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PARTICLE ACCELERATION BY RESONANT ABSORPTION OF RADIATION

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Abstract

The paper reconsiders in a quantum approach the efficient gyroresonance absorption of laser light by gyrating charges, assuming to be at quasi-atomic states; the configuration (in the comoving frame) is analogous to traps in atomic physics. Applying also angular momentum conservation, kinematical relations are obtained, which describe the dynamical behaviour of this interaction; previous results appear modified. A synchronous resonance absorption can be maintained during acceleration mainly due to the Doppler-upshifted divergent laser beam. With a 10^{12} W laser, an efficiency of only 1 % and 10^8 $e^\pm$ per bunch ($\sigma_z = 30$ cm), an acceleration from 250 MeV to 1 TeV within ~ 1 m is expected. To test this plasma-density independent concept with existing apparatus in accelerators seems feasible. Furthermore, stimulated resonance interaction and spontaneous collective emission of cyclotron radiation are discussed; a possible beam energy compression, and a non-invasive continuous beam energy measurement with $\sim 10^{-5}$ accuracy (even per beam crossing), are also expected.

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1. Introduction

The known investigations of radiation pressure cover a wide spectrum. A few relevant examples are: a) The acceleration of atoms, in the direction of the laser beam, by repeated resonance radiation absorption. The atoms return spontaneously to the initial state, emitting randomly a photon after each excitation. This ‘spontaneous’ force is limited by the rate $f = \tau^{-1}$ at which spontaneous decays can occur (τ is the lifetime of the excited level) [1]. In atomic physics radiation pressure due to stimulated interaction is not subject to this time-limitation and is suggestive for this work. b) In the prompt Compton scattering f provides no limit, but the small interaction cross-section of electromagnetic waves (EMWs) with free charges ($\sigma^{max} = 0.625 b$) makes it impractical for terrestrial applications. In order to overcome this severe problem, the coherent Compton scattering has already been discussed [2]. In spite of the expected total reflection of EMWs by a relativistic plasma (e.g. a dense bunch of $e^\pm$) the acceleration length for TeV energies becomes impractical owing to kinematics [2].

The radiation pressure mechanism discussed in this work is based on the resonant exchange of energy, momentum and angular momentum between the incident polarized photons and the bound charges undergoing quasi-quantized orbital motion across the magnetic field B , while propagating along B . The angular momentum conservation is stressed, since it provides new simple kinematical relations for this interaction mode, first proposed some 30 years before [3, 4]. The main qualitative and quantitative features of this interaction become apparent, using a much less elaborate formalism than previously proposed [5-9]. This approach allows one to predict the dynamical behaviour of this radiation force, since some of the features are a consequence of the photon picture of the underlying interaction, which was pointed out also before [4]. The configuration of this concept (in the comoving frame) is analogous to the traps of atoms and ions in atomic physics, and therefore, some of their results and concepts are borrowed [10-22].

This interaction mode [23] is efficient, does not require a plasma, whilst the slow spontaneous cyclotron decay allows a quasi unlimited photon absorption. It is the purpose of this work to suggest a design (within the quantum picture of the photon-electron interaction), aimed at moving into the TeV scale, the energy domain of the future super colliders. However, the same reaction and its inverse mode (i.e. *stimulated emission*) [18, 19] might be utilized for beam energy compression and diagnostics.

2. The cyclotron – resonance interaction mode

A right-hand circularly polarized (laser) light, moving parallel to a static magnetic field, can be in resonance with the cyclotron motion of an electron at $\omega_{laser} = \omega_{cyclotron} = \frac{eB}{m_0}$, which is the fundamental gyroresonance frequency [23]. Mainly electrons are discussed in this work, but the same is valid also for other charged particles when taking into account their mass, charge, and lifetime. Classically, if the direction of rotation of the EMW's polarization is the same as the direction of gyration of the electrons, the wave loses its energy in continuously accelerating the electron Larmor motion and it cannot propagate [23]; in the quantum picture this is equivalent to the *resonant photon absorption by the electrons bound to the magnetic field*. This mode of interaction is behind the electron-cyclotron-resonance heating (ECRH), where radiation energy is transformed into kinetic energy of the gyrating charges [23, 24], and $\sim$ MeV electron energies have already been measured [25]. In the quantum picture, to reach this energy [25], the estimated number of the absorbed 28 GHz photons is enormous ($N_\gamma \sim 10^{10}$).

To avoid long interaction lengths let a photon pulse from a laser as well as an electron bunch merge into each other after the bending magnet, while propagating both along the longitudinal magnetic field (Fig. 1a). The energy transfer can continue provided the progressively increasing electron velocity does not destroy the resonance. The (free-space) electron cyclotron frequency is [26]

$$\omega_{cyclotron}^* = eB/m_0\gamma^* . \quad (1)$$

(Quantities with an asterisk refer to the electron frame, where its longitudinal momentum is zero; m_0 is the electron rest mass). The relativistic mass factor $\gamma^* = m^*/m_0$ is calculated from the transverse velocity $v_\perp^*$. For a magnetic field $B = 10$ T the fundamental electron gyrofrequency is (for $\gamma^* = 1$):

$$\omega_{cyclotron}^*/2\pi = \nu_{cyclotron}^* \approx 280 \text{ GHz} \quad (E_\gamma^* = \hbar\omega_{cyclotron}^* \approx 10^{-3} \text{ eV or } \lambda_{cyclotron}^* \approx 1 \text{ mm}).$$

The incident laser light will appear Doppler-shifted in the comoving frame. If the initial electron energy is 250 MeV ($\gamma = 500$), and it propagates parallel to the magnetic field (i.e. $\beta = v/c = \beta_\parallel$ and $\Theta = 0^\circ$ in Fig. 1b), then a laser in the visible (taken to have $E_\gamma^{laser} = 1 \text{ eV}$) can be used:

$$E_\gamma^*(\Theta = \Theta^* = 0^\circ) = E_\gamma^{laser}/2\gamma = 10^{-3} \text{ eV} \quad (2)$$

($\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor). With masers in the 30 GHz range and $B = 1$ T (e.g. in tokamaks), no initial electron energy is actually needed.

In the classical picture of the gyroresonance the radius of the circular orbit about the magnetic field B is given by [27]:

$$R = v_{\perp}^* / \omega_{cyclotron}^* = \gamma m_0 v_{\perp} / qB = \gamma^* m_0 v_{\perp}^* / qB. \quad (3)$$

$v_{\perp}$ is the transverse velocity and the radius increases with the electron's obliqueness and relativistic mass increase ($R \approx 170 \mu\text{m}$ for $v_{\perp}^* \approx c$, $\gamma \approx 1$ and $B = 10 \text{ T}$).

3. Kinematical relations

The kinematical relations derived in this work refer mainly to the comoving (not corotating) frame of reference. A Lorentz transformation will give the experimental conditions in the LAB frame. The photon energy (E_{γ}^*) in the comoving frame of reference is given by the Doppler effect:

$$E_{\gamma}^* = E_{\gamma}^{laser} \cdot \gamma_{\parallel} \cdot (1 - \beta_{\parallel} \cdot \cos\Theta) \quad (4)$$

($\beta_{\parallel} = v_{\parallel}/c$, $\gamma_{\parallel} = 1/\sqrt{1 - \beta_{\parallel}^2}$). Initially, it is assumed that $\beta = \beta_{\parallel}$ ($\Phi = 0^\circ$), and Θ is the angle of incidence in the LAB frame (Fig. 1b).

In the quantum picture of the interaction mechanism all absorbed circularly polarized photons have the same spin component along their direction of flight. Therefore, during photon absorption the electrons are, of course, accelerated longitudinally because of momentum/energy conservation, but at the same time they are forced to make a transverse spiral motion about the magnetic field, for the angular momentum to be conserved. Because of the large number of randomly absorbed photons, the transferred linear transverse photon momenta average to zero. It was noticed already that the electron beam must not have necessarily an initial transverse velocity [5], and this holds also within this work. The total transferred angular momentum (spin) of N_{γ} absorbed photons per electron gives

$$Rp_{\perp} = N_{\gamma} \hbar. \quad (5)$$

Relation (3) can be written in the following form:

$$p_{\perp} = qRB \quad (6)$$

($p_{\perp} = p_{\perp}^*$ is the transverse momentum). Combining Eq. (5) with Eq. (6) means considering simultaneously angular-momentum conservation and the balancing of the

centrifugal repulsion against the centripetal magnetic force ($mv_{\perp}^2/R = qv_{\perp}B$); the radius R , the transverse momentum $p_{\perp}$ and the electron inclination angle Φ , are:

$$R = \sqrt{N_{\gamma}\hbar/qB} = \sqrt{N_{\gamma}\hbar/m_0\omega_{cyclotron}} \approx 6.4 \cdot 10^{-4} \cdot \sqrt{\gamma - \gamma^{initial}} [cm], \quad (7)$$

$$p_{\perp} = \sqrt{N_{\gamma}\hbar qB} = N_{\gamma}\hbar/R = \sqrt{m_0c^2 N_{\gamma}\hbar\omega_{cyclotron}/c} \approx 16 \cdot \sqrt{\gamma - \gamma^{initial}} [keV/c], \quad (8)$$

and

$$\sin\Phi \approx \Phi = \frac{p_{\perp}}{p} = \frac{\hbar c}{RE_{\gamma}^{laser}} = \frac{\lambda^{laser}}{2\pi R} \approx 3.2 \cdot 10^{-2} \cdot (\sqrt{\gamma - \gamma^{initial}}/\gamma). \quad (9)$$

(p is the electron momentum). The conversion factors refer to $B = 10$ T and $E_{\gamma}^{laser} = 1$ eV. For example, at 1 TeV ($N_{\gamma} = 10^{12}$) it follows:

$$R = 0.88 \text{ cm}, \quad p_{\perp} = 23 \text{ MeV}/c, \quad \gamma^* = 46, \quad \gamma_{\parallel}^{final} = 43478 \text{ and } \Phi \approx 23 \text{ } \mu\text{rad}.$$

These values for R and m^* are entirely due to the transferred angular momentum, and not to an initially oblique electron motion relative to the longitudinal magnetic field B . The estimated radius R does not reflect a beam blow-up; it rather shows the spiralling trajectory of the whole electron bunch. *The transverse kinetic energy (~ 23 MeV per electron) will be the relativistic manifestation of the photon spin contribution to the electron energy gain, with ' ~ 23 μ eV per absorbed $\hbar$ ' for these particular conditions: analogously to the torque exerted by a circularly polarized light beam on a doubly refracting quartz plate, first observed by Beth in 1936 [28].*

The transverse momentum $p_{\perp}$ gives the final inclination angle Φ of the gyrating electrons relative to the magnetic field lines ($\Phi \approx 23$ μ rad in the above example). Then, the transverse field seen by the electrons is only a few gauss, and synchrotron radiation will be negligible. However, the cyclotron motion gives rise to the emission of electric dipole radiation with the damping time τ given by [5, 22] :

$$\tau = \frac{3\gamma_{\parallel}c}{4r_0(\omega_{cyclotron}^*)^2} = \frac{3\gamma_{\parallel}(\gamma^*)^2c}{4r_0\omega_{cyclotron}^2} \quad (10)$$

$$(r_0 = e^2/mc^2 = 2.8 \text{ fm})$$

For $B = 10$ T the estimated damping time is : a) $\tau = 26$ sec ($\gamma = \gamma_{\parallel} = 10^3$ and $\gamma^* = 1$) and b) $\tau \approx 10^6$ sec ($\gamma_{\parallel} = 10^5$ and $\gamma^* = 20$). With an acceleration time expected to be below ~ 1 μ sec, this *spontaneous* radiative damping is negligibly small. Furthermore, the spin motion decays via magnetic dipole radiation at a rate that is exceedingly slower than that for the cyclotron decay [22].

Provided the magnetic field size allows further orbital excitation of the gyrating electrons, there is in fact no time-limit for a repeated resonance absorption, avoiding

thus the bottleneck with the spontaneous decay rate. The crucial point is to keep the photon energy E_γ^* , 'seen' in the comoving frame, at resonance during the acceleration. Combining relation (1) with relation (4) the following resonance condition is obtained:

$$E_\gamma^{laser} \cdot \gamma_\parallel \cdot (1 - \beta_\parallel \cdot \cos \Theta_{resonance}) = \hbar \omega_{cyclotron}^* = \frac{\hbar \omega_{cyclotron}}{\gamma^*} \quad (11a)$$

It is obvious that $\gamma_\parallel \cdot \gamma^* \cdot (1 - \beta_\parallel \cdot \cos \Theta_{resonance})$ must remain constant during acceleration. For $E_\gamma^{laser} = 1 \text{ eV}$, $\hbar \omega_{cyclotron} = 10^{-3} \text{ eV}$ (i.e. $B \approx 10 \text{ T}$), $\gamma = \gamma_\parallel \gamma^*$ (s. Fig. 2), relation (11a) together with Fig. 1b give :

$$\cos \Theta_{resonance} = \frac{1 - 10^{-3}/\gamma}{\sqrt{1 - \gamma^{-2}} \cos \Phi} \quad (11b)$$

Using relation (9) to obtain Φ , the calculation with relation (11b) gives:

$$\Theta_{resonance} \approx \Phi \quad (11c)$$

Therefore, only oblique laser photons can give rise to gyroresonance absorption during the acceleration (lower solid line in Fig. 2). Using relations (8), (9), and integrating over the number (N_γ) of the absorbed photons (spins) per electron inside the magnetic field, γ^* , $1/\gamma_\parallel$, Φ and $\Theta = \Theta_{resonance}$ are obtained (Fig. 2).

In the widely discussed autoresonance cyclotron acceleration (ACA) [3-9], with an experimental configuration in fact identical with that assumed in this work, and for the ideal case with angle of incidence $\Theta = 0^\circ$ and index of refraction $n = 1$, the quantity

$$C = \gamma \cdot (1 - \beta_\parallel) \quad (12)$$

was considered as a constant of the motion, i.e. the resonance between the electrons and the EMW is preserved if it is satisfied initially [5]. However, in the ACA scheme continuous acceleration is not expected for oblique propagating EMWs with $\Theta \neq 0^\circ$ and $n \neq 1$ [6, 7]. Let start at resonance with the correct value of C . The angular momentum conservation introduced in this work defines $\beta_\parallel$ *independently* (relation (9) and Fig. 1b), and, with this value of $\beta_\parallel$, C is obtained. The quantity C takes the constant value $C = 0.5 \cdot 10^{-3}$ only asymptotically, and its energy dependence, estimated in this way, is shown in Fig. 2.

This asymptotic behaviour reflects the claimed resonance conservation in the ACA scheme; after all the description with the electric and magnetic field should be somehow adequate. But, one should note the main approximation common to earlier works of the ACA concept, which might be behind this discrepancy: *any feedback of the self-fields of the moving electrons on the wave is ignored*. However, for a quasi unlimited acceleration

pathlength (e.g. in interstellar space), and very weak incident light intensity (i.e. very small number of photons involved), only the quantum approach retains its validity fully.

The expected resonance detuning (for $\Theta = 0^0$) introduces a factor of $\sim (-2)$ in photon energy in the particular case depicted in Fig. 2. Thus, to restore the gyroresonance, this not negligible difference has to be taken into account. The advantage of the current approach is that resonance tuning can be restored in fact indefinitely, since the required photon energy correction can be achieved in a real case by choosing Θ (Fig. 2) or B or E_γ^{laser} according to relation (11) (see also the numerical example below). For example, with an incident divergent laser beam a continuous synchronization can be achieved at the gyroresonance during acceleration, due to the Doppler effect (Fig. 2).

Furthermore, the kinematical relation between the angle of incidence in the LAB (Θ) and in the comoving frame (Θ^*) is

$$\text{tg}\Theta = \frac{1}{\gamma_{||}} \frac{\sin\Theta^*}{(\beta_{||} + \cos\Theta^*)} \quad (13)$$

For a monochromatic light pulse the (ideal) condition $\Theta \ll 1/\gamma_{||}$ [$\Theta^* \ll 90^0$] might not be maintained always throughout the whole acceleration process (e.g. $\gamma^{final} \gg \gamma^{initial}$). If the angle of incidence Θ has to change during acceleration from $\Theta < 1/\gamma_{||}$ [$\Theta^* < 90^0$] to $\Theta > 1/\gamma_{||}$ [$\Theta^* > 90^0$] so that the photon energy remains at resonance, the photon circular polarization will be out of phase with the gyrating charges during the phase transition happening at $\Theta^* = 90^0$ [$\Theta = 1/\gamma_{||}$]. In the quantum picture the transferred photon spin component along the electron trajectory is not, say, $+\hbar$, but $-\hbar$ (Section 4). Then, acceleration is changed to deceleration, since the angular momentum (m_z) will be decreasing, and resonance absorption is changed to stimulated emission (see below and Fig. 3). To avoid this phase transition some alternative solutions are:

- i) choose $1/\gamma_{||} < \Theta \ll 90^0$ (for an efficient energy transfer) from the beginning,
- ii) use a reversed magnetic field after a well-defined distance, if one starts with $\Theta < 1/\gamma_{||}^{initial}$; then, the photon circular polarization remains adapted to the electron's Larmor motion. However, the (suddenly) changing polarity of the static magnetic field might induce undesirable electric forces, and

- iii) introduce an electron inclination angle $\Phi \neq 0$, since it increases $1/\gamma_{||}$ and decreases the required angle of incidence $\Theta_{resonance}$ in relation (11) (see below and Fig. 2).

Examples : a) Take $E_\gamma^{laser} = 1$ eV, $B = 10$ T with $\hbar\omega_{cyclotron}^* = 10^{-3}eV/\gamma^*$, $\gamma^{initial} = \gamma_{||}^{initial} = 5 \cdot 10^2$ (i.e. $\Phi = \Theta_{resonance}^{initial} = \Theta^* = 0$) and $\gamma^{final} = 2 \cdot 10^6$ ($N_\gamma = 10^{12}$). Following relations (8), (9), (11), and by integrating over the number of the absorbed photons (spins), the expected dynamical behaviour is shown in Fig. 2; the lower solid line gives the change of the electron inclination angle Φ , which coincides in fact (relation

(11c)) with the required photon angle of incidence ($\Theta = \Theta_{\text{resonance}}$) for the gyroresonance to occur. A further conclusion coming from these kinematical considerations is that above $\gamma \sim 10^4$ or factor ~ 10 energy gain (Fig. 2), the angle $\Theta_{\text{resonance}}$ approaches $1/\gamma_{\parallel}$ [$\Theta^* \rightarrow 90^\circ$]. In order to decrease Θ^* , the solution iii) mentioned above can be utilized. The stars and dots in Fig. 2 show the new values of $1/\gamma_{\parallel}$ and $\Theta = \Theta_{\text{resonance}}$ [keeping $\Theta^* = 60^\circ$], respectively; the additional electron inclination angle ($\Delta\Phi$) is introduced steadily above $\gamma \approx 2 \cdot 10^3$. The difference between the stars and the dashed line (i.e. $1/\gamma_{\parallel}$) in Fig. 2 gives : $\Delta\Phi \approx +60 \mu\text{rad}$ (at $\gamma = 10^4$) and $\Delta\Phi \approx +5 \mu\text{rad}$ (at $\gamma = 2 \cdot 10^6$). Note, Θ^* decreases further with increasing $\Delta\Phi$. In fact, the axial magnetic field inhomogenities and/or electron beam divergence provide the necessary obliqueness (both are below 10^{-4}). Then, together with the laser beam aperture used above to synchronize the gyroresonance absorption, these otherwise undesirable properties provide practical solutions for a quasi unlimited acceleration. The maximum required value at $\gamma \simeq 10^3$ (Fig. 2) is $\Theta_{\text{resonance}} \approx 0.7 \text{ mrad}$ [$\Theta^* = 60^\circ$]. Then, the photons from a $\sim 1 \text{ mrad}$ laser enter steadily into resonance.

The angle of incidence $\Theta_{\text{resonance}}$ takes the values $35 \mu\text{rad}$ and $25 \mu\text{rad}$, for the intermediate energies of 250 GeV and 500 GeV, respectively (dots in Fig. 2). The angular acceptance at 1 TeV can be widened by $\sim \pm 8 \mu\text{rad}$ using a variable static magnetic field $B \approx (6 - 20) \text{ T}$. In addition, with a photon energy, as well as, γ^{initial} smaller by a factor of 10 (e.g. CO_2 laser), one arrives at $\Theta_{\text{resonance}}^{\text{final}} \approx 50 \mu\text{rad}$. The conclusion is that at the final stage of the acceleration only the low divergent photons enter into resonance, and the final effective blow-up of the incident light pulse is given by a fraction of the photons with $\leq 50 \mu\text{rad}$ divergence (dots in Fig. 2). Therefore, the laser energy transfer efficiency can be $\sim (5 - 10)\%$, and laser defocusing must be taken into account after $L_{\text{defocus}} \approx 20 \text{ m}$ for a beam radius of $\approx 1 \text{ mm}$. For example, to reach 1 TeV final energy, a laser with a peak power of 10^{12} W ($\approx 10^{22} \text{ eV/ns}$), $\sim 1 \text{ mrad}$ aperture, and assuming only 1 % laser power transfer efficiency, should be taken together with a 250 MeV ($\gamma = 5 \cdot 10^2$) $e^\pm$ accelerator as the injector (e.g. the CERN/EPA ring [29] with $\sim 10^8 e^\pm$ per bunch of $\sigma_z \approx 30 \text{ cm}$ length in the LAB frame, an area of $\approx 1 \text{ mm}^2$ and 600 MeV beam energy).

The characteristic time for this interaction (in the comoving frame) is $1/\omega_{\text{cyclotron}}^*$. That is to say, for the resonance interaction between the *merged* photons and electrons to occur, the electrons must perform at least some fraction, say $1/2\pi$, of a complete rotation. The acceleration path length (e.g. for the above mentioned case) in the LAB

frame is

$$L_{\text{accel}} \approx c\gamma_{\parallel}^{\text{final}}/\omega_{\text{cyclotron}}^* = c\gamma_{\parallel}^{\text{final}}\gamma^*/\omega_{\text{cyclotron}} = c\gamma^{\text{final}}/\omega_{\text{cyclotron}} = 320 \text{ m}. \quad (14a)$$

Therefore, the acceleration force (so far) is $F \approx 3 \text{ GeV/m}$. Alternatively, in the quantum picture for the photon beam to interact with an electron, the photons must move relative to the *merged* electron beam (in the comoving frame) by $\sim \lambda_{\text{cyclotron}}^*$. The acceleration pathlength in the LAB frame is given by

$$L_{\text{accel}} \approx \gamma_{\parallel}^{\text{final}}\lambda_{\text{cyclotron}}^* = \gamma_{\parallel}^{\text{final}}\gamma^*\lambda_{\text{cyclotron}} = \gamma^{\text{final}}\lambda_{\text{cyclotron}} = 320 \text{ m}. \quad (14b)$$

In estimating L_{accel} one refers to that part of the laser beam, which enters into resonance interaction with the gyrating charges. The interaction probability is increasing with the electron density, and therefore, the photon interaction length is reduced approximately by the number of electrons per $(\lambda_{\text{cyclotron}}^*)^3$. Taking the CERN/EPA ring [29] as the injector, the maximum charge density during acceleration is expected to be $\rho_e^* \approx 2 \cdot 10^4 \text{ e}^{\pm}/(\lambda_{\text{cyclotron}}^*)^3$ (for $B = 10 \text{ T}$). Therefore, the potential reduction factor for the acceleration length might be as much as $\sim 2 \cdot 10^4$. However, in general, a reduction factor of only ~ 10 would be sufficient, in order to have $L_{\text{accel}} \leq L_{\text{defocus}}$. Assuming a laser energy transfer efficiency of only 1 % and $\sim 10^8 \text{ e}^{\pm}$ per bunch ($\rho_e^* > 2 \cdot 10^2 \text{ e}^{\pm}/(\lambda_{\text{cyclotron}}^*)^3$), one may reach the TeV scale with the same laser within $\sim 1 \text{ m}$. In this case, the acceleration force might even exceed 10 GeV/cm . With a higher laser power, or laser energy transfer efficiency, or initial bunch length, the total number of charges to be accelerated increases linearly in a multiplicative way.

b) With this method even a single charge can be accelerated in external test beams in accelerators. In such a case, the laser power within one wavelength (e.g. $1 \mu\text{m}$ or equivalently for $\sim 10^{-14} \text{ sec}$) comes into question, if only reasonable magnetic field lengths are considered. So, with a ‘modest’ laser ($\sim 10^9 \text{ W}$), final energies in the GeV range might be achieved within some metres of acceleration length, merely due to excess in available energy input (factor $\approx 10^5$).

4. Resonance cross-section

It is not unreasonable to consider the circulating electrons across the magnetic field lines as quasi-atomic bound states at giant orbits (e.g. $R < 1 \text{ cm}$): the nuclear Coulomb force is replaced by the Lorentz force ($F = qv_{\perp}B$). The resonance absorption of a photon excites the electron to the next quasi-discrete orbital state. The number of

the absorbed photons per electron gives the projection (m_z) of the electron angular momentum L along its trajectory (e.g. $m_z = 10^{12}$). In Fig. 3 some cyclotron energy levels are shown for the two electron spin states inside a static magnetic field B . The quantum mechanical energy level spacing is given by $\hbar\omega_{cyclotron}^*$, with $\Delta L = \Delta m_z = 1$ between neighbour states. The excitation/deexcitation occurs by the absorption/emission of electric dipole radiation, whilst level crossing (spin flip) is practically inhibited, since the spin is effectively stable against radiative decay [22]. These are in fact transient *geonium* states [21, 22]. If the electrons are circulating across the magnetic field instead of around the atomic nucleus, the following unique feature, of direct relevance for an effective radiation pressure mechanism, must be stressed: an electron is excited with each absorbed circularly polarized photon continuously to a higher quasi-Bohr-orbit avoiding the limit due to the spontaneous decay rate f (Section 1), and, following relations (7) and (14), the magnetic field size gives the maximum number of such steps to occur. Therefore, one may use (in the comoving frame) the quantum mechanical cross-section for photon resonant excitation from any quasi-atomic state to the next one [30] :

$$\sigma_0 [cm^2] \approx 4\pi \cdot (\lambda_{cyclotron}^*)^2 \approx 2.44 \cdot 10^{-9} \cdot (E_\gamma^*)^{-2} [eV] \quad (15a)$$

For $B = 10$ T and 1 TeV final electron energy, σ_0 takes quite reasonable values :

$$\sigma_0^{initial} \approx 2.5 \cdot 10^{-3} \text{ cm}^2 \quad \text{and} \quad \sigma_0^{final} \approx 6 \text{ cm}^2. \quad (15b)$$

($E_\gamma^* \approx 10^{-3} \text{ eV}/\gamma^*$ or $\lambda_{cyclotron}^* \approx \gamma^* \text{ mm}$). However, the gyrating electron with radius $R \leq 1 \text{ cm}$ can be considered as an oscillating electric dipole with electric dipole moment $\mu = e \cdot R$ and oscillation frequency $\omega_{cyclotron}^* = c/\lambda_{cyclotron}^*$. A classical description is entirely adequate for such macroscopic oscillations. Then, the interaction probability of a driving EMW with the electric dipole at resonance is [30]:

$$\sigma^{max} \approx 6\pi \cdot (c/\omega_{cyclotron}^*)^2 = 6\pi \cdot (\lambda_{cyclotron}^*)^2 \quad (16)$$

Therefore, in the quantum picture, as well as, in the classical approach, and for a 1 mm^2 beam area, such a cross-section reflects the strong coupling between the incident EMW and the electrons, reducing the interaction length (i.e. L_{accel}).

5. Other possible applications

a. Beam energy compression.

The absorbed photon spins are responsible for the onset of the transverse electron motion (e.g. $\Theta^* < 90^\circ$) as already discussed. In the classical picture of this interaction,

and for $\Theta^* > 90^\circ$, the direction of the electron gyration and the EMW's polarization are not corotating, and resonance absorption is suppressed [23]. In the quantum picture, resonance interaction can take place also for $\Theta^* > 90^\circ$, giving rise to *stimulated deexcitation* (Fig. 3). But, because of angular momentum conservation the m_z component of the electron's angular momentum must be reduced by one unit ($-1\hbar$) for each forced deexcitation of the orbital motion. The stimulated emission of cyclotron radiation reduces the transverse but unfortunately also the longitudinal momentum. In contrast to a previous work [31], transverse cooling within this scheme appears—at least at first sight—not to be possible.

The question arises, whether one can narrow the beam energy spread. For this purpose, suppose that the resonance energy requires $\Theta^* = 90^\circ$ for the mean electron energy $\langle E_e \rangle$. Then, because of kinematics (relations (11) and (13)), electrons with energy below or above $\langle E_e \rangle$, need an angle of incidence $\Theta^* < 90^\circ$ or $\Theta^* > 90^\circ$, respectively. Therefore, the lower energetic electrons will gain energy by photon absorption, whilst the higher energetic ones will be decelerated due to the induced emission of cyclotron radiation in the forward direction; in both cases the electrons do not cross $\langle E_e \rangle$ because of phase transition (Section 3). Thus, one expects heating of the electrons for negative detuning and cooling for positive one. At the same time, half of the electrons with $\Theta^* < 90^\circ$ and the other half with $\Theta^* > 90^\circ$, are transversally heated and cooled, respectively. The physical process responsible for this *beam energy compression* is analogous to the cooling in atomic traps by two counterpropagating laser waves or standing waves [12, 14, 18, 19]. Here, because of relativistic kinematics, the laser beam, seen from the comoving frame, is in fact splitted into two parts of actually equal intensity around $\Theta^* = 90^\circ$, with opposite components along the magnetic field lines.

b. Beam diagnostics.

For a given laser energy, the stimulated gyroresonance interaction can be experimentally established, for example, by scanning the applied magnetic field at the expected value. An increasing laser light intensity after the interaction region inside a longitudinal magnetic field in a straight section of the accelerator (downstream), will be the signature for the onset of the stimulated emission. From the threshold width and the measured distribution (relation (11a)), the energy and emittance distribution of the electrons, can be deduced, respectively. Since the electrons pass the limited magnetic field region with the same direction of gyration many times, it is as if the gyration continues, giving rise to a sharper resonance. This can be equivalent to the "oscillatory-fields" in atomic physics [17], with the pulses being separated in time or in space. In this work, the repeatedly induced resonance interaction, together with the feed back of the 'self-amplified' laser

pulses inside the interaction region, must have phase coherency preserved.

Consider, for example, $E_{\gamma}^{laser} = 2$ eV, an axial field of .1 T and a length of 2 m; a realistic case, which does not disturb the fine tuned accelerator (e.g. CERN's LEP collider [29] with a repetition rate of ~ 50 kHz). Taking into account the uncertainty principle, the energy of a circulating single electron can be measured with an expected accuracy of $\sim 10^{-5}$ with $\sim 10^3$ sec integration time. Since the gyrating electrons behave as individual oscillators/"atomic dipoles", the mean energy of the whole bunch (with $\geq 10^8$ electrons) might be measurable with the same accuracy even *per beam crossing*.

Alternatively, for a cyclotron radiation with a wavelength comparable to the bunch length, the electrons are emitting (spontaneously) not independently from each other, but rather collectively [33]. Then, the damping time τ (relation (10)) is reduced by the number N_e of the electrons per bunch (e.g. $N_e \approx 4 \cdot 10^{11}$ [29]): this is the widely discussed *superradiance* [34] (in flight). For the LEP-beam [29], the expected coherent relative energy loss per beam crossing of a 2 m longitudinal magnetic field component of $\sim .1$ gauss strength ($\lambda_{cyclotron} \approx 1$ cm) is $\approx 10^{-13}$ or some 10^8 eV per bunch. The number of the ~ 30 GHz photons expected to be emitted *per beam crossing* is $\sim 10^{12}$, with a statistical fluctuation far below the required accuracy of $(10^{-4} - 10^{-5})$ [32]. The emitted frequency spectrum ($\sim \frac{eB}{m_0\gamma^*} \gamma_{||} \xrightarrow{\gamma^*=1} \frac{eB}{m_0} \gamma$) will reflect the bunch energy and emittance distribution, while the intensity is given by τ^{-1} . Furthermore, emission of cyclotron radiation at higher harmonics [35] can be of practical use.

c. Astrophysics.

It is obvious that wherever charged particles are irradiated inside a static magnetic field by an EMW of appropriate frequency and polarization, this can give rise to acceleration. It has been proposed already that this interaction mode might be behind the acceleration of particles in solar flares [36], the very high energy of cosmic rays [4], etc.. For example, the polar regions of the luminous pulsars might have $\approx 10^8$ T surface dipole field, which is still ~ 10 T at a distance of ~ 200 km ; together with the ultra-wide bandwidth of the emitted electromagnetic radiation, such places appear to be ideal for particle acceleration to very high energies.

6. Discussion

A new variation of radiation pressure is discussed for acceleration purposes of quasi-free charges (bound to the magnetic field). The working principle of the reconsidered linac configuration [3-9] is almost identical with that encountered in electron cyclotron

resonance heating (ERCH) or the time reversed process behind the gyrotrons and the more sophisticated cyclotron-masers [25, 26]. The jump from the observed $\sim$ MeVs in ECRH to the expected TeVs might be allowed, since the number of the absorbed photons to reach the TeV range will be $\sim 10^{12}$ and may be compared with the estimated $\sim 10^{10}$ in ECRH [25]. Therefore, it is not unreasonable to assume that what happens, in principle, at such relatively low energies is valid also in the comoving frame of relativistic electrons under otherwise similar experimental conditions; the rest is relativistic kinematics.

It should be noted that the maximum plasma frequency of the CERN/EPA $e^\pm$ beam is $\nu_{plasma}^* = 9000 \cdot \sqrt{\rho_e^*} \approx 30$ MHz [2, 23]; therefore, plasma interference effects at ~ 280 GHz become negligible. Their contribution can be determined, for example, by making a measurement at a magnetic field strength slightly below or above the resonance value.

The use of still higher magnetic field and laser photon energy, more powerful lasers, and in particular the expected good energy conversion efficiency, make this concept promising for the TeV scale, with a short acceleration path length. An excess in laser power input reflects a further shortening of the acceleration length, whilst in favour of the energy transfer efficiency of this scheme is also the multiphoton absorption: an electron absorbs several photons and goes directly to a higher orbital state [37]. Together with the Doppler-induced synchronization for a part of the incident light at the gyroresonance during acceleration, all these features fit to a realistic configuration towards compact high-energy machines, not only at TeV but also for other purposes at much lower energies.

Finally it is worth remembering that the Liouville theorem applies to conservative forces, and therefore, the use of dissipative processes does not oppose this theorem [15, 20]. The discussed beam energy compression improves the accelerator performance and it can be implemented in existing accelerators. An integration time of $\sim 10^3$ sec can compensate a not foreseen inefficiency and/or reduce the required laser power enormously. A non-invasive precise energy monitoring is essential for a precise mass measurement (M_Z) of the neutral weak boson, as well as of its natural width, which can become a precision test for the Standard Model [32]. Last but not least, such tests can be useful for simulation of celestial processes, associated probably with the unknown cosmic accelerator(s).

To test the suggested mechanism in an accelerator a laser and a solenoidal magnetic field are needed, even though accelerator physicists may not be accustomed to having longitudinal magnetic fields.

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References

- [1] A. Ashkin, Phys. Rev. Lett. **25** (1970) 1321.
- [2] A. G. Morgan, E. J. N. Wilson and K. Zioutas, CERN/PS 90-61 (Di) (1990) and in Proc. Trends in Astropart. Phys., Santa Barbara, CA, World Scientific (1992) 454.
- [3] A. A. Kolomenskii and A. N. Lebedev, Sov. Phys. – Doklady, **7** (1963) 745.
- [4] C. S. Roberts and S. J. Buchsbaum, Phys. Rev. **135**, 2A (1964) A381.
- [5] A. Loeb and L. Friedland, Phys. Rev. **A33** (1986) 1828.
- [6] H. Karimabadi, C. R. Menyuk, P. Sprangle, L. Vlahos, Astrophys. J. **316** (1987) 462.
- [7] K. Hizanidis, L. Vlahos, C. Polymilis, Phys. Fluids **B1**(3) (1989) 682.
- [8] C. R. Menyuk, A. T. Drobot, K. Papadopoulos and H. Karimabadi, Phys. Rev. Lett. **58** (1987) 2071.
- [9] J. L. Vomvoridis, IEEE - **NS-28** (1981) 3418.
- [10] See, for example, the Proceedings of the Intern. School of Physics "E. Fermi", Laser Manipulation of Atoms and Ions, Edited by E. Arimondo, W. D. Phillips and F. Strumia (North-Holland, Amsterdam 1992).
- [11] S. Stenholm, *ibid* (1992) 29.
- [12] C. Cohen-Tannoudji, *ibid* (1992) 99.
- [13] S. Chu, *ibid* (1992) 239.
- [14] W. D. Phillips, *ibid* (1992) 289.
- [15] V. I. Balykin, *ibid* (1992) 423.
- [16] G. Gabrielse, *ibid* (1992) 631.
- [17] N. F. Ramsey, *ibid* (1992) 1, and Rev. Mod. Phys. **62** (3) (1990) 541.
- [18] A. Aspect, J. Dalibard, A. Heidman, C. Salomon, and C. Cohen-Tannoudji, Phys. Rev. Lett. **57** (1986) 1688.

- [19] C. N. Cohen-Tannoudji and W. D. Philips, *Physics Today* **43** (10) (1990) 33.
- [20] D. J. Wineland and W. M. Itano, *Physics Today* **40** (6) (1987) 34.
- [21] H. Dehmelt, *Am. J. Phys.* **58** (1990) 17.
- [22] L. S. Brown and G. Gabrielse, *Rev. Mod. Phys.* **58** (1986) 233.
- [23] F. F. Chen, *Introduction to Plasma Physics*, Plenum Press, New York (1974).
- [24] M. Geisler, J. Kieser, E. Rauchle, R. Wilhelm, *J. Vac. Sci. Technol.* **A8**(2) (1990) 908.
- [25] T. Saito, I. Katanuma, Y. Kiwamoto, T. Kariya, S. Miyoshi,
Phys. Rev. Lett. **59** (1987) 2748.
- [26] P. Sprangle and T. Coffey, *Physics Today* **37**(3) (1984) 44.
- [27] E. J. Konopinski, *Electromagnetic fields and relativistic particles*, McGraw-Hill, New York (1981) 125, 398.
- [28] R. A. Beth, *Phys. Rev.* **50** (1936) 115, and
H. Frauenfelder, E. M. Henley, *Nuclear and Particle Physics*,
A : Background and Symmetries, Benjamin, London (1975) 124.
- [29] The LEP injector chain, CERN - LEP / TH / 83 - 29 (1983) 46.
- [30] J. D. Jackson, *Classical Electrodynamics*, 2nd Edition, J. Wiley, New York (1975) 803, and B. L. Bowers, T. Deeming, *Astrophysics*, Jones and Bartlett Publ., Boston (1984) 114.
- [31] H. Ikegami, *Phys. Rev. Lett.* **64** (1990) 1737.
- [32] L. Arnaudon et al., CERN-PPE / 93-53, CERN-SL / 93-17 (16.3.1993), A. Blondel, *Physics World* (Jan. 1991) 22, and H. Burkhardt and J. Steinberger, *Annu. Rev. Nucl. Part. Sci.* **41** (1991) 55.
- [33] G. P. Williams et al., *Phys. Rev. Lett.* **62** (1989) 261, and
T. Nakazato et al., *Proc. 14th Intern. Conf. High Energy Accelerators*, Tsukuba, Japan (1989).
- [34] M. Gross and S. Haroche, *Phys. Rep.* **93** (1982) 301.

- [35] J. L. Hirshfield, Phys. Rev. **A44** (1991) 6845.
- [36] P. Sprangle and L. Vlahos, Astrophys. J. Lett. Ed. **237** (1983) L95, and
P. Sprangle, L. Vlahos and C. M. Tang, IEEE/NS-**30** (4) (1983) 3177.
- [37] C. Cohen-Tannoudji, J. Dupont-Roc, G. Grynberg, Atom-Photon Interactions,
J. Wiley, New York (1992) 98.

Figure captions.

Figure 1. a) Schematic view of electron acceleration by radiation pressure via the cyclotron-resonance absorption mechanism inside a longitudinal magnetic field. The laser pulse and the electron bunch are merged into each other after the bending magnet.

BM = bending magnet and **M** = solenoidal magnet.

b) Definition of the kinematics used in the text (LAB-frame).

Figure 2. Energy dependence of kinematical quantities during gyroresonance acceleration starting at $\gamma^{initial} = 5 \cdot 10^2$. The magnetic field (~ 10 T) and laser energy (1 eV) satisfy the gyroresonance condition initially (with $\Theta = 0$ and $\beta = \beta_{||}$). The upper solid line shows the expected behaviour of the quantity $C = \gamma \cdot (1 - \beta_{||})$ (rel. (12)). The change of the electron inclination angle Φ and the required angle of incidence ($\Theta = \Theta_{resonance}$) to maintain the gyroresonance are also shown (lower solid line). The dots and stars give the modified values for $\Theta_{resonance}$ and $1/\gamma_{||}$ (dashed line), if an additional transverse electron momentum (~ 5 MeV/c) is introduced steadily above $\gamma \approx 2 \cdot 10^3$, while keeping $\Theta^* = 60^\circ$ (s. text).

Figure 3. Pseudo-atomic states of gyrating electrons inside a static magnetic field for the two electron spin states; the angular momentum L and its projection along the field lines are assigned to the levels. The level spacing is $\hbar\omega_{cyclotron}^*$; level crossing (spin flip) is practically inhibited, since this is a magnetic rather than an electric dipole transition (i.e. the rate is much slower than that for the cyclotron decay [22]).

a)

b)

Figure 1.

Figure 2.

Figure 3.