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Charged particle acceleration by an intense wake-field excited in plasmas by either laser pulse or relativistic electron bunch*

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Abstract

The results from theoretical and experimental studies, as well as from 2.5-dimensional (2.5-D) numerical simulation of plasma wake field excitation, by either relativistic electron bunch, laser pulse, and the charged particle wake field acceleration are discussed. The results of these investigations make it possible to evaluate the potentialities of the wake field acceleration method and to analyze whether it can serve as a basis for creating a new generation of devices capable of charged particle accelerating at substantially higher (on the order of two to three magnitudes) rates in comparison with those achievable in classical linear high-frequency (resonant) accelerators.

Keywords: Charged particle acceleration; Laser pulse; Nonlinear phenomena numerical simulation; Plasma accelerators; Relativistic electron bunches; Wake-fields excitation

1. INTRODUCTION

Collective methods of charged particle acceleration were proposed by Budker (1956), Veksler (1956), and Fainberg (1956). Budker proposed the charged particle acceleration in self–stabilized relativistic electron beam; Veksler suggested the method of ion coherent acceleration by relativistic electron ring in longitudinally varying magnetic field; and Fainberg proposed the plasma–based scheme for charged particle acceleration by space-charge waves in plasma and non-compensated beams. At present, these are the most promising methods for collective acceleration because the electric field amplitude of the space–charge wave in plasma attains a maximum value:

$$E_{\max} = n_p/n_0(4\pi n_0 mc^2)^{1/2}(2\gamma - 1)^{1/2}. \tag{1}$$

This formula was extended by Akhiezer and Polovin (1956) to relativistic cases, where m is the electron mass; c is the speed of light; γ is the relativistic factor; n_p is the maximum density in the space–charge wave; the ratio n_p/n_0 is governed by the way in which the space–charge wave is initiated. Since very large perturbations of the charge density (attaining the value of the unperturbed plasma density n_0) can be obtained, the accelerating fields can reach values of 10^7–10^9 V/cm at plasma density from 10^{15} cm^{-3} to10^{19} cm^{-3}.

2. THE EFFICIENT METHODS FOR PLASMA WAVE EXCITATION

Plasma waveguide accelerator (PWGA) has been defined as: (a) electron beam–plasma interaction in magnetized plasma waveguide (beam–plasma instability) and (b) external ultra-high oscillator (Fainberg, 2000) and co-workers (since 1956).

Plasma beat–wave accelerator (PBWA) has been defined by Tajima and Dawson (1979) as:

$$f_1 - f_2 = f_p,$$

where f_i is the radiation frequency, f_p is the Langmuir frequency (see also Litvak (1964), Rosenbluth and Liu (1972), for detailed information concerning this and the next reference can be seen in Balakirev *et al.* (2002)). PBWA, an electric field of 1.8×10^9 V/cm and energy of

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accelerated particles of 20 MeV were obtained by Clayton *et al*. (1993), and Ebrahim (1994). Amiranoff *et al*. (1995) observed acceleration of electrons that were injected at an energy of 3.3 MeV and accelerated up to 4.7 MeV after plasma, at an energy gain of 1.2 GV/mV by a beat-wave generated in a plasma by two Nd-YAG and Nd-YLF laser wavelengths. Kitagawa *et al*. (2003*a*,*b*) presented the following results from the Institute of Laser Engineering, Osaka University, Japan:

1. Table—Top Beat—Wave Accelerator is under construction.
2. Two Ti: Saphire lasers drive a 500-fs pulse Beat-wave.
3. Will accelerate electrons to > 20 MeV in 2004.

Self–modulated laser wake–field accelerator (SmLWFA) is a self-modulation of laser pulse as defined by Andreev *et al*. (1992), Krall *et al*. (1993), Antonsen and Mora (1992), and Essarey *et al*. (1993); see also Andreev *et al*. (2000). The most impressive results as seen by Nakajima *et al*. (1994), Modena *et al*. (1995), Coverdale *et al*. (1995), Le Blanc *et al*. (1996), Umstadter *et al*. (1996*a*,*b*), and Ting *et al*. (1998) on plasma acceleration of charged particles were obtained on the SmLWFA, that is, an electric field amplitude of 1.5×10^8 V/cm to 2×10^8 V/cm, an energy of accelerated particles of 100 MeV to 300 MeV (see also Faure *et al*. 2000). The extremely large acceleration gradients generated by laser pulses propagating in plasmas can be used to accelerate electrons.

In the standard laser wake–field accelerator (LWFA), a short laser pulse, on the order of a plasma wavelength long, excites a trailing plasma wave that can trap and accelerate electrons to high energy. There are a number of issues that must be resolved before a viable, practical high energy accelerator can be developed. These include Raman, modulation, and hose instabilities that can disrupt the acceleration process. In addition, extended propagation of the laser pulse is necessary to achieve high-electron energy. In the absence of optical guiding, the acceleration distance is limited to a few Raleigh ranges, which is far below that necessary to reach GeV electron energies.

Laser pulse shaping (LPSh) as proposed by Bulanov *et al*. (1996), the particle in cell (PIC) simulation results have been demonstrated that regular wake electric fields may be obtained by a properly shaped laser pulse (sharp steeping of its leading front).

Resonant laser-plasma accelerator (RLPA) is a train of laser pulses with independently adjustable pulse widths and interpulse spacing as proposed by Dalla and Lontano (1994) and Umstadter *et al*. (1994).

Laser wake–fields accelerator (LWFA) is a short laser pulse as defined by Tajima and Dawson (1979), see also Gorbunov and Kirsanov (1987); for relativistic strong pulse see Bulanov *et al*. (1990). To achieve multi GeV electron energies in the laser wake-field accelerator, it is necessary to propagate an intense laser pulse over long distances in plasma without disruption. The physics of laser beams propagating in plasmas has been studied in great detail and there exists sample experimental confirmation of extended guided propagation in plasmas and plasma channels. In addition to these issues, dephasing of electrons in the wake-field can limit the energy gain. Spatially tapering the plasma density may be useful for overcoming electron dephasing in the wake-field. Sprangle *et al*. (2000, 2002) proposed and studied guiding and stability of an intense laser pulse in a uniform plasma channel, and analyzed the wake-field acceleration process in an inhomogeneous channel. The coupled electromagnetic and plasma wave equations were derived for laser pulses propagating in a plasma channel with a parabolic radial density profile, and arbitrary axial density variation. For a uniform channel, Raman and modulation instabilities were analyzed. For a nonuniform channel the axial and radial electric fields associated with the plasma wave were obtained inside and behind the laser pulse. It was shown that by optimally tapering the plasma density, the wake-field phase velocity several plasma wavelengths behind the laser pulse can be equal to the speed of light in vacuum. A three-dimensional (3D) envelope equation for the laser field has been derived that includes non-paraxial effects, wake-fields, and relativistic nonlinearities. In the broad beam, short pulse limits the nonlinear terms in the wave equation that leads to Raman and modulation instabilities cancellation. Long pulses (several plasma λ_p wave lengths) experience substantial modification due to these instabilities. The short pulse LWFA, although having smaller accelerating fields, can provide acceleration for longer distances in a plasma channel. By allowing the plasma density to increase along the propagation path, electron dephasing can be deferred, increasing the energy gain. A simulation example of a GeV channel guided LWFA accelerator is presented. Simulations of Sprangle *et al*. (2002) also show that multi-GeV energies can be achieved by optimally tapering the plasma channel. Kitagawa *et al*. (2003*a*,*b*) presented the following results from the Institute of Laser Engineering, Osaka University, Japan:

1. Laser of 15 J at 1 μm in 0.5 ps was injected into glass capillary of 1 cm in length and 60 μm in diameter and accelerated the plasma electrons to 100 MeV.
2. The electrons are trapped in the wake-field, showing the bump at the maximum energy.
3. 1-D and 2-D PIC codes speculated that a laser wake-field, whose wavelength is close to the laser pulse length, was excited with a gradient of 10 GV/m, accelerating electrons in the capillary.

Plasma wake–fields accelerator (PWFA) defined by Chen *et al*. (1985), Katsouleas (1986), Amatuni *et al*. (1986), Keinigs, and Jones (1987) as short rectangular relativistic electron bunch or periodic train of relativistic electron bunches. Rosenzweig *et al*. (1991) sees it as the Blow out regime of PWFA. In the PWFA, an electric field of 6×10^4 V/cm and energy of accelerated particles of 6 MeV were obtained by Rosenzweig *et al*. (1988), see also Rosenzweig (1990) and Schoessow *et al*. (1993). In blow out regime of PWFA, energy gradients of 700 MeV/m were measured in the experiment E–157 by Lee *et al*. (2000) and Assmann *et al*. (1999). An intense, high-energy electron or positron beam can have focused intensities rivaling those of today's most powerful laser beams. For example, the 5 ps (full-width, half-maximum), 50 GeV beam at the Stanford Linear Accelerator Center (SLAC) at 1 kA and focused to a 3 micron rms spot size yields intensities of 10^{20} W/cm^2 at a repetition rate of 10 Hz. Unlike a ps or fs laser pulse which interacts with the surface of a solid target, the particle beam can readily tunnel through tens of cm of steel. However, as it is shown, the same particle beam can be manipulated quite effectively by the plasma that is a million times less dense than air! This is because of the very strong collective fields induced in the plasma by the Coulomb force of the beam. The collective fields in turn react back onto the beam leading to many clearly observable phenomena. The beam particles can be:

(1) deflected leading to focusing, defocusing, or even steering of the beam;
(2) undulated causing the emission of spontaneous betatron X-ray radiation;
(3) accelerated or decelerated by the plasma fields.

Using the 28.5 GeV electron beam from the SLAC linac, a series of experiments have been carried out that demonstrated clearly many of the above mentioned effects. The results were compared with theoretical predictions and with 2D and 3D, one-to-one, particle-in-cell code simulations. These phenomena may have practical applications in future technologies including optical elements in particle beam lines, synchrotron light sources, and ultrahigh gradient accelerators. As can be seen from spatial distribution of excited wake-field, the electric field can attain high values only over very short distances. Therefore, we think that the energy doubles for a linear SLAC collier problem is not very realistic. Blue *et al*. (2003) and Hogan *et al*. (2003) shown for the first time that a beam of positrons can drive and be used to probe the longitudinal electric field component of the plasma wake-field. When a 28.5 GeV and 2.4 ps long positron beam at the Stanford Linear Center (SLAC) containing 1.2×10^{10} particles propagates through a lithium plasma of electron density 1.8×10^{14} cm^{-3}, the main body of the beam is decelerated at a rate of approximately 49 MeV/m, while a beam slice containing 5×10^8 positrons in the back of the same bunch gains energy at an average rate of $\sim$56 MeV/m over 1.4 m. With such a field structure, the beam energy is transferred from a large number of particles in the core of the bunch to a fewer number of particles in the back of the same bunch. The wake-field thus acts like a transformer with a ratio accelerating electric field to decelerated electric field of $\sim$1.3. The acceleration gradient of 56 MeV/m measured in this proof-of principal experiment can be increased to the GeV/m level in future experiments by a combination of in the drive beam charge, a decrease in the drive beam pulse width (with a corresponding increase in the plasma density), and by employing a plasma channel rather than a uniform plasma. Furthermore, in real application of such a plasma wake-field accelerator, the drive positron bunch will be followed by an optimally placed trailing witness bunch with a sufficient current to both realize high-gradient acceleration and a reasonable beam load and narrow energy spread. These results are critical to the development of future plasma-based linear colliers.

An interesting result has been established by us (Karas‘ *et al*., 1997, 2000), Balakirev *et al*. (2001, 2002), that for a certain relation among the parameters of the plasma-bunch-magnetic field system, the hybrid nature of the wake waves (which are excited by a relativistic electron bunch in a magnetized plasma and are a superposition of the surface and spatial modes) makes it possible to increase the electron energy of the accelerated bunch to a value that is significantly higher than the initial electron energy of the accelerating bunch (even when the bunch is initially unmodulated in the longitudinal direction). We have discussed 2.5-D numerical modeling on the formation of an ion channel as a result of the radial ion motion in self-consistent electromagnetic fields excited by a train of relativistic electron bunches (Karas‘ *et al*., 1997). The parameters of the fully developed channel are determined by the plasma-to-bunch density ratio and the ratio of the bunch radius to the skin depth. The effective dimensions of the channel and its “depth” (i.e., the high ion density at the channel axis) increase monotonically both in time and in the direction opposite to the propagation direction of the bunches. The formed ion channel stabilizes the propagation of relativistic electron bunches, which generate stronger accelerating fields. The results of the wake-field excitation during the self-modulation of a long relativistic electron bunch (Balakirev *et al*. 1998) has shown that the maximum electron density in the bunch becomes comparable to the plasma density and the amplitude of the plasma density perturbations becomes larger than the initial plasma density by a factor of 4.5. This indicates a very strong modulation of both the bunch density and the plasma density. That is why, even in the above case of a low-density bunch (in which the unperturbed electron density is about two orders of magnitude lower than the plasma density), it is incorrect to describe the plasma in the linear approximation. The amplitude of the longitudinal field is about 0.8 of the maximum electric field that can be generated in the plasma, and the amplitude of the radial field is about 0.4 of the maximum possible field. This shows that the driven bunch needs to be placed in the acceleration stability region. An important point is that, the field amplitude increases only over a certain distance along a relativistic electron bunch; hence, it would be of no use to operate with bunches whose length exceeds the distance over which the longitudinal field amplitude is maximum, doing so would provide no additional increase in the excited wake field. The results obtained with allowance for all possible nonlinearities give a better insight into the 3D behavior of relativistic electron bunch in a plasma and may help to ensure the optimum conditions for the wake-field generation during the dynamic self-modulation of the bunches. The results of investigations of the excitation of accelerating fields by an individual relativistic electron bunch or by a train of such bunches in a plasma (in particular, in the presence of an external magnetic field) make it possible to evaluate the potentialities of the wake-field acceleration method.

We would like to note recent and interesting experimental results from Yakimenko *et al*. (2003) on the generation of plasma wake-fields by relativistic electron bunch and on phasing between the longitudinal and transverse fields in the wake. The leading edge of the electron bunch excites a high-amplitude plasma wake inside the over dense plasma column, and the acceleration and focusing wake-fields are probed by the bunch tail. By monitoring the dependence of the acceleration upon the plasma's density, the authors approached the beam-matching condition and average acceleration gradient of 35 MeV/m. These results confirmed that the maximum acceleration gradient in the over dense regime $n_e \gg n_b$, where $n_b = 10^{15}$ cm^{-3} is the average electron density in the bunch, and can be estimated by the following formula (Lee *et al*., 2000):

$$eE_{z,\max} \approx 150[MeV/m]Q[nC]/\sigma_z^2[ps],$$

where Q and σ_z are charge and longitudinal size of electron bunch, respectively.

3. PHYSICAL MECHANISM FOR GENERATION OF VERY HIGH "QUASI-STATIC" MAGNETIC FIELDS

We will now discuss the physical mechanism for generation of very high "quasi-static" magnetic fields in the interaction of an ultra-intense short laser pulse, with a plasma target owing to the spatial gradients and non-stationary character of the ponderomotive force. The interaction between intense laser radiation and matter is known to produce a wealth of nonlinear effects. Those include fast electron and ion generation 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. 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. By means of a 2.5-D numerical simulation on the macroparticles method, it is possible to find the magnetic field spatial and temporal distribution without usage of an adapted parameter unlike the conventional $\nabla nx\nabla T$ mechanism (see for example, Haines, 1997). On the other hand, theoretical model for the generation of a magnetic field proposed by Sudan (1993) is not appropriate, this model has a very large ratio of plasma density to critical density and when the $\nabla nx\nabla T$ contribution is not relevant.

3.1. Generation of an axial magnetic field in plasma

The generation of an axial magnetic field in plasma by a circularly (or elliptically) polarized laser is often referred to as the inverse Faraday effect (IFE). Theoretically described by Steiger and Woods (1972), 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 (Horovitz *et al*., 1997; Lehner, 2000: Najmudin *et al.*, 2001). The conditions under which IFE is possible are still not fully explored. What is theoretically known (Abdullaev & Frolov, 1981) 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 either preformed or developed self-consistently during the interaction. 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 (Haines, 1997). 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 (Haines, 1997).

Along the same lines as Haines (1997) and Davies *et al*. (1997), 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.

Another mechanism of magnetic field generation has been proposed by Kostyukov *et al*. (2002), in framework of classical electrodynamics and Karas' *et al*. (2003), 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 (Kostyukov *et al*., 2002). 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. The intensity of the magnetic field generated in relativistic laser channel was calculated taking into account self-generated static fields, which are neglected in known IFE theories (Kostyukov *et al*., 2002).

These calculations are in agreement with the recent experiments at the Rutherford Appleton Laborato-ry (RAL) which exhibited very large (several megagauss) axial magnetic fields during the propagation of a sub-picosecond laser pulse in a tenuous plasma (Borghesi *et al*., 1998*a*,*b*). The relevant aspect of the RAL experiment is that both fast electrons and the strong magnetic field were measured in the same experiment.

3.2. Nonrelativistic two-dimensional treatment of self-generated magnetic fields

In an under dense longitudinal inhomogeneous plasma, the nonrelativistic 2D treatment of self-generated magnetic fields was presented by Tripathi and Liu (1994), showing that a laser beam propagating along a plasma gradient produces a rotational current which gives rise to a quasi-static magnetic field. An analogous mechanism was considered earlier, whereas the nonlinear mixing of two electromagnetic waves in nonuniform plasma was discussed by Bychenkov *et al*. (1994). 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 under dense plasma was recently studied numerically by Gorbunov *et al*. (1996). The main objective of the work by Gorbunov *et al*. (1996) was to investigate self-generated quasi-static magnetic fields both in the laser pulse body and behind the pulse in the region of the wake-field. These authors treated the laser radiation as linearly polarized and the plasma as uniform and under dense. The analytical work was based on a perturbation theory applied to a set of relativistic cold electron fluid equations and Maxwell's equations. The quasi-static magnetic field generated by a short laser pulse in uniform rarefied plasma is found analytically and compared to 2D 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 of 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 wake-field 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. 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 wake-field accelerator context.

3.3. Magnetic fields in the interaction of an ultra intense short laser pulse

We will now discuss the physical mechanism for generation of very high "quasi-static" magnetic fields in the interaction of an ultra intense short laser pulse, with an over dense plasma target owing to the spatial gradients and non-stationary character of the ponderomotive force. Numerical (PIC) simulations by Wilks *et al*. (1992) of the interaction of an ultra intense laser pulse with an over dense plasma target have revealed non-oscillatory self-generated magnetic fields up to 250 MG in the over dense 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 5×10^{18} W/cm^2 have been measured using Faraday rotation with picosecond resolution, the observations being limited to the region of under dense plasma and after a laser pulse (Fig. 1), see Borghesi *et al*., 1998*a*. A high density plasma jet has been observed simultaneously with the magnetic fields by interferometer and optical emission. Because of the high temporal resolution of the probe diagnostic, a

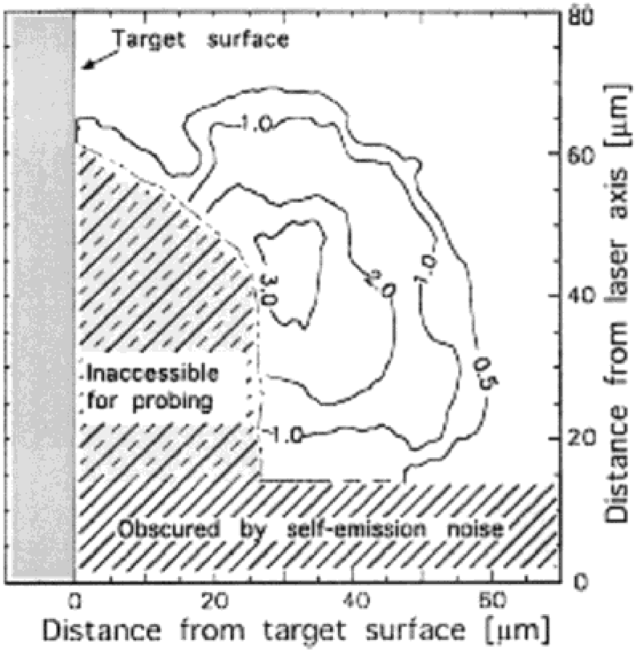

Fig. 1. Magnetic field distribution extracted from the polarigram. The magnitude is in units of megagauss. The plasma region either obscured by self-emission or not accessible for probing is shown (From Borghesi et al., 1998*a*).

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. In papers by Clark *et al.* (2000) and McKenna *et al.* (2003), the first direct measurements of high energy proton generation (up to 18 MeV and 100 MeV, respectively) and propagation into a solid target during such intensive laser-plasma interactions were reported.

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 Haines (1997)).

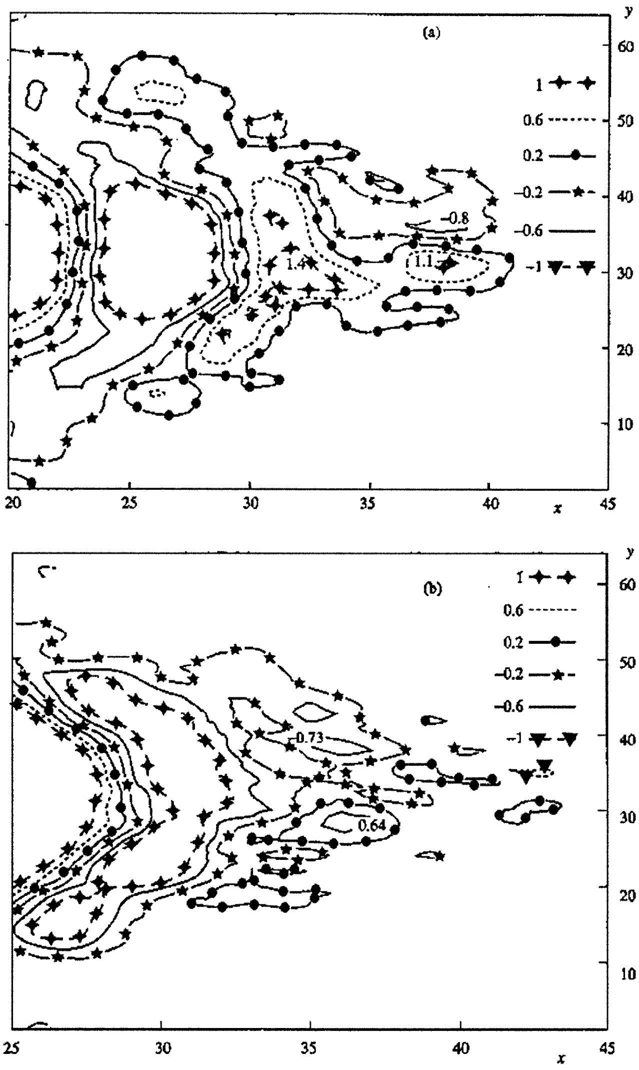

Fig. 2. **(a)** Spatial distribution of magnetic field B_z at different times: $t\omega_{pe} = 200$ (from Batishchev *et al.*, 1994). **(b)** Spatial distribution of magnetic field B_z at different times: $t\omega_{pe} = 200 + p$ (from Batishchev *et al.*, 1994).

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. Such observations are the first evidence of the large magnetic fields which have been predicted to occur during laser-target interactions in dense plasma (Najmudin *et al.*, 2001). 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. Borghesi *et al.* (2002) proposed that due to their particular properties, the beams of the multi-MeV protons generated during the interaction of ultra intense ($I > 10^{19}$ W/cm^2) short pulses with thin solid targets are most suited for use as a particle probe in laser-plasma experiments. The recently developed *proton imaging* technique employs the beams in a point-projection imaging scheme as a diagnostic tool for the detection of electric fields in laser-plasma interaction experiments. In recent investigations carried out at the RAL, a wide range of laser-plasma interaction conditions of relevance for inertial confinement fusion (ICF)/fast ignition has been explored. Among the results obtained will be discussed: the electric field distribution in laser-produced long-scale plasmas of ICF interest; the measurement of highly transient electric fields related to the generation and dynamics of hot electron currents following ultra-intense laser irradiation of targets; the observation in under dense plasmas, after the propagation of ultra-intense laser pulses, of structures identified as the remnants of solitons produced in the wake of the pulse.

Numerical (PIC) simulations by Wilks *et al.* (1992), the interaction of an ultra intense laser pulse with an over dense plasma target have revealed non-oscillatory self-generated magnetic fields up to 250 MG in the over dense plasma, that this non-oscillatory magnetic field is generated 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 5×10^{18} W/cm^2 have been measured using Faraday rotation with picosecond resolution, the observations being limited to the region of under dense plasma and after a laser pulse (see Borghesi *et al.*, 1998*a*,*b*). A high density plasma jet has been observed simultaneously with the magnetic fields by interferometry and optical emission and a field value is consistent with field generated by the thermoelectric mechanism (see for example, Haines, 1997). In paper by Clark *et al.* (2000) the first direct measurements of high-energy proton generation (up to 18 MeV) and propagation into a solid target during such intense (5×10^{19} W/cm^2) 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. Batishchev *et al.*

(1994) solved numerically the problem of high-intensity, linearly polarized electromagnetic pulse incident onto a collision less plasma layer 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 of COMPASS (COMputer Plasma And Surface Simulation) code. The recent review by Balakirev *et al*. (2002) and references therein combine detailed information concerning COMPASS code as well as its possibilities and applications. A general advantage of the complete numerical simulation consists of the possibility of obtaining all necessary information concerning spatial and temporal dynamics of both particles and self-consistent electromagnetic fields, without requiring additional data (reflection and absorption coefficients, changes of either plasma temperature or different plasma parameters) for a given situation concerning the interaction of an intensive electromagnetic pulse with plasmas. We give only the external parameters, both the initial and boundary conditions for particles and fields, and as results of a numerical simulation we attain all characteristics of the plasma together with pulsed self-consistent electromagnetic fields. The most characteristic feature of the action of an intense, normally incident electromagnetic pulse onto ultrahigh-density plasma consists in a "well-digging" effect. Worth nothing is the time-growing sharp nonuniformity of the perturbed plasma layer in the transverse direction. As for the magnetic field, we do not observe a change of its direction, but a significant time-variation of 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 $2\pi\omega_{pe}^{-1}$. Thereby it is shown that the magnetic field oscillates with the doubled frequency of a laser radiation, but it has unchanged direction. The magnetic field oscillations are seen as good at Fig. 2. Now let us look at Figs. 2a and 2b, 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. 2a) after a plasma wave half-period (see Fig. 2b) replaced in this point very low value of magnetic field.

The magnetic field B_z attains its peak value of (0.64) at the point (36.5,29), cf. Fig. 2b. 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 direct current (*dc*) magnetic field is ten times as low as the maximum magnetic field. One should note that in the articles by Wilks *et al*.(1992) and Batishchev *et al*. (1994), the numerical simulation has been made under very optimal conditions: a uniform plasma density makes it sure an 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.

It is important to note, that in a recent article by Baton *et al*. (2003), have place direct experiment evidence of accelerated electron bunches separated by half the period of the laser light at irradiation of thick solid targets by laser beam at relativistic intensities. In Borghesi *et al*. (1998*a*) experiments, instead, a plasma inhomogeneity is very essential, with the result that resonant conditions are fulfilled only in a small plasma region. Subsequently to the interaction pulse, only the "*dc*" magnetic field exists, as measured in the underdense plasma region in the article by Borghesi *et al*. (1998*a*). On the basis of the formula:

$$B_{dc}(MG) = 4.2x(10^{-22}I(W/m^2))^{1/2}/\lambda(\mu m), \tag{2}$$

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 Borghesi *et al*. (1998*a*), and a few tens of MG for the experimental conditions of Clark *et al*. (1998). A difference still on order of value is conditioned that at such intensities only 10% of the incident laser radiation is absorbed.

3.4. 2.5-D numerical simulation on the macroparticles method

By means of a 2.5-D numerical simulation on the macroparticles method, it is possible to find the magnetic field spatial and temporal distribution without making use of an adapted parameter, in contrast with the conventional $\nabla nx\nabla T$ mechanism (see for example Haines, 1997). On the other hand, the theoretical model for the generation of a magnetic field proposed by Sudan (1993) does not appear to be appropriate, this model being valid for a very large ratio of plasma density to critical density and when the $\nabla nx\nabla T$ contribution is not relevant.

4. RESULTS

In this paper, the results from theoretical and experimental studies as well as from 2.5-D numerical simulation of both the plasma wake-field excitation by both relativistic electron bunch or laser pulse and the charged particle wake-field acceleration are discussed. The results of these investigations make it possible to evaluate the potentialities of the wake-field acceleration method and to analyze whether it can serve as a basis for creating a new generation of devices capable of charged particle accelerating at substantially higher (by two to three orders of magnitude) rates in comparison with those achievable in classical linear high-frequency (resonant) accelerators.

By means of a 2.5-D numerical simulation on the macroparticles method it is possible to find the magnetic field spatial and temporal distribution without making use of an adapted parameter, in contrast with the conventional $\nabla nx\nabla T$

mechanism. On the other hand, the theoretical model for the generation of a magnetic field proposed by Sudan (1993) does not appear to be appropriate.

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