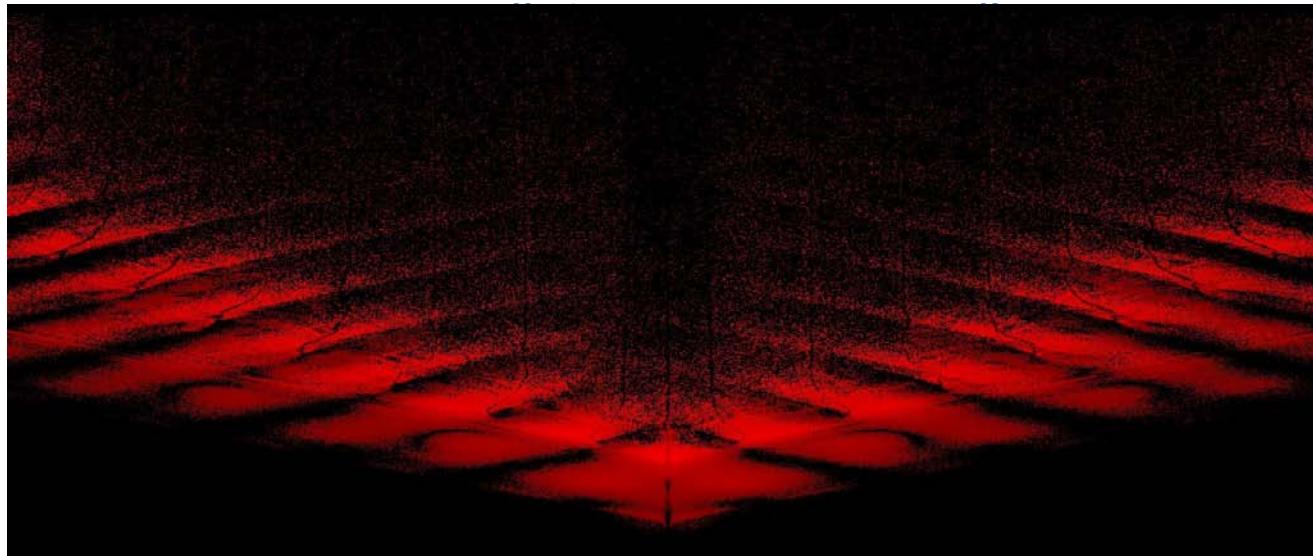


Процессы в экстремальных световых полях

А.М.Сергеев

А.В.Башинов, А.А.Гоносков, Е.С Ефименко, А.А.Муравьев и А.В.Ким



Экстремальные световые поля ?

Рубежи сегодняшнего дня по мощности, интенсивности и длительности лазерных импульсов

$$I \text{ (Вт/см}^2\text{)} = \frac{W \text{ (Дж)}}{\tau \text{ (с)} S \text{ (см}^2\text{)}} = \frac{10 \text{ Дж}}{10^{-14} \text{ с } 10^{-7} \text{ см}^2} = \frac{10^{15} \text{ Вт}}{10^{-7} \text{ см}^2} = 10^{22} \text{ Вт/см}^2$$

- Фемтосекундные длительности импульсов
- Петаваттные пиковые мощности

Масштабы интенсивности и напряженности эл.-м. поля

$$I (\text{Вт}/\text{см}^2) = \frac{10^{15} \text{ Вт}}{10^{-7} \text{ см}^2} = 10^{22} \text{ Вт}/\text{см}^2$$

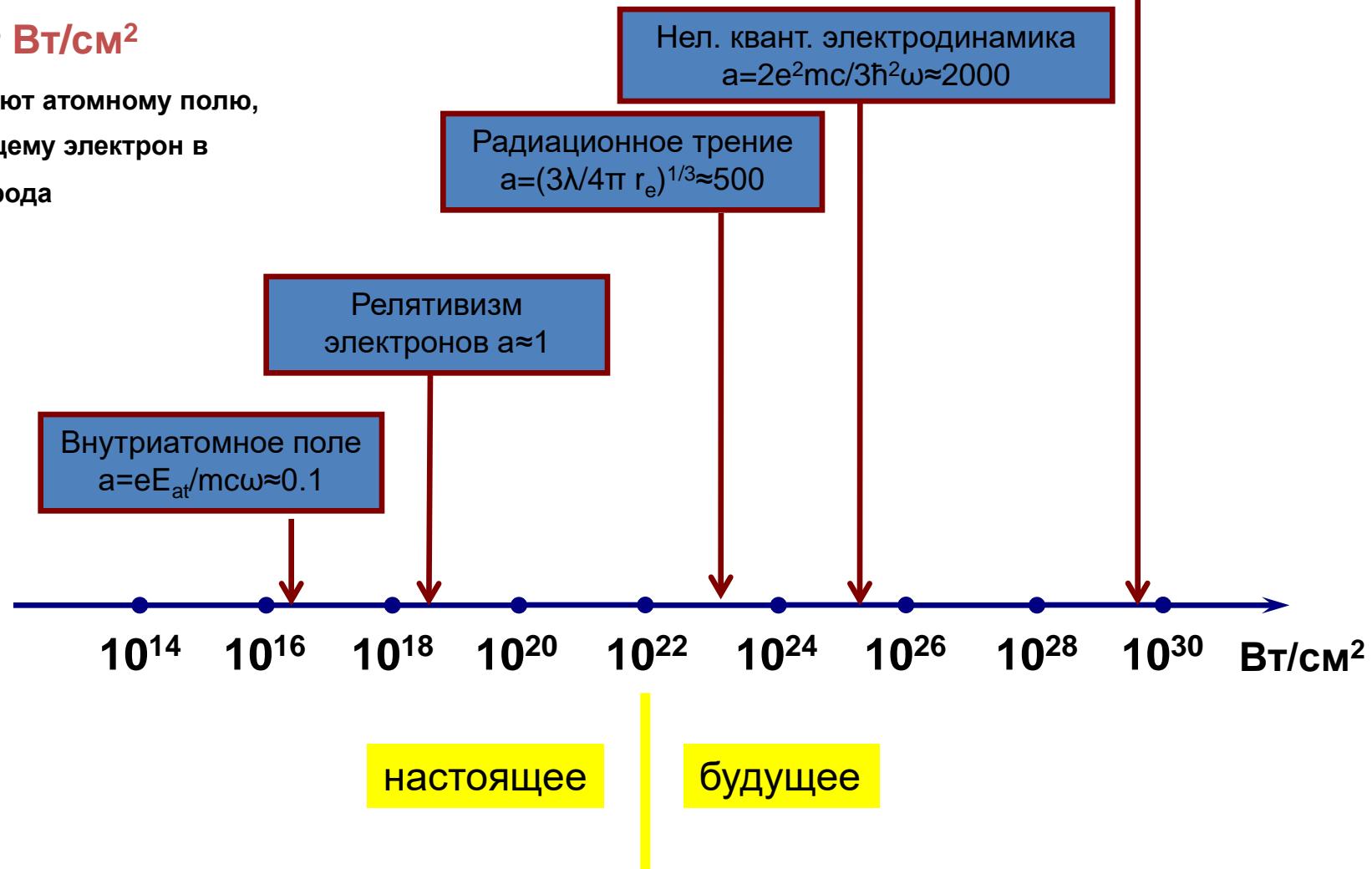
$$a = \frac{e A}{mc^2}$$

Неустойчивость
вакуума
 $a=mc^2/\hbar\omega \approx 500000$

$a \approx 0.1$

$I \approx 3 \cdot 10^{16} \text{ Вт}/\text{см}^2$

Соответствуют атомному полю,
удерживающему электрон в
атоме водорода



Строящиеся мультипетаваттные лазеры:

LULI Apollon 10PW

ELI (ELI-Beamlines, ELI-NP, ELI-ALPS)

SIOM

GIST

ИПФ РАН PEARL10

ELI – Extreme Light Infrastructure

ELI will comprise 4 branches:

- **Attosecond Laser Science**, which will capitalize on new regimes of time resolution (*ELI-ALPS*, Szeged, HU)
- **High-Energy Beam Facility**, responsible for development and use of ultra-short pulses of high-energy particles and radiation stemming from the ultra-relativistic interaction (*ELI-Beamlines*, Prague, CZ)
- **Nuclear Physics Facility** with ultra-intense laser and brilliant gamma beams (up to 19 MeV) enabling also brilliant neutron beam generation with a largely controlled variety of energies (*ELI-NP*, Magurele, RO)
- **Ultra-High-Field Science** centred on direct physics of the unprecedented laser field strength (*ELI 4*, to be decided)

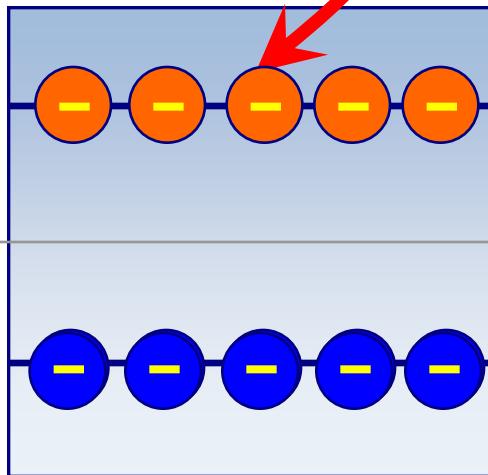




Laser or Parametric Amplification?

Laser
pulse

Pump



Laser medium

Laser amplification

Pump wave

Signal

Nonlinear crystal

Parametric amplification

Superbroadband synchronism $\epsilon = \omega_1 + \omega_2$ in DKDP crystal

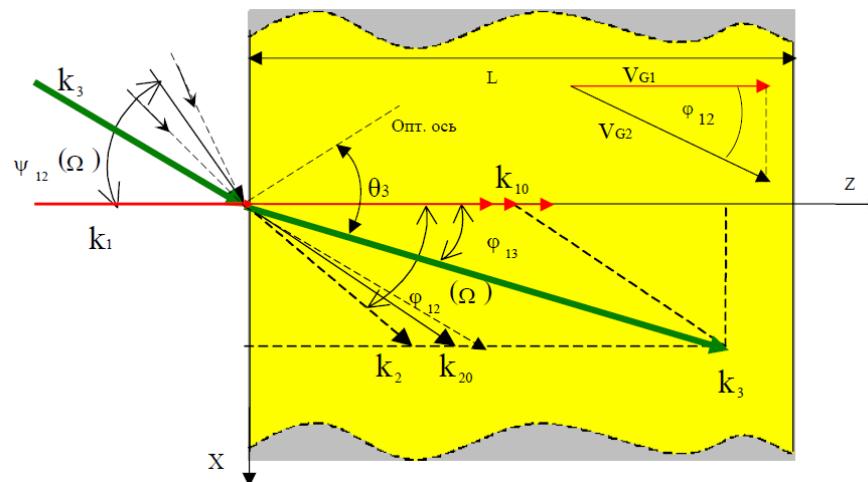
ω_3, k_3 – narrow band pump (ns pulse) – frequency $\omega_3 = \text{const}$

ω_1, k_1 and ω_2, k_2 – broadband signal and idler – variables, $\Delta\omega_1 = -\Delta\omega_2 = \Omega$

$$\Delta \vec{k} = \vec{k}_3(\omega_3) - \vec{k}_1(\omega_{10} + \Omega) - \vec{k}_2(\omega_{20} - \Omega)$$

$$\Delta \vec{k}(\Omega) = \cancel{\vec{k}_3(\omega_3)} - \left(\frac{d\vec{k}_1}{d\omega_1} \cancel{\vec{k}_2(\omega_2)} \right) \cdot \Omega - \frac{1}{2} \left(\frac{d^2\vec{k}_1}{d\omega_1^2} \cancel{\vec{k}_2(\omega_2)} \right) \cdot \Omega^2 + \dots$$

Synchronism
 Broadband Synchronism
 Superbroadband Synchronism



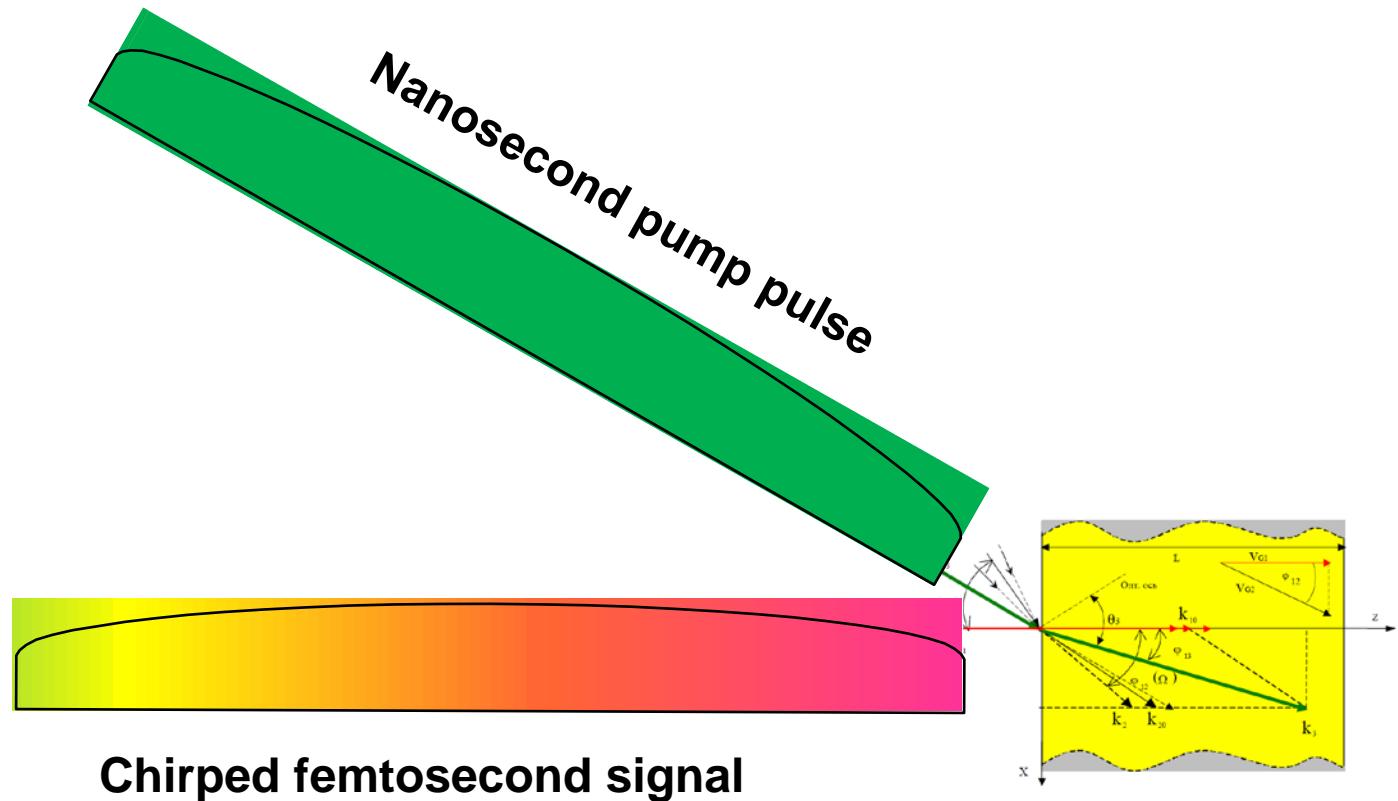
At pumping with second harmonic of Nd:glass laser ($\lambda_3 = 527 \text{ nm}$) in DKDP crystal with 85% deuteration, superbroadband synchronism takes place for :

$$\lambda_1 = 910 \text{ nm}, \lambda_2 = 1250 \text{ nm}, \theta_3 = 37,5^\circ, \phi_{13} = 0.7^\circ$$

$$1/527 = 1/910 + 1/1250$$



Optical Parametric Chirped Pulse Amplification (OPCPA)





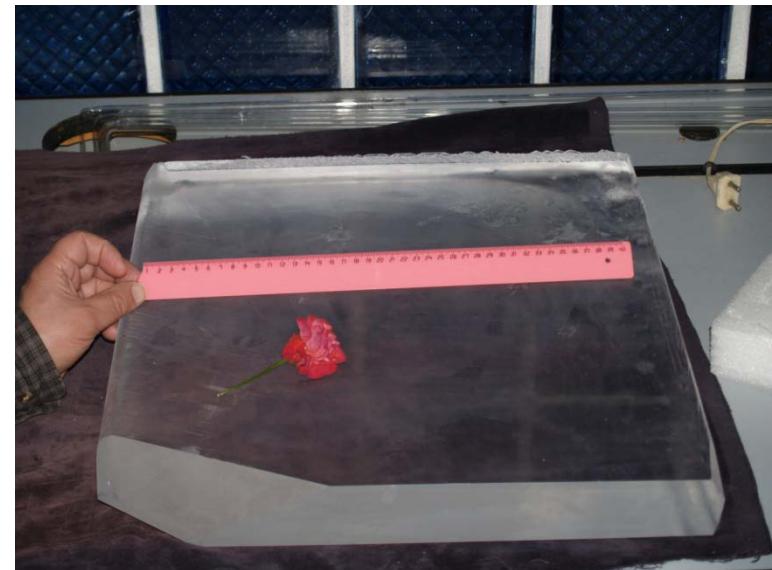
Laser or Parametric Amplification?

Crystal Systems, USA
RSA Le Rubis, France

IAP RAS
Cleveland Crystals, USA



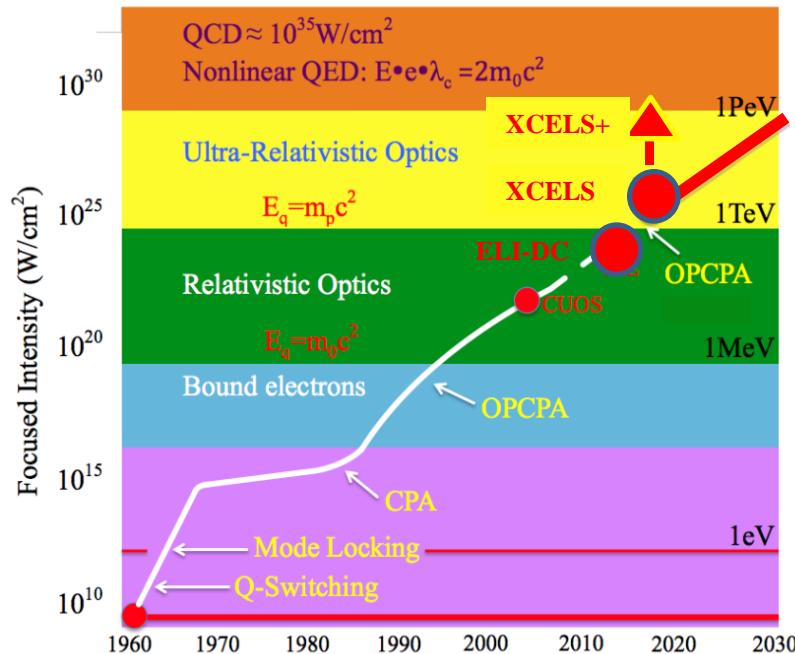
Ti:Sa boule, diameter 192 mm,
height 122 mm.



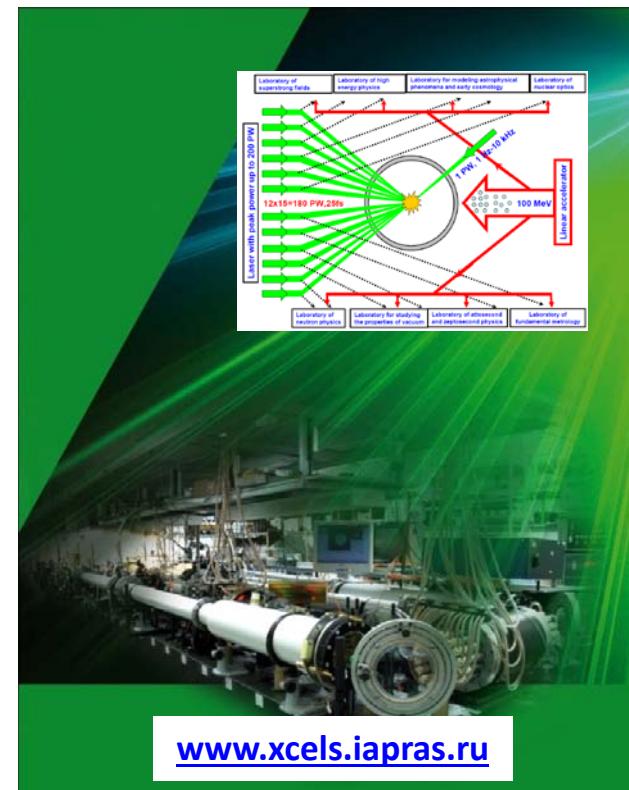
Crystal KDP, 40x40 cm²

Megaproject XCELS

XCELS - world most powerful laser infrastructure that will be built at
the Institute of Applied Physics in Nizhny Novgorod
 to study the properties of matter and vacuum in the presence of extreme light



Ascent to the highest intensity of light,
 "the Extreme Light"

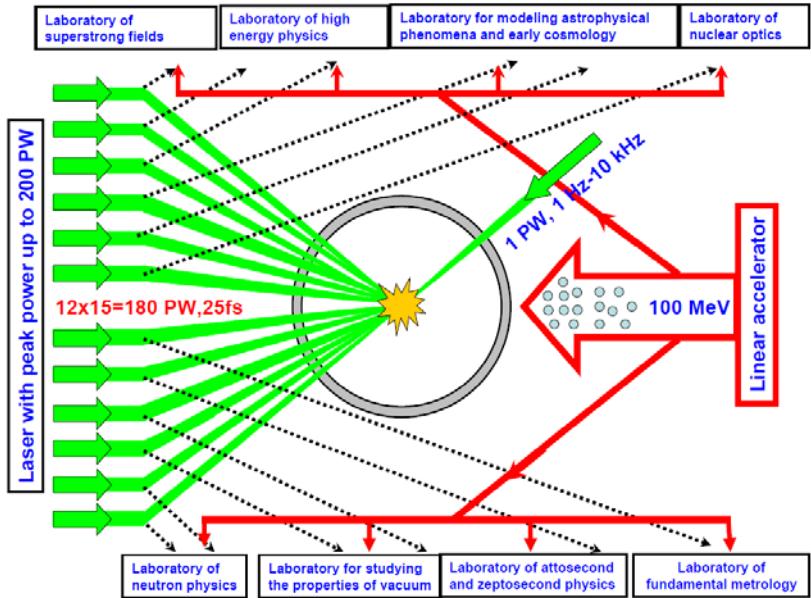


www.xcels.iapras.ru

XCELS - Exawatt Center for Extreme Light Studies

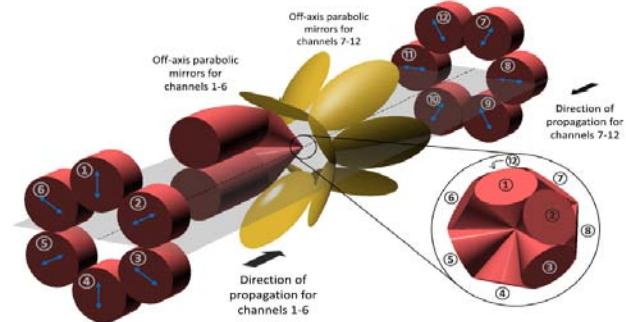
Megaproject XCELS

Laser source for XCELS



XCELS is based on the 200 Petawatt (2×10^{17} Watt) laser facility that exceeds the current record power level by 100 times. It comprises 12 amplification channels, each producing a laser pulse with 400 J energy and 25 femtosecond pulse duration.

A specially designed focusing system provides the ascent to the highest intensity level of $10^{25} - 10^{26}$ W/cm² by combining 12 laser beams. The resulting energy density in the focal area attains 10^{16} J/cm³, several orders of magnitude higher than in the center of the Sun.



XCELS - Exawatt Center for Extreme Light Studies



XCELS: От 10^{22} Вт/см² к 10^{25} Вт/см²

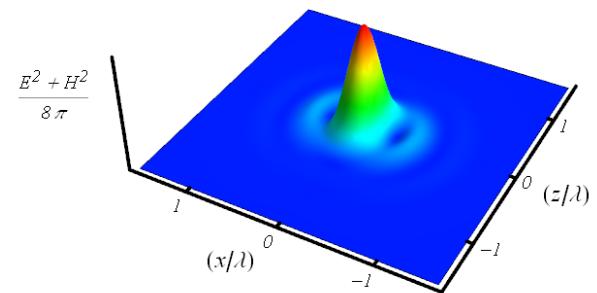
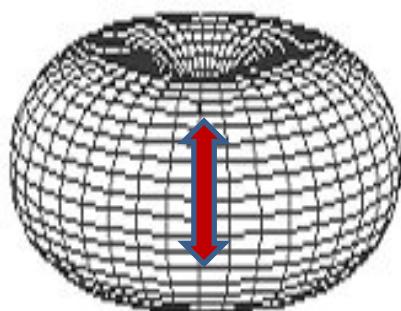
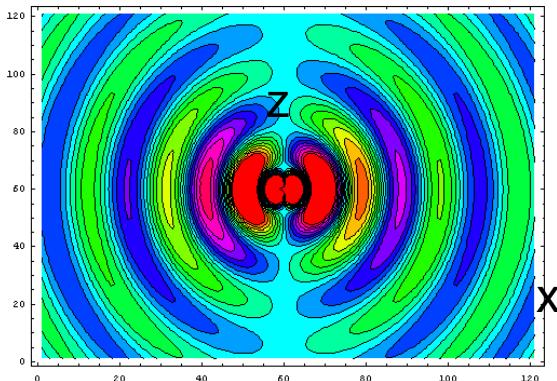
- Today's PW scale lasers provide maximum intensity 10^{22} W/cm²
- Upcoming 10 PW facilities (ELI NP, Apollon) will achieve 10^{23} W/cm²
- Exawatt scale lasers will provide operation at 10^{24} W/cm² – 10^{25} W/cm² where a new and very rich realm of e-e+ plasmas and gamma ray sources exists
- New realm is featured by
 - Ultrarelativistic, ultradense e-e+ plasma
 - GeV Gamma-Ray sources with extreme brilliance
 - Giant magnetic fields and currents
- Exawatt scale lasers enable approach to even higher intensities 10^{26} W/cm² – 10^{28} W/cm² by efficient conversion from fs to as pulses

How to maximize field intensity at given power ?

Rule of thumb for coherent combining of several beams:

To maximize the electric field at focusing point,
radiation of several combining beams should reproduce
configuration of **phase conjugated dipole radiation field**

I. Gonoskov, A. Aiello, S. Heugel, and G. Leuchs, Phys. Rev. A (2012)



$$\text{Minimum focusing volume: } V_{dp} \approx 0.032\lambda^3$$

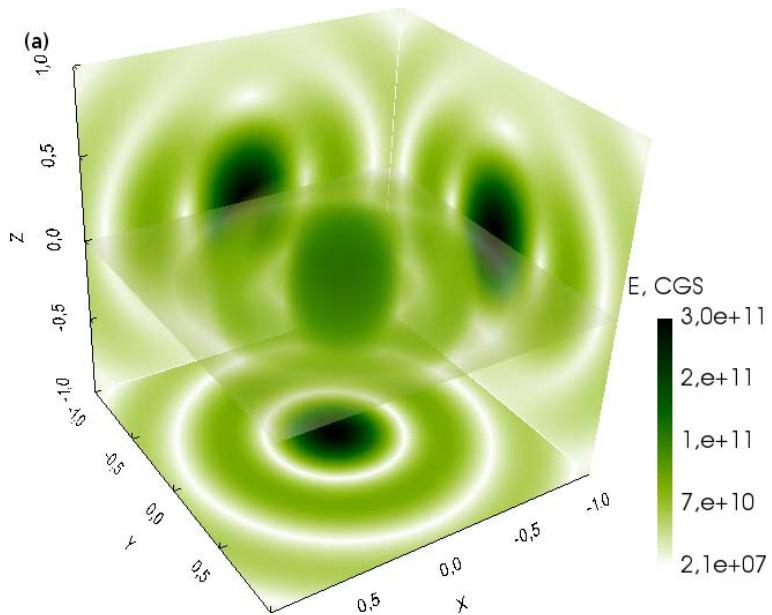
Converging dipole wave as an exact solution of Maxwell equations:

$$\mathbf{E} = -\nabla \times \nabla \times \mathbf{Z}, \quad \mathbf{H} = -\frac{1}{c}\nabla \times \dot{\mathbf{Z}} \quad \mathbf{Z} = \hat{z} \frac{d}{R} [g(t + R/c) - g(t - R/c)]$$

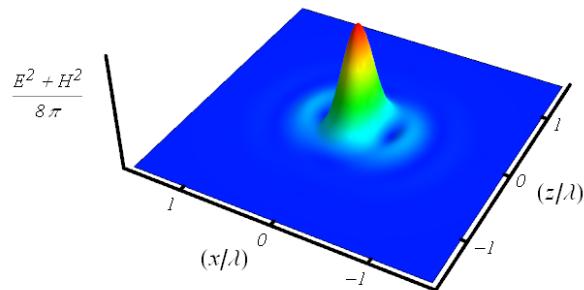
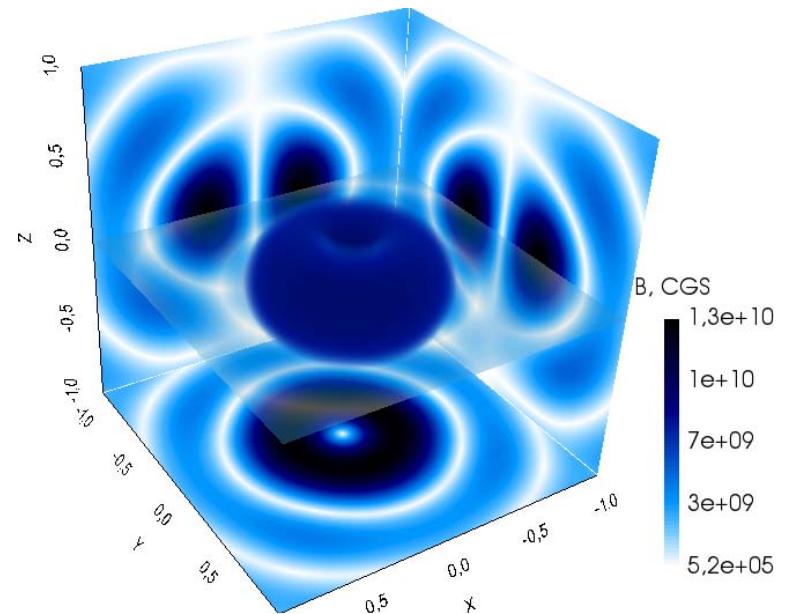
$$\mathbf{E}(0, t) = \hat{z} \frac{4d}{3c^2} \ddot{g}(t) \quad \mathbf{H} = 0 \quad g(\tau) = e^{-(\tau^2/D^2) \ln 4} \sin(\omega\tau)$$

Dipole wave structure

Electric field



Magnetic field

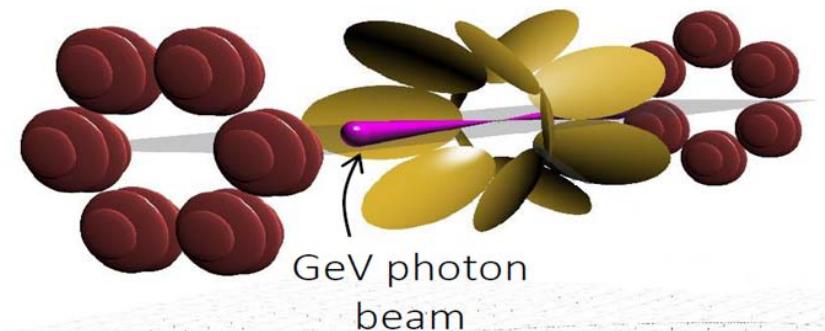
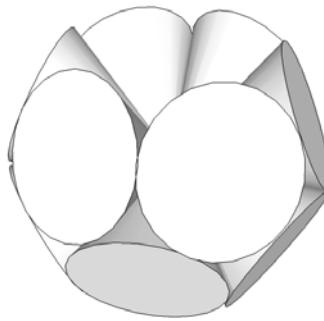


Minimum focusing volume:

$$V_{dp} \approx 0.032\lambda^3$$

How to achieve intensity 10^{23} - 10^{25} W/cm²

Geometry	Power per channel	Intensity, $\times 10^{25}$ W/cm ²	I/I(f=1.2)	Equivalent power (f=1.2)
Single beam (f=1.2)	$P_0=10$ PW	0.06	1	10 PW
Single beam (f=1.2)	$P_0=200$ PW	1.2	1	200 PW
Dipole-Wave	$P_0=200$ PW	16.7	13.9	2800 PW
Double-Belt-12 12× (f=0.96)	$P_0/12$	13.4	11.2	2200 PW



XCELS design: Coherent combining to mimic a converging dipole wave



Amazing new physics of laser-particle-vacuum interaction at light intensity $> 10^{23} \text{ W/cm}^2$

Radiation dominated regime:

Particles become efficient convertors of energy from optical to gamma range



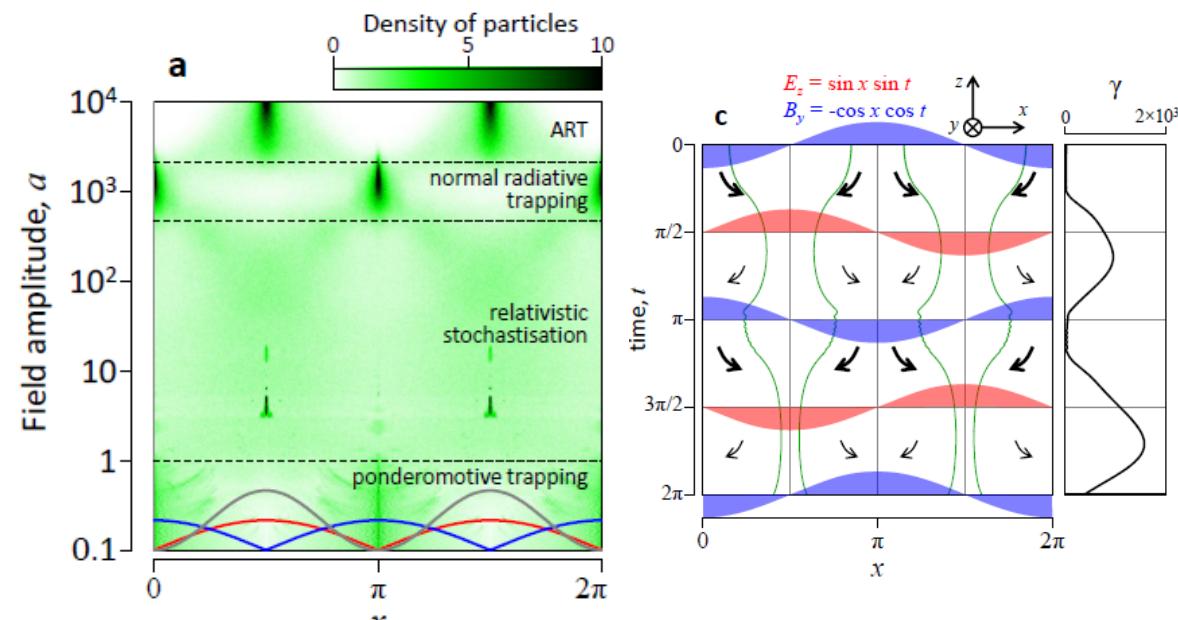
Trajectories of particles change dramatically; no more relativistic Newton mechanics

New sources of gamma radiation: controlled, brilliant, collimated

New state of matter: strongly coupled optical fields, ultrarelativistic electron-positron plasma and gamma radiation

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

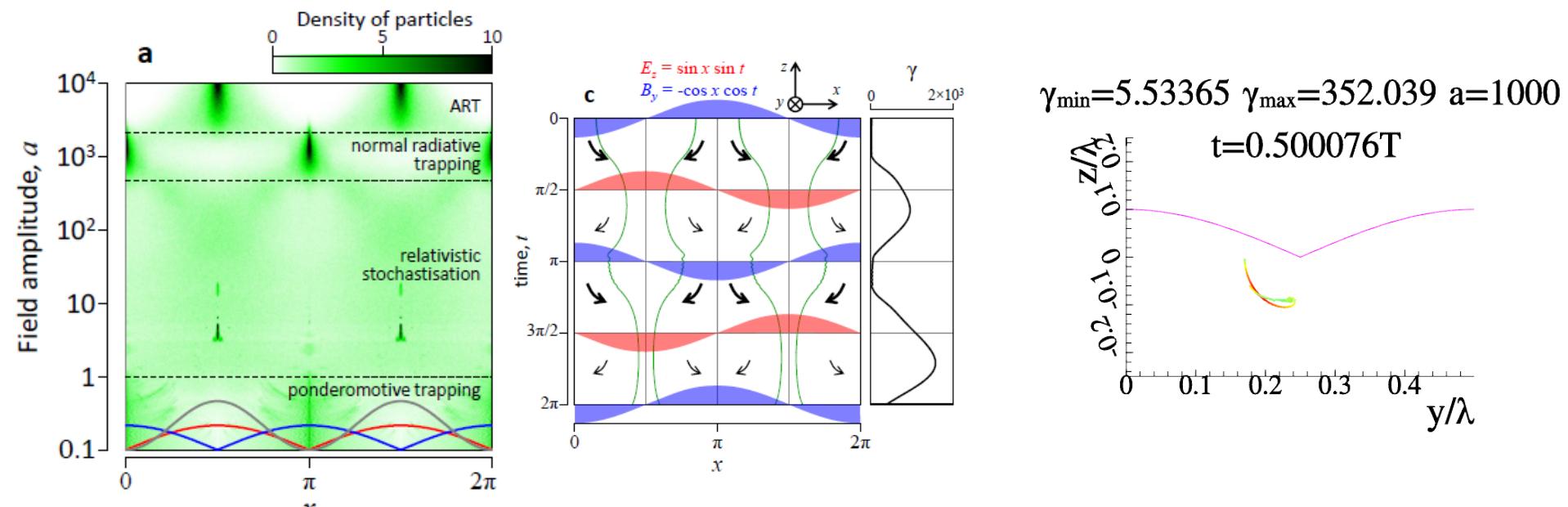
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

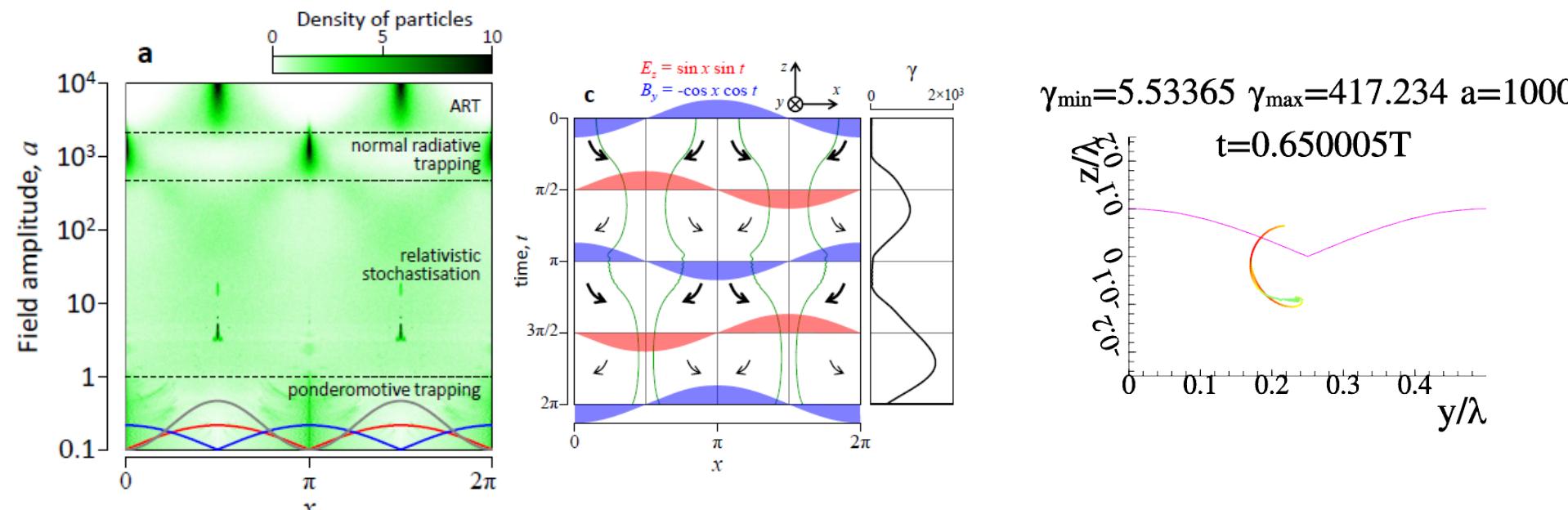
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

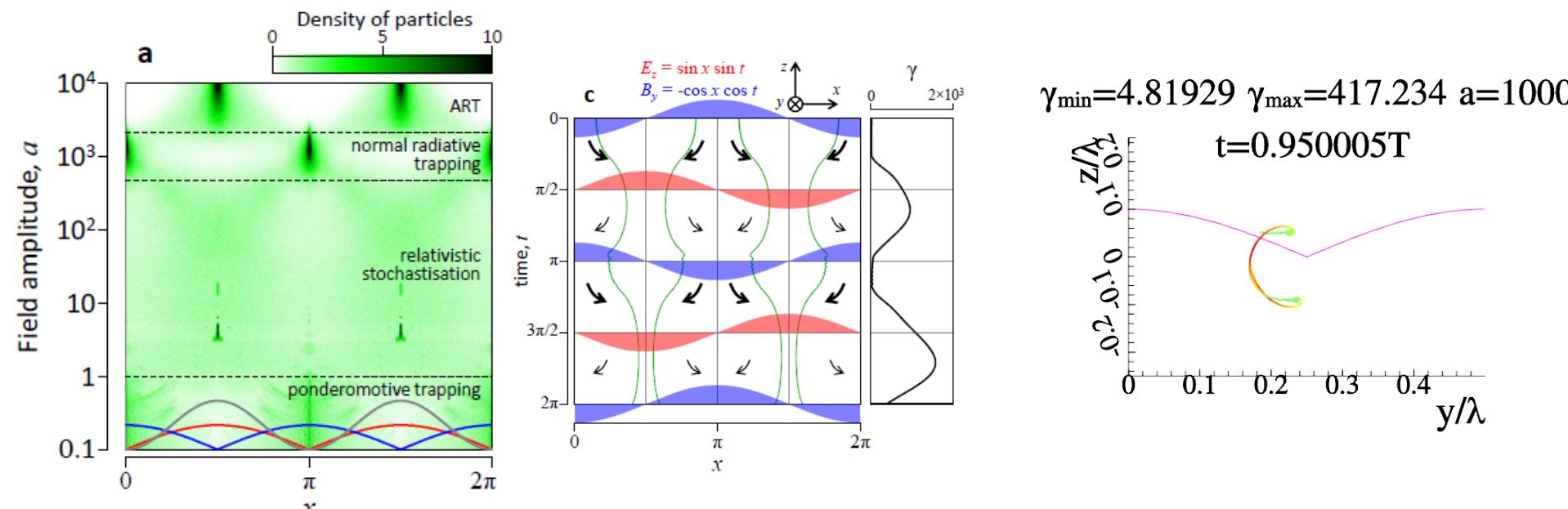
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

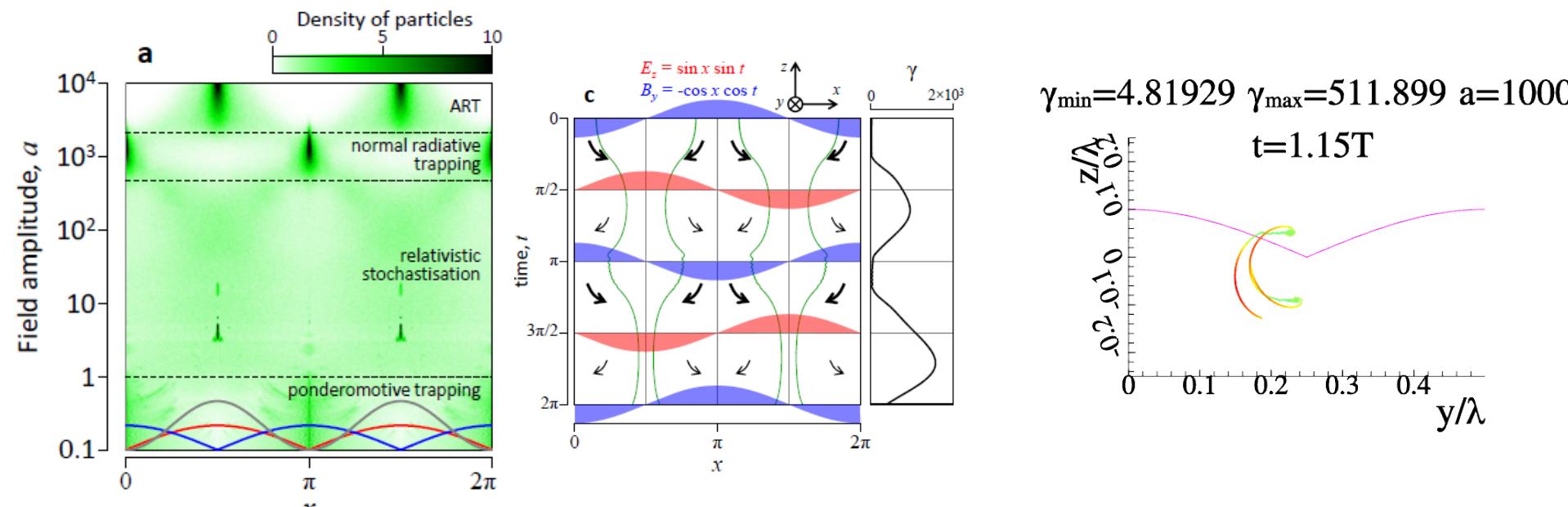
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

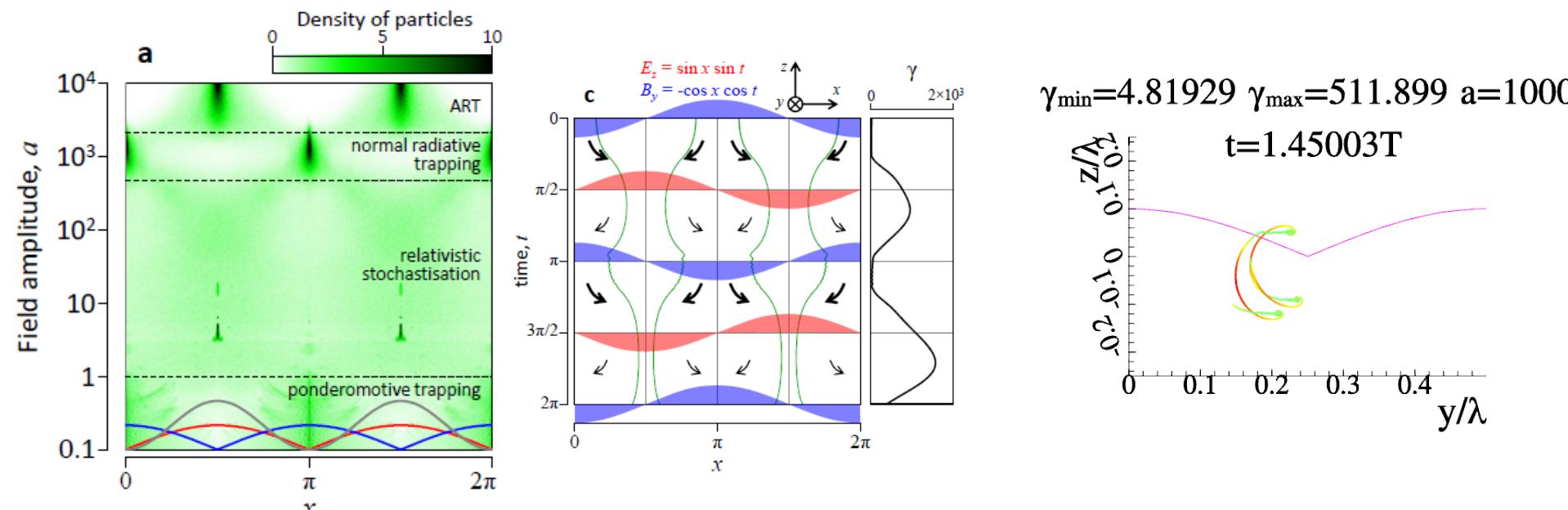
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

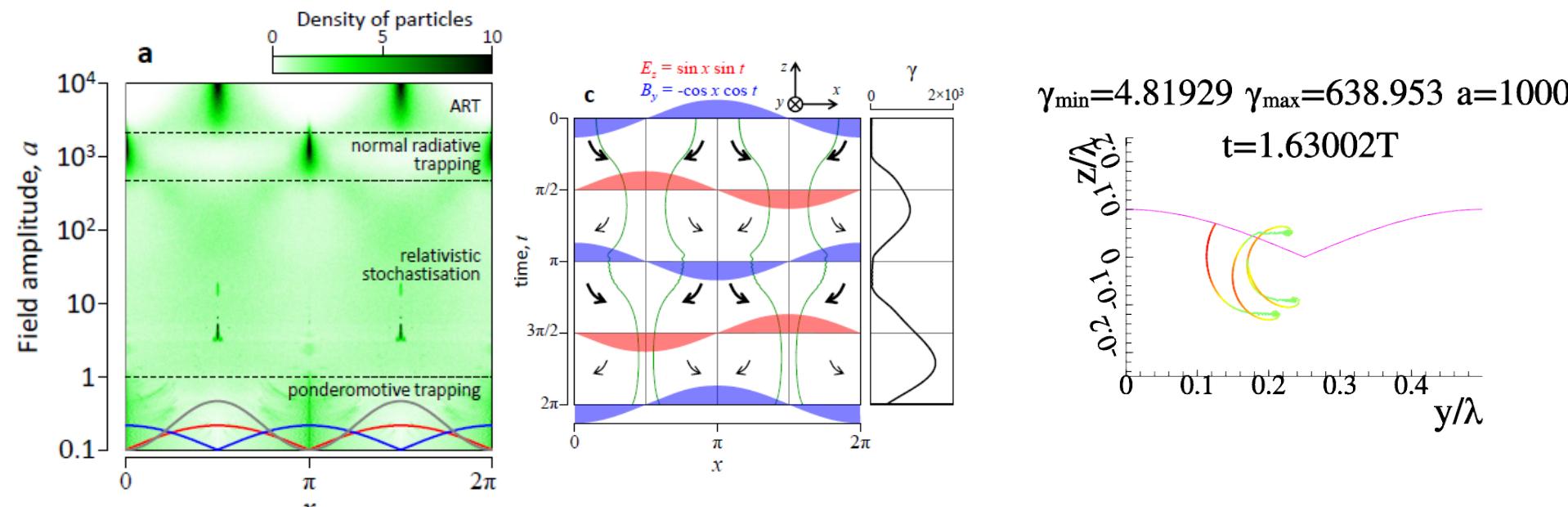
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

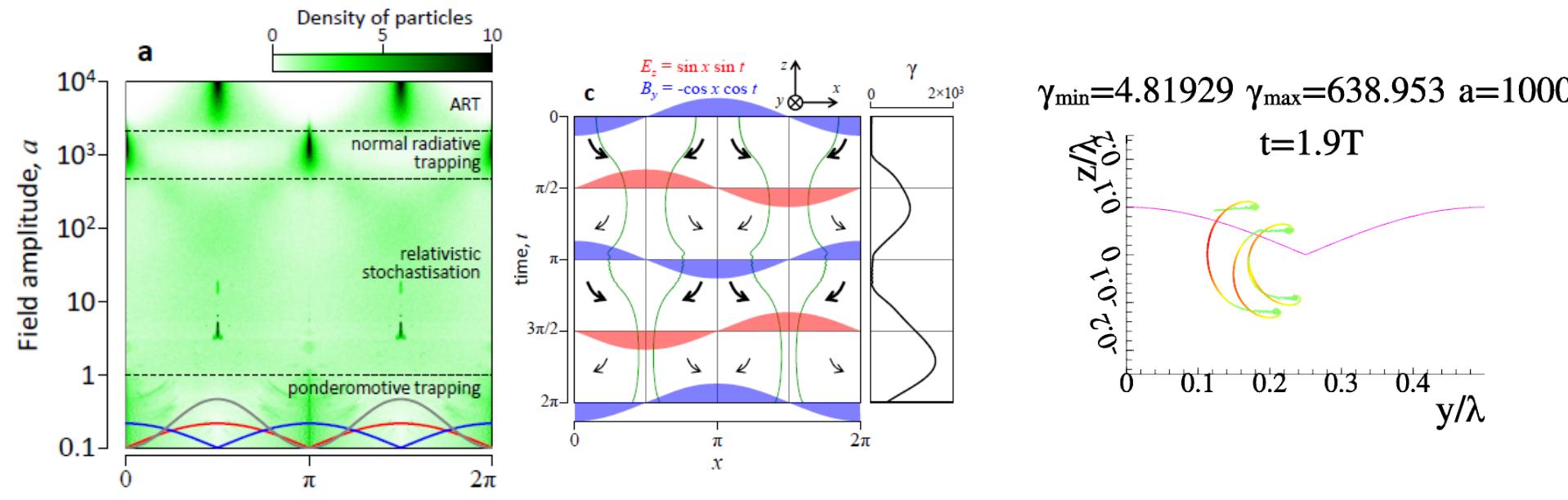
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.



Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

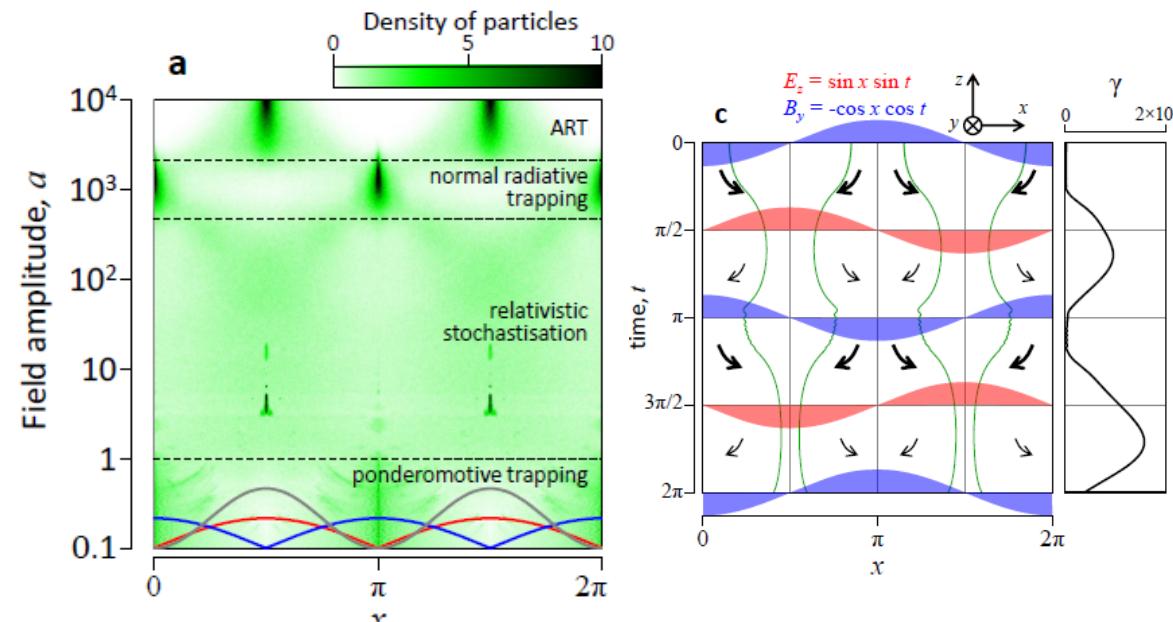
$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Dynamics in Radiation Dominated Regime

Radiation force, i.e. recoil at radiating hard photons at ultrarelativistic motion with acceleration, becomes of the order of the Lorentz force by the laser field. Particle trajectories acquire unusual properties that in turn results in new amazing gamma ray sources.

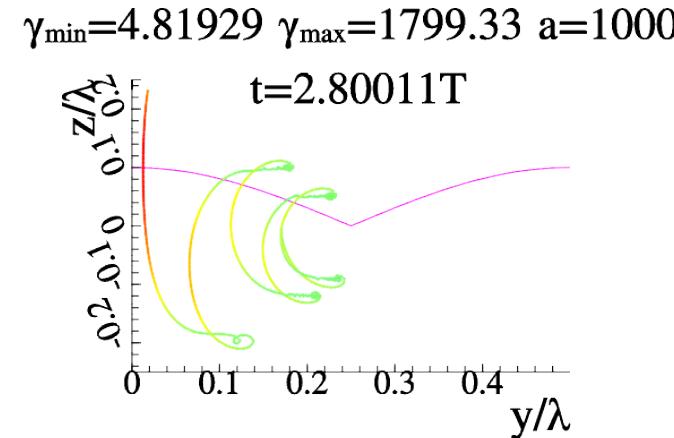


Phenomenon of radiative trapping:

Electrons condense to minima (NRT) or maxima (ART) of electric field

$$I_{th}^{NRT} \approx 5 \times 10^{23} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$

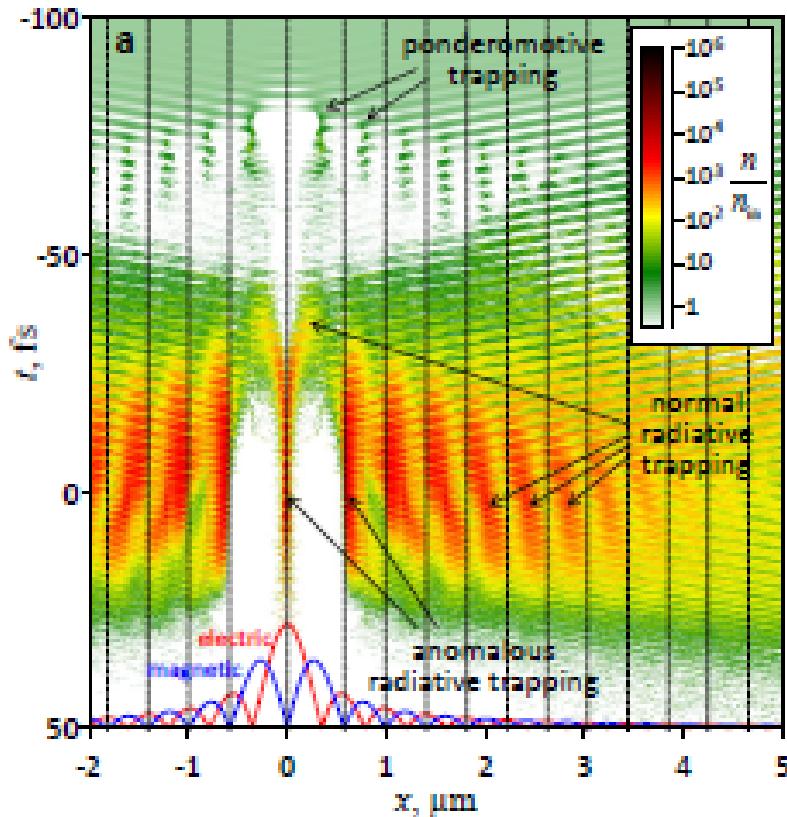
$$I_{th}^{ART} \approx 8 \times 10^{24} \frac{W}{cm^2} \times \left(\frac{0.81\mu m}{\lambda} \right)^{\frac{4}{3}}$$



Attraction to maximum of electric field in standing wave!

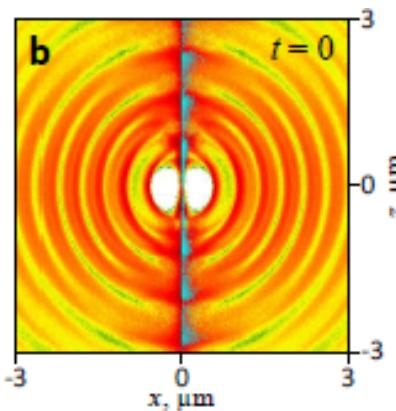
A.Bashinov et al. Quantum Electronics 43(4),291 (2013),
A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)
A.Bashinov et al. Phys.Rev.E 92 (2015)

Electron Trapping and Directed Gamma Rays Excitation at Converging Dipole Wave Laser Focusing

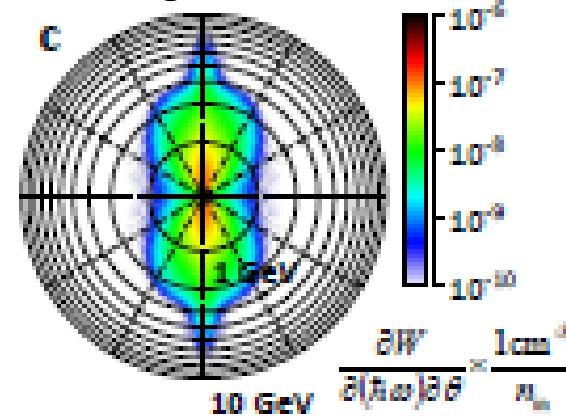


Electron density versus time and radius at 30 fs dipole wave laser pulse focusing with peak total power of 200 PW

A.V.Bashinov et al. Quantum Electronics 43(4),291 (2013),
 A.Gonoskov et al. Phys.Rev.Lett. 113 (2014)

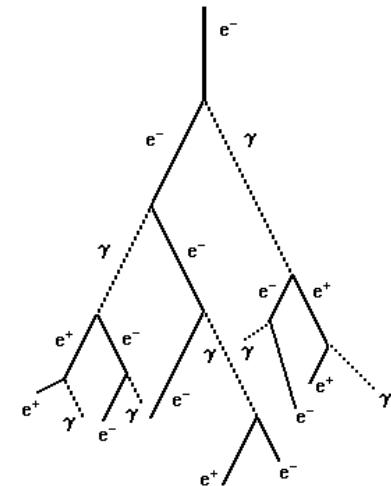
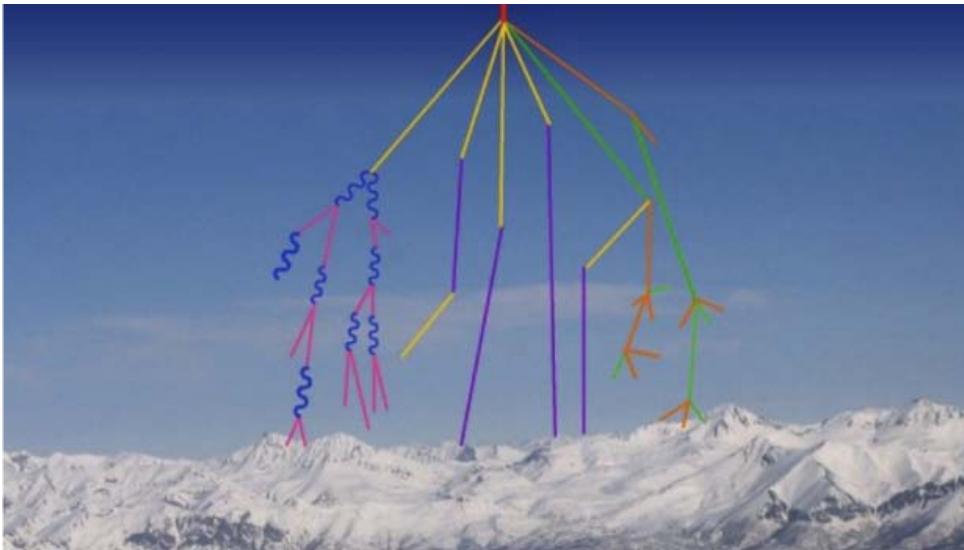


Density distribution at the instance of peak field strength; photons with energy exceeding 3 GeV are shown in cyan



Hard photon emission distribution as a function of angle and energy (radial coordinate, log scale). 0.1% of laser energy is converted to $> 1 \text{ GeV}$ photons

QED cascades



A.R. Bell and J. G. Kirk, Phys. Rev. Lett. (2008)

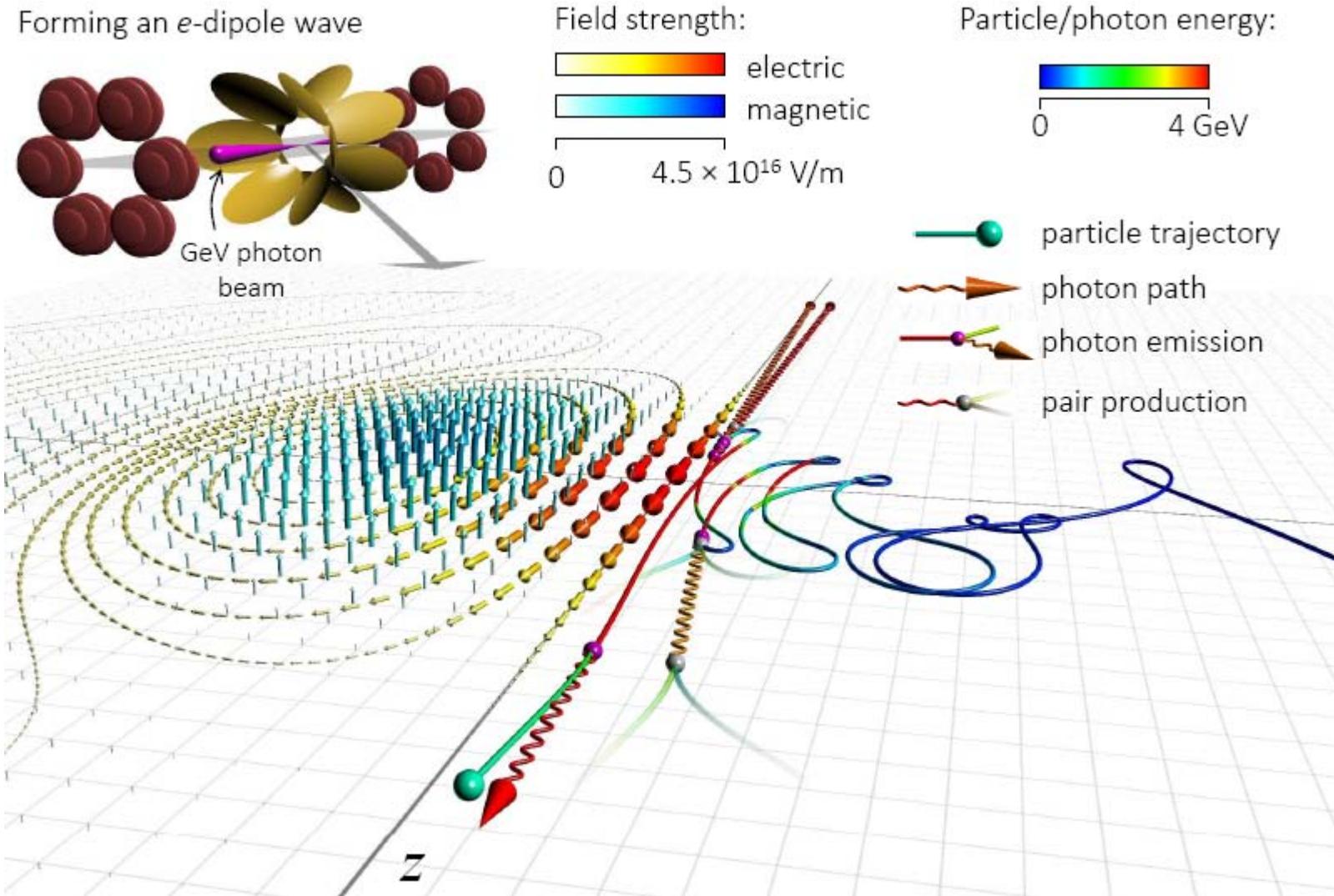
A.M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, Phys. Rev. Lett. (2010)

E. N. Nerush, I. Yu. Kostyukov, A. M. Fedotov, N. B. Narozhny, N. V. Elkina, and H. Ruhl, Phys. Rev. Lett. (2011)

V.F.Bashmakov, E.N.Nerush, I.Yu.Kostyukov, A.M.Fedotov, N.B.Narozhny
Phys. Plasmas (2014)

Message: Vacuum behaves like a rather dense dielectric medium at ionization.
Cascades start at much lower fields (10^{24} - 10^{25} W/cm 2) as compared to Sauter-Schwinger limit (10^{29} W/cm 2)

Anomalous radiation trapping and gamma ray emission

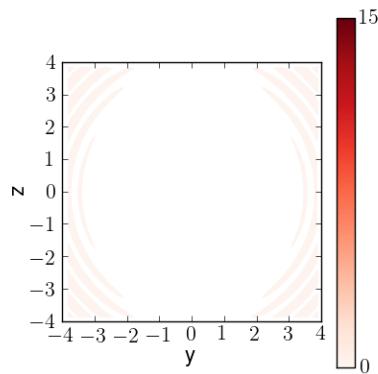




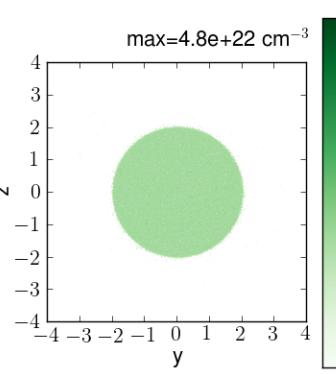
QED cascades in dipole wave

$t = 5.9 \text{ T}$

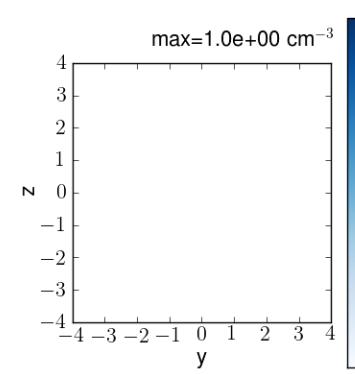
Electric field



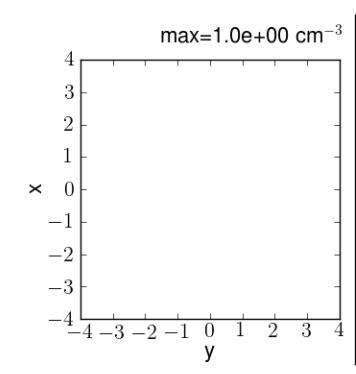
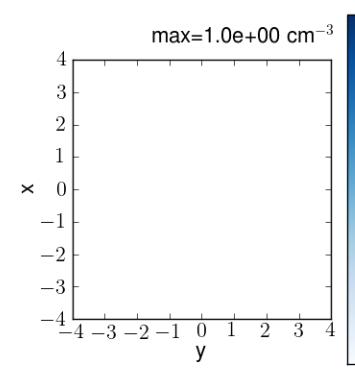
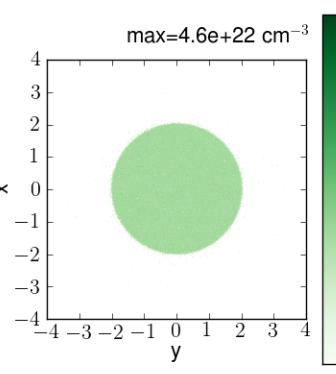
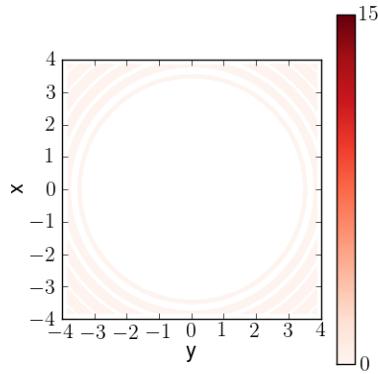
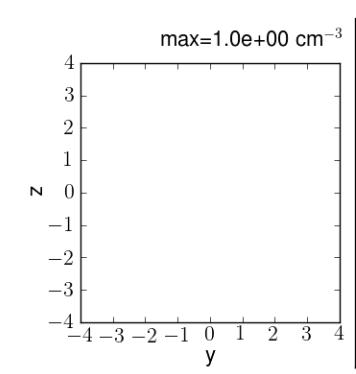
Electron density



Positron density



Photon density



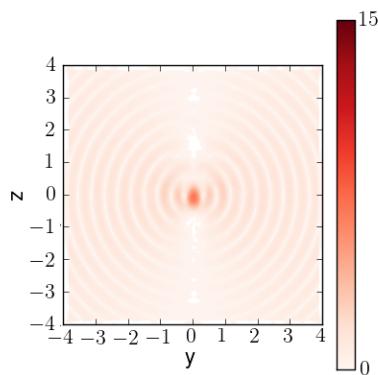
$P=100 \text{ PW}, t=5.9 \text{ T}$



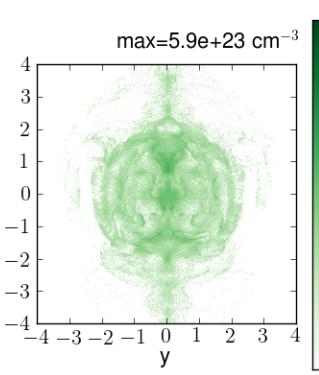
QED cascades in dipole wave

$t = 13.0 \text{ T}$

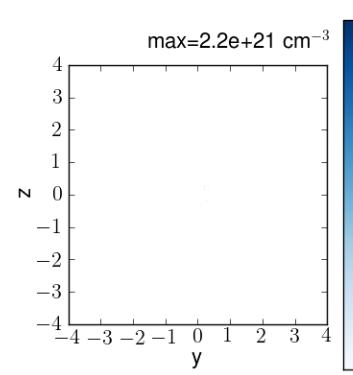
Electric field



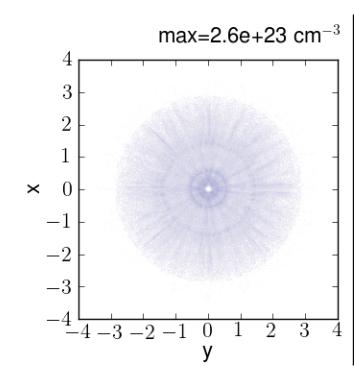
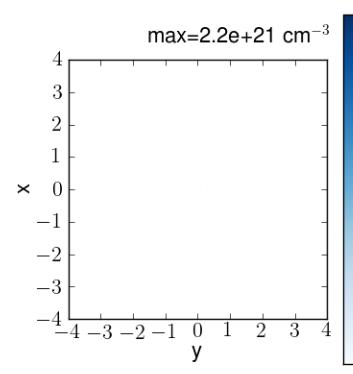
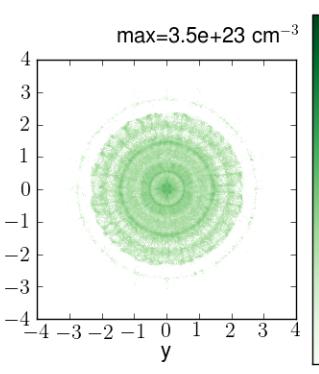
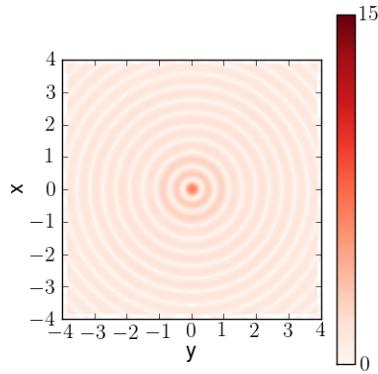
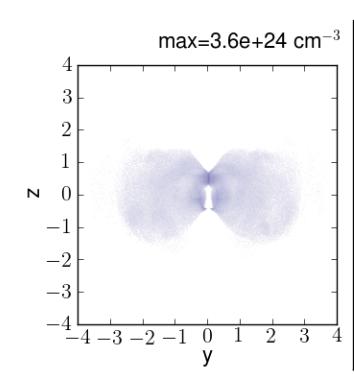
Electron density



Positron density



Photon density



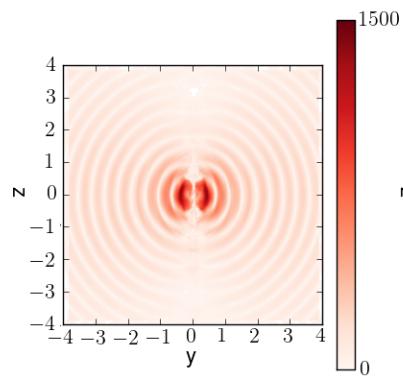
$P=100 \text{ PW}, t=13 \text{ T}$



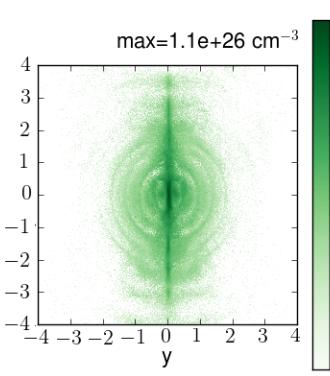
QED cascades in dipole wave

$t = 18.6 \text{ T}$

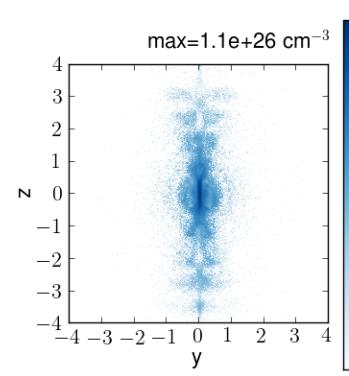
Electric field



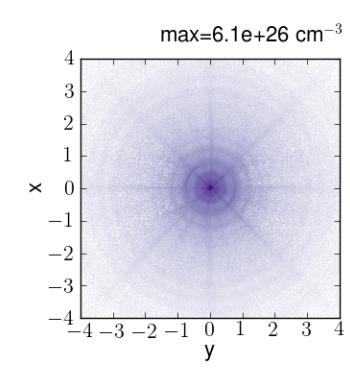
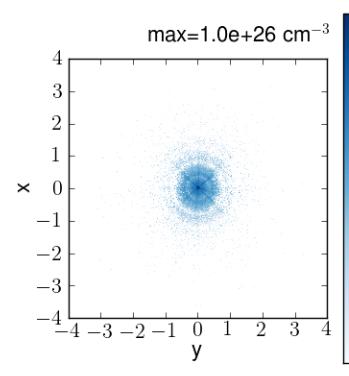
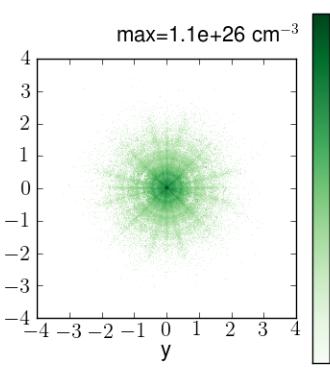
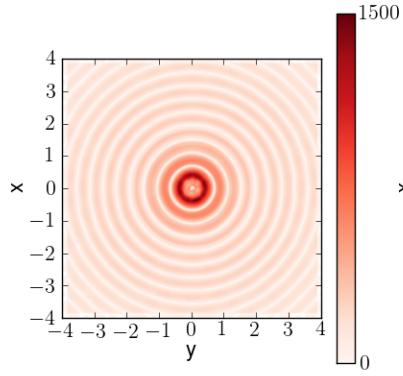
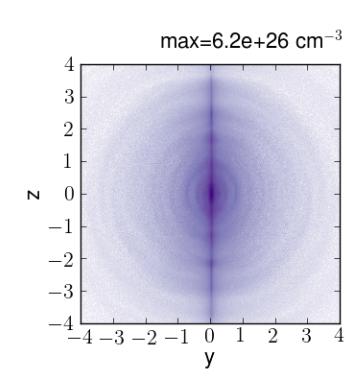
Electron density



Positron density



Photon density

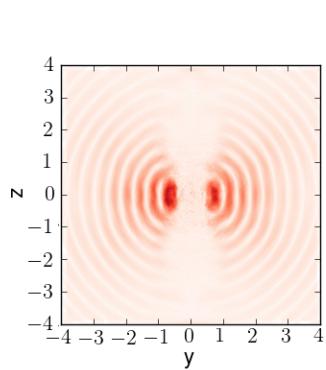


$P=100 \text{ PW}, t=18.6 \text{ T}$

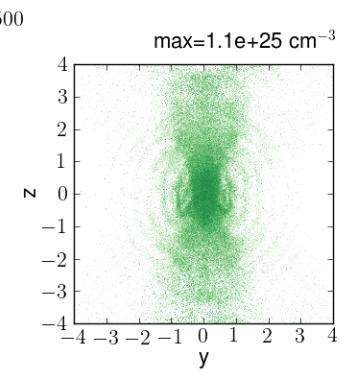
QED cascades in dipole wave

$t = 23.7 \text{ T}$

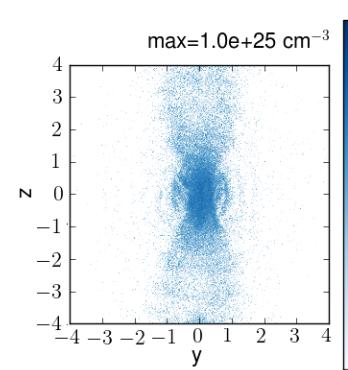
Electric field



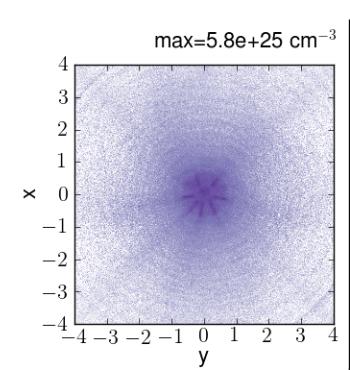
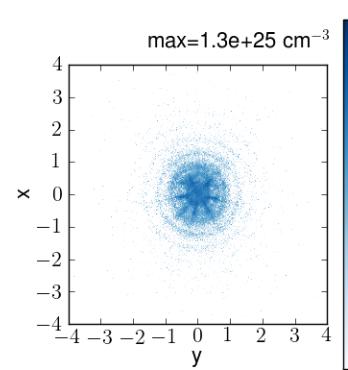
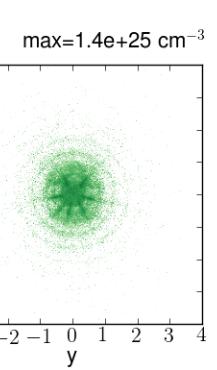
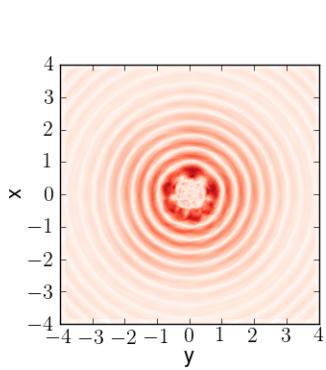
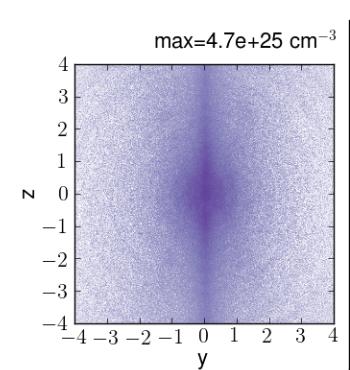
Electron density



Positron density



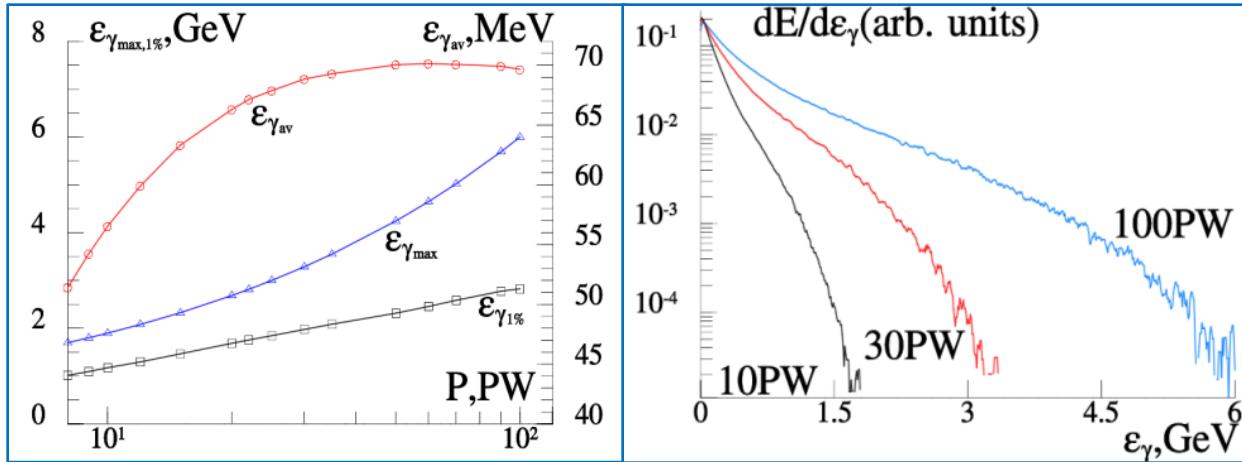
Photon density



- Max electron density $> 10^{26} \text{ cm}^{-3}$,
- Max photon density $6 \cdot 10^{26} \text{ cm}^{-3}$,
- 10^{13} photon/pulse ($E > 100 \text{ MeV}$), 10^{10} photon/pulse ($E > 1 \text{ GeV}$)
- Limitation by optical pulse refraction from plasma

How nuclei behave in this environment? Can we observe $\gamma\gamma$ collision effects?

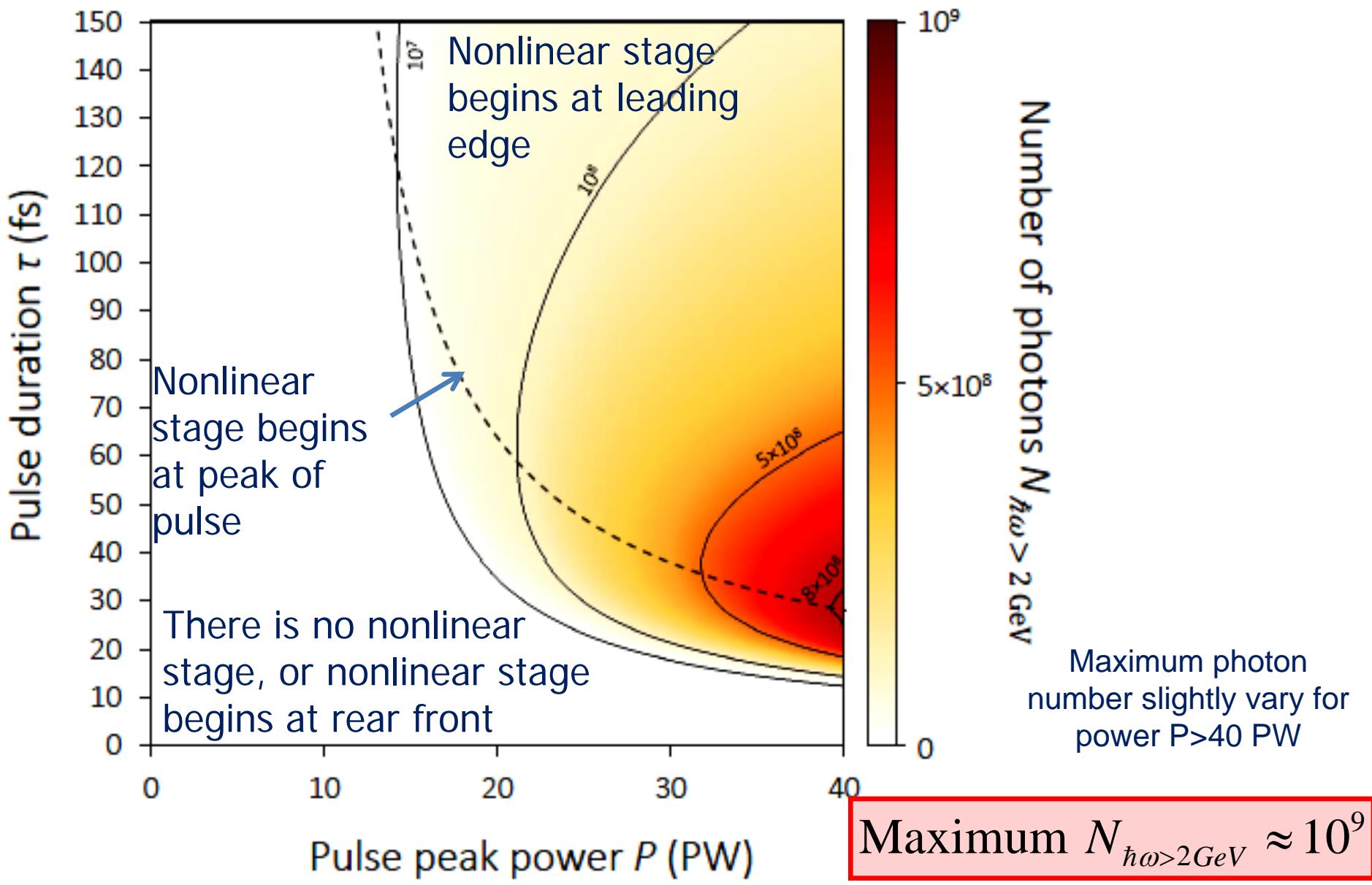
Gamma ray source characteristics



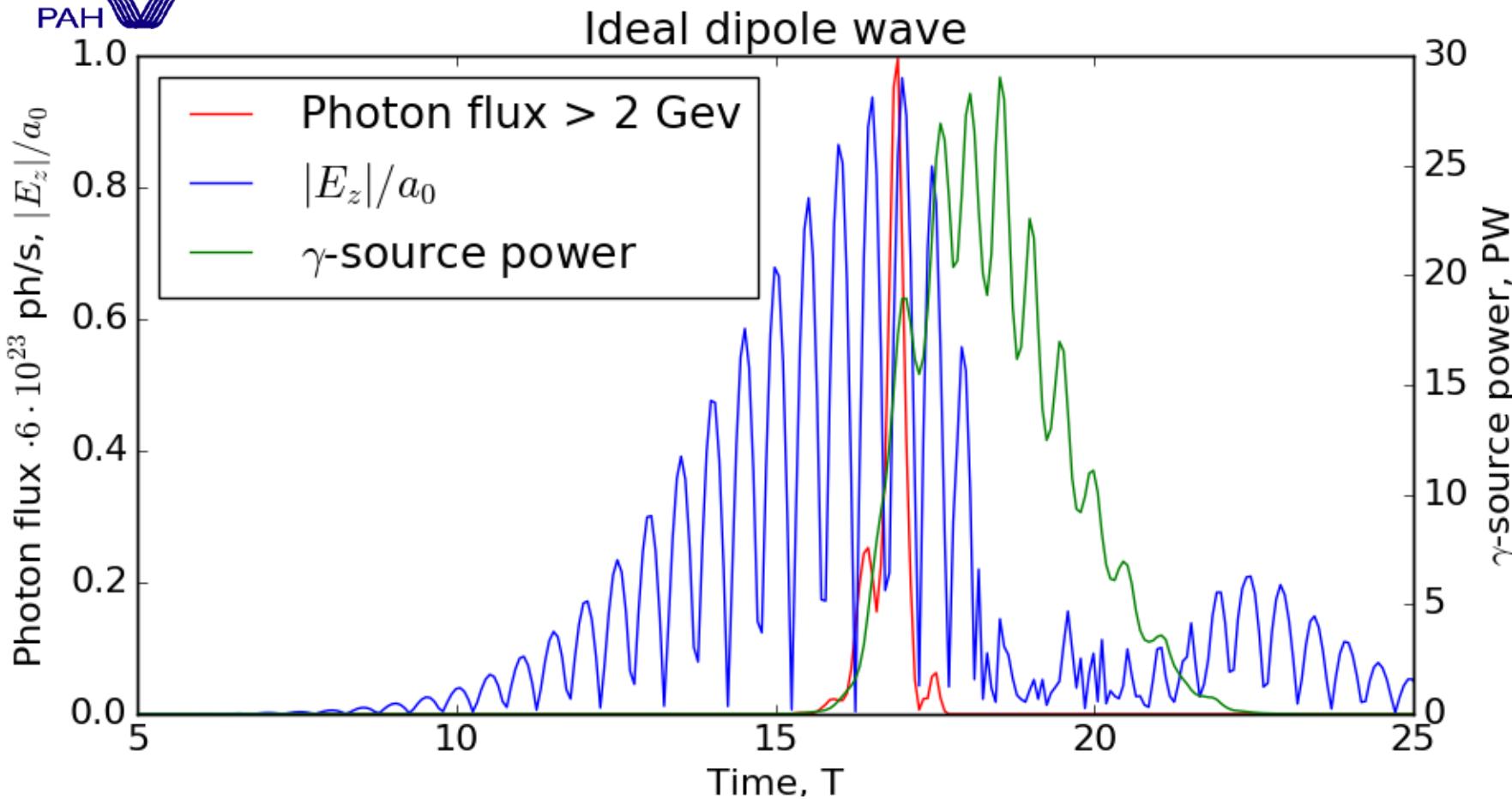
Left. Dependence of average (red line with circles), maximal (blue line with triangles) photon energy and energy at the level 1% (black line with squares) on incoming power P .

Right. Normalized spectra of electron-positron plasma radiation for 10, 30 and 100PW.

Optimization of GeV photon yield



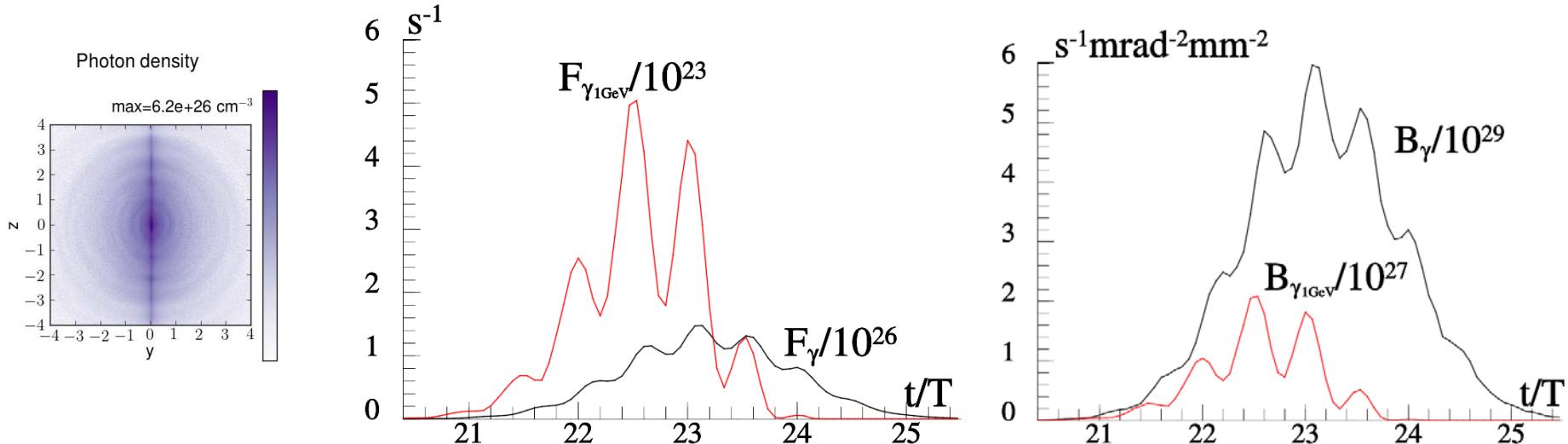
Gamma photon yield for ideal dipole wave



- 2 GeV photons are emitted only near the maximum of the laser pulse producing sub-period gamma burst
- The rear part of the pulse is transformed to gamma quanta with the lower energies almost completely, resulting in overall 34% efficiency

Optimization of GeV photon brilliance

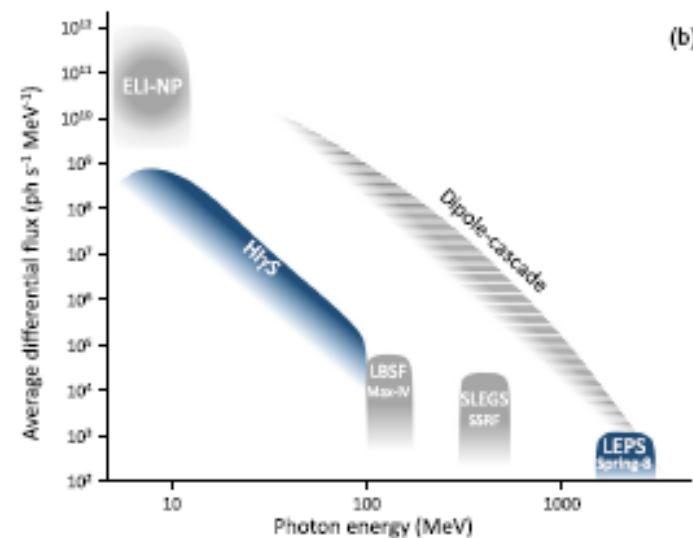
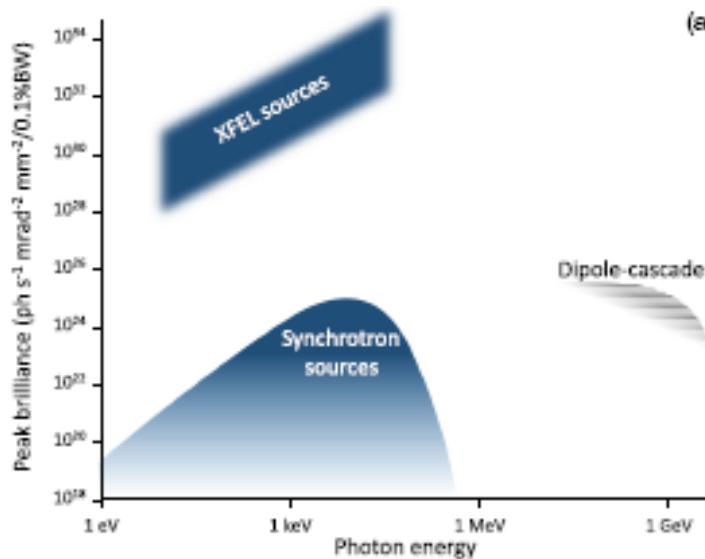
**How to make the most brilliant gamma source?
Do not allow degradation of optical wave structure (shorter pulse)**



In the case of particular experiments for the Gaussian pulse with the peak power $P = 40\text{PW}$, the duration of $\tau = 15 \text{ fs}$ and the density of the target 10^{16} cm^{-3} . The measured flux and brilliance are shown as a function of time. The duration of the generated gamma pulse is 4.5 fs, maximal brilliance is **$6 \times 10^{29} \text{ s}^{-1} \text{ mrad}^{-2} \text{ mm}^{-2}$** , the number of photons for energies $>100\text{MeV}$ is 10^{11} . The photon flux for energies greater 1 GeV is $5 \times 10^{23} \text{ s}^{-1}$, number of photons is 10^9 . The beam width for the gamma photons is **2 mrad**.

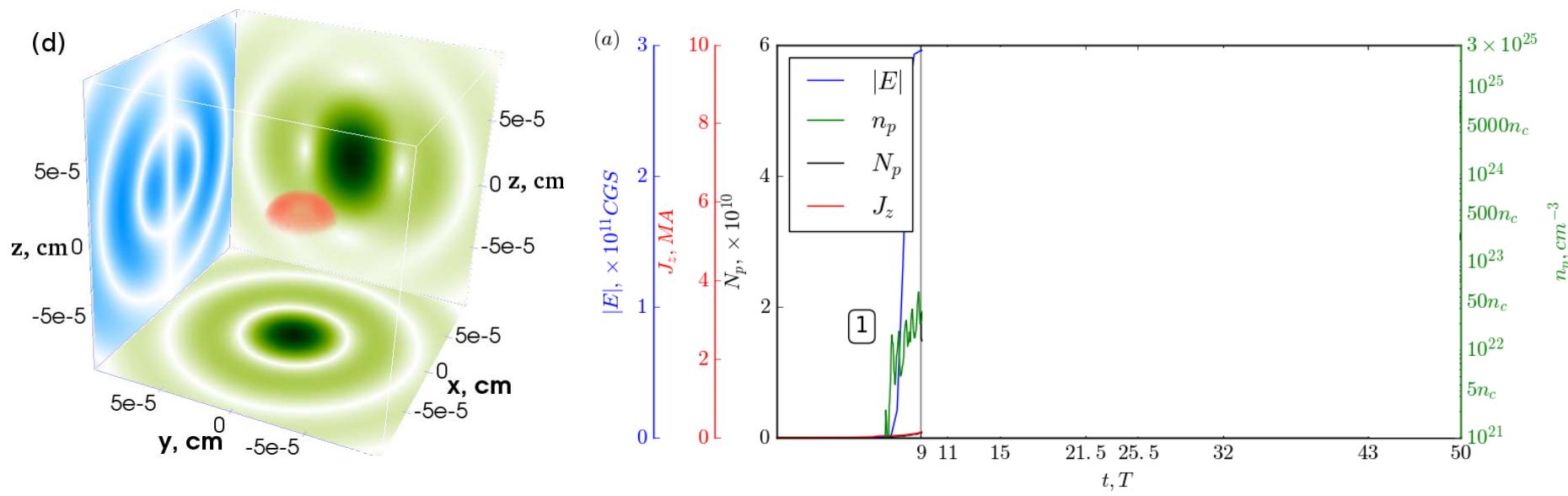
Gamma ray source characteristics

Comparison with existing or planned sources



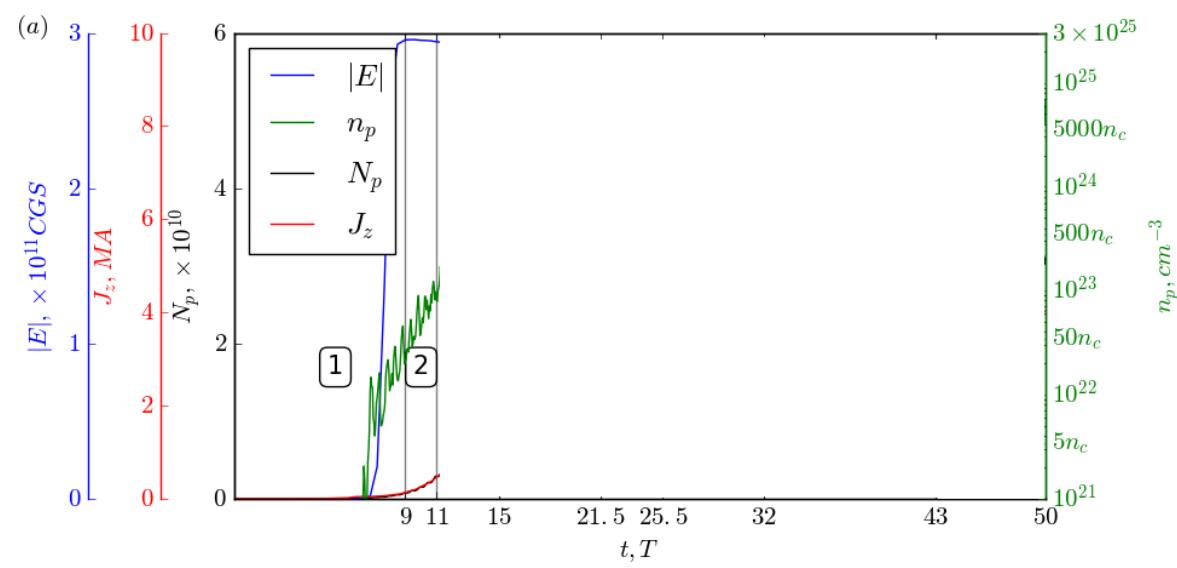
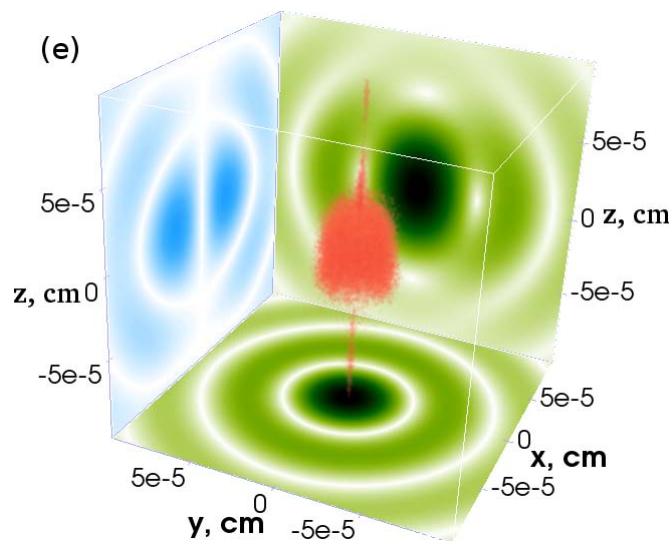
Limitation of cascades and formation of overdense electron-positron plasma states

- 1 stage – compression of the target
- Target is compressed and standing wave is formed



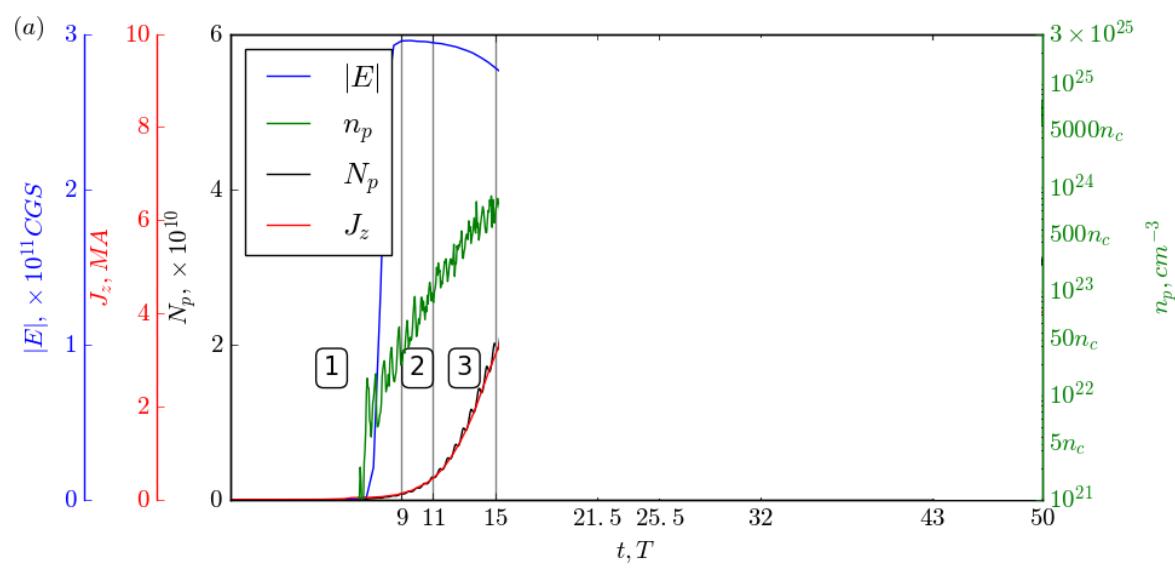
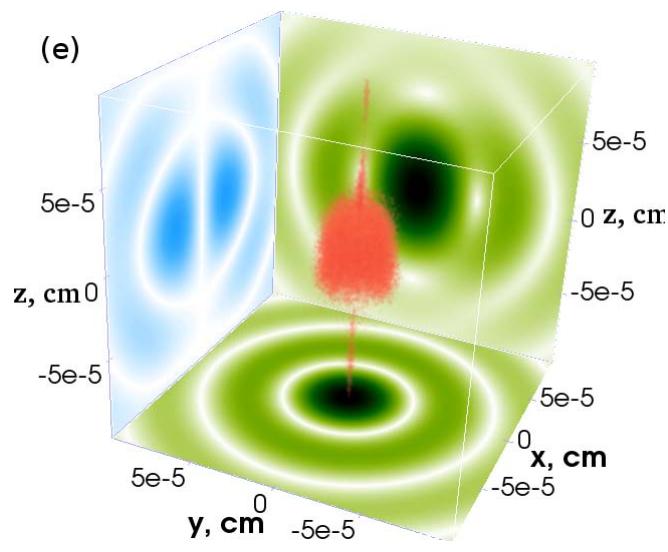
Overdense electron-positron plasma states

- 2 stage – linear cascade
- $P > P_{th}$ (7.2 PW ideal dipole wave)
- ART regime



Overdense electron-positron plasma states

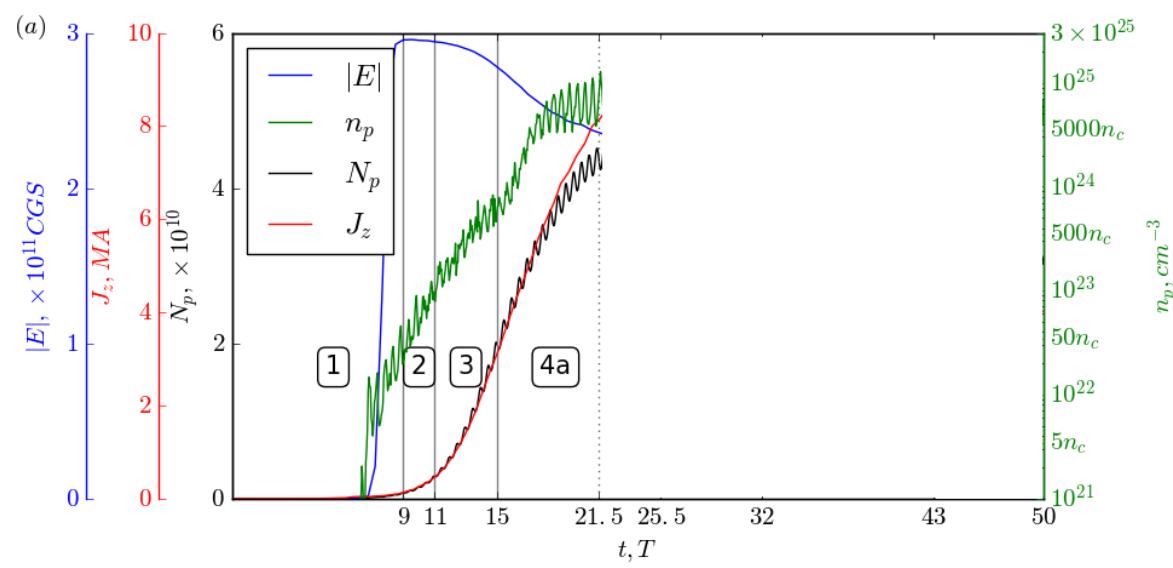
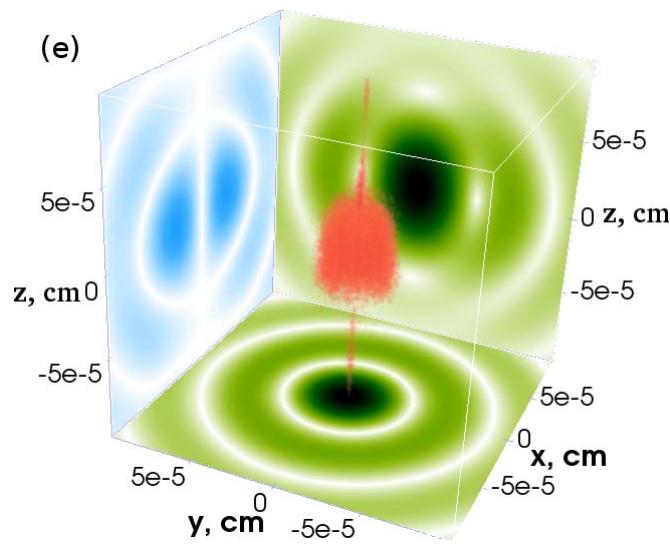
- 3 stage – nonlinear cascade
- Density becomes comparable to γn_c
- Distribution is uniform



Overdense electron-positron plasma states

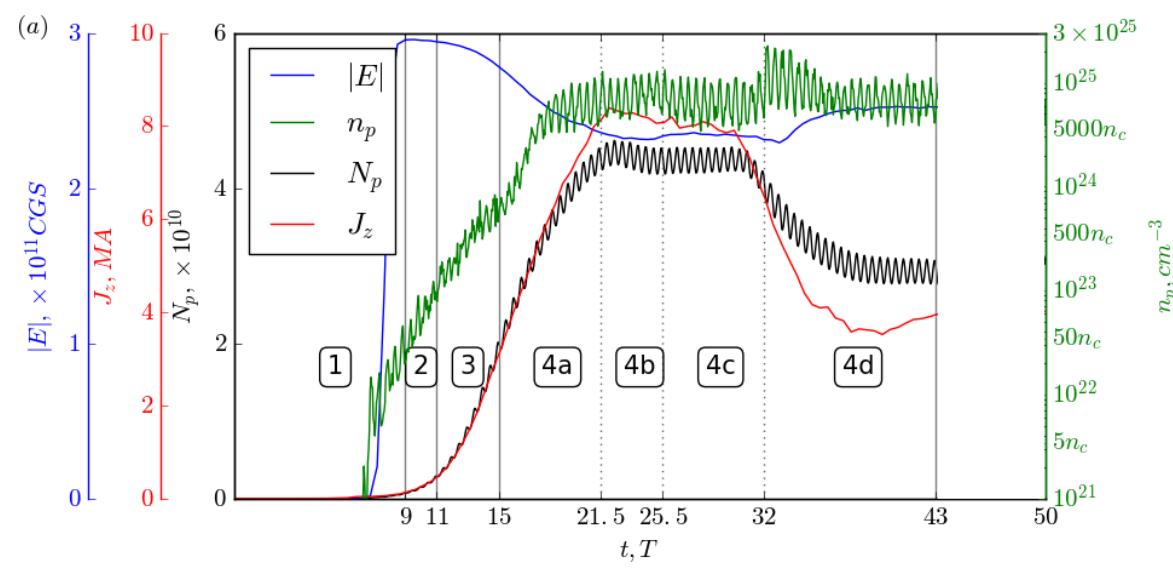
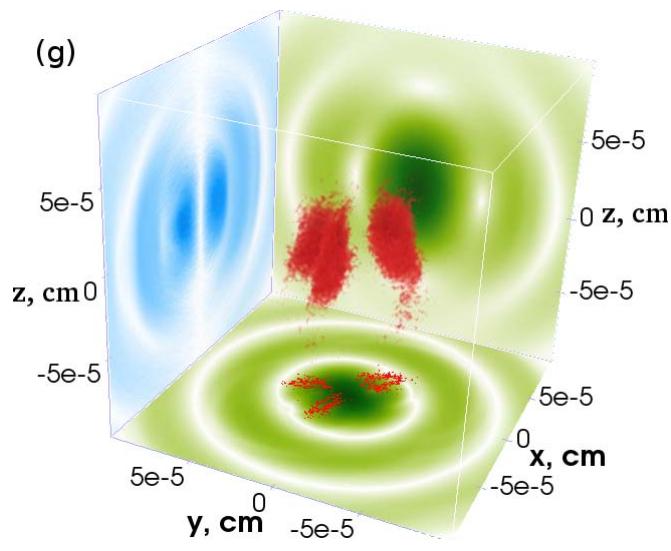
- 4 stage – current (Weibel type) instability
- Density becomes nonuniform

$$\Gamma = \frac{\omega_p}{\sqrt{\gamma_0}} \frac{v_0}{c} \approx \frac{\omega_p}{\sqrt{\gamma_0}}$$



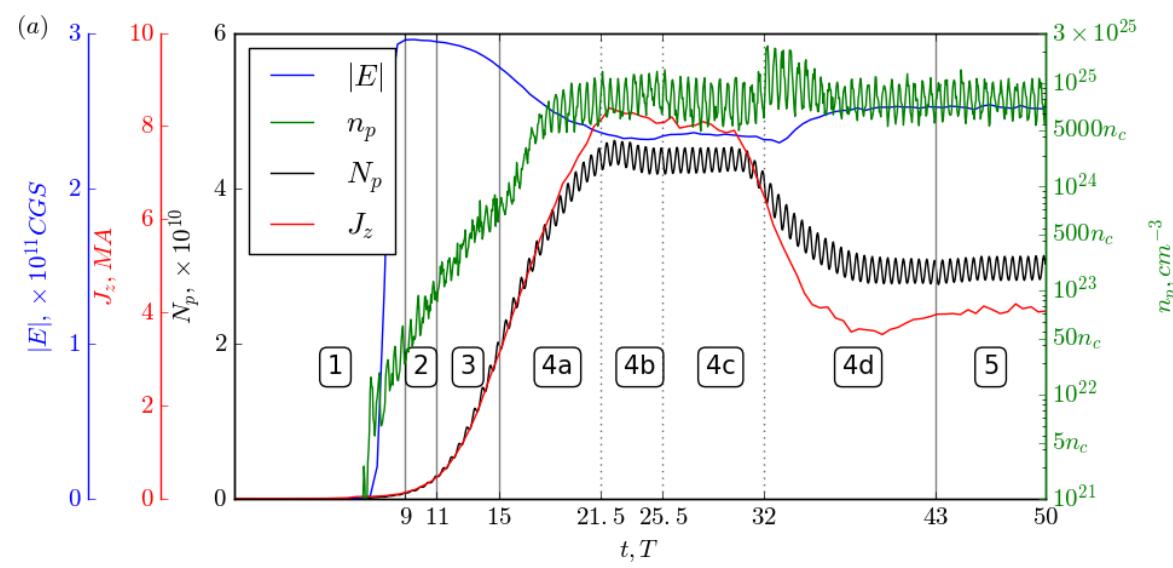
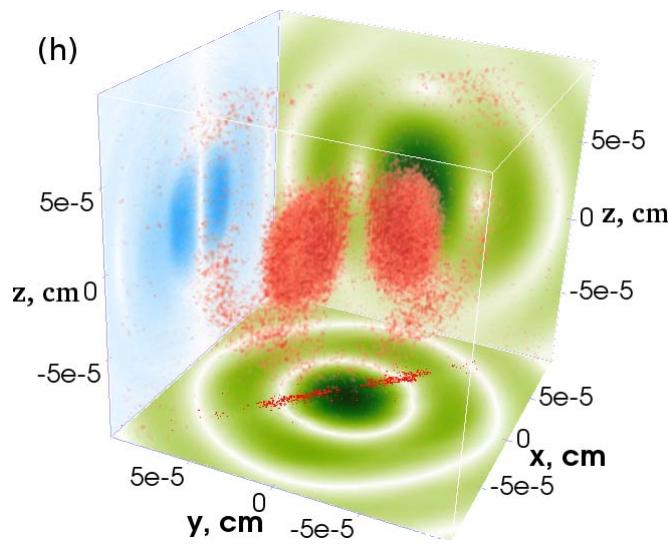
Overdense electron-positron plasma states

- 4 stage – current merger
- Density distribution is a number of sheets
- After each merger relaxation

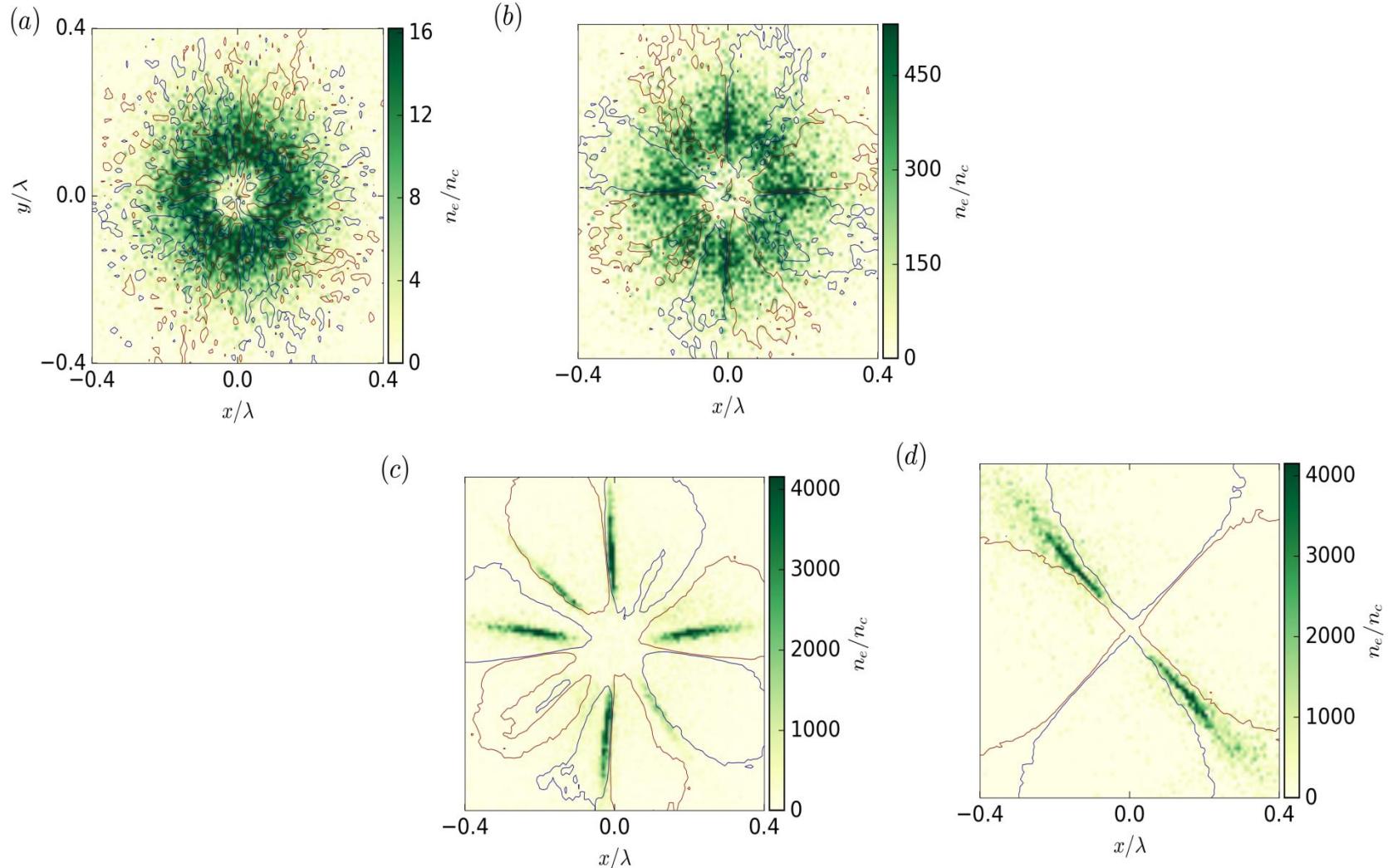


Overdense electron-positron plasma states

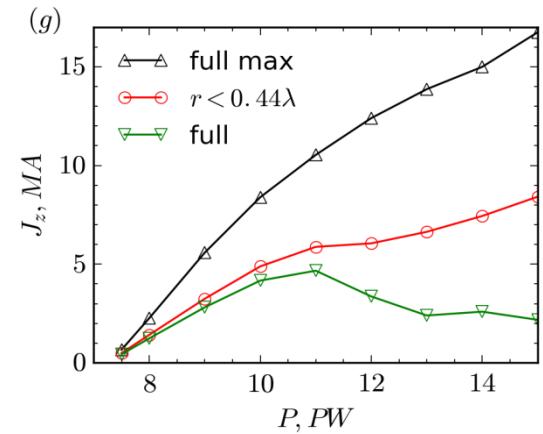
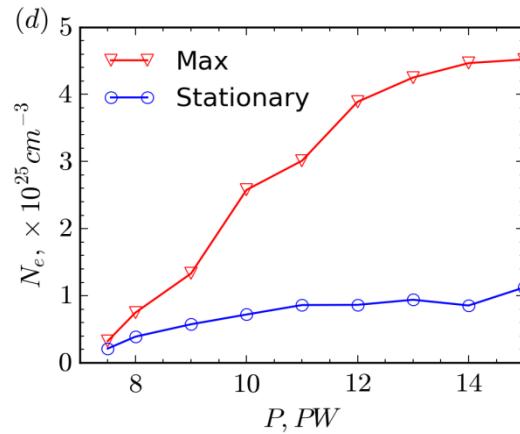
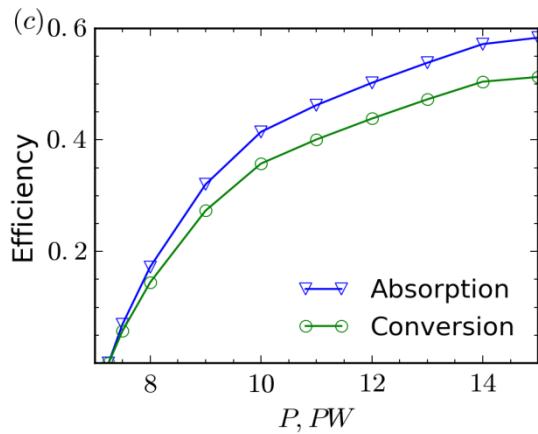
- 5 stage – steady state (for $> 50-100T$)
- Density distribution is two-sheets distribution
- Always reached



Overdense electron-positron plasma states



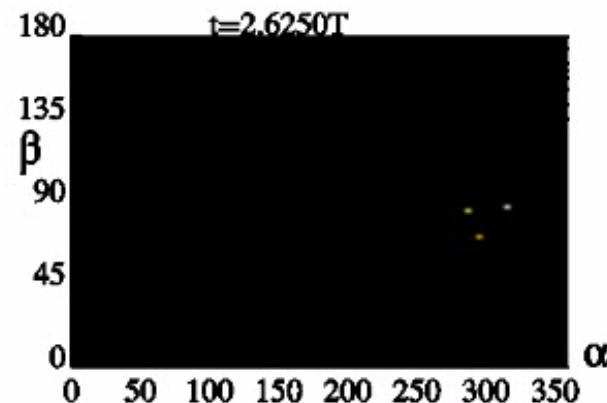
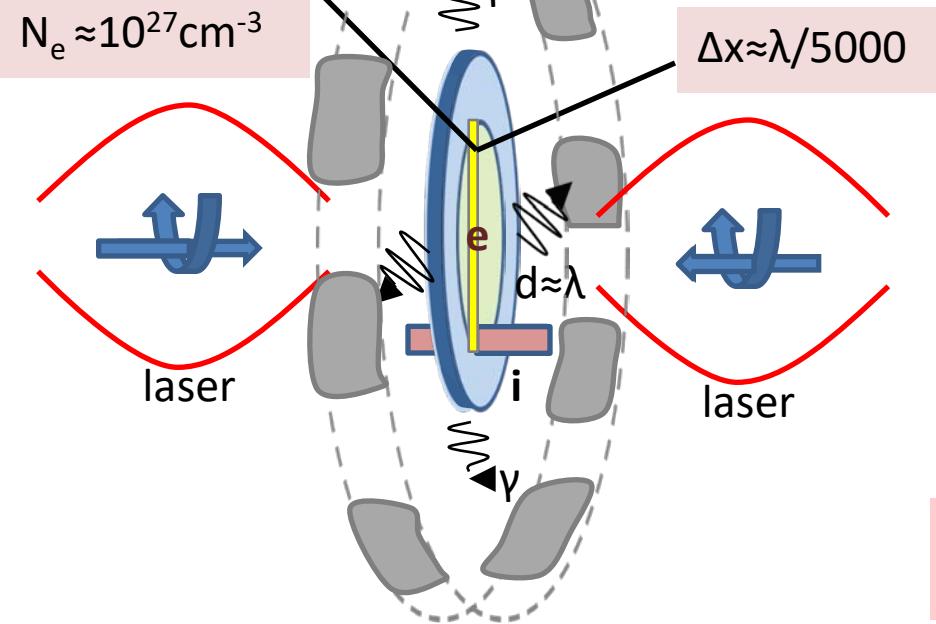
Overdense electron-positron plasma states



- Efficiency up to 60%
- Current $\sim 3\text{-}5 \text{ MA}$ (steady state), $10\text{-}15 \text{ MA}$ (nonlinear stage)
- Pair plasma density $\sim 10^{25} \text{ cm}^{-3}$

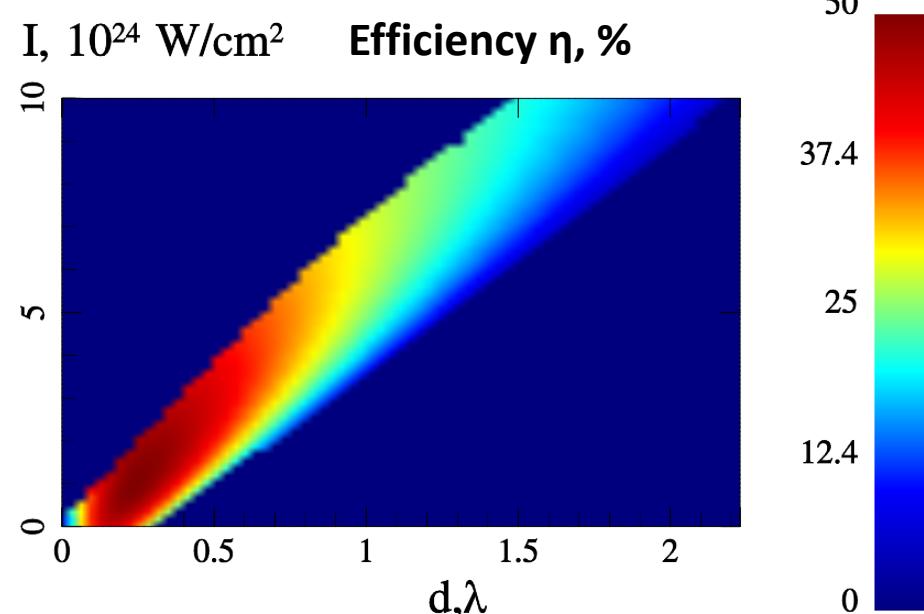
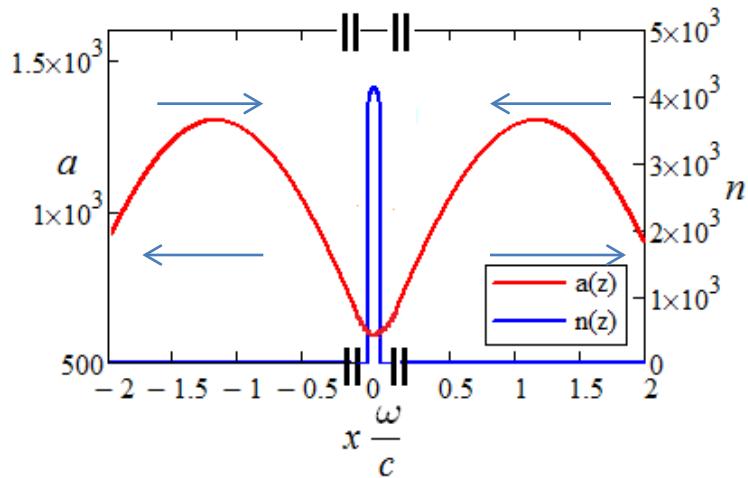


GAMMA LIHGT HOUSE SOURCE WITH CIRCULARLY POLARIZED COLLIDING PULSES



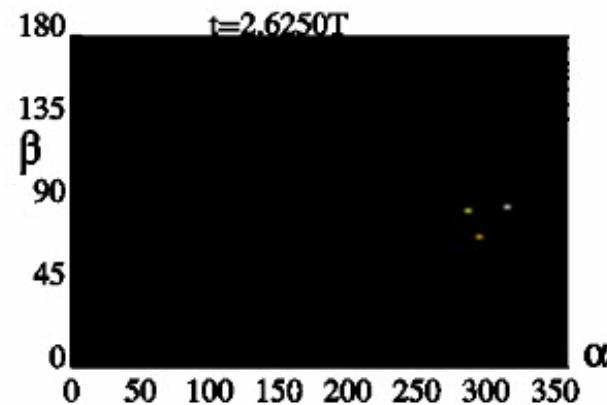
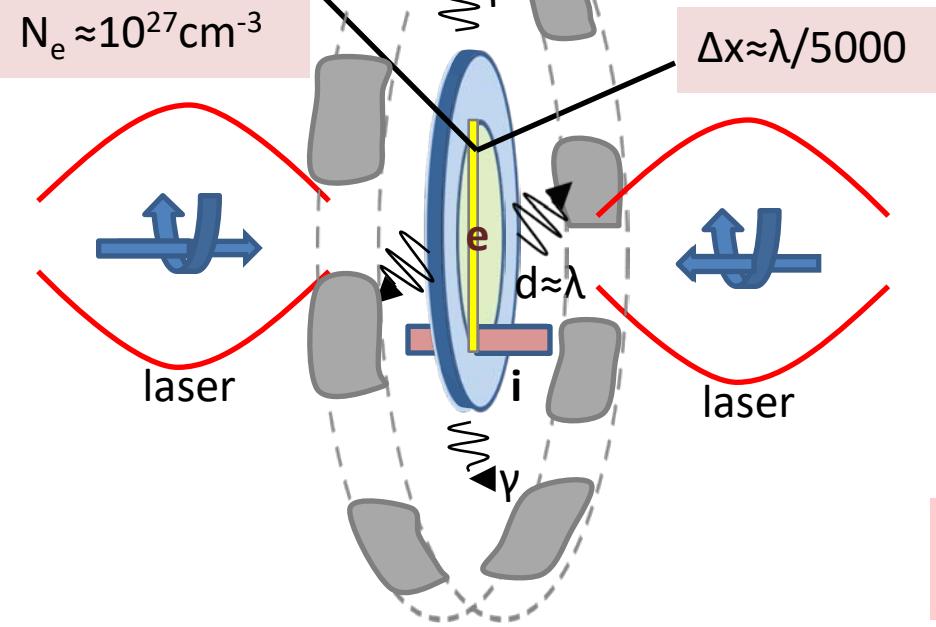
$$\langle E_{ph} \rangle \sim 30 \text{ MeV} \quad \langle E_{el} \rangle \sim 190 \text{ MeV} \quad \langle E_{pos} \rangle \sim 200 \text{ MeV}$$

$$\eta \sim 40\% \quad \eta \sim 5\% \quad \eta \sim 1\%$$



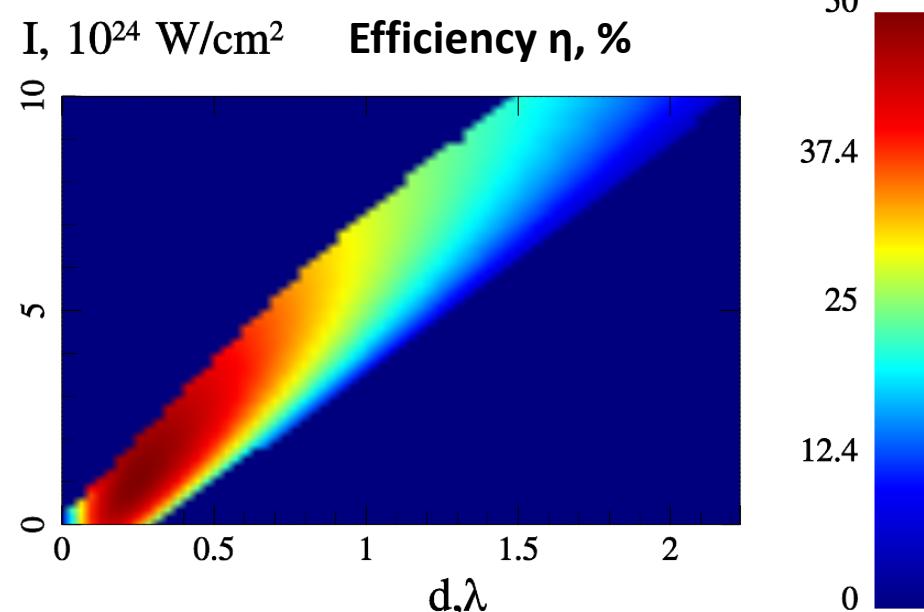
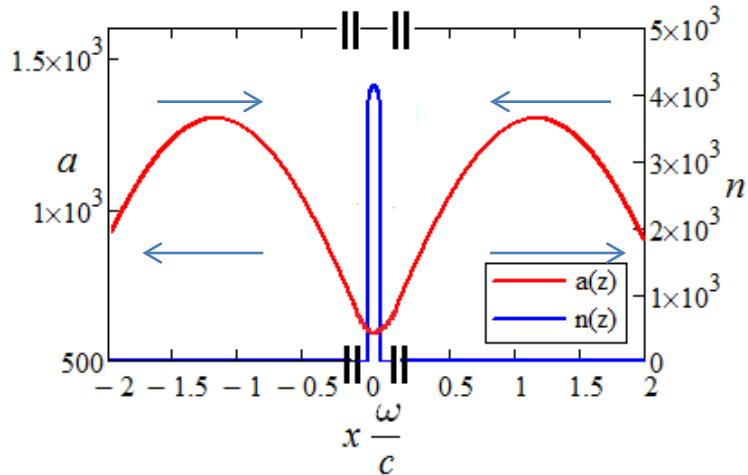


GAMMA LIHGT HOUSE SOURCE WITH CIRCULARLY POLARIZED COLLIDING PULSES



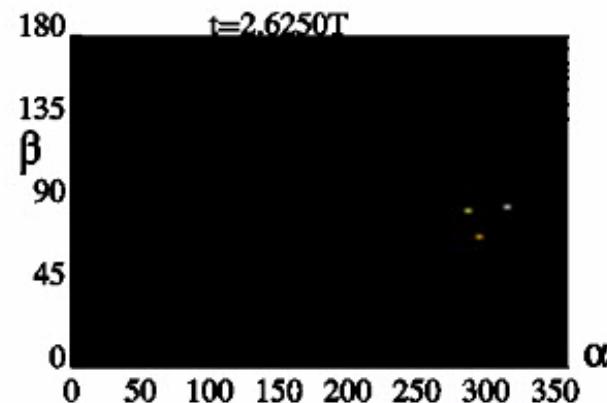
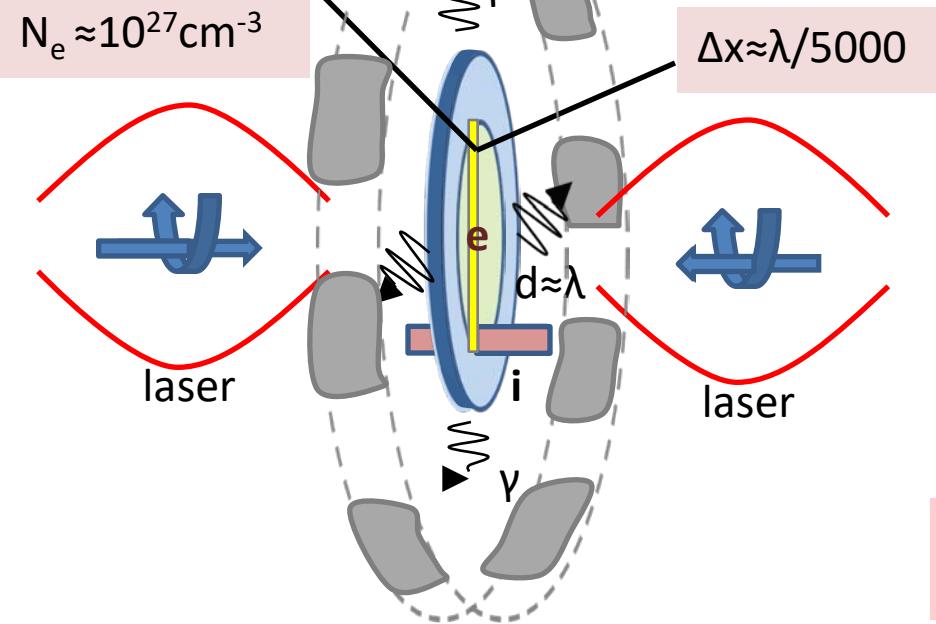
$$\langle E_{ph} \rangle \sim 30 \text{ MeV} \quad \langle E_{el} \rangle \sim 190 \text{ MeV} \quad \langle E_{pos} \rangle \sim 200 \text{ MeV}$$

$$\eta \sim 40\% \quad \eta \sim 5\% \quad \eta \sim 1\%$$



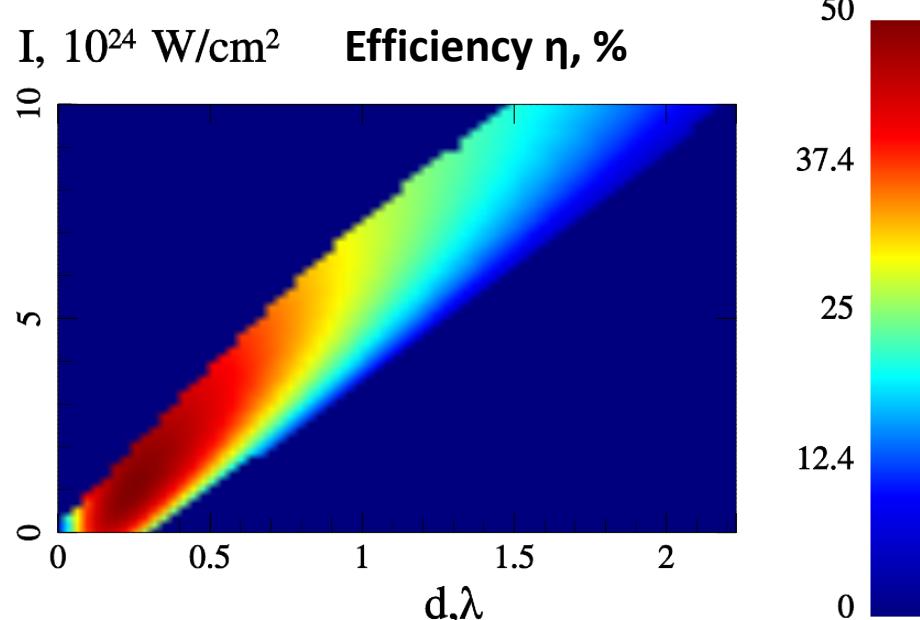
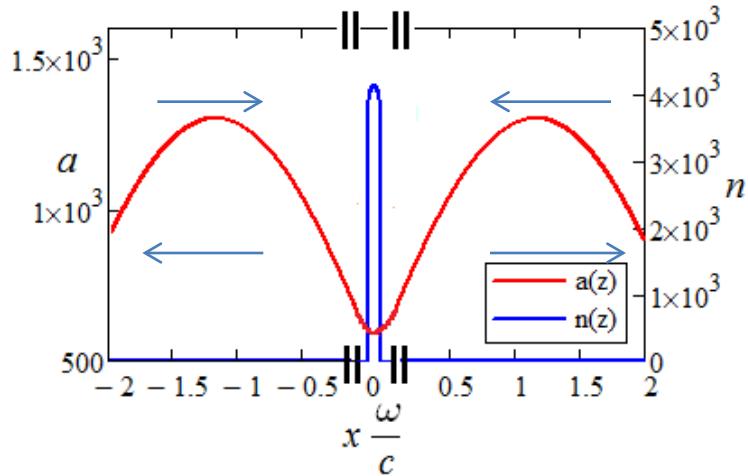


GAMMA LIHGT HOUSE SOURCE WITH CIRCULARLY POLARIZED COLLIDING PULSES



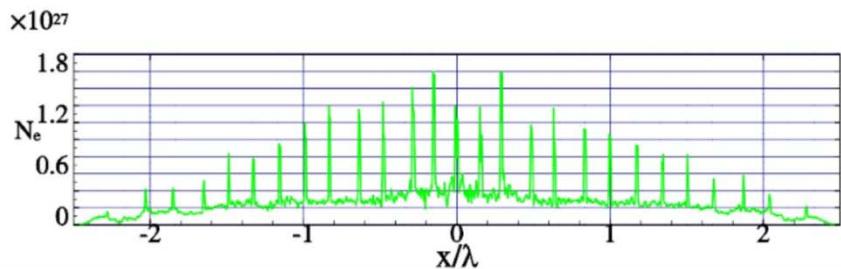
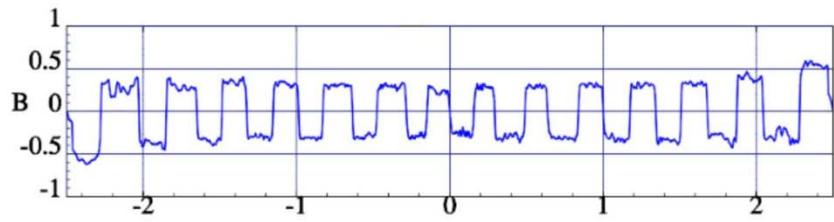
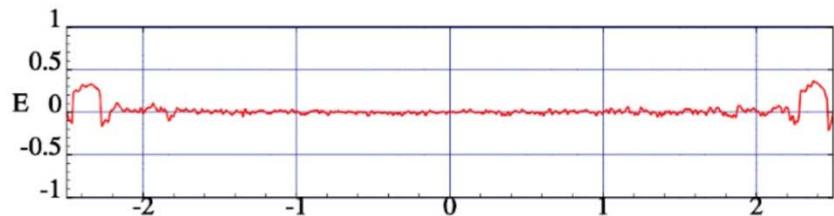
$$\langle E_{ph} \rangle \sim 30 \text{ MeV} \quad \langle E_{el} \rangle \sim 190 \text{ MeV} \quad \langle E_{pos} \rangle \sim 200 \text{ MeV}$$

$$\eta \sim 40\% \quad \eta \sim 5\% \quad \eta \sim 1\%$$





QED cascades in counter-propagating linearly polarized laser pulses and generation of giant magnetic fields



A.Muraviov et al, JETP Lett 2015



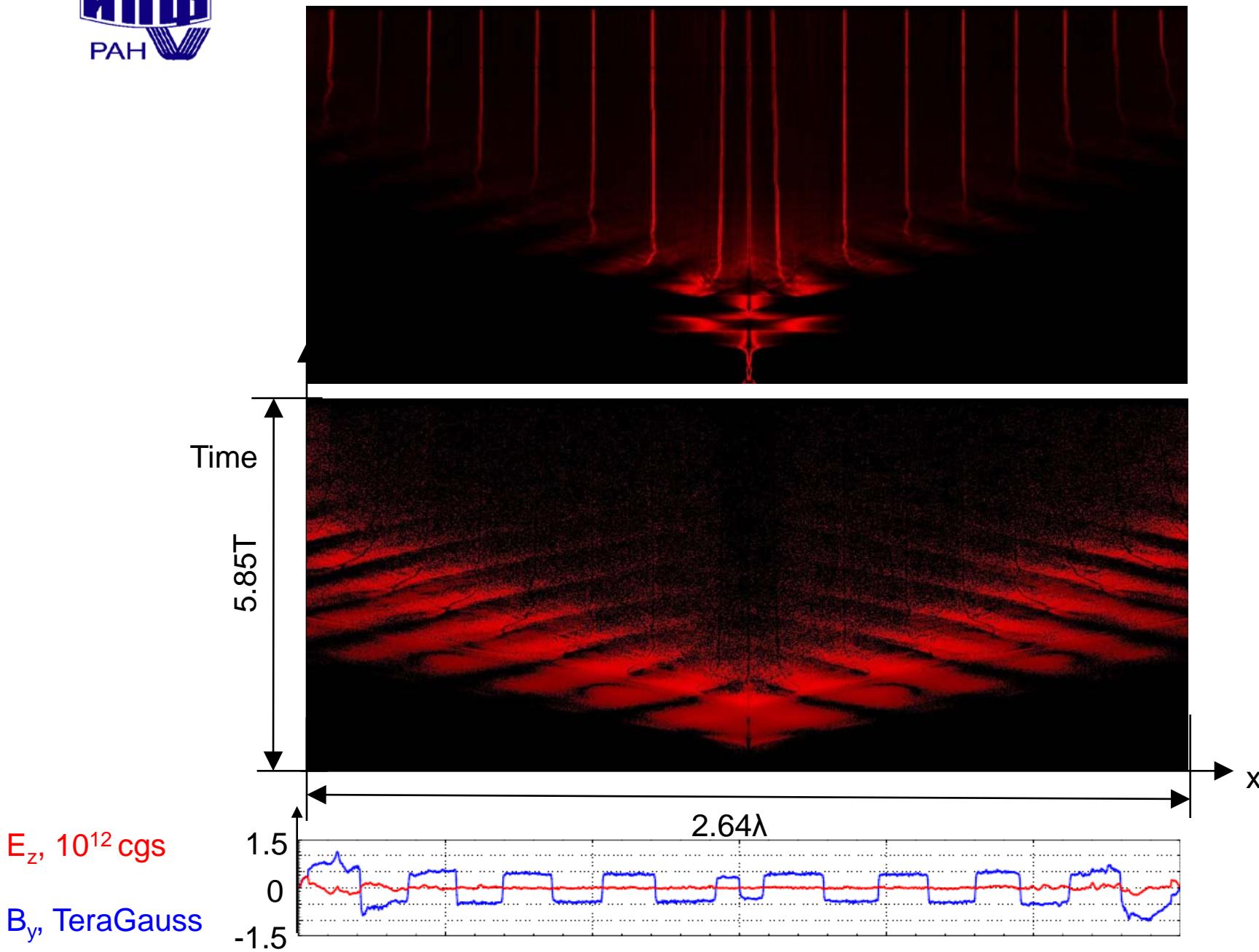
Plasma density time-space map

e-e+ avalanche fine structure and dynamics at $a=5000$
 $(I=7.5 \cdot 10^{25} \text{ W/cm}^2)$

Plasma density in current sheets exceeds 10^{27} cm^{-3}
Quasi-static magnetic field approaches $6 \cdot 10^{11} \text{ G}$



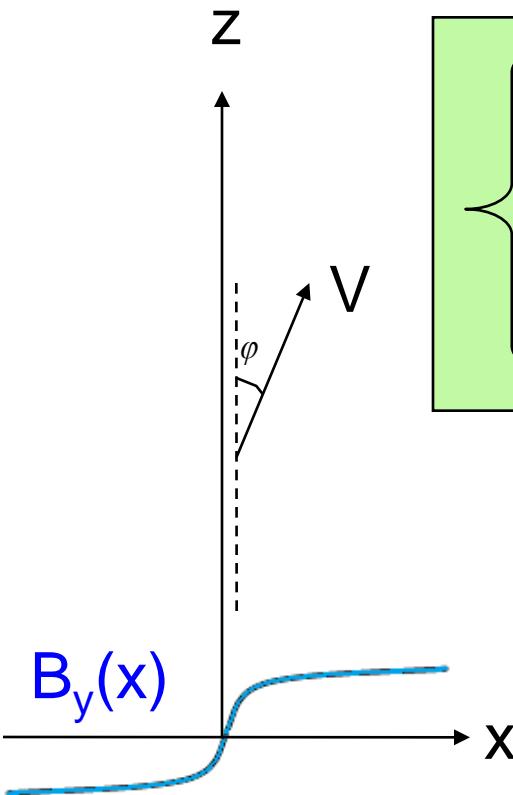
Gamma photon birth and death time-space map



Анализ движения частиц в токовых слоях

Исследование установившегося слоя (E_z уже выдано):

Движение частиц в *постоянной* структуре магнитного поля без учёта радиационных потерь:



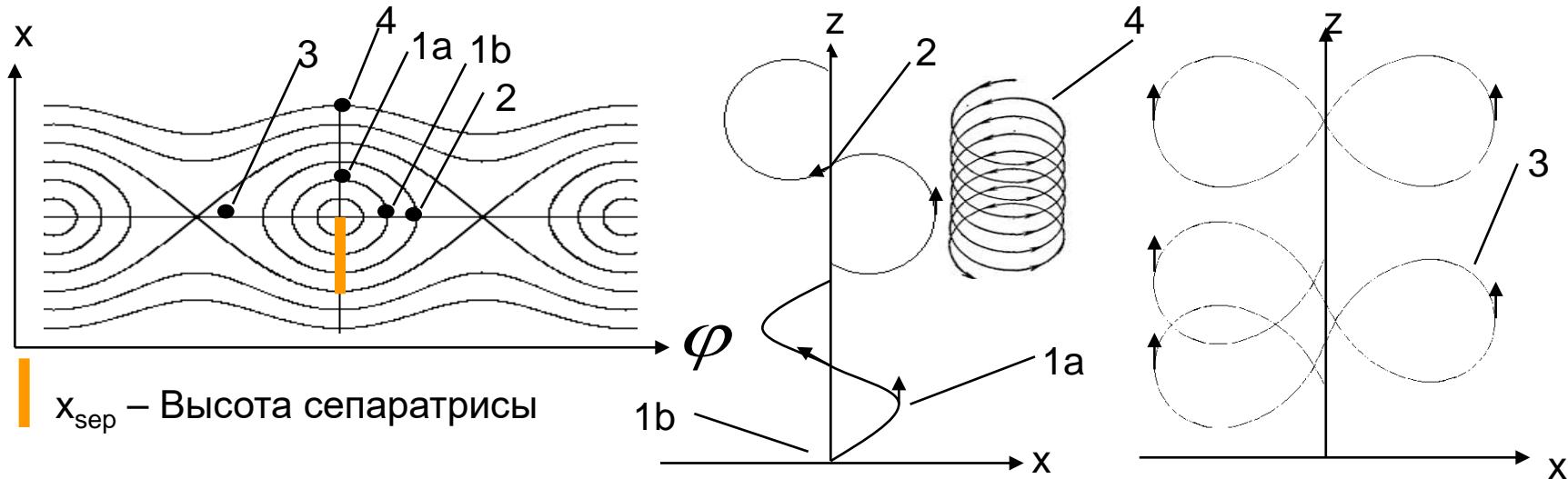
$$\begin{cases} \frac{\partial x}{\partial t} = V \sin \varphi \\ \frac{\partial \varphi}{\partial t} = -\omega = -\frac{eB_y}{mc\gamma} \end{cases}$$

➡ $\frac{\partial^2 \varphi}{\partial t^2} = -\frac{e}{mc\gamma} \frac{\partial B_y}{\partial x} \frac{\partial x}{\partial t} = -\frac{e}{mc\gamma} \frac{\partial B_y}{\partial x} V \sin \varphi$

Вблизи центра токового слоя, где B_y может быть линеаризовано, уравнение принимает **точную форму уравнения маятника**.

Хотя движение в отличающемся от линейного магнитном поле не совпадает точно с движением маятника, монотонность $B_y(x)$ позволяет утверждать, что **топология фазового пространства останется неизменной**.

Траектории электрона в фазовом пространстве и на плоскости xz



Незахваченные траектории (4) лежат снаружи сепаратрисы и соответствуют лармороподобному движению электрона или вращению маятника по полной окружности

Захваченные траектории (1-3) лежат внутри сепаратрисы и соответствуют осцилляциям электрона вокруг нулевой точки магнитного поля или обычным колебаниям маятника

Траектории с меньшим разбросом угла (1) – наиболее **токонесущие** траектории, следовательно именно они в наибольшей степени влияют на структуру магнитного поля.

Модель радиационного трения в виде непрерывной силы

$$F_{rad} = -\frac{-2e^4}{3m^2c^5(1-\frac{V^2}{c^2})} V \left[(E + \frac{1}{c}[VH])^2 - \frac{1}{c^2}(EV)^2 \right]$$

$$\frac{d\gamma}{dt} \sim -\gamma^2 F_\perp^2$$

Учитывая $F_\perp \sim x$ и сделав замену $\mu = \frac{1}{\gamma}$,

Можно получить третье уравнение: $\frac{d\mu}{dt} = Dx^2$

После избавления от констант путем замен, система сводится к:

$$\begin{cases} \frac{\partial \phi}{\partial t} = -\mu x \\ \frac{\partial x}{\partial t} = V(\mu) \sin \phi \\ \frac{\partial \mu}{\partial t} = Dx^2 \end{cases}$$

Адиабатический инвариант ($\phi \ll 1$):

$$\frac{d}{dt}(A^4 \omega) = const$$

$$\omega \sim t^{\frac{2}{5}} \quad A \sim t^{-\frac{1}{10}}$$

Обужение токового слоя при радиационном охлаждении частиц

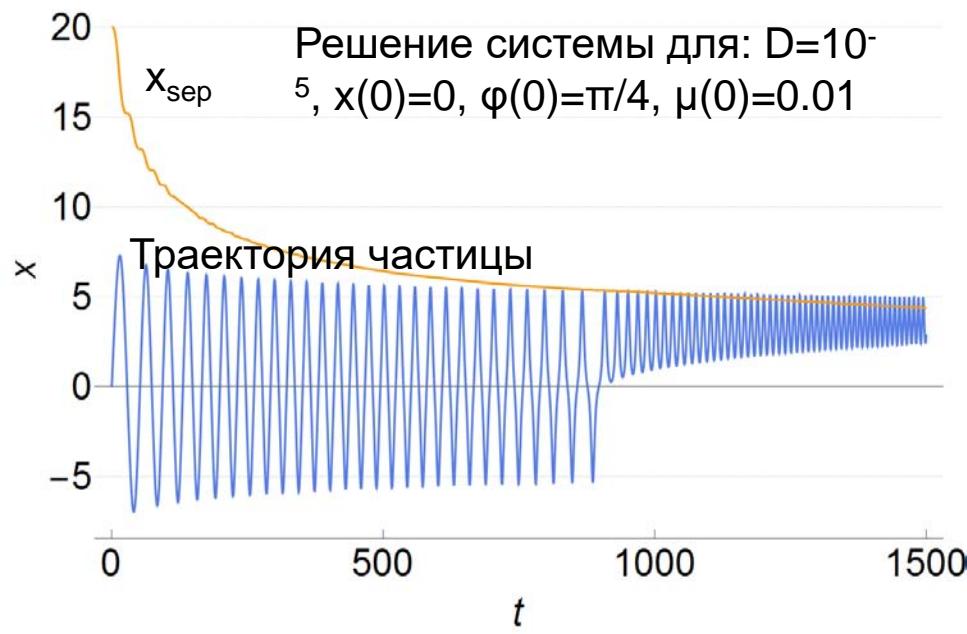
Радиационные потери приводят к постепенному изменению фазовой плоскости. В частности, можно получить:

$$A \sim t^{-\frac{1}{10}}$$

, где A – амплитуда осцилляций частицы

$$x_{sep} = 2\sqrt{\frac{1}{\mu}} \sim t^{-\frac{2}{5}}$$

Сепаратриса сжимается быстрее, чем уменьшается амплитуда.

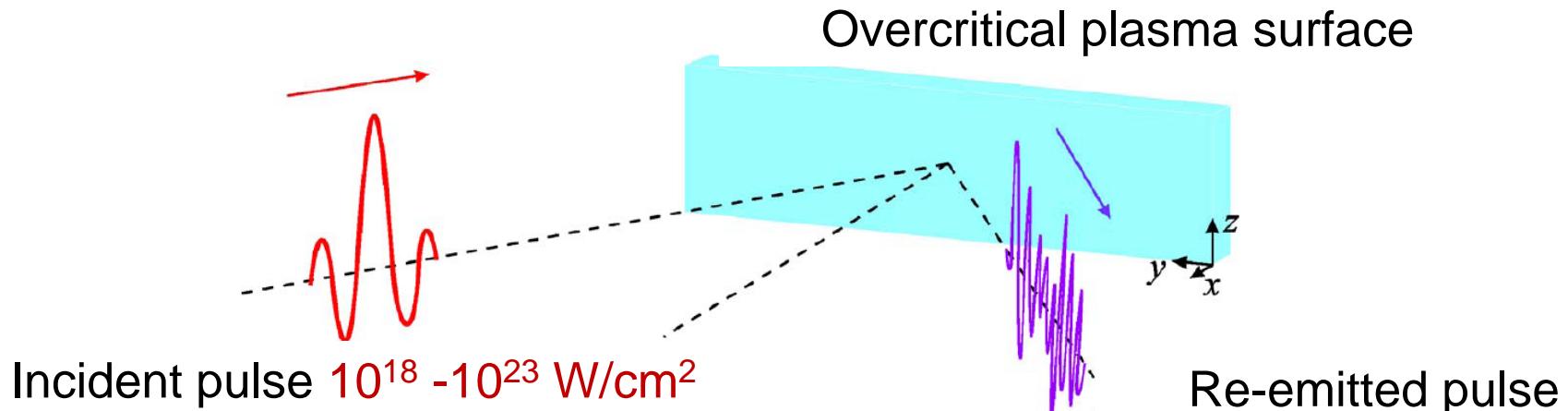


Есть потери частиц с внешних траекторий, испытывающих более сильное магнитное поле

Токовый слой утоньшается с небольшой потерей общего тока



XCELS 10^{26} W/cm²-and-Beyond Program



Oscillating Mirror Model (OMM)

- S.V. Bulanov et al., Phys. Plasmas (1994)
- S.R. Lichters et al., Phys. Plasmas (1996)
- S. Gordienko et al, PRL (2004)
- N. M. Naumova et al, PRL (2004)
- T. Baeva et al., PRE (2006)
- D. an der Brugge et al, Phys. Plasmas (2010)

Incident pulse $>10^{23}$ W/cm²

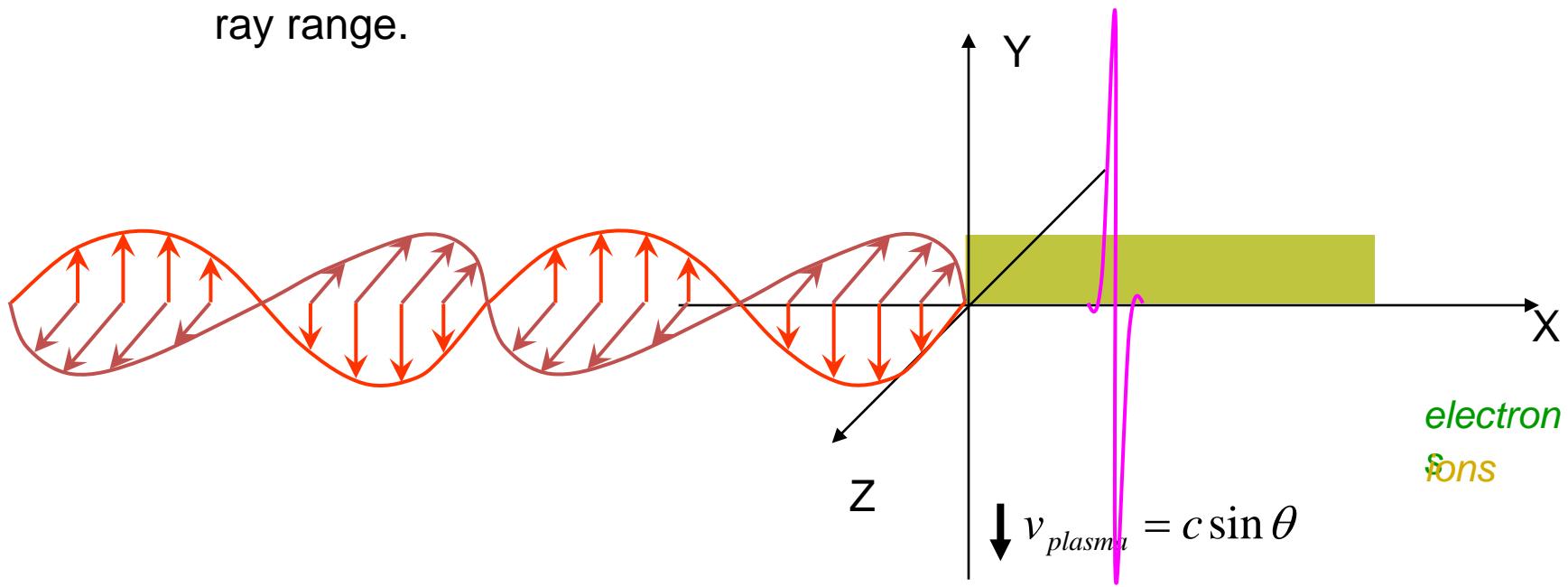
Relativistic Electronic Spring (RES) Model

- A.Gonoskov et al, PRE (2011)
- J.Fuchs et al, EJP (2014)

Effect of Relativistic Electronic Spring

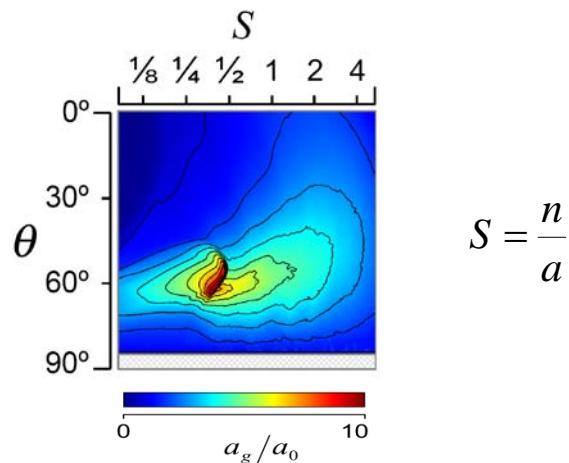
Stages:

- 1) pushing of electrons and the formation of a thin current layer-nanoplasmonic structure, which results in energy transfer from the laser field to the plasma fields and particles;
- 2) backward motion of the electrons towards the incident wave with conversion of energy accumulated in the plasma and laser field energy into the kinetic energy of an ultrarelativistic electron bunch;
- 3) radiation of the attosecond pulse by an electron bunch due to conversion of the kinetic energy and laser field energy to the XUV and X-ray range.

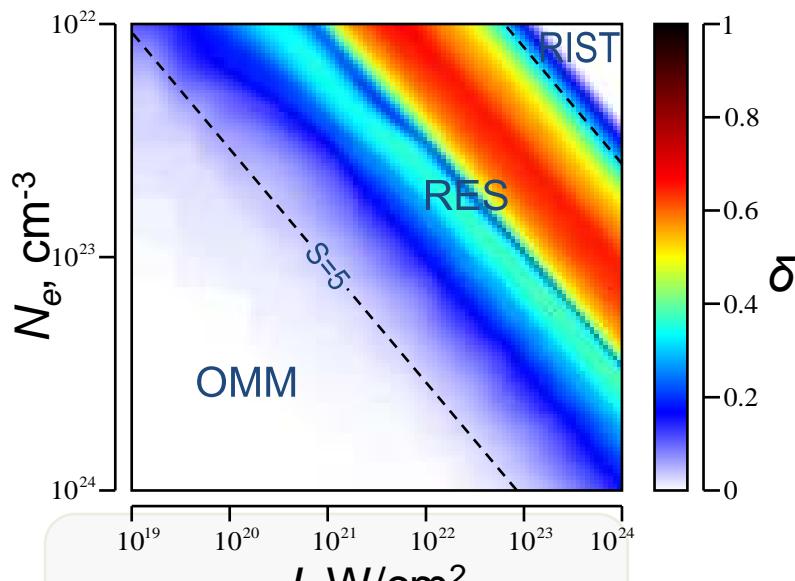




Optimal Conditions and Efficiency of Giant Attosecond Pulse Generation



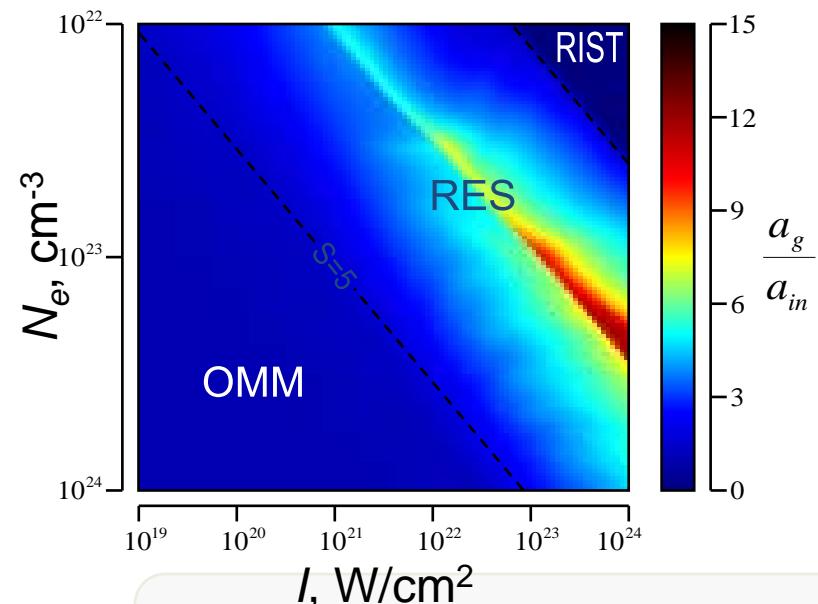
$$S = \frac{n}{a}$$



$\delta = W_{acc} / W_{cycle}$ – coefficient of energy transformation
 a_g/a_{in} – amplitude enhancement

A.Gonoskov et al, Phys. Rev. E (2011)
J. Fuchs et al, EJP (2014)

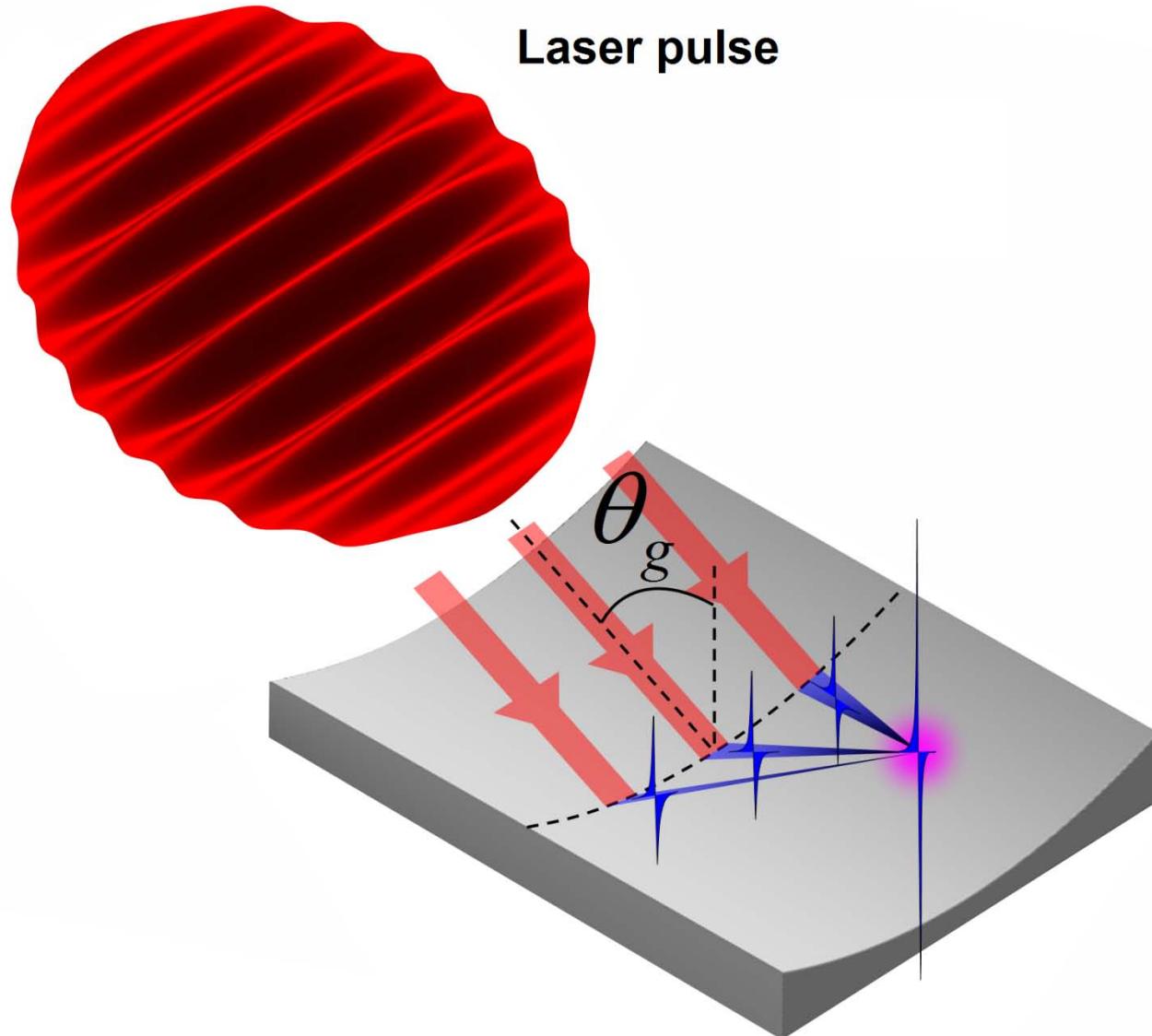
Classification of Interaction Type:
OMM- oscillating mirror
RES - relativistic electronic spring
RIST - relativistically induced solid target transparency



M. Behmke et al, PRL (2011)
experiment



Groove Shape Target and Superluminal Focal Spot

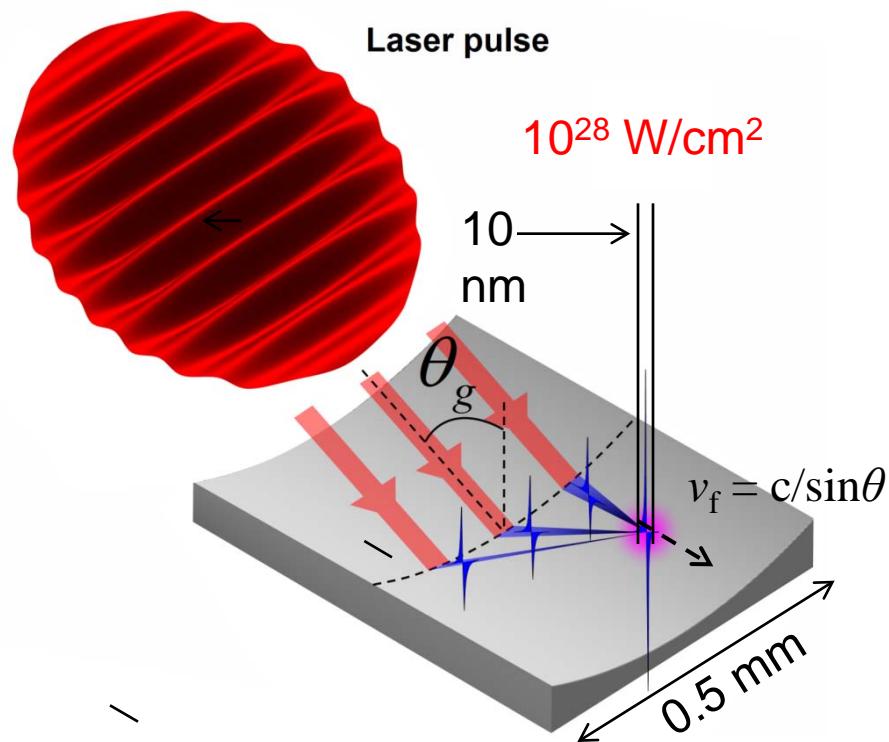


Pair Production from Vacuum with Attosecond Superluminal Probe

For 200 PW and 10^{23}W/cm^2 at the groove target 0.5 mm wide we have 10^{28} W/cm^2 in the volume $V \sim 10 \text{nm}^3$

Number of pairs $N \sim \frac{c\tau V}{\lambda_C^4} \exp\left(-\pi \frac{E_S}{E}\right) \quad \rightarrow \quad N \sim 10^9$

Cascades are strongly suppressed due superluminal motion of the focal area





In Conclusion

- We are at the entrance to a new realm of physical phenomena
- Exawatt-scale lasers will bring particle dynamics in the radiation dominated regime
- QED cascades and radiation trapping of particles produce ultrarelativistic, ultradense e-e+ plasma that efficiently convert optical energy to gamma rays
- Controllable directed gamma ray sources of GeV photons with extreme brilliance will be soon available as a new instrument to study nuclear matter and vacuum physics
- Laboratory astrophysics will be provided with Gigagauss and Teragauss magnetic fields on the Earth
- By energy conversion from femtosecond to attosecond pulses, the Schwinger field can be approached and time-space structure of vacuum can be studied