



Un aperçu de la Science sur APOLLON

Ph. Zeitoun

avec l'aide des groupes de travail CILEX

11/06/2018

Plan

1- Positionnement national et international

2- Salle Longue Focale: Accélération d'électrons

3- Salle Courte Focale: Rayonnement X et Accélération de protons

4- La physique en champs forts

5- Conclusions

Plan

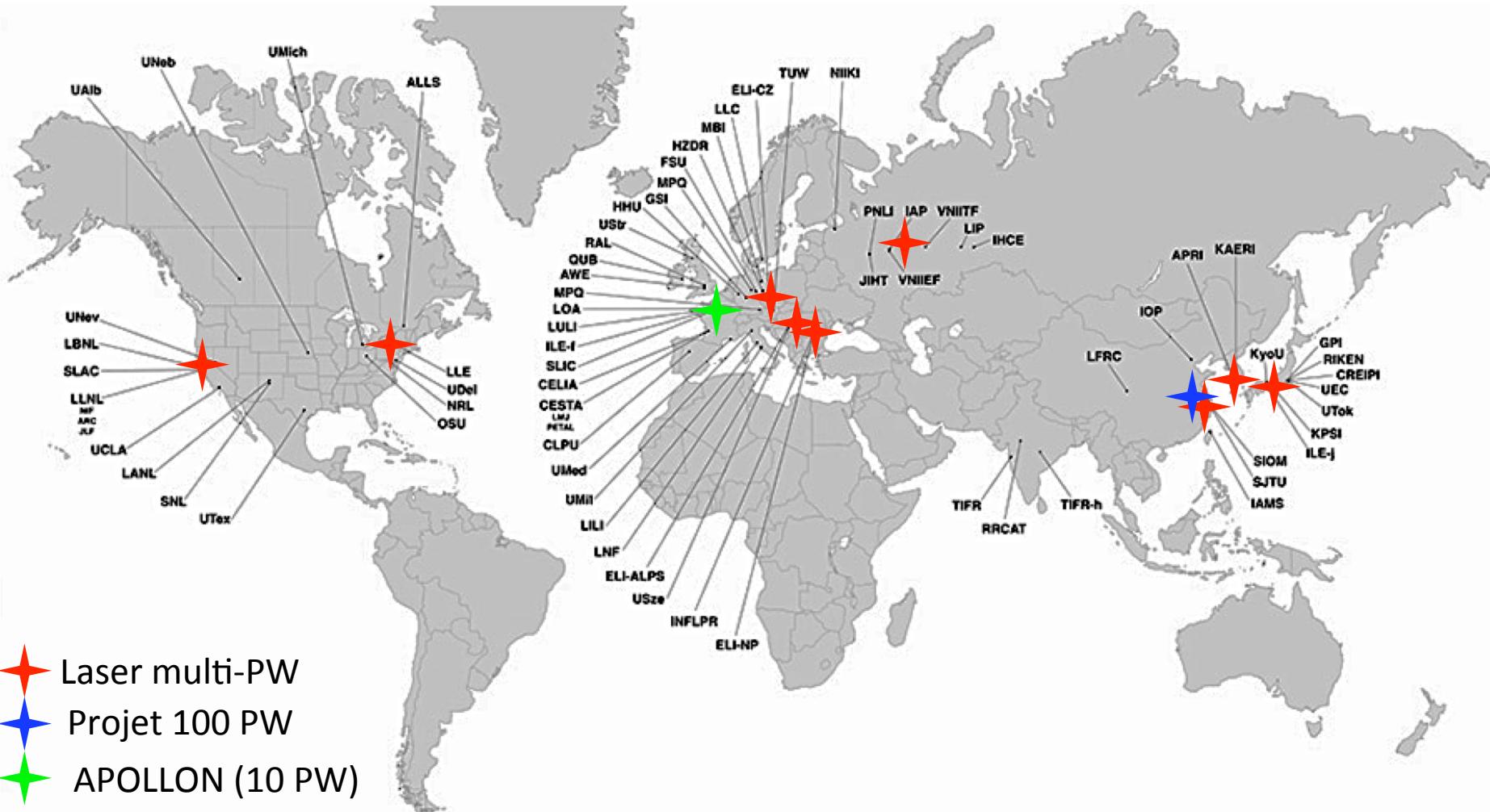
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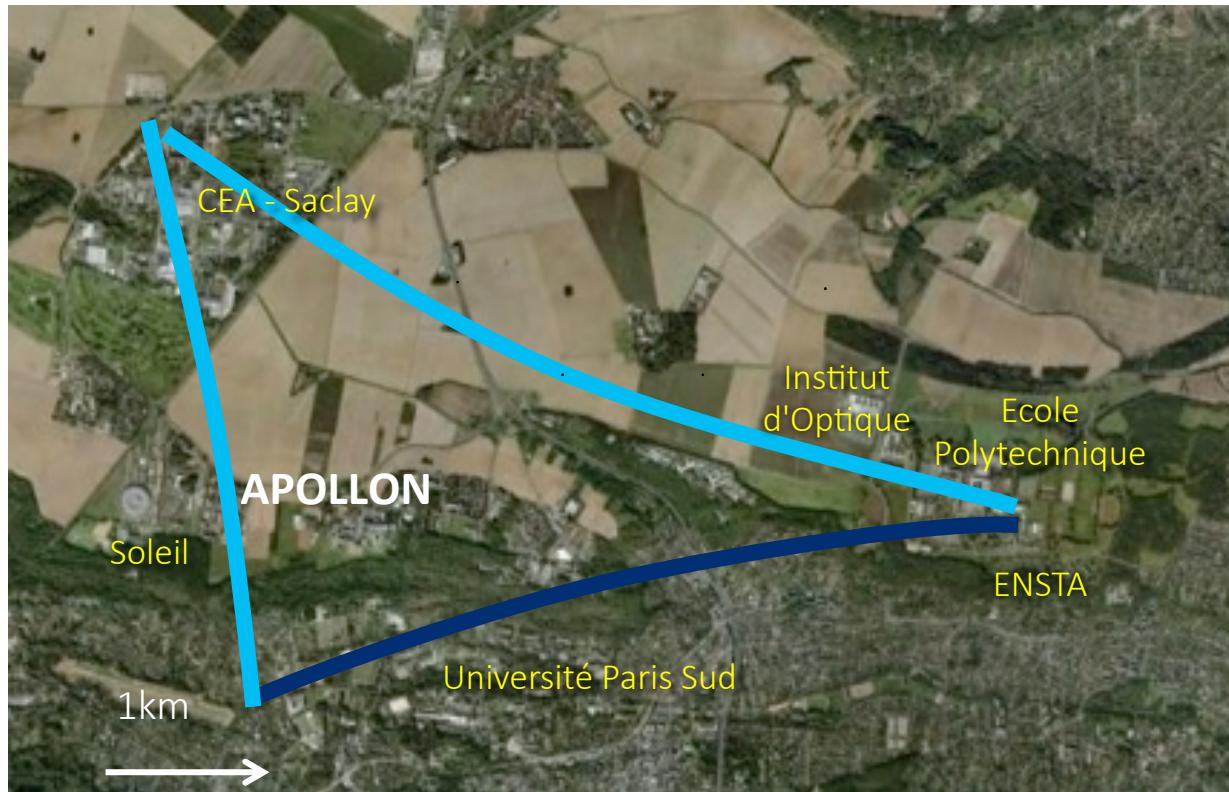
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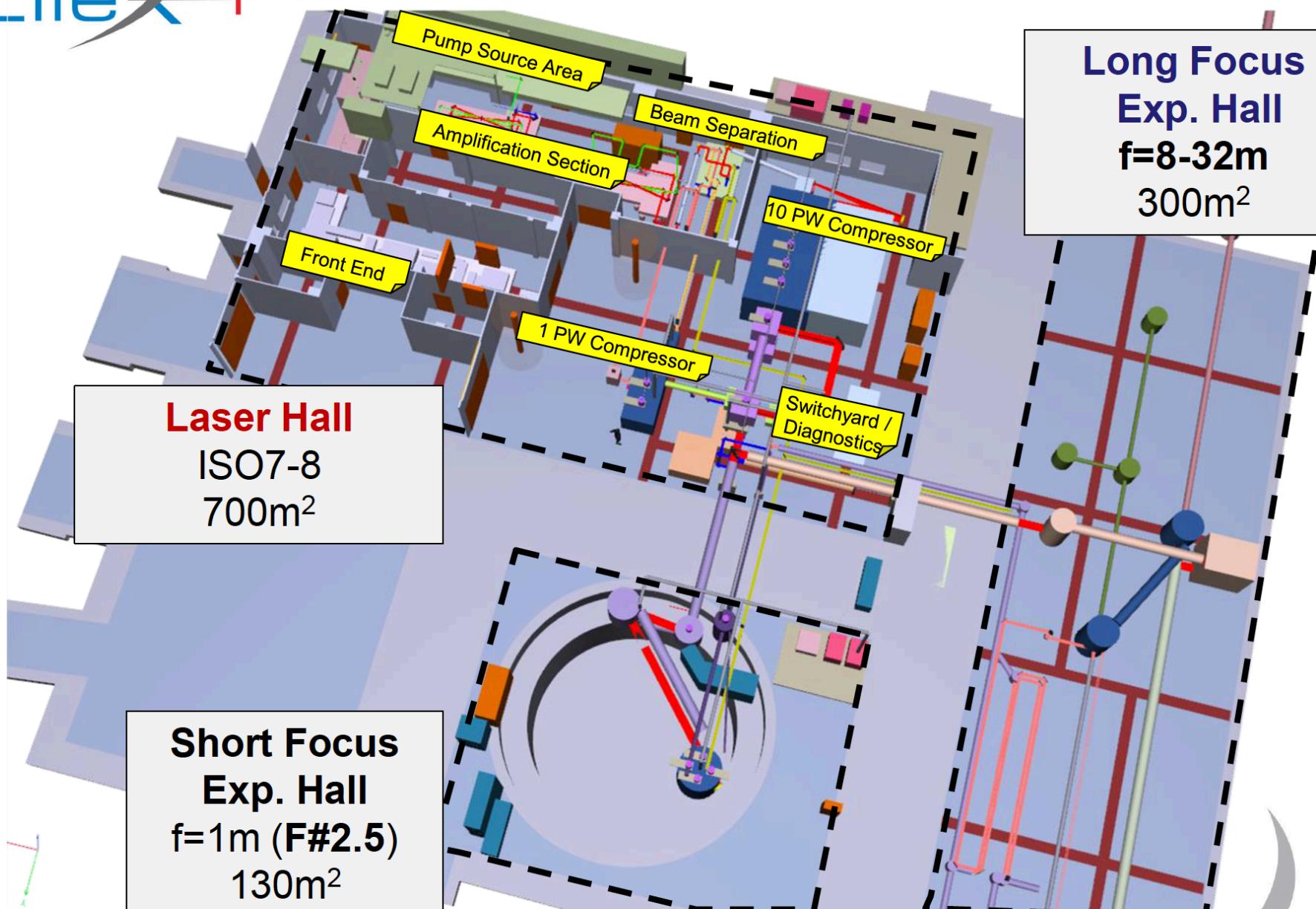
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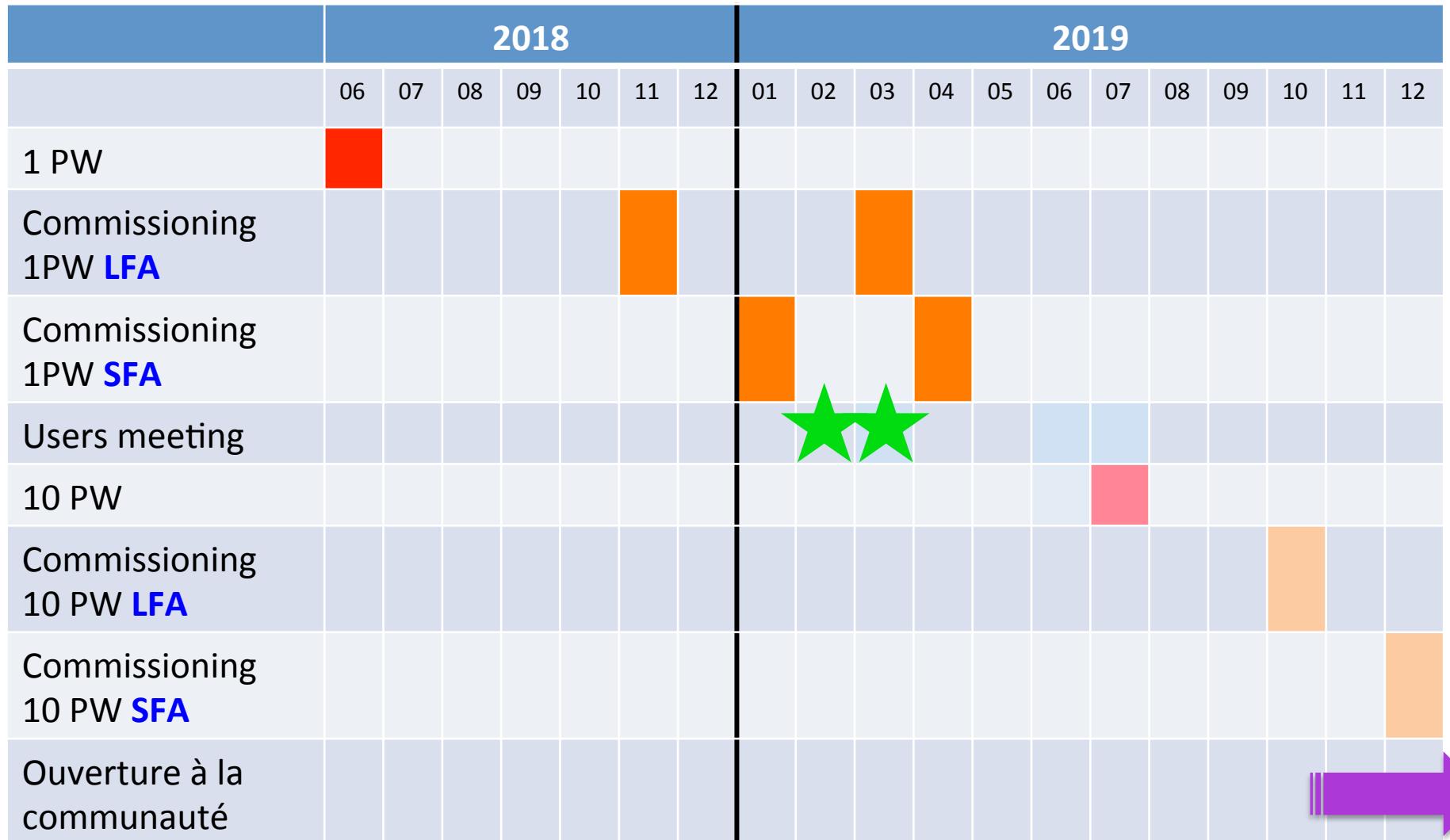


1 projet, 12 laboratoires





Le planning d'APOLLON-CILEX



Plan

1- Positionnement national et international

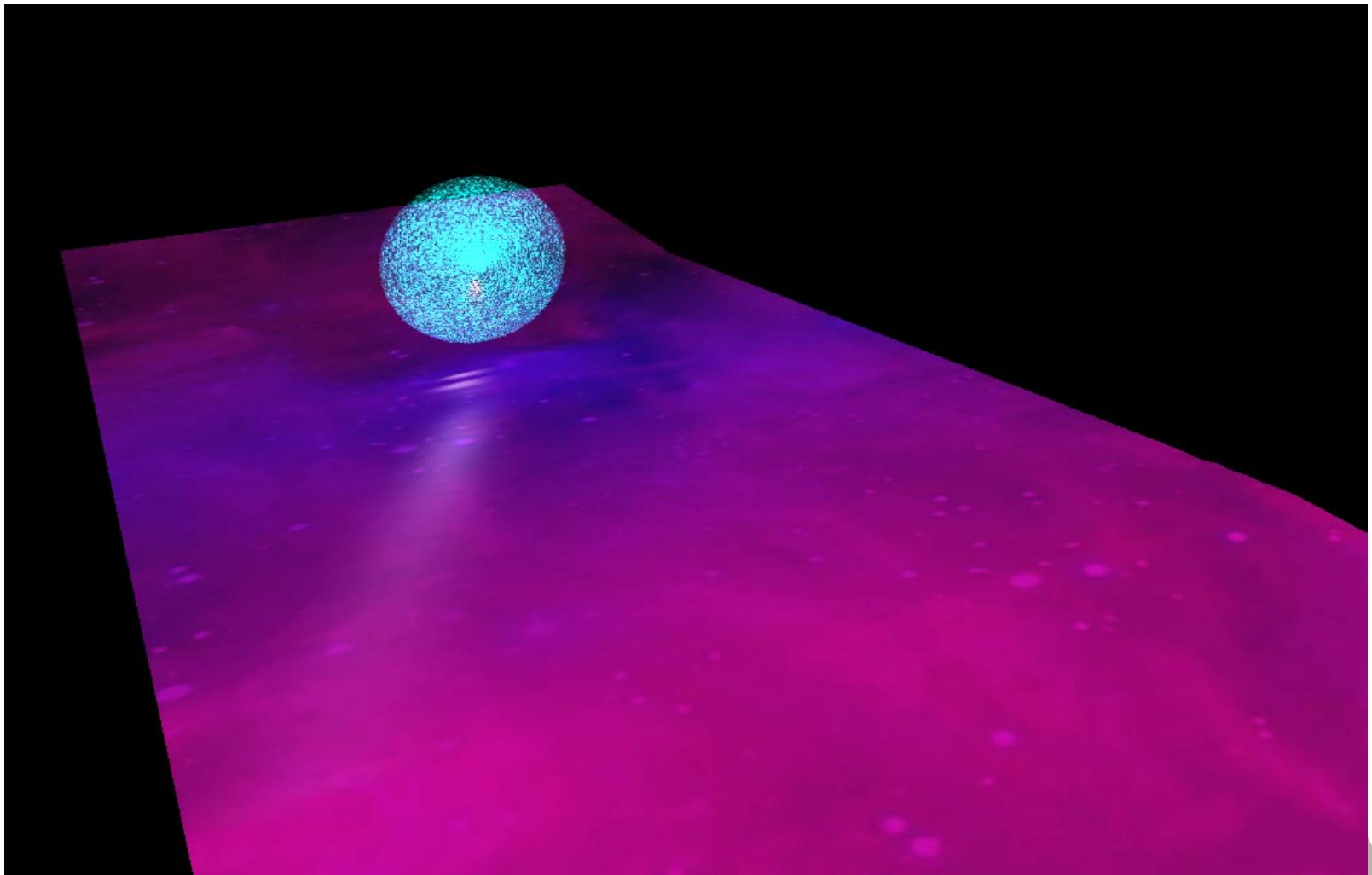
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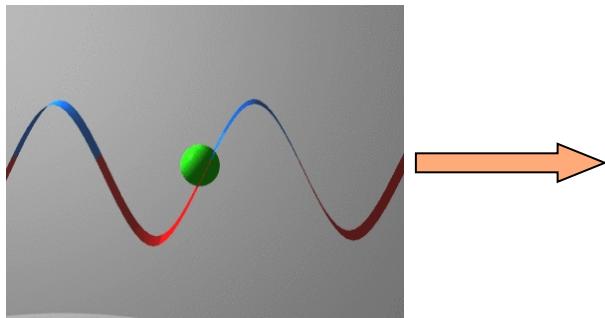
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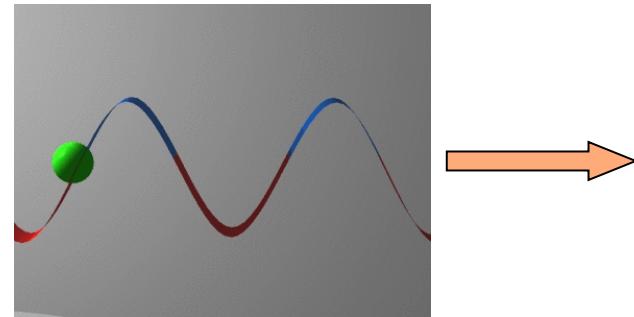
Tajima and J.M.Dawson, Phys.Rev.Lett. **43**, 267 (1979)



Electrons fluides



Electrons piégés



J. Faure, cours "Explore new horizons in modern optics", Vietnam 2017

□ Injection externe:

⇒ Accélérateur classique + plasma (ESCULAP)

E. Baynard et al., N. I. M. A, sous presse 2018

⇒ Plasma + plasma (APOLLON)



□ Injection interne:

⇒ 1 plasma et 2 impulsions lasers (APOLLON)

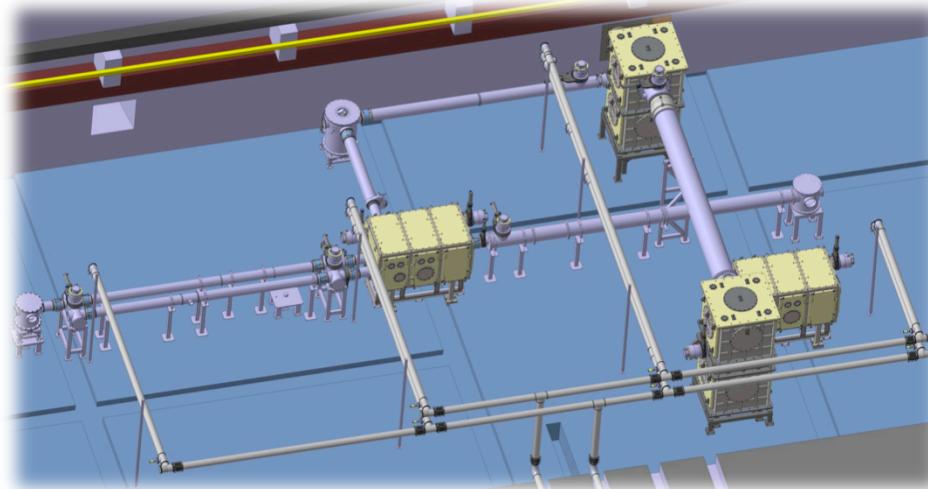
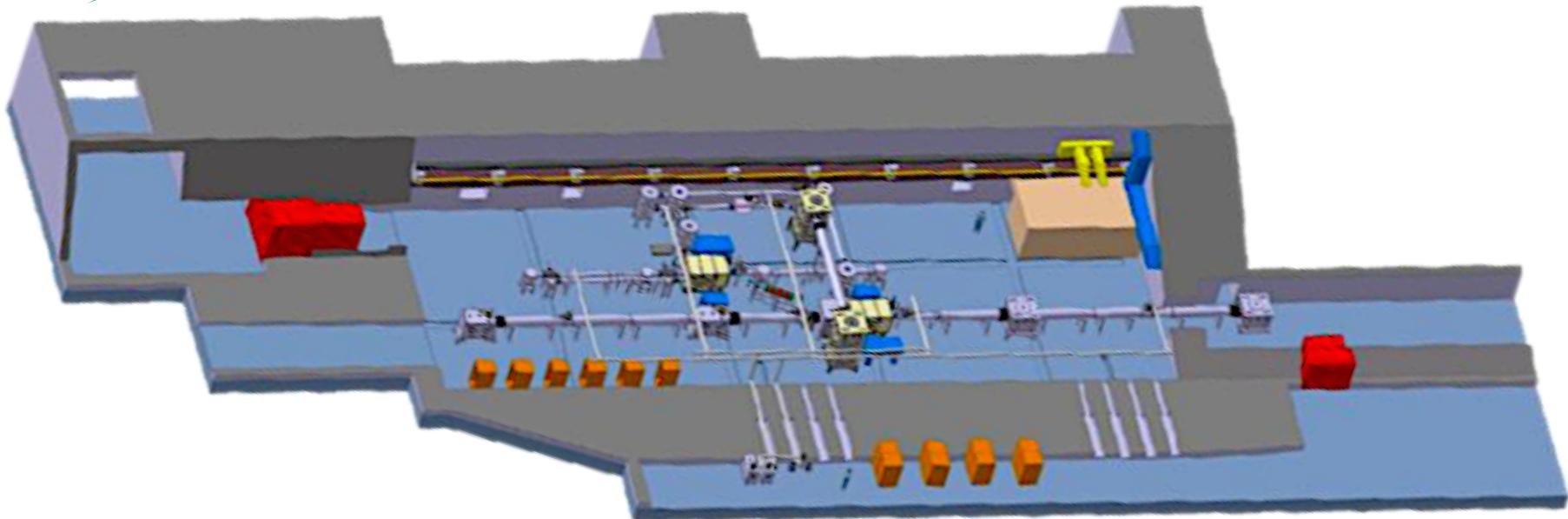


□ Auto-injection :

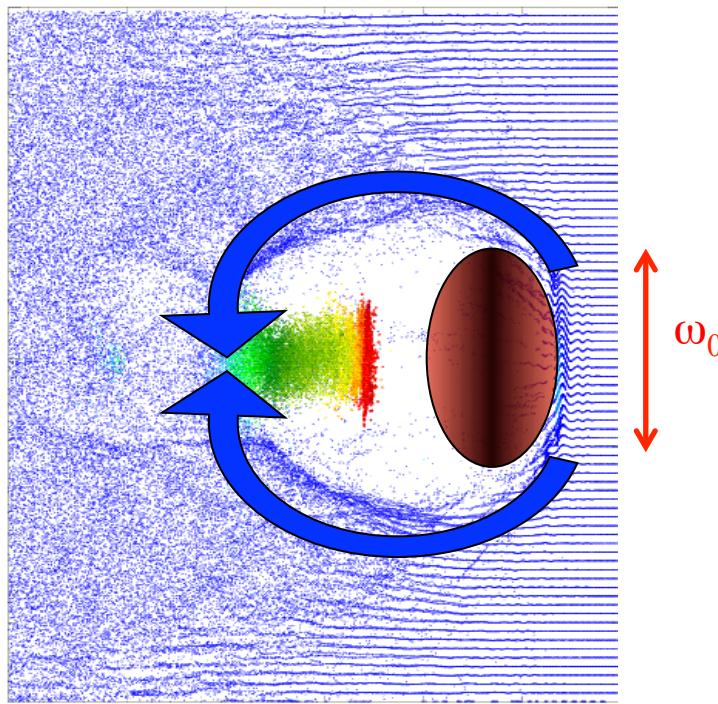
⇒ L'onde plasma est forcée au point qu'elle déferle, piège les électrons et les accélère.

(APOLLON)

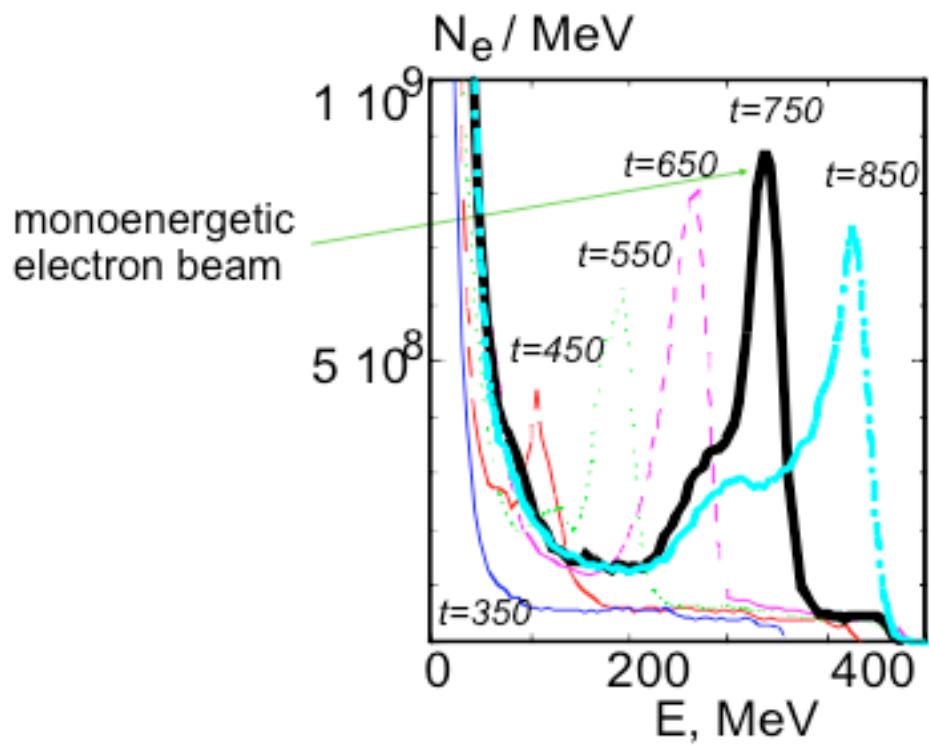
La salle longue focale







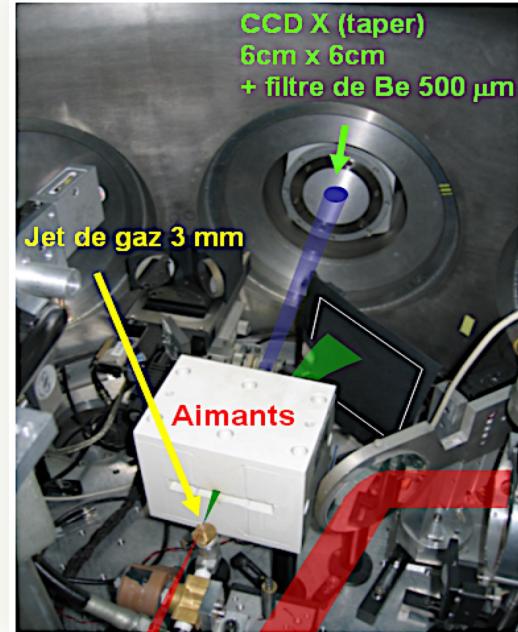
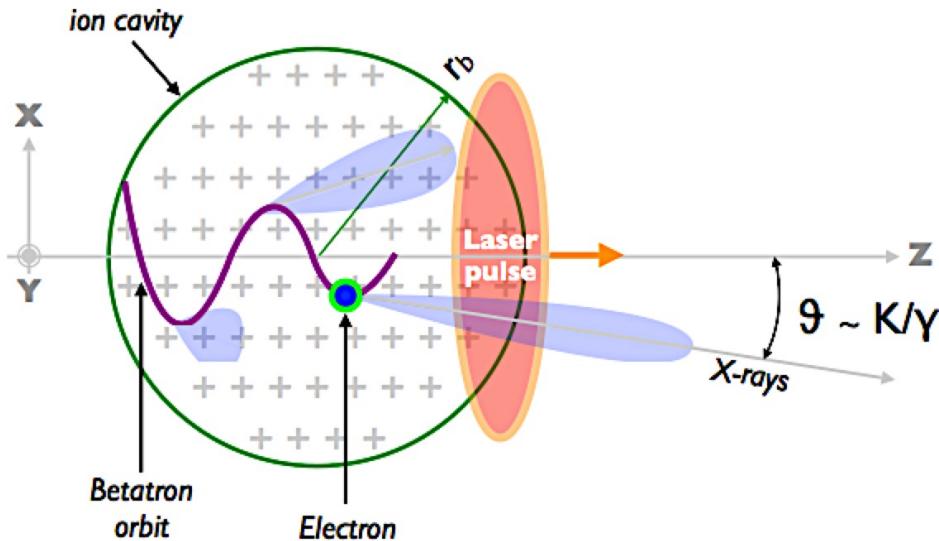
Pukhov & Meyer-ter-Vehn, Appl. Phys. B 2002



□ $a_0 = 8.5 \times 10^{-10} \times \lambda [\mu\text{m}] \times I_0^{1/2} [\text{W/cm}^2] \Rightarrow a_0 = 3 - 9$

□ Conditions de résonnance

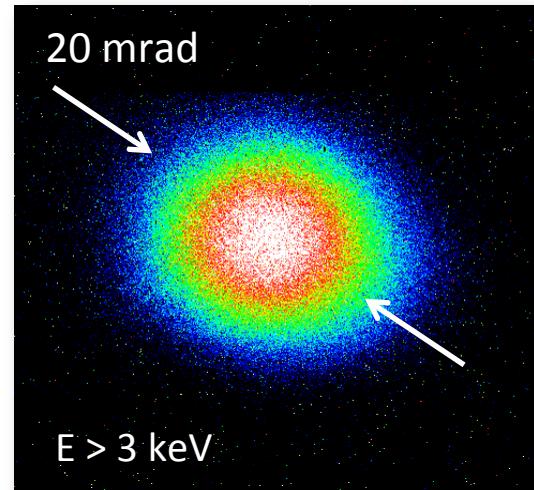
$$c\tau \leq \lambda_p \text{ et } \omega_0 \leq \lambda_p \quad \tau: \text{durée laser}$$

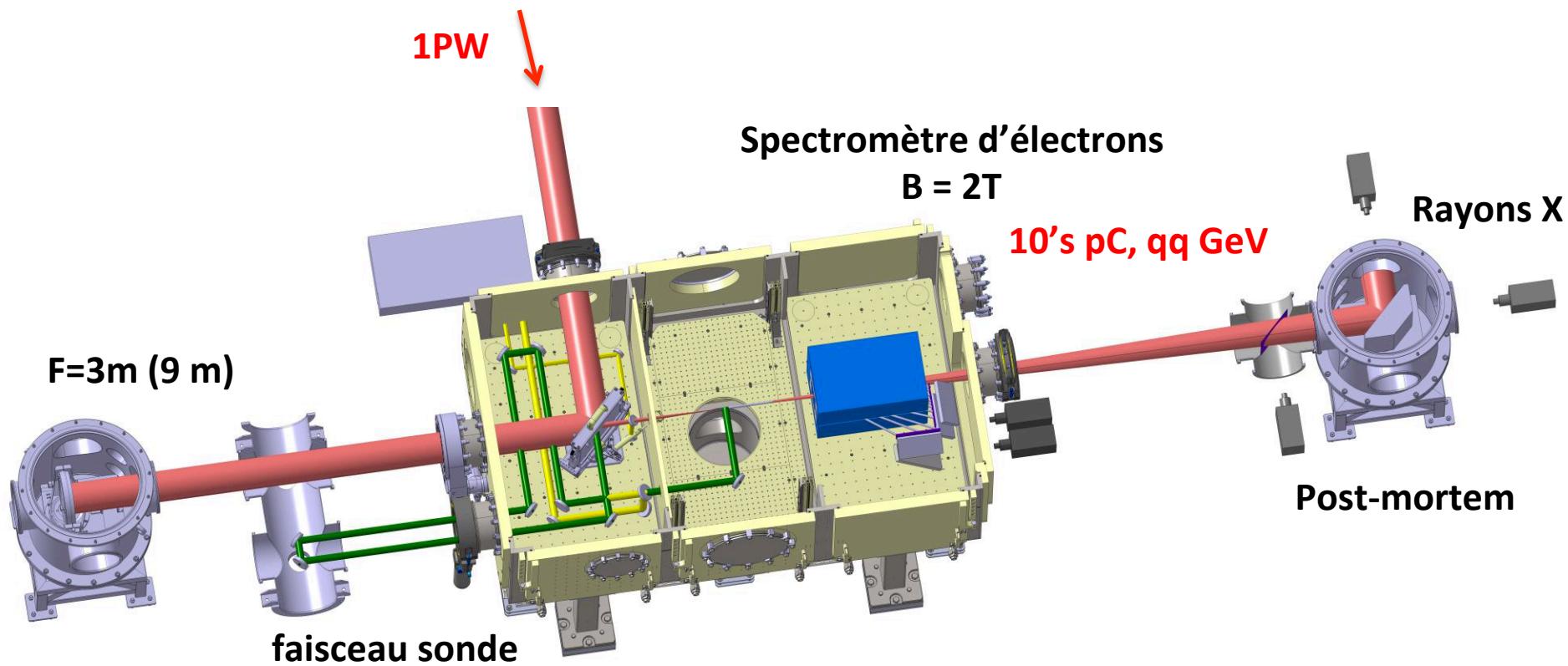


Characteristiques de la source @ LOA:

- 10^5 photons/tir/0.1% BW @ 1 keV
- divergence: 10's mrad
- Durée: 10's fs
- Spectre: 1-10 keV
- Taille de source: 1- 2 microns

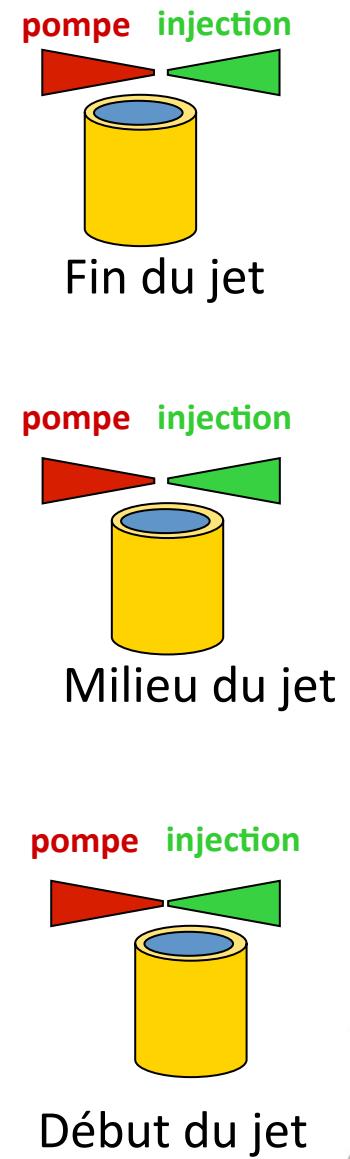
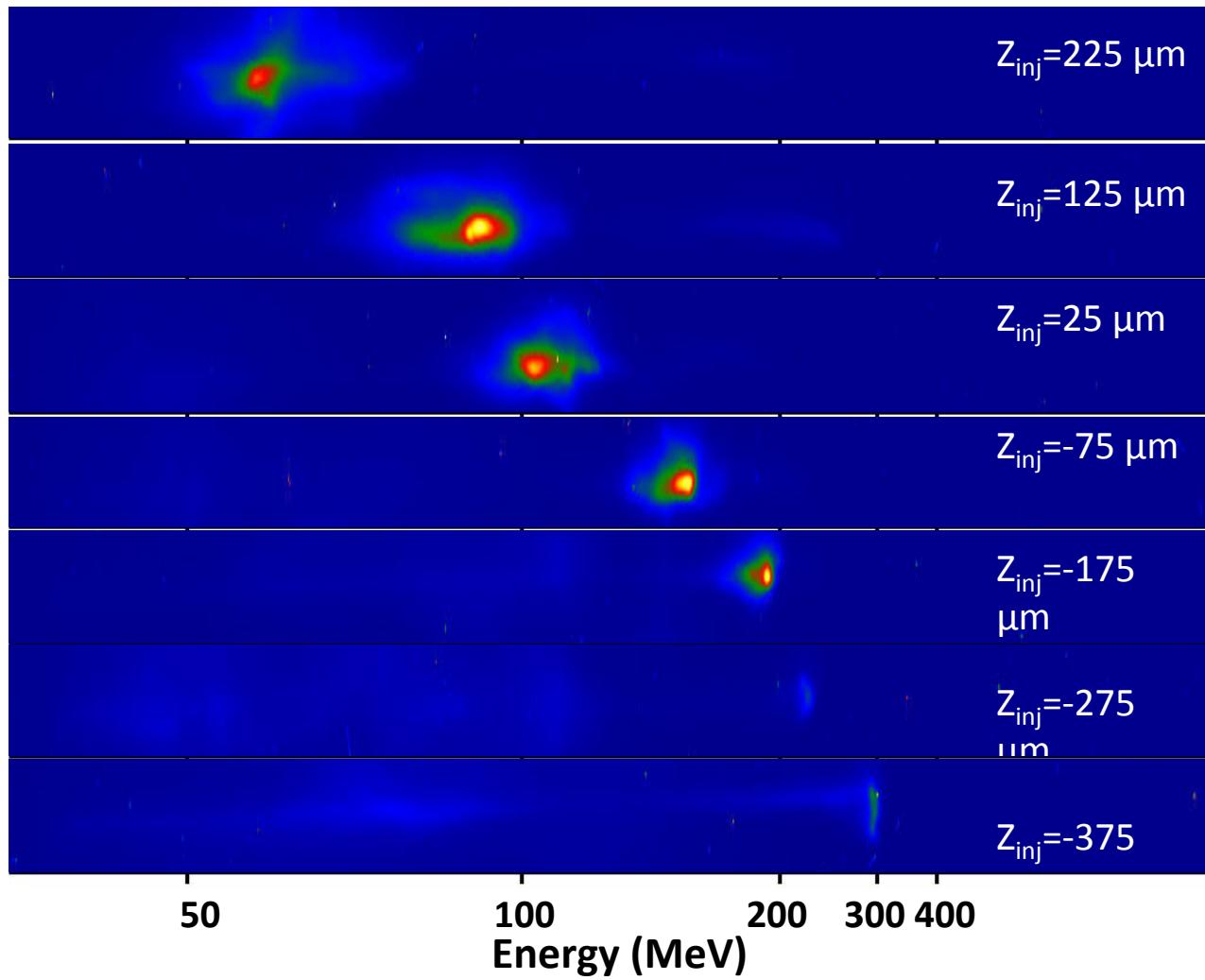
A. Rousse, K. Ta Phuoc et al, Phys. Rev. Lett. 2004





Injection « interne »

J. Faure et al., Nature, 444, 737 (2006)



Modèles d'accélération @ 10 PW

$I = 1.5 \times 10^{22} \text{ Wcm}^{-2}$,
 $a_0 = 43$,
 $n_e = 1.5 \times 10^{19} \text{ cm}^{-3}$

$\Rightarrow 42 \text{ nC}, 2.3 \text{ GeV}$

$I = 1.4 \times 10^{20} \text{ Wcm}^{-2}$,

$a_0 = 5.8$,

$n_e = 2.7 \times 10^{17} \text{ cm}^{-3}$

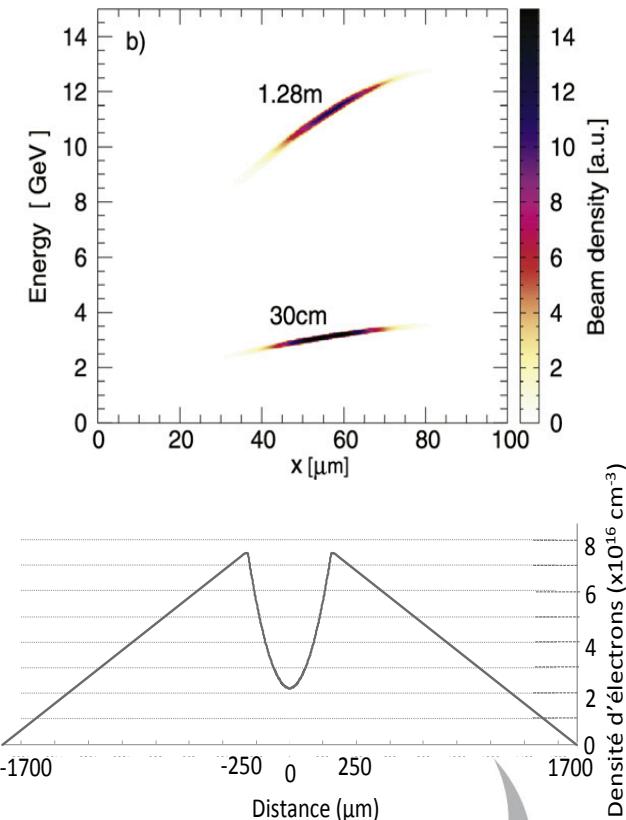
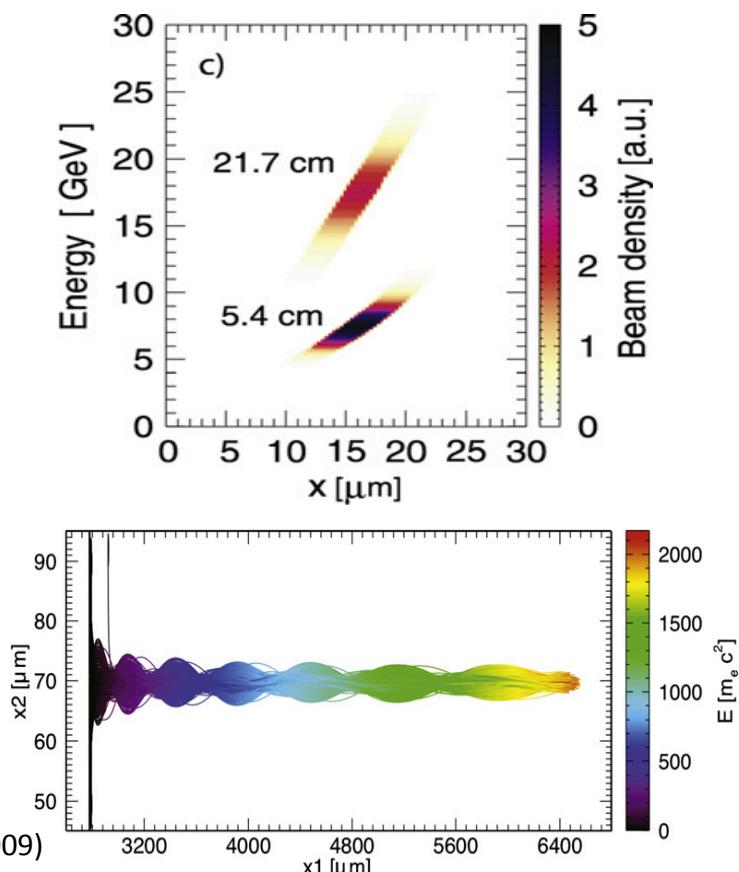
Self-guiding

$I = 1.7 \times 10^{19} \text{ Wcm}^{-2}$,

$a_0 = 2$,

$n_e = 2.2 \times 10^{16} \text{ cm}^{-3}$

Plasma channel guiding

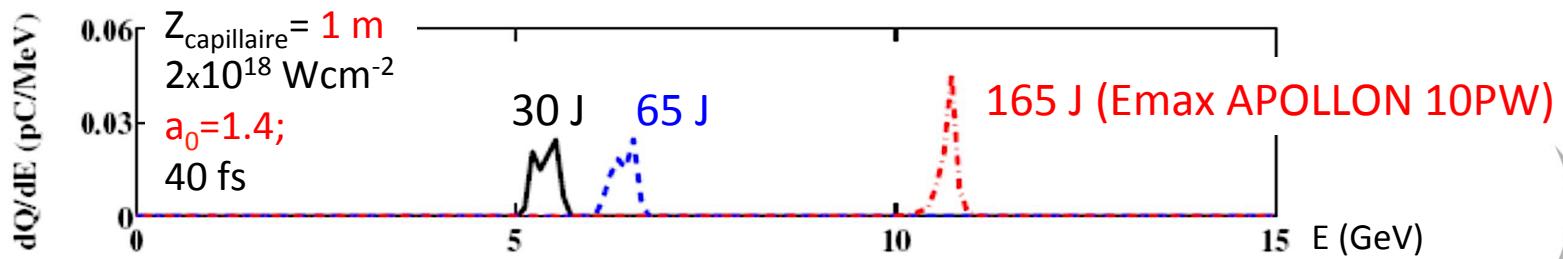
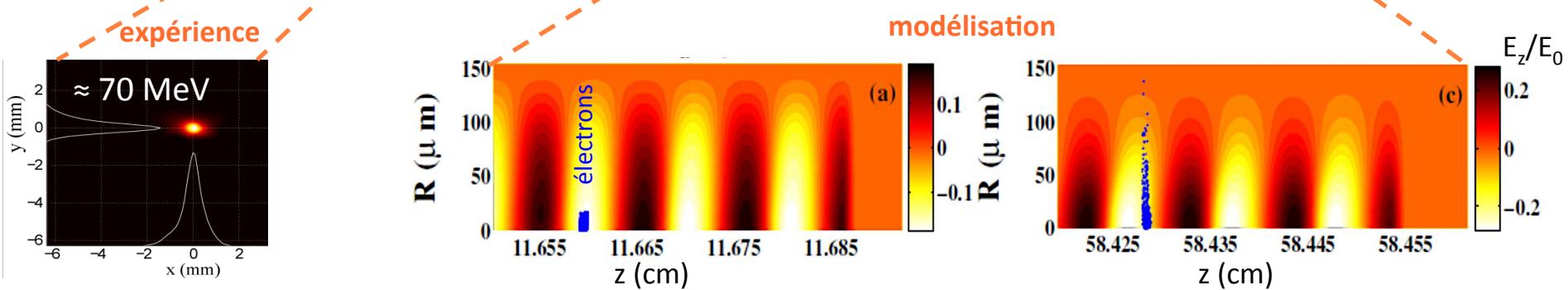
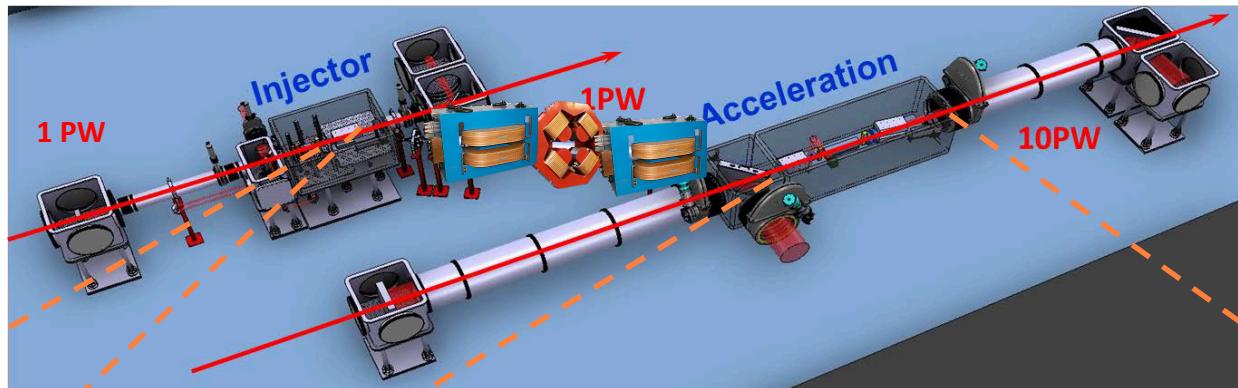


L. Silva et al., C. R. Phys., **10**, 167 (2009)
A. Beck et al., N. I. M. A, **740** 67 (2014)

Cilex Apollon 2^{ème} expérience : vers l'accélération à 2 étages

B. Cros, Nature, **530**, 165 (2016) ; S. Steinke et al, Nature, **530**, 190 (2016)

B. Cros, EAAC2013; T.L. Audet et al, NIMA, **829**, 304 (2016)
 B. Cros et al, Proceedings IPAC 2017



Plan

1- Positionnement national et international

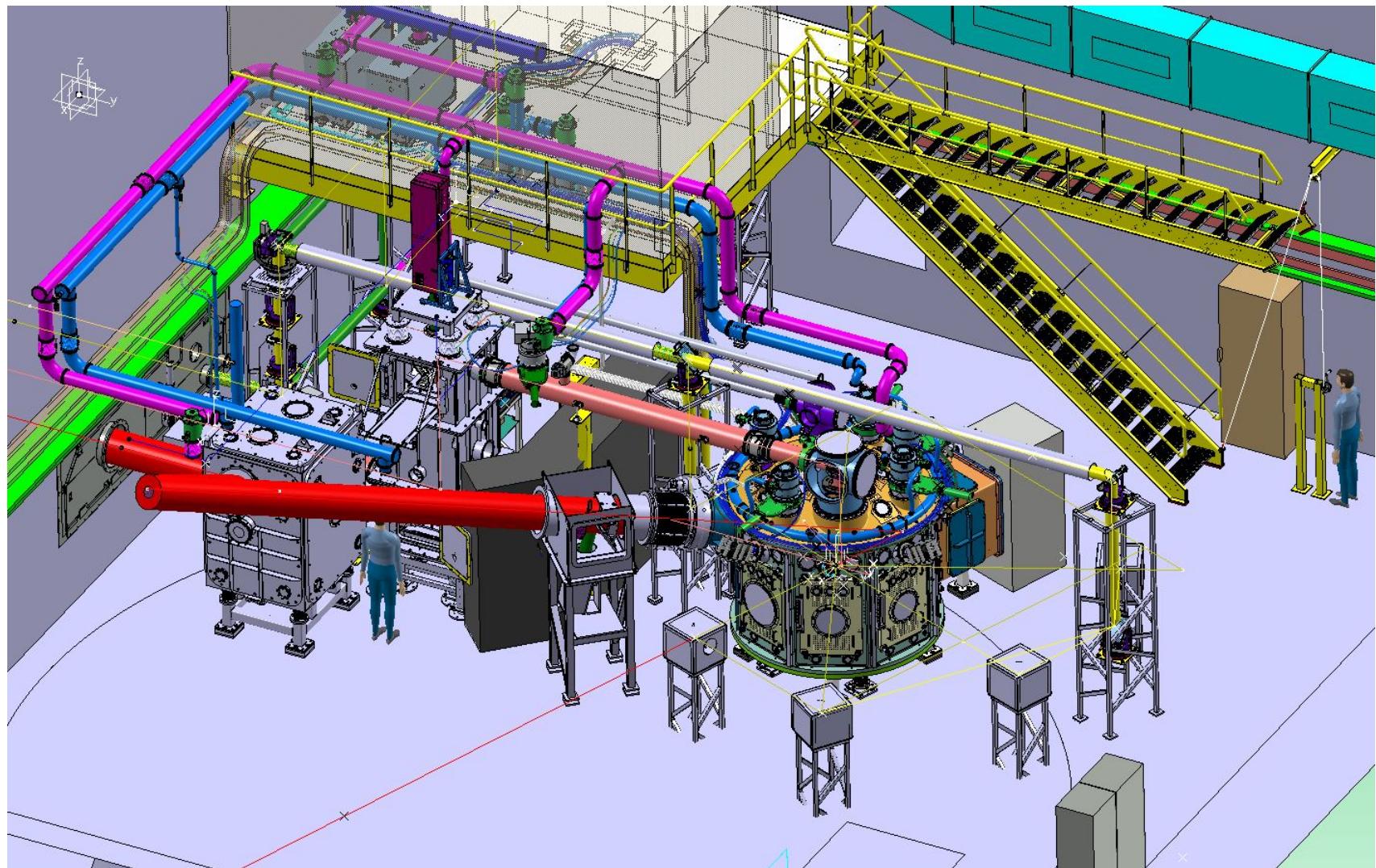
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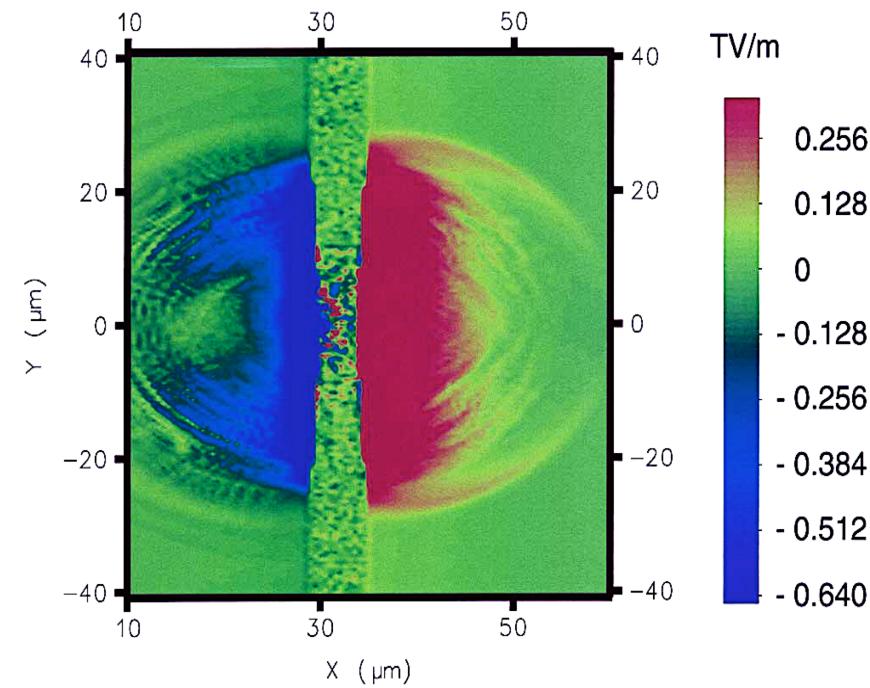
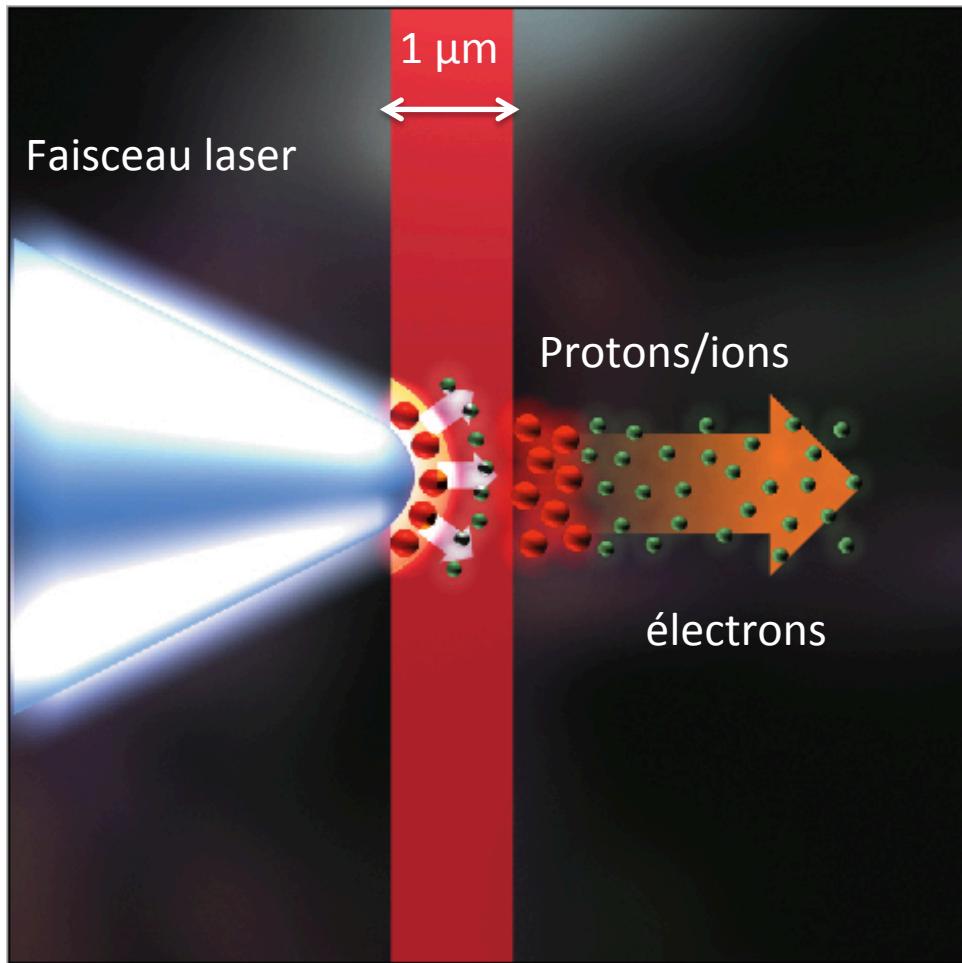
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Schéma de la Salle courte focale



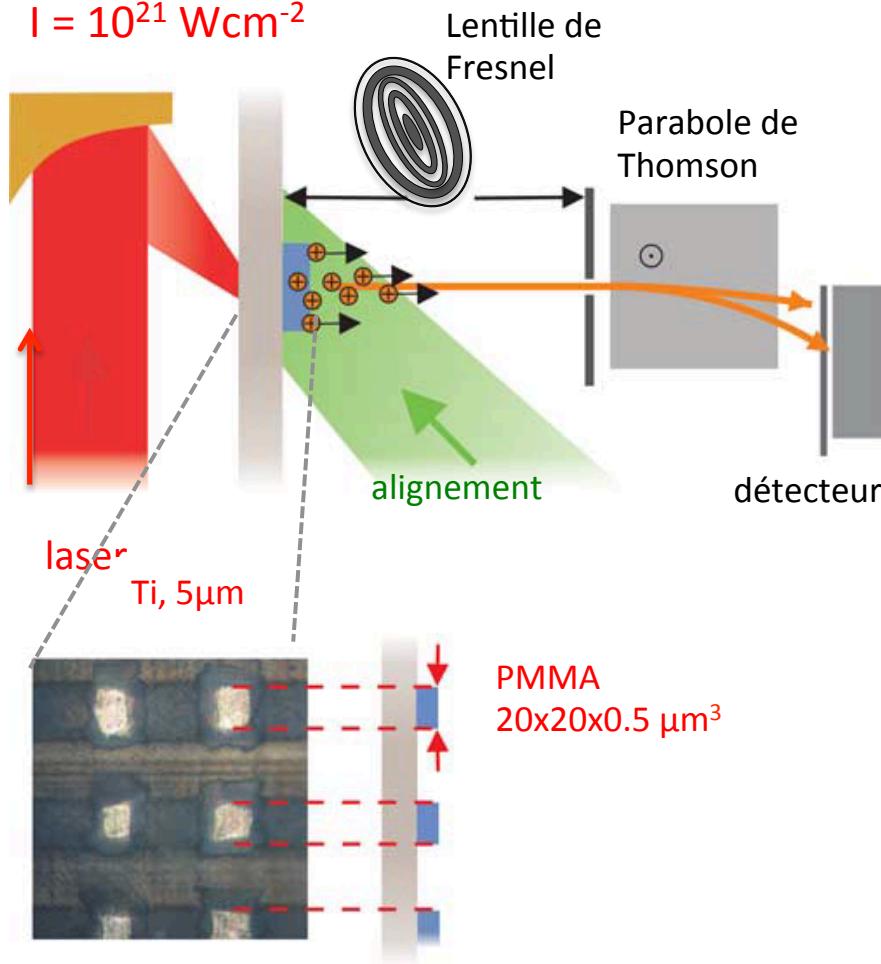




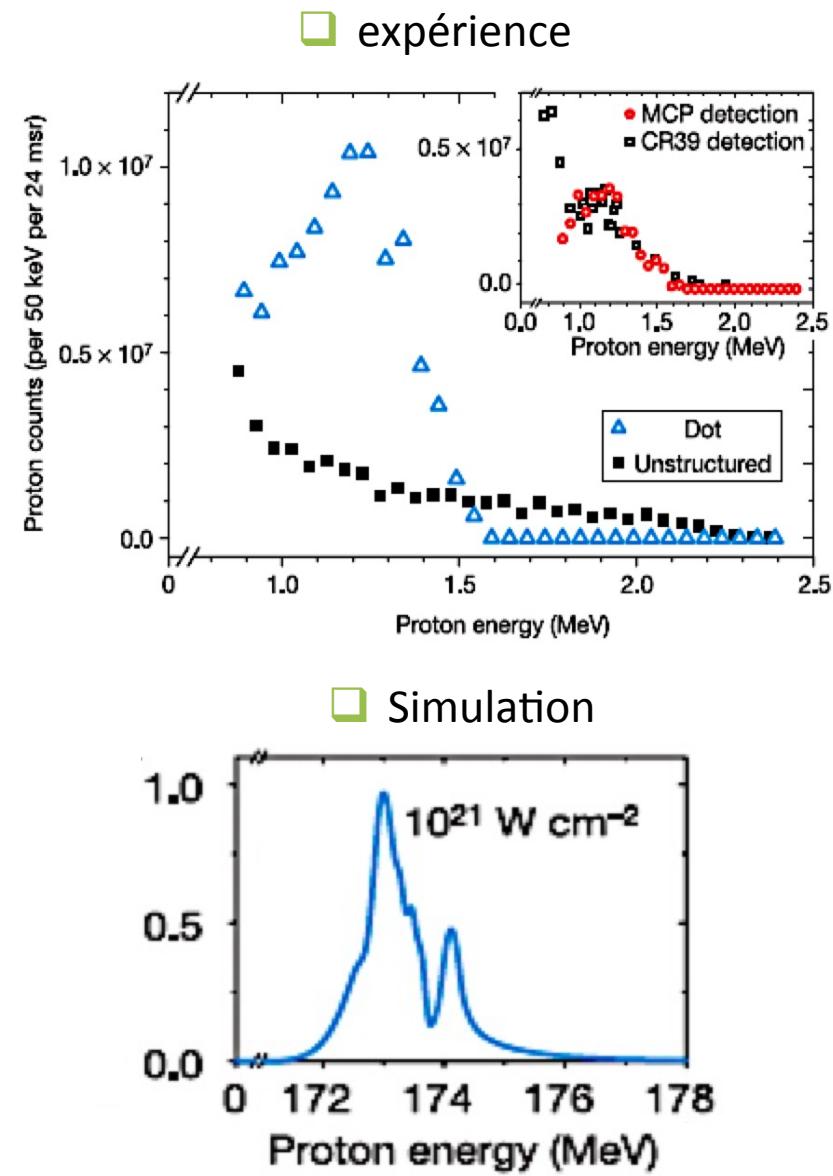
Champs électrostatiques

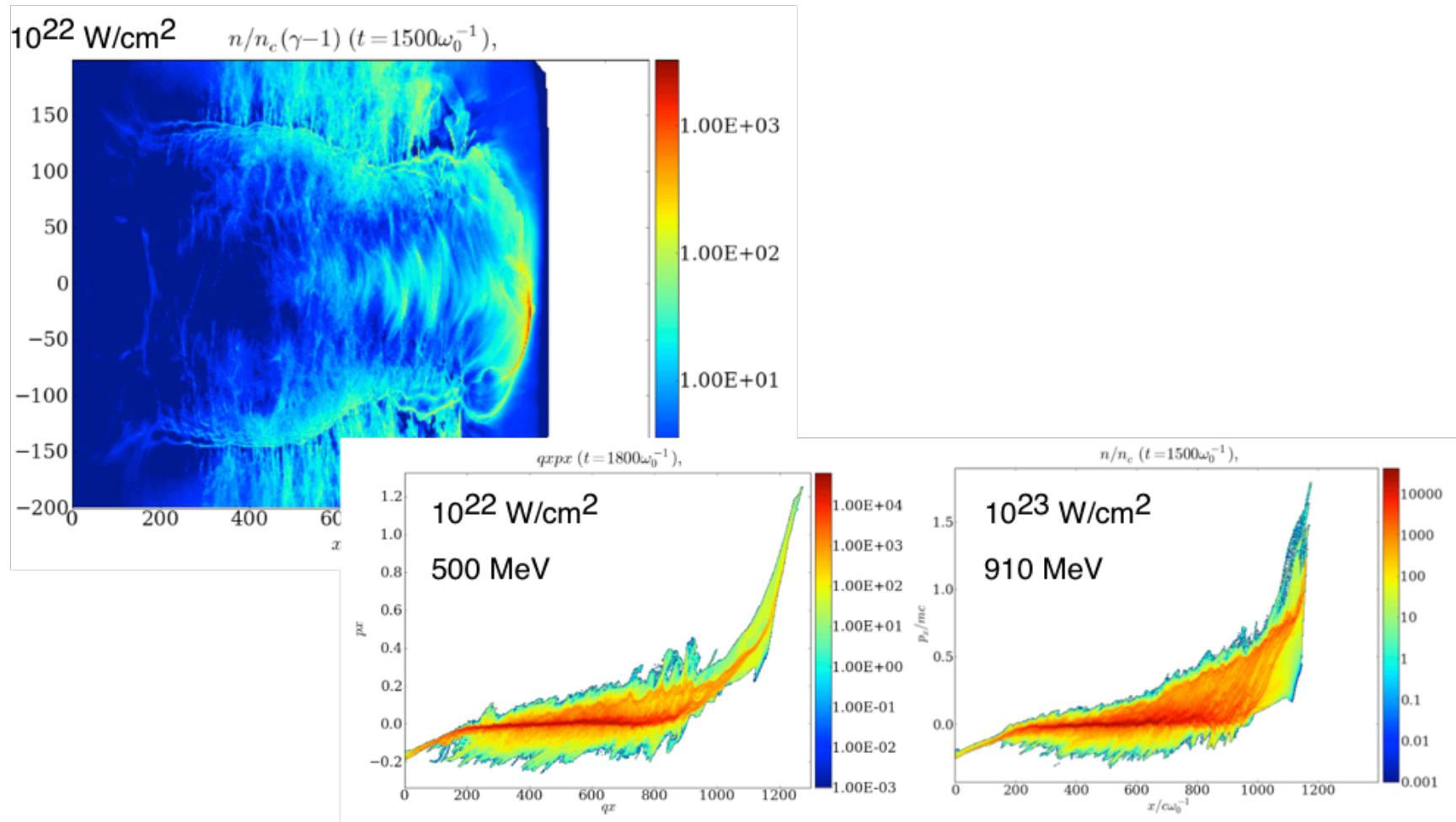
$I=10^{20} \text{ Wcm}^{-2}$, $\tau=36 \text{ fs}$ (image à 64 fs)

$I = 10^{21} \text{ Wcm}^{-2}$



H. Schwoerer et al, Nature, 439, 445 (2006)





E. d'Humières et al, Phys. Plas, **12**, 062704 2005

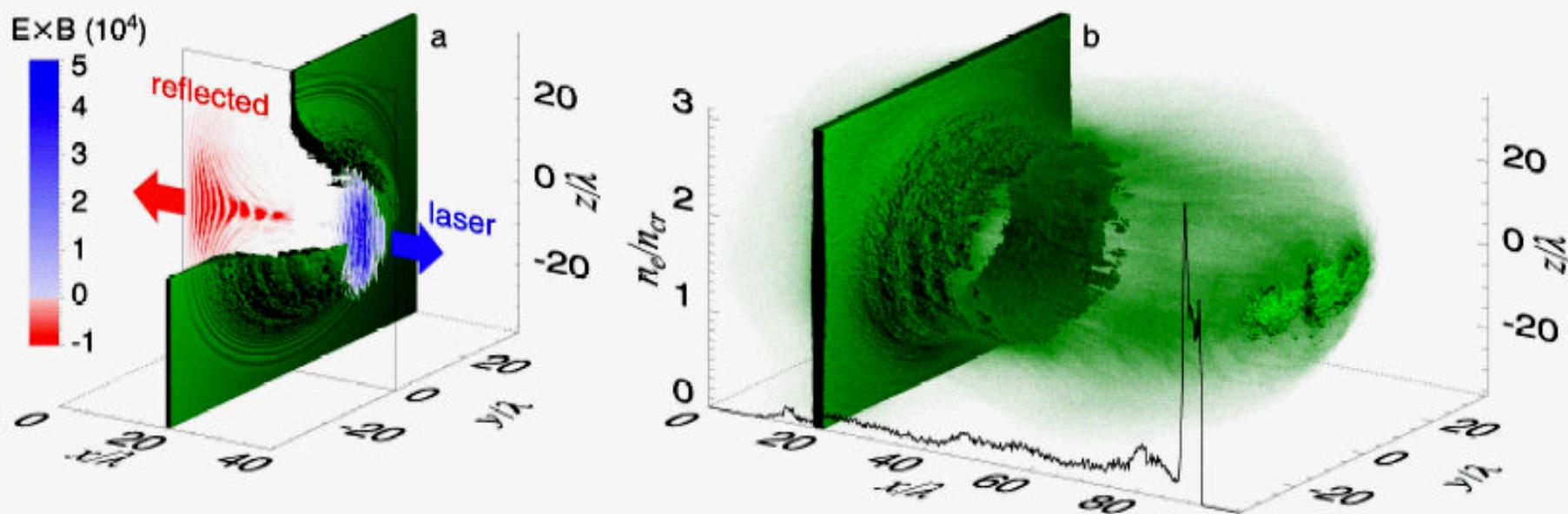
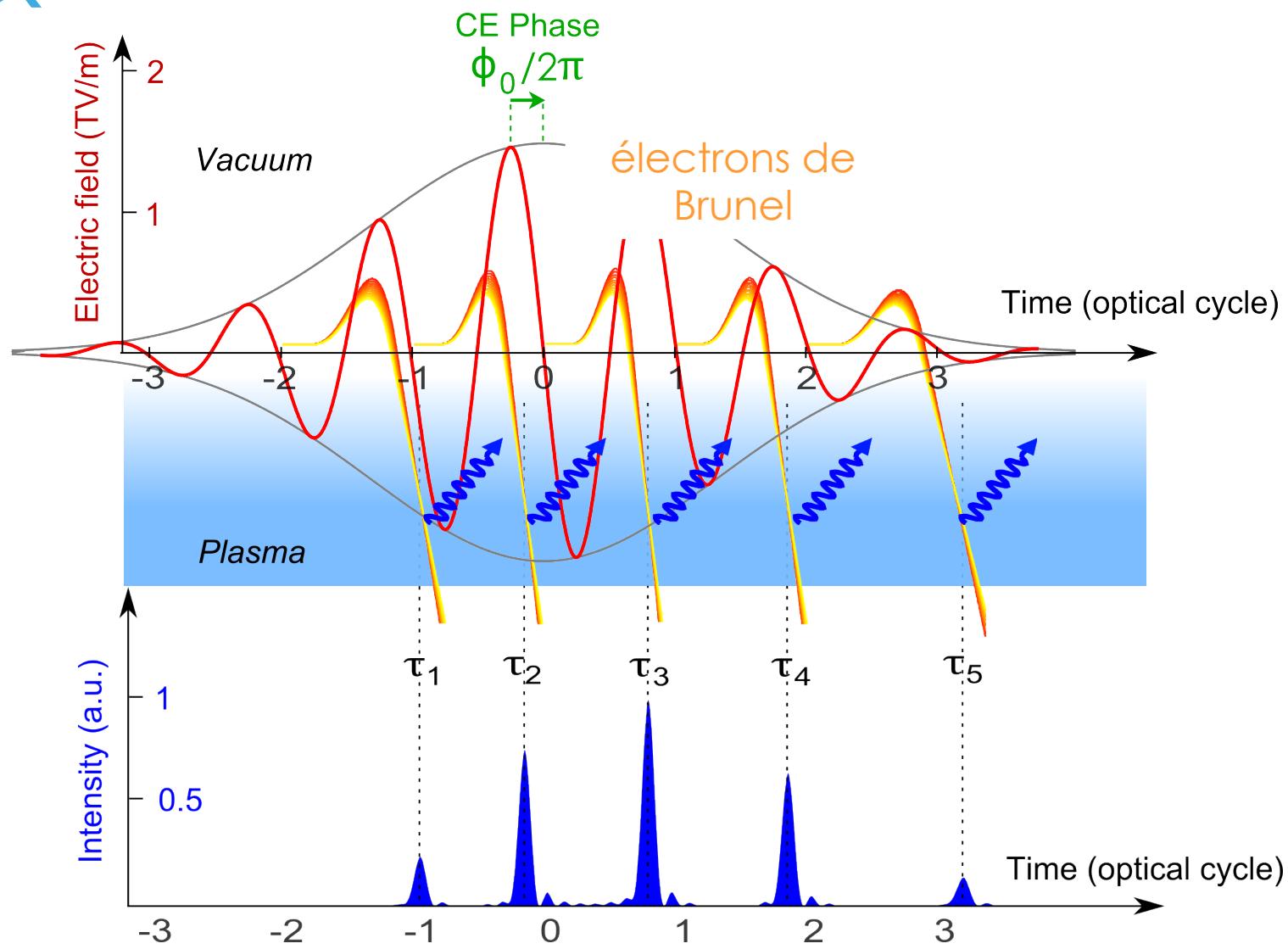


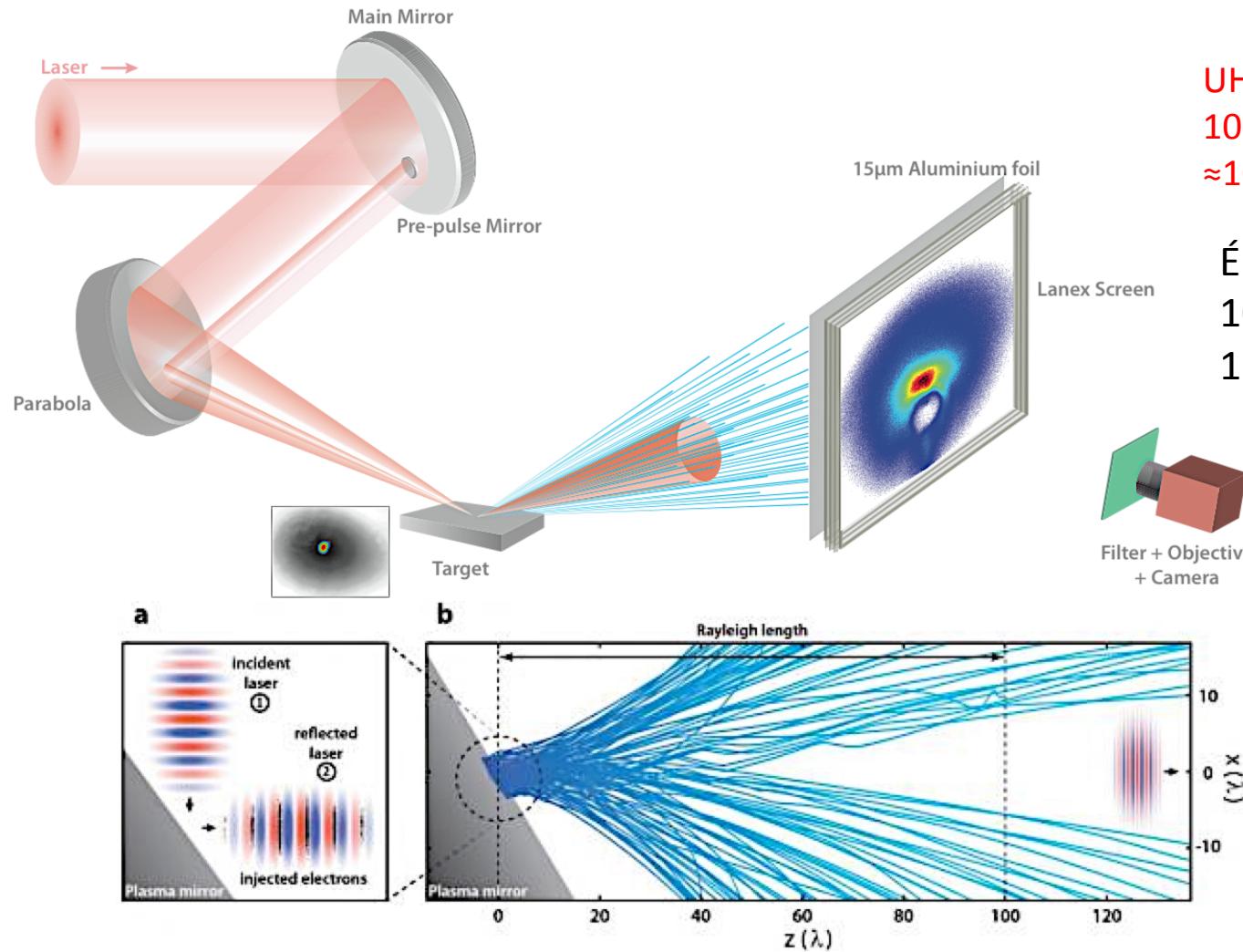
FIG. 1: (color). (a) The ion density isosurface for $n = 8n_{cr}$ (a quarter removed to reveal the interior) and the x -component of the normalized Poynting vector $(e/m_e\omega c)^2 \mathbf{E} \times \mathbf{B}$ in the $(x, y = 0, z)$ -plane at $t = 40 \times 2\pi/\omega$. (b) The isosurface for $n = 2n_{cr}$, green gas for lower density at $t = 100 \times 2\pi/\omega$; the black curve shows the ion density along the laser pulse axis.

Mécanisme dominant pour $I \geq 10^{23} \text{ Wcm}^{-2}$

T. Esirkepov et al, Phys. Rev. Lett., **92**, 17 (2004)

A. Macchi, High Power Laser Science and Engineering , **2**, e10 (2014)





UHI-LYDIL
100 TW, 25 fs, 10 Hz
 $\approx 10^{13}$ contrast

Électrons:
10 MeV,
12 nC

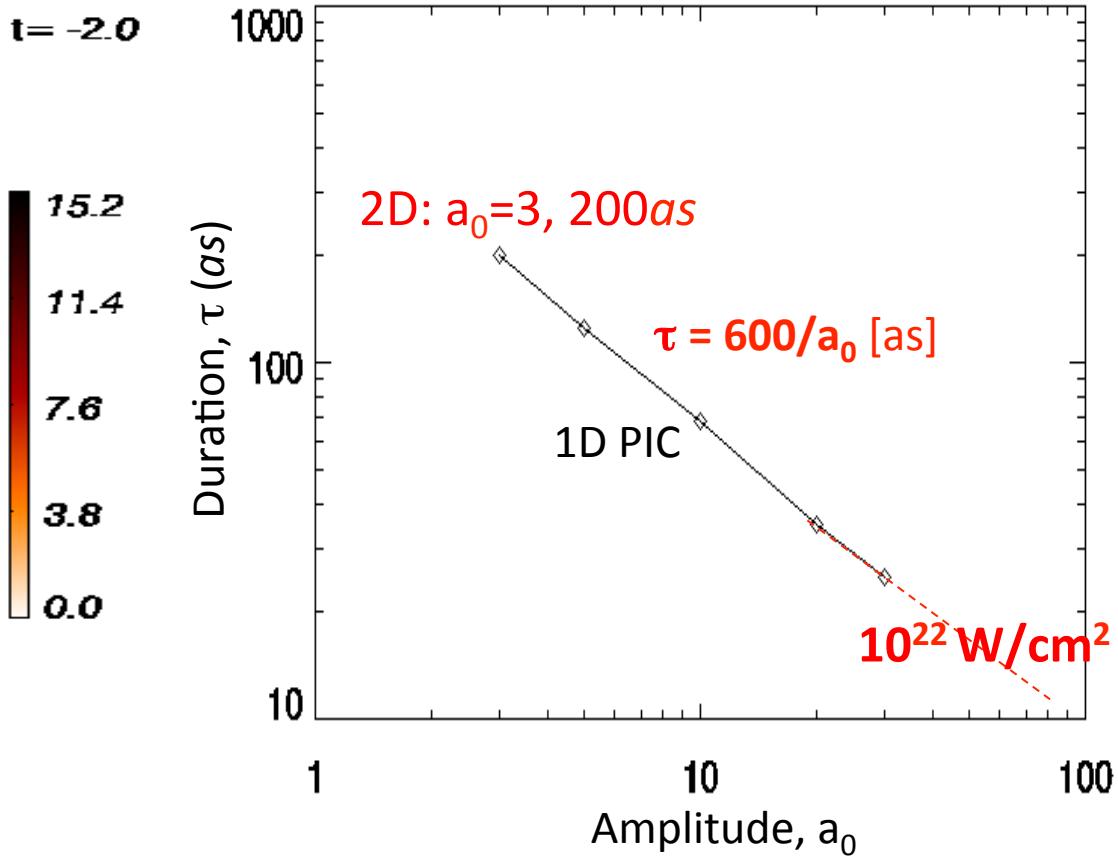
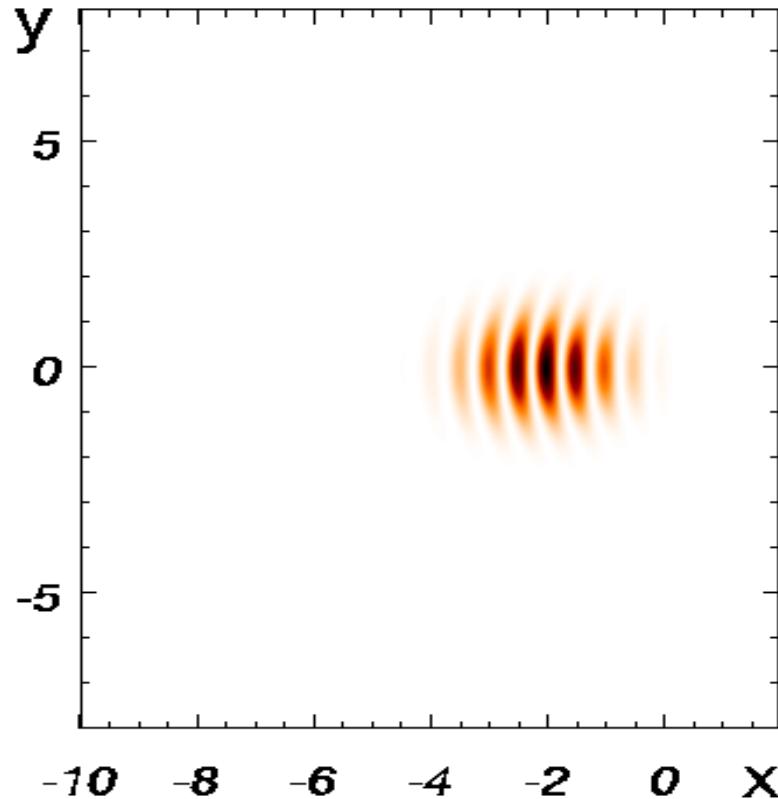
M. Thevenet, et al, Nature Physics, 12 (2016) 355.

E. Esarey, et al, Rev. Mod. Phys. 81, 1229 (2009)

Le régime dit “ λ^3 ”

Diam. tâche focale; durée $\sim \lambda$

$$a_0 = 3 \Rightarrow I \sim 2 \times 10^{19} \text{ Wcm}^{-2}$$



Naumova *et al.* Phys. Rev. Lett. 2004

Nees *et al.* J. Mod. Opt. 2005

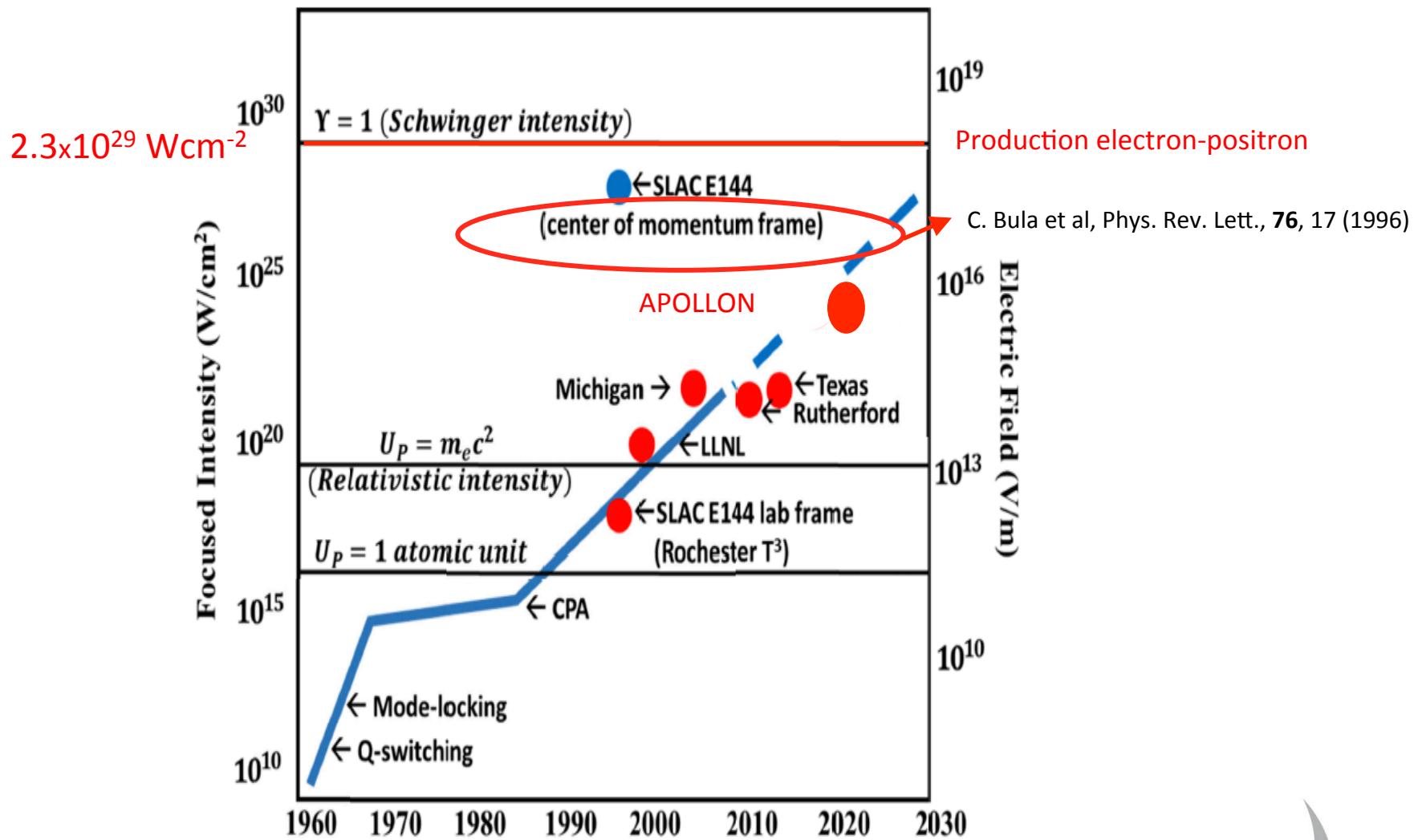
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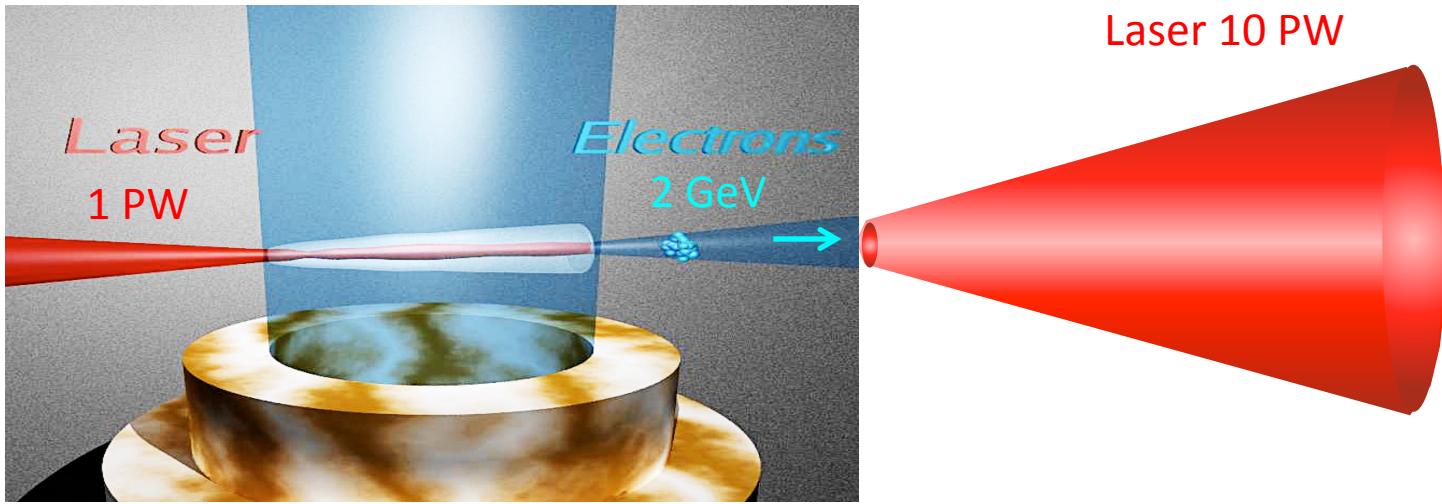
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- Dans le centre de masse:

$$\gamma = 4\,000 \Rightarrow \gamma^2 = 1.6 \times 10^7 \Rightarrow I_{cm} = 5 \times 10^{22} \times 1.6 \times 10^7 = 8 \times 10^{29} \text{ Wcm}^{-2}$$

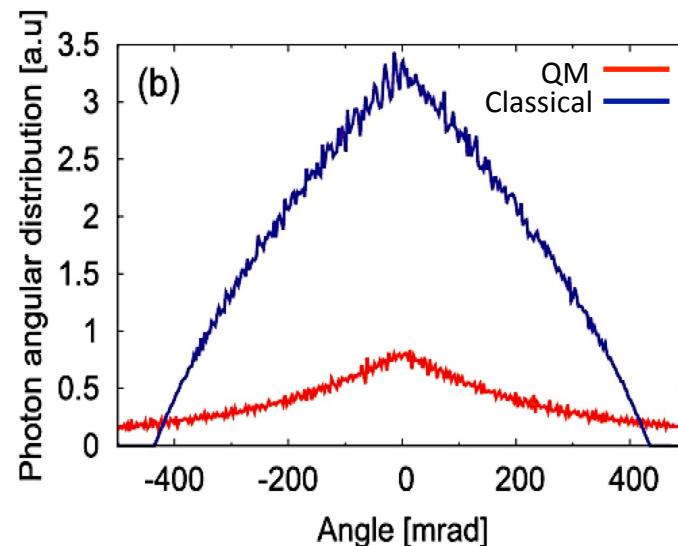
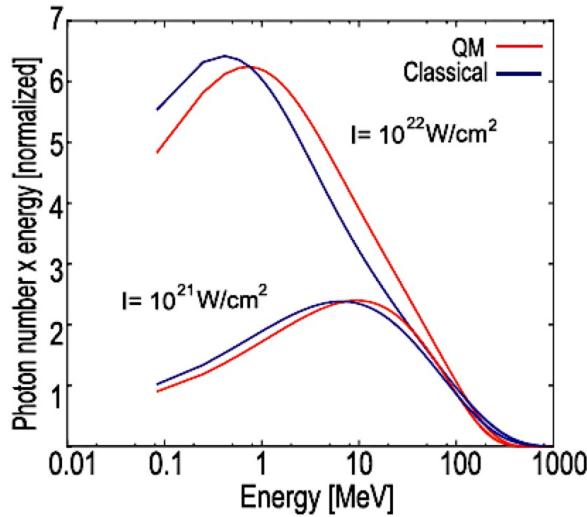
$$I_{Schwinger} = 2.3 \times 10^{29} \text{ Wcm}^{-2}$$

Ong et al, Phys. Plasmas **23**, 053117 (2016)

Radiation reaction

"The issue of "radiation reaction" (RR) is one of the **oldest and most fundamental problems in electrodynamics**" in A. Di Piazza et al, Rev. Mod. Phys., **84**, 3, 1177 (2012)

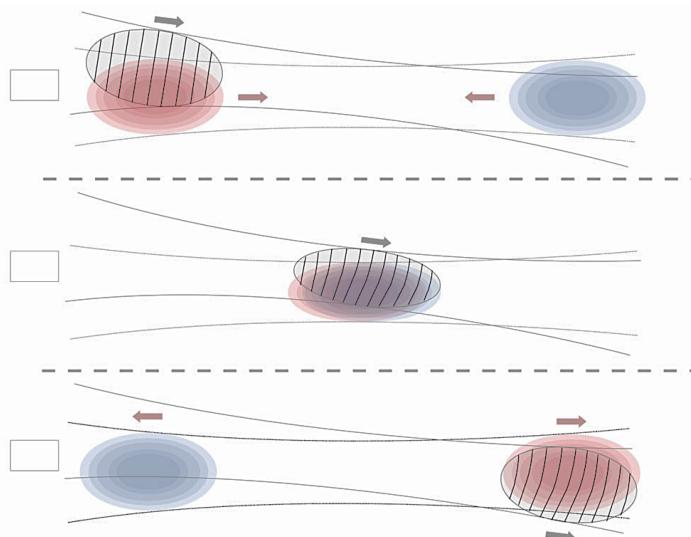
- "During the radiation emission, energy and momentum are lost, and it leads to **radiation reaction force** which is in the opposite direction of motion. As a result, the dynamic of electron is modified."
- "This configuration is widely utilized in the production of high energy radiation such as **Thomson backscattering**. (...) At these intensities ($a_0 \gg 1$), **the processes become nonlinear** and the effect of **radiation reaction** also comes into play. (...) Therefore, the production of γ rays at such intensities becomes subject of great interest to us." in Ong et al, Phys. Plasmas **23**, 053117 (2016)



- Classical radiation-dominated regime (CRDR) $R_C = \frac{2}{3} \alpha \frac{\hbar \omega_0}{mc^2} \gamma_0 a_0^2 (1 + \beta_x)$

$$E=2 \text{ GeV}, \gamma = 4000, a_0=224 \Rightarrow R_C = 3.8 (>1)$$

Biréfringence du vide induite par laser

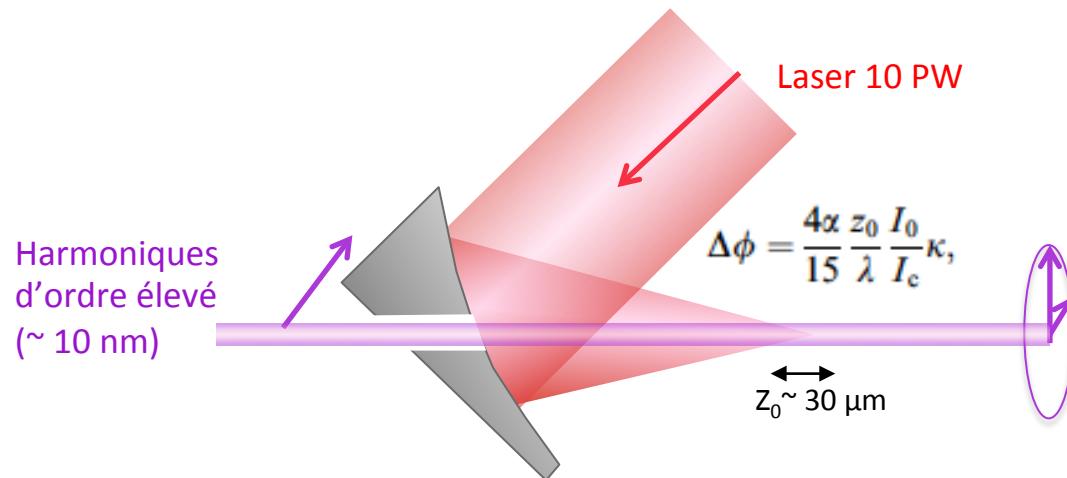


X. Sarazin et al, Eur. Phys. J. D (2016) 70: 13

$$\theta_{r,\max} = 2 \times 10^{-13} \times \left(\frac{w_0}{10 \mu\text{m}} \right)^{-3} \times \frac{I}{1 \text{ J}} \text{ rad.}$$



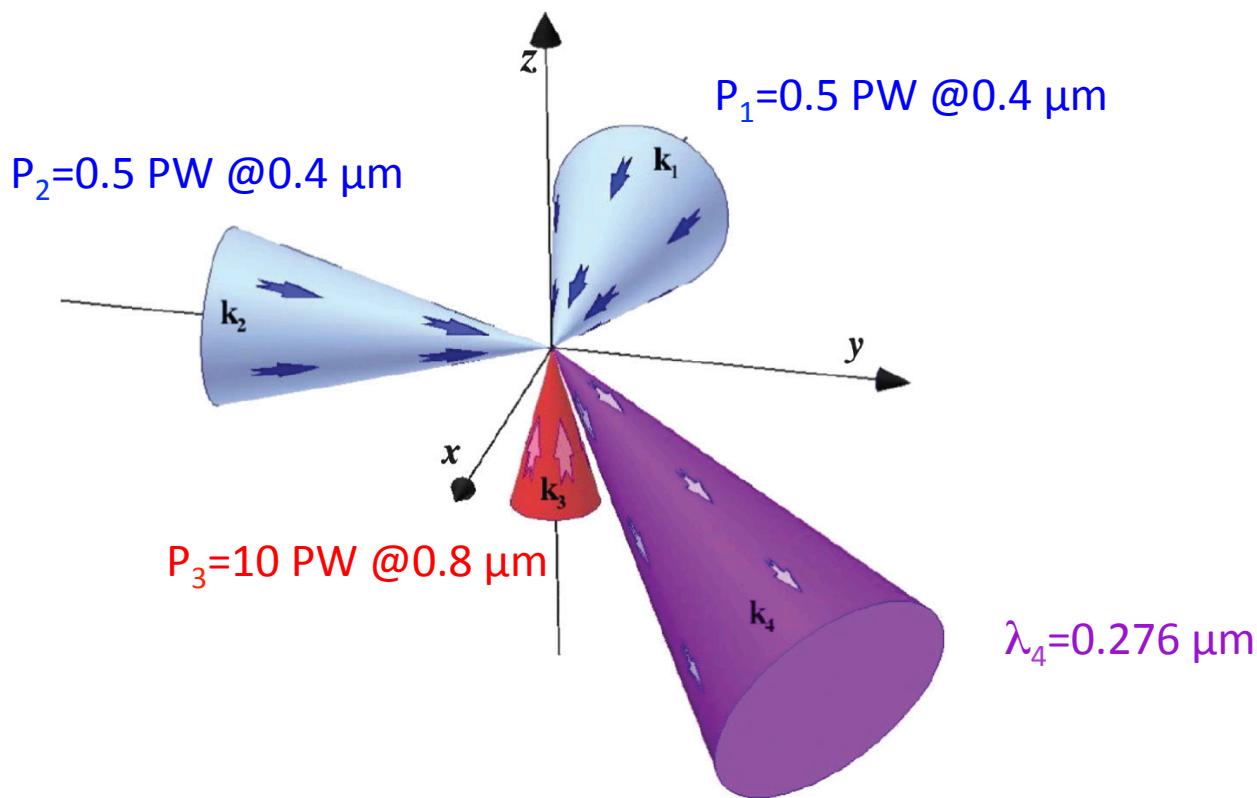
APOLLON 10 PW,
Waist = 5 μm => 0.2 nrad
Waist = 2 μm => 3.7 nrad



T. Heinzl et al., Optics Comm. 267 318–321 (2006)

$$\uparrow = \circlearrowleft + \circlearrowright$$

APOLLON 10 PW
 $n_g = 1 + 7 \times 10^{-9}$ $n_d = 1 + 4 \times 10^{-9}$
 $\Delta\phi = 2\pi z_0 (n_g - n_d) / \lambda \sim 6 \times 10^{-5} \text{ rad}$
 $\delta^2 = 3.6 \times 10^{-9}$



$$N_\gamma \approx 0.25 \frac{P_1[\text{PW}]P_2[\text{PW}]P_3[\text{PW}]}{(\lambda_4[\mu\text{m}])^3}. \Rightarrow N_{0.276\mu\text{m}} \sim 30 \text{ photons /tir}$$

J. Lundin et al, Phys. Plasmas **14**, 064503 (2007)
E. Lundström, et al, Phys. Rev. Lett. **96**, 083602 (2006)

F. Moulina et al, Opt.Commun. **164**, 137 (1999)
D. Bernard et al., **10**, 1, pp 141–145 (2000)

Conclusions

- ❑ APOLLON est en une installation de physique fondamentale, entourée d'installations laser plus versatiles où les applications sociétales devraient se développer.
- ❑ APOLLON va maintenir la France au premier rang de la communauté internationale des lasers ultra-intenses.
- ❑ 3 schémas d'accélération seront étudiés, un quatrième est en projet à l'université Paris-Sud; des électrons de ≈ 20 GeV devraient être produits.
- ❑ APOLLON devrait produire des protons relativistes (≈ 1 GeV) ...pour des applications en nucléosynthèse par spallation.
- ❑ Des études fondamentales de QED non-linéaire sont réalisables.
- ❑ Le passage à 10 PW va ouvrir de nombreux nouveaux horizons.



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Merci de votre attention



— TERRE D'AVENIRS —

