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SHORT COMMUNICATION

Using petawatt laser pulses of picosecond duration for detailed diagnostics of creation and decay processes of B-mesons in the LHC

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The co-incidence of the lifetime of B-mesons in the range of ps with the technology of laser pulses of about picoseconds (ps) or shorter duration with up to petawatt (PW) power will provide diagnostic techniques revealing very fine details about the timing of the generation of B-mesons within the collision area of the large hadron collider LHC. The fine structure of the time dependence as well as the degree of dependence of the polarization directions of the decay products as e.g. protons, antiprotons, π-mesons and others may be detected by taking into account the acceleration processes by the nonlinear (ponderomotive) forces in the laser focus and the colliding area where the high laser powers are essential.

Generation of very large numbers of B-mesons in the large hadron collider (LHC) was considered as a very first field of gaining new insights into high energy physics (Gershon, 2008) using the LHCb detector before the other detectors may be successful with measurements about Higgs particles and others. A combination of the experiments with the interaction of the petawatt-picosecond laser pulses is evident as it was proposed with laser pulses with the then lower powers (Hora, 1992) for interaction within the collider region. Initially, the combination of laser interaction with the collider region of an electron accelerator was following the results of an experiment (Boreham *et al.*, 1979). For historical details, see Hora (1991, p. 305)

For the laser interaction with the much heavier charged B-mesons or other heavy charged particles, only the presently available PW laser pulses may be considered. These lasers using the CPA (chirped pulse amplification) technique (Mourou *et al.*, 2002) are either neodymium glass lasers or titanium-sapphire lasers or those using the Schäfer technique for excimer lasers (Szatmari *et al.*, 1988, Sauerbrey, 1996). This work was essential for discovering an anomaly of laser-plasma interaction for application to inertial fusion energy (Hora *et al.*, 2007; Ghoranneviss *et al.*, 2008, Hora *et al.*, 2008). Today, tabletop lasers with pulses up to 100 TW power and a pulse sequence of seconds or shorter are available for synchronizing with the colliding events in the LHC.

The experiment by Boreham *et al.* (1979) was aiming to prove the action of the nonlinear (ponderomotive) forces at laser interaction in plasmas (Hora, 1969). After the characteristic property of producing a density minimum (caviton) by the nonlinear force was confirmed by several experiments (Hora, 1991, see Chapter 10.4), it was of interest whether the free electrons in a laser focus will receive a radial acceleration by the negative gradient of high-frequency electric laser field $\mathbf{E}$, given by $-\nabla\mathbf{E}^2$, as it was known as ponderomotive force in electrostatics. The general expression of the nonlinear force density in plasma (after eliminating gas dynamic, thermokinetic forces is given by

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

where $\mathbf{H}$ is the laser field vector, $\mathbf{1}$ is the unity tensor, ω the laser radian frequency, c the vacuum speed of light, and $\mathbf{n}$ is the (complex) refractive index. The prove of the correctness of equation (1) was given from the fact that these and only these terms of the forces were derived from momentum conservation for the non-transient case (Hora, 1969) and by symmetry reasons for the transient case (Hora, 1985). A further proof was given from Lorentz- and gauge-invariance

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(Rowlands, 2006). For simplified geometry, the force (1) can be reduced to

$$\mathbf{f}_{NL} = -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) = (\mathbf{n}^2 - 1)\nabla \mathbf{E}^2/(8\pi). \quad (2)$$

When plasma effects can be neglected for sufficiently large Debye lengths (Boreham *et al.*, 1979), single electron motion can be considered. It should be mentioned that the evaluation of the single particle motion enforced the use of the Maxwellian exact description of the laser beam with the then necessary tiny longitudinal field components (Hora, 1981, section 12.3; Cicchitelli *et al.*, 1990) indicating that neglection of tiny quantities in linear physics can lead to completely wrong results compared with the correct theory in precise nonlinear physics (Hora, 2000).

The result of the force is given by acceleration of the electron through the gradient of the laser field where the kinetic energy of the quiver motion of the electron in the laser field with its energy ε_{oc} is converted into translative energy $\varepsilon_{trans} = \varepsilon_{oc}/2$

$$\varepsilon_{trans} = E^2 e^2/(4\omega^2 m) \quad (3)$$

where E is the amplitude of the laser field and e is the charge and m the mass of the electron. The general quiver energy of the electron in a laser field of intensity I is

$$\varepsilon_{os} = mc^2[(1 + 3I/I_{rel})^{1/2} - 1] \quad (4)$$

The relativistic threshold intensity, where the quiver energy is mc^2 (Hora, 1981, 1991) is

$$I_{rel} = 3m^2\omega^2 c^3/(8\pi e^2) \quad (5)$$

The experiment (Boreham *et al.*, 1979) measured the emission of electrons form the cylindrical focus of a neodymium glass laser beam (wavelength $\lambda = 1.053\ \mu m$, relativistic threshold intensity $3.68 \times 10^{18} W/cm^2$) with axial maximum intensity $I = 10^{16} W/cm^2$ in low density helium from where the electrons after ionisation received an energy of 1 keV in radial direction of the laser beam. The theoretical value, Eq. (3), is 1.039 keV. The photon energy which goes into the kinetic energy of the quiver motion of the electron has a momentum ε_{trans}/c resulting in a forward component of the electron velocity parallel to the axis of the laser beam. This was calculated (Hora *et al.*, 1984) and measured in full agreement (Meyerhofer *et al.*, 1996).

What was interesting in these experiments is that there was a definite limit for the maximum emission energy of the electrons (Boreham *et al.*, 1979) and the maximum relativistic forward shift (Meyerhofer *et al.*, 1996). Beyond these values, nothing should be measured theoretically. But there was a whole spectrum of electron energies and shift angels due to the fact that electrons were emitted from parts of the laser beam and at times where the laser intensity I is lower than the maximum value. This was also evaluated by Meyerhofer *et al.* (1996). These spectra describe the whole spatial and temporal property of the laser pulse by functional-analytical folding of the distribution functions of the involved integral equations. For the experiment of laser interaction with the electrons in the LEP (Large Electron Positron Collider) (Hora, 1992), these properties were first of all of interest only about the electron distributions and again about the laser pulse properties. An effect on the generation of charged Z-particles was discussed.

For an application of the PW-ps laser pulses interacting with the colliding protons and the generated charged B-mesons and their subsequent longer living charged decay products, one has to take into account the comparably large masses of these particles requiring then the now available very high laser powers and intensities. First one has to confirm that the relativistic threshold intensity I_{rel} for these heavy particle is much higher than the quiver energy such that the subrelativistic branch of Eq. (5) is valid. Further it is interesting what maximum energy gain $\Delta\varepsilon$ the particle can reach by the laser field in order to check whether this change can be measured in the particle detectors for comparison with and without laser interaction.

For a modest tabletop laser to be added to the LHCb diagnostics one may consider a 100 TW laser pulse of 1 ps duration focused to 20 μm diameter. This pulse has a length of 0.3 mm and the temporal and/or radial intensity profile can be varied by the usual techniques such that a wide range of functional-analytical variations is possible for the evaluation of measured spectra of added energies or bending directions against the cases without laser interaction. For these interaction the following values result for neodymium glass lasers:

(1) charged B-mesons:

$$I_{rel} = 3.9 \times 10^{26}\ W/cm^2 \quad \Delta\varepsilon = 424\ eV$$

(2) protons (from LHC or protons or antiprotons form the B-decay):

$$I_{rel} = 1.2 \times 10^{25}\ W/cm^2 \quad \Delta\varepsilon = 2.41\ keV$$

(3) charged π-mesons from decay of B-mesons:

$$I_{rel} = 2.73 \times 10^{23}\ W/cm^2 \quad \Delta\varepsilon = 31.5\ keV$$

If these energy gains $\Delta\varepsilon$ from the laser interaction are too small, an increase by the use of more than 10 times higher laser power or by smaller focus diameter may lead to 100 to 1000 times higher values. However, the installation of the lasers near the LHC colliding volume may be a question of available space.

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