Extreme Field Limits in the Interaction of Electromagnetic Waves with Matter

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Ginzburg Conference on Physics
28th May – 2nd June 2012
Lebedev Institute
Moscow, Russia

Three Books

V. L. Ginzburg and S. I. Syrovatskii, The Origin of Cosmic Rays (Rergamon, Oxford, 1964)

V. L. Ginzburg, The Propagation of Electromagnetic Waves in Plasmas (Pergamon, Oxford, 1970)

V. L. Ginzburg, Applications of electrodynamics in theoretical physics and astrophysics (CRC, 1989)

Acknowledgment

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Stanford University, CA, USA

Preface

•The critical electric field of quantum electrodynamics, called also the Schwinger field, is so strong that it produces electron-positron pairs from vacuum, converting the energy of light into matter. Since the dawn of quantum electrodynamics there has been a dream on how to reach it on Earth. With the rise of the laser technologies this field becomes feasible through construction of extreme power lasers or/and with the sophisticated usage of nonlinear processes in relativistic plasmas. This is one of the most attractive motivations for extreme power laser development, i.e. producing matter from vacuum by pure light in fundamental process of quantum electrodynamics in the nonperturbative regime.

• Recently were realized that the laser with intensity well below the Schwinger limit can create an avalanche of electron-positron pairs similar to a discharge before attaining the Schwinger field. It was also realized that the Schwinger limit can be reached using an appropriate configuration of laser beams.

• In the experiments on the collision of laser light and high intensity electromagnetic pulses generated by relativistic flying mirrors, with electron bunches produced by a conventional accelerator and with laser wake field accelerated electrons the studying of extreme field limits in the nonlinear interaction of electromagnetic waves is proposed. The regimes of dominant radiation reaction, which completely changes the electromagnetic wave-matter interaction, will be revealed. This will result in a new powerful source of high brightness gamma-rays. A possibility of the demonstration of the electron-positron pair creation in vacuum in a multi-photon processes can be realized. This will allow modeling under terrestrial laboratory conditions neutron star magnetospheres, cosmological gamma ray bursts and the Leptonic Era of the Universe.

Photon Science and Technology

USA

X-FEL (SLAC, 2010)
NIF (LLNL, 2009)

NIF

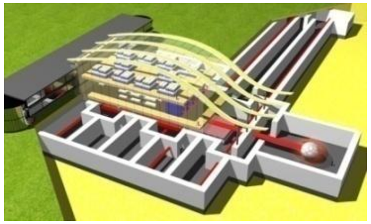
EU

LMJ, ILE

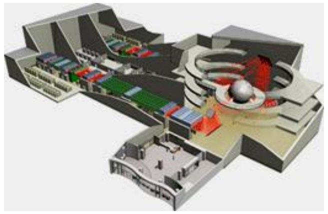
ELI, HiPER, X-FEL (2006)

ELI started
(Czech Rep., Romania, Hungary, 2010)

ELI



HiPER

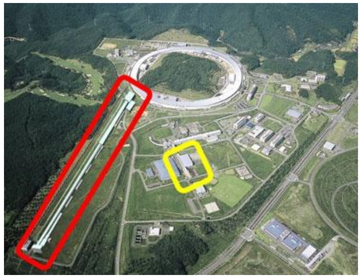


JAPAN

LFEX (ILE Osaka, 2003-2010)

X-FEL (RIKEN, 2006 – 2010)

SPring-8
X-FEL



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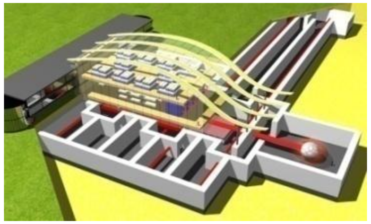
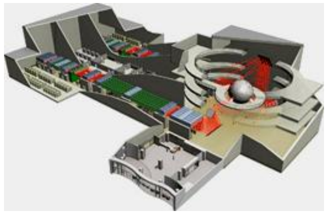


$\mathcal{P} > 100\,\mathrm{PW}$

$I > 10^{25}\,\mathrm{W/cm^2}$

HiPER



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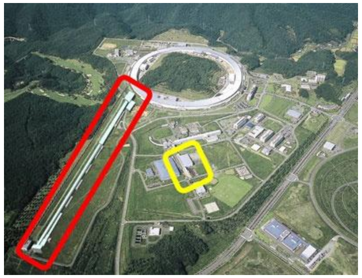
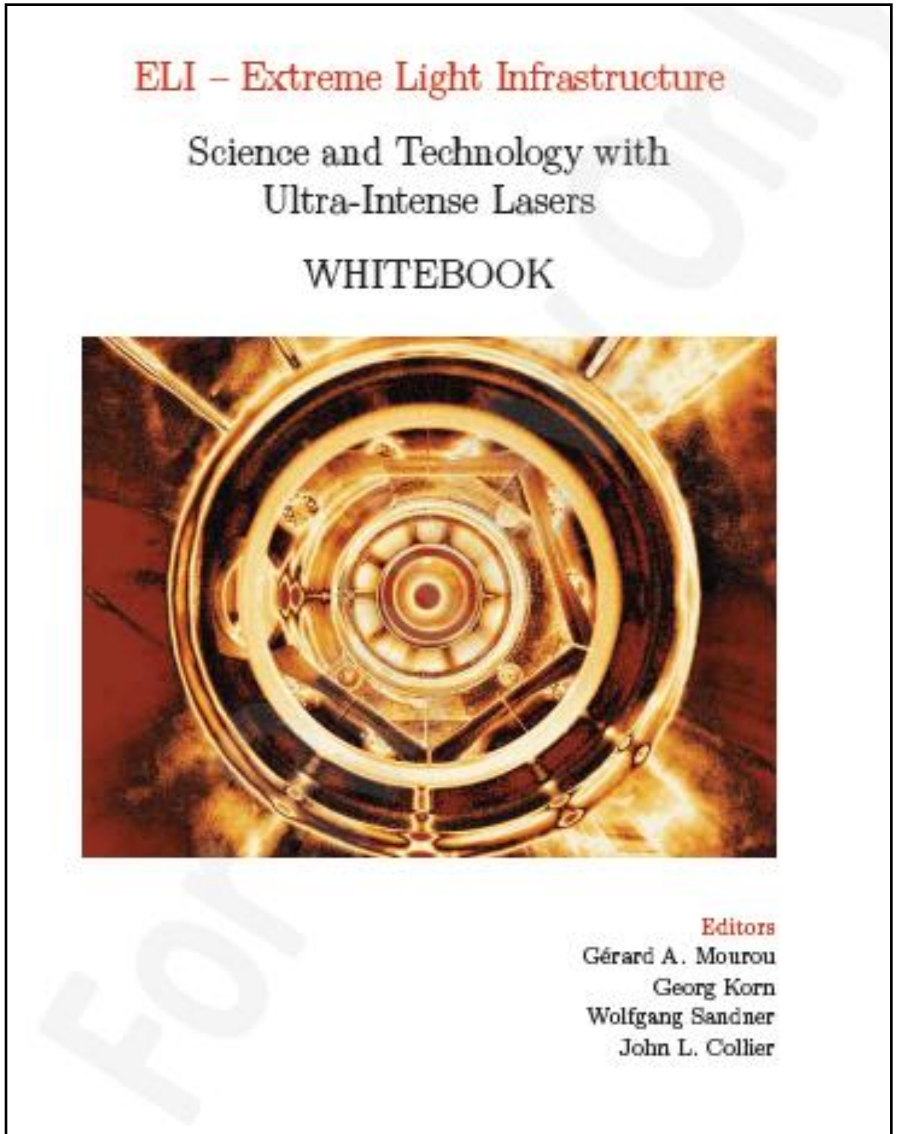



ELI – Extreme Light Infrastructure
Science and Technology with Ultra-Intense Lasers
WHITEBOOK
Editors
Gérard A. Mourou
Georg Korn
Wolfgang Sandner
John L. Collier

ELECTRON-POSITRON PLASMA

e^- - e^+ Plasma in the Terrestrial Laboratories

- Sub-MeV e^+ from radioactive isotopes or accelerators are used in material science:

  A. P. Mills, Science 218, 335 (1982); P. J. Schultz and K. G. Lynn, Rev. Mod. Phys. 60, 701 (1988); A.W. Hunt et al., Nature (London) 402, 157 (1999); D.W. Gidley, et al., Annu. Rev. Mater. Res. 36, 49 (2006); B. Oberdorfer, et al., Phys. Rev. Lett. 105, 146101 (2010)

- e^+ emission tomography:

  M. E. Raichle, Nature (London) 317, 574 (1985)

- Basic antimatter science such as antihydrogen experiments:

  M. Amoretti, et al., Nature (London) 419, 456 (2002);
  G. Gabrielse et al., Phys. Rev. Lett. 89, 213401 (2002)

- Bose-Einstein condensed positronium:

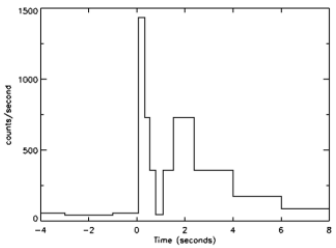
  P. M. Platzman and A. P. Mills, Phys. Rev. B 49, 454 (1994)

- Basic plasma physics:

  C. M. Surko and R. G. Greaves, Phys. Plasmas 11, 2333 (2004)

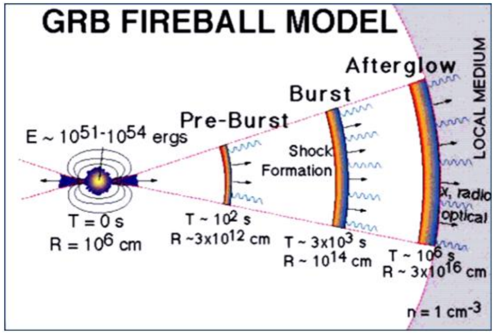
e - e+ Plasma in Space:

Gamma Ray Bursts   etc

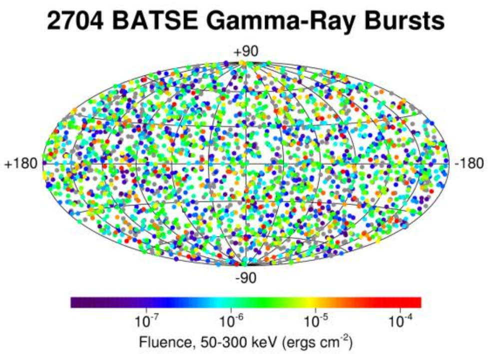


First GRB detected by Vela, 1967

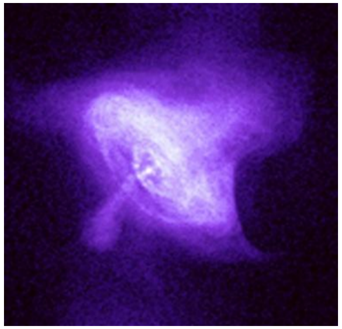
$E_{GRB} \approx 10^{53} erg$

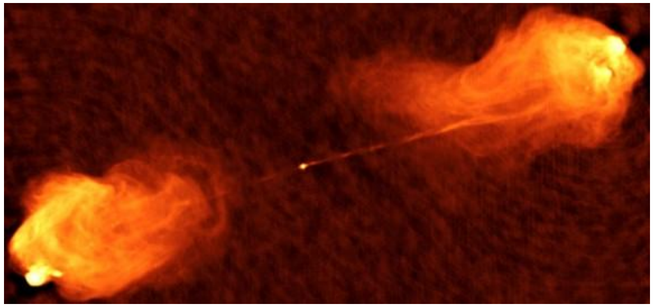


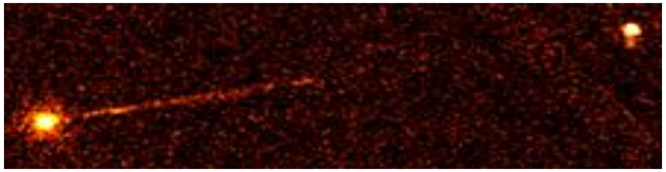
$(e^- \ e^+ \ p \ \gamma)$ - plasma



Meszaros, P., & Rees, M. J. 1992, MNRAS, 257, 29
Meszaros, P., & Rees, M. J. 1993, ApJ, 405, 278

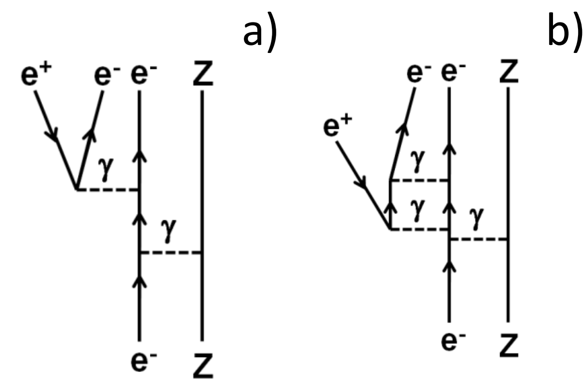




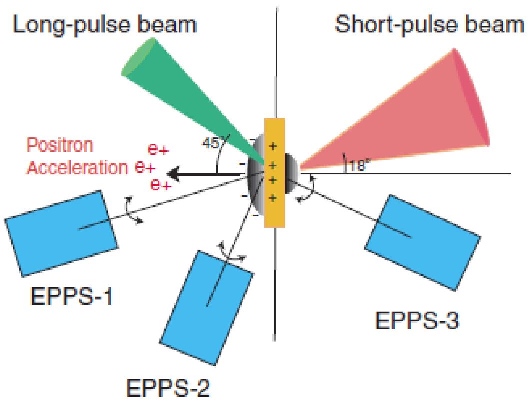


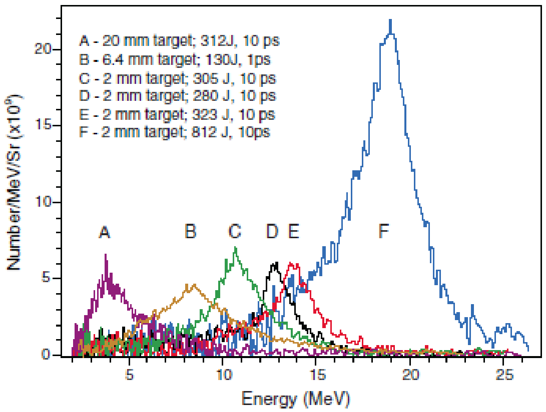
R. Blanford talk

$e^- e^+$ pairs created in laser plasmas



- $e^- e^+$ **generation in laser-solid target interaction (trident + Bethe-Heitler processes)**





a) *trident*

$$e^- + Z \to 2e^- + e^+ + Z$$

b) *bremsstrahlung*

$$e^- + Z \to \gamma + e^- + Z$$

pair production

$$\gamma + Z \to e^- + e^- + Z$$

C.Gahn, et al., Phys. Plasmas 9, 987 (2002)
H.Chen, et al., Phys. Plasmas 16, 122702 (2009)
H.Chen, et al., Phys. Rev. Lett. 105, 015003 (2010)

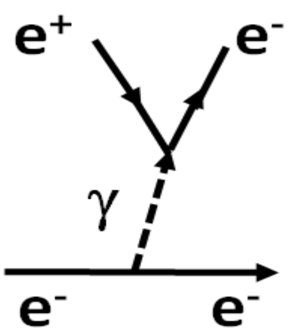
$$\sigma_{e^- Z \to e^+ e^- e^- Z} = (14/27\pi) r_e^{\,2} (\alpha Z)^2 \ln\left(1 + p^2/m_e^2 c^2\right)$$

$$r_e = e^2/m_e c^2, \qquad \alpha = e^2/\hbar c = 1/137$$

Breit-Wheeler process of e⁻ e⁺ generation

Breit-Wheeler process of e⁻ e⁺ generation $\hbar\omega + \hbar\omega' \rightarrow e^+ + e^-$ **with** $\sigma_{\omega\omega\rightarrow e^+e^-} \approx \alpha^2 r_e^2$

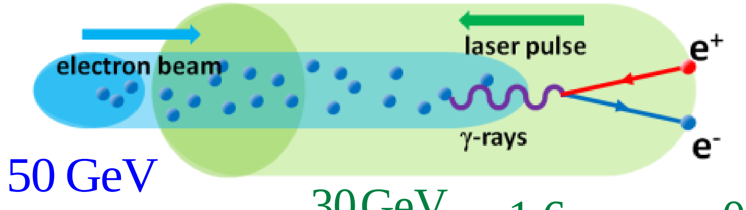
if $\hbar^2\omega\omega' > m_e^2 c^4$



Multiphoton inverse Compton
&
Multiphoton B-W processes

$$e^- + N\hbar\omega_0 \rightarrow \hbar\omega_\gamma + e^-$$

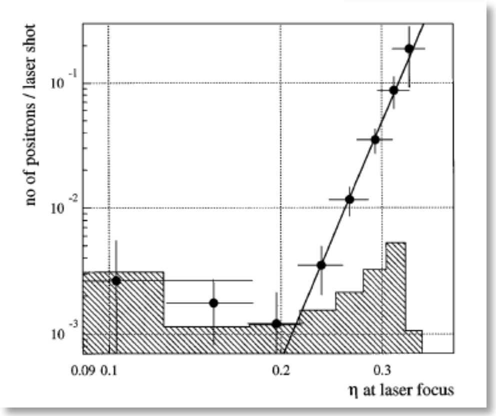
$$\hbar\omega_\gamma + N\hbar\omega_0 \rightarrow e^+ + e^-$$



$1.6\,ps \quad a_0 \approx 0.3$

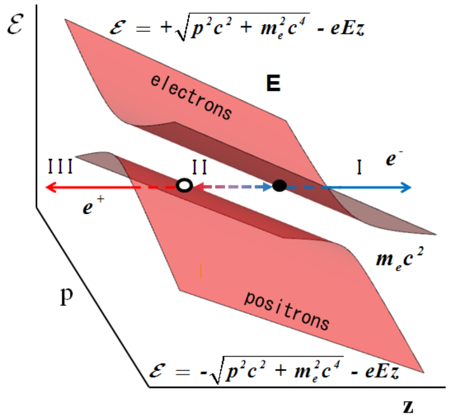
$$\chi_e = \frac{E}{E_S}\gamma_e \approx 0.3$$

$$\chi_\gamma = \frac{E}{E_S}\frac{\hbar\omega_\gamma}{m_e c^2} \approx 0.15$$



G. Breit, J. A. Wheeler, Phys. Rev. 46, 1087 (1934)
D. L. Burke, et al., Phys. Rev. Lett. 79, 1627 (1997)

"Schwinger" mechanism of e^-e^+ pair creation



The energy is plotted against the momentum and coordinate (the electric field is parallel z-axis). The solution to the Dirac equation shows that the ψ - function is large only in the regions I and III. In the region II, it decreases exponentially. Therefore the transmission coefficient through region II, which gives the pair creation probability, has the order of magnitude

$$\exp\left(-\pi m_e^2c^3 / |e| E\hbar\right)$$

Quasiclassical regime (F. Sauter, 1931)

$$w = A\exp\left(-\frac{2}{\hbar}\int_{z_1=-m_ec^2/eE}^{z_2=+m_ec^2/eE} |p(z)|\,dz\right)$$

$$= A\exp\left(-\frac{4m_e^2c^3}{|e|E\hbar}\int_0^1\sqrt{1-\xi^2}\,d\xi\right)$$

$$\propto \exp\left(-\frac{\pi E_S}{E}\right)$$

Probability (W.Heisenberg, H.Euler, 1936)

$$w = \frac{1}{4\pi^3}\left(\frac{|e|E\hbar}{m_e^2c^3}\right)^2\frac{m_ec^2}{\hbar}\left(\frac{m_ec}{\hbar}\right)^3\exp\left(-\frac{\pi m_e^2c^3}{|e|E\hbar}\right)$$

Upper Limit on the EM wave amplitude

We reach a limit when the nonlinear QED with the electron-positron pair creation in the vacuum comes into play, at the "Schwinger electric field", which corresponds to so strong electric field that it starts to create the electron-positron pairs at the Compton length $\lambda\!\!\!^{-}_C = \hbar / m_e c$ **, i.e.**

$$E_S = \frac{m_e^2 c^3}{e\hbar} = \frac{m_e c^2}{e \lambda\!\!\!^{-}_C}$$

It corresponds to the intensity $\approx 4 \times 10^{29} W / cm^2$

O. Klein (1929)
F. Sauter (1931)
W.Heisenberg, H.Euler (1936)
J. Schwinger (1951)
E.Brezin, C.Itzykson (1970)
V. S. Popov (1971)
V.I.Ritus (1979)
A. Ringwald (2001)

V. S. Popov, Phys. Lett. A 298, 83 (2002)
N. B. Narozhny et al., Phys. Lett. A 330, 1 (2004)
S. S. Bulanov et al., Phys. Rev E 71, 016404 (2005)
S. S. Bulanov et al., JETP, 102, 9 (2006)
A. Di Piazza et al., Phys. Rev. Lett. 103, 170403 (2009)
R. Schutzhold, Adv. Sci. Lett. 2, 121 (2009)
G. V. Dunne et al., Phys. Rev. D 80, 111301(R) (2009)
C. K. Dumlu, G. V. Dunne, Phys. Rev. Lett. 104, 250402 (2010)
R. Ruffini et al., Phys. Rep. 487, 1 (2010)

Rate of Pair Generation

$$\mathfrak{F} = \frac{\boldsymbol{E}^2 - \boldsymbol{B}^2}{2} = \frac{F_{\mu\nu}{}^2}{4} = inv, \quad \mathfrak{G} = (\boldsymbol{E}\cdot\boldsymbol{B}) = \frac{F_{\mu\nu}F_{\mu\nu}{}^*}{4} = inv$$

$$\mathfrak{E} = \sqrt{\sqrt{\mathfrak{F}^2 + \mathfrak{G}^2} + \mathfrak{F}}, \quad \mathfrak{B} = \sqrt{\sqrt{\mathfrak{F}^2 + \mathfrak{G}^2} - \mathfrak{F}}$$

are the electric and magnetic fields in the frame where they are parallel

$$W = \frac{e^2 E_S^2}{4\pi^3 \hbar^2 c}\,\mathfrak{e}\mathfrak{b}\coth\left(\frac{\pi\mathfrak{b}}{\mathfrak{e}}\right)\exp\left(-\frac{\pi}{\mathfrak{e}}\right)$$

$$\mathfrak{b} = \mathfrak{B}/E_S, \quad \mathfrak{e} = \mathfrak{E}/E_S$$

for $\mathfrak{e} \to 0$ the rate $W_{e^+e^-} \to 0$

at $\mathfrak{b} \to 0$ the rate $W_{e^+e^-} = \frac{e^2 E_S^2}{4\pi^2 \hbar^2 c}\,\mathfrak{e}^2 \exp\left(-\frac{\pi}{\mathfrak{e}}\right)$

The number of e⁺e⁻ pairs $N_{e^+e^-} = \iint W_{e^+e^-}\,dV dt = \frac{c\tau l_x l_y l_z}{64\pi^4 \lambda\!\!\!^{-}{}_C^4}\,\mathfrak{e}_m^4 \exp\left(-\frac{\pi}{\mathfrak{e}_m}\right)$

The number of electron-positron pairs produced in the focus of a single pulse or two colliding pulses

I, W/cm^2	E_0/E_s	N_e, single pulse	N_e, two pulses
2.5×10^{26}	4×10^{-2}	-	14
5×10^{26}	5.7×10^{-2}	-	2.6×10^{7}
5×10^{27}	0.18	25	
1×10^{28}	0.25	3×10^{7}	

S. S. Bulanov, N. B. Narozhny, V. D. Mur, V.S. Popov, JETP, 102, 9 (2006)

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$5\text{x}10^{27}$	0.18	25	
$1\text{x}10^{28}$	0.25	$3\text{x}10^{7}$	

The backreaction should be taken into account

S. S. Bulanov, N. B. Narozhny, V. D. Mur, V.S. Popov, JETP, 102, 9 (2006)

The number of electron-positron pairs produced in the focus of a single pulse or two colliding pulses

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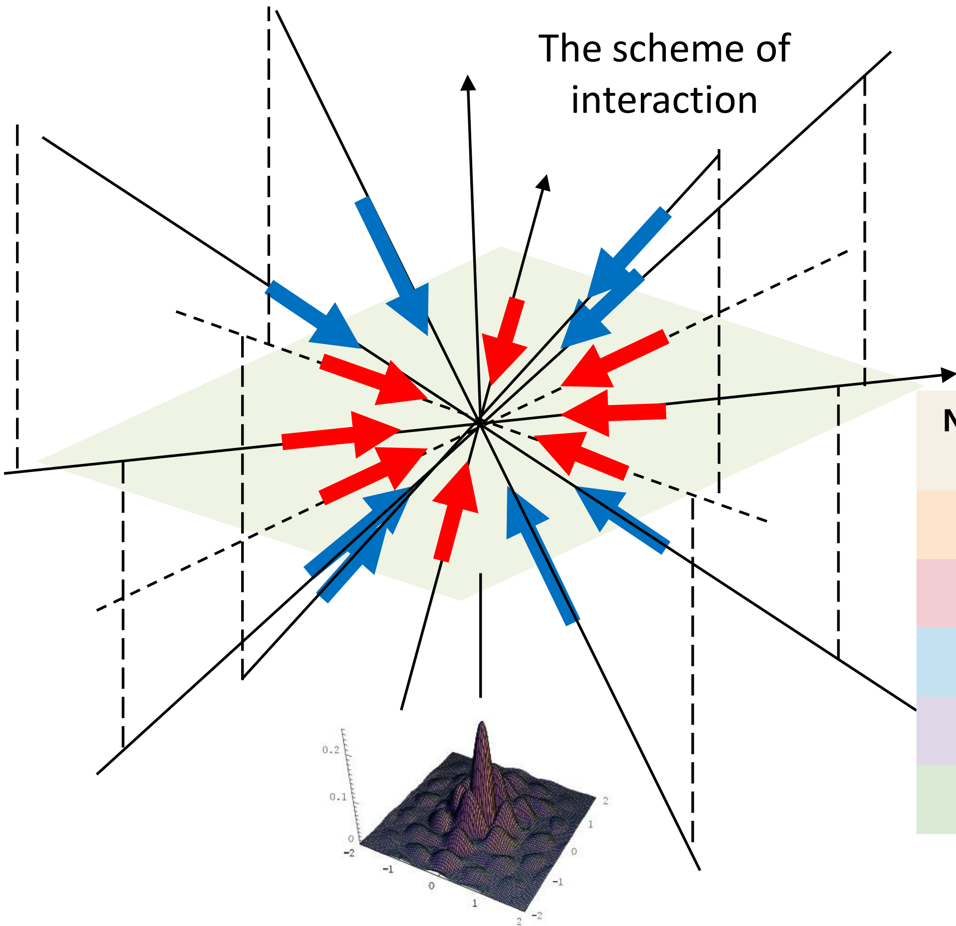
S.S. Bulanov, A.M. Fedotov, F. Pegoraro, Phys. Rev. E 71, 016404 (2005)
R. Ruffini et al., Phys. Lett. A 371, 399 (2007)

S. S. Bulanov, N. B. Narozhny, V. D. Mur, V.S. Popov, JETP, 102, 9 (2006)

A Way to Lower the Threshold of Pair Production from Vacuum

Multiple Colliding EM pulses:



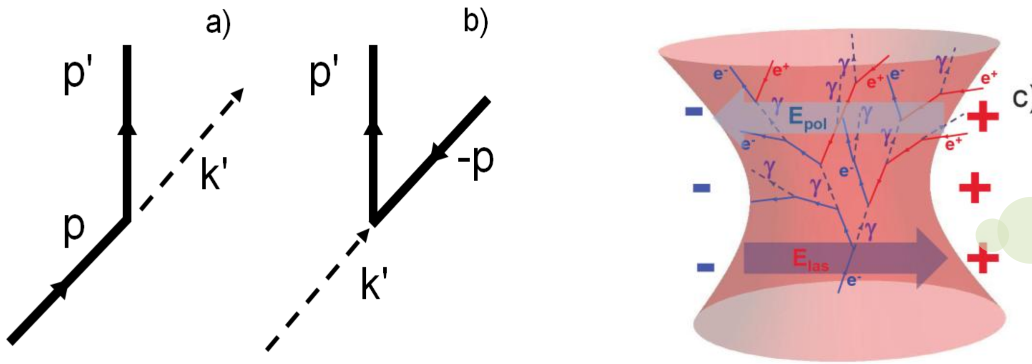
N pulses	$N_{\pm}$ at W=10 kJ	W(kJ) to produce one pair
2	9.0×10^{-19}	40
4	3.0×10^{-9}	20
8	4.0	10
16	1.8×10^{3}	8
24	4.2×10^{6}	5.1

S. S. Bulanov, V. D. Mur, N. B. Narozhny, J. Nees, V. S. Popov, Phys. Rev. Lett. 104, 220404 (2010)

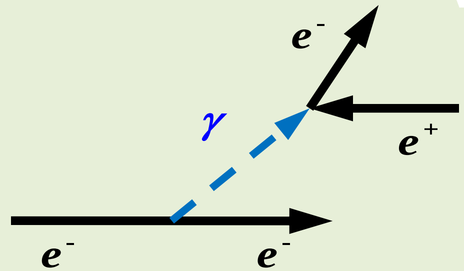
What is better, circular or linear table top accelerators, for reaching the quantum limits?

Electromagnetic cascades induced by pairs

$$\chi_e = \frac{e\hbar\sqrt{\left(F_{\mu\nu}p_\mu\right)^2}}{m_e^3c^4} = \gamma_e\frac{E}{E_S} \gg 1 \quad \rightarrow \quad n_+ \approx n_- = \frac{E}{4\pi e\lambda_0}$$



$$I \geq 10^{25} W/cm^2$$



D.L.Burke et al., PRL 79, 1626 (1997)

$$\chi_e \approx 0.3, \quad \chi_\gamma \approx 0.15$$

•A. R. Bell and J. G. Kirk, "Possibility of Prolific Pair Production with High-Power Lasers " Phys. Rev. Lett. 101, 200403 (2008)
•A. M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, "Limitations on the Attainable Intensity of High Power Lasers" Phys. Rev. Lett. 105, 080402 (2010)
•S.S.Bulanov, T. Zh.Esirkepov, A.Thomas, J.Koga, S.V.Bulanov, "On the Schwinger limit attainability with extreme power lasers" Phys. Rev. Lett. 105, 220407 (2010)
•E. N. Nerush, I. Yu. Kostyukov, A. M. Fedotov, N. B. Narozhny, N. V. Elkina, H. Ruhl, "Laser Field Absorption in Self-Generated Electron-Positron Pair Plasma" Phys. Rev. Lett. 106, 035001 (2011)
•N. V. Elkina, A. M. Fedotov, I. Yu. Kostyukov, M. V. Legkov, N. B. Narozhny, E. N. Nerush, H. Ruhl "QED cascades induced by circularly polarized laser fields" Phys. Rev. ST Accel. Beams 14, 054401 (2011)

$e^- e^+ \gamma$ plasma via the multi-photon B-W process

Key dimensionless Lorentz invariant parameters :

$$a = \frac{e\sqrt{\left(A_\mu\right)^2}}{m_e \omega c} = \frac{eE}{m_e \omega c}$$

$$\chi_e = \frac{e\hbar\sqrt{\left(F^{\mu\nu} p_\mu\right)^2}}{m_e^3 c^4} = \sqrt{\left(\gamma_e \frac{\boldsymbol{E}}{E_S} + \frac{\boldsymbol{p}\times\boldsymbol{B}}{m_e c E_S}\right)^2 - \left(\frac{\boldsymbol{p}\cdot\boldsymbol{E}}{m_e c E_S}\right)^2} \approx \frac{E}{E_S}\frac{p_\perp}{m_e c}$$

$$\chi_\gamma = \frac{e\hbar^2\sqrt{\left(F^{\mu\nu} k_\mu\right)^2}}{m_e^3 c^4} = a\frac{\hbar^2 \omega_0 \omega_\gamma}{m_e^2 c^4} \qquad \left[N\omega_0 + \omega_\gamma \to e^+ e^-\right]$$

Probability of pair creation

$$W_{\|}(\chi_\gamma) = \frac{3}{32}\frac{e^2 m_e^2 c^3}{\hbar^3 \omega_\gamma}\left(\frac{\chi_\gamma}{2\pi}\right)^{3/2} \exp\left(-\frac{8}{3\chi_\gamma}\right) \quad \text{for } \chi_\gamma \ll 1$$

$$W_{\|}(\chi_\gamma) = \frac{27\,\Gamma^7(2/3)}{56\pi^5}\frac{e^2 m_e^2 c^3}{\hbar^3 \omega_\gamma}\left(\frac{3\chi_\gamma}{2}\right)^{2/3} \quad \text{for } \chi_\gamma \gg 1$$

The number of absorbed laser photons: $N_l \approx a$

Photon mean-free-path before the pair is created: $l_{m.f.p} = \dfrac{\lambda_0}{0.2\pi\alpha\, a} \approx 220\dfrac{\lambda_0}{a}$

A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP 19} 529 (1964); ibid., 1191 (1964);

A. I. Nikishov, and V. I. Ritus, 'Interaction of Electrons and Photons with a Very Strong Electromagnetic Field', Sov. Phys. Usp. 13, 303 (1970)

V. I. Ritus, 'Quantum Effects of the Interaction of Elementary Particles with an Intense Electromagnetic Field', Tr. Fiz. Inst. Akad. Nauk SSSR 111, 5 (1979)

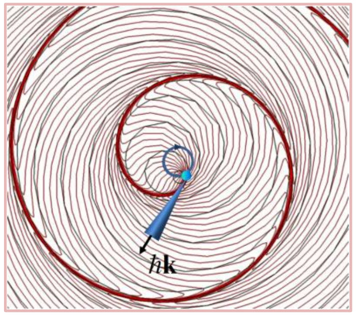
K. T. McDonald, "Fundamental Physics During Violent Acceleration", AIP Conf. Proceed. 130, 23 (1985)

A. I. Titov, H. Takabe, B. Kampfer, A. Hosakae et al., "Enhanced subthreshold e+e− production in short laser pulses", Phys. Rev. Lett. (2012)

Colliding EM Waves:

Circularly Polarized v.s. Linearly Polarized

Credit: T. Shintake

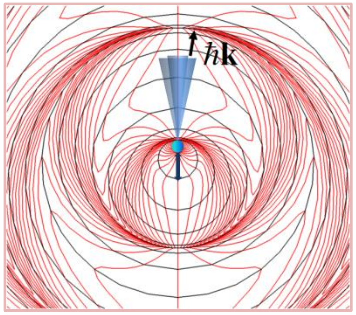


power emitted by electron rotating in CP wave :

$$P_{C,\gamma} = \frac{2r_e}{3ƛ}\omega_0 m_e c^2 \gamma_e^2 (\gamma_e^2 - 1) \propto \gamma_e^4$$

maximum frequency :

$$\omega_{\max} = 0.29\omega_0 \gamma_e^3$$



power emitted by electron oscillating in LP wave :

$$P_{L,\gamma} = \frac{r_e}{3ƛ}\omega_0 m_e c^2 (\gamma_e^2 - 1) \propto \gamma_e^2$$

maximum frequency :

$$\omega_{\max} = 2\omega_0 \gamma_e^2$$

S.S.Bulanov, T. Zh.Esirkepov, A.Thomas, J.Koga, S.V.Bulanov, "On the Schwinger limit attainability with extreme power lasers" Phys. Rev. Lett. 105, 220407 (2010

Colliding EM Waves:

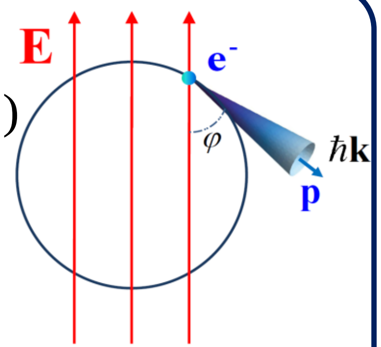
Circularly Polarized v.s. Linearly Polarized

Circularly Polarized

energy balance

$$a_0^2 = (\gamma_e^2 - 1)(1 + \varepsilon_{\text{rad}}^2 \gamma_e^6)$$

$$\tan\varphi = -\frac{1}{\varepsilon_{\text{rad}} \gamma_e^3}$$



radiation friction important at:

$$a_0 = \varepsilon_{\text{rad}}^{-1/3} \approx 400$$

i.e. at $I = 4.5 \times 10^{23}$ W/cm^2

quantum recoil important at:

$a \approx a_S^2 \varepsilon_{\text{rad}}$ with $a_S = m_e c^2 / \hbar\omega \approx 4.1 \times 10^5$

i.e. at $I = 4 \times 10^{24}$ W/cm^2

Linearly Polarized

energy balance

$$\mathcal{E}^+ \approx \omega_0 m_e c^2 a_0 = \mathcal{E}^- \approx \varepsilon_{rad} \omega_0 m_e c^2 \gamma_e^2$$

$$\varepsilon_{rad} = 2\pi r_e / \lambdabar \approx 10^{-8}$$

radiation friction important at:

$$a_0 = 2\varepsilon_{rad}^{-1}$$

i.e. at $E = 3 m_e^2 c^4 / e^3 = 3 \times 137 E_S$

quantum recoil important at:

$\hbar\omega_m \approx m_e c^2 \gamma_e$ i.e. $a \approx m_e c^2 / 0.21 \hbar\omega_0$

i.e. at $I \gg 10^{29}$ W/cm^2

Ya. B. Zel'dovich, A.F. Illarionov, Sov. Phys. JETP 34, 467 (1972);
S. V. Bulanov, T. Zh. Esirkepov, M. Kando, J. K. Koga, S. S. Bulanov, "Lorentz-Abraham-Dirac vs Landau-Lifshitz radiation friction force in the ultrarelativistic electron interaction with electromagnetic wave (exact solutions)", Phys. Rev. E, 84, 056605 (2011)

Threshold for the $e^- - e^+$ Avalanche:

Circularly Polarized v.s. Linearly Polarized

$$\chi_e \approx \frac{E}{E_S}\frac{p_\perp}{m_e c} \approx \frac{E}{E_S}\left(\frac{a_0}{\varepsilon_{rad}}\right)^{1/4} \sin\varphi \approx 1,$$

where $\sin\varphi \approx 1/\varepsilon_{rad}\gamma_e^3$,

at $a_0 > \varepsilon_{rad} a_S^2 \approx 1.5\times 10^3$

with $a_S = \dfrac{m_e c}{\hbar\omega_0} \approx 4.1\times 10^5$

avalanche threshold:

$I^* = 4\times 10^{24}$ W/cm^2

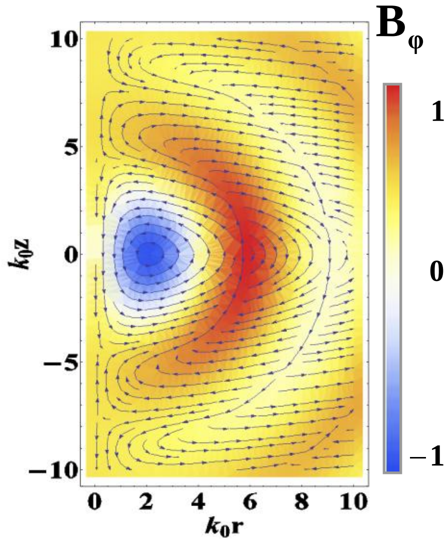
$\chi_e \approx \chi_\gamma \approx \dfrac{E}{E_S} \Rightarrow$ no any avalanches

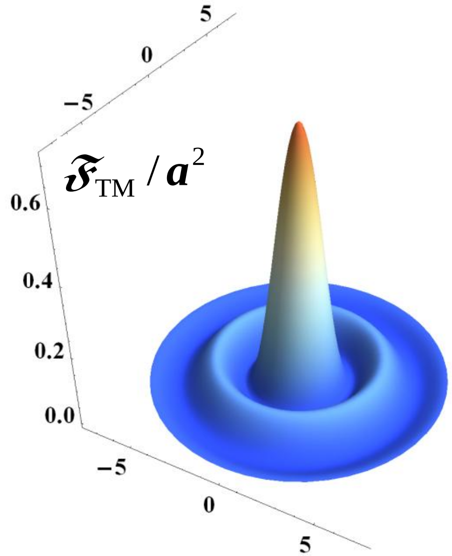
when particle velocity is parallel to its acceleration

INSTABILITY OF ELECTRON TRAJECTORY ??!!

We must take into account small but finite magnetic field

3D EM configuration TM - mode





TM configuration:

Magnetic field

$$\boldsymbol{B}(R,\theta) =$$

$$= \boldsymbol{e}_\phi \frac{B_0 \sin(\omega_0 t)}{(8\pi k_0 R)^{1/2}} J_{n+1/2}(k_0 R) L_n^l(\cos\theta)$$

Electric field

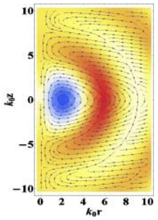
$$\boldsymbol{E} = i k_0^{-1} (\nabla \times \boldsymbol{B})$$

The vector field shows r- and z-components of the poloidal electric field in the plane (r,z): $\boldsymbol{E}(r,z)$

The color density show toroidal magnetic field distribution $B_\phi(r,z)$

The first Poincare invariant $\mathfrak{F}_{\mathrm{TM}} / \boldsymbol{a}_0^2 = (\mathbf{E}^2 - \mathbf{B}^2) / 2\boldsymbol{a}_0^2$

Threshold for e⁻ e⁺ avalanche in 3D TM configuration



INSTABILITY : e⁻(e⁺) trajectory in r, z - plane $\omega_0 t \ll 1, a_0 \gg 1$

$$p_z(t) = m_e c\, a_0 \omega_0 t,$$

$$p_r(t) = m_e c \frac{a_0 k_0 r_0 \omega_0 t}{2^{3/2}} I_1\left(\frac{\omega_0 t}{2^{3/2}}\right),$$

$$r(t) = \frac{a_0 r_0}{2^{3/2}} I_1\left(\frac{\omega_0 t}{2^{3/2}}\right) + \frac{a_0 r_0 \omega_0 t}{16}\left[I_0\left(\frac{\omega_0 t}{2^{3/2}}\right) + I_2\left(\frac{\omega_0 t}{2^{3/2}}\right)\right]$$

with $k_0 r_0 = (2.5 a_0 / \pi a_S)^{1/2}$; growth rate : $\Gamma = \omega_0 / 2^{3/2}$

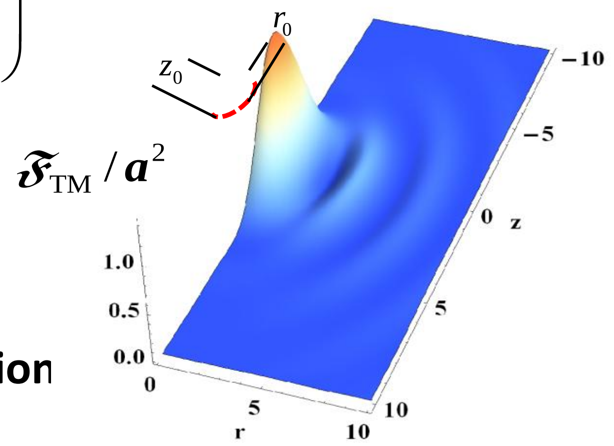
THRESHOLD : assuming $\omega_0 t \approx 0.1\pi$ we find that the avalanche will start at $a_0 / a_S \approx 0.105$

which corresponds to $I^* \approx 4 \times 10^{27}$ W/cm²

The pairs are created in a small 4-volume near $\mathfrak{F}_{\mathrm{TM}}$ maximum

with the characteristic size

$$\pi r_0^2 z_0 c t_0 = \frac{5^{3/2}\lambda_0^4}{16\pi^5}\left(\frac{a_0}{a_S}\right)^2$$



Here normalized Schwinger field is

$$a_S = \frac{m_e c^2}{\hbar\omega_0} = 5.1\times10^5$$

Integrating over the 4-volume the probability of the pair creation we obtain the number of pairs produced per wave period,

$$N_{e^+e^-} = \iint W_{e^+e^-}\, dV dt = \frac{5^{3/2}}{4\pi^3} a_0^4 \exp\left(-\pi \frac{a_S}{a_0}\right)$$

The first pairs can be observed for an one-micron wavelength laser intensity of the order of $\approx 10^{27}$ W/cm^2, which corresponds to $a_0 / a_S = 0.05$, i.e. a characteristic size, r_0, Is approximately equal to $0.04\lambda_0$

Towards antimatter creation in vacuum by present day lasers (experiments to conduct in next several years)

S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, and G. Korn,
"On the design of experiments for the study of extreme field limits in the interaction of laser with ulrarelativistic electron beam"
Nucl. Instr. Meth. Phys. Res. A, 660, 31 (2011)

S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, N. N. Rosanov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, and G. Korn ,
"Extreme field science"
Plasma Physics and Controlled Fusion, 53, 124025 (2011).

Multi-photon creation of e⁻ e⁺ γ plasma during ultrarelativistic electron beam collision with the EM pulse

$$\chi_e = \frac{E}{E_S}\left[\frac{(m_e^2c^2 + p_0^2)^{1/2} + |p_0|}{m_e c}\right] = a\frac{\hbar\omega_0}{m_e c^2}\left[\frac{(m_e^2c^2 + p_0^2)^{1/2} + |p_0|}{m_e c}\right]$$

The electron is not scattered aside by the PW, 30 fs laser ponderomotive force if

$$\gamma_e > c\tau_{las}a / 2w_{\perp} \approx 500$$

For $1\,\mu\mathrm{m}$ **PW laser pulse focused to a few micron focus spot the amplitude is** $a = 10^2$

the parameter χ_e **becomes equal to unity for** $\gamma_0 = 2.5\times 10^3$

i.e. for the electron energy of about of 1.3 GeV.

Gamma-ray photon generation via the nonlinear Thomson scattering

When a counter-propagating electron collides with the laser pulse its longitudinal momentum decreases:

$$p_x = -|p_0| + m_e c \frac{a^2 m_e c}{2[(m_e^2 c^2 + p_0^2)^{1/2} + |p_0|]}$$

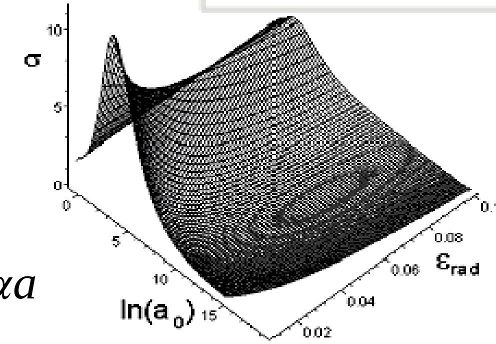
In the boosted frame of reference where the electron is at the rest the laser frequency is related to the laser frequency in the laboratory frame as

$$\bar{\omega}_0 = \frac{\omega_0}{\sqrt{1+a^2}} \sqrt{\frac{1-\beta_0}{1+\beta_0}}$$

The energy of emitted photon is $\hbar\bar{\omega}_\gamma = 0.3\hbar\bar{\omega}_0 a^3$

The number of emitted photons during one wave period is $N_\gamma \approx \frac{3\pi}{4}\alpha a$

Cross section of nonlinear Thomson scattering



J. Koga, et al 'Nonlinear Thomson scattering in the strong radiation damping regime', Phys. Plasmas 12, 093106, 2005
T. Nakamura et al., PRL (2012)

What the values of χ_e and χ_γ for 1.25 GeV LWFA electrons colliding with the FM generated EM wave?

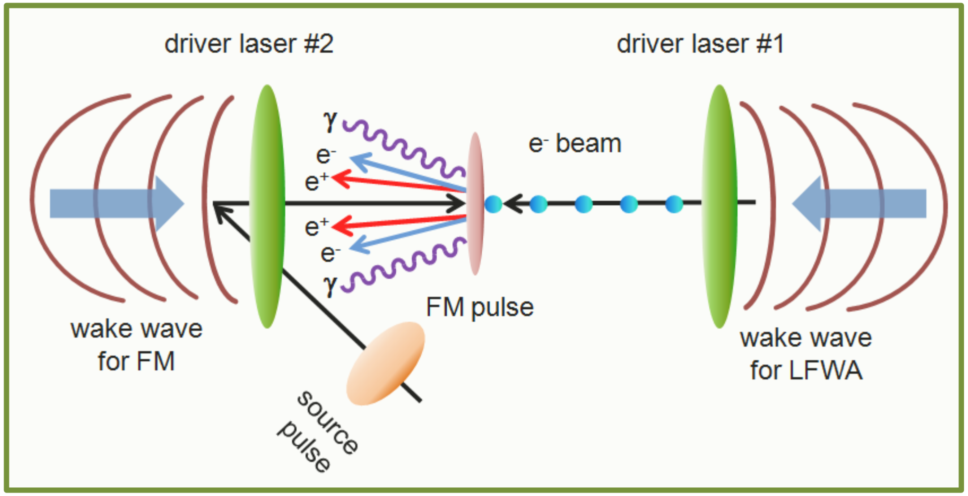
We assume 1 PW, *a*=150, 1.25 GeV (LWFA) electron energy, γ_{ph}=5 ($E=2\gamma_{ph}E_0$, $\omega=4\gamma^2_{ph}\omega_0$):

$$\chi_e = \frac{E}{E_S}\left[\frac{(m_e^2c^2+p_0^2)^{1/2}+|p_0|}{m_e c}\right] \approx 2\gamma_e\gamma_{ph}\frac{E}{E_S} = 10\times\frac{2\times150\times2500}{5.1\times10^5} \approx \mathbf{15}$$

& (in multi-photon inverse Compton scattering regime)

$$\chi_\gamma = \frac{E}{E_S}\frac{\hbar\omega_\gamma}{m_e c^2} = 1.2\gamma_e\gamma_{ph}a\frac{\hbar\omega_0}{m_e c^2}$$

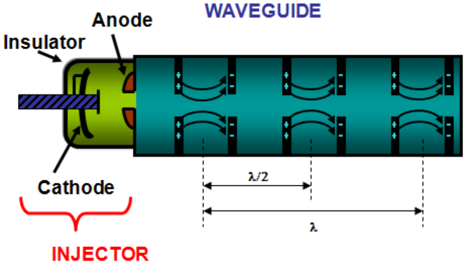
$$= \frac{1.2\times5\times10^2\times2.5\times10^3}{5.1\times10^5} \approx \mathbf{3}$$



Laser Wake Field Accelerator

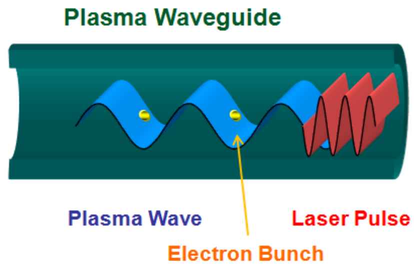
Classical and LWF Accelerators

E-field$_{max}$ ≈ 10 MV/m
R>R$_{min}$ Synchrotron radiation



RF cavity

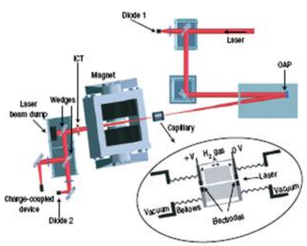
Theory



Ultrahigh axial electric fields
Compact electron accelerators
Plasma wakefields:
E > 10 GV/m, fast waves
Plasma channel: Guides laser pulse and supports plasma wave

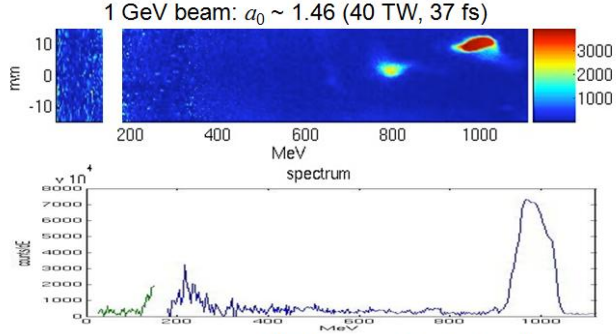
Experiment

1.0 GeV Beam Generation



Laser: 1.5 J/pulse
Density: $4x10^{18}$ cm^{-3}
Capillary: 312 mm diameter and 33 mm length

1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)



Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Charge: > 30.0 pC

W.P.Leemans et al, Nature Physics, 418 (2006)

T. Tajima, J. M. Dawson (1979) ; W.P. Leemans et al., Nature Phys. 418 (2006) APRI-GIST: 3GeV (2012)

Laser Wake Field Accelerator in Extreme Field Limit

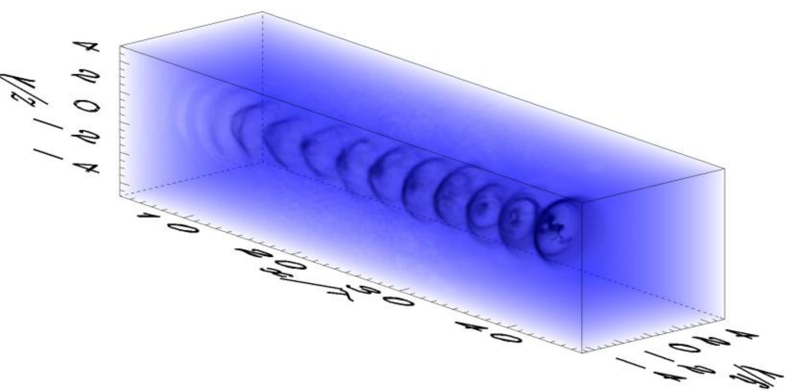
Scaling of LWFA accelerated electrons $\mathcal{E}_e = m_e c^2 \gamma_{ph}^2 a^3$

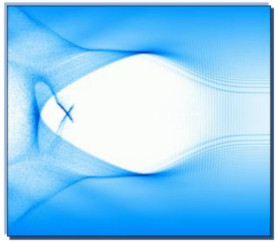
Where $\gamma_{ph} = \frac{\omega_0}{\omega_{pe}} = \left(\frac{n_{cr}}{n_0}\right)^{1/2}$ **and** $a = \frac{eE_0}{m_e \omega_0 c}$

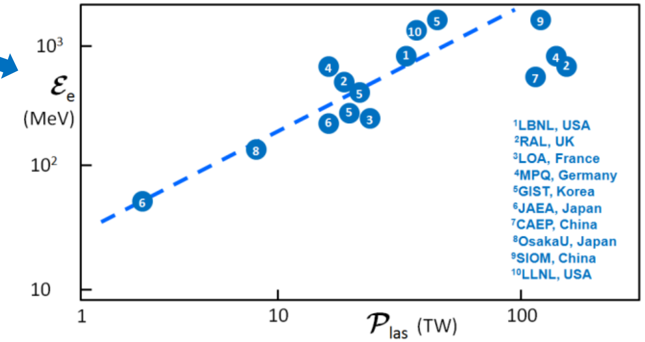
As a result of the laser pulse self-focusing* we have $a = \left(\kappa \frac{\mathcal{P}}{\mathcal{P}_{cr}} \frac{n_0}{n_{cr}}\right)^{1/3}$

with $\kappa < 1$ **the power** $\mathcal{P}$ **and** $\mathcal{P}_{cr} = \frac{2 m_e^2 c^5}{e^2} = 17\ GW$

These yield $\mathcal{E}_e = \kappa\, m_e c^2 \frac{\mathcal{P}}{\mathcal{P}_{cr}}$ $\approx TeV$ **for 100 PW laser**

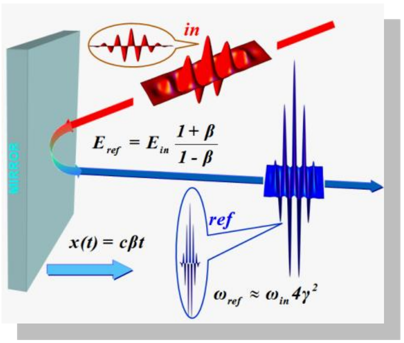




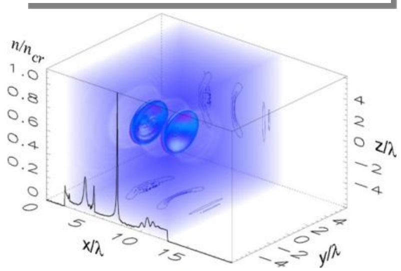


* G. A. Askar'yan, A. G. Litvak, …..

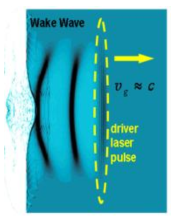
EM Pulse Intensification and Shortening by Flying Mirror

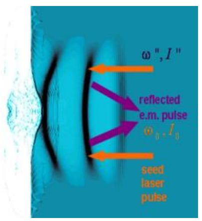


Theory

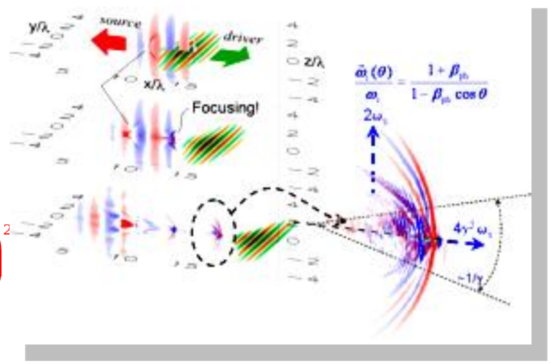


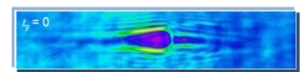
Experiment

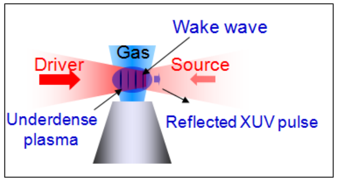


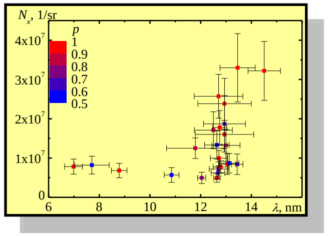


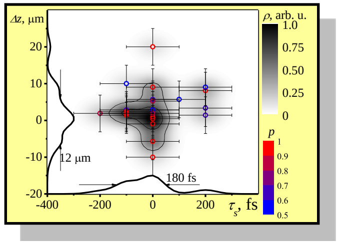
$$\omega'' = \frac{c+v_{ph}}{c-v_{ph}}\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{max}}{I_0} \approx \kappa\,\gamma_{ph}^6\left(\frac{D}{\lambda}\right)^2$$











λ_x = 14.3 nm

$\Delta\lambda_x$ = 0.3 nm, $\Delta\lambda_x/\lambda_x$ = 0.02

Reflected pulse duration: τ_x ~ 1.4 fs

(femtosecond pulse)

paraboloidal relativistic mirrors formed by the wake wave left behind the laser driver pulse

M. Kando, et al., Phys. Rev. Lett. 99, 135001 (2007)
A. S. Pirozhkov, et al., Phys. Plasmas 14, 080904 (2007)
M. Kando, et al., Phys. Rev. Lett., 103, 235003 (2009)

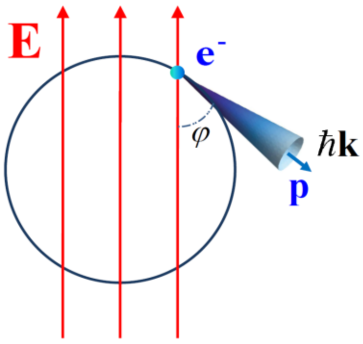
S.V.Bulanov, T. Esirkepov, T. Tajima, "Light intensification towards the Schwinger limit", Phys. Rev. Lett. 91, 085001 (2003)

These estimations are too optimistic….

What is the role of the radiation damping?

Radiation friction effects

$$m_e c^2 \frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{2e^2}{3c} g^\mu$$



The radiation friction force in the Landau-Lifshitz form is given by

$$g^\mu = \frac{2e^2}{3m_e c^3}\left[\frac{\partial F^{\mu\nu}}{\partial x^\lambda}u_\nu u_\lambda - \frac{e^2}{m_e c^2}\left(F^{\mu\lambda}F_{\nu\lambda}u^\nu + \left(F_{\nu\lambda}u^\lambda\right)\left(F^{\nu\kappa}u_\kappa\right)u^\mu\right)\right]$$

Retaining the main order terms, we obtain equation for the *x*-component of the electron momentum

$$\frac{dp_x}{dt} = -4\varepsilon_{rad}\omega_0 a^2(2t)\frac{p_x^2}{m_e c}, \qquad \varepsilon_{rad} = \frac{2r_e}{3\lambda\!\!\!^-}$$

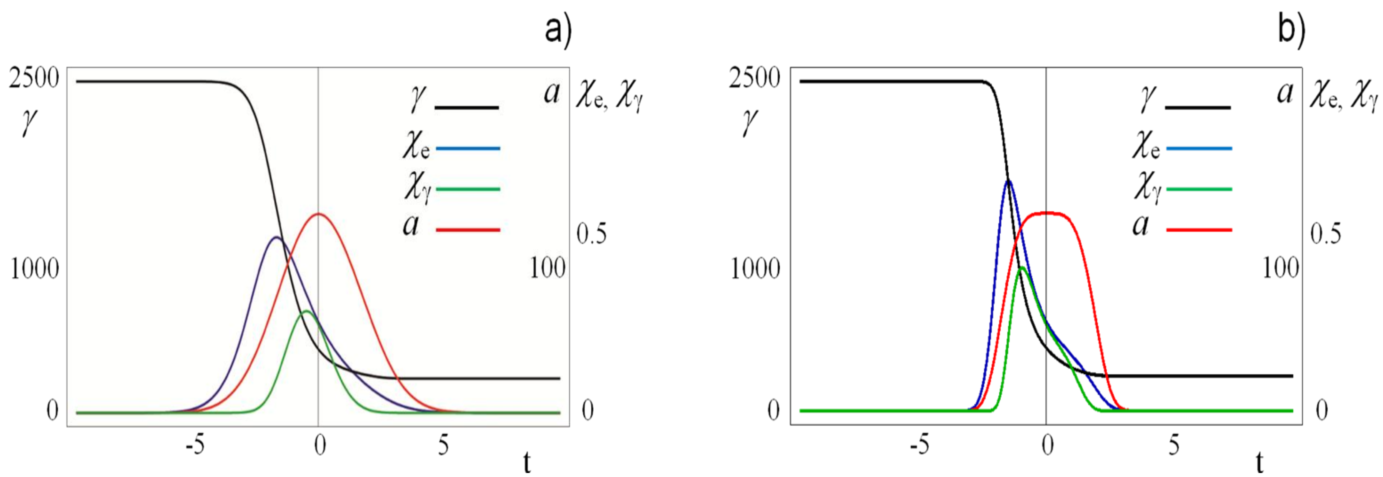
Its solution is

$$p_x(t) = \frac{p_x(0)m_e c}{m_e c + 4\varepsilon_{rad}\omega_0 p_x(0)\int_0^t a^2(2t')dt'}, \quad p_x(t)\underset{t\to\infty}{\rightarrow}\frac{m_e c}{4\varepsilon_{rad}\omega_0\tau_{las}a_0^2}$$

L. D. Landau, and E. M. Lifshitz, The Classical Theory of Fields, Pergamon, 1975

I. Pomeranchuk, "Maximum Energy that Primary Cosmic-ray Electrons Can Acquire on the Surface of the Earth as a Result of Radiation in the Earth's Magnetic Field", J. Phys. USSR, 2, 65 – 69, 1940

Numerical solution of equations of the electron motion in the laser field with the radiation friction taken into account



Time dependence of the electron and photon parameters for a 1.25 GeV electron beam interaction with a PW (a=150, 9 fs) laser pulse. a) Gaussian pulse; b) Super-Gaussian (m=4) pulse. The electron energy before and after the interaction with the laser pulse equals 1.25 GeV and 0.25 GeV, respectively. The parameter χ_e reaches the maximum value 0.5 and χ_γ is equal to 0.3.

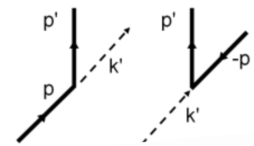
Parameters of Experiment

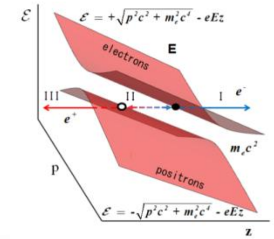
	e (150 MeV) +PW Laser	LWFA e (1.25 GeV) +PW Laser	LWFA e (1.25 GeV) +FM pulse
γ_e	300	2500	2500
a_0	100	100	10
χ_e	0.05	0.5	2.5
$a_{rad}=(\varepsilon_{rad}/\gamma_e)^{-1/3}$	60	30	6

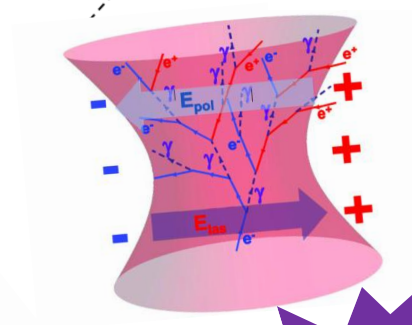
Extreme Field Limits
in high intensity laser interaction with matter and vacuum

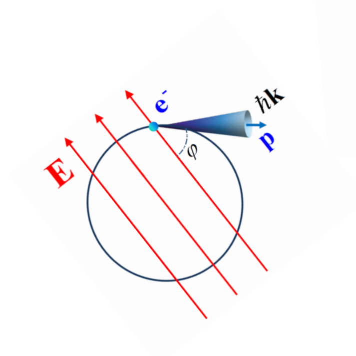
Focused intensity (W/cm²)

non - perturbative QED $E \le E_S = m_e^2 c^3 / e\hbar$	10^{29} nonlinear - dissipative vacuum
multiphoton QED processes $e + N\,\hbar\omega_0 \rightarrow \hbar\omega_\gamma + e'$ $\hbar\omega_\gamma + N\,\hbar\omega_0 \rightarrow e^- + e^+$	$10^{27}/\gamma_e^2$ lepton - gamma - plasma
radiation reaction $a_0 > (\lambdabar / r_e)^{1/3} \approx 400$	$10^{24}/\gamma_e^2$ X, γ - rays
relativistic nonlinear optics $a_0 = eE_0 / m_e\omega_0 c > 1$	$10^{23}/\gamma_e^{2/3}$ plasma
bound electrons $E_0 \le e^2 / a_B = m_e^2 e^5 / \hbar^4$	10^{18}









Conclusion

Development of the Extreme Field Science will allow for exploring novel physics, for studying the processes of high importance for fundamental physics, for laboratory modeling of processes of key importance for relativistic astrophysics.

The experiments in this field will allow modelling in a terrestrial laboratory the state of matter in cosmic Gamma Ray Bursts and other objects.

It will open at first stage a way for developing new type of hard EM radiation sources: multi- MeV, several fs, gamma-ray burst.

Thank you for listening to me!