SIMULATION OF PLASMA WAKEFIELD EXCITATION BY A SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES

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Numerical simulations of plasma wakefield excitation by a long sequence of low-density relativistic electron bunches are performed with hybrid 2.5D code LCODE. For the resonant sequence, wakefields of up to 300 bunches add coherently until the wave nonlinearity comes into play.

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1. INTRODUCTION

The intense plasma wakefield excitation by a single dense bunch has allowed to achieve accelerating gradient above 40 GeV/m and to double energy of 42 GeV-bunch by a plasma afterburner of the length less than 1m [1]. The question arises to what limit the wakefield can grow if it is excited by a long sequence of low-density electron bunches. To address this question, we study self-consistent dynamics of only 500 short electron bunches in the uniform plasma. Even for this reduced number of bunches comparatively to experiments [2-3], the problem needs huge simulation area and computation time and can be solved only with the fluid description of plasma.

We present results of numerical simulation of plasma wakefield excitation by a sequence of relativistic electron bunches, made with 2.5D quasi-static code LCODE [4] that treats plasma as a cold electron fluid and the bunches as ensembles of macro-particles. Parameters are taken close to those of plasma wakefield experiments [2-3], in which electron beam represented by a regular sequence of 6000 electron bunches, each of energy 2 MeV, charge 0.32 nC, rms length $2\sigma_z$=1.7cm, rms radius σ_r=0.5 cm, and rms angular spread σ_θ=0.05mrad excites wakefield in the plasma of density $n_p=10^{11}$ cm^{-3} and length of about 1m, so that the repetition frequency of the bunches coincides with the plasma frequency ω_p (so called resonant sequence).

2. RESULTS OF SIMULATION

To begin with, we consider dynamics of first 31 bunches in the plasma. We use the cylindrical coordinate system (r,z) and plot plasma and beam densities at some z as functions of the dimensionless time $\tau=\omega_p t$. From Fig.1 we see that, at the middle of the plasma, the bunches are already focused by the wakefield, and the focusing is non-uniform. This looks like compression of bunches both in radial and longitudinal directions, though, of course, at these times and beam energies, radial relative shifts of beam particles prevail. Because of the complicated shape of bunches, the excited wave (Fig.2) looks like a nonlinear one, with the wave period being longer near the axis. However, it is not nonlinear yet, that is, the period of remaining wakefields will be exactly $2\pi/\omega_p$ if we break the sequence after the 31-th bunch. As the bunch sequence evolves, the wakefield also evolves, and location of defocusing regions shifts with respect to the bunches. For a bunch slice to be defocused, it is sufficient to fall into the defocusing field only once for a relatively short period of time. As a consequence, at the end of the plasma the bunches are mostly defocused (Fig.3), and the wakefield is lower.

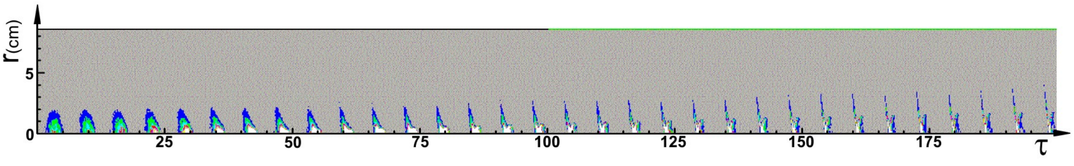

Fig. 1. Temporal evolution of the beam density in the middle of the plasma (at z=50 cm from the injection point)

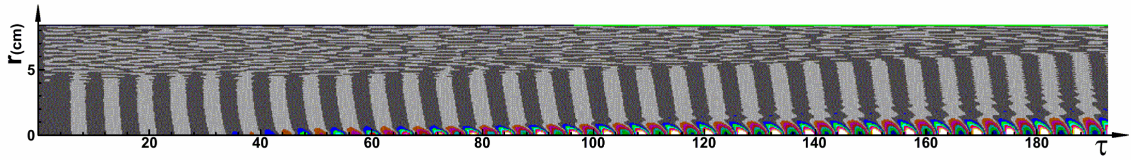

Fig. 2. Temporal evolution of the plasma electron density at z=50 cm

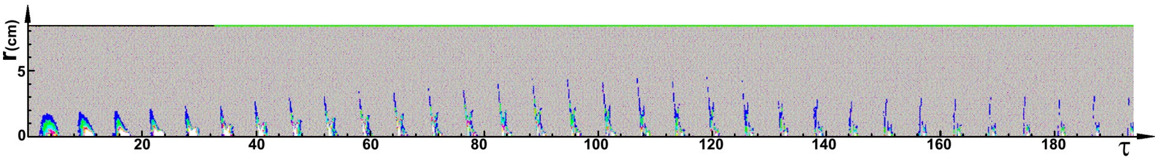

Fig. 3. Temporal evolution of the beam density near the end of the plasma (z=85 cm)

Fig. 4 shows the dimensionless density of plasma electrons $\tilde{n}_e = n_e/n_p$ (n_e is electron density)in the middle of the plasma after passage of 200 bunches (near the saturation level). The wave is clearly nonlinear, with the value of positive perturbation being almost twice greater than the value of negative perturbation.

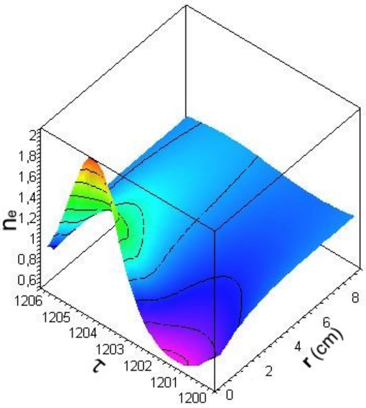

Fig. 4. Electron density perturbation at z=50 cm during one period after passage of 200 bunches

For the sequence of 500 bunches (Fig.5), we observe that 100 bunches lose their energy linearly, i.e. coherently deposit energy in plasma wakefield excitation (Fig.6).

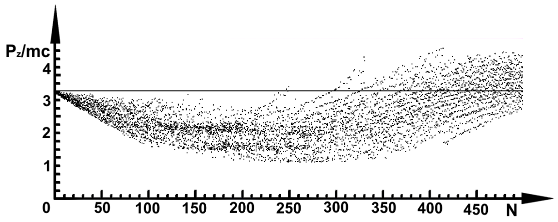

Fig. 5. Longitudinal momenta of 500 bunches as they pass the middle of the plasma (z=50cm)

The next portion of bunches (up to approximately 300th bunch) continues to lose their energy and contribute to wakefield build-up, but at a smaller rate. Subsequent bunches fall half-and-half in deceleration and acceleration phases of the excited wakefield, so that the wakefield amplitude saturates at the magnitude of 3 MeV/m.

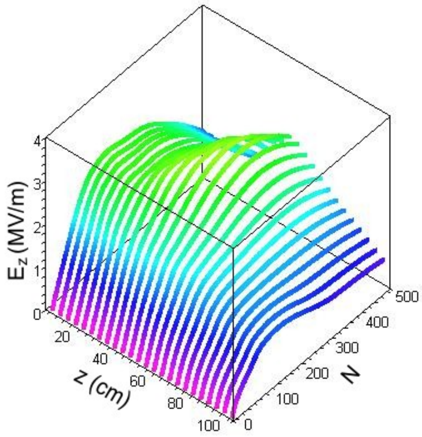

Fig. 6. The amplitude of the on-axis electric field as a function of the coordinate along the plasma and the number of bunches

The overall picture of wakefield excitation is seen from Fig.6 that shows the temporal growth of longitudinal electric field E_z in different plasma cross-sections. Near the entrance, the bunches have a perfect Gaussian-like shape, and the field grows linearly until the wave gets nonlinear and goes out of resonance with the sequence. At z ~ 50 cm, the effect of bunch pinching comes into play, and we observe faster field growth and a higher saturation level. The maximum electric field here is as high as 10% of the wavebreaking limit. Near the end of the plasma, the bunches are mostly defocused, and the excited wakefield is low.

Now we consider behavior of 1st, 20th, 100th, and 300th bunches in detail (Figs. 7-9). The 1st bunch propagates through the plasma with no change; it is shown mainly for reference.

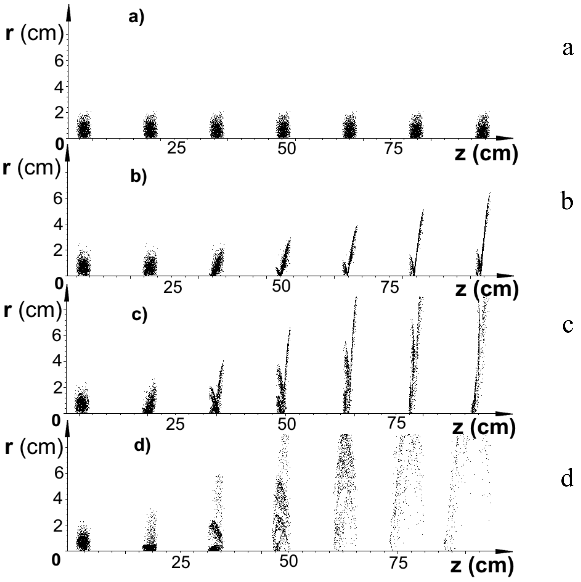

Fig. 7. Evolution of the bunch shape in plasma; 1st (a), 20th (b), 100th (c), and 300th (d) bunch at seven instants as they move through the plasma

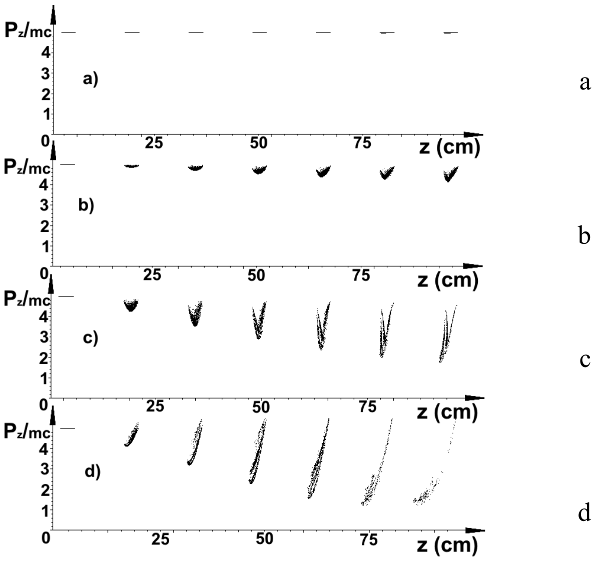

Fig. 8. Phase space portraits of the 1st (a), 20th (b), 100th (c), and 300th (d) bunch at the seven instants

The 20th and 100th bunches (ones at the stage of field growth) are decelerated by the excited plasma wakefield, and the deceleration rate is highest at bunch centers. This phasing of the wave is very natural: the plasma wave which provides the highest deceleration rate grows faster than any other wave and eventually becomes the dominant one. Once a bunch is completely in the decelerating phase, its front half is defocused and lost on the walls. For 20th and 100th bunches this happens near the end of the plasma and causes the observed decrease of the field amplitude there.

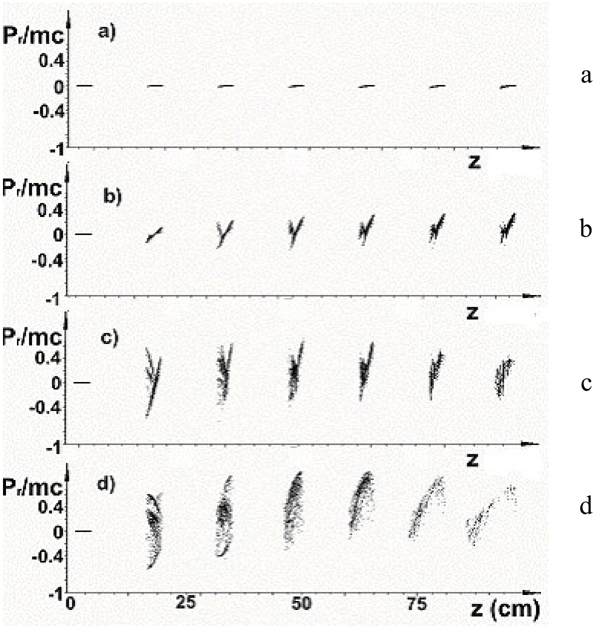

Fig. 9. Radial momenta of the 1st (a), 20th (b), 100th (c), and 300th (d) bunch at the seven instants

The 300th bunch evolves differently. From the very beginning, it propagates in the developed wakefield and is strongly compressed as a whole. Reasons for this kind of phasing are not clear yet. When passing through regions of high E_z, the bunch loses much of its energy and reduces the average longitudinal velocity. This backward shift could be favorable for transverse confinement of the bunch, but instead we observe transverse widening in all cross-sections of the bunch. Probably, this happens due to large transverse momenta (Fig. 9) acquired by bunch particles in regions of strong focusing. These momenta are sufficient for beam particles to escape radially when the bunch enters the low wakefield region near plasma exit.

3. CONCLUSION

It is shown that sequence of only about 300 relativistic electron bunches contributes to wakefield growth. The maximal wakefield of the order of 3 MV/m, i.e., 10% of the wavebreaking limit, is achieved in the middle of the plasma length. The electron density perturbation up to 60% is observed.

ACKNOWLEDGEMENTS

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВОЗБУЖДЕНИЯ КИЛЬВАТЕРНОЙ ВОЛНЫ В ПЛАЗМЕ ПОСЛЕДОВАТЕЛЬНОСТЬЮ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ

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С помощью гибридного 2.5-мерного кода LCODE проведено численное моделирование возбуждения кильватерных полей в плазме длинной последовательностью релятивистских электронных сгустков небольшой плотности. Для резонансной цепочки кильватерные поля 300 сгустков складываются когерентно, пока существенной не становится нелинейность волны.

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ЗБУДЖЕННЯ КІЛЬВАТЕРНОЇ ХВИЛІ В ПЛАЗМІ ПОСЛІДОВНІСТЮ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ

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За допомогою гібридного 2.5-вимірного коду LCODE проведено чисельне моделювання збудження кільватерних полів у плазмі довгою послідовністю релятивістських електронних згустків невеликої густини. Для резонансного ланцюжка кільватерні поля 300 згустків додаються когерентно, поки не стає суттєвою нелінійність хвилі.