Laser Electron Acceleration and its Future

Toshi Tajima
Blaise Pascal Chair, ENS, Palaiseau
and
LMU, MPQ, Garching

Pascal Lecture Plan
(tentative, need your feedback)

- Dec.9: Third Lecture “Laser Ion Acceleration”
- February: “High Field Science”
- March: “Photonuclear Physics”
- April: “Medical Applications”
- …..
What is **collective force**?

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; Ogata, 2006)
- **Collective deceleration** (Tajima & Chao, 2008; Ogata, 2009)
- Plasma lens (Chen, 1987; Toncian et al. 2006)
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 \( v = c \)

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

\[ \lambda_p = 2\pi / k_p \quad k_p v_{ph} = \omega_{pe} \]

\[ \omega_{pe} = \left( 4\pi ne^2 / m_e \right)^{1/2} \] (The density cusps. Cusp singularity)
Thousand-fold Compactification

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

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

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

Superconducting linacrf- tube (Fermilab)

\[ \text{~40cm} \]

\[ \text{Gas tube} \]

\[ 0.1 \text{mm} \]

\[ \approx 0.03 \text{mm} \]
Monoenergy electron spectra: from few-cycle laser (LWS-10)

(K. Schmid, L. Veisz et al., PRL, 2009)

Large electron spectrometer 2 – 400 MeV

- No thermal background!
- Energies: 13.4 MeV, 17.8 MeV, 23 MeV
- FWHM energy spread: 11%, 4.3%, 5.7%
- ~10 pC charge

Small electron spectrometer:

- Electron energies below 500 keV
- No thermal background!
- 4.1 MeV (14%); 9.7 MeV (9.5%)
MPQ Laser Acceleration Effort (2)

Reproducible acceleration conditions

\[ E \approx 169.7 \pm 2.0 \text{ MeV} \]

1.1% peak energy fluctuation!

\[ \Delta E/E \approx 1.76 \pm 0.26\% \text{ RMS} \]

→ Essential property for future table-top FEL operation

Source size image: provides emittance measurement, given the resolution can be improved

Electron trapping width

\[ v_{tr,e} \sim c \sqrt{a_0} \]

(J. Osterhoff, ..., S. Karsch, et al., PRL 2008)
Toward Coherent Control of Wakefields: Frequency-domain Holography

(Mattis et al., 2006)

M. Downer (UTexas)
Snapshot of wakefields: phase sensitive instantaneous single-shot detection

Figure 3 Strongly driven wake with curved wavefronts. a, Probe phase profile \( \Delta \phi_p(r, \zeta) \) for an \( \sim 30 \) TW pump, \( N_{\text{He}}^{\text{e}} = 2.2 \times 10^{20} \) cm\(^{-2} \) in the He\(^+ \) region. b, Simulated density profile \( \rho(r, \zeta) \) near the jet centre. c, Same data as in a, with the background \( \rho_0 \) subtracted to highlight the wake. d, Evolution of the reciprocal radius of wavefront curvature behind the pump (data points), compared with calculated evolution (dashed lines) for indicated wake potential amplitudes. Each data point (except at \( \zeta = 0 \)) averages over three adjacent periods. The horizontal error bars extend over the three periods averaged, and the vertical error bars extend over the range of fitted curvature values averaged.

(Matlis et al, 2006)
Phase and Phase Language is Critical

temporal phase expansion (stacking of fields):

\[ \phi(t) = \phi_o + \frac{\partial \phi}{\partial t} (\Delta t) + \frac{1}{2} \frac{\partial^2 \phi}{\partial t^2} (\Delta t)^2 + ... = \phi_o - \omega_o \Delta t - \frac{1}{2} b (\Delta t)^2 - ... \]

\[ \Rightarrow \omega_o \equiv - \frac{\partial \phi}{\partial t} \equiv \text{ref. freq.} \quad b \equiv - \frac{\partial^2 \phi}{\partial t^2} = \text{linear chirp parameter} \]

\[ \Rightarrow \omega(t) \equiv \omega_o + b (\Delta t) + ... \] (chirp, b means temporal dependence of frequency)

spectral phase expansion (stacking of spectral components):

\[ \varphi(\omega) = \varphi_o + \frac{\partial \varphi}{\partial \omega} (\Delta \omega) + \frac{1}{2} \frac{\partial^2 \varphi}{\partial \omega^2} (\Delta \omega)^2 + ...; \quad \varphi \equiv z \beta \]

\[ \Rightarrow T_o \equiv \frac{\partial \varphi}{\partial \omega} \equiv \text{ref. group delay} \quad \& \quad \frac{\partial^2 \varphi}{\partial \omega^2} (\Delta \omega) \equiv \text{group delay dispersion} = \text{GDD} \]

\[ \Rightarrow T = T_o + \frac{\partial^2 \varphi}{\partial \omega^2} (\Delta \omega) + ... = T_o + \text{GDD} + ... \] (GDD means spectral dependence of time delay)

(P. Bolton)

\[ T_o \equiv z \frac{\partial \beta}{\partial \omega} \quad \text{where} \quad \frac{\partial \beta}{\partial \omega} \equiv \frac{1}{v_{\text{group}}} \quad \& \quad \text{GDD} \equiv z \frac{\partial^2 \beta}{\partial \omega^2} (\Delta \omega) \]

\[ \text{where} \quad \text{GVD} \propto \frac{\partial^2 \beta}{\partial \omega^2} = - \frac{1}{v_{\text{group}}^2} \frac{\partial v_{\text{group}}}{\partial \omega} \]
Polarization-Gated (PG) FROG: Single Pulse Dynamics—a Finesse Approach

The pulse to be measured is split into a replica pair and one replica pulse (the 'gate') is delayed with a polarization rotation $\sim 45^\circ$.

In an isotropic medium, Kerr-induced birefringence by the gate pulse yields an autocorrelation.

The two pulses are coincident.

Grating provides spectral resolution for a 2D FROG trace.

FROG Trace

$$E_{\text{sig}}(t, \tau) = E_{\text{ir-test}}(t)E_{\text{ir-gate}}(t - \tau)^2$$

$$I_{\text{FROG}}(\omega, \tau) = \int_{-\infty}^{\infty} E_{\text{sig}}(t, \tau) \exp(-i\omega t) \, dt$$
Single Shot Phase-Preserved fs Metrology of the Laser system and Laser-Plasma Interaction

Laser pulse spectrum modified in plasma;
Dynamical information of ultrafast interaction 'encoded' onto the laser waveform
Extract spectrum and phase of the transmitted laser pulse.

**Feed back** info to laser by simple feedback, neural net, genetic algorithm,....

FROG (Frequency Resolved Optical Gating) Measurement

- Input pulse
- Wakefield
- Fast electrons
- Transmitted pulse

Change due to interaction with plasma

\[ S_{in}(\omega), \phi_{in}(\omega) \]

\[ S_{out}(\omega), \phi_{out}(\omega) \]

(PIC Simulation) (Experiment) (PIC Simulation)
Another Finesse Single-shot Diagnosis: Electro-Optical Method

- can be noninvasive
- important for future accelerators
- all-optical:
  - optical controls in ideal laser setting
  - can apply optics sophistication
- jitterless (probe synchronized with laser driver)
- ultrafast – single bunch profile
  (~ 100 fsec)
- high repetition rate – multi-bunch timing jitter
- potential for feedback and beam (facility) control

Use reference ‘pi’ field instead of ‘pi’ voltage:

$$\text{transmission, } T(E) \propto \sin^2 \left( \frac{\varphi_o}{2} - \frac{\pi}{2} \frac{E}{E_\pi} \right)$$

$$\Rightarrow \text{want } \text{low } E_\pi$$
EO Example: Spatial-Temporal Transcription with Pockels Effect

- require ultrashort probe and thinnest possible EO crystal
- optional horizontal line focus of probe at crystal

P. Bolton
Laser-driven Soft-X-Ray Undulator Radiation

Characteristic undulator radiation spectrum
Intra-Operative Radiation Therapy (IORT)

**LWFA electron sources: technology transferred to company**

**NOVAC7**
(HITESYS SpA)  
RF-based

- El. Energy < 10 MeV  
  (3, 5, 7, 9 MeV)
- Peak curr. 1.5 mA
- Bunch dur. 4 µs
- Bunch char. 6 nC
- Rep. rate 5 Hz
- Mean curr. 30 nA
- Releas. energy (1 min)  
  @9 MeV (≈dose)  
  18 J

**CEA-Saclay**

experim. source

- El. Energy > 10 MeV  
  (10 - 45 MeV)
- Peak curr. > 1.6 KA
- Bunch dur. < 1 ps
- Bunch char. 1.6 nC
- Rep. rate 10 Hz
- Mean curr. 16 nA
- Releas. energy (1 min)  
  @20 MeV (≈dose)  
  21 J

Collective deceleration

Beam dump: **harder to stop** and more **hazardous radioactivation**

Gas (plasma) **collective force** to shortstop the HE beams
- the shorter the bunch is, the easier to stop
  (ideally suited for laser wakefield accelerated beams)
- little radioactivation (good for environment)
  
  example of ‘**Toilet Science**’ that tends **downstream**
  (as opposed to ‘Kitchen Science’ of 20th C that tends **upstream**)

- possible energy recovery

Tajima and Chao, (2008 applied for patent)
H. C. Wu et al. (2009)
High energy beam dump: a nasty business

Stopping range

Radiation length of high energy charged particles

1. Stopping length increases rapidly as energy ↑
2. Amount of radiation increases rapidly as energy ↑
3. Fraction of useful interaction decreases rapidly as energy ↑
Stopping power due to collective force

**Bethe-Bloch stopping power** in matter

Plasma stopping power due to individual force

\[-(dE / dx)_{\text{ind}} = (F / \beta^2) \ln(m_e v^2 / e^2 k_D)\]

That due to collective force (perturbative regime)

\[-(dE / dx)_{\text{coll}} = (F / \beta^2) \ln(k_D v / \omega_{pe})\]

\[F = 4\pi e^4 n_{e,m} / m_e c^2 = e^2 k_{pe,m}^2\]

(Ichimaru, 1973)

Plasma stopping power due to short-bunch **wakefield** (wavebreak regime)

\[-(dE / dx)_C = m_e c \omega_{pe} (n_b / n_e)\]

(Wu et al, 2009)

Greater by **several orders** in gas over Bethe-Bloch in solid
Wakefield Decelerator: attention to the downstream

Can we employ collective force to tackle this problem?

- stop short in mm, rather than in m
- dump without much radiation/activation
- convert its energy into electricity

(Tajima and Chao, 2008)
Collective deceleration over mm

Results of computer simulation

isomorphic, regardless of energies

(Wu et al, 2009)
To enhance the conversion, avoid trapping

Technique of **phase velocity modulation** (PVM)

(Wu et al. 2009)
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 \( \approx 20 \, \text{MV/m} \rightarrow 50\,\text{km for 1 TeV} \)

* Size of facility is costly \( \rightarrow \) 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 \( \rightarrow \approx 100 \, \text{MV/m} \)
  - Acceleration with laser driven structures \( \rightarrow \approx 1 \, \text{GV/m} \)
  - Acceleration with beam driven structures
  - Acceleration with laser driven plasmas \( \rightarrow \approx 10 \, \text{GV/m} \)
  - Acceleration with beam driven plasmas
### Examples of TeV Collider Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Laser</th>
<th>Plasma</th>
<th>CLIC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS Energy (GeV)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>2.4</td>
<td>3.5</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Luminosity in 1% of Ecms</td>
<td>~2</td>
<td>1.3</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Bunch charge ($10^{10}$)</td>
<td>3.80E-06</td>
<td>1</td>
<td>0.37</td>
<td>2</td>
</tr>
<tr>
<td>Bunches / train</td>
<td>193</td>
<td>125</td>
<td>312</td>
<td>2820</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>1.50E+07</td>
<td>100</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>11.6</td>
<td>20</td>
<td>9.2</td>
<td>36.2</td>
</tr>
<tr>
<td>Emittances $\epsilon_{nx}/\epsilon_{ny}$ (mm-mrad)</td>
<td>1e-4 / 1e-4</td>
<td>2 / 0.05</td>
<td>0.7 / 0.02</td>
<td>10 / 0.04</td>
</tr>
<tr>
<td>IP Spot sizes sx/sy (nm)</td>
<td>1.0 / 1.0</td>
<td>140 / 3.2</td>
<td>140 / 2</td>
<td>554 / 3.5</td>
</tr>
<tr>
<td>IP bunch length sz ($\mu$m)</td>
<td>0.1 $\rightarrow$ 300</td>
<td>10</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Drive beam / Laser / RF Power (MW)</td>
<td>58</td>
<td>58</td>
<td>36.8</td>
<td>80</td>
</tr>
<tr>
<td>Gradient (MV/m)</td>
<td>400</td>
<td>25000</td>
<td>100</td>
<td>31.5</td>
</tr>
<tr>
<td>Two linac length (km)</td>
<td>~4</td>
<td>~6</td>
<td>14</td>
<td>47</td>
</tr>
<tr>
<td>Drive beam / Laser / RF generation eff.</td>
<td>60%</td>
<td>45%</td>
<td>49%</td>
<td>53.95%</td>
</tr>
<tr>
<td>Drive beam / Laser / RF coupling eff.</td>
<td>20%</td>
<td>35%</td>
<td>25%</td>
<td>49.01%</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>12%</td>
<td>15.70%</td>
<td>12.10%</td>
<td>17.90%</td>
</tr>
<tr>
<td>Site Power (MW)</td>
<td>~137</td>
<td>~170</td>
<td>~150</td>
<td>300</td>
</tr>
</tbody>
</table>
Collider application: Early version (1997)

Studies of Laser-Driven 5 TeV $e^+e^-$ Colliders in Strong Quantum Beamstrahlung Regime

M. Xie¹, T. Tajima², K. Yokoya³
and S. Chattopadhyay¹

¹Lawrence Berkeley National Laboratory, USA
²University of Texas at Austin, USA
³KEK, Japan

Abstract.

We explore the multidimensional space of beam parameters, looking for preferred regions of operation for a $e^+e^-$ linear collider at 5 TeV center of mass. Due to several major constraints such a collider is pushed into certain regime of high beamstrahlung parameter, $T$, where beamstrahlung can be suppressed by quantum effect. The collider performance at high $T$ regime is examined with IP simulations using the code CAIN. Given the required beam parameters we then discuss the feasibility of laser-driven accelerations. In particular, we will discuss the capabilities of laser wakefield acceleration and comment on the difficulties and uncertainties associated with the approach. It is hoped that such an exercise will offer valuable guidelines for and insights into the current development of advanced accelerator technologies oriented towards future collider applications.

INTRODUCTION

It is believed that a linear collider at around 1 TeV center of mass energy can be built more or less with existing technologies. But it is practically impossible to go much beyond that energy without employing a new, yet largely unknown method of acceleration. However, apart from knowing the details of the future technologies, certain collider constraints on electron and positron beam parameters are considered to be quite general and have to be satisfied, e.g. available wall plug power and the constraints imposed by collision processes: beamstrahlung, disruption, backgrounds, etc. Therefore it is appropriate to explore and chart out the preferred region in parameter space based on these constraints, and with that hopefully to offer valuable guidance.

With a plasma density of $10^{17}$ cm$^{-3}$, such a gradient can be produced in the linear regime with more or less existing T³ laser, giving a plasma dephasing length of about 1 m [13]. If we assume a plasma channel tens of μm in width can be formed at a length equals to the dephasing length, we would have a 10 GeV acceleration module with an active length of 1 m. Of course, creating and maintaining a plasma channel of the required quality is no simple matter. To date, propagation in a plasma channel over a distance of up to 70 Rayleigh lengths (about 2.2 cm) of moderately intense pulse (~ $10^{15}$ W/cm$^2$) has been demonstrated [14]. New experiment aiming at propagating pulses with intensities on the order of $10^{16}$ W/cm$^2$ (required for a gradient of 10 GeV/m) is underway [15].

| Table 1. Beam Parameters at Three Values of Beam Power |
| CASE | $f_0$ (MHz) | $N(10^9)$ | $\frac{\sigma_z (\mu m)}{\beta_0}$ | $\frac{\sigma_x (\mu m)}{\beta_0}$ | $\frac{\sigma_y (\mu m)}{\beta_0}$ | $\frac{\sigma_z (\mu m)}{\beta_0}$ |
| I | 2 | 0.5 | 50 | 2.2 | 22 | 0.1 | 0.32 |
| II | 20 | 1.6 | 156 | 25 | 62 | 0.56 | 1 |
| III | 200 | 6 | 416 | 310 | 188 | 3.5 | 2.8 |

| Table 2. Results Given by the Formulas |
| CASE | $T$ | $D_T$ | $F_{side}$ | $2\pi$ | $\sigma_x$ | $\sigma_y$ | $\sigma_z$ | $L_p$ (cm$^{-1}$ s$^{-1}$) |
| I | 3485 | 0.93 | 0.89 | 0.72 | 0.2 | 0.19 | 1 |
| II | 651 | 0.29 | 0.89 | 0.72 | 0.2 | 0.12 | 1 |
| III | 138 | 0.881 | 0.91 | 0.72 | 0.2 | 0.072 | 1 |

| Table 3. Results Given by CAIN Simulations |
| CASE | $n_p$ | $\sigma_x/E_0$ | $\sigma_y/E_0$ | $n_p$ | $L_p$ (W cm$^{-1}$) | $L_p$ (W cm$^{-1}$) |
| I | 1.9 | 0.38 | 0.42 | 0.28 | 0.83 | 1.1 |
| II | 0.97 | 0.26 | 0.36 | 0.12 | 0.65 | 0.80 |
| III | 0.84 | 0.21 | 0.32 | 0.06 | 0.62 | 0.75 |

Although a state-of-the-art T³ laser, capable of generating sub-ps pulses with 10s of TW peak power and a few J of energy per pulse [11], could almost serve the need for the required acceleration, the average power or the repetition rate of a single unit is still quite low, and wall-plug efficiency inadequate. In addition, injection scheme and synchronization of laser and electron pulse from

Incorporated collider physics at collision point (beamstrahlung, Oide limit, etc.)
Figure 34. A conceptual plasma fiber accelerator with laser staging amplification in situ. The separation between the modules is characterized by the sum of the focal length and the pump depletion length. An example of $X_\omega Cl$ lasers is taken.
Multi-stage acceleration

Particle Dynamics and its Consequences in Wakefield Acceleration in a High Energy Collider

S. Cheshkov, T. Tajima, W. Horton and K. Yokoya*

Department of Physics and Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712 USA
* KEK National Laboratory for High Energy Physics, Japan

Abstract. The performance of a wakefield accelerator in a high energy collider application is analyzed by use of a nonlinear dynamics map built on a simple theoretical model of the wakefield generated by the laser pulse (or whatever other method) and a code based on this map [1]. The crucial figures of merit for such a system other than the final energy include the emittance (that determines the luminosity). The more complex the system is, the more “opportunities” the system has to degrade the emittance (or entropy of the beam). Thus our map guides us to identify where the crucial elements lie that affect the emittance. If the focusing force of the wakefield is strong when there

Transverse focusing/defocusing need to be mitigated. Plasma channel ideal
Toward energy frontier (earliest version, 1985) (3)

Self-similar collision (beamstrahlung) toward ‘a point’ (enhanced luminosity) possible?

→ flat beam profile control

(Tajima, 1985)
Renewed interest in $\gamma - \gamma$ Collider

Large amount of cost down possible by $\gamma \gamma$ collider
perhaps half (or even a third)
clearer Higgs physics than $e^+e^-$ collider
likely Higgs mass $\sim 120\text{GeV}$ (← input from LHC)

New:
Study Group started at KEK-JAEA,
ELI discussion (Sept, 2008)
$\rightarrow$ a new strategy for HEP?
more affordable
Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator

Table-top X-ray FEL
1000 times higher energy
3rd-generation Synchrotron Light Source

PeV=10^{12} eV
“New paradigm”
Leptogenesis
SUSY breaking
Extra dimension
Dark matter
Supersymmetry
TeV=10^{12} eV
“Standard model”
Higgs
Quarks
Leptons
100 GV/m

Plasma Acceleration Technology

1000 times shorter time resolution

1 ps = 10^{-12} s
1 fs = 10^{-15} s

Rhodopsin
\sim 200 fs

Photosynthetic reaction in leaves
\sim 100 fs

Photo-switching of metal-to-insulator

Can we meet the challenge?

atto-, zeptosecond

A. Suzuki @KEK(2008)
When can we reach to 1 PeV?

(Suzuki, 2009)

(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)
When can we reach to 1 PeV?

Laser plasma accelerator experiments

V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4
Evolution of Accelerators and their Possibilities (Suzuki, 2008)

- **2020s**
  - **ILC**
  - **E=200 MV/m**
  - **2.5-5 GeV ERL**

- **2030s**
  - **Two-beam LC**
  - **E=10 GV/m**
  - **10cm-10GeV Plasma Channel Accelerator**

- **2040s**
  - **Laser-plasma LC**

**Table-top high energy accelerator**

**Earth-based space debris radar**
Meeting Suzuki’s Challenge:
Laser acceleration toward ultrahigh energies

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>case I</th>
<th>case II</th>
<th>case III</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</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>
</tr>
<tr>
<td>plasma density</td>
<td>cm(^{-3})</td>
<td>5.7x10(^{16})</td>
<td>5.7x10(^{15})</td>
</tr>
<tr>
<td>acceleration length</td>
<td>m</td>
<td>2.9</td>
<td>29</td>
</tr>
<tr>
<td>spot radius</td>
<td>(\mu)m</td>
<td>32</td>
<td>100</td>
</tr>
<tr>
<td>peak power</td>
<td>PW</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>pulse power</td>
<td>ps</td>
<td>0.23</td>
<td>0.74</td>
</tr>
<tr>
<td>laser pulse energy</td>
<td>kJ</td>
<td>0.5</td>
<td>1.6</td>
</tr>
</tbody>
</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)
Zettawatt Laser

Tom Connell / Wildlife Art Ltd.

KECK telescope

NIF

Beyond ELI

5MJ @ 10ns
530nm

10m

1028 W/cm²!

∅1micron

stretcher

compressor

KDP crystal

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

parabolic mirror

100m² gratings

1MJ
10fs

∅10 m

100m²

0.1 Zettawatt

Tajima, Mourou (PR, 2002)

Beyond ELI

0.1 Zettawatt

10m

Tajima, Mourou (PR, 2002)
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
A limit on the variation of the speed of light arising from quantum gravity effects

A list of authors and their affiliations appears at the end of the paper

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, $\hbar_{\text{Planck}} \approx 1.62 \times 10^{-35} \text{ cm}$ or $E_{\text{Planck}} = M_{\text{Planck}} = 1.22 \times 10^{19} \text{ GeV}$), 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\(^1\). Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in γ-ray burst (GRB) light-curves\(^2\). 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 $E_{\text{Planck}} = M_{\text{Planck}}^2$). For $E_{\text{ph}} \ll E_{\text{Planck}}$, the leading term in a Taylor series expansion of the classical dispersion relation is $|\nu_{\text{ph}}/c - 1| \approx (E_{\text{ph}}/M_{\text{QG}, n} c^2)^n$, where $M_{\text{QG}, n}$ is the quantum gravity mass for order $n$ and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm (\Delta E / M_{\text{QG}, 1} c^2) D/c$ 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 LV\(^2\)\(^1\)\(^1\)\(^2\). Individual spikes in long\(^3\) (of duration $> 2$ 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

(Abdo et al, 2009)
γ-ray signal (GRB) from primordial GRB

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

PeV γ (from e-) Can explore this

(Abdo, et al., 2009)
Conclusions

• Laser electron acceleration: experimentally well established; its unique properties getting known
• Laser has come around to match the condition set 30 years ago; Still some ways to go to realize the dream (such as ELI)
• GeV electrons; 10 GeV soon; 100GeV considered; TeV laser collider contemplated; PeV ?
• Beam control: greater attention necessary
• Other applications: already beginning, soon to flourish: radiolysis, intraoperative therapy, bunch decelerator, nuclear detection, compact FEL source, compact radiation sources, ultrafast diagnosis,…
• Combination of laser accelerated electrons and other beams: new dimensions for science and applications
Centaurus A: cosmic wakefield linac?

Merci Beaucoup
et a la Prochaine Fois!