ABOUT POSSIBILITIES OF WIDE R.F. WELLS, BASED ON SLOWLY VARYING COHERENT LIGHT FIELDS

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Abstract

Slowly varying in space and time laser fields may form wide (N>>1 wavelengths) r.f. wells of various types. Their depth may reach N times of 0.5MV for non-relativistic electrons. They are capable to localize and accelerate large plasmoids (clusters). Some results of analytical and numerical studies of structures and of corpuscular-optical properties of large r.f. wells, including Mathieu stability condition, are described. These results may be useful for designs of future laser accelerators of charged particles.

1 INTRODUCTION

Recent investigations of laser acceleration of charged particles deal mainly with acceleration of relativistic electrons by plasma waves produced by ultrahigh-power lasers [1,2]. The present study is devoted to collective acceleration of positive ions by means of electrons of plasmoids in moving RF wells (HF traps) of laser field in vacuum. RF wells are formed by short (nsec) and frequency-modulated (chirped) pulses filtered from ultra-short laser pulses. They trap electron component of plasmoids (small, radio-transparent plasma bunches) by AG focussing of electrons which accelerate ions [3-7]. The alternative method [8] leads to technical difficulties. Basic results in the theory of RF wells were obtained by M.A. Miller [9]. Detailed review of basic theoretical and experimental studies of RF wells is given in [10]).

An advantage of the present variant as compared to the direct laser acceleration of ions [1] is the full use of the ratio ion/electron mass (or classic radius), ~2000 or more; it gives gain of intercepted intensity of laser field. HF recuperation (possible losses are ~1% per reflection) will give high effectiveness of the acceleration.

2. SOME PROPERTIES OF SMALL RF WELLS.

Analysis of results [3-7] of a plasmoid behavior in a simplest variant of small RF wells in cylindrical wave $E_{011}(\varphi, r, z)$, corresponding to a resonator with a radius R , shows the properties of small RF wells with trapped plasmoids:

a) long-term stability (~500 000 time units R/c (1 t.u. = 16 λ/c), or ~30 000 HF periods) and possibility of acceleration with slow loss of trapped charged is possible, if initial density is small, ~0.01 of the critical value $n_c = 10^{15}/\lambda^2 \ m^{-3}$ (here wavelength λ in meters); the corresponding ratio Coulomb field/laser field at an edge of a plasmoid is ~0.2; optimal form of RF wells corresponds to the ratio of radial/longitudinal wave-numbers k_r/k_z ~1; dimensions of the trapped plasmoids are small, ~0.1λ; laser field amplitude in RF wells is $E \approx m_e c^2 / 2e\lambda \approx 250$ kV/λ, similarly to Mathieu -Hill condition of stability in AG systems;

b) computed cartoons of the dynamics (Maxwell-Vlasov equations, PIC self-consistent model) of axially-symmetric plasmoids show, that electrons and protons are thermalized to ~200 eV, which is the depth of small RF well, plasmoid dimensions and the gradient of quasi-potential; the distributions of electrons and protons go to Maxwell's; electrons are normalized between ~1 000 and ~5 000 time units, protons - between ~20 000 and ~100 000 t.u., which corresponds to their mass ratio ~2 000; no instabilities of accelerated plasmoids are seen; this process may be treated as two phenomena- the randomization of phases of particles in the outer part of a plasmoid due to the field nonlinearities,

and the interchange of energy between particles in its inner part due to Coulomb force;

c) during computed acceleration time~30 000 periods with a gradient ~2 GeV/m = 200 eV/0.1λ (λ=1 mkm) ~2/3 of protons are lost, and a neutral plasmoid becomes negative; it ensures longitudinal stability of accelerated ions;

d) a grating of radio-transparent plasmoids centered in zeros of a standing e.m. wave may act as a plasma structure, which reflects external field of the "forming" laser frequency; this stratified plasma may guide another e.m. "exciting" wave with a lower frequency to excite slow accelerating wave in the focal zone.

e) typical numbers of accelerated protons are ~1000 (with ~3000 electrons) per a plasmoid; the focal spot may contain ~1000 of plasmoids with final energy of protons ~20 MeV at a way ~1 cm (in case of a ~50 J/psec 1 mkm TTT laser); acceleration gradient is ~2 GeV/m, acceleration time is ~30 000 periods of the field; initial density of plasmoids is ~0.01 of the critical value.

Proof-of principle experiments with small RF wells are possible on the base of a TTT laser equipped with a set of passive optical elements; they split, stretch and chirp the short pulse of the laser, and scan its crossed beams with trapped charged plasmoids along the acceleration line.

3. POSSIBILITIES OF LARGE RF WELLS.

More interesting results ("large" RF wells with dimensions, say, tens λ. and corresponding much larger accelerating gradients, ~20 GeV/m or more, larger numbers of particles, less halo losses and less tight tolerances) are expected [3-7] in case of realization of RF wells based on slowly varying envelopes [9,10].

Linearization of the equation of motion $d\vec{p}/dt = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$ of a particle in a running e.m. wave gives 3 Mathieu equations for small oscillations near a fixed point. Conditions of stability are analogous to the case of AG focussing. But the characteristic Floquet indices for different coordinates differ N times as much, N being here a large ratio of longitudinal to transversal wave-numbers. So destructive binding resonances may be avoided. In case of a 1-dimensional RF barrier, if envelope length is, e.g., ~10λ, then an amplitude E ~3 MV/λ may be used. So the expected accelerating gradient is ~10 times higher, RF wells are ~100 times deeper, e.g., 20 keV; their volume is ~1000 times wider, and the rate of halo losses -much lower as compared to small RF wells.

After a choice of field symmetry and form of one of its components the other components are found from Maxwell equations, and trajectories of particles are computed. Some examples are given below. 3-dimensional RF wells may be synthesized by means of superposed 2-dimensional RF wells with different frequencies [9,10]. Besides of it, a synthesis of 3-dimensional 1-frequency toroidal RF well ("self-closed cylinder") or a polyhedron, approximating it, is possible.

In rectangular coordinates the field of almost parallel plane waves ($\partial/\partial z = 0$) may be defined beginning from the expression of the barrier slope, $E_y = E_m(y)\sin\psi_x$, $\psi_x = \omega t - k_x x$. Maxwell equations give $E_x = -E_m^{'}(y)\cos\psi_x$ and $kk_x cB_z = \left(E_m^{''} - k_x^2 E_m\right)\sin\psi_x$.

If envelope function is approximated in the focal region by Gauss function, $E_m(y) = E_0\exp\left(-k_y^2 y^2\right)$, and the condition $\omega/c \equiv k \approx k_x >> k_y$ is satisfied, the y-width of the envelope is $N\lambda,\ N = k_x/k_y >> 1$), then Maxwell equations give the approximate formula $E_x = -E_m^{'}(y)\cos\psi_x$ and a corresponding formula for B_z. Numerical studies of motion have confirmed reflection of charged particles from these barriers.

In cylindrical coordinates φ, r, z (corresponding here to the above y, x, z) the field of a circular cylindrical barrier may be defined by the same symmetry condition ($\partial/\partial z = 0$) and expression of a radially wide profile of $E_r(y) = E_m(r)\cos\psi$, $\psi = \omega t - k_L R_0 \varphi$, $R_0 >> \lambda$. Maxwell equations give in this case $E_\varphi = \left[E_m(r) + rE_m^{'}(r)\right]M^{-1}\cos\psi$, and $cB_z = (\lambda/2\pi)\times$ $\left[(E_m/r)\left(M + M^{-1}\right) + 3E_m^{'}/M + rE_m^{'''}/M\right]\times$ $\omega^{-1}\sin\psi$, $M = k_L R_0$. This radially wide barrier may be effective ($E_r >> E_\varphi$), if the curvature is small ($M^{-1} << 1$, $R_0 >> \lambda$).

The other high cylindrical barrier ("hose") is based on a cylindrical wave $E_{01}(\varphi, r)$, with the E-field oscillators squeezed in the z-direction, $E_z = E_0 J_0(k_r r)\sin(\omega t - k_z z)$, and the corresponding E_r, B_φ.

In spherical coordinates r, θ, φ (they correspond to the above φ, r, z) one may prescribe a radially wide axially-symmetric ($\partial/\partial\varphi = 0$) wave, running along the meridians: $E_r = E_m(r)\sin\psi$, $\psi = \omega t - k_L R_0 \theta$. Maxwell equations give $E_\theta = \left(2E_m + rE_m^{''}\right)ctg\theta\sin\psi$ and the corresponding B_φ. The necessity to exclude polar regions is seen.

Realization of some high RF barriers is possible by means of confocal resonators. The expression of a resonant function in case of Hermite indices $m = l = 1$ for AG focussing is the sum

$$E_\varphi/E_0 = u\exp\left(-u^2/2\right)\sin\psi + v\exp\left(-v^2/2\right)$$

$\cos\psi$, $\psi = \omega t - k_z z$; $u = x(2\pi/L\lambda)^{1/2}$, $v = y(2\pi/L\lambda)^{1/2}$; E_z and B_φ are found from Maxwell equations.

Near z-axis one has $E_\varphi/E_0 \approx r\sin(\psi + \alpha)$, $tg\alpha = y/x$. So, small r-oscillations are describer by Mathieu equation. The transversal motion is described by 2 coordinates, $x(t)$ and $y(t)$, or $r(t)$ and $\alpha(t)$. Numerical results for a 1-dimensional Gauss barrier give a hope for the case of this RF hose (tube) as well as the above cylindrical "hose".

A drawback of open resonators is relatively large width of focused light beams. To have thinner beams one may use wider field sources and focussing insertions. An alternative is a cone-like multi-layered grating of plasmoids between the field source and the acceleration zone. This capillar-like grating is fixed by one frequency and guides the second, lower frequency, to the acceleration zone. Similar systems are studied [11, 12] for matching the laser pulse and pellet structure for laser-based acceleration and inertial fusion experiments.

Results of numerical studies of an electron motion in the "hose" of the above cylindrical wave $E_{01}(\varphi, r)$ are shown at the Fig. 1.

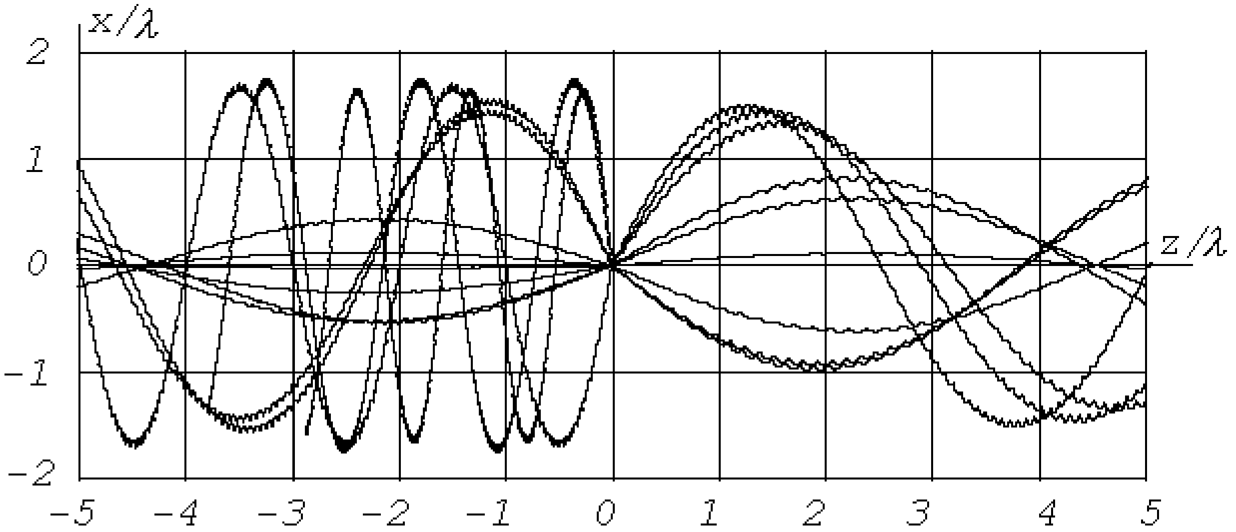

Figure 1: Shown are the trajectories of 20 electrons moving during 160 of periods in plane (z,x).

The particles in Fig.1 diverge from the (0,0) point with relativistic pulses p/(mc) = βγ = 0.15 (i.e. energy 5.7KeV) under accidental angles and then they are focused to the axis by the fielf of the wave. Due to calculations no one particle overruns the radial potential barrier situated at r ≈ 2.5 λ

4 CONCLUSION

Collective accelerators of ions for various uses may be designed on the base of certain structures of coherent light field. These structures are formed by linear filtration of ultra-intense laser radiation and distribution of it in the space and time in accordance with the conditions of alternating gradient focussing of the electron component of plasmoids. Intermediate capillar-like plasma structures may be useful for lowering the surface field density. The reported data may be useful for more rigorous theoretical and engineering studies of collective accelerators and related problems

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