High Field Science:
A Second Wave of Laser

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Laser probing nonlinearities in matter

\[ \Delta x \sim \frac{\hbar}{p} \]

Rutherford’s (accelerator) approach
discover particles (colliders)

vs

\[ \Delta x = \frac{eE}{\omega^2 m} \]

\[ \hbar \omega \]

Laser approach
nonlinear optics, spectroscopy
Nonlinear QED: \( E \cdot e \cdot \lambda_c = 2m_0c^2 \)

- Ultra-Relativistic Optics
  - \( E_Q = m_pc^2 \)
- Relativistic Optics
  - \( E_Q = m_0c^2 \)
- Bound electrons
  - CPA
    - mode locking
    - \( Q \) switching


Focused Intensity (W/cm²)

1 eV 1 MeV 1 TeV 1 PeV
Chirped Pulse Amplification did it!

D. Strickland and G. Mourou 1985
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: $v << c$,
   
   $a_0 << 1$: $\delta x$ only

b) Relativistic optics: $v \sim c$
   
   $a_0 >> 1$: $\delta z >> \delta x$

\[ a_0 = \frac{eA_0}{mc^2} = \frac{eE_0 \lambda}{mc^2} \]
Wakefield: Nonlinearity-driven, Collective

Collective phenomenon = all particles in medium participate

Nonlinearities of plasma and water waves

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

Wave breaks at $v < c$

(Wave-head hard to overtake trough. $\rightarrow$ density cusp singularity)

(Wave-head overtakes trough)
Thousand-fold Compactification

Laser Wakefield Acceleration (LWFA): $10^{3-4}$ fold gradient

Laser pulse

~0.03mm

plasma

(gas tube)

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

Superconducting linacrf- tube (Fermilab)

~40cm

$E_{\text{max}} \approx 32 \text{MV/m}$
GeV electrons from a centimeter LWFA
(a slide given to me by S. Karsch)

310-μm-diameter channel capillary

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

density \(4.3 \times 10^{18} \text{ cm}^{-3}\).
laser intensity \(10^{18} \text{ W/cm}^2\)

Lee mans et al., Nature Physics, september 2006

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Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density \(10^{18} \text{ W/cm}^2\) shone on plasmas of densities \(10^{18} \text{ cm}^{-3}\) can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

(emphasis by S. Karsch)
Table-top Brilliant Undulator X-ray Radiation from LWFA


Observed undulator radiation spectrum
Livingston Chart and Recent Saturation

(Suzuki, 2009)

(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)
World Lab goal =
Put SLAC on a football field

Initiatives considered, emerging: French; CERN; KEK; LBL

SLAC’s 2 mile linac (50GeV)

Laser acceleration =
- no material breakdown (→ 3/4 orders higher gradient); however:
- 3 orders finer accuracy, and
  2 orders more efficient laser needed
Laser driven collider concept

Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration (Darmstadt, 10)
A. Suzuki (KEK)

1000 times higher energy

\[ 1 \text{ PeV} = 10^{15} \text{ eV} \]

“New paradigm”

- Leptogenesis
- SUSY breaking
- Extra dimension
- Dark matter
- Supersymmetry

\[ 1 \text{ TeV} = 10^{12} \text{ eV} \]

“Standard model”

- Higgs
- Quarks
- Leptons

Laser Acceleration Technology
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

$$\gamma_{ph} = (n_{cr} / n_e)^{1/2}$$

Adopt:

NIF laser (3MJ) $\rightarrow$ 0.7PeV

(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. Also overlays energy versus arrival time for each
Feel vacuum texture: PeV energy $\gamma$

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

$\gamma < c_0$

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

Coarser, lower energy texture

Finer, higher energy texture

$0.1\text{PeV}$

$1\text{km}$

$10^{-34}\text{cm}$

$10^{-34}\text{cm}$

$10^{-32}\text{cm}$

$10^{-32}\text{cm}$
What is vacuum?

An observer (bug) in crystal looks at vacuum:

- vacuum「真(true)空(nothing)」

Phonon: excitation of vacuum:

- Photon: distortion of vacuum「色=(即是)空」

Strong field breaks vacuum:

- vacuum produces e+e- pair「空=(即是)色」

QED vacuum breakdown:

\[ P \propto e^{-E_\omega/E} \]

\[ \lambda_c = \left( \frac{2m_e^2}{eE} \right)^{1/2} \]

Strong laser field:

\[ eE\lambda \approx e\sqrt{2m_e^2} \]

Laser wavelength

(Naumova Mourou)
Intense laser probes matter / vacuum nonlinearity

Crystal nonlinearity →

second harmonic generation (Franken et al)

(a)

(b)

(c)

Learn from Nonlinear Optics of matter for vacuum:

QED nonlinearity

Vacuum nonlinearity by light-mass field (dark energy, axion,..)

→ 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)
Conclusions

- Laser: intensity sees no plateau/ceiling since 1990
- Nonlinearities of matter by Laser: nonlinear optics (atomic or solid nonlinearity) : Rutherford method vs Laser method
- Nonlinearity of relativistic plasma \(\rightarrow\) laser wakefield
- Laser wakefield acceleration: experimentally well established; unique properties getting known/applications spawn out
- GeV electrons; 10 GeV soon; 100GeV world lab suggested; TeV laser collider contemplated; PeV frontier *(primordial GRBs in the lab)*
- Vacuum nonlinearities: Heisenberg QED vacuum probed by intense laser by phase contrast imaging
- Vacuum nonlinearities with weakly coupling light energy fields (meV- neV): co-propagating intense lasers to find beat resonance \(\leftarrow\) axion-like particles, dark energy fields
- High Fields Science: emerging, carves out new frontier, horizon yet to be seen --------a second wave of laser revolution---------
Centaurus A: cosmic wakefield linac?

Merci Beaucoup!