High fields computational challenges

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Contents

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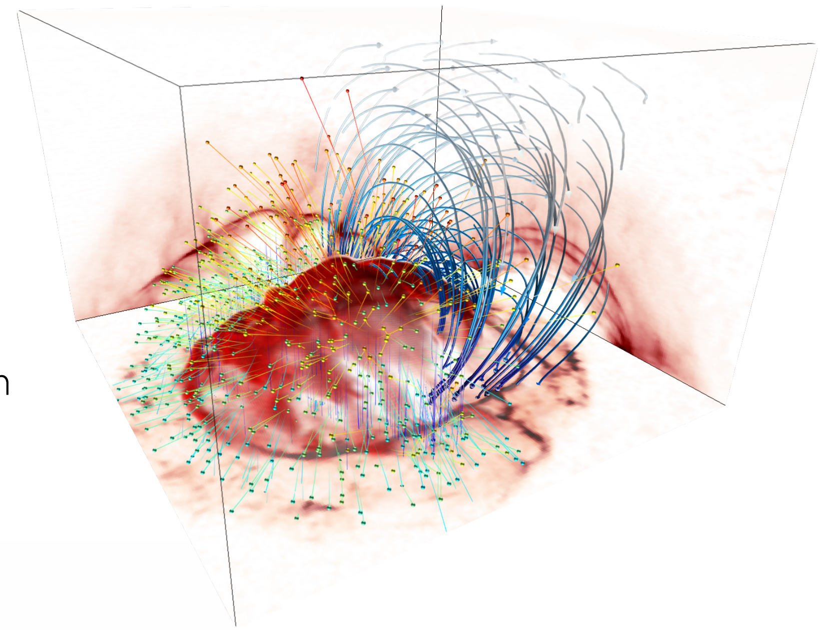
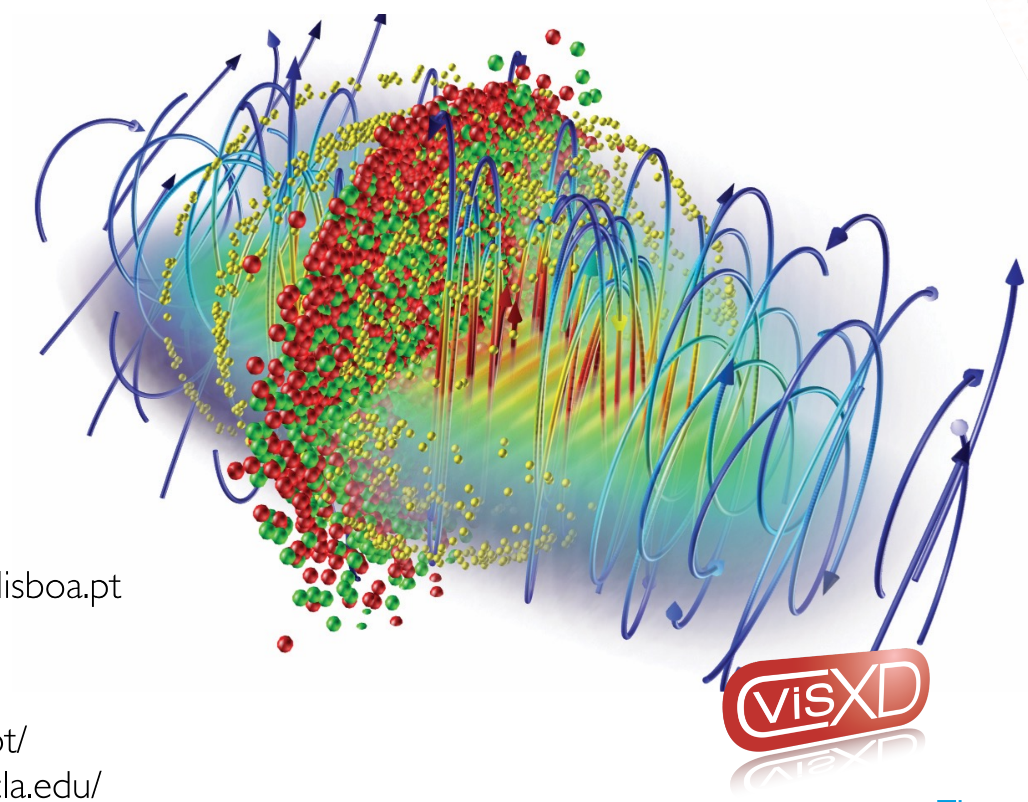
OSIRIS 3.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





code features

- Scalability to ~ 1.6 M cores
- Dynamic Load Balancing
- GPGPU and Xeon Phi support
- Particle merging
- **QED module**
- Quasi-3D
- Current deposit for NCI
- Collisions
- **Radiation reaction**
- Ponderomotive guiding center

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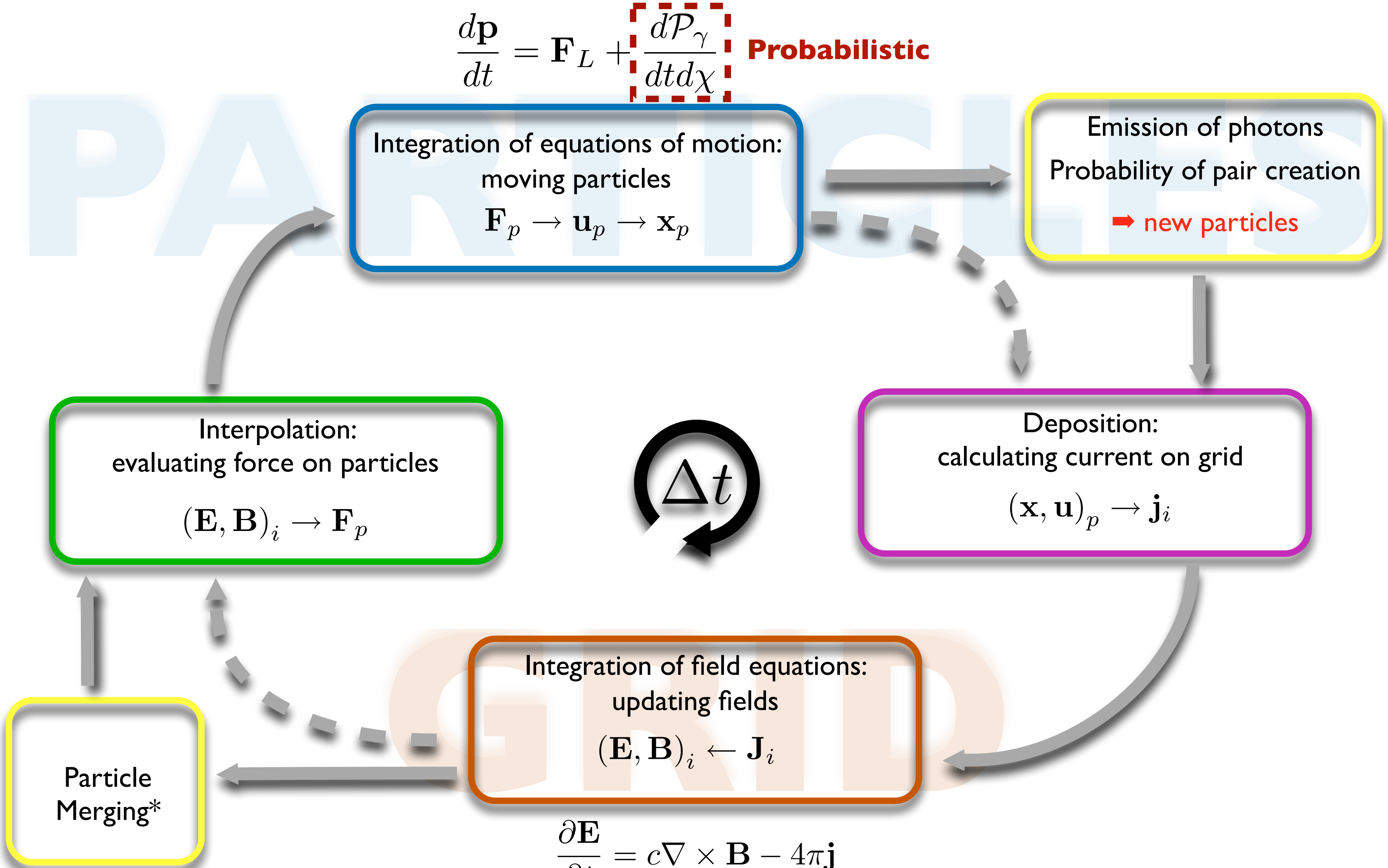
http://plasmasim.physics.ucla.edu/

OSIRIS-QED PIC LOOP

UCLA | TÉCNICO LISBOA



$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

E.N Nerush et al., *PRL* 106, 035001 (**2011**)
C. P. Ridgers et al., *PRL,* 108, 165006 (**2012**)
M. Lobet et al., *PRL* 115, 215003 (**2015**)
A. Gonoskov et al., *PRE* 92, 023305 (**2015**)
*M. Vranic et al., *CPC* 191, 65-73 (**2015**)

The fundamental χ parameter

- **Schwinger field**

$$E_s = \frac{m^2c^3}{e\hbar}$$

→ **Pair creation probability :**

$$W \propto \exp(-\pi E_s/E)$$

- **Let us introduce the parameter**

$$\chi = \frac{E}{E_s}$$

- **And generalized in any frame**

$$\chi = \frac{1}{E_s}\sqrt{(\gamma\mathbf{E} + \frac{\mathbf{p}}{mc}\times\mathbf{B})^2 - (\frac{\mathbf{p}}{mc}\cdot\mathbf{E})^2}$$

$$\chi \simeq \frac{\gamma E_\perp}{E_s}$$

Other configuration with lower E should allow pair creation ! ←

Implementation of QED effects

Radiation Reaction

Different types of Radiation reaction models

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \begin{cases} \mathbf{F}_{rad} & \text{Continuous damping rate*} \\ \frac{d^2P}{dt\,d\chi_\gamma} & \text{QED probabilistic approach**} \end{cases}$$

Implementation in PIC codes

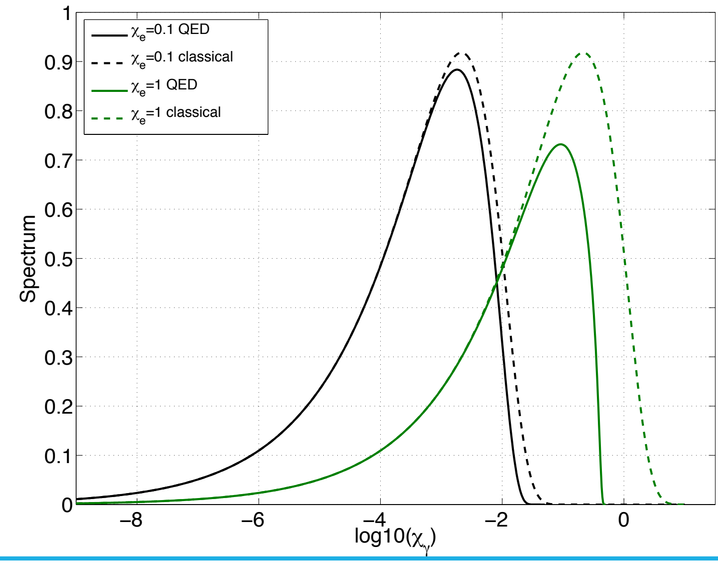
- Continuous damping rate: particle pusher with $\mathbf{F}_{rad}$ $\quad \gamma < 10$
- QED probabilistic approach: particle pusher + Monte Carlo module
  - every Δt : probability of photon emission
  - Select a photon in QED synchrotron spectrum
  - Update particle momentum due to quantum recoil
- The QED approach can be generalized to any external EM fields under the conditions: $t_{carac}(\vec{E},\vec{B}) \gg t_{coh} \implies a_0 \gg 1$
  - quasi-static fields
  - weak fields $\quad \chi_e^2 \gg \mathrm{Max}(f,g) \quad (f,g) \ll 1$

$f = F_{\mu\nu}^2/E_{crit}^2 \quad g = F_{\mu\nu}^{*}F_{\mu\nu}/E_{crit}^2 \quad E_{crit} = m^2c^3/e\hbar \quad \chi_{e,\gamma} = \frac{|F_{\mu\nu}p^{\nu}_{e,\gamma}|}{E_{crit}mc}$

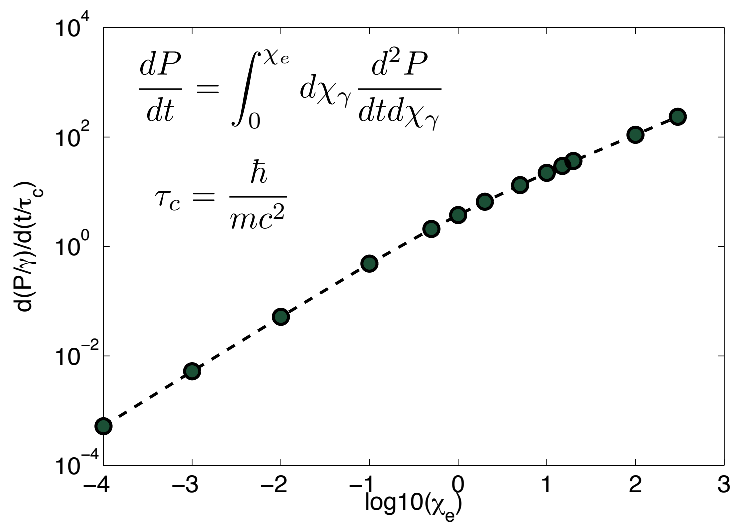
* Landau & Lifshitz (Theory of Fields)

** A.I. Nikishov & V.I. Ritus (1967), N.P. Kelpikov (1954), V.N. Baier & V.M. Katkov (1967)

Synchrotron Spectrum

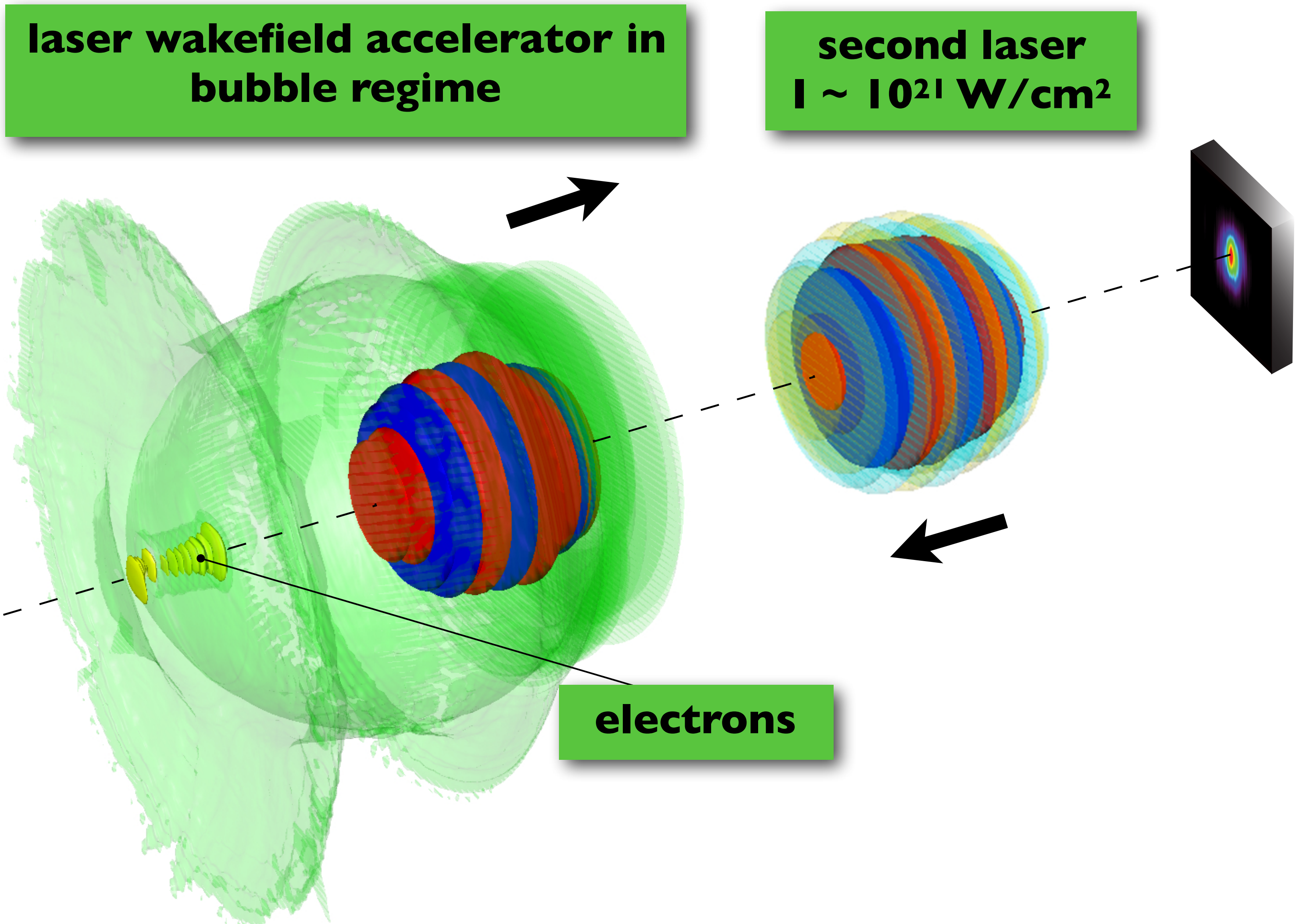


Emission rate



All-optical radiation reaction

~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm^2



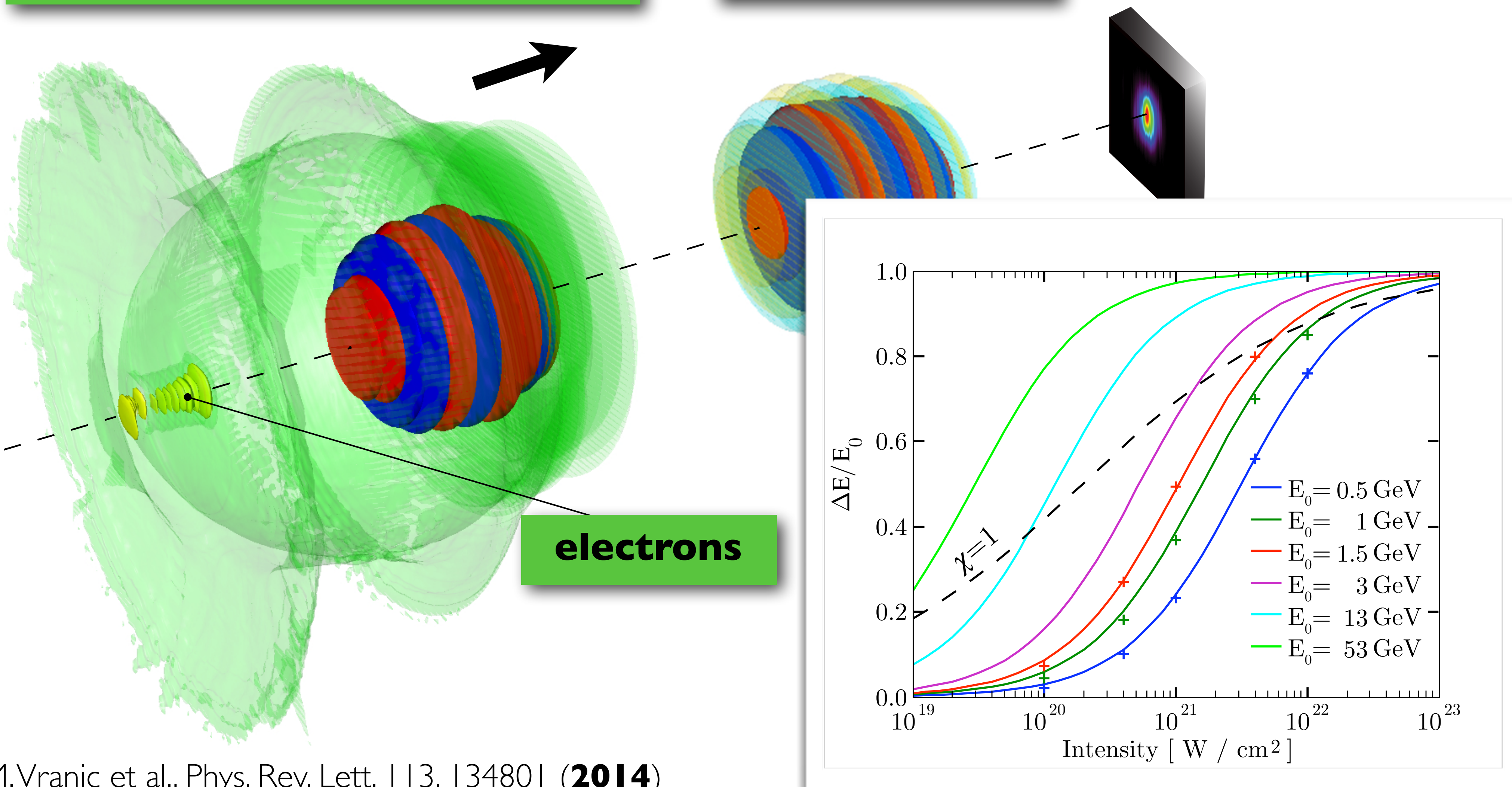
M. Vranic et al., Phys. Rev. Lett. 113, 134801 (**2014**)

All-optical radiation reaction

~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm²

laser wakefield accelerator in bubble regime

second laser
$I \sim 10^{21}$ W/cm²



M.Vranic et al., Phys. Rev. Lett. 113, 134801 (**2014**)

Pairs can be produced already at $\chi \simeq 1$

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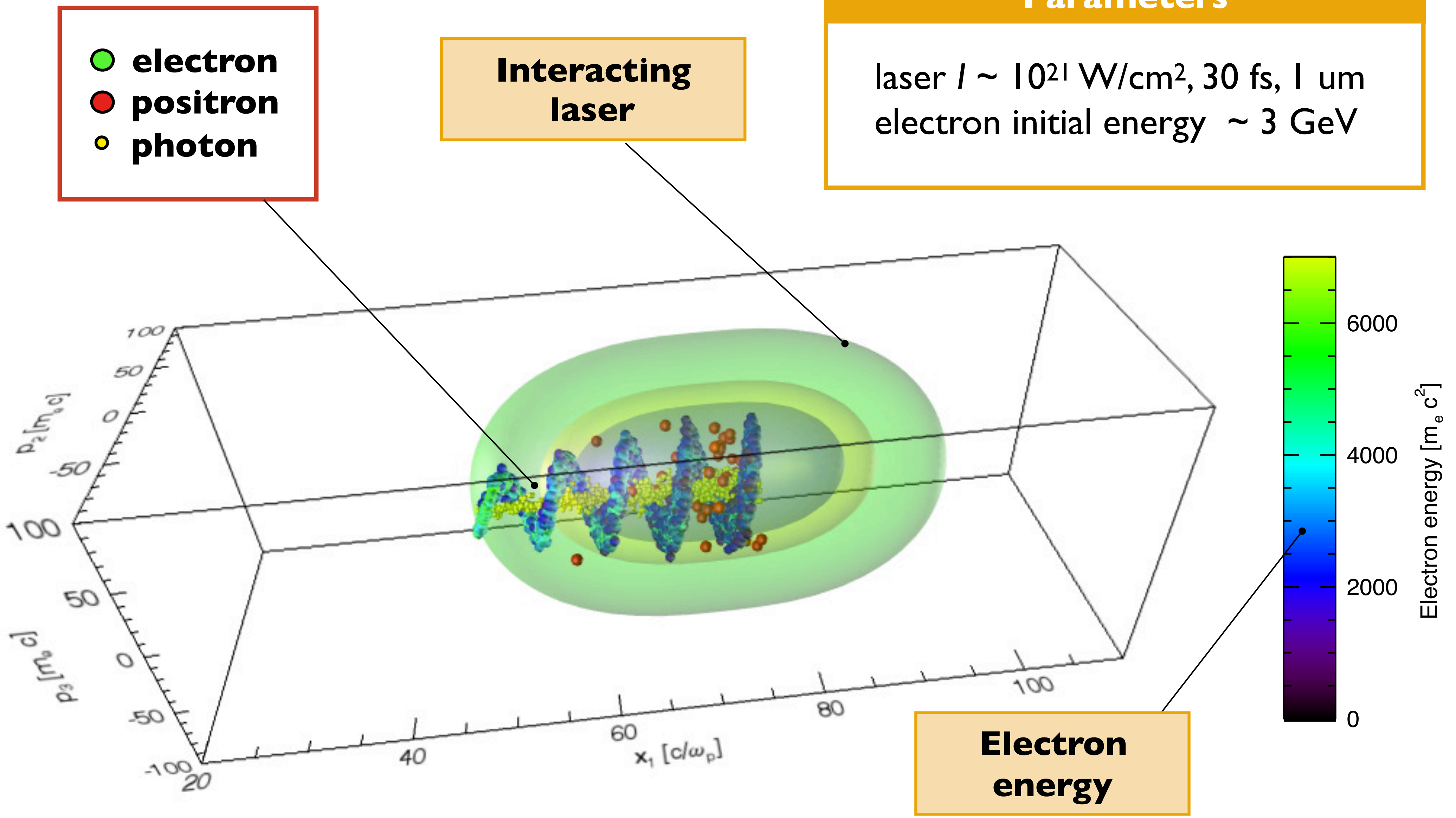
~ 200 pairs obtained per 1 000 000 interacting electrons

Parameters

laser I ~ 10^{21} W/cm^2, 30 fs, 1 um
electron initial energy ~ 3 GeV



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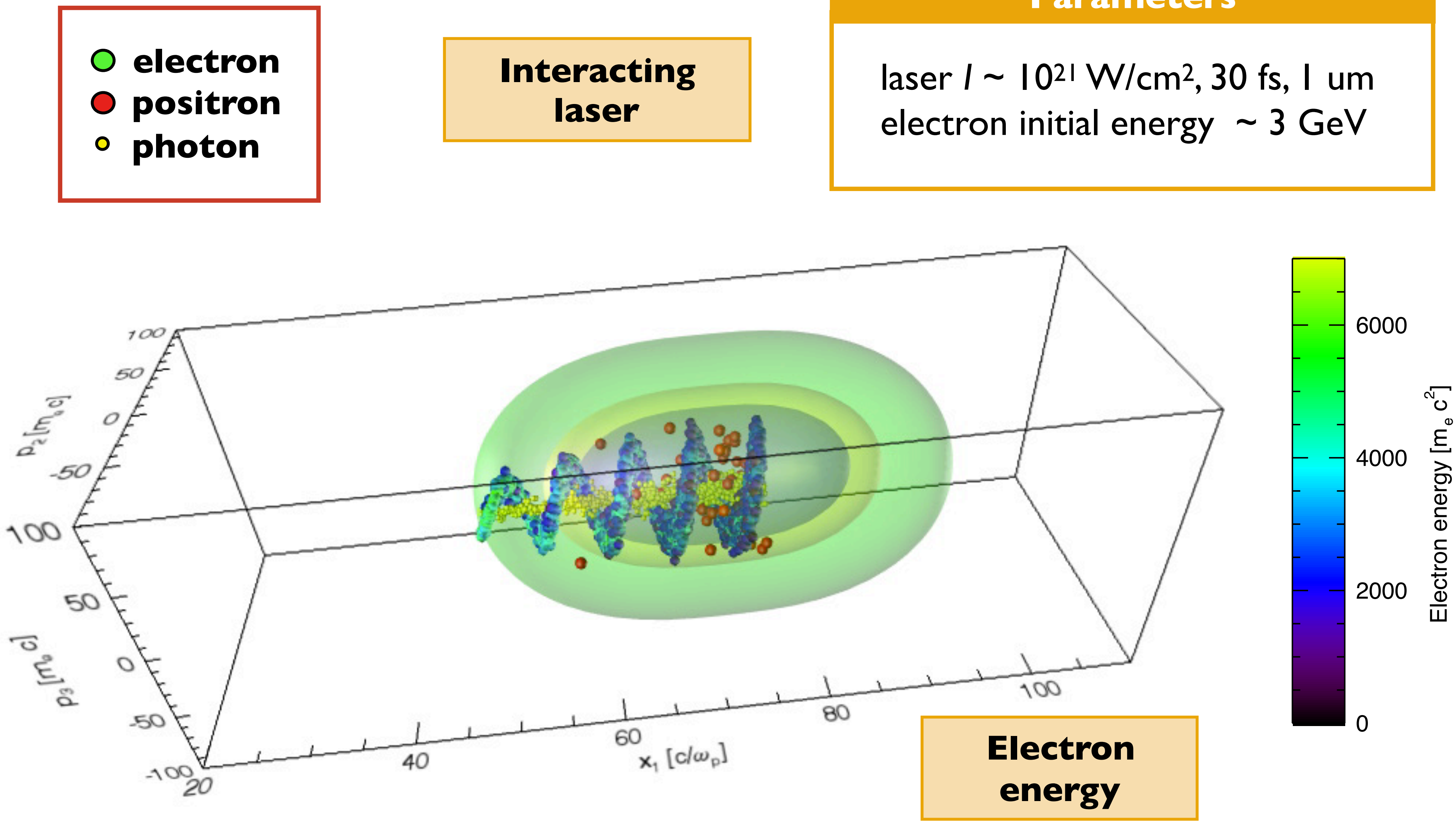


Standing waves configurations

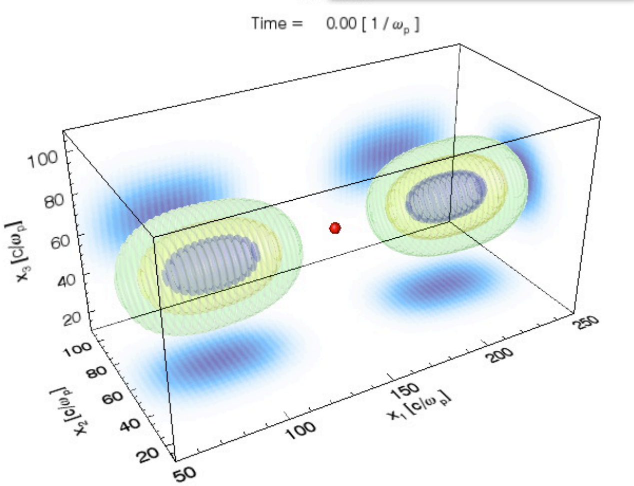
Linear	Double clockwise	Clockwise-anti

Parameters

- absorbing boundaries
- a0 = 1000
- λ0 = 1μm
- W0 = 3.2 μm
- τ = 60 fs

Linear

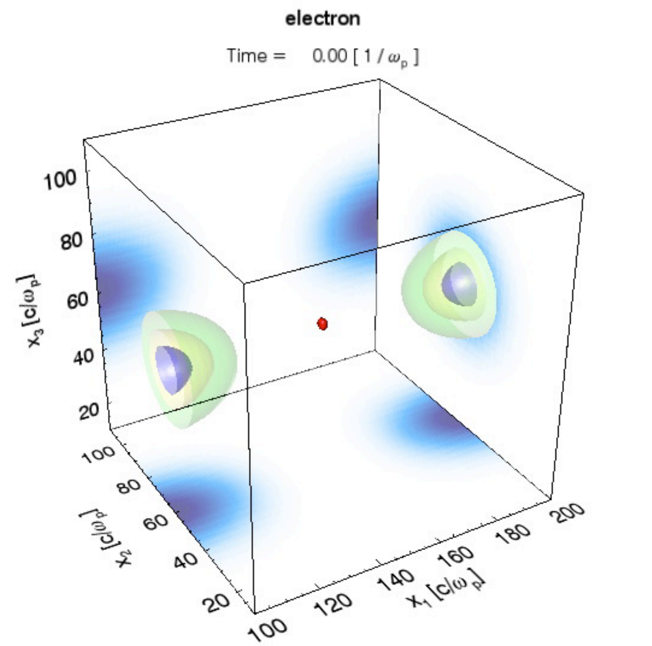
- **electron**
- **positron**



Particles remain in the x_1-x_2 plane

Double clockwise

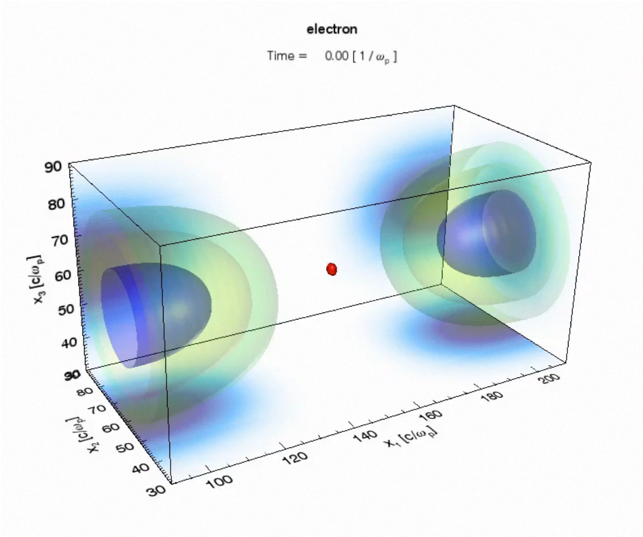
- **electron**
- **positron**
- **photon**



Particles explore the whole space

Clockwise-anti

- **electron**
- **positron**
- **photon**



Particles rotate mainly in the x_2-x_3 plane

A.R Bell and J. G Kirk PRL, 101, 200403 (**2008**) T.Grismayer et al., *PRE* 95, 023210 (**2017**)

Standing waves configurations

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Linear	Double clockwise	Clockwise-anti
● electron ● positron	● electron ● positron ● photon	● electron ● positron ● photon

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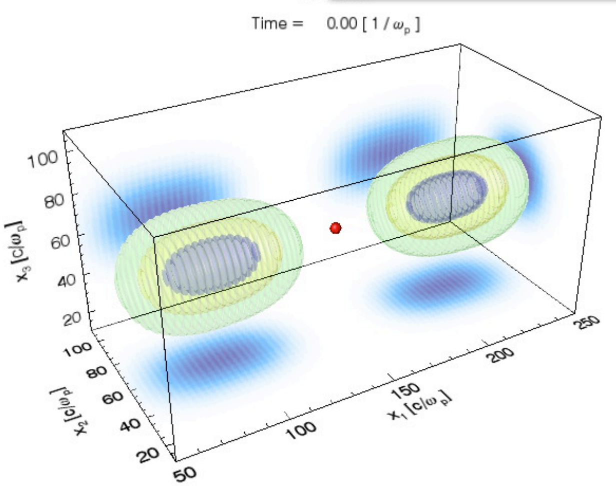
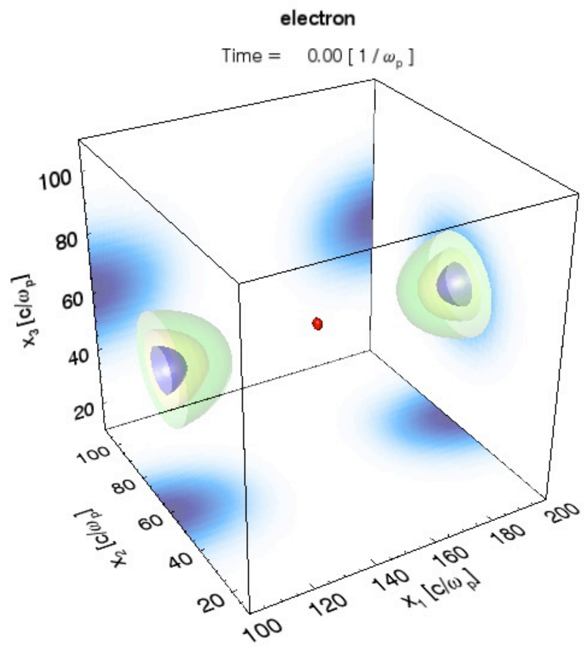
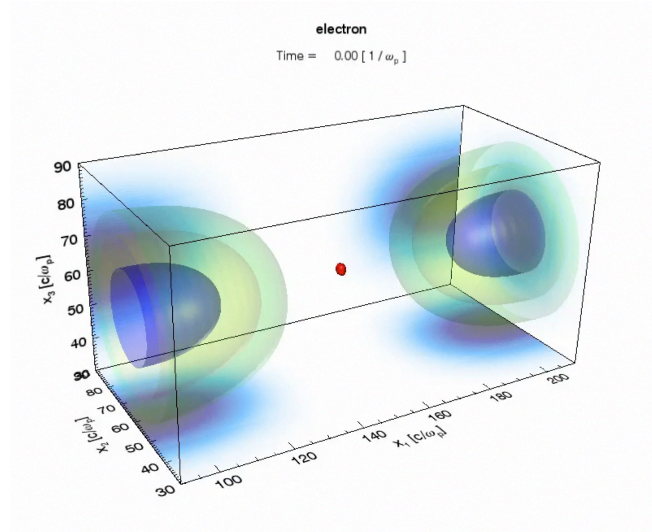


Particles remain in the x_1-x_2 plane



Particles explore the whole space



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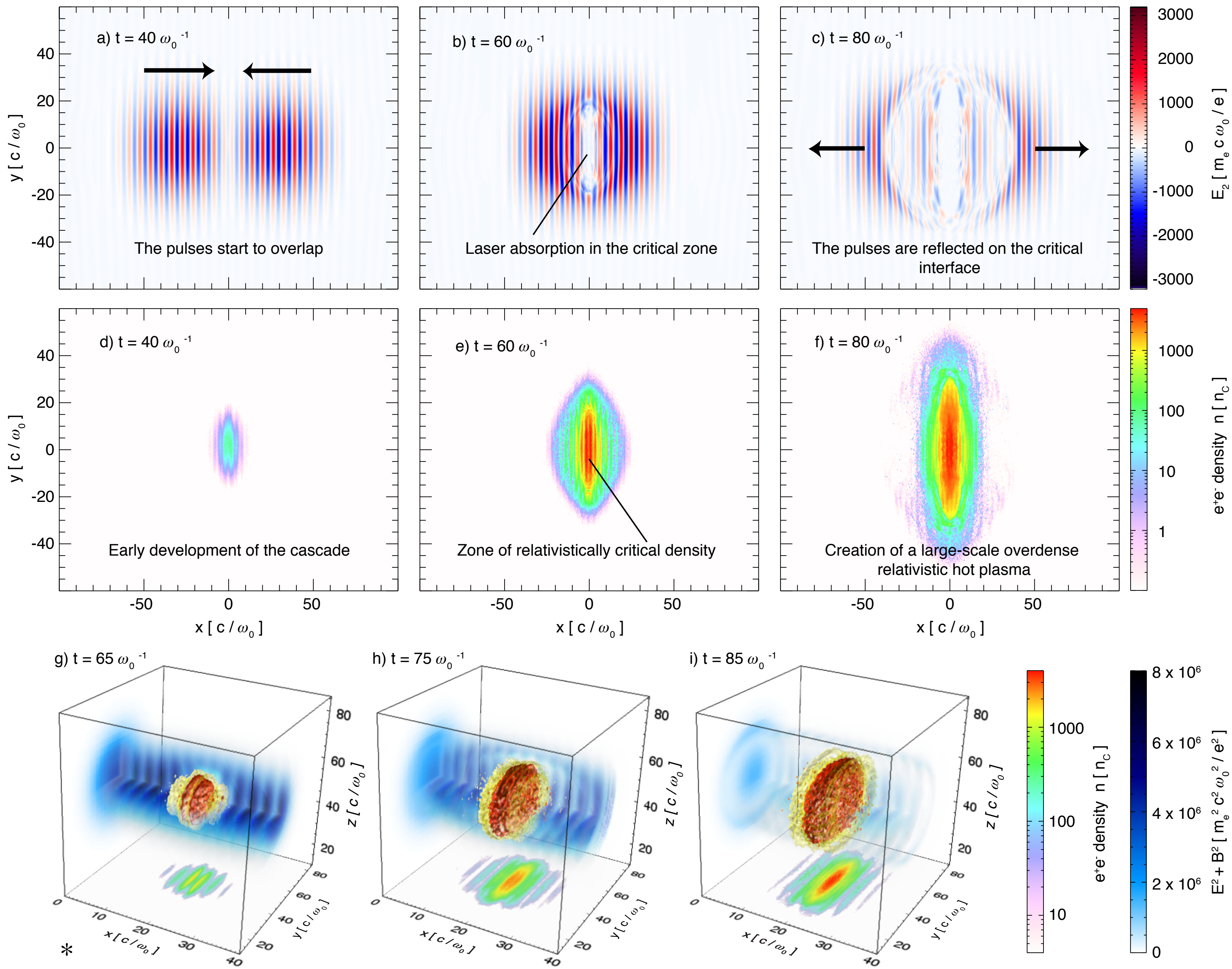
Interaction between self-consistent created pair plasma and the lasers



T. Grismayer et al., *PRE* 95, 023210 (**2017**)
T. Grismayer et al., *PoP* 23, 056706 (**2016**)

Heisenberg-Euler QED corrections

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Heisenberg-Euler corrections to Maxwell's Equations

- Electron-positron fluctuations give rise to an effective polarization and magnetization of the vacuum which can be treated in an effective form as corrections to Maxwell's equations*.

$$\frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{E} = 0 \qquad \vec{\nabla} \cdot B = 0$$

$$\vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = 0 \qquad \vec{\nabla} \cdot D = 0$$

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{B} = \mu_0 \vec{H} + \vec{M}$$

- With the effective vacuum polarization and magnetization

$$\vec{P} = 2\xi \left[2(E^2 - c^2B^2)\vec{E} + 7(\vec{E} \cdot \vec{B})\vec{B} \right]$$

$$\vec{M} = -2\xi \left[(2(E^2 - c^2B^2)\vec{B} - 7(\vec{E} \cdot \vec{B})\vec{E} \right]$$

- **Relevance for extreme astrophysical scenarios?**

J.Pétri, Mon. Not. Roy. Astron. Soc (**2015**)

- **Unprecedented intensities will allow to probe the quantum vacuum! What laser properties will be affected?**

eli beamlines

STFC Central Laser Facility

A. Di Piazza et.al, Rev. Mod. Phys. 84, 1177–1228 (**2012**).

- **Extract observable consequences of fundamental QED predictions.**

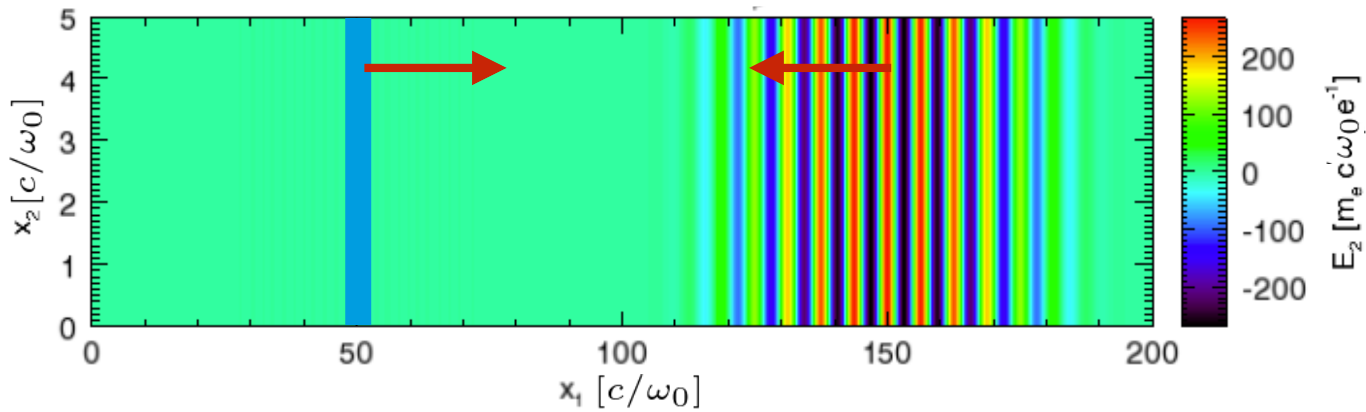
* W. Heisenberg and H. Euler, Z. Physik 98, 714 (**1936**).

P. Carneiro et al., arxiv: 1607.04224 (**2016**) A.P. Domenech and H. Ruhl arxiv:1607.00253 (**2016**)

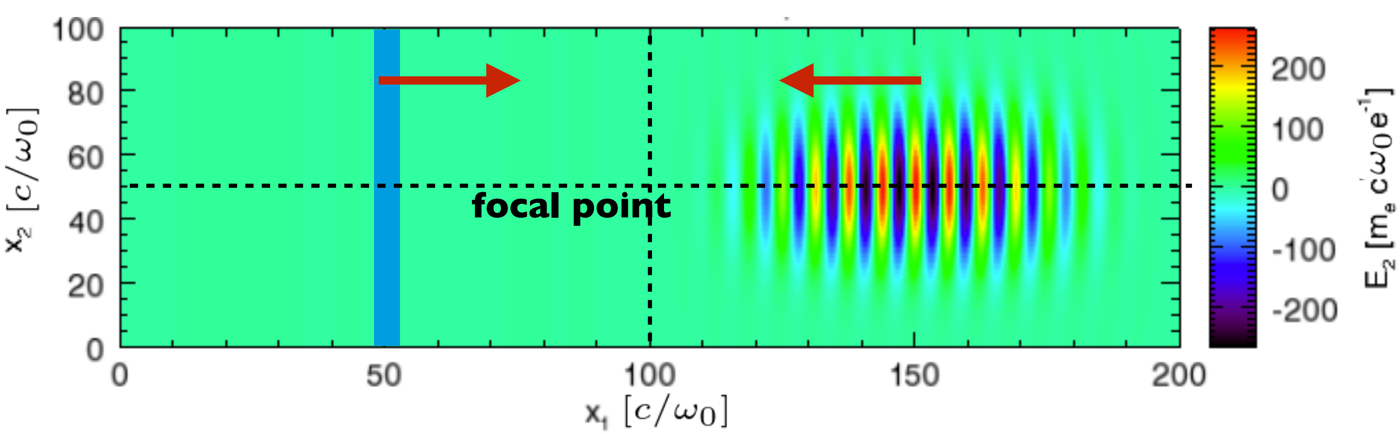
Vacuum Birefringence

Plane Wave transverse pump profile vs Gaussian pump beam profile

Plane Wave Transverse Pump Profile



Gaussian Pump Beam Profile



Pump pulse

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

$$\lambda_0 = 1 \ [\mu m]$$

Gaussian transverse profile

$$W_0 = 20 \ [c/\omega_0]$$

Probe pulse

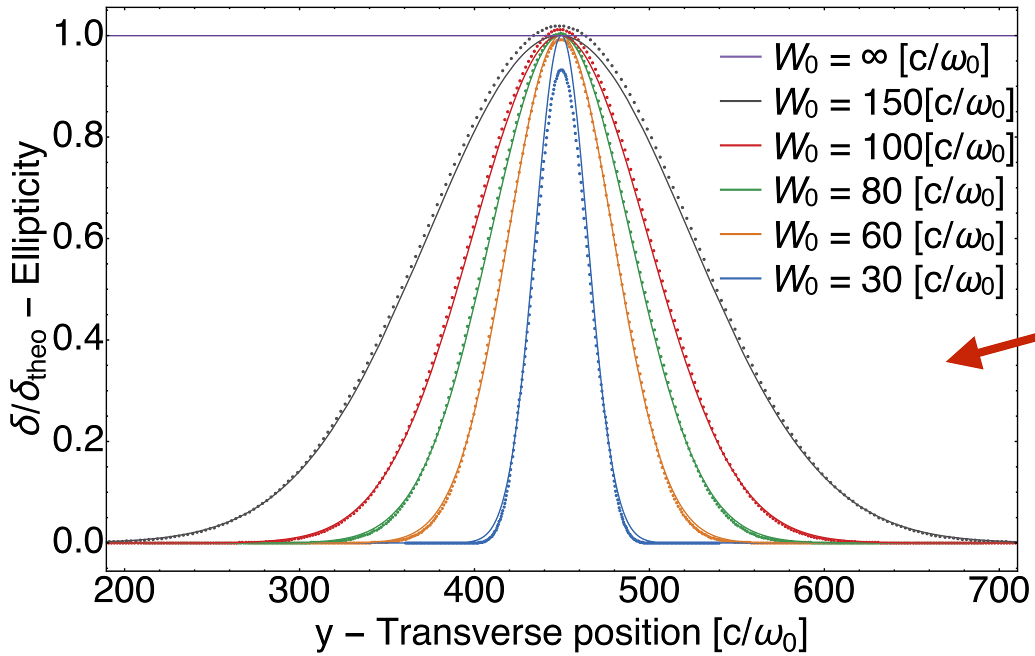
$$I_p = 10^{18} \ [W/cm^2]$$

$$\lambda_p = 10 \ [nm]$$

$$pol_p = \frac{\pi}{4} [rad]$$

V. Dinu et al., *PRD* 89, 125003 (**2014**)
S. Bragin et al., arxiv: 1704.05234 (**2017**)   F. Karbstein et al., *PRD* 92, 071301 (**2015**)

Plane Wave transverse pump profile vs Gaussian pump beam profile

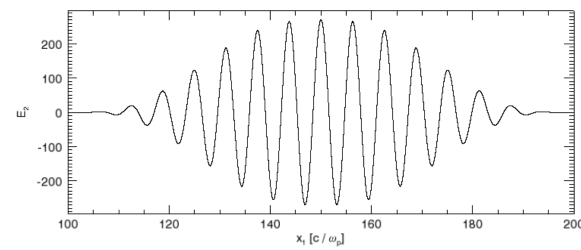


● Numerical result - Gaussian profile

— Theoretical result - Gaussian profile*

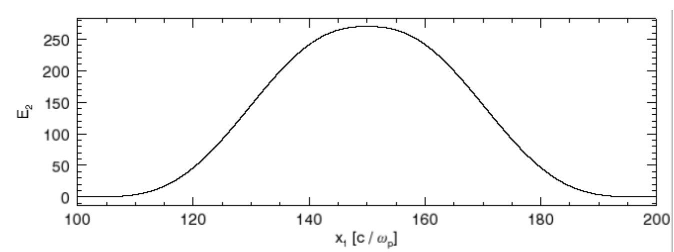
Oscillating gaussian profile

$$\delta = \frac{3}{2}\sqrt{\pi}k_p\sigma\xi E_0^2$$



Non-oscillating gaussian profile

$$\delta = 3\sqrt{\pi}k_p\sigma\xi E_0^2$$



* V. Dinu et al., Physical Review D 90, 045025 (**2014**)

OSIRIS vs CAIN*

OSIRIS

Pusher

Usual Boris-Pusher with classical and/or quantum radiation reaction with recoil

Beam field solver

Solves solves self-consistently Maxwell's equations for all particles in the box (beam + new created particles)

QED processes (first principles)

- Non-linear Compton scattering
- Breit-Wheeler pair production (spin averaged)
- Linear Compton scattering

CAIN

Pusher

Crank-Nicolson or subsampling trajectory with 4th order Runge-Kutta

Beam field solver

- Solves Poisson equation for transverse instantaneous electric field applied to each slice considering only the charges in the beam.
- The transverse magnetic field obeys

$$\mathbf{E} = -\boldsymbol{\beta} \times \mathbf{B}$$

QED processes with Spin effects

- Non-linear Compton scattering
- Breit-Wheeler
- Bethe-Heitler
- Landau-Lifschitz pair production with spin effects
- Linear Compton scattering

* P. Chen et al., SLAC-PUB-6583 (**1994**) and https://ilc.kek.jp/~yokoya/CAIN/cain235 (**2003**)

Disruption regimes for e-e+ colliding beams

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Disruption parameter

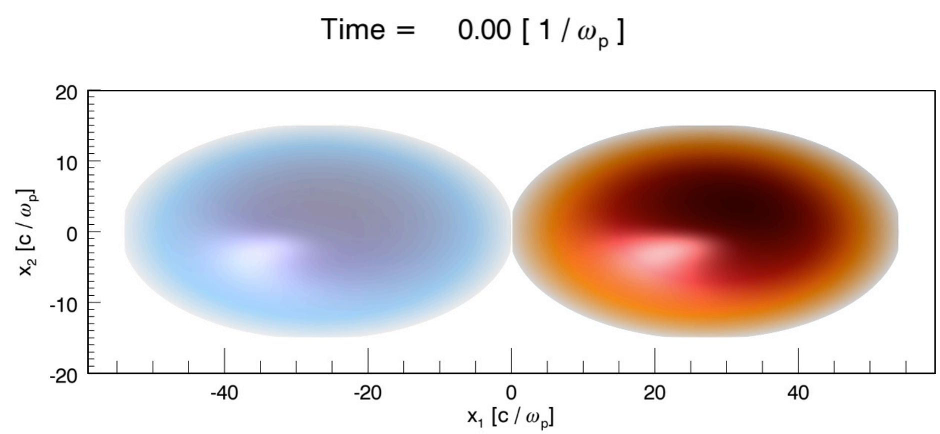
The disruption parameter relates to the number of pinching points of the beams during their interaction time

$$E_\perp \simeq B_\perp \sim e n_0 \sigma_0$$

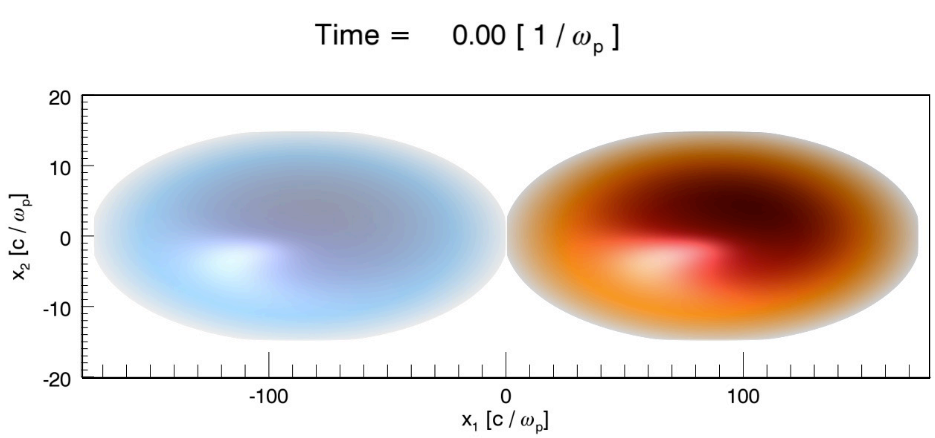
$$E_\parallel \sim E_\perp / \gamma$$

$$D = \frac{r_e N \sigma_z}{\gamma \sigma_0^2}$$

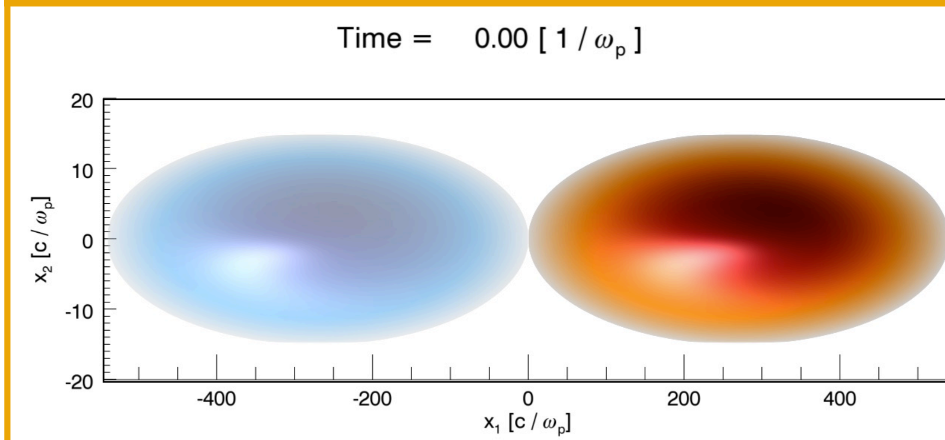
Low disruption regime D<1



Transition regime 1<D<10



Confinement regime D>10



Electron beam density

Positron beam density

P. Chen, S. Rajagopalan and J. Rosenzweig, *PRE* 40 (**1989**)
P. Chen and K. Yokoya et al., *PRD 38* (**1988**)
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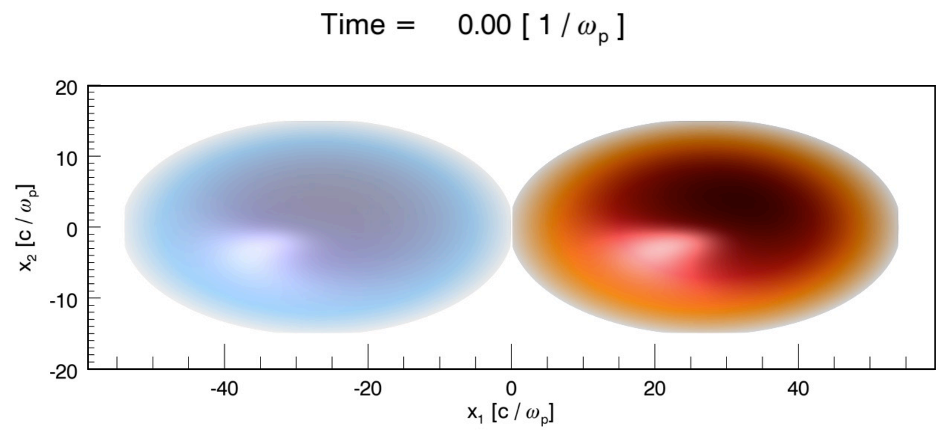

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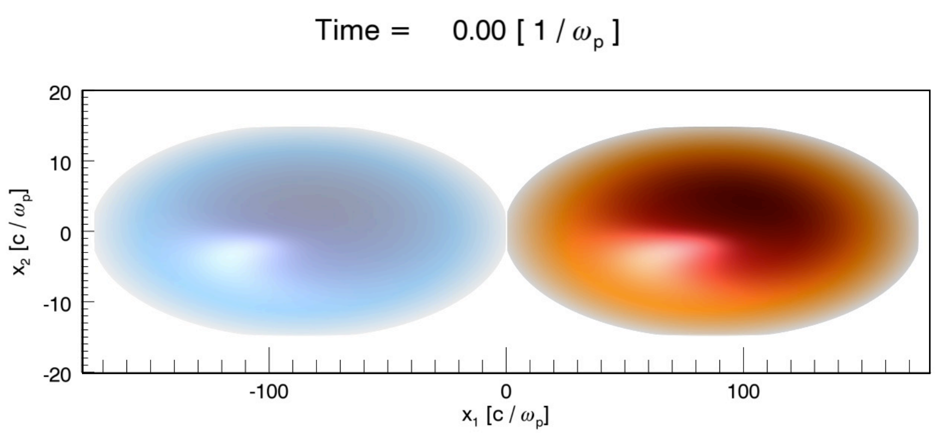

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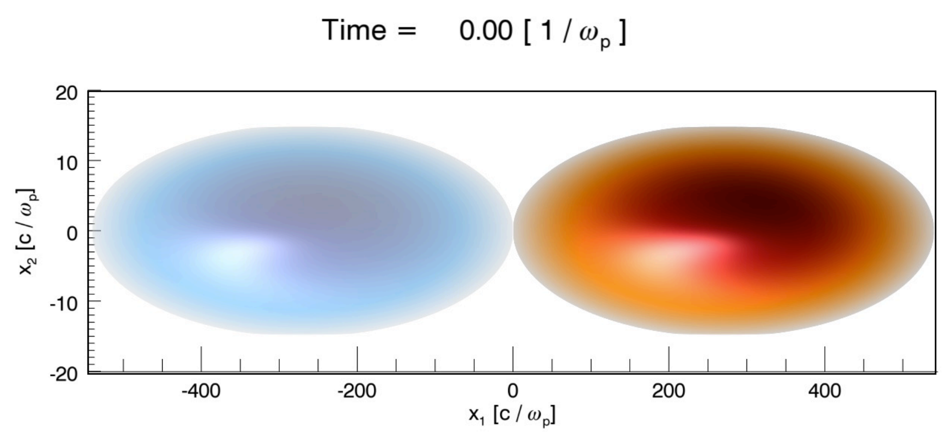

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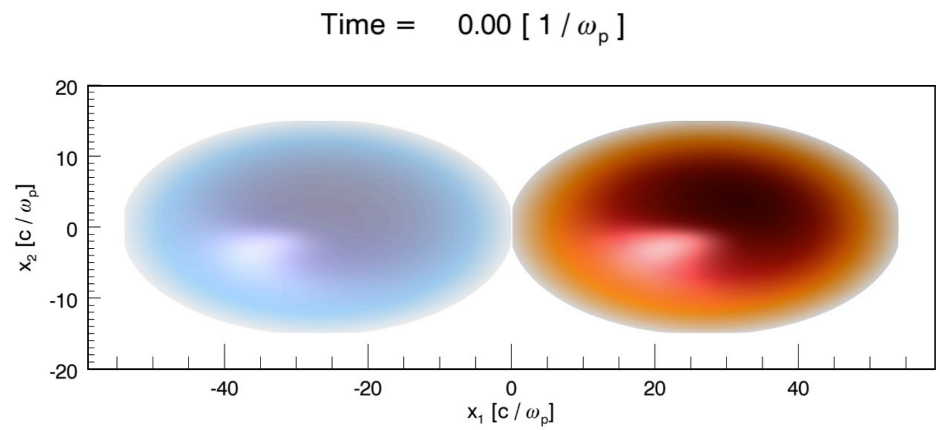

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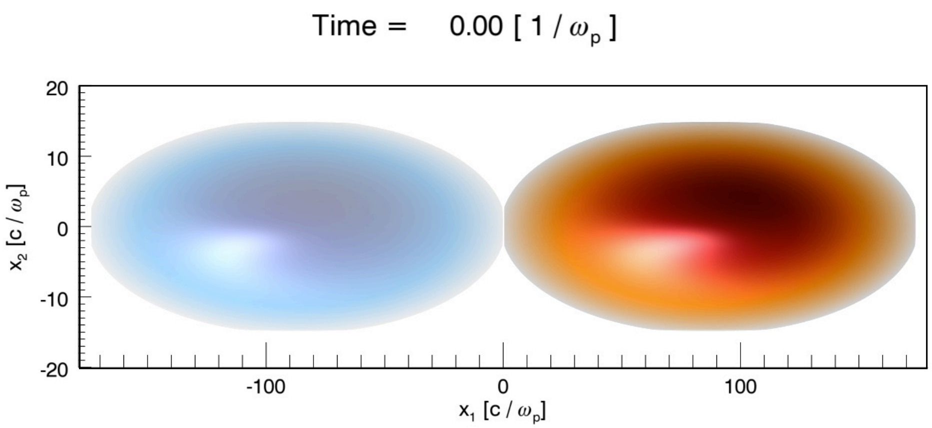

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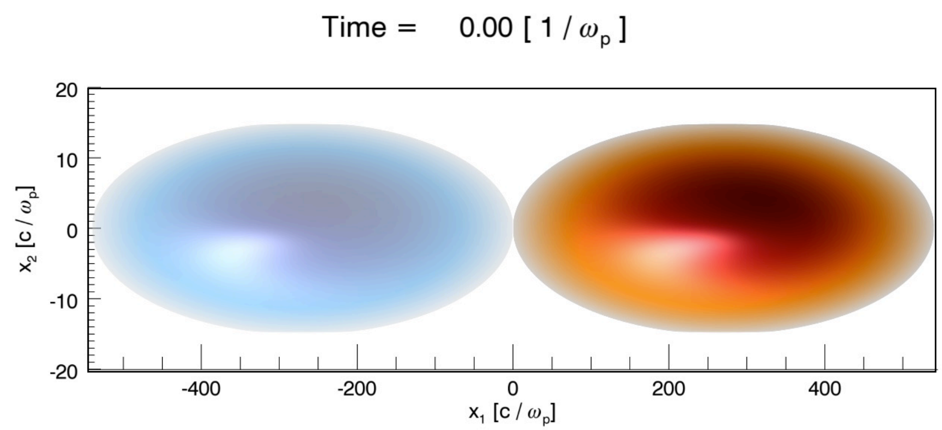

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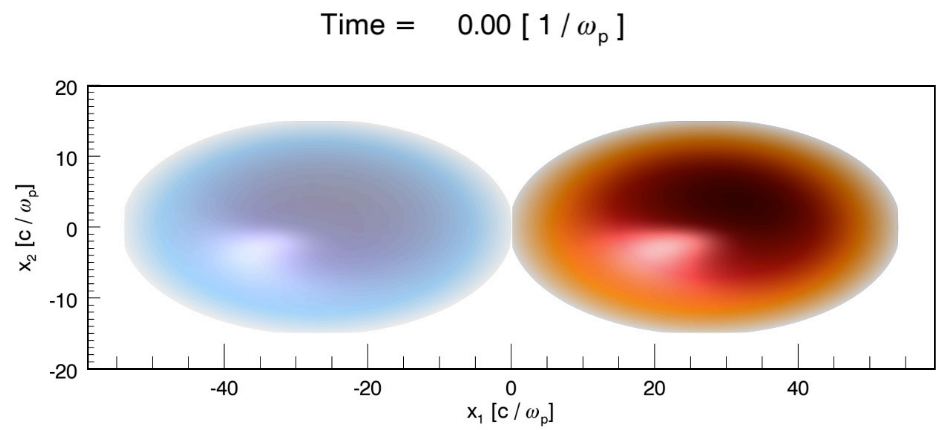

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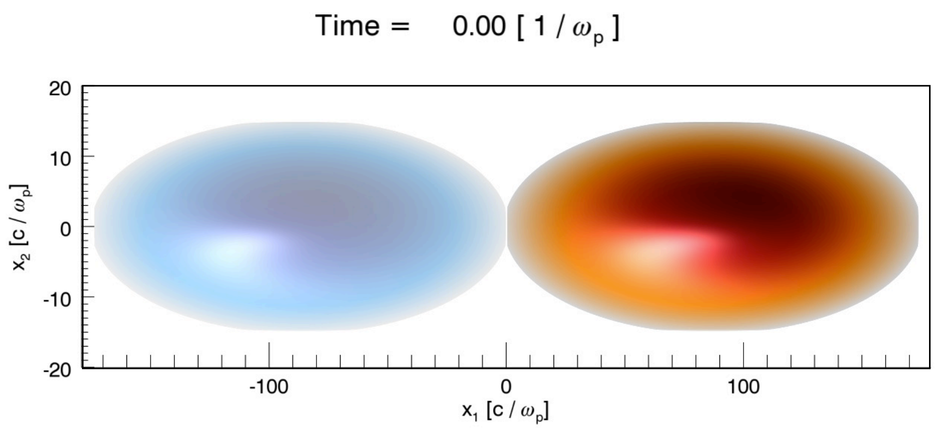

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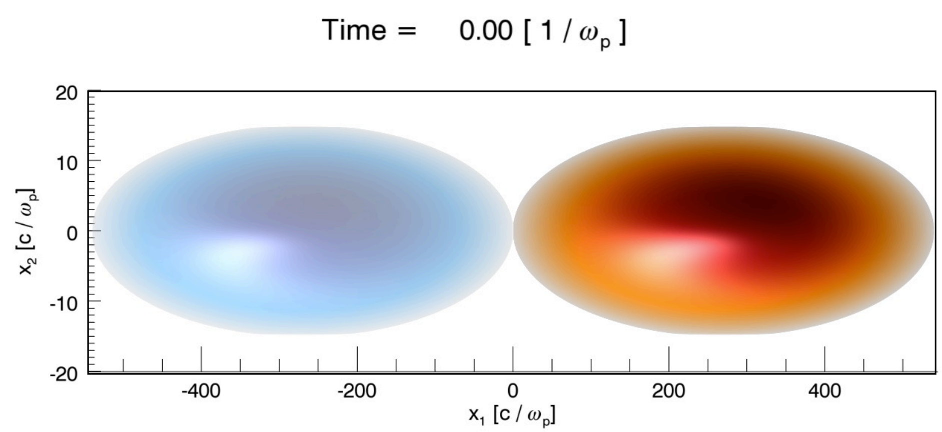

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Energy loss of the beam: classical vs quantum

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Quantum regime

Parameter χ measures the closeness to the quantum regime, with E_s the Schwinger limit

$$\chi = \frac{\gamma E}{E_s}$$

Classical *vs* quantum

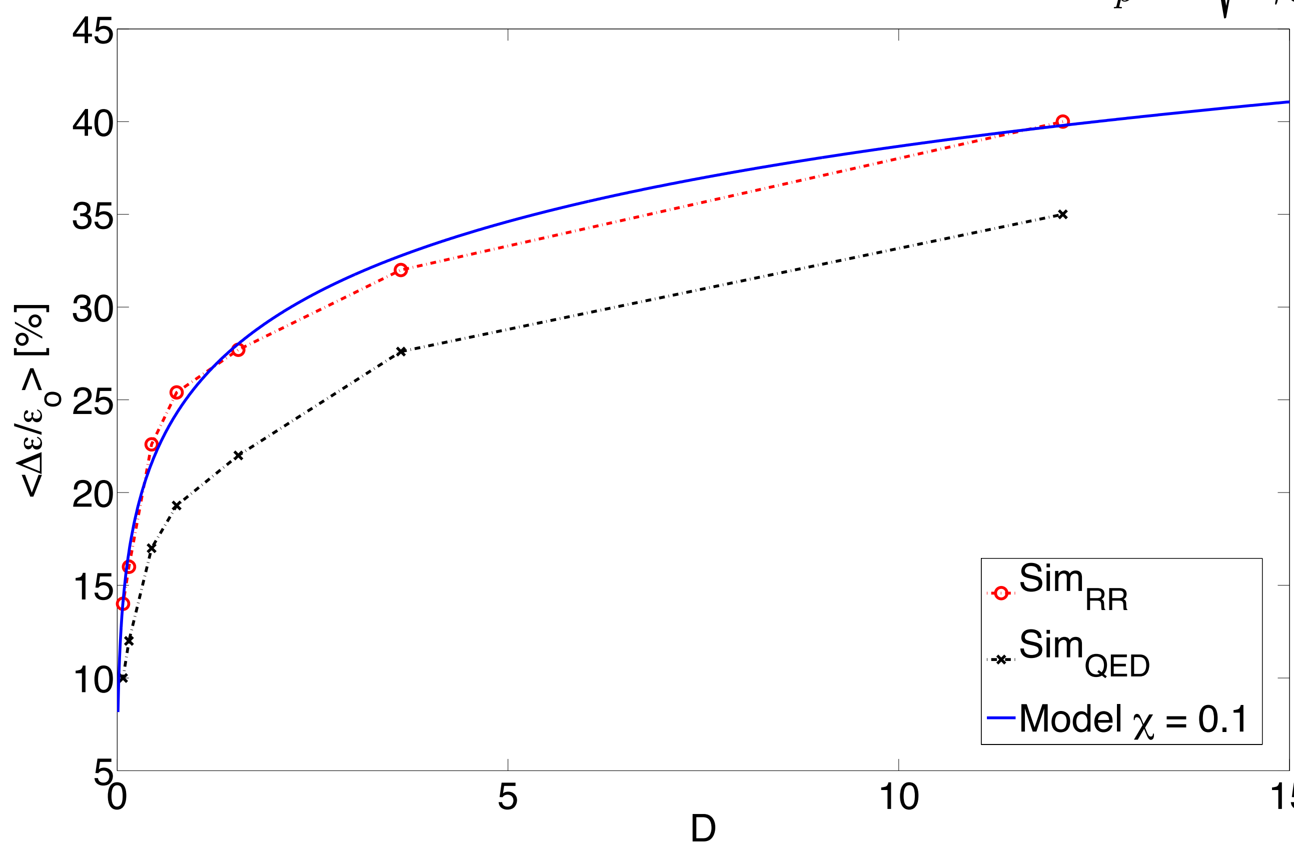
Close to the quantum regime ($\chi \rightarrow 1$), the classical model overestimates the radiative losses, thus a quantum approach is required

Energy loss of the beam close to the quantum regime

Average energy loss derived from the classical Landau-Lifshitz radiation reaction force

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle = 1 - \frac{\mathrm{atan}(\sqrt{b})}{\sqrt{b}}$$

$$b = \frac{\pi}{3}(2\pi)^{1/4}\alpha\frac{mc^2}{\hbar\omega_p}\chi_0^2\sqrt{\frac{D}{\gamma_0}}$$



Tabletop LWFA frontier and new objectives

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Fast development of plasma wakefield acceleration technology

Single-stage up to 5 GeV

Multi-stage configuration

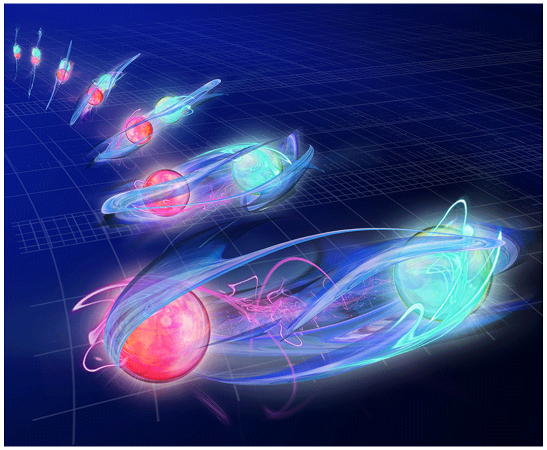
	LWFA parameters
N [10^{10}]	2-6
Energy [GeV]	5-30
Length [μm]	3
Spot size [μm]	1x1
D	10^{-5} - 10^{-2}

New LWFA beams colliders may approach the quantum regime $\chi \sim 1$

courtesy of http://www.klassikmagazine.com/seb-janiak-artist/

Beam particles can emit ɣ ray interacting with the oncoming beam EM field

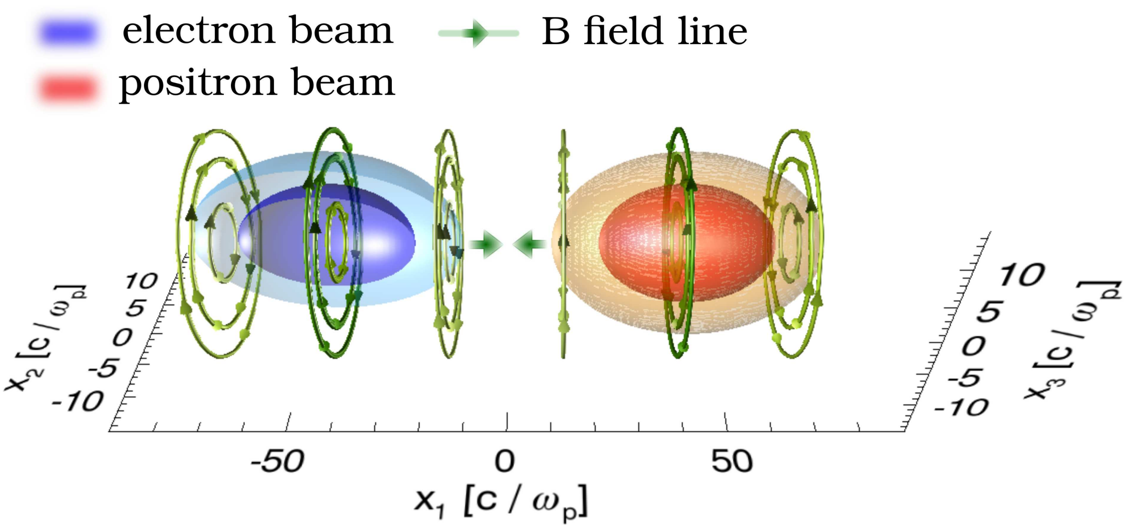
Hard photons can decay in pairs



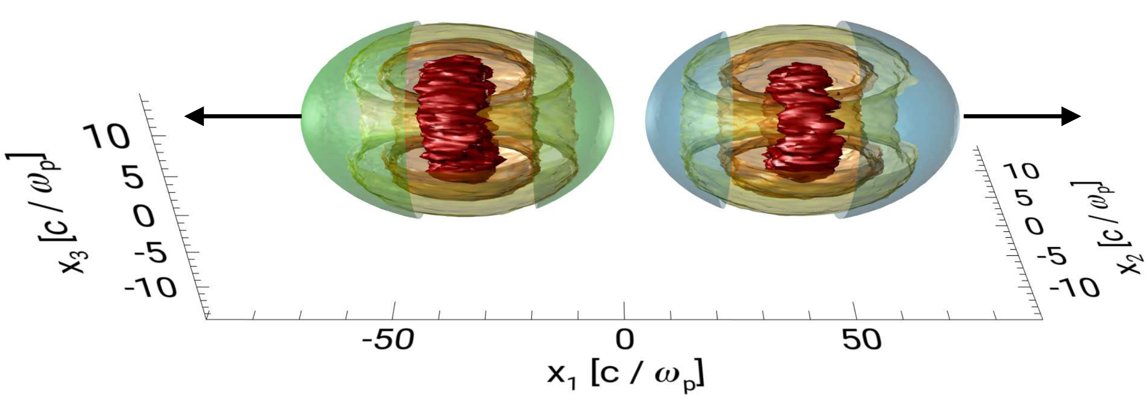
courtesy of http://physics.aps.org/articles/v9/67

Beamstrahlung approaching the QED regime

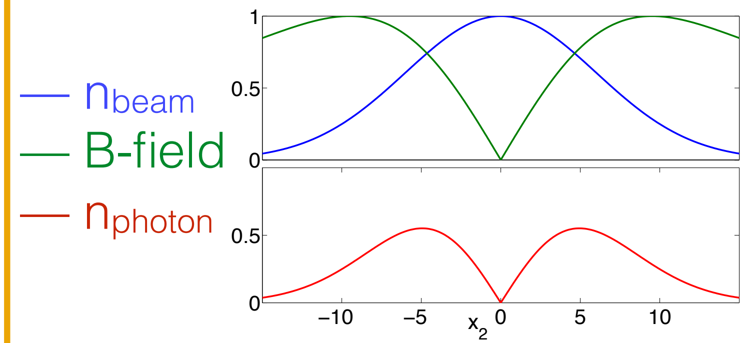
Before interaction



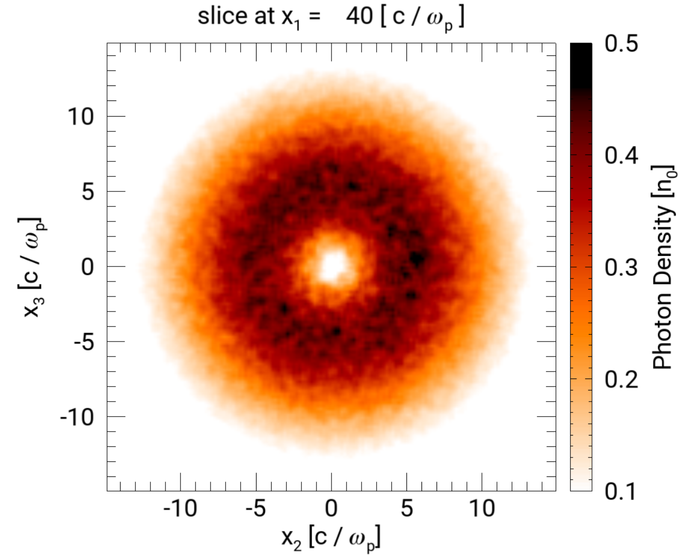
After interaction



Profiles



If the beam density profile is not disrupted, the produced photon beam shows a characteristic hole, where the B field is null



Photon and pairs QED model for D<1

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Particles trajectories are close to straight lines

the transverse density profile is constant

$$\rho(x) = \frac{e^{-x^2/2\sigma_o^2}}{\sqrt{2\pi}\sigma_o}$$

The model accounts for QED processes

The time average probability for photon emission

$$g(\xi, x) = \int_{-\infty}^{\infty} \frac{d^2P}{dt d\xi} dt$$

Differential probability rate for pair creation ($\chi_e \lesssim 1$)

$$W_p \simeq \frac{3\pi\alpha}{50} E(x,t) e^{-8/3\xi\chi_e}$$

Photon emission process

Average intensity

$$I = n_o c \epsilon_e \int_{-\infty}^{\infty} \frac{\int_0^1 \xi g d\xi}{\int_0^1 g d\xi} \rho dx$$

Energy spectrum

$$S(\xi) = \int_{-\infty}^{\infty} \xi g(\xi, x) \rho(x) dx$$

Probability a photon generated at t' will decay in a pair along the remaining interaction time of the two beams

$$\mathcal{P}_{\gamma \to p}(\xi, t', x) = \int_{t'}^{\infty} W_p dt = \frac{\sqrt{\pi}}{2} \tau \left[1 - \mathrm{erf}\left(\frac{t'}{\tau}\right)\right] W_p|_{t=0}$$

Characteristic time

$$\tau = \sigma_z / \sqrt{2 + 16/3\xi\chi_e(x)}$$

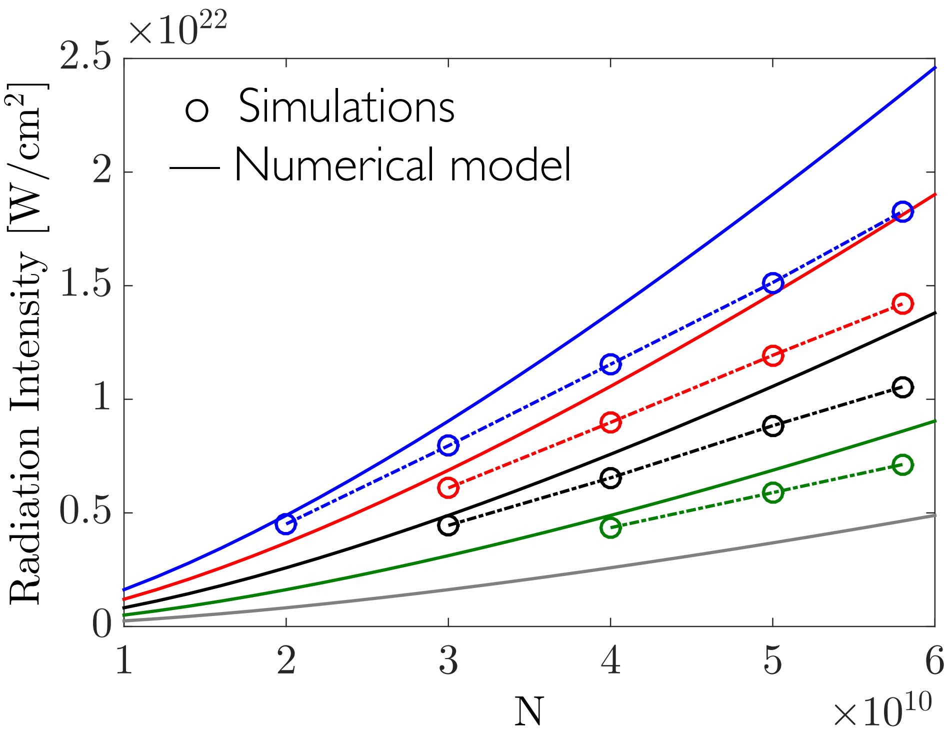
Time delay

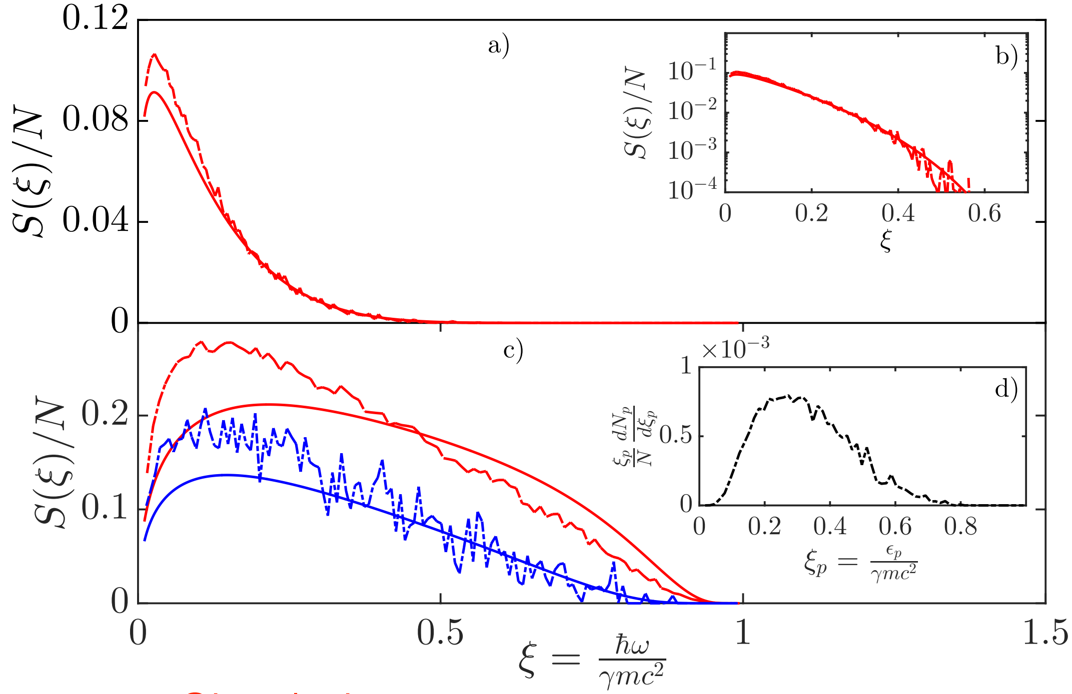
Max. probability to decay

Photon decay process generates pairs

$$N_p = N \int_x \rho \int_{-\infty}^{\infty} \int_0^1 \frac{d^2P}{dt' d\xi} \mathcal{P}_{\gamma \to p} d\xi dt' dx$$

Prediction of beamstrahlung radiation





2D simulations for beam energies of 30, 25, 20, 15, 10 GeV

Beam dimensions

$\sigma_0 = 1\mu\text{m} \quad \sigma_z = 3\mu\text{m}$

Simulation

Model

i) 2D simulation, 5 GeV, 2×10^{10} particles
ii) 2D simulation, 30 GeV, 5.8×10^{10} particles
iii) 3D simulation, 30 GeV, 5.8×10^{10} particles

The model overestimates the radiation intensity and energy spectrum, when a relevant number of pairs is produced during the interaction

Secondary pairs from 2D-3D simulations

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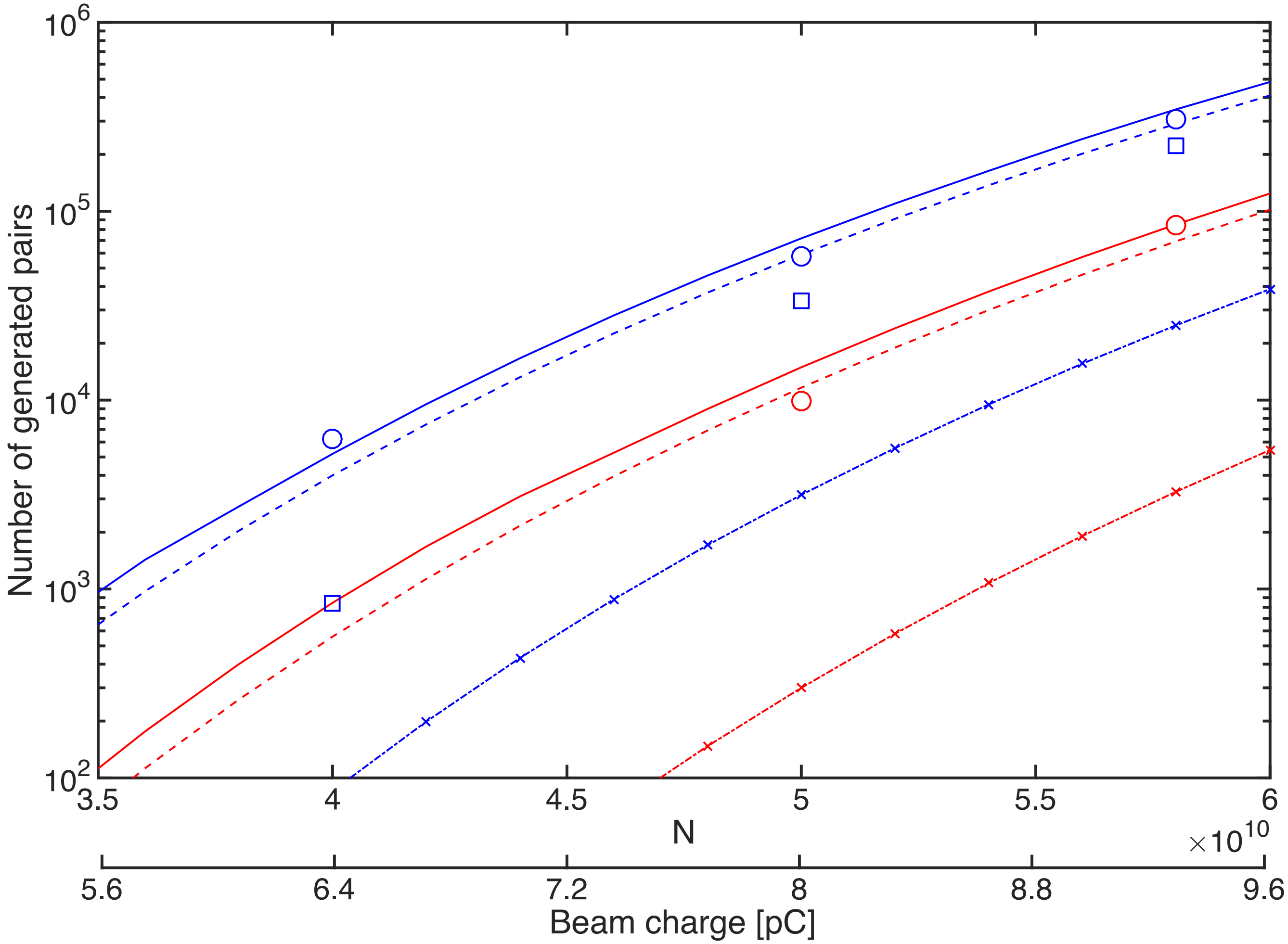

25 GeV

- o o Simulations
- — Numerical model
- - - Analytical model
- +- -+ Previous works*

30 GeV

- o o Simulations
- □ □ Simulations (flat beam)
- — Numerical model
- - - Analytical model
- +- -+ Previous works*

Beam dimensions

$\sigma_0 = 1\mu\mathrm{m} \quad \sigma_z = 3\mu\mathrm{m}$

(R~2.2)

Our model agrees with QED-PIC simulations and predicts higher number of pairs with gaussian beams than uniform beams

* P. Chen, V Telnov at Phys. Rev. Lett 63, 1796 (1989)
F. Del Gaudio, et al., to be submitted

(FACET II) 10 GeV e- / 300 MeV e+

Comparing FACET-II Electron Beam and PW laser

SLAC

	FACET-II	100GeV
Energy [GeV]	10	100
Beam peak current [kA]	200	1000
Beam size σr,σz [nm]	40, 500	10, 10
Number of electrons	10^{10}	10^{10}
Beam density [cm^{-3}]	10^{24}	$7\ 10^{25}$
Radial electric field [V/m]	$3\ 10^{14}$	$6\ 10^{15}$
Laser intensity equivalent to electric field [W/cm^2]	10^{22}	$5\ 10^{24}$
Laser power equivalent focussed into 2 μm [PW]	1.5	600
$\chi = 2\gamma \cdot E/E_s$ seen by 300 MeV beam	0.3	
χ seen by beam in 100TW laser focussed to 2 μm	2.3	
χ seen by 100 GeV beam		1800
$\alpha\chi^{2/3}$		1
Beam power [I_{peak} E] [PW]	2	100
Beam power density [W/cm^2]	$4\ 10^{25}$	$3\ 10^{28}$

~100Hz rep. rate / ~fs duration / 10's nm focus / radial polarization

Courtesy of V. Yakimenko

(FACET II) 10 GeV e- / 300 MeV e-

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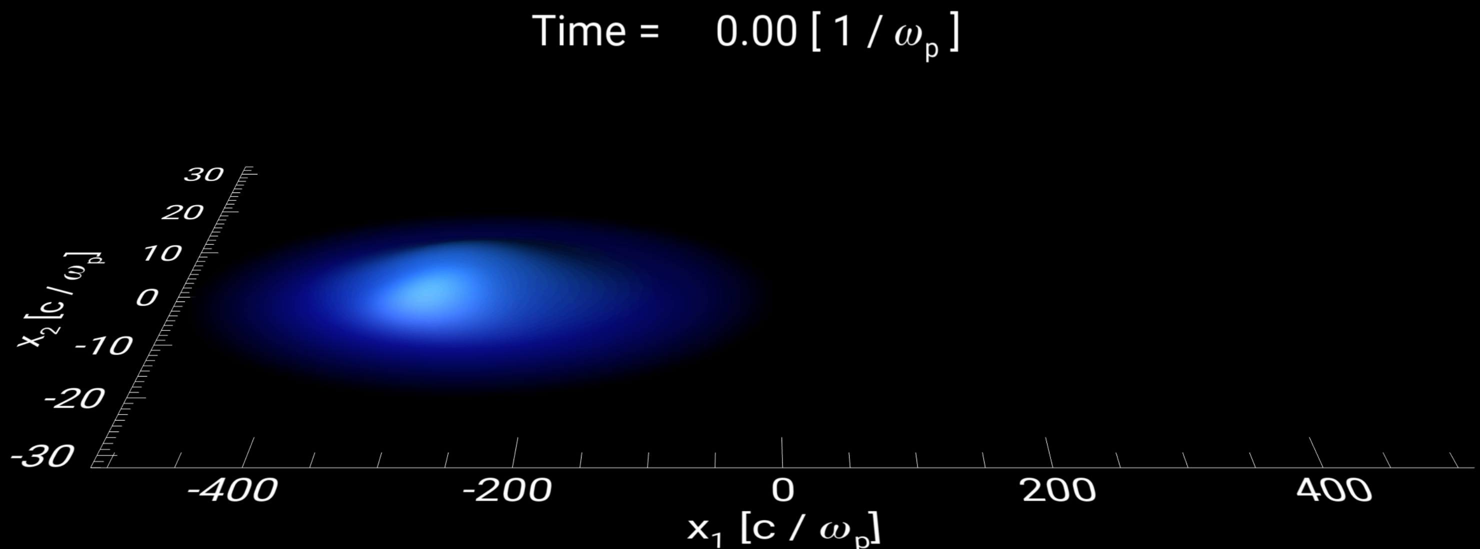
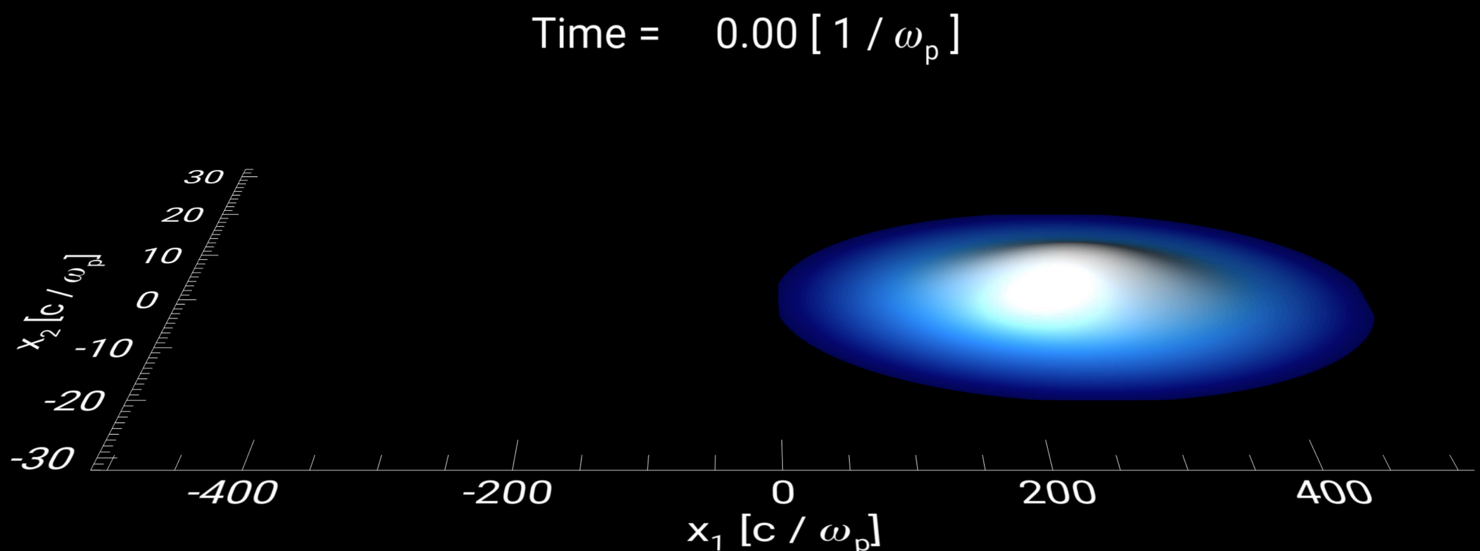
Electron density (10 GeV)

D = 0.05
χ = 8



Electron density (300 MeV)

D = 15
χ = 0.3



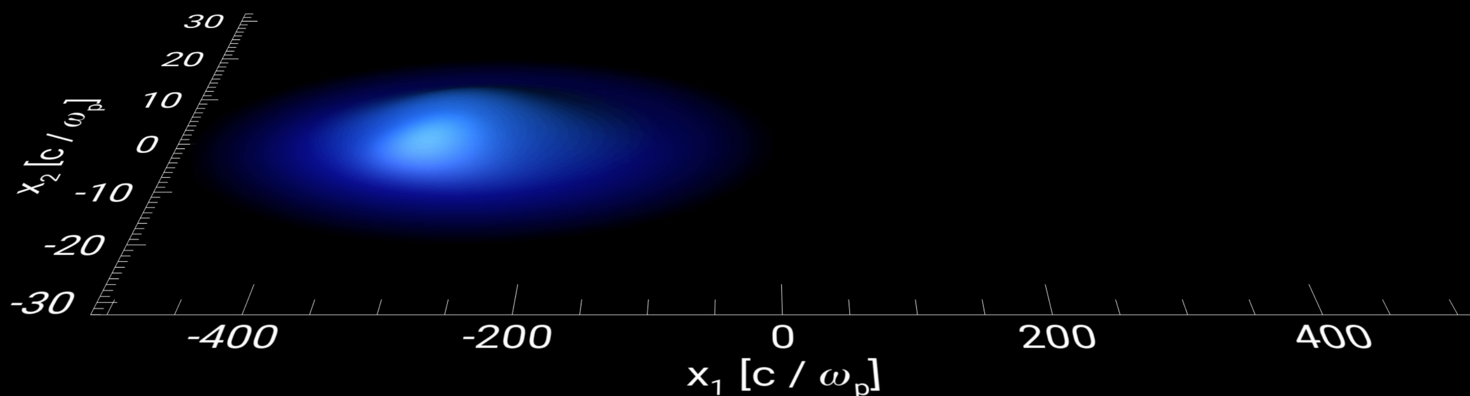
(FACET II) 10 GeV e- / 300 MeV e-

TÉCNICO LISBOA

Electron density (10 GeV)

D = 0.05
χ = 8

Time = 0.00 [1 / ω_p]



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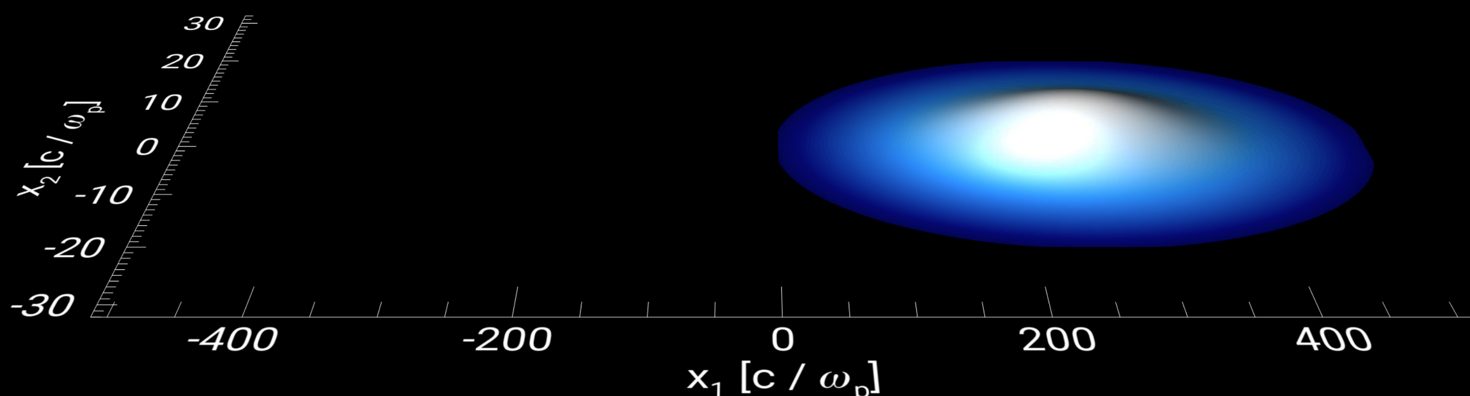

(FACET II) 10 GeV e- / 300 MeV e-

Electron density (10 GeV)

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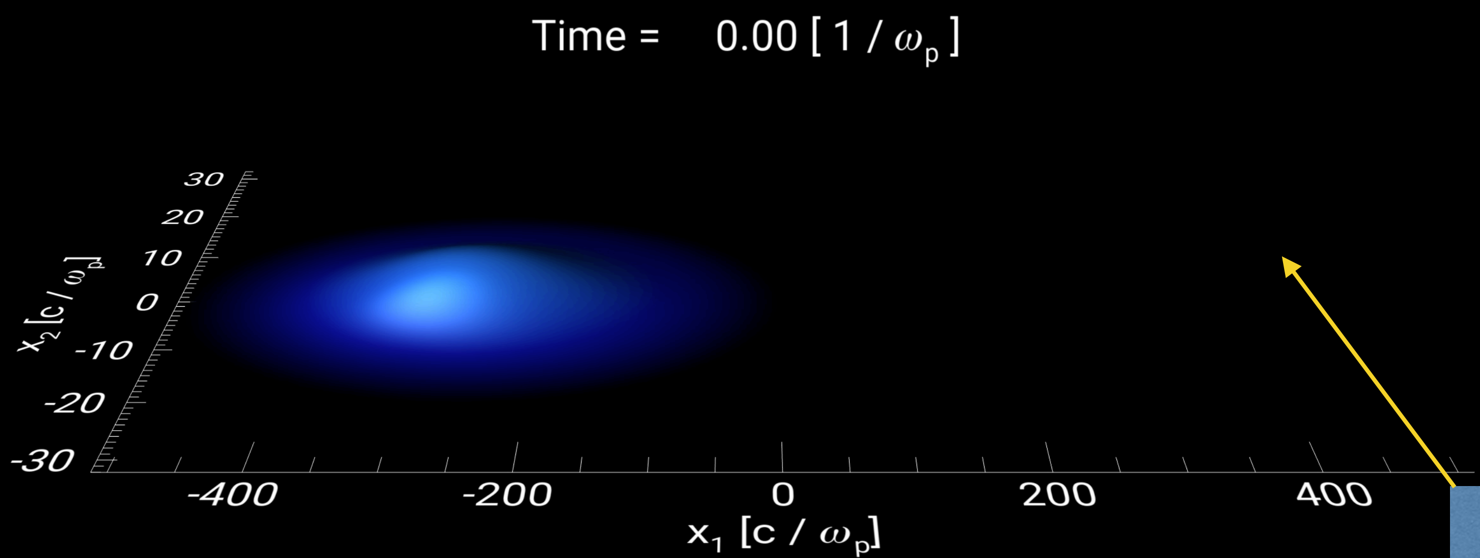
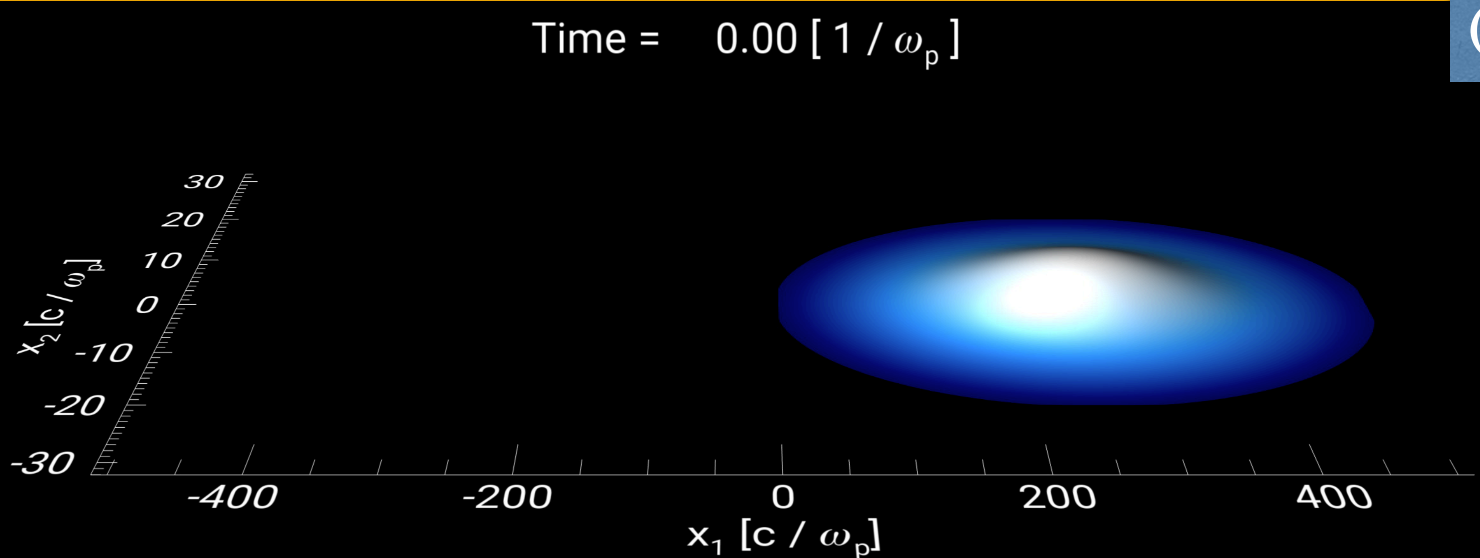


New pairs being created (5 pairs per e-)

Electron density (300 MeV)

D = 15
χ = 0.3



(FACET II) 10 GeV e- / 300 MeV e+

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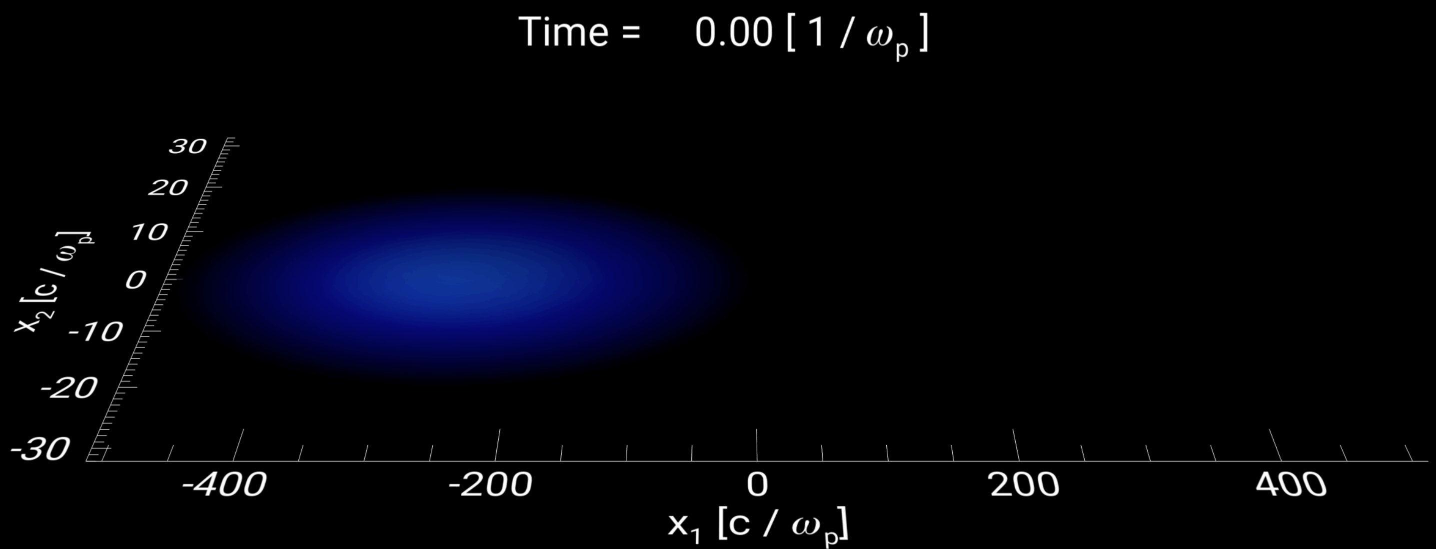
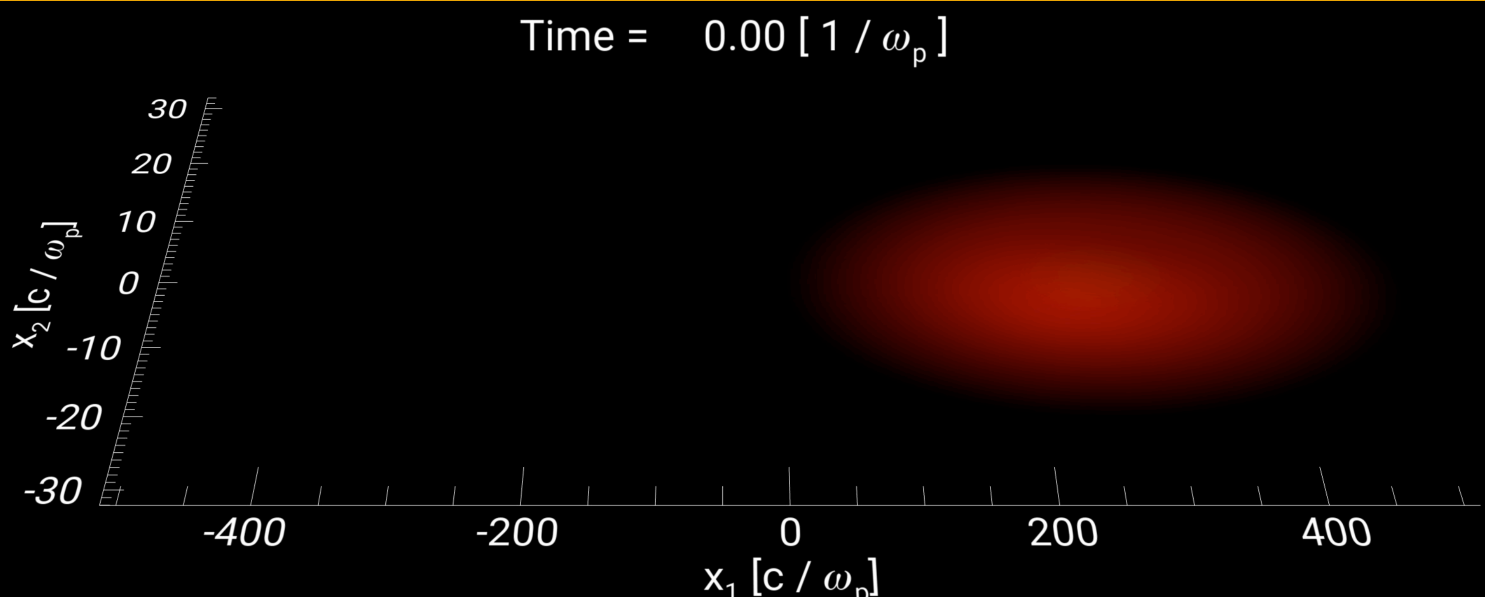
Electron density (10 GeV)

D = 0.05
χ = 8



Positron density (300 MeV)

D = 15
χ = 0.3



(FACET II) 10 GeV e- / 300 MeV e+

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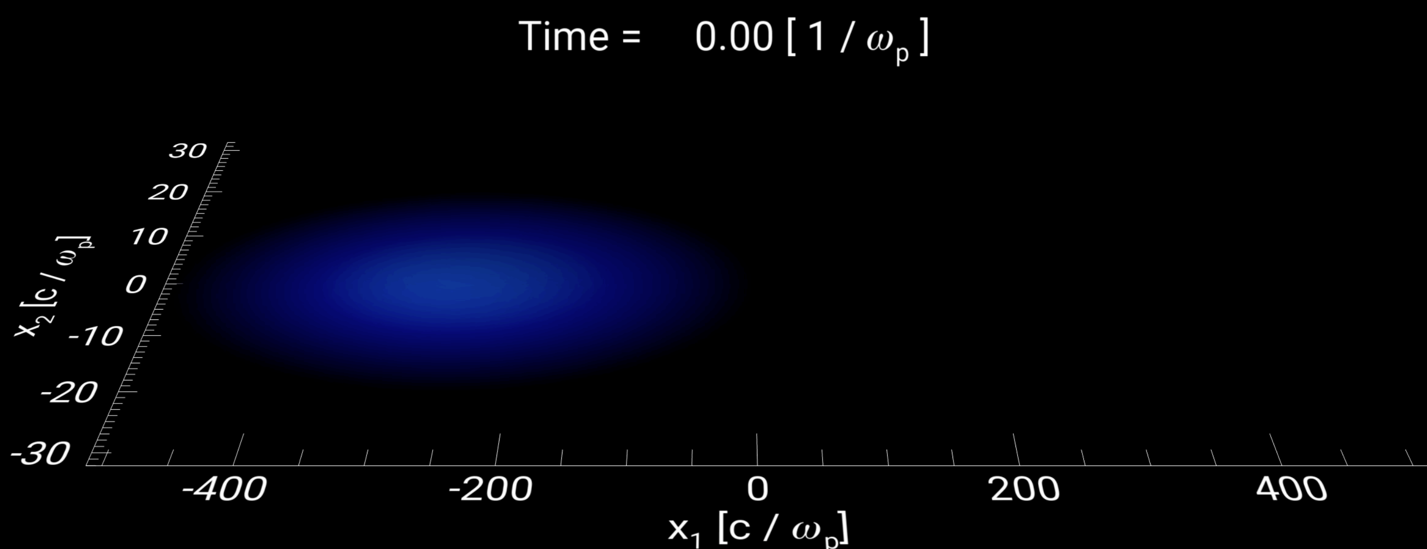
Electron density (10 GeV)

D = 0.05
χ = 8



Positron density (300 MeV)

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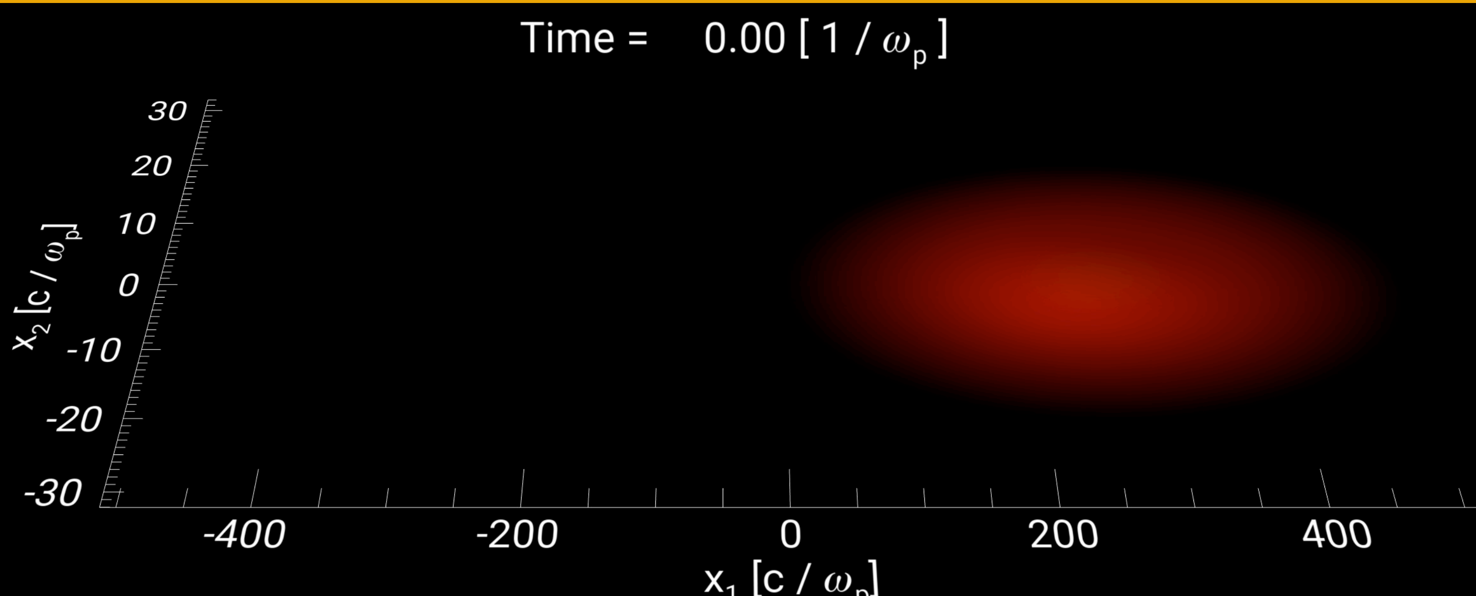
χ = 0.3



(FACET II) 10 GeV e- / 300 MeV e+

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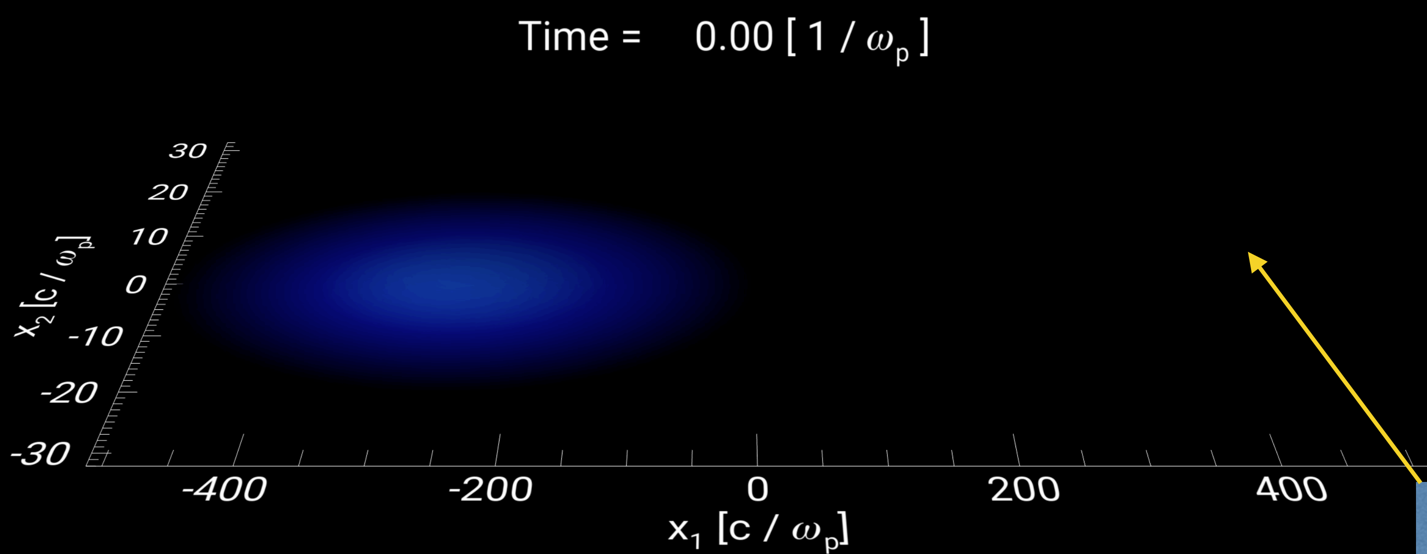
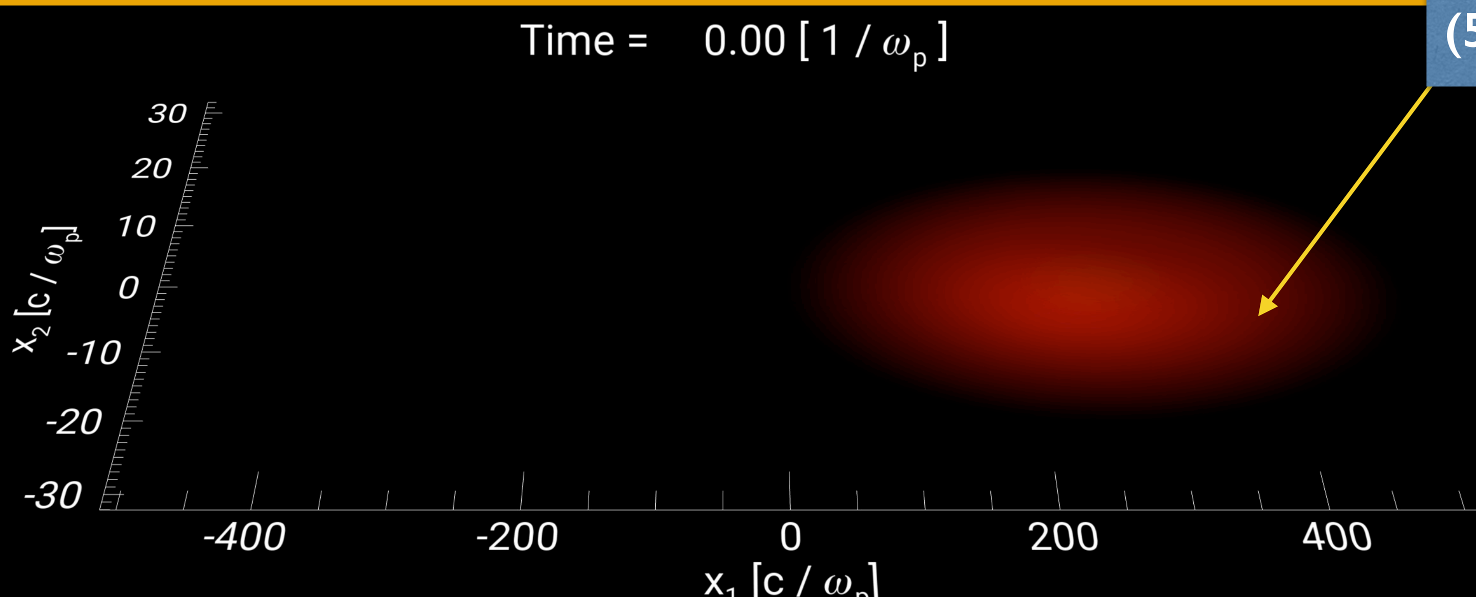
χ = 8



Positron density (300 MeV)

D = 15
χ = 0.3



New pairs being created (5 pairs per e-)

(FACET II) misaligned by σ: kink instability

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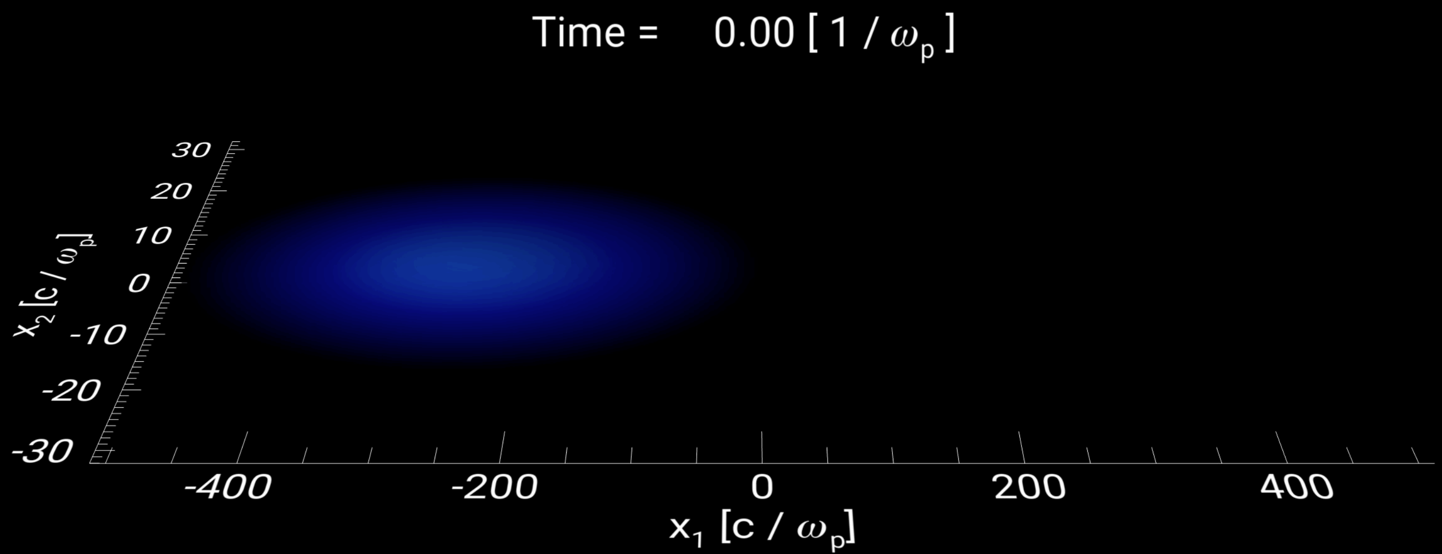
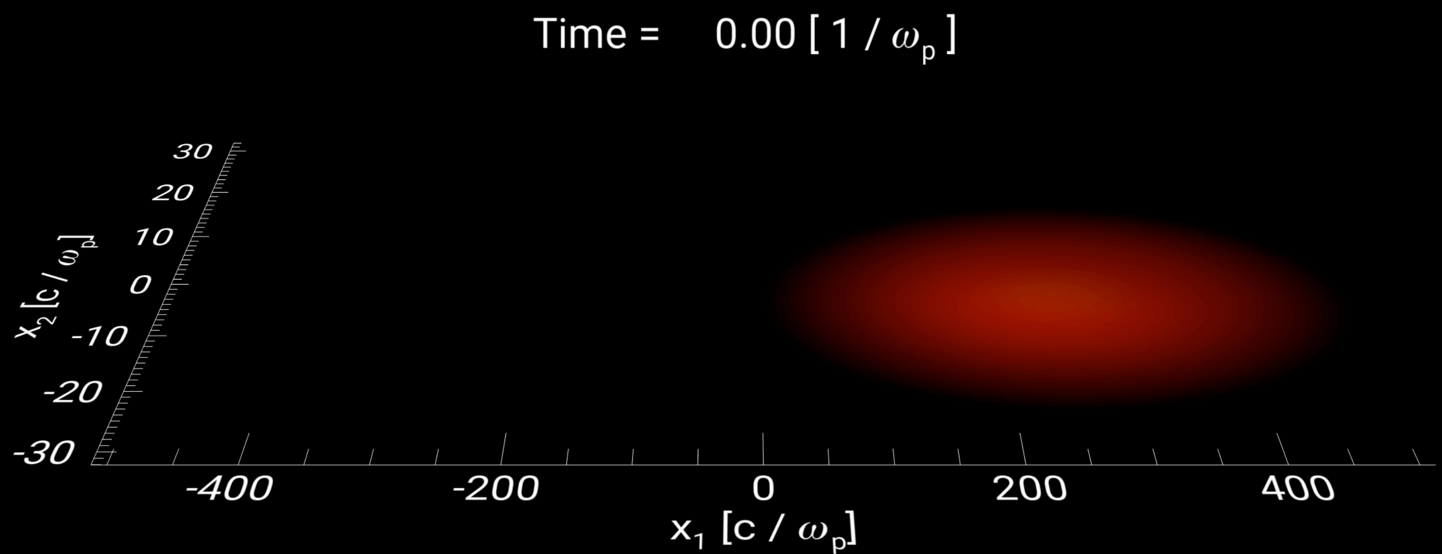
Electron density (10 GeV)

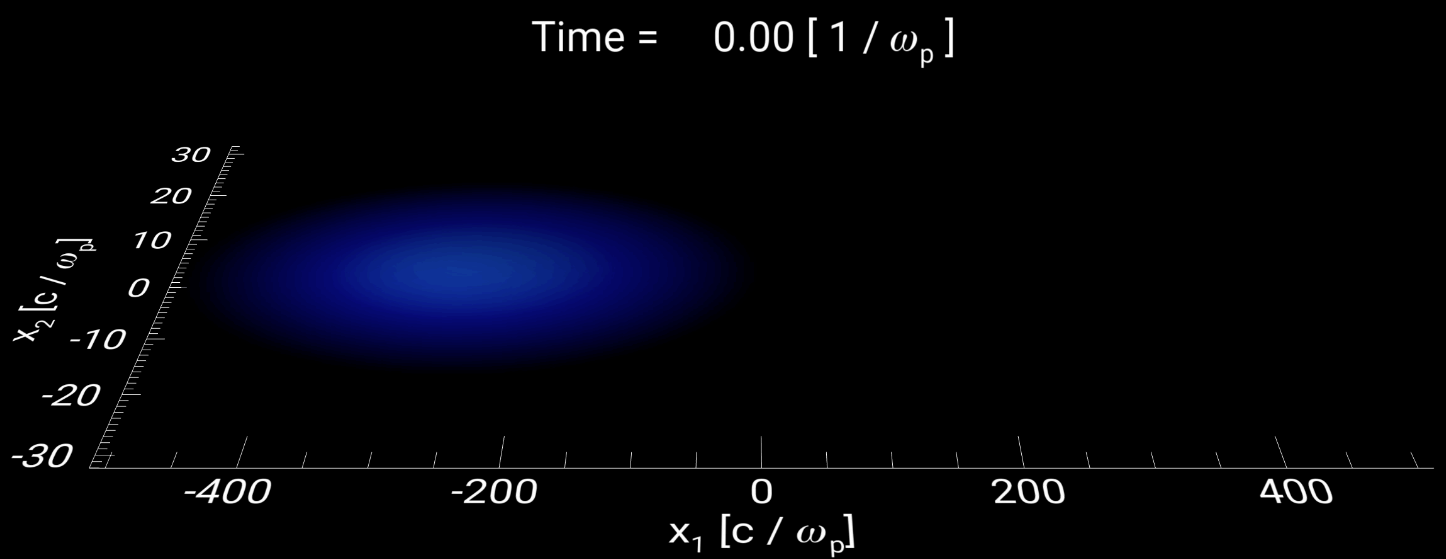


Positron density (300 MeV)

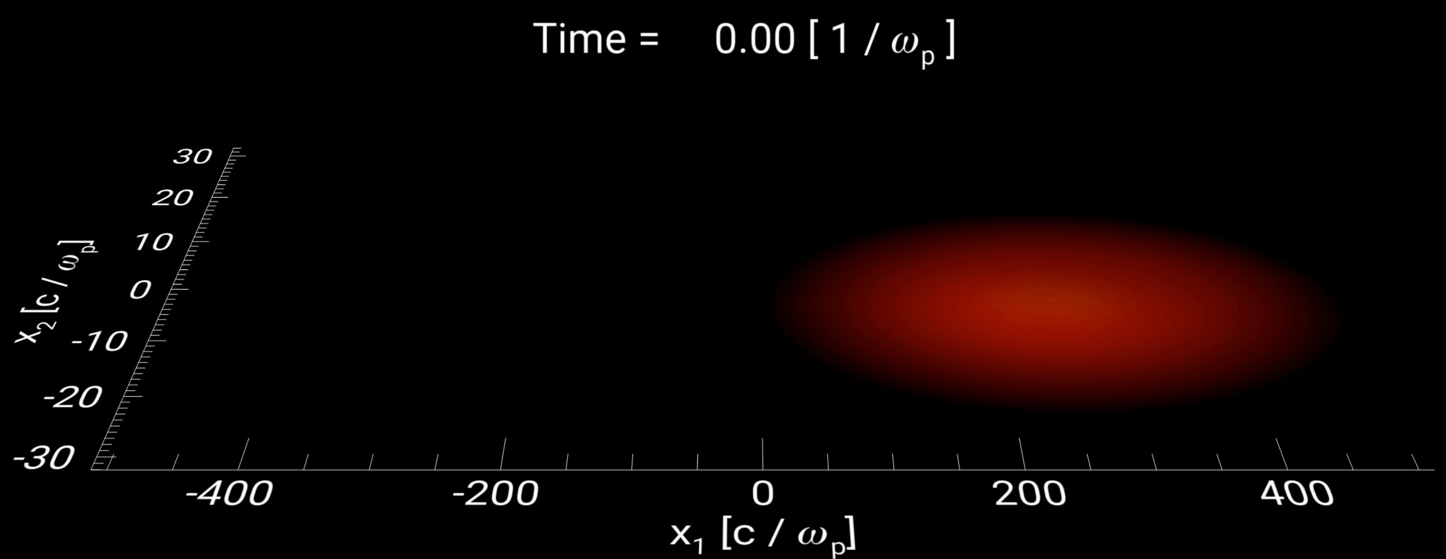


(FACET II) misaligned by σ: kink instability

Electron density (10 GeV)



Positron density (300 MeV)



Conclusions

TÉCNICO LISBOA

New Tools to tackle a variety of extreme plasma physics problems

- Classical Radiation Reaction higher energy particles radiate more
- QED module (Non-linear Compton scattering, Breit-Wheeler, ….)
- Vacuum polarization solver

These tools have used to simulate various scenarios with intense lasers

- Counter propagating electron beam - laser
- Counter propagating laser - laser : QED cascades
- Counter propagating optical laser - X-rays laser : vacuum birefringence

QED-PIC simulations can be envisaged to simulations beam-beam physics

- High disruption regime can be simulated self-consistently
- New QED cross-sections need to be developed and added to fully study beam-beam physics for SFQED