Modeling high-energy astrophysics phenomena with ultra-intense lasers

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NIF Laser System

- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm

NIF is 50 times more energetic than any previous laser
EU decided to construct 3 ELI Modules (10PW) in East Europe (Total cost = 800 M Euro)

Site selection: decision on Oct. 1, 2009

Overall cost: ≈800M€
The European XFEL: the world’s brightest x-rays

Injector at DESY campus

Experimental Hall in Schenefeld

Undulator Tunnels

Linear Accelerator

2 km long

17.5 Billions electron-Volts

First users: 2016
Exploring Solid-Density HED Plasmas and Ultra-Intense Laser-Matter Interactions at the European XFEL

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on behalf of the Helmholtz Beamline User Consortium

HEDS2013
24-25. April 2013, Yokohama, Japan

Dresden, September 2011
- HERMES Project at SACLAC-

High Energy density Revolutions of Matter in Extreme States

- Cooperation with
  RIKEN, NIMS, Ehime Univ., Okayama Univ., Hiroshima Univ., Kumamoto Univ., Okinawa Coll., JAERI etc (20 institutions).

- 3 steps of HERMES project
  - 1st step (installation from 2012 operation 2013-2014):
    50-100J long (0.1-10Hz) + 40TW short (10Hz) + Double XFEL beams
  - 2nd step (installation from 2013 operation from 2015):
    400J long (0.1Hz) + 500TW short (1Hz) + Laser particle beams (500TW) (RIKEN)
  - Final step (~2020): expectation
    >kJ long + >10PW

Almost approved
FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
Debate on Vacuum

There is a God shaped vacuum in the heart of every man which cannot be filled by any created thing, but only by God, the Creator, made known through Jesus.

Blaise Pascal

『パンセ』Pensées、1669年。

Blaise Pascal (1623-1662)
Quantum Vacuum

Heisenberg’s Uncertainty Principle (1927)

\[ \Delta p \Delta x \geq \frac{1}{2} \hbar \]

\[ \Delta E \Delta t \geq \frac{1}{2} \hbar \]

Electron and Positron

\[ \Delta t = 10^{-21} \text{s} \]
Schwinger Limit (1951) E-field

\[ \Delta \varepsilon \Delta t \sim \hbar \]
\[ \Delta \varepsilon \sim mc^2 \]
\[ eE\Delta t \sim p \sim mc \]

\[ E_{CR} = \frac{m^2 c^3}{e\hbar} \]

\[ E = 1.3 \times 10^{16} \text{ V/cm} \]
\[ I = 4 \times 10^{29} \text{ W/cm}^2 \]
Possibility of Prolific Pair Production with High-Power Lasers

A. R. Bell
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(Received 8 August 2008; published 11 November 2008)

Prolific electron-positron pair production is possible at laser intensities approaching $10^{24}$ W cm$^{-2}$ at a wavelength of 1 $\mu$m. An analysis of electron trajectories and interactions at the nodes ($B = 0$) of two counterpropagating, circularly polarized laser beams shows that a cascade of $\gamma$ rays and pairs develops. The geometry is generalized qualitatively to linear polarization and laser beams incident on a solid target.

I $\sim 10^{24}$W/cm$^2$ $\sim 10^{-5}I_{SL}$

Magic is the seed electrons in plasma

Induced Vacuum Breakdown and Radiation Damping
Considered interaction processes

Interaction with matter

- Hard photon emission
  - $e^- + Z \rightarrow e^- + Z + \gamma$
- Pair production
  - $\gamma + Z \rightarrow e^- + e^+ + Z$

Interaction with strong field

- Hard photon emission
  - $e^- + n\gamma_L \rightarrow e^- + \gamma_h$
- Pair production
  - $\gamma_h + n\gamma_L \rightarrow e^- + e^+$
Mean-free path of linear BW process

\[ \hbar \omega_1 = 1 \text{eV} \quad \beta^2 > 0 \]

\[ I_L > 10^{24} \text{W/cm}^2 \]

\[ l = \frac{1}{n\sigma} = 5 \times 10^{-8} \text{cm} \quad \sigma \approx 10^{-25} \text{cm}^2 \]
Circularly Polarized Laser

\[ x(t) = \frac{ca_0}{\omega} \sin\left(\frac{1}{\gamma} \omega t\right) \]

\[ y(t) = \pm \frac{ca_0}{\omega} \cos\left(\frac{1}{\gamma} \omega t\right) \]

\[ \gamma = 1 + \frac{1}{2}a^2 \]

\[ a_0 = \sqrt{\frac{u_{os}}{c}} = \frac{eE_0}{m\omega c} \]

\[ a_0 = 0.85 \lambda_{\mu m}^2 \sqrt{I_{18}} \]
Pair Production by Avalanche Effect (Chain Reaction) with Radiation Damping

\[ I_L > 10^{24} \text{W/cm}^2 \]

\[ l = \frac{1}{n\sigma} = 5 \times 10^{-8} \text{cm} \]

\[ \gamma = 1 + \frac{1}{2}a^2 \]

\[ a_0 = 10^3 \quad \Rightarrow \quad \gamma = 10^6 \]

\[ \hbar^2 \omega_1 \omega_2 = 4m^2c^4 = (1\text{MeV})^2 \]
We are preparing an integrated simulation code of
Non-linear QED Plasma Physics to predict
phonomena demonstrated in 10-15 years.

Rotating field, circularly polarized laser field:
\[
\vec{E} = \{E_0 \cos(\omega_0 t), E_0 \sin(\omega_0 t), 0\}
\]

Simulation parameters:
\[ a = 2e3 \quad \hbar \omega = 1 \text{ eV} \]

(by Nina Elkina, LMU)
Radiation Damping

(1) Equations of motion with radiation reaction

\[
\frac{d\alpha}{d\tau} = -\frac{e}{m_e c^2} F^{\alpha\beta} \frac{dx_\beta}{d\tau} - \frac{I_c \alpha}{mc^2}, \\
\frac{dx_\alpha}{d\tau} = c \rho_\alpha + \frac{\tau_0 f_{Le}}{m_e}, \quad \tau_0 = \frac{2e^2}{3m_e c^3}.
\]

Sokolov+, PoP (2011)

⇒ Particle motion with energy reduction rate I

(2) Equations of motion + random walk model

• Event generator (total probability of emission / pair production)
• Additional photon / pair with theoretical spectrum
Chain Reaction of Pair Production Occurs

Is $10^{24}$ W/cm$^2$ enough efficiently to convert laser energy to relativistic pair plasmas,
We are installing QED and NL-QED in our Multi-d, Rel. PIC Code (Coll. Kato)

A. N. Timokhin

Time-dependent pair cascades in magnetospheres of neutron stars I. Dynamics of the polar cap cascade with no particle supply from the neutron star surface.

A. N. Timokhin1,2*  
Simulation scheme

We have developed a new simulation scheme that includes both QED processes and plasma dynamics.

1. The simulation scheme is based on the PIC model
Radiation and pair production in high-intensity pulse laser

Situation

- Radiating electron dynamics & Emission spectrum
- Efficiency of pair production mediated by hard photons
Comparison with SLAC experiment

Pulse laser $5 \times 10^{17}$ [W/cm$^2$]

47 [GeV] e's

Positron spectrum (simulation)

46.6 [GeV] electron beam (~2000 shot)

~35 [GeV] detection limit
O(1000) tracks for ~26 [GeV]

Experimental result

Bamber+ (1999)
Chain reaction of pair production

Laser condition: $I = 10^{23}$ [W/cm$^2$], $P_w = 7$ [$\mu$m], $\lambda = 1$ [$\mu$m]

Initial electron energy: 4[GeV]

extracted electron (red), positron (blue) and photon (purple)

((3rd generation))
Generated positron number

positron number per one incident electron

Intensity = \(5 \times 10^{23}\) (red), \(5 \times 10^{22}\) (blue), \(5 \times 10^{21}\) (purple) [W/cm\(^2\)]

pulse length \(P = 7\) [\(\mu\)m], wave length \(\lambda = 1\) [\(\mu\)m]

colliding pulse laser (inserted)

Intensity = \(5 \times 10^{23}\) [W/cm\(^2\)]

Pulse length \(P\) [\(\mu\)m] & wave length \(\lambda\) [\(\mu\)m]

- Purple \((P = 7.00, \lambda = 1.00)\)
- Blue \((P = 1.75, \lambda = 1.00)\)
- Red \((P = 7.00, \lambda = 0.25)\)
Nonlinear QED

\[ \gamma + n\omega \rightarrow e^- + e^+ \]
Collision of Two Light Quanta

G. Breit* and John A. Wheeler,** Department of Physics, New York University
(Received October 23, 1934)

The recombination of free electrons and free positrons and its connection with the Compton effect have been treated by Dirac before the experimental discovery of the positron. In the present note are given analogous calculations for the production of positron electron pairs as a result of the collision of two light quanta. The angular distribution of the ejected pairs is calculated for different polarizations, and formulas are given for the angular distribution of photons due to recombination. The results are applied to the collision of high energy photons of cosmic radiation with the temperature radiation of interstellar space. The effect on the absorption of such quanta is found to be negligibly small.

\[ d\sigma^{BW} = \frac{1}{32\pi s} \frac{p^2}{|k|} |T^{BW}|^2 d\cos\theta_{kp} \]

\[ \sigma^{BW}_{\text{tot}} = \frac{e^4}{4\pi s\gamma^4} \left\{ (2\gamma^4 + 2\gamma^2 - 1) \arcsin(\sqrt{1 - \gamma^2}) - \gamma(1 + \gamma^2) \sqrt{1 - \gamma^2} \right\} \]

\[ \gamma^2 = \frac{1}{1 - v^2} = \frac{E_p^2}{M_e^2} \]

\[ \sigma_{\text{tot}}(\gamma\gamma \rightarrow e^+e^-) \]

\[ s^{1/2}_{\text{thr.}} = 2M_e \]

\[ \omega'_{\text{thr}} = \frac{M_e^2}{\omega} \]

\[ \omega'_{\text{thr}} \approx 250 \text{ GeV} \oplus \omega = 1 \text{ eV} \]

\[ \omega'_{\text{thr}} \approx 250 \text{ keV} \oplus \omega = 1 \text{ MeV} \]
Joint Works with Titov (Sasha) on Non-linear QED Physics

1. **Laser pulse shape dependence of Compton scattering**
   A.I. Titova, Kämpferc, T. Shibata, A. Hosaka, and H. Takabe
   Submitted to Physical Review A, October 2013

2. **Breit-Wheeler process in very short electromagnetic pulses**
   AI Titov, B Kämpfer, H Takabe, A Hosaka
   Physical Review A 87 (4), 042106(2013)

3. **Enhanced Subthreshold e+ e- Production in Short Laser Pulses**
   AI Titov, H Takabe, B Kämpfer, A Hosaka

4. **Neutrino pair emission off electrons in a strong electromagnetic wave field**
   AI Titov, B Kämpfer, H Takabe, A Hosaka
   Physical Review D 83 (5), 053008(2011)

5. **Dimuon production by laser-wakefield accelerated electrons**
   AI Titov, B Kämpfer, H Takabe
   Physical Review Special Topics: Accelerators and Beams 12 (11), 111301(2009)
Volkov (D.M. Volkov (1935))

Dirac Equation in EM Wave

\[(i\gamma^\mu D_\mu + m)\psi = 0; \quad D_\mu = \partial_\mu + ieA_\mu, \quad A_\mu = A_\mu(\varphi), \quad \varphi = k^\mu x_\mu\]

\[\downarrow\]

Analytically solvable

Volkov Solution

\[\psi = \left[1 + \frac{ekA}{2kp}\right] \frac{u}{\sqrt{2p_0}} e^{is}; \quad S = -px - \int_0^{kx} d\varphi \left[\frac{e(pA)}{kp} - \frac{e^2A^2}{2(kp)}\right]\]

\[k, p\text{：电磁波, 電子の運動量, } u\text{：自由スピノル}\]

簡単のため 4 元ベクトルの積を \(ab = a^\mu b_\mu\) と書く
The Volkov Exact Solution of Dirac Equation

The Volkov wave function of an electron in the field of a circularly polarized electromagnetic wave is derived in Exercise 3.20 (from now on we set $\hbar = c = 1$).

$$\psi_p(x) = \sqrt{\frac{m}{q_0 V}} \left(1 + \frac{e}{2k \cdot p} k A\right) u(p)$$

$$\times \exp \left(iea \frac{\epsilon_1 \cdot p}{k \cdot p} \sin k \cdot x - iea \frac{\epsilon_2 \cdot p}{k \cdot p} \cos k \cdot x - iq \cdot x\right)$$

where $u(p)$ is a Dirac unit spinor (we suppress the spin index $s$). The plane-wave of this solution is characterized by an “effective momentum”

$$q^\mu = p^\mu + \frac{e^2 a^2}{2k \cdot p} k^\mu = p^\mu + \eta^2 \frac{m^2}{2k \cdot p} k^\mu,$$

which satisfies the dispersion relation

$$q^2 = m^2 + e^2 a^2 = m_*^2, \quad m_* = m \sqrt{1 + \eta^2}.$$
We obtained enhancement by short pulse effect and nonlinearity

FIG. 4. The same as in Fig. 3 but for symmetrized Fermi shape envelope. The solid, dot-dashed, and dashed lines are for $b/\Delta = 0.1$, 0.3 and 0.5, respectively. The corresponding approximate solutions are shown by symbols “+”, “×”, and “∗”, respectively.
Non-linear QED effect (1)
Multi-photon Breit-Wheeler Process

FIG. 1: The total cross section of $e^+e^-$ pair production as a function of the total energy in c.m.s., $\sqrt{s}$, for the finite pulse with $\Delta = \pi N$. The dashed and thick solid curves correspond to $N = 2$ and 5, respectively. The thin solid curve is for IPA. The thin dashed curve, labelled as B-W, corresponds to Breit-Wheeler process. Left and right panels correspond to $\xi = 0.01$ and 0.1, respectively.

Normalized Intensity of PW, EW, ZW

\[ a(z, t) = \frac{eA_x(z, t)}{mc^2} \]

\[ \xi^2 = \frac{4\pi\alpha(\hbar c)^2}{(m_e c^2)^2 \omega_\gamma^2 c} I \]

\[ \lambda = \frac{2\pi\hbar c}{\omega_\gamma} \]

E = 10 TeV
We can produce highly relativistic pair plasma with $10^{1000}$ (HE Astro. AGN-jet, BH-jets, GRBs)

$1 \text{ fm} = 10^8 \text{ fm}$

$1 \text{ fs} = 3 \times 10^7 \times 1 \text{ fm/c}$

We may also be able to create Pion-pair plasma to study collective phenomena like wave and turbulence in strong force
Avalanche must be important in QGP formation

Glasma decays into Quark Gluon Plasma

Very strong classical color gauge fields \( \geq (1 \text{GeV})^2 \)

(dense small x gluons inside of heavy ions)

( with Asakawa, OU )
1 m = 10^7 fm
1 fs = 3 \times 10^7 \times 1\text{fm/c}

\text{Nonlinear QED plasma}

10 fm
10\text{fm/c} = 30 \times 1\text{fm/c}

\text{Nonlinear QCD plasma}

\text{EXA-Laser}

10^6

\text{LHC, RHIC}
Conclusion

• Induced Vacuum Breakdown may efficiently convert laser energy to pair plasma energy
• Integrated simulation code is under construction
• Electron beam and laser interaction allows pair plasma production at $I \sim 10^{23-24}\ W/cm^2$
• Nonlinear QED effect has been studied and the threshold energy will reduce in short pulse
• We may do a model experiment of e-p fireball in the next generation laser facility