

SOME RESULTS OF THEORETICAL STUDY OF THE LASER-BASED COLLECTIVE ACCELERATOR (SCANATOR)

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Abstract

RF wells (HF traps, proposal of W.Paul) are studied and used in radiospectroscopy and in laser cooling systems.

Preliminary analytical estimations show the possibility of collective acceleration of ions by means of RF wells in a system of crossed scanning frequency-modulated (chirped) light beams, which form running RF wells in the zone of intersection of the beams [1]. This system is similar to electron-ring collective accelerator [2-4], especially in case of toroidal wells in the cylindrical field $E_{0mn}(\varphi, r, z)$ with the difference that the "outer" HF focussing of electrons [2] is present in it, but is absent in the case of electron rings [2].

Starting from analytical estimations, which give rough values of the basic parameters, including the effects of interaction of many charged particles, several computer programs were developed. "One-particle" programs (low density cases) give the possibility to find approximately the rz -dimensions of the zone of stable oscillations of an electron (of a radio-transparent plasmoid) in an RF well and the dependence of them on the values of several parameters (EM waves amplitude, phase, frequency, polarization, Brillouin angle $\theta = \arctg(k_r/k_z)$).

"Multi-particles" programs are used for finding the tolerable densities of the electron and ion components of plasmoids and for final checking of the acceleration concept in various regimes, including long computations (~50 000 RF periods).

1 METHODS AND RESULTS OF ONE-PARTICLE NUMERICAL STUDIES

The vector equation of motion of a charged particle $d\mathbf{p}/dt = e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ was solved for the case of cylindrical axially symmetric standing wave E_{0mn} with various values of 8 parameters: 4 initial conditions (r_0, r'_0, z_0, z'_0), the field amplitude parameter $eE_m \lambda / mc^2$, Brillouin angle θ , the field phase φ (the field was written as $E_z \sim \cos(\omega t + \varphi)$ etc), and the initial acceleration value. Some RF wells in the "rectangular" field E_{lmm} , which approximates the crossed beams were modeled too, and have shown

much similarity to the cylindrical case. Several hundred trajectories were computed for the times up to ~20 000 RF periods.

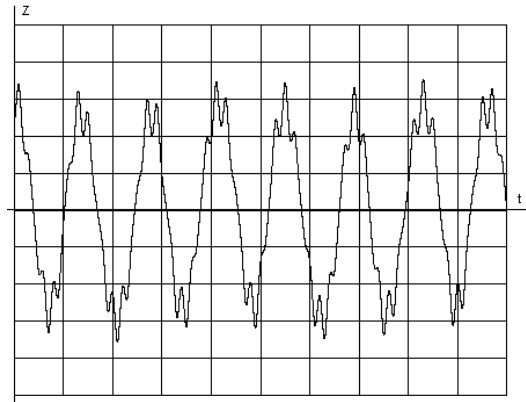


Figure 1

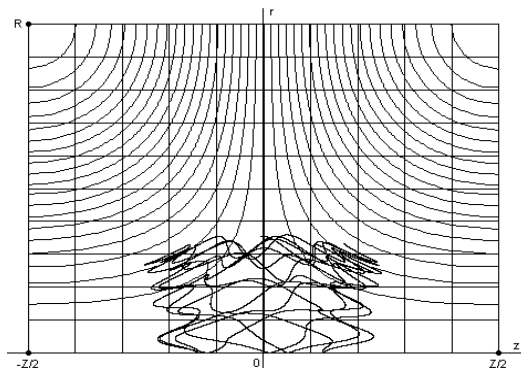


Figure 2.

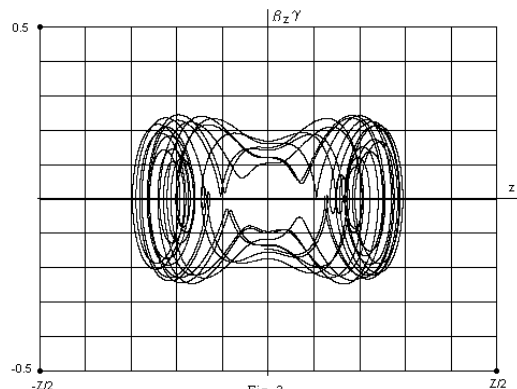


Figure 3.

The results for the axially-symmetric case were displayed and cartooned as $r(t), z(t), r(z), v(t)$,

and phase pictures $r'(r)$, $z'(z)$. Some typical trajectories are shown at the Fig-s 1-3 ($z(t)$, $r(z)$, $z'(z)$). They are similar to usual betatron oscillations in strong focusing systems. Some part of the computations was done for the case of simultaneous motion of many non-interacting particles.

In case of adiabatically growing field the capture of uniformly distributed in the rz -plane electrons was demonstrated.

The main conclusion is that the maximal dimensions of RF wells are $< \lambda/6$ in case of the optimal phase of the field, and the optimal Brillouin angle is:

$$\theta \sim 45^\circ \pm 15^\circ.$$

Acceptable values of the amplitude parameter for the present case of nonlinear motion in RF wells (space nonlinearities of RF field, and dynamic nonlinearities—vector product of the velocity and magnetic induction, relativistic mass) are close to the values based on the linearized equations.

Some aspects of these studies are similar to the study [5] of RF wells and “islands” in the case of “combined” traps (RF + a magnetostatic field).

2 METHODS AND RESULTS OF MULTI-PARTICLES NUMERICAL STUDIES

The axially-symmetric relativistic motion of many electromagnetically interacting electrons and protons was modeled in the rz -plane by the PIC method (2.5 measurements, r, r', z, z' , and the full velocity v , rectangular toroidal macroparticles). Full system of Maxwell's equations and the equations of macroparticles motion were solved for electrons and ions in the co-moving (with the accelerated plasmoid) ideal cylindrical resonator tuned to the same wave E_{011} as in the 1-particle case. The code was written in C++ language. The number of macroparticles in the calculations was usually $\sim 50\,000$, the grid sizes about 30×30 . The use of moving frames leads to large economy of computation time. Special checks (longitudinal waves in tubular beams, transverse waves in plasma columns, several modes in an empty cylindrical resonator) have shown the precision better than several %. So the use of this “computational” resonator is justified for the present case, when the plasmoid is relatively small, $\sim \lambda/6$ or less. The additional physical parameters in the multi-particle case are the initial densities of electrons and protons in the charged plasmoid and some computational parameters (the numbers of computation cells and steps per RF period, *etc*). Preliminary values of the densities were chosen with the account of Kapchinski — Vladimirski equilibrium and its stability studies [6,7], which lead to the AG focusing depression by the space charge up to $\sim 30\%$. Approximately the same values

were found on the base of Mattieu equation. The corresponding parameter of optimal initial conditions (Courant-Snyder invariant or “quasienergy” [8]) should be equal for all particles in the ideal case, which leads to uniform density. In other words, inner electrons of a plasmoid must have large velocities, and outer electrons—small velocities. Realization of corresponding injection and capturing process is not studied but seems not to give much gain. Full amplitude of the field was turned on at the initial moment. So the initial conditions were uniform density and zero velocity for both electrons and ions, which lead to very non-uniform density and losses $\sim 20\%$ of the particles at the initial several hundreds of periods.

The number of the physical parameters was 5 (field amplitude, Brillouin angle, initial acceleration, 2 densities). Some typical shots of electrons (upper bunches) and ions (lower bunches) are shown at the Fig-s 4-6 for the times 406, 79977 and 650007 time units $2.2 \lambda/33c$. The initial distribution of electrons and protons was chosen (for the economy of cells) as a spheroid, corresponding to the RF well dimensions found in the preliminary 1-particle modeling. Fig.7 shows the numbers of electrons and protons in the accelerated RF well as functions of time (in units $2.2\lambda/c$): after an initial relatively swift (~ 1000 field periods) loss the self-consistent evolution process leads to acceleration of the particles during $\sim 50\,000$ periods with a relatively small loss. The form of both bunches, electron and proton, is gradually normalized, and then a slow “evaporation” of particles takes place. This process is similar to halo formation in the case of RFQ linac [9].

The computed cartoons show the alternating focusing-defocusing rz -oscillations, and the lag of accelerated ions from electrons, and of the electrons — from the RF well center. Optimal amplitude of the field was found to be

$$E_m \approx mc^2 / R e,$$

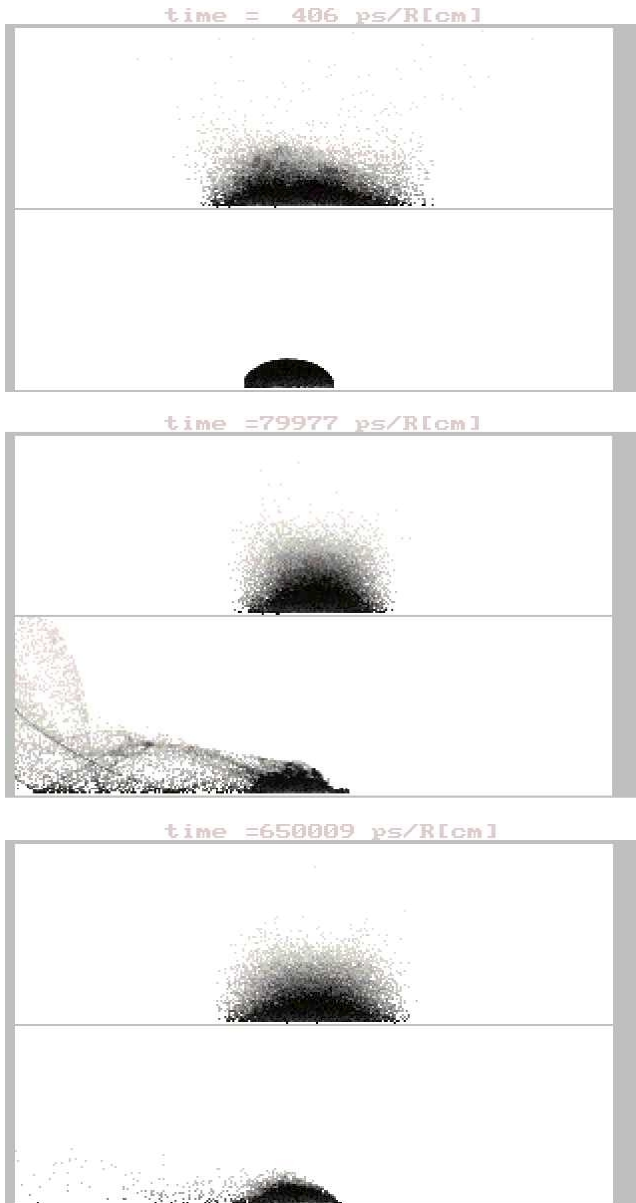
where R is the radius of the resonator, $R = 2.2 \lambda$ for the present case of Brillouin angle $\theta \approx 60^\circ$, e is the electron charge.

The number of accelerated particles per plasmoid (which decreases with the increase of the acceleration) was found to be ~ 3000 electrons and ~ 1000 protons. The initial value of the acceleration (it decreases with growth of mass of the ions) was chosen in one of the computational runs to be $0.000\,001 c^2/R$, which corresponds to the acceleration gradient $dW/dz = Ma \approx 500$ MeV/m.

3 CONCLUSION

The numerical modeling confirms the possibility of collective acceleration by charged plasmoids in RF wells.

The encouraging computational results of the present studies show, amongst other, the desirability of theoretical nonlinear analysis of the problem which might lead to its better understanding.



Figures 4-6

ACKNOWLEDGEMENTS

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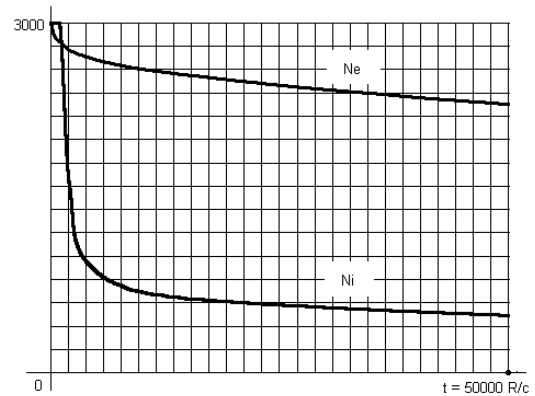


Figure 7

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