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Plasmoids in R.F. Wells***

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ABOUT THE REALIZATION OF LASER ACCELERATION SCHEMES BASED ON PLASMOIDS IN R.F. WELLS

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Abstract

The laser acceleration of plasmoids [1] is investigated theoretically. Preliminary studies suggest that this configuration, which is based on the forced oscillations of finite pieces of plasma contained in moving or vibrating r.f. wells, has very much simplified plasma physics compared to that of other plasma-based ion acceleration schemes. It is necessary to consider the case when the applied electric field, E , of frequency ω , is large, $E \leq e/4\pi\epsilon_0 r\lambda$, where r is the Classical electron radius and when the plasma density, n , is high $n < 1/r\lambda^2$. Realization of this proposal requires the development, amongst other things, of biresonant accelerating systems including oversized single-mode tube-like resonators and the connection of this resonator to a terawatt FELs. If these problems, which will be delineated, are overcome and progress in optics gives one reason to believe they can be then gradients of ~ 10 GeV/m can be attained. Preliminary design of a linac, based upon this proposal and of a proof-of-principle experiment are presented.

1 INTRODUCTION

Accelerator based on plasmoids in wells (APW) schemes may be treated as an intermediate variant between collective accelerators [1, 2] and classical linacs. Strong concentrated e.m. waves [3] create r.f. wells [4, 5] which localize the plasmoids. The r.f. wells may be deep (\sim keVs), if the e.m. field amplitude is $E_m \approx mc^2/e\lambda$, mc^2 , e being the electrons rest energy and charge, λ the field wavelength [6, 7]. Three schemes of acceleration are possible: moving well accelerator, (MWA), plasmoids grating accelerator (PGA) and moving plasmoids grating accelerator. Having in mind the necessity of detailed analytical and numerical studies of basic processes in the conceptual accelerators we consider here (after a short review of preliminary results) some aspects of realization of the MWA and the PGA scheme.

The MWA is a collective accelerator and, as such, can accelerate of all atomic numbers and, consequently, is of general interest. The PGA is subject to the same guiding and energy transfer restrictions of any plasma accelerator. That is, without some form of guiding the efficiency (beam energy / laser energy) is very low. The subject of guiding is not addressed in this paper, but would, of course, have to be addressed in future work. We can envision at least two possible ways in which guiding can be achieved. The first is to form a number of lines of plasmoids so as to make a "dielectric tube" around the accelerated beam and thus to guide the accelerating laser

beam. The second method, is to have the accelerator within an overmoded tube and to have "tube guiding". The overmoding must be sufficient so as to reduce the surface field to a manageable intensity. So, in the rest of this paper we address the basic physics of the PGA, but realize that we are deferring a vital element to the future.

An approximate description of the e.m. fields is given by cylindrical waves $E_{omn}(\phi, r, z) = TM_{omn}$ in an oversized tube (Fig. 1).

$$E_z = E_m J_0(R) \sin Z \sin \omega t, \text{ etc.},$$

$$R = k_r r, z = k_z z. \quad (1)$$

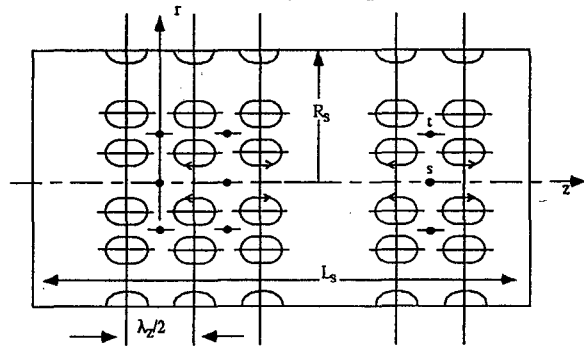


Fig. 1 R.F. wells in the field E_{omn} .

The r.f. wells localize spheroidal (s) or toroidal (t) plasmoids near the nodes of the e.m. field (Fig. 1). Linearized equations of rz -motion near a center of a well ($r = z = 0$) are:

$$y''(x) + (a_{r,z} + 2q_{r,z} \sin 2x)y = 0, \quad (2)$$

where $y = r$ or z , $2x = \omega t$, $q_z = -2q_r = eE_m \lambda \cos \theta_b / \pi mc^2$, $\theta_b = \arctg(k_r / k_z)$ = the Brillouin angle; $a_{r,z}$ are proportional to the Coulomb gradient. Azimuthal symmetry gives an integral $mr^2 (d\phi / dt) = const$. The curves $r(t)$ and $z(t)$ are similar to betatron oscillations in AG systems. These results are supplemented by [8]. The condition of strong AG focussing in an r.f. well

$$q_z \approx 0.5, \quad (3)$$

is similar to the wave-breaking limit [1,2].

A limit for plasma density in r.f. wells for small fields, $q_z \ll 1$, is $n < m\omega^2 \epsilon_0 / 2e^2$ [4,5]. This value was confirmed for strong fields, $q_z \approx 0.5$ by numerical simulation [6b].

These results suggest the possibility of accelerating field E_a (gradient of ponderomotive potential), $E_a \approx 0.1 E_m$. The ratio of the axial and surface cylindrical fields is

$$E_m / E_s = \pi (R_s \sin \theta_b / \lambda)^{1/2}. \quad (4)$$

Equations (3) and (4) define the tube radius:

$$R_s \lambda = (q_z m c^2 / e E_s)^2 / (\cos^2 \theta_b \sin \theta_b). \quad (5)$$

One may see that minimal demands are required of the plasma, namely, stability of small (several Debye lengths) plasmoids in r.f. wells.

2 SCHEMES OF THE MOVING WELLS ACCELERATOR (MWA) AND PLASMOIDS GRATING ACCELERATOR (PGA)

A schematic of a MWA (Fig. 2) consists of an oversized (e.g. axially symmetric) converging waveguide 1 with diffraction gratings (azimuthal grooves) at the ends. Two counter propagating waves (ω_{1a} , ω_{2a}) are excited by lasers 1A and 2A. The z-velocity of r.f. wells (plasmoids) $V(z) = (\omega_1 - \omega_2) / [k_1(z) - k_2(z)]$ may be increased by a factor of 2-3 in each section. Each section must have larger difference of frequencies $\omega_1 - \omega_2$, than the preceding one. Possible values of basic parameters are $\lambda_{1,2} \sim 20 \mu\text{m}$, $R_s \sim 5\text{mm}$, $L_s \sim 10\text{cm}$, accelerating gradient 5GV/m ; laser energy $W_{em} \sim 10\text{J/section}$. Positive ions may be accelerated from $\beta_z \sim 0.001$ to $\beta_z \sim 0.3$ in ~ 6 sections.

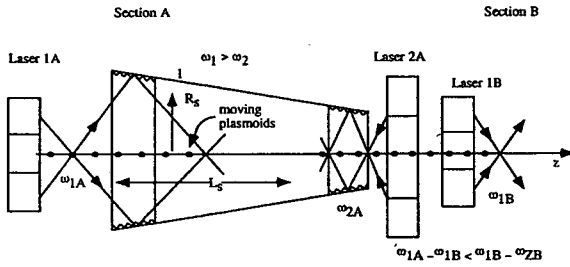


Fig 2. Schematic of a MWA Section.

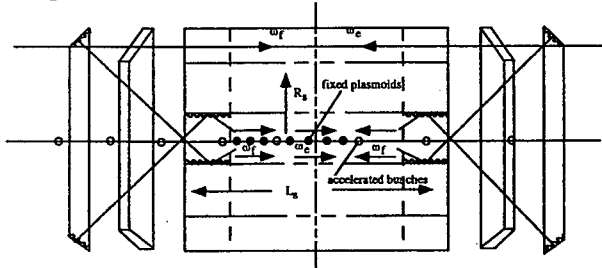


Fig. 3 Schematic of a PGA section.

A schematic of a section of the PGA (Fig. 3) is similar to an axially symmetric version of the usual ring optical open resonator but with plasmoids and accelerated bunches along its z-axis. It consists of 3 coaxial tubes 1,2,3, two coaxial cut cones (or washers) 4 and two ring-like Fabri-Perot etalons 5. Another possible variant is beads of plasma forming a grating are formed mechanically, without a forming field. Single-mode for both frequencies is ensured, as in usual single-mode lasers, by diffraction gratings (azimuthal grooves) at the ends of the tube 1 and cones 4, and by the Fabri-Perot etalons 5. Crossed action of the grooves (2-dimensional filtering) is possible, if the number of half-zigzags in the tube 1 is odd.

The grating of plasmoids is formed and fixed by the forming field E_{omn}^f , and then a slow wave is excited along it by the exciting wave E_{om}^e , whose frequency is somewhat lower,

$$\omega_e / \omega_f = \beta_b (\theta / \pi) \cos \theta_{bf}, \quad (6)$$

β_b being the accelerated beam (bunches) velocity, θ = phase advance of the slow wave per cell of the grating, θ_{bf} = the Brillouin angle of forming field. E.g. if $\beta_b = 1$, $\theta = \pi/2$, $\cos \theta_{bf} = 0.9$, then $\omega_e / \omega_f = 0.45$.

The focussing of positive particles accelerated in the PGA may be ensured by some excess of electrons in the plasmoids. In case of acceleration of electrons the defocussing by the slow accelerating wave is much less [7] than the AG focussing by the forming field.

The e.m. field energy per unit length of the tube 1 is

$$W_{em} / L \approx 1/2 \epsilon_0 E_s^2 \pi R_s^2, \quad (7)$$

e.g., $\sim 100 \text{ J/m}$, if $\lambda = 20 \mu\text{m}$, $R_s = 5\text{mm}$, $E_s = 1\text{GV/m}$.

An experimental section may have the diameter $2R_s = 1\text{cm}$, length $L_s = 6\text{cm}$, and the field energy $\sim 10 \text{ J}$ ($\lambda = 20 \mu\text{m}$). Some parameters of 3 variants of experimental PGA sections (wavelength, tube radius R_s and length L_s , field amplitude E_m , accelerating field E_a , accelerated particles energy $L_s E_a$, e.m. field energy in the tube W_{em}) are given in the Table 1 for the $E_s = 1 \text{GV/m}$:

Table 1: Three variants of experimental PGA sections.

λ μm	R_s cm	L_s cm	E_m GV/m	E_a GV/m	$L_s E_a$ MeV	W_{em} J
20	0.5	6	50	5	300	6
30	0.3	4	30	3	120	2
100	0.1	1.2	10	1	12	0.05
	-1	-1	-1	-1	-2	-3

The last line of the table gives the degree of dependence of the above parameters on the wavelength λ . The accelerated particles may be positive ions, electrons and positrons. The first variant seems to be preferable.

Comparison of beam currents in the PGA and usual linacs is based on an assumption that the number of accelerated particles per bunch is ~ 0.1 of the number of electrons in a plasmoid ($\sim 0.01 \lambda / r_e$), and the number of bunches per unit length is $\sim 2\lambda^{-1} r_e$; it shows that both currents may be \approx equal in case of spheroidal plasmoids (in the case of toroidal wells larger values are possible).

3 A MODEL FOR A PROOF-OF-PRINCIPLE EXPERIMENT

This model (Fig. 4) is based on an existing Nd-glass plane polarized laser with a wavelength $\lambda_e \sim 1 \mu\text{m}$, pulse energy $\sim 1\text{J}$, and pulse length $c\tau \sim 1\text{mm}$ and power 300 GW . A periodical dielectric structure ("beads") replaces the plasmoid grating fixed by the forming field. The density of these "beads" must be about $0.3n_c = 3 \times 10^{20} \text{ cm}^{-3}$.

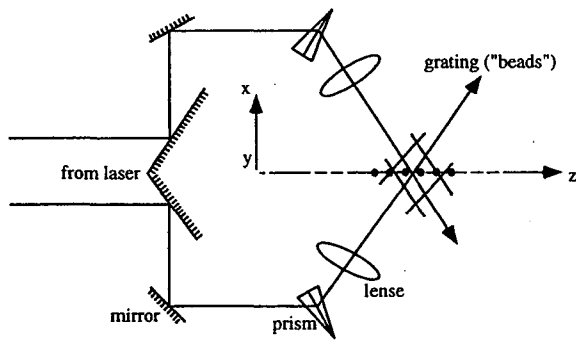


Fig. 4 Scheme of proof-of-principle experiment.

The period of this structure should be in accordance with usual linac rule (6) $\lambda_r/2 = 0.2\mu\text{m}$. Only one wavelength $\lambda = \lambda_c$ is used in this case: inertia of the plasma ions gives the possibility to use this grating during a short time ~ 3 psec. The model consists of a beam splitter, 2 mirrors, 2 prisms and 2 lenses, which give a pair of intersecting beams. The dielectric grating ("beads" with a period $\sim \lambda/5$) is placed at the point of beams crossing. The focal length of the lenses is $\sim 1\text{m}$, the light beams width at the region of crossing is $\sim 1\text{mm}$. The amplitude parameter must be $q_z \approx 0.4$, in order to have strong AG focussing. It gives the amplitude of field $E_m = 1\text{TV/m}$ in the focal (crossing) region. Plane polarization of the laser field leads to one dimensional focussing instead of 2-dimensional, in the case of a cylindrical field, so we expect some defocussing in the 2nd direction; the principal effect will be present. Two-dimensional focussing may be realized by means of a second set of elements, as shown in Fig 4, but disposed in the orthogonal plane (y instead of x). The expected value of accelerating gradient is $E_a \approx 100 \text{ kV}/\lambda = 10^{11} \text{ V/m}$, which corresponds to an energy gain in the focal region ($\sim 1\text{mm}$) 100 MeV.

4 CONCLUSIONS

Preliminary analytical and numerical studies of charged particles motion in the cylindrical field $\text{TM}_{0mn}(\varphi, r, z)$ show the existence of deep ($\sim \text{keVs}$) 3-dimensional r.f. wells (h.f. traps), steady or moving, for electrons (positrons) at field densities $\sim 1\text{MV}/\lambda$. Preliminary numerical studies of plasmoid dynamics confirm the above data up to the plasma densities $\sim 50\%$ of the critical ($\omega = \omega_p$) value. Various schemes for the acceleration of positive ions, electrons and positrons by means of plasmoids, captured in r.f. wells, are discussed. Expected values of accelerating gradient are $\sim 100 \text{ keV}/\lambda$. Two variants of experimental models are proposed: a section of accelerating structure (plasmoids grating in a tube with a diameter $\sim 1\text{cm}$ and length $\sim 6\text{cm}$, e.m. field energy $\sim 6\text{J}$ wavelengths $\lambda = 20$ and $40 \mu\text{m}$, energy gain 300 MV, and a proof-of-principle experiment (dielectric "beads" grating, Nd-glass laser, energy $\sim 1\text{J}$, pulse length $c\tau \sim 1\text{mm}$, energy gain $\sim 100 \text{ MV}$).

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