Unruh Effect and Some High Energy Experiments

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1. The Formula and Physics of the Unruh Effect (Brief reminding)

Unruh Effect (UE)-According to quantum field theory (QFT) and general relativity every body (or particle), with acceleration a' in its instantaneous rest frame (IRF) is immersed in «thermal bath» of Planckian photons with a temperature

$$T_U = \frac{\hbar a'}{2\pi kc}$$

Unruh Radiation (UR)-the interaction of these photons with an Unruh detector (or particle) in IRF results in UR, observable in the laboratory frame (LF). UR is a relative to the Hawking radiation [2] of black holes with Planckian spectrum

$$T_H = \frac{\hbar c^3}{8\pi kGM} \Rightarrow \frac{\hbar g}{2\pi kc}$$

Here we say adieu to theory (see [3,4] and references therein).

1. W. Unruh, Phys. Rev, D14, 870, 1976.
2. S. Hawking, Nature, 248, 30, 1974; Commun. Math. Phys. 43, 199, 1975.
3. H.C. Rosu, Gravitation Cosm. 7, 1, 2001; Arxiv:gr-qc, 9406012, 2001.
4. L.C.B. Crispino, A. Higuchi, G.E.A. Matsas, Rev. Mod. Phys.80, 787, 2008.

2. Unruh and Larmor Radiation

2a.Larmor Radiation (LR). According to classical field theory (see J.D. Jacks,3-th Ed.) a charge e moving with velocity β=v/c and acceleration a radiates power

When $\vec{v} \perp \vec{a}; \ \gamma \succ\succ 1; \ \theta \prec\prec 1;$

$$\frac{dP_{\perp}^{L}}{d\Omega} \approx \frac{2}{3}\frac{e^2 a^2}{c^3}\gamma^6 \frac{1}{(1+\gamma^2\theta^2)^3}\left[1-\frac{4\gamma^2\theta^2\cos^2\phi}{(1+\gamma^2\theta^2)^2}\right]$$

$$P_{\perp}^{L} = \frac{2}{3}\frac{e^2}{c^3}a^2\gamma^4$$

For $\gamma \approx 1 \quad P_{\uparrow\uparrow}^{L} = 5.7x10^{-51}a^2 \ \ (in \ \ cgs)$

This ang. Dist. of LR has typical rel. rad. patterns with max at θ≈1/γ (M-type, blind spot around v) and min. at φ=0 (with resp v and a).

2b. Unruh Radiation (UR). As we (also, K.T. McDonald,. P. Chen et al) understood. The UR in IRF arises [5,6] due to absorption an emission of a thermal bath photon by Unruh detector (or due to scattering on electron). In LF following [7] one can roughly estimate UR power after the transformation IRF-LF. of the Compton (Thomson) scattered bath photons on electron in IRF. For $\gamma \approx 1$

$$P^{Un} = \int \frac{dP_{Pl}}{cd\nu} \sigma_{Th} d\nu = \frac{\hbar r_0}{90\pi c^6} a^4 \Rightarrow 4.1x10^{-118} a^4 \quad (in \quad cgs)$$

Therefore, UR and LR powers become ~ equal when a ~ $3x10^{33}$ cm/s^2 ~ $3x10^{30}$g. If a is achieved by E then E ~ $2x10^{17}$ V/cm >> >> E_{cr} ~ $m^2 c^3 /2\pi eh$ ~ $1.3x10^{16}$ V/cm. (J.Schwinger e^+e^-)

5. W. Unruh, R. Wald, Phys. Rev. D29, 1047, 1984.
6. H. Kolbenstvedt, Phys. Rev. D38, 1118, 1988.
7. K.T. McDonald, Proposal for SLAC exp E144, Prep. DOE/ER/3072-38, 1986.

Another interpretation to UR was given begining [8-10]

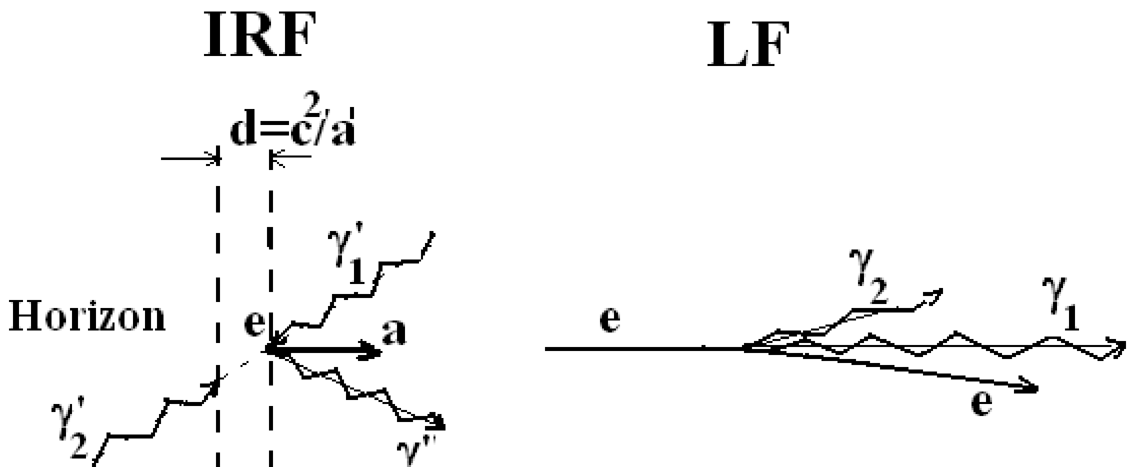


Fig.1

According to EPR correlation a second γ.. For some processes the second «idler» photon can be neglected, so that our interpretation is correct.

2c. Analogy with WW

Without discussing the explanations of well [11-13]and less [14] known observations by UE and omitting proposed LE experiments (see [3,4]) we discuss only proposed exp. with HE electrons for testing the UE.

8. R. Schutzhold, G. Schaller, D. Habs, Phys.Rev. Lett. 97, 121302, 2006.
9. R. Schutzhold, G. Schaller, D. Habs, Phys.Rev. Lett. 100, 091301, 2008.
10. ELI, EU Project, http://www.extreme-light-infrastructure.eu.
11. J. Bell, J.M. Leinaas, Nucl. Phys. B212, 131, 1983 (Spin).
12. S.Barshay, W. Troost, Phys. Lett. B73, 437, 1978 (Strong interactions).
13. S.M. Darbinian, K.A. Ispirian, A.T. Margarian, Yad. Fiz. 54, 600, 1991 (Quarks UR).
14. I.I. Smolyaninov, Arxiv Cond, Matt./0510743, 2008 (Fs IR Photoluminescence of Au tips)

3. High Energy Experimental Proposals

According to modern theoretical approaches (see the review [4]) to UE, it «does not need experimental confirmation any more than free Quantum Field Theory does». Nevertheless, having no, say, accurate contribution of radiation reaction, etc, it is of interest to observe experimentally the difference between the predictions of some processes taking into account UE and those predicted by known theories, say, QED, as background.

3a.UR and Backg. Rad. of Channeled Particles (e+cryst→e+cryst+γ)[1

It has been proposed [15] to measure the spectral distribution of the radiation of high energy channeled particles. By comparing the results on the expected UR produced due to Compton scattering of the Unruh bath Planck photons on channeled particles and the most intense «background», bremsstrahlung, one can «reveal» the manifestation of UE. First let us make some simple estimates: Due to strong fields the channeled particles undergo large

15. S.M. Darbinian, K.A. Ispirian, A.T. Margarian, Preprint YerPhI-1188(65)-89, 1989.

$$a'_{\perp}(cm/s^2) \approx 10^{25}\gamma;\ \ KT(MeV) \approx 4.4x10^{-8}\gamma;$$

$$for\,\gamma \approx 10^8 \quad a'_{\perp} \approx 10^{33}\,cm/s^2;\ \ kT \approx 4.4\,MeV$$

Using T, $dN_{Pl}(T)/dw'_1$ of Planck ThR, $d\sigma/dw'_2$ of Compton scattering, integrating over angles and w'_1 one can derive UR in IRF. Then transforming to LF and integrating over angles in [15] it has been calculated the spectr. distrib of UR and bremsstrahlung (Fig. 2)

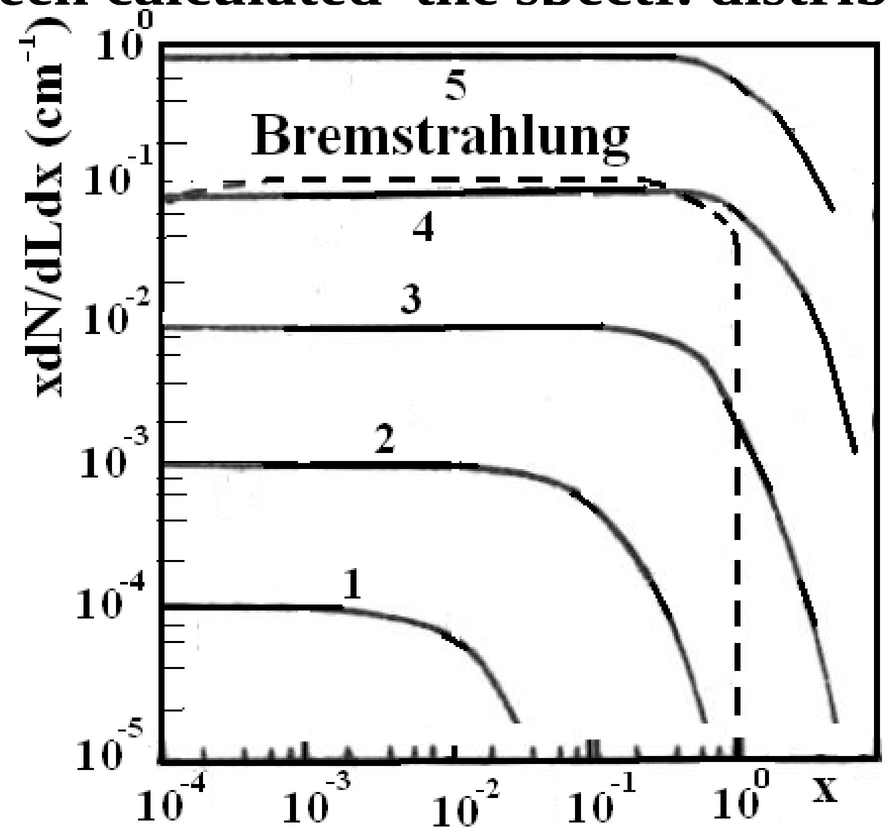


Fig.2 The dependence of the intensity of bremstrahlung (dashed curve) and of UR for $\gamma=10^5, 10^6, 10^7, 10^8, 10^9$ (solid curves1, 2, 3, 4, 5), respectively, upon $x=h\omega/E_e$ For diamond (110) and entrance angle 0.

$x = \hbar\omega_0/\gamma mc$

As it is seen paticles energy with gamma >10^8 are necessary...

3b. UR and Background SR of TeV Electrons in Constant Magnetic Fields (e+H→e+H+γ) [16]

If v ⊥ H, $a'_\perp = \gamma eH/m\beta$ and KT(MeV)= 1.8×10^{-9} γH(G) and after calculations similar to [15] in the work [16] it has been calculated.

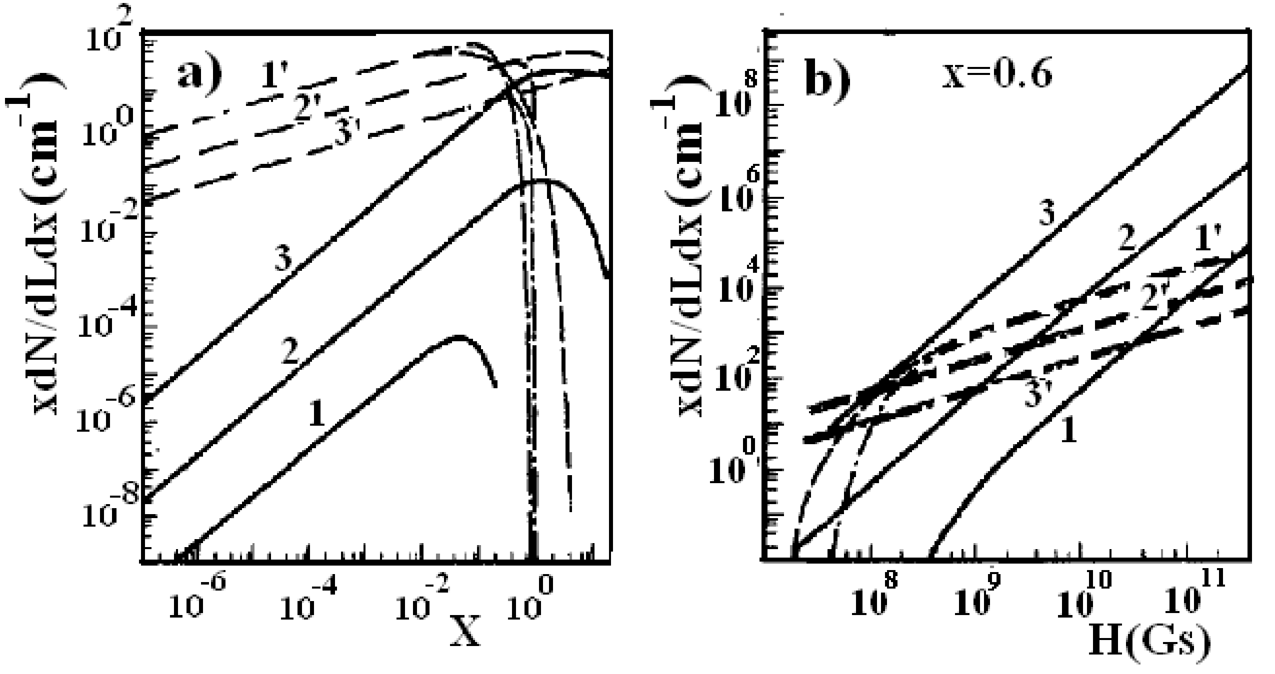


Fig.3 The dependence of the intensity of SR (dashed curve) and of UR for γ= 10^5, 10^7 and 10^9 (solid curves 1, 1';2, 2' and 3, 3'), resp-ly, a) upon $x=hw/E_e$ for H=5×10^7 G and b) upon H(G) for x=0.6.

16. S.M. Darbinian, K.A. Ispirian, M.K. Ispirian, A.T. Margarian, Pisma JETP,51,97, 1990.

3c. UR and Background Radiation of TeV Electrons in ↑↓ Laser Beams ($e+LB \rightarrow e+LB+\gamma$) [16]

In laser beams with 100% circular polarization and $\eta = e\varepsilon/m\omega$ Where η is the laser beam parameter, ε(V/cm)= $20(W/cm^2)^{1/2}$ and ω frequency, $a'_\perp = 2\omega\gamma\eta(1+\eta^2)^{1/2}$ and $KT(MeV) = (\gamma\omega/\pi)\eta(1+\eta^2)^{1/2}$.

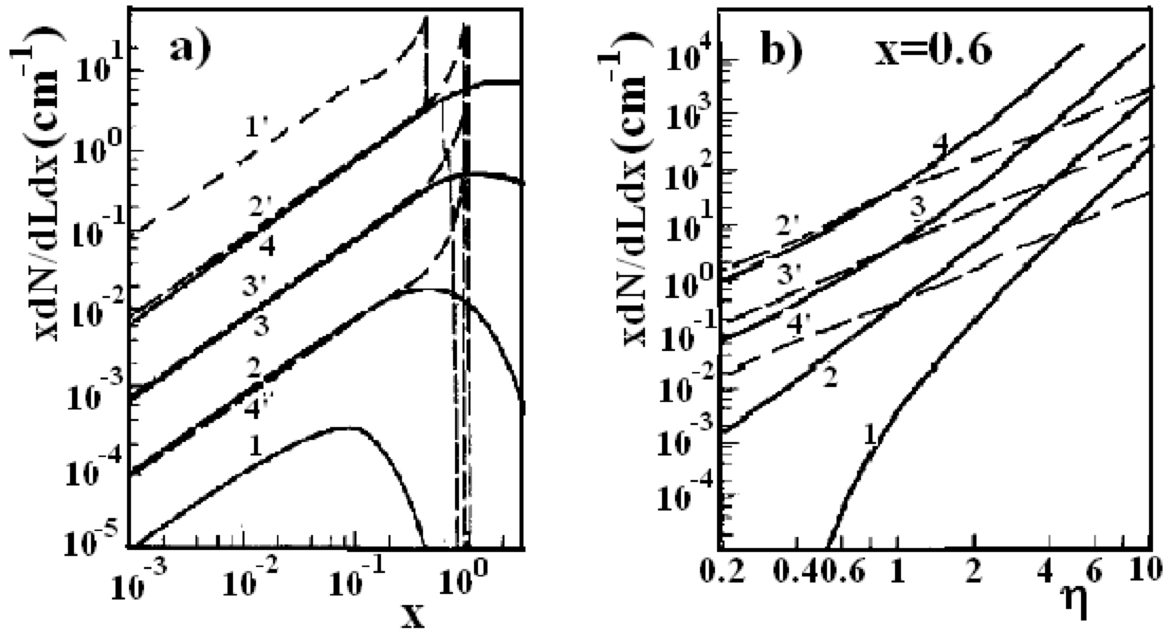


Fig.4. The dependence of the number of quanta per cm of QED radiation [17] (dashed curve) and of UR for $\gamma = 10^5, 10^6, 10^7$ and 10^8 (solid curves 1, 1';2, 2'; 3, 3' and 4,4'), respectively, a) upon x for $\eta=0.4$ and b) upon η for $x=0.6$. Again it is seen that $\gamma>10^8$ or $\eta>1.5$ an

17. N.B. Narojniy, A.I. Nikishov, V.I. Ritus, Zh. Eksp. Teor. Fiz. 47, 931, 1964.

3d. Unruh and Background QED e+e- Pair Production and Energy losses on Linear Colliders (e+Bunch→e+Bunch+e^++e^-) [18]

For e^+ e^- -colliders the SR parameter $Y=\gamma H/H_{cr}$ (H_{cr}=m2/e=1.44x10^{13}G) is equal to ([19] and R.Palmer)

$$Y = \frac{5\gamma r_0^2 N_{e^+e-}^{bunch}}{6\alpha\sigma_z\sigma_y(1+\sigma_x/\sigma_y)}$$

As above a'=γeH/m=Ym and KT(MeV)=1.8x10^{-15}γH=8.1x10^{-2}Y. Among all mechanisms for e^+e^-- production the dominant is e(+γ_{UR})+(bunch)→e+(bunch)+e+e- . Therefore we calculate

$$\frac{dn_{e^+e^-}}{dt'\,d\omega_1'} = \frac{dn_{Pl}}{d\omega_1'}\sigma_{ee}(\omega_1')$$

Where σ_{ee} (ω'_1) is for γe→ee$^+$e$^-$ (Berestetski, Motz...). We calculate also Compton and beamstrahlung [19] and obtain

$$\gamma\frac{dN_{\gamma,ee}}{dL} = 1.76\int_{0,4}^{\infty}\frac{y^2dy}{\exp(my/KT)-1}\sigma_{\gamma,ee}(y)$$

18. S.M. Darbinian, K.A. Ispirian, M.K. Ispirian, A.T. Margarian, Pisma JETP,54,235, 1991.
19. R. Noble, Nucl. Instr. and Meth. A256, 427, 1987.

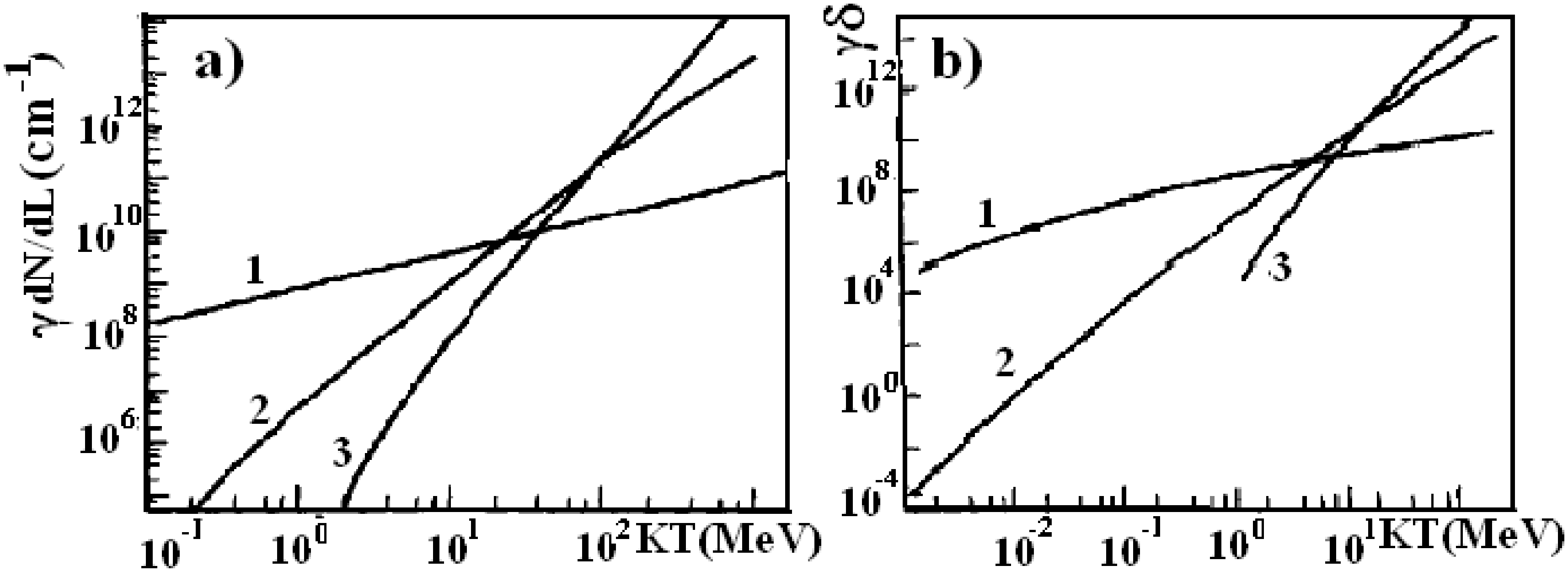


Fig.5. The dependence of total number of quanta per cm a) and fraction of energy losses b) multiplied by γ for beamstrahlung [19], UR and Unruh e+e-pair production processes (curves 1, 2 and 3), respectively.

As it is seen the dominant processes are
Beamstrahlung for KT<40 MeV
Total UR for 40<KT<100 MeV
Total Unruh pair production for KT>100 MeV.
After 1990 we have published only [14] on UE of quarks

3e. UR and Backg. LR in Standing Wave Produced by Two↑↓ Linearly Polarized Laser Beams e+(SW)→e+(SW)+γ [20]with angul. discrimin

If ω_L and η are for Lbeam then in the produced standing wave [20]

$$a' = 2c\eta\omega_L \cos\omega_L t' \;\; and\ in\ LF\ P_{LR} = (8/3) r_0 mc\eta^2\omega_L^2 \cos^2(\omega_L t);$$

$$P_{UR} \approx (12 r_0 \hbar/\pi c)(\eta\omega_L)^3 \log(\eta/\pi)$$

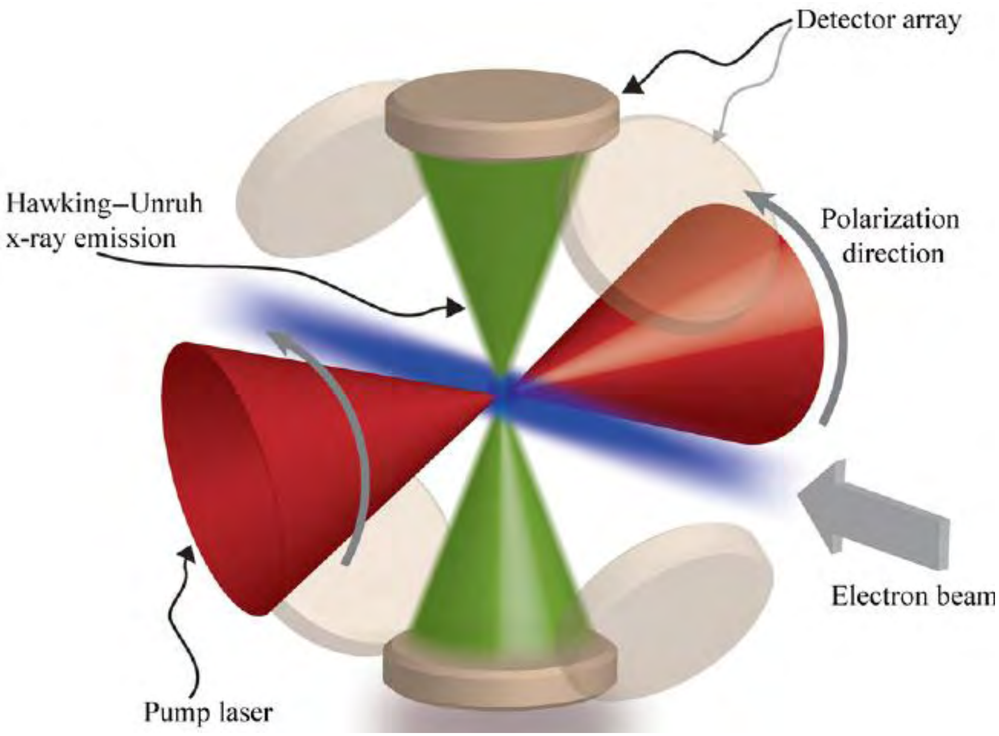
P_{UR} is calculated assuming that the electron makes in addition to the harmonic also «quivering» or «backreaction» oscillations due to abs&emit. of Unruh bath (ZPF) photons. The ratio of the radiated energies ($\Delta I_{UR}/\Delta I_{LR}$) ≈ ($18h\omega L/\pi mc^2$)ηlog(η/π) per laser half-cycle for a Petawatt laser with η~100 and ω_L~2×10^{15} s^{-1} is equal to ~3×10^{-4}. To save the situation they calculate in LF the angular distribution of UR for $\gamma=(1+4\eta^2\sin^2\omega_L t)^{1/2} \approx \eta >>1$ and θ<<1

$$\frac{dP_{UR}}{dt} \approx \frac{4 r_0 \hbar}{\pi^2 c}\frac{\omega_L^3\eta^3}{(1+\eta^2\theta^2)^3}$$

which has max at θ=0. The authors of [20] first proposed to use the «blind spot» in LR which has min at φ≈0 and θ close to 0. They say that detecting photons within Δφ≈10^{-3} and Δθ<<1/ η UR will dominate over LR (Unfortunately, no photon detection absolute rate is given)

20. P. Chen, T. Tajima, Phys. Rev. Lett. 83, 256, 1999.

3f. UR and Backg. LR of HE Electrons in Two↑↓ Circularly Polarized Laser Beams (e+(LB)→e+(LB)+γ) [21] with angul. + spectr. discrimination.



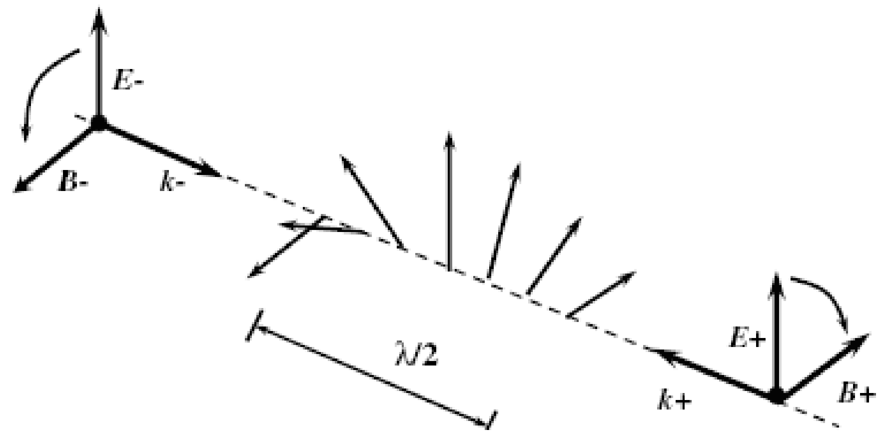


Fig. 7. The 2 laser beams with Polarizations (B=0, no HHG)

Fig. 6 The proposed experimental arrangement [21]

With PlR and σ_T [21] gives T (or a) UR power for N electrons and for γ~70 and

$$P_{U,\text{lab}} = \frac{N e^8 E_0^4 \hbar}{1440\pi^3 c^{10} m^6 \varepsilon_0^2}.$$

21. G.Brodin, M.Marklund, R.Bingham, R.G.Evans Class. Quantum Grav. 25, 145005, 2008

the number of UR phot. Per shot with ~ characterteristic energy

$$N_U = 0.084\left(\frac{E_p}{15\mathrm{J}}\right)^2\left(\frac{0.5\times 10^{15}\mathrm{W}}{P}\right)\left(\frac{800\ \mathrm{nm}}{\lambda_L}\right)\left(\frac{n_e}{10^{21}\ \mathrm{cm}^{-3}}\right),$$

$$\hbar\omega_{\mathrm{char}} = 582\left(\frac{I}{10^{22}\ \mathrm{W\ cm}^{-2}}\right)\left(\frac{\lambda_L}{800\ \mathrm{nm}}\right),$$

Table. Laser parameters from which one can calculate the length T(s) = Energy(J)/Power (W) , electric field E(V/cm)≈20x(IW(cm-2))$^{1/2}$, η≈6x10^{-13}x[I(Wcm^{-2})]1/2xλ(nm) and hν$_{char}$.

Laser type	Energy (J)	Power (PW)	Intensity (Wcm^{-2})	Wavelength (nm)
Ti:sapphire	1	0.03	10^{21}	800
Astra–Gemini	15	0.5	10^{22}	800
AG upgrade	15	0.5	$\leqslant 10^{24}$	800
Vulcan	250	0.5	5×10^{20}	1054
Omega EP	$\geqslant$2500	0.25	6×10^{20}	1054
HiPER 1	4500	150	5×10^{24}	1054
HiPER 2, ELI	37500	2500	5×10^{26}	1054

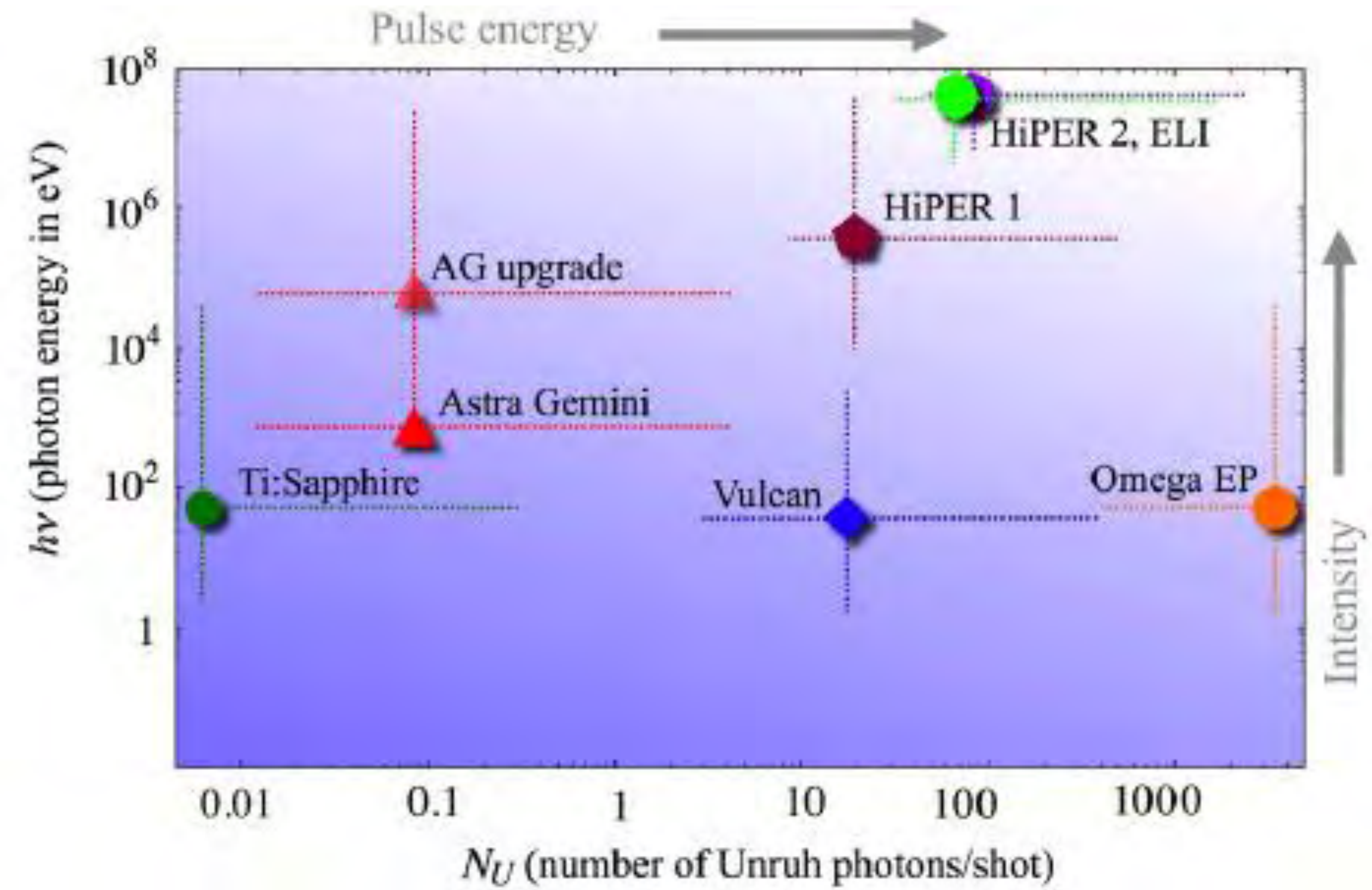


Fig.8. Characteristic hν (eV) vs NUR per shot for lasers of Table for n_e=10^{21} cm^{-3}.

3g. Unruh and Backg. Production of Photon Pairs by Electrons in Laser Fields (e+(LB)→e+(LB)+γ+γ) [21-25] with ang+spectr+pol. +coincidence discrimination

In [22] a=const, in [23]for periodic a assuming 1) η<<1, 2). In IRF for Unruh γγ-pair $k'_1+k'_2=\omega'=\gamma\omega_L<<m$ (Thomson), while for Larmor one Has 1 photon $k'=\omega'=\gamma\omega_L$ it is given the probabilities

$$P^{\gamma\gamma}_{Unruh}=\frac{\alpha^2_{QED}}{4\pi}\left[\frac{E}{E_{cr}}\right]^2,\quad P^{\gamma}_{Larm}=\alpha_{QED}\left[\frac{eE}{m\omega}\right]^2$$

(The one phot. LR is the same inverse Compton, see also A. Higuchi, PRD45,R3308, 1992).

For E_e=150 MeV (γ=300), $N_b=10^{10}$, ω_L=2.5 eV (in IRF ω'=1.5 keV), T_L=168 fs (100 cycles), $I_L=10^{18}$ W/cm^2 (giving in IRF $E/E_{cr}\sim10^{-3}$) $P_U=10^{-11}$; $P_L=10^{-2}$. Saving the situation and using the ang. discr. for U γ γ and L γ γ (see Fig.6) and ang. discrimination $\Delta\theta<10^{-2}$ rad. one can increase the effect/noise ratio from 10^{-9} up to 7×10^{-6}.

22=8. R. Schutzhold, G. Schaller, D. Habs, Phys. Rev. Lett. 97, 121302, 2006.
23=9. R. Schutzhold, G. Schaller, D. Habs, Phys. Rev. Lett. 100, 091301, 2008.
24. P.G. Thirolf et al, Towards Exp. Sign. 0f UE, Unpubl. MAP, Munich Adv. Phot. >2008.
25. F.Bell, On Generation of X-Ray Pairs; A Verification of UE arxiv:0809.1505, 2008.

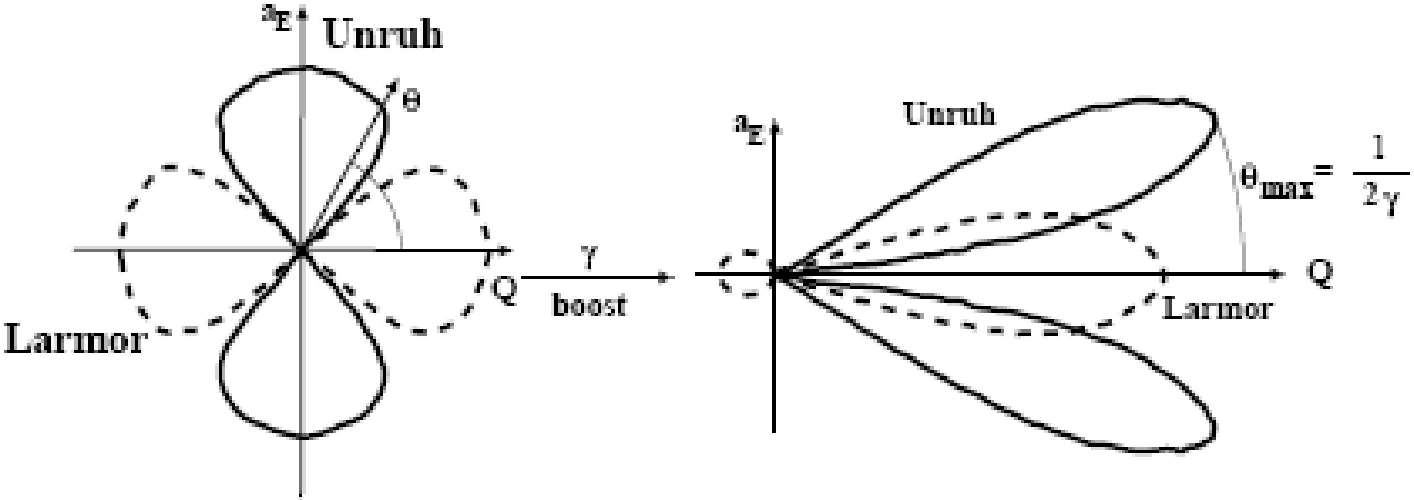


Fig. 6.

Fig. 1: Angular characteristics for Larmor and Unruh radiation before (left) and after the Lorentz boost (right). The acceleration direction by the electric field is indicated by a_E.

The 3D dependence of $d^2\sigma_{\gamma\gamma,\gamma}^{U,L}/d\omega_1 d\Omega_1$ upon ω_1 and θ_1 for ω_L=2.5 eV and fixed other parameters given in caption of Fig.7. Unfortunately, the cross sections are given only qualitatively by colors.

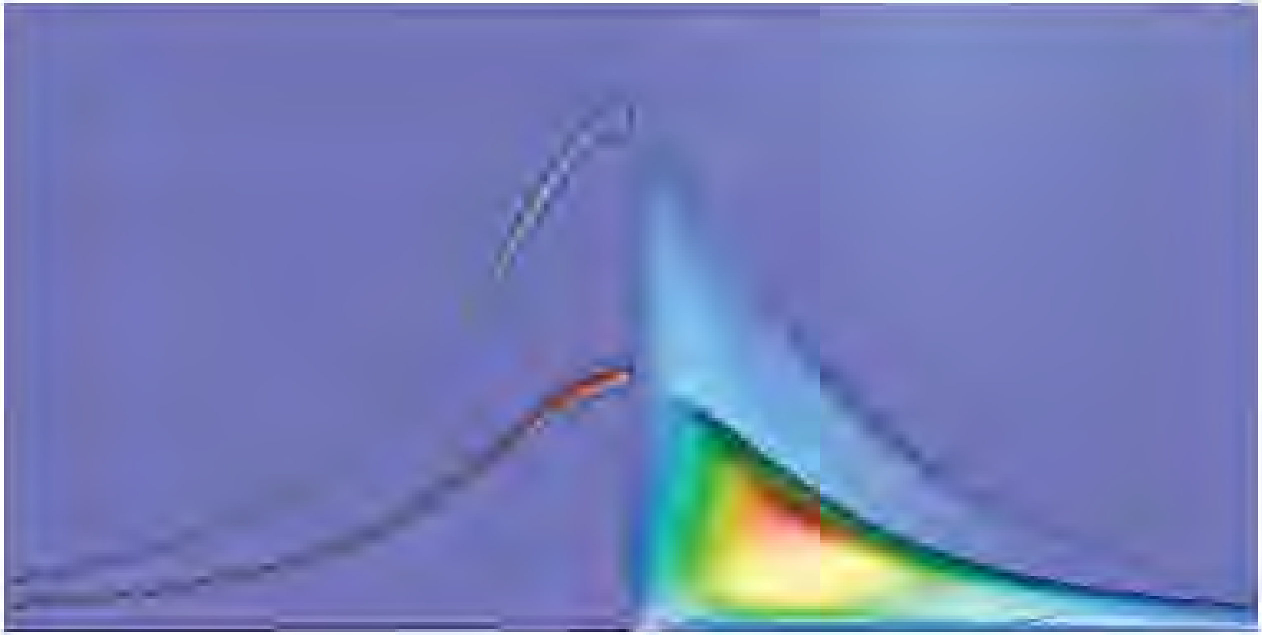


FIG. 1 (color). E-ϑ plot of the one-photon probability of classical (Larmor, left half of image) and quantum (Unruh, right) radiation in the laboratory frame (averaged over rotations around beam axis). An electron with a boost factor of $\gamma = 300$ hits a counterpropagating optical Gaussian laser pulse with an intensity of 10^{18} W/cm^2 and a width of 100 cycles. The photon energy E ranges from zero (bottom) to 2 MeV (top) and ϑ varies from zero (middle) to 1/100 (left and right boundary). In the chosen color coding (not the same in the two images), red indicates a large and dark blue a vanishing probability. The black isolines denote the same values in both pictures and show that the quantum radiation dominates in certain phase-space regions (which could

Fig. 7.

For the proposed arrangement for ELI [22-24] besides 1 photon UR there is a background additional process not discussed in [22-24]. Inverse double (γe→eγγ see Jauch, Rohrlich) Compton scattering (IDCS) having the same kinematics, which must be discussed here following [25]. The 3D double diff. cross section for IDCS is shown in Fig. 8

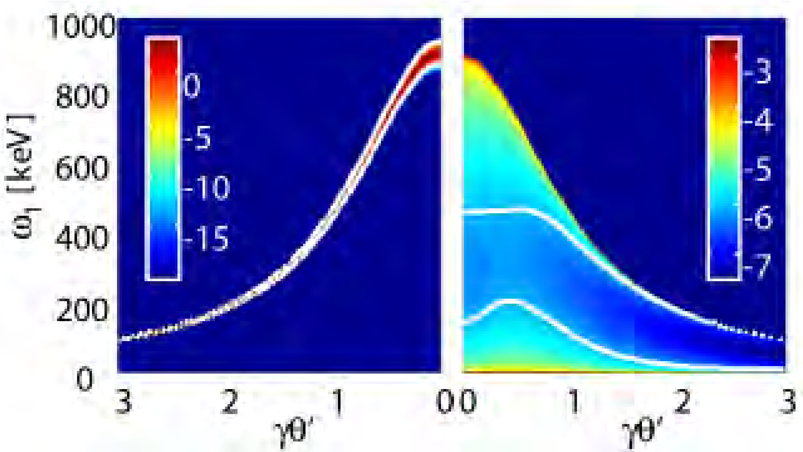


Fig.8.

FIG. 7: (Color) Isodensity plot of the double differential cross section for single (left side) and double (right side) Compton scattering. Again, the scale is logarithmic, i.e., the number -6 at the color code means 10^{-6}b/keV·sr. Note that the color codes for both sides are rather different. The white contour lines in both sides correspond to 10^{-6}b/keV·sr. If the cross sections are multiplied by the luminosity of eq.(4.4) one obtains the yield pairs/(keV·sr·electron). The figure is drawn in such a way that a qualitative comparison with Fig.1 of Schüitzhold et al.[9] can be made.

«Unfortunately» it is impossible to compare yields of two-photon yields of Unruh and IDCS given in Figs 7 and 8, respectively, because no exact numbers are given in Fig. 7 [23] in contrast to Fig.8 [25], where the yields are given as color and number.

As the author of [25] writes there are 3 possibility:

1)The yields Unruh < IDCS. Then the proposed experiment on ELI is not reasonable.

2)The yields Unruh > IDCS. Then it will be impossible to explain the agreement between exp. data on DCS (Jauch, Rohrlich) with QED.

3)The yields Unruh ~ IDCS. Then the UE and QED Physics are the same.

Nevertheless the experiment proposed for ELI is very important..... and there are 3 factors the use of which can enhance the chances

1)Measurement of the polarization.

2)Coincidence between the produced ~ (200-500) keV 2 photon pairs.

3)Electron beam microbunching which makes the processes coherent (~N_e^2 instead of ~N_e. The authors of [23] dare to speak about two entangled X-rays FEL the production of which is important as opt....

The proposed for ELI experimental arrangement, principle of Compton polarimetry and the prototype 1.8 mm thick Ge detector array (GSI, J of Phys.68, 411, 2007) are shown in Figs. 9- 11, respectively.

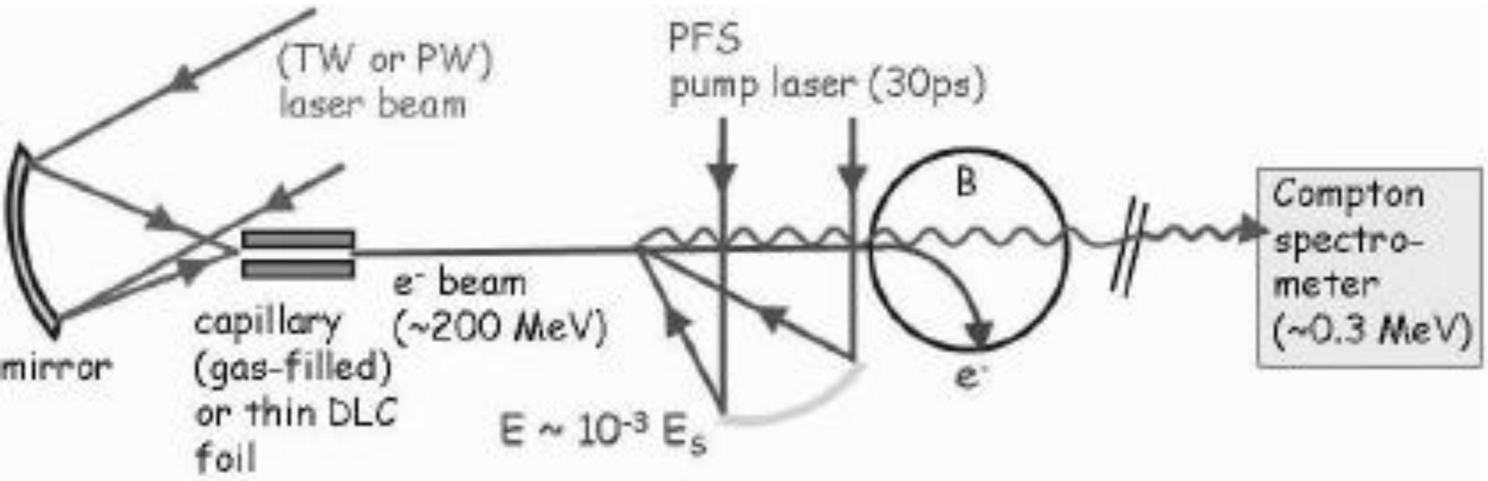


Fig. 9.

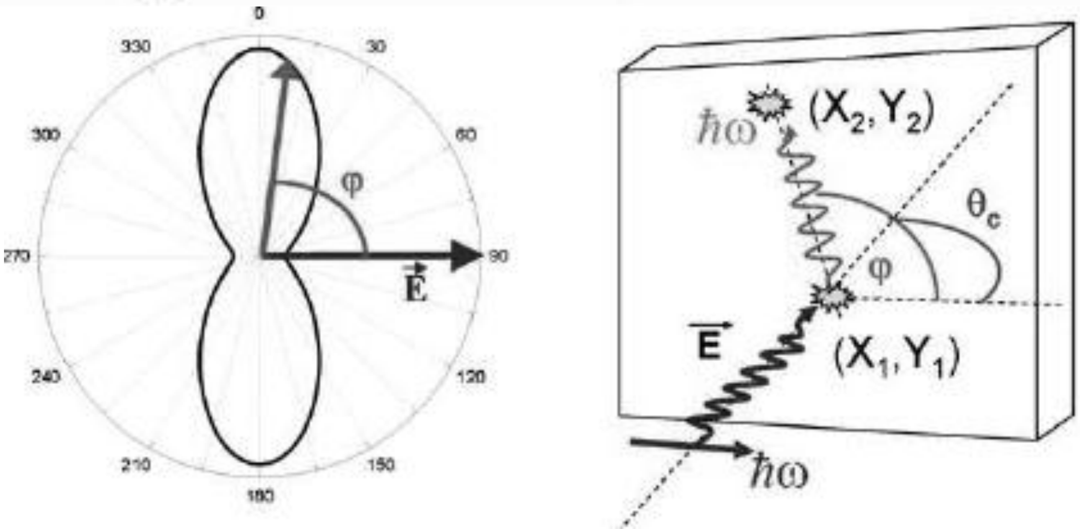


Fig. 10

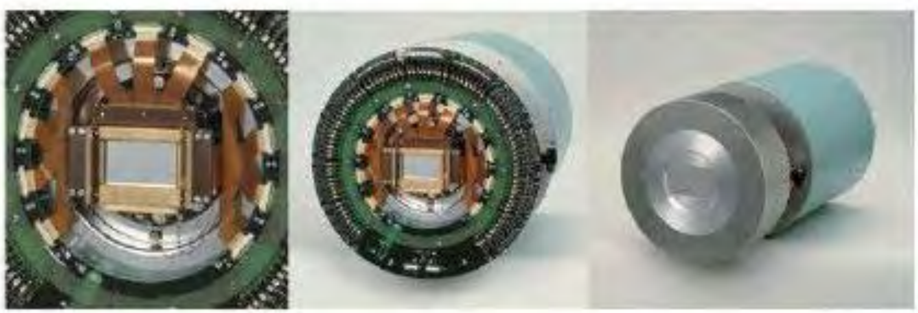


Fig. 11

4. Conclusions

There is no doubt that as it is written in [24]

Understanding the structure of the quantum vacuum is one of the key challenges of contemporary fundamental physics, since theoretical efforts to describe the observed energy density of the vacuum amounting to 5 $\mathrm{GeV/m^3}$ drastically fail by 10^{124} (microscopic approach via string theory) and 10^{-121} (via cosmological considerations), respectively.

Therefore, after launching ELI in 2010 we shall wait for the results of the 2 last, most realistic, experiments on UE.

Thank you

For listening and for occasion returning me to the problems of physical ether after many years.