Radiation Dominated Electromagnetic Shields

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## Extreme Field Limits in High Power Laser Interaction with Matter & Vacuum

<table>
<thead>
<tr>
<th>Focused intensity (W/cm(^2))</th>
<th>Non-perturbative QED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E \leq E_s = m_e^2 c^3 / e\hbar)</td>
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<table>
<thead>
<tr>
<th>Multiphoton QED Processes</th>
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<tbody>
<tr>
<td>(e + N \hbar \omega_0 \rightarrow \hbar \omega_\gamma + e')</td>
</tr>
<tr>
<td>(\hbar \omega_\gamma + N \hbar \omega_0 \rightarrow e^- + e^+)</td>
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<table>
<thead>
<tr>
<th>Radiation Reaction</th>
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<tbody>
<tr>
<td>(a_0 &gt; (\chi / r_e)^{1/3} \approx 400)</td>
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</table>

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<tr>
<th>Relativistic Nonlinear Optics</th>
</tr>
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<tbody>
<tr>
<td>(a_0 = eE_0 / m_e \omega_0 c &gt; 1)</td>
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</table>

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<thead>
<tr>
<th>Bound Electrons</th>
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<tbody>
<tr>
<td>(E_0 \leq \varepsilon^2 / a_B = m_e^2 e^5 / \hbar^4)</td>
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<table>
<thead>
<tr>
<th>Nonlinear - Dissipative Vacuum</th>
</tr>
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<tbody>
<tr>
<td>(10^{27} / \gamma_e^2)</td>
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<thead>
<tr>
<th>Lepton - Gamma - Plasma</th>
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<tbody>
<tr>
<td>(10^{24} / \gamma_e^2)</td>
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</table>

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<thead>
<tr>
<th>X, (\gamma) - Rays</th>
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</thead>
<tbody>
<tr>
<td>(10^{23} / \gamma_e^{2/3})</td>
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<tr>
<th>Plasma</th>
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<tr>
<td>(10^{18})</td>
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</table>

\(\gamma\)-ray flash

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Extreme power lasers

Relativistic construction

Schwinger field

Optimal configuration of laser beams

QED $e^- e^+ \gamma$ plasma
Extreme power lasers
Relativistic construction
Optimal configuration of laser beams

QED
\(\text{e}^-\text{e}^+\gamma\) plasma

Schwinger field

N. B. Narozhny
Electron-positron pairs can be created before the laser field reaches the Schwinger limit, due to a large phase volume occupied by a high-intensity EM field.


Multiple 10kJ beam system provides necessary conditions for \( e^- e^+ \) pairs creation.

<table>
<thead>
<tr>
<th>Number of pulses</th>
<th>Number of ( e^- e^+ ) with 10kJ pulses</th>
<th>Required power (kJ) to create one pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( 9 \times 10^{-19} )</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>( 3 \times 10^{-9} )</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>( 1.8 \times 10^3 )</td>
<td>8</td>
</tr>
<tr>
<td>24</td>
<td>( 4.2 \times 10^6 )</td>
<td>5.1</td>
</tr>
</tbody>
</table>

3D EM configuration TM - mode

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

The color density shows toroidal magnetic field distribution.

The first Poincare invariant

$$\mathcal{F}_{TM}/a_0^2 = (E^2 - B^2)/2a_0^2$$

**TM configuration:**

Magnetic field

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

Electric field

$$E = ik_0^{-1}(\nabla \times B)$$

4 regimes

<table>
<thead>
<tr>
<th>a</th>
<th>RR</th>
<th>RR,Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>a*</td>
<td>I</td>
<td>Q</td>
</tr>
</tbody>
</table>

Dimensionless amplitude

\[ a = \frac{eE}{m_e \omega c} \]

At \( a = a^* \) emitted energy becomes equal to the energy received from EM wave.

\[ a^* = \left( \frac{3\lambda}{4\pi r_e} \right)^{1/3} \]
\[ r_e = \frac{e^2}{m_e c^2} \]

The radiation reaction measure:

\[ \varepsilon_{rad} = \frac{2q^2 \omega}{3mc^3} \approx 1.1804 \times 10^{-8} \left( \frac{q^2 m_e}{e^2 m} \right) \left( \frac{1\mu m}{\lambda} \right) \]

When the recoil of the emitted photon is significant, the emission probability is characterized by \( \chi_e \) parameter (Lorentz and gauge inv)

\[ \chi_e = \left( \frac{\gamma_e}{E_S} \right) \left[ (\mathbf{E} + \mathbf{\beta} \times \mathbf{B})^2 - (\mathbf{\beta} \cdot \mathbf{E})^2 \right]^{1/2} \]

At \( \chi_e = \chi_e^* < 1 \) QED effects come into play.
Four Interaction Domains

Curves $I_R(\omega)$, $I_Q(\omega)$ and $I_{R-Q}(\omega)$, $I_{Q-R}(\omega)$ subdivide $(I, \omega)$ plane to 4 domains:

I) Relativistic electron - EM field interaction with neither radiation friction nor QED effects

II) Electron - EM wave interaction is dominated by radiation friction

III) QED effects important with insignificant radiation friction effects

IV) Both QED and radiation friction determine radiating charged particle dynamics in the EM field

\[
I_R = \frac{m_e^4 c^5 e^2}{144 \pi h^4} \left( \frac{\omega}{\omega_1} \right)^{4/3} = 3.8 \times 10^{23} \left( \frac{\omega}{\omega_1} \right)^{4/3} \frac{W}{cm^2}
\]

\[
I_Q = \frac{m_e^4 c^5 e^2}{144 \pi h^4} \left( \frac{\omega}{\omega_1} \right)^4 = 3.8 \times 10^{23} \left( \frac{\omega}{\omega_1} \right) W/cm^2
\]

\[
I_{R-Q} = \frac{m_e^4 c^5 e^2}{9 \pi h^4} = 5.6 \times 10^{24} \frac{W}{cm^2}
\]

\[
I_{Q-R} = 87 \frac{c^5 h^8 \omega^4}{e^{14}} = 8.2 \times 10^{21} \left( \frac{\omega}{\omega_1} \right)^4 \frac{W}{cm^2}
\]
What Can be Measured?

Cross Section $\sigma$ and Electron Energy $\gamma_e$ v.s. EM Wave Amplitude:

Dependences of $\lg(\sigma / \sigma_T)$ & $\lg \gamma_e$ on $\lg a_0$

1) $\omega = \omega_1 / 12.5$ (I $\rightarrow$ II)
2) $\omega = \omega_1$ (I $\rightarrow$ IV)
3) $\omega = 12.5 \omega_1$ (I $\rightarrow$ III)

High Power Gamma-Ray Source

Concept of high power gamma-flash generation:


Conversion efficiency vs. Laser power [PW]
High-efficiency $\gamma$-ray flash generation via multiple-laser scattering in ponderomotive potential well


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Electron–positron cascades in multiple-laser optical traps.
4 s-waves, $a_0=250$, $n_0=16n_c$

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$a_0=500$ $n_e$ $n_{BW}$

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$a_0=500$ photon density

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$a_0=500$ trajectories

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D. Khikhlukha
Survey of random walk, Lévy flights, limit circles, attractors and structurally determinate patterns

Charged particle dynamics in multiple colliding electromagnetic waves. Survey of random walk, Lévy flights, limit circles, attractors and structurally determinate patterns

S. V. Bulanov, T. Zh. Esirkepov, J. K. Koga, S. S. Bulanov, Z. Gong, X. Q. Yan and M. Kando

doi:10.1017/S0022377817000186
Lévy Flights

\[ \frac{\partial f}{\partial t} + \frac{\partial}{\partial x} (v f) = D \frac{\partial^2 f}{\partial x^2} \]

Sharks’ hunting style

Brownian motion
Radiation Dominated Electromagnetic Shield (TE+TM)

\[
\frac{dp}{dz} = -\frac{2}{\pi} \varepsilon_{\text{rad}} p^2 \alpha_0^2 \rho_0^2 \left\{ \frac{z^2 \left[ \sin(z) - z \cos(z) \right]^2 + \left[ (z^2 - 3) \sin(z) + 3z \cos(z) \right]^2}{z^8} \right\}
\]

\[
p(z) = \frac{p_0}{1 + (2/\pi)p_0 \varepsilon_{\text{rad}} \alpha_0^2 \rho_0^2 \Phi(z)}
\]
Electron Stopping and Trapping

\[ \gamma = (a_0 / \varepsilon_{rad})^{1/4} \]
Strong nonlinear friction

Anomalous Radiative Trapping in Laser Fields of Extreme Intensity

Obtained with PIC simulation

Attractors and chaos of electron dynamics in electromagnetic standing waves

Obtained with Wolfram Mathematica
Paradoxical Stabilization of Forced Oscillations by Friction

Kapitza pendulum
(also called Stephenson-Kapitza pendulum, inverted pendulum)

Statically unstable equilibrium position of a rigid pendulum is stabilized by small fast vertical oscillations of the pivot point.

Simple but fundamental model

\[ \ddot{x} = -\frac{dU(x)}{dx} + F(x, t) \]

Assume \( x = X(t) + \xi(t) \)

\[ \ddot{X} + \ddot{\xi} = -\frac{dU(X)}{dX} - \xi \frac{d^2U(X)}{dX^2} + F(X, t) + \xi \frac{dF(X,t)}{dX} \]  

(*) Series expansion for \( |\xi| \ll F/\partial_x F: \)

\[ F(X + \xi, t) \approx F(X, t) + \xi \frac{dF(X,t)}{dX} \]

Kapitza method

Constant potential + high-frequency force

slowly varying

\[ \dot{\xi} = F(X, t) \]  

(1) collect the greatest terms:

\( \dot{\xi} \propto \omega^2, \quad \omega \gg \dot{X}/X \)

Slowly varying and fast oscillating terms should cancel out separately.

(2) collect the slowest terms:

Time-averaging:

\[ \langle \xi \rangle = \frac{1}{T} \int_0^T \xi \, dt \]

\[ \langle \xi \rangle = \langle \dot{\xi} \rangle = \langle \ddot{\xi} \rangle = 0, \]

\[ \langle x \rangle = \langle X \rangle \approx X. \]

Landau & Lifshitz, Mechanics
Friction tug vs ponderomotive force

Simple but fundamental model \( \ddot{x} + K(F(x, t))\dot{x} = F(x, t) \).

Strong high-frequency friction \( K \) High-frequency driving force

Assume \( x = X(t) + \xi(t) \)

Expand in powers of \( \xi \):
\[
\ddot{X} + \dot{\xi} + \left( K + \xi K' \frac{dF}{dX} \right) \left( \dot{X} + \dot{\xi} \right) = F(X, t) + \xi \frac{dF}{dX} \quad (\ast)
\]

Greatest fast oscillating terms \( \ddot{\xi} + K\dot{\xi} = F(X, t) \) \( (1) \)

Slowly varying terms \( \ddot{X} + \left( \langle K \rangle + \left( \xi K' \frac{dF}{dX} \right) \right) \dot{X} = \langle \xi \frac{dF}{dX} \rangle - \langle \xi \dot{\xi} K' \frac{dF}{dX} \rangle - \langle K \dot{\xi} \rangle \) \( (2) \)

Let’s assume \( F(x, t) = f(x) \sin(\omega t) \), \( K(F) = \nu F^{2n} \).

Then we can solve (1) and do time-averaging in (2).

If \( K \) is even function of \( F \), then \( \langle K \rangle > 0 \).

Fast oscillating solution: \( \xi \approx \kappa f \frac{\sin(\omega t) - \cos(\omega t)}{\omega (\kappa^2 + \omega^2)} \), \( \kappa = \langle K \rangle = \frac{\nu}{2^{2n}} \binom{2n}{n} f^{2n} \).

Slowly varying term:
\[
\ddot{X} + \kappa \dot{X} = -\frac{d}{dX} \frac{f^2}{4(\kappa^2 + \omega^2)} + \frac{d}{dX} \frac{n^2 \kappa^2 f^2}{(n + 1)(\kappa^2 + \omega^2)^2}
\]

ponderomotive force \(<\) friction tug for \( \nu > \frac{2^{2n}(n!)^2(n+1)^{1/2} \omega}{(2n)! (4n^2-n-1)^{1/2} f^{2n}} \)
Friction tug vs ponderomotive force

\[ \ddot{x} + \nu[f(x)\cos(\omega t)]^4 \dot{x} = f(x) \cos(\omega t). \]

- **Nonlinear friction**
- **Driving force**

\[ f(x) = f_0 \exp(-x^2/l_0^2), \quad l_0 = 10, \quad \omega = 1, \quad f_0 = 3. \]

\( \nu = 0 \) (no friction)

Ponderomotive force pushes particles out

Friction tug overcomes ponderomotive force

\( \nu = 0.2 \)
Paradoxical stabilization of forced oscillations by strong nonlinear friction

\[ \ddot{x} + \nu [f(x) \cos(\omega t)]^4 \dot{x} = f(x) \cos(\omega t) \]

\( f(x) = f_0 \exp(-x^2/l_0^2) \)

\( f(x) = f_0 \cos^2(2\pi x/l_0) \)

\( f_0 = 3 \)
\( \nu = 0.2 \)
\( l_0 = 10 \)
\( \omega = 1 \)
\( f_0 = 8 \)
\( \nu = 0.25 \)

William Thomson (Lord Kelvin):

“I never satisfy myself until I can make a mechanical model of a thing”

Thank you for your attention!