LASER-BASED COLLECTIVE ACCELERATOR—SCANATOR

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Abstract

Several groups investigate accelerators based on plasma waves, which are excited by powerful short laser or electron pulses (look, *e.g.*,[1] and references therein). A recent advanced study [2] is devoted to the plasma wakefield acceleration of short bunches of 30 GeV electrons from the SLAC to 31 GeV in a 1-meter section. The other study [3] is numerical modeling of acceleration of short bunches of ions in plasma channels by a super intense laser pulse. These schemes are based on ***free*** oscillations of the plasma and hence they directly depend on the plasma tolerances and instabilities.

The present variant of acceleration is based on ***forced*** oscillations of the charged plasma in laser-generated moving or standing RF wells (HF traps, ponderomotive- or quasipotential wells, M.A. Miller's force, light pressure; look [4-11] and references therein). This way leads to several schemes [8-11] of regular acceleration, based on far fields. The dependence on plasma parameters is decreased in this variant. One of these schemes [11], namely MWA (moving well accelerator), is detailed and discussed in this report.

Certain vacuum modes of fast electromagnetic waves (far field) trap charged particles, electrons (positrons) in the 1-st turn, near the minimums of the envelope [4-7] or near the zeros of the carrier frequency [8-11]. Both types of RF wells ("envelope wells" and "carrier wells") may be distant from the radiating surfaces, hence the electric breakdown problems are moved aside and concentrated fields with very high amplitudes may be used. The RF wells may be effective (gradient of the quasi-potential ~tens % of the field amplitude E_m), if the amplitude is large, $E_m \sim mc^2 / e\lambda$, *e.g.,* 1 TV/m in case of electrons and a 1-μm laser. This effect may be treated as 3-dimensional alternating gradient focussing of the electron component of plasmoids. The computed dimensions of plasmoids in case of carrier RF wells are ~λ/6 or smaller, and their density is sub-critical, so they are not larger than several Debye lengths. It simplifies the plasma stability problems.

Motion and acceleration of an RF well takes place, if the given structure of its field in the moving frames (e.g., a cylindrical wave $E_{0mn}(\varphi, r, z)$) is generated by corresponding laboratory sources (the moving and laboratory fields are connected by Lorentz transforms). The self fields of the plasmoids with sub-critical density are relatively weak, so the RF wells are defined by the laser system and by the intermediate rigid structures, and some part of plasma tolerances problems is solved on the base of progress in optics.

Only 2 modes of the TM field are discussed in the present work, namely, the cylindrical wave E_{omn}, and the "rectangular" wave E_{lmn}– for the case of crossed beams. The fields are described as products of Bessel and sine-cosine functions in the 1-st case and products of sine-cosine functions in the 2-nd case.

1 THE STRUCTURE OF THE FIELD AND THE SCHEME OF THE ACCELERATOR

The field structure (Fig.1; the signs + are centers of RF wells) is based on A.M. Sessler's idea [12] to use crossed beams of a small laser instead of the expensive system [13] of oversized resonators with kilojoules of stored optical energy. The RF wells exist in many points in the zone of intersection of the focused laser beams.

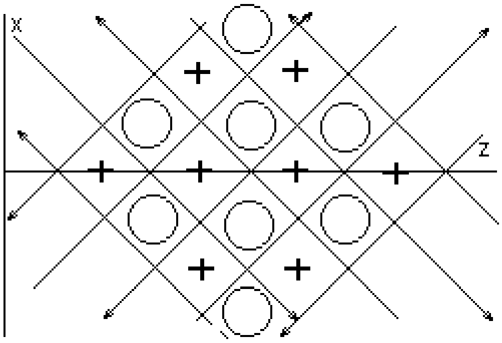

Fig 1. Scheme of the field and RF wells.

These beams are crossed and focused (Fig.2) at the center P of an RF well, which is accelerated along the z-axis, if the field parameters have the proper variations, as described below. 4 beams (left ones at the Fig.2) have an increasing instantaneous frequency $\omega_1(t)$ and decreasing slopes $\theta_1(t)$ to the z-axis, and the other 4 beams (right ones) –a decreasing frequency $\omega_2(t)$ and increasing slopes $\theta_2(t)$ (they may become obtuse during the acceleration). The programs of the frequencies and angles variations are defined by Lorentz-transformed values of the RF well parameters, ω, θ, prescribed in the moving frames. The frequency ω may be constant, but the inevitable variation of the angle θ, *i.e.*, of the RF well form, limits its values near 45 ± 15^o.

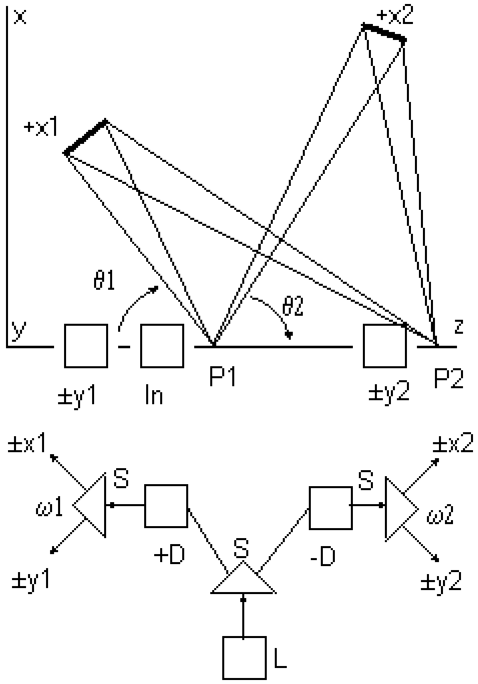

Fig 2. Scheme of the scanator.

The sources of these beams (focused dispersion radiators at the Fig.2) are centered at 8 points ($\pm x_1$; 0), (0;$\pm y_1$), ($\pm x_2$; 0) and (0; $\pm y_2$), symmetric in the planes *xz* and yz. The number of these partial beams may vary, in principle, between 6 and infinity (cylindrical waves).

During the acceleration the beams are scanned (from left to right at the Fig.2). This process is realized by linear transforms (filtering) of the primary short (wide-band) pulse of the feeding laser. This pulse is split into a pair of pulses, and each of them is stretched and frequency-modulated (FM, chirped) by means of, positive and negative dispersion elements [14]. The length of the FM pulses is equal to the time of acceleration of the ions at the given path P_1-P_2. The initial frequencies may be equal in the case of zero energy of injection. This pair of FM pulses is split into 8 pulses, which are fed to the focused at the point P dispersion radiators (*e.g.*, curved diffraction gratings). These radiators transform the FM into the angle scan of 8 beams (or 2 conical beams in case of cylindrical waves).

Coherent quadrupole oscillations of electrons in the moving plasmoids, forced by RF wells, lead to quadrupole polarization of the plasmoids and to the coherent quadrupole radiation (which might be stored by a resonator [13]).The lag of ions leads to dipolar polarization, which accelerates them, and to dipolar coherent radiation (which leads to the pumping of energy to the accelerated plasmoids and to re-radiation from the upper to the lower frequency, similarly to processes in a FEL-scattron.

The lags of the ion center from the electron center and of the latter – from the RF well center must be small (say, 0.01 λ), if the number of accelerated ions must be large; its increase leads to a decrease of the number of accelerated ions. Some excess of electrons ensures the longitudinal autofocalization of ions.

Incoherent oscillations of electrons in RF wells give the bremsstrahlung (“synchrotron “radiation), which might be useful as a means of cooling the trapped particles to decrease their halo (evaporation from the wells). But its power in the present case is very low, as may be seen from the known formula for the power radiated by an electron with an acceleration *a*:

$P = 2E_0 r_e a^2/3c^3$, r_e =classic radius of theelectron. The ratio of energy, radiated per period of harmonic oscillation of the electron, to its rest energy, is $W_1/E_0 \approx 13\,\beta_m^2\, r_e/\lambda$. Using the values of the velocity amplitude β_m=0.1 and λ =1 μm, one finds W_1/E_0=4x10^{-10}. It corresponds to a small energy ~5 eV during the time of acceleration (say, ~10^5 periods of the field).

The injector may be simply a gas jet similar to that used in printers. Some additional radiators (not shown) may be installed (and fed from the same laser) as correctors, if needed. *E.g.,* transversal (*r*-propagated) beams of the cylindrical mode E_{0m0} may increase the z-width and the volume of the even RF wells and decrease the z-width of the odd ones (or vice versa), and it may increase the number of captured particles.

As the numerical studies [18] show, a stable value of the neutralization factor arises during the initial stage of acceleration of neutral plasmoids.

Estimated parameters of a proof-of- principle model proton accelerator (Fig.1) are given in the Table 1 below:

Table 1. Some parameters of the scanator model.

Laser pulse energy/peak power:	3 J/300 GW
Laser wavelength	~1 mkm
Diameter of the FDR:	7 mm
Length of the acceleration path:	5 cm
Distance radiator-acceleration zone:	15 cm
Maximal angle scans:	~1 grad
FM deviations:	± 1 %
Number of RF wells in the focal region:	~ 500
Focal field density	200 GV/m
Neutralization factor	~0.8

The number of accelerated ions per plasmoid is defined by the ion density and by the plasmoid volume, and it is proportional to the ratio r_e / λ. The accelerated current does not depend on the wavelength λ (at a given relative density n / n_c).

The state of the art of tera- to peta-watt subpicosecond lasers [16,17] gives hope on the realization of the proposed scheme.

The above variant of the "scanator" is based on the "carrier RF wells", which are disposed with z-intervals equal to a half of the z-wavelength. These wells are relatively small, which simplifies the plasma stability problems.

The other possible variant – more wide "envelope RF wells" - corresponds to the case [4-7] of RF barriers or wells in slowly varying HF fields. The width of an envelope RF well is about the scale of the envelope change, say, 10 waves. The depth of envelope RF wells is [4-7] $\Phi = (eE_m / 2m\omega)^2 = A^2$ x126 keV, where $A = eE_m \lambda / 2\pi mc^2$. The upper limit of the product $E_m \lambda$ is simply found in case of a 2-dimensional standing wave (E_x, E_y, B_z):

$$E_y = E_m (y) \sin k_x x \sin \omega t ,$$
$$E_x = - k_y / k_x E_m (y) \cos k_x x \sin \omega t ,$$
$$cB_x = bE_m (y) \cos k_x x \sin \omega t ,$$
$$b = 1 + k_y^2 / k_x^2 ,\ \omega^2 = c^2 (k_x^2 + k_x^2) .$$

In case of slow amplitude modulation, *e.g,*. $E_m (y) = E_0 \cos k_y y$, $k_x / k_y = N$ >>1, one has $|E_y| >> |E_x|$, and the y-motion, which prevails, is described in a linear approximation by Mathieu equation:

$$y''(s) = 2qy \cos 2s ,$$

where $s = 2\omega t$, $q = eE_0 \lambda / N\pi mc^2$.

The condition of stability, q ~1, leads in this case to a tolerable amplitude E_0, N times as much as in the case of carrier wells.

The scheme of the corresponding accelerator is similar to Fig.2.

2 CONCLUSION

A compact proof-of principle collective accelerator ("scanator") may be built on the base of a table-top terawatt laser and a passive optical sys-tem, which splits and transforms the primary laser beam into several frequency-modulated crossed scanning light beams. The ions are accelerated by the electron component of plasmoids (short plasma bunches), which are trapped by moving RF wells (HF traps) of the electromagnetic field in the intersection region. This region is periodically scan-ned along the line of acceleration. An estimation of parameters shows the possibility of acceleration of, say, protons, from a gas jet to 300 MeV, using a table-top terawatt 1-mkm laser and a set of usual optical elements (mirrors, prisms, diffraction gratings etc).

The recent study [15] demonstrates the usefulness of a similar approach (brute force method of guiding of electrons) for laser acceleration of relativistic electrons by means of moving RF wells (FM laser wave and undulator wave) in the inverted FEL. This system may be used also for collective acceleration of relativistic ions (*e.g.*, injected with v >0.3c).

Results of numerical studies of this system, described in the report [18], confirm the basic concept and show the necessity of more detailed studies.

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