Ultra-high field physics with Petawatt and Exawatt lasers

New perspectives in fundamental physics

D. Habs, LMU Munich

A) Technique

- *Ultra-high fields from Petawatt- and Exawatt-Lasers: Phelix (GSI), PFS (Munich), ELI (Paris)*
- *Coherent harmonic focusing:* $E = 10^{18}\ V/m - 10^{22}\ V/m = 10\ MeV/fm$
- *Laser driven electron beams and FELs*

B) Fundamental and Hadron Physics

- e^+e^- *vacuum break down in high E-fields*
- π^0 *vacuum break down in high E-fields*
- *Unruh radiation; large acceleration* $a = 10^{23}$-$10^{32}\ g$, *very small event horizon* $d = c^2/a$

  quantum mechanics & general relativity, entangled states of the vacuum

Ultra-high field physics

Petawatt and Exawatt lasers

PHELIX (GSI)	PFS (MPQ Garching)	ELI (Europe)
2006	end 2007	2010
$\frac{500\,\mathrm{J}}{500\,\mathrm{fs}}$	$\frac{3\,\mathrm{J}}{3\,\mathrm{fs}}$	$\frac{10\,\mathrm{kJ}}{10\,\mathrm{fs}}$
3 shots/h	10/s	2/min
$\frac{1\,\mathrm{PW}}{(3\,\mu\mathrm{m})^2} \approx 10^{22}\,\mathrm{W/cm^2}$	$\frac{1\,\mathrm{PW}}{(1\,\mu\mathrm{m})^2} \approx 10^{23}\,\mathrm{W/cm^2}$	$\frac{1\,\mathrm{EW}}{(1\,\mu\mathrm{m})^2} \approx 10^{26}\,\mathrm{W/cm^2}$
$a_0 = 90$	$a_0 = 270$	$a_0 = 2700$
$E = 2 \cdot 10^{14}\,\mathrm{V/m}$	$E = 10^{15}\,\mathrm{V/m}$	$E = 10^{16}\,\mathrm{V/m}$
$E_{\mathrm{CHF}} = 2 \cdot 10^{17}\,\mathrm{V/m}$	$E_{\mathrm{CHF}} = 4 \cdot 10^{18}\,\mathrm{V/m}$	$E_{\mathrm{CHF}} = 1 \cdot 10^{21}\,\mathrm{V/m}$

relativistic units:

$E_0 = 3 \cdot 10^{12}\,\mathrm{V/m}$ $\qquad I_0 = 1.4 \cdot 10^{18}\,\mathrm{W/cm^2}$

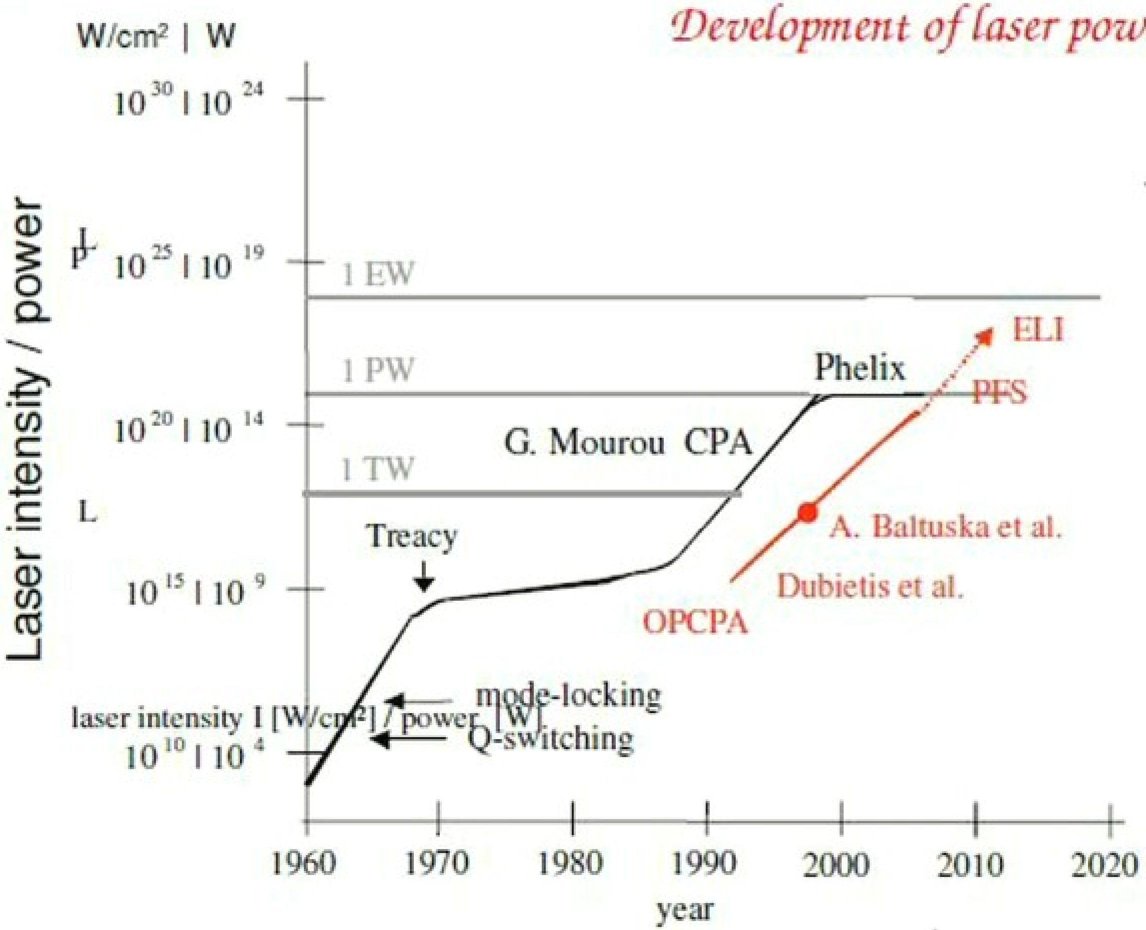
$E = a_0 \cdot E_0$ $\qquad I = a_0^2 \cdot I_0$

Schwinger limit for e^+e^- :

$E = 1.3 \cdot 10^{18}\,\mathrm{V/m}$

Ultra-high field physics

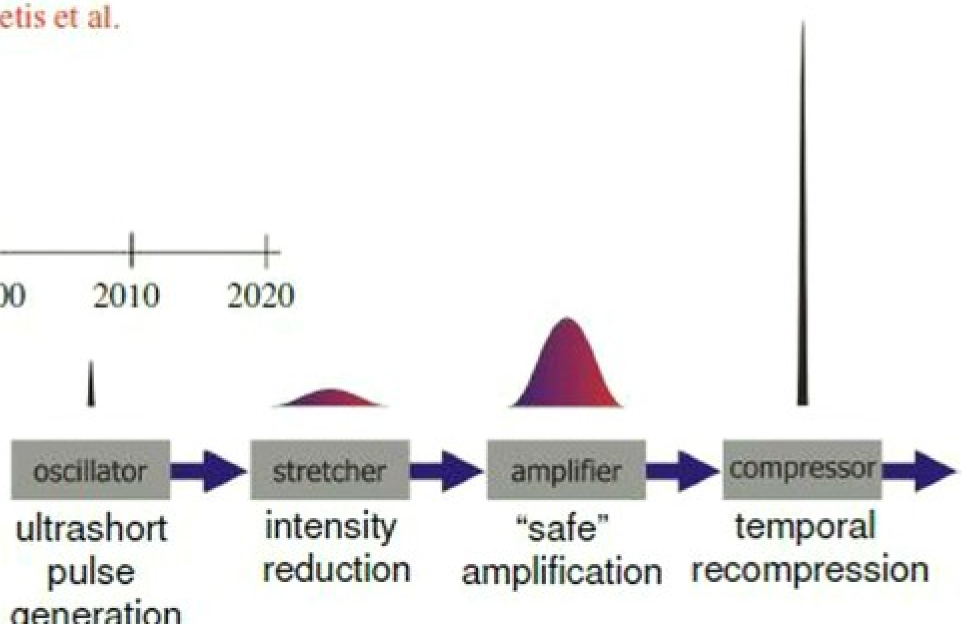
Development of laser power



1 PW = 10^6 nuclear power plants

to $(1 \mu m)^2$ => 10^{23} W/cm²

CPA
Chirped Pulse Amplification



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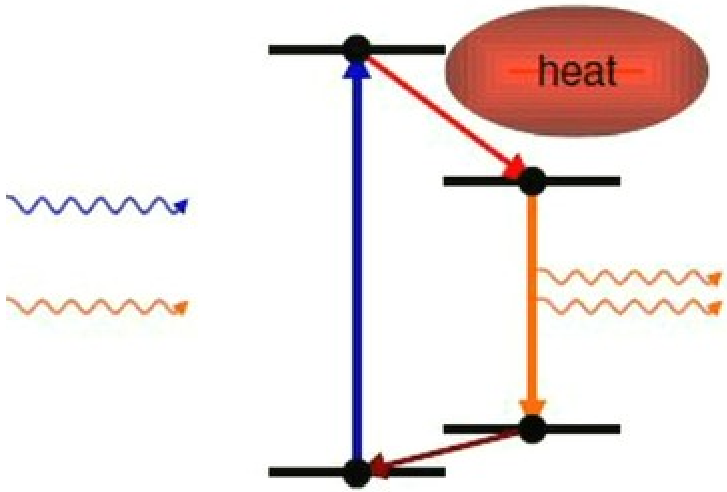
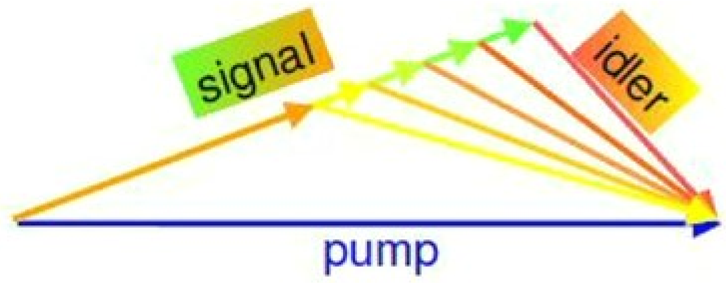
Laser Amplifier vs OPA (Optical Parametric Amplification)

Conventional laser amplifier:



OPA:



- ☺ Energy storage medium, easy pumping
- ☹ heat generation
- ☹ bandwidth limited by level structure

- ☺ no heat load
- ☺ broad and engineerable bandwidth
- ☹ exact synchronization needed

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Optical Parametric Chirped Pulse Amplification (OPCPA)

1992 Dubietis et al.
non-linear crystals BBO, KDP, periodically poled materials
three wave interaction; pump photon → signal + idler, full octave bandwidth

- ☺ low thermal effect
- ☺ great wavelength flexibility
- ☺ high gain per single pass
- ☺ reduced amplified spontaneous emission
- ☺ high contrast ratio
- ☺ high quantum efficiency
- ☺ high amplified signal beam quality
- ☺ scalability to high energies

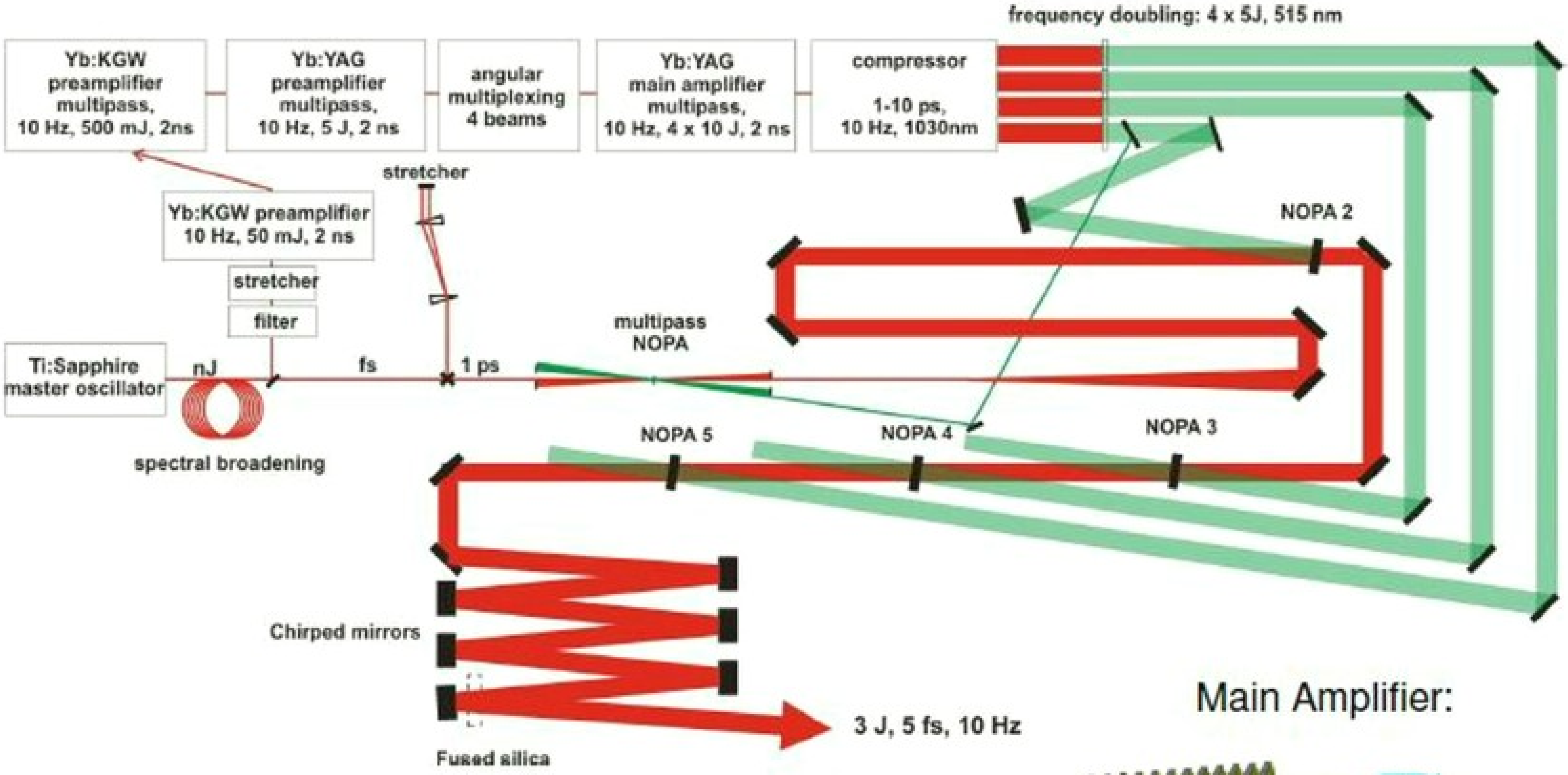
- ☹ precise pump + signal synchronisation
- ☹ amplified parametric fluorescence during pump pulse
- ☹ limited aperture of nonlinear crystal
- ☹ lack of pump energy accumulation

Achievements:

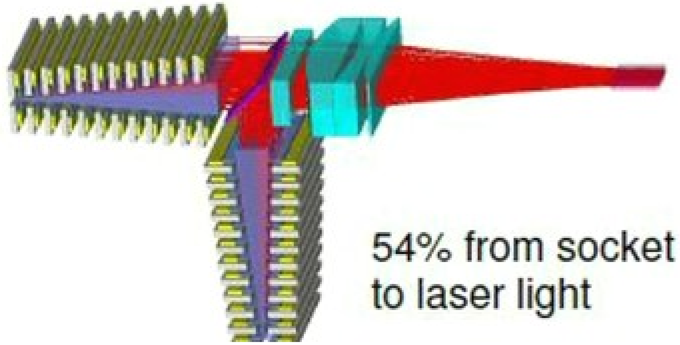
360 TW (2004); 34% conversion efficiency; $4 \cdot 10^{-11}$ contrast; 3.9 fs short pulse duration; high repetition rate; high average power output; multiple pump beams

Ultra-high field physics

Petawatt Field Synthesizer (PFS) @ MPQ



Main Amplifier:



54% from socket to laser light

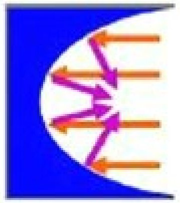
- Ti:Sapphire oscillator seeds pump and OPCPA beamline
→ optical synchronization
- 4-6 main single pass OPA stages in vacuum
- bulk glass / chirped mirror compressor
- 40 J, 10 Hz CPA Yb:YAG pump laser

Ultra-high field physics

Relativistic compression

relativistic laser intensity → strongly enhanced by relativistic interaction

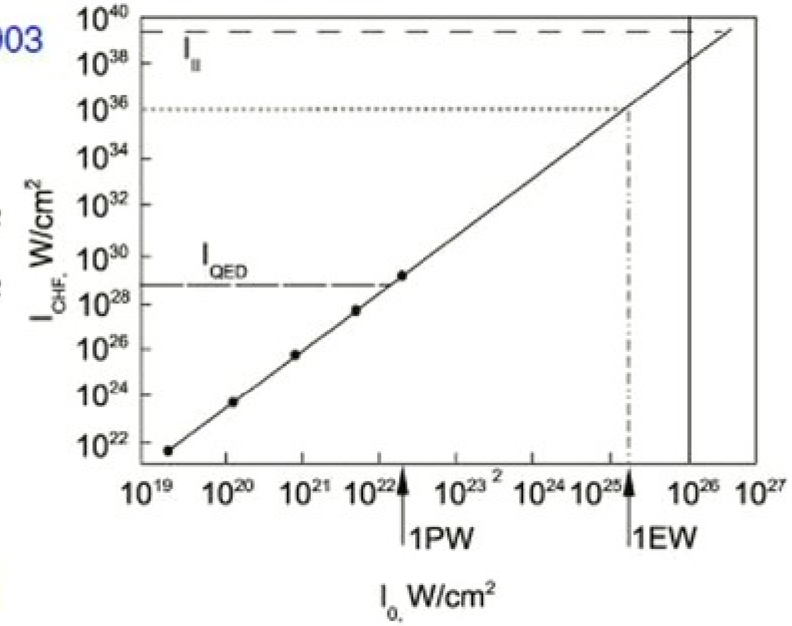
Resting mirror: S. Gordienko et al., PRL **94** (2005) 103903



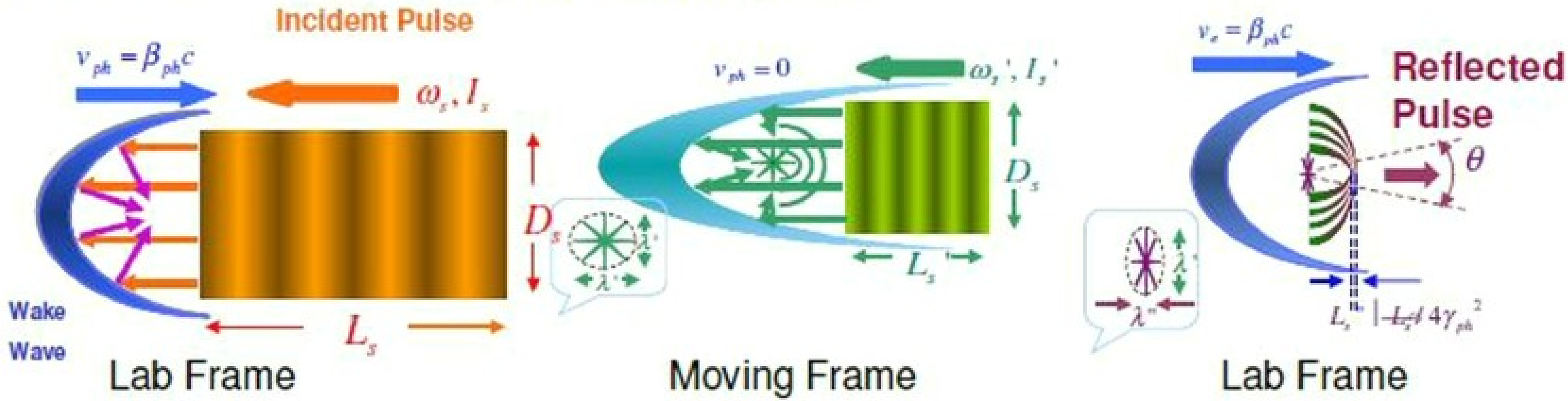
laser intensity $I_0 = a_0^2 \cdot 1.37 \cdot 10^{18}\,\mathrm{W/cm^2}$

coherent focused harmonic $I_{\mathrm{CHF}} = a_0^5 \cdot 1.37 \cdot 10^{18}\,\mathrm{W/cm^2}$

$$\left.\begin{array}{l} I_0 = 2 \cdot 10^{22}\,\mathrm{W/cm^2} \\ a_0 \approx 150 \end{array}\right\} \Rightarrow \begin{array}{l} I_{\mathrm{CHF}} = 5 \cdot 10^{29}\,\mathrm{W/cm^2} \\ \approx I_{e^+e^-} \end{array}$$

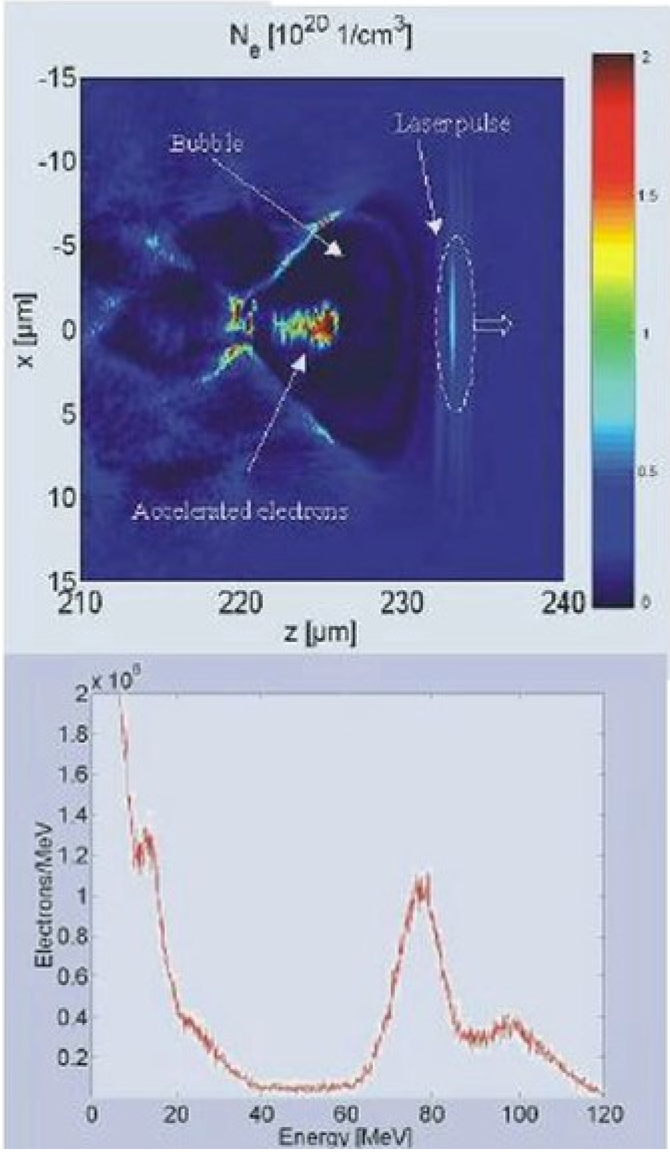


Flying mirror: S. V. Bulanov, PRL **91** (2003) 085001



Ultra-high field physics

Bubble acceleration of electrons



Theory: A. Pukhov, J. Meyer-ter-Vehn
Appl. Phys. **B 74** (2002) 355

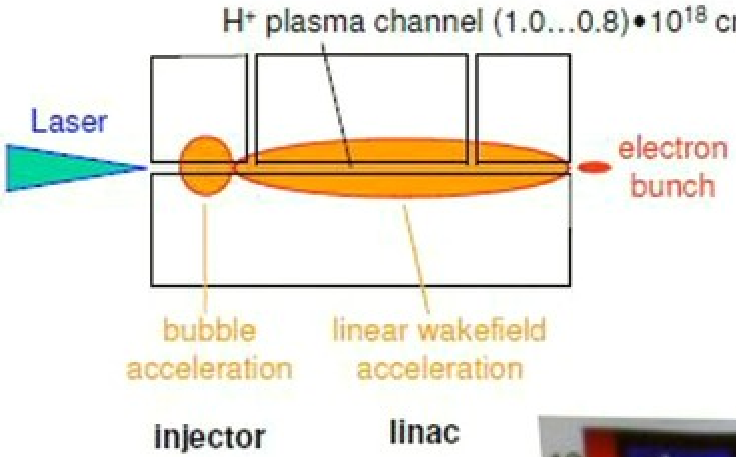
Electrons are pushed sidewards,
pulled back by cloud of positive ions λ_p
reinjected by wave-breaking;
stem of electrons;
soliton-like cloud structure;
transverse oscillating electric laser field
rectified into stationary longitudinal ion field

Result unexpected for published laser pulses:

Self focusing, self shortening

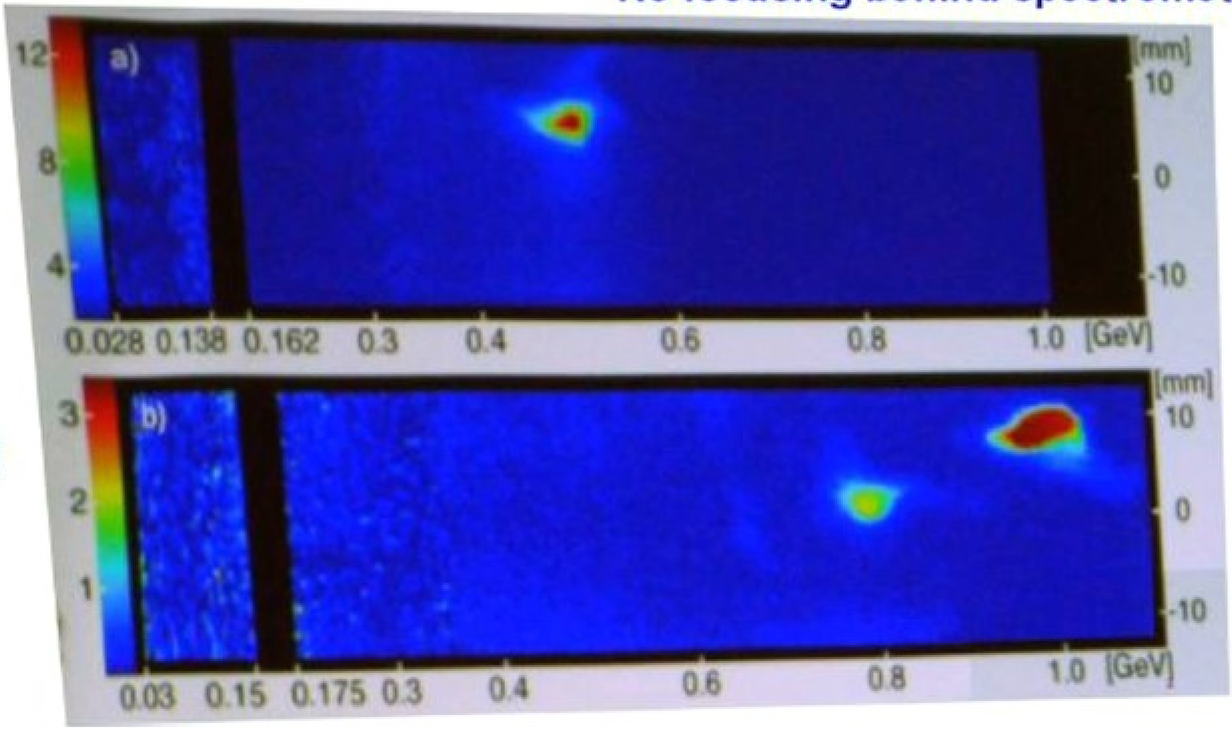
Ultra-high field physics

Laser capillary acceleration



- bubble acceleration, nonlinear wave breaking
  injection of electrons
- linear wave breaking acceleration in plasma channel
  mode guiding of laser

No focusing behind spectrometer!

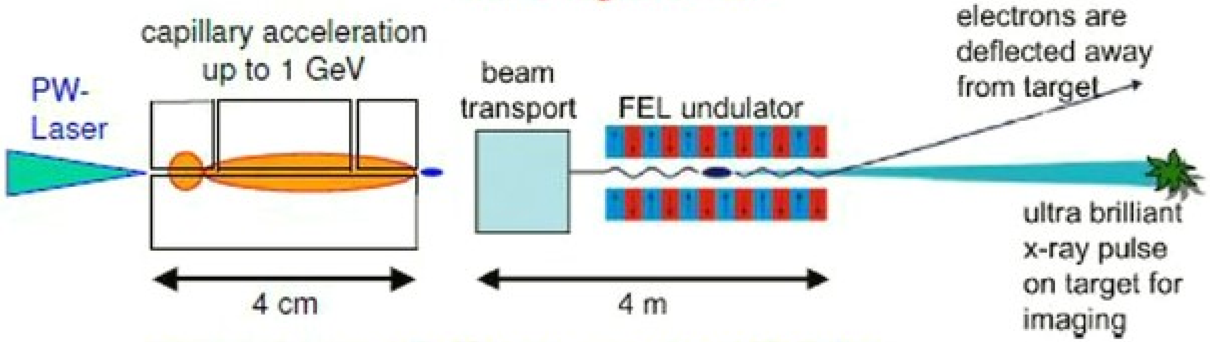


C. Geddes et al.

40 TW, 40 fs
up to 1.2 GeV,
350 pC,
$\Delta E/E < 2.5\%$, prob. 0.2%
probably $\epsilon_n = 1\pi$ mm mrad
$\Delta\theta < 1.6$ mrad

Ultra-high field physics

Table-top X-FEL



Comparison TT X-FEL vs. DESY X-FEL

Electron beam energy:	1 GeV	17 GeV
Accelerator length:	4 cm	3 km
Undulator length:	3 m	240 m
Emission wavelength:	1 Å	1 Å
Peak brilliance:	10^{34}	10^{34} photons/(s mm^2 mrad^2 0.1% BW)
Photons per bunch:	10^{12}	10^{12}
Repetition rate	0.01-1 kHz	56 kHz

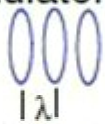
$$\frac{\sigma_\gamma}{\gamma} < \rho \quad ; \quad \frac{\varepsilon_n \lambda_u}{4\,\lambda_{\mathrm{FEL}}\,\beta} < \rho$$

- We have 10 x larger ρ and therefore reduced requirements on energy spread and emittance
- We have 20 x smaller electron beam energy, therefore:
- Maximum Energy $E_{\gamma max}$ limited by quantum fluctuations:

$$E_{\gamma max}(\mathrm{DESY}) \approx 15\ \mathrm{keV} \Leftrightarrow E_{\gamma max}(\mathrm{TT\text{-}XFEL}) \approx 100\ \mathrm{MeV}$$

Ultra-high field physics

Table-top FEL with laser-accelerated e^- beam

SASE-FEL: Self-Amplification of Spontaneous Emission
spontaneous undulator radiation acts back on electrons
micro-bunching  coherent emission

emission wavelength of FEL: $\lambda_L = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

gain length (ideal) of FEL: $L_{\mathrm{gain}} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$

Pierce parameter: $\rho = \frac{1}{2\gamma}\left[\left(\frac{I}{I_a}\right)\cdot\left(\frac{\lambda_u A_u}{2\pi\sigma_x}\right)^2\right]^{1/3}$, $(A_u \approx K)$

Gain length (real) of FEL: $L_{\mathrm{gain}}^{\mathrm{Xie\,Ming}} = L_{\mathrm{gain}}(1+\Lambda)$, $L_{\mathrm{sat}} \approx 15 \cdot L_{\mathrm{gain}}$

Main advantage of laser-accelerated electron beam: ~ 100 kA (classical: max 1 kA)

→ larger Pierce parameter

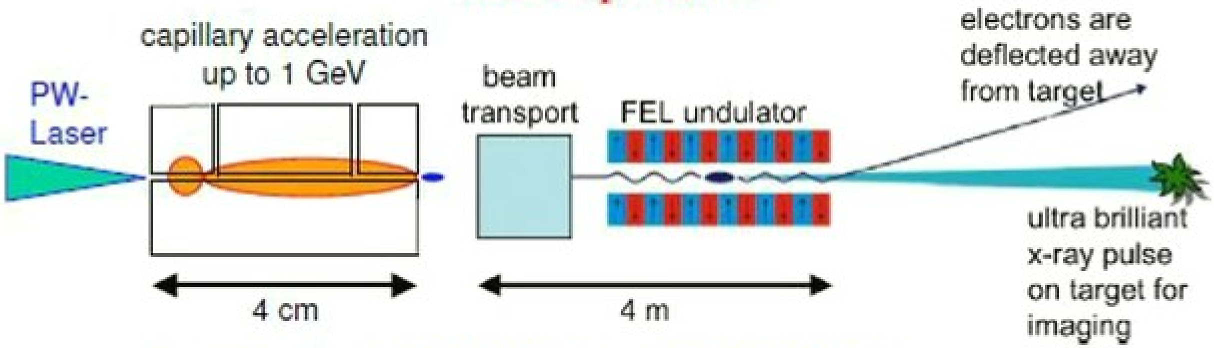
Saturation power: $P_{\mathrm{sat}} \sim \left(\frac{1}{1+\Lambda}\right)^2 \cdot (I \cdot \lambda_u)^{4/3}$

Same output power → smaller undulator parameter λ_u

Same emission wavelength → smaller electron beam energy (γ)

Ultra-high field physics

Table-top X-FEL



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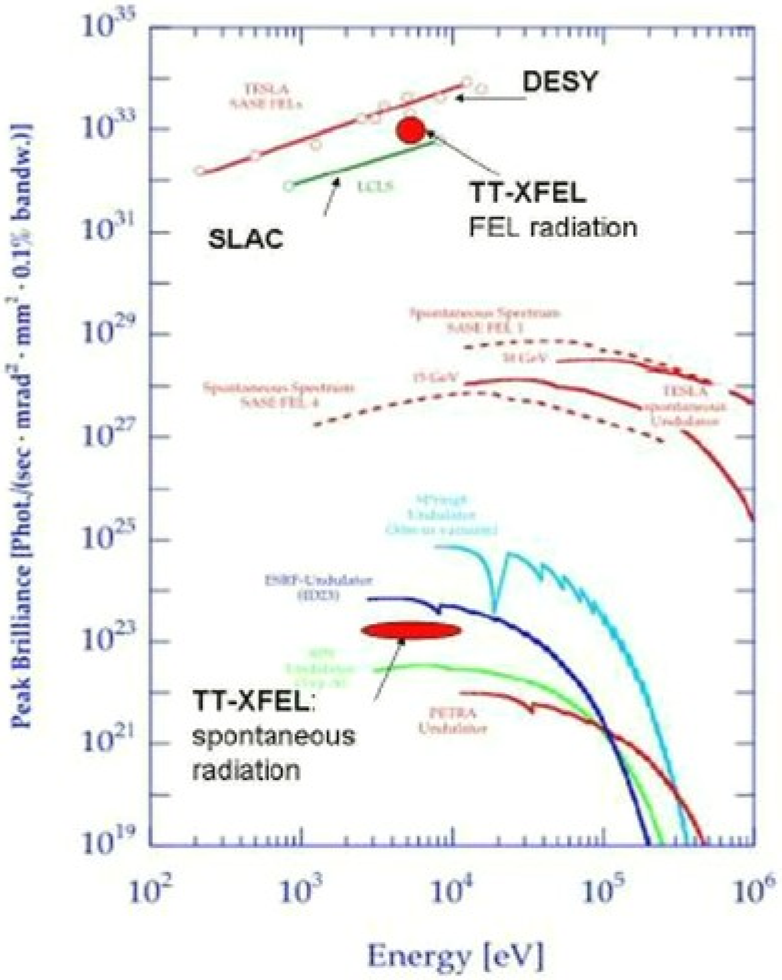
Ultra-high field physics

Undulator radiation

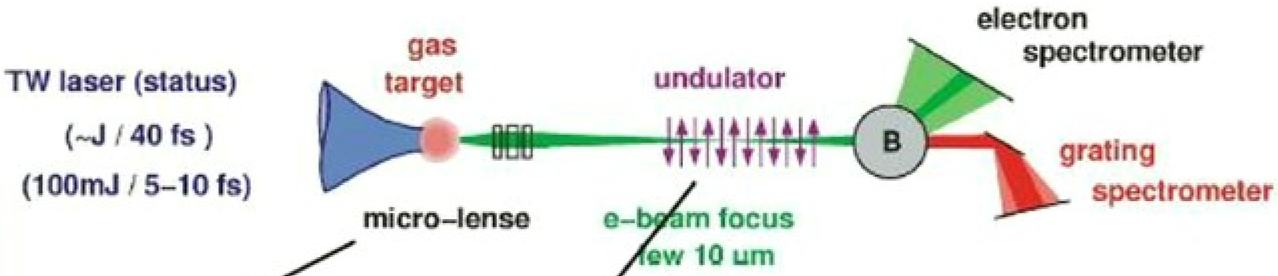


$$
\begin{aligned}
E_e &= 0.9\,\mathrm{GeV} \\
\lambda_\mathrm{u} &= 1.5\,\mathrm{m} \\
\varrho &= 0.002 \\
\text{undulator length} &= 3\,\mathrm{m} \\
E_\gamma &= 5\,\mathrm{keV}
\end{aligned}
$$

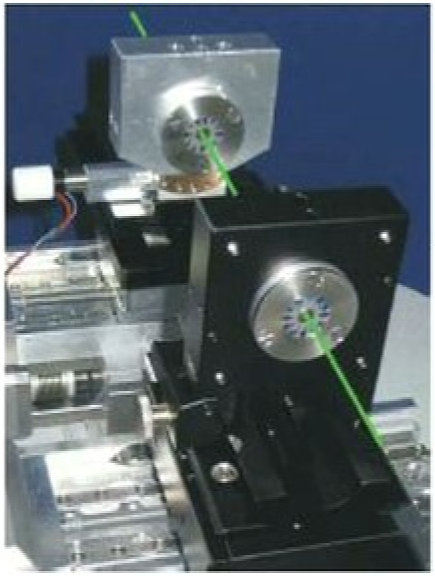
Tests at MAMI with classical electrons beams (1.5 keV – 1 MeV) together with H. Backe (Mainz)

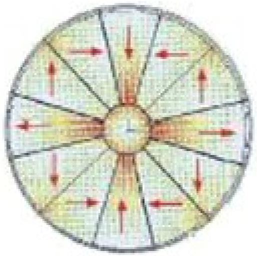
Ultra-high field physics

Table-top FEL with laser accelerated e⁻ beam (II)

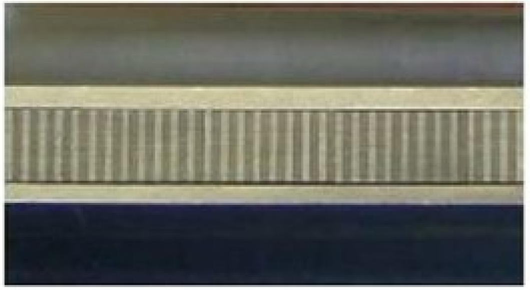


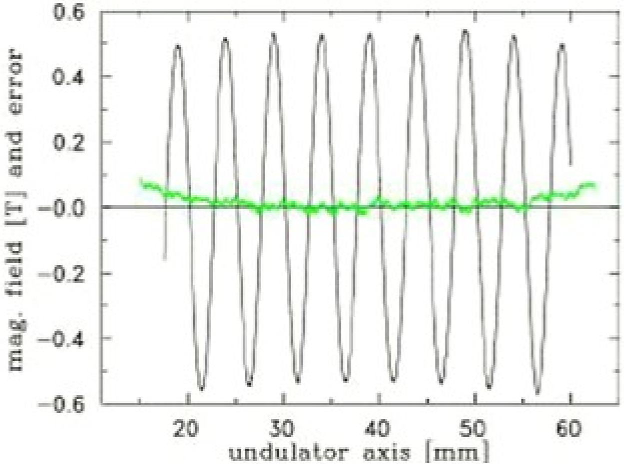
Miniaturized magnetic lens





Short period undulator





Ultra-high field physics

Advantages of table-top X-FEL

• compact	→	new applications, e. g. in hospitals
• cheap	→	more FELs are required, expensive classical FELs totally overbooked
• fs pulses	→	laser acceleration naturally very short pulses ideally suited for single molecule imaging
• fs timing	→	for pump-probe experiments classical FELs have ps timing, 4D imaging
• higher X-ray energies	→	due to 10 times larger Pierce parameter (limit of quantum fluctuations at higher energies) → MeV laser
• brilliant micro neutron beam	→	(γ,n)-reaction cold neutrons without moderation peak brilliance neutrons: B_n B_n (classical) $\approx 10^{-30}$ B_{FEL} 10^8 times more brilliant neutron beams can be produced

Ultra-high field physics

Schwinger limit and spontaneous pair creation

critical field strength for e^+e^- pair creation: $E_{(e^+e^-)}$

$$e \cdot E_{(e^+e^-)} \cdot \lambda_c = m_e c^2 = 511\,\text{keV} \quad \text{brings pair from virtual to real world}$$

Compton wavelength $\lambda_c = \dfrac{\hbar}{mc} = \dfrac{200\,\text{MeV}\cdot\text{fm}}{0.5\,\text{MeV}} = 400\,\text{fm}$

Electrical field strength $E_{(e^+e^-)} = \dfrac{m_e^2\,c^3}{e\hbar} = 1.3 \cdot 10^{18}\,\text{V/m}$

Laser intensity $I_{(e^+e^-)} = \dfrac{c\,E^2_{(e^+e^-)}}{4\pi} = 4.6 \cdot 10^{29}\,\text{W/cm}^2$

Laser energy W in volume λ^3: $W = 4\pi\, I_{(e^+e^-)}\,\lambda^3/3c = 6 \cdot 10^7\,\text{J}\left(\dfrac{\lambda}{\mu\text{m}}\right)^3$

critical acceleration $a = \dfrac{e\,E_{(e^+e^-)}}{m_0} = 2.3 \cdot 10^{29}\,\text{m/s} = 2 \cdot 10^{28}\,g$

Fermions:
Pauli blocking

critical field strength for $\pi^+\pi^-$ pair creation: E_π with $m_\pi c^2 = 140\,\text{MeV}$

$$E_\pi = \frac{(m_\pi c^2)^2}{e\hbar c} = 1.0 \cdot 10^{23}\,\text{V/m} \qquad I_\pi = \frac{cE_\pi^2}{4\pi} = 2.4 \cdot 10^{39}\,\text{W/cm}^2$$

Bosons:
Bose condensate

Ultra-high field physics

Spontaneous pair creation close to the Schwinger limit

$$\xi = \frac{E}{E_{e^+e^-}}$$ field strength in units of critical field strength

$$\frac{\text{rate}}{\text{cm}^3\,\text{s}} \sim \alpha^2 \times \text{field energy density} \times \text{barrier penetration factor}$$

$$\sim \alpha^2 \cdot E^2 \cdot e^{-\frac{8}{3\xi}} \sim 10^{50}\,\xi^2\,e^{-\frac{8}{3\xi}}\,\frac{\text{pairs}}{\text{s}\cdot\text{cm}^3}$$

$$10^6/\text{Å}^3(0.1\,\text{as}) \quad \text{at} \quad a_{e^+e^-}$$

high field expels electrons

target leptons produced in the high field region by pair creation

Ultra-high field physics

Vacuum breakdown to e^+e^- in high E-fields

no experimental observation until now!

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

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

very different predictions: $10^8\, e^+e^-$ $\quad 10^{18}\,\mathrm{W/cm^2}; 1\,\mu\mathrm{m}, 10\,\mathrm{fs}$

H. K. Avetissian et al., Phys. Rev. **E 66** (2002) 016502

$0.09\, e^+e^-$ $\quad 4 \cdot 10^{27}\,\mathrm{W/cm^2}; 1\,\mu\mathrm{m}, 10\,\mathrm{fs}$

V. S. Popov et al., Phys. Lett. **A 330** (2004) 1

$10\, e^+e^-$ $\quad 10^{20}\,\mathrm{W/cm^2}; 1\,\mu\mathrm{m}, 10\,\mathrm{fs}$

D. G. Blaschke et al., Phys. Rev. Lett. **96** (2006) 140402

strongly nonlinear QED, exponential tunnel factor difficult to estimate.

more simple estimates in the allowed region beyond the Schwinger limit.

dependence on field-invariants $F = \vec{E}^2 - \vec{B}^2$ and $G = \vec{E} \cdot \vec{B}$

is there Pauli-blocking? back reaction?

Ultra-high field physics

Vacuum breakdown to π⁰s in high E-fields (I)

$$P_s = e^+e^- \to 2\gamma \; (2 \cdot 511\,\mathrm{keV}) \quad \Longleftrightarrow \quad \pi^0 = \sqrt{1/2}\,(d\bar{d} - u\bar{u}) \to 2\gamma \; (2 \cdot 67.5\,\mathrm{MeV})$$

$$J^{PC} = 0^{-+} \qquad \tau = 0.1\,\mathrm{ns} \qquad\qquad J^{PC} = 0^{-+} \qquad \tau = 0.8 \cdot 10^{-16}\,\mathrm{s}$$

high E-field + virtual $e^+e^- \to$ real e^+e^- $\Longleftrightarrow$ high E-field + virtual $d\bar{d} - u\bar{u} \to$ real confined π^0

$$E_{e^+e^-} = \frac{m_e^2 c^3}{e\hbar} = 1.3 \cdot 10^{18}\,\mathrm{V/m} \qquad\qquad E_{\pi^0} = \left(\frac{135\,\mathrm{MeV}}{1.0\,\mathrm{MeV}}\right)^2 \cdot E_{e^+e^-} = 2.4 \cdot 10^{22}\,\mathrm{V/m}$$

$$R_{e^+e^-} = \frac{\mathrm{rate}}{\mathrm{cm}^3\,\mathrm{s}} \propto \alpha^2 \cdot E^2 \cdot e^{-\frac{8}{3}\frac{E_{e^+e^-}}{E}} = \frac{10^6}{\text{Å}^3}\frac{c}{\text{Å}} \text{ for } E = E_{e^+e^-} \quad \Longleftrightarrow \quad R_\pi = \left(\frac{0.1\,\mathrm{ns}}{0.8 \cdot 10^{-16}\,\mathrm{s}}\right)\left(\frac{1\,\mathrm{MeV}}{135\,\mathrm{MeV}}\right)^2\left(\frac{E_\pi}{E_{e^+e^-}}\right)^2 \cdot R_{e^+e^-} \approx \frac{10^4}{(60\,\mathrm{fm})^3} \cdot \frac{c}{60\,\mathrm{fm}}$$

P_s is ripped apart by strong E-field into accelerated e^+e^- $\Longleftrightarrow$ π^0 consists of confined $q\bar{q}$

π^0 polarized, but stays neutral in its ground state

2 fermions, Pauli blocking

linear production in time of individual e^+e^-

cold boson

condensation into few phase space cells.

exponential growth, until all high-field energy is converted to π^0s.

$$\text{energy} = \frac{10^{38}\,\mathrm{W}}{\mathrm{cm}^2} \cdot (60\,\mathrm{fm})^2 \cdot \frac{60\,\mathrm{fm}}{c} = 5\,\mu\mathrm{J} \mathrel{\hat{=}} \frac{2 \cdot 10^5\,\pi^0}{(60\,\mathrm{fm})^3} \mathrel{\hat{=}} 1/(\mathrm{fm})^3$$

Ultra-high field physics

Vacuum breakdown to π^0's in high E-fields (II)

new π-physics: $10^5\,\pi$ with $1\pi/\mathrm{fm}^3$ interact via attractive resonances $(\sigma, \rho, \ldots)$

Bose-Einstein condensation with small scattering length $0.06\,\mathrm{fm}$

contraction to quark-gluon condensate?

observation of the decay of higher resonances?

contraction to micro-black hole (Stöcker et al.)

Ultra-high field physics

Unruh-radiation and Hawking-radiation

W. B. Unruh (1976)

An observer in a frame with acceleration a sees an isotropic black-body radiation with temperature T_{Unruh}:

$$kT_{\mathrm{Unruh}} = \frac{\hbar a}{2\pi c}$$

quantum field theory & general relativity (with curved coordinates)
particle horizon at $d = c^2/a$, hyperbolic space-time trajectory
beyond d light cannot catch up with particle.
observer cannot see complete space time, complete quantum state
W. Unruh, Phys. Rev. **D 14** (1976) 870

Stephen Hawking (1974)

In the very strong gravitational fields of a black hole with mass M quantum fluctuations result in a thermal radiation with temperature T_{H}:

$$kT_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G M} = \frac{\hbar g}{2\pi c} \qquad \left(g = \frac{c^4}{4GM}\right)$$

black hole has a Schwarzschild radius $R_{\mathrm{Schw}} = \frac{2GM}{c^2}$
From inside the Schwarzschild radius no light can get out.
S. Hawking, Nature **248** (1974) 30; Commun. Math. Phys. **43** (1975) 199

Ultra-high field physics

Naïve plausible estimates

Unruh radiation:	virtual photon of energy E for time $\Delta t \sim \hbar/E$ (uncertainty principle) Force $F = a \cdot \frac{E}{c^2}$ Energy gain $\Delta E = F \cdot \Delta x = F \cdot c \cdot \Delta t = a \cdot \frac{E}{c^2} \cdot c\,\Delta t = \frac{a\hbar}{c} = 2\pi\, kT_{\mathrm{Unruh}}$
Creation of e^+-e^- pair outside Schwarzschild radius:	virtual e^+-e^- pair created with total energy E for time $\Delta t \sim \hbar/E$ maximum distance: $\Delta r = c\,\Delta t \sim c\hbar/E$ difference in gravitational force:

$$\Delta F = \frac{2GM}{r^3} \cdot \Delta r \cdot \frac{E}{c^2} \sim \frac{GM}{r^3}\,\frac{\hbar}{c}$$

For pair creation $\Delta F \cdot \Delta r \approx E$; largest value of E at $r = R_{\mathrm{Schw}}$:

$$E \approx \frac{GM\hbar}{r^3\,c} \cdot \frac{c\hbar}{E} \quad \Rightarrow \quad E \approx \hbar\sqrt{\frac{GM}{r^3}} \approx \hbar\sqrt{\frac{GM}{(2GM/c^2)^3}} \approx \frac{\hbar c^3}{GM} = 8\pi k T_{\mathrm{H}}$$

one real particle can escape while other drops into black hole

Ultra-high field physics

Proposed measurements of Hawking effect and Unruh effect in the laboratory

- Unruh effect in storage rings

$$a \sim 10^{22}\, g, \quad T_{\mathrm{U}} = 1200\,\mathrm{K}$$

incomplete spin polarisation J.S. Bell et al., Nucl. Phys. **B 284** (1987) 488

- Unruh effect in traps

$$a \sim 10^{21}\, g, \quad T_{\mathrm{U}} \sim 2.4\,\mathrm{K}$$

electron in Penning trap J. Rogers, Phys. Rev. Lett. **61** (1988) 2113

- Unruh effect at non-adiabatic Casimir effect

$$a \sim 10^{20}\, g, \quad T_{\mathrm{U}} \sim 1\,\mathrm{K}$$

E. Yablonovitch, Phys. Rev. Lett. **62** (1989) 1742

- Unruh effect at ultra-intense lasers

P. Chen and T. Tajima, Phys. Rev. Lett. **83** (1999) 256

Ultra-high field physics

Unruh-radiation at the Schwinger limit in the laboratory

$$kT_{\mathsf{U}} = \frac{\hbar a}{2\pi c} = \frac{\hbar}{2\pi c}\frac{m_e^2 c^3}{\hbar m_e} = \frac{m_e c^2}{2\pi} = 81\,\mathsf{keV}$$

We observe the Unruh-radiation after Compton-backscattering from the electron for an acceleration a and a velocity β:

$$E_\gamma = kT_{\mathsf{U}}(1+\beta)\gamma \approx kT_{\mathsf{U}} \cdot 2\gamma \qquad (\gamma = 1.15, \beta = 0.5)$$

We work with constant field strength $E_{e^+e^-}$ not constant acceleration.

$$E_\gamma = \frac{\hbar}{2\pi c}\left(\frac{eE_{e^+e^-}}{\gamma \cdot m_e c^2}\right) 2\gamma \approx 160\,\mathsf{keV}$$

with longer interaction the mass of the electron increases with γ and the acceleration a decreases, but the γ-energy remains the same.

Ultra-high field physics

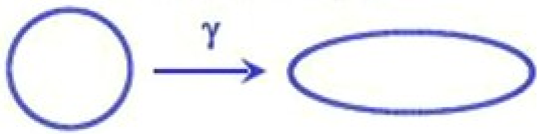
Intensity and angular distribution of Unruh-radiation in the laboratory

Power of Unruh radiation in instantaneous rest frame:

$$\frac{\mathrm{d}U_{\mathsf{Unruh}}}{\mathrm{d}\tau} = \text{scattering cross section} \times \text{energy flux of thermal radiation}$$

$$\begin{aligned}
\sigma_{\mathsf{Thomson}} &= \frac{8\pi}{3} r_0^2 \quad \text{with} \quad r_0 = \frac{e^2}{m_0 c^2} = 2.8\,\text{fm} = \text{classical electron radius} \\
\frac{\mathrm{d}U}{\mathrm{d}\nu} &= \frac{8\pi}{c^3} \frac{h\nu^3}{e^{h\nu/kT} - 1} = \text{Planck energy density} \\
\frac{\mathrm{d}^2 U_{\mathsf{Unruh}}}{\mathrm{d}\tau\,\mathrm{d}\nu} &= \frac{8\pi}{c^3} \frac{h\nu^3}{e^{h\nu/kT} - 1} \cdot \frac{8\pi}{3} r_0^2 \\
\frac{\mathrm{d}^2 U}{\mathrm{d}\tau\,\mathrm{d}\Omega} &= \frac{\hbar r_0^2 a^4}{90\pi c^6} \frac{1}{4\pi} \qquad (\text{Stefan Boltzmann:} \quad T^4 \propto a^4) \\
\frac{\mathrm{d}^2 U}{\mathrm{d}t\,\mathrm{d}\Omega} &= \frac{\hbar r_0^2 a^4}{90\pi c^2} \cdot \frac{1}{4\pi} \cdot \frac{1}{\gamma^3 (1 - \vec{n}\vec{\beta})^3} = \frac{\hbar r_0 a^4}{90\pi c^2} \cdot \frac{1}{4\pi} \cdot \frac{8\gamma^3}{(1 + \theta^2\gamma^2)^3}
\end{aligned}$$

isotropic distribution
forward boost with



but smaller γ-values
strongly weighted due to a^4

for $\gamma_{\max} = 100$ reduced intensity by factor 100,

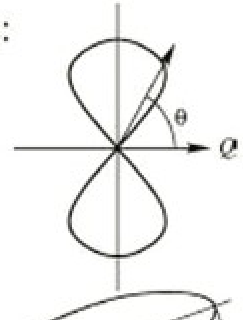
strong forward peaking

Ultra-high field physics

Larmor acceleration at the Schwinger limit

Classical electrodynamics (Jackson): Larmor radiation of particle with acceleration a:

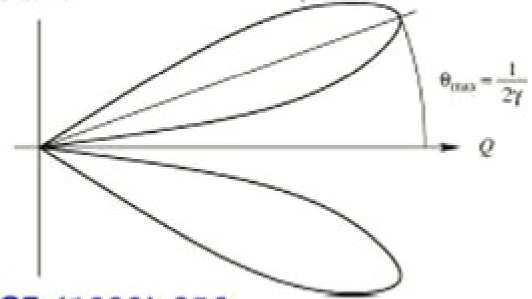
$$\frac{\mathrm{d}^2 U}{\mathrm{d}\tau\,\mathrm{d}\Omega} = \frac{e^2}{4\pi c^3}\, a^2 \cdot \sin^2\theta$$



relativistic invariant $\left(\frac{\mathrm{d}p_\mu}{\mathrm{d}\tau}\cdot\frac{\mathrm{d}p^\mu}{\mathrm{d}\tau}\right)$ and linear acceleration only $\propto a^2$ not $\propto a^4$.

Unruh and Larmor are comparable at $a = 3\cdot 10^{30} g$.

$$\frac{\mathrm{d}^2 U}{\mathrm{d}t\,\mathrm{d}\Omega} = \frac{1}{4\pi}\,\frac{e^2}{m^2c^2}\left(\frac{\mathrm{d}p}{\mathrm{d}\tau}\right)^2 \frac{\sin^2\theta}{(1-\beta\cos\theta)^5}$$



blind spot in acceleration direction. P. Chen and T. Tajima, PRL **83** (1999) 256

$$\frac{\mathrm{d}^2 U}{\mathrm{d}\omega\,\mathrm{d}\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^2}\, e^{i\omega(t-\vec{n}\cdot\vec{r}(t))/c}\,\mathrm{d}t\right|^2$$

Integrand $\neq 0$ for $\dot\beta \neq 0$

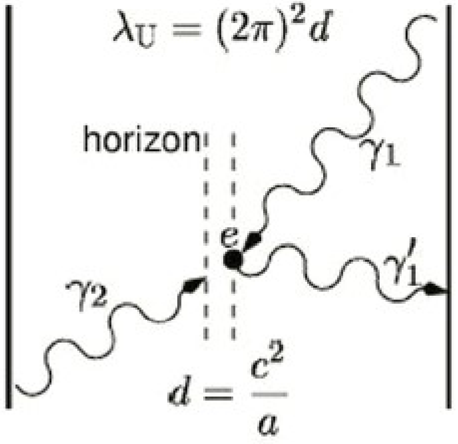
Fourier transformed of E-pulse duration

$\hbar = 6.6\cdot 10^{-22}$ MeV s

$\Delta t = 0.1$ as $\hat{=}$ 7 keV

Ultra-high field physics

Einstein-Podolsky-Rosen correlation



The accelerated electron e converts vacuum fluctuations of its surrounding into a real γ_1 (thermal Unruh) photon. This liberates due to correlated fluctuations a real photon γ_2 from **behind** the electron horizon $d = c^2/a$ with the opposite direction and the same energy.

Photon γ_1 is scattered by the electron resulting in photon γ_1' (Klein-Nishina cross-section; predominantly in forward direction with preserved polarisation)

W. Unruh, R. Wald, Phys. Rev. **D 29** (1984) 1047

In the laboratory we observe the two strongly correlated photons γ_1' and γ_2 including the Lorentz-boost. We can calculate the energy of γ_1' from the energy of γ_2 and the scattering angle. Additionally, the polarisation should be opposite.

Identifying the EPR photons for non-inertial systems would be a further step beyond identifying Unruh photons.

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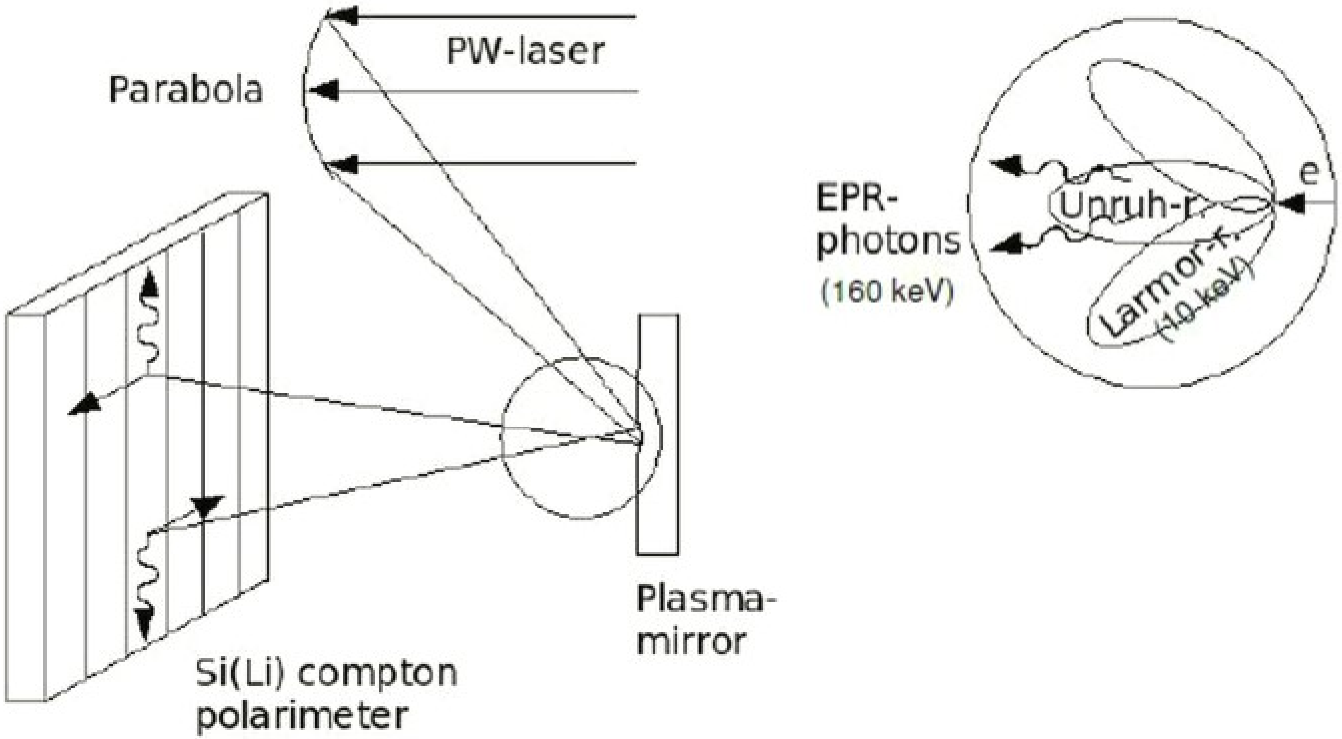
Planned Unruh experiment



- single shot: energy spectra of Larmor & Unruh radiation
  angular distribution of Larmor & Unruh radiation
- study of 511 keV production and high harmonics
- *E*-field (10^{18} V/m for 0.15 as) acceleration of e^+ and e^-,
  10^6 e^+e^- pairs/shot

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Questions and future of Unruh radiation

- Unruh spectrum $\stackrel{?}{=}$ Planck spectrum,
  thermal features distinct from statistical thermodynamics
- Is there an interference term between Larmor and Unruh radiation?
  Addition of driving forces?
- highly correlated state with EPR-correlations
- non-linear terms? Could a virtual e^+e^- pair collect laser photons and emit correlated pairs?
- we learn more about vacuum fluctuations which are important for dark energy
- short pulse Pauli-blocking in phase space for fermions
  reduced e^+e^- production $\Rightarrow$ field strength beyond Schwinger limit possible
  e^+ and e^- are opposite going and compensate applied field
  absolute field stength limit $E_\pi \approx 10^{23}$ V/m
- Bosons have many particles in phase cell, no free quarks, contraction of π cloud, attractive potential?

Ultra-high field physics

Unruh radiation at the highest field strength

electron at $E = 10^{21}\,\mathrm{V/m}$; $a = \lambda \cdot 10^{31} g$; event horizon $d \approx 0.5\,\mathrm{fm}$

$$k \cdot T_{\mathrm{Unruh}} \approx 100\,\mathrm{MeV}$$

π^0 may occur in Unruh-spectrum, if scattered of the electron

a second EPR-π^0 occurs behind the horizon and we should observe two entangled π^0s.

very small event horizon $\quad \longleftrightarrow \quad$ curled-up extra dimensions

Hagedorn temperature $200\,\mathrm{MeV}$: phase transition to quark-gluon plasma