ON SOME SCHEMES OF LASER ACCELERATORS USING PLASMOIDS IN HIGH-FREQUENCY WELLS

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Abstract

The first scheme uses onward-moving HF wells carrying charged or neutral accelerated plasmoids in a device similar to a converging guide. The second scheme uses plasmoids grating in HF wells in a special resonant cavity. Forced oscillations of plasmoids subjected to some additional field give rise to slow e.m. waves which are capable of accelerating charged particles. The third scheme uses a grating of moving plasmoids as an accelerating structure for some additional e.m. field. The first and second schemes may give about 10^8 V/λ , and the third scheme may givean energy gain factor $\sim 4\gamma^2$, γ being the Lorenz -factor of the grating, λ-laser wavelength.

Certain types of electromagnetic fields may localize charged or neutral plasma bunches (plasmoids) in the vicinities of the electric field nodes (quasipotential, ponderomotive or radio-frequency wells, radiowells). F.B.Knox (1957), A.V.Gaponov and M.A.Miller (1957), M.L.Levin (1959) were apparently the first who began the investigation of this phenomenon.

Many references on the theme and summary of results are given in [1,2]. This report is an attempt to draw attention to some possibilities of radio-wells for the laser acceleration of charged particles in special two-frequency resonant cavities.

The idea of laser beat wave acceleration [3-5] suffers from plasma instabilities, inhomogeneities and relativistic detuning. Wake-field plasma wave generation [4,5] needs very high-power short laser or electron pulses and also a stable long plasma. These difficulties justify our consideration of possibilities of a "discrete plasma" consisting of plasmoids grating in radio- -wells supported by a special oversized resonant cavity.

In the simple case of rarefied charged or neutral plasma, $n \ll n_c = \omega^2 mc^2\varepsilon_o/e^2$ (ω-field frequency; e,m-electron charge and mass), the approximate one-particle theory accounted in [1,2] gives the expression for quasipotential $\Pi = q^2mc^2/4$, if $q = eE\lambda/mc^2 \ll 1$. Experiments described [1,2] have confirmed the one- particle theory for the cases $q \ll 1$, $n/n_c < 1/2$. But the condition q <<1 leads to low values of effective field $E = |grad\Pi| \ll E$.

We have studied the nonlinear case $0.2 < q < 0.9$ by computation of precise solutions of the relativistic equation $d(m\vec{v})/dt = e(E+\vec{v}\times B)$ for a non-radiating particle in the given cylindrical field E_{omn} ($E_z = EJ_o(k_r r)\sin k_z z \sin \omega t$ etc). Various values of initial conditions , relative amplitudes q and Brillouien angles $\alpha = arctg\ k_r/k_z$ were used.

The computations showed that for $q < 0.9$ the coupled nonlinear plane oscillations $r(t)$, $z(t)$ are stable and resemble betatron oscillations in usual AG focussing systems; the width of HF wells in rz-plane may have the values $2r_m$,$2z_m$ defined by the conditions $2k_r r_m \simeq 2k_z z_m \simeq 1$; the depth of the wells reaches ~ $0.02m_oc^2$ ~ 10 kev for electrons; the effective holding field reaches ~$0.1E$ when $q\cos\alpha = 0.6 \div 0.9$.

This leads to the assumption that stable spheroidal and toroidal plasmoids of neutral or negative underdense plasma, $n < \hat{n}_c/2$, may exist at field amplitudes $\hat{E} \sim 2m_oc^2/e\lambda$ and electron temperatures T_e ~ 10 kev. In this case the Debye length and the plasmoid dimensions are of the same order of magnitude which ensures the stability. The use of cylindrical waves gives the possibility of high amplitudes E~ 10^{11} V/m for λ ~ 10μm.

The moving radio-wells (HF wells) may be composed of two counterpropagating fast electromagnetic waves with equal or different frequencies. Accordingly one may imagine in the general case a 3-dimensional grating of fixed or moving plasmoids interconnected by the e.m. field of an oversized resonant cavity which has multilayered dielectric reflecting surfaces preventing parasitic modes (volume hologram). This plasmoids'grating is supposed to be formed by means of some adiabatic prosess in the growing e.m. field from initially continuous rare plasma.

At least three types of accelerators ("radiotrons") are conceivable in such discrete plasma systems.

One type [1,2,6] uses onward moving HF wells carrying a chain of plasmoids. Their velocity $v = (\omega_1-\omega_2)/(k+k_2)$ is increased by means of frequency modulation or longitudinal wavenumbers $k_{1,2}(z)$ variation. The scheme of such an accelerator based on a converging waveguide promises an accelerating field E ~10^5 V/λ, e.g. 10^{10} V/m at λ = 10^{-5}m. The maximum current may be estimated on the base of the above- mentioned plasmoids density and dimensions. Such an estimate gives I ~ $10^{-2}\gamma\delta ce/r_e$, where δ = $(\omega_1-\omega_2)/(\omega_1+\omega_2)$. It is interesting that the I does not depend on λ. This scheme may be useful for semirelativistic ions.

Coherent longitudinal electron oscillations in plasmoids around the rear slopes of accelerated radio-wells in this scheme are analogous to the transverse oscillations of electrons in usual FELs of the scattron type. In the linear approximation these longitudinal dipole oscillations are described by Mattieu equation with the right side proportional to accelerating force. They give rise to re-radiation of e.m. field from the higher frequency to the lower one. This scheme may be treated as a reversed scattron charged with ions.

Besides of dipole oscillations, quadrupolar ones exist which are connected with the holding (forming) field E_{omn}. They give rise to the Bragg reflection of this field from plasmoids, because the step of the plasmoids grating corresponds to a half- wave of the partial Brillouien plane waves.

The conditions of e.m. waves penetration through the plasmoids grating may be estimated on the base of the F.Bloch theorem according to which the wave equation for a periodical medium has the solutions $F = A(\vec{r})e^{i\vec{k}\vec{r}} + B(\vec{r})e^{-i\vec{k}\vec{r}}$ where $A(\vec{r})$, $B(\vec{r})$ have the same 3-dimensional periodicity as the medium; real values of $\vec{k}$ correspond to Bragg reflection bands, imaginary ones - to transparent bands. If these results remain partly valid for the plasmoids grating then the corresponding wave function $F(\vec{r})e^{i\omega_e t}$ may describe slow e.m. waves provided ω_e is sufficiently low.

Another type of accelerators based on gratings of plasmoids in radio-wells [6] uses an additional exiting -accelerating field of fast waves E_e. The forming field E_f, e.g. axially symmetric field E_{omn} of a large cavity (m,n>>1) of the hologram type forms and holds the plasmoids grating which serves as accelerating structure for the exiting field E_e. The frequency of the latter field as well as its amplitude must be somewhat lesser than those of the former. The amplitude condition ensures the absence of "electrical breakdown". The frequency condition gives the possibility of slow e.m. waves in the grating. This accelerator may be used for ultrarelativistic particles. The usual defocussing action of the accelerating field is compensated in this system by the AG focussing action of the forming field, which is especially effective for electrons.

Small longitudinal oscillations of electrons in HF wells exposed to the exiting field are described by the Matthieu equation $z''(x) + g(x)z = h(x)$, where $x=\omega_f t$, ω_f - frequency of the forming field; $h=h_m\cos\omega_e t$ -exiting field; $g(x)$ corresponds to the forming field near the center z=0 of the well.

The forced (coherent) oscillations may be written as

$$z(x) = w(x)\int_0^x h(x)w(x)\sin[\Psi(x)-\Psi(x)]dx.$$

Using the approximate expressions for the Floquet amplitude and phase $w \simeq \bar{w}+\tilde{w}\sin\omega_f t$, $\Psi \simeq \Omega t$ ($\Omega < \omega_f/2$) one may obtain a trigonometric polinomial for $z(x)$ which contains the frequencies Ω, ω_e, $\omega_f \pm \omega_e$, $\omega_f \pm \Omega$ and $2\omega_f \pm \omega_e$. The main amplitudes are A_Ω and $A_{\omega e}$. Taking into account the resonant conditions ensured by the hologram for ω_e (as well as for ω_f), one may conclude that the interference will suppress all the exited oscillations with the except of ω_e and ω_f (however for some technical reasons one of the frequencies $\omega_f \pm \omega_e$ may be preferred to ω_e). Oscillations with the frequencies Ω, $\omega_f \pm \Omega$ and higher harmonics caused by nonlinearities are evidently incoherent.

Combining these two schemes it is possible to obtain much higher accelerating gradients, if a moving grating of plasmoids in HF wells, which is accelerated by the first scheme, is used as an accelerating structure for the second scheme. In doing so one must take into account the Dopler effect and change the field frequencies, amplitudes and wavenumbers. For the acceleration of the plasmoids grating one must use two opposite running waves with different frequencies and wavenumbers. And similarly must be changed the exiting field.

If an accelerating structure (plasmoids grating in HF wells) has a velocity β_a in laboratory frames, and the bunches of particles are accelerated in it to a velocity β_b relative to it, then their velocity in laboratory frames is $\beta = (\beta_a+\beta_b)/(1+\beta_a\beta_b)$, and their energy $\gamma=(1+\beta_a\beta_b)\gamma_a\gamma_b$.

If $\gamma_{a,b} \gg 1$, then we have $\gamma \gtrsim 2\gamma_a\gamma_b$ - the same value as for colliding beams, but now - in laboratory frames. In case of using of a pair of such opposite accelerators the interaction energy in the center of mass system is $\gamma \gtrsim 8\,\gamma_a^2\,\gamma_b^2$. For instance, if the grating has a moderate energy $\gamma \gtrsim 5$, then the accelerating gradient gain given by the combined scheme amounts to $2\gamma=10$, and the interaction energy gain for colliding beams is $4\gamma^2 \gtrsim 100$.

So the use of a plasmoids grating in HF wells as a moving accelerating structure may give a high gain in the accelerating gradient and an even more - in the interaction energy.

Of course, many problems of these schemes must be studied.

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