Overview of Simulations for Laser-Driven Positron Sources

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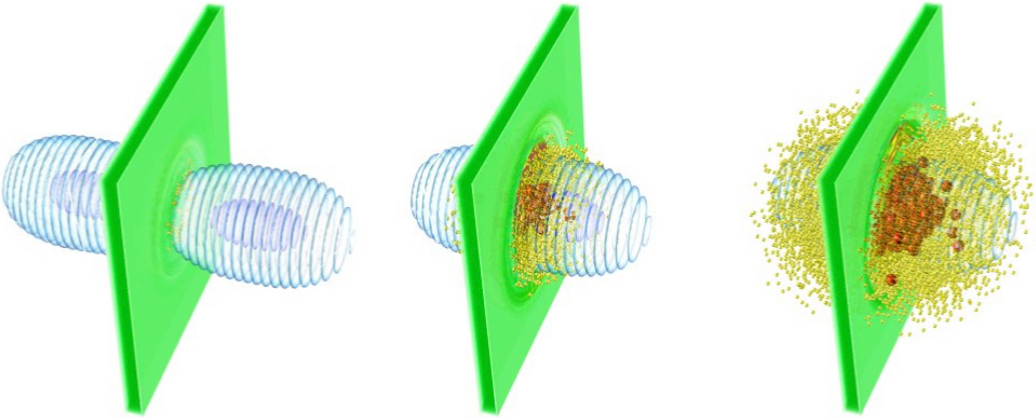

Acknowledgments

Work in collaboration with:

T. Grismayer, R. A. Fonseca, L. O. Silva (IST)

O. Klimo, S. Weber, G. Korn (ELI)

S. Meuren (Princeton)

Simulation results obtained at the IST cluster, SuperMUC (Garching), Fermi (CINECA), Salomon (Ostrava) and MareNostrum (Barcelona).

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Contents

Contents

What can we do with the next generation of lasers?

Opportunities to explore

- study the onset of QED
- study of radiation dominated regime below the QED limit
- new configurations for particle generation and acceleration
- design of efficient GeV photon sources
- study the development of self-generated e+e- plasmas, non-linear and collective effects

Open questions

Can we produce a positron beam worthy of a collider?

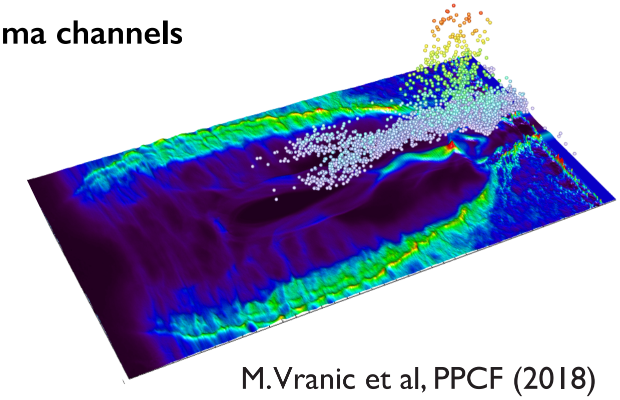
Can we produce an electron-positron plasma with enough particles to be relevant for laboratory astrophysics?

Extreme intensity as a game changer - literature review

New opportunities for particle acceleration

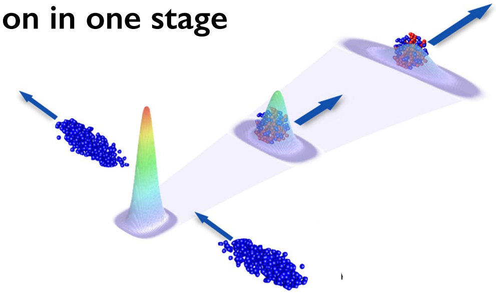
- **Electron acceleration in plasma channels**

B. Quiao eta al, POP (2017)
A. Arefiev et al, POP (2016)
V. Khudik et al, POP (2016)
L. L. Ji et al, PRL (2014)
APS Robinson et al, PRL (2013)
Naseri et al, PRL (2012)
SPD Mangles et al, PRL (2005)
A. Pukhov et al, POP (1999)
M. Jirka et al, in prep.



M. Vranic et al, PPCF (2018)

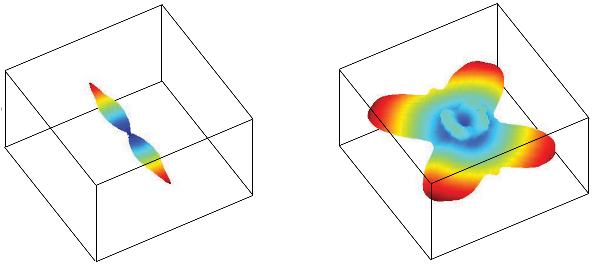
- **Electron-positron production & acceleration in one stage**



M. Vranic et al, SciRep (2018)

Design of tunable high-energy photon sources

N. Lemos, PPCF (2018); F. Albert, POP (2018)
W. Yan, Nat. Phot (2017); Gonoskov, PRX (2017)
A. Arefiev et al, PRL (2016); J. L. Martins et al, PPCF (2016)
K. Ta Phuoc, NatPhot (2012); Z. Gong, PRE (2017)
E. Esarey PRA (1992); S. Kneip, PRL (2009)



T. Grismayer et al, POP (2016)

Extreme intensity as a game changer - literature review

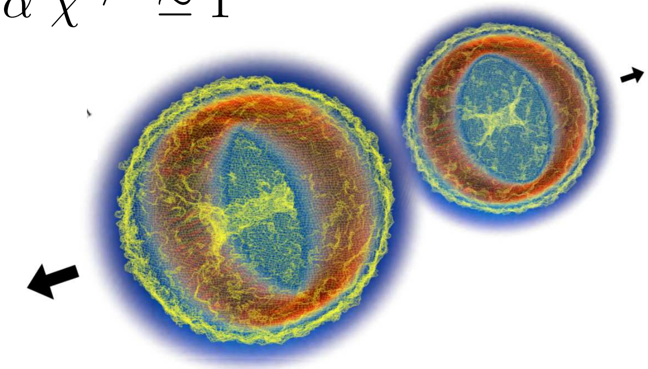
TÉCNICO LISBOA

Study of the classical and quantum radiation reaction

M. Tamburini, NIMR (2011); Neitz & DiPiazza, PRL (2013); Ilderton and Torgrimsson, PLB (2013); Zhidkov, PRSTAB (2014); M. Vranic, PRL (2014); T. Blackburn, PRL (2014); S. Yoffee, NJP (2015); M. Vranic, CPC (2016); M. Vranic, NJP (2016); C. Ridgers, JPP (2017): F. Neil, PRE (2017) and PPCF(2018); J. Cole PRX (2018); K. Poder PRX(2018);

Probing the onset of non-pertubative QED

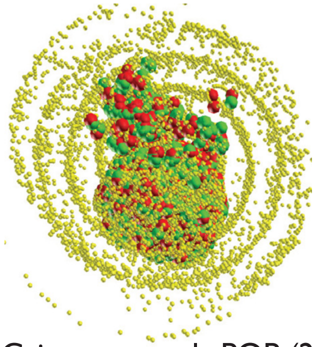
$$\alpha\ \chi^{2/3} \simeq 1$$



V. Yakimenko et al, arXiv:1807.09271
F. Del Gaudio et al, PRAB 22, 023402(2019)
C. Baumann et al., ArXiv:1811.03990

Evolution of self-generated e+e- plasmas

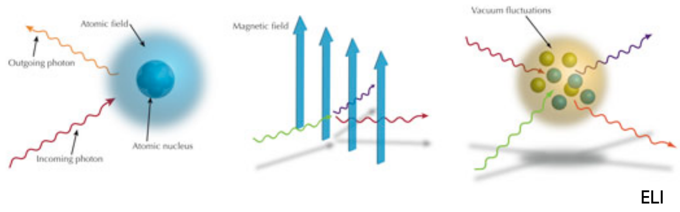
T. Bell and J. Kirk, PRL (2010)
A. Fedotov, PRL (2010)
S. Bulanov, PRL (2010)
E. Nerush, PRL (2011)
N. Elkina, PRSTAB (2011)
C. Ridgers, PRL (2012)
V. F. Bashmakov, POP (2015)
A. Gonoskov, PRE (2015)
M. Jirka, PRE (2016)
T. Grismayer, POP (2016)
X. Ribeyre et al, PRE(2016)
M. Tamburini, Sci Rep (2017)
M. Vranic, PPCF (2017)
X. Zhu, NComm (2017)
T. Grismayer, PRE (2017)
M. Lobet et al, PRAB (2017)
I. Kostyukov et al, PAST (2018)



T. Grismayer et al, POP (2016)

Contents

Regimes of laser interaction with a plasma



QED Photons interaction

Near-future facilities

- Pulse duration : 20-150 fs
- Intensity ~10^{21} - 10^{25} W/cm^2
- Extreme acceleration regime

New facilities open possibilities to explore exotic physics.

Normalised vector potential a_0

- non relativistic
  $a_0 << 1$ $I \sim 10^{18}$ W/cm^2
- weakly nonlinear, relativistic
  $a_0 \sim 1$ $I \sim 10^{18}$ W/cm^2
- relativistic, nonlinear
  $a_0 \sim 10$ $I \sim 10^{20}$ W/cm^2
- quantum
  $a_0 \sim 1000$ $I \sim 10^{24}$W/cm^2

$$a_0 = \frac{eA}{mc^2}$$

$$a_0 \approx 0.8 \times 10^{-9} \sqrt{I \left[\frac{\mathrm{W}}{\mathrm{cm}^2}\right]}\ \lambda[\mu\mathrm{m}]$$

The onset of quantum effects is controlled by χ

Highest value of χ is obtained for relativistic particles counter-propagating with a laser

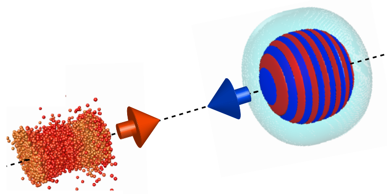
Unity is achieved when particle feels E=Es in its own rest frame

$$E_s = \frac{m^2c^3}{e\hbar} \qquad \chi = \frac{\sqrt{(p_\mu F^{\mu\nu})^2}}{E_s\ mc} \qquad \chi_\gamma = \frac{\sqrt{(k_\mu F^{\mu\nu})^2}}{E_s\ mc}$$

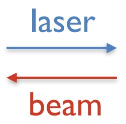
$$\chi_e = \frac{1}{E_s}\sqrt{\left(\gamma\vec{E} + \frac{\vec{p}}{mc}\times\vec{B}\right)^2 - \left(\frac{\vec{p}}{mc}\cdot\vec{E}\right)^2}$$

Classical: $\chi \ll 1$

QED: $\chi \simeq 1$



Counter-propagation

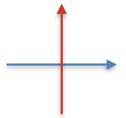


$$\chi \approx 2\ \gamma_0 a_0 \times 2 \times 10^{-6}$$

Co-propagation

$$\chi \approx \frac{a_0}{2\gamma_0} \times 2 \times 10^{-6}$$

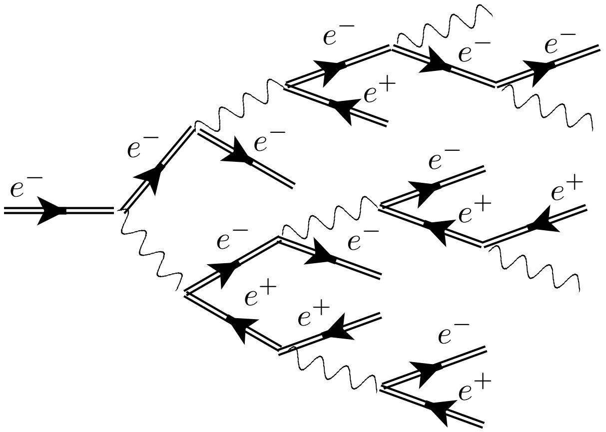
Interaction at 90 deg.



$$\chi \approx \gamma_0 a_0 \times 2 \times 10^{-6}$$

QED cascade

$\chi \gtrsim 1$



Contents

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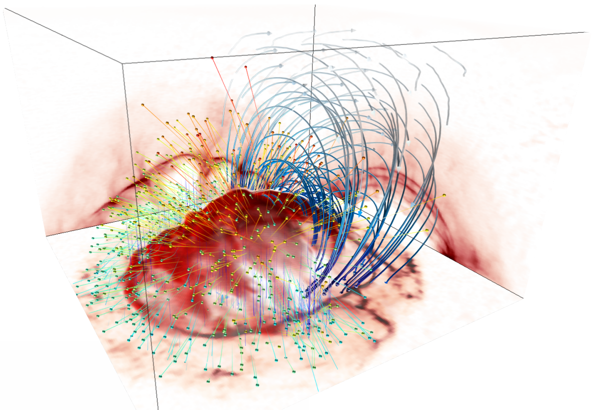
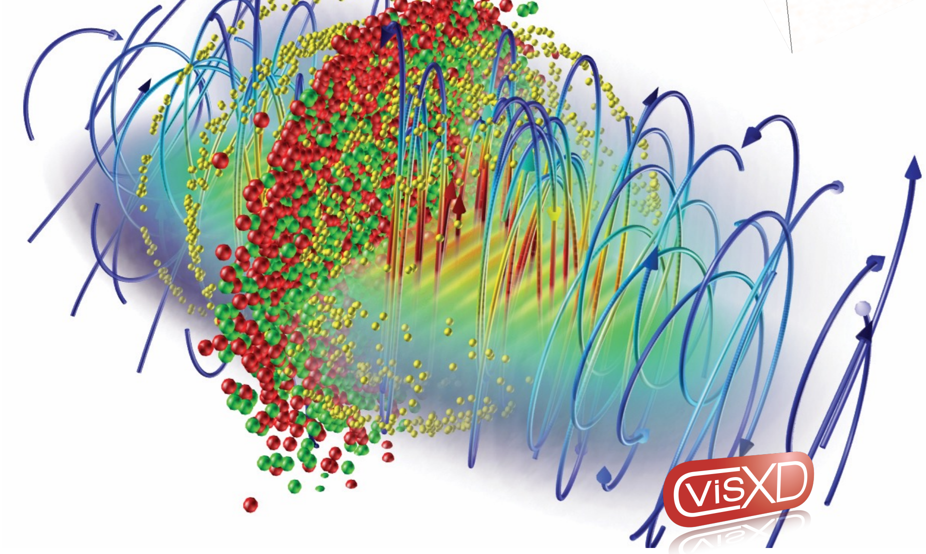
OSIRIS 4.0

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
- SIMD hardware optimized
- Parallel I/O
- **Dynamic Load Balancing**
- **QED module**
- **Particle merging**
- GPGPU & Xeon Phi support

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Towards the exascale

TOP500 List - June 2018; OSIRIS is supported by 9 out of top 10 machines

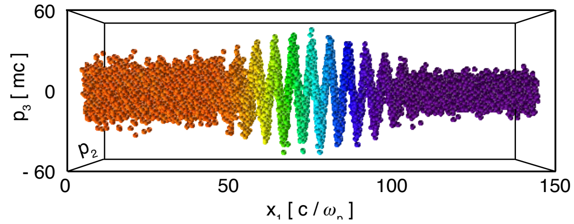
Rank	System	Cores	R_{max} [TFlop/s]	R_{peak} [TFlop/s]	Power [kW]	OSIRIS support
1	Summit, United States	2282544	122300.0	187,659.3	8806	Full (CUDA)
2	Sunway TaihuLight,China	10649600	93014.6	125435.9	15371	No
3	Sierra, United States	1572480	71610.0	119193.6	-	Full (CUDA)
4	Tianhe-2 (MilkyWay-2), China	3120000	33862.7	54902.4	17808	Full (KNC)
5	ABCI, Japan	391680	19880.0	32576.6	1649	Full (CUDA)
6	Piz Daint, Switzerland	361760	19590.0	25326.3	2272	Full (CUDA)
7	Titan, United States	560640	17590.0	27112.5	8209	Full (CUDA)
8	Sequoia, United States	1572864	17173.2	20132.7	7890	Full (QPX)
9	Trinity, United States	979968	14137.3	43902.6	3844	Full (KNL)
10	Cori, United States	622336	14014.7	27880.7	3939	Full (KNL)

What developments are necessary?

Adding classical radiation reaction

- Modelling electron beam slowdown in scattering configurations
- Modeling other configurations where only a fraction of electrons may be subject to RR but where this can alter qualitative behaviour

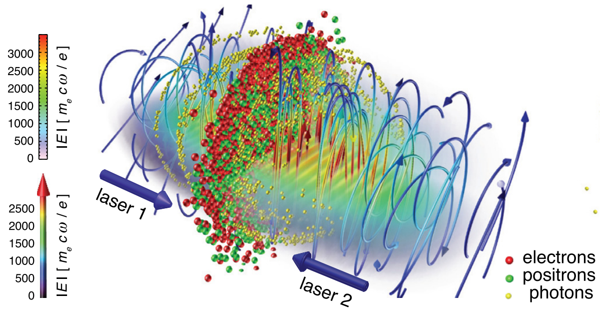
M.Vranic, PRL (2014); M.Vranic, CPC (2016); M.Vranic, PPCF (2018)



Adding quantum processes

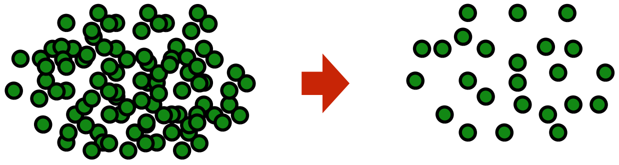
- Modelling the onset of QED, RR from quantum perspective
- Modelling e+e- pair production, and gamma-gamma collisions
- QED cascades, nonlinear regimes where many particles are created and collective plasma dynamics can alter the background fields

M.Vranic, NJP (2016); T. Grismayer, POP (2016); T. Grismayer, PRE (2017); J. L. Martins, PPCF (2016); M.Vranic, PPCF (2017); M.Vranic, SciRep (2018); F. Del Gaudio PRAB (2019)



Adding performance improvements (particle merging, advanced load balancing schemes) + collision module for photons

- Essential for all the configurations with strong QED effects



M.Vranic, CPC (2015); F. Del Gaudio, in preparation

QED loop in OSIRIS

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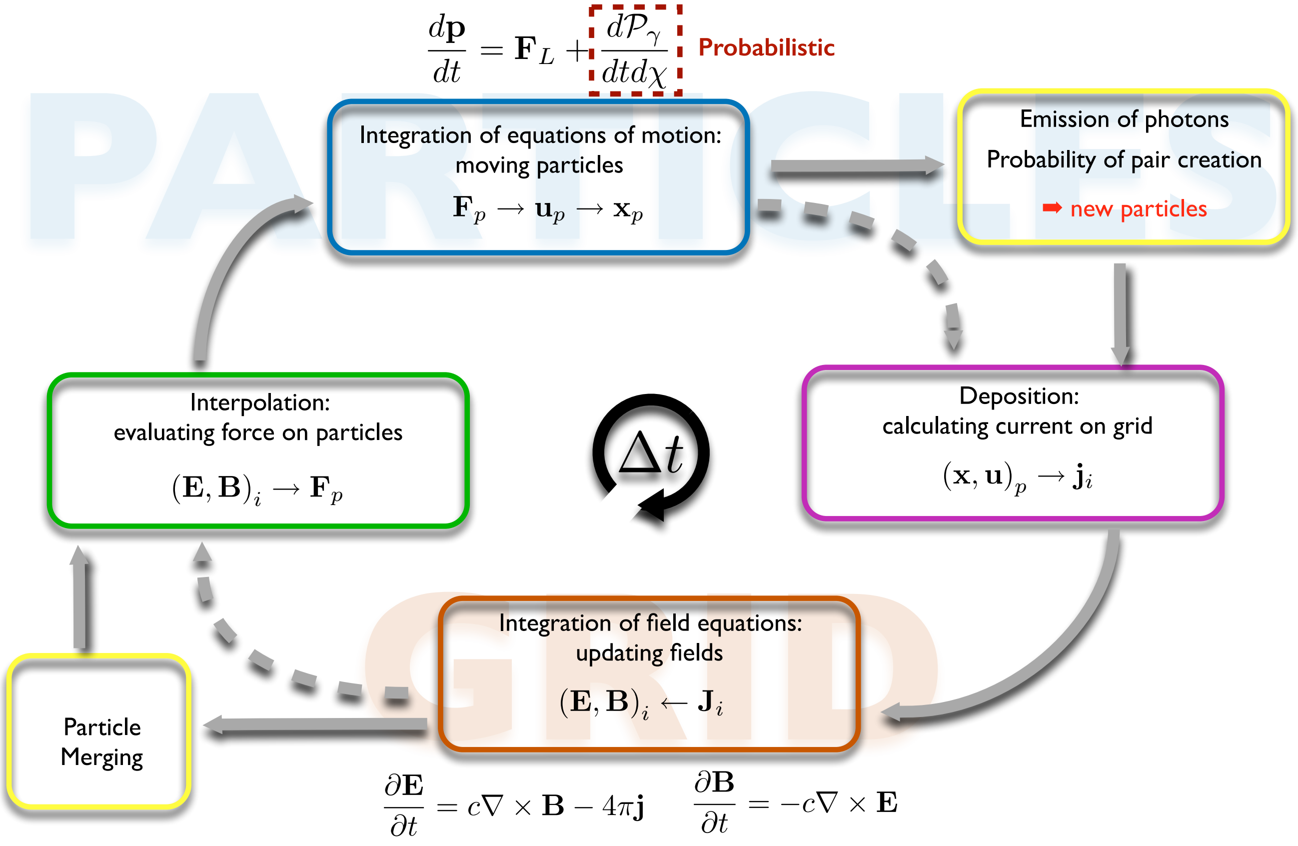
http://plasmasim.physics.ucla.edu/



$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \boxed{\frac{d\mathcal{P}_\gamma}{dt d\chi}}$$ Probabilistic

Integration of equations of motion:
moving particles
$\mathbf{F}_p \to \mathbf{u}_p \to \mathbf{x}_p$

Emission of photons
Probability of pair creation
➡ new particles

Deposition:
calculating current on grid
$(\mathbf{x}, \mathbf{u})_p \to \mathbf{j}_i$

Δt

Integration of field equations:
updating fields
$(\mathbf{E}, \mathbf{B})_i \leftarrow \mathbf{J}_i$

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

Particle
Merging

Interpolation:
evaluating force on particles
$(\mathbf{E}, \mathbf{B})_i \to \mathbf{F}_p$

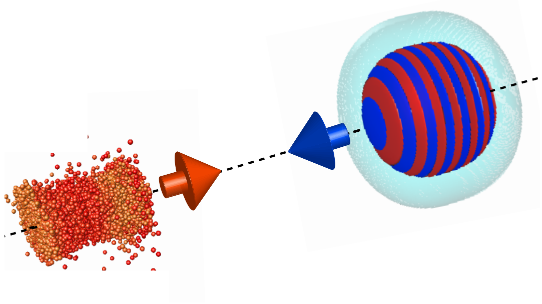
E.N Nerush et al. PRL (2011), C. P. Ridgers et al. , PRL. (2012), N.V. Elkina et al. PRSTAB (2011),
A. Gonoskov et al., PRE (2015), T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

Contents

- **Challenges**
  open questions and directions for the future
- **Regimes of interaction and relevant parameters**
- **Preparing advanced computational tools**
  changes required to tackle the new regimes
- **Positrons from laser-electron beam scattering**
- **Positrons from QED cascades**

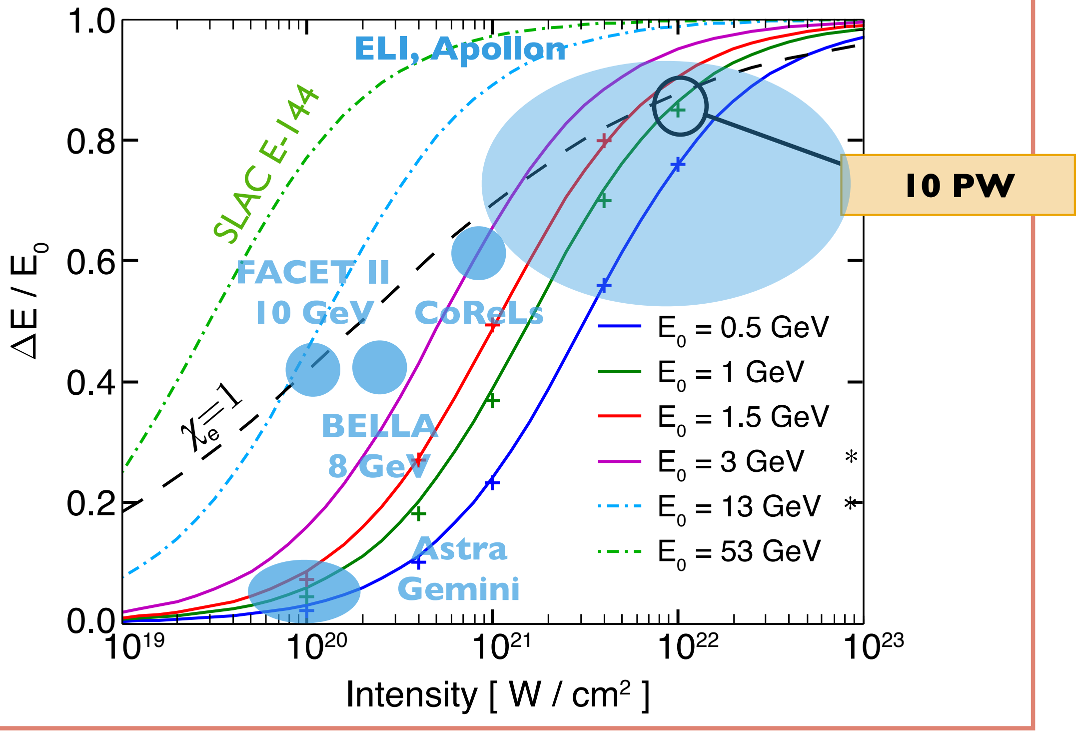
How much energy can be converted to photons in a laser - electron beam scattering?

For highly relativistic beams, most of the energy comes from the electrons (rather than the scattering laser)



$$\chi \sim \xi_e\,[\mathrm{GeV}] \times \frac{a_0}{100}$$

Relative energy loss as a function of electron initial energy and the laser intensity (30 fs lasers)

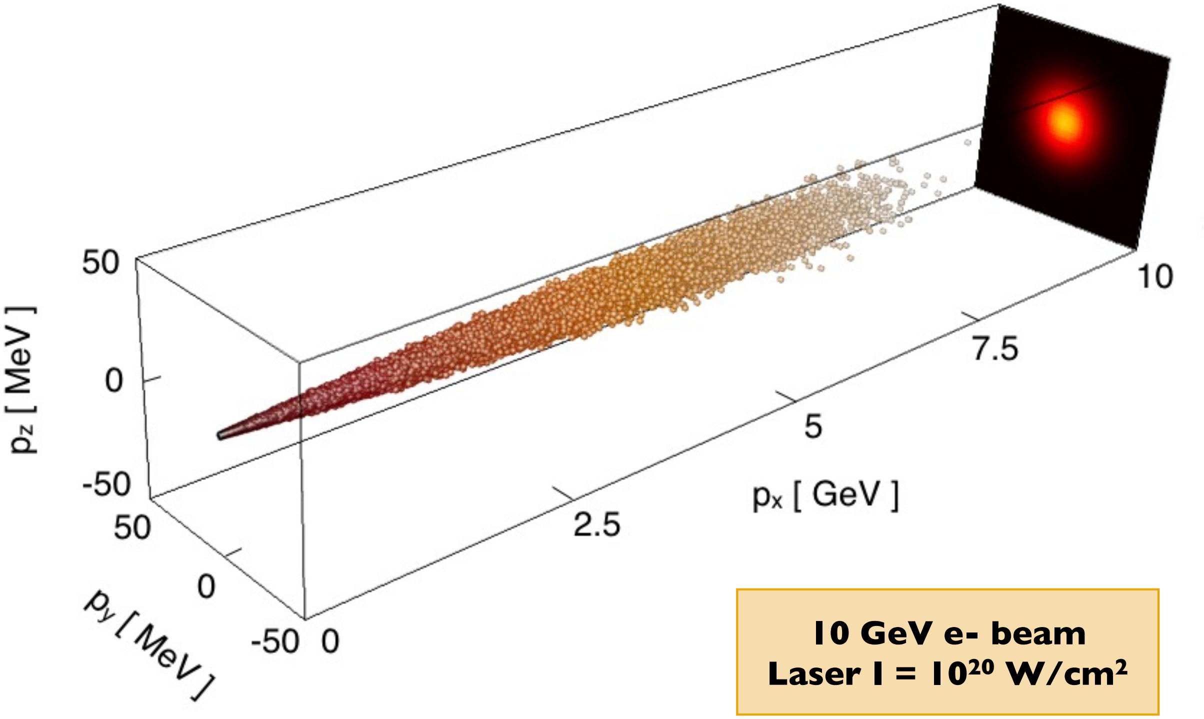


Parameters for SFQED experiment planned at FACET-II

A large amount of beam energy can be converted to high-frequency photons (hard X-rays and Gamma-rays)

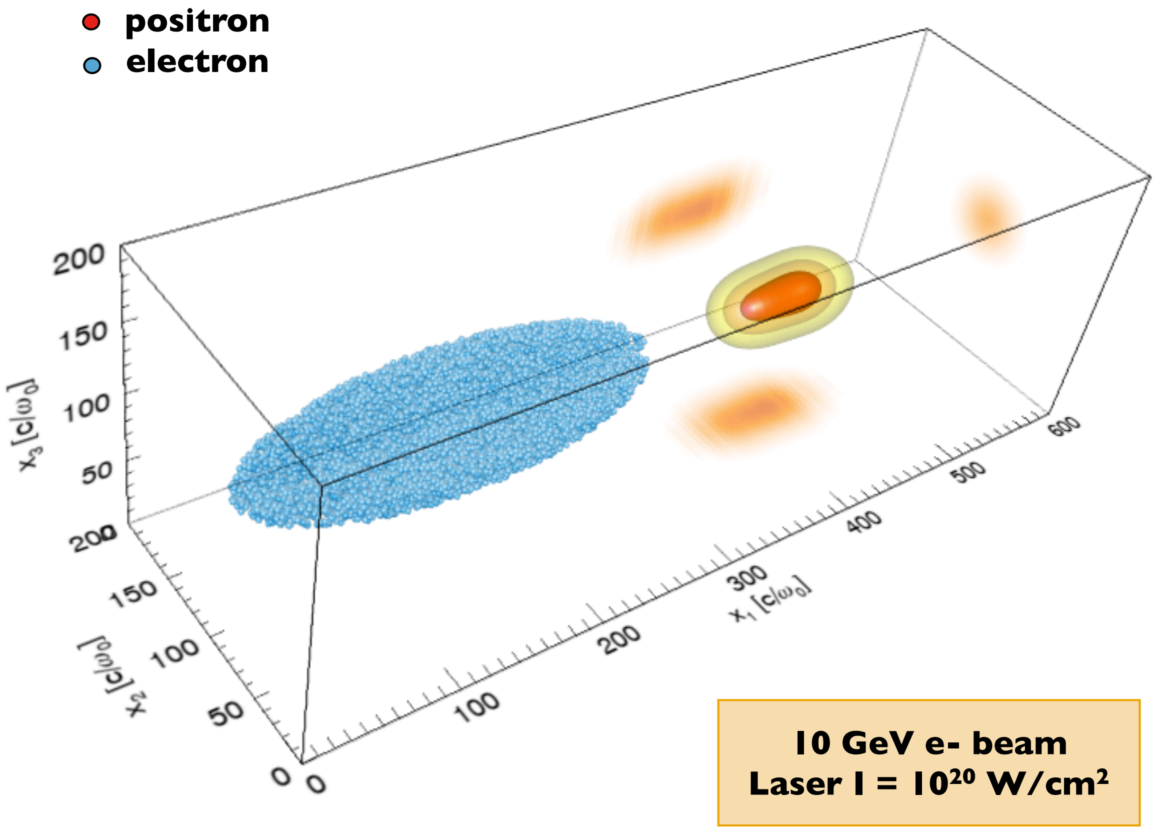
Photon source properties

- divergence < 1 mrad
- tunable energy range (cutoff > 1 GeV)
- possible to attain very high energies (~10 GeV)

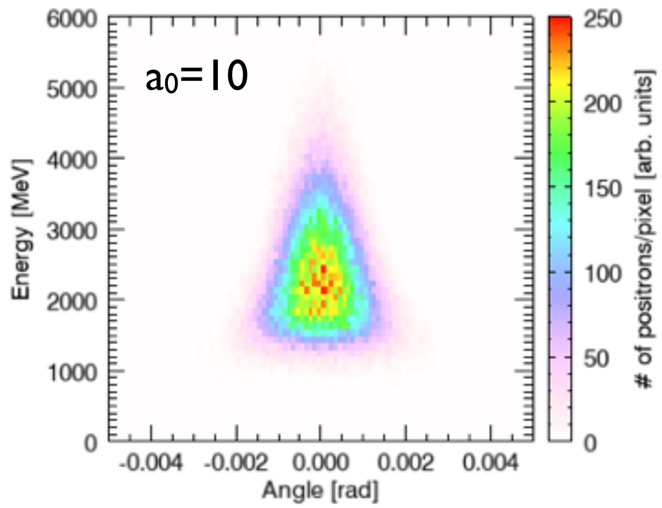


10 GeV e- beam
Laser I = 10^{20} W/cm^2

A fraction of radiated photons decays into electron-positron pairs



Positrons: energy vs angle

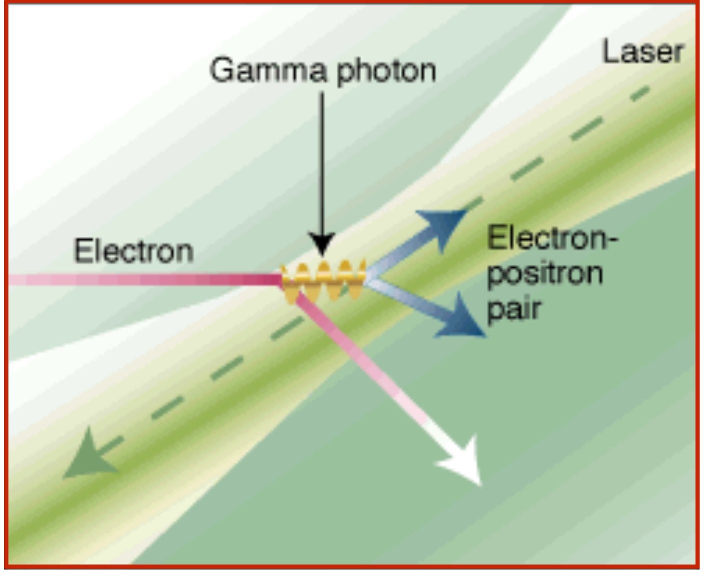


10 GeV e- beam
Laser I = 10^{20} W/cm^2

1 nC electron beam gives
~ 0.2 pC of positrons

SLAC E-144 experiment, BW process*

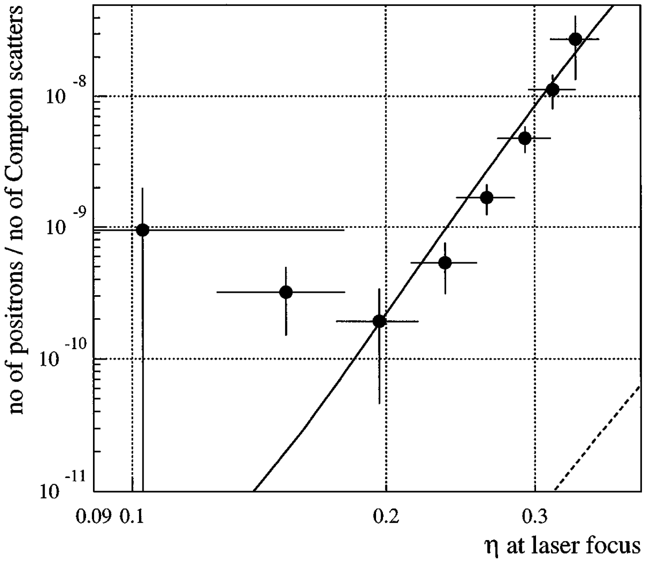
Setup



Laser: 1.6 ps, 1 um, I = 10^{18} W/cm^2

Electron energy: 46.6 GeV

~ 100 positrons



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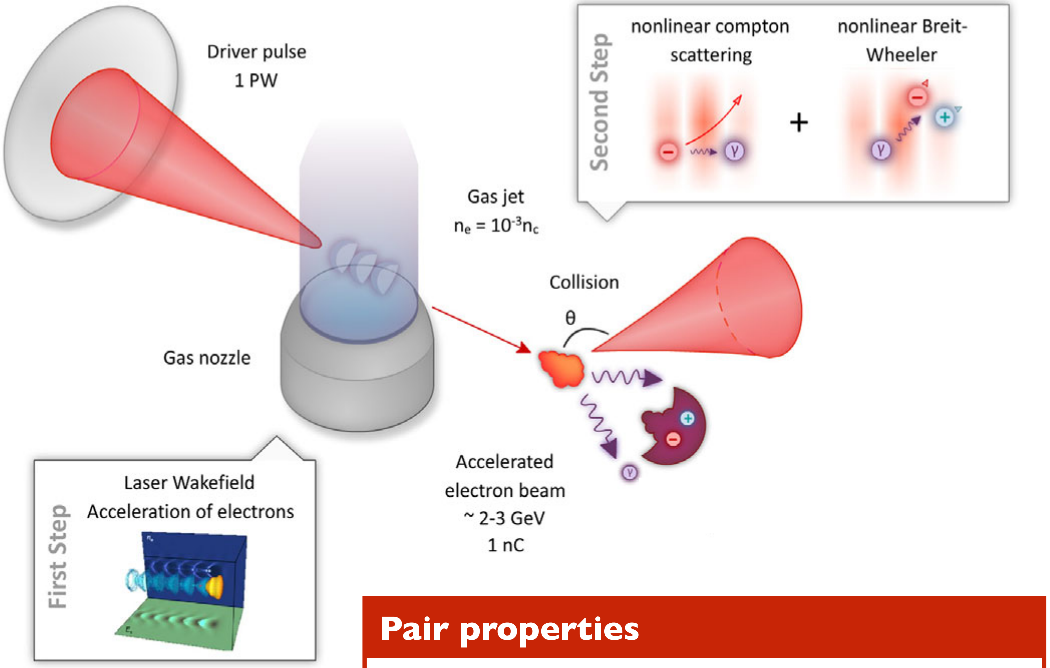
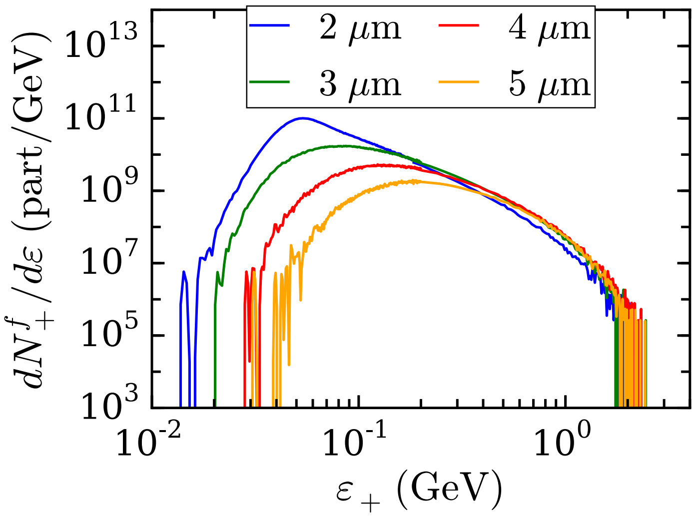
* D.L. Burke et. al., Phys. Rev. Lett.. 79, 1626-1629 (1997)

One pair per electron in a head-on collision



2-3 GeV e- beam, 1 nC
Laser of 15 fs
I = 10^{22}-10^{23} W/cm^2

Positron spectrum

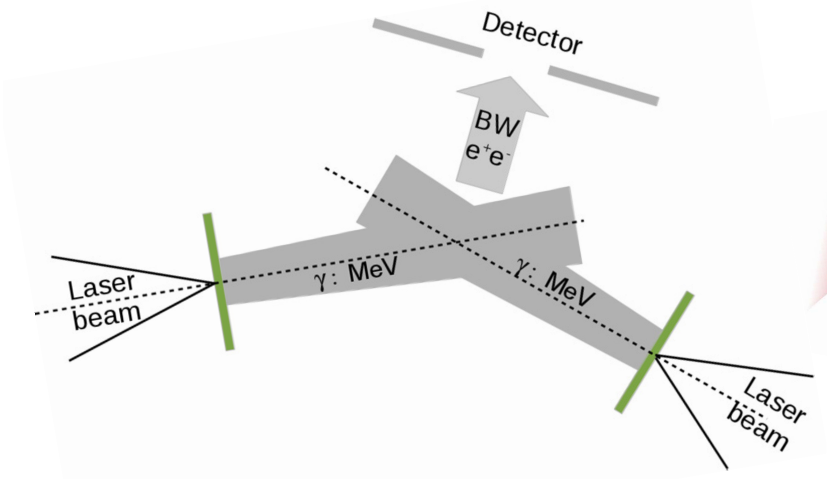


Pair properties

~10^{10} particles, max. energy 2 GeV

M. Lobet et al., PRAB 20, 043401(2017)

Configurations involving solid targets or cones

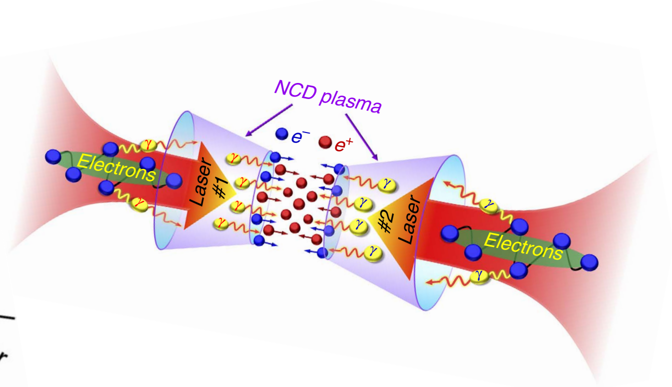


150 fs, I = 10^{20}-10^{21} W/cm^2

Breit-Wheeler pairs

~10^4 positrons, ~MeV energy

X. Ribeyre et al., PRE 93, 013201 (2016)



3.3 fs, I = 3x10^{22} W/cm^2

Breit-Wheeler pairs

~10^{11} e+ below 2 GeV

Zhu et. al., Nat. Commun 7,13686 (2016)

Bethe-Heitler pairs

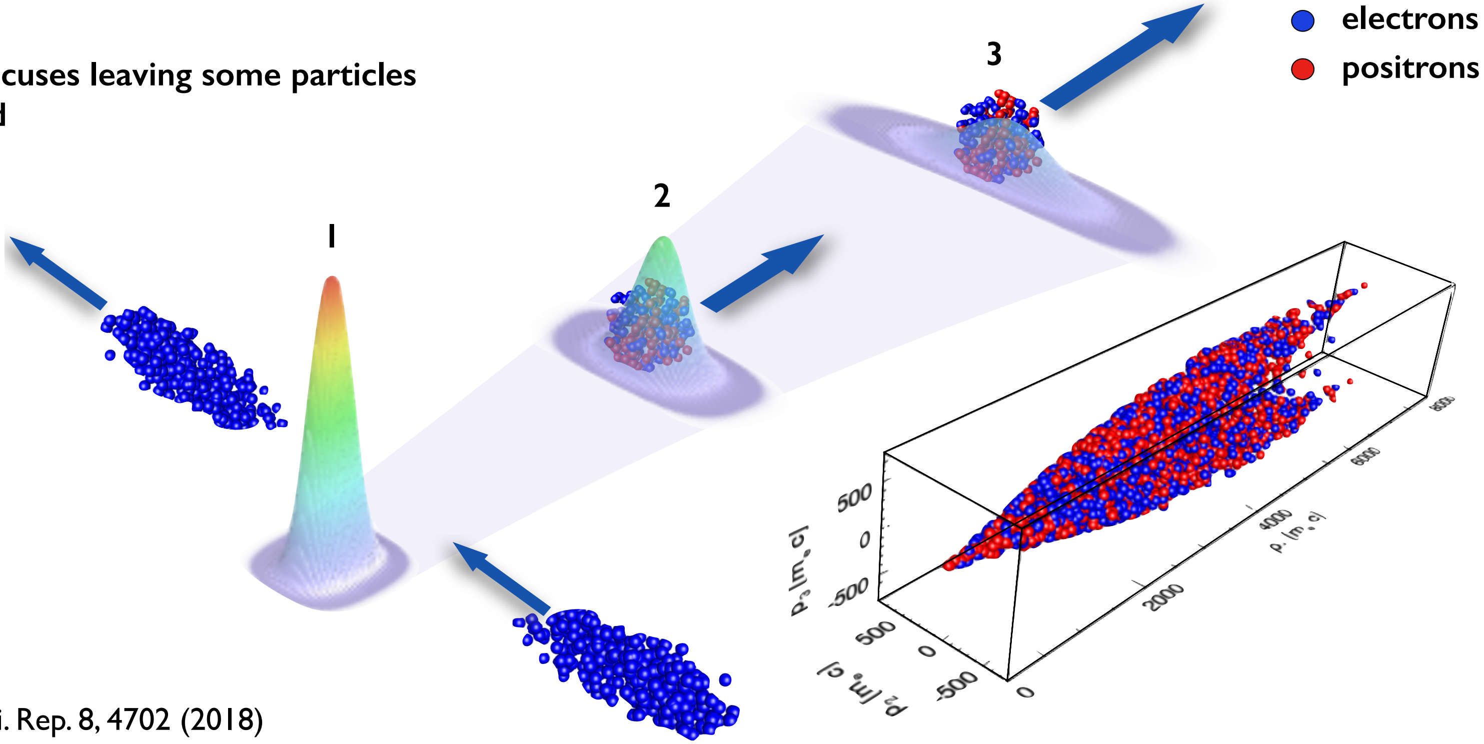
G. Sarri et al., Nat. Comm., 6, 6747 (2015)

H. Chen, F. Fiuza, A. Link et al., PRL, 114, 21 (2015)

Creating an e+e- beam from laser - e- scattering at 90°

1. LWFA electrons collide with the laser; pairs are produced in the highest field region
2. E+e- beam is accelerated by the laser in vacuum
3. Laser defocuses leaving some particles accelerated

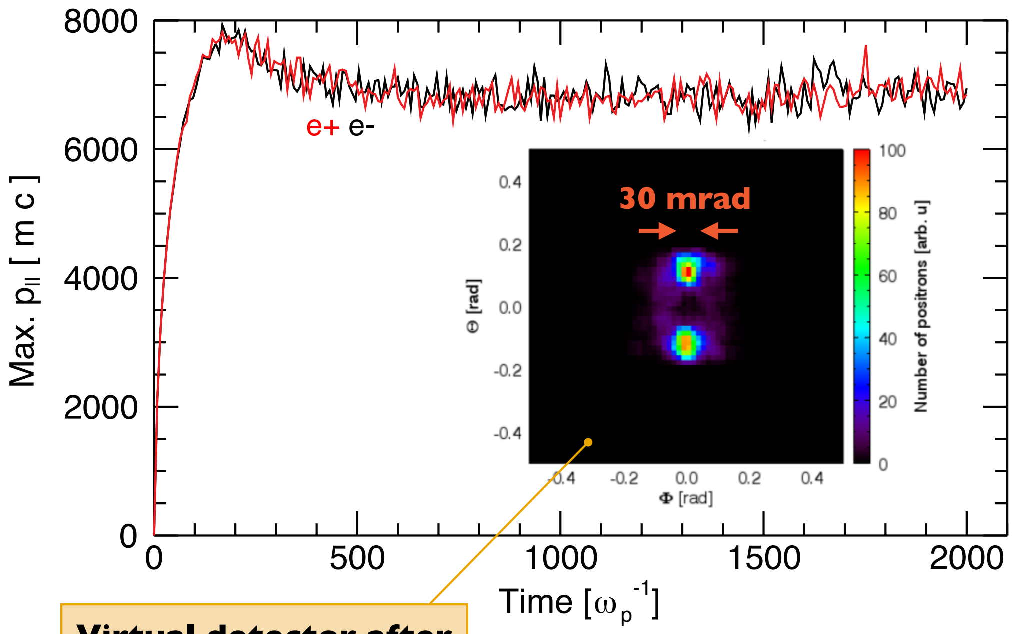
Pair creation and acceleration are decoupled!



M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

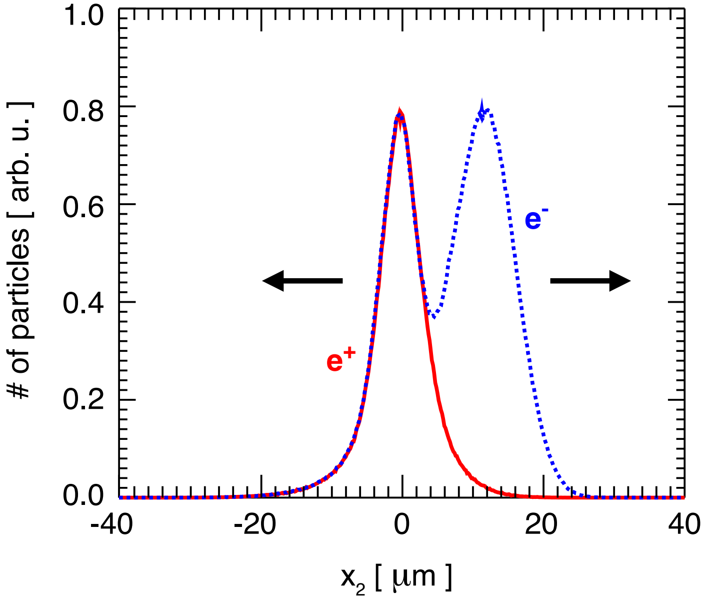
Final e+e- beam can be collected separately from initial electrons

~ 30 mrad beam divergence on detector for laser a_0=600, 50% e+ and 50% e-



Virtual detector after 200 um propagation

For 2 GeV e- beam, you can get one pair per e-

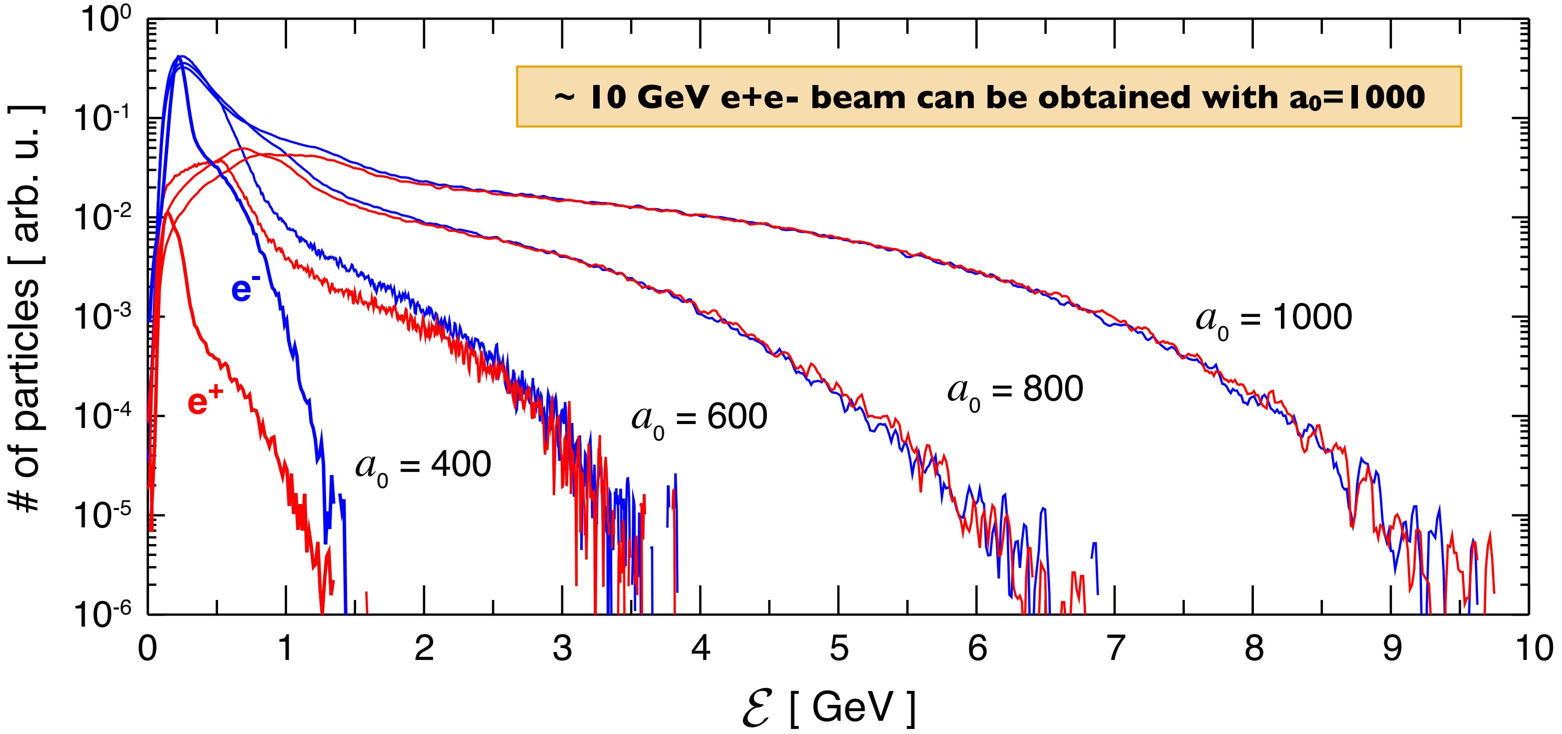


M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

At energies > 2 GeV, e- and e+ have equal spectra

50 % of the positrons are above 2 GeV for a_0=1000

E+e- spectra at 50 um distance from focal plane for W_0=3.2 um

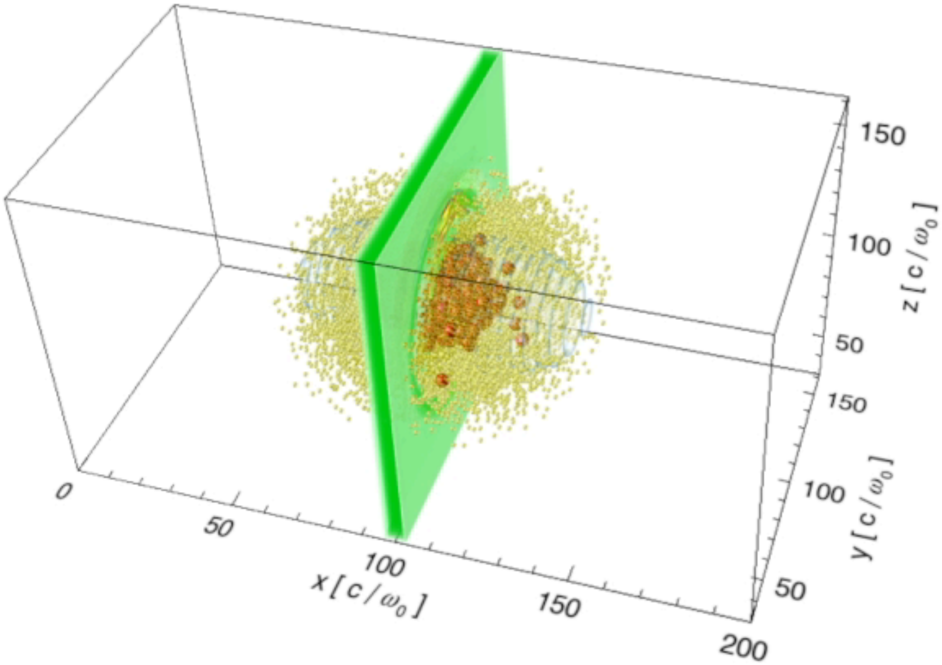


~ 10 GeV e+e- beam can be obtained with a_0=1000

M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

Contents

Positrons from a hydrogen ice target



Target parameters

initial n =10 nc
1 um thickness

Laser parameters

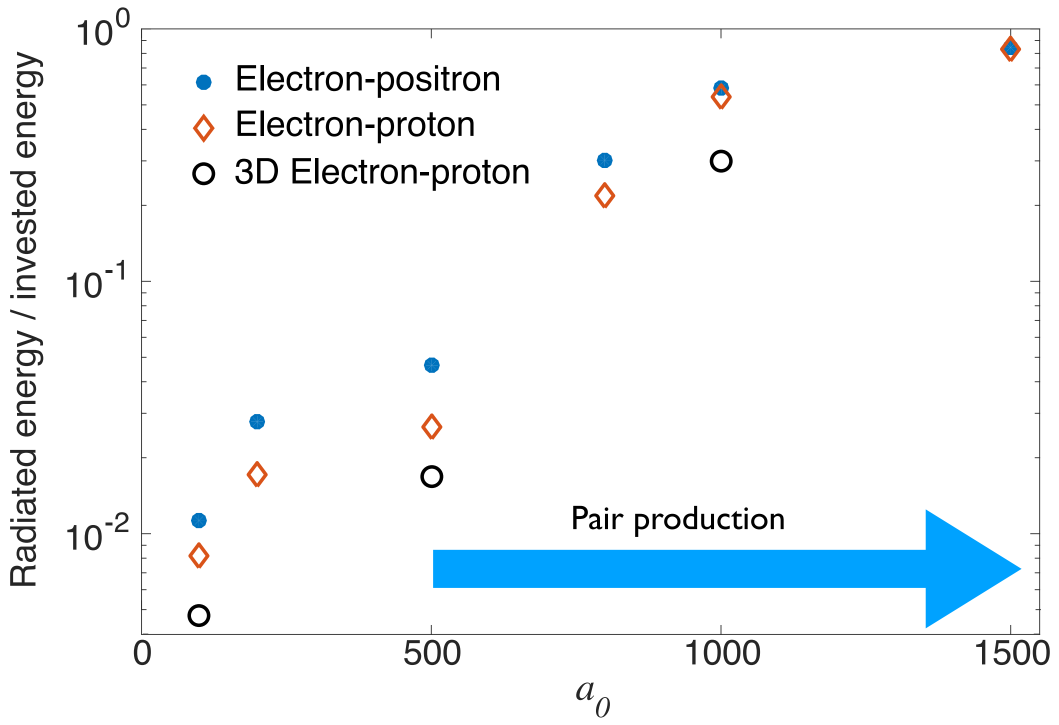
$I \sim 10^{24}$ W/cm^2
30 fs, 1 um wavelength

M.Vranic et al., POP submitted (2019)

With currently available targets, we could transfer more than 50% of energy to gamma-rays

We get ~ a pair per interacting particle at a0=500

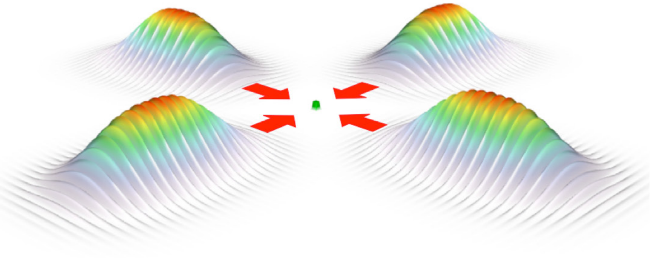
Conversion to gamma-rays in a 10 nc, 1 um thick target



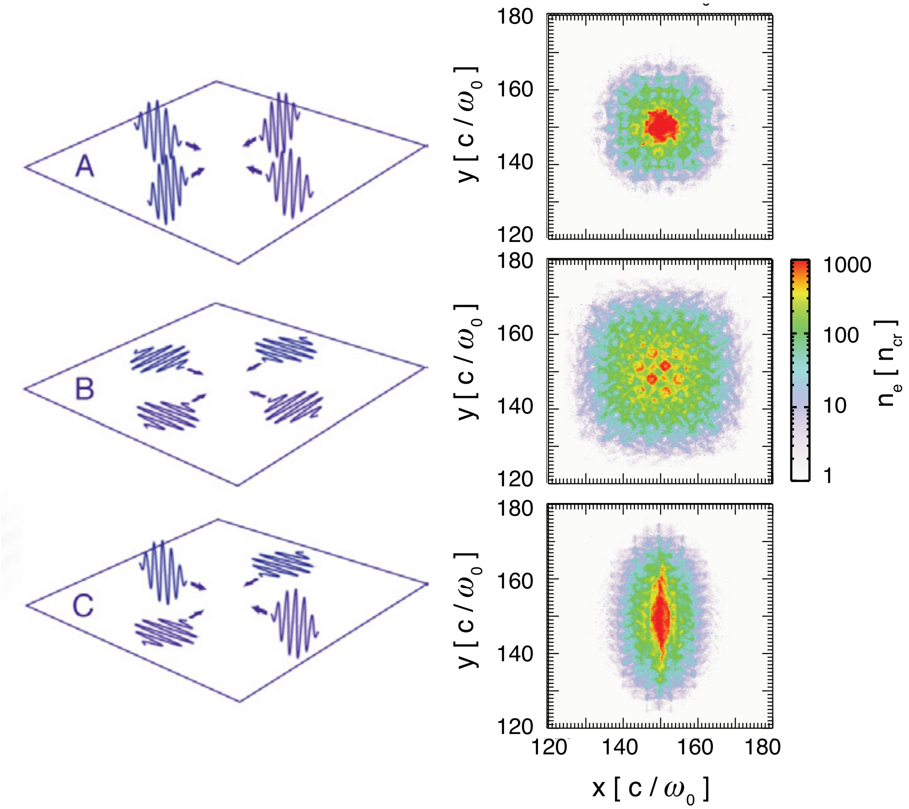
* M.Vranic et al., POP submitted (2019)

Optical traps can confine e+e- pairs

Different polarisation combinations yield different microstructures



M. Vranic et al., PPCF 59, 014040 (2017)



Parameters needed to start creating ~ one e+ per e-

Facility	Electron energy	Laser intensity required for $\chi \simeq 1$
FACET	10 GeV	10^{20} W/cm^2
FACET*	20 GeV	2 x 10^{19} W/cm^2
AWAKE	50 GeV	4 x 10^{18} W/cm^2
Two-laser cascade		3 x 10^{23} W/cm^2

Conclusions

TÉCNICO
LISBOA

- **It is essential to include additional physics to PIC codes for modelling the next generation of laser experiments.**

  Performance developments are also necessary to tackle the new computational challenges associated with exponential growth of the number of particles, intrinsic load imbalance etc.

- **Classical vs. quantum radiation reaction can be studied in future experiments. Especially interesting is crossing the quantum threshold from radiation-dominated regime.**

- **Scattering relativistic electrons off a laser at 90 degrees of incidence allows to both create and accelerate a neutral e+e- beam in a single stage.**

- **QED cascades can create abundant plasma and lead to a very efficient energy transfer from the laser into gamma-rays.**