LASER ACCELERATION UP TO BLACK HOLES AND B-MESON DECAY*

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Abstract

Studies about laser produced pair production are followed up from early stages. The pair production by vacuum polarization was discussed with laser produced acceleration up to the values at black holes leading to the discovery of a difference between Hawking and Unruh radiation. It was clarified that production of anti-hydrogen is at least million times more efficient than by present day accelerator technology. Another application of the ultrahigh laser fields is to focus them into the collision area of the LHC with the possibility to study the details of the *B*-meson dacay. This offers an access to detect more details about CP violation and B_s mesons and possible signs of new particles on the horizon. The available lasers with picosecond pulses are developed to exawatts power what is interesting also for studying ultra-intense shock waves in astrophysics and resulting nuclear reactions.

INTRODUCTION AND INITIAL RESULTS

Using the very high intensity laser radiation with the electric and magnetic fields $\boldsymbol{E}$ and $\boldsymbol{H}$ far above any values applied before, led to very many new physics phenomena and last not least to the realization that the opened nonlinear physics opens a new dimension of exploration where indeed the linear physics needs to be based on higher accuracy data than needed before [1]. Examples appeared where results in linear physics were completely wrong compared to the truth in nonlinear physics in contrast to earlier happening gradual differences or approximations only. This all developed not only due to techniques to produce higher and higher laser intensities, mostly realized by chirped pulse amplification CPA [2], but also from realizing to generate relativistic effects. After first considerations how to produce relativistic conditions for pair production of electrons [3] the conditions were elaborated for the laser fields producing quiver motion of electrons with energies above mc^2 [4].

The steps to conclude the conditions for producing anti-protons [5] were parallel to estimations [6] and experiments where indications for the generation of the very first laser produced positrons were reported [7]. With respect to the quiver motion and drift for proton pair production, the advantages of long wave length laser pulses were of interest [8]. After estimations with anti-hydrogen for space research became known, the solution with lasers were of interest because the efficiency was more than one million times higher with lasers due to the available much higher particle density than with accelerator techniques. It was proved that a mission to the next fix star within a reasonable time of 50 years can only be done with laser produced anti-hydrogen fuel [9].

Thanks to the CPA technique, sub-picosecond laser pulses of 2 PW produced the first considerable number of positrons [10] finally arriving [11] at record intensities positron beam above any other method.

PAIR PRODUCTION BY VACUUM POLARIZATION

Pair production in vacuum was from the beginning considered [3][4][5] where a laser intensity above 10^{28} W/cm^2 was needed [12] and specified to the well known higher value later. The acceleration of the electrons by the electric field of the laser was close to the values of the Hawking radiation and the Unruh radiation at the black holes. This was studied in connection with the black body radiation which fields are of the same order and where the electrons at thermal equilibrium were not longer following the Fermi-Dirac statistics [13]. Further studies clarified that there was a difference between the Hawking and the Unruh radiation [14] with a relation to the Casimir effect [15][16]. These results were based on the theory of electron acceleration in vacuum [17] as a basically nonlinear effect [1]. The essential aspects of these studies are as follows.

The Unruh effect is a phenomenon whereby an accelerated observer travelling through a true vacuum state—that is the ground state |0> which will be referred to here as the Minkowski vacuum—will experience themselves to be immersed in a thermal blackbody distribution of particles [16]; Before comparing the thermal radiation experienced by an accelerated observer to the Hawking radiation of a black hole a brief digression into the physical nature of the vacuum is appropriate.

The Minkowski vacuum is a physical vacuum with pairs of virtual particles manifesting for short durations continuously and, unlike the pre-quantum field theory vacuum, has observable effects on physical systems (e.g. the fine structure of the atomic hydrogen spectrum and the Casimir effect). Taking the Casimir effect as an example, two parallel mirrors placed in a vacuum will experience an attractive force inversely proportional to the forth power of the distance separating them as a result

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of the quantum fluctuations of the vacuum. Essentially long wavelength virtual particles cannot manifest between the conducting mirrors resulting in a decreased energy density between the mirrors compared with the vacuum surrounding them where there is no such restriction. The Casimir effect is symbolic of the physical nature of the quantum vacuum.

The quantum field is best decomposed for an accelerated observer using a different basis than the standard momentum basis used in quantum field theory; this basis being related to the standard basis by the Bogoliubov transformations. These transformations play an integral part in analyses of the Unruh effect. The particle number operator differs too and does not give zero when applied to the Minkowski vacuum state (which is not identical to the Rindler vacuum state). The result is, as stated above, that an accelerated observer in a pure vacuum will experience themselves in a heat bath with a blackbody distribution.

Thus a state without particles to an inertial observer will be seen to contain particles by an accelerated observer. The dependence of temperature upon acceleration is, $T = 2\pi c k_B a/\hbar$, where c is the velocity of light, and a is the acceleration. If a is interpreted as the acceleration at the event horizon of a black hole then the same equation describes the temperature of the thermal radiation emitted from a black hole via the process of Hawking radiation. The similarity of the equations and the equivalence principle of general relativity hint that the mechanisms for the radiation may be the same but this is not the case. Consider the following.

Hawking radiation is sometimes described as resulting from pair production near the horizon of a black hole with one of the virtual particles escaping and becoming real and the other disappearing into the black hole [15]. All observers experience Hawking radiation while only accelerated observers experience the Unruh effect. Furthermore, an observer on earth is effectively in an accelerated coordinate system via the equivalence principle and hence should observe the surrounding vacuum to have a temperature due to the Unruh effect but the earth does not emit Hawking radiation and neither do other gravitational bodies without event horizons. The Unruh effect results from a different mechanism to that of Hawking radiation; it is local, being experienced only by accelerated observers [14].

PETAWATT LASER PULSES FOR B-MESON DIAGNOSTICS

The present day available PW laser pulses of sub-picosecond duration and the next higher powers can be used for important studies of the details of B-meson diagnostics because their lifetimes are on the same time scale. This diagnostics at collider beam interactions with lasers was studied before [18] for the conditions of the Large Electron Positron (LEP) collider and can now be extended for the conditions of *B*-mesons, e.g. at the Large Hadron Collider LHC or similar *B*-meson factories [19].

A prototype of this technique was given by the interaction of 10^{16} W/cm^2 laser intensities in low density helium [20]. It was expected from theory that a radial emission of electrons from the focus should convert half of the quiver energy of the electrons into energy of translative motion. The measured radially emitted keV electrons corresponded exactly to the expected theory. The conservation of the momentum of the photons leads to a slightly forward direction parallel to the laser axis. This was measured in [21] in agreement with the earlier prediction [22]. In the same way, the charged particles generated in the focus of the collider when being in the focus of the laser beam, will get an upshift of energy and a change of direction. The PW laser pulses and even the better exawatt (EW) laser pulses of few fs duration [23] can then follow up the timing of generating or annihilating process of the *B*-meson generation and the decay processes. The importance is evident for further analyzing the different types of *B*-mesons where insights of the CP violation strange bosons B_s will be interesting on the way of a “possible new particles on the horizon” [24].

The theory is based on electro-dynamic interaction of the laser radiation with the particles as known from plasma interaction as the nonlinear force given by [25]

$$\begin{aligned} \boldsymbol{f}_{\mathrm{NL}} = {} & \nabla\bullet[\boldsymbol{EE} + \boldsymbol{HH} - 0.5(\boldsymbol{E}^2 + \boldsymbol{H}^2)\mathbf{1} \\ & + (1+(\partial/\partial t)/\omega)(\boldsymbol{n}^2-1)\boldsymbol{EE}]/(4\pi) \\ & - (\partial/\partial t)\, \boldsymbol{E} \times \boldsymbol{H}/(4\pi c) \end{aligned} \qquad (1)$$

(see Eq. 8.88 of Ref. 1991 [25]) where **1** is the unity tensor, c the vacuum speed of light. The value $\boldsymbol{n}$ is the (complex) refractive index determined by the laser frequency ω and the electron-ion collision frequency ν of a plasma

$$\boldsymbol{n} = 1 - (n_e/n_{ec})/(1 + i\nu/\omega), \qquad (2)$$

where n_e is the electron density, n_{ec} is the critical electron density where the plasma frequency ω_p is equal to the laser frequency ω. The dielectric properties of the vacuum polarization are to be included appropriately for the pair production in vacuum. The derivation of this force with inclusion of the dielectric plasma properties for the non-transient case since 1969 [25] was based on momentum conservation. The final complete transient case, Eq. (1), is known since 1985 based on symmetry where it was proved later that this and only this is the Lorentz and gauge invariant description of the nonlinear force.

For simplified one-dimensional geometry and perpendicular laser irradiation, the force (1) can be reduced to the time averaged value

$$\begin{aligned} \boldsymbol{f}_{\mathrm{NL}} &= -(\partial/\partial x)(\boldsymbol{E}^2+\boldsymbol{H}^2)/(8\pi) \\ &= -(\omega_p/\omega)^2(\partial/\partial x)(E_v{}^2/\boldsymbol{n})/(16\pi), \end{aligned} \qquad (3)$$

where E_v is the amplitude of the electric field in vacuum. The last expression is reminding of the formulation of the ponderomotive force in electrostatics and is sometimes called “radiation pressure acceleration”.

The relativistic limits for the emission of the charged particles from the collider area with a laser focus are given for laser intensities of neodymium glass lasers [19]

(1) charged B-mesons
$I_{rel} = 1.2\times10^{25}$ W/cm^2 $\Delta\varepsilon = 2.41$ keV

(2) protons or antiprotons from the *B*-decay
$I_{rel} = 3.9\times10^{26}$ W/cm^2 $\Delta\varepsilon = 424$ eV

(3) charged π-mesons from *B*-mesons decay:
$I_{rel} = 2.73\times10^{23}$ W/cm^2 $\Delta\varepsilon = 31.5$ keV

The size of the lasers for PW-fs pulses are comparably compact such that the diagnostics with an additional laser focus may not be a too difficult problem. The signals from the detectors for comparable cases with and without the laser will then be done by functional analytical folding of the information about the time dependence of creation, decay and annihilation processes of the numerous types of charged particles,

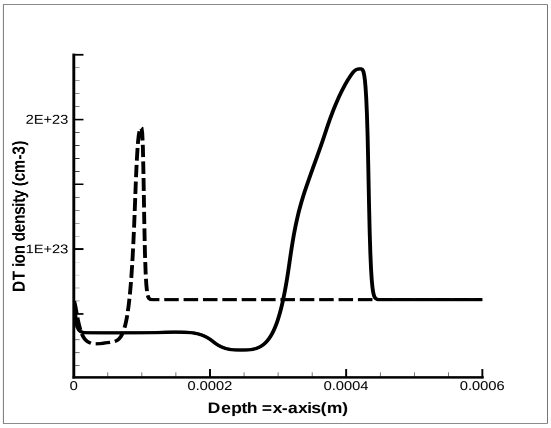

Figure 1. Genuine two fluid hydrodynamic computations [32][33] of the ion density in solid DT after irradiation of a laser pulse of 10^{20} W/cm^2 of ps duration at the times 22 ps (dashed) and 225ps after the initiation.

EXAWATT LASER PULSES FOR SHOCK WAVES AND NUCLEAR REACTIONS

Studies with the advanced PW to EW laser pulses are important also for exotic conditions of shock waves in astrophysics [26], ultrahigh accelerations and for related interactions including nuclear mechanisms. The essential difference to the usual thermal pressure generation processes in plasmas is the direct conversion of laser energy into particle motion. This can be seen from the nonlinear forces including the optical response since 1969 [25] expressed in Eq. (1). The then predicted ultrahigh accelerations were first measured by Sauerbrey by the Doppler effect at target interaction with above TW-ps laser pulses. The nonlinear force driven accelerations were 10^{20} cm/s^2 [27] in contrast to comparable accelerations with thermal-pressures of 10^{15} cm/s^2 [28]. The high acceleration was in full agreement with the theory [29] and could then be used to ignite solid state density fusion fuel deuterium tritium DT [30]. This is a rather simplified scheme of igniting hydrogen-boron11 with producing less radioactive radiation per generated energy than burning coal [31].

In order to show the velocity of the reacting fusion flame – similar to cases in astrophysics – Fig. 1 shows the computations of the ion density in frozen DT at ps laser irradiation of 10^{20} W/cm^2. The reaction front at the interaction following the ps ignition at later times when propagating through the solid density DT can be seen where compressions up to four times the solid state are generated within the moving short depth shock wave. This numerical result automatically agrees with the factor four of the Rankine-Hugoniot shock wave theory. The shock velocity of 1550 km/s is in the range known for this type of interaction. For later times the fusion flame shows more and more a deviation of the density profile differing from the simplified shock wave theory. This is evident from the output of the fast velocity of the generated alpha particles when moving into the untouched solid DT by gradually changing there the conditions of densities and temperatures. However the velocity of the entire flame is remarkably unchanged. More properties are given in the references, however, the genuine two-fluid computations arrive at many more details than known from the one-fluid computation [30][31]. It is important to note that these studies are aimed to apply ps laser pulses in the range of 30 PW up to nearly EW. Generalizing the preceding computations [30][31], the genuine two-fluid hydrodynamics [32][33] is used in order to follow up the details of the generated very high electric fields in the shock fronts and to confirm most of the other results calculated before with the usual one fluid hydrodynamics. The results are interesting for astrophysical cases and for shock ignition of fusion [34] where in contrast to the thermal pressure process, the new research now was generalized to non-thermal nonlinear force direct conversion of laser energy into plasma motion to reach the ultra-high accelerations.

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