The Frontier of High Field Science

Toshiki Tajima

Faculty of Physics, LMU, and MPQ, Garching

To Fukushima: With sympathy and camaraderie

Excerpt from ‘Greetings from Chair: Epochal Lasers, Epochal Year’ in ICUIL Newsletter Toshiki Tajima, ICUIL Chair

‘………………As Professor S. Gales has told us, the impact of progress of nuclear physics will be felt on the way to make progress in nuclear engineering such as the nuclear waste monitoring and management. Even though Fermi has made an impressive beginning of nuclear energy and engineering, few breakthroughs that rival his have happened. This is why I have been advocating the importance of what I called ‘toilet science’ as opposed to the predominant conventional efforts in ‘kitchen science’, where the latter focuses on the upstream side of energy and matter while the former on the downstream. In other words, the former tries to understand the science how best we can clean up what the nuclear energy production brings out. ……………

In retrospect of the recent nuclear reactor catastrophe after the most powerful earthquake in the recorded history of Japan, I believe that it is even more urgent to make further progress in ‘toilet science’ of nuclear energy. We are fortunate and proud that the ELI research and the intense laser research around ICUIL (and SPIE*) as a whole can make such a contribution to the society in its urgent problems.’


* I acknowledge Prof. Katarina Svanberg, President of SPIE, for her message toward this crisis.
High energy **gammas** and notch-detectors for nuclear resonance fluorescence

Narrow $\gamma$ beam

Hole burning, ultra-high resolution

Isotope sample

Isotope second scatterer

NRF

$\gamma$-ray beam dump

• **Tomography**

• $^{235}$U/$^{238}$U ratio

change in scattering rate

**(Bertozzi, Hajima, Habs, ..)**

**Gamma beam**: directed, energy-specific, brilliant $\leftarrow$ **laser** Compton (see Barty, Habs)

**May be employed for Fukushima reactors upon cleanup**
Extreme Light

-Photons with extremely high energy
  example already mentioned and later
  (see also Barty 8080B, Habs)

-Photons with extremely high fields
  (and coherence)
  main topic today here (see also 8075,
  8079A, 8079B, 8080A, 8080B)
Extreme Light Infrastructure

Czech

Hungary

Romania

........

(G. Mourou, L. Giesen)
Content

1. Ever higher intensity lasers
2. Ultrafast optics toward attosecond science
3. How can we reduce the pulse length?
   Answer---- intensity!
4. ‘Intensity - Pulse Duration Conjecture’
5. Examples of attosecond pulses and beyond
6. Confluence of ultrafast optics and high field science
7. Atom streaking in as → vacuum streaking in zs
8. Attosecond metrology of γ signals at the energy frontier
Energy frontier ← High field science, high intensity laser

relativistic optics: relativistic coherence
cf. quantum optics: quantum coherence

Quantum optics
Cold Atoms
feV-neV

2010

Cohen-Tannoudji, Chu, Ketterle, …

(see also Session 8072B)

1eV

Relativistic Optics, RMP, Mourou (2006)

GeV-TeV

2010

High field science

High energy Physics (fundamental physics)
QCD $\sim 10^{35}$ W/cm$^2$
Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_e c^2$

Ultra Relativistic Optics
$E_o = m_p c^2$

Relativistic Optics
$E_o = m_e c^2$

Bound electrons

Q-switching

Mode locking

Boiled vacuum

Schwinger field

Relativistic ions

Keldysh field

Relativistic electrons

Plasma

Atoms

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities

ICUIL, Barty
Intensification of Laser

\[ I = \frac{J}{\tau} \]

2 paths:

#1: increase the laser energy (or fluence \( J \)); \textit{the larger, the better}

#2: decrease the laser pulse length \( \tau \); \textit{the shorter, the better}
Does $\tau = J/I$ hold?

To reduce $\tau$
From trivial statement of $I = J/\tau$

↓

The nontrivial assertion:
“*In order to compress the pulse further, we need to increase the intensity of laser*”

Is this true?
The Conjecture

(← physics: “Matter is nonlinear”

“The more rigid nonlinearity, the more intense to manipulate it”)

Pulse intensity →

Pulse duration

Mourou / Tajima, 2011
Nonlinearities in atom, plasma, and vacuum

Atomic nonlinear potential

Plasma electron nonlinear relativistic motion

Vacuum nonlinearity

Keldysh field for laser atomic ionization

Schwinger field for vacuum breakdown
Relativistic nonlinearity under intense laser

Plasma free of binding potential, but its electron responses:

a) Classical optics: \( v << c \),
   \[
   a_0 << 1: \quad \delta x \text{ only}
   \]

b) Relativistic optics: \( v \sim c \)
   \[
   a_0 >> 1: \quad \delta z >> \delta x
   \]

\[
A_0 = \frac{eA_0}{mc^2} = \frac{eE_0 \lambda}{mc^2}
\]
Pulse Progress from fs to as

Corkum and Krausz (2007)

**Figure 1** Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1984 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making even shorter laser pulses. However, at 6 fs (three periods of light), a radically different technology was needed. Its development took 15 years. Now attosecond technology is providing radically new tools for science and is yet again opening new fields for application.

**Figure 2** Creating an attosecond pulse. a–d, An intense femtosecond near-infrared or visible (henceforth: optical) pulse (shown in yellow) extracts an electron wavepacket from an atom or molecule. For ionization in such a strong field $\Psi_0$, Newton's equations of motion give a relatively good description of the response of the electron. Initially, the electron is pulled away from the atom (a, b), but after the field reverses, the electron is driven back (c) where it can ‘recollide’ during a small fraction of the laser oscillation cycle (d). The parent ion sees an attosecond electron pulse. This
The Coherent Wake Emission

(R. Hoerlein, 2010)

Glass Target (Density $\approx 2.6 \text{ g/cm}^3$):

Plexiglass Target (Density $\approx 1.3 \text{ g/cm}^3$):


attosecond pulse generation

- compress the reflected radiation into attosecond pulses and
- inherit a peaked density distribution.
- Complete modulation of e.m. field occurs. This is relativistic engineering

Naumova et al. (2004)

Efficiency of attosecond phenomena: ~15% converted to attosecond pulses, ~15% to e.m. pulses and ~15% converted to attosecond electron bunches.

Attosecond e. m. pulses
Attosecond e⁻ bunches

a=10, 15fs, f/1, n=25n_{cr}
Isolated attosecond EM pulses
3D simulation

Relativistic oscillating mirror of solid surface

Bulanov (1994)
Nees (2005)

$a_0=3, \tau=5\text{fs}, f/1, n=1.5n_{\text{cr}}$
Relativistic flying mirror and shorter pulses

Esirkepov (2009) --- Einstein’s flying mirror made of LWFA

\[ \tilde{\omega} = \frac{c-V}{c+V} \omega \approx \frac{1}{4\gamma^2} \omega \]

\[ \tilde{\omega} = \frac{c+V}{c-V} \omega \approx 4\gamma^2 \omega \]

Laser Piston

Flying Mirror (LWFA)

(see also Tajima, Wednesday)
Ultrasound science ← High field science, Large-energy laser

High field science

ELI pillars:
- attosecond science
- high energy beams
- photonuclear physics
- high field science

Large-energy laser
(NIF/LMJ...)

Ultrafast science (attosecond, ...)

LMU
Streaking of atomic electron Keldysh field and beyond

Self-focusing in air / vacuum

Critical power for self-focusing in matter / plasma / vacuum:

χ₃ (air) nonlinearity

\[ P_{cr} = \frac{\lambda^2}{(2\pi n_0 n_2)} \sim \text{GW} \]

relativistic plasma nonlinearity

\[ P_{cr} = \frac{mc^5}{e^2(\omega/\omega_p)^2} \sim 17 (\omega/\omega_p)^2 \text{ GW} \]

vacuum nonlinearity

\[ P_{cr} = \frac{(90/28)c E_s^2 \lambda^2/\alpha}{\sim 10^{15} (\lambda/\lambda_{1\mu})^2} \text{ GW} \]

e.g. X-ray of 10keV, \( P_{cr} \sim 10\text{PW} \)
‘ELI Long-term Ambition’ =

Studying the **Atomic** Structure to the **Vacuum** Structure

(Mourou)

\[
\text{Srchwinger intensity} / \text{Keldysh intensity} = \alpha^{-6} \sim 10^{14}
\]

Vacuum self-focusing / $\chi_3$ self-focusing power $\sim \alpha^{-6} \sim 10^{15}$

Does the **atomic** world repeat itself in **vacuum**?

Keldysh field?

Schwinger field
Streaking vacuum (1)  
(from atomic physics to vacuum physics)

Uiberacker et al. (2007)

Gamma photon ‘ionization’
XUV streaking
→ zeptosecond dynamics

size

\[ \lambda_C = \alpha a_B \]

depth of potential

\[ \Phi = \alpha^2 W_B \]

Nikishov (1964)
Nonperturbative:

Multiphoton:

XUV photon ionization
Laser streaking
→ attosecond dynamics
Streaking vacuum 2 (learning from atoms)

**Atoms:**
Keldysh field \( E_K = \frac{W_B}{a_B} \)

Atoms: Keldysh

Goulielmakis (2008)

**Vacuum:**
Schwinger/Nishikov field
\[ E_{SN} = E_{S\sigma} \left( \frac{m_{\sigma} c^2}{\hbar \omega} \right) \]

Scwinger field
\[ E_{Se} = \alpha^{-3} E_K \]

Keldysh parameter \( \gamma_K \)
\[ \gamma = \frac{e \sqrt{2m}}{|e|E_0} \]

Streaking resolving power (Itatani 2002; Kienberger 2004):
\[ \Delta t = \sqrt{\frac{\hbar \omega m}{eA_0 p_0}} \sim \sqrt{\frac{\hbar \omega \epsilon_0}{a_0}} / \omega \sim zs \]

real spacetime mapping (instead of spectroscopy) of structure/dynamics of vacuum (QED and perhaps QCD)
Gluon Plasma, Nuclear Wake, String Theory

J. Ulery (2007)

• **Monojet** (or jet suppression) in BNL and CERN heavy ion collision.

• Superstring theory (Maldacena Conjecture) on heavy ion collisions
  
  Quantum Gluon Plasma (QGP)

  Maldacena method: QCD wake
  (Chesler/Yaffe 2008)

  Deflected Jets

  Conical Emission

• Monojet could be caused by:
  
  **Collective deceleration of quark** in the nuclear wakefield

  (Homma, BNL collab 2010)
String theory sees wakefield(!?)

All particles in the medium participate = collective phenomenon

Kelvin wake

No wave breaks and wake peaks at $v \approx c$

Wave breaks at $v < c$

(The density cusps. Cusp singularity) (see 8079A)

(Plasma physics vs. superstring theory?)
Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator

compact, ultrastrong atto-, zeptosecond (I have tried to show this)

Can we meet the challenge?

A. Suzuki @KEK(2008)
Theory of wakefield toward extreme energy

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

In order to avoid wavebreak,

\[ a_0 < \gamma_{ph}^{1/2}, \]

where

\[ \gamma_{ph} = \left( \frac{n_{cr}}{n_e} \right)^{1/2} \]

Adopt:

- NIF laser (3MJ) \[ \rightarrow 0.7 \text{PeV} \]
  (with Kando, Teshima)
Energy-dependent photon speed?
Observation of primordial Gamma Ray Bursts (GRB)
(limit is pushed up close to Planck mass)

Lab PeV $\gamma$ (from e-) can explore this with control
Feel vacuum texture: PeV energy $\gamma$

Laser acceleration $\rightarrow$ controlled laboratory test to see quantum gravity texture on photon propagation (Special Theory of Relativity: $c_0$)

$C < c_0$

$(0.1\text{PeV})$  $(1\text{PeV}: \text{fs behind})$

PeV $\gamma$ (converted from $e^-$)

Coarser, lower energy texture

Finer, higher energy texture

1km
[**γ-assisted Schwinger process**—see p.27]

High energy γ- induced Schwinger breakdown (Narozhny, 1968)
CEP phase sensitive electron-positron acceleration
Attosecond electron streaking
γ- energy tagging possible

Goulielmakis(2008)
Conclusions

1. Extreme Light: $\gamma$-beams; high field lasers
2. Quantum Optics $\leftrightarrow$ Relativistic Optics (rel. coherence)
   2. To reduce the pulse length, need to increase the intensity
3. Ultrafast Optics $\leftrightarrow$ High Field Science
4. Highest energy laser $\rightarrow$ Shortest pulses
5. Attosecond $\rightarrow$ Zeptosecond
6. Vacuum physics can learn from Atomic physics
   e.g. laser streaking of atom
7. Vacuum physics $\leftrightarrow$ Atomic physics
8. High energy LWFA toward PeV with highest energy laser $\rightarrow$ examine Einstein’s relativity, Quantum gravity w/ $\gamma$-assisted attosecond Schwinger process
Thank you!

(Mourou, 2010)