A Lecture on:
Laser Acceleration and Relativistic Engineering

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20th C: Discovery of Quantum Energy

\[ mc^2 = E \] ‘Matter is energy’

Quantum energy (1905)

Chicago pile (1942)

\[ pc = E \] ‘Light quanta’

Photon (1905)

\[ \sqrt{(pc)^2 + (mc^2)^2} = E \] ‘Relativistic matter’

What is quantum beam?

⇒ 21st C: Quantum beam technology
Progress in Laser Power

Schwinger limit

Zettawatt Laser

Laser Intensity Limit: \( I = \frac{\hbar v}{c^{2}} \cdot \frac{\Delta v_{g}}{\sigma} = \frac{P_{g}}{\lambda} \)

(“Mourou limit”)

Relativistic Optics: \( v_{ao} \sim c \)
(large ponderomotive pressures)

Bound Electrons: \( E = \frac{e^{2}}{a_{0}} \)

Nonlinear Optics (Bloembergen)

Nonlinear QED: \( E \cdot e \cdot \lambda_{c} = 2m_{c}c^{2} \)

Relativistic Engineering

Vacuum breakdown
Nonlinear optics in vacua

Extreme Field Science

High Field Science

1st Asian Summer School
On Laser Plasma Acceleration and Radiations

Progression:
- 1960: CPA
- 1970: Q-switching
- 1980: Mode-locking
- 1990: Nonlinear Optics (Bloembergen)
- 2000: Zettawatt Laser
- 2003-2008:
  - 2003: Schwinger limit
  - 2008: 10^{29}

Energy Ranges:
- eV
- MeV
- TeV
- PeV

Power Ranges:
- 10^21
- 10^23
- 10^29
**Intense Lasers: Self-Organization of Light Pulses**

Laser Self-Focus due to Nonlinear Polarization in Neutral Gas

Laser Self-Focus due to Relativistic Nonlinearity

Laser filament ~ 20 m (Michigan U.)

Optimal Conditions for Long Propagation
1) weak focus
2) negative frequency chirp

Plasma Channel Formation (Michigan U.)

Optimal Conditions for Long Propagation
Select laser spot size smaller than plasma wavelength
Zettawatt Laser
w/Mourou (PR, 2002)

5 MJ @ 10 ns
530 nm

5 MJ @ 10 ns
100 m² gratings

100 m²

10 m

0.1 Zettawatt

1 MJ
10 fs
100 m²

seed pulse

10²⁸ W/cm²!

1 micrometer

KDP crystal

F_{sat} \approx 1 \text{ J/cm}^2

NIF

stretcher
compressor

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Deformable mirror

+V
−V

10 m
- Laser Revolution
- Laser Acceleration
  Injectors
  Beyond Fermi in Ultrahigh Energy Cosmic Rays (UHECR)
  Ion Acceleration
- Zettawatt Laser: Ultimate Field?
- Relativistic Engineering
  Relativistic Flying Mirror
- Nonlinear Coherent QED
- General Relativity and Optics
- Cross-Fertilization between Lasers and Beams
Fermi PeV Accelerator

\[ \alpha = \frac{k^2}{ec} \]
What is collective force (協同力)？

How can a Pyramid or 万里長城 be built?

Individual particle dynamics vs. Coherent movement

Collective acceleration
Collective radiation (N²radiation)
Collective ionization (N²ionization)
Wake: a Collective Phenomenon

Kelvin Ship Wake

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

Relativistic Wake Peaks

\[ \lambda_p = \frac{2\pi}{k_p} \quad k_p v_{ph} = \omega_{pe} \]
\[ \omega_{pe} = \left( \frac{4\pi n e^2}{m_e} \right)^{1/2} \]

Non-relativistic Wave Breaks
Compactification of accelerator

**Laser accelerator**: $10^{3-4}$ orders of magnitude greater gradient and $10^{3-4}$ orders of magnitude smaller emittance

Transverse laser field $\Rightarrow$ longitudinal plasma oscillations (rectification)

Relativity helps acceleration

In relativistic regime, photon $\otimes$ electrons couple stronger.
Figure 2 Laser propagation with and without channel. The plasma size after the
propagation of the drive pulse shows the radial extent of ionization, indicating the extent of
diffraction of the laser as it propagates through the plasma. The profile of the laser spot at
the exit of the plasma was viewed using a solid mirror inserted into the beamline and an
f/10 achromatic lens that imaged the laser spot directly onto a CCD (mode imager)
camera providing 10 μm resolution. In the channel-guided accelerator, the plasma (a)
was similar to the guiding channel indicating that the drive laser pulse was confined to the
channel. The laser mode at the channel exit is a well defined spot of 24 μm FWHM
containing 10% of the input energy (b). This indicates the effectiveness of the channel in
maintaining the drive beam intensity and mode over many diffraction lengths. The spot is
circular, confirming that the guiding channel is cylindrically symmetric. The reduction in
energy from the input spot is due to a combination of leakage from the channel and
depletion of the laser energy to excite the wake. When the channel was off, the
interferometer showed blow out of the drive pulse after a few hundred micrometres (c),
and the mode imager showed a diffuse transmitted spot (d).
News in 2004

Figure 3 Single-shot electron beam spectrum and divergence of the channel-guided accelerator, showing a bunch containing $2 \times 10^9$ electrons in a narrow distribution at $86 \pm 1.8$ MeV and 3 mrad divergence FWHM with contrast $>10:1$ above background. This distribution is qualitatively different from the exponential distribution obtained in past (unchannelled) laser acceleration experiments. The magnetic spectrometer consists of a slit 82 cm from the gas jet, a bend of 55° in a dipole magnet to provide dispersion, and a phosphor screen (LANEX Fast backed by an aluminium foil to reject laser light) imaged by a CCD camera. Single-shot energy range is $\pm 15\%$ about a central value selectable from 1 to 80 MeV, and resolution is $dE/E = \pm 2\%$. The vertical beam size is obtained in the undispersed direction, allowing the simultaneous determination of (vertical) divergence and energy. Since electron beams observed on the phosphor before the magnet were typically round in shape, this vertical divergence measurement is representative.
NGC 6888, also known as the Crescent Nebula, is a cosmic bubble of interstellar gas about 25 light-years across. Created by winds from the bright, massive star seen near the center of this composite image, the shocked filaments of gas glowing at optical wavelengths are represented in green and yellowish hues. X-ray image data from a portion of the nebula viewed by the Chandra Observatory is overlaid in blue. Such isolated stellar wind bubbles are not usually seen to produce energetic x-rays, which require heating gas to a million degrees celsius. Still, NGC 6888 seems to have accomplished this as slow moving winds from the central star's initial transition to a red supergiant were overtaken and rammed by faster winds driven by the intense radiation from the star's exposed inner layers.
Its core hidden from optical view by a thick lane of dust, the giant elliptical galaxy Centaurus A was among the first objects observed by the orbiting Chandra X-ray Observatory. Astronomers were not disappointed, as Centaurus A's appearance in x-rays makes its classification as an active galaxy easy to appreciate. Perhaps the most striking feature of this Chandra false-color x-ray view is the jet, 30,000 light-years long. Blasting toward the upper left corner of the picture, the jet seems to arise from the galaxy's bright central x-ray source -- suspected of harboring a black hole with a million or so times the mass of the Sun. Centaurus A is also seen to be teeming with other individual x-ray sources and a pervasive, diffuse x-ray glow. Most of these individual sources are likely to be neutron stars or solar mass black holes accreting material from their less exotic binary companion stars.
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?

PeV γ from Crab Nebula
Particle Cancer Therapy (without Surgery)

Before and After:
Upper jaw tumor
(Dr. Hishikawa, 2006)

Superiority of beam therapy

Prostate cancer
rectum

X-ray IMRT
Beam therapy

Dose distribution

 Depth [cm]
Compact proton therapy by laser acceleration

Compactification and propagation of therapy

先端X線治療（IMRT）との比較
JST Project in Japan started

X-ray therapy

Conventional accelerator

Compact laser accelerator

Farrington Daniels award (Tajima, 2005)
Innovation of cancer medicine

- Compact and inexpensive machine for (every) hospital
- ARMD (age-related macular degeneration); cancer therapy of eye, throat, neck
- Early cancer cure (small beams)
- Scanning therapy

Concentrated dose on retina
(Miyajima, JAEA, 2005)
$E_z = \pm 10$

$E_x = \pm 4$

$t = 7.00$

t = 40.00

t = 80.00

electrons

Gold
protons
We notice that the electrons are not completely expelled from the region irradiated by the laser light. Even if only a portion of the electrons is accelerated and heated by the laser pulse, the electric field due to charge separation appears to be strong enough to accelerate the protons up 100 MeV. The heavy ions have a wide energy spectrum while the protons form a quasi-monoenergetic bunch. The relative energy spread is approximately $\Delta / \langle \rangle = 0.1$. The proton beam remains localized in space for a long time.

The following parameters can be used to demonstrate experimentally this scheme. The laser pulse intensity is of the order of $10^{20}-10^{21} \text{W/cm}^2$, its duration is about 20-50 wavelengths (70-166 femtoseconds for 1 micron laser), the spot size is about 10 microns. The target is the foil with the width 0.1-0.5 micron. The foil consist of the high-Z material like Gold. To facilitate the expelling of electrons and thus to increase the electrostatic potential one can use as rarefied target as possible. It can be golden foam or Cesium dough. The hydrogenous coating should be sufficiently thin and its transverse size should be smaller than the laser pulse spot size to avoid the influence on the electrostatic potential. The coating should contain sufficient number of protons. For the coating with transverse size 5 micron the typical width is 10-20 nanometers. Multi-layer target with decreasing atomic weight of the layers can be used to increase the acceleration effect.
Approach beyond the Horizon

• Laser technology revolution ⇒ High Field Science
• Control of laser and target ⇒ high quality beam
• Intense laser brings in exciting prospect, but ….
• **Relativistic Engineering**, conscious effort and technology to control and combine lasers and accelerators to cause relativistic flow of matter, can bring in property and states that may not be achieved otherwise
• **Laser ⊗ Laser** brings in something beyond our horizon
• **Laser ⊗ Accelerator** also provides views beyond the horizon
Example of Crossing of Laser and Beams

Kansai Research Establishment = Lasers X SPring8

SPring-8 88GeV e-beams X laser(FEL)

New Paradigm for nuclear physics and nuclear energy

(Ejiri et al.)
(Omori et al.)

Polarized $e^+$, \ldots

Photonuclear physics
Photonuclear transmutation
Polarized positrons for collider
Crossing of SPring-8 electrons with laser led to high energy $\gamma$’s, which interacted with nuclei to create new hadronic matter $\Theta$, an example.

New development of Photonuclear Physics

Serendipitous discovery of pentaquark (5 quark hadron), 2003
Gamma Ray Flux by Compton Scattering

Flux of gamma rays generated by Compton scattering off electrons

\[ \frac{dN_\gamma}{dt} = 2 \times 10^2 I_e(A) \sigma \frac{dN_{\text{las}}}{dt} \]

where \( I_e \) is the electron beam current, \( dN/dt \) is the photon flux of either gamma rays or laser, \( A_{\text{eff}} \) is the effective crosssection of laser, \( \sigma \) is Thomson crosssection.

If the photon number over a particular period (say a year) required is set to be at \( 10^{26} \) over a year, and 100kW FEL is assumed, the required product of the current and the reflection number at the confining mirrors becomes \( 10^6 \).

If the number of reflections of the mirrors is \( 10^5 \), the electron current required is 10A.

The energy required for gamma rays is about \( 5 \times 10^{13}/\eta \) J/yr, where \( \eta \) is about 0.03. On the other hand the electric production is \( 3 \times 10^{16} \) J/yr.

\( \eta \) is about 3% according to Konai.
Theoretical estimate of efficiency of the $\gamma$ ray generation

A rough estimate of the overall efficiency $\eta$ to produce gamma photons from the Compton scattering of laser photons off electron beams in the ring (when the scattering high energy electron is accepted in the ring after the scattering):

$$\eta = \frac{N_e \varepsilon_e}{\Delta(N_e \varepsilon_e) / \eta_{ac} + N_l \varepsilon_l / \eta_l} = \frac{\varepsilon_\gamma / \eta_{ac} + \frac{A_{\text{int}} \varepsilon_l}{N_e \sigma Q \eta_l}}{1 / \eta_{ac} + \left(\frac{A_{\text{int}}}{N_e \sigma Q \eta_l}\right) \frac{1}{\varepsilon_l} \frac{1}{\varepsilon_\gamma} \frac{1}{\eta_l}}$$

where $A_{\text{int}}$ is the area of interaction between electron and laser beams, $Q$ the laser cavity $Q$ factor, $\sigma$ the Thomson crosssection, $\eta_{ac}$ and $\eta_l$ are the accelerator efficiency including the rf efficiency and synchrotron radiation loss and the laser efficiency, $N_e$ the number of electrons interacting with laser, $\varepsilon_l$ is the laser photon energy (about $10^{-12}$ smaller than the gamma photon energy $\varepsilon_\gamma$). $\Delta(N_e \varepsilon_e)$ is the energy loss of the scattered electron.
Waste Separation and Transmutation

129I gas

MA: マイナーアクチニド
FP: 核分裂生成物

Valuable metals (Ru, Rh, Pd, Tc) 4.5t/y

Low heat glass 160本/y

Sr-Cs 焼結体

燃料製造・再処理（乾式） 8~12t/y

Transmutation

FP 31t/y

発熱FP (Sr, Cs) 3.7t/y

FP (Sr, Cs) 23t/y

高温ガス

その他FP 23t/y

群分離/核変換導入

High level waste
（FP: 31t/y
MA: 1~1.5t/y）

導入無し

Glassed 800本/y

Cooling 30~50y

Deep earth

300m以深に埋設
約千年は人工バリア
それ以降は天然バリア
で閉じ込め

再処理（六ヶ所）処理能力: 800t/y

水本氏（原研）による

Transmutation
少量のFPで地層処分容易

冷却後に最終処分

低発熱・MA無しのため地層処分容易
Petwatt Laser

SPring-8

$\gamma = 16000$

Light electron ring = “something new” (laser XSR)

Electrons see:
- vacuum breakdown
- general relativistic effects,
- ...

$I_0$ enhances $\rightarrow I = \gamma^2 I_0$
Relativistic Engineering

Control of matter and energy by laser in relativistic regime (cf. Laser control of matter)
- rectification from transverse to longitudinal energy and flow of matter
- focusing, guidance, convergence
- energy multiplication (“photon acceleration”)
- phase space manipulation of matter
Toward Schwinger Field

wake plasma wave
(electron density modulations)

\[ \nu_{ph, wake} = \nu_{gr, driver} \approx c \]

\( n_e = 10^{17} \text{ cm}^{-3} \)

reflected \( \lambda_s = 4\gamma \lambda_s \)

\( \gamma \approx 100 \)

150 J @ 3 fs
\( \lambda_d = 1 \text{ \mu m} \)
\( I_d = 10^{18} \text{ W/cm}^2 \)

1 J @ 3 fs
\( \lambda_s = 1 \text{ \mu m} \)
\( I_s = 10^{17} \text{ W/cm}^2 \)

Intensity in focus
\[ \tilde{I}_s \approx 32 \left( \frac{D_M}{\lambda_d} \right)^2 \gamma^3 I_s \approx 10^{30} \text{ W/cm}^2 \]
\[ v = \beta c \]
\[ \omega_s' = \omega_s \sqrt{\frac{1 + \beta}{1 - \beta}} \approx 2\gamma \omega_s \]
\[ L'_s \approx L_s / (2\gamma) \]
Focal spot diameter \( \sim \lambda'_s \approx \lambda_s / (2\gamma) \)
\[ \tilde{\omega}_s = \omega_s \frac{1 + \beta}{1 - \beta} \approx 4\gamma^2 \omega_s \]
Focal spot size \( \parallel \sim \lambda'_s \approx \lambda_s / (4\gamma^2) \)
\( \perp \sim \lambda'_s \approx \lambda_s / (2\gamma) \)
\[ \frac{\tilde{I}_{sf}}{I_s} \approx \kappa \left(\frac{D}{\lambda_s'}\right)^2 \left(\tilde{\omega}_s / \omega_s\right)^2 \approx 64\kappa \left(\frac{D}{\lambda_s}\right)^2 \gamma^6 \]
Nonlinear QED
Pair Generation from Vacuum
Quantum Field Theory

\[ w = \frac{1}{\pi^2} \frac{\alpha c}{\hat{\lambda}^4} \left( \frac{E}{E_s} \right)^2 \exp \left( \frac{-\pi E_s}{E} \right) \]

Julian Schwinger

Pair Creation: Vacuum boiling

Note the similarity of Schwinger expression to the Keldysh atom ionization \( \leftarrow \) from the ‘structure’ of vacuum / atom
Vacuum Tunneling

Pair creation rate \((s^{-1} \text{ cm}^{-3})\)

\[ w = \frac{1}{\pi^2} \frac{\alpha c}{\lambda^4} \left( \frac{E}{E_s} \right)^2 \exp \left( -\frac{\pi E_s}{E} \right) \]

How many pairs?

\[ N = w \cdot V \cdot T_p \]

Focal volume \( V = 10^{-12} \text{ cm}^3 \)

Pulse duration \( T_p = 10 \text{ fs} \)

\[ I \sim 10^{30} \text{ W/cm}^2 \quad n = 10^{24} \text{ pairs} \]

\[ I \sim 10^{26} \text{ W/cm}^2 \quad n = 1 \text{ pair} \]
Ultra-high Intensity

General Relativity

and Black Holes

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Laser Plasma Acceleration and Radiations
Violent acceleration vs gravitation

Equivalent to be near a Black Hole Dimension?
Temperature of vacuum?
Stuff in it?
Structure of it?
Is Optics in General Relativity?

The acceleration $a_e$ experienced by an electron is enormous

$$a_e = \omega \cdot c \cdot a_0$$

$$a_0 = 1 \rightarrow a_e = 10^{25} \text{ g}$$

$$a_0 = 10^5 \rightarrow a_e = 10^{30} \text{ g}$$

This type of acceleration is found near the Schwartzschild radius $R_s$ of a Black Hole.

$$a_e = \frac{GM}{R_s^2}$$

What would be the size and mass of a black hole associated with the same gravitational field?
Finite Horizon and Leakage of Wavefunction

The distance to finite horizon is

$$d = \frac{c^2}{a_e} \approx \frac{\lambda}{2\pi a_0}$$

4 + nD Gauss Law for Planck distance

$$M_{P_4}^2 \sim (r_n)^n M_{P_{4+n}}^{n+2}$$

$$r_n \sim 10^n \frac{30}{17} \text{ cm}$$

N. Arkani-Hamed et al. (1999)

Up to $n=4$ extra-dimensions could be tested.
From Quantum Optics to Quantum Field Theory
From Schrödinger to Schwinger

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1eV  MeV  TeV
Fundamental Physics by non-luminosity paradigm?

- E.g. Prof. Humitaka Satoh: possibility of violation of Lorentz invariance (some astrophysical evidence)
- Possibility of PeV electrons by relativistic engineering of intense lasers
- Possibility of PeV gamma photons: new decay channel due to the Lorentz variance, if present (Satoh)
“Don’t Say I can’t, Just do it” : President T. Hiruma, Hamamatsu Photonics
謝謝！