New regimes of energetic particle production and radiation generation in the ultra high intensity regime and basics of the associated simulation tools

Emmanuel d'Humières
Université de Bordeaux-CNRS-CEA, CELIA, Talence, France
Institut Universitaire de France

M. Lobet, X. Ribeyre, O. Jansen, S. Jequier and Vladimir Tikhonchuk
Université de Bordeaux-CNRS-CEA, CELIA, Talence, France

M. Grech
LULI, Ecole Polytechnique - CEA - CNRS - UPMC, Palaiseau, France

C. Ruyer, A. Debayle, X. Davoine and L. Gremillet
CEA/DAM-DIF, Arpajon, France

dhumieres@celia.u-bordeaux1.fr

Particle and radiation sources from laser plasma interaction in the context of ELI and Apollon

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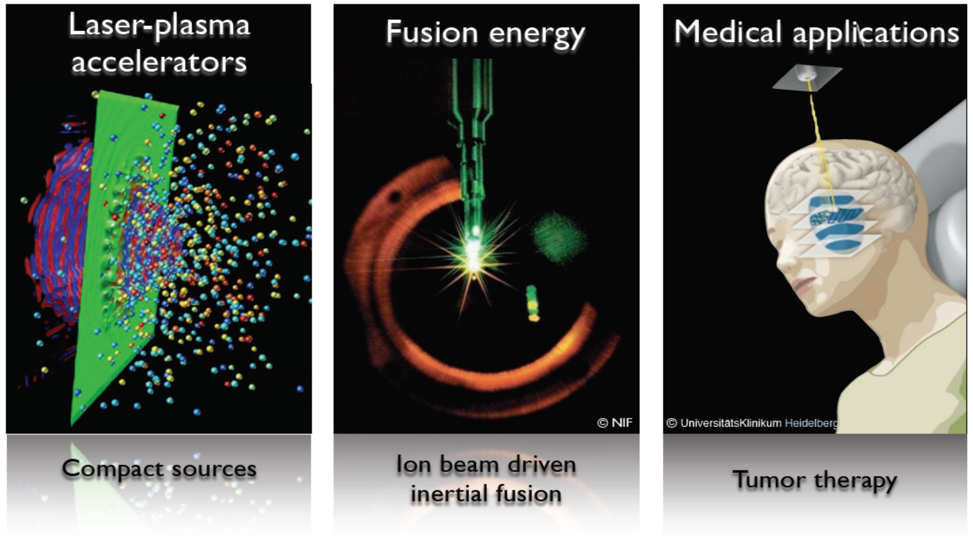
• New installations coupling PW and 10 PW short pulse lasers are now being constructed in Europe.

• Laser ion acceleration which saturates in terms of maximum energy at ~100 MeV for protons and ~1 GeV for Carbon ions can strongly benefit from these new systems (existing mechanisms, new mechanisms).

• New gamma sources will be developed.

• e^-e^+ plasmas will be generated.

• These new sources have potential important applications in fundamental physics, laboratory astrophysics and medicine.



→ New simulation tools are needed

→ Theoretical and numerical studies are crucial to prepare the arrival of these new laser systems.

Outline

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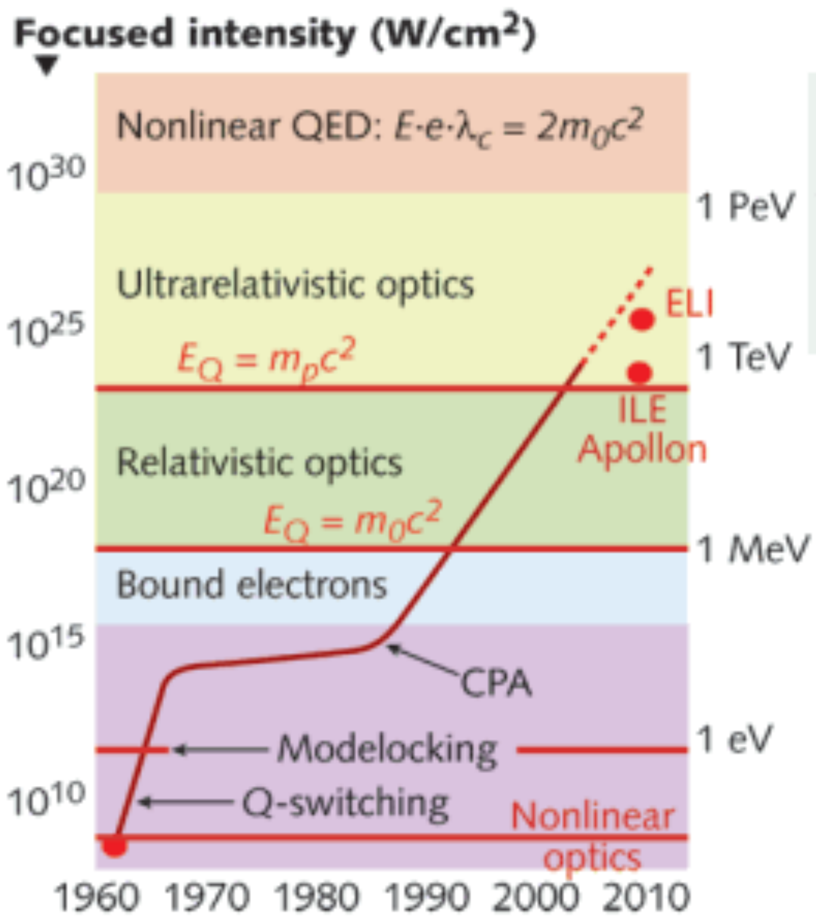
- Development of Particle-In-Cell codes to simulate laser plasma interaction in the Ultra High Intensity regime
- Numerical simulation of laser ion acceleration and energetic radiation emission in the Ultra High Intensity regime
- QED experiments on Cilex-Apollon or ELI: Collision of a 10 PW-laser with a wakefield-accelerated electron beam
- Collisionless shocks in electron-positron plasmas using extreme-light laser pulses
- Possibility of pair creation in the collision of gamma-ray beams produced by high intensity laser plasma interaction
- Conclusions and perspectives

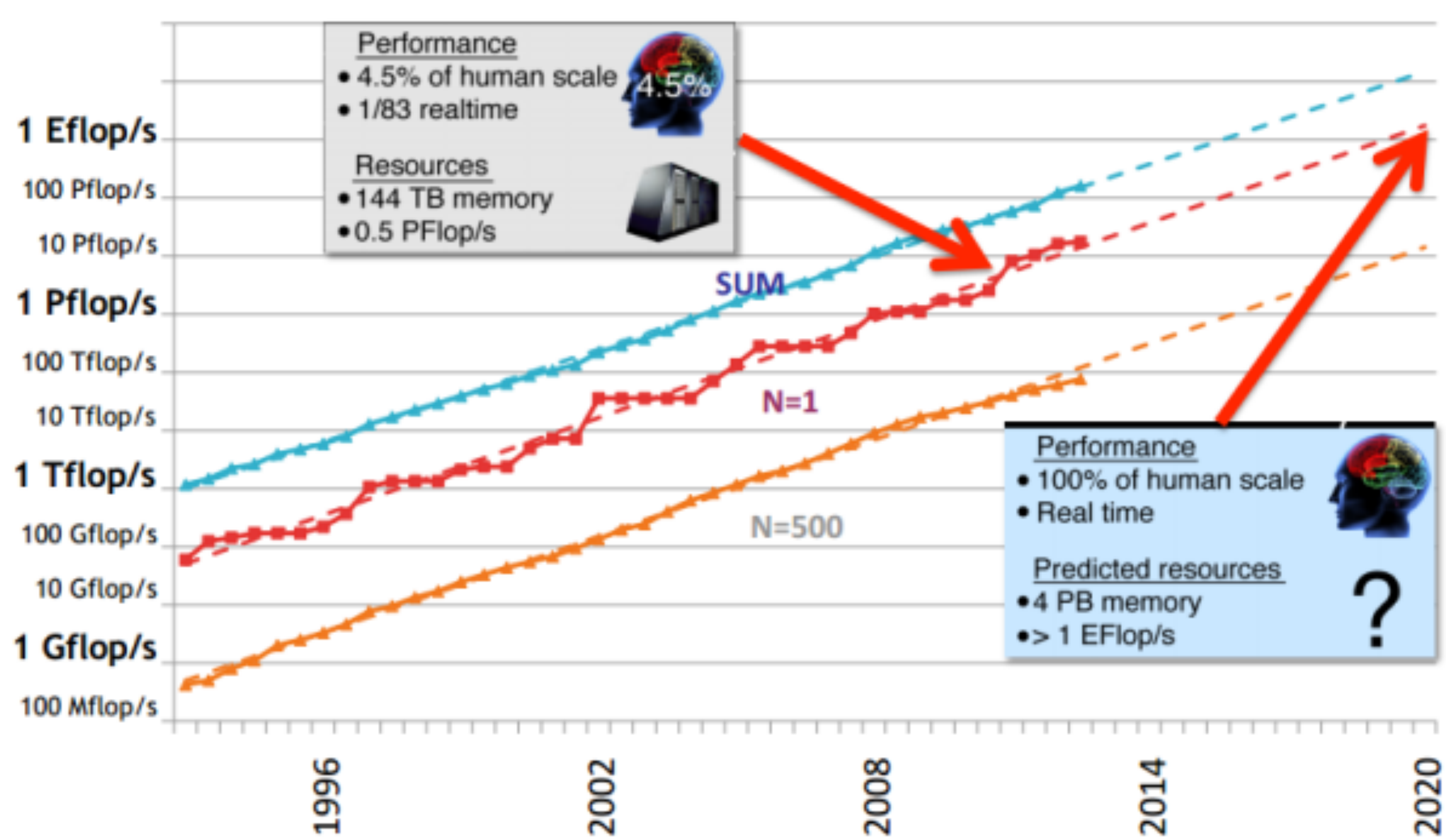
Development of Particle-In-Cell codes to simulate laser plasma interaction in the Ultra High Intensity regime

Laser intensity increase and computing power increase versus time



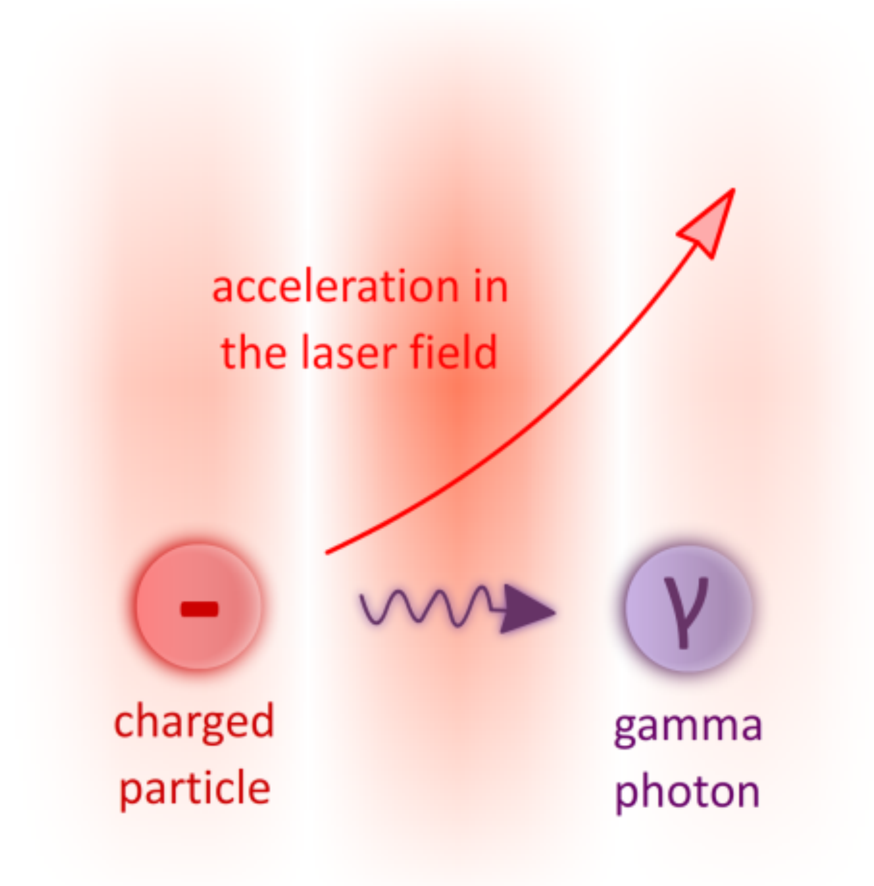
Ultrarelativistic intensity is defined with respect to the proton $E_Q = m_pc^2$, intensity ~10^{24} W/cm²

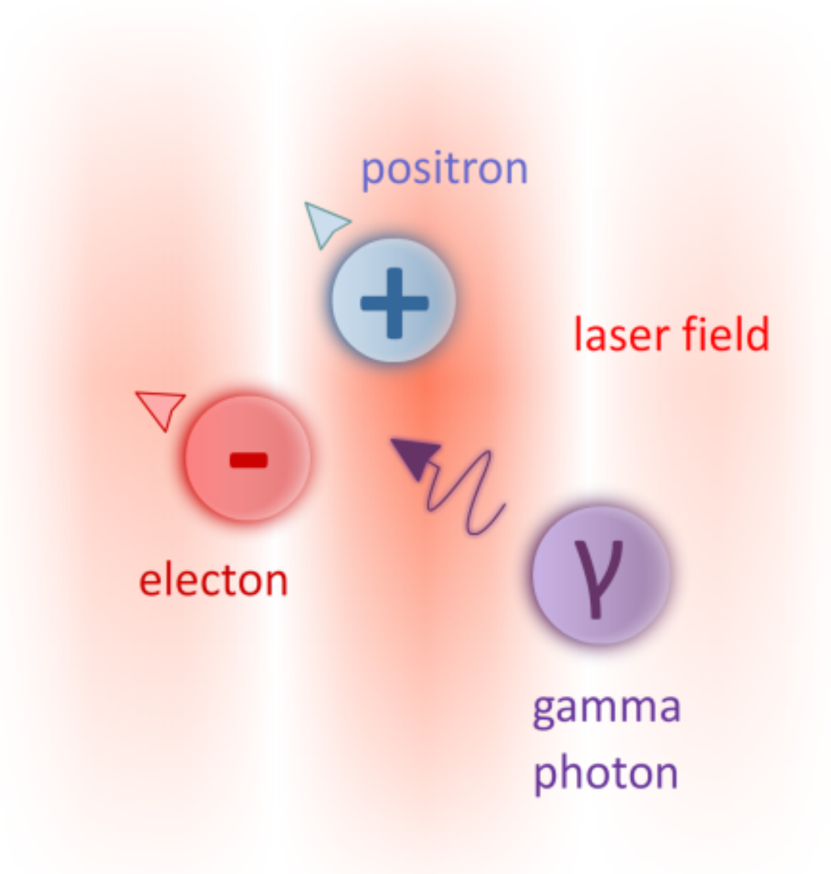
Towards Exascale



Radiative and QED effects[1] in ultra-intense laser plasma interaction[2,3]

Apollon (10 PW, 100J, 15 fs) → **ELI** (100 PW) → **IZEST** (> 1EW)





Non-linear Compton scattering: high-frequency photon emission in the laser field

Multiphoton Breit-Wheeler: $e^- e^+$ pair generation in the laser field ($I > 10^{23}\ \mathrm{Wcm}^{-2}$)

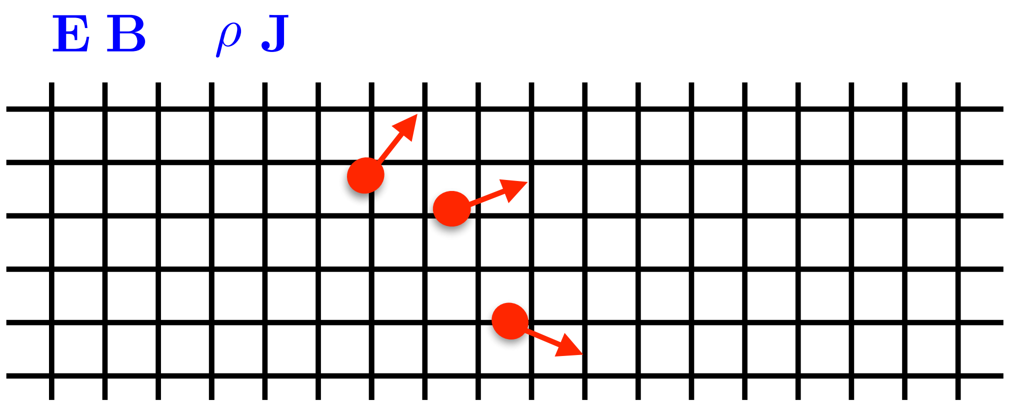
- Implementation of these mechanisms in the PIC code CALDER

And competition with Bethe-Heitler and Trident processes when using solid foils

[1] – A. Di Piazza *et al.*, Rev. Mod. Phys. **84**, 1177 (2012) – A. Bell *et al.*, Phys. Rev. Lett. **101**, 200403 (2008).
[2] – A. Zhidkov *et al*, PRL **88**, 185002 (2002) – M. Tamburini *et al*, NJP **12**, 123005 (2010) – R. Capdessus *et al*, PRL **110**, 215003 (2013)
[3] – C. P. Ridgers *et al*, PoP **20**, 056701 (2013) – C. S. Brady *et al*, arXiv preprint 1311.5313 (2013) – L. L. Ji *et al*, PoP **21**, 023109 (2014)

The Particle-In-Cell (PIC) Method

capture collective effects by solving the Vlasov-Maxwell Eqs.



- Vlasov Eq. is solved using so-called macro-particles

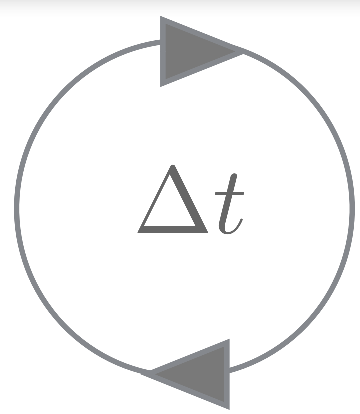
$$f_s(t,\mathbf{x},\mathbf{p}) = \sum_N w^N\, S(\mathbf{x}-\mathbf{x}^N(t))\,\delta(\mathbf{p}-\mathbf{p}^N(t))$$

Interpolation

$$\forall N\ [\mathbf{E},\mathbf{B}] \rightarrow [\mathbf{E}^N,\mathbf{B}^N]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla\times\mathbf{B}$$
$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$



Pusher

$$\forall N \quad \begin{aligned} d_t\mathbf{p}^N &= \mathbf{F}_L^N \\ d_t\mathbf{x}^N &= \mathbf{p}^N/(m\,\gamma) \end{aligned}$$

Projection

$$\forall N\ [\mathbf{x}^N,\mathbf{p}^N] \rightarrow [\rho,\mathbf{J}]$$

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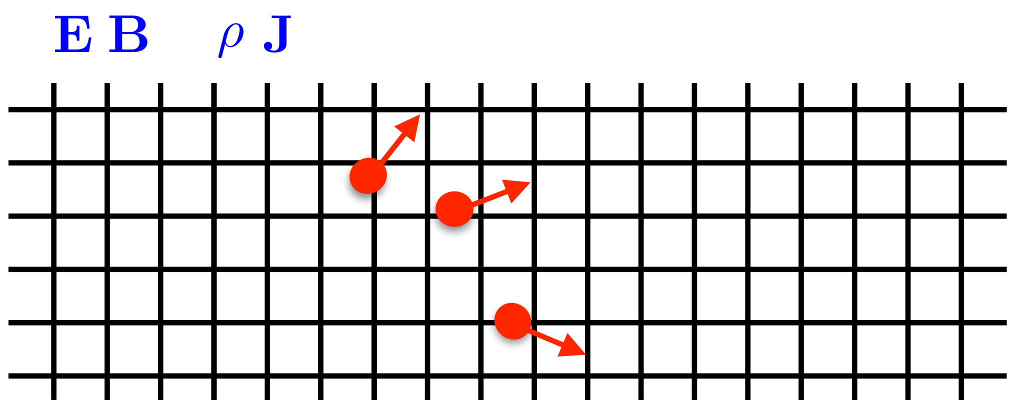
capture collective effects by solving the Vlasov-Maxwell Eqs.



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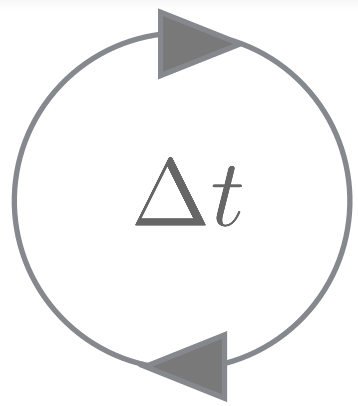

Projection

$$\forall N\ [\mathbf{x}^N,\mathbf{p}^N] \rightarrow [\rho,\mathbf{J}]$$

Modified Electron Pusher

$$\chi_e = \left|\frac{F^{\mu\nu}}{E_S}\frac{p^\nu}{m_e c}\right|$$

$\chi_e < 10^{-5}$ classical relativistic push.

$\chi_e < \chi_e^{th}$ radiation reaction force

$\chi_e > \chi_e^{th}$ Monte-Carlo method

Photon Pusher

for > 1.022 MeV photons:

$$\epsilon_\gamma > 2\, m_e c^2$$

$$\chi_\gamma = \left|\frac{F^{\mu\nu}}{E_S}\frac{\hbar k^\nu}{m_e c}\right|$$

multiphoton Breit-Wheeler process

Implemented in the PIC code CALDER

Lobet et al., arXiv:1311.1107 (2013)

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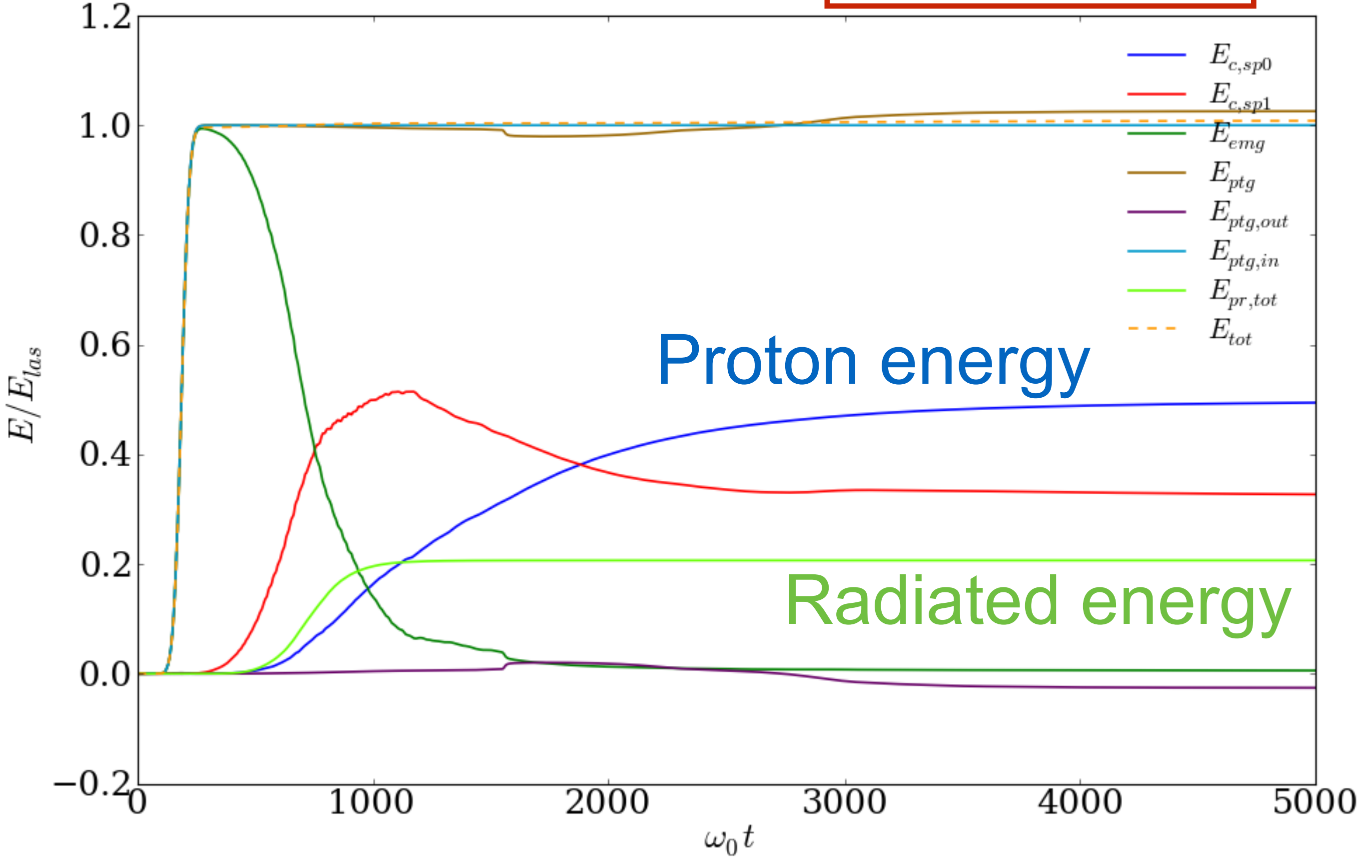
Numerical simulation of laser ion acceleration and energetic radiation emission in the Ultra High Intensity regime

Simulations of laser ion acceleration with low density targets in the ultra-high intensity regime

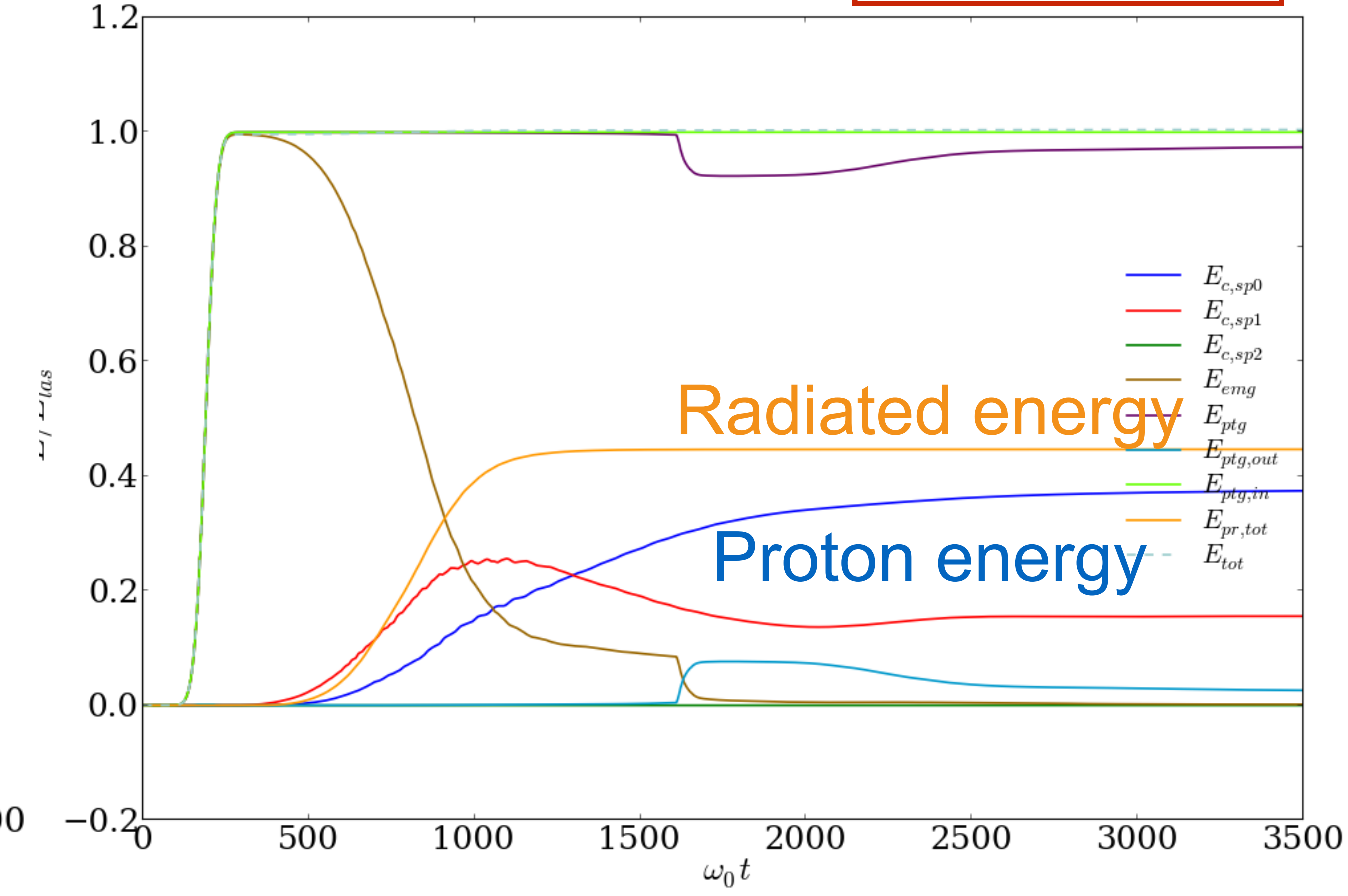
Calder: Monte Carlo emission and pair production modules have been implemented (M. Lobet et al. arXiv.1311.1107v2)

Energy time evolution for I=10^{22} W/cm^2 (left) and for I = I=10^{23} W/cm^2 (right) for a 2 n_c, 190 microns long cos^2 target. The laser comes from the left side of the simulation box.

I=10^{22} W/cm^2



I=10^{23} W/cm^2

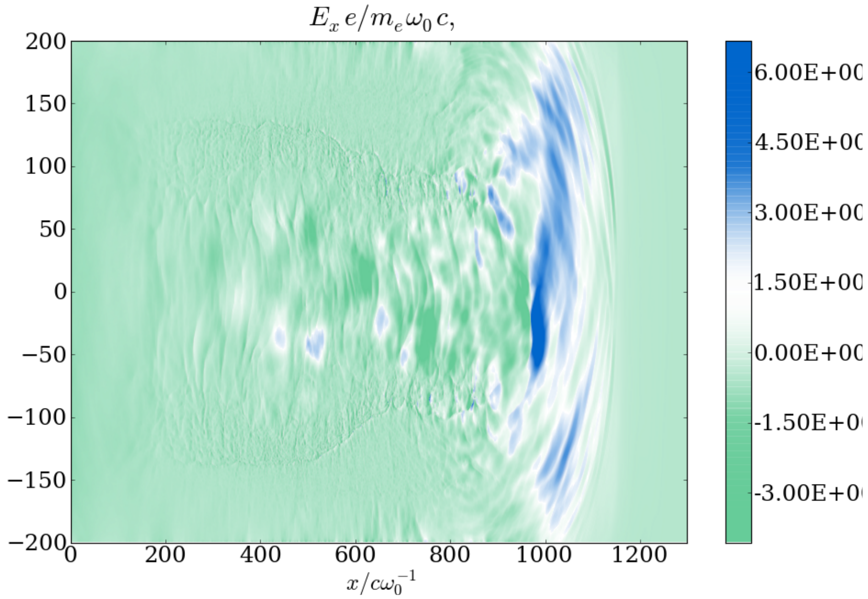


→ Competition with radiation emission

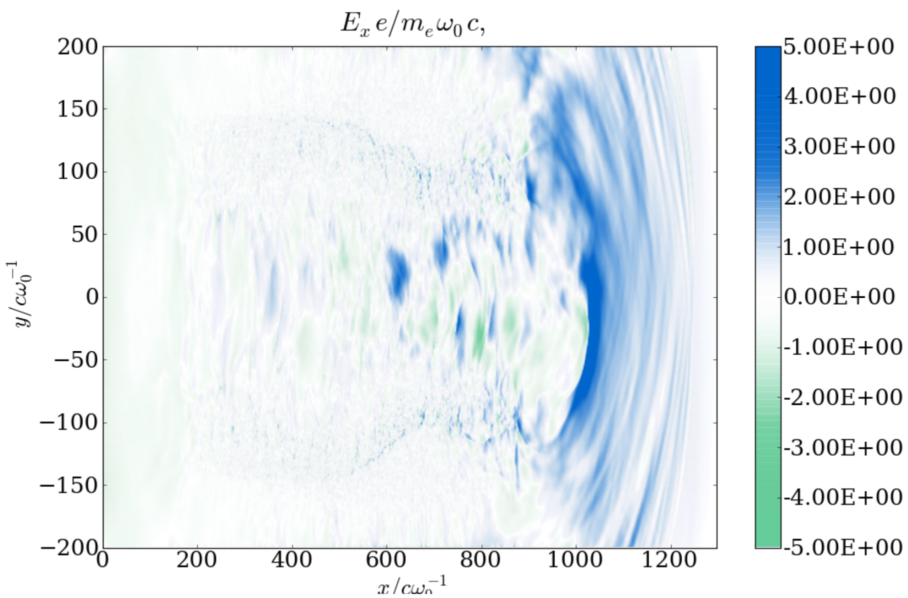
Simulations of laser ion acceleration with low density targets in the ultra-high intensity regime

$I=10^{22}$ W/cm^2 for a 2 n_c, 190 microns long cos^2 target. The laser comes from the left side of the simulation box.

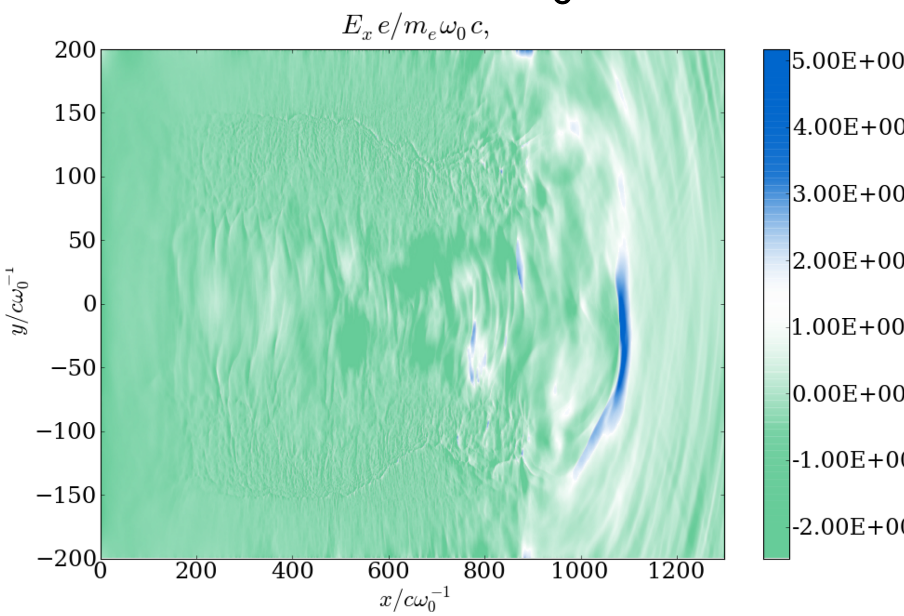
$t=1400\omega_0^{-1}$

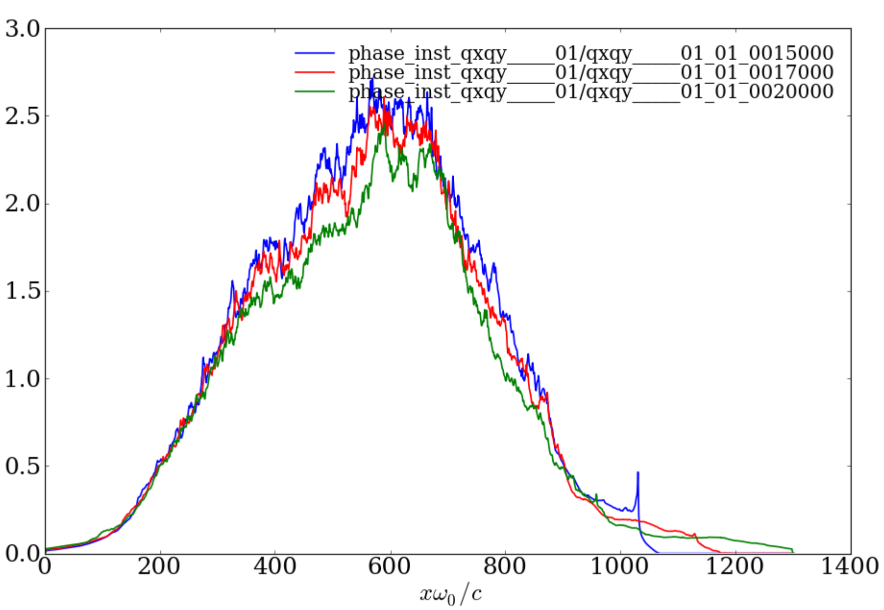


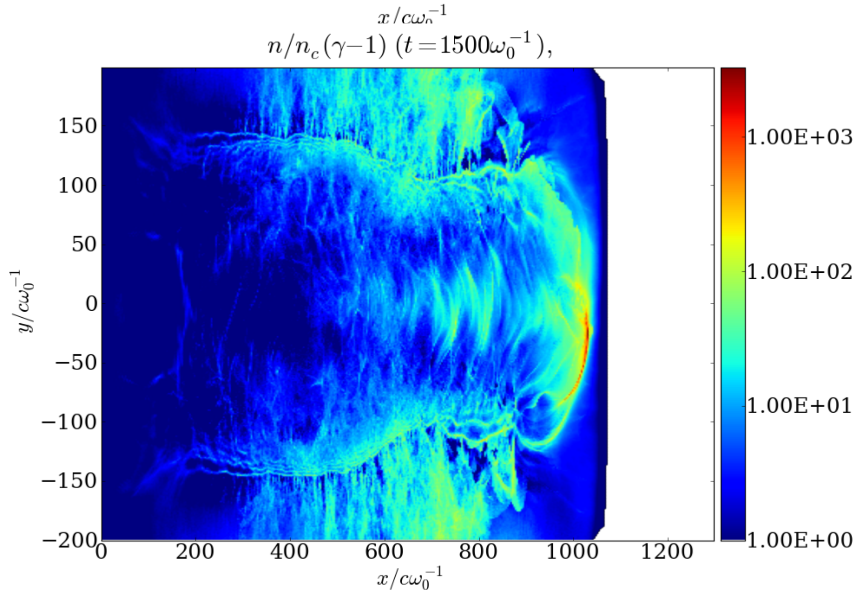
$t=1500\omega_0^{-1}$

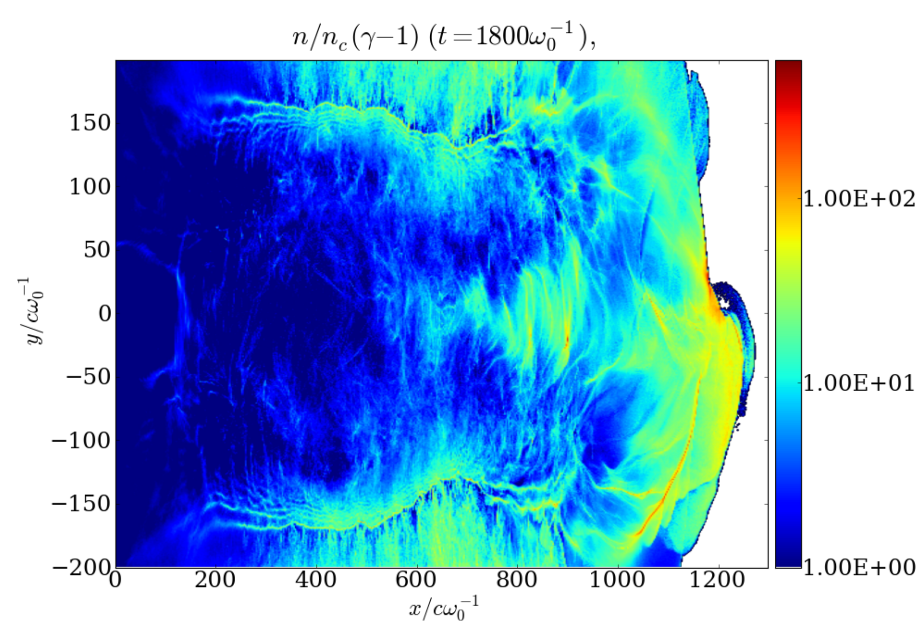


$t=1600\omega_0^{-1}$





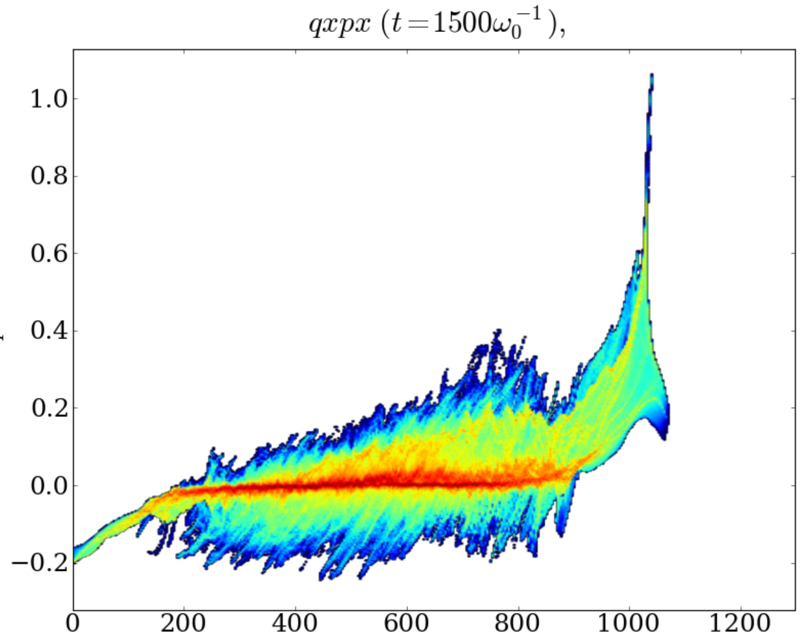


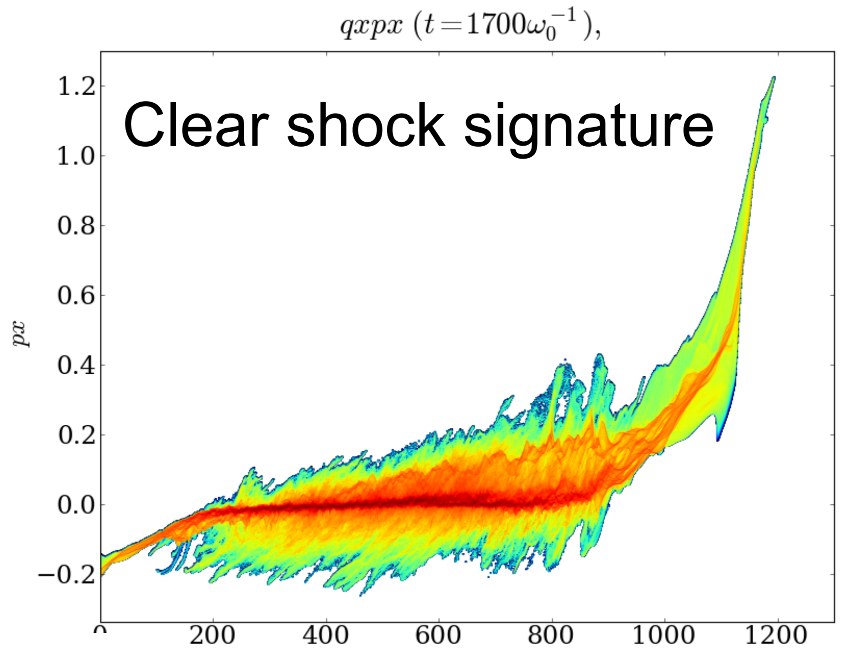


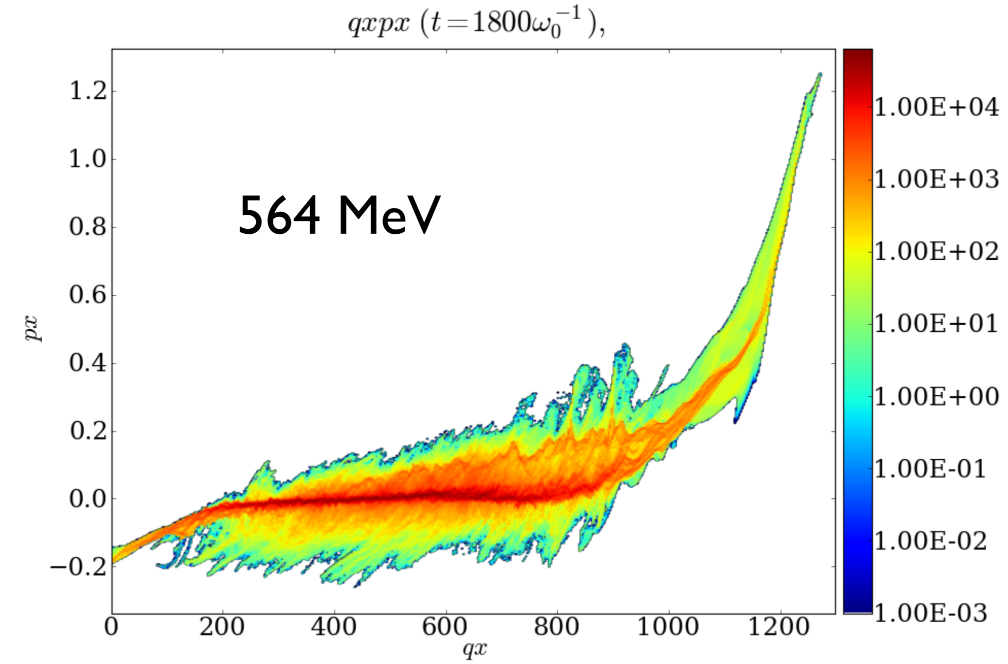
Simulations of laser ion acceleration with low density targets in the ultra-high intensity regime

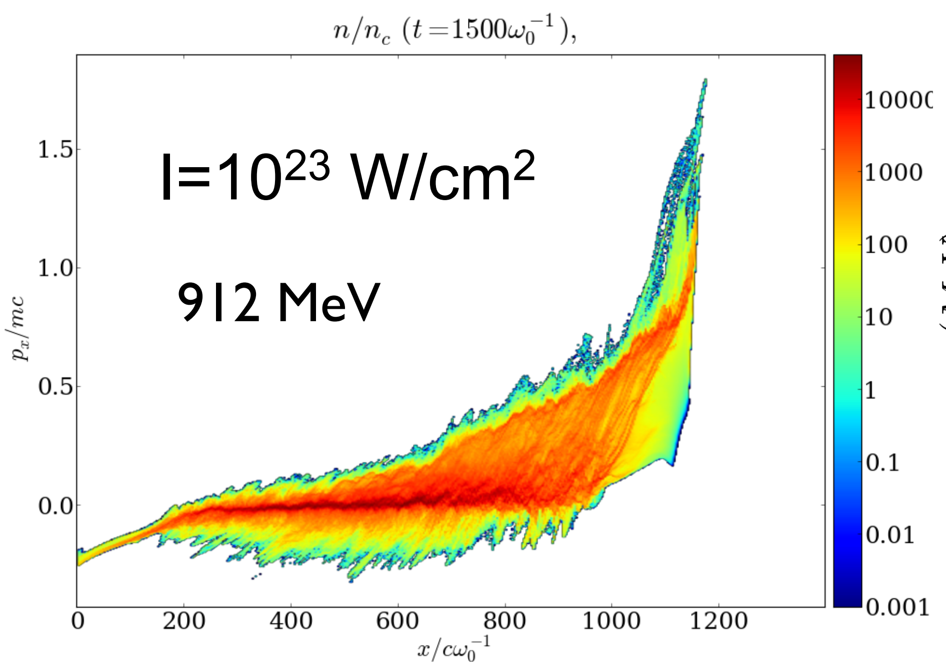
Proton phase space at various times for I=10^{22} W/cm^2 for a 2 n_c, 190 microns long cos^2 target. The laser comes from the left side of the simulation box.

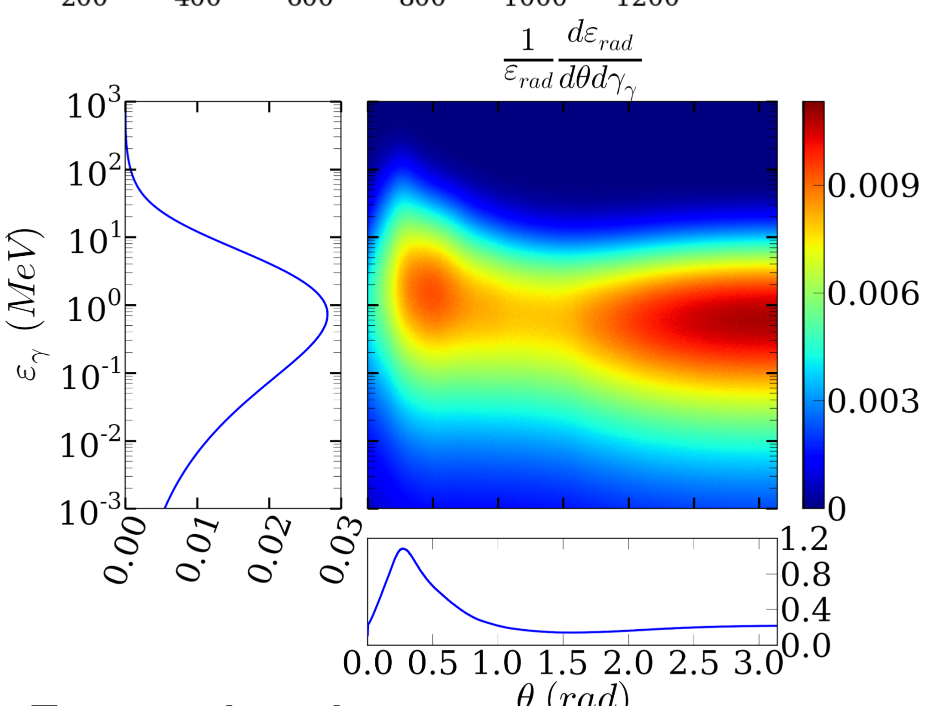
→ Competition with radiation emission

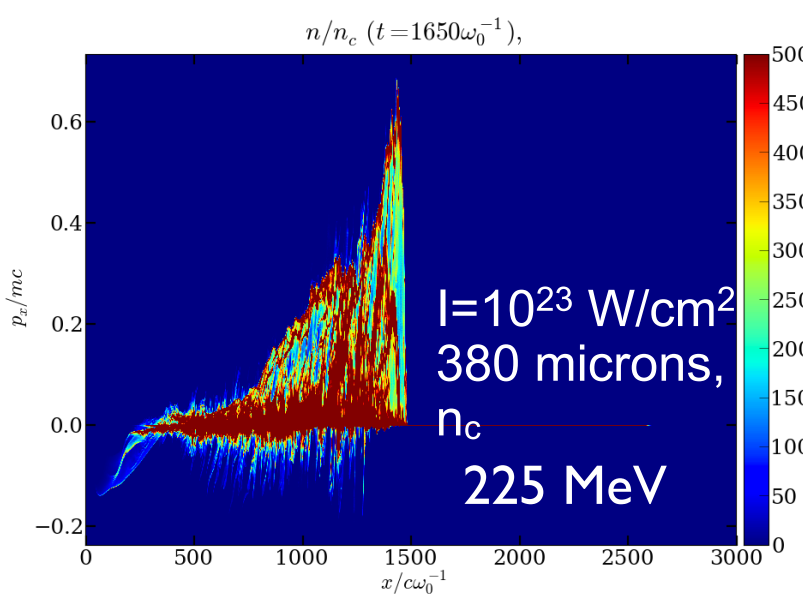












→ Relativistic ion beams

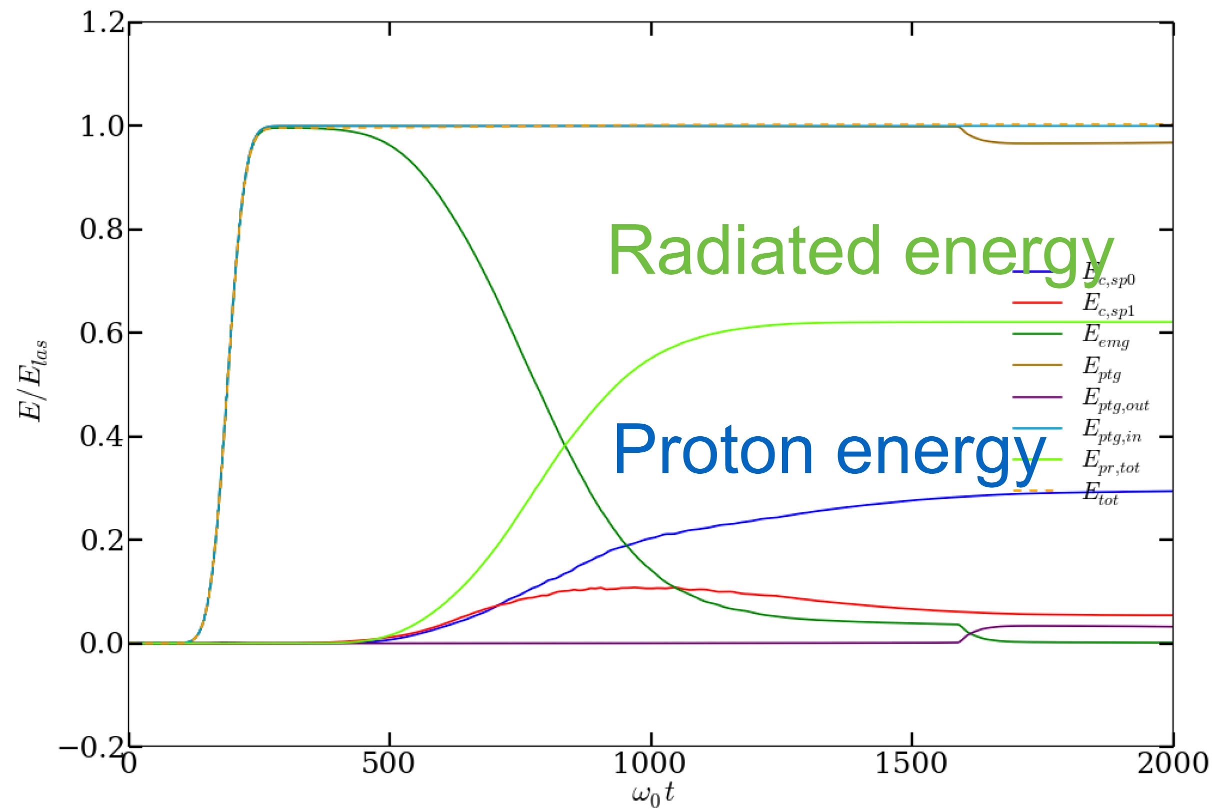
Emitted radiation properties

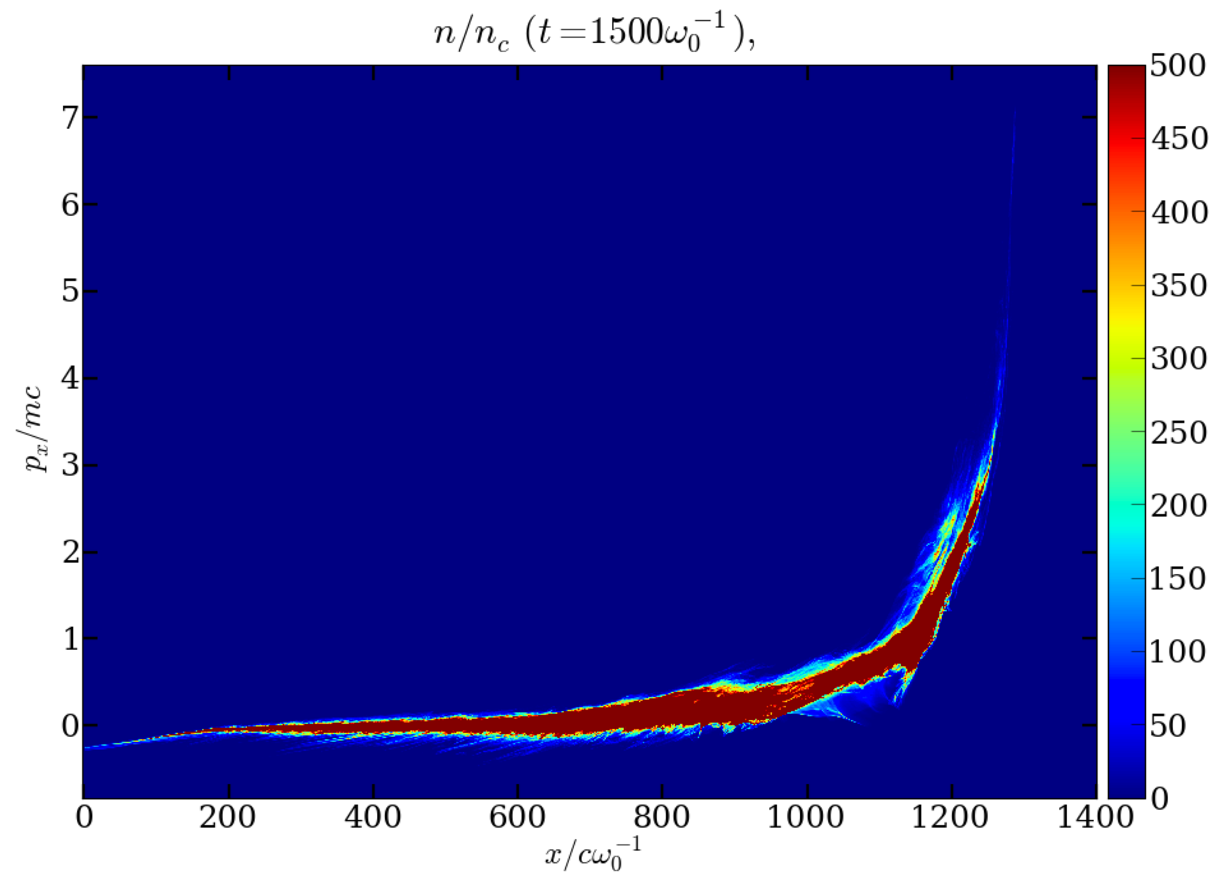
Simulations of laser ion acceleration with low density targets in the ultra-high intensity regime

Calder: Monte Carlo emission and pair production modules have been implemented

Energy time evolution and proton phase space for I $=5\times10^{23}$ W/cm^2 for a 4 n_c, 190 microns long cos^2 target. The laser comes from the left side of the simulation box.

I=5×10^{23} W/cm^2

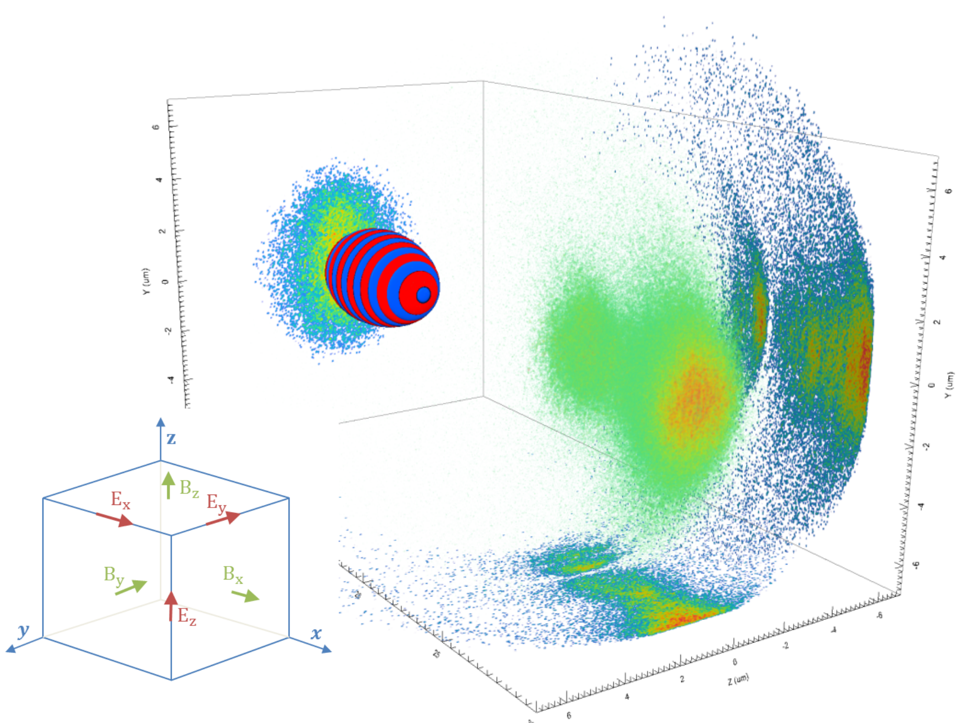




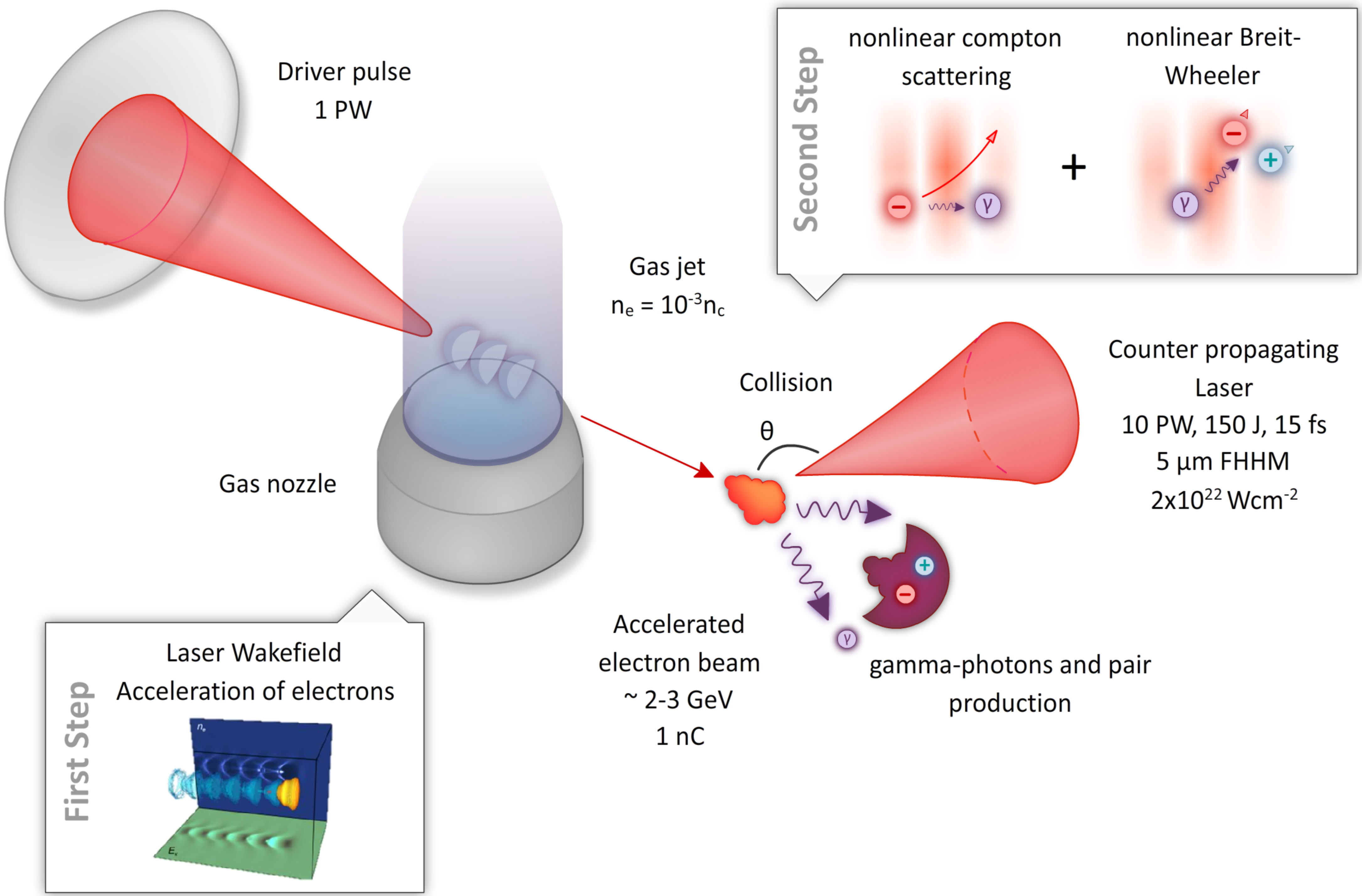
→ Competition with radiation emission

Maximum proton energy through shock acceleration: 6.25 GeV

QED experiments on Cilex-Apollon or ELI: Collision of a 10 PW-laser with a wakefield-accelerated electron beam

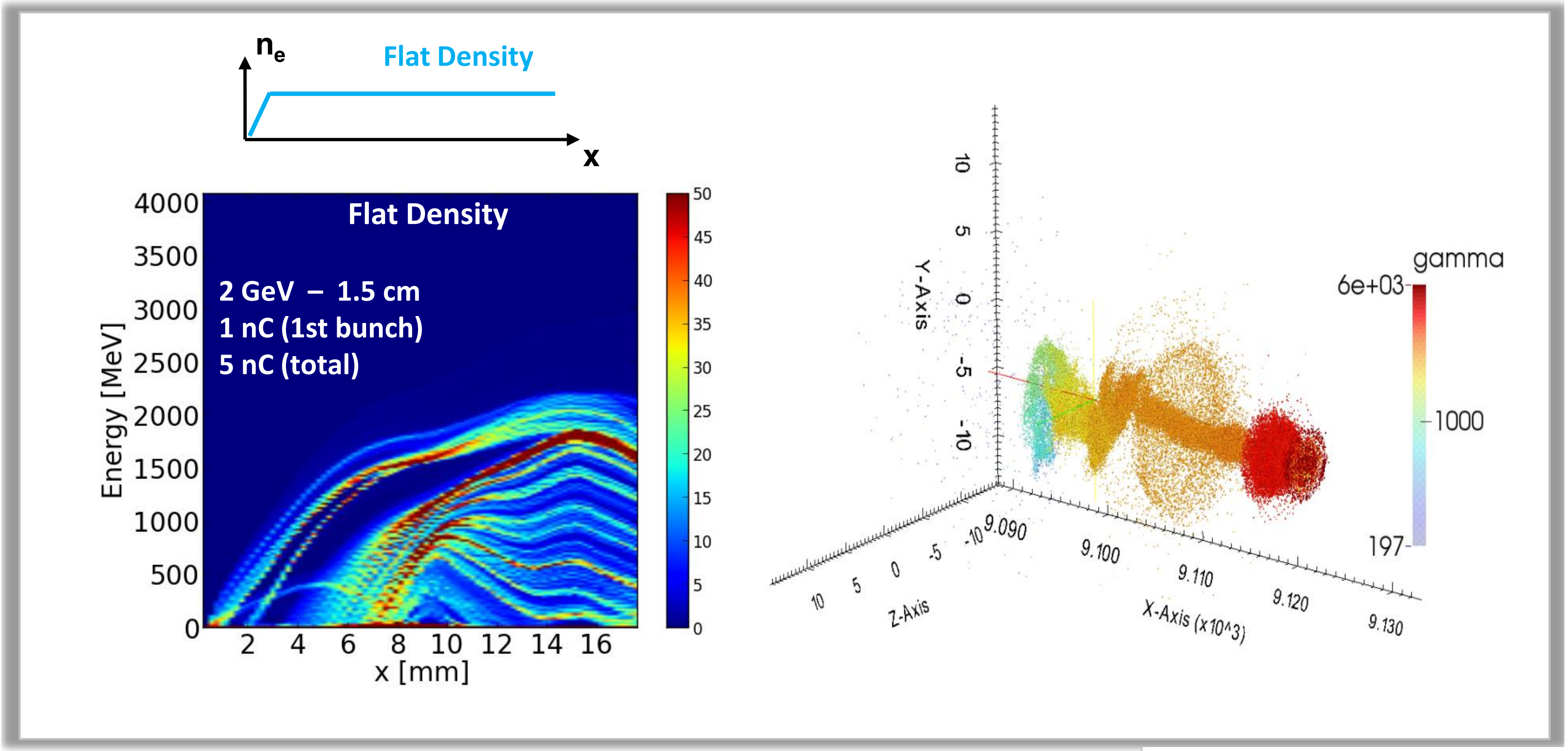


Simulation results: collision between a GeV electron beam with a counter-propagating laser



First step: Optimizing the electron energy, acceleration up to 3 GeV in a LWFA with a 15 J laser

- λ = 0.8 μm, E = 15 J, T = 30 fs, W_{FWHM} = 23 μm, P_0 = 460 TW, a_0 = 6
- $n_e = 0.001 n_c = 1.7 \times 10^{18}$ cm^{-3}
- LWFA scaling laws [2]: 2 GeV, 1 nC, 1 cm



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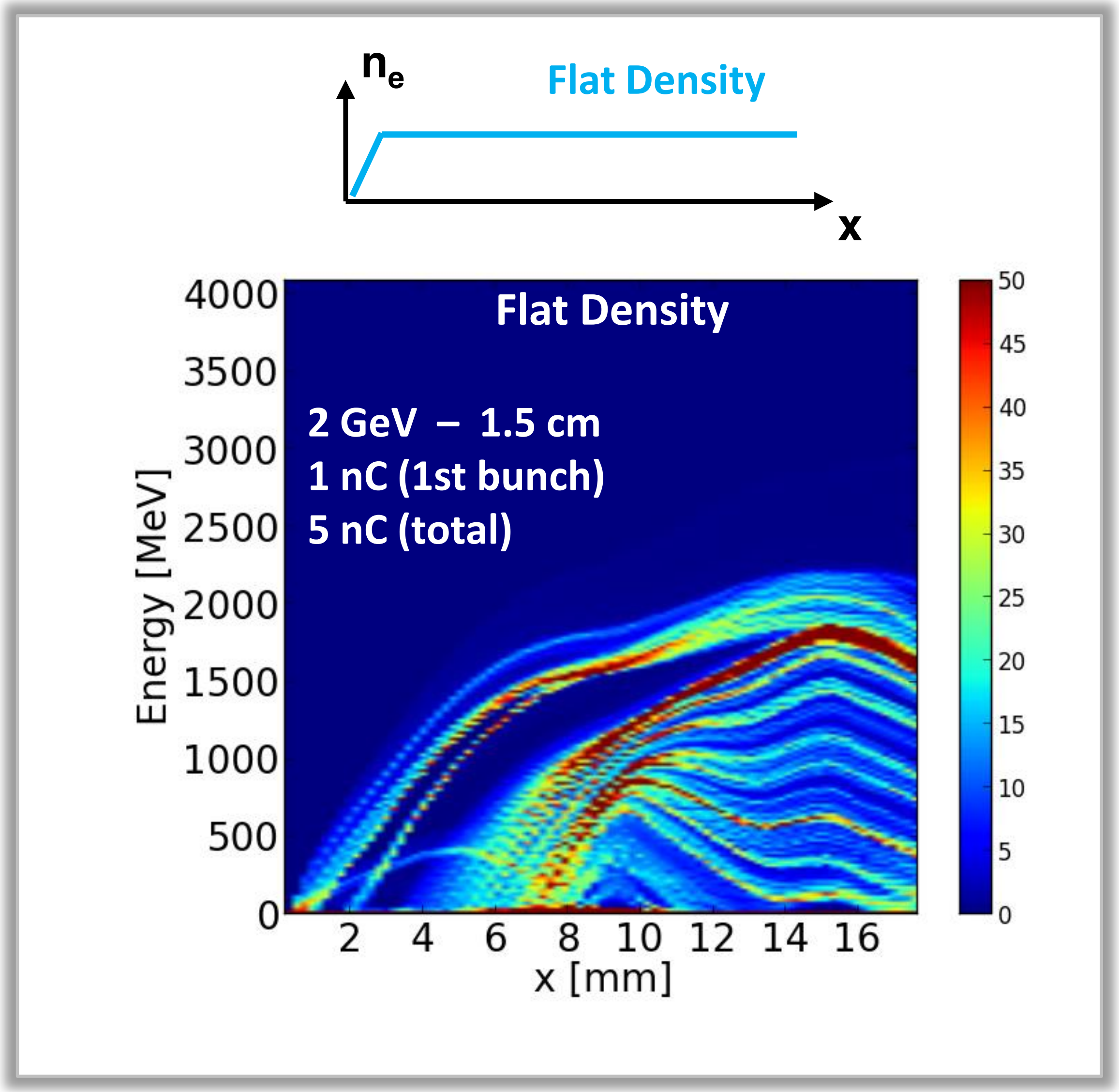

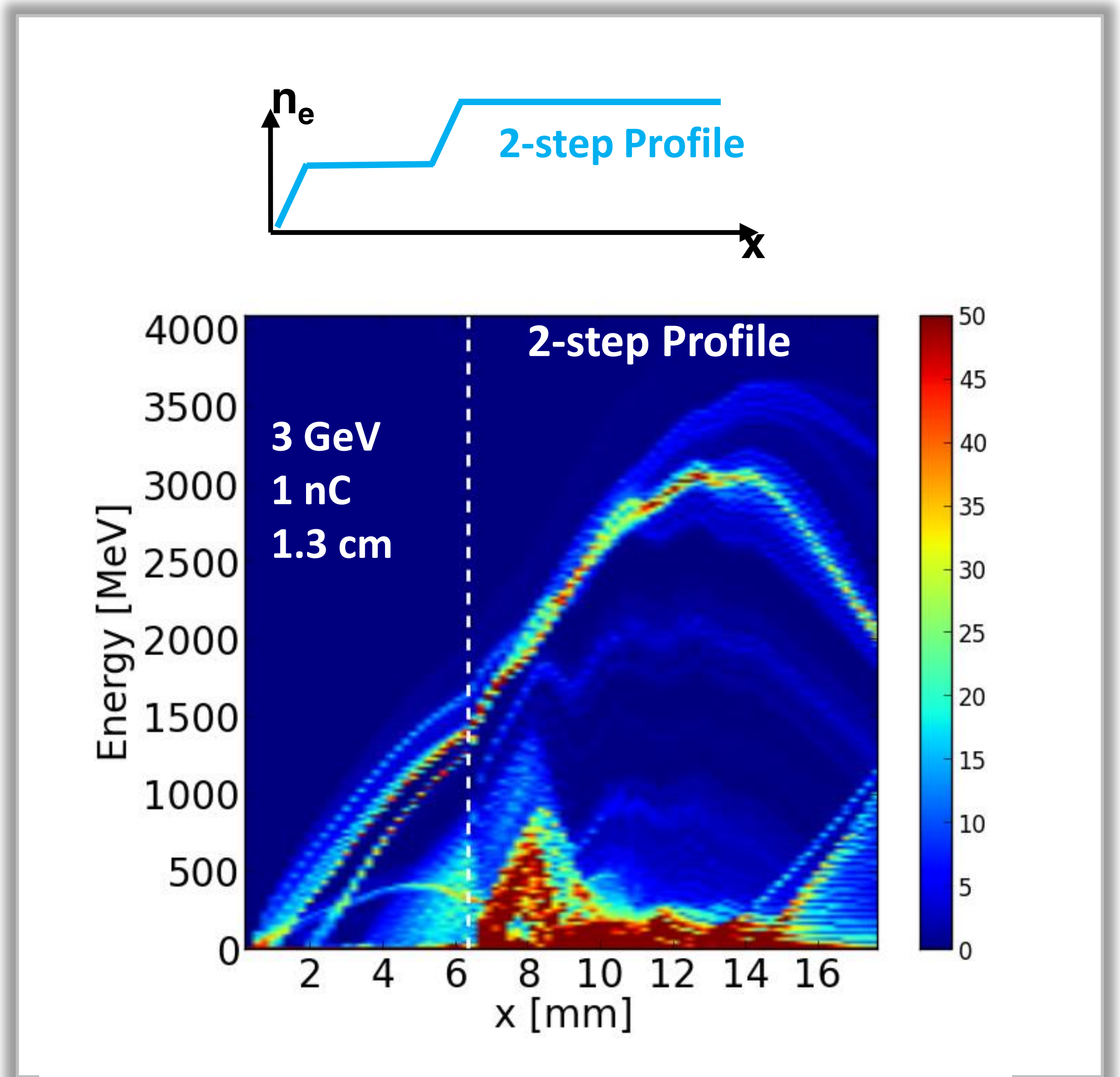

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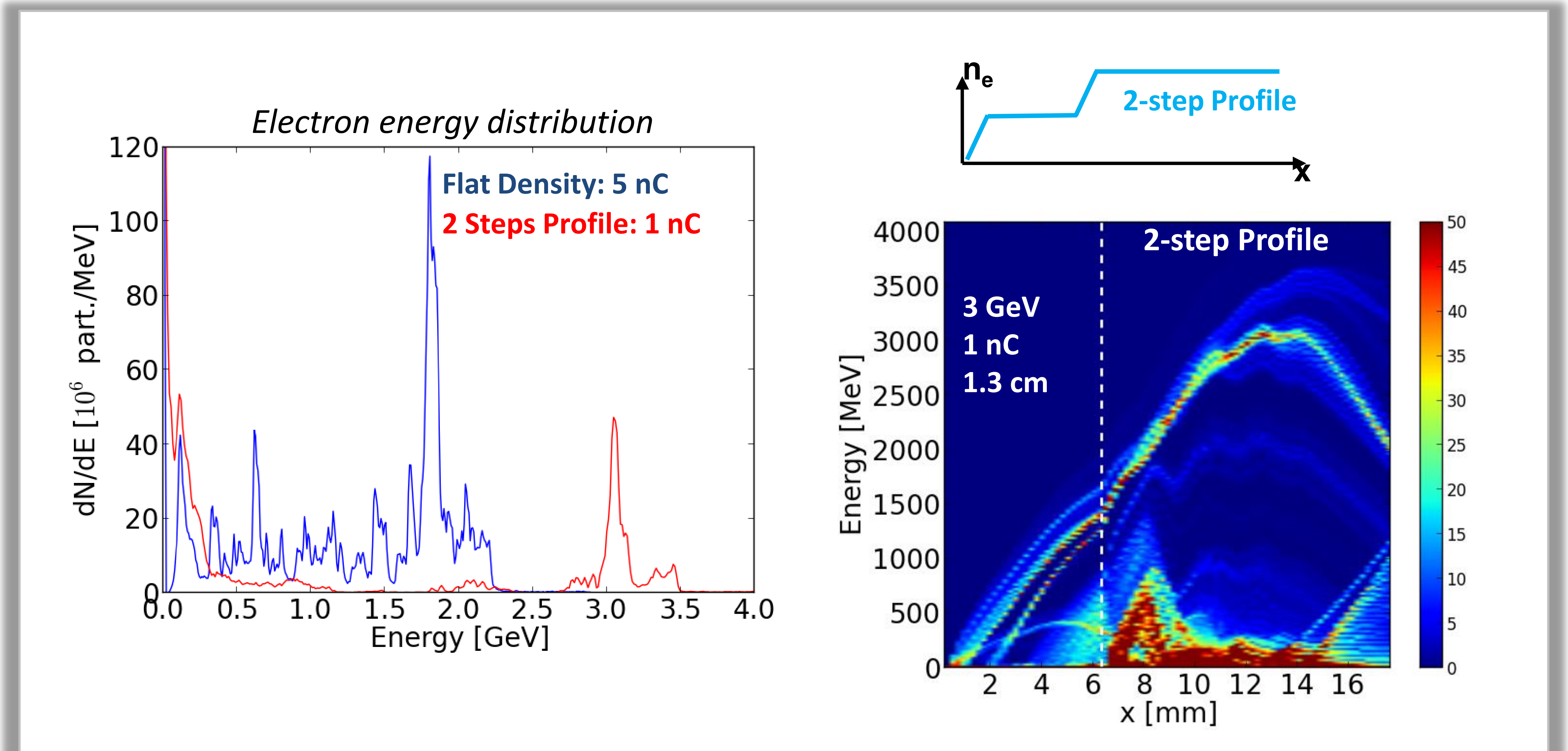
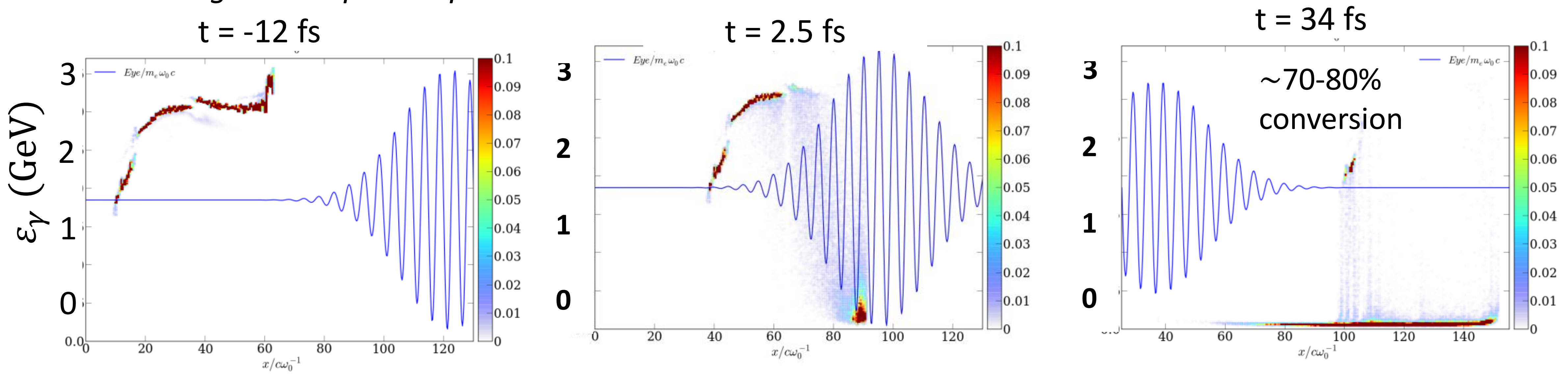


[1] A. Lifschitz *et al.*, JoCP 228, 1803-1814 (2009), [2] Lu et al., PRSTAB 10, 061301 (2007)

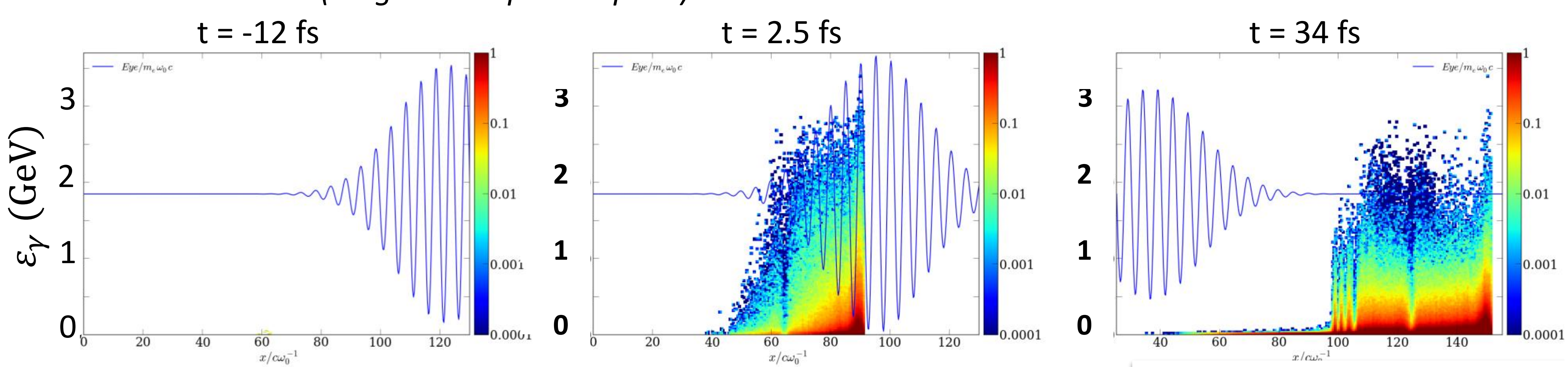
Second step: collision with a counter-propagating laser pulse, the γ-photon emission

- First simulation case: P_0 = 4.7 PW, W_{FWHM} = 2 μm, a_0 = 219, $I_0 = 10^{23}$ W/cm^2
- Strong deceleration of the electron beam with generation of GeV photons before the maximal laser intensity

Electron longitudinal phase space:

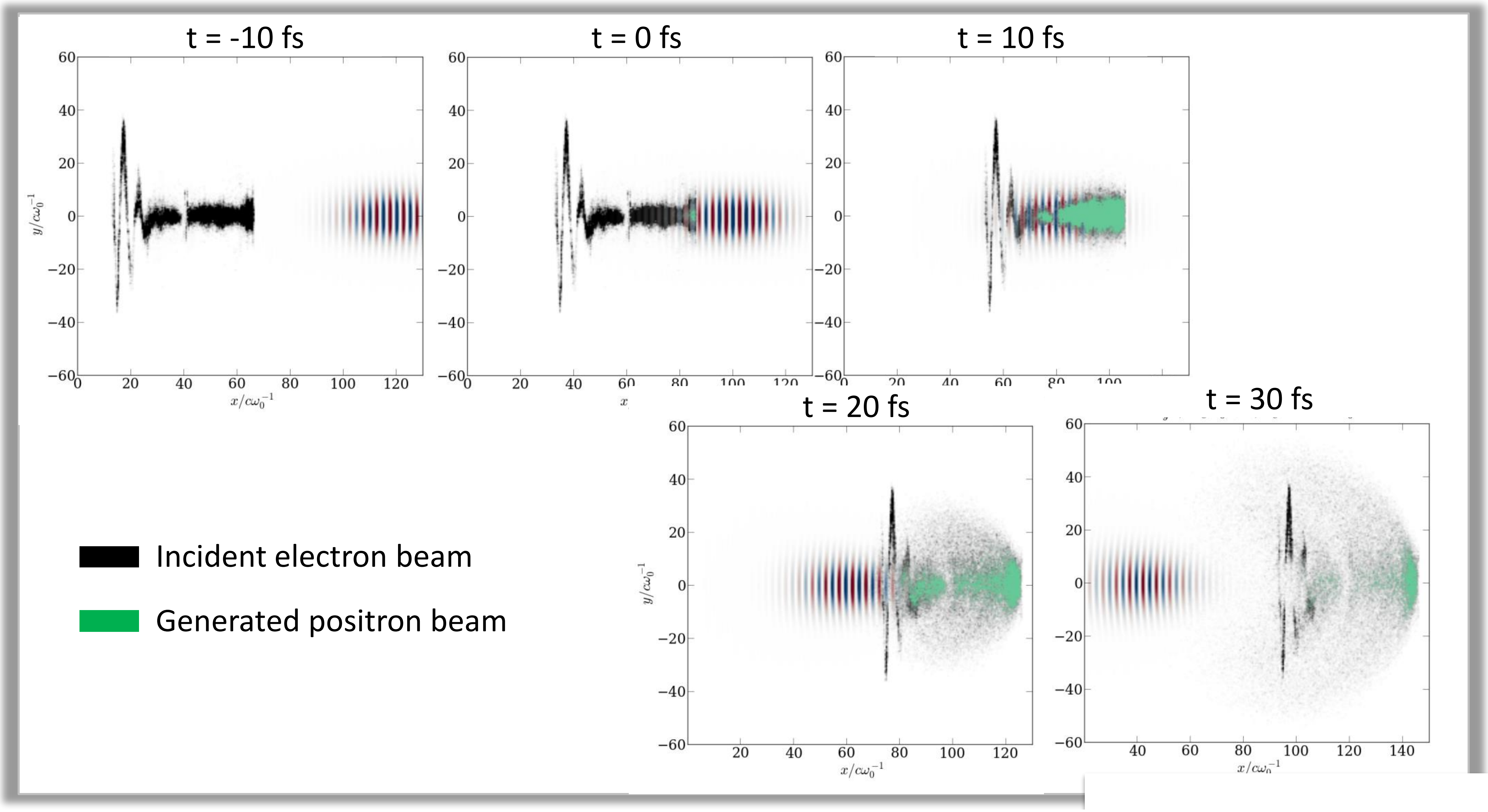


Photon distribution (longitudinal phase space):



Second step: collision with a counter-propagating laser pulse, the pair production

- Positron charge: 1.2 nC (7.5×10^9 positrons)
- High divergence

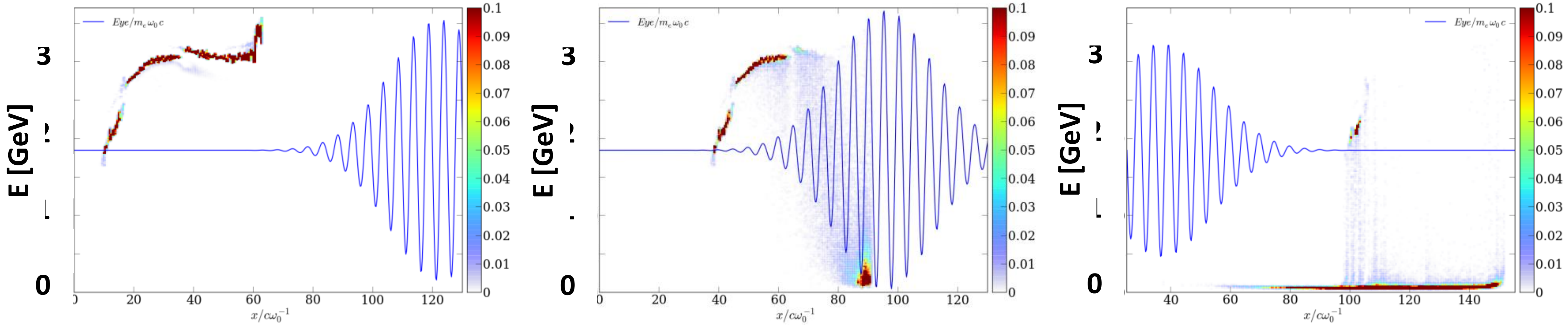


Second step, collision with a counter-propagating laser pulse: pair production and energy distribution

- The pairs are created few femtoseconds after the photon emission, near the intensity peak of the wave, and loss their energy by radiation in the tail of the laser

Electron longitudinal phase space:

t = -12 fs	t = 2.5 fs	t = 34 fs



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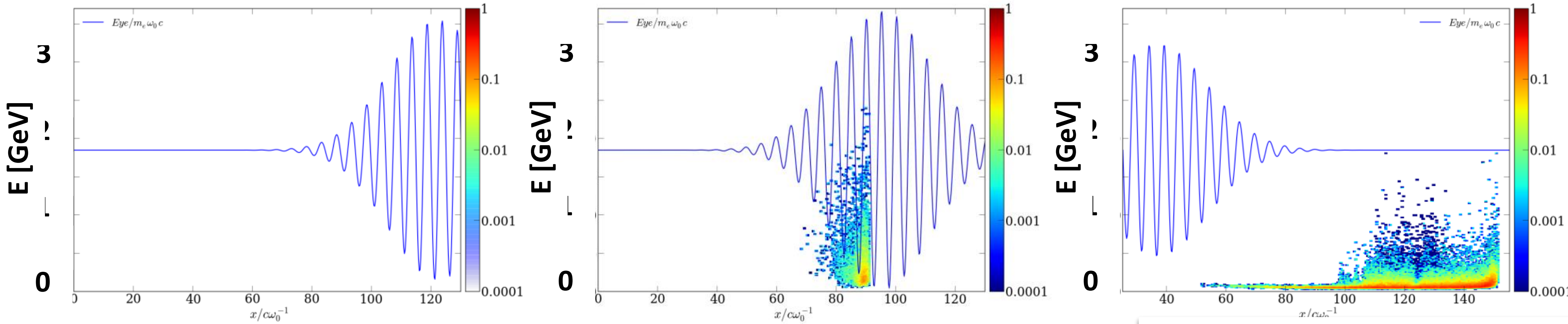
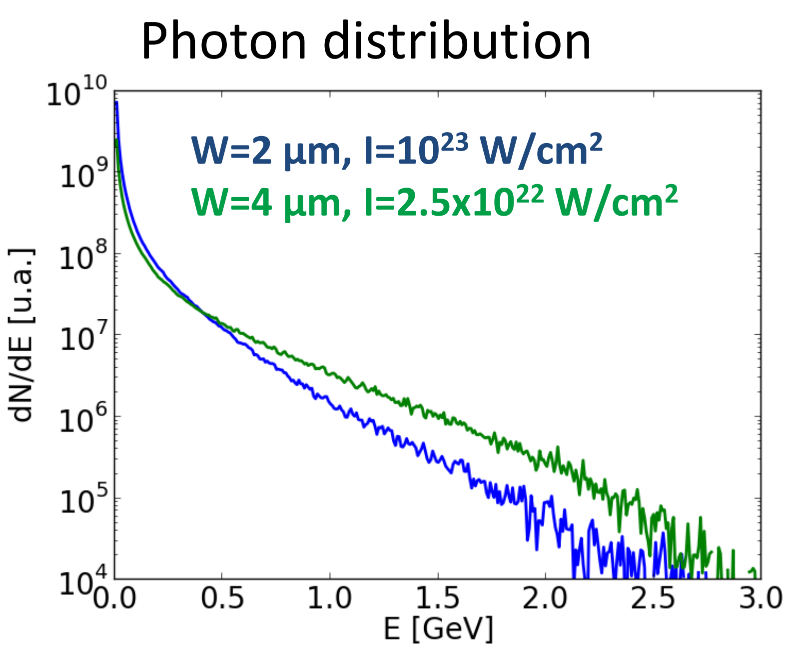
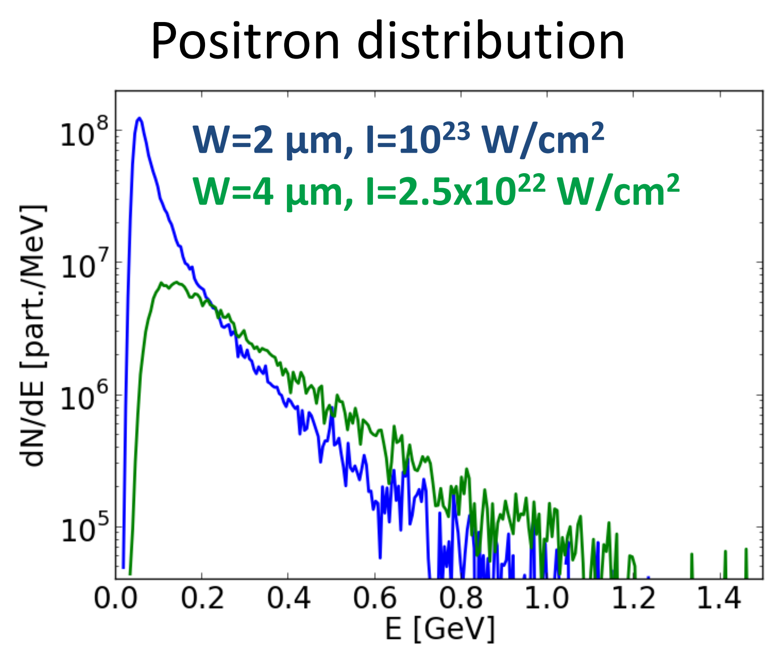
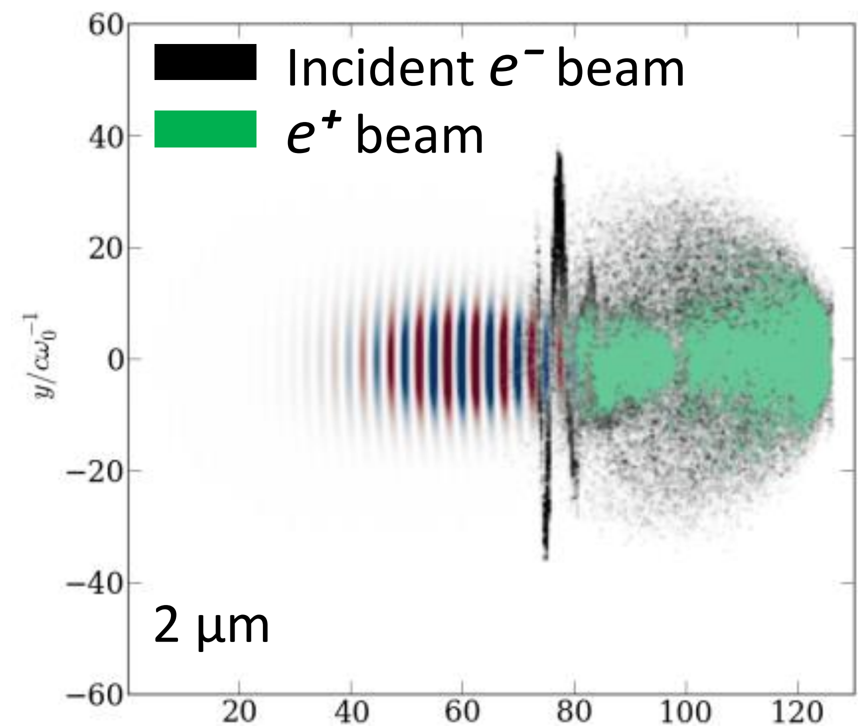
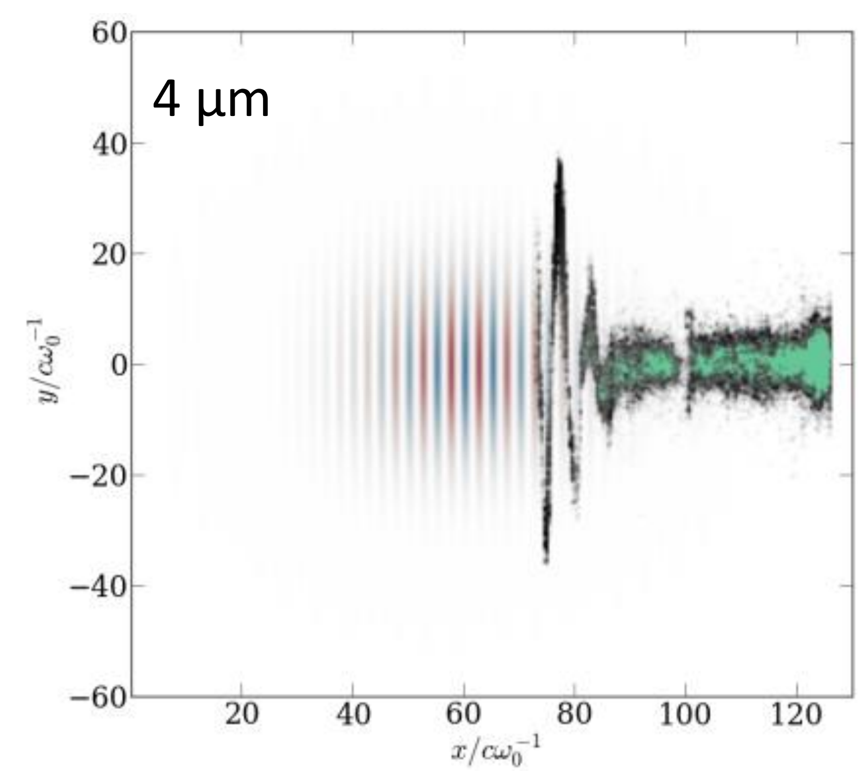


Influence of the laser focal spot and intensity: more positrons at 2 µm, more energetic positrons and reduced divergence at 4 µm









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	W_{FWHM} = 2 µm 10^{23} W/cm^2 a_0 = 219	W_{FWHM} = 4 µm 2.5x10^{22} W/cm^2 a_0 = 110
Charge	1.2 nC	274 pC
Div. $\boldsymbol{P}_z$ (⊥ pol. plan)	350 mrad	5.5 mrad
Div. $\boldsymbol{P}_y$ (// pol. plan)	520 mrad	70 mrad
<E>	101 MeV	262 MeV

Intermediate conclusions

- The next generation of laser will lead to novel physical effects including the emission of high-frequency radiation and the generation of electron-positron pairs

- First experiments accessible with Apollon or ELI: collision between a laser-wakefield accelerated electron beam and a counter-propagating laser pulse

    - The photon emission occurs few laser wavelength before the main intensity peak

    - Divergence due to electron wriggling and transverse field gradients => divergence
    reduced with larger focal spot

    - Positron charge number maximized with the intensity

    - Positron average energy decreases with the intensity

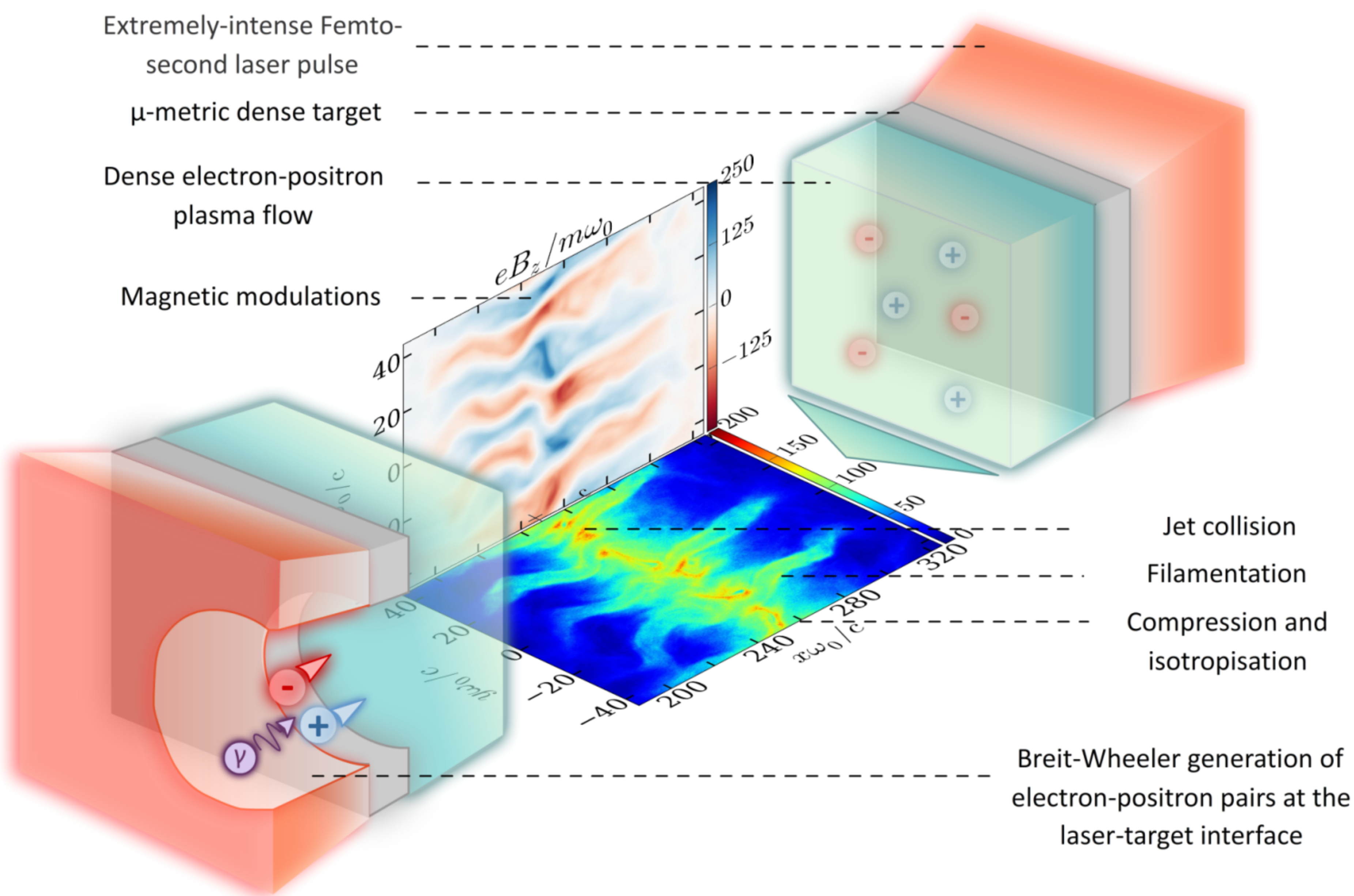
Collisionless shocks in electron-positron plasmas using extreme-light laser pulses

Two-target configuration for the study of the Weibel instability in colliding e^-e^+ jets

Could be transposed to e^-p plasma collisions using low density targets

- High laser intensity necessary to generate sufficiently dense pair plasmas
- Large focal spot necessary to minimize transverse spreading of pair plasma and generate many filaments

$\Rightarrow$ Total laser energy > 200 kJ



CALDER PIC Simulation

- **Laser:** plane wave, wavelength $\lambda_0 = 1\ \mu\text{m}$, Gaussian profile of $125\omega_0^{-1}$ (65 fs) FWHM, linear polarization, amplitude $a_0 = 800$ ($I \sim 8.9 \times 10^{23}\ \text{Wcm}^{-2}$)
- **Target:** fully-ionized Al^{13+} slab of $32c\omega_0^{-1}$ ($5\ \mu m$) thickness + preplasma of $12.5c\omega_0^{-1}$ ($2\ \mu m$) thickness

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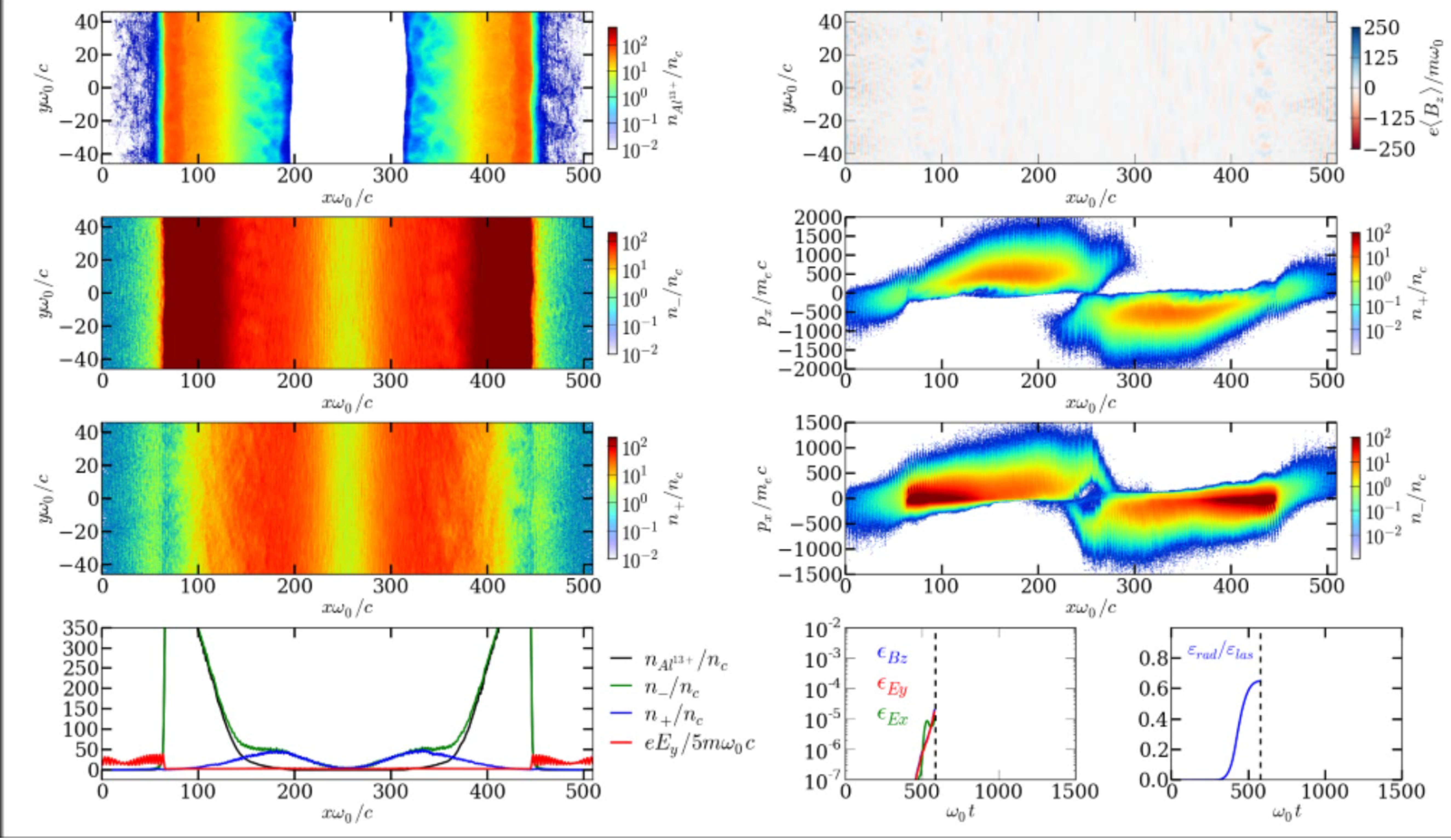
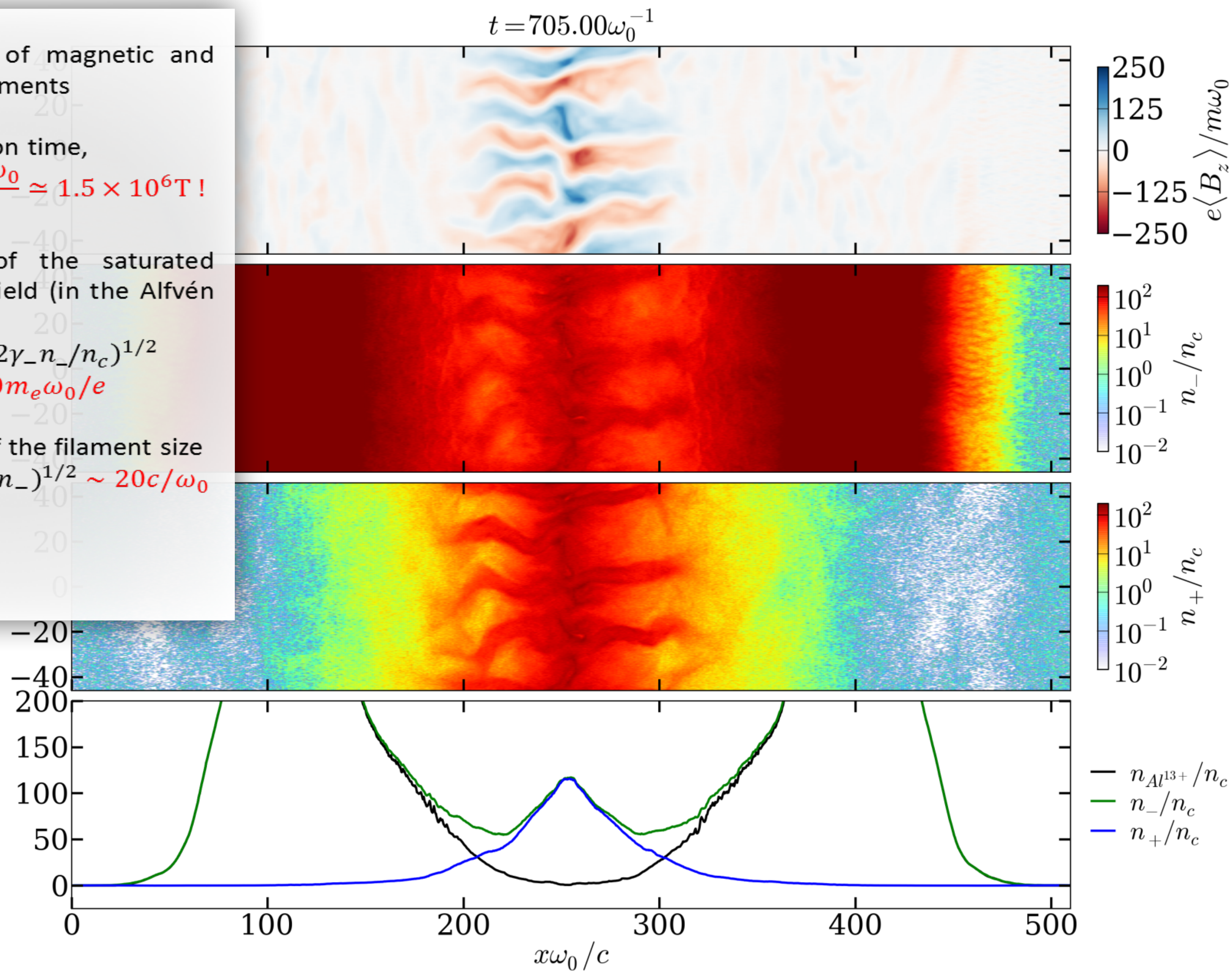
e^-e^+ generation at the laser solid interface



Saturated magnetic fluctuations exceed 10^6 T!

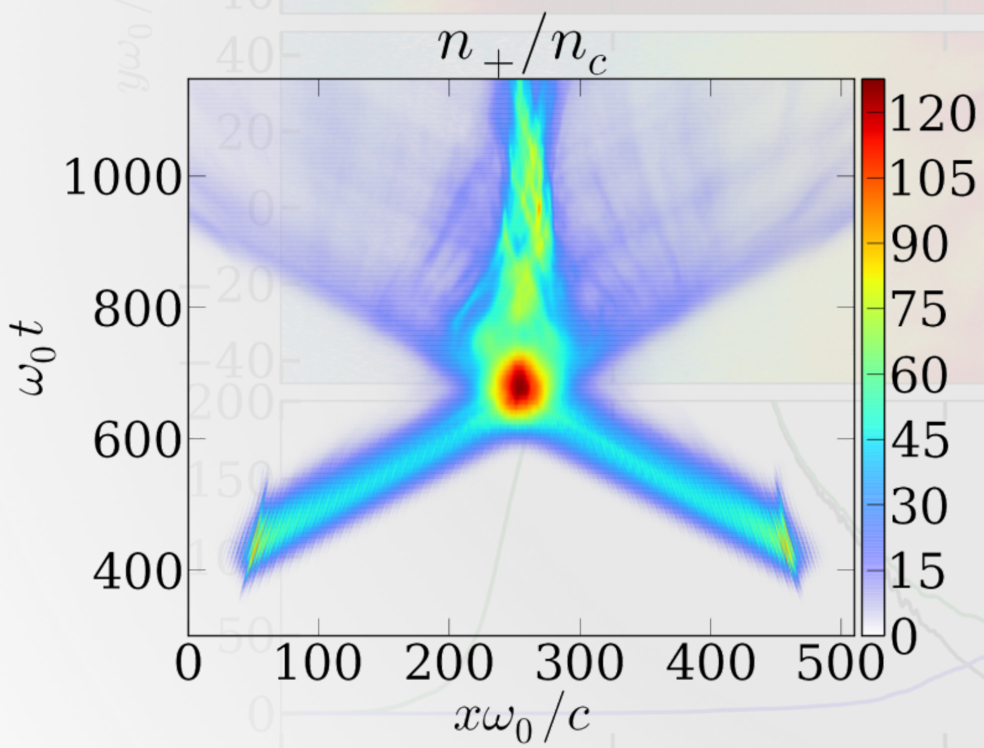
- Formation of magnetic and density filaments
- At saturation time,
  $B_z \simeq 150 \frac{m_e \omega_0}{e} \simeq 1.5 \times 10^6 \text{T}$!
- Estimate of the saturated magnetic field (in the Alfvén limit)
  $B_{z,sat} = (2\gamma\_n\_/n_c)^{1/2}$
  $\sim 100 m_e \omega_0 / e$
- Estimate of the filament size
  $\lambda \sim 2\pi(n_c \gamma\_/n\_)^{1/2} \sim 20c/\omega_0$



Neglecting radiation losses significantly lowers the compression ratio

With the radiation losses

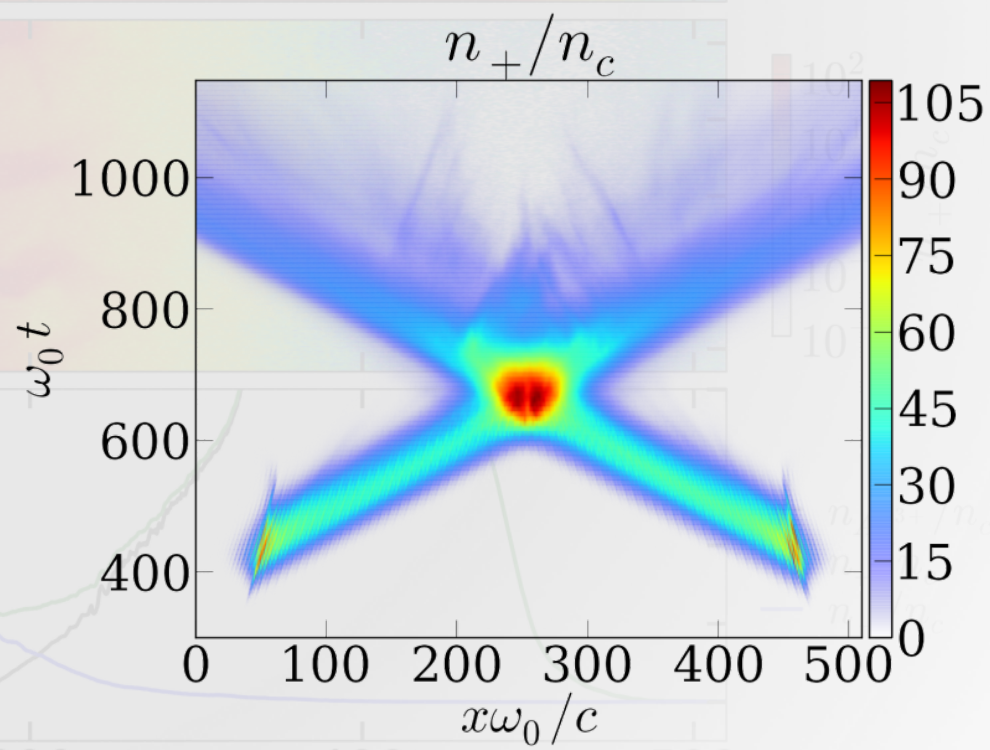
- Accumulation of matter in the overlap region up to a density peak $n_{peak} \sim 128 n_c \sim 2.85 n_{\pm}$.
- The measured compression ratio ~ 3 approaches the expected value in a strong 2-D relativistic shock.



Compression ratio ~ 2.85

Without the radiation losses

- The highest-energy particles undergo weaker deflections through the turbulent region.
- This weaker scattering decreases the compression ratio down to ~ 2.4 without radiation.
- The compressed structure is not confined at larger times, in contrast to the radiative case.



Compression ratio ~ 2.4

Intermediate Conclusions

- First **fully-integrated simulation** of neutral pair plasma laser-induced generation and collision
- This scheme requires **200 kJ - 60 fs** laser pulse such as might be available on future **compressed NIF/LMJ-class** laser systems

- **strong MT magnetic fields** develop in the overlapping region
- **ultra-fast isotropization & thermalization** (if not complete) of electron & positron is demonstrated
- **compression up to 2.85** is obtained, which is not yet enough for a shock to develop
- **radiation in the strong MT B-field enhances compression**

Possibility of pair creation in the collision of gamma-ray beams produced by high intensity laser plasma interaction

Photon-Photon collision and pair production in astrophysics[1]

Breit-Wheeler process[2]
Collision of two light quanta

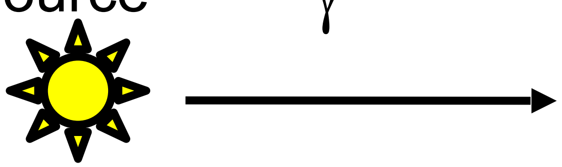
$$\gamma + \gamma \longrightarrow e^+ + e^-$$

- Absorption of high-energy photons in the Universe[3], **cut-off in high energy gamma rays**

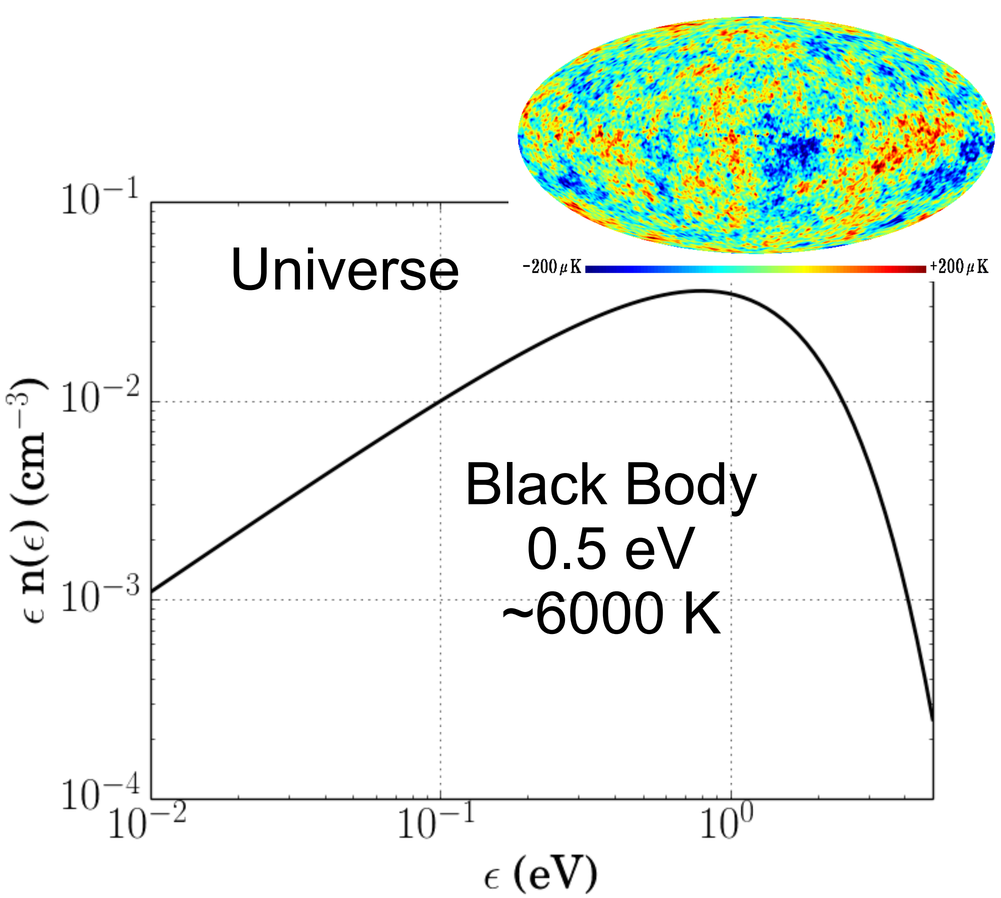
Nikishov[3] (1962) first showed that the maximum of absorption in universe is around 1 TeV

Source

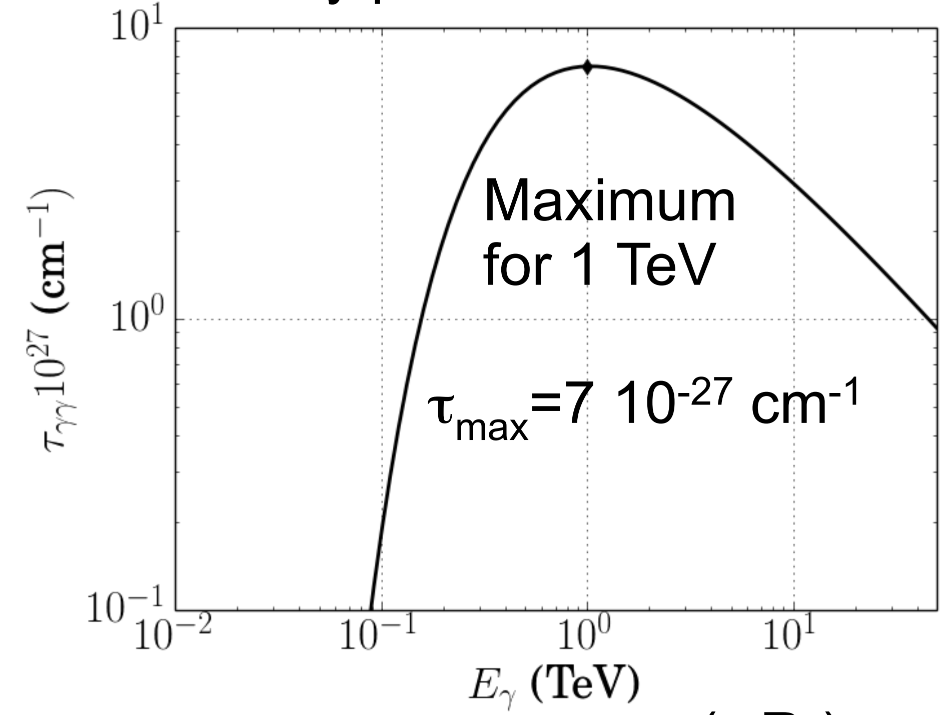
γ



R_c= distance Source-Observation (Cygnus A)



Absorption (opacity) by pair creation

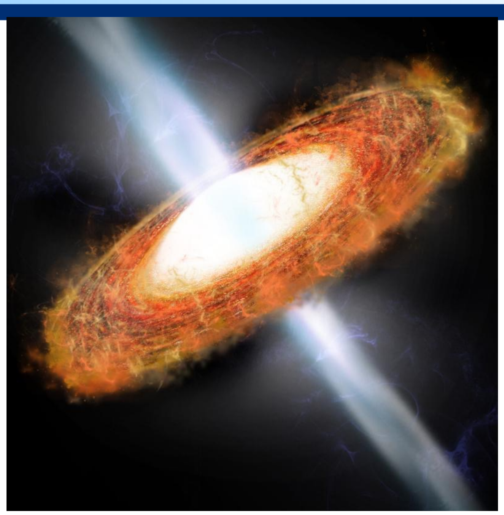


Attenuation: $\eta = \exp(\tau R_c)$

$R_c = 6.6\ 10^{26}$ cm = 213 Mpc $\quad \eta = \exp(4.6)$

[1]Ruffini, R. et al. Physics Reports, 487, 1-140 (2010)
[2]Breit, G. and Wheeler J. A. PRL **15** (1934)
[3]Nikishov A. I., JETP **14** (1962), Gould, R. J. PRL **155**, 5 part 1, part2 (1967), Kneitske, T.M. et al. A&A 413, 807 (2004)

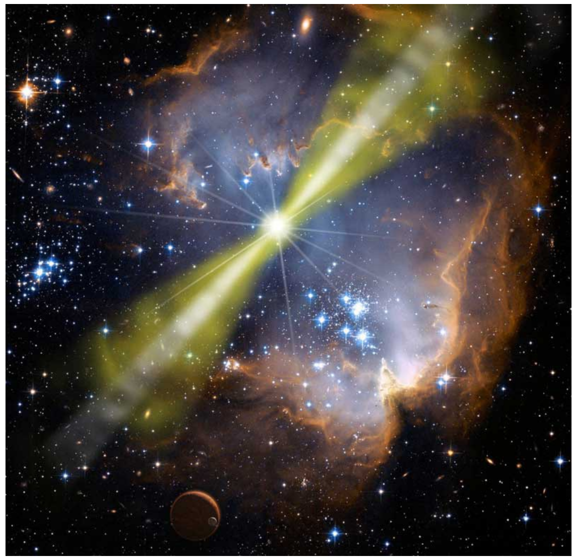
Photon-Photon collision and pair production in astrophysics


Artiste composition

Breit-Wheeler process
Collision of two light quanta

$$\gamma + \gamma \longrightarrow e^+ + e^-$$

- e^+/e^- pair production in AGN (Active Galaxy nuclei), Blazar, Quasar[1]


Artiste composition

- e^+/e^- pair production in
  - GRB[2] (Gamma ray burst), Supernovae, Hypernovae…
  - In pulsar – electron-positron pair plasma
  - Merging neutron start, black hole
  - Accretion disk

→ Controls energy release in astrophysical processes

[1]Bonometto, S. and Ress, M. J. MNRAS, **152** 21-25 (1971)

[2]Piran, S. Rev. Mod. Phys. 76 (2004)

Pair creation with two real photons has not been observed in laboratory

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

S. C. Berridge, W. M. Bugg, K. Shmakov, and A. W. Weidemann
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996

C. Bula, K. T. McDonald, and E. J. Prebys
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

C. Bamber,* S. J. Boege,† T. Koffas, T. Kotseroglou,‡ A. C. Melissinos, D. D. Meyerhofer,§ D. A. Reis, and W. Ragg‖
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 2 June 1997)

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

PACS numbers: 13.40.–f, 12.20.Fv, 14.70.Bh

See also Pike, O. J. et al. Nature Photonics, 8, 434, (2014)

The production of an electron-positron pair in the collision of two real photons was first considered by Breit and Wheeler [1] who calculated the cross section for the reaction

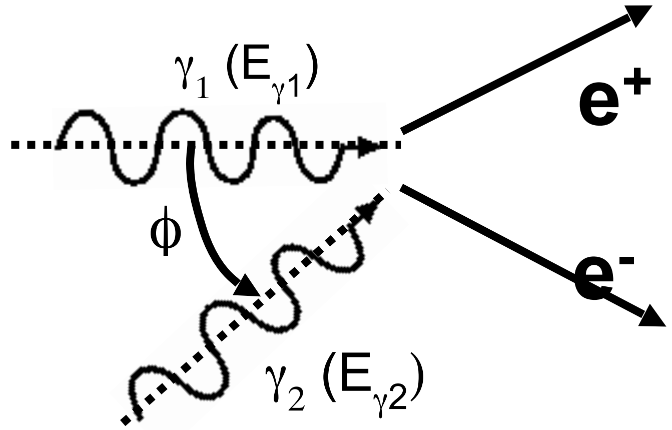
$$\omega_1 + \omega_2 \rightarrow e^+ e^- \quad (1)$$

to be of order r_e^2, where r_e is the classical electron radius. While pair creation by real photons is believed to occur in astrophysical processes [2], it has not been observed in the laboratory up to the present.

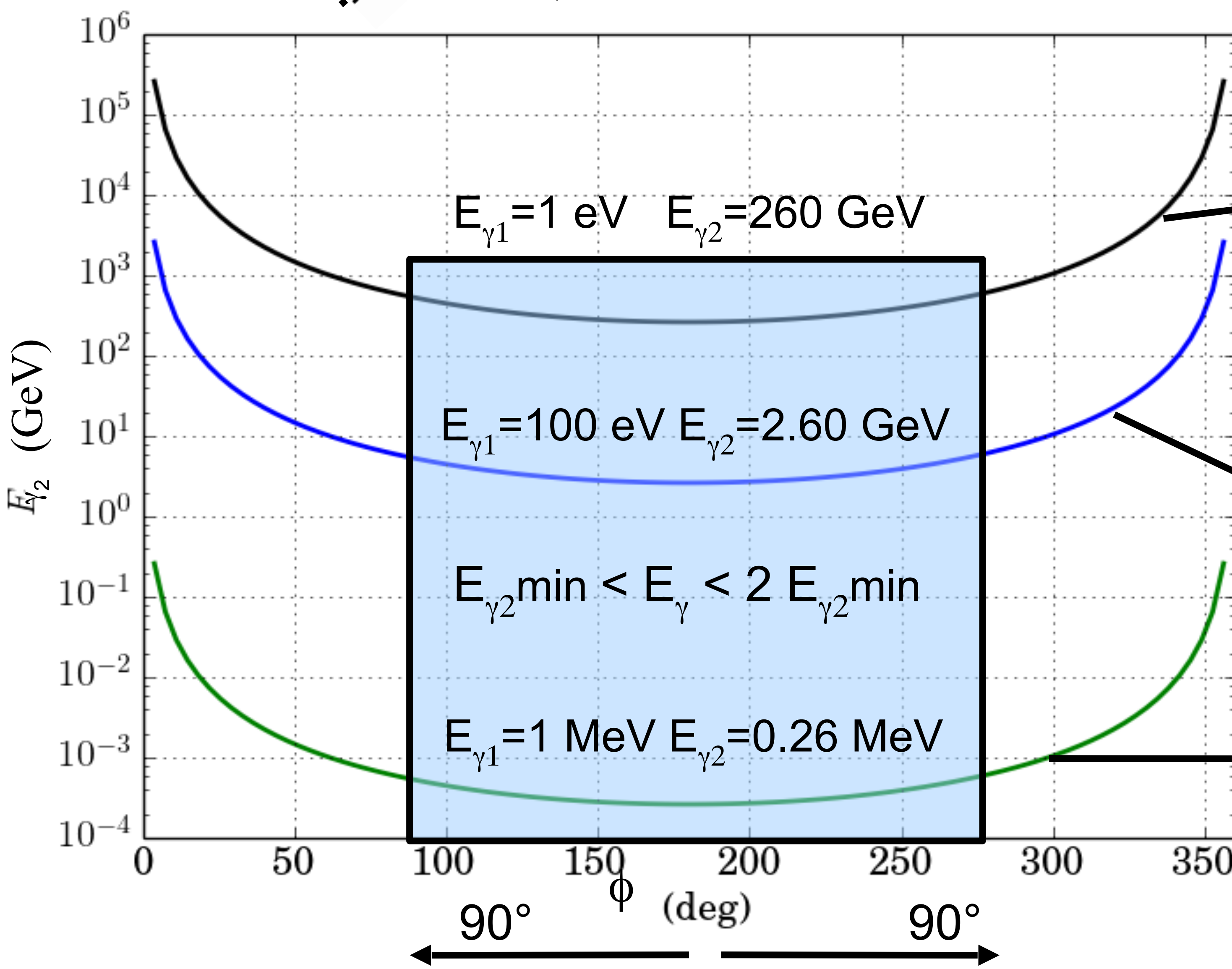
approaches or exceeds unity. Here the laser beam has laboratory frequency ω_0, reduced wavelength λ_0, root-mean-square electric field $\mathcal{E}_{\rm rms}$, and four-vector potential A_μ; e and m are the charge and mass of the electron, respectively, and c is the speed of light.

For photons of wavelength 527 nm a value of $\eta = 1$ corresponds to laboratory field strength of $\mathcal{E}_{\rm lab} = 6 \times 10^{10}$ V/cm and intensity $I = 10^{19}$ W/cm². Such intensities are now practical in tabletop laser systems based on chirped-pulse amplification [6].

Search for other experimental configurations



$$E_{\gamma_2} = \frac{2m_e^2c^4}{E_{\gamma_1}(1-\cos(\phi))}$$



Perturbative regime, i.e.
Non-linear Breit-Wheeler

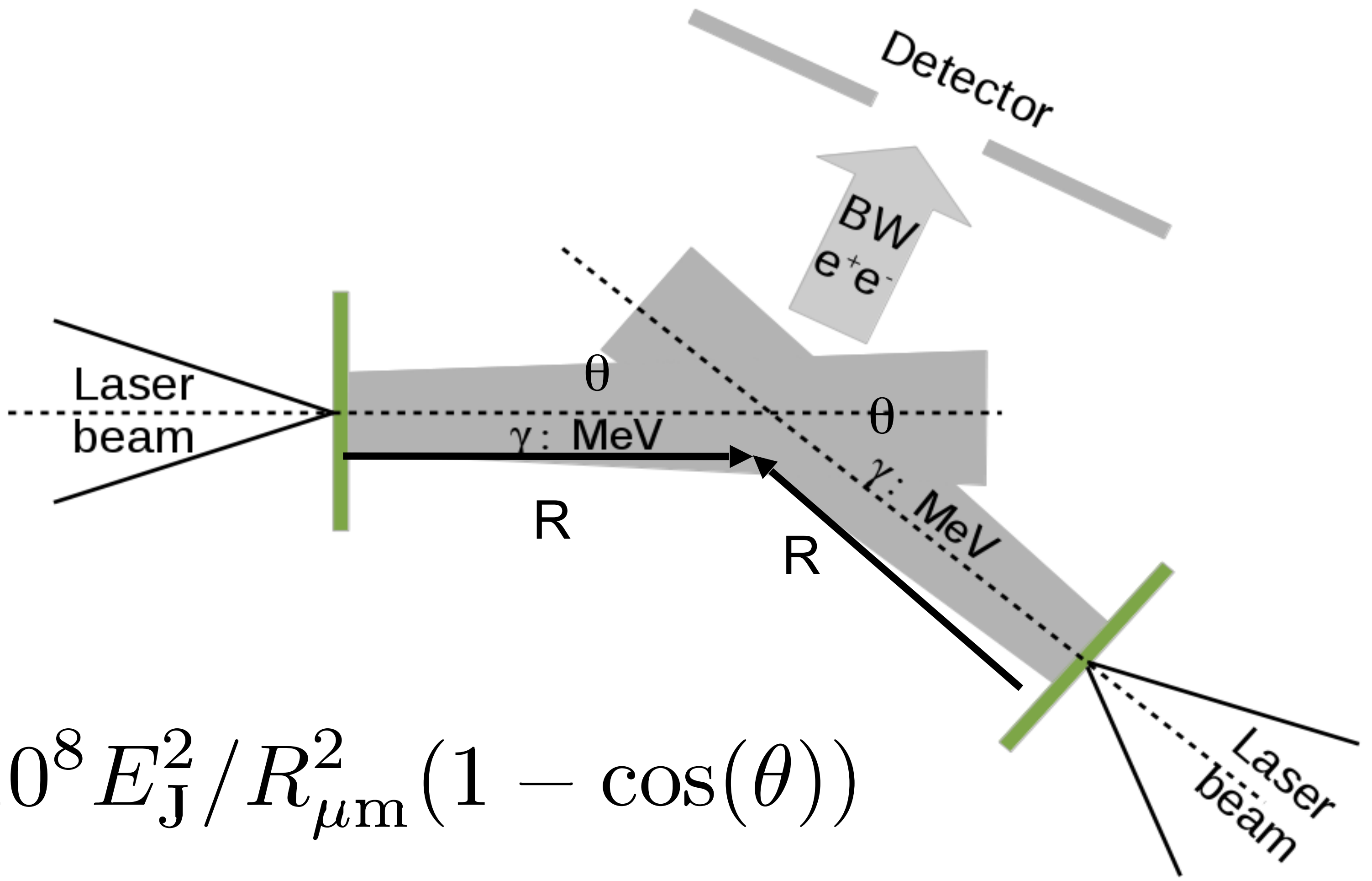
SLAC E-144 exp.

Non-perturbative regime, i.e.
linear Breit-Wheeler
Real photon-photon collision

(1) γ **photon- photon bath collision (Pike et al.)**

(2) MeV-MeV photon collision

(2) Collision of MeV-MeV photons in vacuum



θ : γ–beam divergence

R : distance between γ source and photons collision zone

$$N_p = 10^8 E_{\mathrm{J}}^2 / R_{\mu\mathrm{m}}^2 (1 - \cos(\theta))$$

MeV-MeV photons collision

$$\mathrm{E_J} = 1 - 10\,\mathrm{J} \text{ and } \mathrm{R} = 500\,\mu\mathrm{m} \quad \theta = 30^\circ$$

Pair production : per shot $\mathrm{N}_p = 3 \times 10^3 - 3 \times 10^5$

Need for high-intensity collimated MeV photon beams

γ–ray sources in MeV range

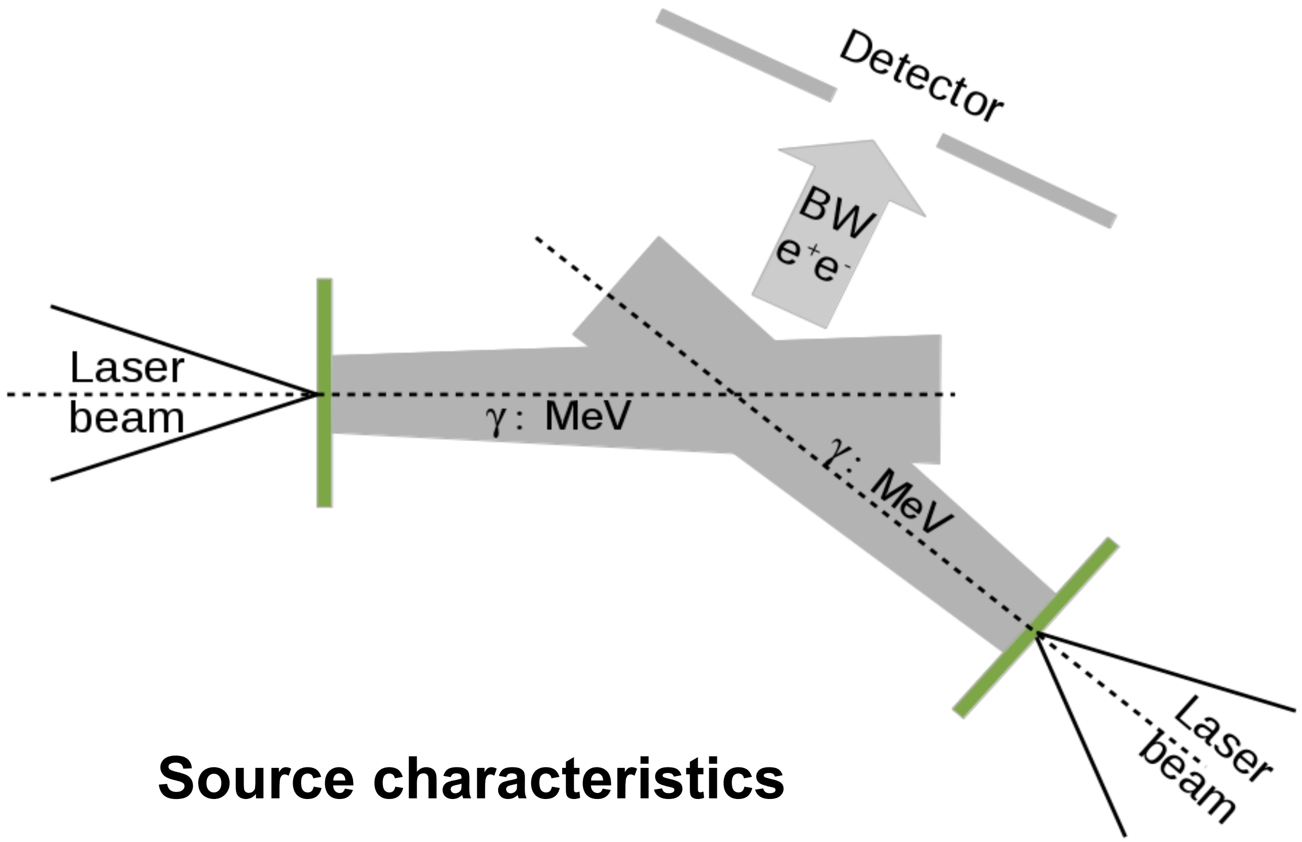
Performances comparison between different γ–ray sources

Sources	Bremss.	Betatron	Compton	Synch.
γ energy	3–50 MeV	1-7 MeV	1–10 MeV	1–10 MeV
Beam energy	1–2 J	1 μJ	10 μJ	1–10 J
Efficiency	2×10^{-2}	10^{-6}	10^{-5}	10^{-2}
Divergence (θ)	$\sim$15°	$\sim$ 1°	$\sim$1°	$\sim$ 30°
Reference	[23]	[29]	[32]	[30],
N_p from Eq.(3) at $R = 500$ μm	$\sim 10^4$	10^{-5}	$\sim 10^{-5}$	$\sim 10^4$

Synchrotron radiation sources seem to be a good choice for pair production
Possibility to use gas targets (low noise sources)

[23]Henderson A. et al. High Energy Density Physics **12**, 46 (2014)
[29]Cipiccia S. et al. Nature Physics **7**, 867 (2011)
[32]Sarri G. et al. PRL **113,** 224801 (2014)
[30]Capdessus, R. et al. PRL **110** (2013), Capdessus, R. PoP **21** (2014)

Collision of MeV-MeV photons from PIC simulations



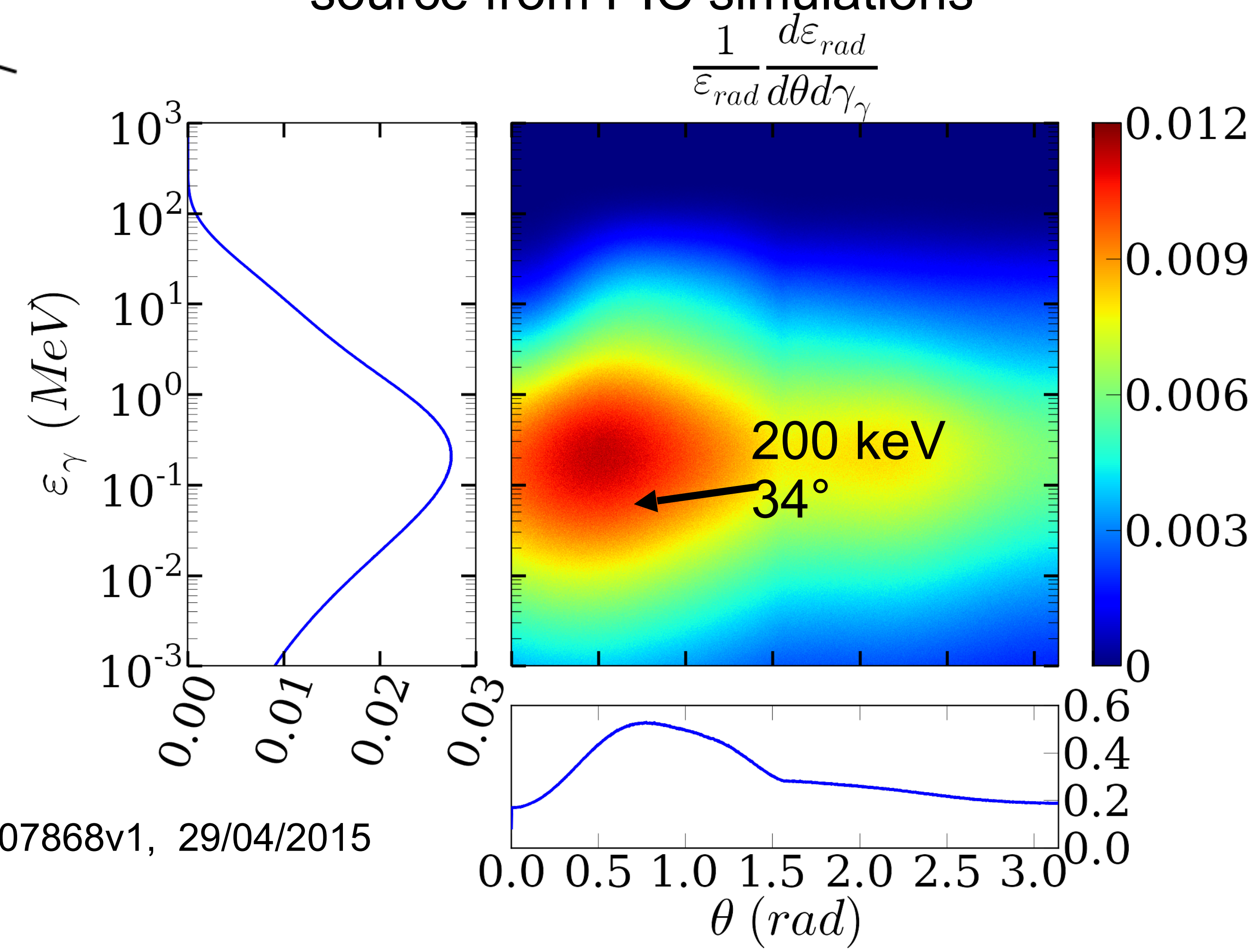
-Laser parameters (ELI Facility)

λ_L=0.8 μm, τ_L=15 fs,
150 J, 10 PW
Φ_L=3 μm, 0.05 Hz

I =10^{23} W/cm^2

-Target properties Aluminium
(1.7 g/cc, n_{Al}=60 n_c)

Normalized spectrum of photon source from PIC simulations[1]



Source characteristics

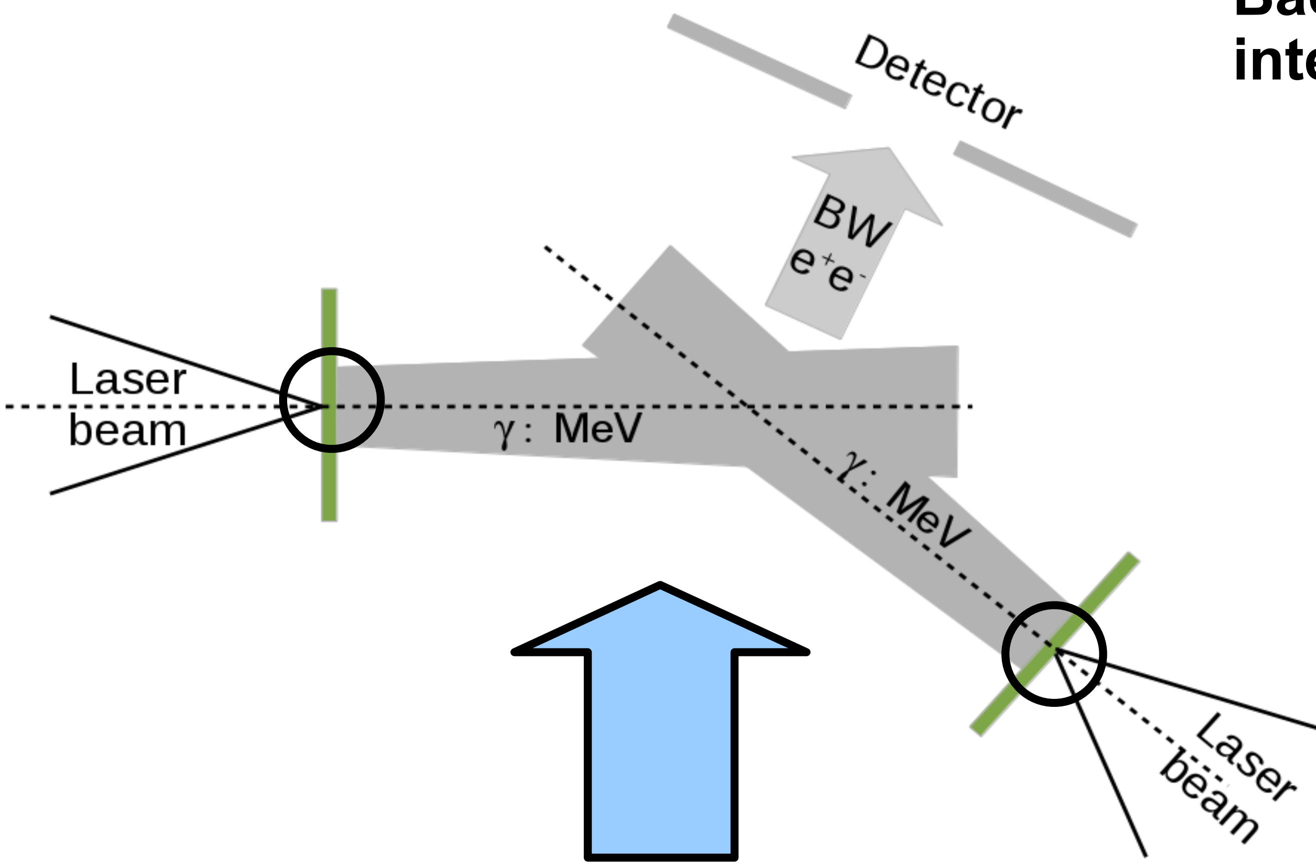
- Conversion: 10-20 % of laser energy
- 10^{13} photons up to 1 MeV
- 10^{12} photons in 1-3 Mev range
  Forward emitted [0, π]

Pair production with pure BW process

- Head on collision : **10^8 pairs**
- At R=500 μm distance : **10^4 pairs**

[1]Lobet, M. et al. ArXiV:1311.1107 (2013), Ribeyre X. et al. arXiv:1504.07868v1, 29/04/2015

Other e+e- pair production can perturb the detection of BW pairs



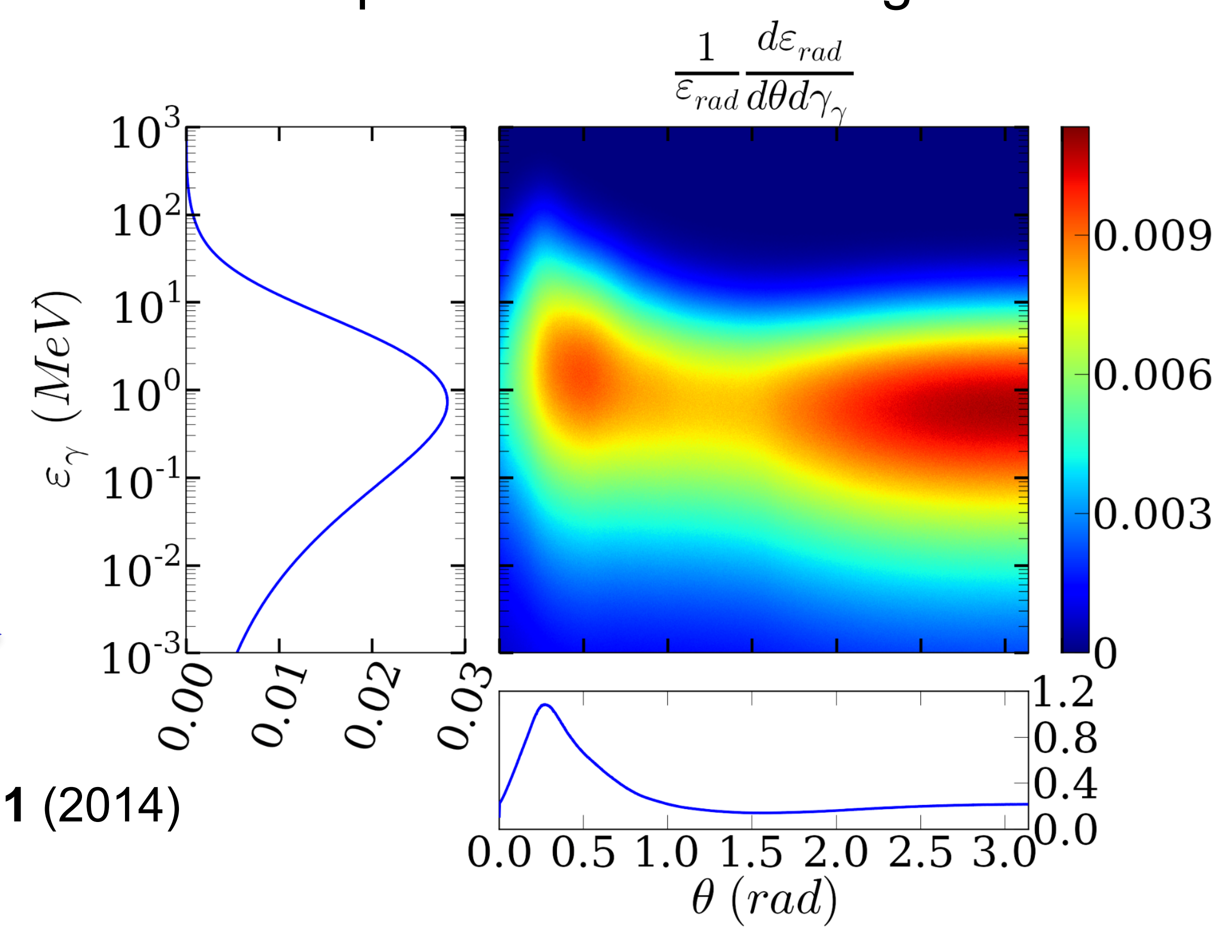
Background pairs production during laser target interaction from PIC simulations

- Non-linear BW pairs : **10^5**
- Trident pairs : **10^7**
- Bethe-Heitler pairs : **10^9**

Number of Bethe-Heitler pairs ten times higher than Breit-Wheeler pairs if we collide the photons near the target foil

For the pure BW pair production in vacuum we need to separate the source from the collision zone.

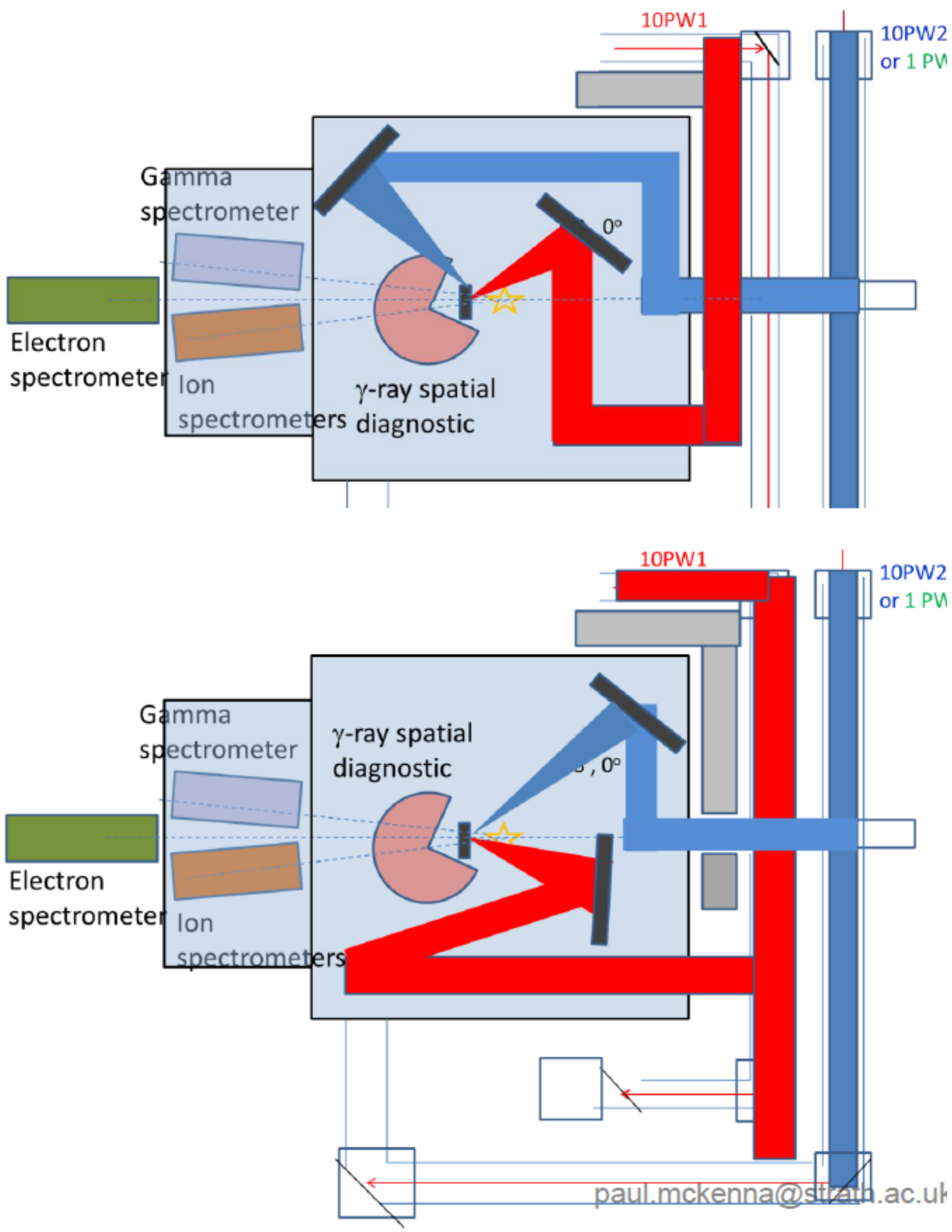
Use low density target and high repetition rate laser to improve S/N ratio.



[1]Capdessus, R. et al. PRL **110** (2013), Capdessus, R. et al. PoP **21** (2014)

Beam geometry on ELI -NP laser facility

Laser-based Nuclear Physics pillar of ELI
that will focus on high-intensity laser-based nuclear physics (Bucharest-Magurele Romania).



Two 10 PW beams (100 J, 15 fs). Intensity on target $10^{23} - 10^{24}$ W/cm², 0.05 Hz

With different beams interaction angles (operational 2018)

Intermediate conclusions

Pure Breit-Wheeler pairs creation :
- Never observed experimentally
- Great interest for fundamental physics and astrophysics

Three experimental schemes

- **250 GeV - eV Photons** collider : SLAC experiment:
  0.01-0.2 pair per shot : Non-linear process

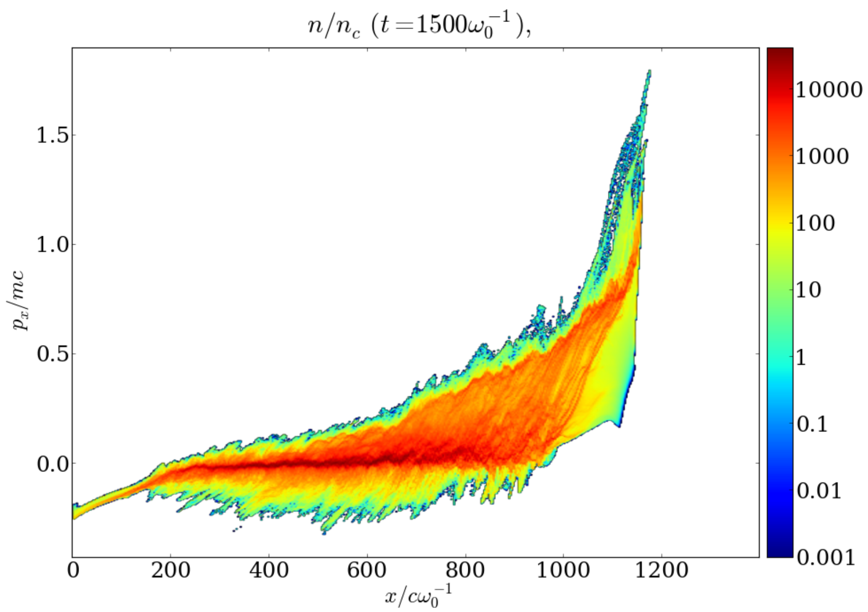
[1] Ribeyre X. et al. arXiv: 1504.07868v1, 29 Apr 2015

- **GeV - 100 eV Photons** collider
  Until **10^4** pair per shot (1 shot per day)
  Possible experiment on LMJ-PETAL facility
  But important perturbations due to other pair creation processes

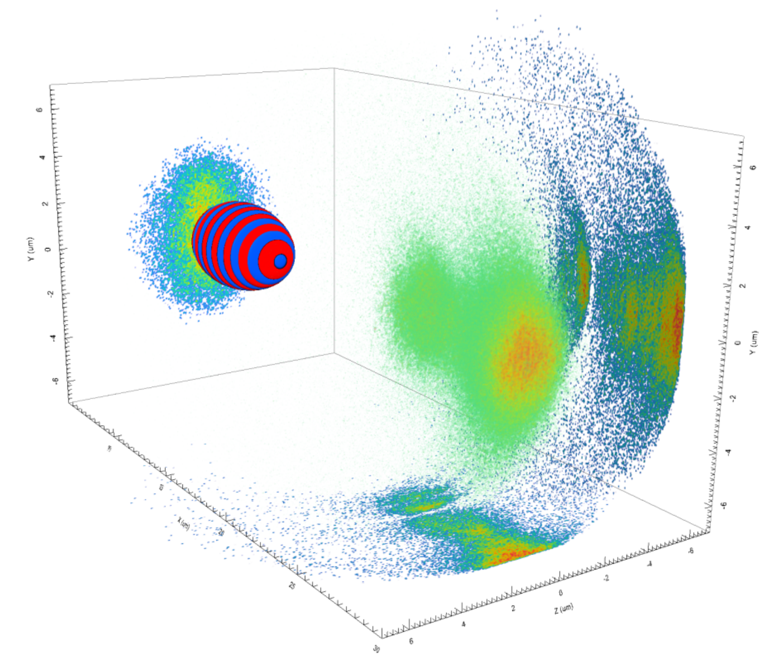
- **MeV - MeV Photons** collider **10^4** pair per shot[1]
  (laser repetition rate > **1 shot per min**)
  Possible experiment on ELI or Apollon facilities
  Need a separation between photon sources and photons collision zone
  Shielding and localized B fields (J. Santos et al. accepted by NJP) to filter other pairs

Further Studies: - Source optimisation : PIC simulations of MeV synchrotron photon source
- Monte Carlo simulations of pairs production during Photon-Photon collision[2]
- Toward experimental proposal

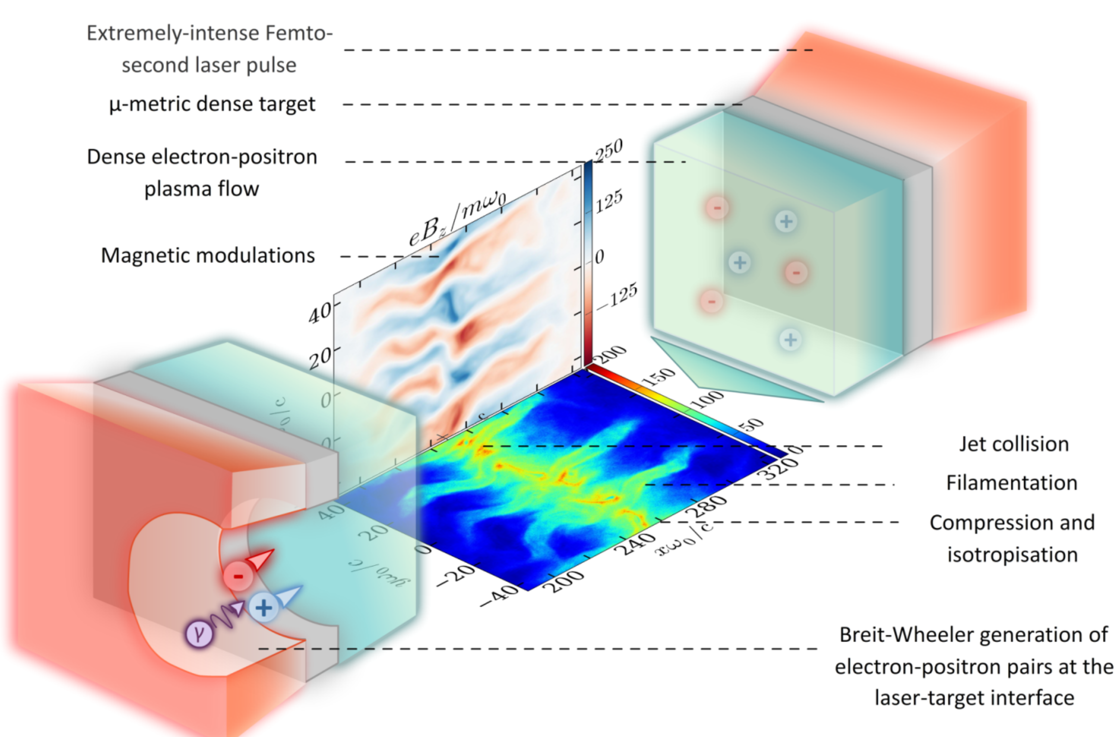
General conclusions and perspectives



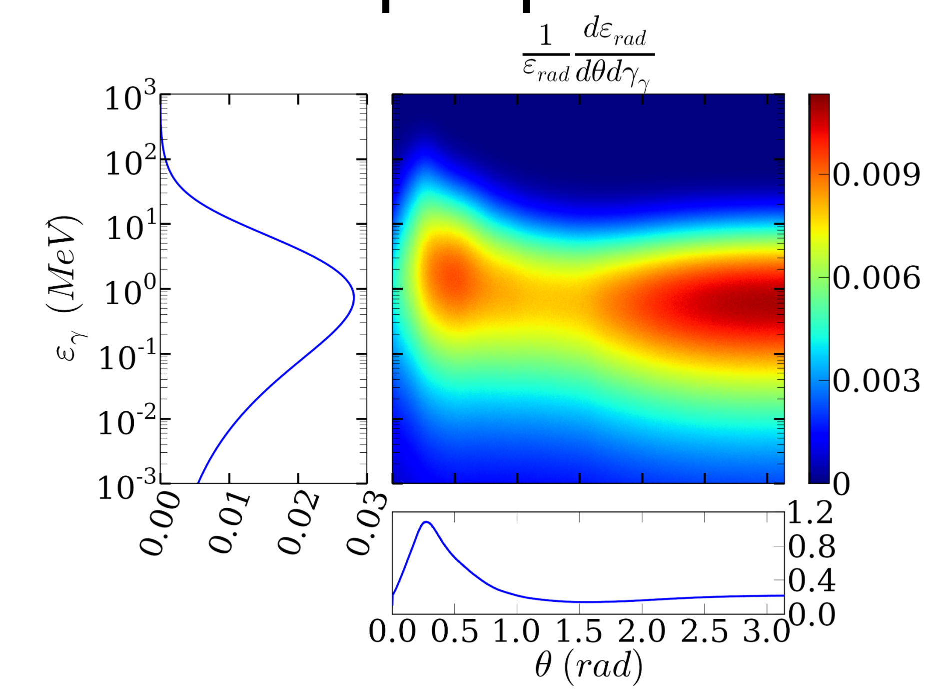
Relativistic laser accelerated ion beams



e-e+ pair plasmas



e-e+ pair plasmas collisions



Intense γ beams to study the pure BW process