DE LA RECHERCHE À L'INDUSTRIE

Simulation PIC de l'interaction laser-plasma à ultra-haute intensité et applications aux lasers PETAL et APOLLON

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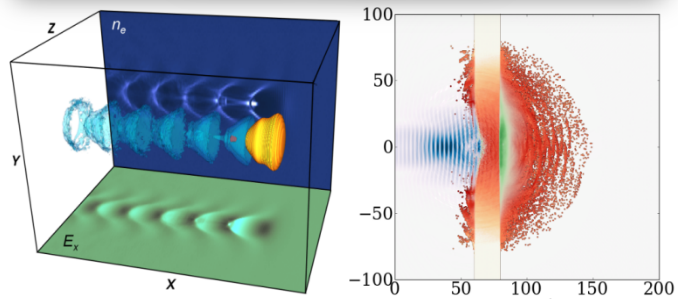
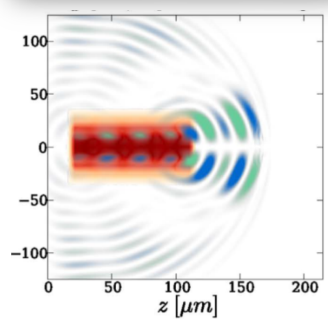
Forum ILP – 11/06/2018

Utilisation des lasers UHI pour diverses applications

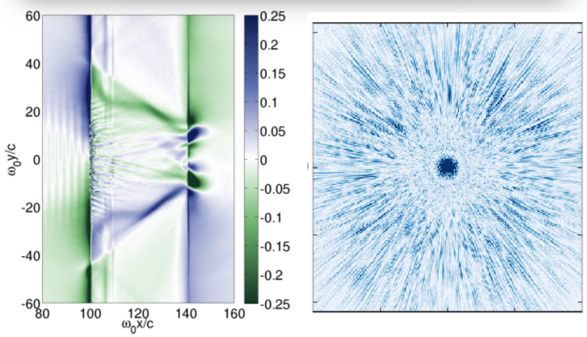
Sources de particules



Sources X, γ, THz



Etudes fondamentales



Lasers « habituels » : ~30 fs, ~100 TW, ~J, ~$10^{18\text{-}20}$ W/cm^2

PETAL : ~kJ, ~500 fs, ~PW, W_0~50 µm

APOLLON : ~100 J, ~10 PW, ~10^{23} W/cm^2

Objectif 1 : Présenter une sélection d'études réalisées autour d'APOLLON et PETAL

Objectif 2 : Montrer les développements réalisés dans le code CALDER afin de modéliser ces cas

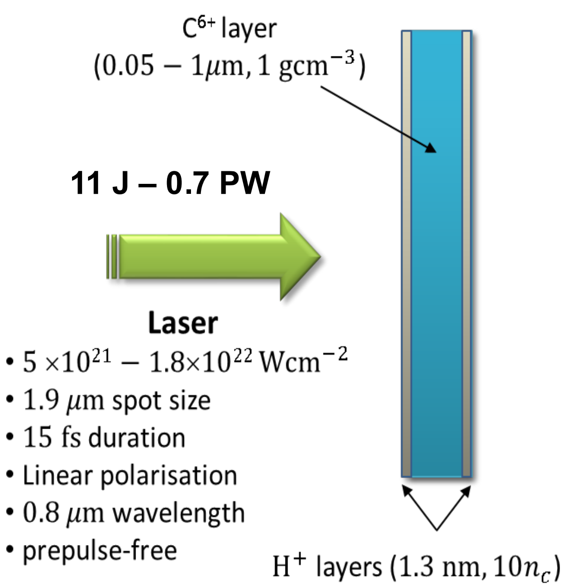
- Ajout de modèles physiques/numériques

Accélération d'ions avec APOLLON (1 PW)

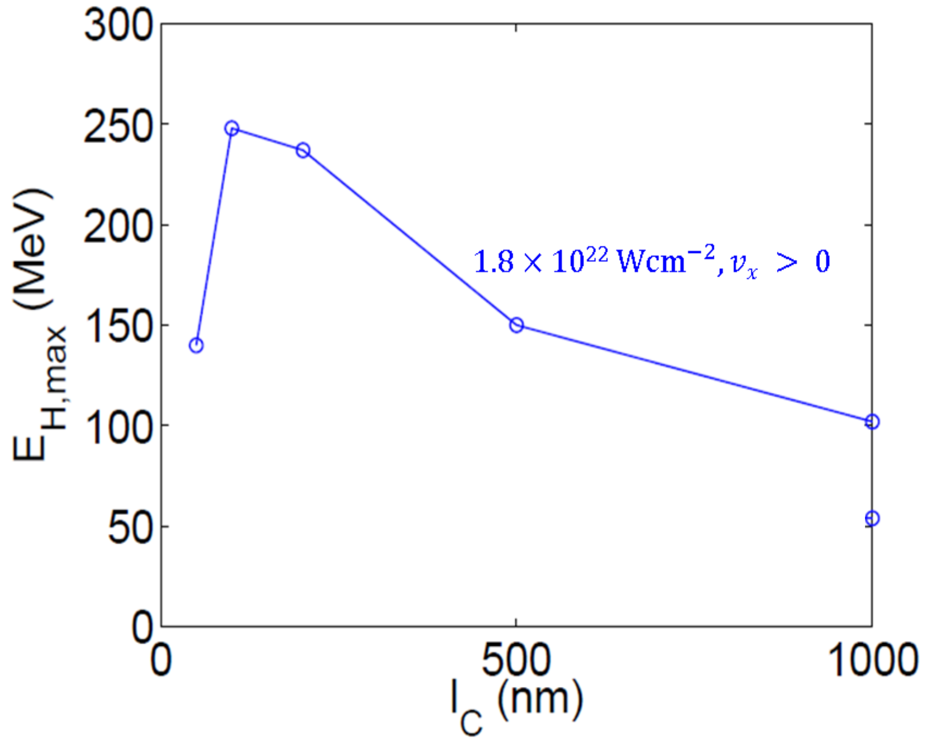
Optimisation de l'épaisseur de la cible

Prospective study of ion acceleration under Apollon laser conditions

2D PIC (CALDER) simulations



Maximum proton energies

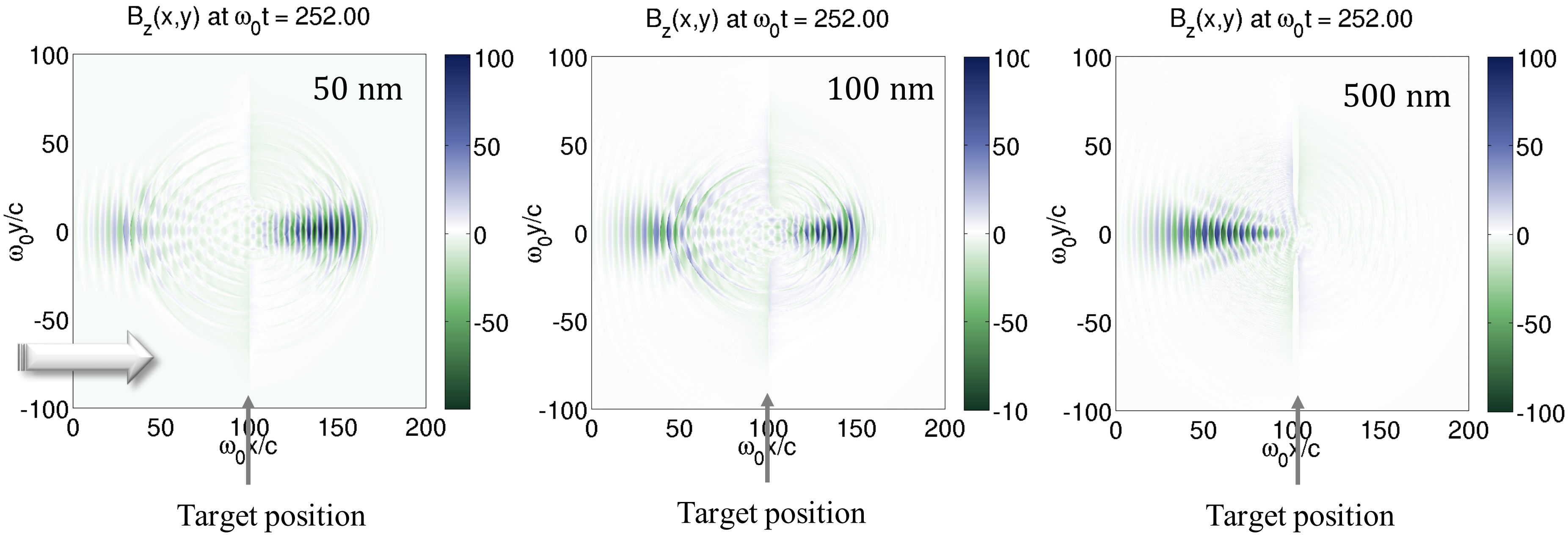


- Peak proton energies (~ 250 MeV) achieved for $100 - 200$ nm targets irradiated at $1.8\times10^{22}\ Wcm^{-2}$.
- Optimum target thickness close to theoretical estimate[1], $l_{opt}/\lambda_L \simeq (a_L/\pi)n_c/n_e$.

[1] T. Esirkepov *et al.*, Phys. Rev. Lett. **96**, 105001 (2006)

Maximum proton energies obtained for comparable laser reflection and transmission[1,2]

Magnetic field [10^4 T] at 1.8×10^{22} Wcm^{-2}



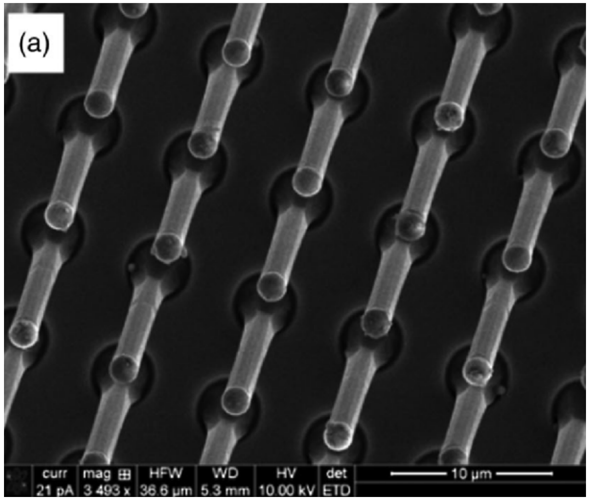
Thickness	Transmission	Reflection
50 nm	80%	10%
100 nm	50%	30%
500 nm	0.2%	75%

- In the optimal targets, ion acceleration proceeds through a mix of "leaky" RPA and rear-side TNSA

[1]E. d'Humières *et al.*, Phys. Plasmas **12**, 062704 (2005)
[2]T. Esirkepov *et al.*, Phys. Rev. Lett. **96**, 105001 (2006)

Accélération d'ions avec APOLLON (150 J – 5 PW)

Modélisation de cibles ou faisceaux laser plus complexes ou réalistes

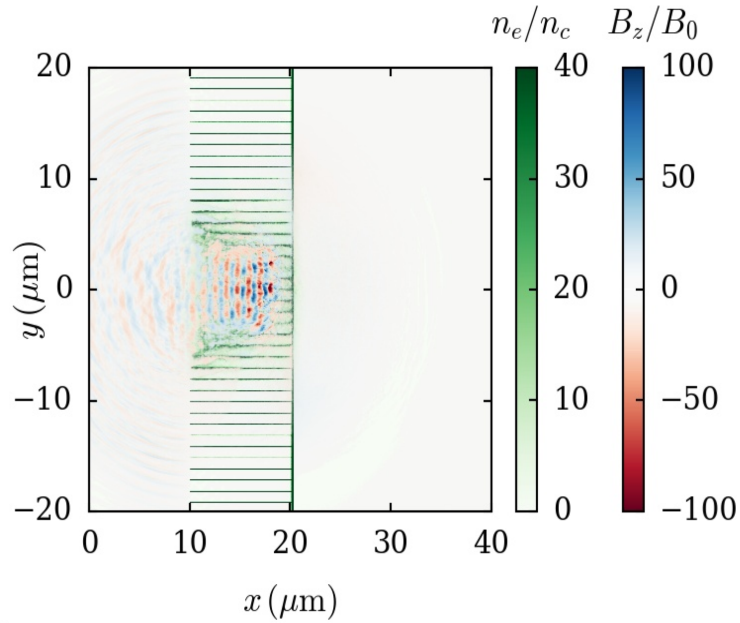


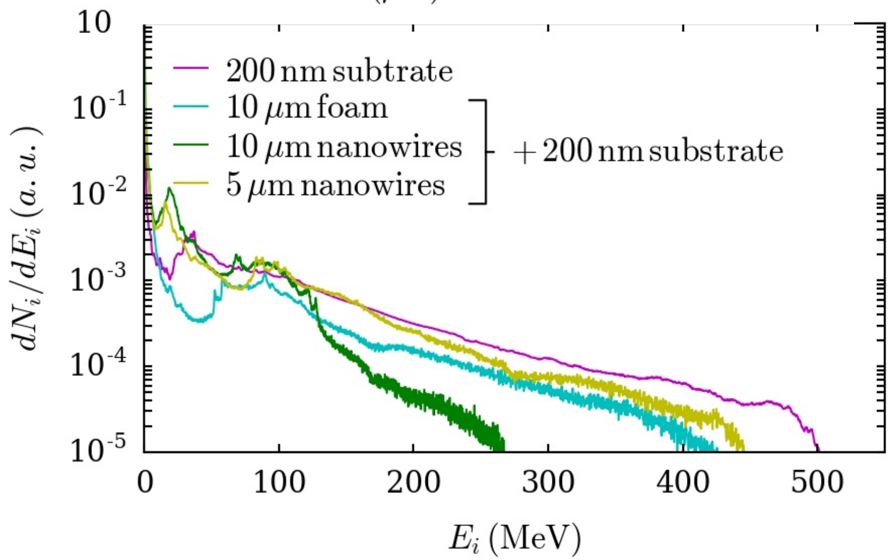
C. Bargsten *et al.,* Sci. Adv. **3**, 1601558 (2017).
S. Jiang *et al.,* Phys. Rev. Lett. **116**, 085002 (2016).

Étude PIC du potentiel des nanofils pour l'accélération ionique dans les conditions Apollon[1]

- **Laser parameters (~150 J, 5 PW):**
  - $I_L = 10^{22}$ Wcm^{-2} ($a_L = 85$)
  - $\tau_L = 30$ fs
  - $w_L = 5\ \mu$m
- **Nanowire-array parameters:**
  - $5 - 10\ \mu$m length.
  - 35nm width.
  - $1\ \mu$m interwire spacing

  $\Rightarrow n_{av} = 16 n_c \simeq 0.03 n_{sol}$
  - Nanowires coated on a $100 - 300$ nm thick CH_2 foil.
- **Preliminary results:**
  - 200 nm planar foil: $E_{p,max} \simeq 500$ MeV.
  - $5\ \mu$m nanowires + 200 nm foil: $E_{p,max} \simeq 440$ MeV.
  - Equivalent-density ($n_e = 16 n_c$) foam + 200 nm planar foil: $E_{p.max} \simeq 420$ MeV.
  - Ion acceleration takes place in the relativistic transparency regime: $T \simeq 24\%$ for $L = 5\ \mu$m wires + 200 nm foil.





[1]B. Martinez, thèse CEA/DIF/DPTA (2018).

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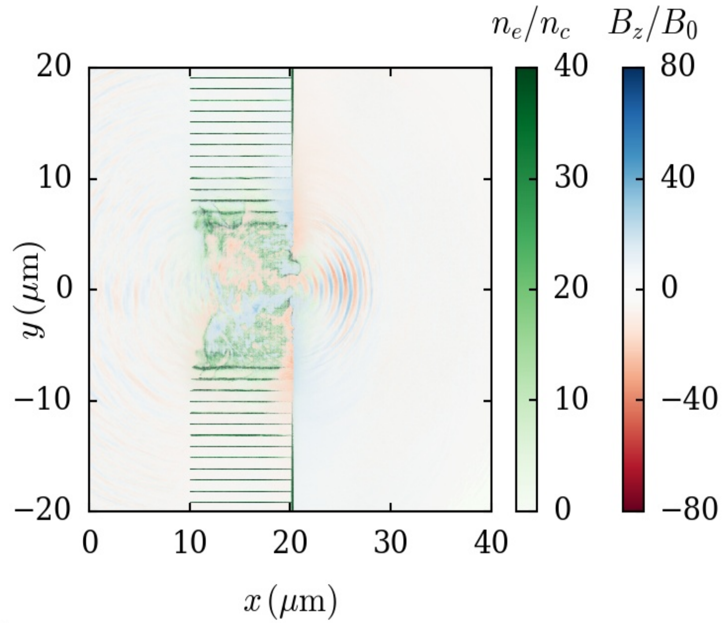
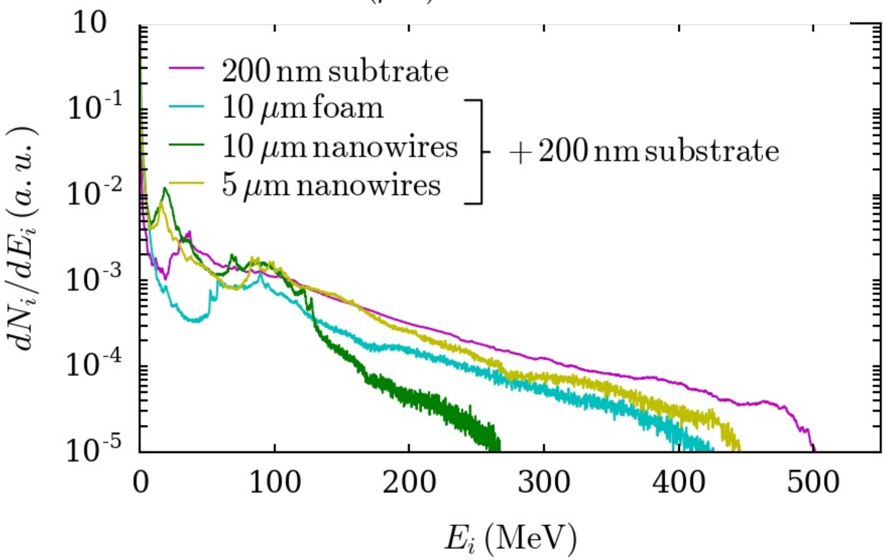
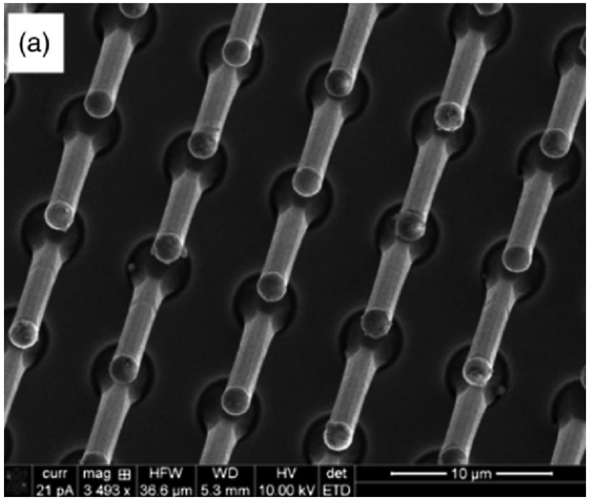




[1]B. Martinez, thèse CEA/DIF/DPTA (2018).

Production de rayonnement sur cibles solides (APOLLON)

Ajouts de modèles physiques

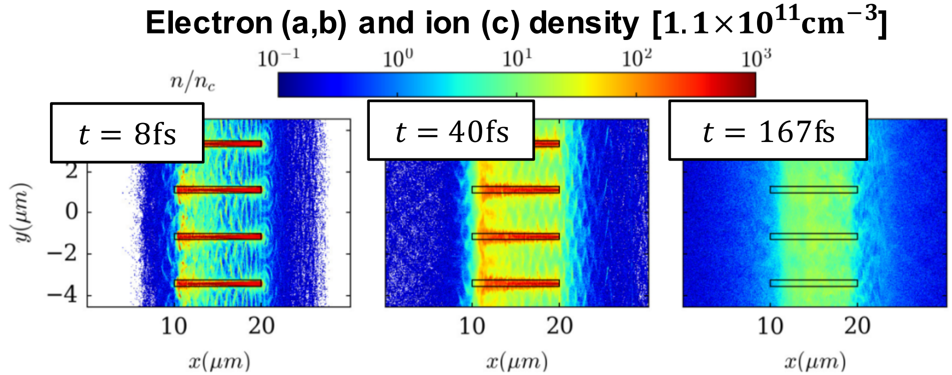


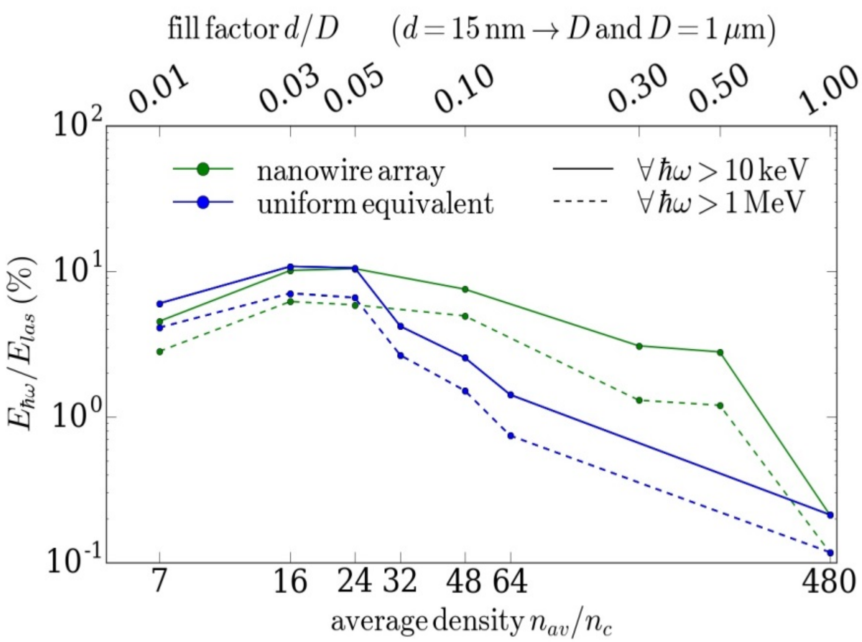
C. Bargsten *et al.,* Sci. Adv. **3**, 1601558 (2017).
S. Jiang *et al.,* Phys. Rev. Lett. **116**, 085002 (2016).

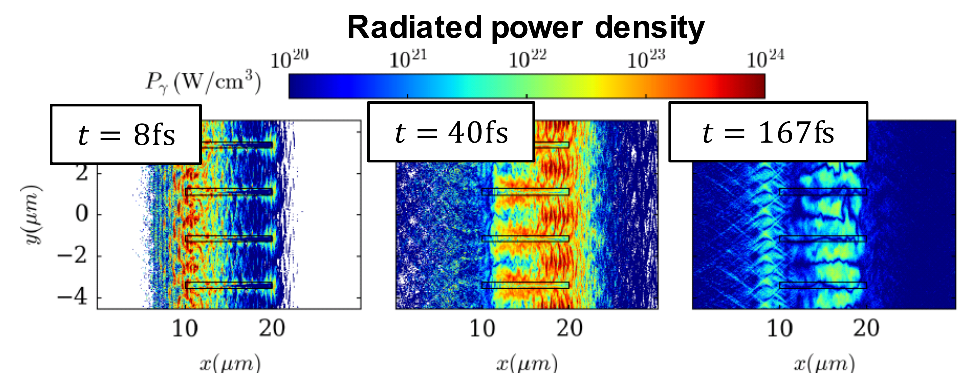
Grand potentiel[1] des micro-fils en tant que sources synchrotron X/γ intenses avec $I_L > 10^{22}\ \mathrm{Wcm^{-2}}$

Laser parameters:
- $I_L = 10^{22}\ \mathrm{Wcm^{-2}}$
- $\tau_L = 30\ \mathrm{fs}$
- planar wave

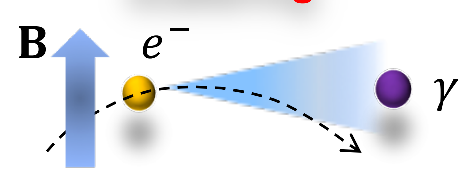
Wire parameters:
- solid-density carbon
- $L = 10\ \mu m$
- $D = 1\ \mu m - 2.25\ \mu m$
- $d = 0.3\ \mu m$







Synchrotron emission / nonlinear inverse Compton scattering

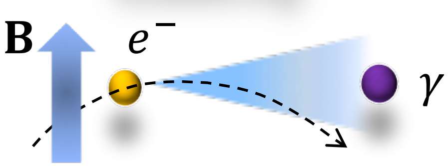


[1] B. Martinez *et al.*, submitted to Plasma Phys. Control. Fusion (2018).

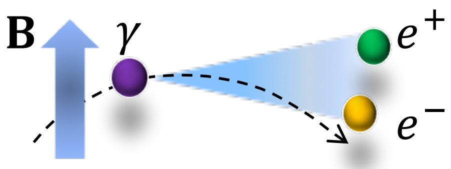
Laser-particle interactions at intensities $\gtrsim 10^{22}$ Wcm^{-2} trigger strong radiative and quantum electrodynamics (QED) effects[1,2]

- Photon and pair generation processes mediated by an *electromagnetic field*

Synchrotron emission / nonlinear inverse Compton scattering

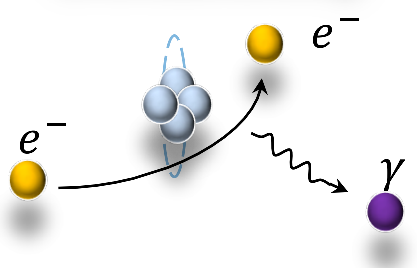


Multi-photon Breit-Wheeler

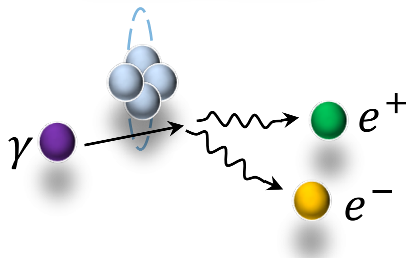


- Photon and pair generation processes mediated by an *atomic Coulomb field*

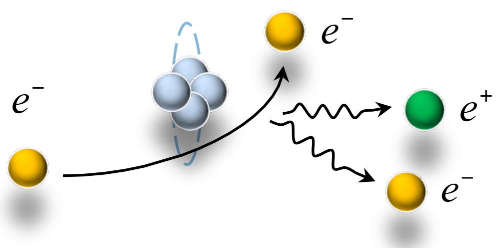
Bremsstrahlung



Bethe-Heitler



Coulomb Trident



- Plasma and QED processes become significantly coupled at intensities $\gtrsim 10^{22}$ Wcm^{-2}
  $\Rightarrow$ Need of self-consistent QED models within PIC codes[3-6].

[1]A. Bell *et al*., Phys. Rev. Lett. **101**, 200403 (2008)
[2]A. Di Piazza *et al*., Rev. Mod. Phys. **84**, 1177 (2012).
[3]R. Duclous *et al*., Plasma Phys. Control. Fusion **53**, 015009 (2011).
[4]A. Gonoskov *et al*., Phys. Rev. E **92**, 023305 (2015).
[5]M. Lobet *et al*., J. Phys.: Conf. Ser. **688**, 012058 (2016).
[1]B. Martinez, thèse CEA/DIF/DPTA (2018).

Synchrotron/Bremsstrahlung competition in Cu foils of varying thickness irradiated at $I = 10^{22}$ Wcm^{-2}

Laser parameters

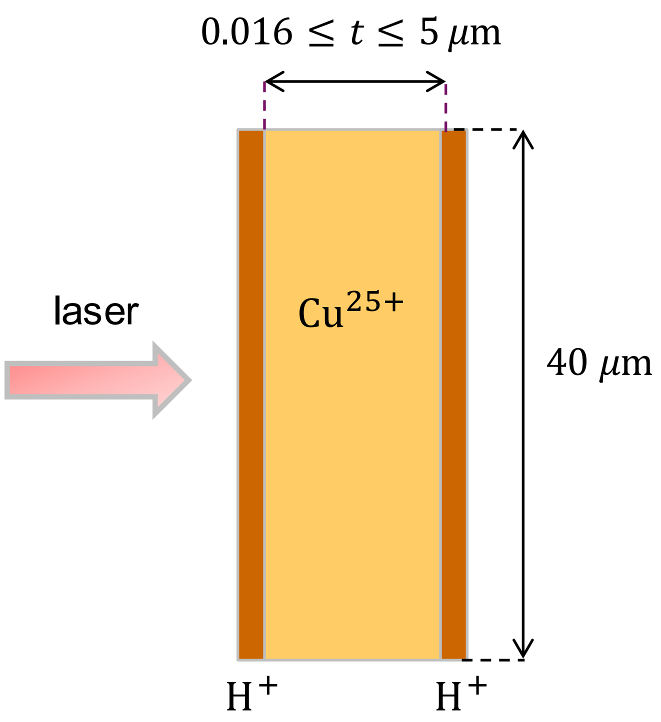
- $I_{max} = 10^{22}$ Wcm^{-2}.
- $\lambda_0 = 1\ \mu$m.
- Spot size $w_0 = 5\ \mu$m (Gaussian envelope).
- Duration $\tau_0 = 50$ fs (Gaussian envelope).

Target parameters

- Pre-ionized, Cu^{25+} target of $40\ \mu$m width and variable thickness.
- Solid density, $n_{Cu} = 80 n_c$.
- 3 nm thick proton layers at front and back sides with $n_H = 50 n_c$.
- Sharp density gradients at target sides.

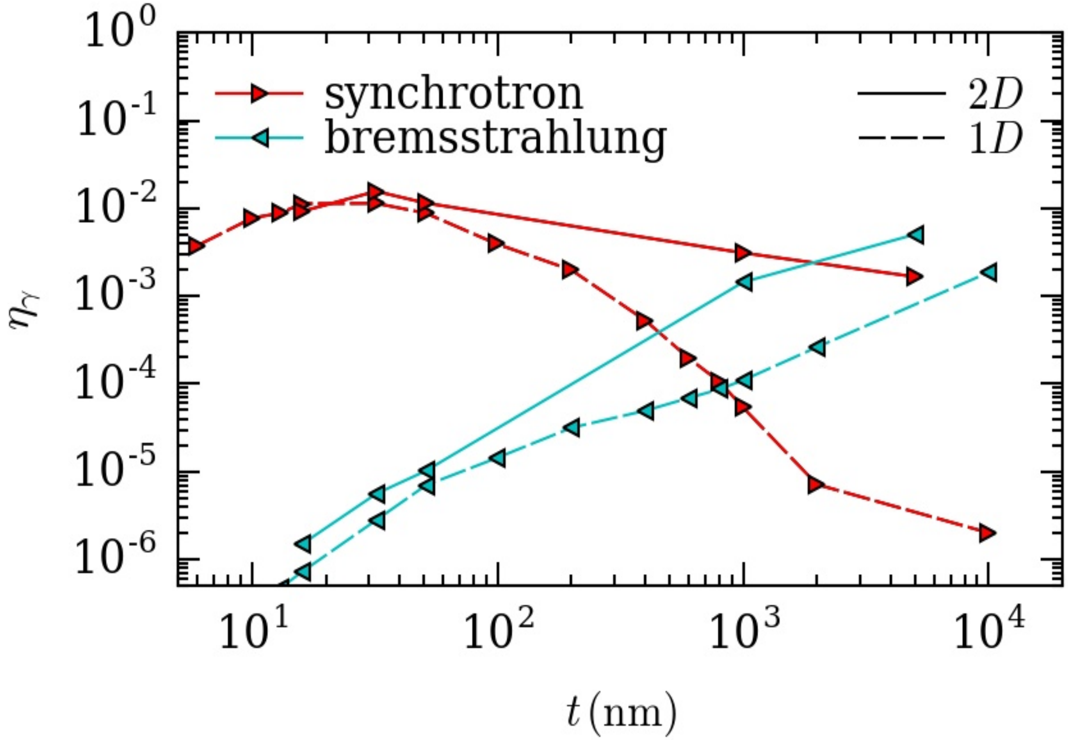
2D numerical setup (CALDER code)

- $\Delta x = \Delta y = 3.2$ nm.
- Domain size $64 \times 64\ \mu$m^2.
- Total duration $\sim 0.5 - 1$ ps.
- From 10 to 20 000 particles per cell.
- Absorbing boundary conditions for fields & particles.
- Field and impact ionization.
- Binary Coulomb collisions.
- Bremsstrahlung and synchrotron emissions.



Synchrotron radiation prevails for $\lesssim 2\ \mu m$ foils, while Bremsstrahlung increasingly dominates in thicker foils

Synchrotron & Bremsstrahlung conversion efficiencies



- Synchrotron emission occurs during laser pulse, with maximum yield $\sim 1.6\%$ in $\sim 30\ \mathrm{nm}$ thick foil.
- Bremsstrahlung occurs during fast-electron relaxation, with maximum yield $\sim 0.5\%$ in $10\ \mu m$ foil.

Production de rayonnement sur cibles solides (PETAL)

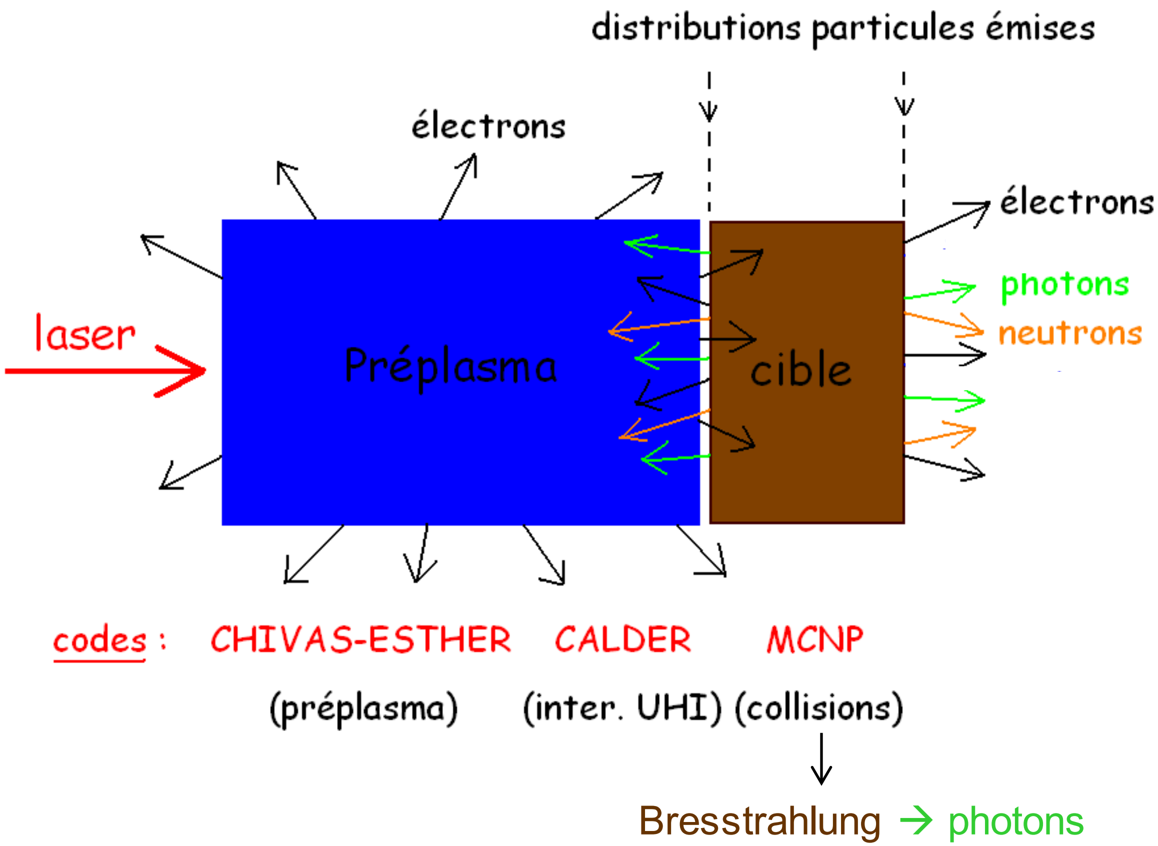
Couplage de codes

Cible épaisse : couplage CHIVAS/ESTHER – CALDER – MCNP

Caractéristiques laser : E_{laser} = 1,3 kJ, f_{FWHM} = 50 μm, 1 ps, a_0 = 7.93, contraste = 10^7

Cible de **tantale de 2 mm d'épaisseur**

Cas simulés (2D/3D) avec CALDER : n_e/n_{cr} = 0.1-10, L_p = 30 μm



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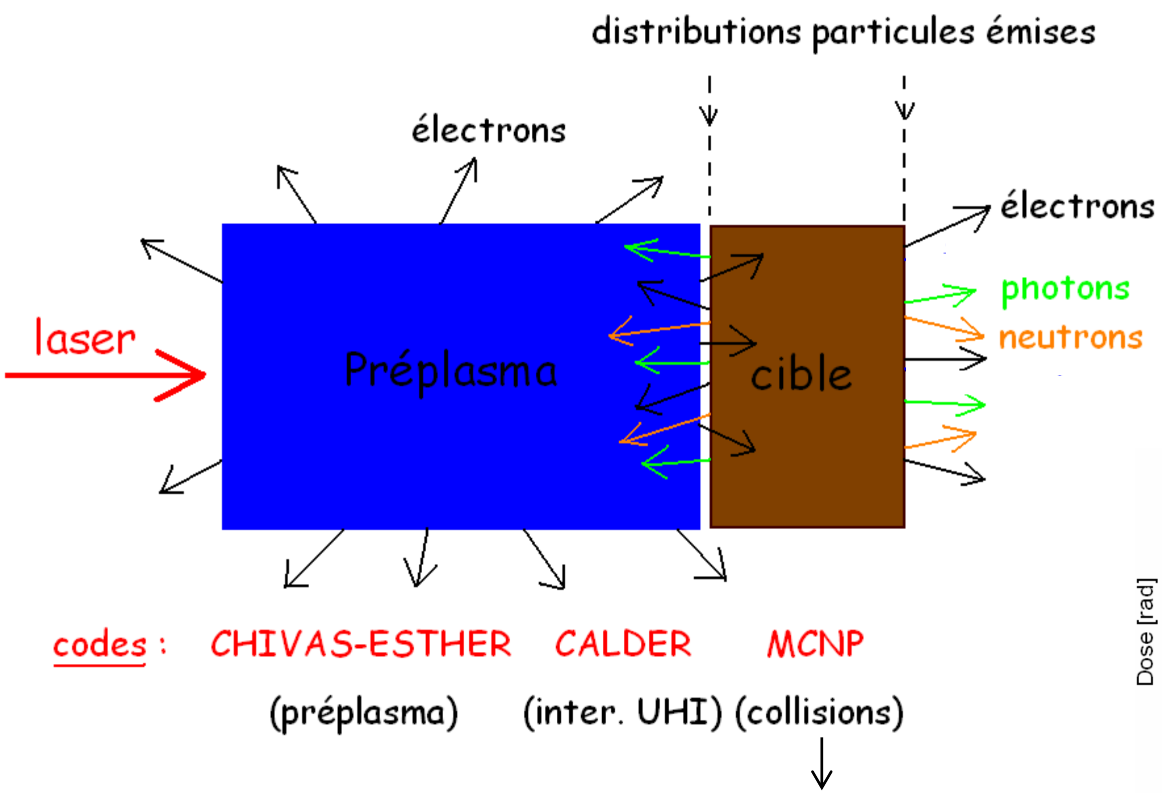
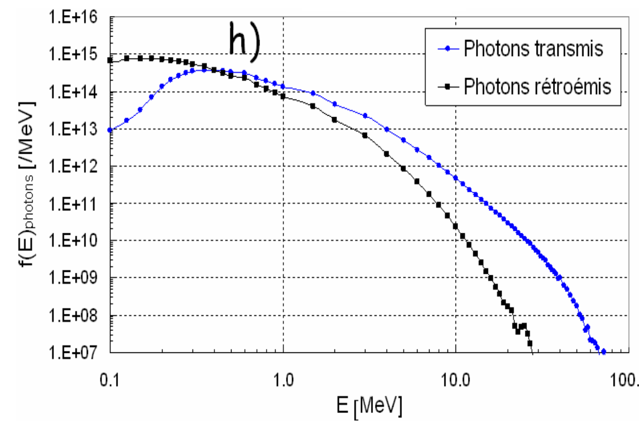
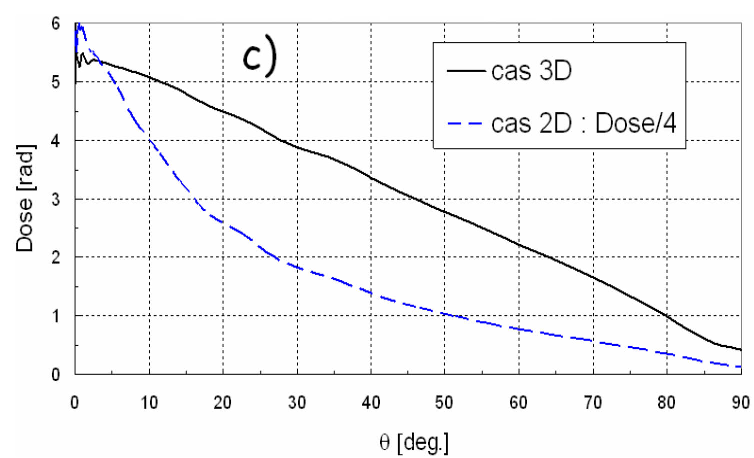


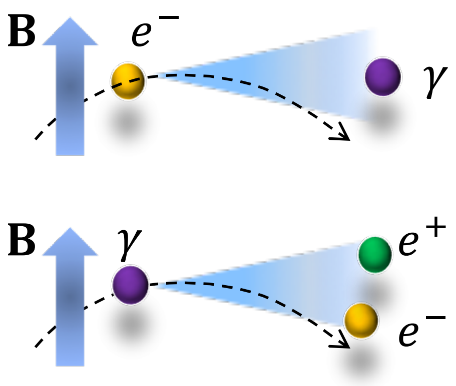
Bresstrahlung → photons



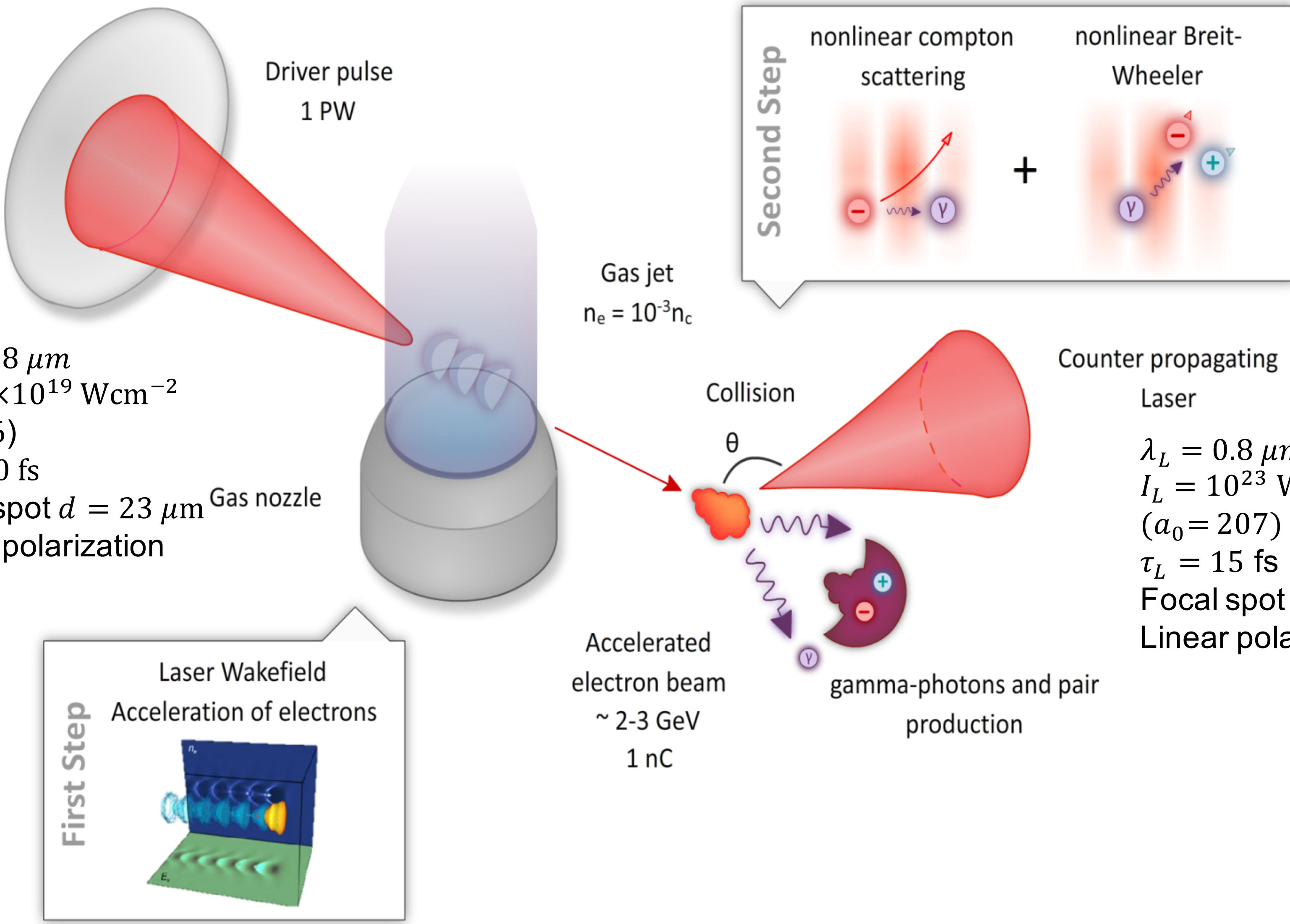


Effets QED et sources de positrons (APOLLON)

Couplage CALDER-CIRC / CALDER 3D



Pair production on the upcoming multi-PW CILEX-Apollon laser system[1]

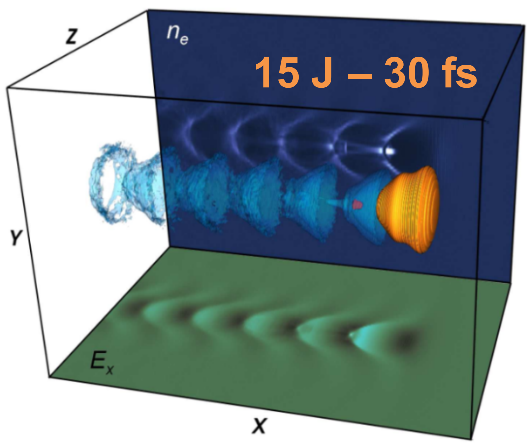


$\lambda_L = 0.8\ \mu m$
$I_L = 8{\times}10^{19}\ \mathrm{Wcm}^{-2}$
$(a_0 = 6)$
$\tau_L = 30$ fs
Focal spot $d = 23\ \mu m$
Linear polarization

$\lambda_L = 0.8\ \mu m$
$I_L = 10^{23}\ \mathrm{Wcm}^{-2}$
$(a_0 = 207)$
$\tau_L = 15$ fs
Focal spot $d_L \geq 2 \mu m$
Linear polarization

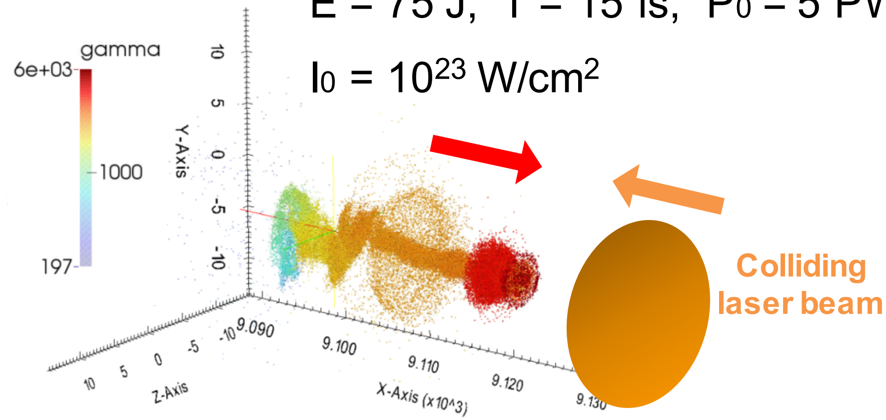
[1] M. Lobet *et al.*, PRAB **20**, 043401 (2017).

Pair production on the upcoming multi-PW CILEX-Apollon laser system[1]

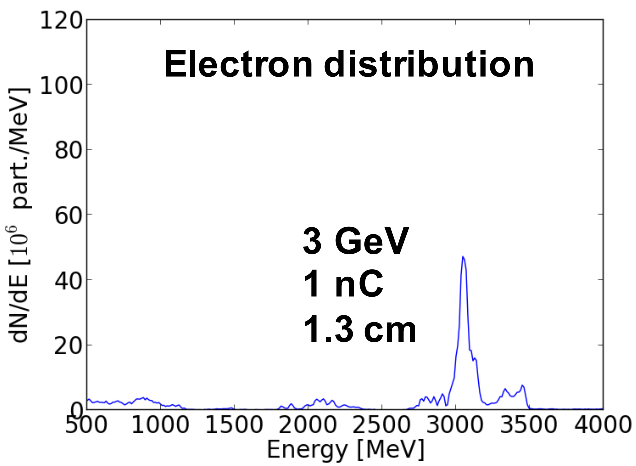


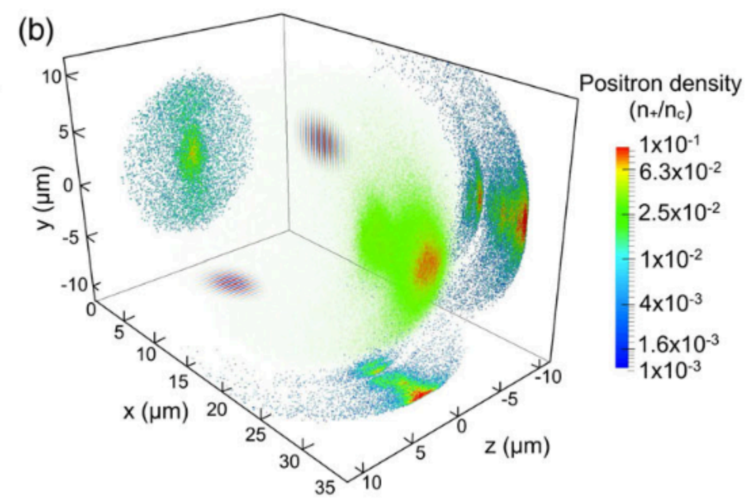
E = 75 J, T = 15 fs, P_0 = 5 PW

$I_0 = 10^{23}$ W/cm^2



Simulation with CALDER-CIRC → Simulation with CALDER 3D





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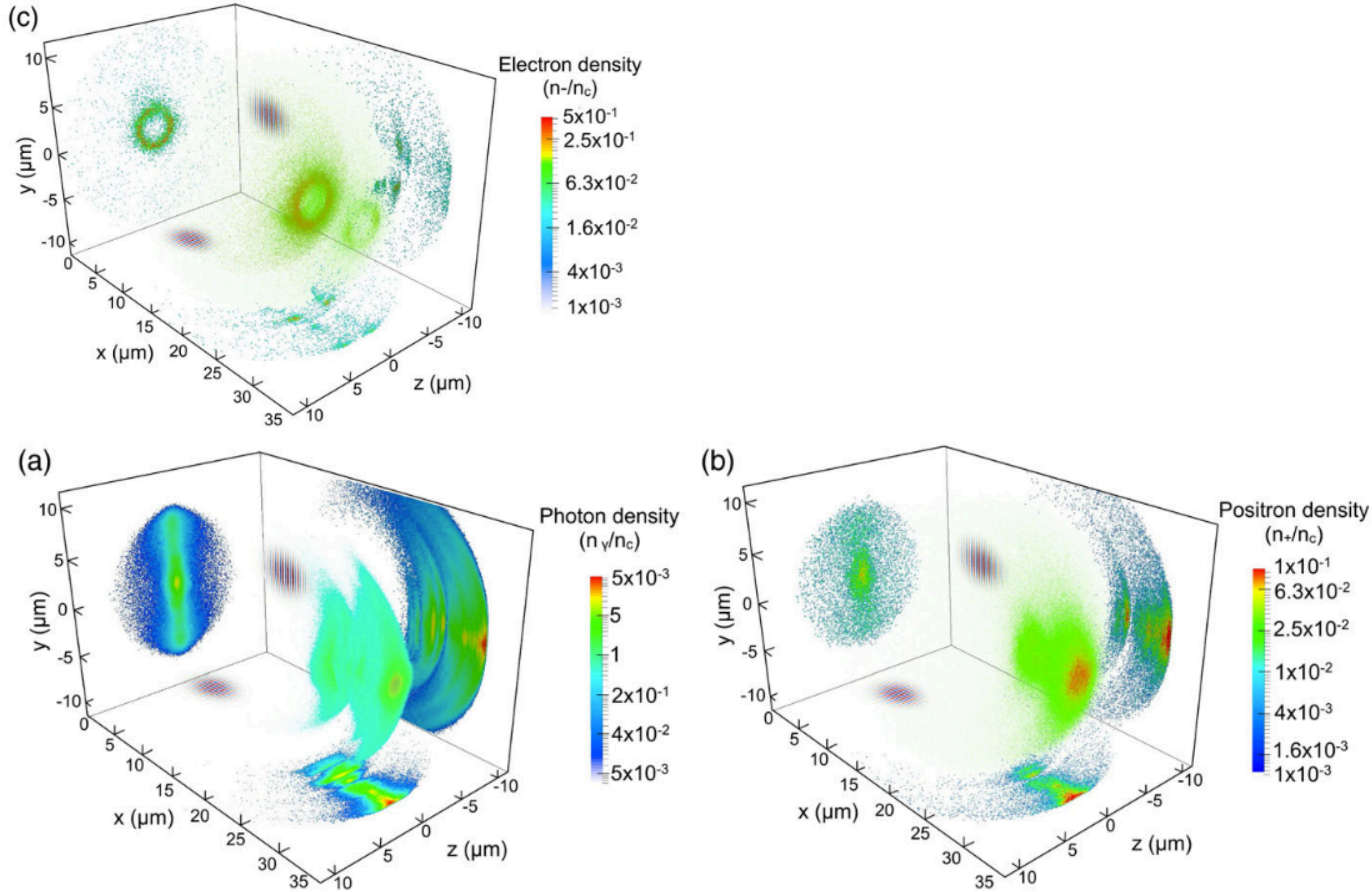

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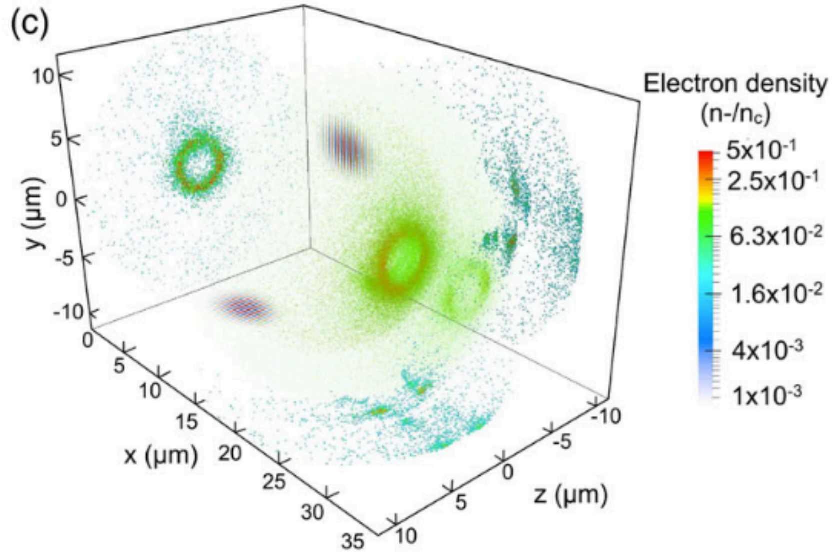
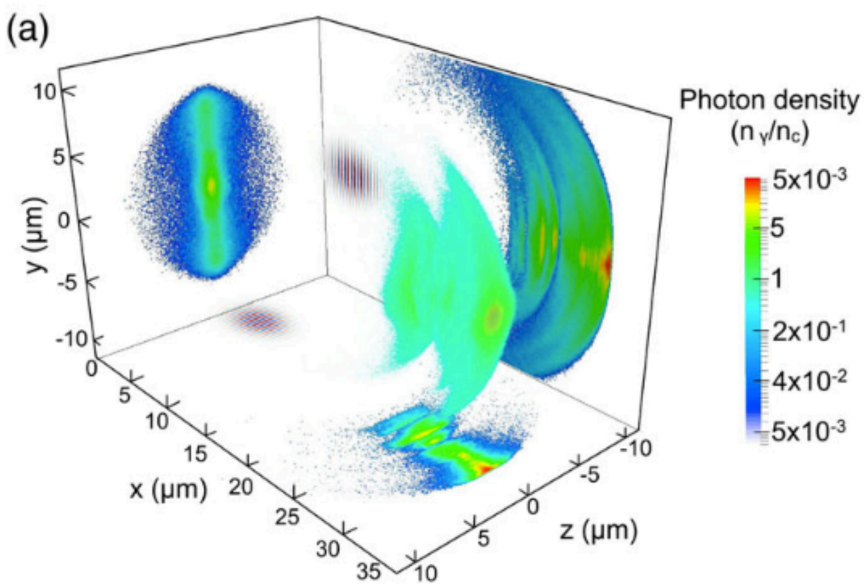
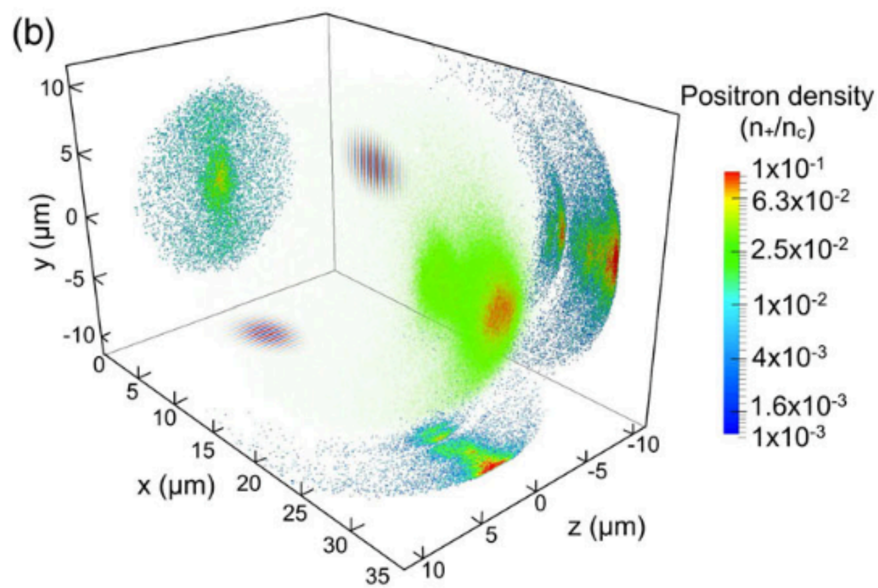


	W_{FWHM} = 2 µm 10^{23} W/cm² a_0 = 219	W_{FWHM} = 4 µm 2.5×10^{22} W/cm² a_0 = 110
Charge	1.2 nC	274 pC
<E>	101 MeV	262 MeV



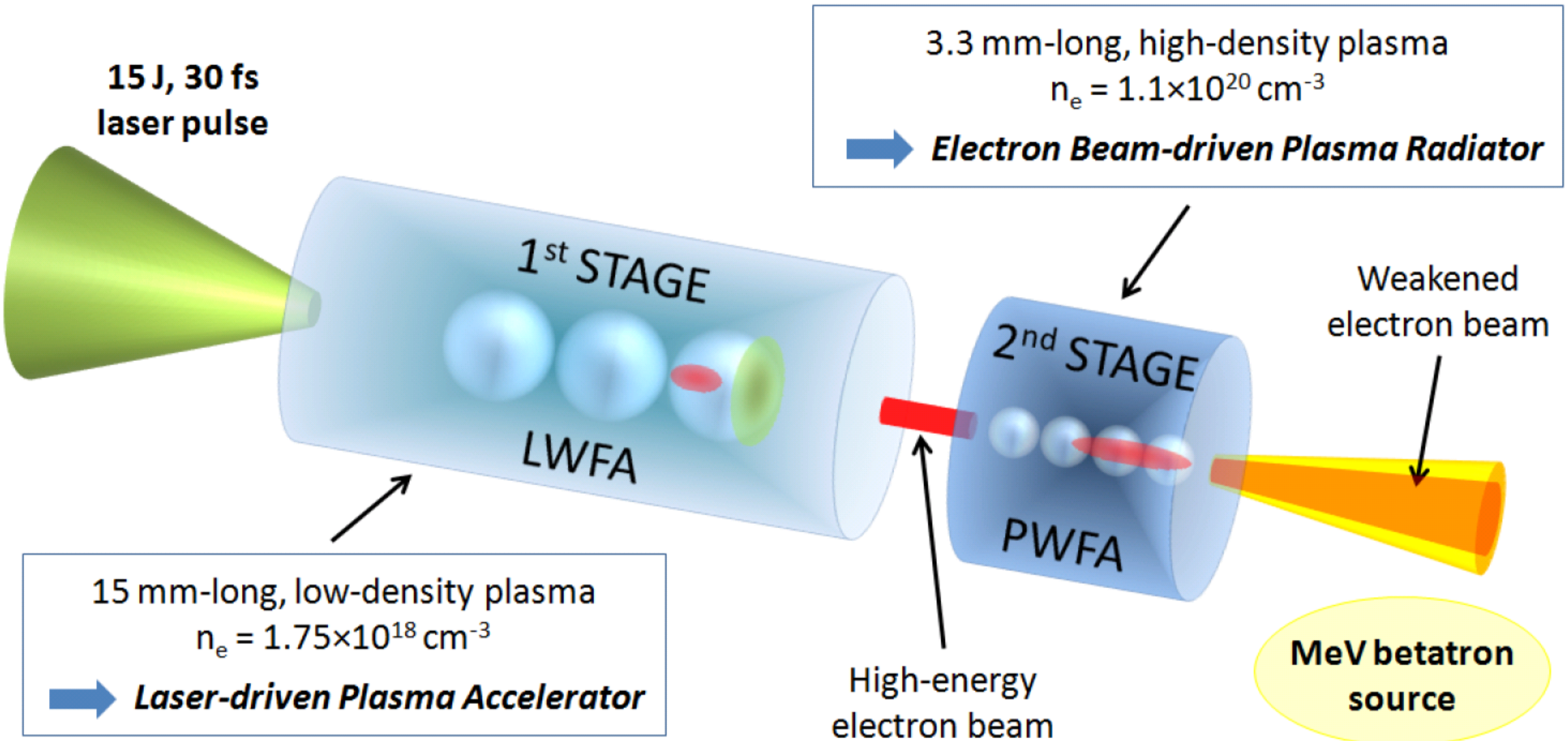


[1]M. Lobet *et al.*, PRAB **20**, 043401 (2017).

Source X bêtatron avec un schéma à deux étages (APOLLON)

Couplage CALDER-CIRC / CALDER 3D

Two-stage scheme with a beam-driven plasma radiator to boost the betatron radiation



Acceleration optimization (low n_e)

Radiation optimization (High n_e)

Simulation with CALDER CIRC

Simulation with CALDER 3D

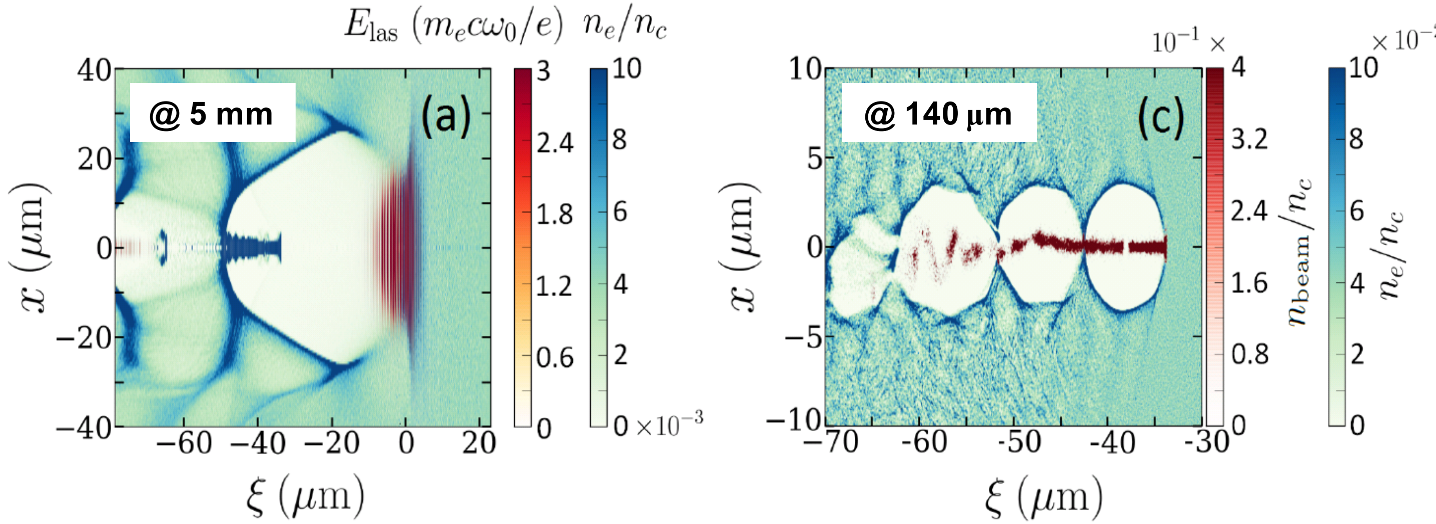
J. Ferri *et al.*, PRL, accepted.

Simulation of the two-stage scheme: Efficient beam-driven regime in the second stage

Laser:
$a_0 = 6$
$\tau_0 = 30$ fs
$W_0 = 23$ µm
$E_0 = 15$ J

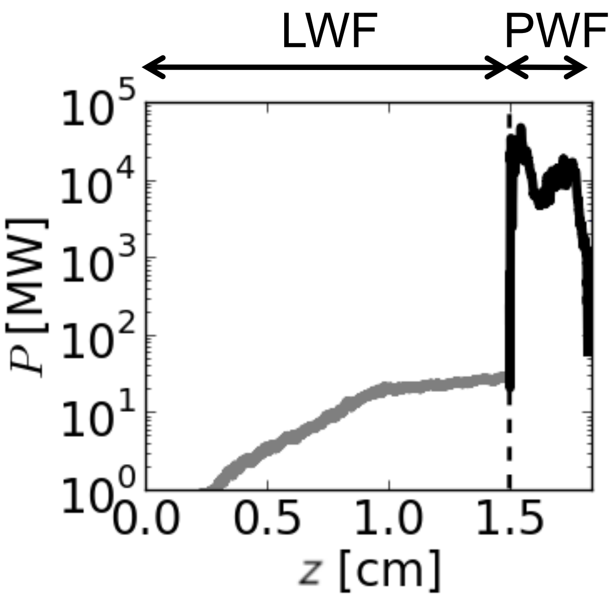
Beam:
Acc. on 1.5 cm
~1.8 GeV
~5 nC (> 350 MeV)

$n_e = 1.75 \times 10^{18}$ cm^{-3} → $n_e = 1.1 \times 10^{20}$ cm^{-3}



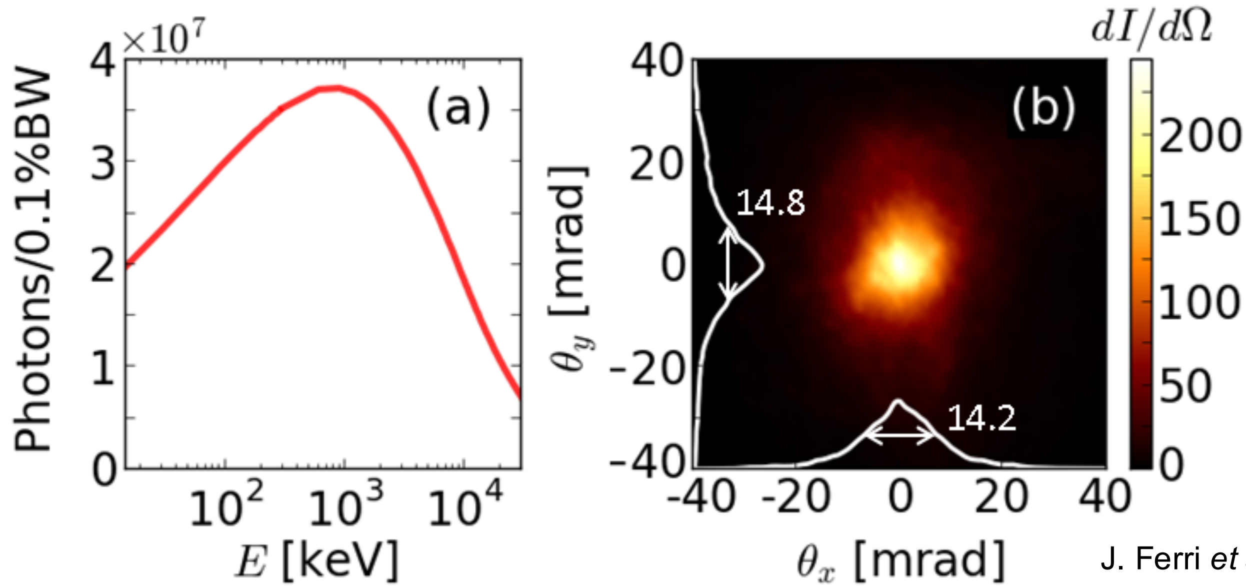
$E_z > 2.5$ TeV/m

Production of a MeV-photon source with short duration and small source size



After 3.3 mm in the 2nd stage:

- 90 % of the beam energy is depleted
- P_{rad} increases by 3 orders of magnitude
- $E_c = 9$ MeV
- $B = 4 \times 10^{23}$ phot/s^{-1}/mm^2/mrad^2/0.1%BW

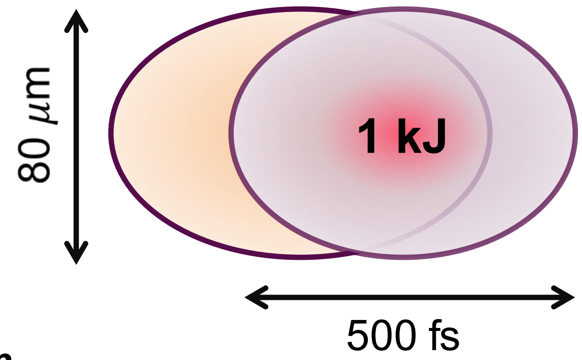


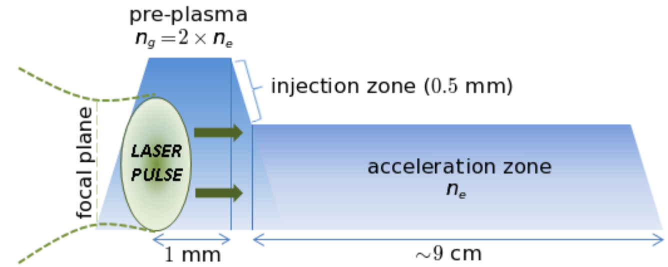
J. Ferri *et al.*, PRL, accepted.

Source X bêtatron avec PETAL

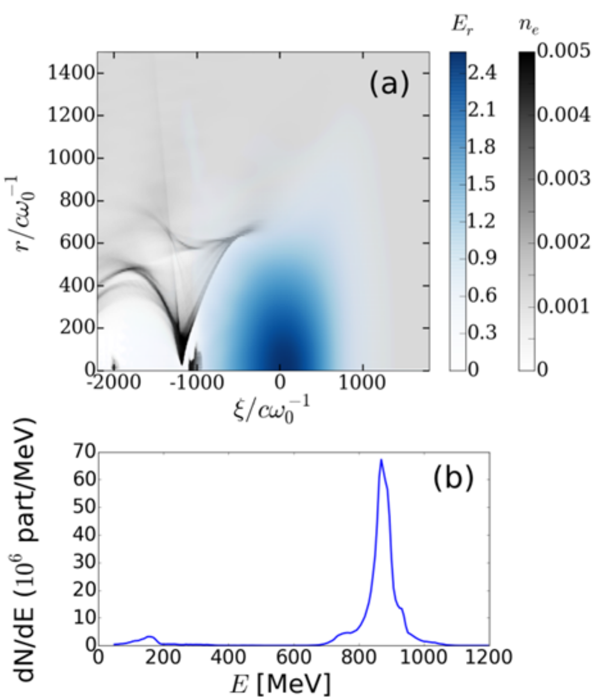
Study of the blowout regime with PETAL

Parameters :
$a_0 = 4$
$W_0 = 80\ \mu m$
$n_e = 2.8 \times 10^{16}\ cm^{-3}$



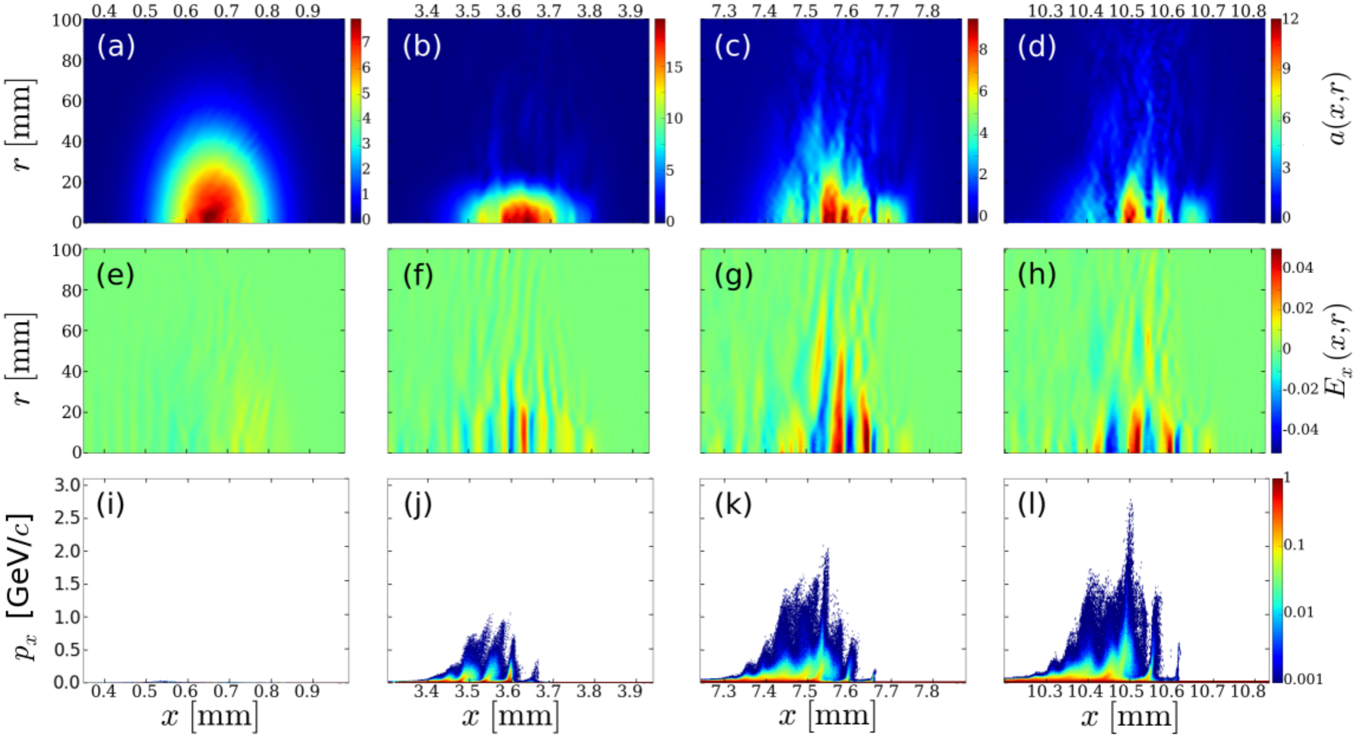


Acceleration after 4 cm



- In the matched regime (scaling laws): > 10 PW are needed for a 500 fs laser pulse
- Gradient injection needed.
- Acceleration of a quasi-monoenergetic beam up to 1.6 GeV in 9 cm.
- Energy gain limited due to laser defocusing (scaling law: dephasing length ~ 3 m ; the energy gain after 3 m is ~ 40 GeV)

Other possibility: transition to the self-modulated regime by increasing the plasma density



Paramètres :

$a_0 = 7{,}5$

$\tau_0 = 500$ fs

$W_0 = 42$ µm

$P = 2{,}2$ PW

$n_e = 1.1 \times 10^{18}$ cm^{-3}

→ Self injection leads to a Maxwellian distribution and energies > 1GeV

Comparison of the Betatron source properties (PETAL)

n_e [cm^{-3}]	Charge [nC]	N_X	θ_{FWHM} [mrad]	Size [µm]	Duration [fs]	E_X [mJ]	Brillance
BLOWOUT REGIME							
2.8×10^{16}	0.82	7.0×10^{9}	4	7.1	20	0.003	3.6×10^{22}
SELF-MODULATED REGIME							
2.8×10^{17}	6.9	7.6×10^{10}	18	25.3	255	0.03	1.0×10^{20}
5.6×10^{17}	18.2	4.6×10^{11}	42	25.6	257	0.31	1.7×10^{20}
1.1×10^{18}	38.7	1.5×10^{12}	47	25.7	257	1.52	5.6×10^{20}
2.8×10^{18}	49.8	1.8×10^{12}	75	29.0	291	1.76	1.8×10^{20}

Self-modulated regime: more robust, more photons and easier to implement

Blowout regime: X-ray source with higher quality

Conclusion

Etude théorique de l'interaction laser UHI–Plasma, intérêt mais aussi besoin d'adaptation du :

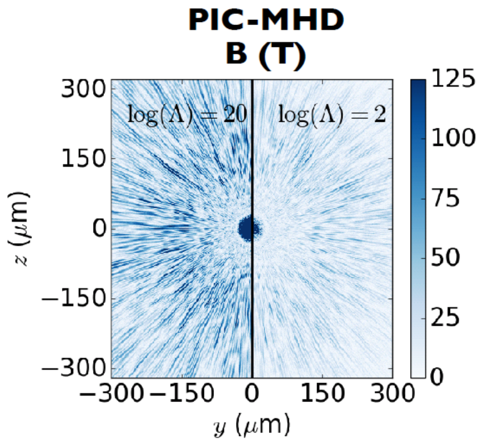
- aux développements lasers importants (APOLON, PETAL, ELI, etc.)
- aux évolutions rapides des puissances de calculs

Ajout de nouveaux modèles physiques (collisions, effets radiatifs, QED, MHD, etc.)

Evolution des schémas numériques

Couplage de codes

Adaptation HPC



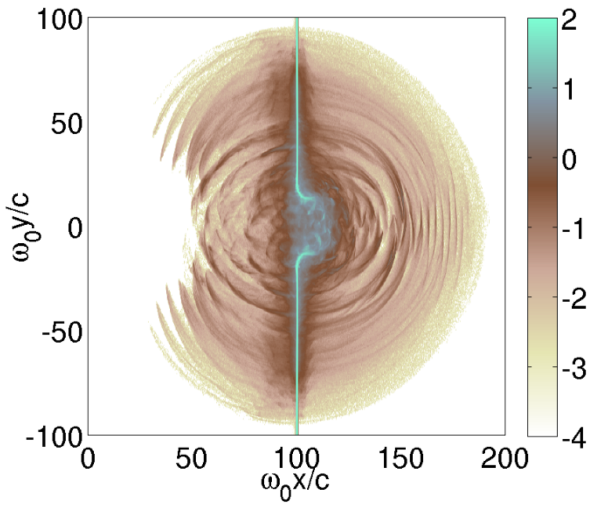
C. Ruyer *et al.*, en préparation

Recherche candidats pour thèse(s) et post-doc(s)

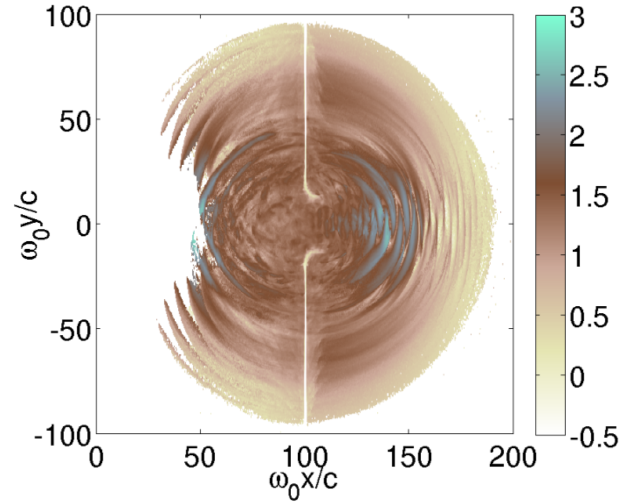
Ultrafast electron heating and expansion promote relativistic plasma transparency for thicknesses < 200 nm

$I_L = 1.8 \times 10^{22}\ \mathrm{Wcm^{-2}},\ l = 100$ nm

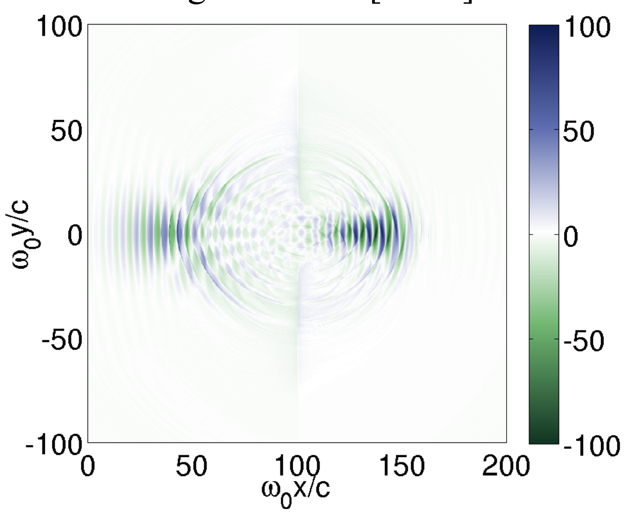
Electron density [$10^{21}\mathrm{cm^{-3}}$]



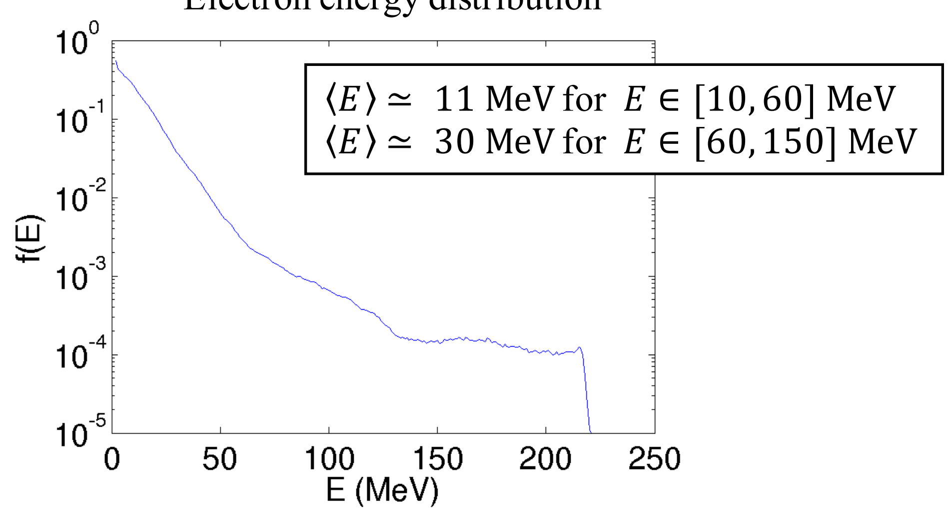
Mean electron energy [511 keV]



Magnetic field [10^4T]



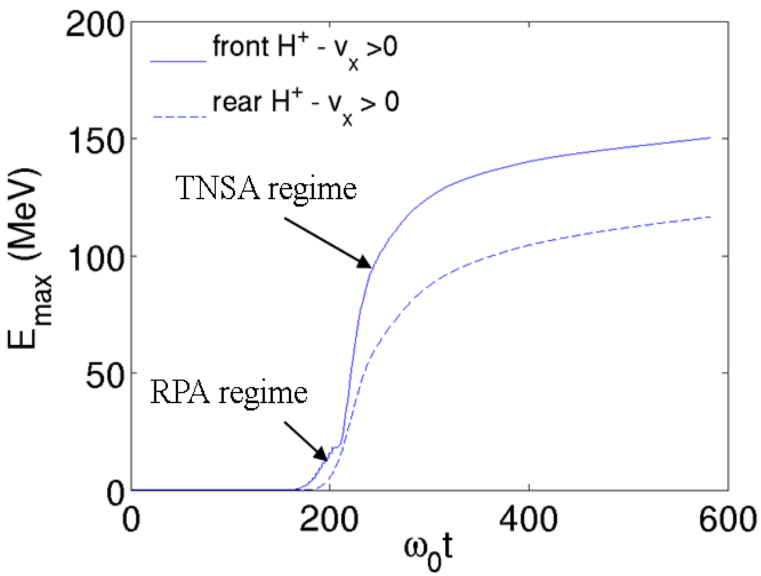
Electron energy distribution



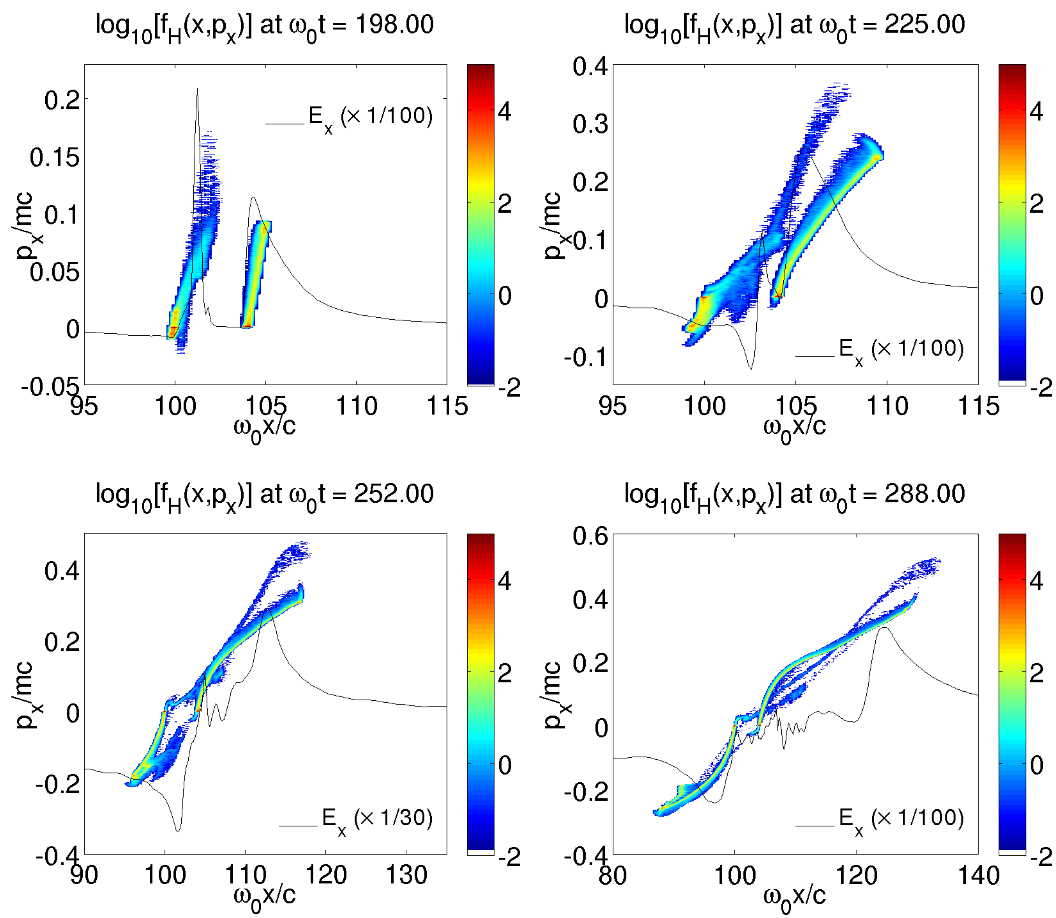
Two-staged RPA/TNSA ion acceleration arises for $l \geq$ 500 nm foil targets

$I_L = 1.8\times10^{22}\,\mathrm{Wcm^{-2}},\ l = 500\ \mathrm{nm}$

Maximum proton energy



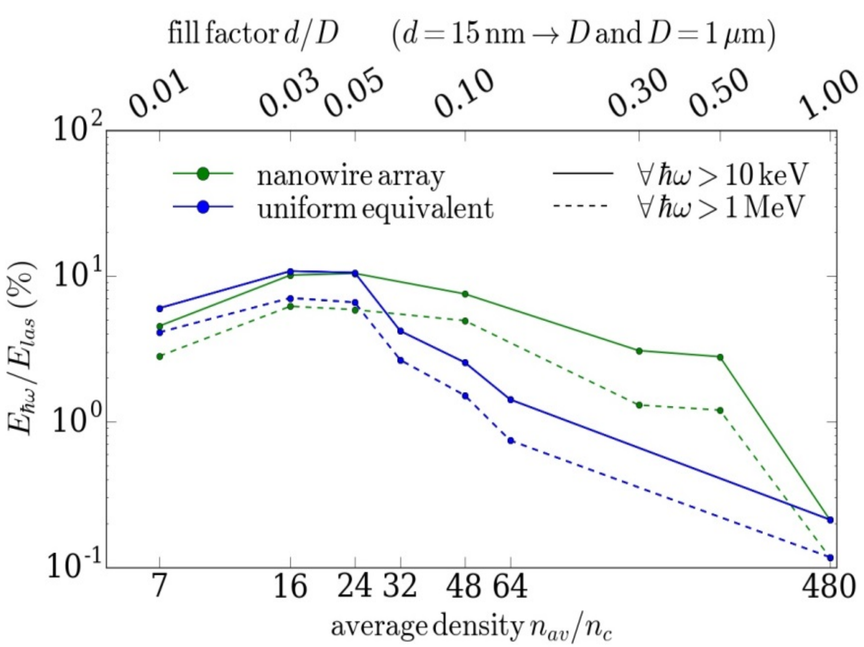
$x - p_x$ proton phase space

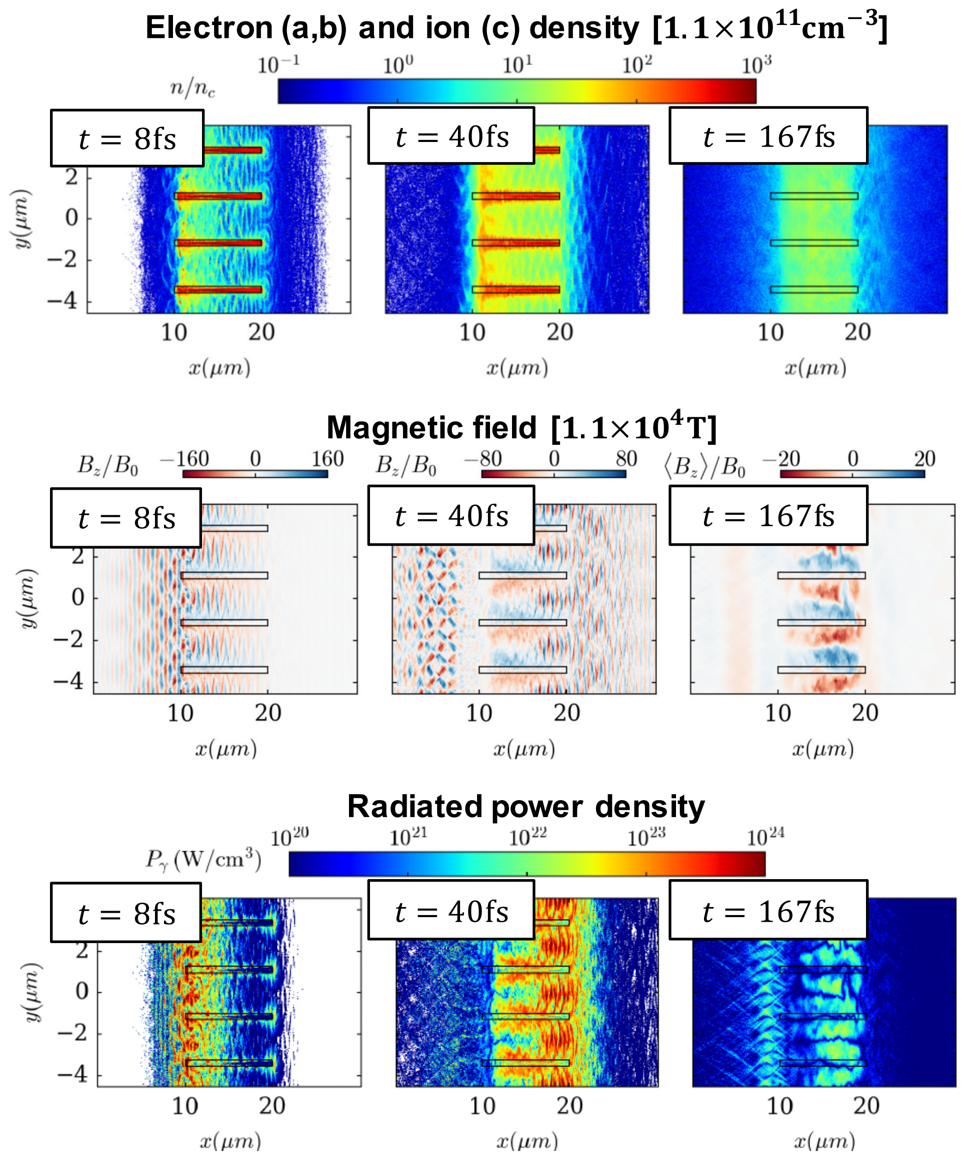


Grand potentiel[1] des micro-fils en tant que sources synchrotron X/γ intenses avec $I_L > 10^{22}$ Wcm^{-2}

Laser parameters:
- $I_L = 10^{22}$ Wcm^{-2}
- $\tau_L = 30$ fs
- planar wave

Wire parameters:
- solid-density carbon
- $L = 10\ \mu m$
- $D = 1\ \mu m - 2.25\ \mu m$
- $d = 0.3\ \mu m$





[1] B. Martinez *et al.*, submitted to Plasma Phys. Control. Fusion (2018).

A unified Bremsstrahlung model accounting for atomic and plasma screening effects has been implemented in CALDER[1]

- Relativistic Bremsstrahlung cross-section[2]:

$$\frac{d\sigma}{dk} = \frac{Z^2}{k}\left[\left(1+\left(\frac{\gamma_{1f}}{\gamma_1}\right)^2\right)(I_1+1) - \frac{2}{3}\frac{\gamma_{1f}}{\gamma_1}\left(I_2+\frac{5}{6}\right)\right]$$

  where I_1 et I_2 are integrals involving the atomic electron form factor[2]

$$F_e(u) = -\frac{1}{\epsilon_0}\int_0^{\infty} \Delta V(r) e^{iur} dr$$

- Screening effects in arbitrarily ionized plasmas are modeled using the effective potential[4]

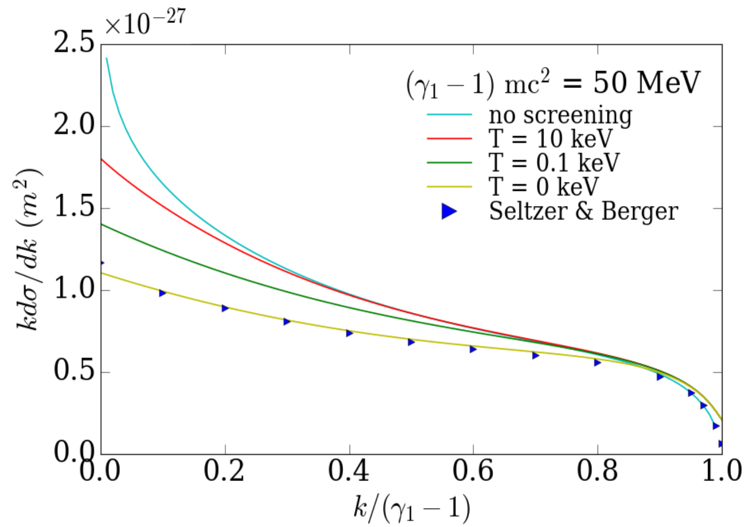
$$V_{FD}(r) = \frac{Ze}{r}\left[\left(1-\frac{Z^*}{Z}\right)\frac{e^{-r/L_F}}{r} + \frac{Z^*}{Z}\frac{e^{-r/L_D}}{r}\right]$$

  with L_D and L_{TF} being the Debye and Thomas-Fermi screening lengths.

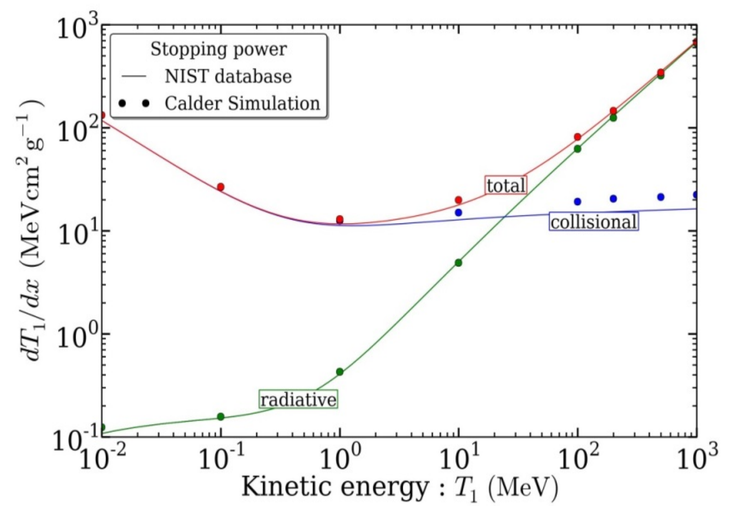
- Bremsstrahlung implemented in Calder using a Monte Carlo particle-pairing algorithm[1].

- Similar treatment for Bethe-Heitler e^-e^+ pair production[1].

Cross-section vs. Cu target temperature



Radiative/collisional/total stopping powers: CALDER vs. ESTAR[5]

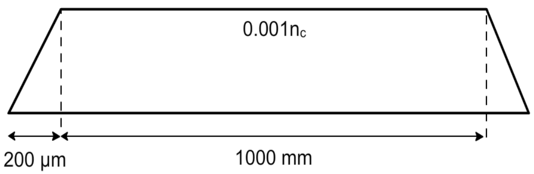


[1]B. Martinez *et al.*, to be submitted (2018).
[2]M. Seltzer and M.J. Berger, At. Data Nucl. Data Tables **35**, 345 (1986)
[3]H.W. Koch and J.W. Motz, Rev. Mod. Phys. **31** 920 (1959)
[4]E. Nardi and Z. Zinamon, Phys. Rev. A **18** 1246 (1978)
[5]https://physics.nist.gov/Star

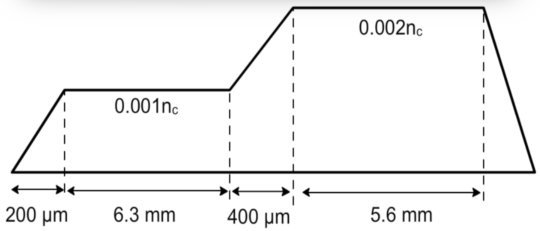
Generation of a 3 GeV electron bunch with a 0.5-PW laser pulse and a tailored plasma profile.

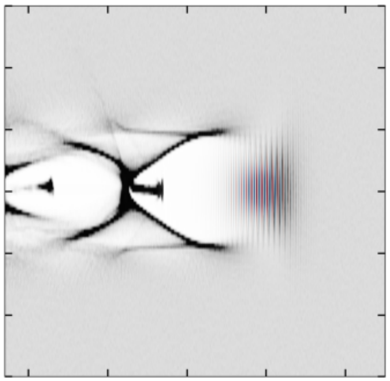
- **Laser:** $\lambda_L = 0.8\ \mu\text{m},\ E_L = 15\ \text{J},\ \tau_L = 30\ \text{fs},\ d_L = 23\ \mu\text{m}, a_0 = 6,\ P_L \sim 0.5\ \text{PW}.$
- **Plasma:** $n_e = 0.001 n_c$

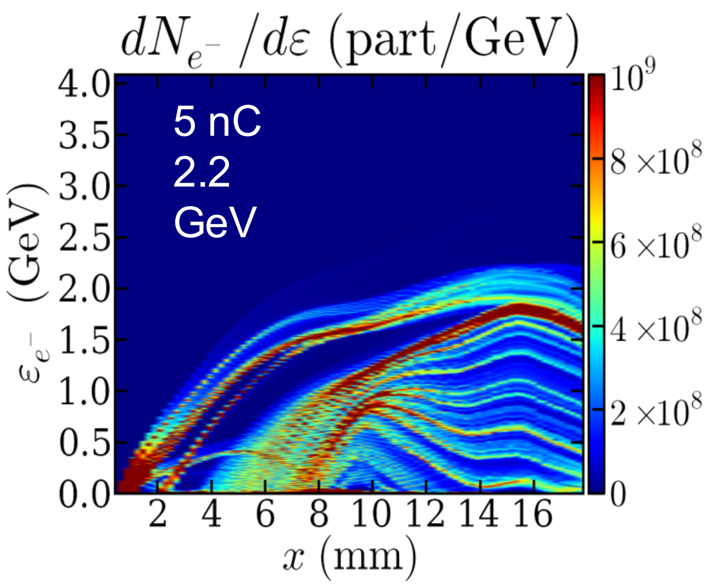
Flat density profile

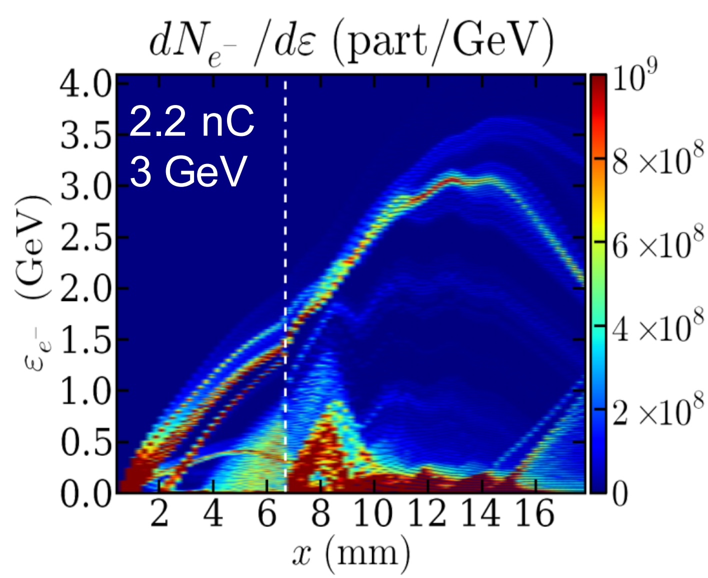


Two-step density profile



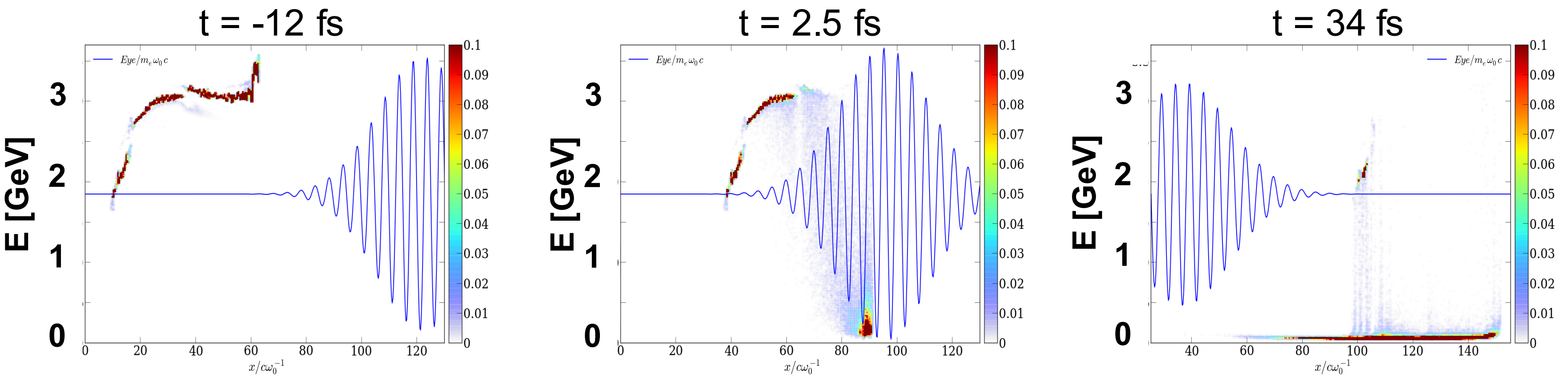




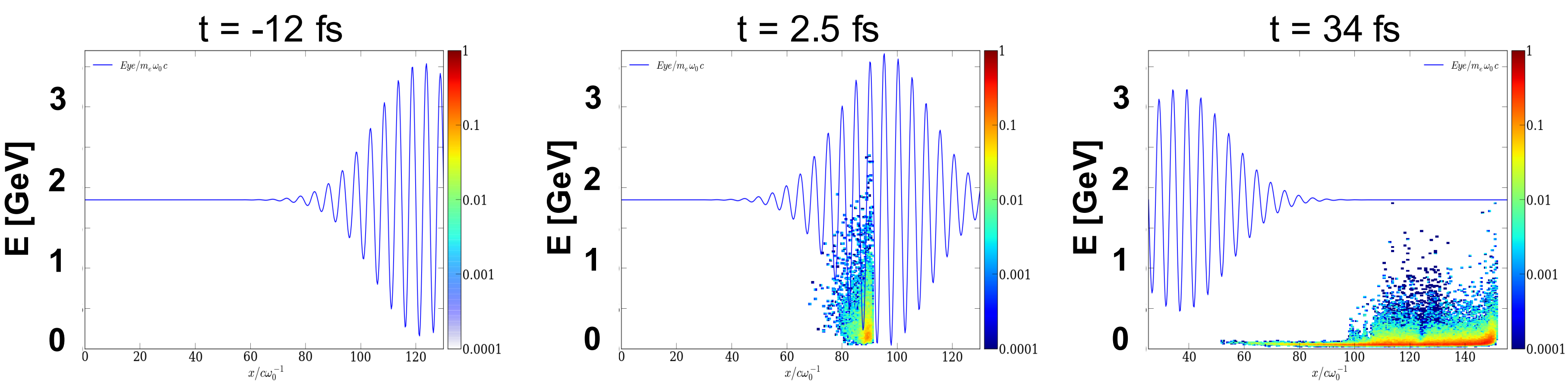


Pair production on the upcoming multi-PW CILEX-Apollon laser system[1]

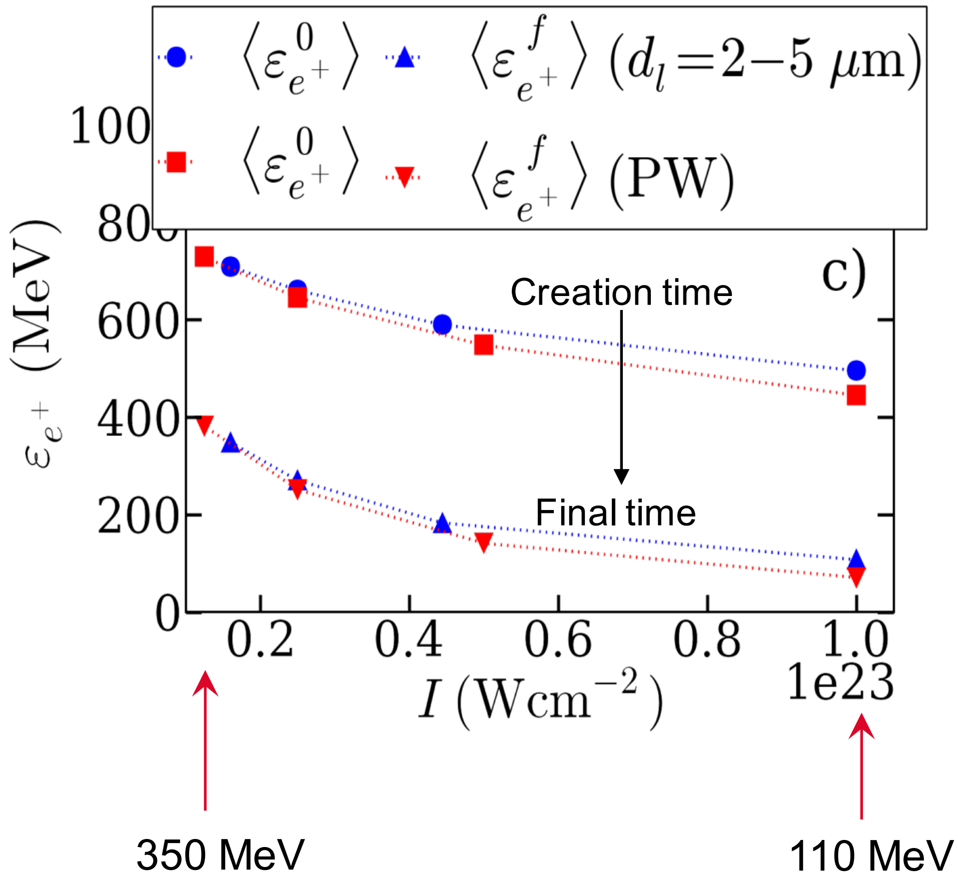
- Electron longitudinal phase space



- Positron longitudinal phase space

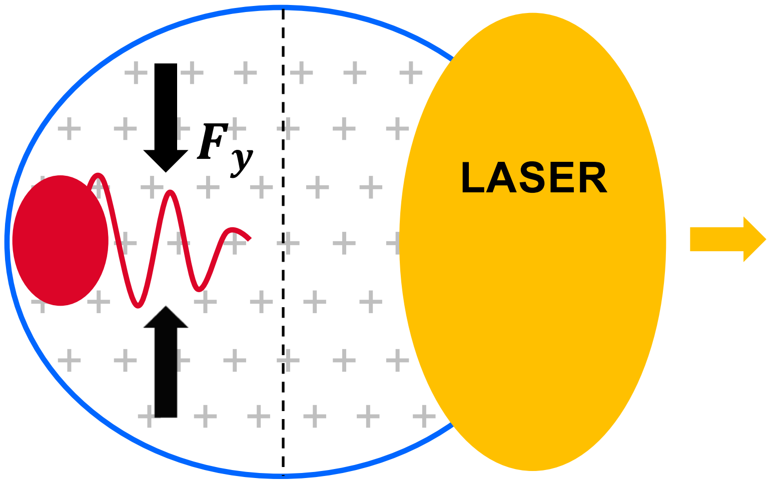


At fixed laser energy, the mean positron energy decreases with the laser intensity



- For both the focused and plane waves, the average positron energy decreases as
$$\langle \varepsilon_+ \rangle [\mathrm{MeV}] \sim 490 I_{22}^{-0.8}$$
- As I_L rises, low-energy photons can more easily decay into pairs, thus enhancing the number of low-energy positrons and, correspondingly, lowering $\langle \varepsilon_+ \rangle$.
- During their subsequent interaction with the laser, the positrons radiate a larger fraction of their energy at higher I_L, which further contributes to the decrease in the final $\langle \varepsilon_+ \rangle$.

Betatron source: Interest for a 2-stage scheme



$$\begin{cases} P_{rad} \propto K^2 \gamma n_e \\ E_c \propto K \gamma \sqrt{n_e} \end{cases}$$

$$F_y \propto r n_e$$

Laser Wakefield accelerator : $\Delta E \propto n_e^{-1}$

=> a compromise on the density used is needed

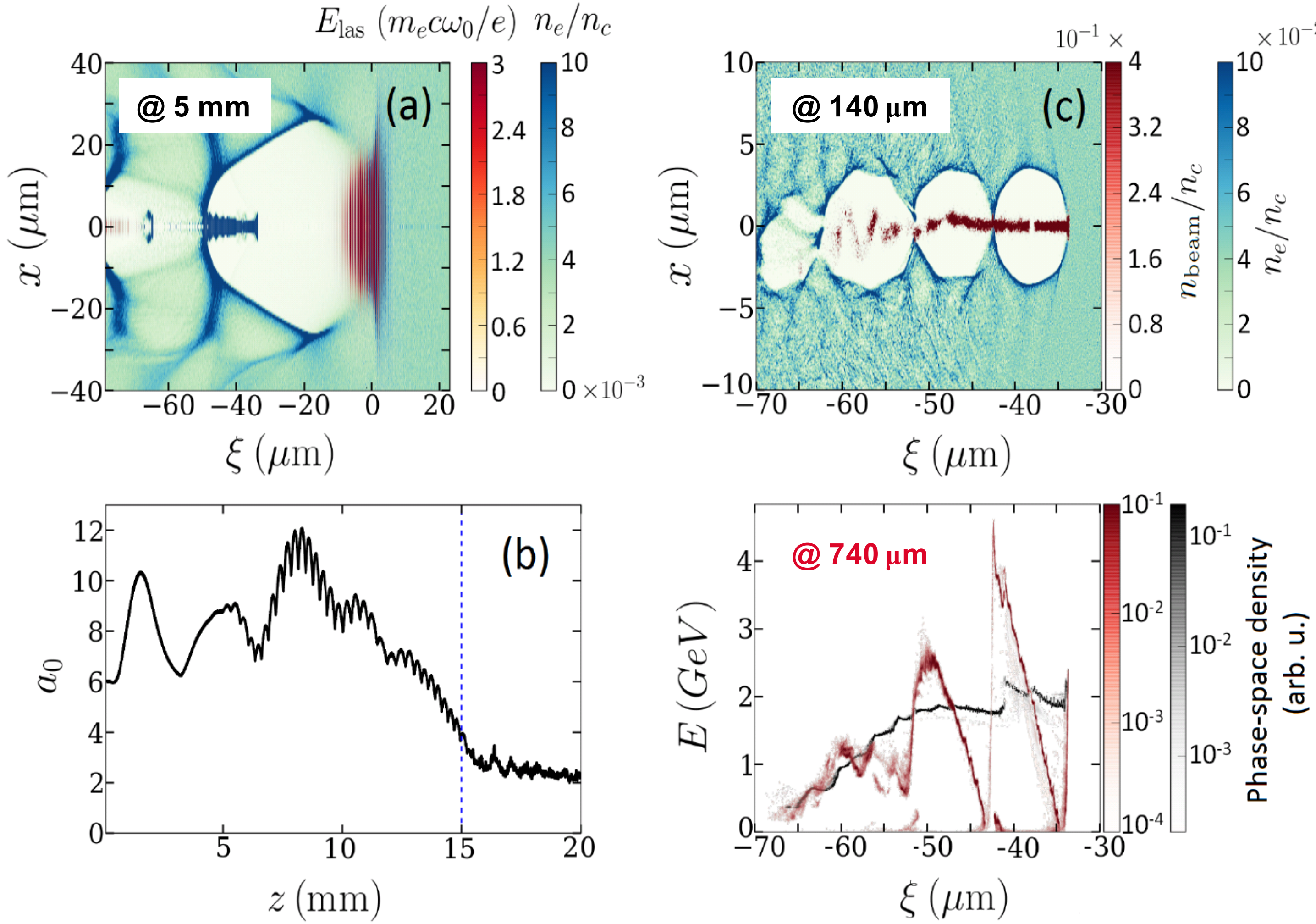
idea: the source performance could benefit from a decoupling between the acceleration (low n_e) and radiation (high n_e) parts => 2-stage scheme.

Simulation of the two-stage scheme: Efficient beam-driven regime in the second stage

Laser:
$a_0 = 6$
$\tau_0 = 30$ fs
$W_0 = 23$ µm
$E_0 = 15$ J

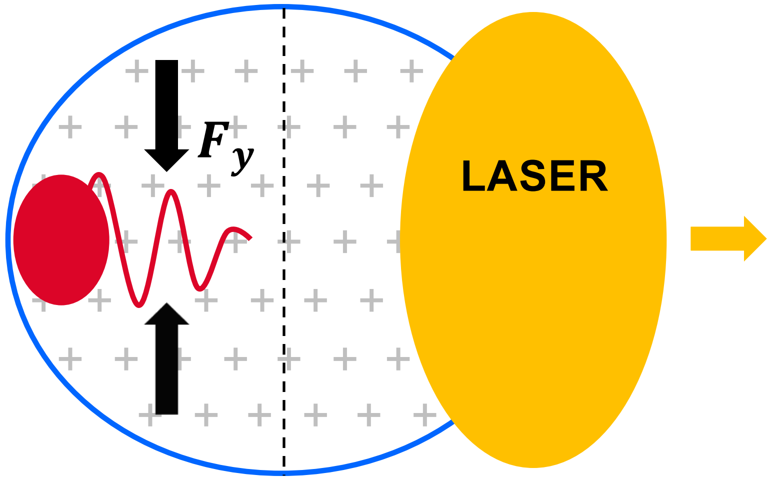
Beam:
Acc. on 1.5 cm
~1.8 GeV
~5 nC (> 350 MeV)

$n_e = 1.75 \times 10^{18}$ cm^{-3} → $n_e = 1.1 \times 10^{20}$ cm^{-3}

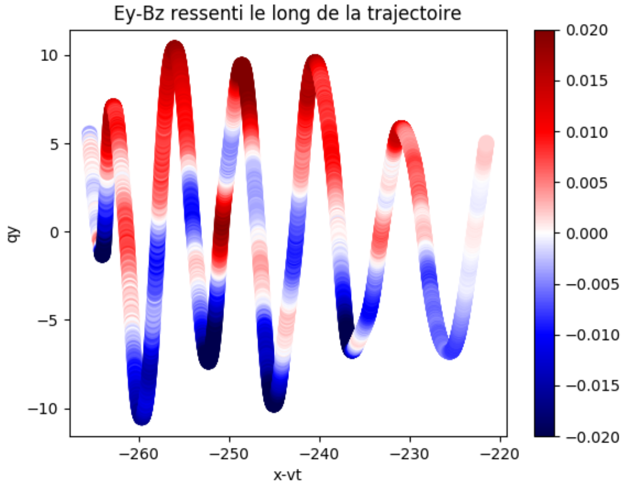


$E_z > 2.5$ TeV/m

The choice of the numerical scheme to solve Maxwell equations is important for betatron sources



Standard Yee solver



New solver