ON THE MECHANISMS OF STRONG MAGNETIC FIELD EXCITATION AT THE INTERACTION OF ULTRAINTENSE SHORT LASER PULSE WITH AN PLASMA TARGET

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By means of a 2.5 - dimensional numerical simulation on the macroparticles method it is possible to find the magnetic field spatial and temporal distribution without usage an adapted parameter unlike of the conventional $\nabla n x \nabla T$ mechanism. On the other hand, theoretical model for the generation of a magnetic field proposed by R. Sudan is not appropriate, this model being very large ratio of plasma density to critical density and when the $\nabla n x \nabla T$ contribution is not relevant.

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1. INTRODUCTION

The interaction between intense laser radiation and matter is known to produce a wealth of nonlinear effects. Those include fast electron and ion generation [1–5] indicating that ultra-strong electric fields are produced in the course of the laser–plasma interaction. An equally ubiquitous, although less studied, effect accompanying laser–matter interaction is the generation of ultra-strong magnetic fields in the plasma [6–11]. Magnetic fields can have a significant effect on the overall nonlinear plasma dynamics. Extremely high (few megagauss) azimuthal magnetic fields play an essential role in the particle transport, propagation of laser pulses, laser beam self-focusing, penetration of laser radiation into the overdense plasma and the plasma electron and ion acceleration.

2. INVERSE FARADAY EFFECT

The generation of an axial magnetic field in the plasma by a circularly (or elliptically) polarized laser is often referred to as the inverse Faraday effect (IFE). First theoretically described by Pitaevskii [12] and Steiger and Woods [13] it results from the features of the electron motion in a circularly polarized electromagnetic wave. During the interaction of the plasma electrons with the circularly polarized laser pulse, electrons absorb both the laser energy and the angular momentum of the laser pulse. In particular, the angular momentum absorption leads to the electron rotation and generation of the axial magnetic field by the azimuthal electron current. Naturally, IFE does not occur for a linearly polarized laser pulse since it does not possess any angular momentum. IFE has since been measured in several experiments [9,14, 15]. The conditions under which IFE is possible are still not fully explored. What is theoretically known [16] is that there is no magnetic-field generation during the interaction of the inhomogeneous circularly polarized electromagnetic waves with the homogeneous plasma. Magnetic field can be produced in the presence the strong plasma inhomogeneity [17–19] either preformed or developed self-consistently during the interaction. More recently a mechanism has been proposed for the generation of an axial magnetic field through the transfer of the spin of the photons during the absorption of a transversely nonuniform circularly polarized radiation [20]. The magnetic field thus generated has a magnitude proportional to the transverse gradient of the absorbed intensity and inverse proportional to the electron density, the latter sealing being in contrast to earlier theories of IFE [20]. Along the same lines as [20], it has been demonstrated that in laser-plasma interactions strong axial magnetic fields can be generated through angular (spin) momentum absorption by either electron-ion collisions or ionization. Yet another mechanism of magnetic field generation has been proposed (in framework of classical electrodynamics) [21], based on the resonant absorption by energetic electrons of a circularly polarized laser pulse. The resonance occurs between the fast electrons, executing transverse (betatron) oscillations in a fully or partially evacuated plasma channel, and the electric field of the laser pulse. The betatron oscillations are caused by the action of the electrostatic force of the channel ions and self-generated magnetic field. This type of resonant interaction was recently suggested as a mechanism for accelerating electrons to highly relativistic energies [21,22]. When a circularly polarized laser pulse is employed, its angular momentum can be transferred to fast resonant electrons along with its energy. The resulting electron beam spirals around the direction of the laser propagation, generating the axial magnetic field [21]. In [21] the intensity of the magnetic field generated in relativistic laser channel was calculated taking into ac-count self-generated static fields, which are neglected in known IFE theories [17–19]. Calculations [21] are in agreement with the recent experiments at the Rutherford Appleton Laboratory (RAL) [15] which exhibited very large (several megagauss) axial magnetic fields during the propagation of a sub-picosecond laser pulse in a tenuous plasma. The relevant aspect of the RAL experiment is that both fast electrons and the strong magnetic field were measured in the same experiment.

3. MAGNETIC FIELD EXCITATION IN UNDERDENSE PLASMA

In an underdense longitudinal inhomogeneous plasma the nonrelativistic two-dimensional treatment of self-generated magnetic fields was presented in the article [23], showing that a laser beam propagating along a density plasma gradient produces a rotational current which gives rise to a quasi-static magnetic field. An analogous mechanism was considered earlier in the paper [24] whereas the nonlinear mixing of two electromagnetic waves in a nonuniform plasma was discussed in the work [25]. They investigated a circularly polarized pulse for which the generation of low-frequency electromagnetic field is due to the inverse Faraday effect. In the extremely strong relativistic regime the magnetic field generated by the laser beams in underdense plasma was recently studied numerically [26]. The main objective of the work [18] was to investigate self-generated quasi-static magnetic fields both in the laser pulse body and behind the pulse in the region of the wakefield. Authors treated the laser radiation as linearly polarized and the plasma as uniform and underdense. The analytical work was based on a perturbation theory applied to the set of relativistic cold electron fluid equations and Maxwell's equations. The quasi-static magnetic field generated by a short laser pulse in a uniform rarefied plasma is found analytically and compared to two-dimensional particle-in-cell simulations .It is shown that a self-generation of quasi-static magnetic fields takes place in fourth order with respect to the parameter v_E/c where v_E and c are the electron quiver velocity and the light speed, respectively. In the wake region the magnetic field possesses a component which is homogeneous in the longitudinal direction and is due to the steady current produced by the plasma wakefield and a component which is oscillating at the wave number $2k_p$,, where k_p is the wave number of the plasma wake, a known property of nonlinear plasma waves [27,28]. Numerical particle simulations confirm the analytical results and are also used to treat the case of high intense laser pulses with $v_E/c > 1$. The resultant magnetic field has a focusing effect on relativistic electrons in the plasma wakefield accelerator context.

4. MAGNETIC FIELD EXCITATION IN OVERDENSE PLASMA

Further we discuss the physical mechanism for generation of very high "quasi-static" magnetic fields in the interaction of an ultraintense short laser pulse with an overdense plasma target owing to the spatial gradients and non -stationary character of the ponderomotive force. Numerical (particle – in - cell) simulations by Wilks et al. [10] of the interaction of an ultraintense laser pulse with an overdense plasma target have revealed non-oscillatory self-generated magnetic fields up to 250 MG in the overdense plasma, that this nonoscillatory magnetic field around the heated spot in the center of the plasma, the magnetic field generation being attributed to the electron heating at the radiation-plasma interface. The spatial and temporal evolution of spontaneous megagauss magnetic fields, generated during the interaction of a picosecond pulse with solid targets at irradiances above 5 x 10^{18} W/cm^2 have been measured using Faraday rotation with picosecond resolution, the observations being limited to the region of underdense plasma and after a laser pulse Fig.1, [6]. A high density plasma jet has been observed simultaneously with the magnetic fields by interferometry and optical emission.

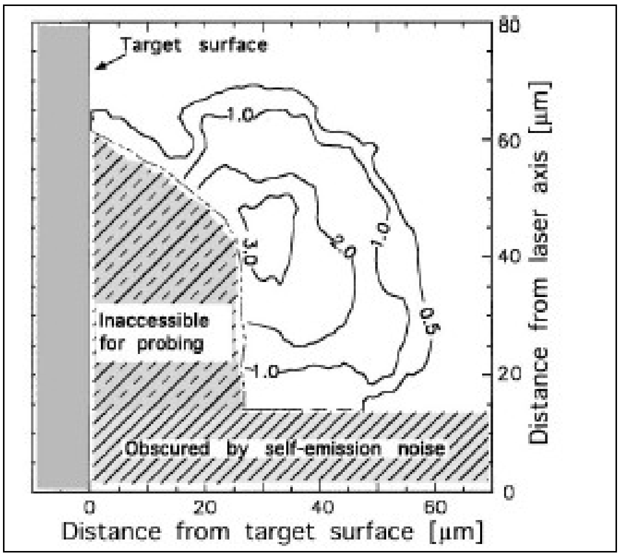

Fig.1. Magnetic field distribution extracted from the polarigram. The magnitude is in units of megagauss. The plasma region either obscured by selfemission or not accessible for probing is shown, (from [6])

Because of the high temporal resolution of the probe diagnostic, a quantitative measurement of the transient nature of the fields has been obtained for the first time. Interestingly, no Faraday rotation was detected immediately after the interaction, a possible reason being that the fields were still limited to regions not accessible for probing. After 5 ps the typical signatures corresponding to a toroidal field surrounding the laser axis (i.e., a dark and a bright pattern on opposing sides of the axis, in the proximity of the target surface) began to appear. The strongest rotations were detected between 6 and 12 ps after the interaction. As expected, the dark-bright pattern reverses as the angle between the polarizers is changed from a value below 90° to a value above 90°. The sense of rotation is the same as observed in previous measurements in longer pulse regimes and is consistent with fields generated by the thermoelectric mechanism (see for example [30]). In paper [7a] the first direct measurements of high energy proton generation (up to 18 MeV) and propagation into a solid target during such intense laser plasma interactions were reported. Measurements of the deflection of these energetic protons were carried out which imply that magnetic fields in excess of 30 MG exist inside the target. The structure of these fields is consistent with those produced by a beam of hot electrons which has also been measured in these experiments. The intensity on target of laser radiation was up to 5×10^{19} W/cm^2 and was determined by simultaneous measurements of the laser pulse energy, duration, and focal spot size. The largest magnetic fields available terrestrially (~10^2 MG) are generated by explosive ionization of a solid target with an intense ultrashort laser pulse [7b]. In paper [7c] presented first experimental measurements of the temporal evolution of megagauss magnetic fields generated at the critical layer, on femtosecond time scales. The field generation and decay mechanism are identified and the role of resonance absorption (RA) was examined by authors of paper [7c]. The field evolution was explained to be due to currents generated by fast electrons [8a] and plasma return currents damped by turbulence induced resistivity [8b]. Authors of paper [7c] first demonstrated ultrashort, megagauss magnetic pulses , with a peak magnitude of 27 MG and 6 ps (FWHM) duration generated by a p-polarized laser pulse (10^{16} W/cm^2, 100 fs). They observed no significant Faraday rotation but large and easily measurable ellipticity change. Authors emphasized that in agreement with their observation a magnetic field generation primarily occurs near the critical surface (n_e ~10^{21} cm^{-3}), the region of maximum laser absorption. Moreover, it is the magnetic field in the overdense region that determines hot electron transport into the bulk. This indicates that a magnetic field (B) is essentially perpendicular to the laser pulse propagation direction in agreement with previous reports for RA generated magnetic fields [7b]. Such observations are the first evidence of the large magnetic fields whose have been predicted to occur during laser - target interactions in dense plasma [10].

5. RESULTS OF NUMERICAL SIMULATION

In [29] the problem of high-intensity, linearly polarized electromagnetic pulse incident onto a collisionless plasma layer is solved numerically in a Cartesian coordinate system in a 2.5-D formulation (z is the cyclic coordinate and there are three components of the momentum) by means COMPASS (COMputer Plasma And Surface Simulation) code. The recent review [30] and references therein combine a detailed information concerning COMPASS code as well as its possibilities and applications. One of general advantage of the complete numerical simulation is possibility as well as at the laboratory experiments obtain all necessary information concerning spatial and temporal dynamics of both particles and self-consistent electromagnetic fields without usage of additional data (reflection and absorption coefficients, changes of either a plasma temperature or different plasma parameters) in given situation at a interaction intensive electromagnetic pulse with plasmas. We give only the external parameters, the both initial and bounded conditions for particles and fields and as results of a numerical simulation we attain all characterictics of plasmas together with pulsed self-consistent electromagnetic fields. In given problem we consider at the initial time, a cold motionless neutral two-component (ions and electrons with a real ratio of their masses) plasma with uniform density fills the whole right-hand part of rectangular domain $X\times Y=L_x\times L_y=128\times 64\, c/\omega_{pe}$ (c is the speed of light, ω_{pe} is the electron plasma frequency). The line $x = L_b=40\, c/\omega_{pe}$ represents the plasma-vacuum boundary. The system is periodical along the y-coordinate; the plasma particles are reflected elastically from the right-hand and left-hand boundaries. The initial and boundary conditions for the electromagnetic fields (they are measured in units $m_e\omega_0 c/e$) are the following: $E(t<0)=B(t<0)=0$; $E_y(x=0,\ y,\ t>0)=B_z(x=0,\ y,\ t>0)=A(y)\cos(\omega_0 t)$; $A(y)=A_0\exp((y-L_y)/l_0)^2$, where $\omega_0 = \omega_{pe}/2$ is the frequency of the incident electromagnetic radiation. The radiation intensity A_0 provides a kinetic momentum of about $3m_ec$ to be carried by oscillations; $l_0=10\, c/\omega_{pe}$.

The most characteristic feature of the action of an intense, normally incident electromagnetic pulse onto an ultrahigh-density plasma consists in a “well-digging” effect. The depth of the “well” in the plasma profile increases with time and is $15\, c/\omega_{pe}$ at time $500\,\omega_{pe}^{-1}$. Worth nothing is the growing in time sharp nonuniformity of the perturbed plasma layer in the transverse direction.

Thereby it shown that the magnetic field oscillates with the doubled frequency of a laser radiation, but it has unchanged direction. The magnetic field oscillations are saw good at Fig.2. Now let us look at Figs.2,a and 2,b, which present two instantaneous magnetic field B_z distributions separated in the time by $\pi\omega_{pe}^{-1}$ (a plasma wave half-period). It will be noted that a maximum of magnetic field (1.1) in the point (38,31) in the time $t\omega_{pe}=200$ (see Fig.2,a) after a plasma wave half-period (see Fig.2,b) replaced in this point very low value of magnetic field.

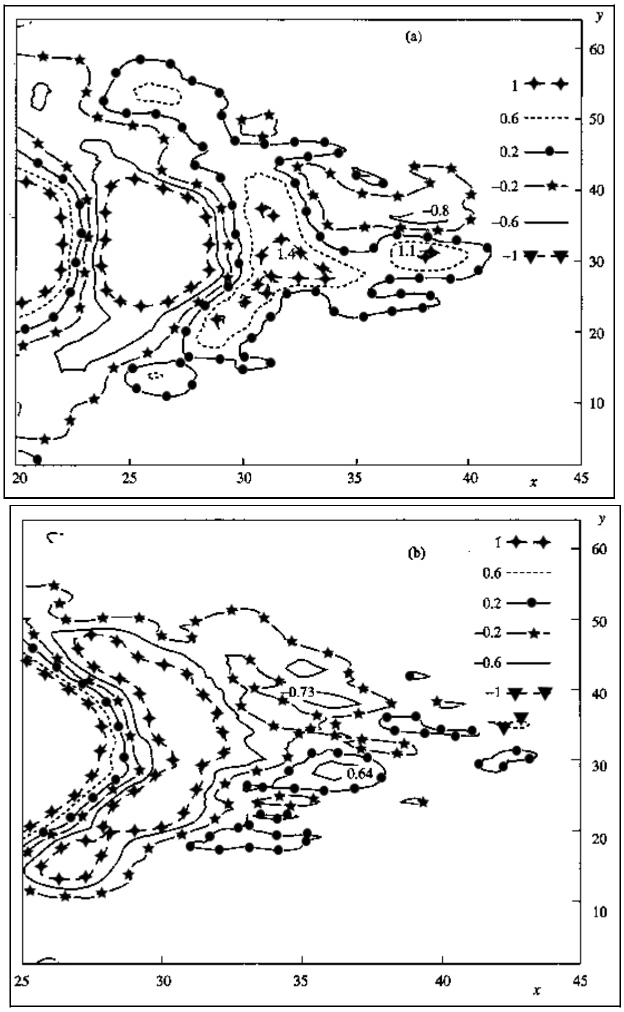

Fig.2 (from [29]) Spatial distribution of magnetic field B_z at different times: $t\omega_{pe}=200$(a); $t\omega_{pe}=200+\pi$ (b)

The magnetic field B_z attains its peak value of (0.64) at the point (36.5,29), cf. Fig.2,b. It is shown that the magnetic field B_z is consistent with a linearly modulated current flowing along the line $y=L_y/2$. We do not observe this field to change its direction, but its strength varies significantly in time. Hence, the magnetic field cannot be considered as quasi-static because it varies by more than an order of magnitude over a time of $2\pi\omega_{pe}^{-1}$.

The magnitude of the "dc" magnetic field is ten times as low as the maximum magnetic field. One should note that the numerical simulation has been made under very optimal conditions: a uniform plasma density makes it sure a own plasma oscillation resonance with a longitudinal modulation density of particles in a wave as well as a maximum frequency of nonlinear Tomson scattering spectrum. In experiments a plasma inhomogeneity was very essential, with the result that resonant conditions were fulfilled only in a small plasma region. Afterwards the interaction pulse, only the "dc" magnetic field exists, as measured in the underdense plasma region in [6].

On the basis of the formula $B_{dc}(MG) = 4.2x(10^{-22}I(W/m^2))^{1/2}(\lambda(\mu m))^{-1}$, where I is the intensity of the incident laser radiation) one obtains a "dc" magnetic field magnitude of few MG for the experimental parameters of [6], and a few tens MG for the experimental conditions of [7]. A difference still on order of value is conditioned that at such intensities only 10% of the incident laser radiation is absorbed in agreement with [31].

By means of a 2.5 - dimensional numerical simulation on the macroparticles method it is possible to find the magnetic field spatial and temporal distribution without usage an adapted parameter unlike of the conventional $\nabla nx\nabla T$ mechanism (see for example [6,32]). On the other hand, theoretical model for the generation of a magnetic field proposed by Sudan [10b] is not appropriate, this model being very large ratio of plasma density to critical density and when the $\nabla nx\nabla T$ contribution is not relevant.

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