QED cascades and pair plasma dynamics in a converging E-dipole laser wave

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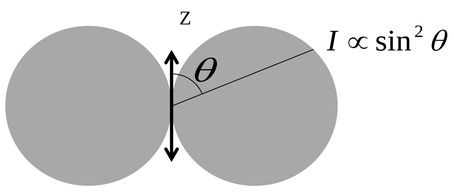
To obtain extreme laser fields, the XCELS project proposes focusing 12 multipetawatt beams that can be modeled by a converging E-dipole wave. It is known that QED cascades initiated in the high field region may strongly influence electromagnetic field structures, thus limiting attainable laser intensities. First, we analyze the linear stage, when QED cascades develop in the given field structure, which is realized when the back reaction of the produced pair plasmas can be neglected. At this stage, the number of pairs and gamma photons grows exponentially. We determine the threshold of vacuum breakdown which results from balance of two processes: pair production and convective particle losses in inhomogeneous electromagnetic fields. A detailed look into the family of particle trajectories is given and the spectrum of emitted hard photon is analyzed. Taking into account good directivity of radiation pattern and accessibility of GeV range of photon energy we propose a concept of ultra-bright gamma-ray source based on interaction of generated electron-positron plasma with tightly focused laser field. For 40 PW peak power 15 fs laser pulse the maximum flux of photons with energy greater 1 GeV is 5 10^{23} photons per second within cone half-angle of 0.05 radian. With further increase of pair plasma density the nonlinear stage, when pairs are generated self-consistently, comes into play. By supercomputer modeling we study in details plasma-field structures generated during the interaction of a converging E-dipole wave with a target, particularly their evolution at the transient stage towards the quasistationary regime.

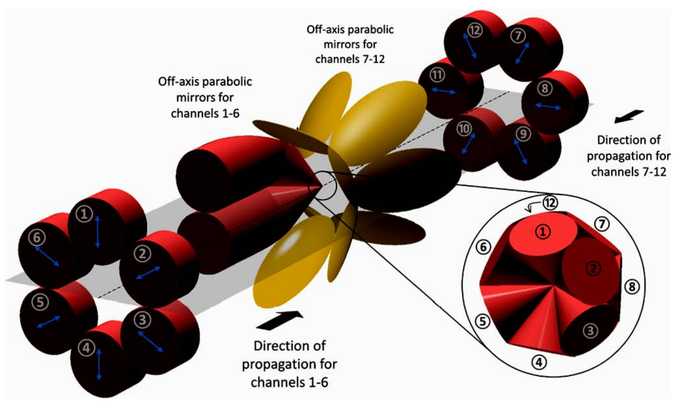
E-dipole wave

$$\mathbf{Z} = \mathbf{z}_0 \frac{d}{R}\left[g(t+R/c) - g(t-R/c)\right]$$

$$\mathbf{E} = -\nabla\times\nabla\times\mathbf{Z}, \quad \mathbf{B} = -\frac{1}{c^2}\nabla\times\dot{\mathbf{Z}}$$

$$g(\tau) = e^{-(\tau^2/D^2)\ln 4}\sin(\omega\tau)$$





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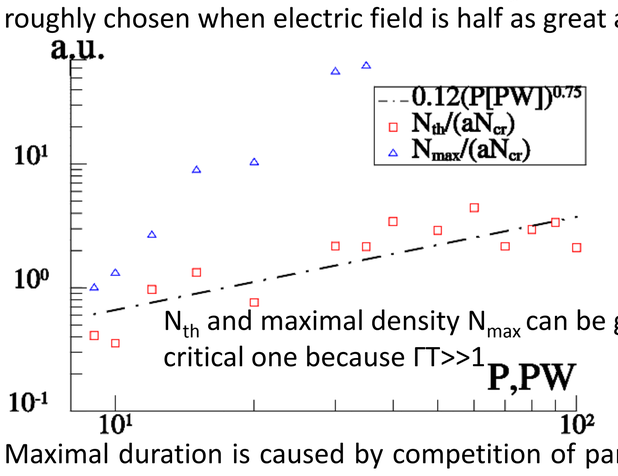
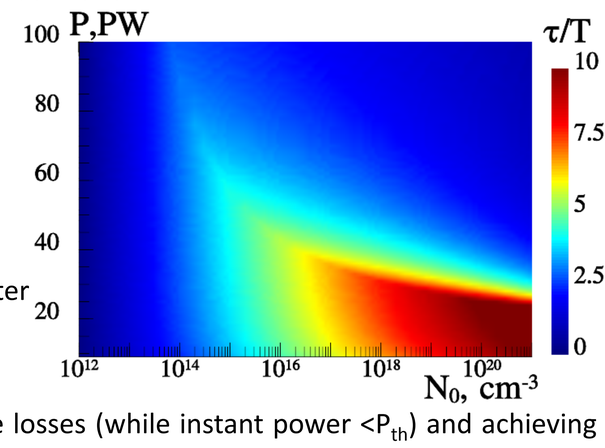
Converging E-dipole pulse

Linear regime of laser-plasma interaction (QED cascade develops in a given field structure) ends when plasma density becomes near critical (aN_{cr}). Threshold plasma density N_{th} of nonlinear regime is roughly chosen when electric field is half as great as vacuum one.

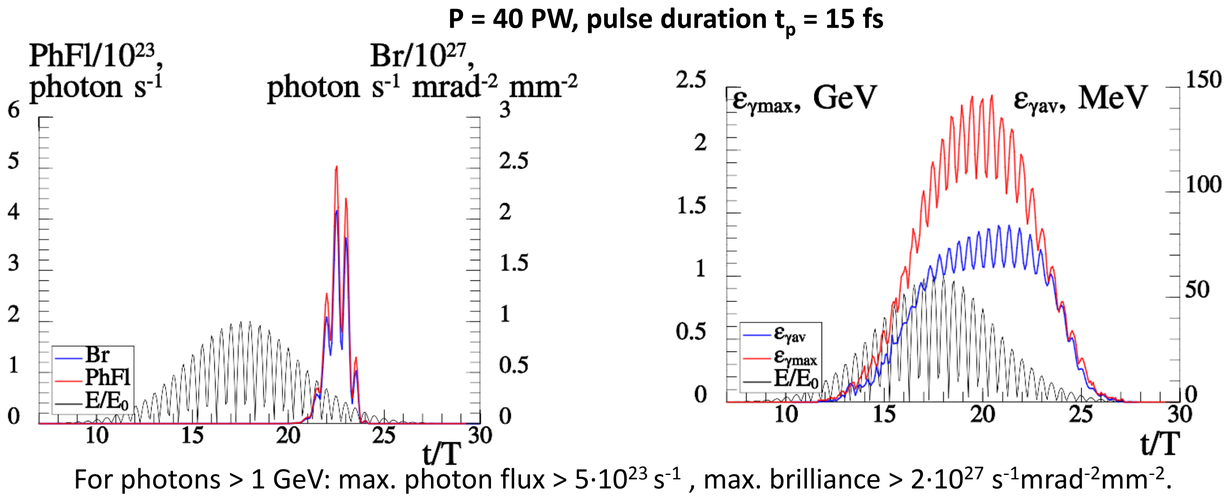


N_{th} and maximal density N_{max} can be greater critical one because ΓT>>1



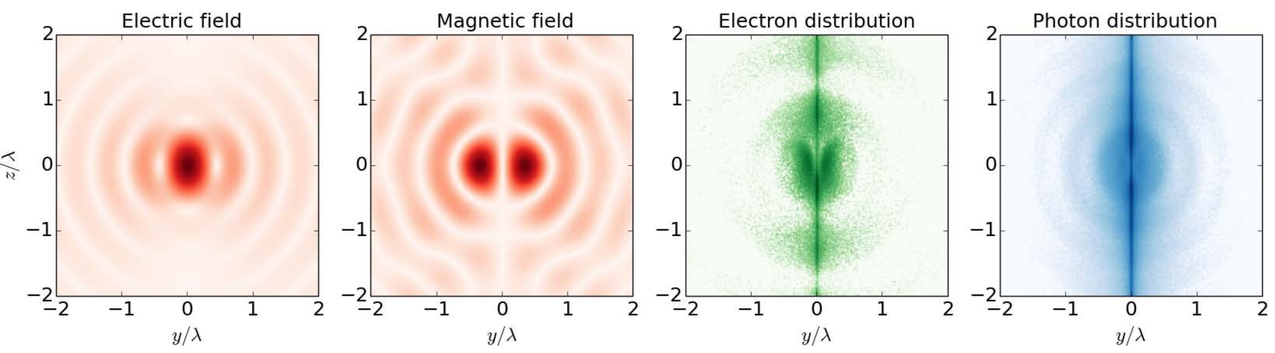
Maximal duration is caused by competition of particle losses (while instant power <P_{th}) and achieving of critical density due to cascade growth.

3D PIC simulation for target density $N_0=10^{16}$ cm^{-3} and pulse parameters feasible on XCELS: P = 40 PW, pulse duration t_p = 15 fs

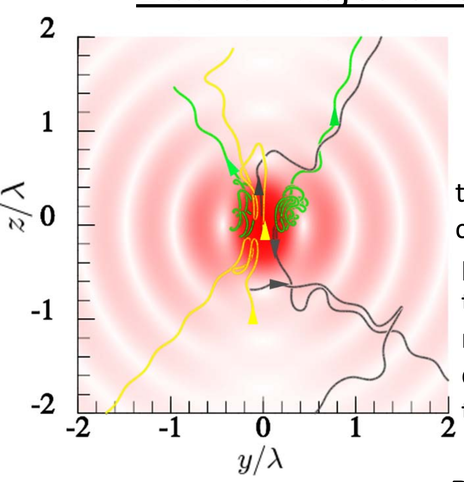


For photons > 1 GeV: max. photon flux > $5\cdot10^{23}$ s^{-1} , max. brilliance > $2\cdot10^{27}$ $s^{-1}mrad^{-2}mm^{-2}$.
Total photon number with energy >100 MeV is $1.4\cdot10^{11}$ and $1.5\cdot10^{9}$ with energy >1GeV.
Duration of gamma ray pulse is 1.5T

Structure of QED cascade in a standing E-dipole wave



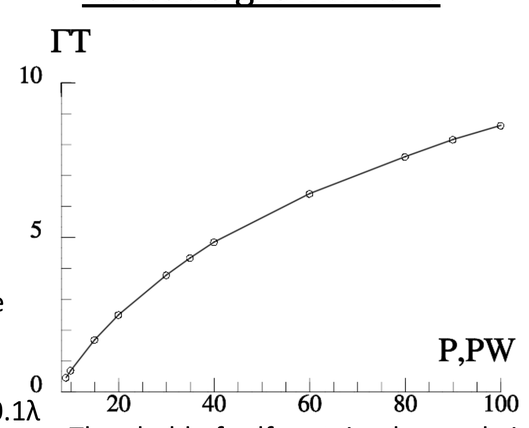
Electron trajectories



Electrons:
- trapped (green)
- pulled (yellow)
- runaway (grey)

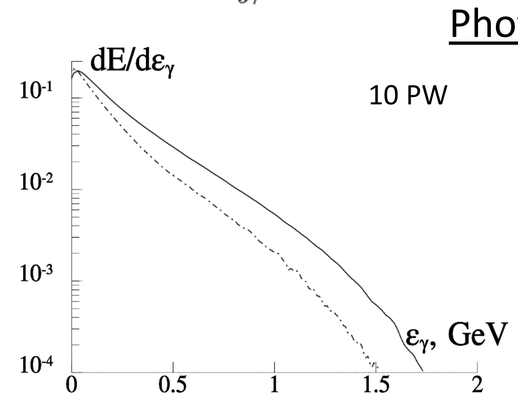
trapped trajectories correspond to ART pulled and runaway trajectories form the most dense particle distribution with thickness less than 0.1λ

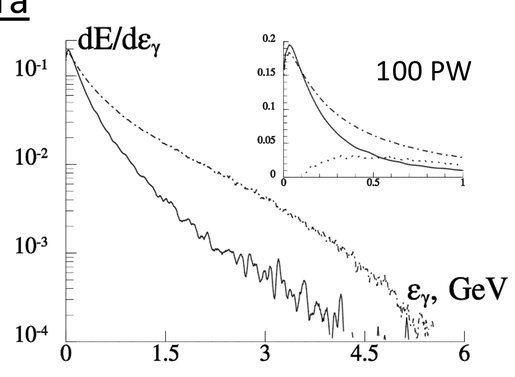
Cascade growth rate



Threshold of self-sustained cascade is about P_{th}=8PW

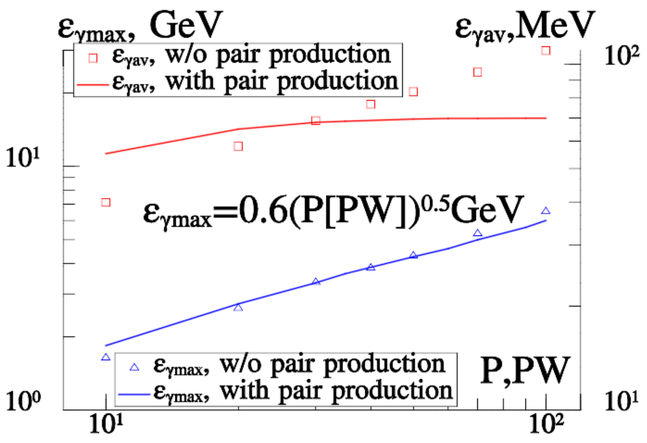
Photon spectra





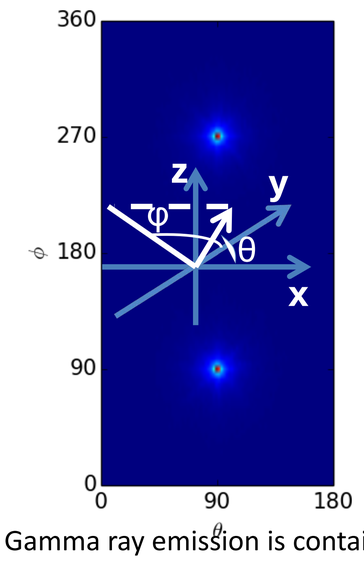
Dash-dotted line – spectra without cascade, solid line – spectra with cascade, (in the inset) dotted line – difference between these spectra, maximum corresponds to maximum probability of photon decay

Cascade increases number of high energy photon for power < 30 PW and decreases it for power > 30 PW



Maximal photon energy proportional to $P^{0.5}$

Radiation pattern

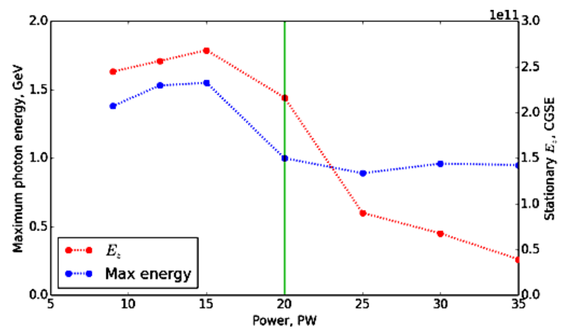


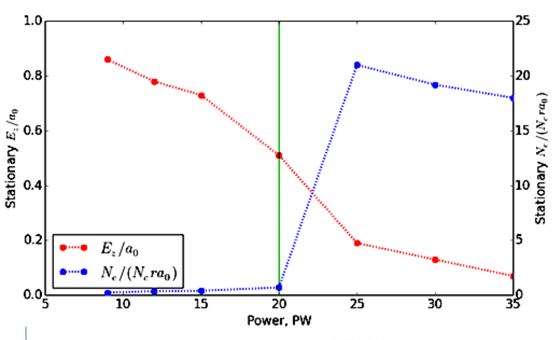
Gamma ray emission is contained within a cone half-angle 0.05rad

Quasystationary regime

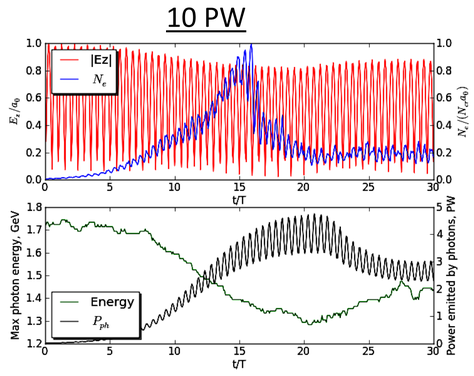
2 regimes, threshold ~ 20PW

1. Cascade structure remains the same, but amplitude is lower, $N_e < N_{cr}$
2. Cascade structure changes significantly, $N_e > N_{cr}$

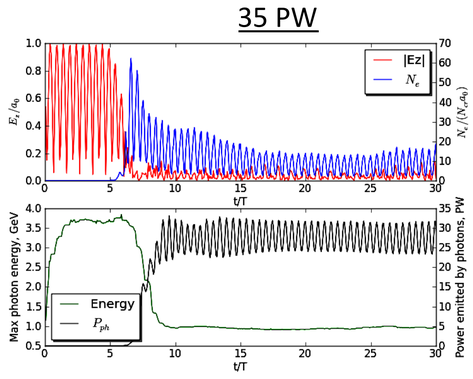


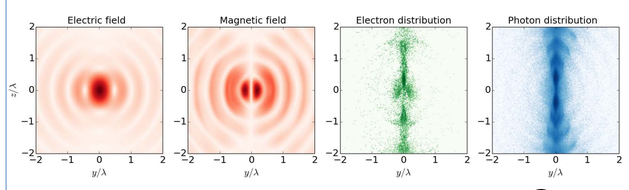


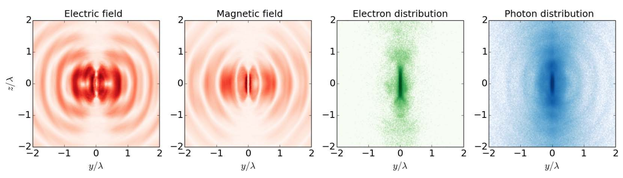
10 PW



35 PW







Conclusions

- We studied the structure of linear stage of QED cascade in a standing E-dipole wave.
- Particles trajectories and the spectrum of emitted hard photon are analyzed. It is shown that maximal photon energy is proportional to $P^{0.5}$ and for 100 PW scales up to 6 GeV
- For 40 PW 15 fs laser pulse the following characteristics of the gamma ray source can be obtained. For photons > 1 GeV max. photon flux > $5\cdot10^{23}$ s^{-1} , max. brilliance > $2\cdot10^{27}$ $s^{-1}mrad^{-2}mm^{-2}$, duration of gamma ray pulse is 1.5T
- We demonstrated formation of field-plasma structures and showed that there are two different quasistationary regimes.