Relativistic Optics and High Field Science

Toshi Tajima
Faculty of Physics, LMU, MPQ, Garching, Germany
and
Blaise Pascal Chair of Ecole Normale Superieure of France

International Committee for Ultra Intense Lasers

Inaugurated in 2004, Oxford under IUPAP

(above: initial Committee members)

Chair: T. Tajima,
Co-chair: C. Barty, W. Sandner

www.ICUIIL.org
Can the society continue to support ever escalating accelerators?

Accelerator = crown-jewel of 20th C science
Demise of SSC (Super collider)

By largest machine to probe smallest of structure of matter

- size: $10^2$km
- energy: 20TeV
- cost: $10B$

US:
Texas site decided (1989)

US Government decided to terminate its work: 1993

Dream Beams Symposium

MPQ Garching
Feb. 26 – 28, 2007

High intensity laser driven beams
What is **collective force**? : Secret behind **laser** accelerator

How can a Pyramid have been built?

**Individual** particle dynamics  →  **Coherent** and **collective** movement

**Collective acceleration** (Veksler, 1956; Tajima & Dawson, 1979)
- Collective radiation ($N^2$ radiation)
- Collective ionization ($N^2$ ionization)

→ **Laser** driven collective accelerating field
Wakefield: a Collective Phenomenon

Kelvin wake

\[ \omega = \sqrt{kg} \]
\[ x = X_1 \cos \theta \left( 1 - \frac{1}{2} \cos^2 \theta \right) \]
\[ y = X_1 \cos^2 \theta \sin \theta \]
\[ -\pi / 2 < \theta < \pi / 2 \]

No wave breaks and wake **peaks** at \( v \approx c \)

Wave **breaks** at \( v < c \)

\[ \lambda_p = \frac{2\pi}{k_p} \quad k_p v_{ph} = \omega_{pe} \]
\[ \omega_{pe} = \left( \frac{4\pi n e^2}{m_e} \right)^{1/2} \]  
(The density cusps. Cusp singularity)
Thousand-fold Compactification

*Laser wakefield*: thousand folds gradient (and emittance reduction?)

- Laser pulse
- Plasma
- Gas tube
- Superconducting linacrf- tube
  -(Fermilab)

\[ E_{\text{max}} \approx 100,000 \text{MV/m} \]

\[ E_{\text{max}} \approx 32 \text{MV/m} \]

\[ 0.1 \text{mm} \]

\[ \sim 0.03 \text{mm} \]
At ICTP Summer School (1981), Prof. Salam summoned me and discussed about laser wakefield acceleration.

Salam: ‘Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged’. (1981)

He organized the Oxford Workshop on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream

*High field science*: spawned
Laser technology invented (1985)

Chirped pulse amplification (CPA) invented:
  to overcome the gain medium nonlinearities in spatially expanded amplification to temporal expansion:
    smaller, shorter pulse, more intense, higher reprise,
  all simultaneous.

(Professor Gerard Mourou: ELI Coordinator)

→ many table-top TW and PW lasers world-wide
→ first Chair, ICUIL (International Committee for Ultra Intense Lasers)
→ toward EW laser (Extreme Light Infrastructure ELI)

→ First LWFA experiments
  (Nakajima et al 1994; Modena et al 1995)
→ now drives High Field Science
310-μm-diameter channel capillary

\[ P = 40 \text{ TW} \]

density \(4.3 \times 10^{18} \text{ cm}^{-3}\).

Lee mans et al., Nature Physics, september 2006
Key issues of future colliders

(T. Raubenheimer, SLAC, 2008)

Beam Acceleration

* Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is \( \sim 20 \text{ MV/m} \) → 50km for 1 TeV

* Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields

* Many paths towards high gradient acceleration
  - High gradient microwave acceleration \( \sim 100 \text{ MV/m} \)
  - Acceleration with laser driven structures \( \sim 1 \text{ GV/m} \)
  - Acceleration with beam driven structures \( \sim 10 \text{ GV/m} \)
  - Acceleration with laser driven plasmas
  - Acceleration with beam driven plasmas
Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator

compact, ultrastrong a

Can we meet the challenge?

atto-, zeptosecond

A. Suzuki @KEK(2008)
Evolution of Accelerators and their Possibilities (Suzuki, 2008)

- **2020s**
  - ILC
  - Energies: $E=40$ MV/m

- **2030s**
  - Two-beam LC
  - Energies: $E=200$ MV/m

- **2040s**
  - Laser-plasma LC
  - Energies: $E=10$ GV/m

- **2050s**
  - Earth-based space debris radar

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- **2.5-5 GeV ERL**
  - Superconducting L-band linac

- **Ultra-HV Voltage STEM with Superconducting RF cavity**

- **10cm-10GeV Plasma Channel Accelerator**

- **Earth-based space debris radar**

- **Table-top high energy accelerator**
Additional way preparing for the future in Fundamental Physics

• **Collider paradigm** (‘high momentum’ approach)
  quantum mechanics $\Delta E \Delta t \sim \hbar \rightarrow \mathcal{L} \propto E^2$

• **Non-collider approaches** (‘high field’ approach)
  *relativity*: the higher the energy, the pronounced the effect
  horizon $\sim 1/\alpha$ (extradimensions?)
  $\alpha = g$ (Einstein’s Equivalence Principle)?
  Unruh($\alpha$)-Hawking($g$) radiation?
  special theory (*no preferred frame*? ; $c(\varepsilon)$?)
  extreme field physics (merger of research on special
  and general theories of *relativity*; Can $E$ also warp
  space; $c(|E|^2)$ )
  what is vacuum? (QED, QCD(axion), dark energy, …)

(Gies, Marlund, Di Piazza, Dunne, Schuetzhold, Heinzl, Reiss, DeKieviet, Rafelski, Zayakin, Smilga, Cohen, Thirolf, Weinfurter, Labun,.. discussed)
Quantum Gravity:

“Why is the sky blue?”
(for extreme high energy gamma rays)

  high energy $\gamma$ has dispersion:
  $\omega = kc + (\text{extra mass-like term?})$, i.e. $c(\mathcal{E})$
- May be regarded as scattering off quantum fluctuations of vacuum (gravitational origin).
- Other proposals, such as H. Sato (1972); Coleman-Glashow (1997), ….
  breakdown of Lorentz invariance?
  (cosmic $\gamma$ rays cease to exist beyond certain energy)

*May be testable in PeV energy regimes.*
A limit on the variation of the speed of light arising from quantum gravity effects

A cornerstone of Einstein’s special relativity is Lorentz invariance—the postulate that all observers measure exactly the same speed of light in vacuum, independent of photon-energy. While special relativity assumes that there is no fundamental length-scale associated with such invariance, there is a fundamental scale (the Planck scale, $l_{\text{Planck}} \approx 1.62 \times 10^{-35} \text{ cm}$ or $E_{\text{Planck}} = M_{\text{Planck}} c^2 \approx 1.22 \times 10^{19} \text{ GeV}$), at which quantum effects are expected to strongly affect the nature of space-time. There is great interest in the (not yet validated) idea that Lorentz invariance might break near the Planck scale. A key test of such violation of Lorentz invariance is a possible variation of photon speed with energy\(^{1,2}\). Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in \(\gamma\)-ray burst (GRB) light-curves\(^3\). Here we report the detection of emission up to \(\sim 31 \text{ GeV}\) from the distant and short GRB 090510. We find no evidence for scale (when \(E_{\text{ph}}\) becomes comparable to $E_{\text{Planck}}$). For \(E_{\text{ph}} \ll E_{\text{Planck}}\), the leading term in a Taylor series expansion of the classical dispersion relation is $|v_{\text{ph}}/c - 1| \approx (E_{\text{ph}}/M_{\text{QG},c} c^2)^n$, where $M_{\text{QG},c}$ is the quantum gravity mass for order $n$ and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm (\Delta E/M_{\text{QG},c}) D/c$ in the arrival time of photons emitted together at a distance $D$ from us, and differing by $\Delta E = E_{\text{high}} - E_{\text{low}}$. At cosmological distances this simple expression is somewhat modified (see Supplementary Information section 4).

Because of their short duration (typically with short substructure consisting of pulses or narrow spikes) and cosmological distances, GRBs are well-suited for constraining $\text{LV}^{2,11,12}$. Individual spikes in long\(^5\) (of duration $\geq 2$ s) GRB light-curves (10–1,000 keV) usually show\(^4\) intrinsic lags: the peak of a spike occurs earlier at higher photon-energies. However, there are either no lags or very short lags

\begin{center}
(Abdo et al, 2009)
\end{center}
$\gamma$-ray signal (GRB) from primordial GRB

Energy-dependent Photon mass? limit is pushed up to near Planck mass

PeV $\gamma$ (from e-) Can explore this

(Abdo, et al., 2009)
Meeting Suzuki’s Challenge toward PeV

\[
\Delta E \approx 2m_0c^2a_0^2\gamma_{\nu \phi}^2 = 2m_0c^2a_0^2 \left( \frac{n_{cr}}{n_e} \right), \quad \text{(when 1D theory applies)}
\]

\[
L_d = \frac{2}{\pi} \lambda_p a_0^2 \left( \frac{n_{cr}}{n_e} \right), \quad L_\rho = \frac{1}{3\pi} \lambda_p a_0 \left( \frac{n_{cr}}{n_e} \right)
\]

<table>
<thead>
<tr>
<th></th>
<th>case I</th>
<th>case II</th>
<th>case III</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_o)</td>
<td>10</td>
<td>3.2</td>
<td>1</td>
</tr>
<tr>
<td>energy gain</td>
<td>GeV</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>plasma density</td>
<td>cm(^{-3})</td>
<td>5.7x10(^{16})</td>
<td>5.7x10(^{15})</td>
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<tr>
<td>acceleration length</td>
<td>m</td>
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<tr>
<td>spot radius</td>
<td>(\mu m)</td>
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<td>100</td>
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<td>peak power</td>
<td>PW</td>
<td>2.2</td>
<td>2.2</td>
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<tr>
<td>pulse duration</td>
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<tr>
<td>laser pulse energy</td>
<td>kJ</td>
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<td>1.6</td>
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</table>

Even 1PeV electrons (and \(\gamma\) s) are possible, albeit with lesser amount
→ exploration of new physics such as the **reach of relativity** and quantum gravity
(correlating with primordial gamma-ray burst [GRB] observation)?
(laser energy of 10MJ@plasma density of 10\(^{16}\)/cc; maybe reduced with index 5/4)
When can we reach 1 PeV?: Suzuki Challenge

(Suzuki, 2009)

Laser plasma accelerator experiments

V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4
The Crab Pulsar, a city-sized, magnetized neutron star spinning 30 times a second, lies at the center of this composite image of the inner region of the well-known Crab Nebula. The spectacular picture combines optical data (red) from the Hubble Space Telescope and x-ray images (blue) from the Chandra Observatory, also used in the popular Crab Pulsar movies. Like a cosmic dynamo the pulsar powers the x-ray and optical emission from the nebula, accelerating charged particles and producing the eerie, glowing x-ray jets. Ring-like structures are x-ray emitting regions where the high energy particles slam into the nebular material.

Can we see manifestation of quantum gravity, Lorentz variance in high energy γ? How PeV electrons accelerated?

The Crab Pulsar, a city-sized, magnetized neutron star spinning 30 times a second, lies at the center of this composite image of the inner region of the well-known Crab Nebula. The spectacular picture combines optical data (red) from the Hubble Space Telescope and x-ray images (blue) from the Chandra Observatory, also used in the popular Crab Pulsar movies. Like a cosmic dynamo the pulsar powers the x-ray and optical emission from the nebula, accelerating charged particles and producing the eerie, glowing x-ray jets. Ring-like structures are x-ray emitting regions where the high energy particles slam into the nebular material.
EM Pulse Intensification and Shortening by the Flying Mirror toward the Schwinger field

(Bulanov, Esirkepov, Tajima, 2003)

3D Particle-In-Cell Simulation

A lot of ideas for new attosecond pulses
Hawking radiation

What is ‘vacuum’? Does ‘something’ emerge from ‘nothing’?
「空」＝「色」？　「混沌」⇔「秩序」？
vacuum = ‘matter’ ?  chaos ⇔ information ?
Explore relativity with strong fields (Unruh radiation)

\[ I = 10^{17} \text{[W/cm}^2\text{]} \Rightarrow E \approx 10^{12} \text{[V/m]} \]
\[ \Rightarrow k_B T = 0.06eV \Rightarrow \sim 10eV \text{ (blue shift in lab. frame)} \]

- **Unruh radiation**

- **Larmor scattering**

**Rindler frame**
- Observer in Rindler 1
- Strong correlation between absorption and emission despite of causal disconnection
  - G. Unruh PRD 29 1047-1056, 1984

**Inertial frame**
- No correlated pair in background process

**Correlated pair radiation**
- Negative frequency mode in Rindler 2

(Chen, Tajima 1999)
Nonlinear Optics in vacuum

What is vacuum?
Can vacuum be nonlinear?
Is $c$ constant?
What contribute to nonlinear vacuum?

Higher order QED and QCD

Euler-Heisenberg effective action in constant Abelian field $U(1)$ can be expressed as

$$L_{\text{1-loop}}^{\text{LO+NLO}}(A_\mu) = -\frac{1}{90} \frac{\pi^2}{m^4} \left[ \left( \frac{\alpha}{\pi} F^2 \right)^2 + \frac{7}{4} \left( \frac{\alpha}{\pi} F F_\perp \right)^2 \right] + \frac{1}{315} \frac{\pi^4}{m^8} \left[ 4 \left( \frac{\alpha}{\pi} F^2 \right)^3 + \frac{13}{2} \frac{\alpha}{\pi} F^2 \left( \frac{\alpha}{\pi} F F_\perp \right)^2 \right]$$

If $U(1) \rightarrow U(1) + \text{condensed SU(3)}$ due to self-interacting attractive force of gluons

$$\frac{\alpha}{\pi} F^2 \rightarrow \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle + \frac{\alpha}{\pi} q^2 F^2 \quad \left\langle 0 \left| \frac{\alpha_s}{\pi} G^2 \right| 0 \right\rangle \approx (2.3 \pm 0.3) \times 10^{-2} \text{GeV}^4$$

(K.Homma, 2007)

Focus on only light-light scattering amplitude after the substitution

$$L_{\text{1-loop}}^{\text{LO+NLO}}(A_\mu + G^a_{\mu\nu}) = -\frac{1}{90} \frac{\pi^2}{m^4} \left[ \left( \frac{\alpha}{\pi} F^2 \right)^2 + \frac{7}{4} \left( \frac{\alpha}{\pi} F F_\perp \right)^2 \right]$$

$$+ \sum_{i=u,d} \frac{1}{315} \frac{q_i^2 \pi^4}{m_i^8} \left[ 12 \left( \frac{\alpha}{\pi} F^2 \right)^2 \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle + \frac{13}{2} \left( \frac{\alpha}{\pi} F F_\perp \right)^2 \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle \right]$$

QCD effect dominates pure QED 1-loop vacuum polarization to light-light scattering

$$\frac{2\text{nd - term}}{1\text{st - term}} = \sum_{i=u,d} \frac{24 q_i^2 \pi^4}{m_i^8} \frac{1}{m_e^4} \left\langle \frac{\alpha}{\pi} G^2 \right\rangle \approx e^{9 \pm 2.5} \quad m_u \approx \frac{1}{2} m_d \approx 5 \pm 1.5 \text{MeV}, \quad q_u^2 = 4 q_d^2 = \frac{4}{9}$$

Check of Euler-Heisenberg yet to come. Any deviation from it?

$\rightarrow$ axion field?; extended fields (such as dark energy, Tajima-Niu, 1997, etc.)?
Homma proposes: experimental test

Measure instantaneous variation of refractive index in Electro-Optical crystal by external electric fields.

\[ \delta n = f(r_{EO}) E_T \]

\[ E_T = \frac{\gamma e}{4\pi\varepsilon_0 n^2 R^2} \]

\[ \delta l \approx \frac{c}{n} \Delta t = \frac{R}{\gamma\beta n} \]

\[ \Delta t \approx \frac{R}{\gamma\nu} \]

\[ \Delta x \approx \frac{R}{\gamma} \]

\[ \Delta y \approx R \tan(\cos^{-1}(0.5)^{1/3}) \]

\[ \delta \Gamma = \frac{2\pi}{\lambda} \delta n \delta l = \frac{f(r_{EO})}{2\varepsilon_0 n^3} \frac{e}{\lambda \beta R} \]

(Homma, 2007)
Detection of (light) fields-particles missed by collider: exploring new fields such as axion......

A.Chou et al., PRL (2008) observed no signal so far (Note: claim of axion by PVLAS was withdrawn)
High Field Science and other (telescope, collider) approaches

- \( \log_{10}(\text{Energy Density}) \) [GeV/fm³]
- \( \log_{10}(\text{System Size}) \) [fm]

- Horizon (\( h \approx 0.7, \Omega = 1.0 \))
- Gamma ray burst at \( 10^{10} \) LY (telescope)
- Rest proton \( e^+e^- \) \( \sqrt{S} = 1 \) TeV collider
- \( \text{AuAu} \sqrt{S} = 40 \) TeV (RHIC)
- \( \text{pp} \sqrt{S} = 14 \) TeV (LHC)
- High laser field \( \lambda \approx 1 \mu m, \Delta T \approx 500 \) fs

(K. Homma)
High amplitude photon-photon interaction

B. King et al., Nature Photon. 4, 92(2010)
Conclusions

Why strong-field physics…?

• “…exploring some issues of fundamental physics that have eluded man’s probing so far” (Tajima’01)

• QFT: high energy (momentum) vs. high amplitude

• “Fundamental-Physics” discovery potential:
  • ALPs: hypothetical NG bosons (axion, majoron, familon, etc.)
  • MCPs: minicharged particles
  • paraphotons
  • sub-millimeter forces
  • …

• high physics/costs ratio

(H. Gies discussed at Extreme Light Infrastructure (ELI) Meeting, 2008)
20th Century physics began with Einstein, including theory for laser. 21st Century laser may test and even challenge Einstein.

Help make 2005 another Miraculous Year!
Relativity Helps Acceleration (for Ions, too!)

In relativistic regime, photon x electrons and even protons couple stronger.

(Tajima, 1999 @LLNL; Esirkepov et al., PRL, 2004)
Beyond laser intensity $10^{24}$ W/cm$^2$ ions move relativistically like $e^-$. Relativistic and monoenergetic ion beam may constitute compact colliders of ions → QCD vacuum exploration.

(Bulanov et al, 2004)
Societal impact and contributions

some examples:

• Compact cancer hadron therapy devices (JAEA, LIBRA, SAPHIR, Dresden collaborations; will be discussed more)

• Intraoperative Radiation Therapy (IORT): INFN + CEA (Saclay)

• Untrafast radiolysis (LOA etc.)

• Injector for ultrabright X-ray sources (for medicine etc.) (LBL, MPQ etc.)
Compactification of Laser Ion Accelerator for Cancer Therapy

Radiation Dose Distribution

Comparative Radiation [%]

Depth from Body Surface [cm]

Building Size, > $100 M

Size Down Cost Down

10m, $10 M

(Hyogo Ion Beam Medical Center)
Conclusions

• **Collective acceleration driven by intense laser**: leap by many orders ($\geq 3$), GeV electrons; 10 GeV soon; 100GeV considered; TeV laser collider contemplated; PeV possible?

• **High momentum approach vs high amplitude approach**: high field science’s new paradigm

• Test of Einstein’s relativity (special and general theories), nonlinear QED (and QCD), high acceleration (=gravitational) physics, radiation dominant regime, quantum gravity, nonlinear optics in vacuum

• **Societal applications**: already beginning, soon to flourish (e.g., cancer therapy, radiolysis)

• Compact new paradigm of fundamental physics in 21st Century