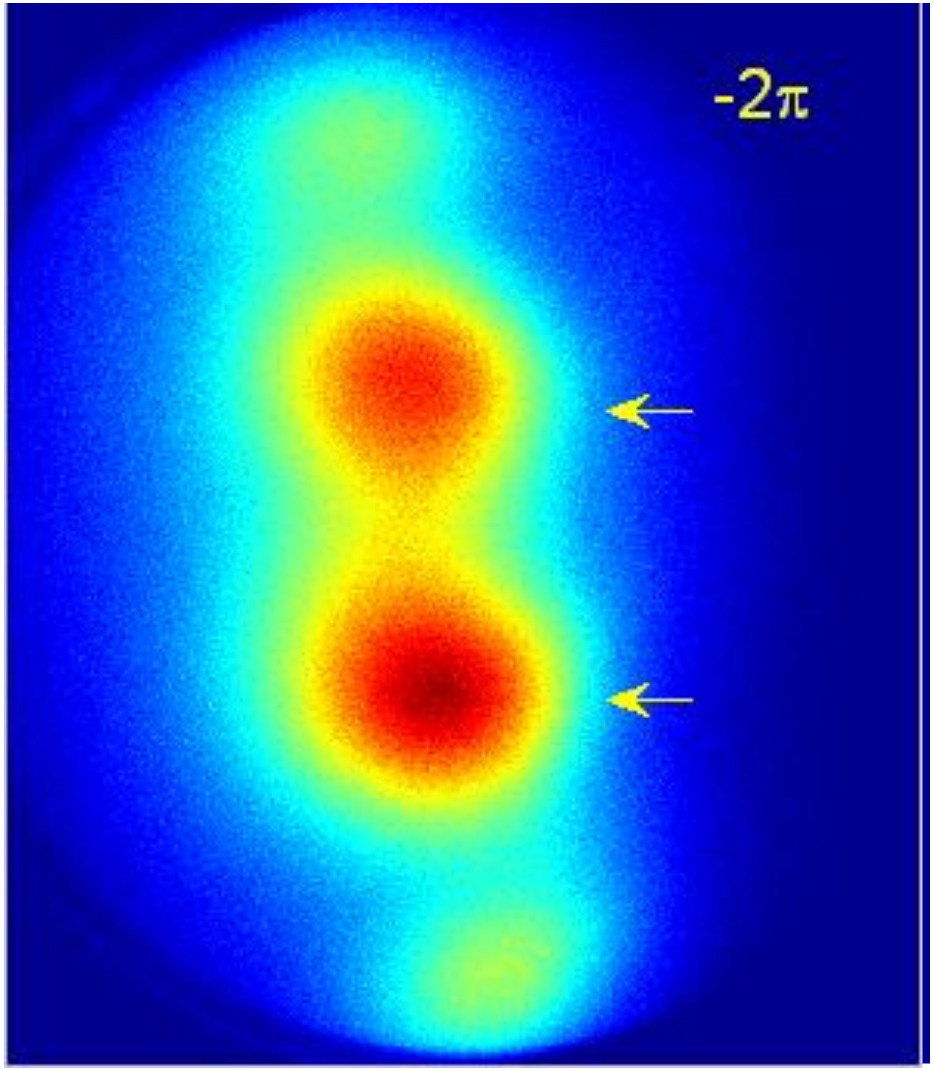
Benefits

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

H. Vincenti and F. Quéré, PRL ***108****, 113904 (2012)*

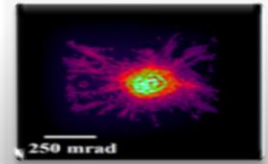
Experimental demonstration (collab. LOA)

Footprint of the XUV beam in the far field



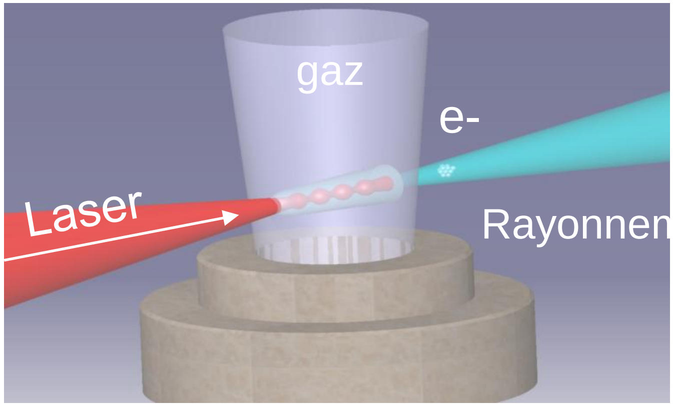
Single attosecond pulses from plasma mirrors <u>at kHz rep rate</u>

J. Wheeler et al., Nature Photonics ***6****, 829–833 (2012)*



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**
- $\omega_p^{-1} \approx \tau$ ➡ **large amplitude plasma wave in the wake of the laser pulse** travelling @ $v_{ph} = v_g$ ***laser***

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

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

- ***Radiotherapy***
- ***Femtosecond radiolysis***
- ***XFEL***
- ***Ultrashort and sub-mm γ-ray sources***
- ***Fast ignitor***
- ***Pump-probe experiments***

Properties of electron bunches

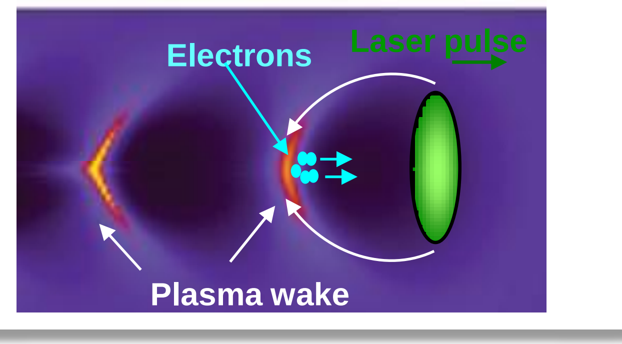
The « Bubble regime » :

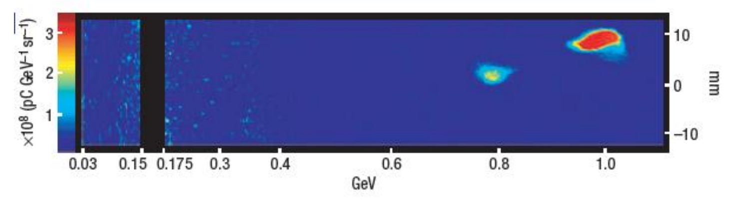
$$a_0 = \frac{eE_L}{m_0 c \omega_L} = 0.85 \left(\frac{\lambda_L}{\mu m}\right) \left(\frac{I_L}{10^{18}\, W/cm^2}\right)^{1/2} >> 1$$

- radial dimension = longitudinal dimension $<\lambda_p$
- injection at c^{ste} phase
- $a_0=(\omega_0/\ \omega_p)^{2/5}$ Laser pulse self-focusing
- $k_pR=k_pw_0=\sqrt{a_0}$ Bubble formation
- $\tau c=2\ w_0/3$ $L_{deph}=L_{abs}$
- signature : monoenergetic spectra

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

Pukhov and Meyer-Ter Vehn, 2002





Nature Phys. (2006)

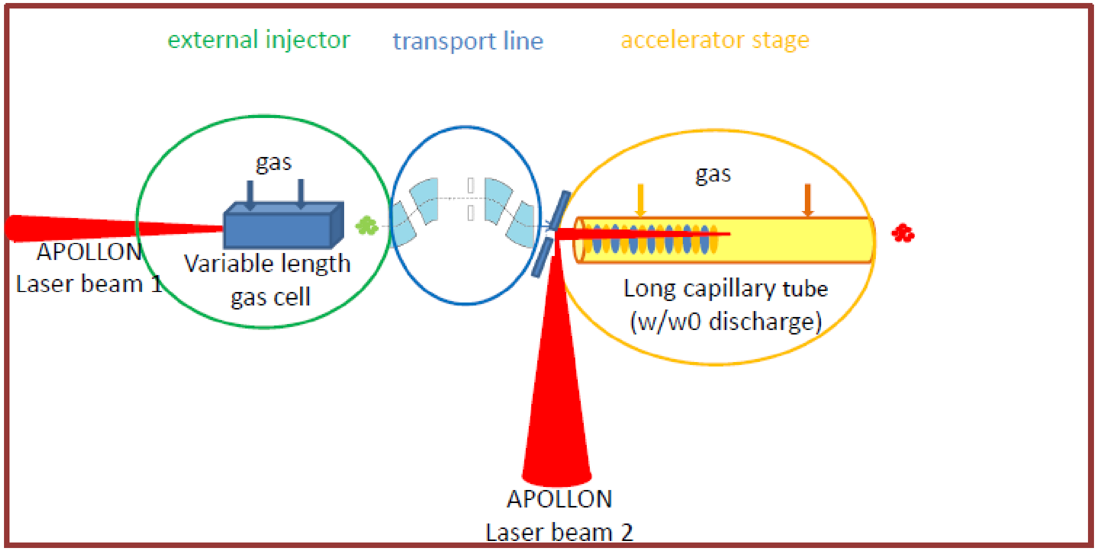
Properties of electron beams :

- ➢ electrons of 100's of MeV up to GeV
- ➢ low divergence (~ mrad)
- ➢ short duration ($<\tau_{laser}$)
- ➢ Charge : several nC

	UHI100	LUIRE	APOLLON-10P
E	3 J	15 J	150 J
a_0	4	4.5	5.6
w_0	13 μm	21.5 μm	40 μm
τ	30 fs	48 fs	90 fs
n_0	2.5×10^{18} cm^{-3}	10^{18} cm^{-3}	4×10^{17} cm^{-3}
L_{deph}	6.5 mm	2.3 cm	11 cm
E	1 GeV	2.5 GeV	8.5 GeV
Q	0.4 nC	0.7 nC	1.6 nC

Towards higher energies….

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



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

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

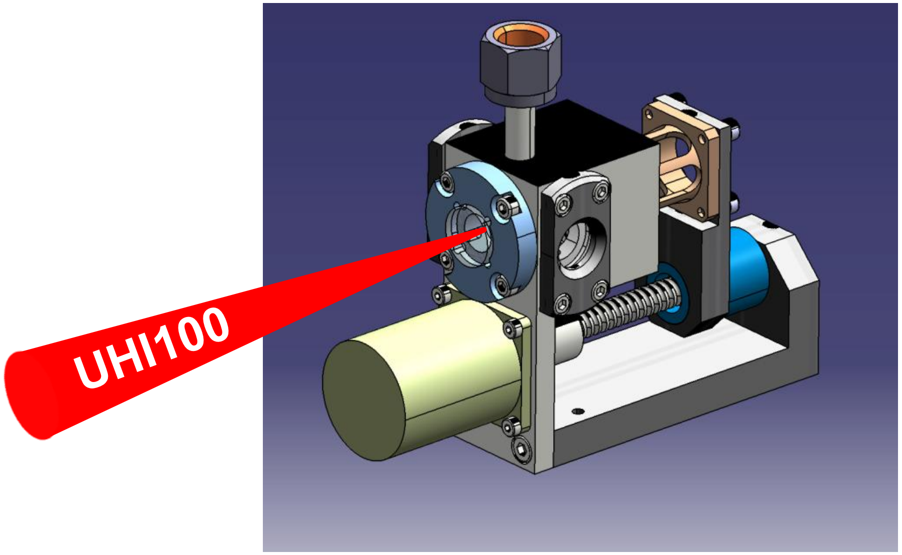
Project: set up and study an electron source as an external injector into the accelerator stage

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:

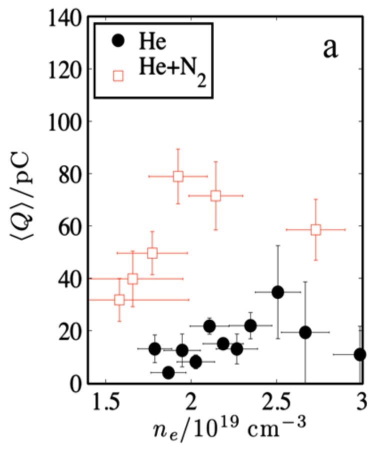


- gas cell → stability
- ΔL → Vary the E
- différential pumping → reduce the density gradients at entrance/exit of the injector
- gas mixture (several % of impurities) → Electron trapping control

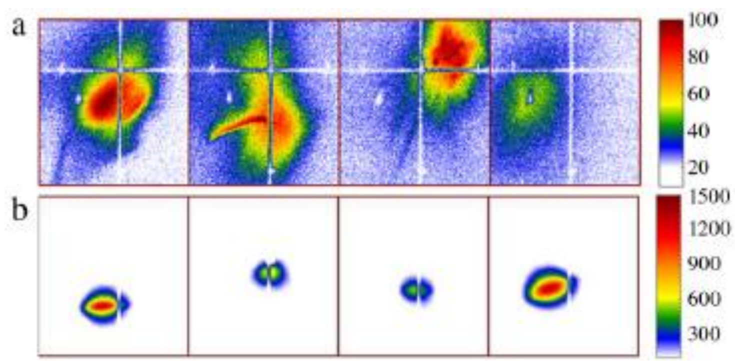
Ionisation injection

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

- Experimental results



Pur He



He +1% Ar

increasing of the electron bunch charge of 1 order of magnitude
and decreasing of the beam divergence by a factor of 2 compared to pur He

- ***Theory of ionization-induced trapping in laser-plasma accelerators***
  M. Chen, E. Esarey,a) C. B. Schroeder, C. G. R. Geddes and W. P. Leemans, PoP, 2012

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

C. Mc Guffey , Phys. Rev. Lett. ***104****, 025004 (2010)*

Research axis on LPA

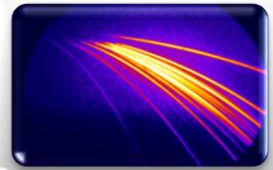
- Generation of a reproducible, stable and controlable LPA as injector for 2-stage LPA

  EquipeX CILEX on APOLLON-10P

And also ….

- Harmonic generation in the laser propagation axis

- Spatio-temporal caracterisation of the laser pulse → pulse compression by propagation through the plasma

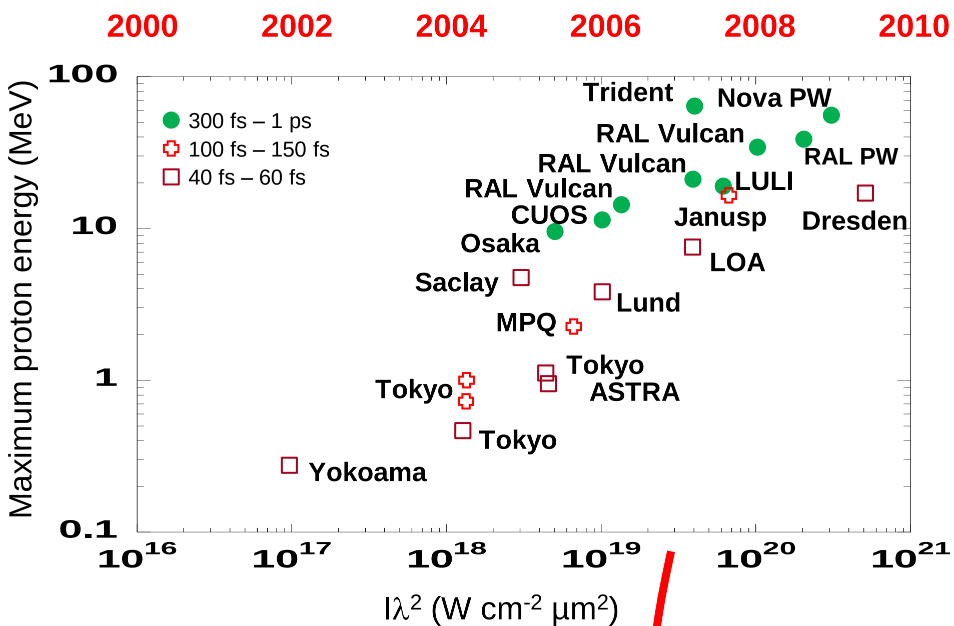


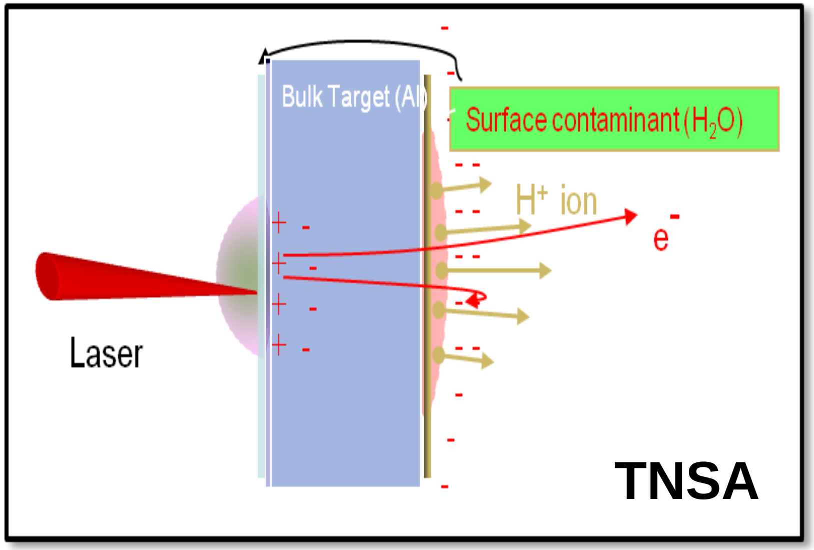
PROTON ACCELERATION

Laser driven ion acceleration: the TNSA mechanism

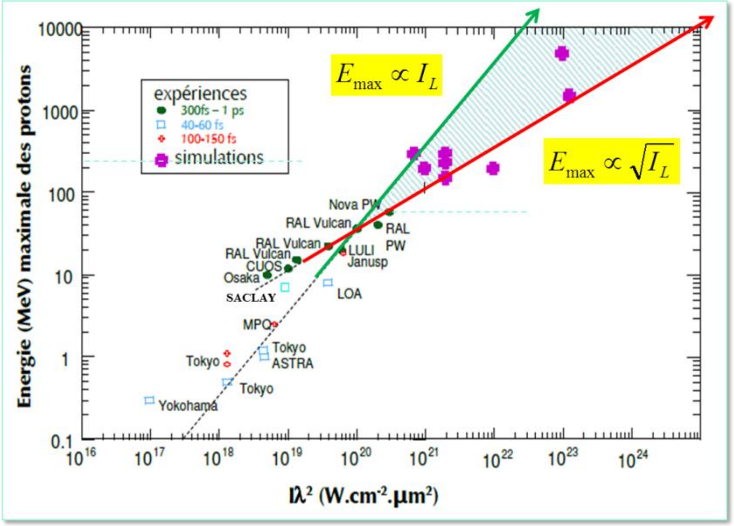
"…turning a light beam into a matter beam"

> 10 years of intense and ever-increasing research





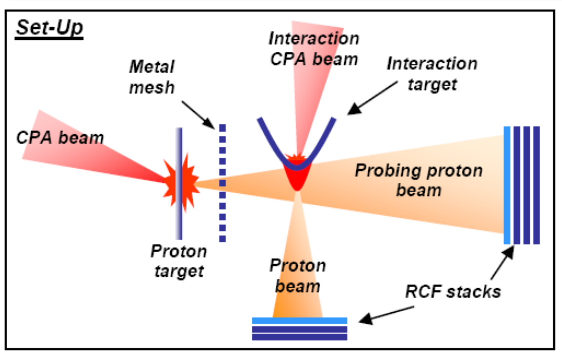
- Short duration ~ ps
- Divergence ~ 10
- Laminarity
- Emittance ~ 0.002 π mm mrad
- Energy ~ dozens of MeV
- Flux ~ $10^{11\text{-}13}$ (E > 3 MeV)

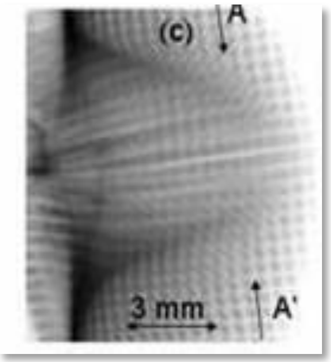


S.C. Wilks et al., Phys. of Plasmas ***8****, 542 (2001)*

Applications

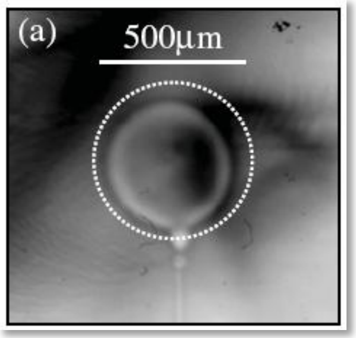
Probing electric fields in plasma





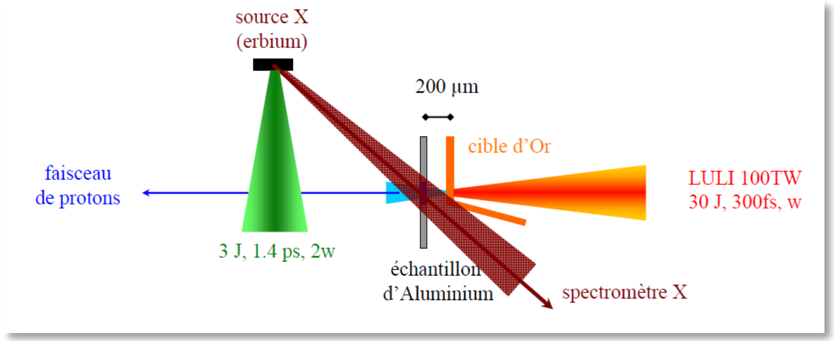
*L. Romagnani et al, PRL **95,** 195001 (2005)*

Probing dense plasmas



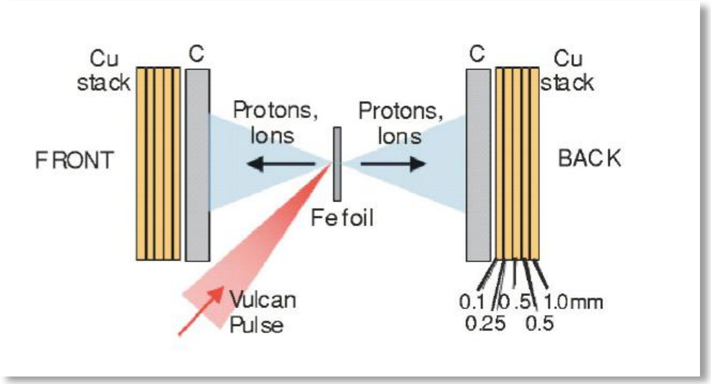
*A. J. Mackinnon et al, PRL **97**, 045001 (2006)*

Isochoric heating



*A. Mancic et al., Phys. Rev. Lett. **104**, 035002 (2010)*

Medical isotopes production



*McKenna et al. PRE **70**, 036405 (2004)*

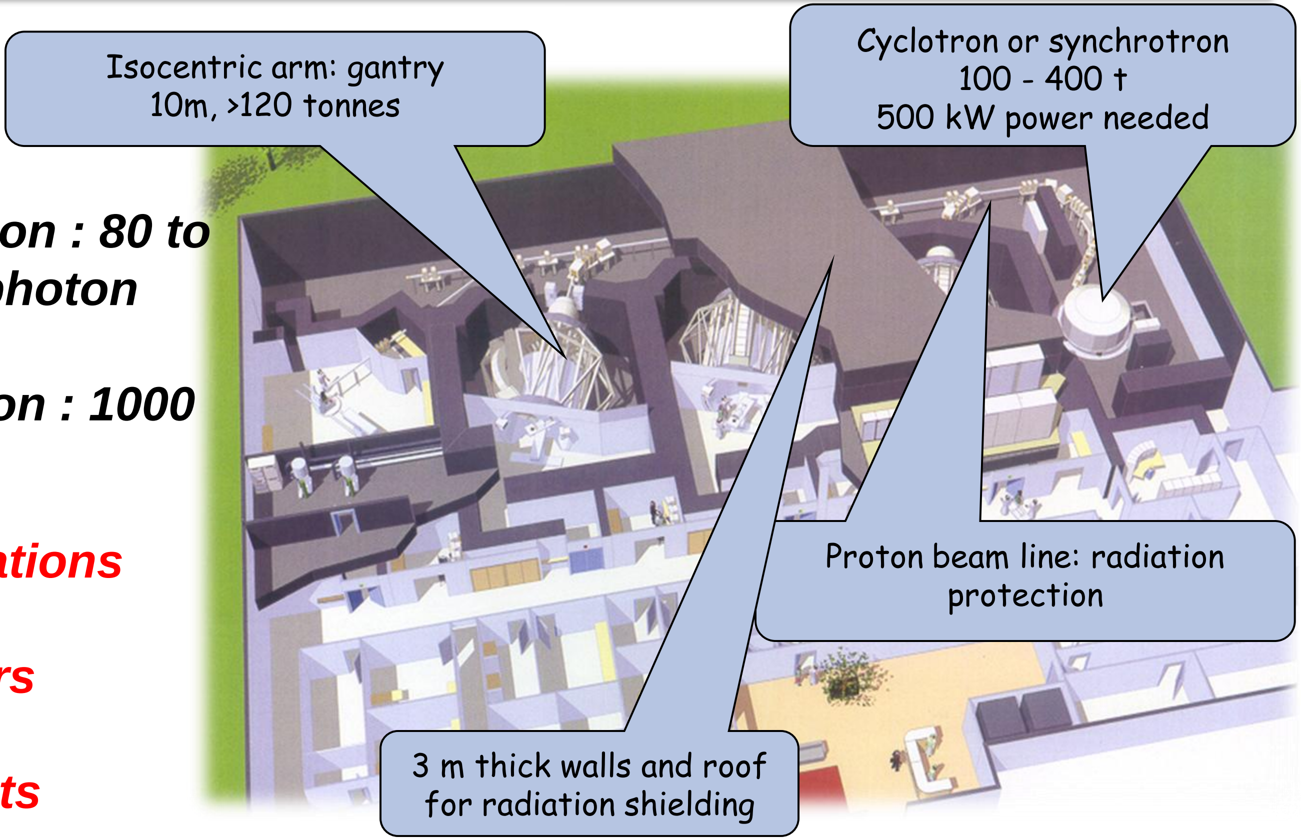
Applications : proton therapy – some numbers

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



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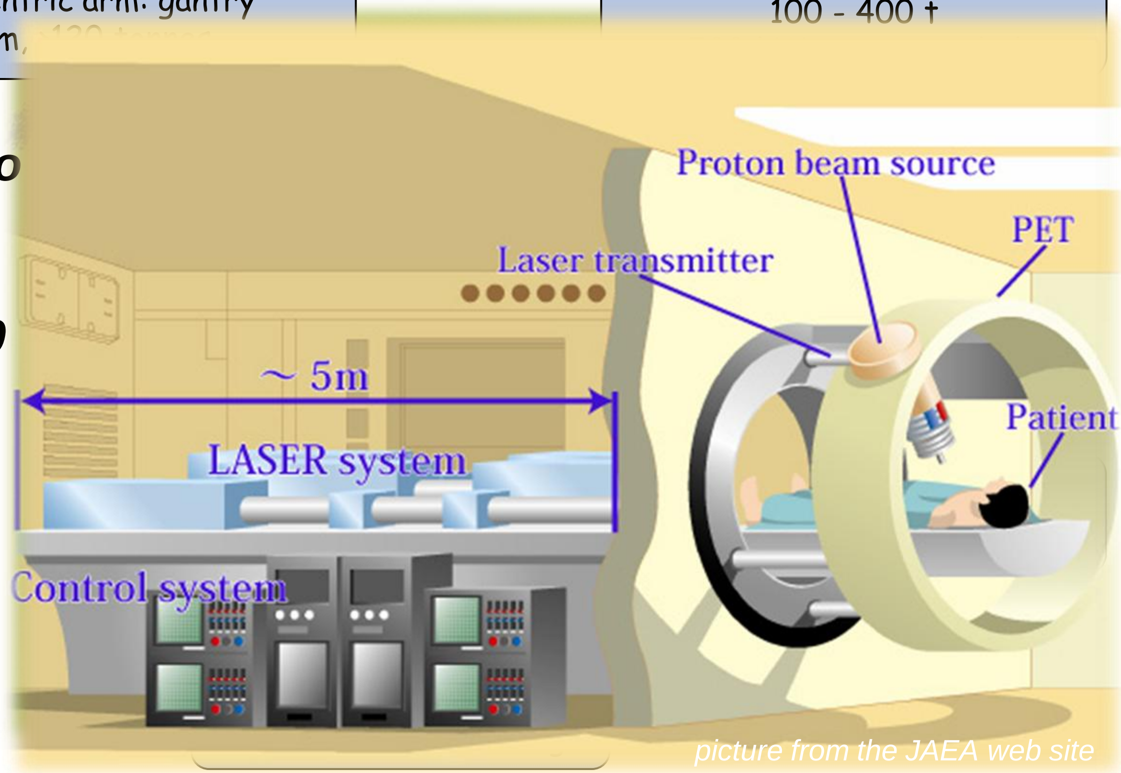
Isocentric arm: gantry
10m,

Cyclotron or synchrotron
100 - 400 t



picture from the JAEA web site

– ***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

The SAPHIR consortium on laser-driven protontherapy

SAPHIR: **S**ource **A**ccélérée de **P**rotons par laser de **H**aute **I**ntensité pour la **R**adiothérapie (***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

Increasing E_{max}

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

Spectrum tailoring

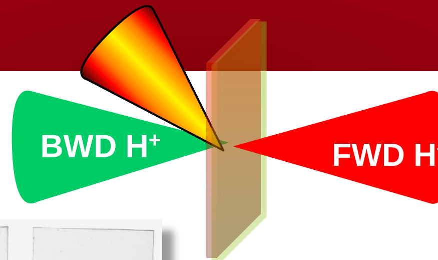
- RPA
- Engineered targets

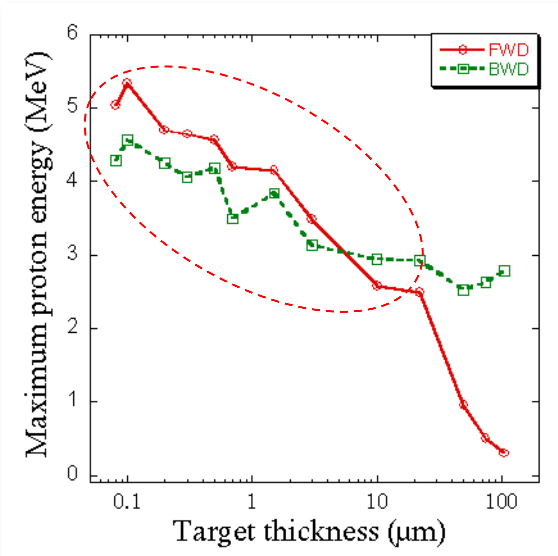
Divergence tailoring

- Laser-driven microlens
- Engineered targets

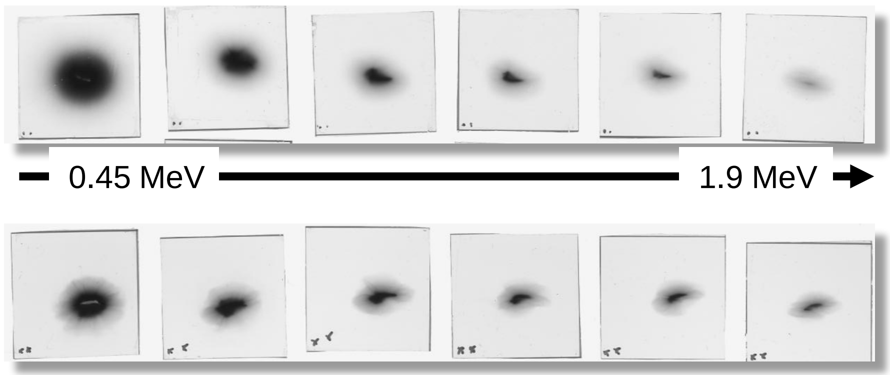
- Upstream study of main physical mechanisms in proton acceleration
- Setting scaling laws
- Exploration of new acceleration mechanisms

Proton emission under UHC conditions

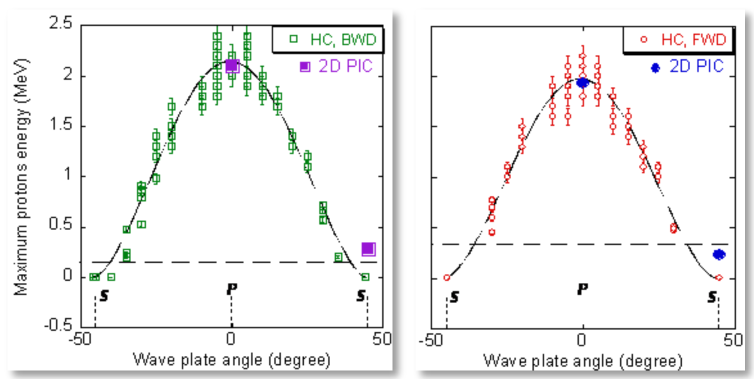




BWD



FWD



- E_{max} FWD ≈ E_{max} BWD
- θ FWD ≈ 0.7 * θ BWD
- Flux FWD ≈ Flux BWD
- Laminarity FWD and BWD
- Emittance FWD ≈ Emittance FWD

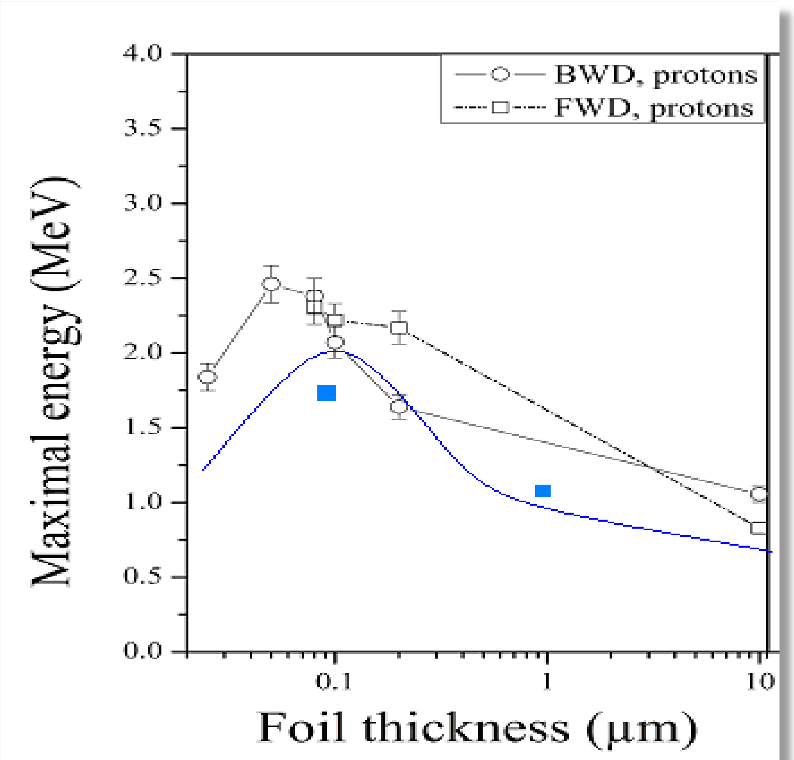
  ≈ 0.1 π*mm*mrad

Heating mechanism: Brunel effect

Quasi-symmetrical acceleration
TNSA model applies to both sides

T. Ceccotti et al., Phys. Rev. Lett., ***99****, 185002 (2007)*

Ultra thin targets @ ultra high contrast: an analytical model



A Andreev et al, Phys. Rev. Lett. ***101****, 155002 (2008)*

- 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

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

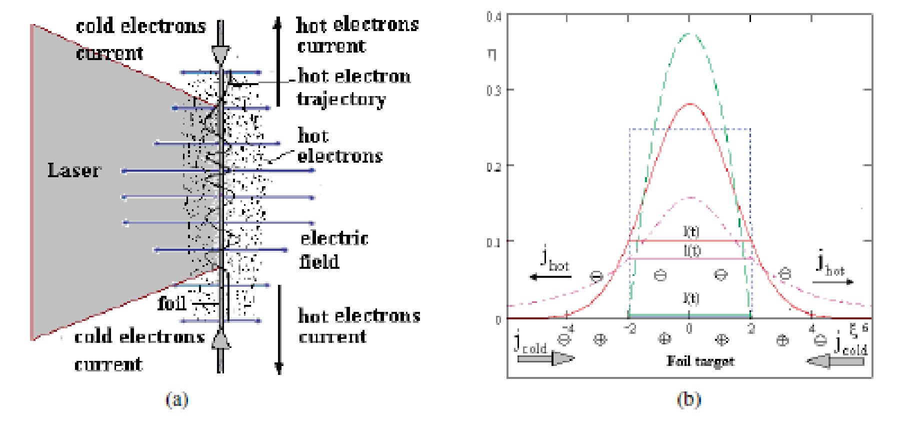
$$\varepsilon_{i\max_{1,2}} \approx \frac{3\pi Z_{1,2} e^2 (Z_2 n_{i_2} \ell_{i_2} \pm Z_1 n_{i_1} \ell_{i_1}) r_{De}}{\sqrt{1+(\ell_{i_2}/r_{De})^2}} + \left(\frac{2\sqrt{2}T_{e_0}}{3^{3/4}} f^{3/2} \pm 4\pi e^2 Z_1 n_{i_1} \ell_{i_1} r_{De}\right) \frac{Z_{1,2}}{\sqrt{1+(r_{De}/\ell_{i_2})^2}}$$

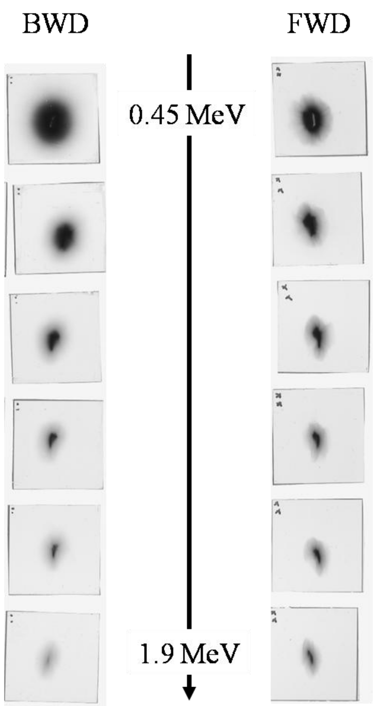
$$\ell_{i_2}^{opt} \approx \lambda_L \frac{n_{cr}}{Z n_{i_2}} \left(5 + I_{18}^{3/4} \left(\frac{t_L}{30\,fs}\right)^{3/4}\right) \left(\frac{Z n_{i2}}{6 \cdot 10^{23} cm^{-3}}\right)^{-1/2}$$

$$\begin{aligned} N_H &= \int_{-\infty}^{-\ell_H} n_{HC}\theta(\varepsilon_{i_1}(z_0) - \varepsilon_{thr}) dz_0 + \int_{-\ell_H}^{0} n_H \theta(\varepsilon_{i_1}(z_0) - \varepsilon_{thr}) dz_0 \\ &= n_{HC}(\ell_s \ln(\varepsilon_{i\max_1}/\varepsilon_{thr} - \ell_H))\theta(\ell_s \ln(\varepsilon_{i\max_1}/\varepsilon_{thr} - \ell_H)) \\ &+ n_H \ell_H \theta(\ell_s \ln(\varepsilon_{i\max_1}/\varepsilon_{thr} - \ell_H)) \\ &+ n_H \ell_s \theta(\ell_H - \ell_s \ln(\varepsilon_{i\max_1}/\varepsilon_{thr})) \\ N_C &= \int_{-\infty}^{-\ell_H} n_C \theta(\varepsilon_{i_2}(z_0) - \varepsilon_{thr}) dz_0 = n_C(\ell_s \ln(\varepsilon_{i\max_2}/\varepsilon_{thr} - \ell_H)) \\ &\times \theta(\ell_s \ln(\varepsilon_{i\max_2}/\varepsilon_{thr} - \ell_H)) \end{aligned}$$

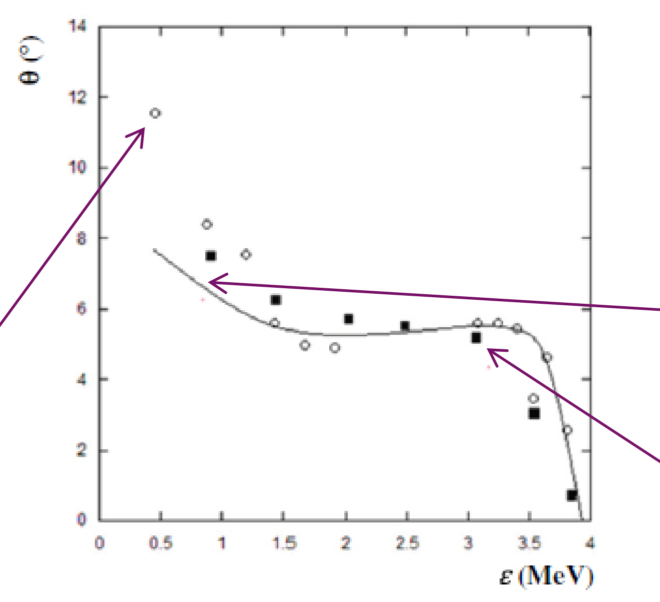
Ion beam divergence @ ultra-high contrast

Lateral expansion of the fast electron cloud during the ion acceleration





Experimental data



Deviation of the traveling ions from the target normal

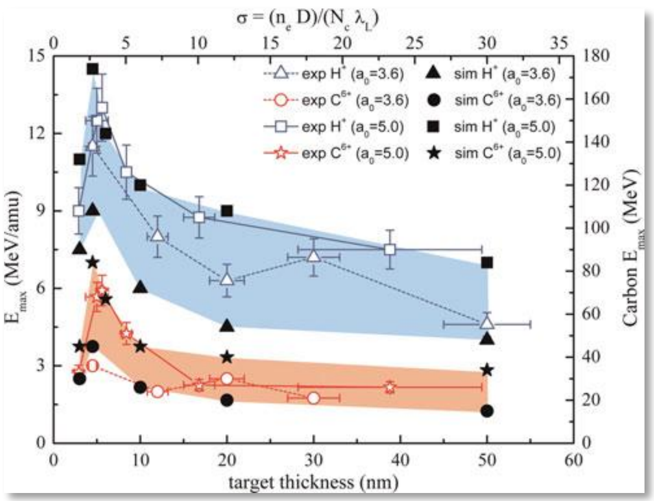
Analytical model for the divergence of fast ion beams

+

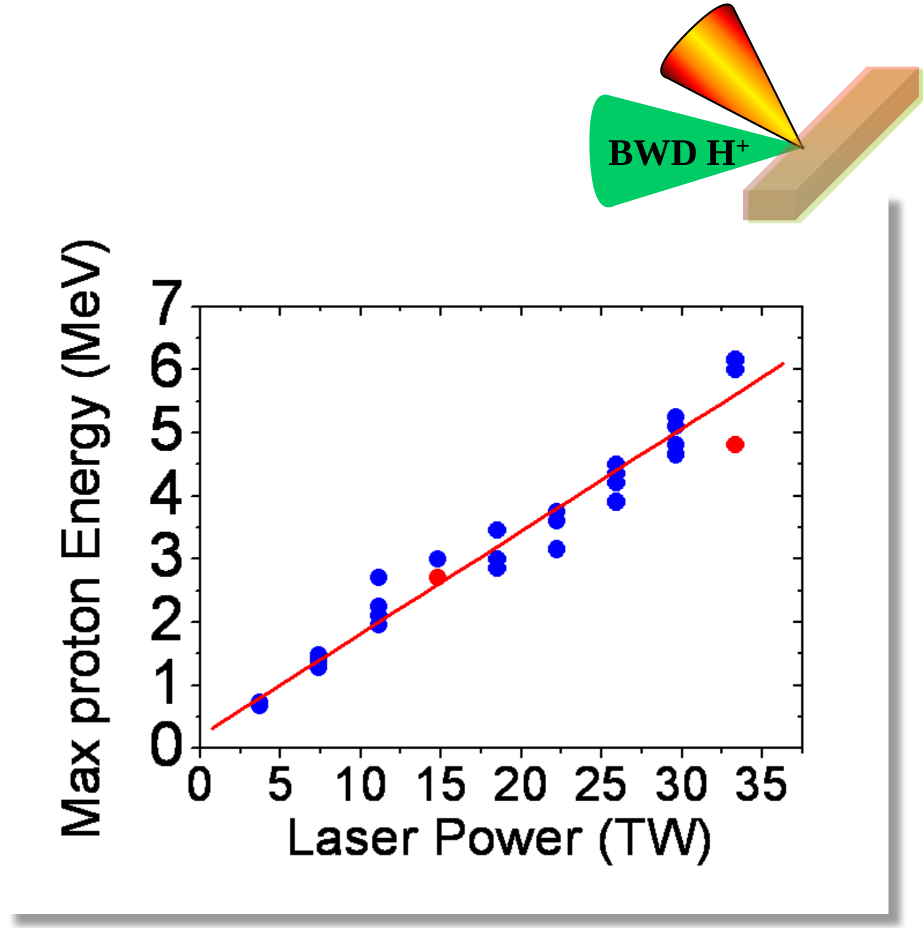
2D PIC simulations

A.Andreev, et al, New J. Phys. **12** 045007*(2010)*

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



*Steinke et al., Las. Part. Beams, **28**,215(2010)*



100 MeV protons → 500 TW @ UHC

*M. Passoni et al, AIP Conf. Proc. **1153**, 159 (2009)*

Engineered targets on UHI100: I - foam targets

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

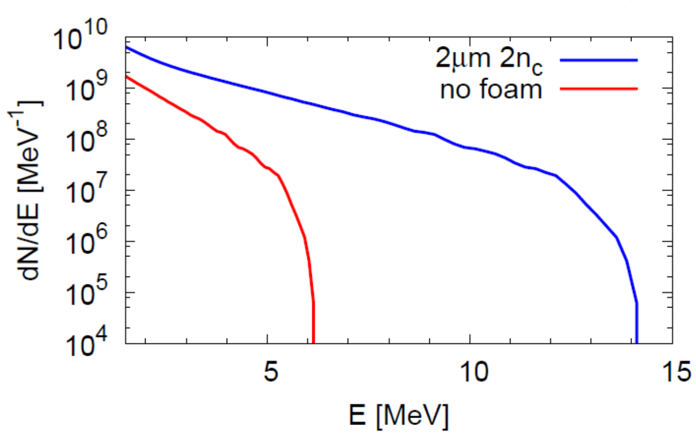
"Advanced" TNSA regime

multilayered targets: thin solid foil + low-density layer

Interest in <u>"intermediate", near critical conditions</u> $n_e \sim n_c$

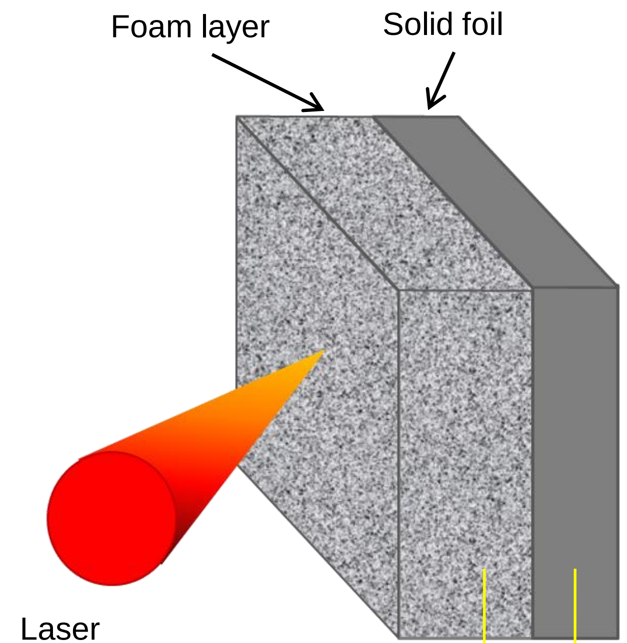
Scalings predicts more efficient absorption and fast electron generation

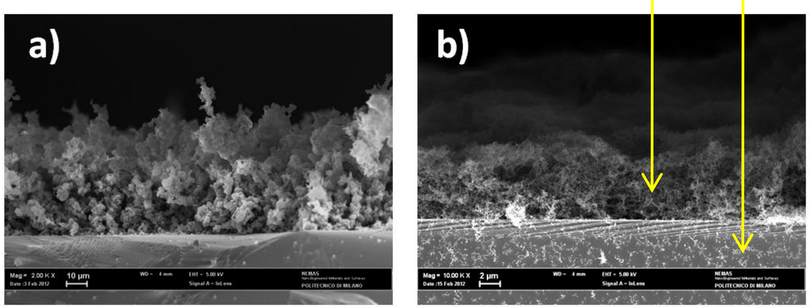
$P = 32\,TW$ $\tau = 25fs$ $w_0 = 3\mu m$ $U = 0.8J$ $I = 3.4\,10^{20}\mathrm{W/cm^2}$ $(a_0 = 10)$



- exponential with a cut-off (like TNSA)
- thin foam ($l_f = 2\mu m$, $n_f = 2n_c$)
  $\Rightarrow$ cut-off energy increased by a factor ~ 2.5!

$\rightarrow$ **Sgattoni** *et al* **PRE 85, 036405 (2012)**



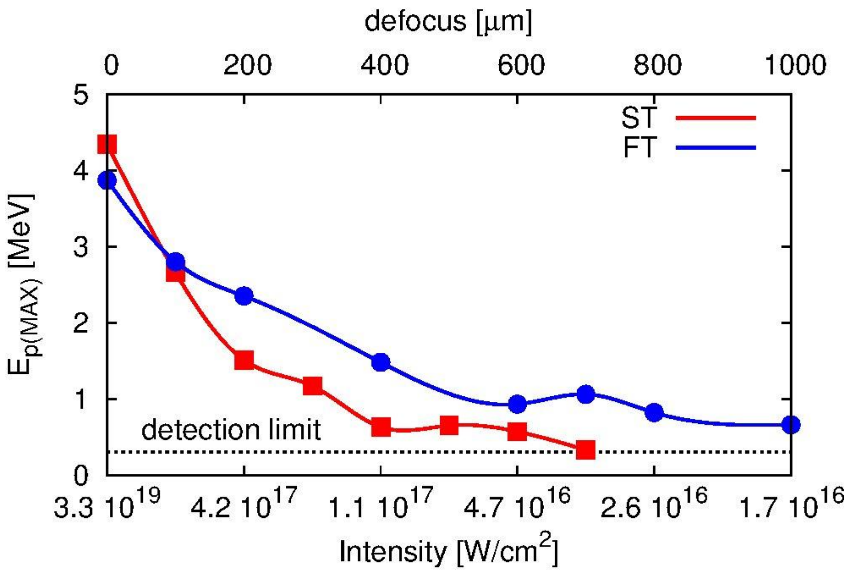


@NANOLAB POLIMI: ***Pulsed Laser Deposition***

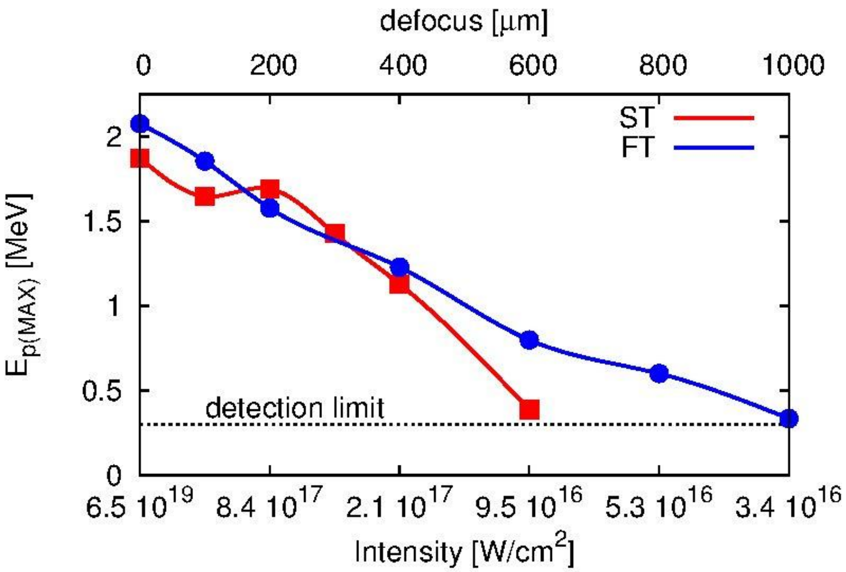
Nanostructured Carbon ***grown*** on aluminium

Engineered targets on UHI100:
I - foam targets

High Contrast
Al 1,5 μm + foam ~10 μm



Low Contrast
Al 10 μm + foam ~ 23 μm

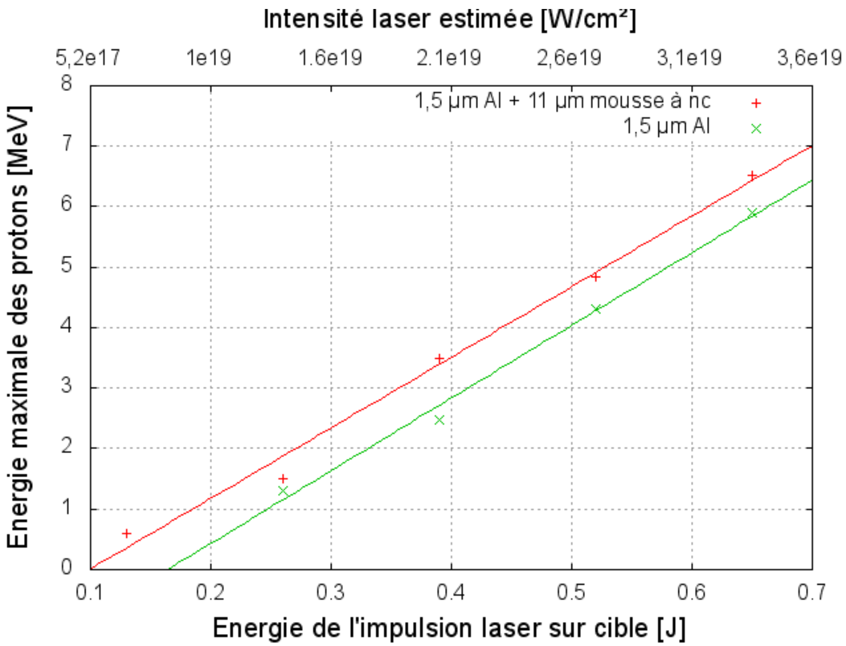


At HC and LC , FT similar to ST at maximum focalization / intensity

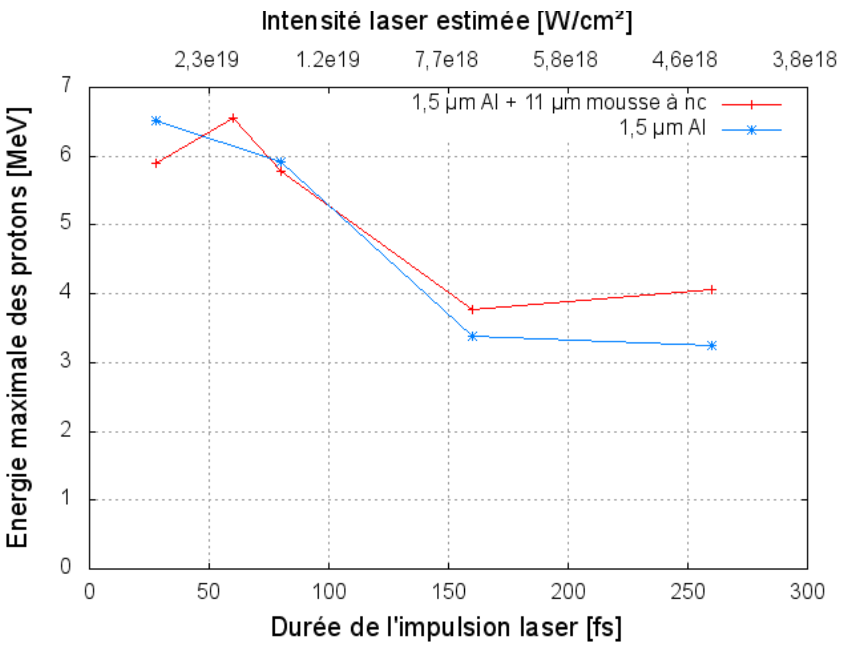
At low intensities, FT energies > ST energies

Engineered targets on UHI100:
I - foam targets

Energie de l'impulsion variable



Durée de l'impulsion variable



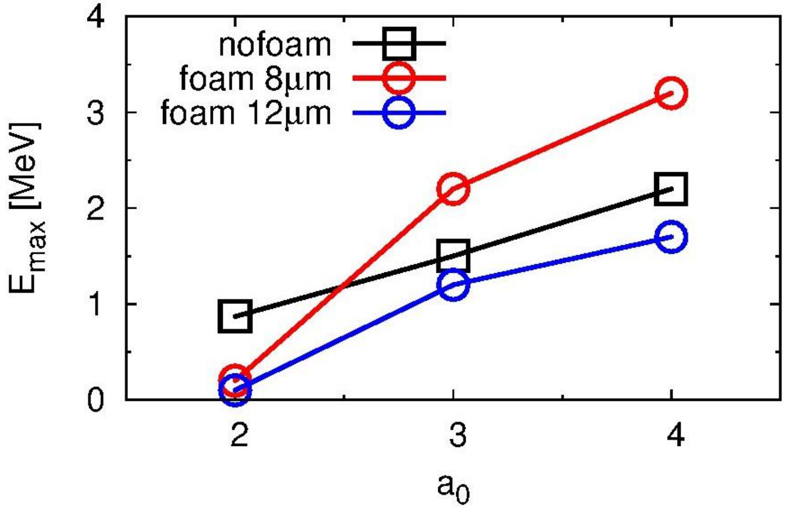
Comportement similaire pour des cibles simples et des cibles mousse si :

variation de l'intensité = variation de l'énergie ou de la durée de l'impulsion

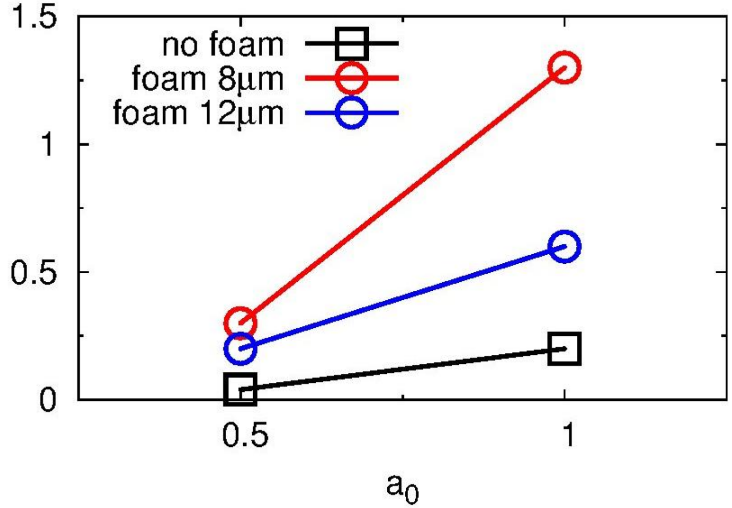
Engineered targets on UHI100:
I - foam targets

2D-PIC simulations (ALaDyn)

Foam total ionization
$n_e=2n_c$



Foam partial ionization
$n_e=0.66n_c$



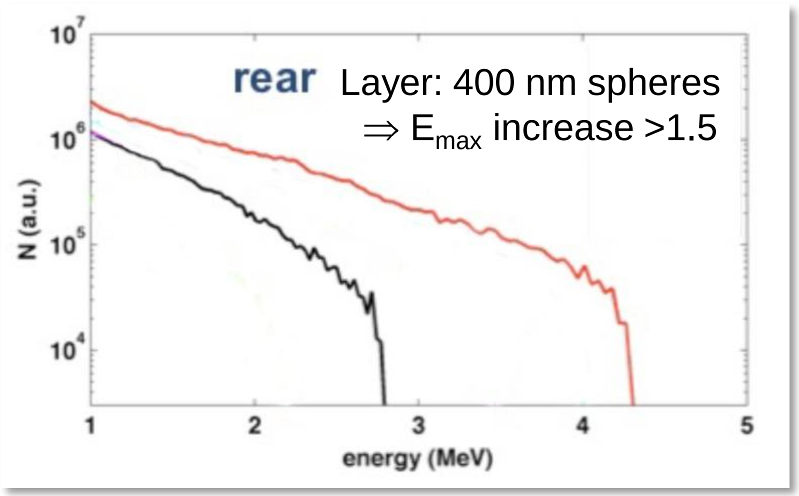
Underdense foam
considerable advantage
over ST (at low intensities)

M. Passoni et al., to be submitted

Engineered targets on UHI100: II - ‘μ-spheres’ targets

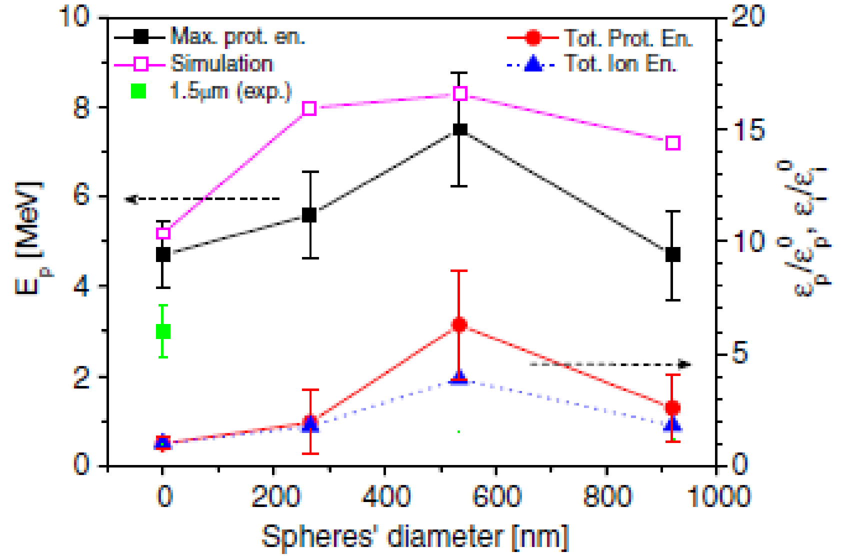
Laserlab joint experiment: CEA/IRAMIS, LULI, Czech Technical University, INO (PI A. Macchi)

2D3V relativistic EM (parallel) PIC code



O Klimo et al., New Journal of Physics 13 053028, (2011)

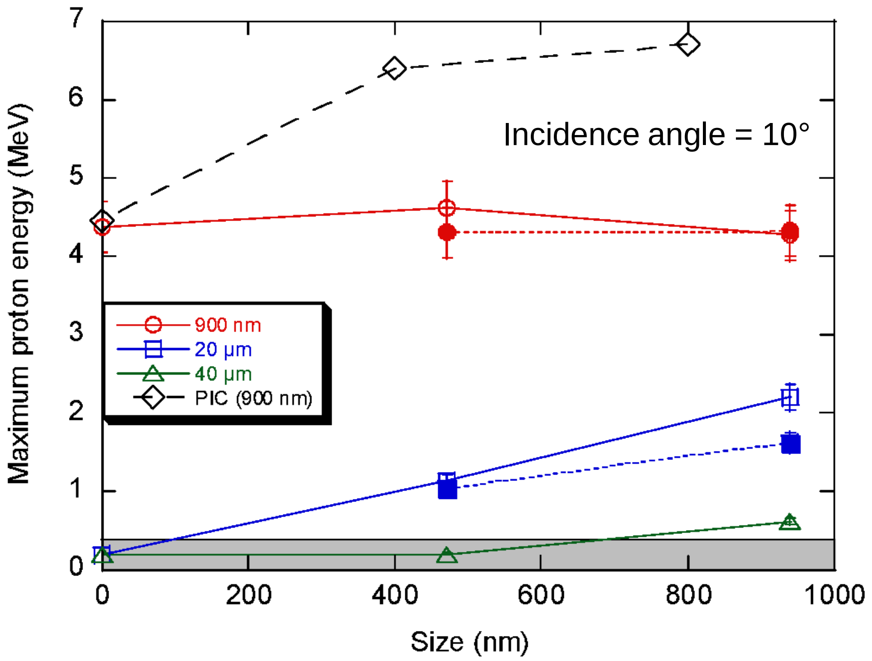
Target : thin (μm thick) plastic foil (substrate) with a mono-layer of hexagonally-packed micrometer polystyrene spheres on its surface.

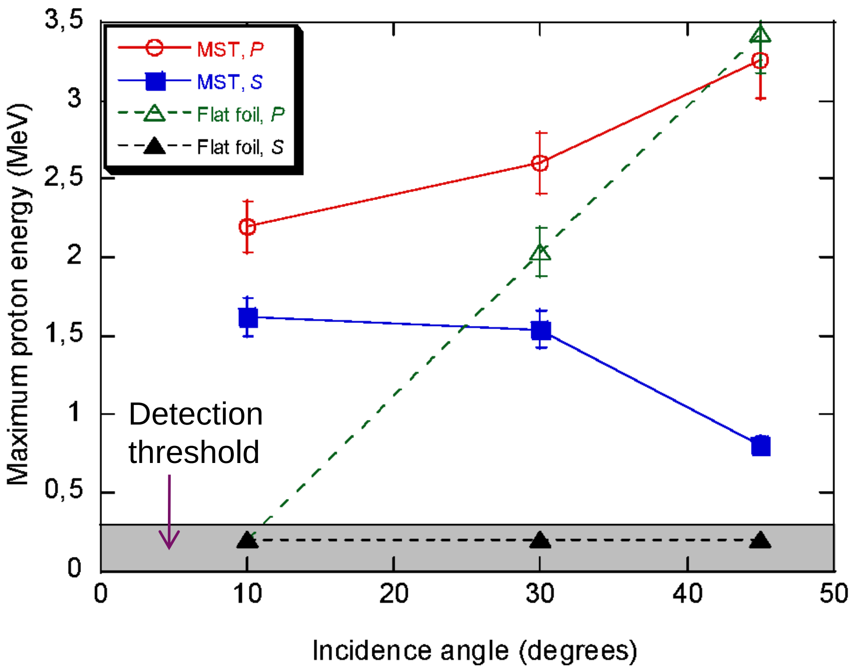


D. Margarone et al., PRL, 109, 234801 (2012)

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

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

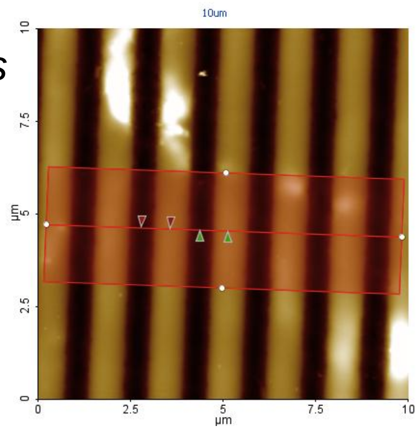
V. Floquet et al., *Micro-sphere layered targets efficiency in laser driven proton acceleration*, submitted to APL

Engineered targets on UHI100: III - 'grating' targets

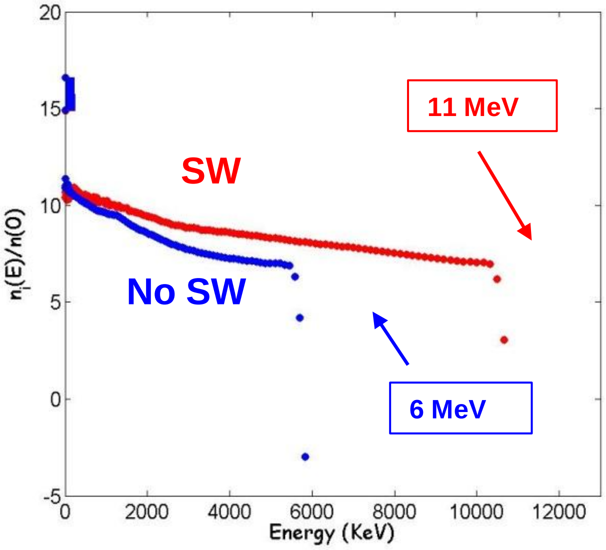
Laserlab joint experiment: CEA/IRAMIS, LULI, Czech Technical University, INO (PI A. Macchi)

- Solid foils with periodic surface modulation may allow resonant excitation of **Surface Waves (SW)**
- Previuos investigations only at modest intensities $I \leq 10^{16}$ W/cm²

SEM picture of engraved Mylar foils



$I=10^{19}$ W/cm²



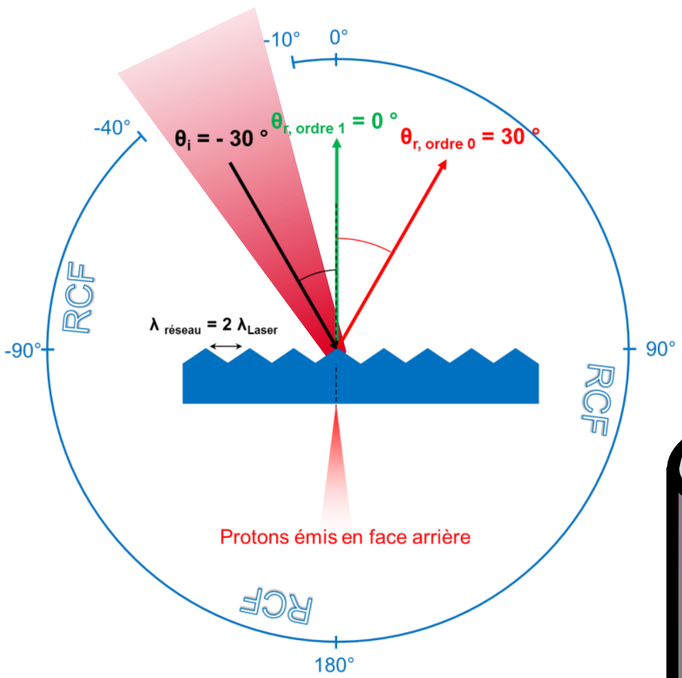
SW excitation → **Proton cut-off energy increase (~x 2)**

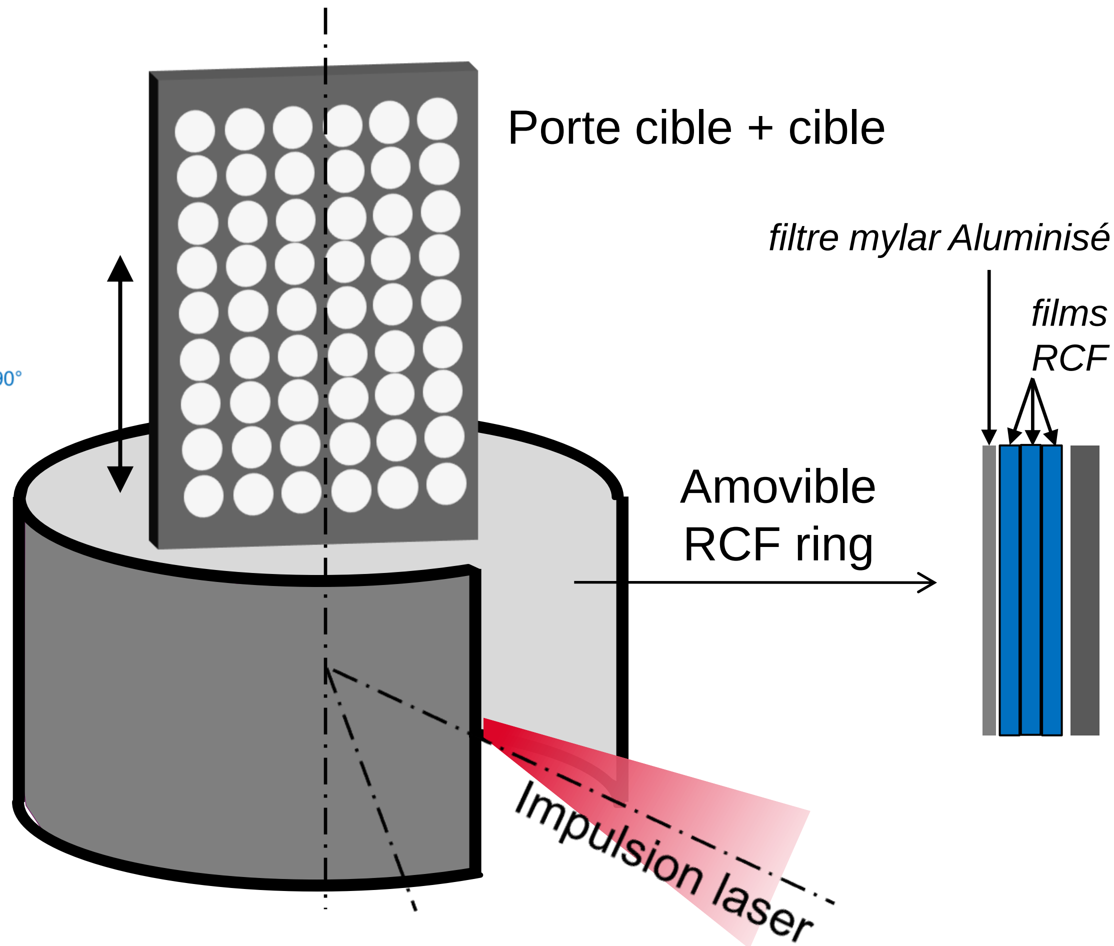
- 3 substrate thicknesses (800 nm, 20 µm and 40 µm)
- 2λ periodic engraving, 500 and 300 nm deep
- Proton E_{max} as a function of incidence angle

M. Raynaud, Physics of Plasmas 14, 092702, (2007)

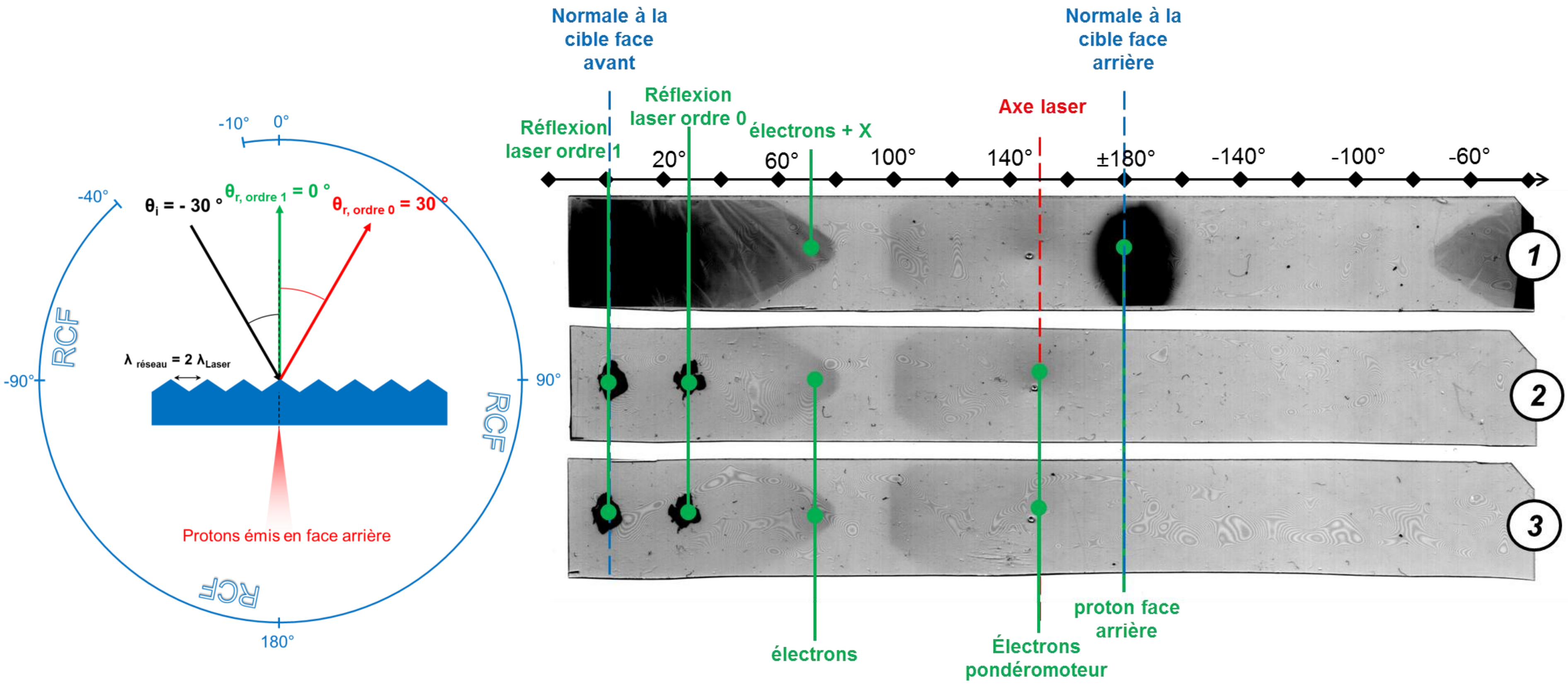
Engineered targets on UHI100: III - 'grating' targets

Détection des électrons, protons et rayonnement X sur ~ 330



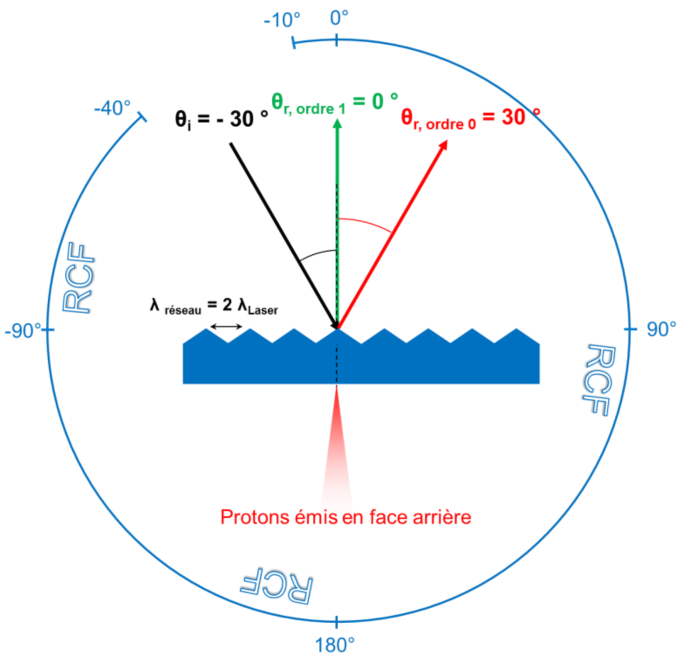


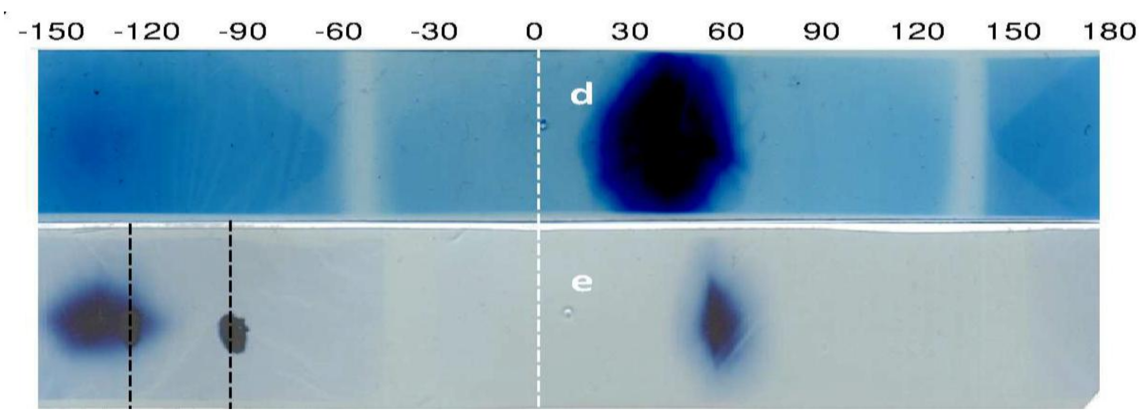
Engineered targets on UHI100: III - ‘grating’ targets



- Motif réseau préservé lors de l’interaction (contraste laser 10^{12})
- Direction d’émission principale des électrons: ~ 90°
- Pas d’influence sur la direction d’émission des protons en face arrière

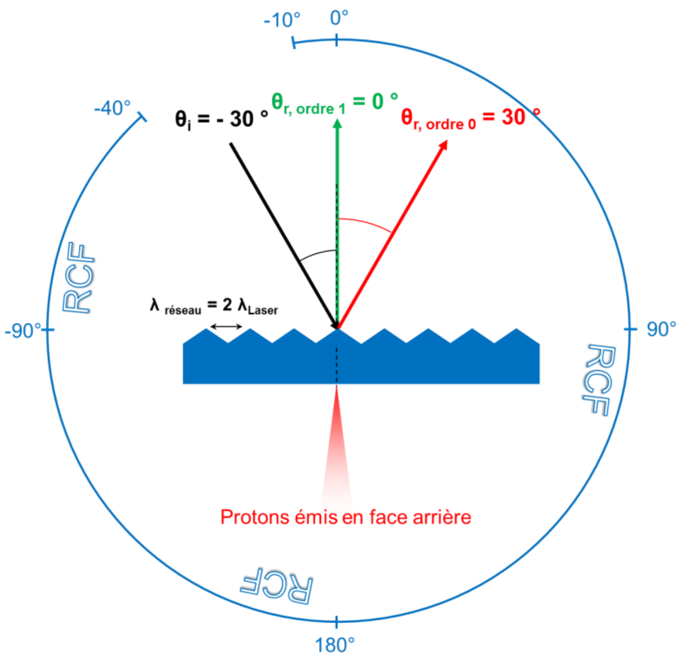
Engineered targets on UHI100: III - 'grating' targets

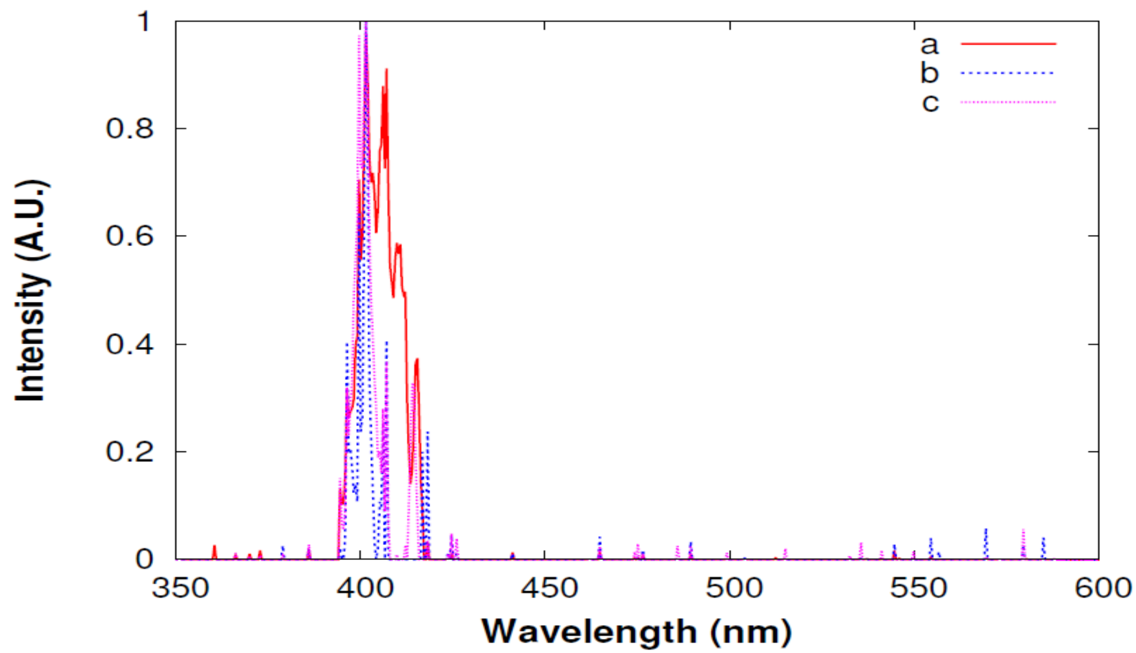




- Bas contraste => pas d'émission électrons (d)
- Changement de l'angle d'incidence => shift angle émission électrons (e)

Engineered targets on UHI100: III - ‘grating’ targets

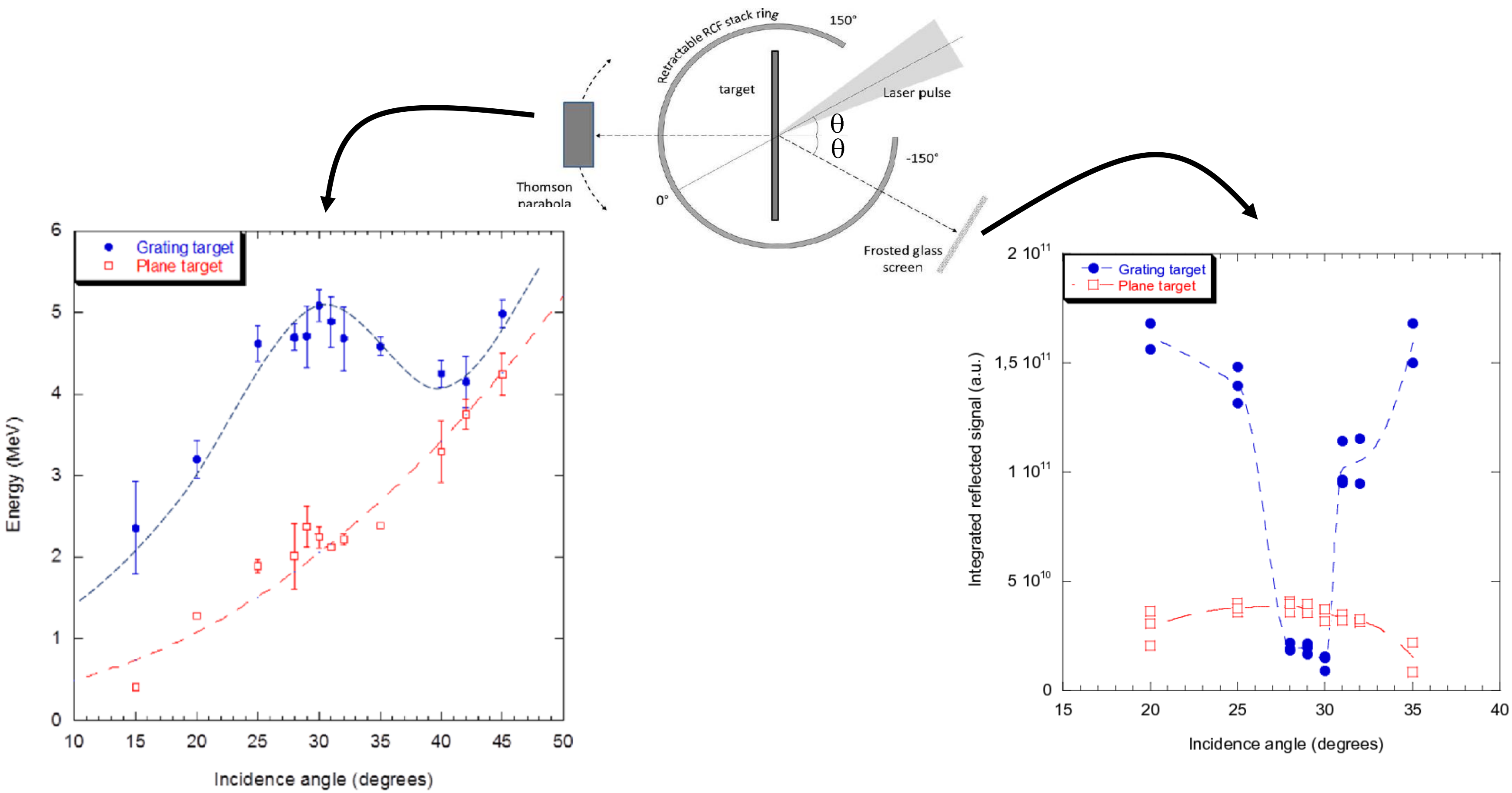




No evidence of an optical emission close to the 3/2 ω wavelength.

- 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

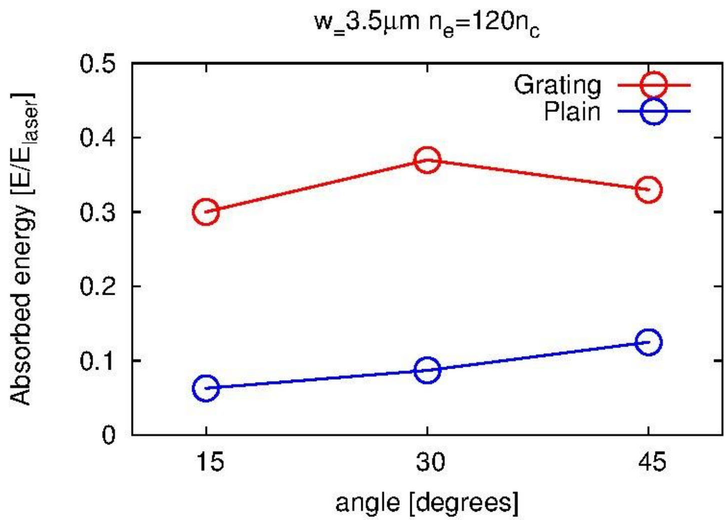


- Grating target shows a clear maximum at resonance angle (30°)
- For the same angle, reflected

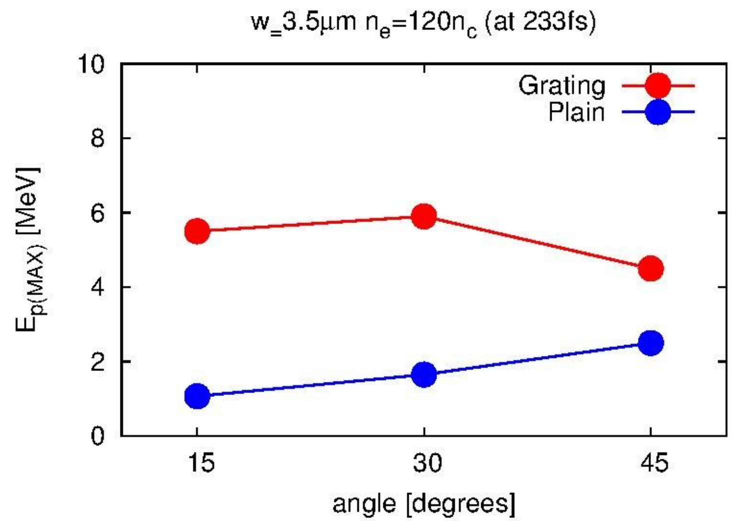
T. Ceccotti et al., submitted to PRL

Engineered targets on UHI100: III - ‘grating’ targets

Absorbed energy



Proton cut-off energy



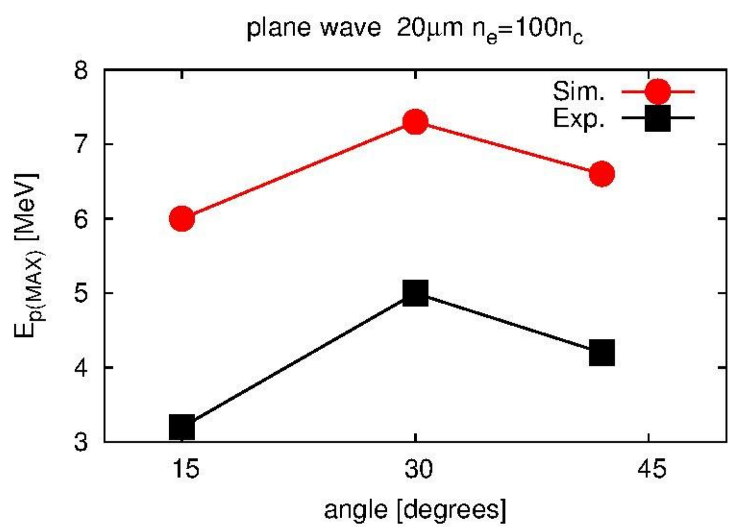
Thin target focussed target

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°



Thick target plane wave

CONCLUSION AND PERSPECTIVES

Conclusions

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

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« ELECTRONS »: sandrine.dobosz@cea.fr

« PROTONS »: tiberio.ceccotti@cea.fr

Perspectives

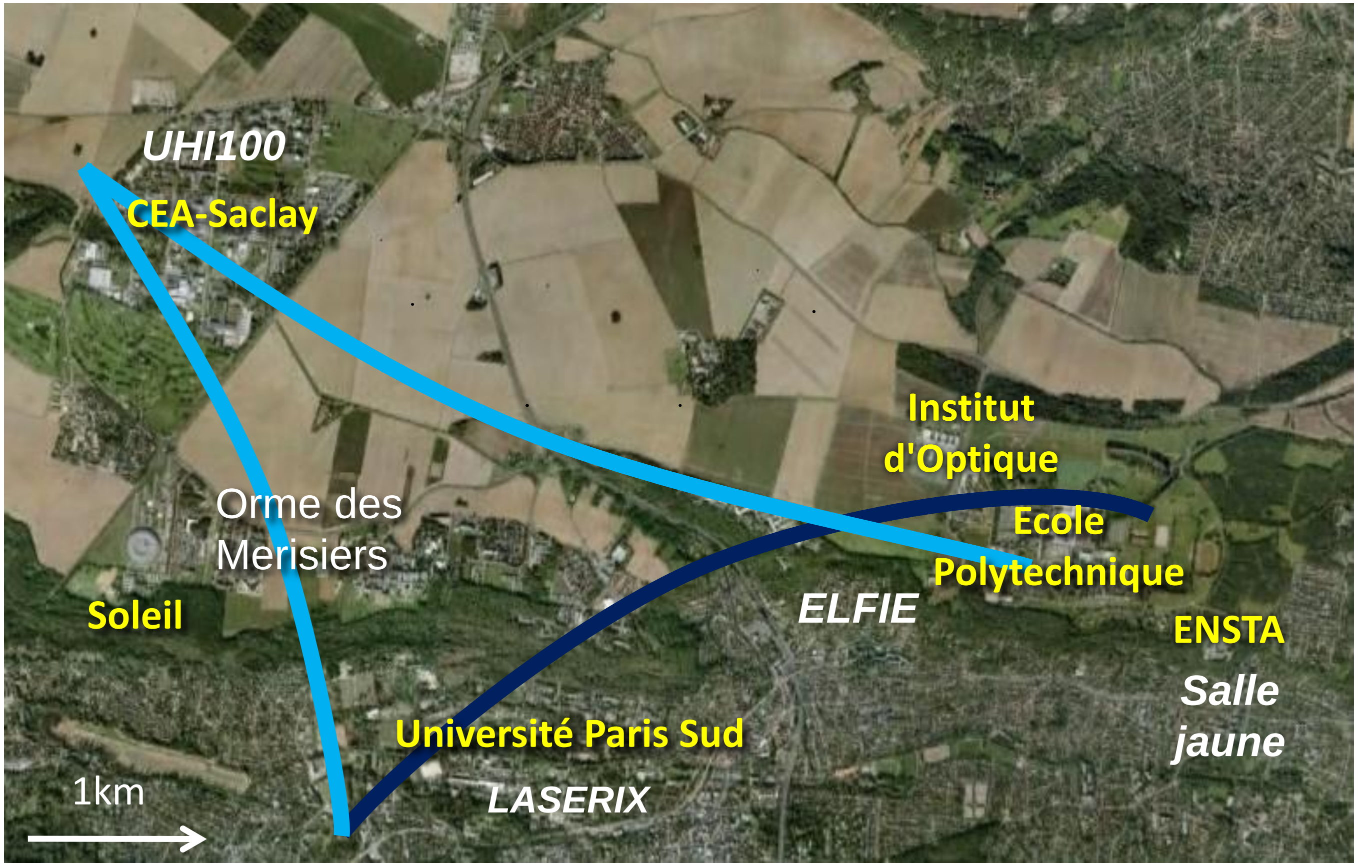
CILEX Centre interdisciplinaire lumière extrême

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

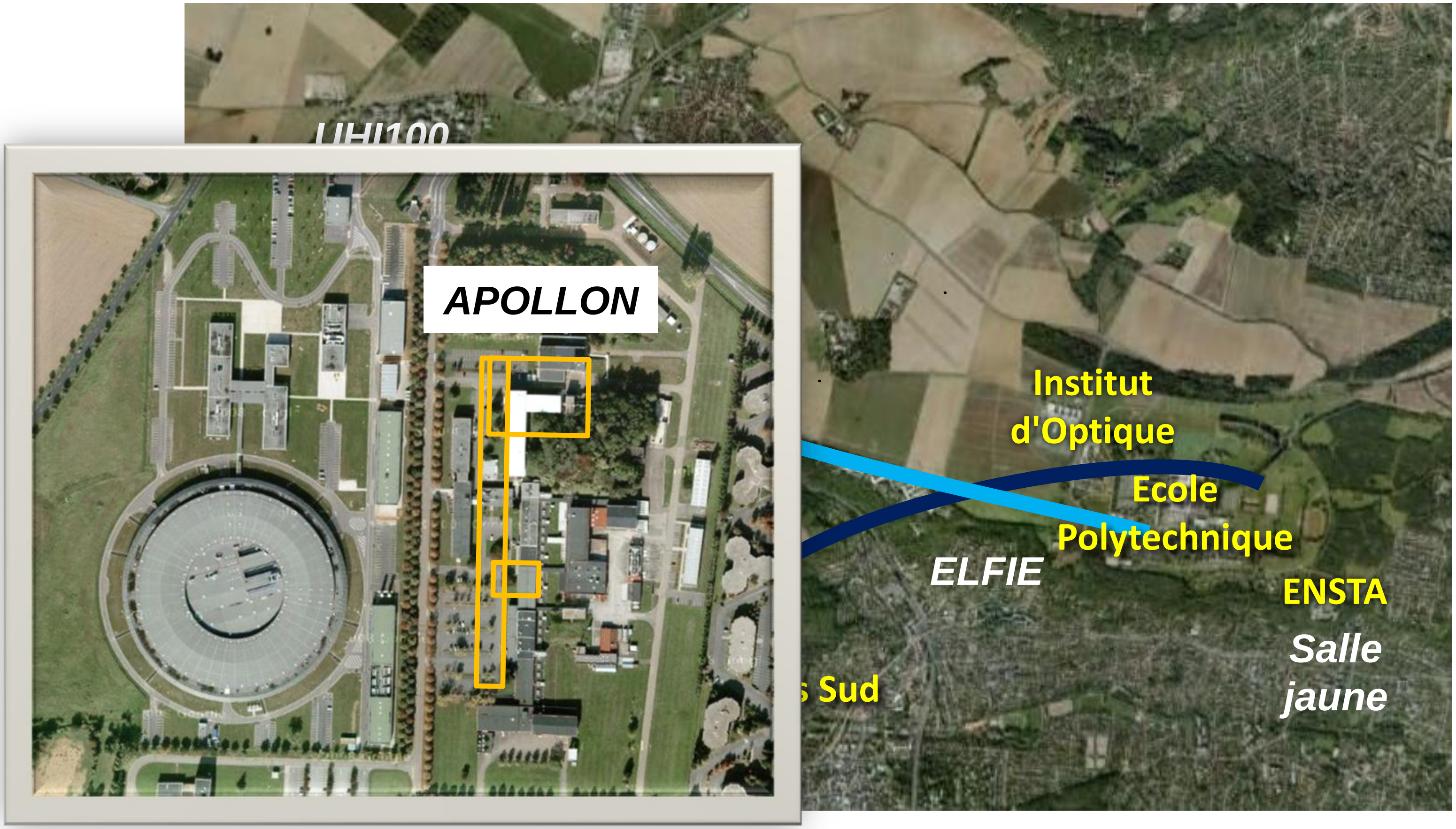
CILEX = APOLLON (20 M€) + SATELITTE FACILITIES + BUILDING REHABILITATION + EXPERIMENTAL SET-Up (20 M€)

Developing new instruments and an interdisciplinary centre CILEX will be devoted to address physics at unexplored power densities



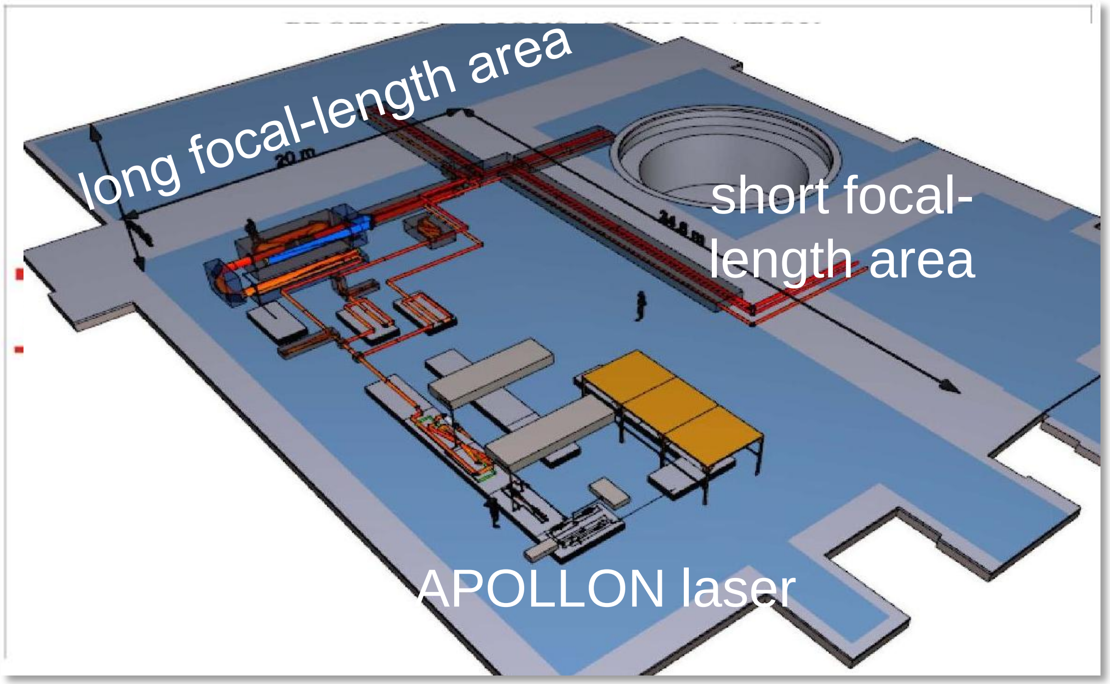
A "laser and plasma labs" Campus on the « Plateau de Saclay »

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

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