High Field Science

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1. Laser intensity and nonlinearities
2. Relativistic Nonlinearity = Laser Wakefield Acceleration
3. Radiation Pressure Acceleration x LWFA toward TeV over cm
4. ICAN: toward fiber laser with 100MW @ 50%
5. Prof. Suzuki’s Challenge:
   1000 times higher energies, 1000 times shorter time scales
6. PeV acceleration to probe quantum gravity fluctuations
7. Ultrafast science: toward attosecond, zeptosecond, yoctosecond(?)
8. Integration of high field science and ultrafast science
9. Exploration of vacuum
10. High field science as a tool to explore light-mass new fields (dark matter such as ALP and dark energy)
Nonlinearities in atom, plasma, and vacuum

Atomic nonlinear potential

Plasma electron nonlinear relativistic motion

Vacuum nonlinearity

Keldysh field for laser atomic ionization

Laser wakefield

Schwinger field for vacuum breakdown

Compact high energy colliders
Compact accelerator applications
PeV acceleration for quantum gravity

Nonlinear QED fields
General relativistic effects
Vacuum probe (s.a. Dark energy)
Relativistic nonlinearity under intense laser

Plasma free of binding potential, but its electron responses:

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

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

\[
\delta z \sim a_0^2
\]

\[
\delta x \sim a_0
\]
Wakefield: a Collective Phenomenon

All particles in the medium participate = 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)

(Plasma physics vs. String theory?)
Laser driven collider concept

Each Stage: ~100J laser (ELI class)

Leemans and Esarey (Phys. Today, 2009)
ICFA-ICUIL JTF on Laser Acceleration (Darmstadt, 2010)
ICFA-ICUIL Joint Task Force on laser acceleration (Darmstadt, 2010)

W. Leemans, Chair

Collider subgroup
List of parameters (W. Chou)

Table 1
Collider parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>1 TeV</th>
<th>10 TeV (Scenario I)</th>
<th>10 TeV (Scenario II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per beam (TeV)</td>
<td>0.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>1.2</td>
<td>71.4</td>
<td>71.4</td>
</tr>
<tr>
<td>Electrons per bunch ($\times 10^{9}$)</td>
<td>4</td>
<td>4</td>
<td>1.3</td>
</tr>
<tr>
<td>Bunch repetition rate (kHz)</td>
<td>13</td>
<td>17</td>
<td>170</td>
</tr>
<tr>
<td>Horizontal emittance $\gamma \varepsilon_x$ (nm-rad)</td>
<td>700</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Vertical emittance $\gamma \varepsilon_y$ (nm-rad)</td>
<td>700</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$\beta^*$ (mm)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Horizontal beam size at IP $\sigma^*_x$ (nm)</td>
<td>12</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vertical beam size at IP $\sigma^*_y$ (nm)</td>
<td>12</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Luminosity enhancement factor</td>
<td>1.04</td>
<td>1.35</td>
<td>1.2</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$ (μm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Beamstrahlung parameter $\Upsilon$</td>
<td>148</td>
<td>8980</td>
<td>2800</td>
</tr>
<tr>
<td>Beamstrahlung photons per electron $n_\gamma$</td>
<td>1.68</td>
<td>3.67</td>
<td>2.4</td>
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<tr>
<td>Beamstrahlung energy loss $\delta_\epsilon$ (%)</td>
<td>30.4</td>
<td>48</td>
<td>32</td>
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<tr>
<td>Accelerating gradient (GV/m)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Average beam power (MW)</td>
<td>4.2</td>
<td>54</td>
<td>170</td>
</tr>
<tr>
<td>Wall plug to beam efficiency (%)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>One linac length (km)</td>
<td>0.1</td>
<td>1.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
ICFA-ICUIL JTF Conclusions  
(April, 2010; Darmstadt)

- Science of LWFA (US, Europe, Asia) matured to extend toward HEP accelerators
- Laser technology lacking suited for HEP accelerators: laser efficiency, average power
- Technologies to rectify emerging and credible: 1. thin disk; 2. ceramic; 3. fiber laser,..
- ICFA-ICUIL collaboration: important guide of direction

→ Bridge Lab between HEP and Laser communities
  “Symposium on Bridgelab for Laser Accelerator: Route toward Reality”
  L’orne (Paris), Jan. 14, 2011 (Organizers: Mourou, Tajima, ….)
TeV ion acceleration in ELI regime

Snowplow LWFA of ions injected by RPA

$$\varepsilon_i = \frac{1}{6} a_0^2 \left( \frac{n_c}{n_e} \right) mc^2$$

0.5TeV over dephasing length of 1cm

Zheng et al., 2010
TeV Ion Energy Scalings (RPA x LWFA)

TeV over cm @ $10^{23}$W/cm$^2$  (Zheng et al. 2010)
Etat de l’Art
2005 HEEAUP 2005

(Mourou, 2005)

100MW High Energy Physics

1 kW de puissance moyenne

1 W de puissance moyenne

Laser Fusion
15MW

Linear Accelerator
100MW

150J/.1Hz
Jena

100J/10Hz
Luli

Commercia
Fiber vs. Bulk Lasers

- High Gain fiber amplifiers allow ~50% total plug-to-optical output efficiency
- Single mode fiber amplifier reached multi-kW optical power.
- Large bandwidth (100fs)
- Immune against thermo-optical problems
- Excellent beam quality
- Efficient, diode-pumped operation
- High single pass gain
- Can be mass-produced at low cost

→ ICAN Consortium formed (Nov. 25, 2010)
Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator

Can we meet the challenge?

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

\[ \Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2 \left( \frac{n_{cr}}{n_e} \right), \]  

(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:

\[ \text{NIF laser (3MJ)} \rightarrow 0.7 \text{PeV} \]  

(with Kando, Teshima)
γ-ray signal from primordial GRB

Energy-dependent photon speed? Observation of primordial Gamma Ray Bursts (GRB) (limit is pushed up close to Planck mass)

Lab PeV γ (from e-) can explore this with control

Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. b also overlays energy versus arrival time for each
Feel vacuum texture: PeV energy $\gamma$

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

$c < c_0$

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

PeV $\gamma$ (converted from $\text{e}^-$)
Attosecond Resolution of PeV $\gamma$ Arrivals

(Kando, 2010)

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

Goulielmakis(2008)
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 1964 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...

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 (e), 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 'recolide' during a small fraction of the laser oscillation cycle (d). The parent ion sees an attosecond electron pulse. This
Electron ejection is synchronized with **attosecond pulse generation**

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

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

The Mourou Conjecture

(← physics: “Matter is nonlinear”
“The rigider nonlinearity, the more intense to manipulate it”)

\[ P = \frac{E}{T} \]
Yoctosecond coherent $\gamma$-beam

The Mourou-Tajima Conjecture tells us that ys coherent gamma pulse may be generated by Yottawatt/cm$^2$

Go beyond 10KeV coherent X-rays: solid is not dense enough

How can one make an Einstein mirror that can backscatter gamma rays (several 100MeV)?

Suggest: the imploded ultra-relativistic shell to increase the density by $10 \times 10 \times 10$.

The relativistic flying object with $\gamma = 100$. The lab frame density enhanced by $10^5$

Takes large energy $\sim$ MJ, Yottawatt/cm$^2$

$\rightarrow$ yielding 100ys coherent gamma rays

*Can we streak a nucleus with this gamma beam? : Photonuclear Physics.* (Any other new physics?)
Relativistic flying mirror and shorter pulses

Esirkepov (2010)

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

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

Laser Piston

Flying Mirror

Tajima/Mourou/Moses(2010): use NIF ---ultra-relativistic imploding mirror → ys!
MJ laser → Zettawatt → ultrashort pulse

Tajima, Mourou (PR, 2002)

0.1 Zettawatt

KECK telescope

10m

5MJ @ 10ns, 530nm

100m² gratings

10 fs

10²⁸ W/cm²!

10m

100m²

KDP crystal

F_{sat} ≈ 1 J/cm²

parabolic mirror

Deformable mirror

+V

- V

1 MJ

10²⁸ W/cm²!
Nuclear Wake?

- Broadened and maybe double humped structure on the away-side in 2-particle correlations.
- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- Jet quenching: collective deceleration by wakefield?
  - LWFA method, or Maldacena method?
High energy physics ← High field science, high intensity

- High field science
- High energy Physics (fundamental physics)
Ultrafast science ← High field science, Large-energy laser

- High field science
- Ultrafast science (attosecond, ...)
- Large-energy laser (NIF/LMJ...)
Self-focusing in air to vacuum

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

- $\chi_3$ nonlinearity

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

- Relativistic plasma nonlinearity

$$P_{cr} = \frac{m c^5}{e^2 (\omega/\omega_p)^2} \sim 17 (\omega/\omega_p)^2 \text{ GW}$$

- 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)

Does the atomic world repeat itself in vacuum?

Keldysh field

\[ \gamma_K = \omega \sqrt{2m\Phi/cE}, \]

Keldysh parameter

Schwinger intensity / Keldysh intensity = \( \alpha^{-6} \sim 10^{14} \)

Vacuum self-focusing /\( \gamma_3 \) self-focusing power = \( \alpha^{-6} \sim 10^{15} \)

Vacuum parameter

\[ \gamma_V = 1/a_0. \]

\( \gamma_V \geq 1. \)

= Path toward superSchwinger

Vacuum structure

Schwinger field

- Virus: \( 10^{-7} \text{ m} \)
- Molecule: \( 10^{-9} \text{ m} \)
- Atom: \( 10^{-10} \text{ m} \)
- Nucleus: \( 10^{-14} \text{ m} \)
- Proton: \( 10^{-15} \text{ m} \)
- Quark: Less than \( 10^{-18} \text{ m} \)
Self-focusing and **laser** acceleration in vacuum

→ **Laser** acceleration in vacuum by self-focused X-ray crossed with **laser**?

Can we repeat LWFA and plasma physics in vacuum?

**Laser** vacuum acceleration with ‘snowplow’

Ashour-abdalla, et al. (1981)
Why quantum vacuum physics?

- Heisenberg-Euler/Casimir in mathematical physics
  - QFT in strong fields or with boundaries
  - functional determinants

- applied quantum vacuum physics
  - quantum fluctuations as a building block
  - dispersive forces in micro/nano machinery

- fundamental effect of QFT
  - ($\sim$ Lamb shift, $g - 2, \ldots$)

- fundamental physics
  - search for new physics
  - new particles or forces

H. Gies (2008)
Light Propagation in a $B$ field.

\[ 0 = \partial_{\mu} f_{\mu \nu} - \frac{8}{45} \frac{\alpha^2}{m^4} F_{\alpha \beta} F_{\mu \nu} \partial_{\mu} f^{\alpha \beta} - \frac{14}{45} \frac{\alpha^2}{m^4} \tilde{F}_{\alpha \beta} \tilde{F}_{\mu \nu} \partial_{\mu} f^{\alpha \beta} \]

\[ P_{cr} \approx 10^{24} \left( \frac{\omega_1 (at 1 \mu)}{\omega} \right)^2 \text{W} \]

(Mourou/Tajima/Bulanov (2006))
What is vacuum?

Crystal

An observer (bug) in crystal looks at vacuum

Vacuum

「真(true)空(nothing)」

Phonon: excitation of vacuum

Vacuum produces $\text{ee}$ pair

Photon: distortion of vacuum

Vacuum produces $\text{e+e-}$ pair

QED vacuum breakdown

Compton length $\lambda_c$

$P \propto e^{-E_e/E}$

Strong laser field

Laser wavelength

$eE \lambda = a_0 (m_e c)$

(Naumova Mourou)
Intense laser probes matter / vacuum nonlinearity

Crystal nonlinearity $\rightarrow$
second harmonic generation (Franken et al)

(a)

Learn from Nonlinear Optics of matter for vacuum:

(b)

QED nonlinearity

(c)

Vacuum nonlinearity by light- mass field (dark energy, axion,..)
$\rightarrow$ second harmonic
QED vacuum probe by intense laser

Heisenberg-Euler Langrangian: tiny nonlinearity, never observed
  --- intense laser needed; sensitive probe, avoid blinding laser

**Phase contrast imaging** (refractive index → diffraction, noise reduction)

(with Homma, Habs)
Learning from laser parametric scattering: low energy (meV - neV) fields (vacua)

Proposed scheme of co-parallel intense laser probe of vacuum

Many orders of magnitude gain in resonant coupling and sensitivity over long interaction:
Nonlinearity of vacuum
\( \omega + \omega \rightarrow 2\omega \) (SHG a la Franken)

cf. Brillouin forward scattering beat / optical parametric excitation = phonon mediating (Nambu-Goldston boson)

Mass of light fields (dark energy fields, axion-like fields) resonates with specific crossing angle of co-propagating lasers
Scope of High Field Science vs traditional approaches

(with Homma, Habs)
Thank you
有難うございます
(Mourou, 2010)