arXiv:hep-ph/0304139 v1 15 Apr 2003

DESY 03-039
hep-ph/0304139

BOILING THE VACUUM WITH AN X-RAY FREE ELECTRON LASER*

A. RINGWALD
Deutsches Elektronen-Synchrotron DESY,
Notkestraße 85,
D-22607 Hamburg, Germany
E-mail: andreas.ringwald@desy.de

X-ray free electron lasers will be constructed in this decade, both at SLAC in the form of the so-called Linac Coherent Light Source as well as at DESY, where the so-called TESLA XFEL laboratory uses techniques developed for the design of the TeV energy superconducting electron-positron linear accelerator TESLA. Such X-ray lasers may allow also for high-field science applications by exploiting the possibility to focus their beams to a spot with a small radius, hopefully in the range of the laser wavelength. Along this route one obtains very large electric fields, much larger than those obtainable with any optical laser of the same power. We consider here the possibility of obtaining an electric field so high that electron-positron pairs are spontaneously produced in vacuum (Schwinger pair production) and review the prospects to verify this non-perturbative production mechanism for the first time in the laboratory.

1. Introduction

Spontaneous particle creation from vacuum induced by an external field was first proposed in the context of e^+e^- pair production in a static, spatially uniform electric field[1] and is often referred to as the Schwinger[2] mechanism. It is one of the most intriguing non-linear phenomena in quantum field theory. Its consideration is theoretically important, since it requires one to go beyond perturbation theory, and its eventual experimental observation probes the theory in the domain of strong fields. Moreover, this mechanism has been applied to many problems in contemporary physics, ranging from black hole quantum evaporation[3] and e^+e^- creation in the vicinity of charged black holes[4], giving rise possibly to gamma ray bursts[5], to particle production in hadronic collisions[6] and in the early universe[7], to mention only a few. One may consult the monographs[8] for a review of further applications, concrete calculations and a detailed bibliography.

*Invited talk presented at the Workshop on QUANTUM ASPECTS OF BEAM PHYSICS, January 7–11, 2003, Hiroshima, Japan.

It is known since the early 1930's that in the background of a static, spatially uniform electric field the vacuum in quantum electrodynamics (QED) is unstable and, in principle, sparks with spontaneous emission of e^+e^- pairs[1]. However, a sizeable rate for spontaneous pair production requires extraordinary strong electric field strengths $\mathcal{E}$ of order or above the critical value

$$\mathcal{E}_c \equiv \frac{m_e\, c^2}{e\, \lambda\!\!\!^{-}_e} = \frac{m_e^2\, c^3}{e\, \hbar} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}\,. \tag{1}$$

Otherwise, for $\mathcal{E} \ll \mathcal{E}_c$, the work of the field on a unit charge e over the Compton wavelength of the electron $\lambda\!\!\!^{-}_e = \hbar/(m_e c)$ is much smaller than the rest energy $2\, m_e c^2$ of the produced e^+e^- pair, the process can occur only via quantum tunneling, and its rate is exponentially suppressed, $\propto \exp[-\pi\, \frac{\mathcal{E}_c}{\mathcal{E}}]$.

Unfortunately, it seems inconceivable to produce macroscopic static fields with electric field strengths of the order of the critical field (1) in the laboratory. In view of this difficulty, in the early 1970's the question was raised whether intense optical lasers could be employed to study the Schwinger mechanism[9,10]. Yet, it was found that all available and conceivable optical lasers did not have enough power density to allow for a sizeable pair creation rate[9,10,11,12,13,14,15,16,17,18,19]. At about the same time, the thorough investigation of the question started whether the necessary superstrong fields around $\mathcal{E}_c$ can be generated microscopically and transiently in the Coulomb field of colliding heavy ions with $Z_1 + Z_2 > Z_c \approx 170$[20]. At the present time, clear experimental signals for spontaneous positron creation in heavy ion collisions are still missing and could only be expected from collisions with a prolonged lifetime[21].

Meanwhile, there are definite plans for the construction of X-ray free electron lasers (FEL), both at SLAC, where the so-called Linac Coherent Light Source[22,23] (LCLS) is under construction, as well as at DESY, where the so-called TESLA XFEL uses techniques developed for the design of the TeV energy superconducting e^+e^- linear accelerator TESLA[24,25,26]. Such X-ray lasers may possibly allow also for high-field science applications[27,28,29,30,31]: One could make use of not only the high energy and transverse coherence of the X-ray beams, but also of the possibility to focus them to a spot with a small radius σ, hopefully in the range of the laser wavelength, $\sigma \gtrsim \lambda \simeq \mathcal{O}(0.1)$ nm. In this way one might obtain very large electric fields,

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

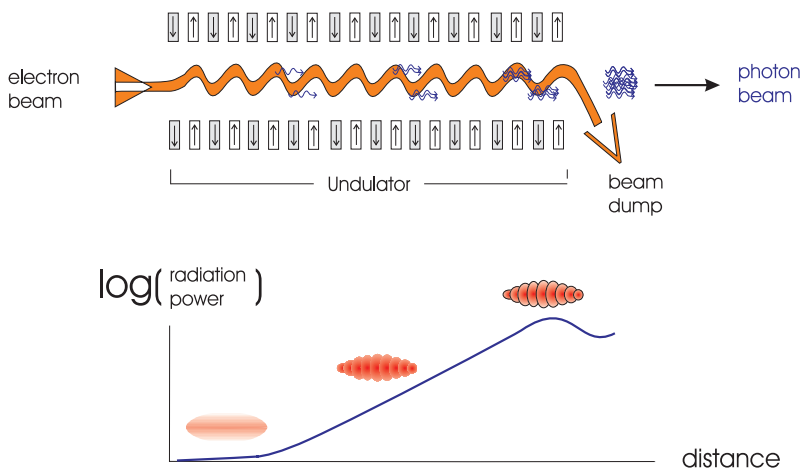

Figure 1. Principle of a single-pass X-ray free electron laser in the self amplified spontaneous emission mode[26].

much larger than those obtainable with any optical laser of the same peak power P. Thus, X-ray FELs may be employed possibly as vacuum boilers[28].

In this contribution, I will review recent work on spontaneous e^+e^- pair production at the focus of future X-ray FELs[32,33,34,35] and discuss the prospects to verify this non-perturbative production mechanism for the first time in the laboratory.

2. X-Ray Free Electron Lasers

Let us start by briefly reviewing the principle of X-ray free electron lasers.

Conventional lasers yield radiation typically in the optical band. The reason is that in these devices the gain comes from stimulated emission from electrons bound to atoms, either in a crystal, liquid dye, or a gas. The amplification medium of free electron lasers[36], on the other hand, is *free*, i.e. unbounded, electrons in bunches accelerated to relativistic velocities with a characteristic longitudinal charge density modulation (cf. Fig. 1).

The basic principle of a single-pass free electron laser operating in the self amplified spontaneous emission (SASE) mode[37] is as follows. It functions by passing an electron beam pulse of energy E_e of small cross section and high peak current through an undulator – a long periodic magnetic structure (cf. Fig. 1). The interaction of the emitted synchrotron radiation, with opening angle

$$1/\gamma = m_e c^2/E_e = 2 \cdot 10^{-5} \ \ (25 \ \mathrm{GeV}/E_e) \ , \tag{3}$$

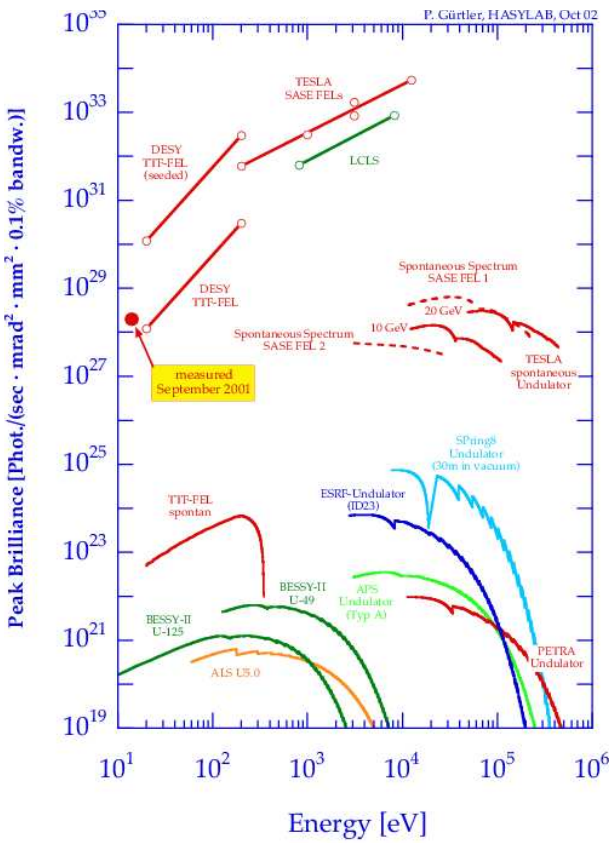

Figure 2. Spectral peak brilliance of X-ray FELs and undulators for spontaneous radiation at TESLA, together with that of third generation synchrotron radiation sources[26]. For comparison, the spontaneous spectrum of an X-ray FEL undulator is shown.

where m_e is the electron mass, with the electron beam pulse within the undulator leads to the buildup of a longitudinal charge density modulation (micro bunching), if a resonance condition,

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K_U^2}{2}\right) = 0.3\ \mathrm{nm}\ \left(\frac{\lambda_U}{1\,\mathrm{m}}\right)\left(\frac{1/\gamma}{2\cdot 10^{-5}}\right)^2\left(\frac{1+K_U^2/2}{3/2}\right)\ , \quad (4)$$

is met. Here, λ is the wavelength of the emitted radiation, λ_U is the length of the magnetic period of the undulator, and K_U is the undulator parame-

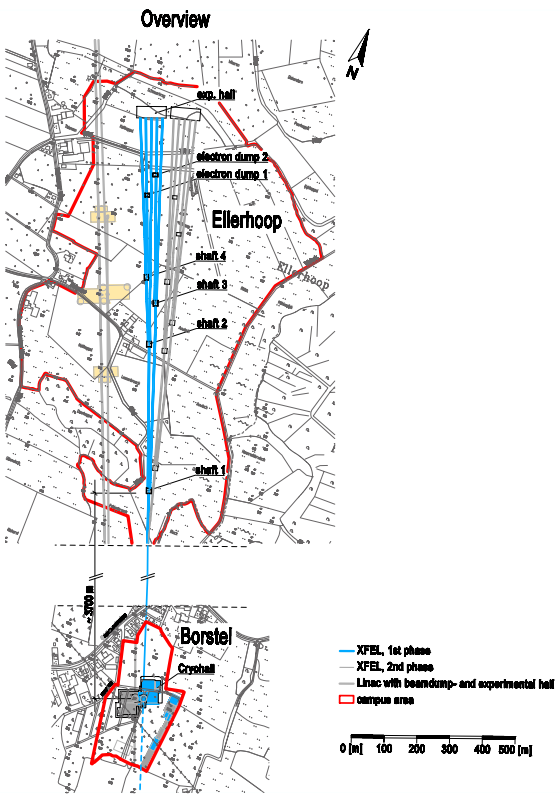

Figure 3. The TESLA XFEL campus North-West of the DESY laboratory[26], whose commissioning is expected in 2010. The XFEL electron beam is accelerated by a dedicated 20 GeV linear accelerator (linac) starting at a supply hall $\approx$ 4 km south of the XFEL laboratory. The XFEL linac tunnel runs under a small angle of 2° with respect to the tunnel of the future TESLA linac, which is shown in grey color.

ter,

$$K_{\mathrm{U}} = \frac{e\lambda_{\mathrm{U}} B_{\mathrm{U}}}{2\pi m_e c}\,, \tag{5}$$

which gives the ratio between the average deflection angle of the electrons in the undulator magnetic field B_{U} from the forward direction and the typical opening cone of the synchrotron radiation. The undulator parameter should be of order one on resonance. The electrons in the developing micro bunches eventually radiate coherently – the gain in radiation power P,

$$P \propto e^2\, N_e^2\, B_{\mathrm{U}}^2\, \gamma^2\,, \tag{6}$$

over the one from incoherent spontaneous synchrotron radiation ($P \propto N_e$) being proportional to the number $N_e \geq 10^9$ of electrons in a bunch (cf. Fig. 2) – and the number of emitted photons grows exponentially until saturation is reached. The radiation has a high power, short pulse length, narrow bandwidth, is fully polarized, transversely coherent, and has a tunable wavelength.

The concept of using a high energy electron linear accelerator for building an X-ray FEL was first proposed for the Stanford Linear Accelerator[22]. The LCLS at SLAC is expected to provide the first X-ray laser beams in 2008. The feasibility of a single-pass FEL operating in the SASE mode has been demonstrated recently down to a wavelength of 80 nm using electron bunches of high charge density and low emittance from the linear accelerator at the TESLA test facility (TTF) at DESY[38] (cf. Fig. 2). Some characteristics of the radiation from the planned X-ray FELs at the TESLA XFEL laboratory[26] (cf. Fig. 3), whose commissioning is expected in 2010, are listed in Table 1.

Table 1. Properties of X-ray FELs at the TESLA XFEL laboratory.

	unit	SASE 1	SASE 3	SASE 5
wavelength	nm	$0.1 \div 0.5$	$0.1 \div 0.24$	$0.4 \div 5.8$
bandwidth (FWHM)	%	0.08	0.08	$0.29 \div 0.7$
peak power	GW	37	22	$110 \div 200$
average power	W	210	125	$610 \div 1100$
photon beam size (rms)	μm	43	53	$25 \div 38$
peak power density	W/m^2	$6 \cdot 10^{18}$	$3 \cdot 10^{18}$	$6 \cdot 10^{19}$

3. Semi-classical Rate Estimates

We now turn to the main subject of our contribution, namely the spontaneous pair production at the focus of future X-ray FELs. We will elaborate in this section on a simplified approximation concerning the electromagnetic field of the laser radiation which retains the main features of the general case but nevertheless allows to obtain final expressions for the pair production rate in closed form. This should be sufficient for an order-of-magnitude estimate of critical parameters to be aimed at to get an observable effect.

It is well known that no pairs are produced in the background of a light-like static, spatially uniform electromagnetic field[2], characterized invariantly by

$$\mathcal{F} \equiv \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \equiv -\frac{1}{2} \left(\mathbf{E}^2 - c^2 \mathbf{B}^2 \right) = 0 \,, \tag{7}$$

Table 2. Laser parameters and derived quantities relevant for estimates of the rate of spontaneous e^+e^- pair production. The column labeled "Optical" lists parameters which are typical for a petawatt-class (1 PW = 10^{15} W) optical laser, focused to the diffraction limit, $\sigma = \lambda$. The column labeled "Design" displays design parameters of the planned X-ray FELs at DESY (Table 1). Similar values apply for LCLS. The column labeled "Focus: Available" shows typical values which can be achieved with present day methods of X-ray focusing: It assumes that the X-ray FEL X-ray beam can be focused to a rms spot radius of $\sigma \simeq 21$ nm with an energy extraction efficiency of 1 %. The column labeled "Focus: Goal" shows parameters which are theoretically possible by increasing the energy extraction of LCLS (by the tapered undulator technique) and by a yet unspecified method of diffraction-limited focusing of X-rays.

Laser Parameters				
	Optical	**X-ray FEL**		
	Focus: Diffraction limit	Design	Focus: Available	Focus: Goal
λ	1 μm	0.4 nm	0.4 nm	0.15 nm
$\hbar\,\omega = \frac{hc}{\lambda}$	1.2 eV	3.1 keV	3.1 keV	8.3 keV
P	1 PW	110 GW	1.1 GW	5 TW
σ	1 μm	26 μm	21 nm	0.15 nm
$\triangle t$	500 fs ÷ 20 ps	0.04 fs	0.04 fs	0.08 ps
Derived Quantities				
$S = \frac{P}{\pi\sigma^2}$	$3 \times 10^{26}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$5 \times 10^{19}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$8 \times 10^{23}\ \frac{\mathrm{W}}{\mathrm{m}^2}$	$7 \times 10^{31}\ \frac{\mathrm{W}}{\mathrm{m}^2}$
$\mathcal{E} = \sqrt{\mu_0\, c\, S}$	$4 \times 10^{14}\ \frac{\mathrm{V}}{\mathrm{m}}$	$1 \times 10^{11}\ \frac{\mathrm{V}}{\mathrm{m}}$	$2 \times 10^{13}\ \frac{\mathrm{V}}{\mathrm{m}}$	$2 \times 10^{17}\ \frac{\mathrm{V}}{\mathrm{m}}$
$\mathcal{E}/\mathcal{E}_c$	3×10^{-4}	1×10^{-7}	1×10^{-5}	0.1
$\frac{\hbar\omega}{m_e c^2}$	2×10^{-6}	0.006	0.006	0.02
$\eta = \frac{\hbar\omega}{e\,\mathcal{E}\,\lambda_c}$	9×10^{-3}	6×10^{4}	5×10^{2}	0.1

$$\mathcal{G} \equiv \frac{1}{4}\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv c\,\mathbf{E}\cdot\mathbf{B} = 0\,, \tag{8}$$

where $F^{\mu\nu}$ is the electromagnetic field strength tensor and $\tilde{F}^{\mu\nu} = (1/2)\,\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$ its dual. It has been argued that fields produced by focusing laser beams are very close to such a light-like electromagnetic field, leading to an essential suppression of pair creation[12]. Yet, in a focused wave there are regions near the focus where $\mathcal{F} < 0$ and pair production is possible[9,27]. For other fields, $\mathcal{F}$ and $\mathcal{G}$ do not vanish, and pair production becomes possible, unless $\mathcal{G} = 0$, $\mathcal{F} > 0$, corresponding to a pure magnetic field in an appropriate coordinate system[2]. In particular, one expects pair creation in the background of a spatially uniform electric field oscillating with a frequency ω, say

$$\mathbf{E}(t) = (0, 0, \mathcal{E}\cos(\omega t))\,, \qquad \mathbf{B}(t) = (0, 0, 0)\,, \tag{9}$$

which has $\mathcal{G} = 0$, $\mathcal{F} < 0$. As emphasized in Refs.[13,15,16,28], such a field

may be created in an antinode of the standing wave produced by a superposition of two coherent laser beams with wavelength

$$\lambda = \frac{2\pi c}{\omega}\,, \tag{10}$$

and, indeed, it may be considered as spatially uniform at distances much less than the wavelength.

Thus, for definiteness, we assume that every X-ray laser pulse is split into two equal parts and recombined to form a standing wave with locations where the electromagnetic field has the form (9) and where the peak electric field is given by Eq. (2). Alternatively, one may consider pair creation in the overlap region of two lasers, whose beams make a fixed angle to each other[19]. Furthermore, we assume that the field amplitude $\mathcal{E}$ is much smaller than the critical field, and the photon energy is much smaller than the rest energy of the electron,

$$\mathcal{E} \ll \mathcal{E}_c\,, \qquad \hbar\omega \ll m_e c^2\,; \tag{11}$$

conditions which are well satisfied at realistic X-ray lasers (cf. Table 2). Under these conditions, it is possible to compute the rate of e^+e^- pair production in a semi-classical manner, using generalized WKB or imaginary-time (instanton) methods[10,11,18,19,39]. Here, the ratio η of the energy of the laser photons over the work of the field on a unit charge e over the Compton wavelength of the electron,

$$\eta = \frac{\hbar\omega}{e\mathcal{E}\lambda\!\!\!^{-}_e} = \frac{\hbar\,\omega}{m_e c^2}\,\frac{\mathcal{E}_c}{\mathcal{E}} = \frac{m_e c\,\omega}{e\,\mathcal{E}}\,, \tag{12}$$

plays the role of an adiabaticity parameter. Indeed, the probability that an e^+e^- pair is produced per unit time and unit volume,

$$w = \frac{\mathrm{d}\, n_{e^+e^-}}{\mathrm{d}^3x\,\mathrm{d}t}\,, \tag{13}$$

depends on the laser frequency only through the adiabaticity parameter η and reads, in the limiting cases of small and large η, as follows[32,35]

$$w \simeq \frac{c}{4\,\pi^3 \lambda\!\!\!^{-}_e{}^4} \times \tag{14}$$

$$\times \begin{cases} \frac{\sqrt{2}}{\pi}\left(\frac{\mathcal{E}}{\mathcal{E}_c}\right)^{\frac{5}{2}} \exp\left[-\pi\,\frac{\mathcal{E}_c}{\mathcal{E}}\left(1-\frac{1}{8}\eta^2+\mathcal{O}(\eta^4)\right)\right]\,, & :\eta \ll 1\,, \\ \sqrt{\frac{\pi}{2}}\left(\frac{\hbar\,\omega}{m_e c^2}\right)^{\frac{5}{2}} \sum_{n>2\frac{m_e c^2}{\hbar\omega}} \left(\frac{e}{4\eta}\right)^{2n} \mathrm{e}^{-2\left(n-2\frac{m_e c^2}{\hbar\omega}\right)} \times & \\ \times\, \mathrm{Erfi}\left(\sqrt{2\left(n-2\frac{m_e c^2}{\hbar\omega}\right)}\right) & :\eta \gg 1\,, \end{cases}$$

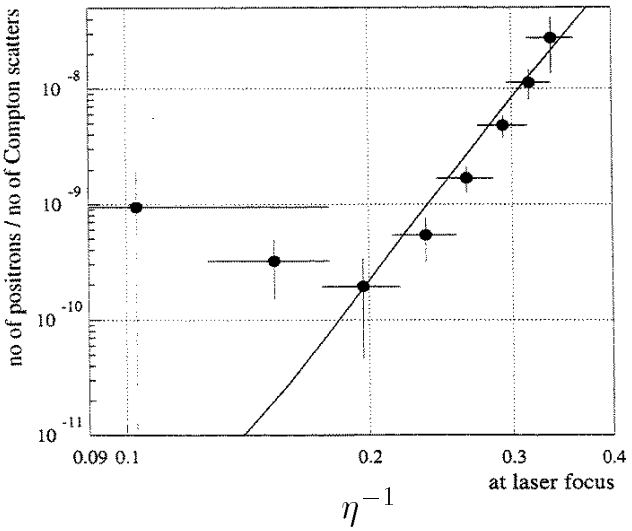

Figure 4. The positron rate per laser shot as a function of the inverse of the adiabaticity parameter, η^{-1}, as measured by the SLAC experiment E-144[40]. The line is a power law fit to the data which gives $R_{e+} \propto \eta^{-2n}$, with $n = 5.1 \pm 0.2\,(\mathrm{stat})^{+0.5}_{-0.8}\,(\mathrm{syst})$.

where Erfi is the imaginary error function. This result agrees in the adiabatic high-field, low-frequency limit, $\eta \ll 1$, with the non-perturbative Schwinger result[2] for a static, spatially uniform field, if a proper average over an oscillation period is made. In the non-adiabatic low-field, high-frequency limit, $\eta \gg 1$, on the other hand, it resembles a perturbative result: it corresponds to the $\geq n$-th order perturbation theory, n being the minimum number of quanta required to create an e^+e^- pair: $n \gtrsim 2\,m_e c^2/(\hbar\omega) \gg 1$.

At this point it seems appropriate to discuss the question whether – as argued in Ref.[27] – the non-perturbative Schwinger pair creation mechanism has already been demonstrated by the SLAC experiment E-144[40]. This experiment studied positron production in the collision of 46.6 GeV/c electrons with terawatt optical ($\lambda = 527$ μm) laser pulses. In the rest frame of the incident electrons, an electrical field strength of about 38 % of the critical field (1), $\mathcal{E} \simeq 5 \cdot 10^{17}$ V/m, was reached. The values of the adiabaticity parameter η probed were therefore in the range $\eta \simeq 3 \div 10$ (cf. Fig. 4), i.e. in the non-adiabatic, perturbative multi-photon regime. Correspondingly, in Refs.[40,41] the data were convincingly interpreted in terms of

multi-photon light-by-light scattering. Indeed, the observed positron production rate scales as $R_{e^+} \propto \eta^{-10}$ (cf. Fig. 4). This is in good agreement with the fact that the rate of perturbative multi-photon reactions involving n laser photons is proportional to η^{-2n} for $\eta \gg 1$, Eq. (14), and with the kinematic requirement that five photons are needed to produce a pair near threshold.

For an X-ray laser ($\hbar\omega \simeq 1 \div 10$ keV), the adiabatic, non-perturbative, strong field regime, $\eta \lesssim 1$, starts to apply for $\mathcal{E} \gtrsim \hbar\omega\, \mathcal{E}_c/(m_e c^2) \sim 10^{15 \div 16}$ V/m (cf. Eq. (12)). An inspection of the rate (14) leads then to the conclusion that one needs an electric field of about $0.1\,\mathcal{E}_c \sim 10^{17}$ V/m in order to get an appreciable amount of spontaneously produced e^+e^- pairs[32]. To this end one needs either a terawatt X-ray or a tens of exawatt optical laser.

In Table 2 we have summarized the relevant parameters for the planned X-ray FELs[32]. We conclude that the power densities and electric fields which can be reached with presently available technique (column labeled "Focus: Available" in Table 2) are far too small for a sizeable effect. On the other hand, if the energy extraction can be improved considerably, such that the peak power of the planned X-ray FELs can be increased to the terawatt region, and if X-ray optics can be improved[42] to approach the diffraction limit of focusing, leading to a spot size in the 0.1 nanometer range, then there is ample room (c. f. column labeled "Focus: Goal" in Table 2) for an investigation of the Schwinger pair production mechanism at X-ray FELs. At the moment it is hard to predict whether this goal will be reached before the commissioning of exawatt-zettawatt optical lasers[43].

4. Quantum Kinetic Studies

More information about the details of the Schwinger mechanism accessible at the focus of an X-ray laser can be obtained via approaches based on quantum kinetics. In Refs.[33,34], quantum Vlasov equations, derived within a mean-field treatment of QED[44], were employed to obtain a description of the time evolution of the momentum distribution function for the particles produced via vacuum decay in the background of a spatially uniform external electric field of the form (9). It was found that – for realistic laser parameters (cf. Table 2) – pair production will occur in cycles that proceed in tune with the laser frequency (cf. Fig. 5). The peak density of produced pairs, however, is frequency independent, with the consequence that several hundred pairs could be produced per laser period, in accord with the

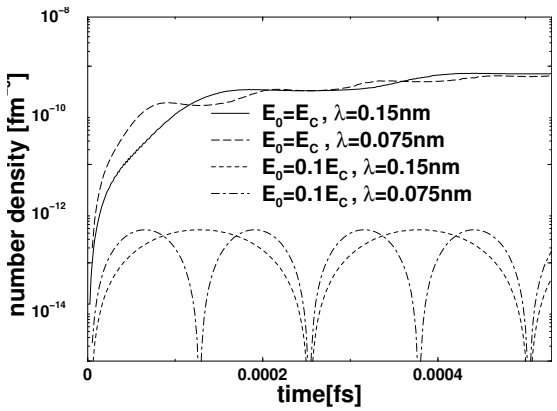

Figure 5. Time evolution of the number density of produced e^+e^- pairs at the focus of an X-ray laser[33]. In strong fields, particles accumulate, leading to the almost complete occupation of available momentum states. In weak fields, repeated cycles of particle creation and annihilation occur in tune with the laser frequency.

Schwinger rate. For even higher peak electric fields, $\mathcal{E} \gtrsim 0.25\,\mathcal{E}_c$ – possibly achievable at a 9 TW X-ray FEL (cf. Table 2) – particle accumulation and the consequent formation of a plasma of spontaneously produced pairs is predicted[34] (cf. Fig. 6). The evolution of the particle number in the plasma will exhibit then non-Markovian aspects, and the plasma's internal currents will generate an electric field whose interference with that of the laser leads to plasma oscillations[34]. This feature persists even if – in distinction to Refs.[33,34] – one takes into account collision terms in the quantum Vlasov equations[45].

5. Conclusions

We have considered the possibility to study non-perturbative spontaneous e^+e^- pair creation from vacuum for the first time in the laboratory. We have seen that for this application still some improvement in X-ray FEL technology over the presently considered design parameters is necessary. Intensive development in technical areas, particularly in that of X-ray optics, will be needed in order to achieve the required ultra-high power densities. It should be pointed out, however, that even though progress to achieve such a demanding goal is rather slow and laborious, the rewards that may be gained in this unique regime are so extraordinary that looking into TESLA XFEL's or LCLS's extension to this regime merits serious considerations.

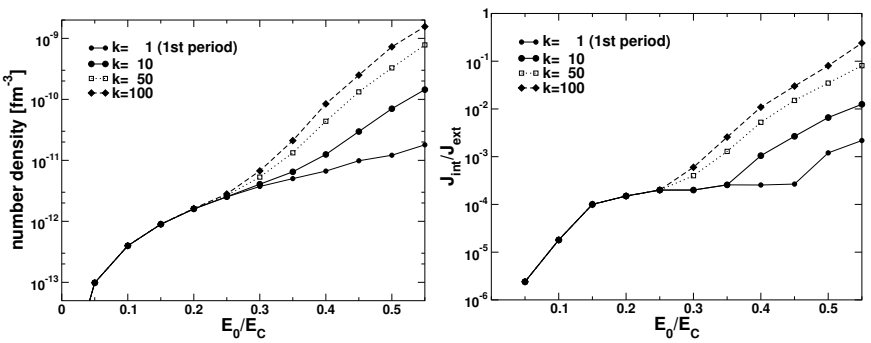

Figure 6. *Left:* Peak particle number density versus laser field strength[34]. The qualitative change at $E_0 \approx 0.25\,E_c$ marks the onset of particle accumulation. *Right:* Internal to external peak current ratio[34]: field-current feedback becomes important for $E_0 \gtrsim 0.25\,E_c$.

No doubt, there will be unprecedented opportunities to use these intense X-rays in order to explore some issues of fundamental physics that have eluded man's probing so far.

References

1. F. Sauter, Z. Phys. **69**, 742 (1931); W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936).
2. J. Schwinger, Phys. Rev. **82**, 664 (1951).
3. S. W. Hawking, Nature **248**, 30 (1974); Commun. Math. Phys. **43**, 199 (1975); T. Damour and R. Ruffini, Phys. Rev. D **14**, 332 (1976); G. W. Gibbons and M. J. Perry, Proc. Roy. Soc. Lond. **358**, 467 (1978); S. P. Gavrilov and D. M. Gitman, Phys. Rev. D **53**, 7162 (1996); M. K. Parikh and F. Wilczek, Phys. Rev. Lett. **85**, 5042 (2000).
4. T. Damour and R. Ruffini, Phys. Rev. Lett. **35**, 463 (1975).
5. G. Preparata, R. Ruffini and S. S. Xue, Astron. Astrophys. **338**, L87 (1998); J. Korean Phys. Soc. **42**, S99 (2003); R. Ruffini, C. L. Bianco, P. Chardonnet, F. Fraschetti, L. Vitagliano and S. S. Xue, astro-ph/0302557; L. Vitagliano, these proceedings; S. S. Xue, these proceedings.
6. A. Casher, H. Neuberger, and S. Nussinov, Phys. Rev. D **20**, 179 (1979); B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rept. **97**, 31 (1983); T. S. Biro, H. B. Nielsen, and J. Knoll, Nucl. Phys. B **245**, 449 (1984).
7. L. Parker, Phys. Rev. **183**, 1057 (1969); N. D. Birrell and P. C. Davies, *Quantum Fields in Curved Space* (Cambridge University Press, 1982).
8. W. Greiner, B. Müller, and J. Rafelski, *Quantum Electrodynamics of Strong Fields* (Springer-Verlag, Berlin, 1985); A. A. Grib, S. G. Mamaev, and V. M. Mostepanenko, *Vacuum Quantum Effects in Strong Fields* (Atomiz-

dat, Moscow, 1988; Friedmann Laboratory Publishing, St. Petersburg, 1994); E. S. Fradkin, D. M. Gitman, and Sh. M. Shvartsman, *Quantum Electrodynamics with Unstable Vacuum* (Springer-Verlag, Berlin, 1991).
9. F. V. Bunkin and I. I. Tugov, Dokl. Akad. Nauk Ser. Fiz. **187**, 541 (1969) [Sov. Phys. Dokl. **14**, 678 (1970)].
10. E. Brezin and C. Itzykson, Phys. Rev. D **2**, 1191 (1970).
11. V. S. Popov, Pisma Zh. Eksp. Teor. Fiz. **13**, 261 (1971) [JETP Lett. **13**, 185 (1971)]; V. S. Popov, Zh. Eksp. Teor. Fiz. **61**, 1334 (1971) [Sov. Phys. JETP **34**, 709 (1972)]. V. S. Popov, Pisma Zh. Eksp. Teor. Fiz. **18**, 435 (1973) [JETP Lett. **18**, 255 (1974)]; V. S. Popov, Yad. Fiz. **19**, 1140 (1974) [Sov. J. Nucl. Phys. **19**, 584 (1974)].
12. G. J. Troup and H. S. Perlman, Phys. Rev. D **6**, 2299 (1972).
13. V. S. Popov, Zh. Eksp. Teor. Fiz. **62**, 1248 (1972) [Sov. Phys. JETP **35**, 659 (1972)]; V. S. Popov and M. S. Marinov, Yad. Fiz. **16**, 809 (1972) [Sov. J. Nucl. Phys. **16**, 449 (1973)].
14. N. B. Narozhnyi and A. I. Nikishov, Zh. Eksp. Teor. Fiz. **65**, 862 (1973) [Sov. Phys. JETP **38**, 427 (1974)].
15. V. M. Mostepanenko and V. M. Frolov, Yad. Fiz. **19**, 885 (1974) [Sov. J. Nucl. Phys. **19**, 451 (1974)].
16. M. S. Marinov and V. S. Popov, Fortsch. Phys. **25**, 373 (1977).
17. J. I. Katz, Astrophys. J. Supp. **127**, 371 (2000).
18. G. Dunne and T. Hall, Phys. Rev. D **58**, 105022 (1998).
19. H. M. Fried, Y. Gabellini, B. H. McKellar, and J. Avan, Phys. Rev. D **63**, 125001 (2001).
20. Ya. B. Zel'dovich and V. S. Popov, Usp. Fiz. Nauk **105**, 403 (1971) [Sov. Phys. Usp. **14**, 673 (1972)]; B. Müller, J. Rafelski, and W. Greiner, Z. Phys. **257**, 62 (1972); *ibid.* **257**, 183 (1972).
21. W. Greiner and J. Reinhardt, in *Quantum Aspects of Beam Physics*, Proc. 15th Advanced ICFA Beam Dynamics Workshop, Monterey, Calif., 4-9 Jan 1998, ed. P. Chen (World Scientific, Singapore, 1998), p. 438.
22. J. Arthur *et al.* [LCLS Design Study Group Collaboration], SLAC-R-0521 (1998).
23. I. Lindau, M. Cornacchia and J. Arthur, in *Workshop On The Development Of Future Linear Electron-Positron Colliders For Particle Physics Studies And For Research Using Free Electron Lasers*, eds. G. Jarlskog, U. Mjörnmark and T. Sjöstrand (Lund University, 1999), pp. 153-161.
24. R. Brinkmann, G. Materlik, J. Rossbach and A. Wagner, Hamburg, Germany: DESY (1997) 1183 p. Hamburg DESY - DESY-97-048 (97/05,rec.Sep.) 1183 p. (ECFA 97-182).
25. G. Materlik and T. Wroblewski, in *Workshop On The Development Of Future Linear Electron-Positron Colliders For Particle Physics Studies And For Research Using Free Electron Lasers* , eds. G. Jarlskog, U. Mjörnmark and T. Sjöstrand (Lund University, 1999), pp. 39-58.
26. G. Materlik and T. Tschentscher, *TESLA: The superconducting electron positron linear collider with an integrated X-ray laser laboratory. Technical design report. Pt. 5: The X-ray free electron laser*, DESY-01-011; R. Brinkmann

et al., *TESLA XFEL: First stage of the X-ray laser laboratory. Technical design report, supplement*, DESY-02-167
27. A. C. Melissinos, in *Quantum Aspects of Beam Physics*, Proc. 15th Advanced ICFA Beam Dynamics Workshop, Monterey, Calif., 4-9 Jan 1998, ed. P. Chen (World Scientific, Singapore, 1998), p. 564.
28. P. Chen and C. Pellegrini, in *Quantum Aspects of Beam Physics*, Proc. 15th Advanced ICFA Beam Dynamics Workshop, Monterey, Calif., 4-9 Jan 1998, ed. P. Chen (World Scientific, Singapore, 1998), p. 571.
29. P. Chen and T. Tajima, Phys. Rev. Lett. **83**, 256 (1999).
30. T. Tajima, "Fundamental Physics with an X-Ray Free Electron Laser," to be published.
31. A. Ringwald, in Workshop on *Electromagnetic Probes of Fundamental Physics*, Erice, Sicily, Italy, 16-21 Oct 2001, hep-ph/0112254.
32. A. Ringwald, Phys. Lett. B **510**, 107 (2001).
33. R. Alkofer, M. B. Hecht, C. D. Roberts, S. M. Schmidt and D. V. Vinnik, Phys. Rev. Lett. **87**, 193902 (2001).
34. C. D. Roberts, S. M. Schmidt and D. V. Vinnik, Phys. Rev. Lett. **89**, 153901 (2002).
35. V. S. Popov, JETP Lett. **74**, 133 (2001) [Pisma Zh. Eksp. Teor. Fiz. **74**, 151 (2001)]; JETP **94**, 1057 (2002) [Zh. Eksp. Teor. Fiz. **121**, 1235 (2002)].
36. J. M. Madey, J. Appl. Phys. **42**, 1971 (1906).
37. A. M. Kondratenko and E. L. Saldin, Part. Accel. **10**, 207 (1980); R. Bonifacio, C. Pellegrini, and L. M. Narducci, Opt. Commun. **50**, 373 (1984).
38. J. Andruszkow *et al.* [TESLA Collaboration], Phys. Rev. Lett. **85**, 3825 (2000).
39. S. P. Kim and D. N. Page, Phys. Rev. D **65**, 105002 (2002).
40. D. L. Burke *et al.*, Phys. Rev. Lett. **79**, 1626 (1997).
41. C. Bamber *et al.*, Phys. Rev. D **60**, 092004 (1999).
42. J. B. Hastings *et al.*, "X-ray Laser Physics", in *LCLS – The First Experiments* (September 2000).
43. T. Tajima and G. Mourou, Phys. Rev. ST Accel. Beams **5**, 031301 (2002); T. Esirkepov, S. Bulanov and T. Tajima, these proceedings.
44. S. A. Smolyansky, G. Röpke, S. M. Schmidt, D. Blaschke, V. D. Toneev and A. V. Prozorkevich, hep-ph/9712377; S. M. Schmidt, D. Blaschke, G. Röpke, S. A. Smolyansky, A. V. Prozorkevich and V. D. Toneev, Int. J. Mod. Phys. E **7**, 709 (1998); Y. Kluger, E. Mottola and J. M. Eisenberg, Phys. Rev. D **58**, 125015 (1998); J. C. Bloch, C. D. Roberts and S. M. Schmidt, Phys. Rev. D **61**, 117502 (2000).
45. R. Ruffini, L. Vitagliano and S. S. Xue, Phys. Lett. B **559**, 12 (2003); S. S. Xue, these proceedings.