UDC 533.9

CHARGED PARTICLE (CP) ACCELERATION BY AN INTENSE WAKE-FIELD (WF) EXCITED IN PLASMAS BY EITHER LASER PULSE (LP) OR RELATIVISTIC ELECTRON BUNCH (REB)

V.A.Balakirev, I.V.Karas', V.I.Karas', V.D.Levchenko*, M.Bornatici**
NSC "Kharkov Institute of Physics & Technology", Kharkov, Ukraine, karas@kipt.kharkov.ua
****Keldysh Institute of Applied Mathematics of RAS, Moscow, Russia,*** lev@KELDYSH.ru
*****INFM, Dipartimento di Fisica "A. Volta", Università degli Studi di Pavia, Pavia, Italy,*** bornatici@fisicavolta.unipv.it

In the present paper the results from theoretical and experimental studies as well as from 2.5-D numerical simulation of both the plasma WF excitation by either REB or LP and the CPWF acceleration are discussed. The results of these investigations make it possible to evaluate the potentialities of the WF acceleration method and to analyse whether it can serve as basis for creating a new generation of devices capable of accelerating CP at substantially higher (by two to three orders of magnitude) rates in comparison with those achievable in classical linear high-frequency (resonant) accelerators.

Collective methods of CP acceleration were proposed by Budker [1], Veksler [2], Fainberg [3]. Budker [1] proposed the CP acceleration in self–stabilized relativistic electron beam; Veksler [2] suggested the method of ion coherent acceleration by relativistic electron ring in longitudinally varying magnetic field; Fainberg [3] proposed the plasma–based scheme for CP acceleration by space-charge waves in plasma and non-compensated beams. At present this is one of the most promising methods for collective acceleration because the electric field amplitude of the space–charge wave (SCW) in a plasma attains a maximum value

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

(formula extended [4] to relativistic case) m is the electron mass; c is the light speed; γ is the relativistic factor; n_p is the maximum density in the SCW; the ratio n_p/n_0 is governed by the way in which the SCW 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.

The efficient methods for plasma wave excitation:

-**PWGA**–plasma waveguide accelerator–a) electron beam–plasma interaction in magnetized plasma waveguide (beam – plasma instability); b) external ultra-high oscillator – Y.B. Fainberg and co-workers (since 1956);

-**PBWA**–plasma beat–wave accelerator–f_1–f_2 =f_p (f_i is the radiation frequency, f_p is the Langmuir frequency) Tajima and Dawson (1979 a detailed information concerning this and next references you can you see in [5]); in BWA, an electric field of 1.8x10^9 V/cm and energy of accelerated particles of 20 MeV were obtained C. Clayton, C. Joshi, C. Darrow, K.A. Marsh, A. Dyson M. Everett, A. Lai, W.P. Leemans, D.Umstadter, R. Williams, Y. Kitagava, T. Matsumoto, T. Minamihata, K. Sawai, K. Matsuo, K. Mima, K. Nishihara, H. Azechi, K.A. Tanaka, H. Takabe, and S. Nakai (1992,1993);

-**SmLWFA**-self–modulated laser wake–field accelerator self-modulation of laser pulse N.E. Andreev et al (1992); J. Krall et al (1993); T.M. Antonsen, P. Mora (1992); P Sprangle et al (1992); The most impressive results on plasma acceleration of CP were obtained in the SmLWFA, i.e. an electric field amplitude of 1.5-2x10^8 V/cm, an energy of accelerated particles of 100-300 MeV K. Nakajima et al. (1994); A. Modena, Z. Najmudin, A.E Dangor et al(1995); D. Umstadter, J.K. Kim, E. Dodd (1996). The extremely large acceleration gradients generated by laser pulses propagating in plasmas can be used to accelerate electrons. In the standard 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 Rayleigh ranges, which is far below that necessary to reach GeV electron energies.

-**LPSh**-laser pulse shaping S.V. Bulanov, T.J. Esirkepov, N.M. Naumova, F. Pegoraro, I. Pogorel'sky A.M. Pukhov (1996);

-**RLPA**-resonant laser-plasma accelerator – train of laser pulses with independly adjustable pulse widths and interpulse spacing S. Dalla, M. Lontano (1994); D. Umstadter, E. Esarey, J. Kim (1994);

-**LWFA**–laser wake–fields accelerator – the short laser pulse T. Tajima, J.M. Dawson (1979); L.M. Gorbunov, V.I. Kirsanov (1987); for relativistic strong pulse S.V. Bulanov et al. (1989); P. Sprangle et al. (1990). To achieve multi GeV electron energies in the laser wakefield accelerator, it is necessary to propagate an intense laser pulse over long distances in a 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 wakefield can limit the energy gain. Spatially tapering the plasma density may be useful for overcoming electron dephasing in the wake-field. P. Sprangle, J.R. Penàno, B. Hafizi, R.F. Hubbard, A. Ting, D.F. Gordon, A. Zigler, T.M. Antonsen, Jr. (2000-2002) proposed and studied guiding and stability of an intense laser pulse in a uniform plasma channel and analyzed the WF 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 WF phase velocity several plasma wavelengths behind the laser pulse can be equal the speed of light in vacuum. A three-dimensional envelope equation for the laser field has been derived that includes nonparaxial effects, WF, and relativistic nonlinearities. In the broad beam, short pulse limit the nonlinear terms in the wave equation that lead to Raman and modulation instabilities cancel. 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 also show [6] that multi-GeV energies can be achieved by optimally tapering the plasma channel.

-**PWFA**–plasma wake–fields accelerator – the short rectangular REB or periodic train of REBs P. Chen, J.M. Dawson, R.M.Huff and T.Katsouleas; Blow out regime of PWFA J. B.Rosenzweig et al. (1991). In the-PWFA, an electric field of $6x10^4$ V/cm and energy of accelerated particles of 6 MeV (can see in [5] reference J.Rosenzweig, D.Cline, B.Cole et al. (1988)); in blow out regime of PWFA, energy gradients of 700 Mev/m were measured in the experiment E–157 S. Lee, T. Katsouleas, P. Muggli, W. Mori, C.Joshi, R.Hemker, E.S.-Dodd, C.E.Clayton, K.Marsh et al. (2000); project "Energy doubler for a linear collider" S. Lee, T. Katsouleas, P.Muggli, W. Mori, C. Joshi, R. Hemker, E.S. Dodd, C.E. Clayton, K. Marsh et al. (2002) [7]. 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 in [7] 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 [7]. The results were compared with theoretical predictions and with two-dimensional and three-dimensional, one-to-one, particle-in-cell code simulations [7]. 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 WF [7], the electric field can attain high values only over very short distances. Therefore we think that the energy doubler for a linear SLAC collider problem is not very realistic.

An interesting result has been established by us [5]: 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 REB in a magnetized plasma and are a superposition of the surface and spatial modes) makes it possible to increase the electron energy (EE) of the accelerated bunch to a value that is significantly higher than the initial EE of the accelerating bunch (even when the bunch is initially unmodulated in the longitudinal direction). We have discussed 2.5-dimensional 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 REB. 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 REB, which thus generate stronger accelerating fields. The results of the wake-field excitation during the self-modulation of a long REB 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 REB; hence, it would be of no use to operate with bunches whose length exceeds the distance over which the longitudinal field amplitude is maximum, because 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 three

-dimensional behaviour of REB 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 REB 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.

Further more, 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. [8] of the interaction of an ultraintense laser pulse with an overdense plasma target have revealed nonoscillatory self-generated magnetic fields up to 250MG in the overdense 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 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 [9]. 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 [10]). In paper [11] the first direct measurements of high-energy proton generation (up to 18 MeV) and propagation into a solid target during such intense (5 x 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. In [12] we solved numerically the problem of high-intensity, linearly polarized electromagnetic pulse incident onto a collisionless 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 [5] and references therein combine a 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 characterictics 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 an 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 $2\pi\omega_{pe}^{-1}$. The magnitude of the "dc" magnetic field is ten times as low as the maximum magnetic field. One should note that in [8, 12] 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, 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 [9]. On the basis of the formula:

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

(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 [9], and a few tens of MG for the experimental conditions of [11]. 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 [13]. 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 making use of an adapted parameter, in contrast with the conventional $\nabla n x \nabla T$ mechanism (see for example [10]). On the other hand, the theoretical model for the generation of a magnetic field proposed by Sudan [14] does not appear to be appropriate, this model being valid for a very large ratio of plasma density to critical density and when the $\nabla n x \nabla T$ contribution is not relevant.

The work was supported in part by the Cariplo Foundation (Como, Italy) and INTAS project # 01-233.

REFERENCES

1. G.I. Budker Proceedings of the CERN Symposium on High Energy Accelerators and Pion Physics, Geneva, 1956, **1,** 68.
2. V.I.Veksler Ibid, 80.
3. Ya.B. Fainberg Ibid, 84.
4. A.I. Akhiezer R.V. Polovin *Zh. Esp. Teor. Fiz.*, 1956, **30,** 696
5. V.A. Balakirev, V.I. Karas`, I.V. Karas` // *Plasma Phys. Rep.*, 2002, **28,** 125.
6. P. Sprangle, J.R. Penano, B. Hafizi, R.F. Hubbard, A. Ting, D.F. Gordon, A. Zigler, T.M.Jr. Antonsen // *Physics of Plasmas*, 2002,**9**, 2364; Sprangle P. et al., *Phys. Rev. Lett.*, 2000, 85, 5110, and references therein.
7. C. Joshi, B. Blue, C.E. Clayton, E. Dodd, C. Huang, K.A. Marsh, W.B. Mori, S. Wang, M.j. Hogan, C. O`Connell, R. Siemann, D. Watz, P. Muggli, T. Katsouleas, S. Lee // *Physics of Plasmas*, 2002, **9**, 1845; Clayton C. et al., *Phys. Rev. Lett.*, 2002, 88, 154801, and references therein.
8. S.C. Wilks, W.L. Kruer, M. Tabak, and A.B.Langdon // *Phys. Rev. Lett.*,1992, **69**, 1383; S.G. Wilks, *Phys. Fluids*, 1993, **B5**, 2603; Mason R.J. and M. Tabak M., *ibid.* **80**, 524 (1998).
9. M. Borghesi, A.J. MacKinnon, A.R. Bell, A. Gailard, and O. Willi // *Phys.Rev. Lett.*, 1998, **81**,112.
10. M.G. Haines, // *Phys. Rev. Lett.*, 1997, **78**, 254.
11. E.L. Clark, K. Krushelnick, J.R. Davies, M. Zepf, M. Tatarakis, F.N. Beg, A. Machcek, P.A. Norreys, Santala, I. Watts, and A.E. Dangor, // *Phys. Rev. Lett.*, 2000, **84**, 670.
12. O.V. Batishchev, V.I. Karas', V.D. Levchenko, and Yu.S. Sigov, // *Plasma Phys. Rep*, 1994, **20**, 587.
13. D.F. Price, R.M. More, R.S. Walling, G. Guethlein, R.L. Shepherd, R.E. Stewart, and W.E. White, // *Phys. Rev. Lett.,* 1995, **75**, 252.
14. R.N. Sudan, // *Phys. Rev. Lett.*, 1993, **20**, 307