Fundamental High-Field Science at an X-Ray FEL Facility

A. Ringwald

http://www.desy.de/~ringwald

Scientific and Technical Issues (STI) Round-Table Meeting
Hamburg/D, June 23, 2004

Free Electron Lasers in X-Ray Band

- New insights into **natural** and **life sciences**
- May possibly allow also for **high-field science** applications:
  - Envisage **focusing** down to **diffraction limit**, $\sigma \gtrsim \lambda_{\rm em} \sim 0.1\ {\rm nm}$

⇒ Very **strong** electric fields and accelerations in reach,

$$\mathcal{E} = \sqrt{\mu_0\, c\, \frac{P}{\pi \sigma^2}} = 1.1 \cdot 10^{17}\, \frac{\rm V}{\rm m} \left(\frac{P}{1\ {\rm TW}}\right)^{1/2} \left(\frac{0.1\ {\rm nm}}{\sigma}\right)$$

$$a = \frac{e\,\mathcal{E}}{m_e} = 1.9 \cdot 10^{28}\, \frac{\rm m}{\rm s^2} \left(\frac{P}{1\ {\rm TW}}\right)^{1/2} \left(\frac{0.1\ {\rm nm}}{\sigma}\right)$$

much larger than obtainable with optical laser of same peak power P

⇒ **X-ray FELs** may be employed possibly as **vacuum boilers**

[Chen,Pellegrini '98; AR '01; . . .]

⇒ **X-ray FELs** may be employed possibly as **violent accelerators**

[Chen,Tajima '99]

Outline:

1. **Boiling the Vacuum with Lasers**

2. **Violent Acceleration – Unruh Effect**

3. **Conclusions**

1. Boiling the Vacuum with Lasers

- **Spontaneous pair creation from vacuum**, induced by an **external field**, was first proposed in the context of e^+e^- **pair creation in static, spatially uniform electric field** [Sauter (1931); Heisenberg,Euler (1936); Schwinger (1951); . . .]

  One of the most intriguing non-linear phenomena in quantum field theory
  - Theoretically important: beyond perturbation theory
  - Eventual experimental observation: probes theory in domain of very strong fields

- Mechanism applied to many problems in contemporary physics:
  - Quantum evaporation of black holes [Hawking (1975); Damour,Ruffini (1976); . . .]
  - e^+e^- creation in vicinity of charged black holes [Damour,Ruffini '75; . . .]
  - Particle production in early universe [Parker (1969); . . .]
  - Particle production in hadronic collisions [Casher, Neuberger, Nussinov (1979); . . .]

- Vacuum in **QED** unstable in a static, spatially uniform electric background field:

$\Rightarrow$ Sparks with spontaneous emission of e^+e^- pairs

– Observable rate requires extraordinary strong electric field strength, of order

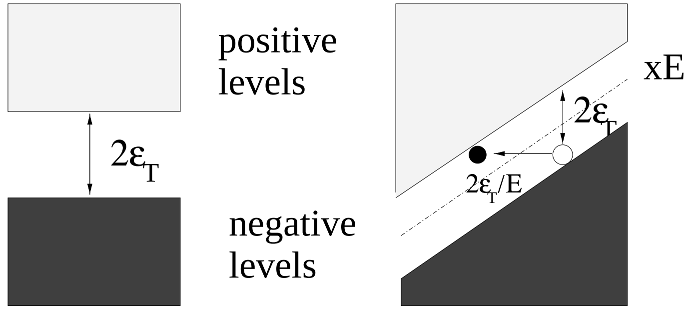
$$\mathcal{E}_c \equiv \frac{m_e\, c^2}{e\, \lambdabar_e} = \frac{m_e^2\, c^3}{e\, \hbar} = 1.3 \cdot 10^{18}\, \frac{\mathrm{V}}{\mathrm{m}}$$

[Sauter (1931); Heisenberg, Euler (1936)]

such that

work of field on unit charge e over Compton wavelength $\lambdabar_e$	$\approx$	**rest energy** of e^+e^- pair
$e\, \lambdabar_e\, \mathcal{E}_c$	$=$	$m_e\, c^2$

- For $\mathcal{E} \ll \mathcal{E}_c$: [Schwinger (1951)]



  – Pair creation: **tunneling**
  – Rate **exponentially suppressed**:

$$w = \frac{\mathrm{d}^4 n_{e^+e^-}}{\mathrm{d}^3x\,\mathrm{d}t} \propto \exp\left[-\pi\,\frac{\mathcal{E}_c}{\mathcal{E}}\right] = \exp\left[-\pi\,\frac{m_e^2\,c^3}{\hbar\,e\,\mathcal{E}}\right]$$

- No human-made macroscopic static fields of order $\mathcal{E}_c$ accessible
- In early 1970's:
  – Critical fields in **nuclear collisions with** $Z_1 + Z_2 \approx 1/\alpha$?
  [Zel'dovich, Popov (1971); Müller, Rafelski, Greiner (1972)]
  – Critical fields **at focus**[1] **or at overlap of crossed**[1] **intense optical lasers**? [Bunkin, Tugov (1969); Brezin, Itzykson (1970); Popov (1971);...; Fried *et al.* (2001)]

[1]No pair creation in plane wave.

- Cleanest experimental setup: Two crossed laser beams ⇒ standing electromagnetic wave ⇒ pair creation in the antinode,

$$\mathbf{E}(t) = (0, 0, \mathcal{E}\cos(\omega t))\,, \qquad \mathbf{B}(t) = (0, 0, 0)\,, \qquad \lambda = \frac{2\pi c}{\omega}$$

- Assume that for realistic lasers

$$\mathcal{E} \ll \mathcal{E}_c = \frac{m_e^2\, c^3}{e\,\hbar}\,, \qquad \hbar\,\omega \ll m_e c^2$$

⇒ Rate of spontaneous e^+e^- creation calculable in **semi-classical** manner

[Brezin,Itzykson (1970); Popov (1971);...]

- The ratio

$$\eta \equiv \frac{\hbar\,\omega}{e\,\mathcal{E}\,\lambda\!\!\!^{-}_e} = \frac{\hbar\,\omega}{m_e c^2}\,\frac{\mathcal{E}_c}{\mathcal{E}} = \frac{m_e c\,\omega}{e\,\mathcal{E}} \equiv \frac{\mathcal{E}_\omega}{\mathcal{E}}\,.$$

independent of $\hbar$ and plays role of an **adiabaticity parameter**

- The laser frequency ω enters in the semi-classical formulae only through the adiabaticity parameter η. For limiting cases:

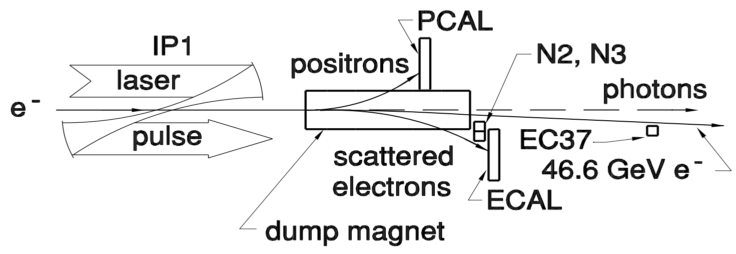
$$w \equiv \frac{\mathrm{d}^4 n_{e^+e^-}}{\mathrm{d}^3x\,\mathrm{d}t} \simeq \frac{c}{4\,\pi^3 \lambda\!\!\!^{-}{}_e{}^4} \begin{cases} \ldots \exp\left[-\pi\,\frac{\mathcal{E}_c}{\mathcal{E}}\right], & : \quad \eta \ll 1\,, \\ \sum_{n>2\frac{m_e c^2}{\hbar\omega}} \ldots \eta^{-2n} & : \quad \eta \gg 1\,, \end{cases}$$

$\eta \ll 1$: Adiabatic high-field, low-frequency limit agrees with **non-perturbative Schwinger result** for a static, spatially uniform field.

$\eta \gg 1$: Non-adiabatic low-field, high-frequency limit resembles **perturbative result:** corresponds to $\geq n$-th order perturbation theory, n being the minimum number of quanta required to create an e^+e^- pair: $n \gtrsim 2\,m_e c^2/(\hbar\omega) \gg 1$

- Non-perturbative Schwinger pair creation from vacuum already observed at SLAC experiment E-144?

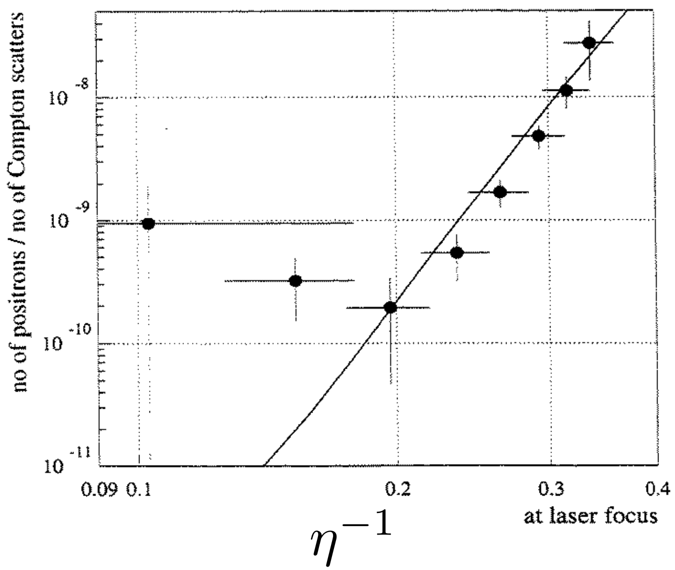
[Burke *et al.* (1997); Melissinos (1998)]



[Burke *et al.* (1997)]

$\Leftarrow$ e^+e^- pair production in collision of 46.6 GeV/c electrons with TW optical laser pulses $\Rightarrow$ in the rest frame of the incident electrons

$$\mathcal{E} \sim 5 \cdot 10^{17}\ \mathrm{V/m}, \quad \eta \sim 3$$



$\Rightarrow$ **Perturbative, multi-photon regime**, but not far away from Schwinger regime

- Minimum necessary power for observable effect: [AR (2001)]

	λ	σ	$\triangle t$	$P_{\rm min}$	$S_{\rm min}$	$\mathcal{E}_{\rm min}$
Focused XFEL:	0.1 nm	0.1 nm	0.1 ps	2.5 TW	$7.8 \cdot 10^{31}$ W/m^2	$1.7 \cdot 10^{17}$ V/m
(≈ “aim”)	0.1 nm	0.1 nm	0.1 fs	4.5 TW	$1.4 \cdot 10^{32}$ W/m^2	$2.3 \cdot 10^{17}$ V/m
Focused XFEL:	0.1 nm	20 nm	0.1 ps	38 PW	$3.0 \cdot 10^{31}$ W/m^2	$1.1 \cdot 10^{17}$ V/m
(≈ “state-of-art”)	0.1 nm	20 nm	0.1 fs	55 PW	$4.3 \cdot 10^{31}$ W/m^2	$1.3 \cdot 10^{17}$ V/m
Focused optical laser:	1 μm	1 μm	10 ps	49 EW	$1.6 \cdot 10^{31}$ W/m^2	$7.7 \cdot 10^{16}$ V/m
diffraction limit	1 μm	1 μm	100 fs	58 EW	$1.8 \cdot 10^{31}$ W/m^2	$8.3 \cdot 10^{16}$ V/m

- Need **tens of EW optical laser** or **TW X-ray FEL**

$\Leftarrow$ Power densities and electric fiels that can be reached with presently available techniques far too small for observable effect (cf. extra table)

- Conceivable **improvements** in **XFEL** technology:
  - X-ray optics, in order to come closer to diffraction limit $\sigma \gtrsim \lambda$
  - Energy extraction, in order to increase power

- Hard to predict whether this goal will be reached before the commissioning of EW-ZW optical lasers ($\gtrsim 2020$?).

Laser parameter

		Optical	XFEL		
		focus: diffraction limit	design **SASE 5**	focus: **state-of-art**	focus: **aim**
wavelength	λ	1 μm	0.4 nm	0.4 nm	0.15 nm
photon energy	$\hbar\,\omega = \frac{hc}{\lambda}$	1.2 eV	3.1 keV	3.1 keV	8.3 keV
max. power	P	1 PW	110 GW	1.1 GW	5 TW
spot radius (rms)	σ	1 μm	26 μm	21 nm	0.15 nm
coherent spike length (rms)	$\triangle t$	500 fs ÷ 20 ps	0.04 fs	0.04 fs	0.08 ps

derived quantities

		Optical	design SASE 5	focus: state-of-art	focus: aim
max. power density	$S = \frac{P}{\pi\sigma^2}$	$3 \cdot 10^{26}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$5 \cdot 10^{19}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$8 \cdot 10^{23}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$7 \cdot 10^{31}\ \frac{\mathrm{W}}{\mathrm{m}^2}$
max. electric field	$\mathcal{E} = \sqrt{\mu_0\, c\, S}$	$4 \cdot 10^{14}\ \frac{\mathrm{V}}{\mathrm{m}}$	$1 \cdot 10^{11}\ \frac{\mathrm{V}}{\mathrm{m}}$	$2 \cdot 10^{13}\ \frac{\mathrm{V}}{\mathrm{m}}$	$2 \cdot 10^{17}\ \frac{\mathrm{V}}{\mathrm{m}}$
max. electric field/critical field	$\mathcal{E}/\mathcal{E}_c$	$3 \cdot 10^{-4}$	$1 \cdot 10^{-7}$	$1 \cdot 10^{-5}$	0.1
photon energy/e-rest energy	$\frac{\hbar\omega}{m_e c^2}$	$2 \cdot 10^{-6}$	0.006	0.006	0.02
Adiabaticity parameter	$\eta = \frac{\hbar\omega}{e\,\mathcal{E}\,\lambda\!\!\!^{-}_e}$	$9 \cdot 10^{-3}$	$6 \cdot 10^{4}$	$5 \cdot 10^{2}$	0.1

- Minimum necessary power for observable effect: [AR (2001)]

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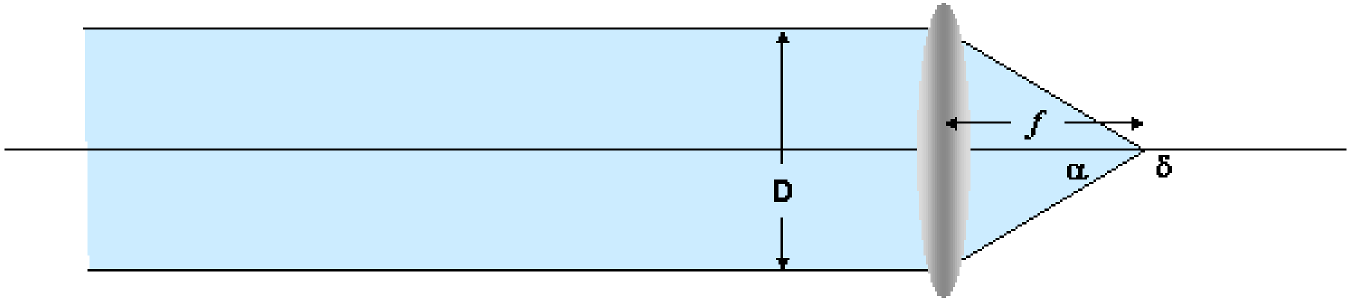
Geometrical optics: Focusing limit



Abbè equation for the resolution limit

$$\delta = \frac{1.22\lambda}{NA} = \frac{1.22\lambda}{n \sin\alpha} \cong 2.44\,\frac{\lambda \cdot f}{D}$$

Parameters

δ = spot diameter (Airy disc)
λ = wavelength
NA = numerical aperture
n = refractive index (~1 for X-rays)

FEL sources:

Beams are highly collimated ⇒ f is optics-sample distance (~10-100 cm)
⇒ D is small (~mm) even at large distance

f = 10 cm, D= 1mm : λ = 10 nm ⇒ δ_{min} ~ 2.4 µm
λ = 1 nm ⇒ δ_{min} ~ 240 nm
λ = 0.1 nm ⇒ δ_{min} ~ 24 nm

B. Lengeler, JSR 6, 1155(99):
FWHM of gaussian beam
⇒ 2.44 → 0.75

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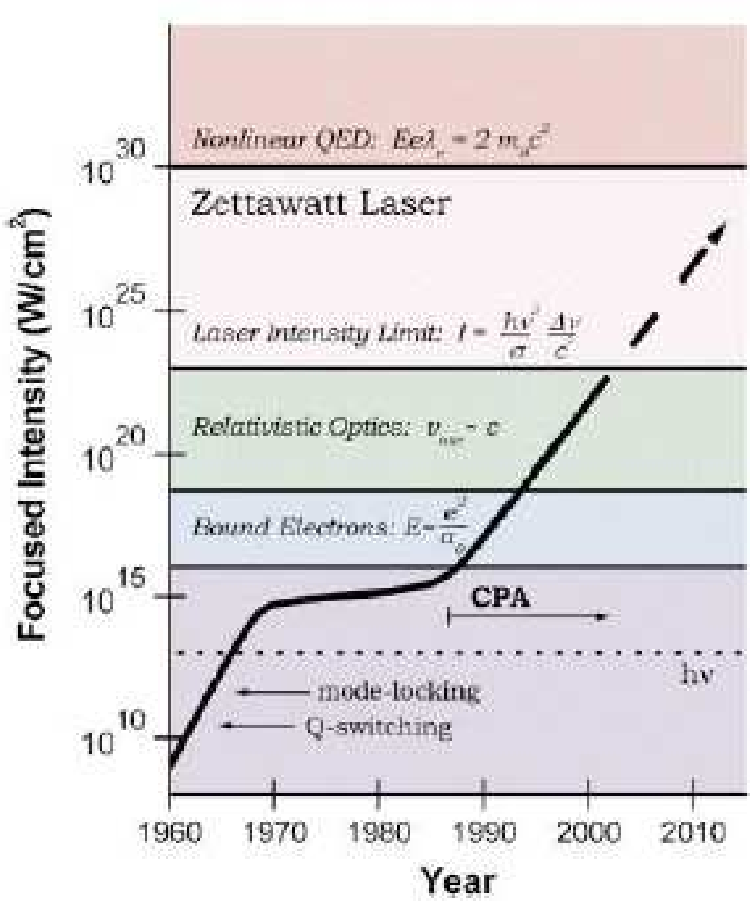


[Tajima,Mourou '02]

2. Violent Acceleration – Unruh Effect

- What is the Unruh effect? [Unruh (1976)]
  - An accelerated observers sees the vacuum fluctuations as a heat bath,

$$T_{\rm Unruh} = \frac{\hbar\, a}{2\,\pi\, c\, k} = 4 \cdot 10^{-21}\ {\rm K} \left(\frac{a}{1\ {\rm m/s^2}}\right)$$

  - Similar situation for an observer in the vicinity of a black hole.

$$T_{\rm Hawking} = \frac{\hbar\, \kappa}{2\,\pi\, k} = 6 \cdot 10^{-8}\ {\rm K} \left(\frac{1\ M_\odot}{M_{\rm bh}}\right) ,$$

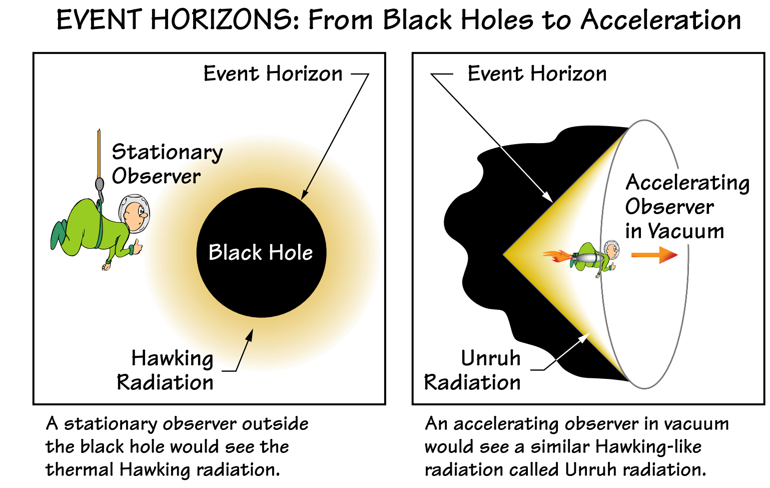


Fig. 1

[P. Chen/SLAC]

- Why interesting?
  - Unruh radiation similar to Hawking radiation [Hawking (1975)]
  - Possibility to study the physics of black holes in the laboratory

- **Experimental detection possibilities discussed:** [Rosu (1996)]

  – Hydrodynamical analogon to Schwarzschild-metric [Unruh (1981)]

  – Depolarisation of electrons in storage rings [Bell, Leinaas (1983÷87)]

  $T \approx 1200$ K at LEP/CERN; but: circular vs. linear Unruh effect? Thermal interpretation?

  – Crystall-“channeling” [Darbinian *et al.* (1989)]

  $a \approx 10^{31}$ m/s^2 for ultra-relativistic particles, $\gamma \sim 10^8$; bremsstrahlungs background problematic

  – Centripetal acceleration [Darbinian *et al.* (1990)]

  need $B \sim 5 \cdot 10^7$ G, $\gamma \sim 10^9$, in order to overcome synchrotron background

  – **Linear acceleration at the focus of an ultra-intensive laser**

  [Chen, Tajima (1999)]

- Accelerate electron in standing laser wave, $a \approx 10^{26}$ m/s^2
  – Modified zero-point fluctuations

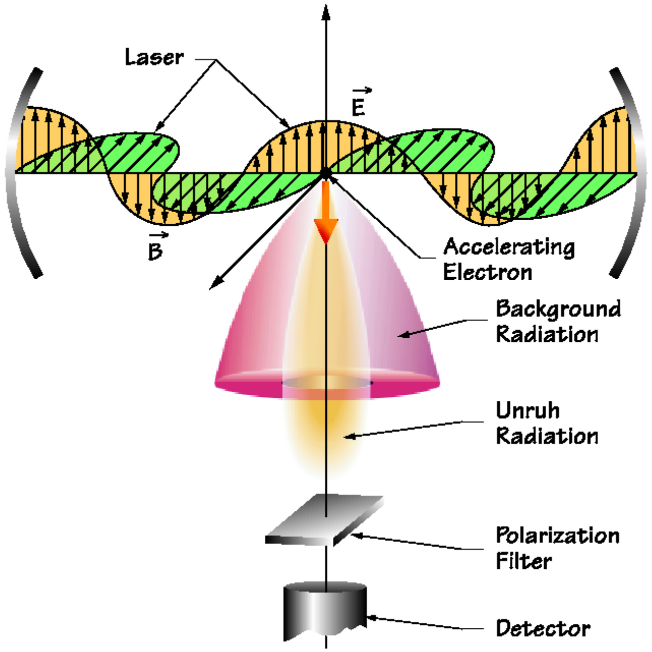
$$\langle E_i(-\tau/2)E_j(+\tau/2)\rangle = \frac{4\hbar}{\pi c^3}\delta_{ij}\frac{(a/c)^4}{\sinh^4(a\tau/2c)}$$

⇒ Additional jittering in the electron movement

⇒ Modified emitted radiation, in addition to classical Larmor radiation

  ∗ tilted thermal spectrum

  ∗ characteristic angular dependence



Schematic Diagram for Detecting Unruh Radiation

[P. Chen/SLAC]

3. Conclusions

- Have considered the possibility to study **non-perturbative spontaneous e^+e^- pair creation from vacuum** for the **first time in the laboratory**

- Still considerable improvement in X-ray FEL technology over presently considered design parameters necessary

- Although achievement of such demanding goal slow and laborious, **rewards that may be gained in this unique regime of high power densities are extraordinary and well worth the effort**