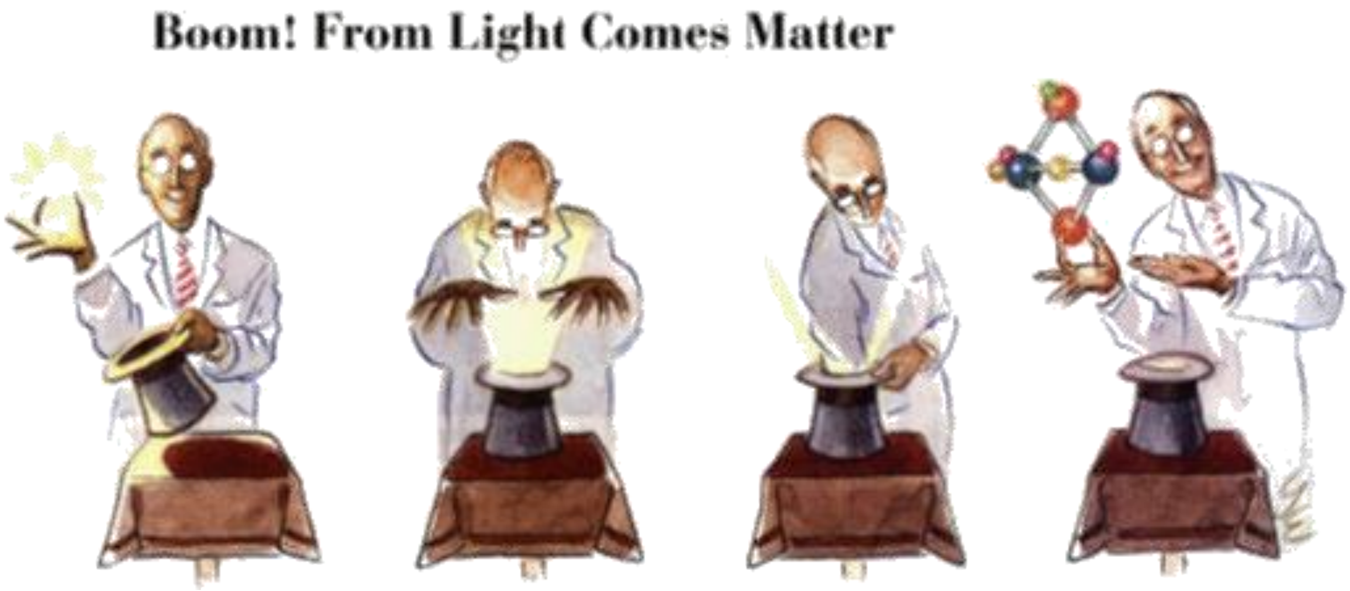
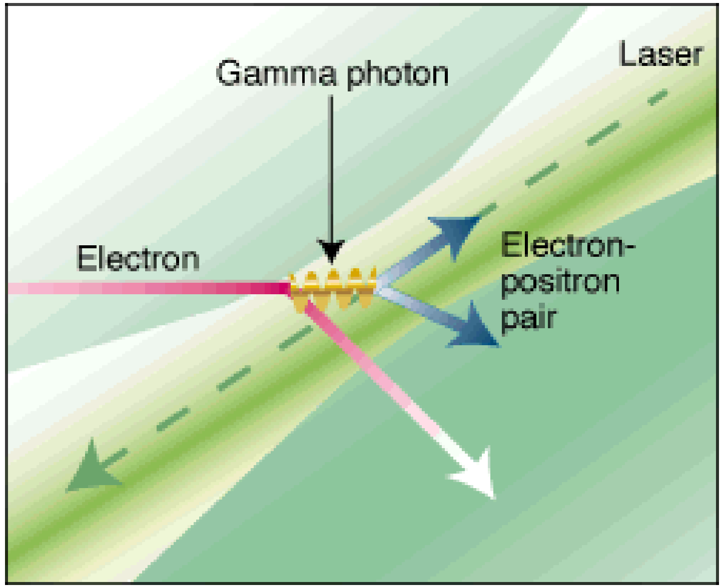


Gil Eisner, Photonics Spectra, Nov . 1997



D. Pugh, Science **277**, 1202 (1997)

Strong-Field QED Physics

Thomas Koffas

Carleton
UNIVERSITY

Many thanks to:
Phil Bucksbaum, Christoph Keitel,
Sebastian Meuren, Kirk McDonald,
David Reis

Fundamental Physics During Violent Accelerations

AIP Conf. Proc. ***130****, 23 (1985)*

When a powerful laser beam is focused on a free electron the acceleration of the latter is so violent that the interaction is nonlinear.

A rather fundamental aside:
An important qualitative feature distinguishes our understanding of the electromagnetic interaction from that of the strong, weak and gravitational interactions. Namely that the latter are fundamentally non-linear, meaning that the bosonic quanta which mediate these interactions can couple to themselves.

As a step towards the elucidation of fundamental non-linear phenomena one could consider the unusual case of very strong electromagnetic fields, in which non-linear effects can be induced.

These have been very old speculations, for example:
J.S. Toll, Princeton PhD thesis (1952)
Birefringence of the vacuum.   Adviser: J.A. Wheeler

Hawking Radiation

An appropriate point of departure is the work of Hawking, in which he associated a temperature T with a black hole:

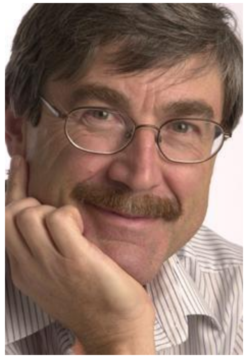
$$T = \frac{\hbar g}{2\pi ck}.$$

Here, $\hbar$ is Planck's (reduced) constant, g is the acceleration due to gravity measured by an observer at rest with respect to the black hole, c is the speed of light in vacuum, and k is Boltzmann's constant.

The significance of this temperature is that the observer will consider himself to be in a bath of black-body radiation of characteristic temperature T.

*S.W. Hawking, Nature **248**, 30 (1974)*
*Comm. Math. Phys. **43**, 199 (1975)*

The Unruh Effect



Contemporaneous with the work of Hawking, several people considered quantum field theory according to accelerated observers.

By the equivalence principle, we might expect accelerated observers to experience much the same thermal bath as Hawking's observer at rest near a black hole.

If a^* is the acceleration as measured in the instantaneous rest frame of an observer, then (s)he is surrounded by an apparent bath of radiation of temperature,

$$T = \frac{\hbar a^*}{2\pi c k}.$$

S.A. Fulling, *Phys. Rev. D* **7**, 2850 (1973)
P.C.W. Davies, *J. Phys. A* **8**, 609 (1975)
W.G. Unruh, *Phys. Rev D* **14**, 870 (1976)

The Unruh Radiation

Of experimental interest is the case when the observer is an electron.
Then, the electron could scatter off the bath of radiation, producing photons which could be detected by inertial observers in the laboratory.
This new form of radiation, which we call Unruh radiation, is (hopefully) to be distinguished from the ordinary (Larmor) radiation of an accelerated electron.

In particular, the intensity of radiation in the thermal bath varies as T^4. Hence, we expect the intensity of the Unruh radiation to vary as $T^4 \propto a^{*4}$.

$$\frac{dU_{\text{Unruh}}}{dt} \approx \frac{8\pi^3 \hbar r_0^2}{45c^2}\left(\frac{kT}{\hbar}\right)^4 = \frac{\hbar r_0^2 a^{*4}}{90\pi c^6}.$$

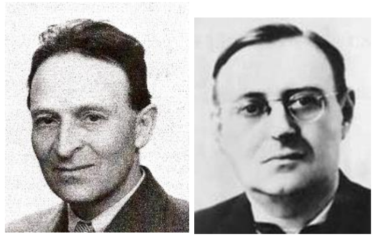
This contrasts with the a^{*2} dependence of the intensity of Larmor radiation,

$$\frac{dU_{\text{Larmor}}}{dt} = \frac{2e^2 a^{*2}}{3c^3} = \frac{60\pi}{\alpha}\left(\frac{E_{\text{crit}}}{E^*}\right)^2 \frac{dU_{\text{Unruh}}}{dt} = \left(\frac{160 E_{\text{crit}}}{E^*}\right)^2 \frac{dU_{\text{Unruh}}}{dt}, \qquad r_0 = \frac{e^2}{mc^2}, \qquad \alpha = \frac{e^2}{\hbar c},$$

where $E_{\text{crit}} = \frac{m^2 c^3}{e\hbar}$ is the QED critical field strength, and $a^* = \frac{eE^*}{m}$ is the acceleration.

The QED critical field was introduced by Sauter (1931), following suggestions of Bohr and Heisenberg as to the resolution of Klein's paradox, i.e., the production of e^+e^- pairs in a strong electric field.

O. Klein, Z. Phys. **53**, 127 (1929)
F. Sauter, Z. Phys. **69**, 742 (1931)



The Unruh Effect

The Unruh radiation effect is a QED correction to Larmor radiation, and is not likely to be directly observed.

Strictly, the Unruh effect, in which an accelerated observer detects a blackbody spectrum in what an inertial observer considers to be empty space, holds only for uniform, linear acceleration.

However, the Unruh effect has been observed in the broader sense of excitations, by a quasi-thermal virtual-photon bath, of electrons in storage rings related to their centripetal acceleration.

Bell and Leinaas noted the Unruh effect gives a qualitative explanation of the limit of 92% of the transverse polarization of electrons in storage rings, ordinarily considered as due to quantum fluctuations in their synchrotron radiation.

*J.S. Bell and J.M. Leinaas, Nucl. Phys. B **212**, 131 (1983)*

For the Unruh effect on damping of transverse oscillations in a linear focusing channel, see KTMcDonald, linearchannel.pdf (1998)

Strong-Field QED

For high acceleration, need strong electromagnetic fields.

The strongest macroscopic electromagnetic fields on Earth are in lasers.

Nonperturbative, strong-field QED is described by two dimensionless measures, η and Υ, of the strength of a plane wave with angular frequency ω_0, and 4-potential $A_\mu = (0, \mathbf{A})$.

1. $$\eta = \frac{e\sqrt{\langle A_\mu A^\mu \rangle}}{mc^2} = \frac{eE_{\rm rms}}{m\omega_0 c} = \frac{eE_{\rm rms}\bar{\lambda}_0}{mc^2},$$

governs the importance of multiple photons in the initial state, and characterizes the "mass shift",

$$\bar{m} = m\sqrt{1+\eta^2},$$

of a (quasi)electron in a "background " electromagnetic wave (laser beam).

*D.M. Volkov, Z. Phys. **94**, 250 (1935), T.W.B. Kibble, Phys. Rev. **150**, 1060 (1966)*
*[For electrons in metals, R. Peierls, Z. Phys. **80**, 762 (1933).]*

2. $$\Upsilon = \frac{\sqrt{\left\langle \left(F^{\mu\nu} p_\nu\right)^2 \right\rangle}}{mc^2 E_{\rm crit}} = \frac{2p_0}{mc^2}\frac{E_{\rm rms}}{E_{\rm crit}} = \frac{2p_0}{mc^2}\frac{\bar{\lambda}_{\rm C}}{\bar{\lambda}_0}\eta, \qquad E_{\rm crit} = \frac{m^2c^3}{e\hbar} = \frac{mc^2}{e\bar{\lambda}_{\rm C}} = 1.3\times 10^{16}\,\frac{\rm V}{\rm cm},$$

governs the rate of "spontaneous" e^+e^- pair creation ("sparking the vacuum") in a wave probed by an electron with 4-momentum $p_\mu = (p_0, \mathrm{P})$.

NOTE: *modern notation is* $\eta\ \alpha\ \xi$ *and* $\Upsilon\ \alpha\ \chi$

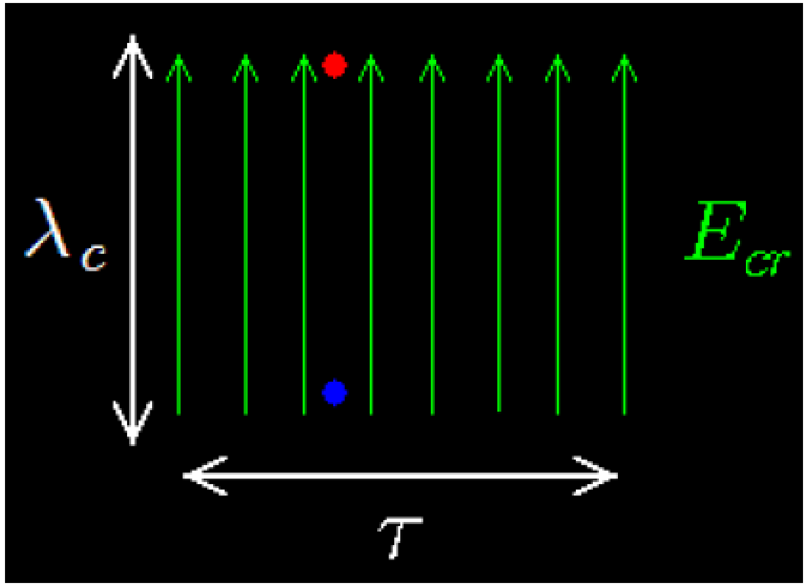
Quantum Vacuum and Critical Fields

- Virtual particles are present
- They live for a very short time ($\tau = э/mc^2$) and cover a very short distance ($\lambda_c = э/mc$)
  - For electrons and positrons: $\lambda_c \approx 10^{-11}$cm and $\tau \approx 10^{-21}$s

Critical Electric Field - physical meaning

The electric field strength for which the energy gain of an electron accelerated over one Compton length equals the electron rest energy:

$$\frac{\hbar}{mc} \times eE_{cr} \simeq mc^2 \approx \mathbf{10^{16} V/cm}$$



Available in highly charged ions but not feasible with current laser technology

$$I_{cr} = \frac{cE_{cr}^2}{8\pi} = 4.6 \times 10^{29} \, {}^{W}\!/_{cm^2}$$

The acceleration of a free electron in this case is so violent that the interaction is nonlinear.

Probing E_{cr} tests QED in a completely different non-perturbative regime

A regime not covered by Standard Model

The strong-field QED regime is largely unexplored

Where to Find Critical Fields

The magnetic field at the surface of a neutron star (magnetar) can exceed the critical field $B_{\mathrm{crit}} = 4.4 \times 10^{13}$ Gauss.

KTMcDonald, magnetars.pdf (1998)

During heavy-ion collisions where the critical field can be exceeded, and e^+e^- production is expected,

$$Z_{\max} \approx \frac{2Ze}{\lambda_C^2} > 2Z\alpha E_{\mathrm{crit}}.$$

*G. Taubes, The One That Got Away? Science, **275**, 148 (1997)*

The Earth's magnetic field appears to be of critical strength as seen by a cosmic-ray electron with $> 10^{19}$ eV.

*I.Y. Pomeranchuk, J. Phys. USSR **2**, 65 (1940)*

The electric field of a bunch at a future e^+e^- linear collider approaches the critical field in the frame of the oncoming bunch ⇒ "Beamstrahlung" limit.

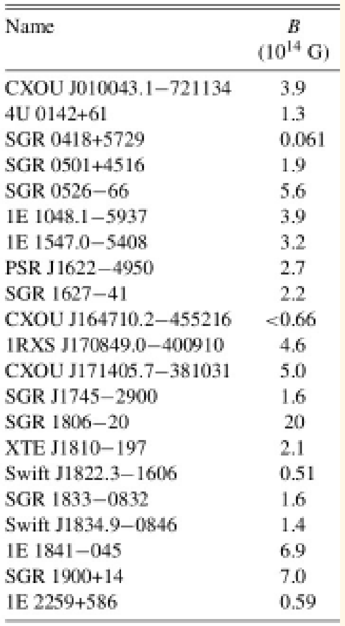
*M. Jacob & T.T. Wu, Phys. Lett. B **197**, 253 (1987)*

Strong Fields in Astrophysics

Extreme magnetic fields: magnetars

Magnetar SGR 1900+14

THE McGILL MAGNETAR CATALOG



Name	B (10^{14} G)
CXOU J010043.1−721134	3.9
4U 0142+61	1.3
SGR 0418+5729	0.061
SGR 0501+4516	1.9
SGR 0526−66	5.6
1E 1048.1−5937	3.9
1E 1547.0−5408	3.2
PSR J1622−4950	2.7
SGR 1627−41	2.2
CXOU J164710.2−455216	<0.66
1RXS J170849.0−400910	4.6
CXOU J171405.7−381031	5.0
SGR J1745−2900	1.6
SGR 1806−20	20
XTE J1810−197	2.1
Swift J1822.3−1606	0.51
SGR 1833−0832	1.6
Swift J1834.9−0846	1.4
1E 1841−045	6.9
SGR 1900+14	7.0
1E 2259+586	0.59

Gamma ray bursts, black holes

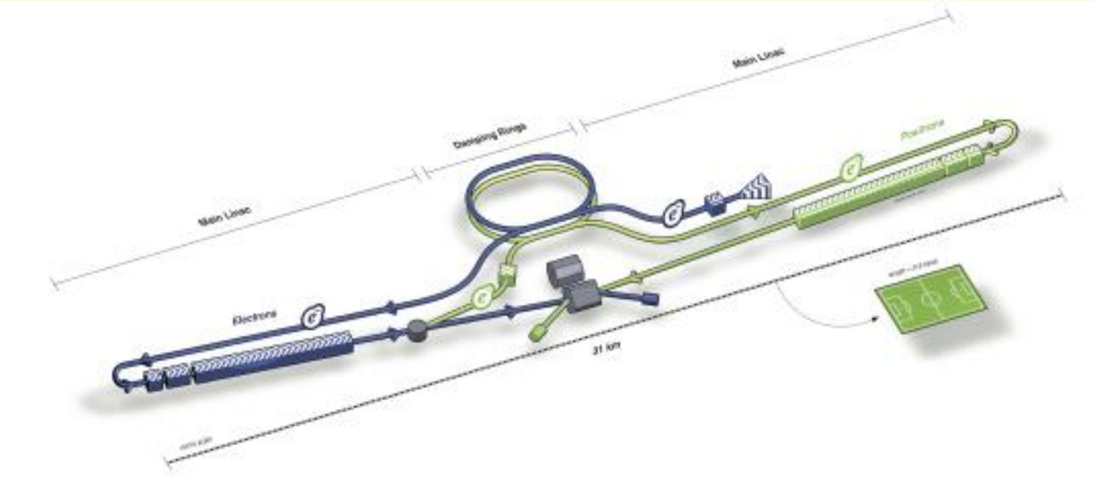
artist's view – quarkmag.com

Ultra-strong electromagnetic fields + highly energetic particles → strong-field QED

- Interior of neutron stars
- Magnetospheres of magnetars: $B \gtrsim B_{cr},\ B_{cr} = m^2c^2/(\hbar e) \approx 0.4 \times 10^{14} G$
    - Vacuum birefringence, electromagnetic cascades
- Central engines of supernovae and γ-ray bursts
- Black holes: energy extraction via the Blandford-Znajek process

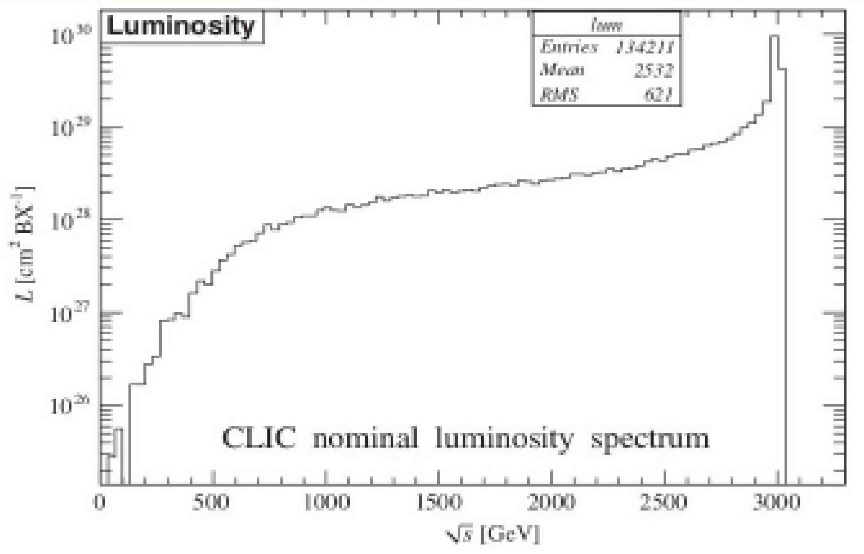
Strong Fields in Future Colliders

Lepton collider (electron-positron)



ILC $E^*/E_{\mathrm{cr}} = 0.1 - 0.3$ $(0.25 - 0.5\,\mathrm{TeV})$
CLIC $E^*/E_{\mathrm{cr}} = 1.5 - 12$ $(0.2 - 1.5\,\mathrm{TeV})$

Stochastic beamstrahlung



SFQED determines energy/luminosity

Esberg et al., PRSTAB **17**, 051003 (2014)

Problems of future Linear Electron-Positron Collider: → strong-field QED

- High luminosity → high charge density → strong fields → beamstrahlung
- Stochastic photon emission + large recoil: non-trivial energy distribution, modified transverse beam structure (beam broadening → focusing quality)

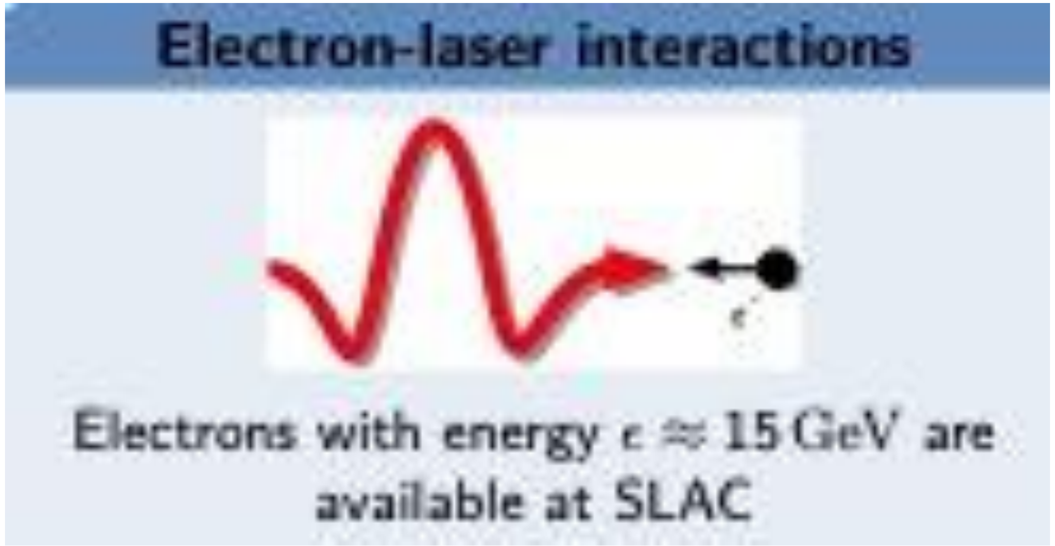
Can this be done in the lab?

In vacuum $I_{cr} = 4.6 \times 10^{29}\frac{W}{cm^2}$ is not achievable in the near future

But the field intensity I is not a Lorentz scalar ($I' \sim \gamma^2 I, \gamma = \epsilon/m$)

The critical intensity could be reached in a boosted frame for which

$\boldsymbol{\gamma \sim 10^3 - 10^4}$



Electron-laser interactions

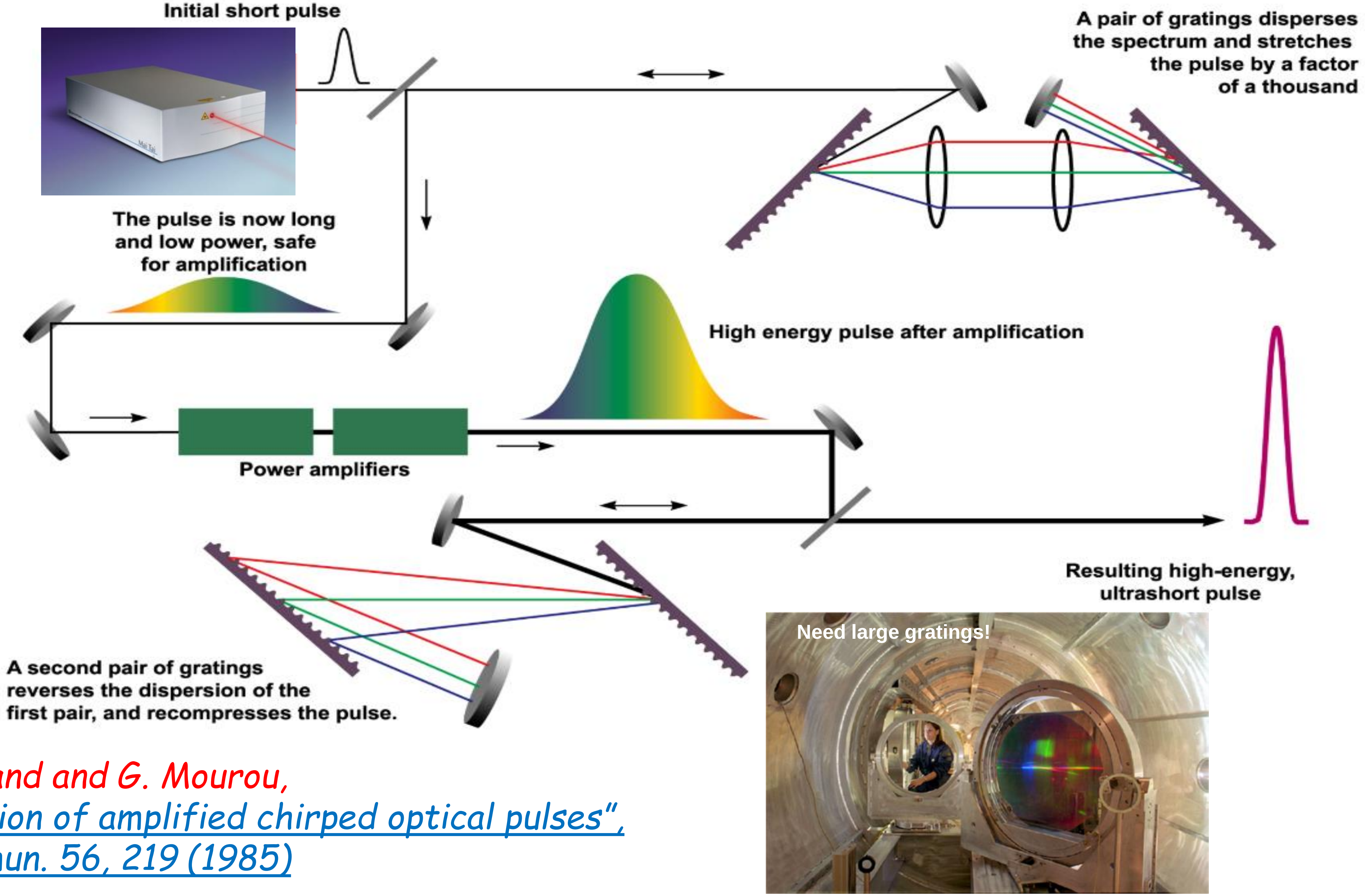
Electrons with energy $\epsilon \approx 15\,\mathrm{GeV}$ are available at SLAC

This still requires a laboratory frame intensity

$\boldsymbol{I \sim 10^{22} W/cm^2}$

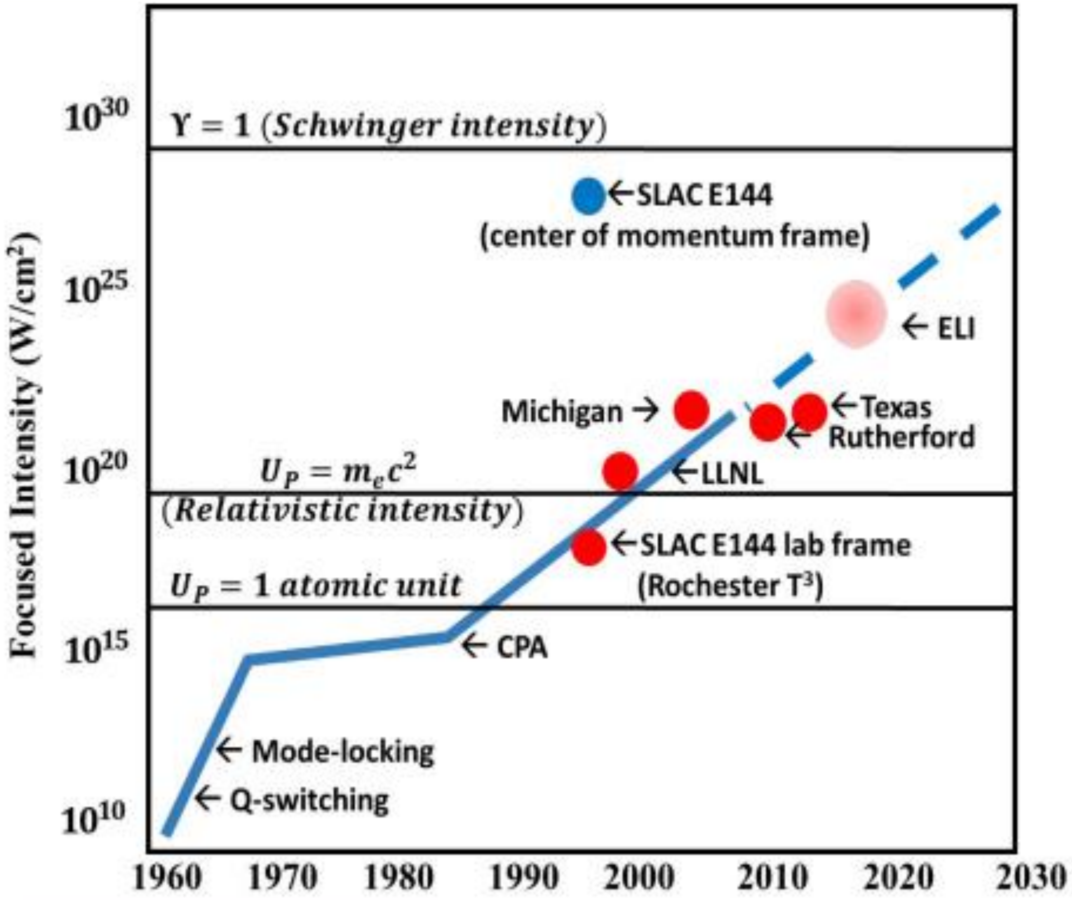
An optical Petawatt system!

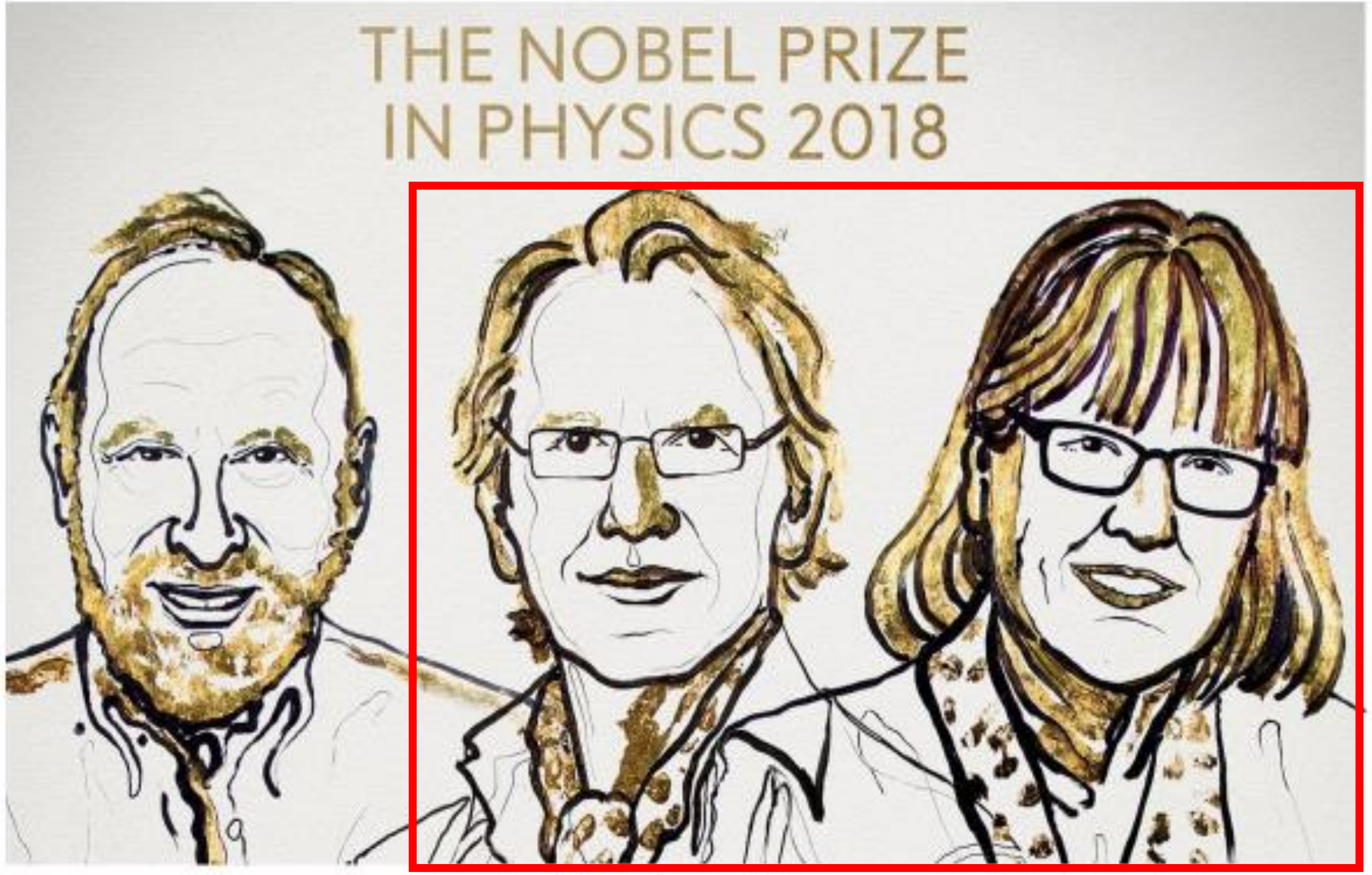
Chirped-pulse amplification-key enabling technology



D. Strickland and G. Mourou,
"Compression of amplified chirped optical pulses",
Opt. Commun. 56, 219 (1985)

A Nobel Prize Effort!





QED critical field:

$$E_{\mathrm{cr}} \approx 1.3 \times 10^{18}\ \mathrm{V/m}$$

$$I_{\mathrm{cr}} \approx 4.6 \times 10^{29}\ \mathrm{W/cm^2}$$

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

Present Electron and Laser Technology

Optical laser technology ($\hbar\omega_L = 1$ eV)	Energy (J)	Pulse duration (fs)	Spot radius (μm)	Intensity (W/cm^2)
State-of-art (Yanovsky et al., Opt. Express (2008))	10	30	1	2x10^{22}
Recent/soon (APOLLON, Vulcan, Astra-Gemini, BELLA, CoReLS etc…)	10-100	10-100	1	10^{22}-10^{23}
Near future (2020) (ELI, XCELS)	10^4	10	1	10^{25}-10^{26}

Electron accelerator technology	Energy (GeV)	Beam duration (fs)	Spot radius (μm)	Number of electrons
Conventional accelerators (PDG)	10-50	10^3-10^4	10-100	10^{10}-10^{11}
Laser-plasma accelerators (e.g. Leemans et al., PRL 2013)	0.1-5	50	5	10^9-10^{10}

$$\xi = 7.5\,\frac{\sqrt{I_L[10^{20}\mathrm{W/cm^2}]}}{\hbar\omega_L[\mathrm{eV}]}$$

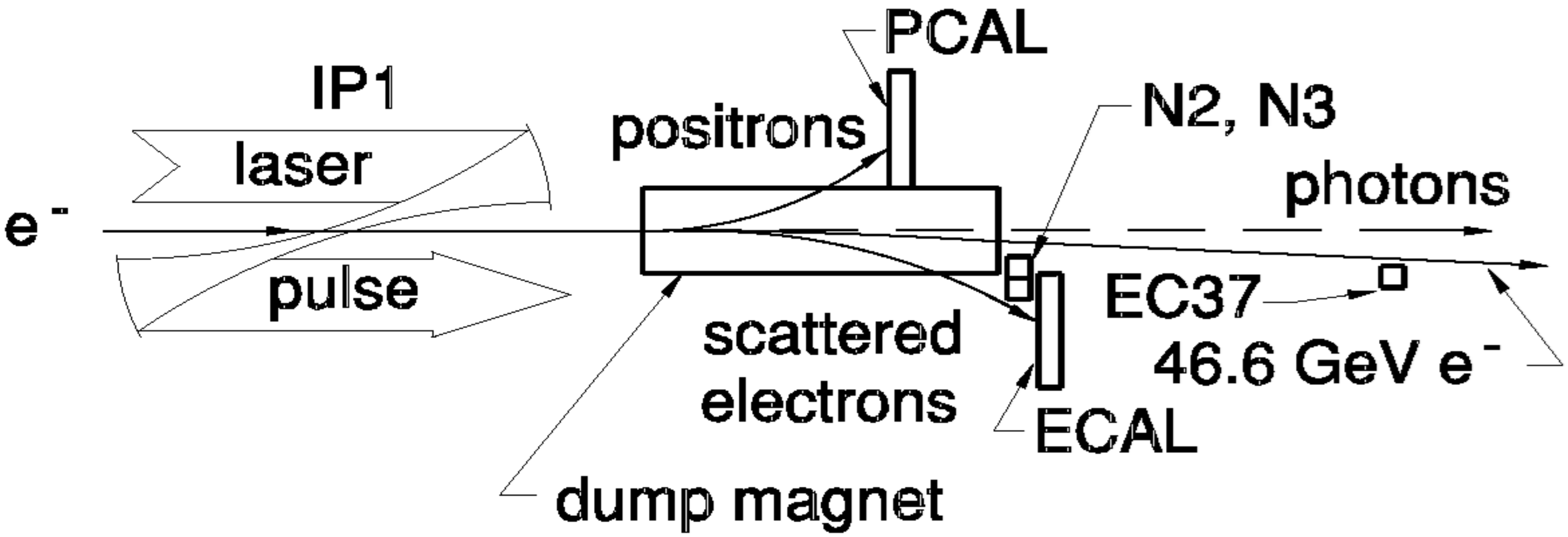
$$\chi = 5.9\ \times 10^{-2}\,\mathcal{E}\,[\mathrm{GeV}]\,\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$

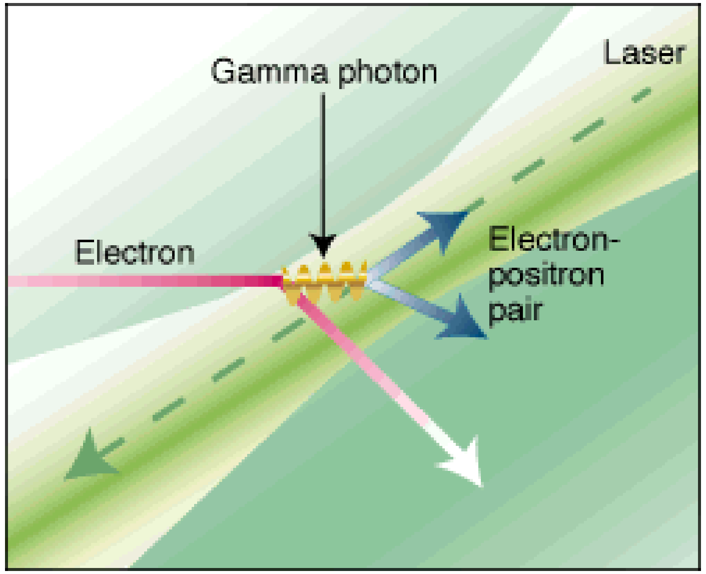
The electric field of a focused TeraWatt laser appears critical to a counterpropagating 50 GeV electron

⇒ SLAC Experiment E-144

NOTE: *modern notation is* $\eta \alpha \xi$ *and* $\Upsilon \alpha \chi$

Physics Motivation for E-144

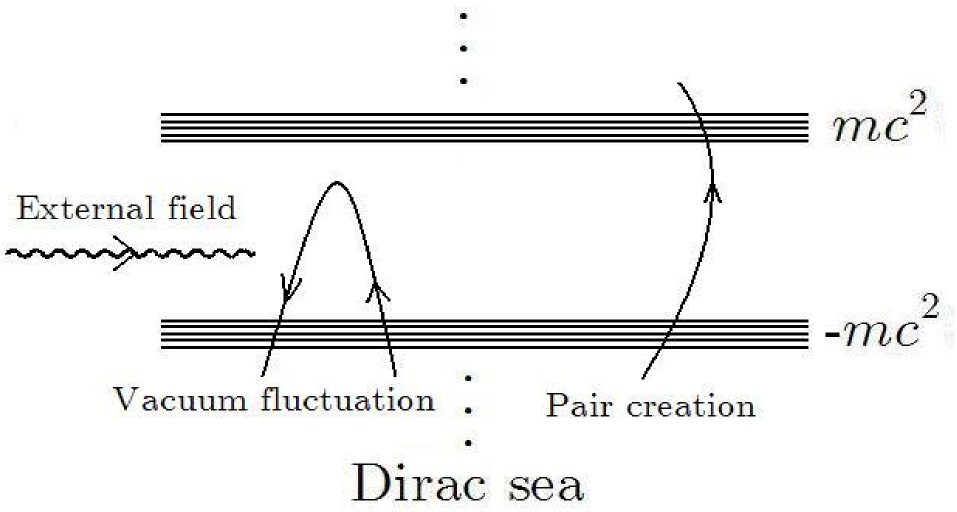




D. Pugh, *Science* ***277***, *1202 (1997)*

- QED has been tested extensively in the weak field regime:
  - Perturbative methods are applicable and theory agrees extremely well with the experiment
- In the case of strong fields perturbative techniques are of limited applicability
  - Processes can be treated within a semi-classical theoretical frame
  - Theory not tested against experimental measurements
- In fields of this strength various non-linear effects become prominent
- In this context the Breit-Wheeler process can be revisited
  - A multi-photon version of it could provide the necessary CM-energy to produce a e^+e^- pair
  - A two-step process in this approach using a laser induced external field:
    - A high energy electron scatters simultaneously off n laser photons, producing a high energy γ: $n\omega + e^- \longrightarrow \gamma + e^-$
    - The γ scatters again off n laser photons, while in the laser field, to produce a pair: $n\omega + \gamma \longrightarrow e^+ + e^-$

From Virtual to Real Pair Production



- The quantum field ground state is characterized by “quantum” fluctuations
  - Short lived virtual e^+e^- pairs are created and then annihilated again
- In the presence of a strong external field the vacuum can become unstable
- Short-lived e^+e^- pairs can then become physically separated
  - Transformed into real particles
  - At the expense of some energy provided by the external field
- For this to happen the work done by such a field over the distance of one electron Compton length should be the mass of the e^+e^- pair

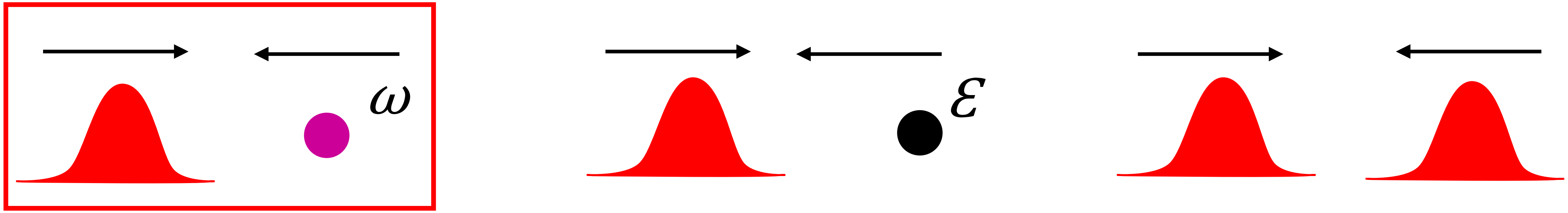
At the high frequency limit: $P \simeq \frac{\alpha\mathcal{E}^2}{\pi}\exp\left(-\frac{\pi}{\Upsilon}\right), \quad \eta \gg 1$ (tunneling result)

At the low frequency limit: $P \simeq \frac{\alpha\mathcal{E}^2}{8}\left(\frac{e\mathcal{E}}{2m\omega}\right)^{4m/\omega}, \quad \eta \ll 1$

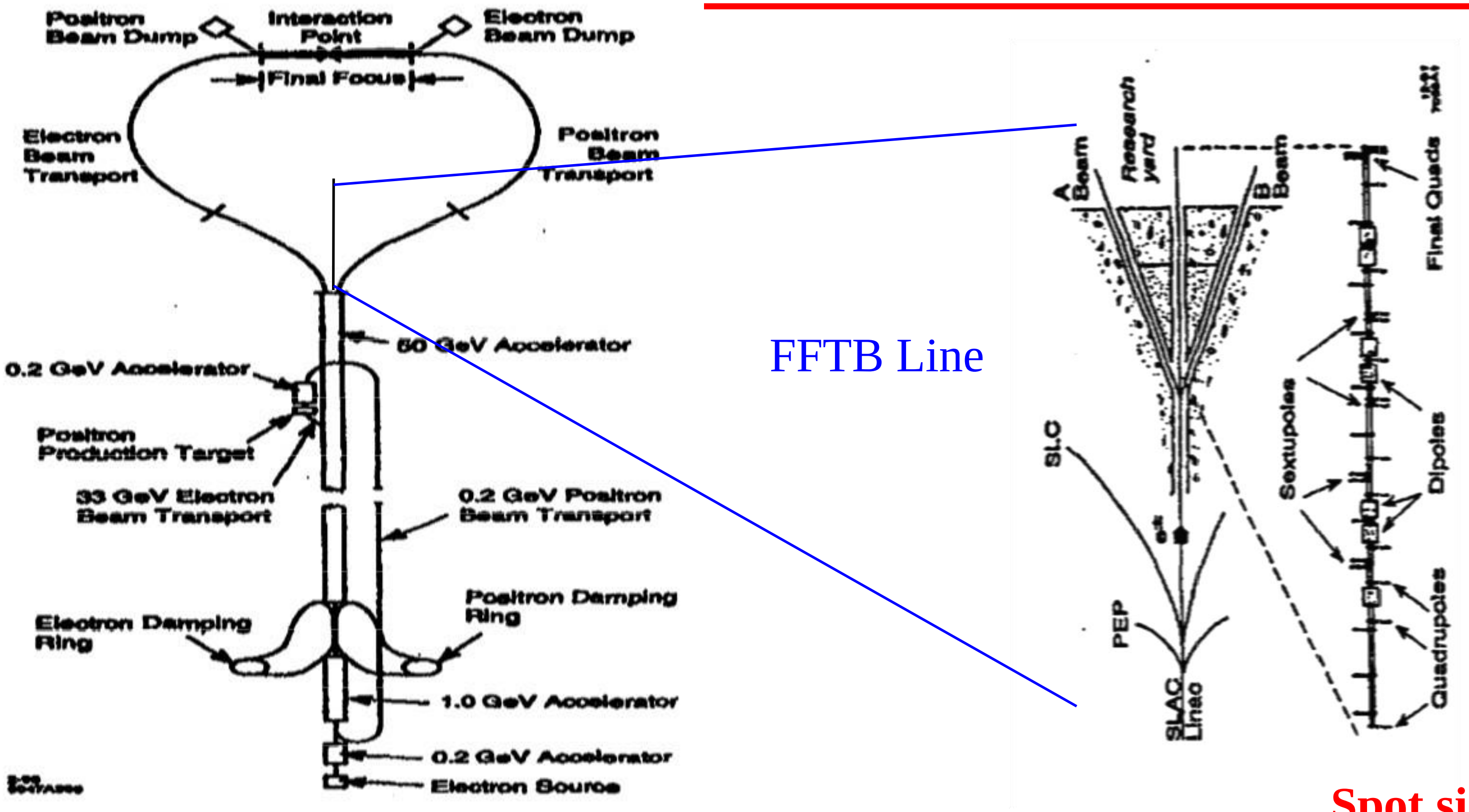
where the exponent can be interpreted as the minimum number of laser photons required to produce a pair

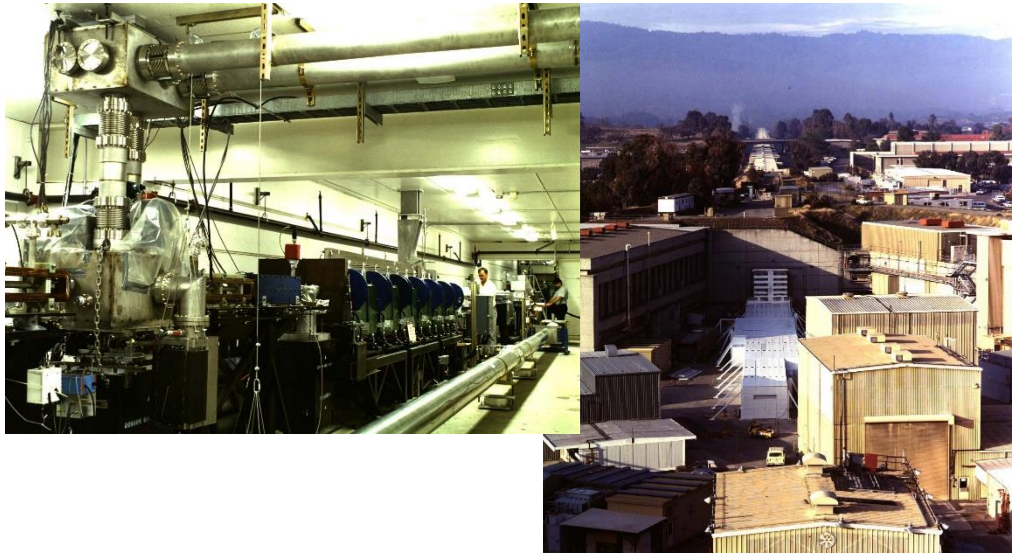
Essentially described in terms of Quantum Mechanical Tunneling Effect

Three main mechanisms of pair production



The Electron Beam





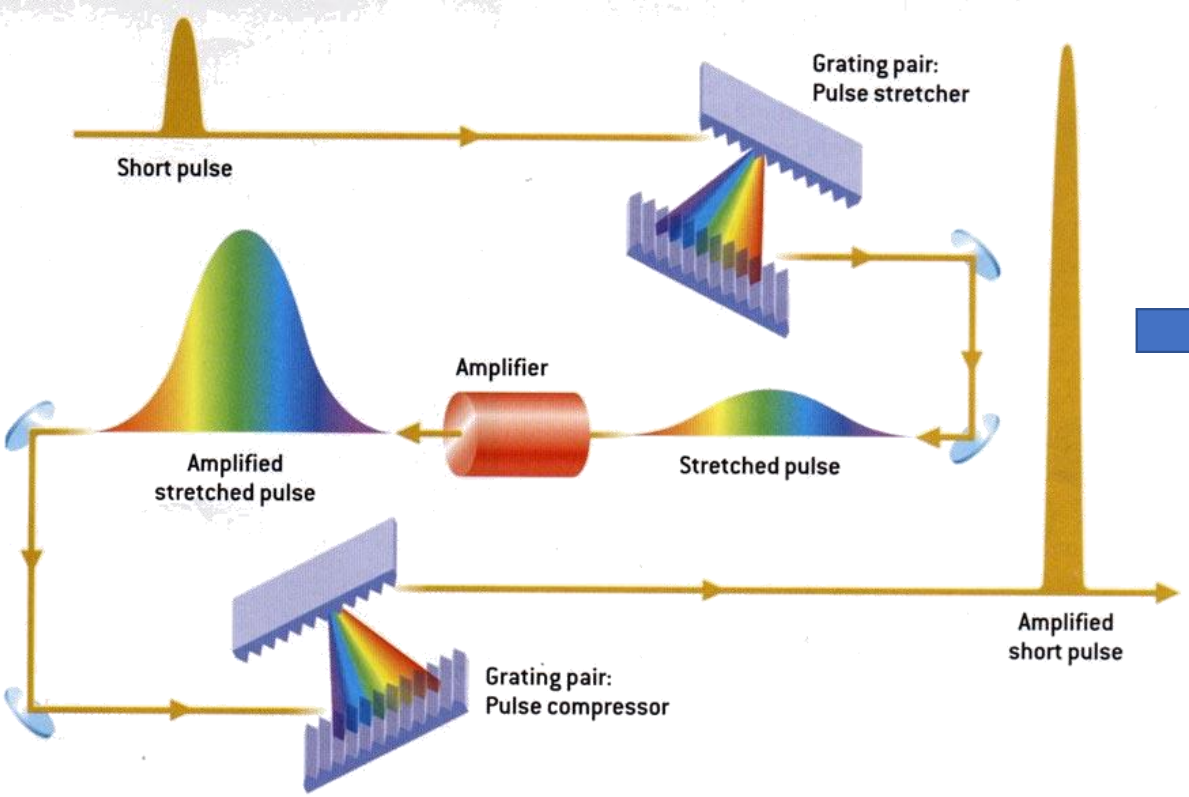
Spot sizes of 20-30μm delivered at the interaction point

- The experiment was installed in the FFTB line:
  - Located at the end of the 2-mile long linac
  - Line designed for focusing electron beams to sub-μm levels
  - No acceleration involved, pure beam optics line
  - Small focal areas increase the number of e^- through the laser beam and hence event rates
- Bunch lengths of <1 mm and beam charges of 5-7×10^9 have been delivered
- Normalized emittance of 3×10^{-5},3×10^{-6} in x,y transverse dimensions respectively
  - A measure of the electron beam size and divergence delivered at the FFTB line

Electron beam carefully tuned and a series of active feedbacks were introduced to ensure extremely low positron backgrounds

~1 positron every 20 minutes!

The Laser Beam



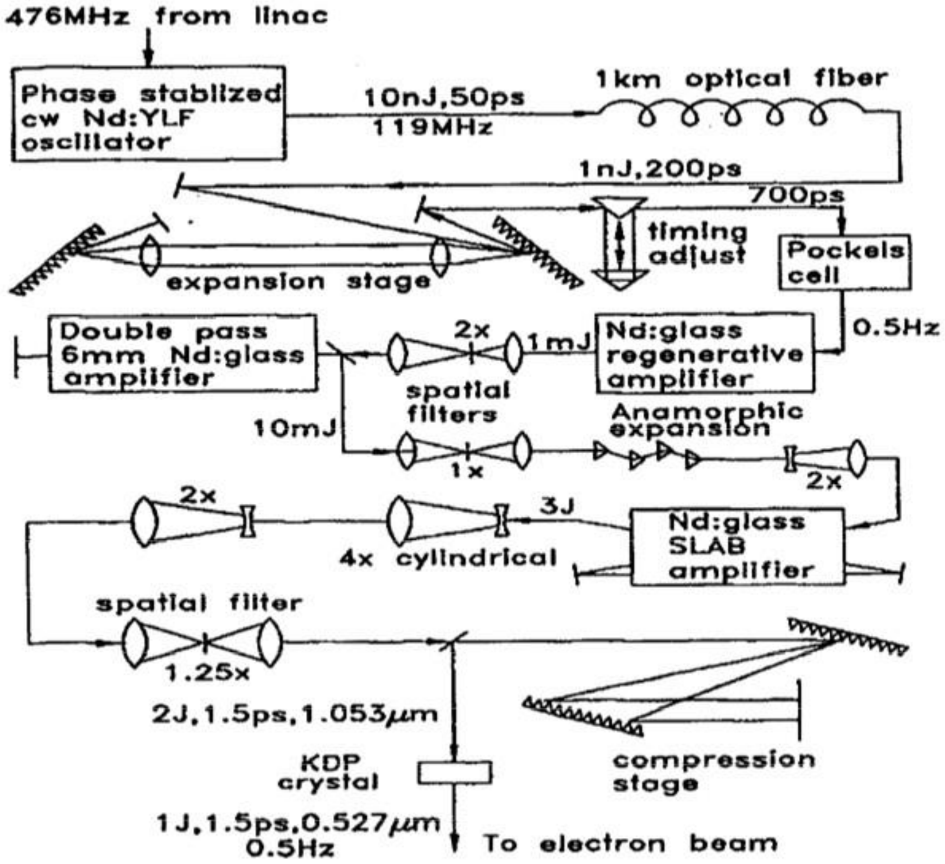
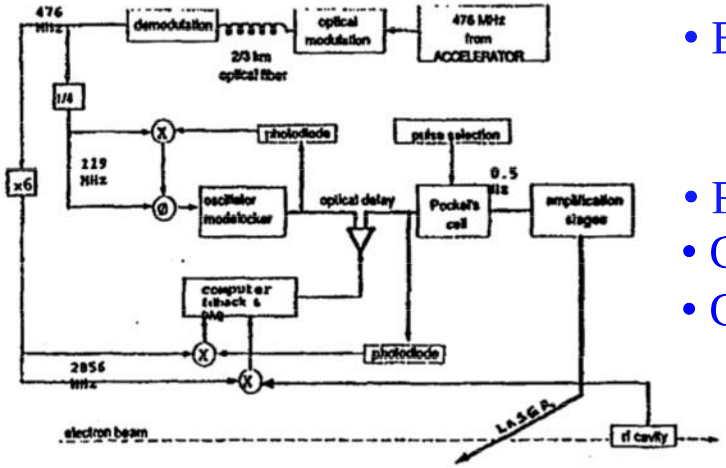


Table Top Terawatt laser system (T^3): Chirped-Pulse Amplification (CPA) in a “slab” amplifier.

E144 laser system: *C. Bamber et al.*, *Laser Phys. 7, 135 (1997)*

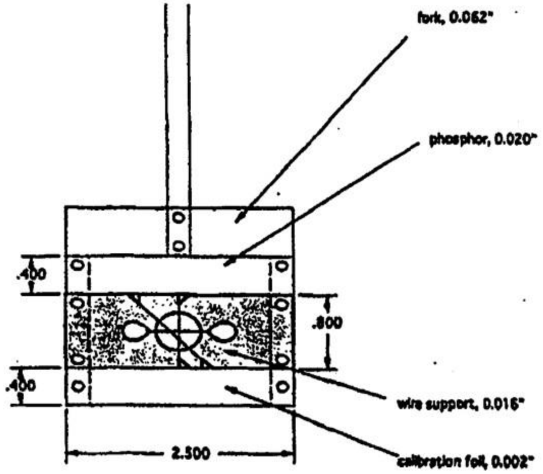
- Delivers both IR (1054 nm) and Green (527nm) pulse
- Maximum energies of 2J (for the IR) and 1J (for the green)
- Focal points were **2-4 times** the diffraction limited ones
- The pulse time widths were **1.5 ps** for both wavelengths
- Intensities **>10^{18} W/cm^2** have been achieved at the focal point

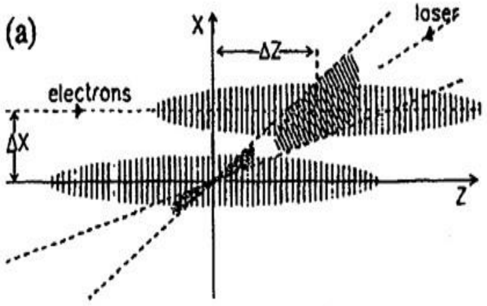
Temporal/Spatial Beam Overlap

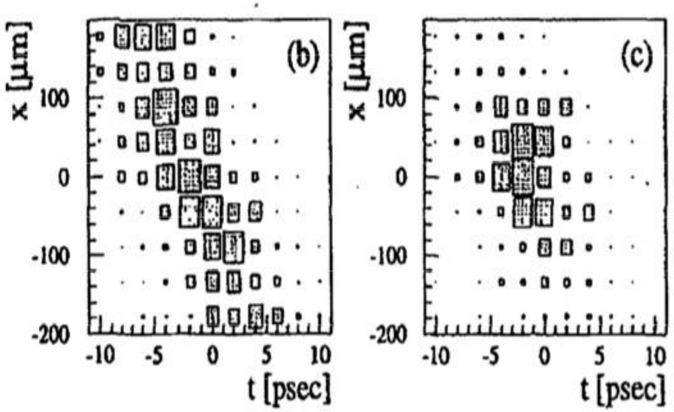


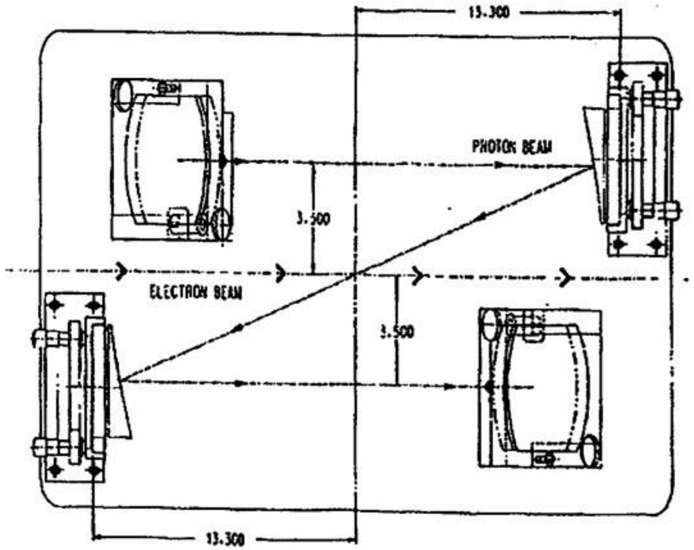
- Ensure timing of 7 ps electron to 1.5 ps laser pulse
  - Laser pulse train at sub-multiple of accelerator RF (476 MHz)
  - Sets the time of the laser pulse launching
- Fine tuning achieved by modulating the length of the laser beam path
- Collected light leakage before IP provides the laser time reference
- Compared to an electron beam based signal from a ringing cavity
  - The optical delay line provides the remaining fine tuning down to ps precision

Electron-laser beams cross at 17^0



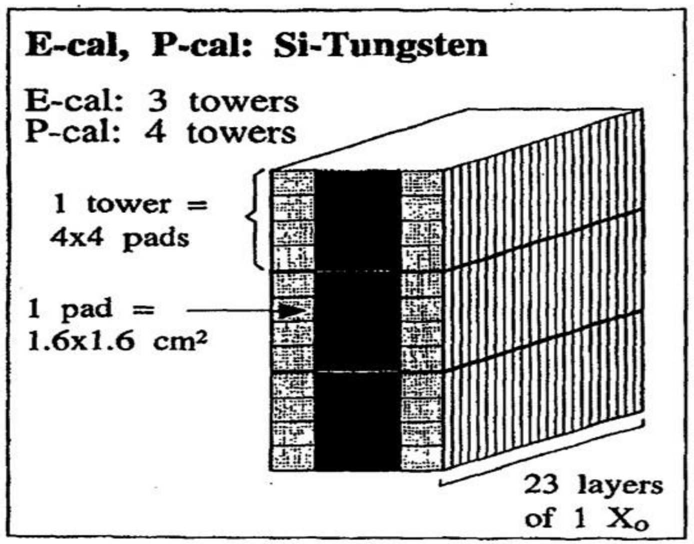




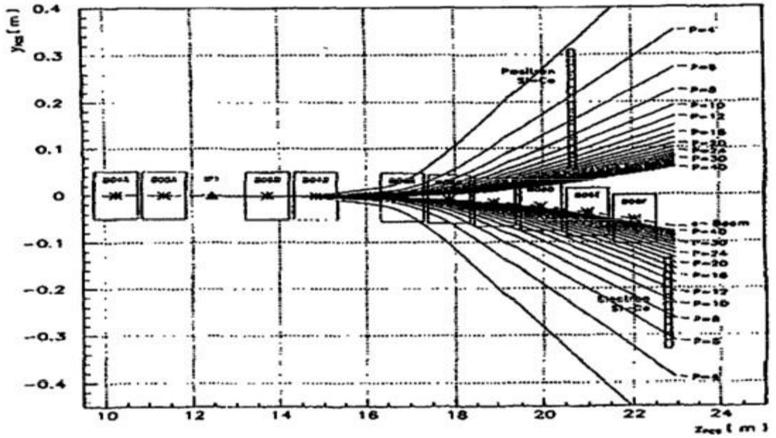


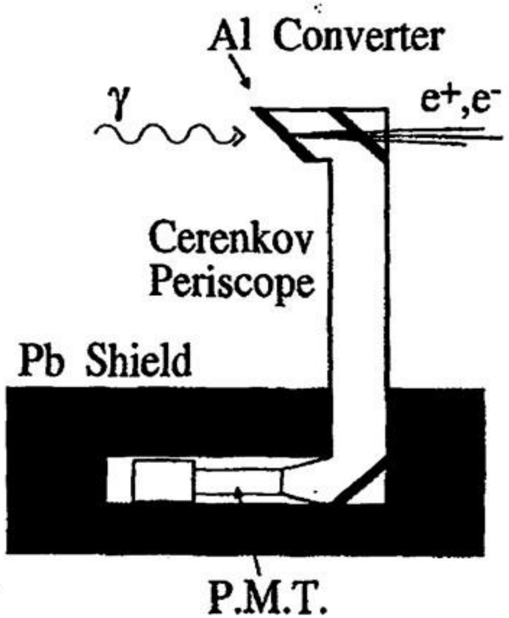
- A device (IP Flag) is placed at the focus of the laser beam
- The electron beam is steered on the wire cross-hair using dither correctors
  - Due to thermal effects, long term drifts will appear
  - Perform X, Y- scans by moving the IP region (essentially laser focus) with respect to electron beam
- There is a strong correlation between the x-position and the time overlap of the two beams

Calorimeters – Cherenkov Monitors



- Two calorimeters used to measure the energy of electrons (ECAL) and positrons (PCAL)
- Both calorimeters are of similar design:
  - Made of alternating layers of Si(300μm thick) and Tungsten (1 X0 thick)
  - Each is divided in 12 rows and 4 columns resulting in $1.6\times1.6\text{cm}^2$ pads
  - Groups of 4 rows per column make a tower; longitudinal layers arranged in segments
- Only middle columns record signal; outer columns used for background subtraction
- Calibration is done using e⁻ beams of variable yet known momenta





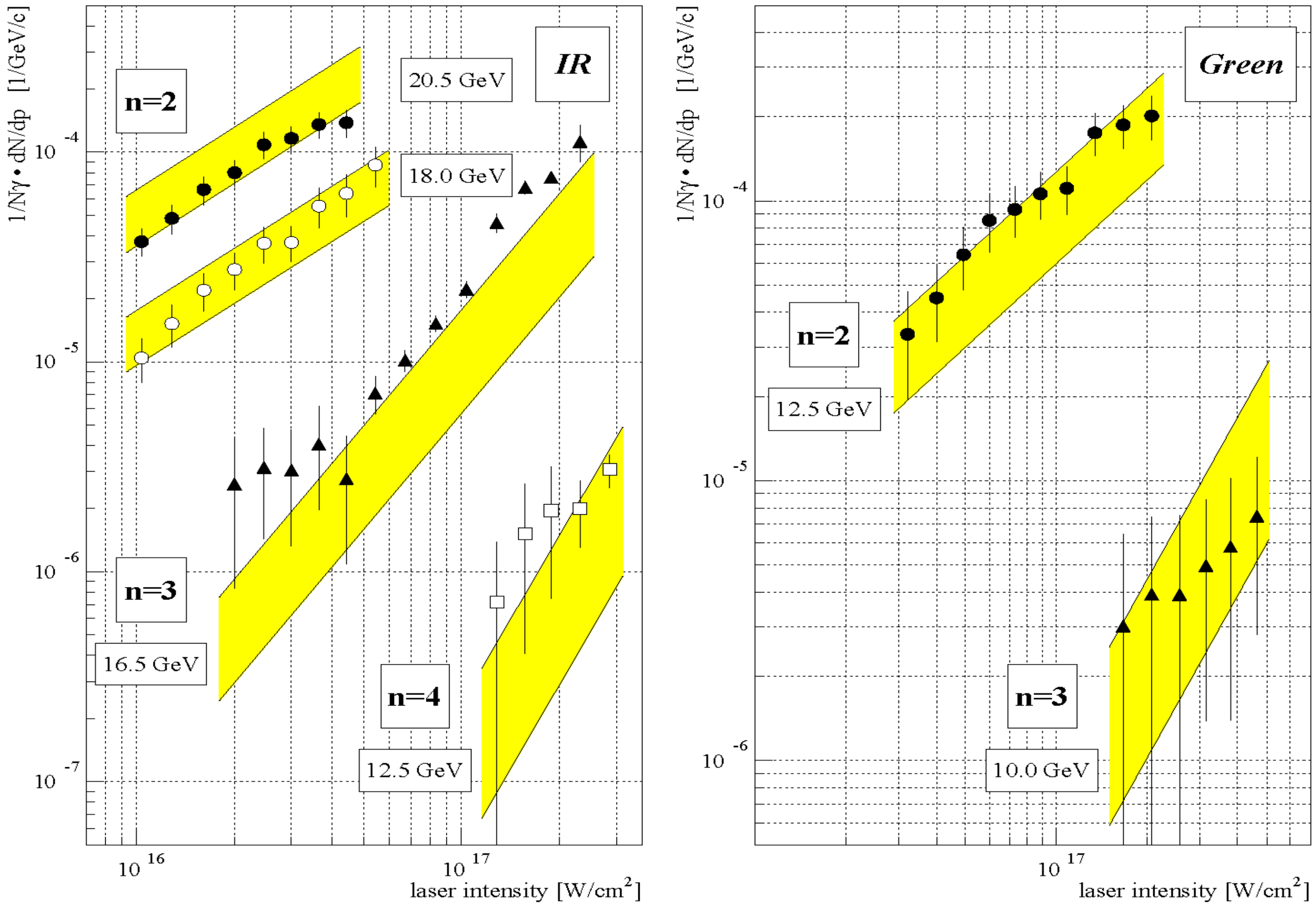
- Cherenkov monitors used to establish quality of interactions at IP
- Several types of Cherenkov monitors are used:
  - 1 air Cherenkov counter that intercepts γ's from the linear Compton scattering (CCM1)
  - 2 air Cherenkov counters that look at linear Compton scattered e⁻ of 37 and 31 GeV (EC37, EC31)
- Also used non-linear monitors intercepting 2nd and 3rd order Compton e⁻ respectively
  - Air Cherenkov counters using ethylene instead of air
  - Cross-calibrated using ECAL and a test e⁻ beam of variable momentum

Non-Linear Compton Scattering

$e + n\omega_0 \rightarrow e' + \gamma$

C. Bula et al. *Phys. Rev. Lett.* ***76**, 3116 (1996)*

Rate



Rate (@ order *n*) $\propto I^{n-1}$,
when normalized to
total scattered photon rate.

Theory based on Volkov states of a (dressed) Dirac electron in a plane wave.

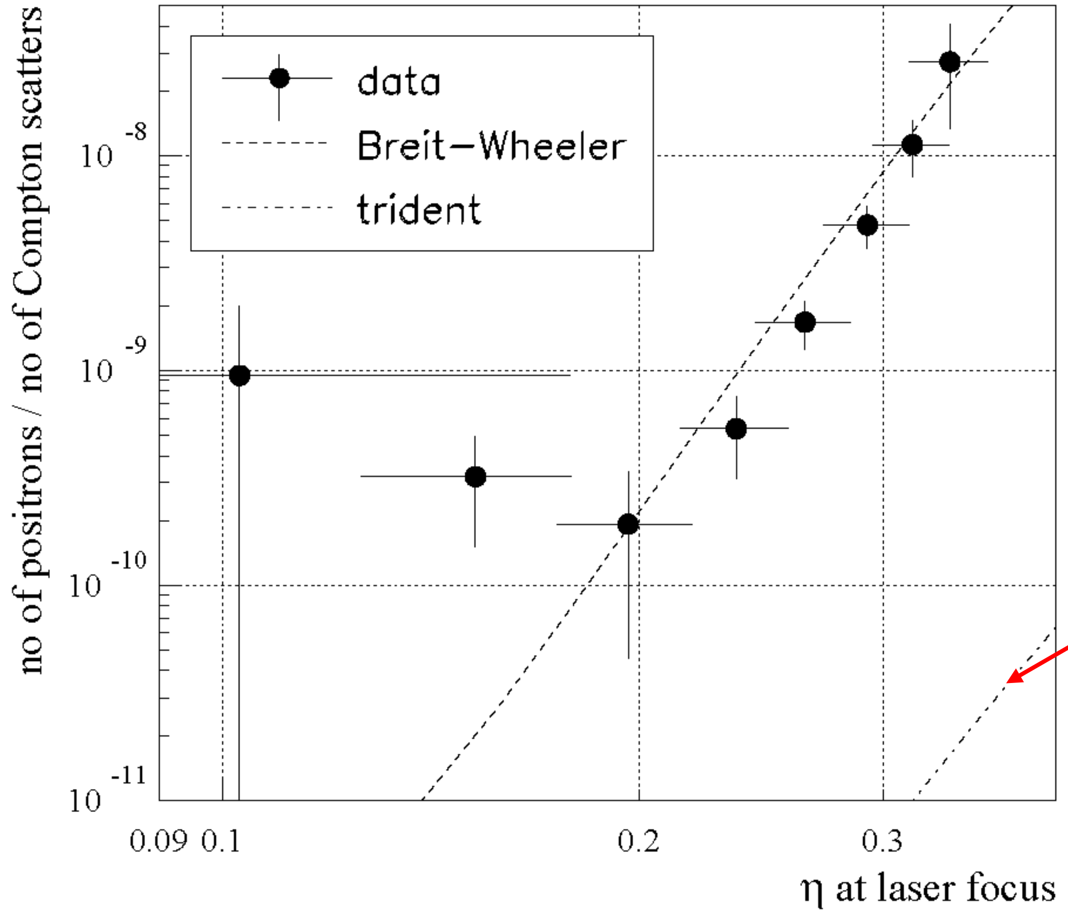
*A.I. Nikishov & V.I. Ritus, Sov. Phys. JETP **19**, 529 (1964)*

*N.B. Narozhny, A.I. Nikishov & V.I. Ritus, Sov. Phys. JETP **20**, 22 (1965)*

Pair Creation by Inelastic Light Scattering

Two-step process: $e + \omega_0 \rightarrow e' + \omega$, then $\omega + n\omega_0 \rightarrow e^+e^-$. 106 ± 14 signal positrons.

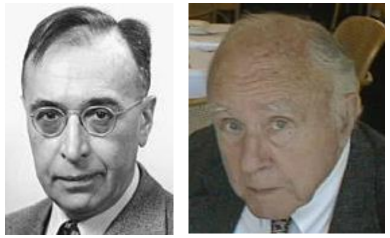
*D. Burke et al., Phys. Rev. Lett. **79**, 1626 (1997), C. Bamber et al., Phys. Rev. D **60**, 092004 (1999)*



Rate ∝ η^{2n}, where
n = 5:1 ± 0.2 (stat.) ± 0.7 (syst.)
⇒ 5 laser photons
(process is below threshold
for 1 photon).

trident = $e + n\omega_0 \rightarrow e' + e^+e^-$.
C. Bula & KTMcDonald, trident.pdf (1998)

Nonlinear Breit-Wheeler scattering,
*G. Breit and J.A. Wheeler, Phys. Rev. **47**, 1087 (1934)*



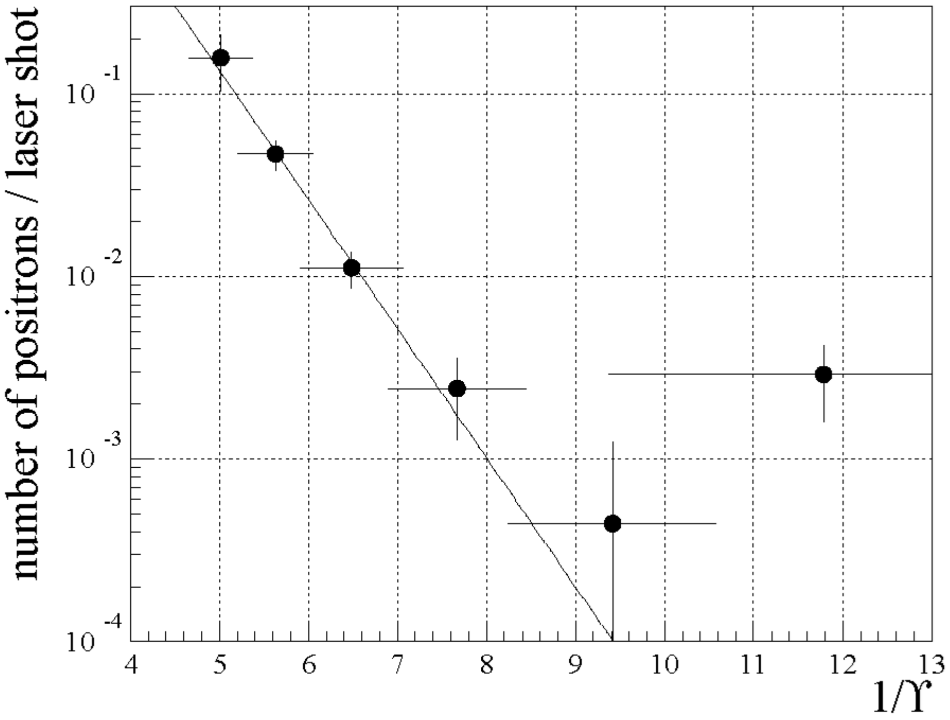
Pair Creation as Barrier Penetration

For a virtual e^+e^- pair to materialize in a field E, the electron and positron must separate by distance d sufficient to extract energy $2mc^2$ from the field:

$$eEd \geq 2mc^2.$$

The probability P of a separation d arising as a quantum fluctuation is related to penetration through a barrier of thickness d:

$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-\frac{2m^2c^3}{e\hbar E}\right) = \exp\left(-\frac{2E_{\text{crit}}}{E}\right) = \exp\left(-\frac{2}{\Upsilon}\right).$$



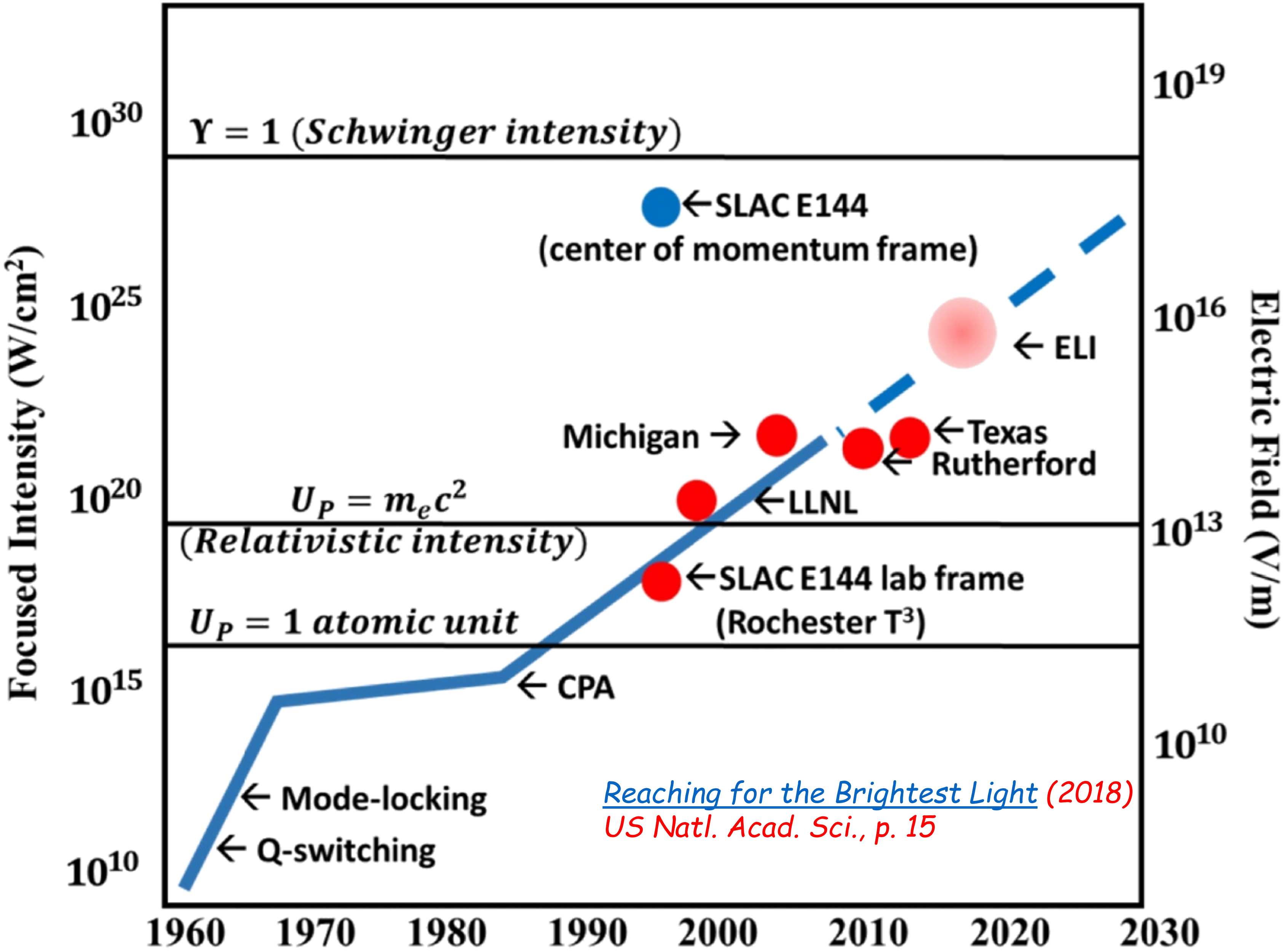
F. Sauter, Z. Phys. **69**, 742 (1931)

W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936)

J. Schwinger, Phys. Rev. **82**, 664 (1951)

$$Rate_{e+} \propto \exp\{[-1.8 \pm 0.2\ (\text{stat.}) \pm 0.2\ (\text{syst.})]/\Upsilon\}.$$

E-144 was Ahead of its Time



Reaching for the Brightest Light (2018)
US Natl. Acad. Sci., p. 15

$\Upsilon \gg 1$?

The technology now exists to have laser fields with $\Upsilon \gg 1$ when probed by GeV electrons.

Is new physics accessible in this regime?

A difficulty is that the interaction length of an electron in a strong wave field is about

$$l_{\text{int}} \approx \frac{\lambda_0}{\alpha \eta^2} \approx \frac{\lambda_0}{\alpha \Upsilon^2}, \quad \text{for optical fields and GeV electrons.}$$

Hence, for $\Upsilon \geq 12$, an electron will scatter in less than one wavelength, losing energy, and reducing its Υ value (and leading to an electromagnetic "shower"). [Beamstrahlung!]

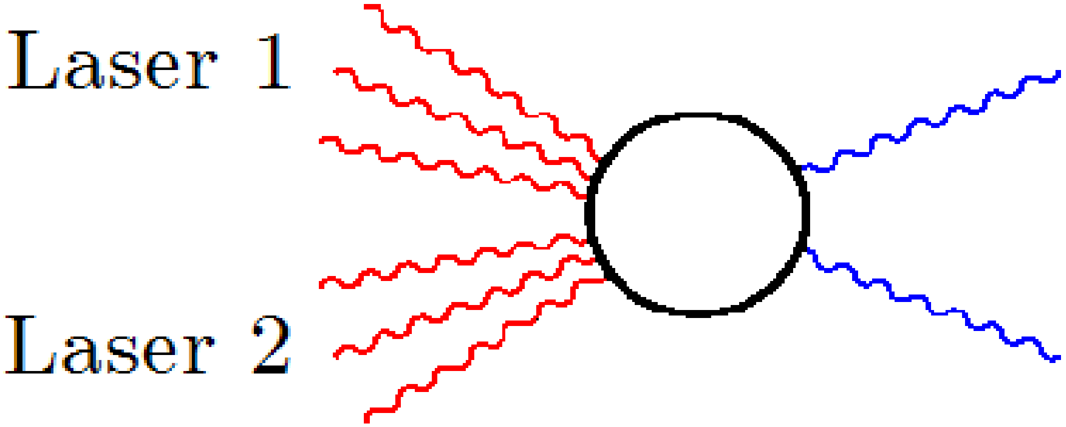
That is, high-energy electrons have low probability to reach a region of $\Upsilon \gg 1$, and the physics of the few unscattered electrons that reach such a region will have a huge background associated with the majority of electrons that scattered on the way in.

There is some interest in the details of the electromagnetic cascades of electron in strong wave fields.

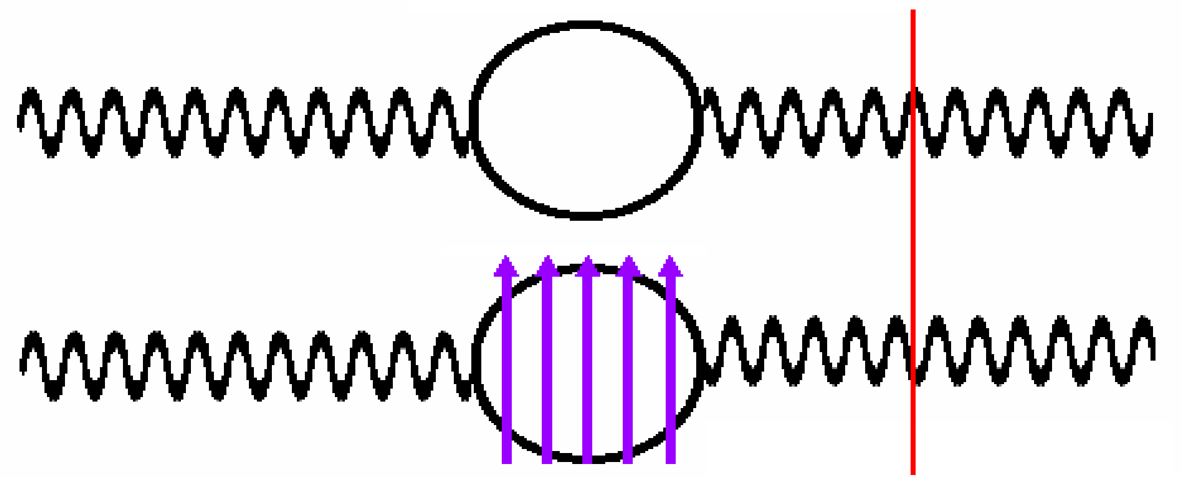
*P. Chen and R.B. Palmer, AIP Conf. Proc. **279**, 888 (1992)*
P. Chen and C. Pellegrini, QAPB, 1 (1998)

A fundamental limit to laser field strength: *AIP Conf. Proc. **130**, 23 (1985)*
$E_{\text{max}} \approx E_{\text{crit}} / \theta$ for a laser beam focused to angle θ, above which "sparking the vacuum".

Potential Effects in Plain Vacuum



Harmonic generation in vacuum in the collision of two strong laser beams

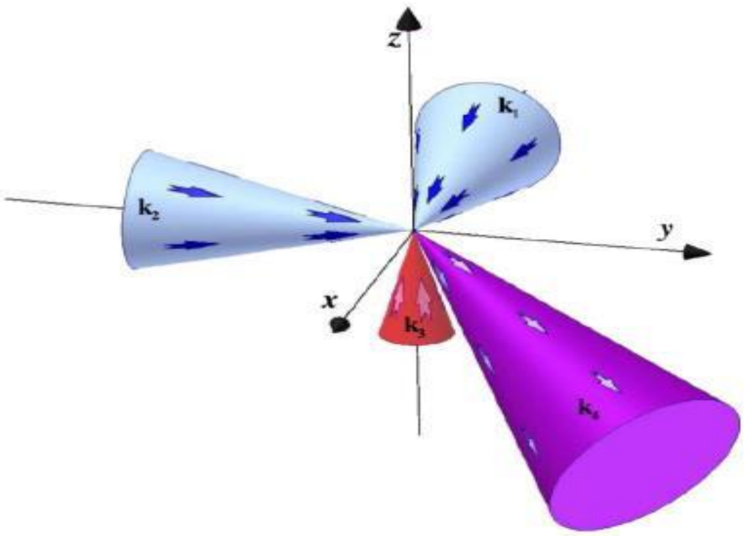


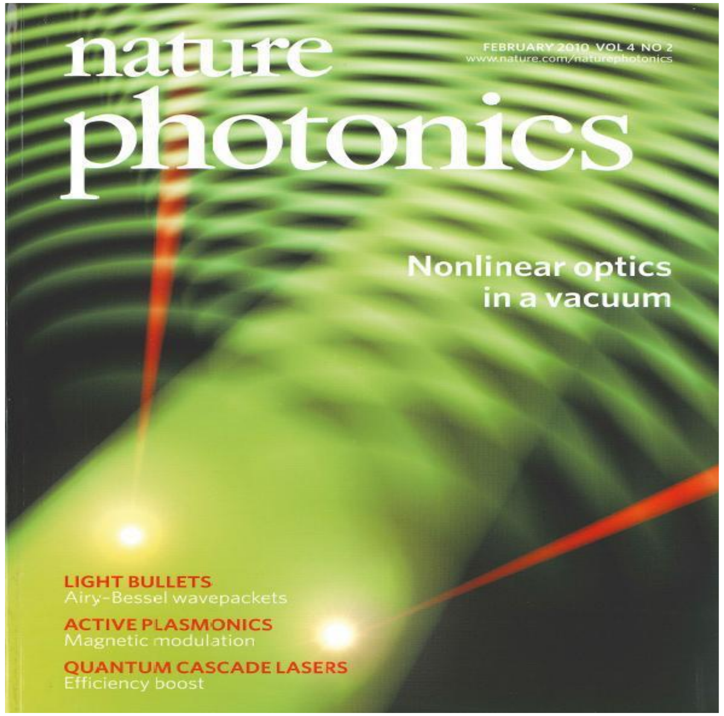
Vacuum refractive indices with phase shifts in the presence of a strong standing wave

Photon-Photon Scattering

- Electron-positron fluctuations can mediate a pure quantum interaction among laser beams in the vacuum in many ways
- Multi-PW laser systems may open the possibility of observing for the first time direct photon-photon scattering in vacuum
  - Three colliding laser pulses stimulate emission in a fourth direction with a new frequency

    Lundstroem et al., Phys. Rev. Lett. 2006





nature photonics

FEBRUARY 2010 VOL 4 NO 2
www.nature.com/naturephotonics

Nonlinear optics in a vacuum

LIGHT BULLETS
Airy–Bessel wavepackets

ACTIVE PLASMONICS
Magnetic modulation

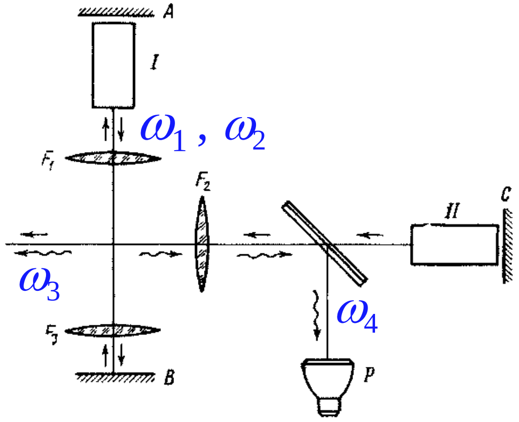
QUANTUM CASCADE LASERS
Efficiency boost

A matterless double-slit setup has been put forward

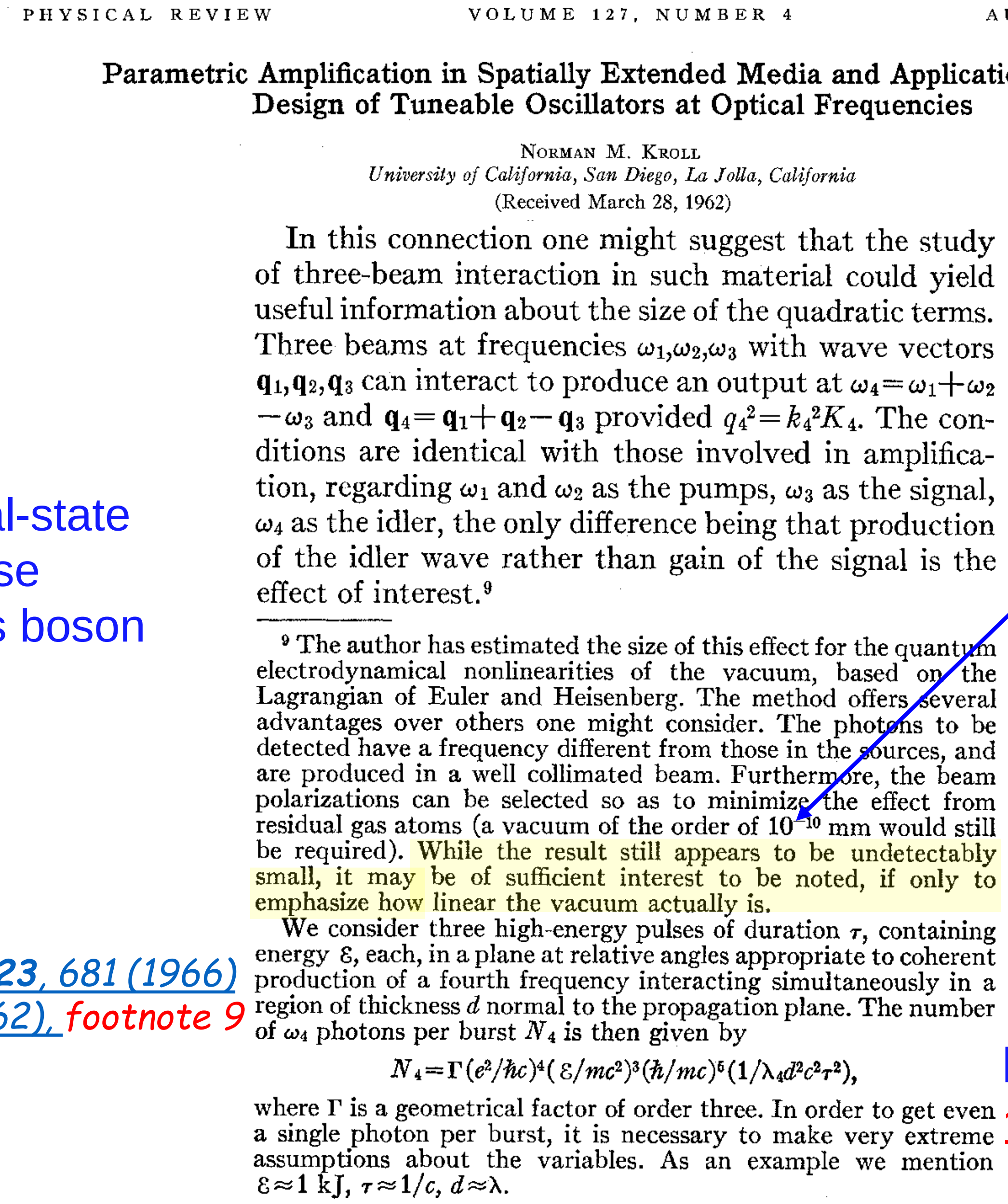
- Photons are created by virtual pair annihilation
  - After head-on collision of a probe laser field and two ultra-intense laser beams
- Form double-slit interference pattern
- Predicted to induce material-like behavior in vacuum
  - Support elastic scattering between photons

Ben King et al., Nature Photonics 2010

Induced Light-by-Light Scattering



$\omega_1 + \omega_2 \to \omega_3 + \omega_4$, where final-state photon ω_3 goes into an intense laser beam ⇒ amplitude gets boson enhancement.



PHYSICAL REVIEW VOLUME 127, NUMBER 4 AUGUST 15, 1962

Parametric Amplification in Spatially Extended Media and Application to the Design of Tuneable Oscillators at Optical Frequencies

NORMAN M. KROLL
University of California, San Diego, La Jolla, California

(Received March 28, 1962)

In this connection one might suggest that the study of three-beam interaction in such material could yield useful information about the size of the quadratic terms. Three beams at frequencies $\omega_1, \omega_2, \omega_3$ with wave vectors $\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3$ can interact to produce an output at $\omega_4 = \omega_1 + \omega_2 - \omega_3$ and $\mathbf{q}_4 = \mathbf{q}_1 + \mathbf{q}_2 - \mathbf{q}_3$ provided $q_4^2 = k_4^2 K_4$. The conditions are identical with those involved in amplification, regarding ω_1 and ω_2 as the pumps, ω_3 as the signal, ω_4 as the idler, the only difference being that production of the idler wave rather than gain of the signal is the effect of interest.[9]

---

[9] The author has estimated the size of this effect for the quantum electrodynamical nonlinearities of the vacuum, based on the Lagrangian of Euler and Heisenberg. The method offers several advantages over others one might consider. The photons to be detected have a frequency different from those in the sources, and are produced in a well collimated beam. Furthermore, the beam polarizations can be selected so as to minimize the effect from residual gas atoms (a vacuum of the order of 10^{-10} mm would still be required). While the result still appears to be undetectably small, it may be of sufficient interest to be noted, if only to emphasize how linear the vacuum actually is.

We consider three high-energy pulses of duration τ, containing energy $\mathcal{E}$, each, in a plane at relative angles appropriate to coherent production of a fourth frequency interacting simultaneously in a region of thickness d normal to the propagation plane. The number of ω_4 photons per burst N_4 is then given by

$$N_4 = \Gamma (e^2/\hbar c)^4 (\mathcal{E}/mc^2)^3 (\hbar/mc)^6 (1/\lambda_4 d^2 c^2 \tau^2),$$

where Γ is a geometrical factor of order three. In order to get even a single photon per burst, it is necessary to make very extreme assumptions about the variables. As an example we mention $\mathcal{E} \approx 1$ kJ, $\tau \approx 1/c$, $d \approx \lambda$.

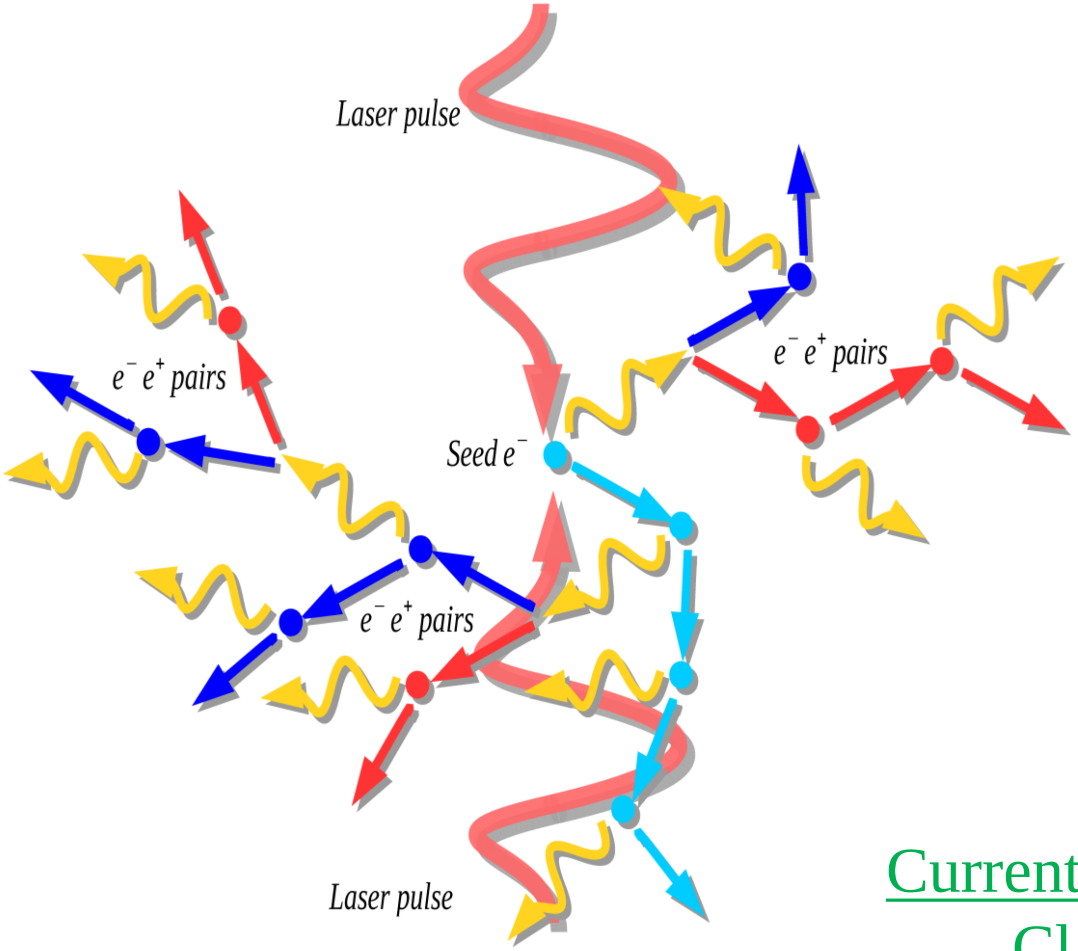
Vacuum should have less than 1 atom in the laser focal volume,
⇒ Separation of atoms
> 10 μm ⇒ < 10^{-9} mm.

[1] A. Varfolomeev, Sov. Phys. JETP ***23****, 681 (1966)*
[2] N. Kroll, Phys. Rev. ***127****, 1207 (1962), footnote 9*

$$\text{Rate} \approx 10^{-6} \frac{(\mathcal{E}[Joules])^3}{(\tau[psec])^2}$$

Extremely small, can reach
1 scatter per pulse if $\mathcal{E}$=10J, τ=30fs

Laser-Driven Seeded QED Cascades



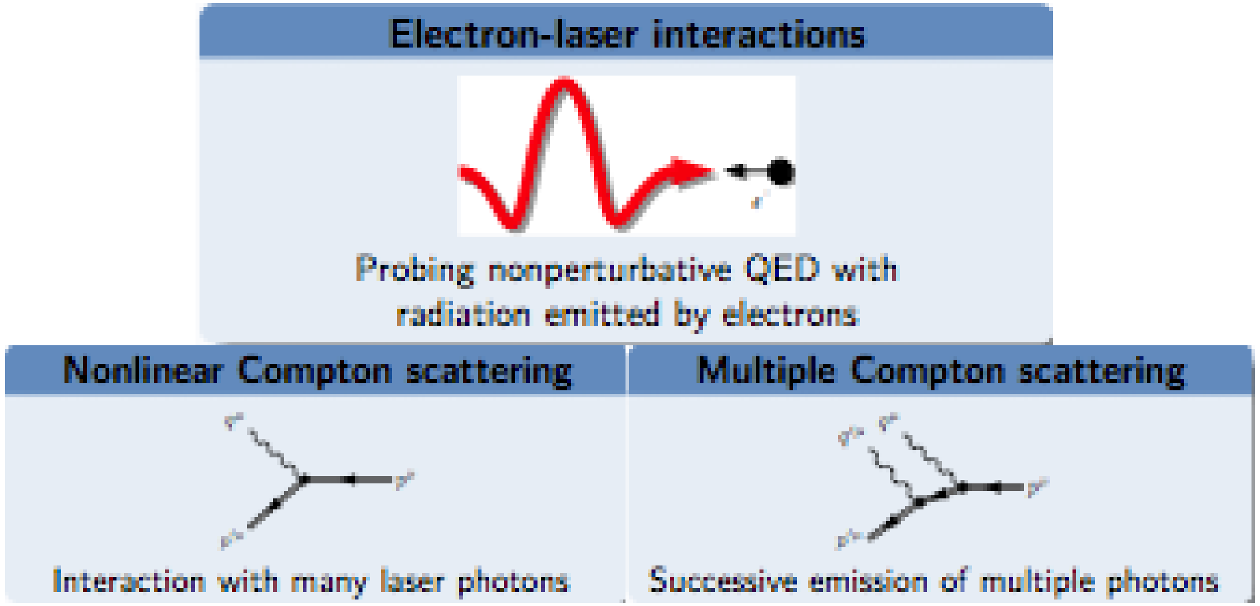
Semi-Classical Approach

- Seed electrons are violently accelerated by the laser fields, emit large numbers of hard (high-energy) photons, which in turn convert in e^+e^- pairs
- The generated e^+e^- pairs are then accelerated by the laser fields and initiate a new generation of particles
- QED cascades are predicted to be developed in collisions of two laser pulses each with an intensity 10^{24} W/cm^2 (*Bell PRL 2008, Kirk PPCF 2009, Bulanov PRL 2010, Nerush PRL 2011*).
- Exponential increase of particles
  - At a certain point, electron-positron plasma is produced

Current understanding: QED-PIC (Particle-in-Cell) approach: Classical propagation + QED process (Monte Carlo)

- Its validity has not been verified
  - Exponential increase of particles?
  - How is the laser field depleted?

Multiple Photon Emissions



Electron-laser interactions

Probing nonperturbative QED with radiation emitted by electrons

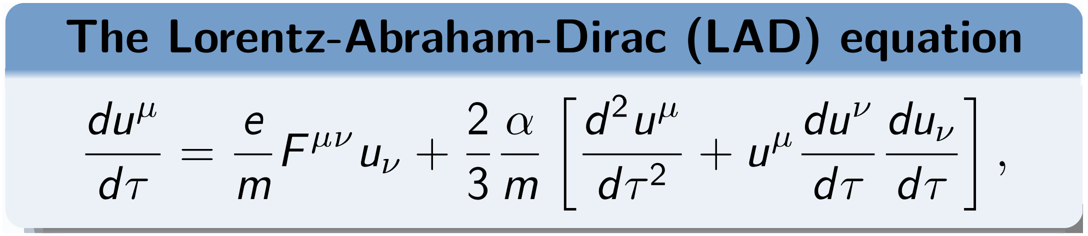
Nonlinear Compton scattering

Interaction with many laser photons

Multiple Compton scattering

Successive emission of multiple photons

- On average an electron emits ≈αη photons per laser cycle
  - If αηNσ1, perturbation theory of the radiation field breaks down → **never tested**
- Each emitted photon induces a large recoil if ϒ≳1
  - Emission processes become correlated → **quantum radiation reaction**
- Attempt to find a consistent solution within classical electrodynamics



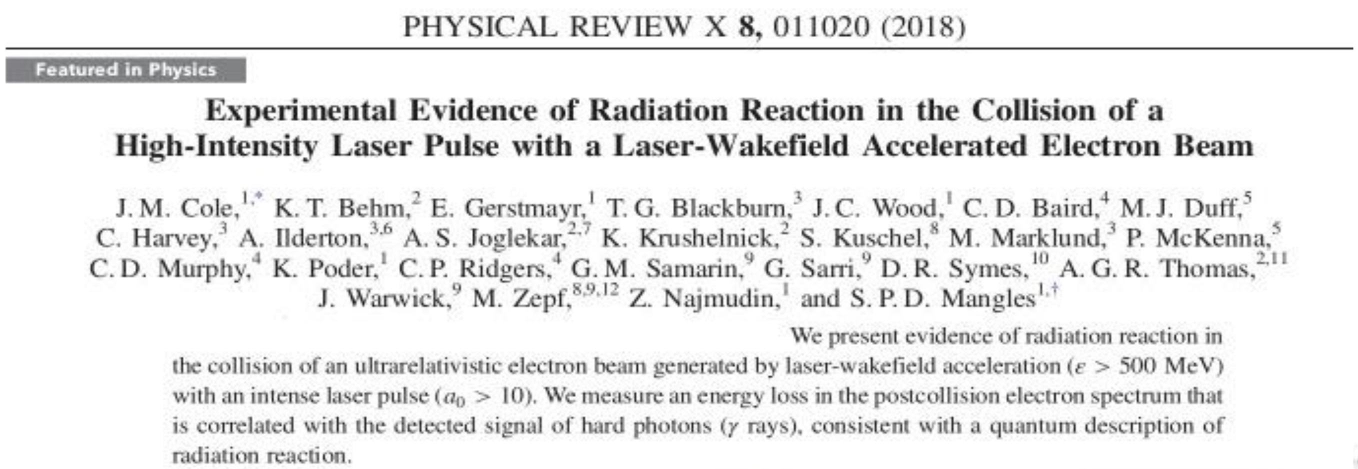
The Lorentz-Abraham-Dirac (LAD) equation

$$\frac{du^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} u_\nu + \frac{2}{3}\frac{\alpha}{m}\left[\frac{d^2 u^\mu}{d\tau^2} + u^\mu \frac{du^\nu}{d\tau}\frac{du_\nu}{d\tau}\right],$$

  - The LAD equation results in unphysical solutions
- **A fundamental question in physics not yet resolved!**

Even with moderate (≈200TW) laser field quantum effects can be studied

Quantum Radiation Reaction



PHYSICAL REVIEW X **8,** 011020 (2018)

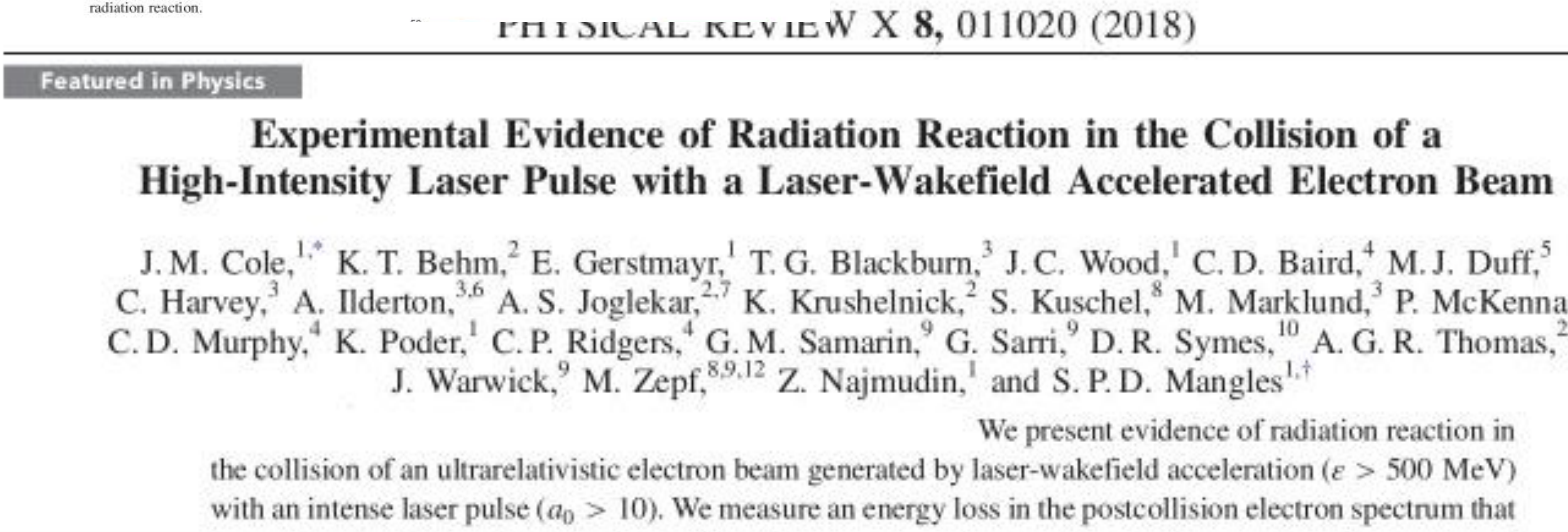
Featured in Physics

Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam

J. M. Cole,[1,*] K. T. Behm,[2] E. Gerstmayr,[1] T. G. Blackburn,[3] J. C. Wood,[1] C. D. Baird,[4] M. J. Duff,[5]
C. Harvey,[3] A. Ilderton,[3,6] A. S. Joglekar,[2,7] K. Krushelnick,[2] S. Kuschel,[8] M. Marklund,[3] P. McKenna,[5]
C. D. Murphy,[4] K. Poder,[1] C. P. Ridgers,[4] G. M. Samarin,[9] G. Sarri,[9] D. R. Symes,[10] A. G. R. Thomas,[2,11]
J. Warwick,[9] M. Zepf,[8,9,12] Z. Najmudin,[1] and S. P. D. Mangles[1,†]

We present evidence of radiation reaction in the collision of an ultrarelativistic electron beam generated by laser-wakefield acceleration ($\varepsilon > 500$ MeV) with an intense laser pulse ($a_0 > 10$). We measure an energy loss in the postcollision electron spectrum that is correlated with the detected signal of hard photons (γ rays), consistent with a quantum description of radiation reaction.

Recent all-optical Laser-Wakefield Accelerated Electrons



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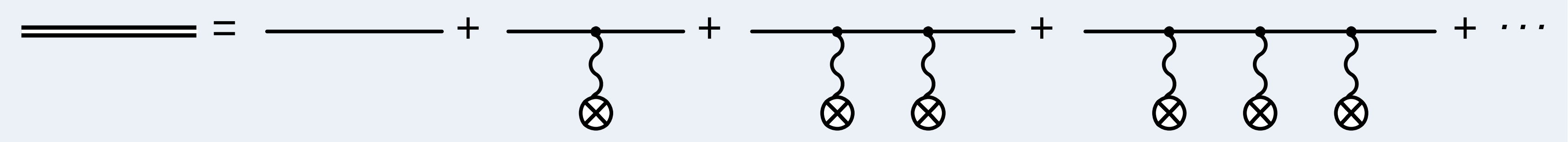
Fully Non-Perturbative QED Regime

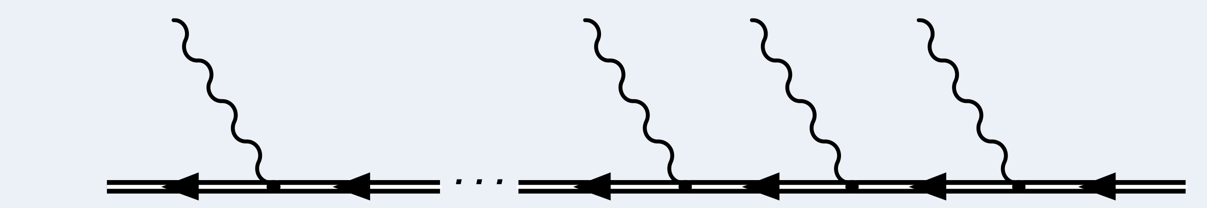
First breakdown of perturbation theory

$\eta\sigma1$: interaction with many laser photons are important:



Second breakdown of perturbation theory

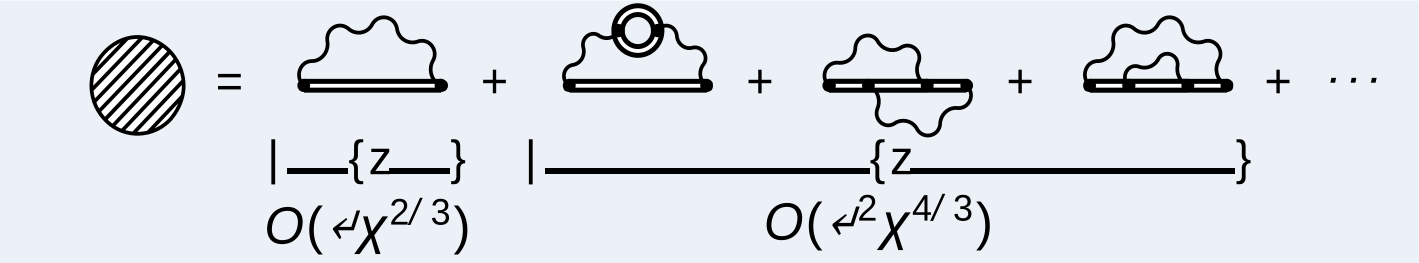
$\alpha\eta\sigma1$: processes with many radiation vertices are important:



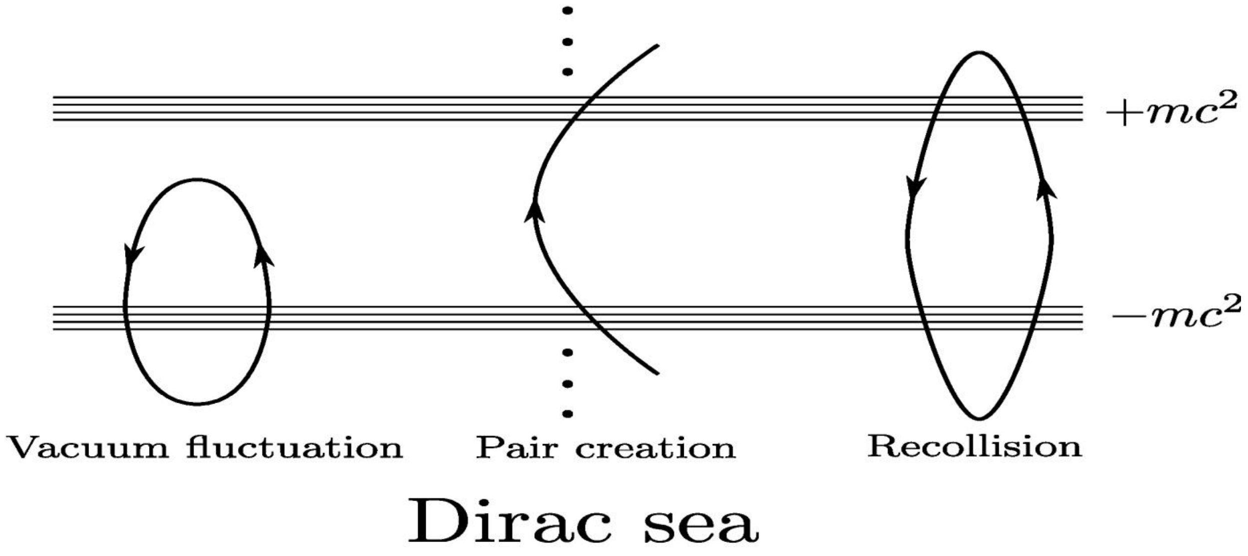
Full breakdown of perturbation theory

Higher order loop corrections are important if $\alpha\eta^{2/3}\sigma1$:

- QED becomes fully non-perturbative (like QCD?)
- So far theoretical calculations are impossible



Recollisions of Laser-Generated e^+e^- Pairs

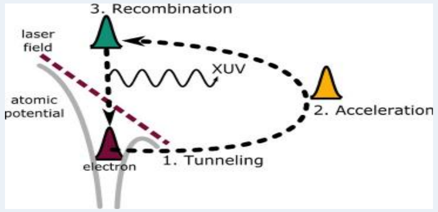


Semi-classical three-step process

1) Pair creation, 2) Acceleration by laser field, 3) Recollision

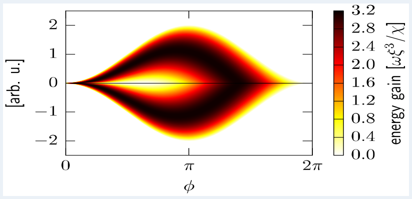
(S. Meuren et al., PRL 114, 143201 (2015))

Atomic physics



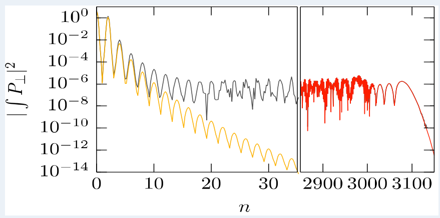
Recollision processes in atoms after tunnel ionization

Strong-field QED



Recollision processes of electron-positron pairs

Polarization operator spectrum



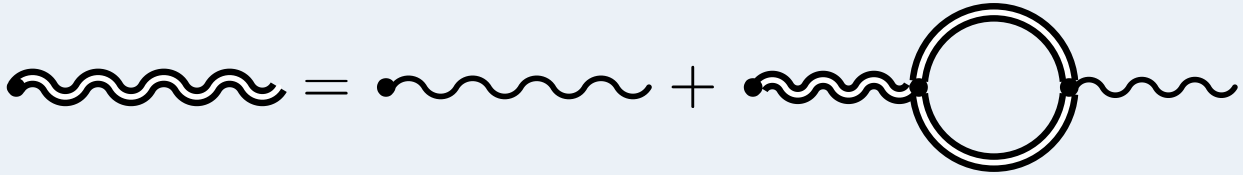
Recollisions lead to plateau region

Vacuum Birefrigence

A strong laser field behaves like a birefringent medium:

- The polarization of a probe photon changes inside the strong field
- Probe photon can be from an x-ray photon beam

Exact photon wave function

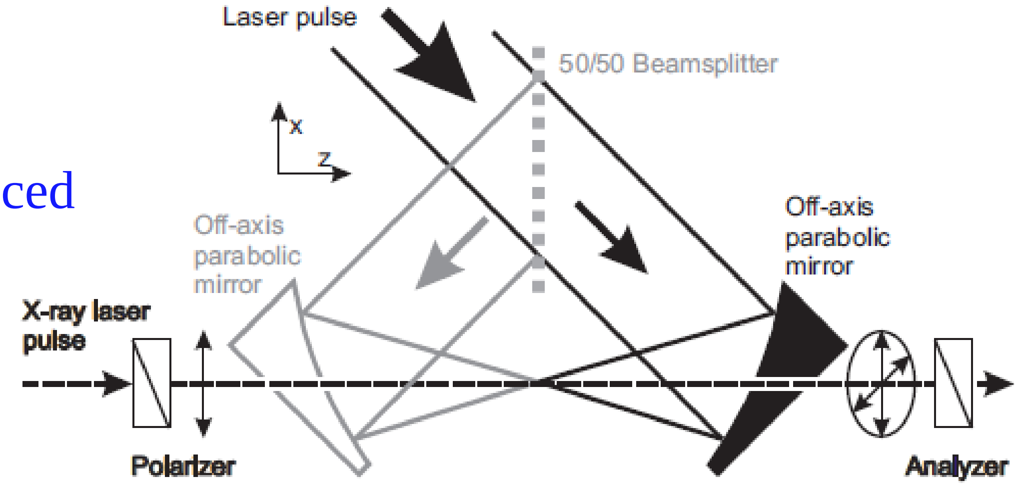


$$\Phi^{\mathrm{in}\,\mu}_{q,j}(x) = \epsilon^{\mu}_{j} \exp\left[- \mathrm{i}qx - \mathrm{i}\frac{1}{2kq}\int_{-\infty}^{kx} d\phi'\, \mathfrak{p}_j(\phi') \right]$$

- The laser pulse induces the phase shift $\delta\Phi \sim \alpha\Upsilon\eta N$ if $\Upsilon \ll 1$
- Limit in the range of $\Upsilon \lesssim 0.1$ to avoid real pair production
- Using very long laser pulses a significant phase shift could be induced
  - Diffraction effects may decrease the overall effect

Heinzl et al., Opt. Commun. (2006)

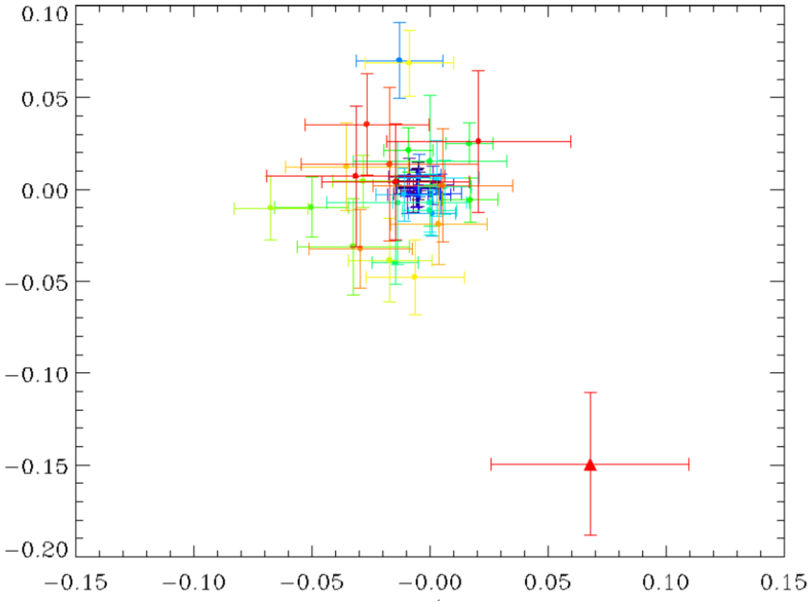
(S. Meuren et al., PRD 91, 013009 (2015))

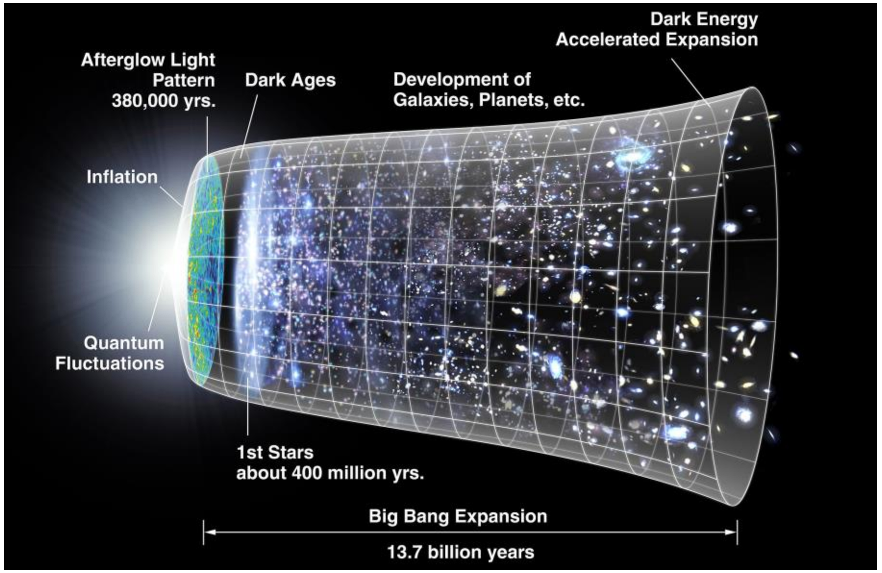


Cosmology & Astrophysics

Hints of vacuum birefringence in optical polarimetry of neutron stars

R. P. Mignani et al. MNRAS, 465, 2017.



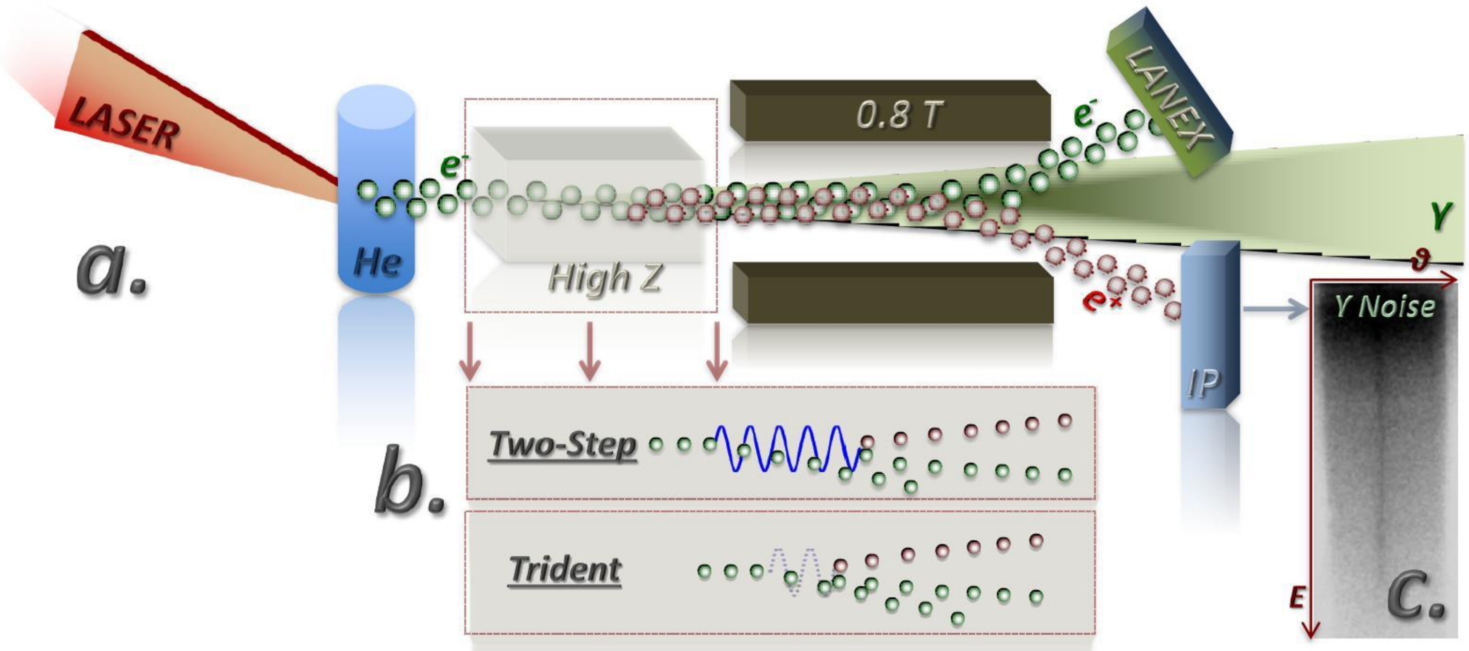


Emission of coherent radio waves in pulsars/ x rays in magnetars, gamma ray bursts…

Electron-photon decoupling primordial nucleosynthesis

Schwinger fields existed 100s after the Big Bang, when T~10^{10}K

Laboratory Astrophysics: Generation of Electron-Positron Pair Plasmas



- 30fs positron jets recorded
- Scaling with charge number Z
- Consistent with two-step process
  - Brem + Bethe-Heitler

- Emitted as collimated jets by energetic objects in the Universe
  - Black holes, pulsars, quasars
- These plasmas play a fundamental role in the dynamics of ultra-massive astrophysical objects
  - Strongly believed to be associated with the emission of ultra-bright gamma-ray bursts
- Poorly understood despite extensive theoretical modelling
  - Primarily due to difficulty in creating matter-antimatter plasmas in the laboratory
- Non-linear processes present in strong-field environments could allow for table-top experiments

Laboratory Astrophysics

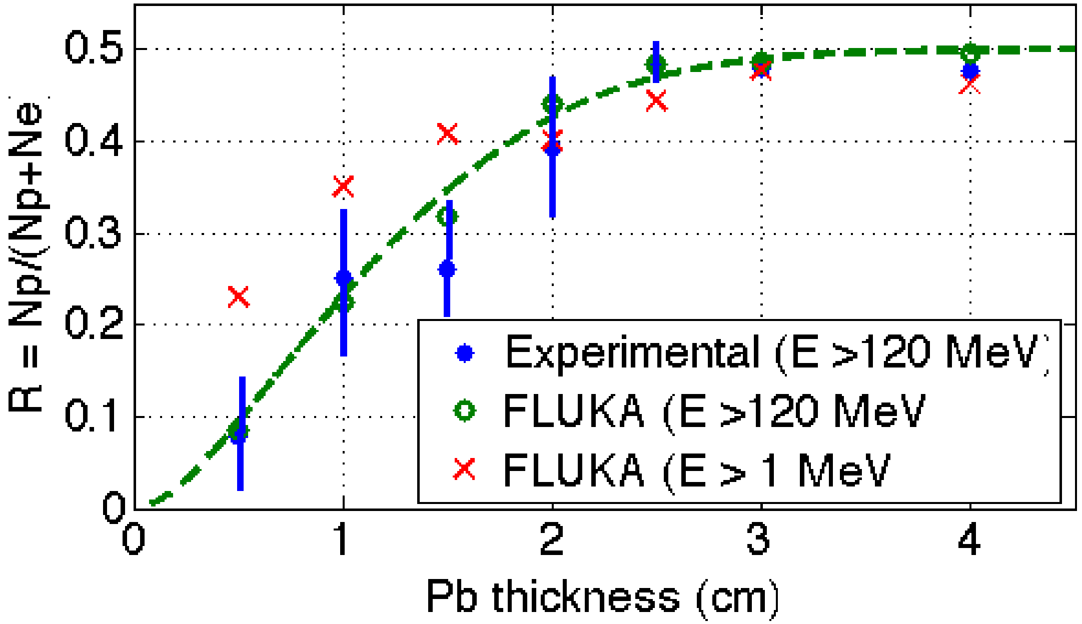
An ultrashort (30fs), ultra-collimated (3mrad)
high energy (E_{MAX} = 150 MeV) positron beam generated.
Overall positron yield: 3×10^{7}
Overall lepton yield: 3×10^{8}
Positron density: 2×10^{14} cm^{-3}
Lepton density: 2×10^{15} cm^{-3}
Intensity: 10^{19} erg s^{-1} cm

Parameters not as in astrophysical jets but with scaling results may become relevant

Gamma ray bursts, black holes

artist's view – quarkmag.com

Follow-up experiment in Astra-Gemini produced neutral electron-positron beam, *G. Sarri et al., Nat. Comm. (2015)*

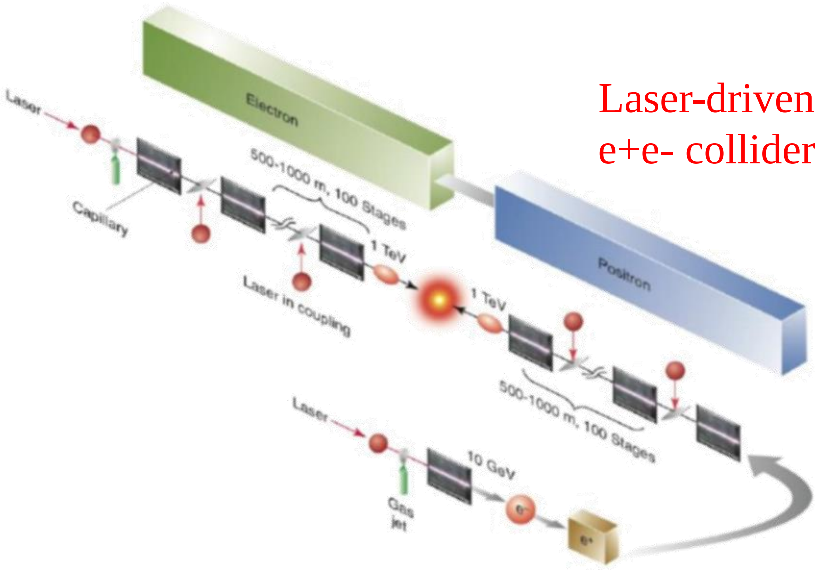


Generation of electron-positron jets with variable % of positrons from 0-50%

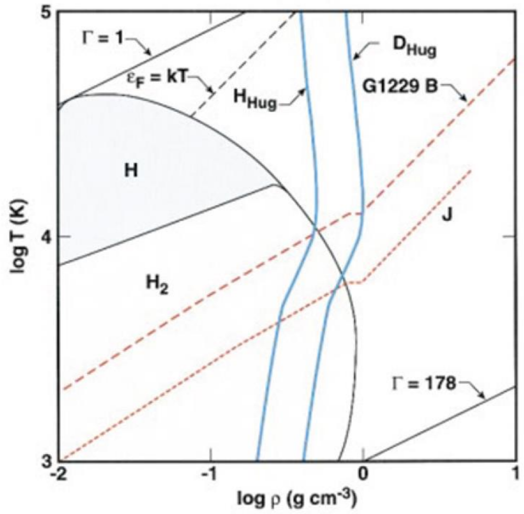
Plasma dynamics much more appropriate and comparable to that observed in astrophysical jets

Many Science Opportunities

- Intensity roadmap to scientific discovery
- Attosecond science
- High energy density science
- Planetary physics
- Laser-driven particle acceleration
- Laser-driven neutron, proton, and positron sources
- Nuclear physics
- Schwinger physics and the ultimate intensity
- Beyond the standard model



Laser-driven e+e- collider



Phase diagram for hydrogen relevant to Jupiter

High-Intensity/Strong-Field Science opportunities have been recognized in previous reports

- Developed largely in the US in the 20th century
- Emerging European and Asian dominance in the 21st century
- Continuing need for laser technology
- Commercial involvement
- Workforce development

Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

FRONTIERS IN High Energy Density Physics

THE X-GAMES OF CONTEMPORARY SCIENCE

NATIONAL RES

THE SCIENCE AND APPLICATIONS OF ULTRAFAST, ULTRAINTENSE LASERS:

Opportunities in science and technology using the brightest light known to man

A report on the SAUUL workshop held, June

REPORT OF THE INTERAGENCY TASK FORCE ON HIGH ENERGY DENSITY PHYSICS

National Science and Technology Council

Committee on Science

Interagency Working Group on the Physics of the Universe

AUGUST 2007

HEARKEN TO THE MISERIES THAT BESET MANKIND. THEY WERE WITLESS ERST AND I MADE THEM TO HAVE SENSE AND BE ENDOWED WITH REASON. THOVGH THEY HAD EYES TO SEE THEY SAW IN VAIN: THEY HAD EARS BVT HEARD NOT. BVT, LIKE TO SHAPES IN DREAMS, THROVGHOVT THEIR LENGTH OF DAYS WITHOVT PVRPOSE THEY WROVGHT ALL THINGS IN CONFVSION:–THEY HAD NO SIGN EITHER OF WINTER OR OF FLOWERY SPRING OR OF FRVITFVL SVMMER, WHEREON THEY COVLD DEPEND, BVT IN EVERYTHING THEY WROVGHT WITHOVT IVDGMENT, VNTIL SVCH TIME AS I TAVGHT THEM TO DISCERN THE RISINGS OF THE STARS AND THEIR SETTINGS. AYE, AND NVMBERS, TOO, CHIEFEST OF SCIENCES.

Opportunities in Intense Ultrafast Lasers; Reaching for the Brightest Light

U.S. National Academy of Sciences, December 2017

http://nap.edu/24939

The study is supported by funding from the DOE Office of Science, NNSA, ONR, and AFOSR.

1st International Strong-Field QED Workshop

Probing strong-field QED in electron-photon interactions

21-23 August 2018

DESY, Hamburg

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

GORDON AND BETTY MOORE FOUNDATION

Stanford PULSE Institute

Link: https://indico.desy.de/indico/event/19493/overview

A report is in preparation to provide input for the European Strategy deliberations

The E-144 Collaboration

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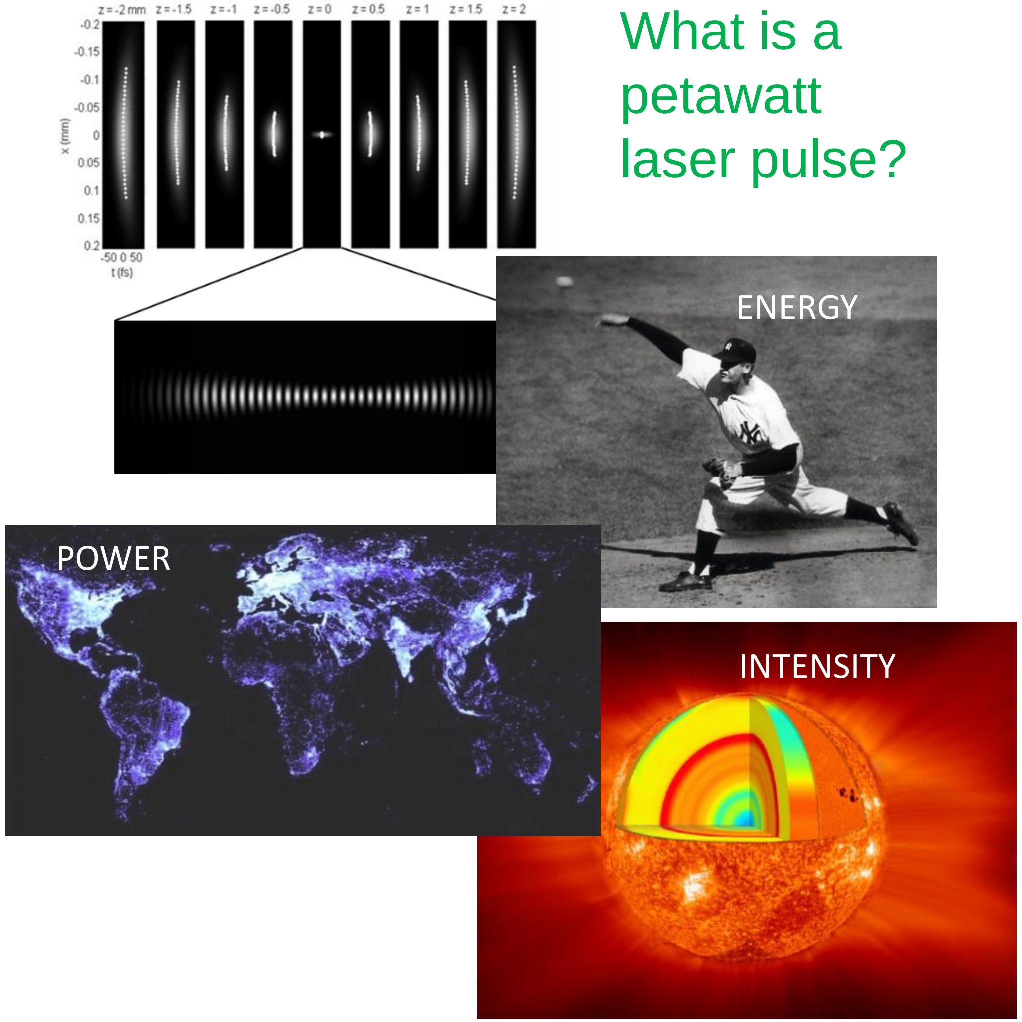
Bonus Slides

What's one Petawatt, after all?

- 100 J in 100 fs, at λ=800 nm, focused to 10μm
- The total **energy**, 100 Joules, is about the kinetic energy of a pitched baseball, or a kicked soccer football.
- The peak **power** is nearly 100x the world’s power consumption rate.
- The focused **intensity** is ten trillion trillion W/m^2, greater than the center of the sun. The rms electric field is 100 trillion trillion V/m.

What is a petawatt laser pulse?



First PW laser at LLNL used Nd:glass, large gratings

1.5 PW (1998)
660 J in 440 ps

M. D. Perry, D. Pennington, B. C. Stuart, G. Tietbohl, J. A. Britten, C. Brown, S. Herman, B. Golick, M. Kartz, J. Miller, H. T. Powell, M. Vergino, and V. Yanovsky, "Petawatt laser pulses," Opt. Lett. 24, 160 (1999).

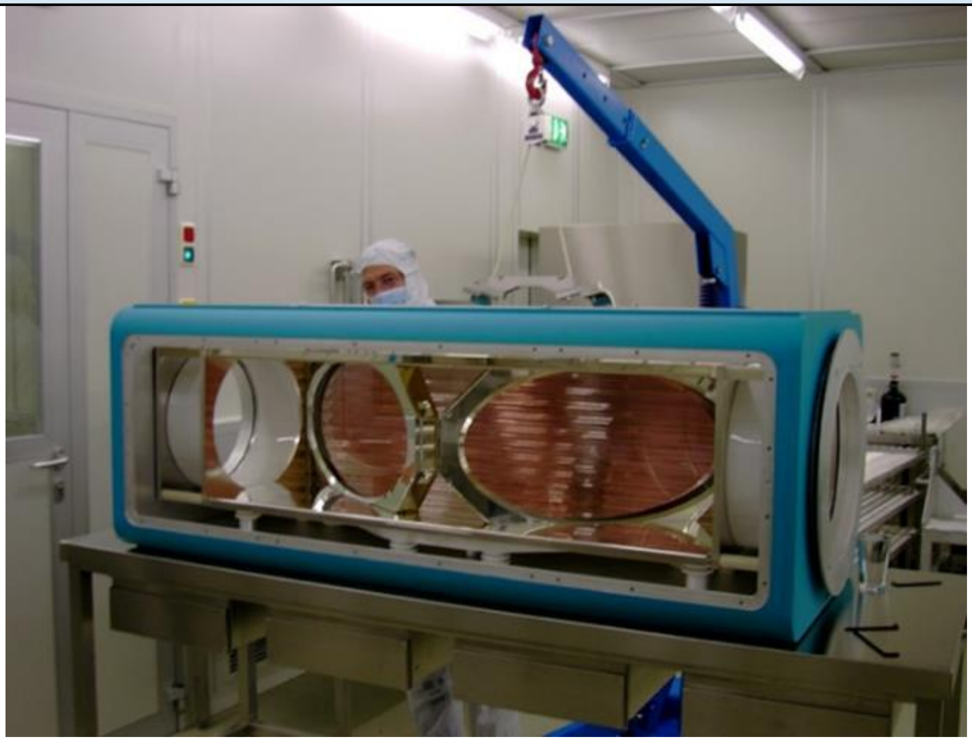
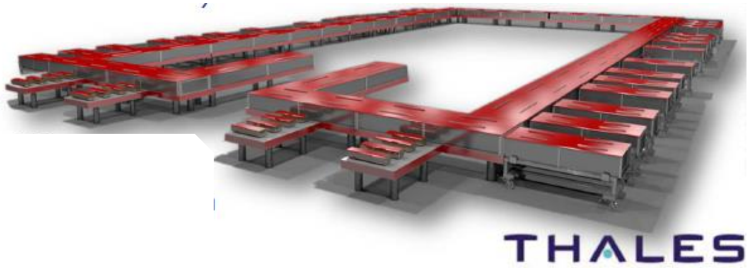


Figure 1. With the Petawatt laser in the background, Livermore's Michael Perry (left) shows how far the technology has come to UC Berkeley Professor Charles Townes, who co-invented the laser.

New technologies have enabled shorter pulses

- **Ti:sapphire**
  - Pumped by another laser, typically with 10-20-ns pulses
  - Large gain bandwidth allows amplification of 20-30-fs pulses
  - Much better thermal properties than Nd:glass allows higher pulse rates
  - Can combine energy from multiple pump lasers for scaling

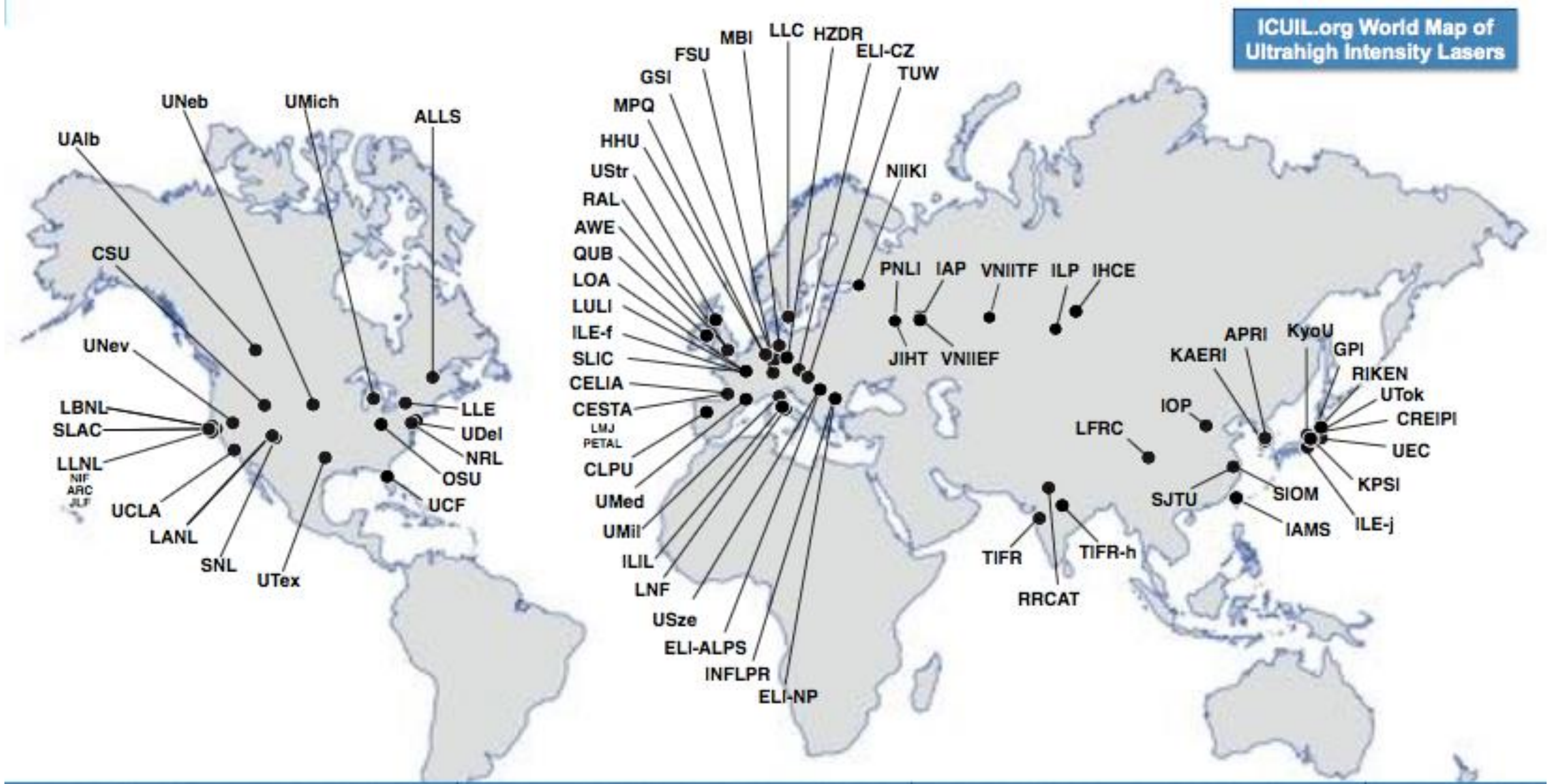


- **OPCPA (Optical Chirped Pulse Parametric Amplifier)**
  - Not a laser, a nonlinear optical device
  - Pumped by another laser, typically with ns-duration pulses and good beam quality
  - To date, 30-70 fs pulses for PW-class sources, lower conversion than Ti:sapphire

The possible future

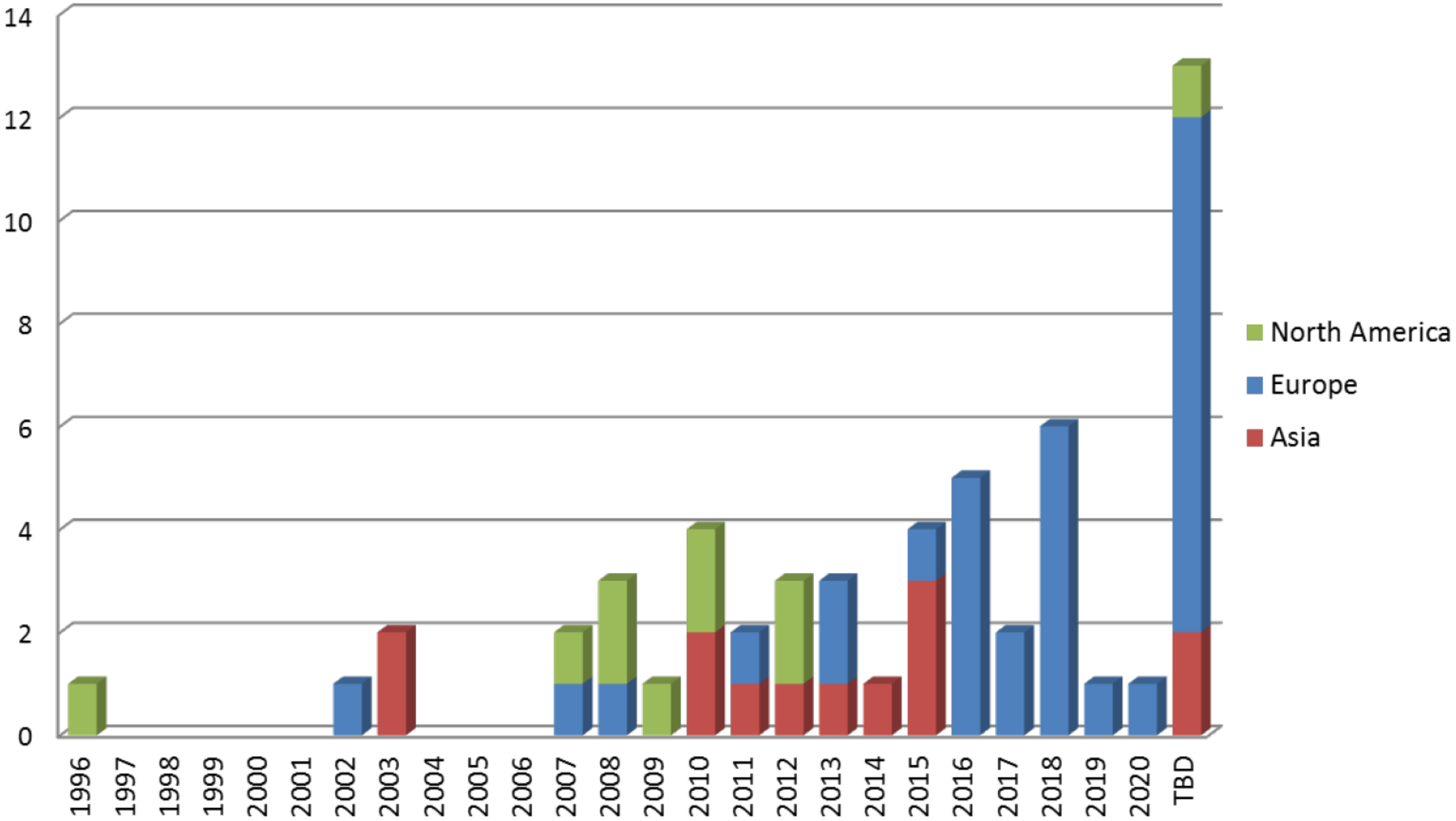
- Higher-pulse rate, PW-class, conventional sources
  - Flashlamps replaced by diode lasers
  - Allow optimized focusing from active feedback, improved productivity and statistics in experimental work
- Directly diode-pumped amplifiers, for higher pulse rates, efficiency
  - Yb-doped, broad-bandwidth media, optimized for efficiency
  - Green-diode-pumped Ti:sapphire
- Beam-combined fiber lasers
  - Substantial challenges in scaling to PW class
- Shorter-pulse OPCPA systems
  - Spectral combination to produce 1-fs-duration pulses
- X-ray Free-Electron Lasers (FELs)
  - Present cost an obstacle

Active international competition; greatest concentration in Europe; rapid growth in China



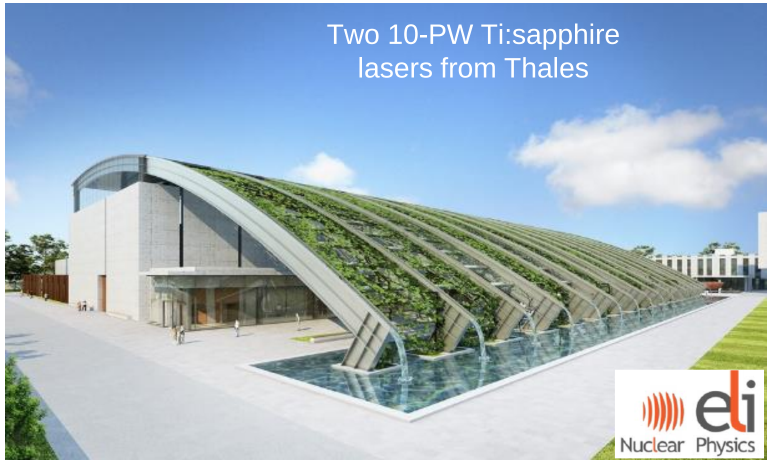
- The pursuit of ultrahigh intensity laser science & applications is now a world wide activity
- Capabilities have evolved beyond the single PI scale to that of international user facilities
- Ultrahigh intensity laser projects now total more than $4B and involve > 1500 FTE's

Dates PW systems come on line: Europe & Asia will dominate



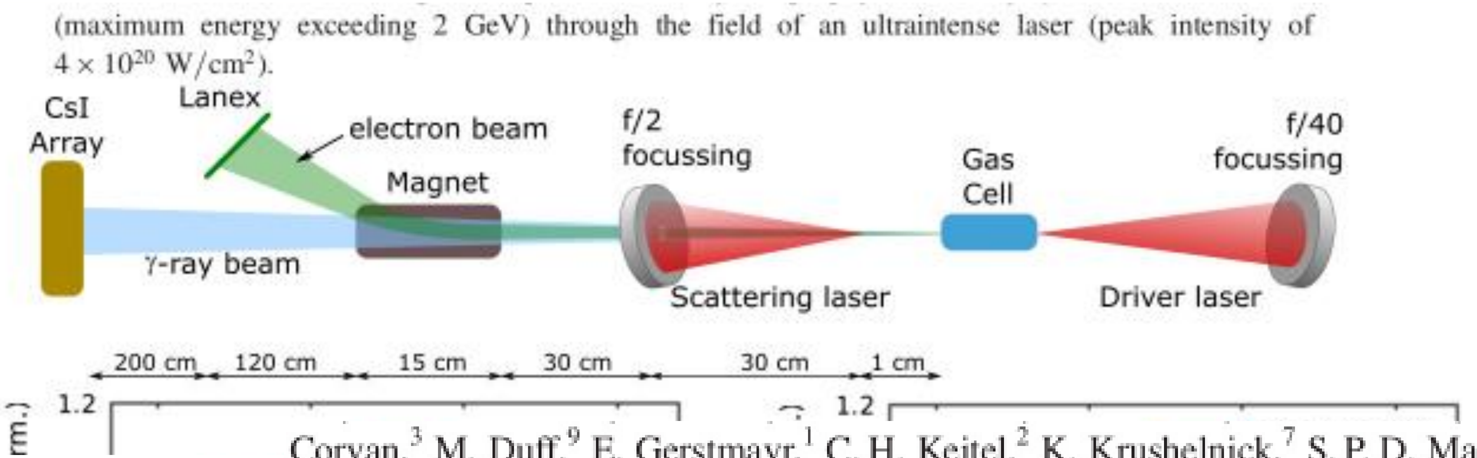
ELI Facilities built or under construction

2 key lasers from US,
Ti:sapphire (LLNL)
and
Nd:glass (National Energetics)

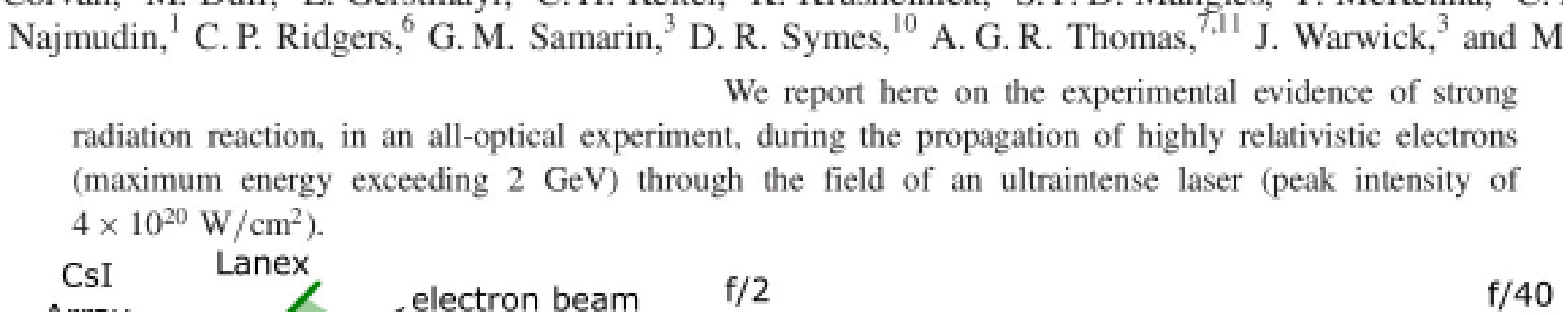

Two 10-PW Ti:sapphire
lasers from Thales


Assorted lasers from EU

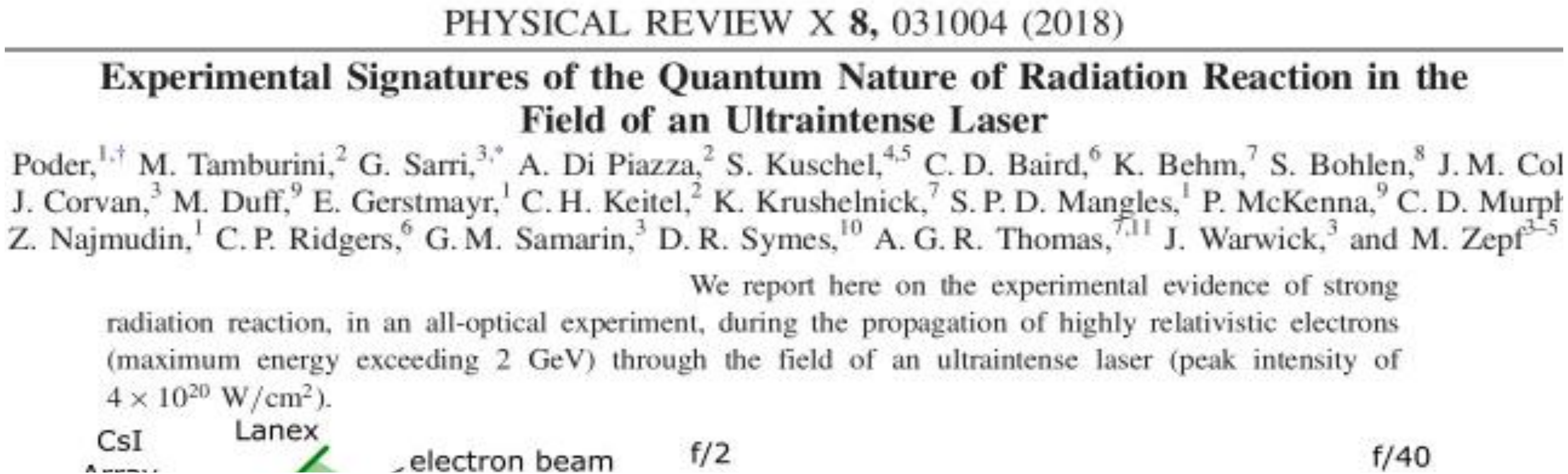
Quantum Radiation Reaction


(maximum energy exceeding 2 GeV) through the field of an ultraintense laser (peak intensity of 4×10^{20} W/cm^2).

Recent all-optical Laser-Wakefield Accelerated Electrons


Corvan,[3] M. Duff,[9] E. Gerstmayr,[1] C. H. Keitel,[2] K. Krushelnick,[7] S. P. D. Mangles,[1] P. McKenna,[9] C.
Najmudin,[1] C. P. Ridgers,[6] G. M. Samarin,[3] D. R. Symes,[10] A. G. R. Thomas,[7,11] J. Warwick,[3] and M

We report here on the experimental evidence of strong radiation reaction, in an all-optical experiment, during the propagation of highly relativistic electrons (maximum energy exceeding 2 GeV) through the field of an ultraintense laser (peak intensity of 4×10^{20} W/cm^2).


PHYSICAL REVIEW X **8,** 031004 (2018)

Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser

Poder,[1,†] M. Tamburini,[2] G. Sarri,[3,*] A. Di Piazza,[2] S. Kuschel,[4,5] C. D. Baird,[6] K. Behm,[7] S. Bohlen,[8] J. M. Col
J. Corvan,[3] M. Duff,[9] E. Gerstmayr,[1] C. H. Keitel,[2] K. Krushelnick,[7] S. P. D. Mangles,[1] P. McKenna,[9] C. D. Murph
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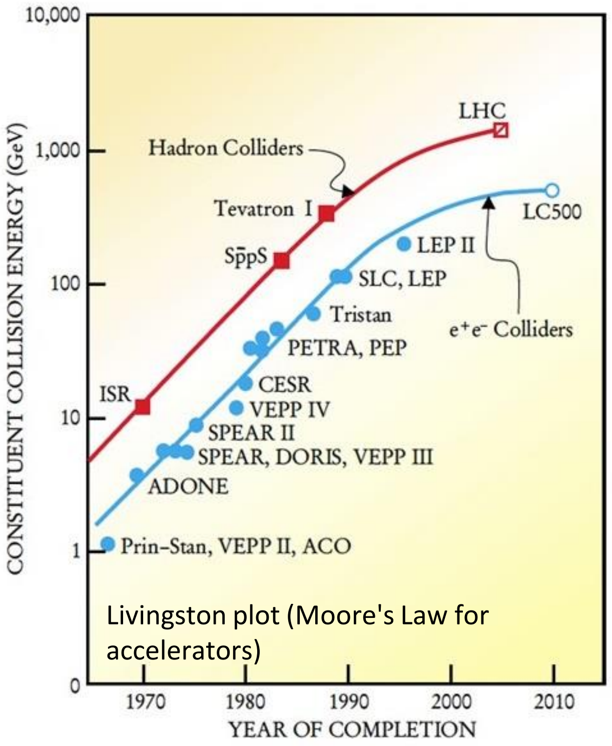
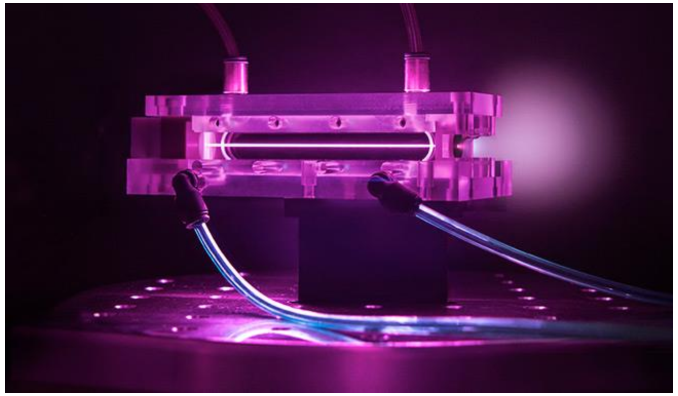
PetaWatt Laser-driven Acccelerators

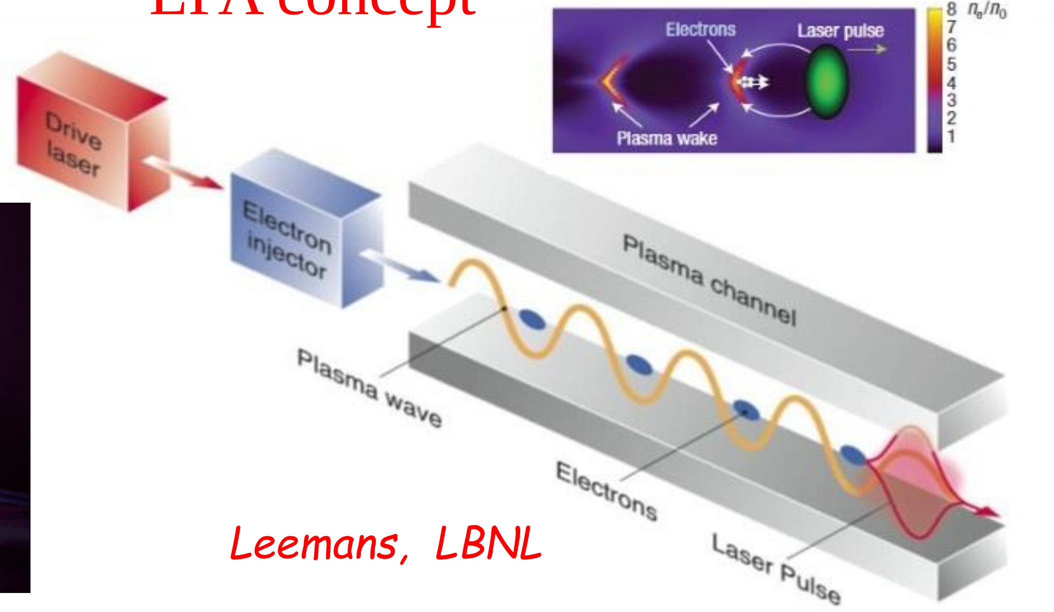


Livingston plot (Moore's Law for accelerators)

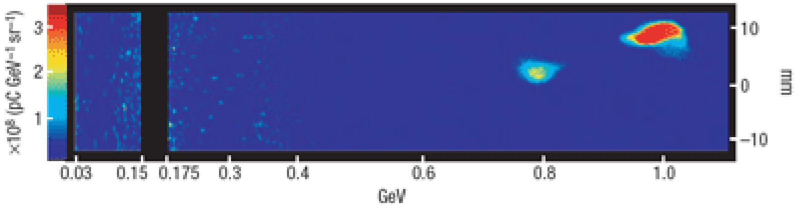


BELLA 9cm plasma accelerator channel

LPA concept



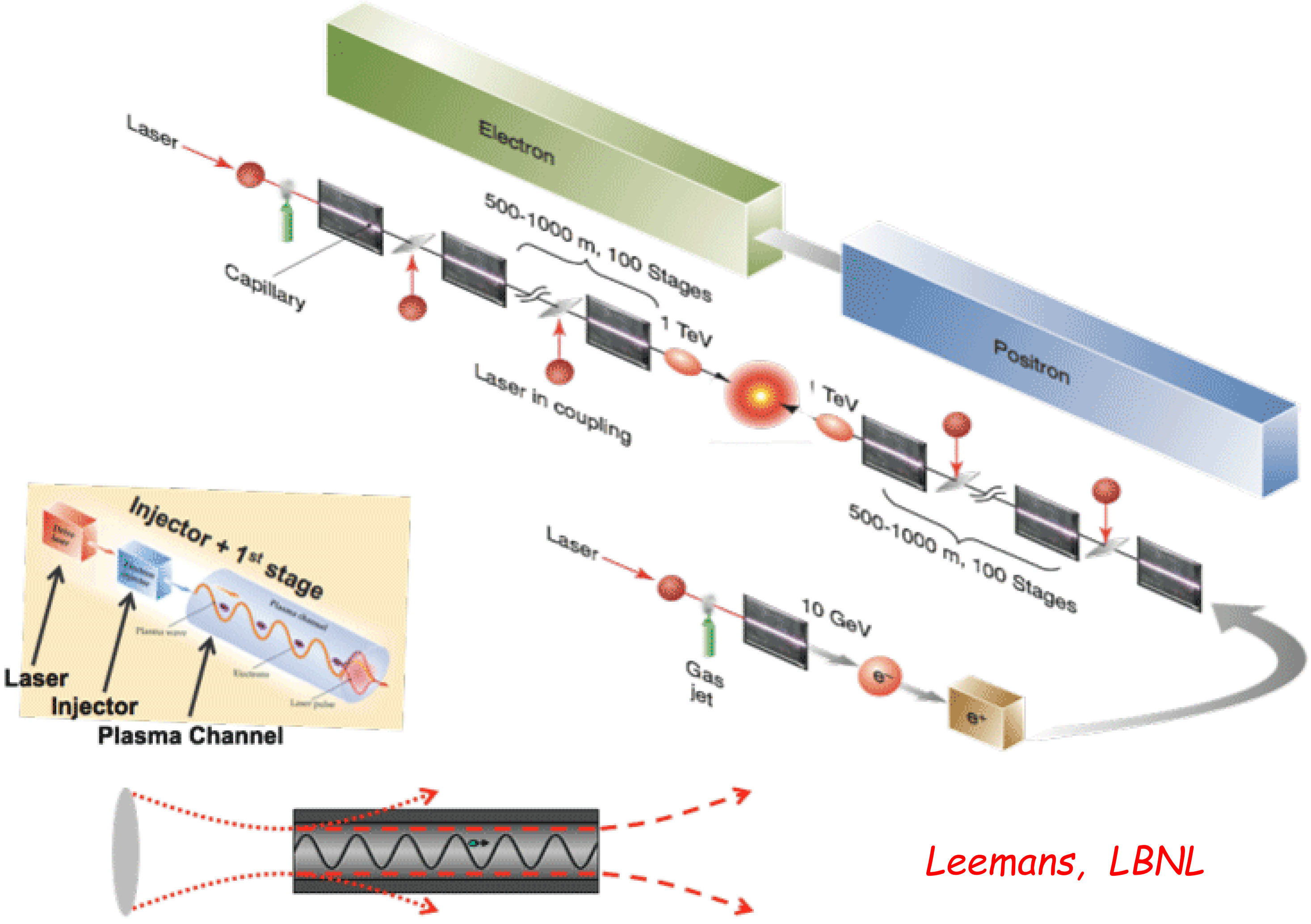
Leemans, LBNL



Magnetic spectrometer data showing the production of high quality electron beam at 1 GeV from a 3 cm plasma structure

- At $I \approx 10^{22} W/m^2$ laser pulses propagate through a plasma
- Generate longitudinal plasma wave which trails the laser pulse
    - Similar to a wake that follows a boat travelling across water.
- In a plasma wave $\mathcal{E} \approx 100\ kV/\mu m$
    - ×1000 the accelerating fields used in the LHC at CERN.
- **Could result in first table-top particle collider!**

A TeV collider would use a lot of lasers…



Leemans, LBNL

Intense Beam Therapies

Petawatt lasers can produce intense 10-100 MeV proton beams for tumor therapy

Target Normal Sheath Acceleration is a mechanism for high intensity pulsed beams.

Target Normal Sheath Acceleration