Self-triggered strong-field QED collisions in laser-plasma interaction

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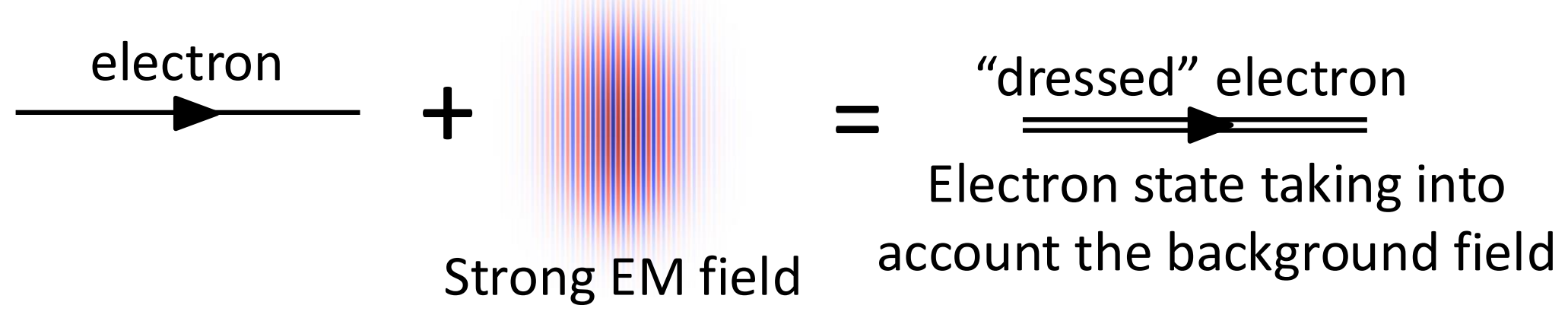
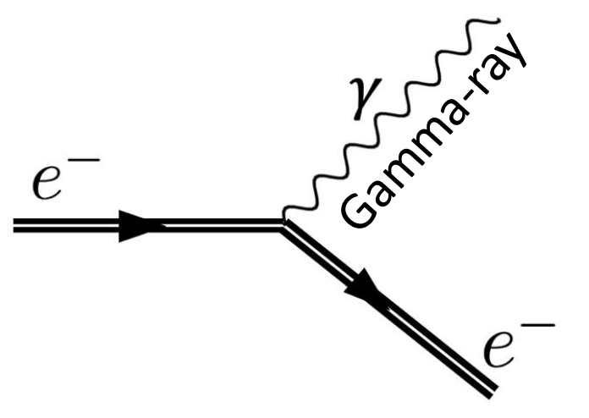
Strong-field quantum electrodynamics (QED) describes the behavior of electrons in intense electromagnetic fields. The theory predicts spectacular phenomena, such as the creation of matter from pure light through light-by-light scattering. Reaching the strong-field QED regime, characterized by $\chi \gtrsim 1$, is an experimental challenge, as it requires the collision of high-energy electrons with ultra-intense laser pulses. This work presents the results of an innovative scheme that enables access to the strong-field QED regime using currently available laser parameters, relying on a single laser and multiple plasma stages. The laser accelerates an electron beam to 11 GeV, self-focuses in a second gas jet, reflects off a foil, and then collides with the electrons to trigger strong-field QED processes.

Strong-field QED

- Predicts electrons behavior in a strong electromagnetic fields

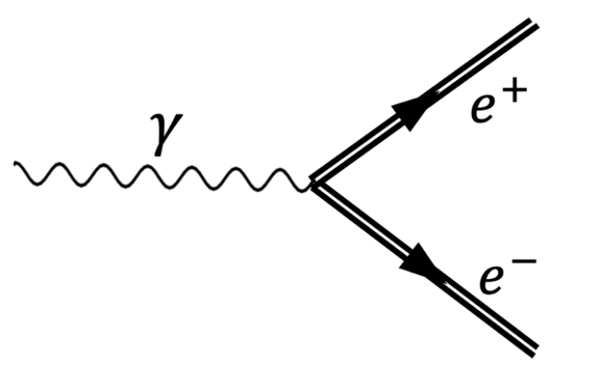


- New and modified processes are taking place



$e^- + n\omega \rightarrow e^- + \gamma$

Non-linear inverse Compton scattering (NICS)



$\gamma + n\omega \rightarrow e^- + e^+$

Non-linear Breit-Wheeler pair creation (NLBW)

- The probability of these processes is a function of χ

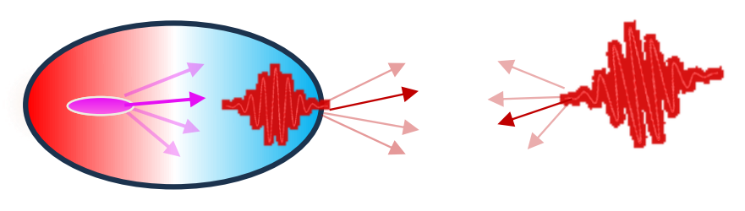
$$\boxed{\chi = \frac{E^\star}{E_{\text{Schwinger}}} \underset{800\text{ nm}}{\sim} \frac{a_0\, \mathcal{E}_{\text{elec}}\,[\text{GeV}]}{84}}$$

χ : ratio between the field experienced by electrons in their rest frame $E^\star$ and the Schwinger field $E_{\text{Schwinger}}$

Processes become probable at $\chi \gtrsim 1$

State of the art

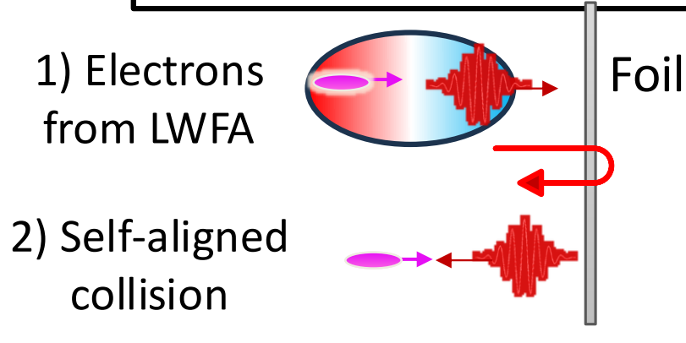
2 beams scheme [1], [2]



✓ Advantage Laser a_0 can be arbitrary high

✗ Disadvantage Shot to shot fluctuations (Collision conditions are hard to know)

Single beam scheme [3], [4]



✓ Advantage Automatic alignment (100 % collision success rate)

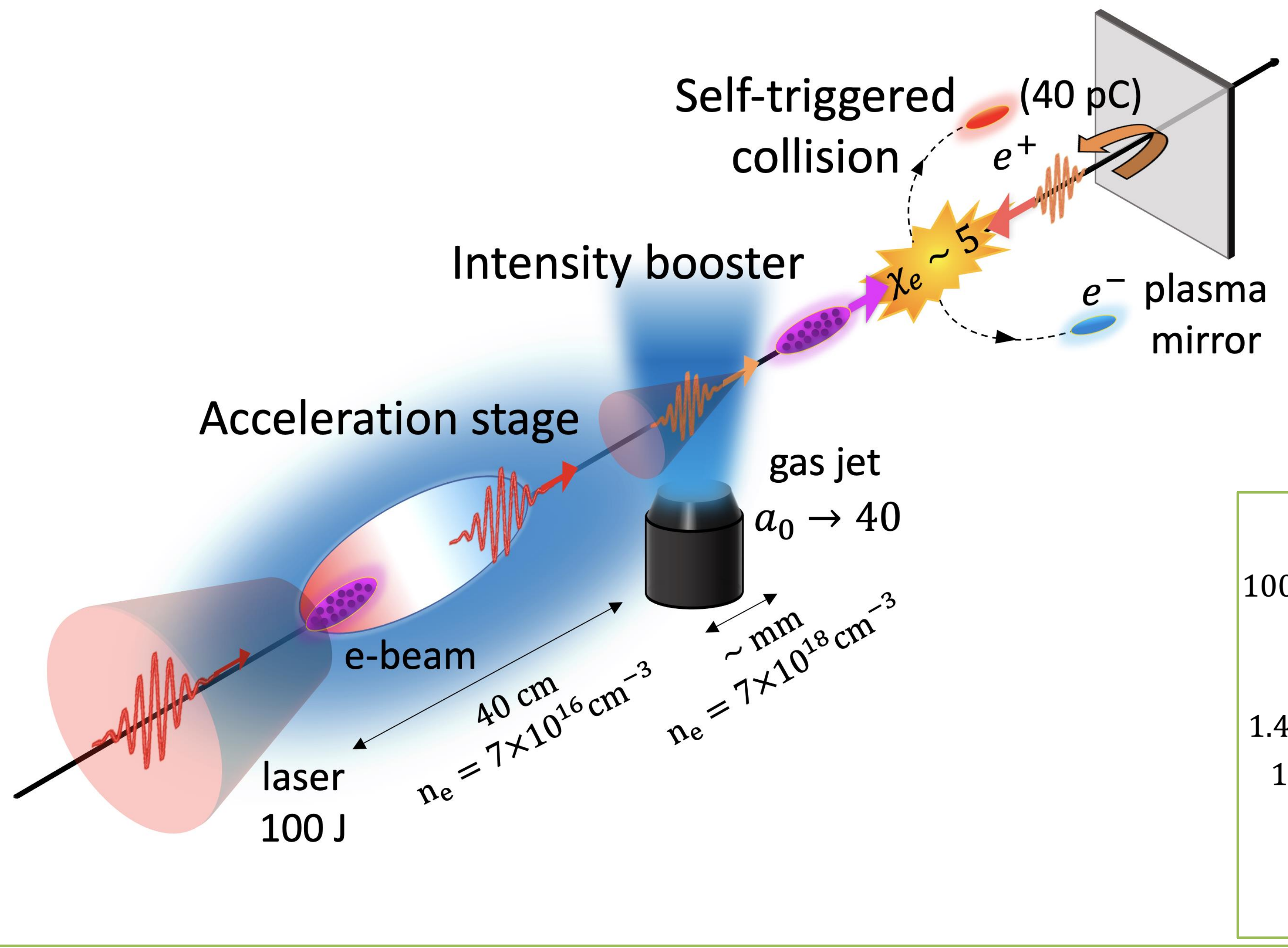
✗ Disadvantage Laser $a_0 \lesssim 4$ (to ensure good LWFA)

To use the automatic alignment of the single beam scheme, the laser a_0 has to be <u>increased before collision</u>.

Double jet scheme[5]

A second (high density) gas jet is inserted between the first gas jet and the foil

1. Laser plasma accelerator generating 10 GeV electron beam.
2. **Intensity booster** : high density gas jet. Increase laser intensity by two orders of magnitude.
3. Thin foil acting as a plasma mirror ensures the automatic alignment.

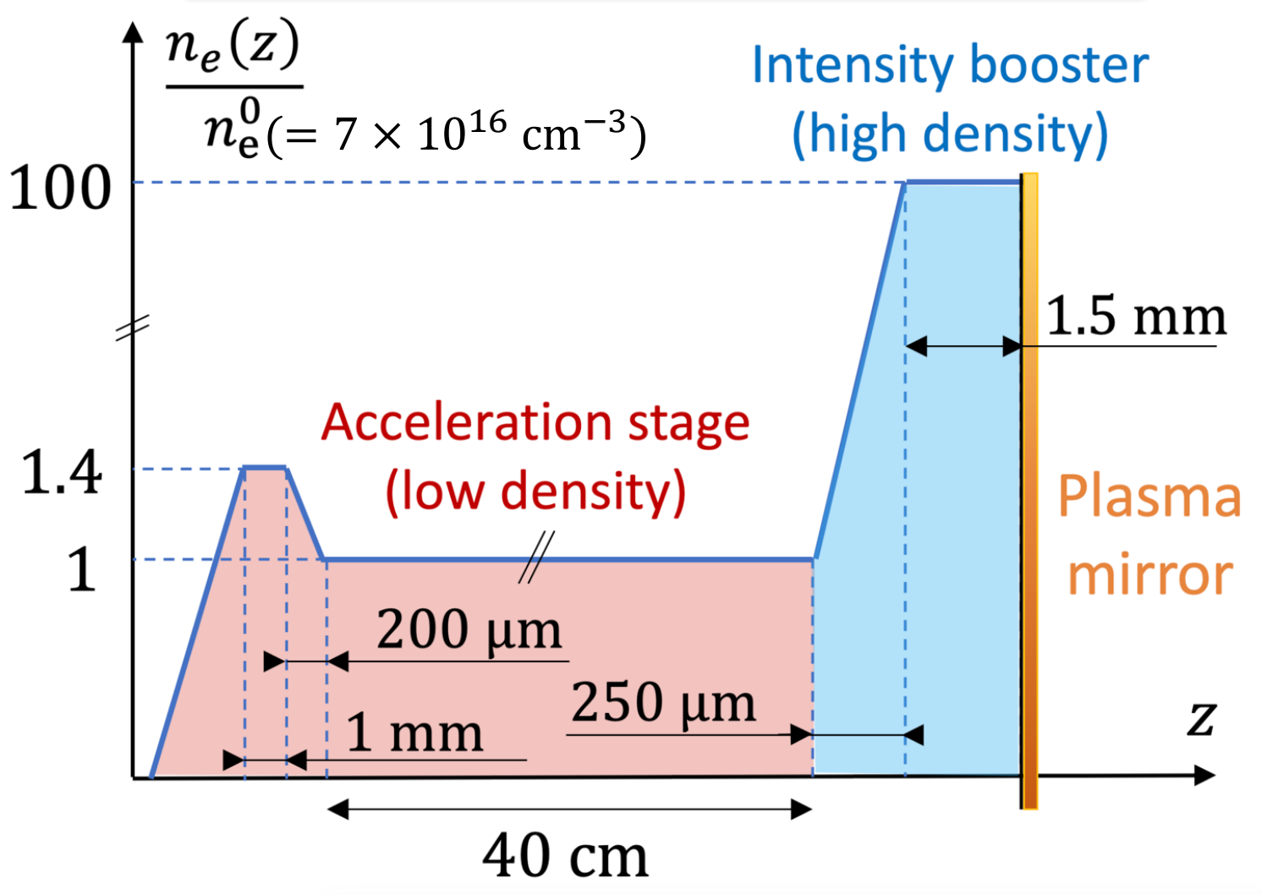


Laser parameters

$E = 100$ J
$\lambda = 800$ nm
$\tau = 20$ fs
Spot size $= 100$ µm

$P = 4.7$ PW
$I = 4 \times 10^{19}$ W/cm^2
$a_0 \sim 4$

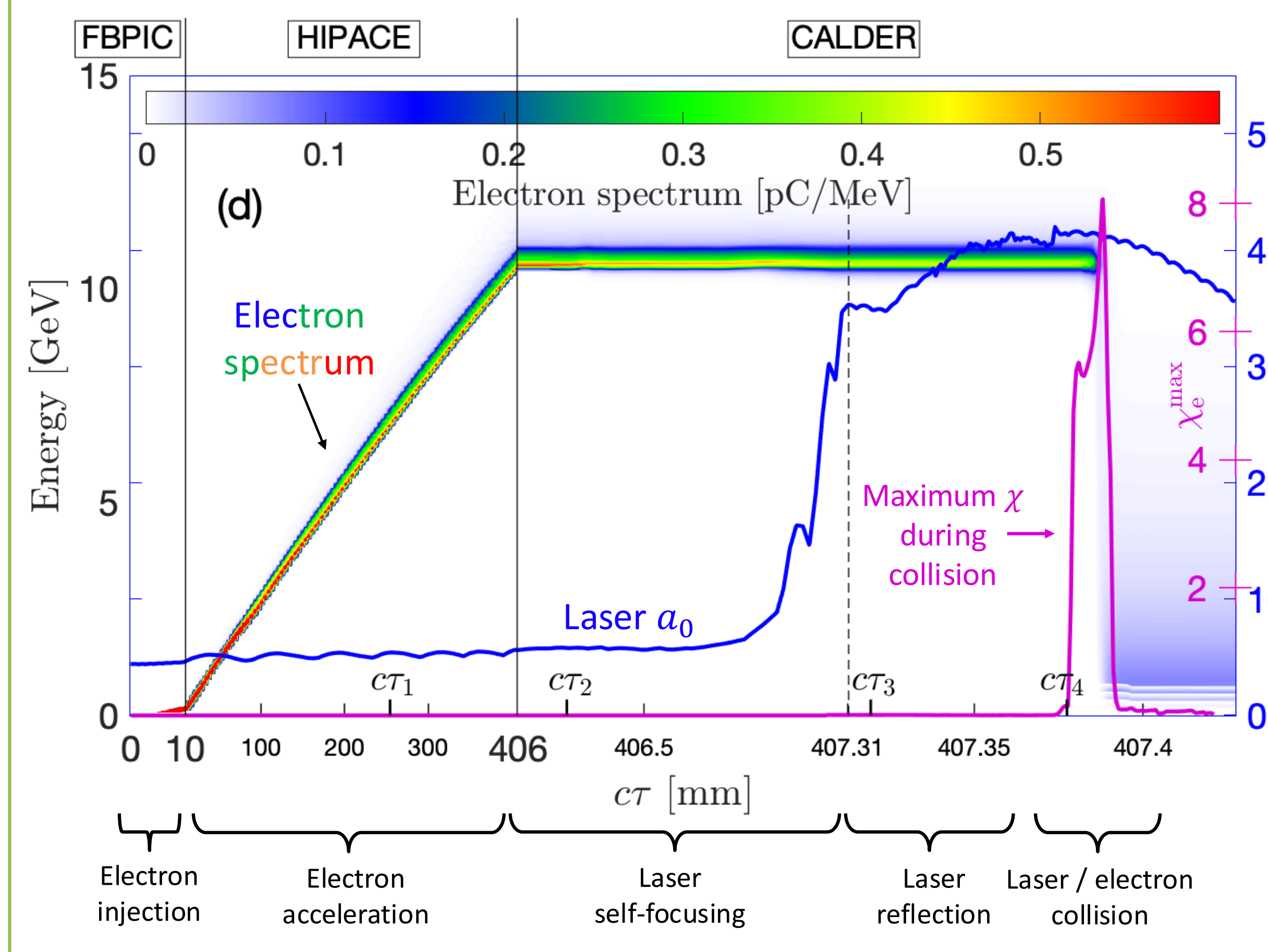
Longitudinal plasma density profile



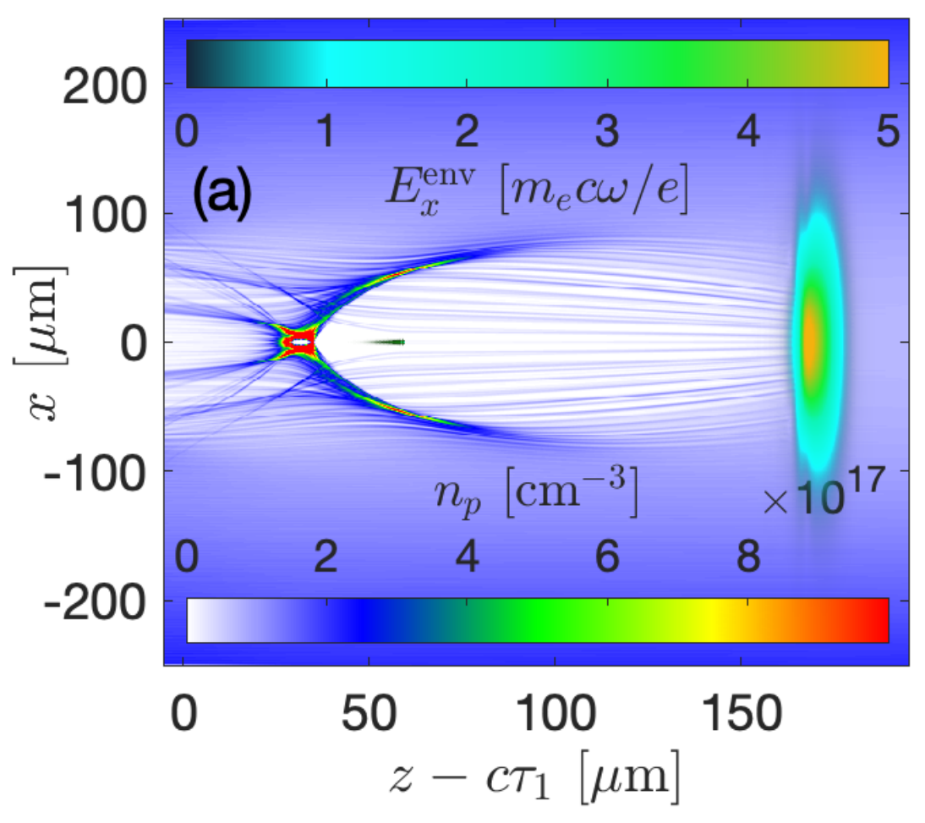
PIC-QED of the setup

3 PIC codes are used to simulate the full setup

1. **FBPIC** : Electron down-ramp injection in the first plasma.
2. **HiPACE ++** : Electron acceleration over 40 cm to reach 11 GeV.
3. **CALDER** : Laser self-focusing, reflection on the foil and electron / laser collision



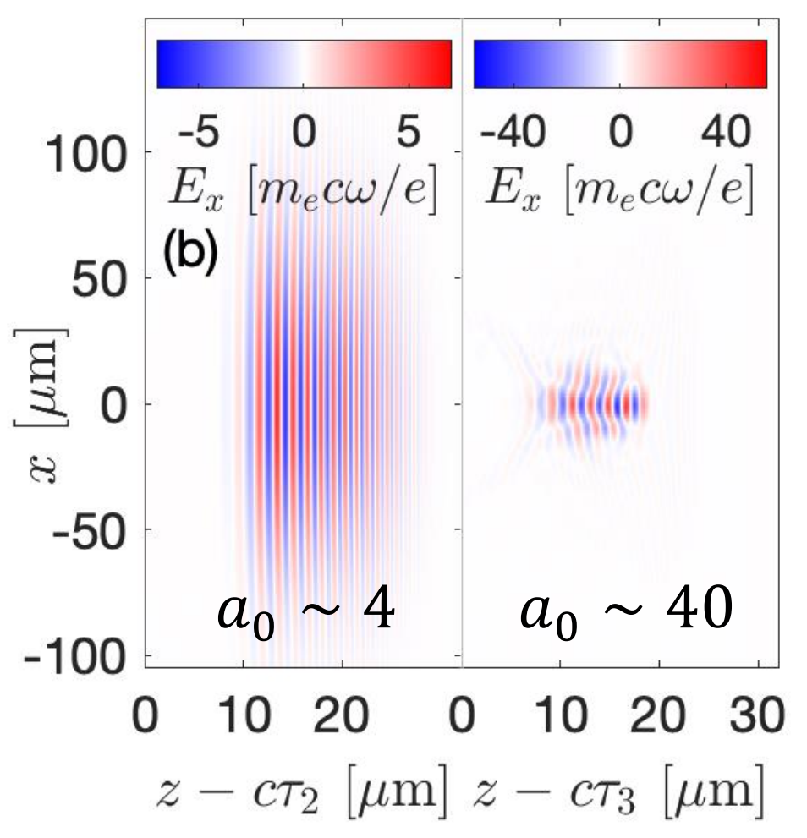
Electron acceleration



Electron beam parameters

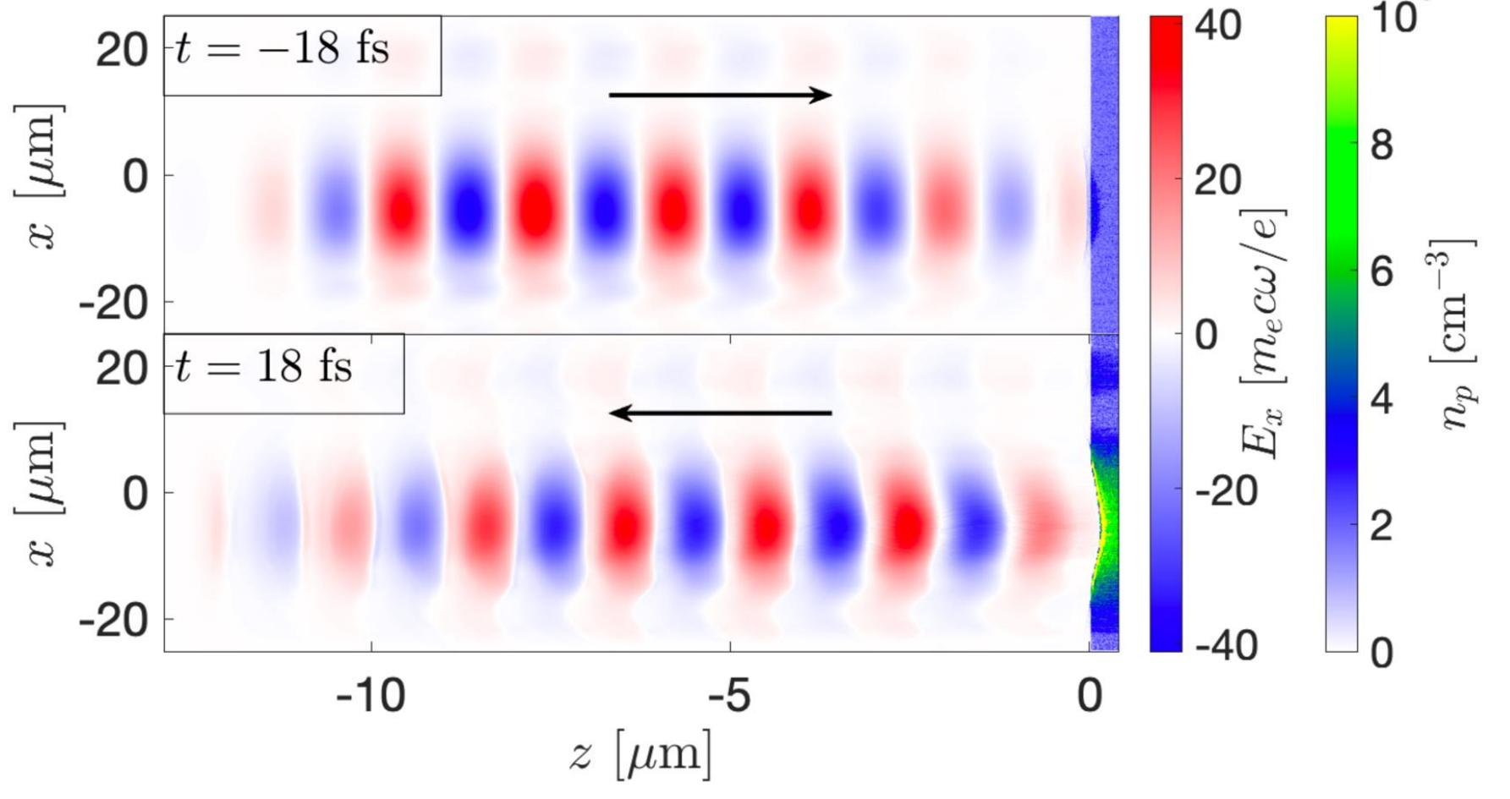
$Q = 140$ pC   div $= 5$ mrad
$\sigma_r = 3$ µm $\varepsilon_n = 4$ mm. mrad

Laser self-focusing



Reflection induces a drop of 7% of laser peak electric field.

Laser reflection on the foil



Strong-field QED observables

After electron acceleration, laser self-focusing and reflection on the foil, the collision parameters are :

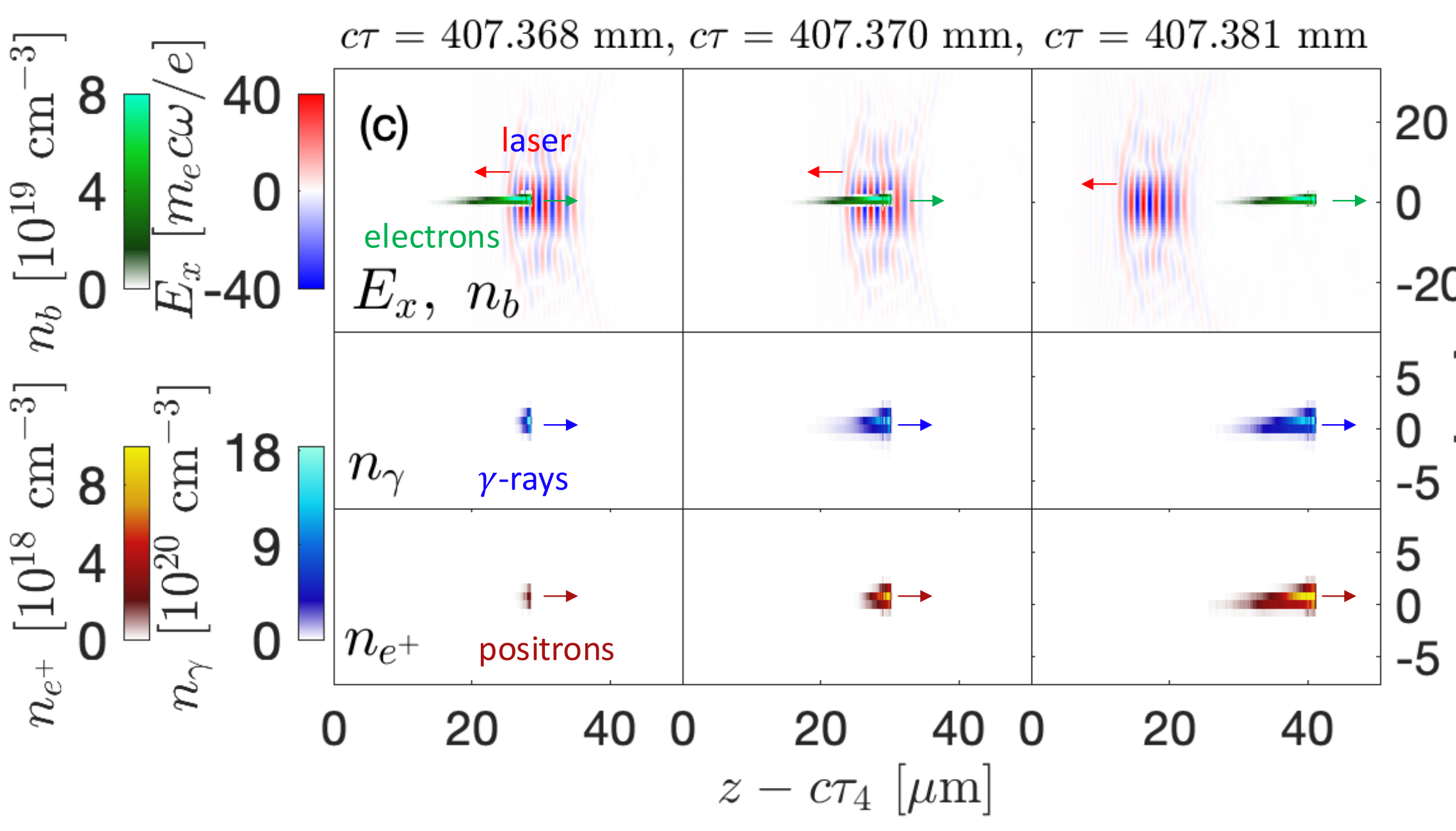
Collision

$a_0 = 40$
$\mathcal{E} = 10$ GeV $\Rightarrow$ $\chi_e \sim 5$

Strong-field QED processes are visible

During the collision, collimated jets of γ-rays and positrons are created.

PIC-QED simulation of the collision



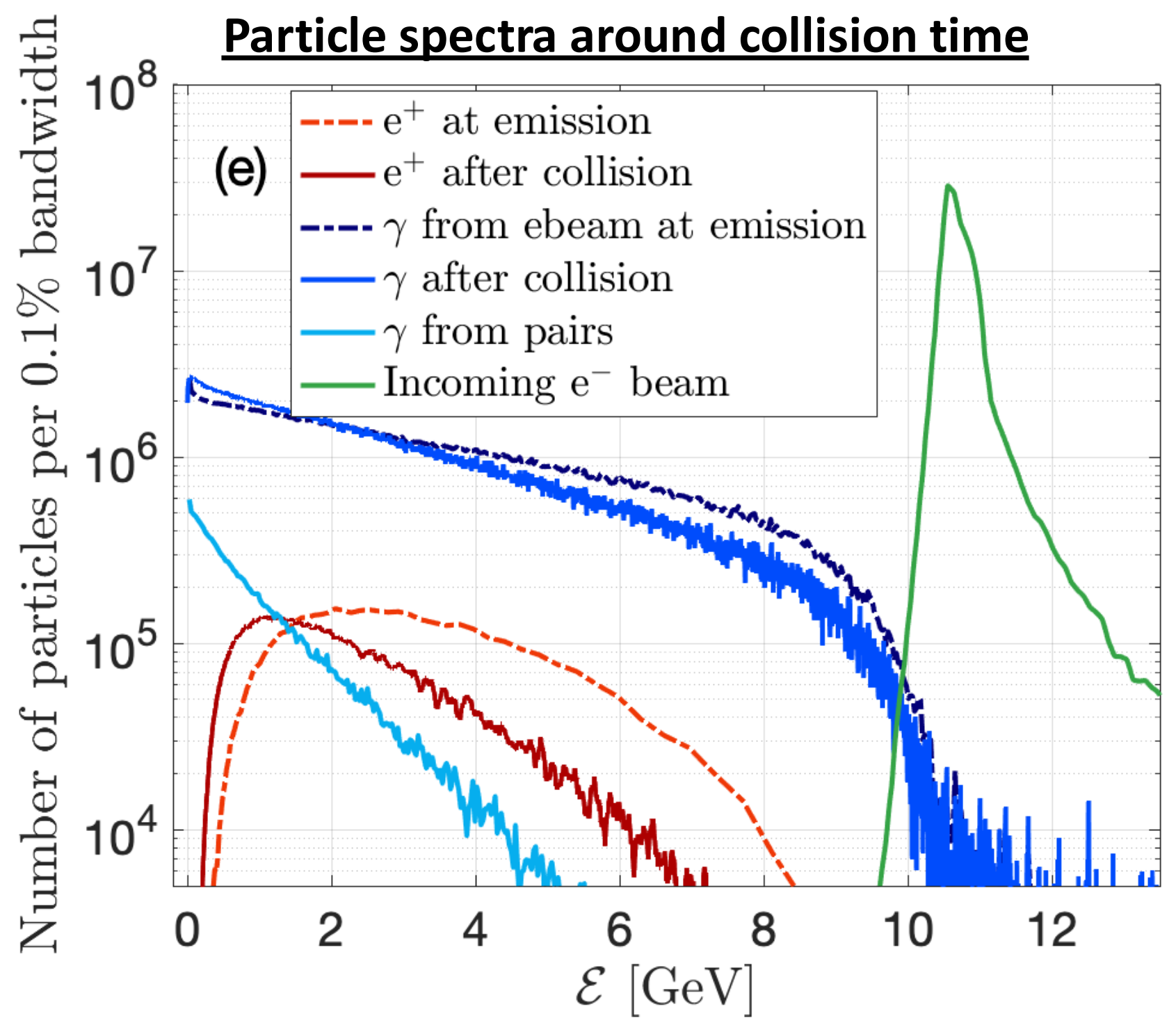
Scenario of the collision

1. The incoming 11 GeV electron beam collides with the laser
2. γ-rays are produced via NICS
3. Positrons are created from the γ-rays and the laser via NLBW
4. After emission, positrons are slowed down by the laser field
5. Because they experience the laser field, positrons emit new γ-rays

40 pC of positron charge is created during collision

It corresponds to 20 % of the original beam charge

Particle spectra around collision time



 # References:
[1] Mirzaie *et al.*, Nature Photonics 18, 1212-1217 (2024).
[2] Cole et al., Phys. Rev. X 8, 011020 (2018).
[3] Ta Phuoc *et al.*, Nature Photonics 6, 308–311 (2012).
[4] Matheron *et al.,* arXiv:2412.19337 (2024).
[5] Matheron *et al.*, arXiv:2408.13238 (2024).

 # Link to the paper:

Matheron *et al.*, arXiv:2408.13238 (2024).