NOVEL AND ADVANCED ACCELERATION TECHNIQUES

2D BEAM DYNAMICS SIMULATION IN LINEAR MODE LPWA CHANNEL WITH PRE-MODULATION STAGE

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Laser plasma wakefield acceleration (LPWA) is one of most popular novel methods of acceleration. The acceleration process differs significantly for linear LPWA mode and bubble (non-linear) modes. The LPWA has two serous disadvantages as very high energy spread and low part of electrons trapped into acceleration. The energy spectrum better than 10% does not observed anyone in simulations or experiments without of especial plasma density distribution. Such simulations and first experiments was done for bubble mode with different injection methods as varying of plasma density into bunching sub-stage, pondermotive injection, etc. But linear mode LPWA is also very interesting to design a compact hundreds-MeV accelerator. 2D beam dynamics in linear mode LPWA is discussed in this report. The waveguide and klystron type beam pre-modulation schemes are studied. The simulation shows that the klystron type pre-modulation can to gives the energy spectrum better than 1.5% for 200…300 MeV beam and to achieve the capturing coefficient 70…80%.

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INTRODUCTION

One of the main directions in accelerator technology, known as the energy frontier, is the development towards higher energies. However, the accelerating gradient in both room temperature and superconducting accelerating structures is limited by the discharge effects and processes on the surface. Even with the best of today's RF technology, the scale of future high-energy accelerators sets to tens of kilometers in length, and the fabrication costs are high in both cases. Compact medium energy facilities would also be enabled by higher acceleration rate to the benefit of smaller laboratories and universities.

A number of ideas for increasing the rate of the energy gain have been discussed in the last few decades. The idea of electrons acceleration in a modulated plasma channel was proposed by Ya.B. Feinberg in the 1950's [1]. Possible schemes for the plasma wakefield acceleration (PWA) differing in ways of modulating the plasma channel were developed later. The first one uses a high energy (tens of GeV) beam of particles to form a plasma wave and accelerate a fraction of the injected particles or a probe beam [2]. Another method is the laser plasma wakefield acceleration (LPWA) [3], in which a laser pulse is used to create a plasma wave. The modulation period of the accelerating field (the wakefield) is $L_w=\lambda_w/2=\pi c/\omega_p$, were c is the speed of light in vacuum, $\omega_p=(4\pi e n_0/m)^{1/2}$ is the plasma frequency, e end m are the elementary charge and mass, and n_0 is the electron density in plasma. Using two lasers with close frequencies ($\Delta\omega \sim \omega_p$) was also suggested for enhancing the accelerating gradient even further.

The advantage of the PWA technique vs. conventional accelerators is obvious: the accelerating gradient in a plasma channel can reach hundreds of GeV/m and hence the accelerator can be very compact. The idea is very popular at present and a number of international collaborations are working on analytical and experimental demonstration of LPWA. Large scale projects based on LPWA are being discussed now.

However, the step from a novel acceleration technique to routinely operating facilities has not been made yet. LPWA has two serious disadvantages: a very high energy spread of the accelerated electrons and only a small fraction of electrons is captured into the process of acceleration. An energy spectrum better than 10% has not been demonstrated either in simulations or experimentally without special methods of beam injection or pre-modulation [4 - 7]. A beam with such a wide energy spread can not be used for the majority of applications including medical and particle physics as the beam can not be transported efficiently. It should be noted that this problem does not apply to beam driven PWA, in which the modulated channel is produced by previously accelerated electrons, and the modulation period is equal to the bunching period [2].

1. BEAM ACCELERATION IN LPWA AND METHODS FOR IMPROVING THE ENERGY SPREAD

Considering LPWA, two regimes are distinguished: the underdense plasma, in which $\pi^2 r_l^2/\lambda_p >> a_0^2/2\gamma_l$, (quasi linear regime) and the non-linear regime with $\pi^2 r_l^2/\lambda_p << a_0^2/2\gamma_l$. Here r_l is the laser spot size, $a_0=eA/W_0$ normalized laser intensity, $\gamma_l=(1+a_0^2/2)^{1/2}$. The electron beam dynamics is different in the two regimes. The theory of the laser-plasma interaction and acceleration in the plasma channel are discussed in [8 - 10].

Both regimes, however, experience the high energy spread and low capturing. Conventional accelerators experienced similar problems in the past, where they were solved by bunching the beams using klystron or waveguide type bunchers, and later producing short bunches with photocathodes. Making a bunch shorter than the accelerating field modulation period L_w in a plasma channel does not seem to be viable. However, pre-modulation (bunching) of the electron beam can still be used as discussed below.

A few methods for improving the energy spread in the non-linear regime have been proposed. The first is to use two plasma stages with constant but not equal plasma densities and a transient stage with varying density between them for the beam modulation [11]. An energy spectrum better than 3% for a 1 GeV beam has been numerically and in experiment has demonstrated a low energy spectrum < ± 3% [12] for a similar distribution of the plasma density (decreasing in the first stage and constant in the second one).

A ponderomotive injection using two synchronized laser pulses was proposed in [13]. Two lasers can also excite a beat wave in the plasma, which is then used for capturing of the shot bunch [14]. With a third laser pulse this method can produce “cooled” electron beams [15]. The method of controlled electron self-injection in wave breaking regime has been also proposed [16], and an energy spread of ± 3% has been demonstrated experimentally.

These methods improve the energy spread to about 3% for a 1 GeV beam. Still, this number is too high for many applications. The electron capturing efficiency also remains problematic. All the methods described above apply to the non-linear or wave breaking regimes. However, the linear LPWA mode is also interesting for practical use. The rate of the energy gain can still be very high, while the laser power requirements are comparatively moderate, meaning that compact, laboratory scale facilities could be designed for accelerating electron beams to hundreds of MeV.

2. PRE-MODULATION SCHEMES IN LINEAR LPWA MODE

Two possible schemes of beam pre-modulation n linear LPWA mode were proposed [17 - 18].

In the first the bunching scheme similar to waveguide buncher in conventional RF lnac was studied. The plasma channel is divided into two stages. The plasma density slowly decreases in the first, pre-modulation stage, and is constant in the second, the main accelerating stage. The following assumptions are made: the beam is injected externally, the amplitude of the electric field does not vary on the scale of the time of flight, the plasma is cold, linear and collisionless, and the space charge field of the injected electrons is much lower than the plasma.

The beam dynamics was studied studied analytically in a way similar to how it is done for electron RF linacs and simulated numerically in 1D approach. Functions $\omega_p(\xi)$ and $E(\xi)$ describe dependencies of the plasma frequency and accelerating field on the longitudinal coordinate $\xi = 2\pi z/\lambda_l$. A variable similar to the wave velocity in a conventional accelerator is introduced $\beta_v(\xi) = 1 - \hat{\omega}_p^2(\xi)^{1/2}$, where $\hat{\omega}_p(\xi) = \omega_p(\xi)\lambda_l / 2\pi c$ is the normalized plasma frequency and λ_l laser wavelength.

Hamiltonian formalism was applied to the above equations for studying the beam-wave system and the standard energy balance equation written and injection conditions were analyzed analytically.

In contrast to conventional RF accelerators, the phase velocity and amplitude of the accelerating field are not independent variables, but functions of the plasma electron density $n_0(\xi)$ and are related as $E = mc\omega_p / e$. Therefore, optimizing the parameters of the plasma channel is a complex problem in LPWA. The linearity condition for the plasma wave can be expressed as $E(\xi)\sqrt{k(\xi)} = E(\xi = 0)\sqrt{k(\xi = 0)}$, and hence the amplitude of the accelerating field only depends on the longitudinal coordinate. Here $k(\xi)$ describes the plasma wave number in the longitudinal direction.

It was shown by means of analytical study and 1D numerical simulation that the beam can be modulated efficiently, the bunch has the minimal phase spread and more than half of electrons are captured. The resulting energy spread is 4% with the capturing coefficient reaching 40…45% front-to-end. But these results do not match well with the analytical study and single particle simulations.

Thus the other beam pre-modulation method was discussed [18]. This scheme is similar to the multigap klystron buncher of conventional RF linac and based on a number of short plasma sub-stages (several λ_l long each) separated by drift gaps. The plasma density distribution in the sub-stages can be simulated using standard functions (step, Gauss, etc.). The step function was chosen for the simulation. The distribution was expanded into series. Changing the number of terms in the series allows for shape adjustment of the plasma density profile. The dimensionless accelerating field distribution in the bunching part is shown in Fig. 1. The phase size $\Delta\varphi$ and energy spread $\Delta\gamma/\gamma$ after pre-modulation stage with are necessary for an efficient capturing into main stage and further acceleration can be achieved with electric field amplitude in bunching stage $E(\xi = \xi_b)/E(\xi = 0)$ =0.85 and a low value of the accelerating field in the bunching part $\hat{e}(\xi = 0)$ =0.009, $\hat{e}(\xi) = eE(\xi)\lambda_l / 2\pi W_0$, ($E$=2.75·$10^{10}$ V/m, n(ξ=0)=8·10^{16} cm^{-3}) for an injection energy W_{in}=10 MeV/m. The beam is accelerated in the main plasma stage with $\hat{e}(\xi = 0)$ =0.033, $z = 1000\lambda_l$ (E=1·10^{11} V/m, n(ξ=0)=1.1·10^{18} cm^{-3}, laser beam intensity $I_0 \approx 1.2 \cdot 10^{15}$ W/cm^{-2}). It has Δγ/γ ≤ 4% at the output while accelerating from 12 to 110 MeV.

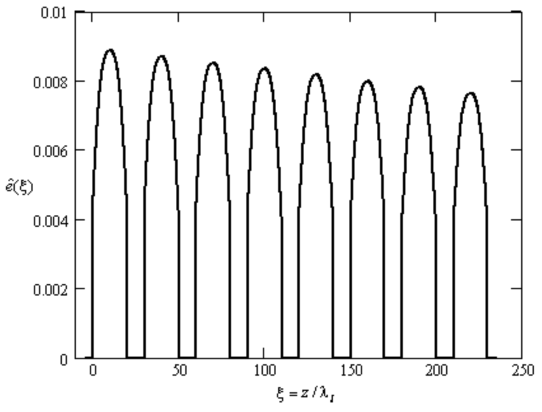

Fig. 1. Accelerating field distribution in bunching part linear mode LPWA with pre-modulation scheme consisting of a number of short plasma sub-stages separated by drift gaps

3. 2D BEAM DYNAMICS SIMULATION

The equations of motion for an electron in a plasma channel in 2D Cauchy form then are:

$$\begin{aligned}
&\frac{\mathrm{d}\gamma}{\mathrm{d}\tau} = \beta_z \hat{e}(\xi)\exp(-p(\rho/\rho_l)^2)\sin\phi,\\
&\frac{\mathrm{d}\xi}{\mathrm{d}\tau} = \beta_z, \qquad\qquad\qquad\qquad\qquad\qquad (1)\\
&\frac{\mathrm{d}\beta_r}{\mathrm{d}\tau} = \beta_z \hat{e}(\xi)(2p\rho/\rho_l^2)\exp(-p(\rho/\rho_l)^2)\cos\phi,\\
&\frac{\mathrm{d}\rho}{\mathrm{d}\tau} = \beta_r,\\
&\frac{\mathrm{d}\phi}{\mathrm{d}\tau} = \beta_z \;\; 1-\hat{\omega}_p^2(\xi) \;\;{}^{-1/2} -1,
\end{aligned}$$

where $\rho = 2\pi r/\lambda_l$ is the normalized transverse coordinate, $\rho_l = 2\pi a\ /\lambda_l$ is the normalized laser spot size, p is the degree in transverse plasma density distribution and γ Lorentz factor.

New BEAMDULAC-LWA2D code [19, 20] version was designed to study the beam dynamics in LPWA channel. The 2D simulation shows that the results of 1D study are all correct. The simulations were done with the following beam and channel parameters: an injection energy before pre-modulation stages W_{in}=10 MeV/m, beam injection size 50 μm and transverse emittance 1π mm·mrad, injection energy spread 10%,

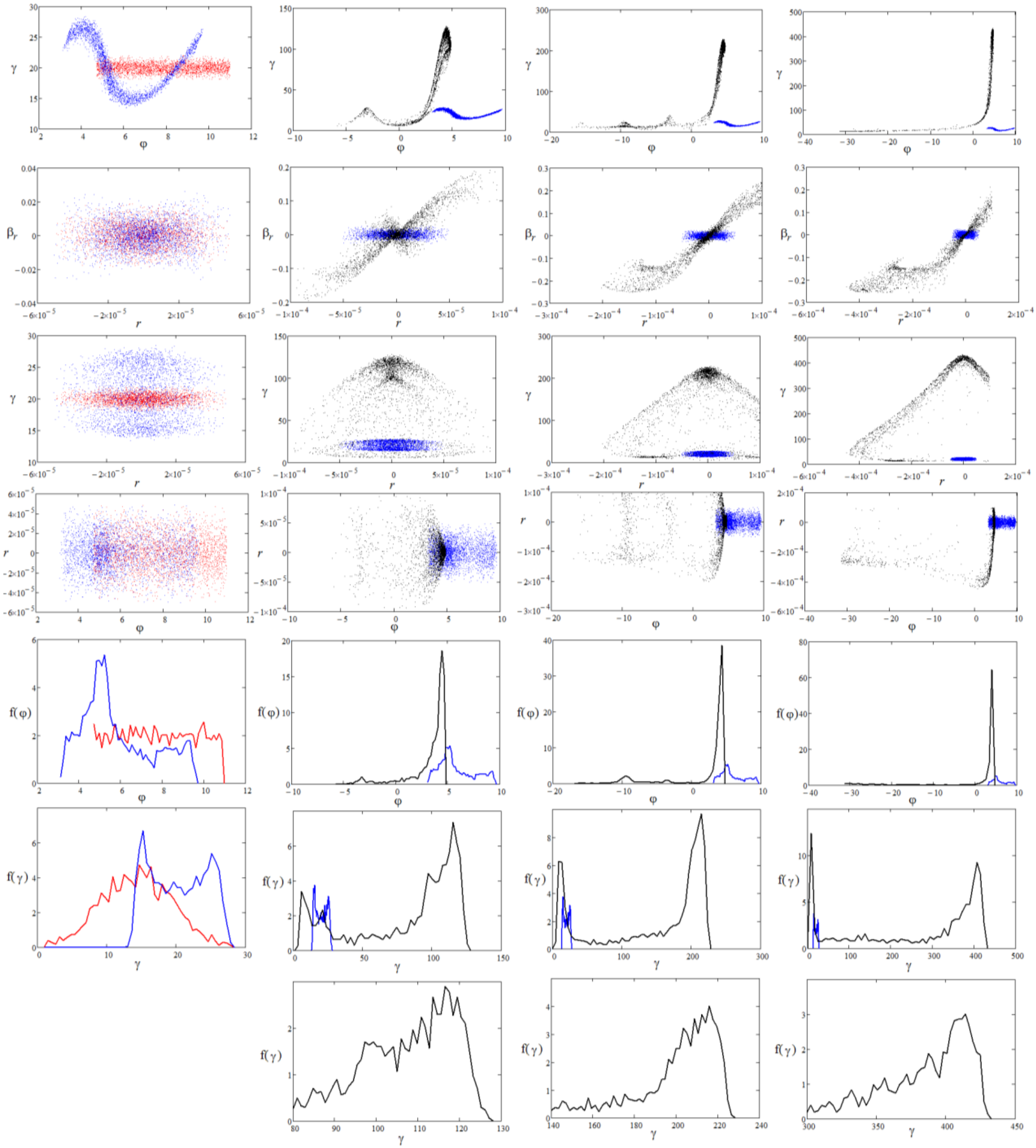

Fig. 2. Results of 2D electrons dynamics simulation for beam after pre-modulation (1^{st} stem), for z = 1000λ_l (2^{nd} stem), z = 1000λ_l (3^{rd}), z = 2000λ_l (last stem) are sown (top to bottom): particles distribution in conventional (γ, φ) and (β_r, r [m]) phase planes and in non-conventional (γ, r) and (r, φ) planes, phase spectrum, total energy spectrum and energy spectrum near peak energy (only for the accelerating stage). Injection distributions are plotted by red points and lines, distribution after pre-modulation by blue and output by black

number of pre-modulation stage 8, total pre-modulation length 240 μm, maximal electric field amplitude for pre-bunching stages decreases from $2.5\cdot10^{9}$ to $2.15\cdot10^{9}$ V/m, laser spot size 100 μm, electric field amplitude for min accelerating stage E=$1.0\cdot10^{10}$ V/m. The results of simulation are presented in Fig. 2 for beam after pre-modulation (1st stem), for $z=1000\lambda_l$ (2nd stem), $z=1000\lambda_l$ (3rd), $z=2000\lambda_l$ (last stem). The peak energies are 120, 210 and 400 MeV respectively. In Fig. 2 are sown (top to bottom): particles distribution in conventional (γ, φ) and (β_r, r [m]) phase planes and in non-conventional (γ, r) and (r, φ) planes, phase spectrum, total energy spectrum and energy spectrum near peak energy (only for the accelerating stage). Injection distributions are plotted by red points and lines, distribution after pre-modulation by blue and output by black.

It is clear that the electrons are effectively bunched and captured into acceleration in the main stage. The spectrum is lower than 3% and decreases with energy. The part of electrons is decapturing of acceleration and part of electrons having maximal energy decreases from 70% for 120 MeV to 40…45% for 400 MeV. But such dependence is typical for conventional RF linac also.

The possible way of decaptured electrons separation is very interesting. It is clear that uncaptured electrons are transported in the accelerating plasma channel without of the acceleration but the transverse motion of hundreds-MeV electrons is very slow and such particles not achieve the channel boundary. But they are transporting having higher readies comparatively captured electrons. The easy diaphragm can be effective used to separate uncaptured and decaptured electrons.

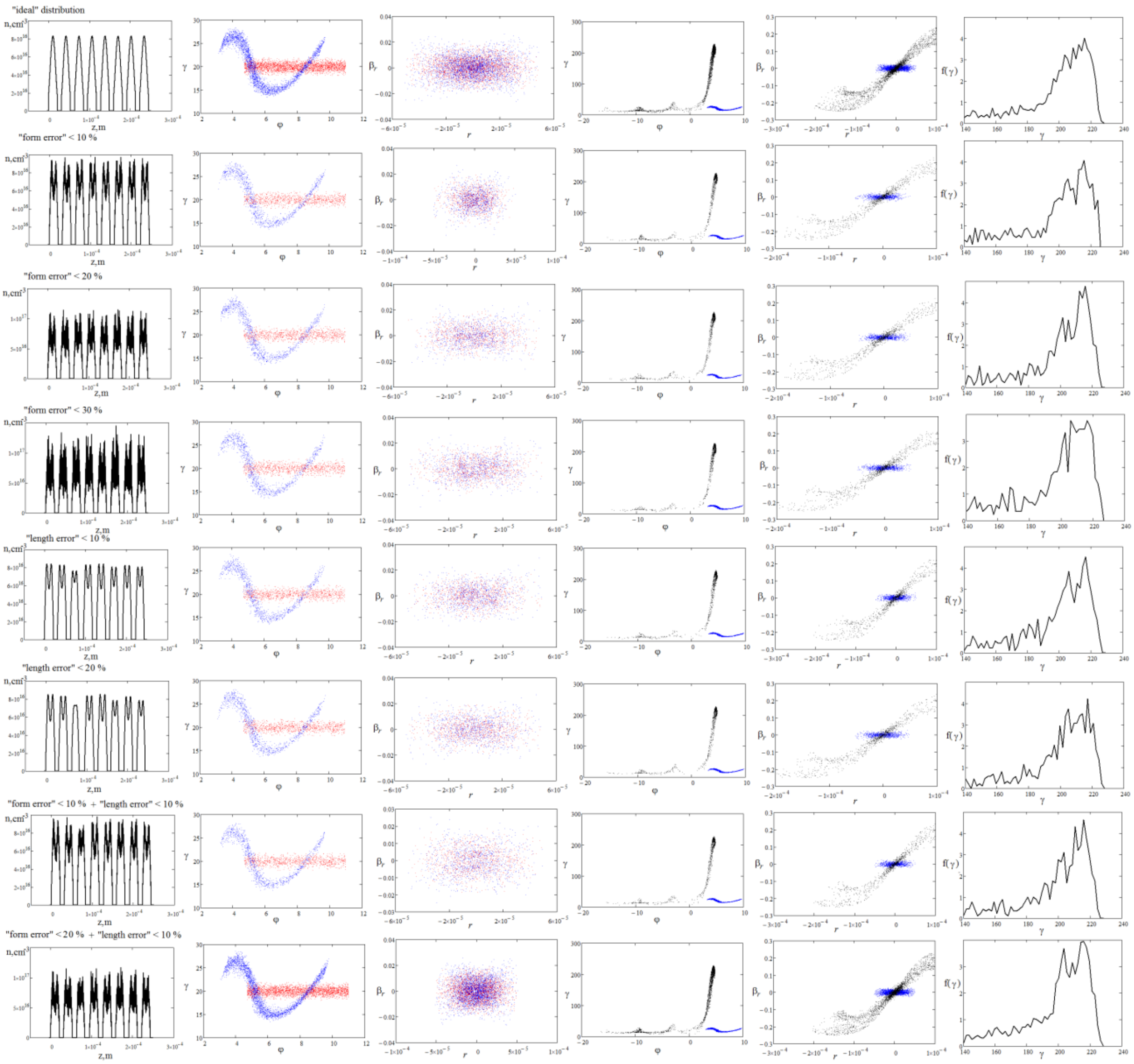

Fig. 3. The results of simulation taking into account plasma density distribution errors are shown (left to right): plasma density distribution, particles distribution in (γ, φ) and (β_r, r [m]) phase planes after pre-modulation stages, particles distribution in (γ, φ) and (β_r, r [m]) phase planes and energy spectrum after main accelerating channel. The figures (top to bottom) are calculated without error of plasma density distribution and taking into account errors for plasma stages forms, stages length and both of them. Injection distributions are plotted by red points and lines, distribution after pre-modulation by blue and output by black

4. SIMULATION OF “REAL” PLASMA DENSITY DISTRIBUTIONS

It is obvious that the all previous simulations were done for “ideal” plasma density distribution in suggestion that necessary for effective pre-modulation distribution can be realized on practice. Thus the distribution errors influence to the beam dynamics should be discussed.

The BEAMDULAC-LWA2D code was modified and pseudo-random error solver was applied in the code. This solver allows doing the pseudo-random correction for plasma stages length, centre of the stem position and density distribution. The correction can be made for each stem independently. But the error of each parameters (and plasma density in each point) will randomize only in user defined limits. Such pseudo-random approach allows to define the limiting conditions for plasma density distribution quality and to discuss the possibility of these distributions experimental realization possibility.

The results of simulation are shown in Fig. 3 (left to right): plasma density distribution, particles distribution in (γ, φ) and ($\beta_{r,}$ r [m]) phase planes after pre-modulation stages, particles distribution in (γ, r) and (r, φ) phase planes and energy spectrum after main accelerating channel. The figures (top to bottom) are calculated without error of plasma density distribution and taking into account errors for plasma stages forms, stages length and both of them. It is clear that the randomized errors influence is not sufficient for stage form errors up to 20%. But the stage length error influenced more sufficiently and plasma stems should be positioned not poorly than 10%. These results are confirms by simulation done taking into account both errors: 10% length error and 20% form error gives very serious deviation of particle distributions in phase spaces and of the spectrum.

CONCLUSIONS

The basic idea of klystron-like beam pre-modulation for linear mode laser plasma wake-field acceleration was discussed. The idea is directed to beam pre-modulation using shot low density plasma stages with gaps between of them. Such idea is similar to known method of multi-gap klystron.

The new code version BEAMDULAC-LWA2D was developed to study the 2D electrons dynamics both in pre-modulation stage and main acceleration stage. It was shown that the beam can be effectively bunched, captured into acceleration in the main stage and accelerated up to hundreds of MeV. The energy spread is not higher than 3% for 100 MeV beams which is much lower than for other LPWA bunching schemes.

The capturing coefficient is high also and it is achieved up to 70…75%. Later some electrons lose from the acceleration but half of external injected beam can be accelerated up to 400…500 MeV. This result is also much better than for other known bunching schemes.

Tolerances of plasma density distributions were also studied.

Using pseudo-random solver added to BEAMDULAC-LWA2D was shown that the maximal deviation of plasma density should not exceed than 20 % of the analytically defined function. But the tolerance of plasma stem length should not exceed 10 %. Such plasma density distributions can be realized in the experiment by plasma filled capillary or a supersonic gas jet.

The simulation taking into account the beam-plasma interactions and self-fields is planned to do in future. The laser intensity attenuation due to plasma excitation should be also discussed.

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REFERENCES

1. Y.B. Fainberg // *Sov. Atomic Energy*. 1959, v. 6, p. 1084.
2. P. Muggli et al. // *Phys. Rev. Lett.* 2008, v. 100, p. 074892.
3. T. Tajima, J.M. Dowson // *Phys. Rev. Lett*. 1979, v. 43 (4), p. 267.
4. G.R. Plateau et al. // *Phys. Rev. Lett.* 2012, v. 109, p. 064802.
5. B.B. Pollock et al. // *Phys. Rev. Lett.* 2011, v. 107, p. 045001.
6. M. Mori et al. // *Phys. Rev. ST AB*. 2009, v. 12, p. 082801.
7. J.U. Kim, N. Hafz, H. Suk // *Phys. Rev. E*. 2004, v. 69, p. 026409.
8. A.I. Akhiezer, R.V. Polovin // *Zh. Eksp. Teor. Fiz.* 1956, v. 30, p. 915.
9. L.M. Gorbunov, V.I. Kirsanov // *Sov. Phys. JETP*. 1987, v. 66, p. 290.
10. E. Esarey, C.B. Schroeder, W.P. Leemans // *Rev. of Modern Phys.* 2009, v. 9, p. 1229.
11. S.V. Bulanov et al. // *Phys. Plasmas*. 2008, v. 15, p. 073111.
12. A.J. Gonsalves et al. // *Nature Physics*. 2011, v. 7, p. 862.
13. D. Umstadter, J.K. Kim, E. Dodd // *Phys. Rev. Lett.* 1996, v. 76, p. 2073.
14. E. Esarey et al. // *Phys. Rev. Lett*. 1997, v. 79, p. 2682.
15. E. Esarey, W.P. Leemans // *Phys. Rev. E*. 1999, v. 59, p. 1082.
16. S.P.D. Mangles et al. // *Nature*. 2004, v. 431, p. 535.
17. S.M. Polozov / *Proc. of. RuPAC*. 2012, p. 251.
18. S.M. Polozov / *NIM A*. 2013, v. 729, p. 517.
19. E.S. Masunov, S.M. Polozov // *NIM A*. 2006, v. 558, p. 184.
20. E.S. Masunov, S.M. Polozov // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”*. 2008, v. 5(50), p. 136.

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МОДЕЛИРОВАНИЕ ДВУМЕРНОЙ ДИНАМИКИ ПУЧКА В КАНАЛЕ ЛАЗЕРНО-ПЛАЗМЕННОГО УСКОРИТЕЛЯ, РАБОТАЮЩЕГО В ЛИНЕЙНОМ РЕЖИМЕ С ПРЕДГРУППИРОВАТЕЛЕМ

С.М. Полозов

Ускорение электронов в плазменном канале, образованном при воздействии лазерного излучения, является в настоящее время одним из наиболее исследуемых новых методов ускорения. Процесс ускорения различается для двух случаев: линейного и нелинейного («пузырькового») режимов. Однако ускорение в плазменном канале имеет два существенных недостатка – широкий спектр энергии пучка на выходе и низкий коэффициент захвата электронов в режим ускорения. Проведенные моделирование и эксперименты показывают, что без применения специальных методов предмодуляции пучка не может быть получен спектр лучше 10%. Для нелинейного режима разработано несколько таких методов и проведены первые эксперименты. Линейный режим ускорения может быть очень перспективен для создания компактного ускорителя электронов в диапазоне энергий сотни мегаэлектронвольт. Рассмотрена двумерная динамика пучка в канале с предгруппирователем волноводного и клистронного типов. Моделирование показывает, что при использовании группирователя клистронного типа можно получить спектр пучка уже 1,5% при энергии электронов 200…300 МэВ и коэффициенте захвата 70…80%.

МОДЕЛЮВАННЯ ДВОВИМІРНОЇ ДИНАМІКИ ПУЧКА В КАНАЛІ ЛАЗЕРНО-ПЛАЗМОВОГО ПРИСКОРЮВАЧА, ЩО ПРАЦЮЄ В ЛІНІЙНОМУ РЕЖИМІ З ПЕРЕДГРУПУВАТЕЛЕМ

С.М. Полозов

Прискорення електронів у плазмовому каналі, утвореному при впливі лазерного випромінювання, є в цей час одним з найбільш досліджуваних нових методів прискорення. Процес прискорення розрізняється для двох випадків: лінійного та нелінійного («бульбашкового») режимів. Однак прискорення в плазмовому каналі має два суттєвих недоліки – широкий спектр енергії пучка на виході і низький коефіцієнт захоплення електронів у режим прискорення. Проведені моделювання та експерименти показують, що без застосування спеціальних методів передмодуляції пучка не може бути отриманий спектр краще 10%. Для нелінійного режиму розроблено кілька таких методів і проведено перші експерименти. Лінійний режим прискорення може бути дуже перспективним для створення компактного прискорювача електронів у діапазоні енергій сотні мегаелектронвольт. Розглянута двовимірна динаміка пучка в каналі з передгрупувателем хвилеводного і клістронного типів. Моделювання показує, що при використанні групувателя клістронного типу можна отримати спектр пучка вже 1,5% при енергії електронів 200…300 МеВ і коефіцієнті захоплення 70…80%.