QUANTUM ELECTRODYNAMICS IN EXTREME LASER FIELDS

TOM HEINZL
EMMI X-RAYS 2010, GSI

08 JUNE 2010

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A significant birthday…

Laser 50

physicsworld

physicsworld.com

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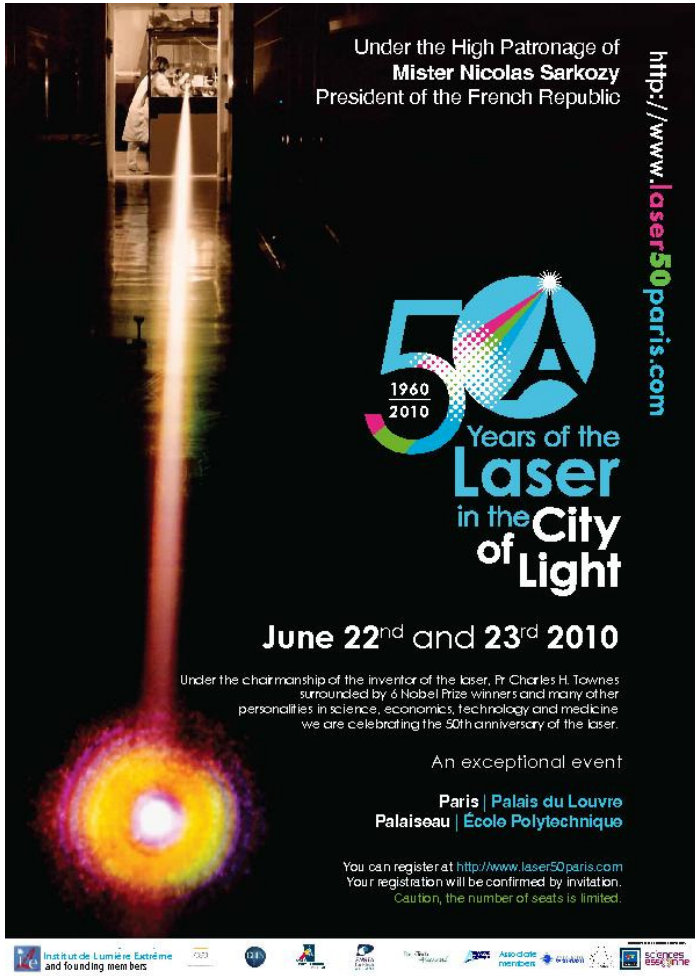
THE LASER AT 50



Under the High Patronage of
Mister Nicolas Sarkozy
President of the French Republic

http://www.laser50paris.com

50 Years of the Laser in the City of Light

June 22nd and 23rd 2010

Under the chairmanship of the inventor of the laser, Pr Charles H. Townes
surrounded by 6 Nobel Prize winners and many other
personalities in science, economics, technology and medicine
we are celebrating the 50th anniversary of the laser.

An exceptional event

Paris | Palais du Louvre
Palaiseau | École Polytechnique

You can register at http://www.laser50paris.com
Your registration will be confirmed by invitation.
Caution, the number of seats is limited.

Institut de Lumière Extrême
and founding members

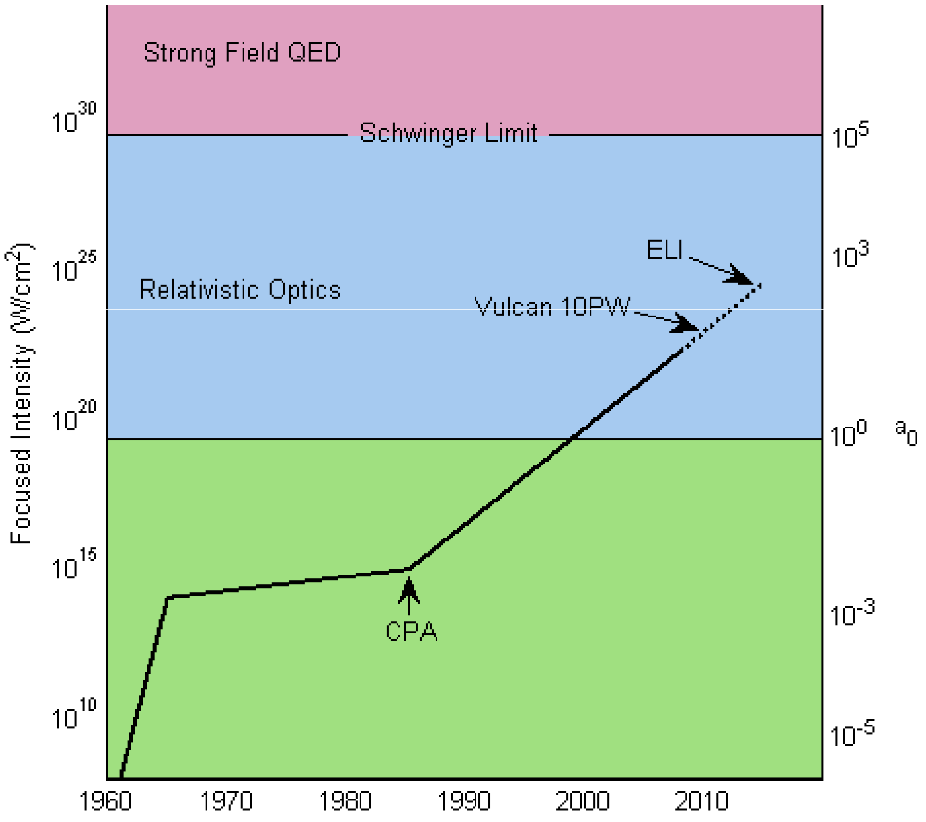
Associate members

sciences essonne

Outline

Introduction

50 Years of Laser Development



(adapted from Mourou, Tajima, Bulanov, RMP **78**, 2006)

- Important parameter: dim.less amplitude

$$a_0 \equiv \frac{eE\lambda\!\!\!^{-}}{mc^2} \sim I^{1/2}$$

- Energy gain of e^- across laser wavelength
- $a_0 \gtrsim 1$: e^- relativistic

Chirped Pulse Amplification (CPA)

- Problems @ ultra-high intensities:

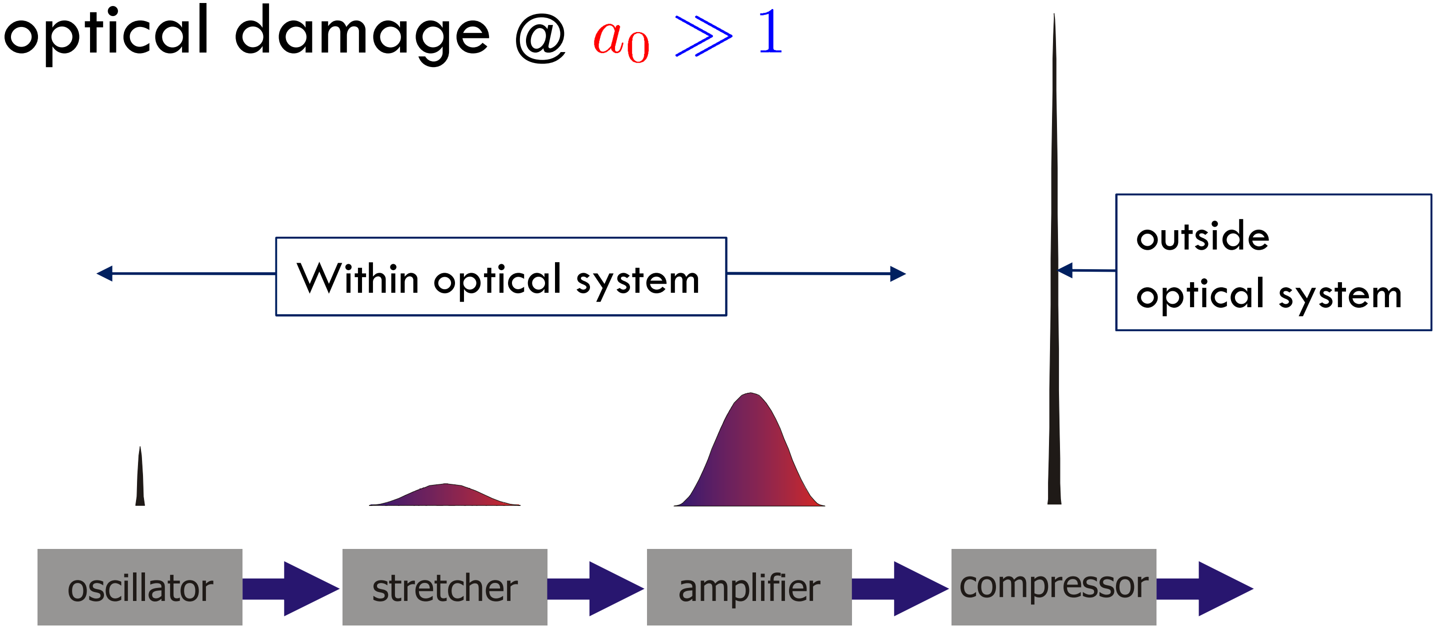
- Beam quality
  - Intensity dependent refractive index: phase delays
  - Self-focussing of beam
  - Beam collapse into beamlets (‘filamentation’)

- Most severe: optical damage to mirrors and lenses

Chirped Pulse Amplification (CPA)

Problem: optical damage @ $a_0 \gg 1$

Solution:



Within optical system

outside optical system

oscillator

stretcher

amplifier

compressor

pulse duration	10 fs	×20000	200 ps		200 ps	/10000	20 fs
energy	1nJ		1nJ	$\times 10^9$	1..10 J		few J
contrast							10^{10}

Courtesy R. Sauerbrey

Strong Fields

Regime of Extremes

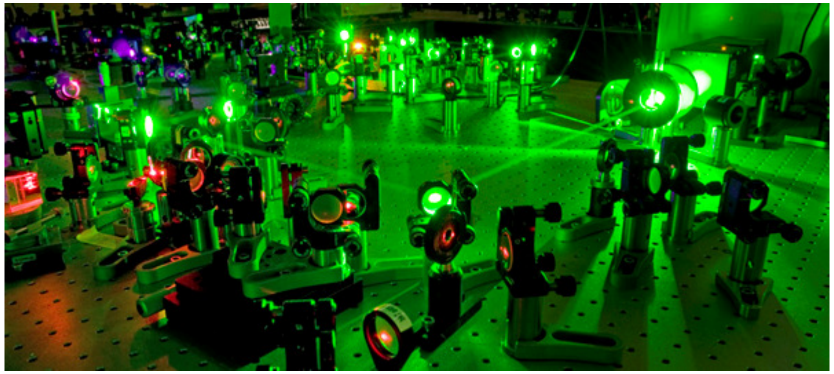
- Current magnitudes:

Power	$P \gtrsim 10^{15}\,\mathrm{W} = 1\,\mathrm{PW}$
Intensity	$I \gtrsim 10^{22}\,\mathrm{W/cm}^2$
Electric field	$E \gtrsim 10^{14}\,\mathrm{V/m}$
Magnetic field	$B \gtrsim 10^{10}\,\mathrm{G} = 10^6\,\mathrm{T}$

- Largest e.m. fields currently available in lab
- But: fields pulsed and alternating

Vulcan 10 PW project

Building (projected)



frontend (finished)

- Central Laser Facility
  Rutherford Lab (UK)

- Specs & details:
  - 300J in 30fs
  - 10 PW
  - 10^{23} Wcm^{-2}
  - Construction by 2012
  - Budget: 15 M£

Extreme Light Infrastructure (ELI)

- collaboration of 13 European countries
- “investigation and applications of laser-matter interaction at the highest intensity level”
- Spec^{s} & details:
  - >100 PW (Exawatt ?)
  - $>10^{25}$ Wcm^{-2}
  - Budget: several 100 M Euro
  - Construction by 2015

ELI cont^{d}

- 4 scientific ‘pillars’:
  1. Particle acceleration & X-ray generation (Prague)
  2. Attosecond science (Szeged)
  3. Laser based nuclear physics (Bucharest)
  4. Ultra-high field science (this talk) (decision 2012)

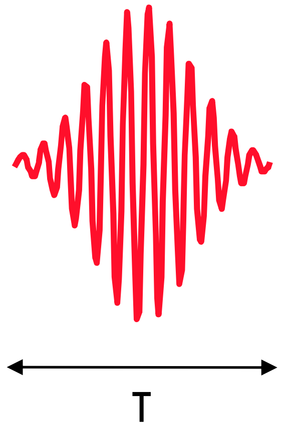

HAMILTONS ARCHITECTS

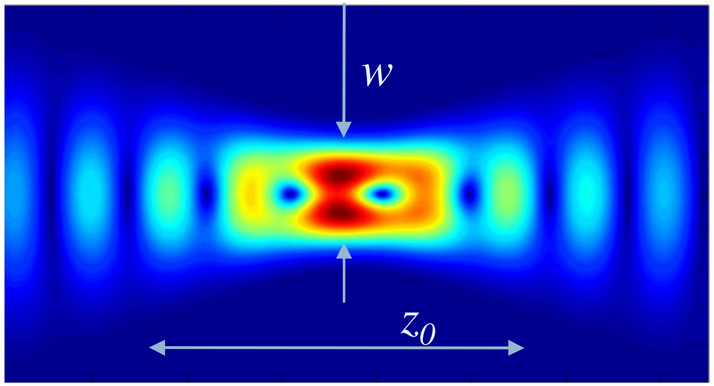
The design by Hamiltons Architects of the ELI Beamlines Facility that will be built in Dolní Břežany.

2. Strong Fields: Theory

Modelling a laser

- In order of increasing complexity:
  - Plane wave ☑
    - Infinite (IPW)
    - Pulsed (PPW)
      - Finite T-duration
      - Infinite transverse extension
  - Gaussian beam: ☒
    - Finite transverse waist w
    - Finite longitudinal extension z_0





Plane waves: peculiarities

- **Null** wave vector $k\,,\ k^2=0$

- Electromagnetic field $\mathsf{F}=(\mathbf{E},\mathbf{B})$
  - only dependent on invariant phase $k\cdot x=\omega t/c-\mathbf{k}\cdot\mathbf{x}$
  - Transverse $k\cdot\mathsf{F}=0$
  - **Null:**

$$E^2-B^2=0\,,\quad \mathbf{E}\cdot\mathbf{B}=0\,,\quad \mathsf{F}^3=0$$

  - No intrinsic invariant scale!
  - Need (probe) momentum p to build invariants
  - E.g. $a_0\sim(\mathsf{F}\cdot p)^2$ (TH, A. Ilderton, Opt. Comm. 2009)

Charge in IPW

- Solution of Lorentz force eq.: rapid quiver motion (momentum $p(\tau)$)
- Charge acquires **quasi-momentum**

$$q \equiv \langle p \rangle = p_{\text{in}} + \kappa(a_0^2)\, k$$

- Longitudinal addition – consequence:
- **Effective mass** squared

$$q^2 = m^2(1 + a_0^2) \equiv m_*^2$$

- *The* basic intensity effect!

(Sengupta 1951, Kibble 1964)

Challenges

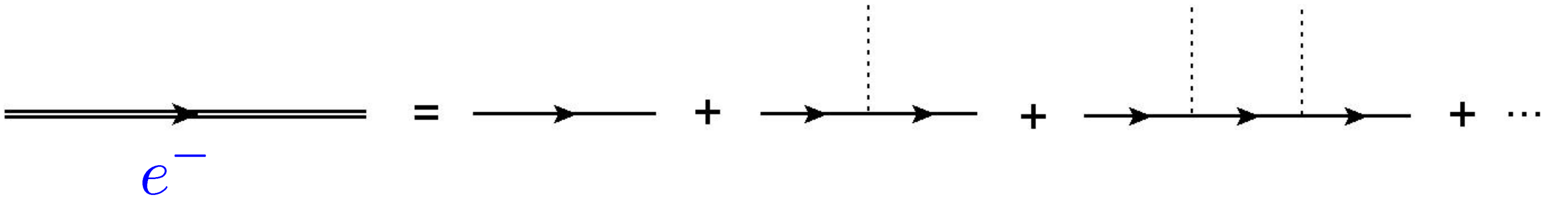
- Pulsed PW and beyond !?
- Inclusion of radiative backreaction !?
  - Lorentz-Abraham-Dirac equation
  - Landau-Lifshitz equation
  - New numerical approach (C. Harvey, TH, N. Iji, K. Langfeld, to appear)

- Experimental signatures !?
  - See examples below..

Strong-field QED I

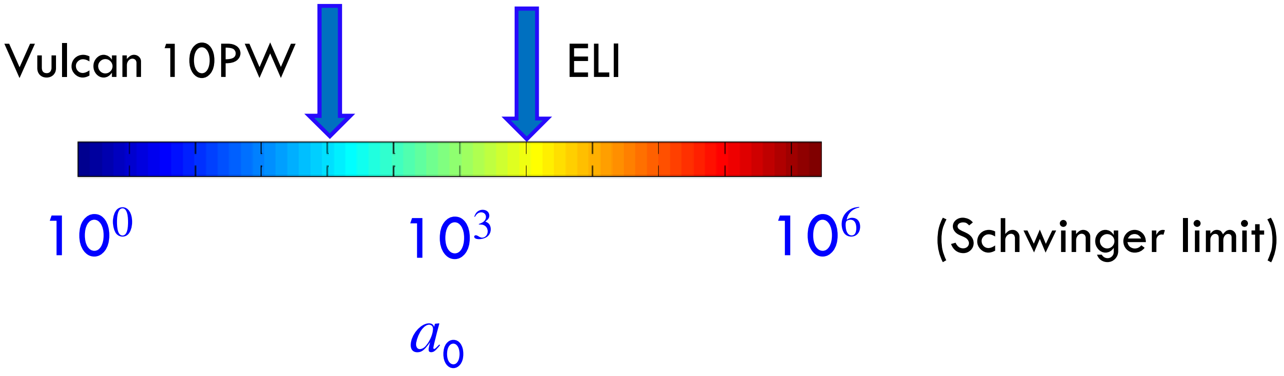
- **Ingredients:**
  - Probe photons

  - Analytic solution of Dirac eq. in *PW* field: Volkov 1935
  - Electrons ‘dressed’ by laser photons (---------)
  - ‘Volkov electron’:



Strong-field QED II

- Furry picture: Transition amplitudes between Volkov electrons → Feynman diagrams
- often: *light-cone* Fourier integrals
- **NB:** no such theory beyond PW
- Main issue in what follows: *Intensity dependence*

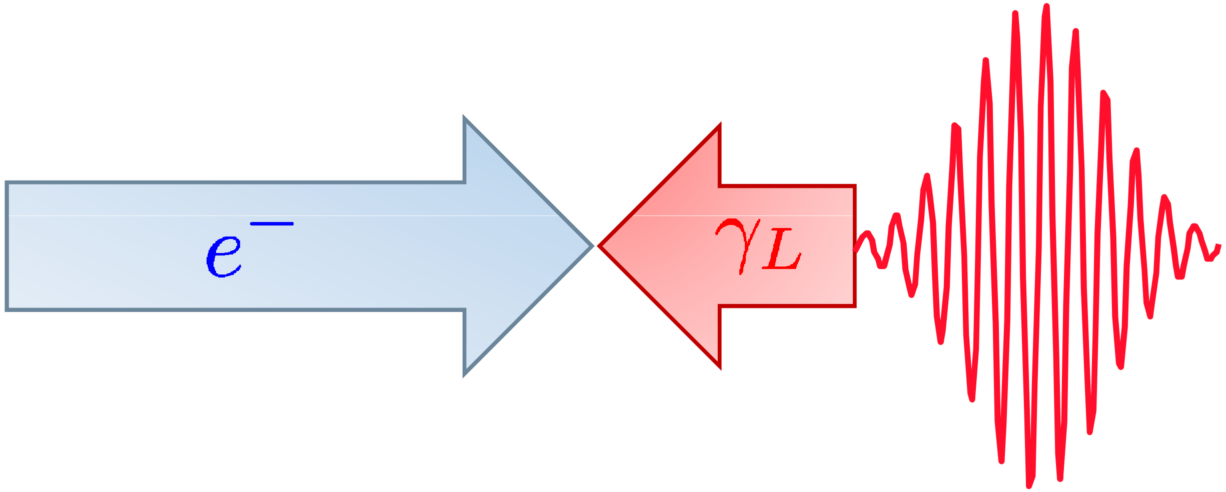


3. Strong Fields: Examples

3.1 Nonlinear Compton Scattering (NLC)

NLC: Scenario

- Ultra intense laser pulse collides with electron beam

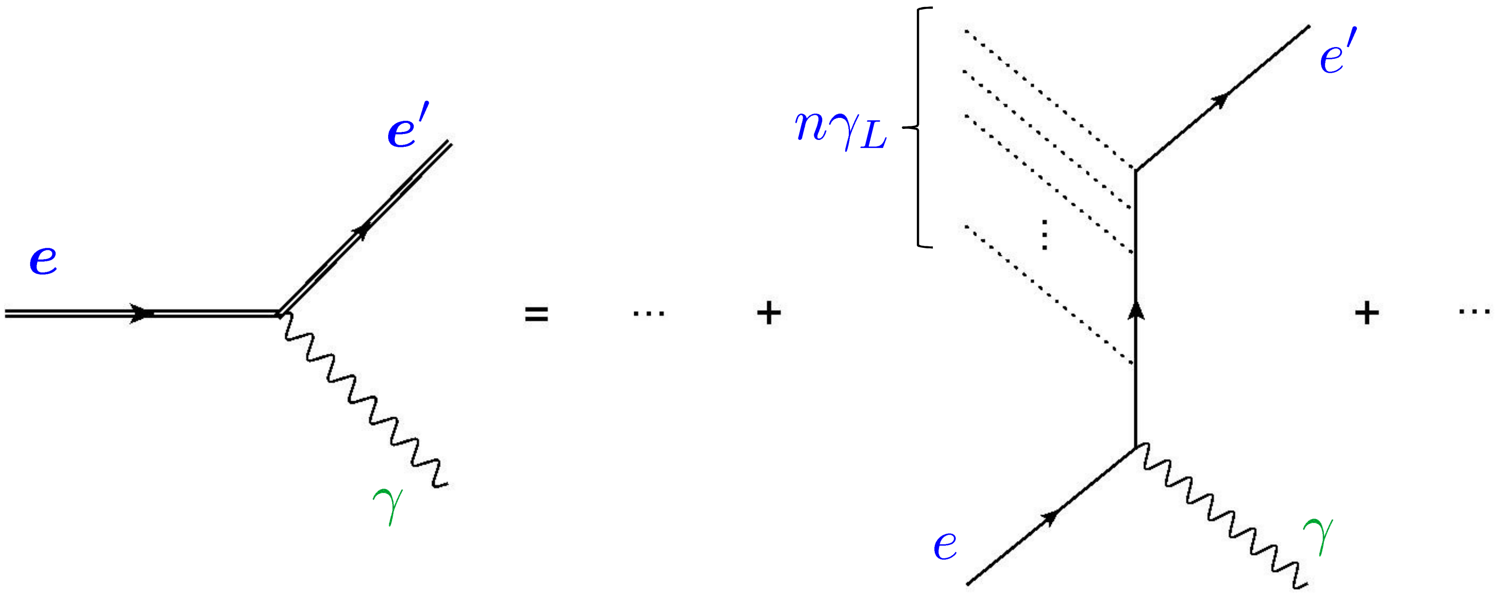


energy γ_e intensity a_0

- **Q**: intensity effects on scattering process?

NLC scattering

- Expand Furry picture diagram →
- Sum over all processes of the type $e + n\gamma_L \to e' + \gamma$



Schott 1912; Nikishov/Ritus 1964,
Brown/Kibble 1964, Goldman 1964

γ emission

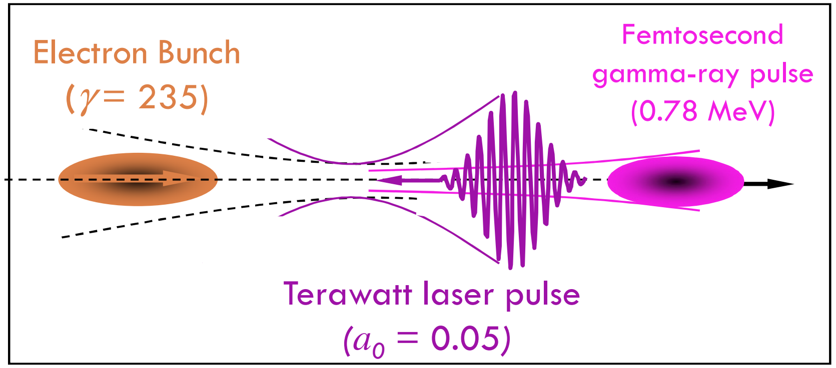
NLC: main features

- No energy threshold!
- Classical limit: Thomson ($\hbar\omega \ll mc^2$)
- For $a_0 < O(1)$: frequency upshift ('inverse Compton')

$$\omega'_{\mathrm{max}} \simeq 4\gamma^2\omega \qquad \text{('Compton edge')}$$

- Used for

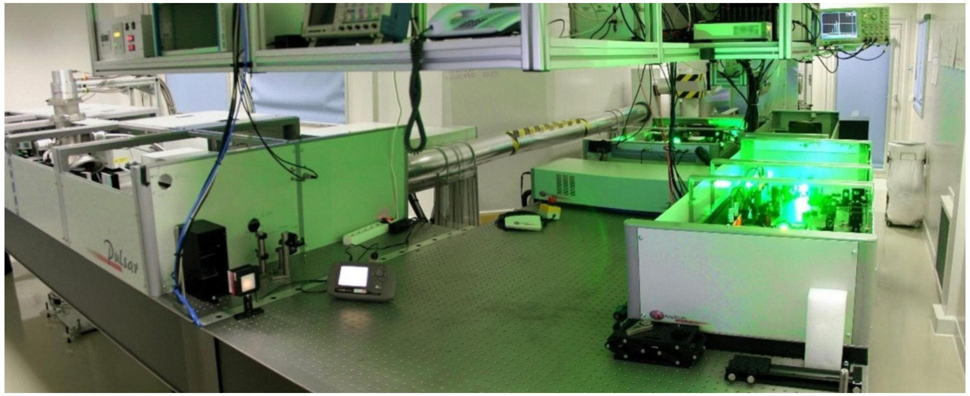
X-ray generation



T-REX, LLNL

Aside: X-ray generation I

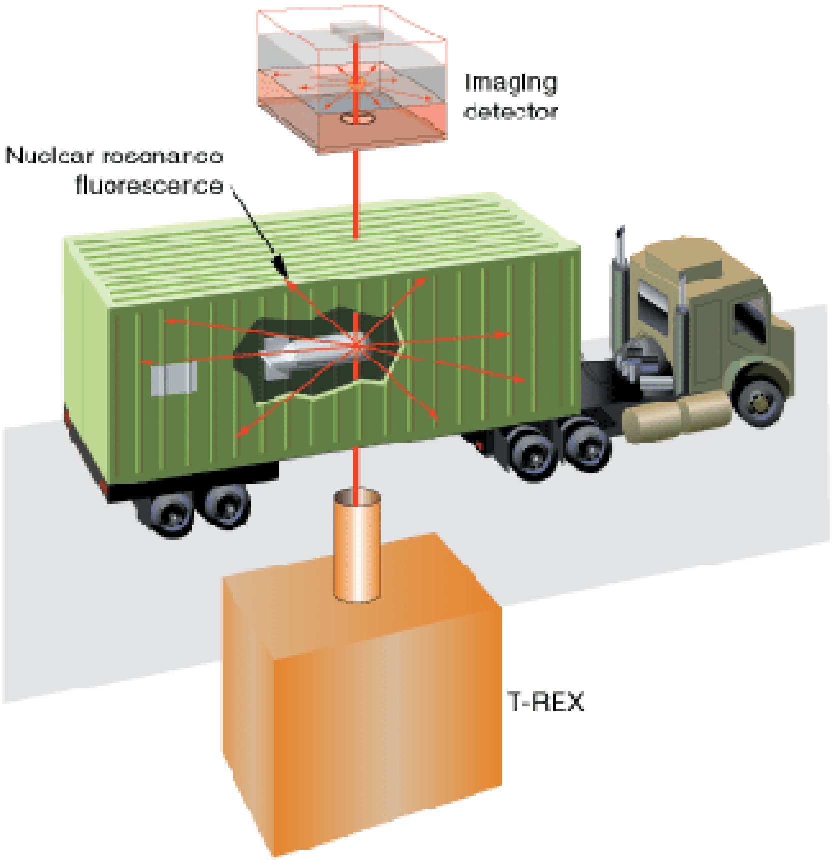
- German facility: Forschungszentrum Dresden-Rossendorf (FZD)
- 40 MeV Linac Elbe
- 150 TW laser Draco
- Petawatt project
- GSI ?



Source: FZD

Aside: X-ray generation II

- Lawrence Livermore NL
- T-REX facility (**T**homson-**R**adiated **E**xtreme **X**-ray Source)
- monochromatic, highly collimated, tunable X-rays and gamma-rays ("laser-like")
- 0.75 MeV gammas produced (2008)



Courtesy M. Downer

NLC cont$^{\text{d}}$

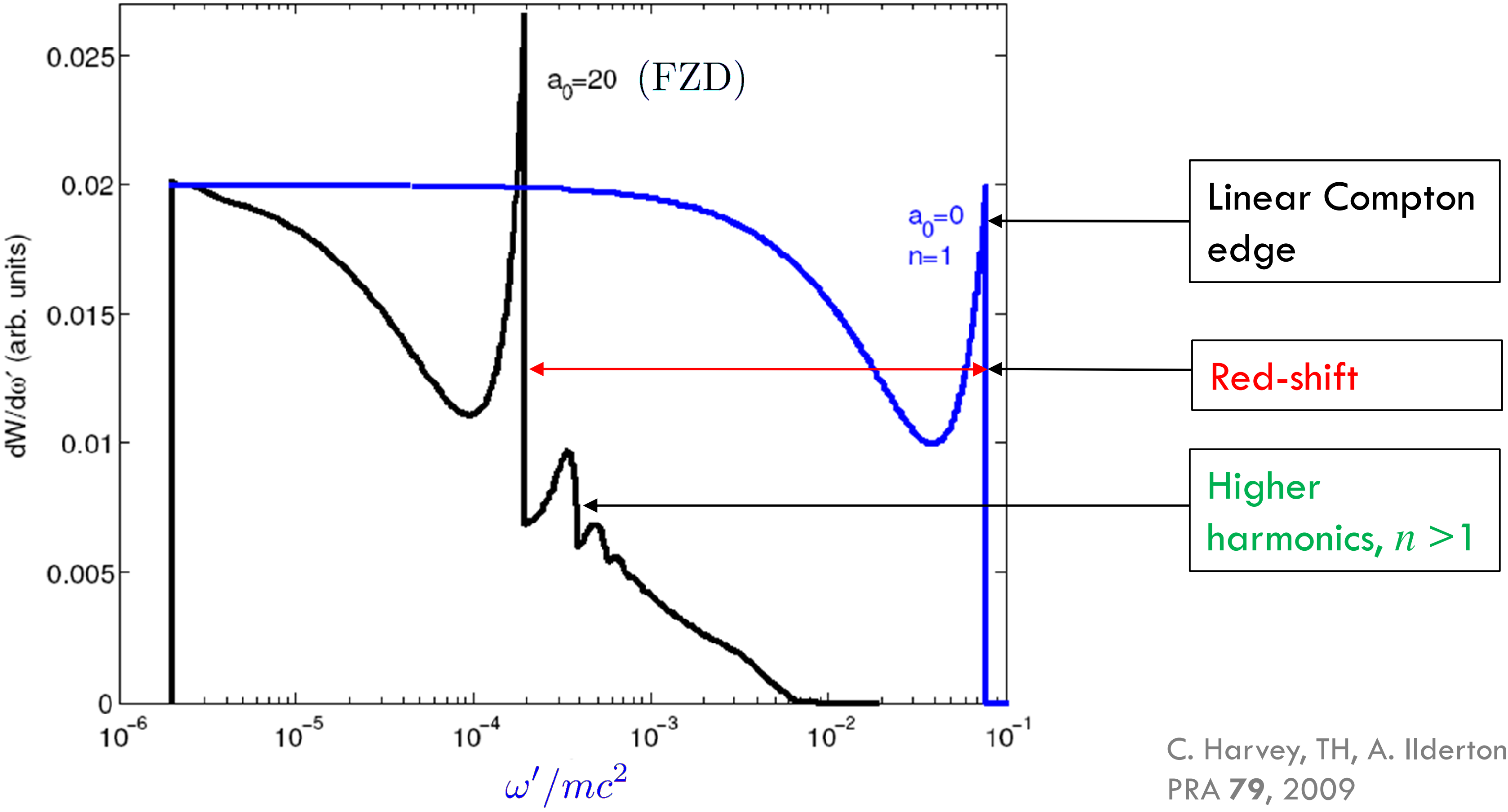
- For high intensity, $a_0 \gg 1$
- **modified** Compton edge

$$\omega'_{n,\mathsf{max}} \simeq 4\gamma_e^2 n\omega/a_0^2\ , \qquad n = 1, 2, \ldots$$

- In particular:
  - Higher harmonics: $n > 1$ ('nonlinear')
  - Overall blueshift maintained as long as $a_0 \lesssim 2\gamma_e$
  - **Redshift** of $n=1$ edge

$$\omega'_{\mathsf{max}} \simeq 4\gamma_e^2\omega \longrightarrow 4\gamma_e^2\omega/a_0^2$$

NLC spectrum: main a_0 effects



Linear Compton edge

Red-shift

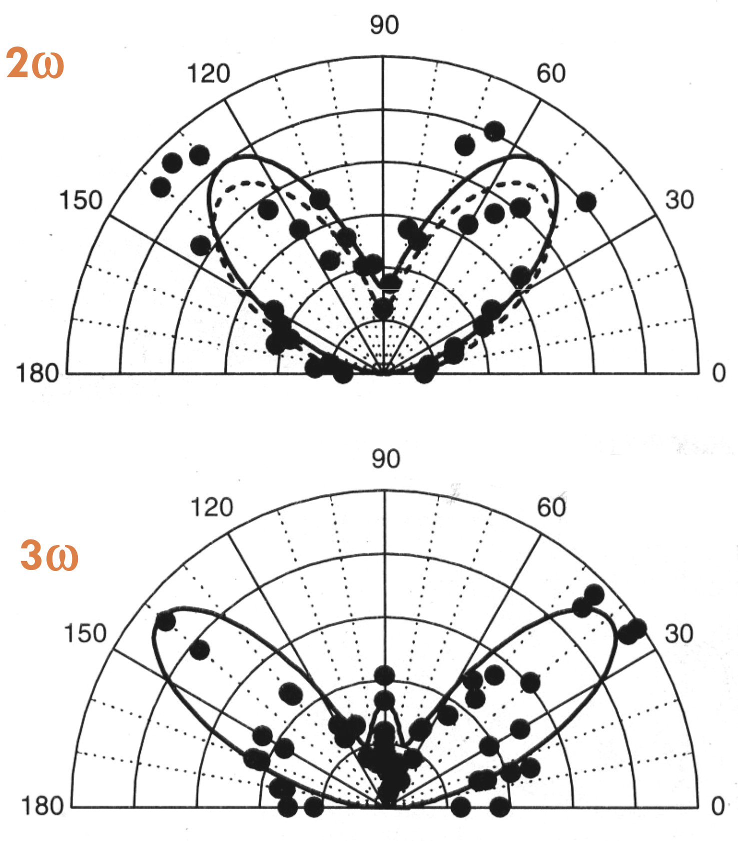
Higher harmonics, $n > 1$

C. Harvey, TH, A. Ilderton, PRA **79**, 2009

Aside: Higher harmonics

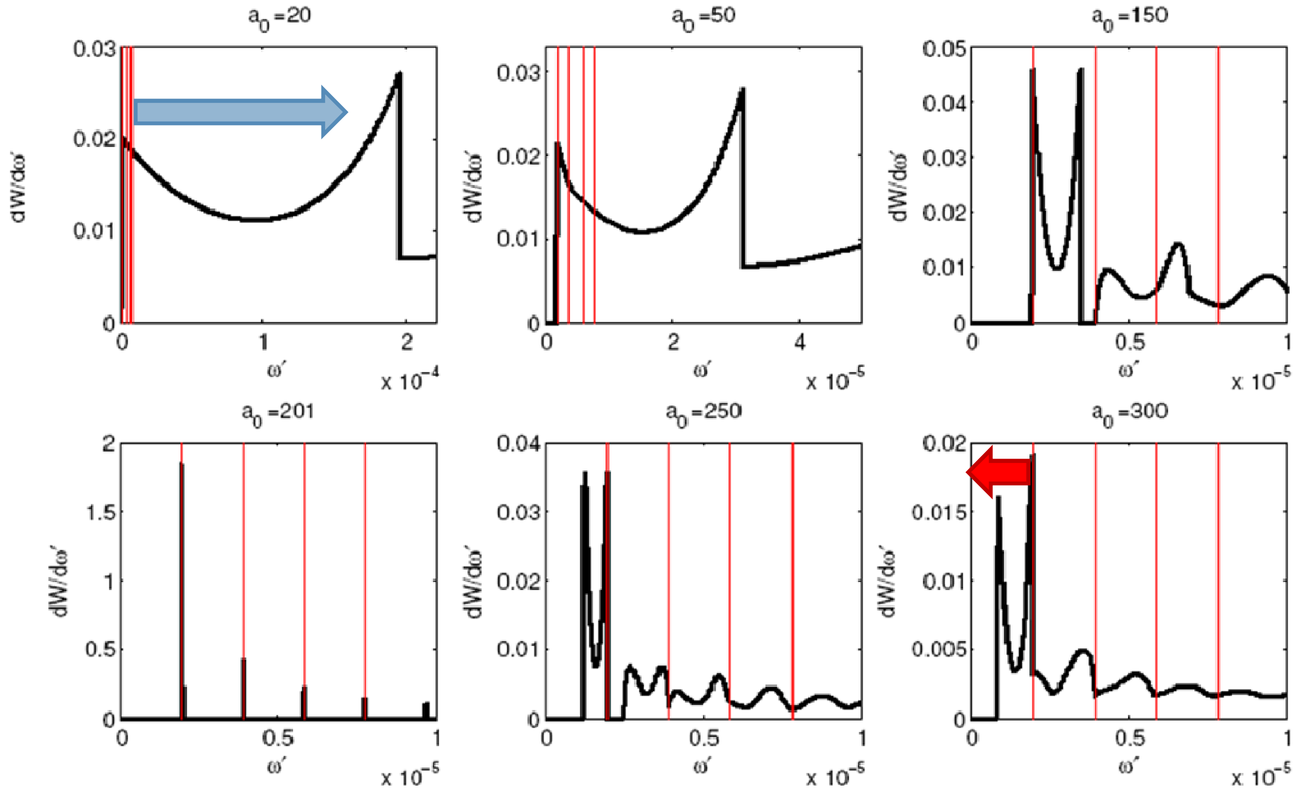
- Harmonics $n=2$ and $n=3$ observed in 'relativistic Thomson scattering' using *linearly* polarised laser ($a_0=1.88$)
- Signal: quadrupole and sextupole pattern in angular distribution

(Chen, Maksimchuk, Umstadter, Nature, 1998)



$\theta = 90^\circ$

a_0 dependence (lab)



Tuning a_0 similar to changing frame: when $a_0 = a_{0c} \simeq 2\gamma$

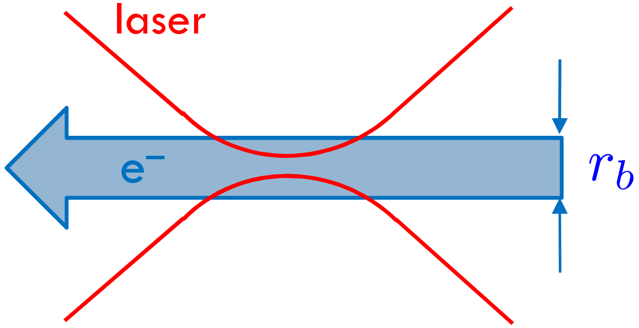
'inverse' Compton → Compton

C. Harvey, TH, A. Ilderton, PRA **79**, 2009

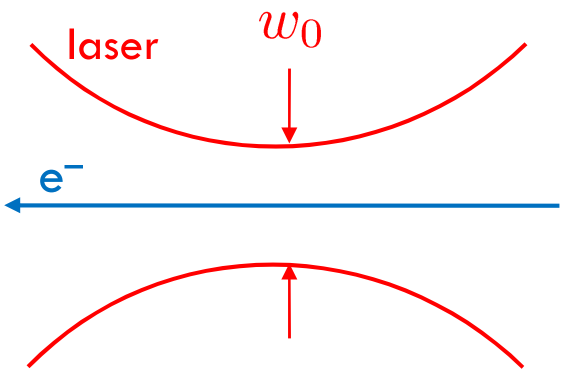
Finite Size Effects

Strongly focussed: $w_0 < r_b$

Weakly focussed: $w_0 \gg r_b$



$$a_0 \gg 1$$



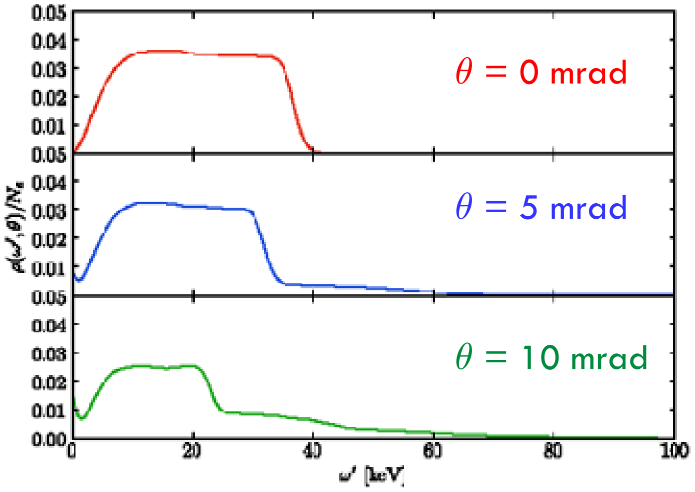
$$a_0 = O(1)$$

Finite Size NL Thomson Spectra

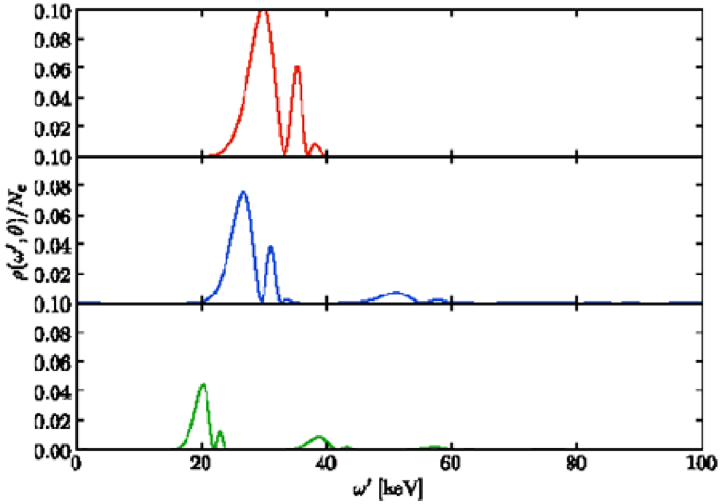
Strongly focussed: $w_0 = 5\ \mu\text{m}$

Weakly focussed: $w_0 = 50\ \mu\text{m}$

$3\ \text{J},\ 20\ \text{fs},\ \gamma_e = 80,\ r_b = 5\ \mu\text{m}$



$a_0 \simeq 6$



$a_0 \simeq 0.6$

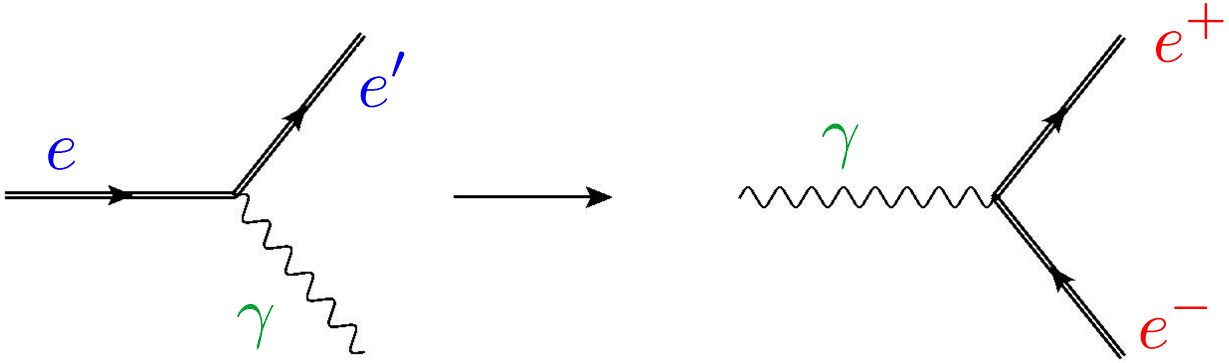
TH, D. Seipt, B. Kämpfer, PRA **81**, 2010

3. Strong Fields: Examples

3.2 Laser Pair Production (PP)

Stimulated PP

- Obtained from NLC via crossing

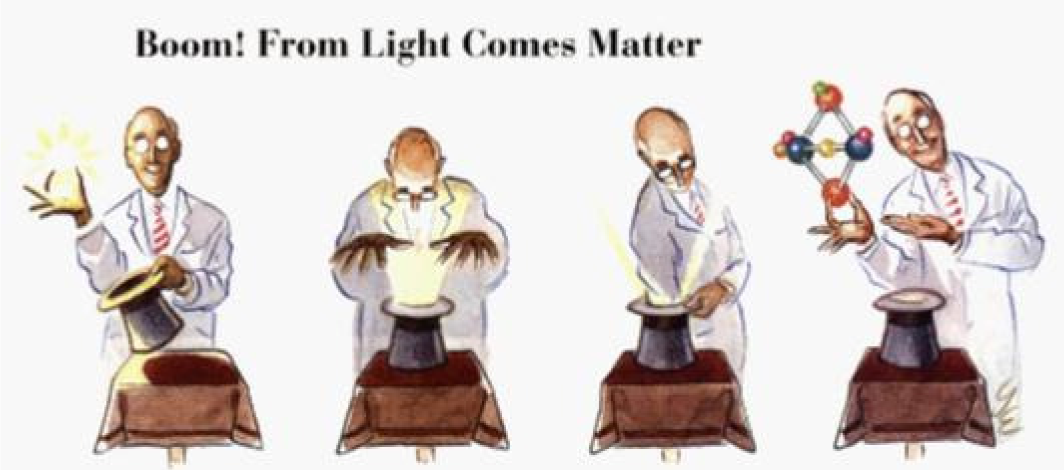


- Main new feature: energy threshold $2m_*^2$
- Experiment SLAC E-144 (1995): combine both processes ...

SLAC E-144 (Bula et al. '96, Burke et al. '97)

- Two stages: $e + n\gamma_L \rightarrow e' + \gamma$ NLC

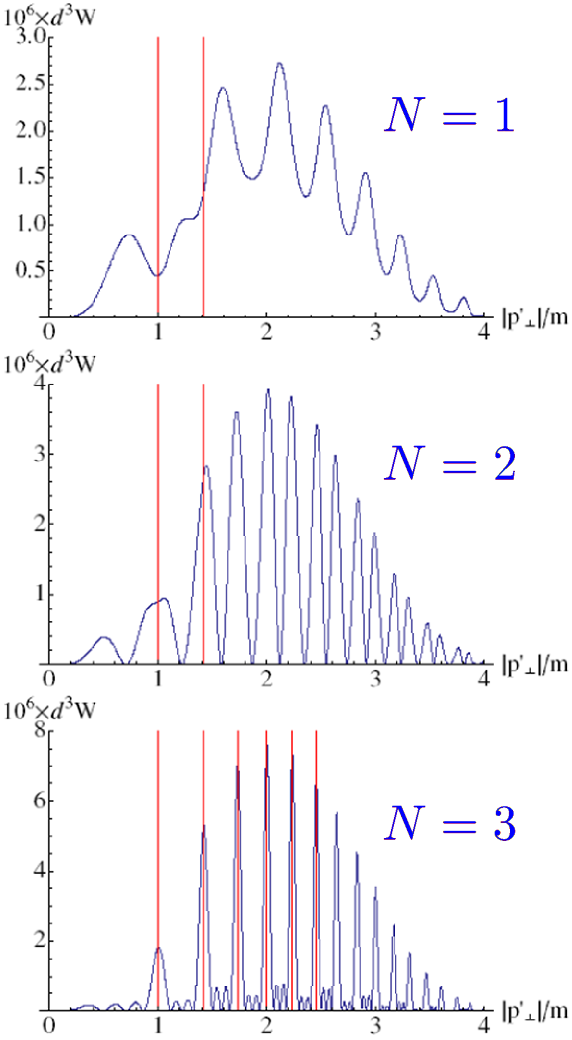
  $\gamma + n\gamma_L \rightarrow e^+ + e^-$ stimulated PP



Gil Eisner, Photonics Spectra 1997

50 GeV $e^- \rightarrow$ 30 GeV $\gamma \rightarrow O(10)$ pairs @ $a_0 \simeq 0.5$

Stimulated PP: finite-size effects

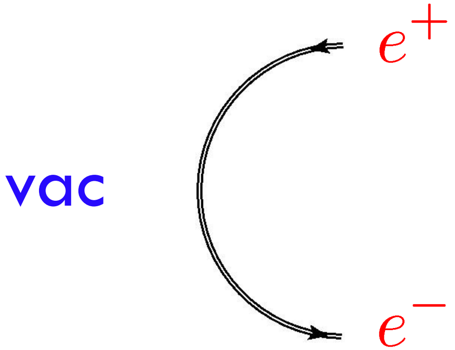


- IPW:
  - triple-diff rate = 'delta comb'
  - above threshold (m_*)
- PPW:
  - dependence on cycles per pulse, N
  - Sub-threshold signals
  - IPW approached for $N \gg 1$

TH, A. Ilderton, M. Marklund, 2010

Spontaneous PP

- Feynman diagram



‘vacuum breakdown’

- Identically **zero** for PW (**B** ‘compensates’ **E**)
- Identically **zero** for pure $\mathbf{B} \neq 0$ (no work done)
- Nonzero for $\mathbf{E} = const$ (Schwinger 1951)
- Key process: “boiling the vacuum”! (Ringwald 2001)

Spontaneous PP cont$^{\mathrm{d}}$

- Schwinger: PP rate exponentially suppressed

$$R_{e^+e^-} \sim \exp(-\pi E_S/E)$$

- with Sauter's critical field strength ('Schwinger limit')

$$E_S = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{18}\ \text{V/m}$$

(Sauter 1931)

- Presence of $\hbar$ and c: QM $\cup$ relativity
- Genuine relativistic QFT regime: strong field QED

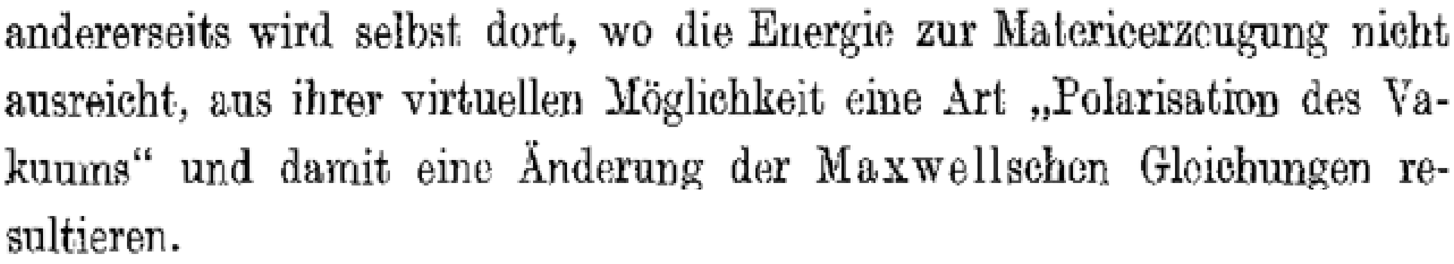
Spontaneous PP cont^{d}

- 'Fighting' exponential suppression:
  - Rate has pre-exponential factor (Marinov, Popov, 1977)
    Laser 4-volume/Compton 4-volume $\simeq 10^{24}$ (Narozhny et al., 2004)
  - Superimpose oscillatory field ('assisted PP')
    (Dunne, Gies, Schützhold, 2008/09)
  - $E \gg B$ for counterpropagating lasers ('standing wave')
    (Gregori et al., Astra Gemini experiment, 2010)
  - More complicated many-beam config.s (Bulanov et al., 2010)
- Upshot: *maybe* PP @ $10^{-2}\ E_S$ and 10^{25} W/cm^2
- ELI spec^{s} – so watch this space!

3. Strong Fields: Examples

3.3 Vacuum Birefringence (VB)

Heisenberg, Euler 1936

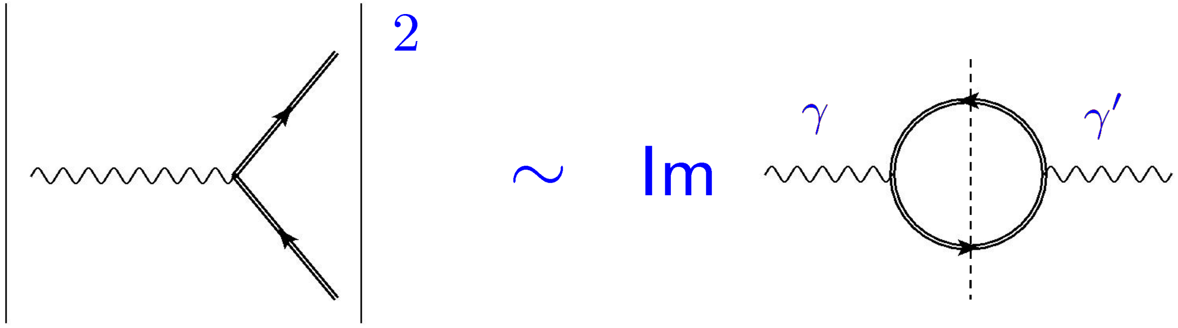


andererseits wird selbst dort, wo die Energie zur Materieerzeugung nicht ausreicht, aus ihrer virtuellen Möglichkeit eine Art „Polarisation des Vakuums“ und damit eine Änderung der Maxwellschen Gleichungen resultieren.

“…even in situations where the [photon] energy is not sufficient for matter production, its virtual possibility will result in a ‘polarization of the vacuum’ and hence in an alteration of Maxwell’s equations.”

Optical Theorem (Kramers-Kronig)

- Total PP rate can be obtained via



Vacuum polarisation Π

- Virtual $e^+ e^-$ ‘dipoles’ feel presence of **E**
- Re Π : change of polarisation state $\gamma \to \gamma'$
- diagonalisation of Π (for X-fields = PW$_{\omega \to 0}$)
- **two** nontrivial eigenvalues →

Vacuum birefringence (Brezin, Itzykson 1970)

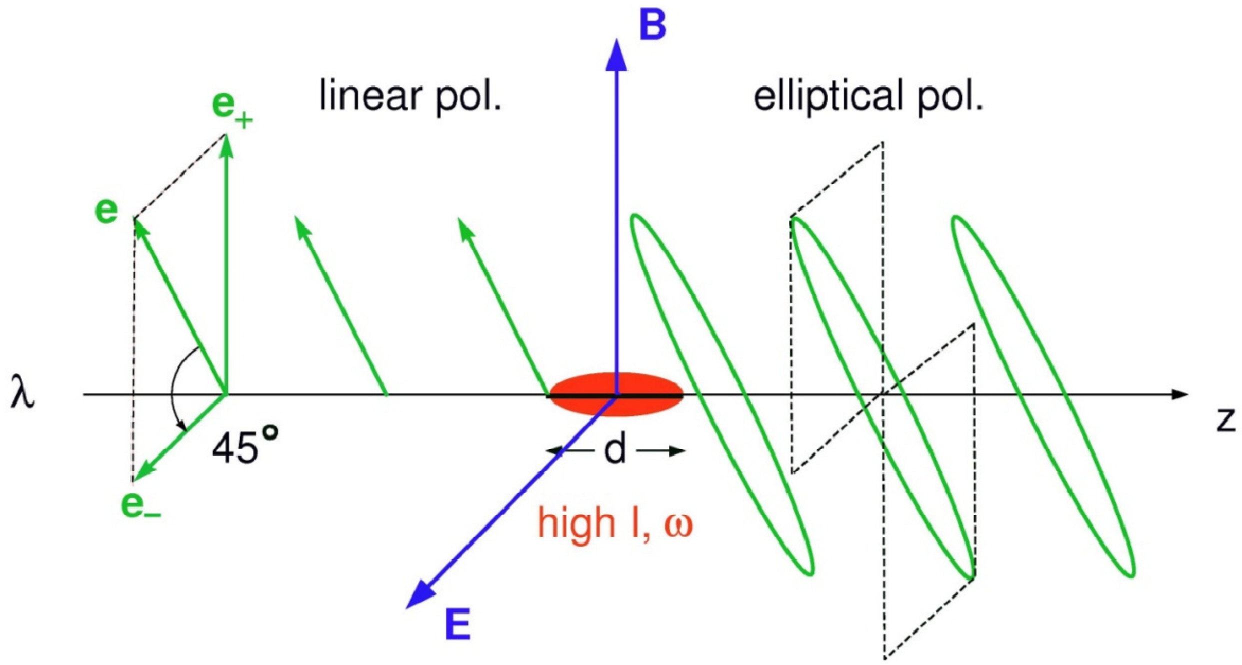
Calcite crystal

- Two indices of refraction (Toll 1952)

$$n_{\pm} = 1 + \frac{\alpha\epsilon^2}{45\pi}\left\{11 \pm 3 + O(\epsilon^2\nu^2)\right\}\left\{1 + O(\alpha\epsilon^2)\right\}$$

- Dim.less (small) parameters:
  - Field strength: $\epsilon \equiv E/E_S$
  - Probe frequency $\nu \equiv \hbar\omega/mc^2$
  - $\alpha = 1/137$

Experiment: measure ellipticity



Phase retardation of e_+

Analysis

- ellipticity (squared)

$$\delta^2 = 3.2 \times 10^5 \left(\frac{d}{\mu\mathrm{m}} \epsilon^2 \nu \right)^2 , \quad \epsilon\nu \ll 1$$

- Power law suppressed…
- Optimal scenario @ ELI
  - large intensity: $\epsilon \simeq 10^{-2}$
  - large probe frequency (X-ray, $\nu \simeq 10^{-2}$):

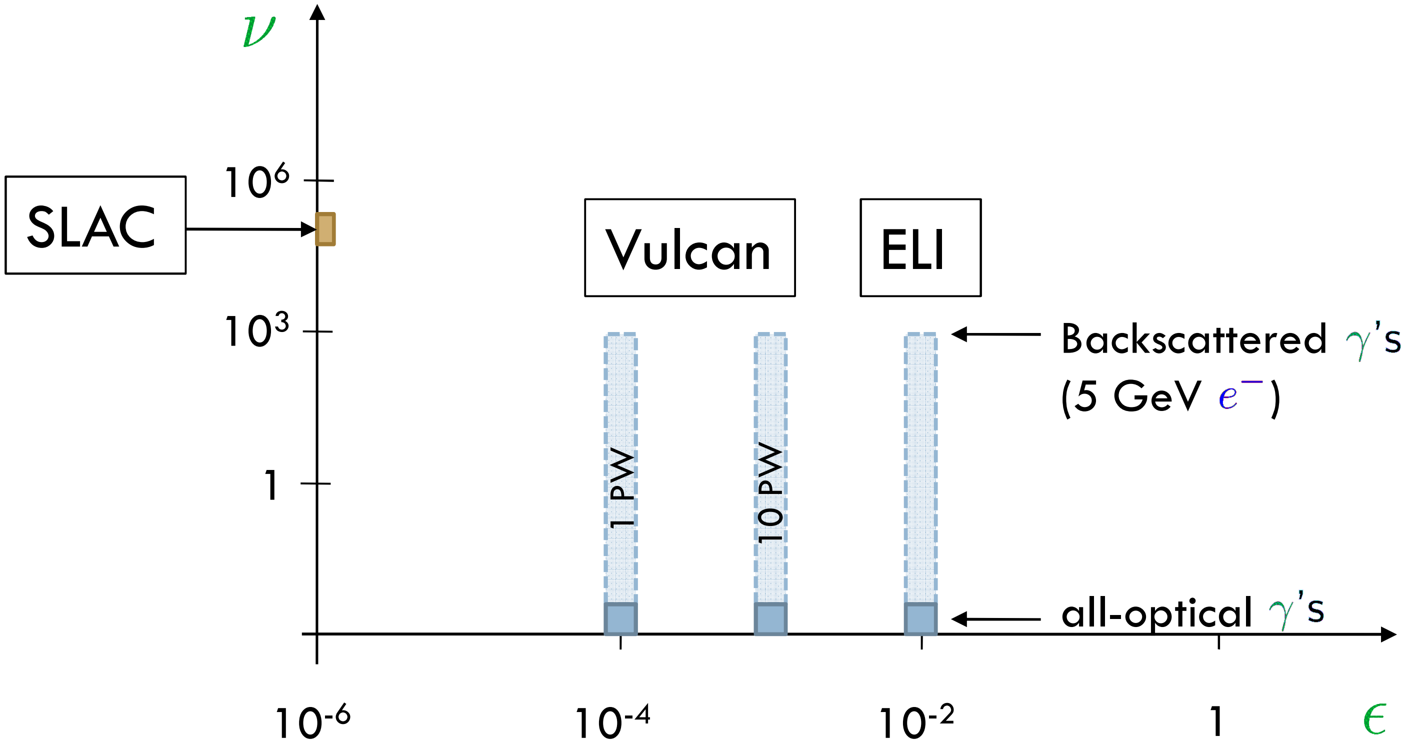
$$\delta^2 \simeq 10^{-7} ... 10^{-4}$$

  - Experimental challenge, but feasible

(Marx, Uschmann, Stöhlker et al., Jena preprint 2010)

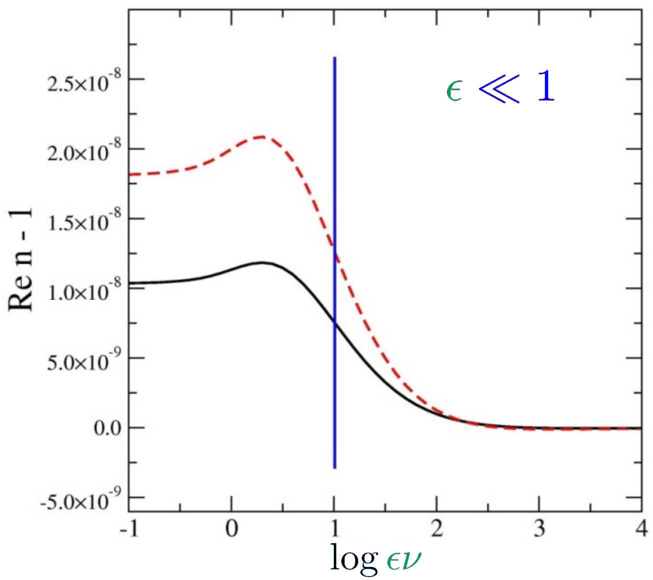
Extended parameter range

- $\nu \gg 1$: Compton backscattering off high-energy e^- (from linac or wake field accelerator)

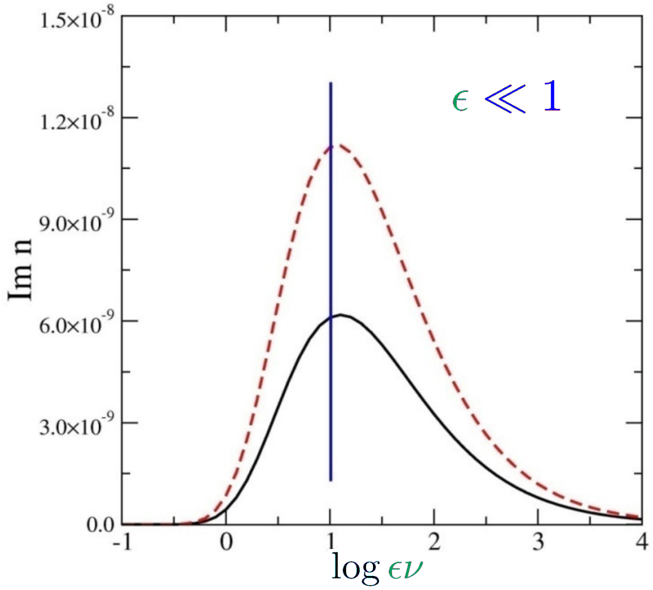


Large-ν birefringence via NLC

- $\epsilon\nu \simeq 3$ for e^-: 3 GeV @ ELI, 10 GeV @ Vulcan10PW



Anomalous dispersion



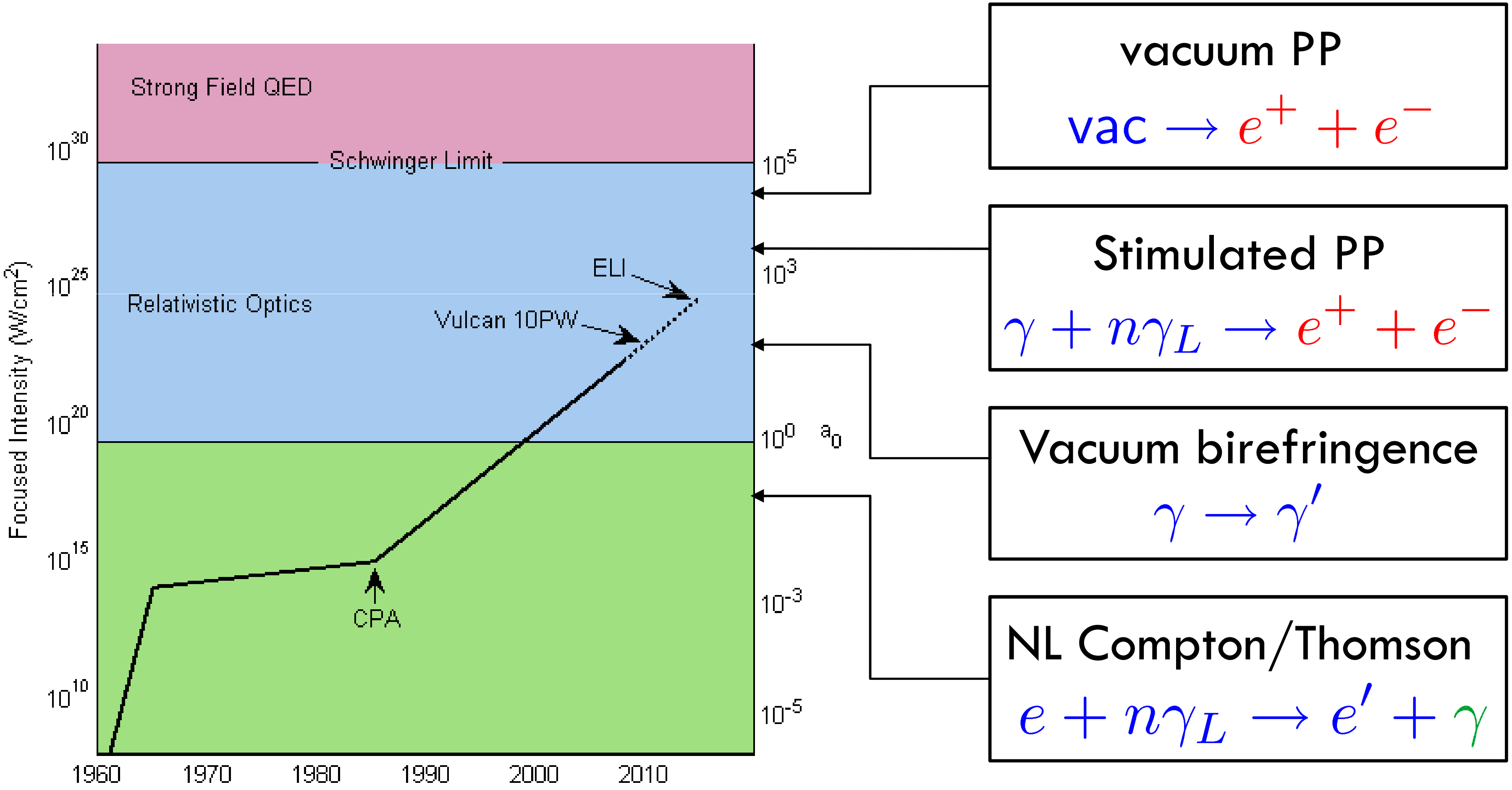
Absorption → PP

(Toll 1952
TH, O. Schröder
2006
Shore 2007)

(K. Langfeld)

- NB: SLAC E-144 had $\epsilon\nu \simeq 0.1$

Summary



vacuum PP

$\text{vac} \rightarrow e^+ + e^-$

Stimulated PP

$\gamma + n\gamma_L \rightarrow e^+ + e^-$

Vacuum birefringence

$\gamma \rightarrow \gamma'$

NL Compton/Thomson

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

Conclusion

- Laser power approaching exawatt regime
- Extreme field physics – Schwinger limit: QED
- Experiments planned or under way
- X-ray generation: $a_0 = O(1)$
- Theory ($\longrightarrow$ a_0 dependence) :
  - Ok for plane wave models
  - Challenge: incorporate realistic laser beam model
    - Beyond plane waves
    - Finite size effects
    - Numerical approaches

Thank you very much indeed…

…for your attention