LONGITUDINAL MOTION STABILITY OF ELECTRONS INSIDE THE PLASMA CHANNEL OF LPWA

S.M. Polozov, V.I. Rashchikov

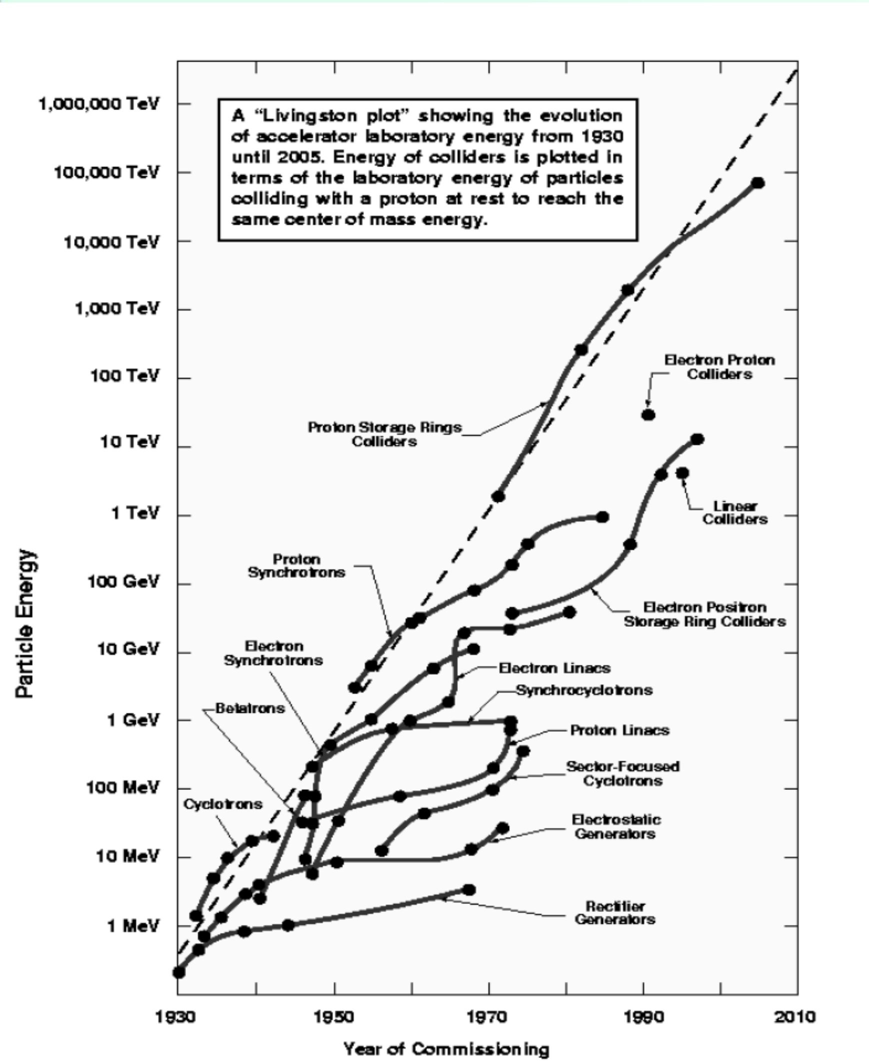
National Research Nuclear University - Moscow Engineering Physics Institute

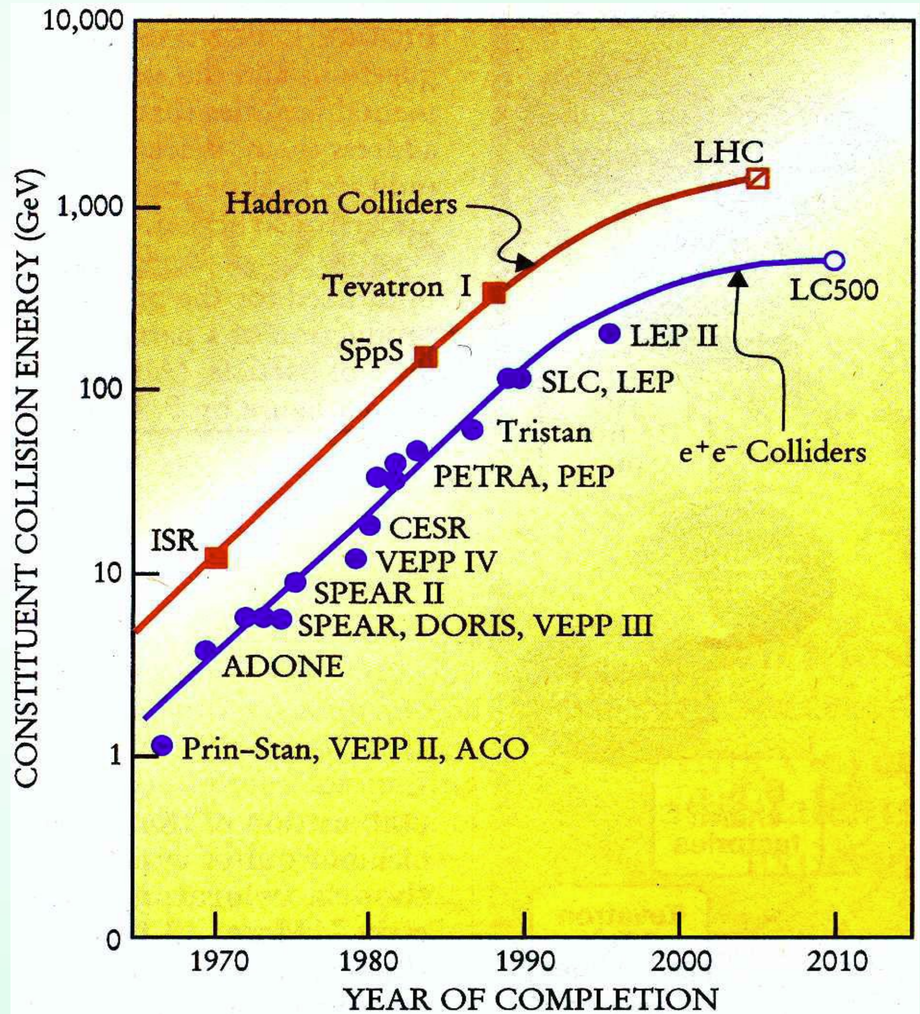
Project is supported by the Ministry of Science and Education of Russian Federation, Agreement No 14.616.21.0086 from 24.11.2017, ID RFMEFI61617X0086 (Federal Targeted Program "Research and development on priority directions of scientific-technological complex of Russia in 2014 -2020 year").

Contents:

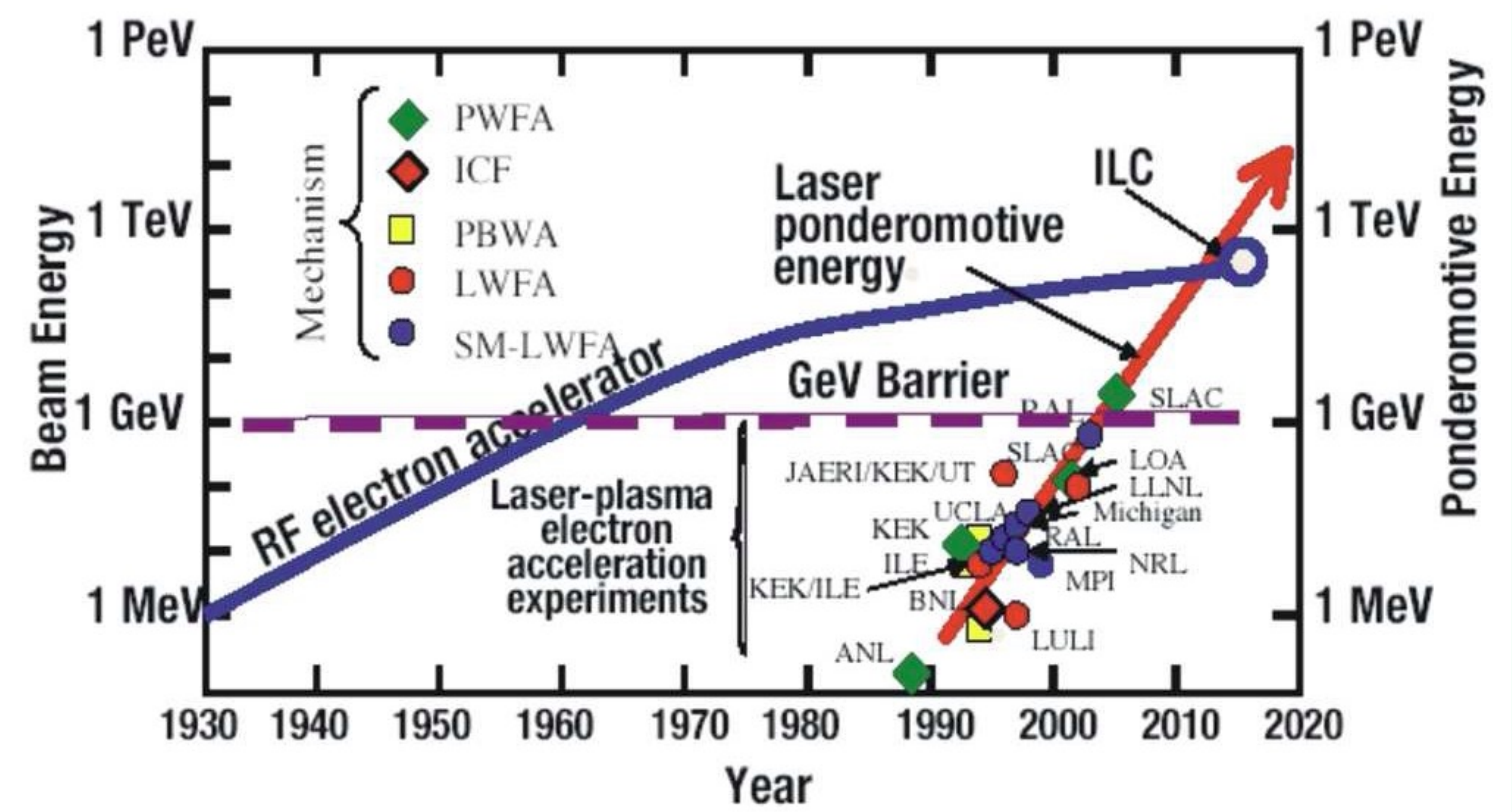
- The "energy gain" problem and LPWA as an possible way to solve them
- Typical laser-plasma accelerated electron parameters
- Beam pre-bunching lead to the higher capturing and lower spectra
- Problem of the longitudinal instability
- Conclusions

LPWA – laser plasma wakefield acceleration is discussed as one of possible ways to solve the problem of the energy gain





Livingstone's Chart



The optimistic picture form 2000th years …

The basic IDEA

of acceleration in plasma channel

Y.B. Feinberg

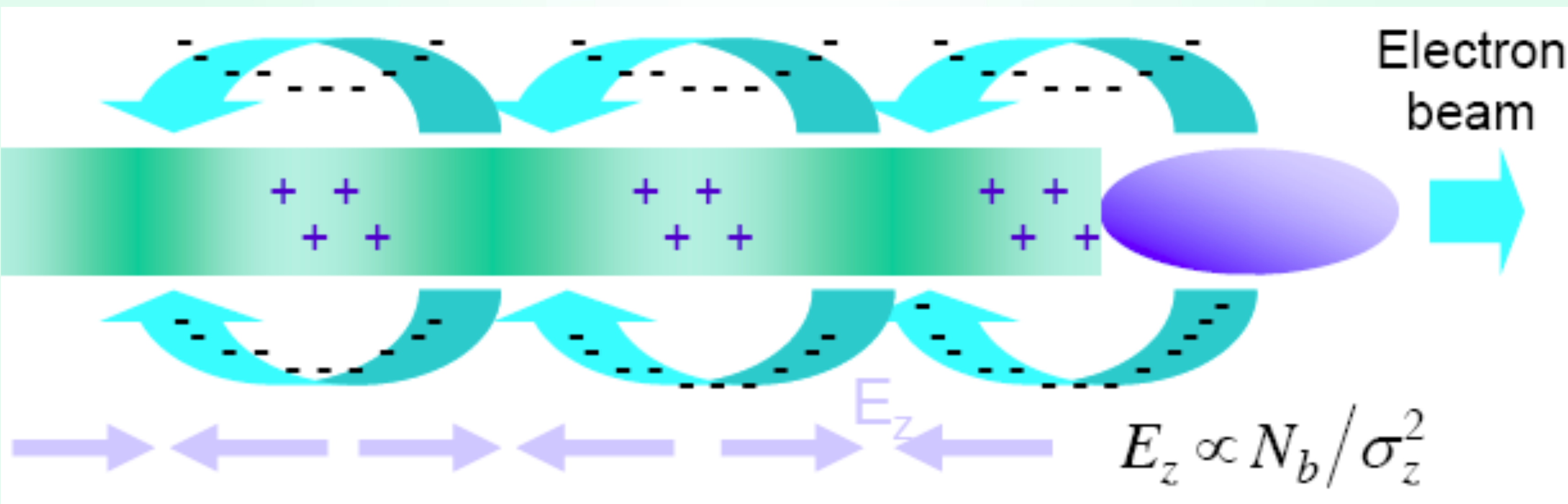
// *Sov. Atomic Energy, vol. 6, 1959, p.1084.*

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

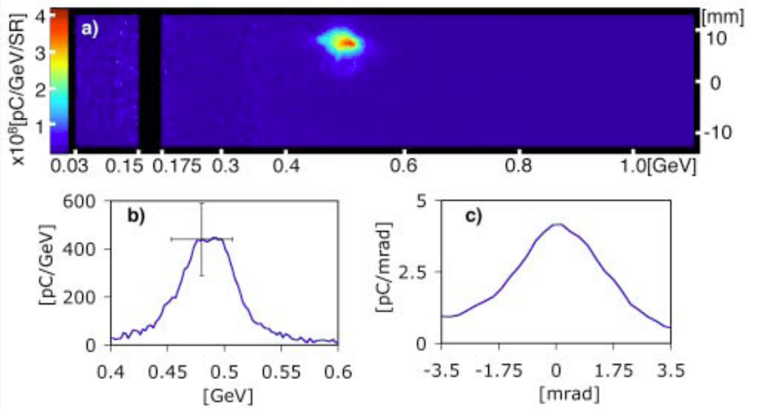
Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

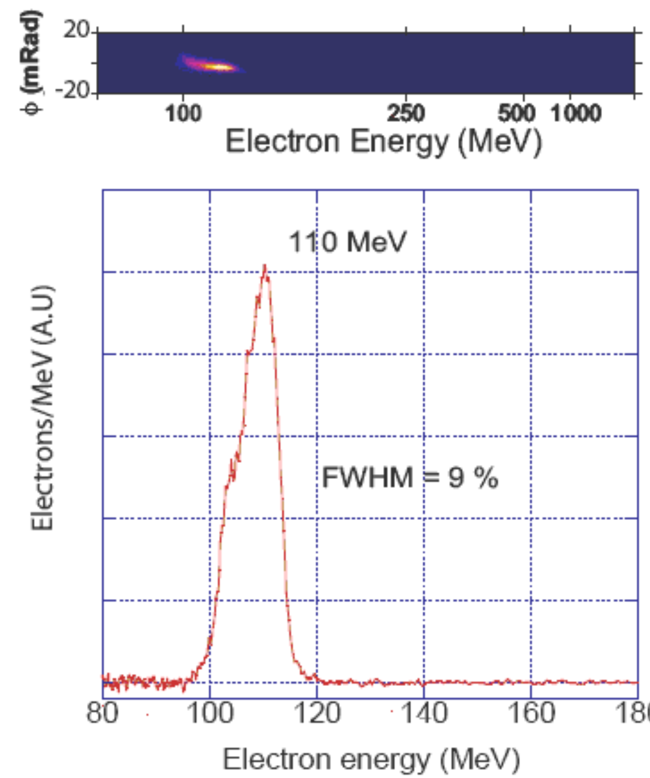
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



- Typical laser-plasma accelerated electron parameters



A. J. Gonsalves, K. Nakamura et al. Proc. of PAC2007



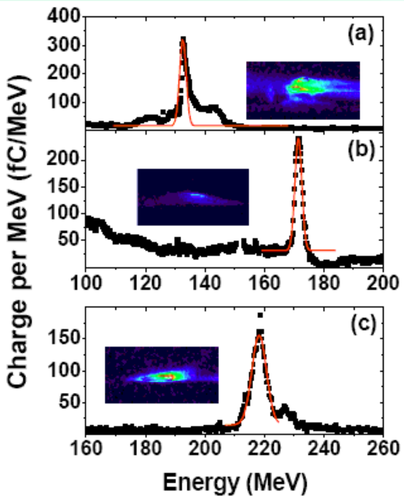
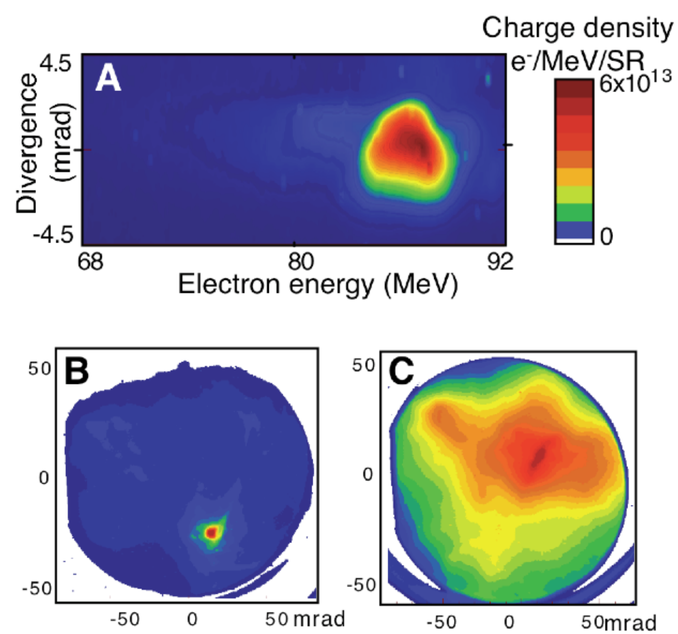


Figure 3: Electron energy spectra showing a bunch (respective false-colour YAG image inset) with (a) central energy = 133 MeV and measured $\sigma_\gamma/\gamma = 0.8\%$, (b) central energy = 171 MeV and measured $\sigma_\gamma/\gamma = 0.7\%$ and (c) central energy = 218 MeV and measured $\sigma_\gamma/\gamma = 1.1\%$. Each red curve is a Gaussian fit and the charge in each bunch is ~0.5 pC.

S. M. Wiggins, G. H. Welsh et al. Proc. of IPAC2011



C.G.R. Geddes, E. Esarey et al. Proc. of PAC2005

V. Leurent, P. Michel, C.E. Clayton et al. Proc. of EPAC'08

A few methods for improving the energy spread in the non-linear regime have been proposed:

- 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 [S. Bulanov at al.].
An energy spectrum better than 3 % for a 1 GeV beam has been numerically and in experiment has demonstrated a low energy spectrum $< \pm 3$ % [A.J. Gonsalves et al.] for a similar distribution of the plasma density (decreasing in the first stage and constant in the second one).
- ponderomotive injection using two synchronized laser pulses was proposed [D. Umstadter, J.K. Kim, E.Dodd]. Two lasers can also excite a beat wave in the plasma, which is then used for bunching [E.Esarey et al.].
- with a third laser pulse this method can produce “cooled” electron beams [E.Esarey, W.P. Leemans].
- method of controlled electron self-injection in wave breaking regime has been also proposed [S. P. D. Mangles et al.], and an energy spread of ± 3 % has been demonstrated experimentally

- Beam pre-bunching lead to the higher capturing and lower spectra

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 idea:

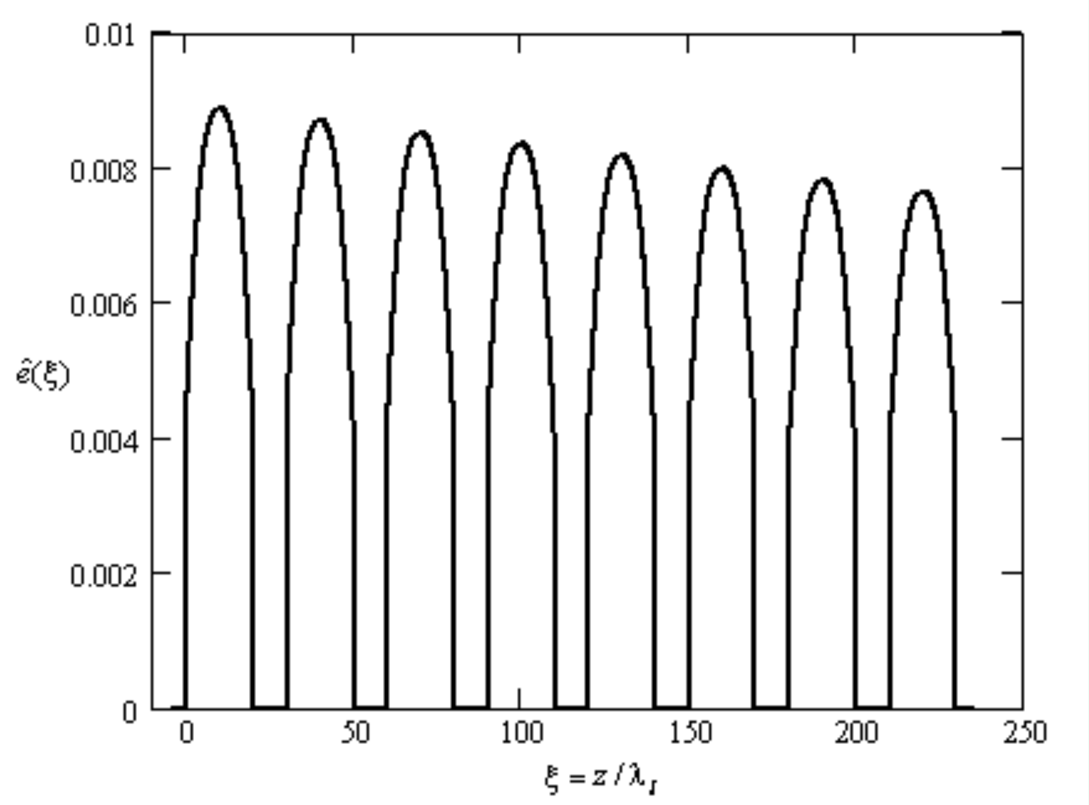
The plasma channel is divided into two stages. The plasma density slowly decreases in the first, pre-modulation stage, and is constant in the second, the main accelerating stage.

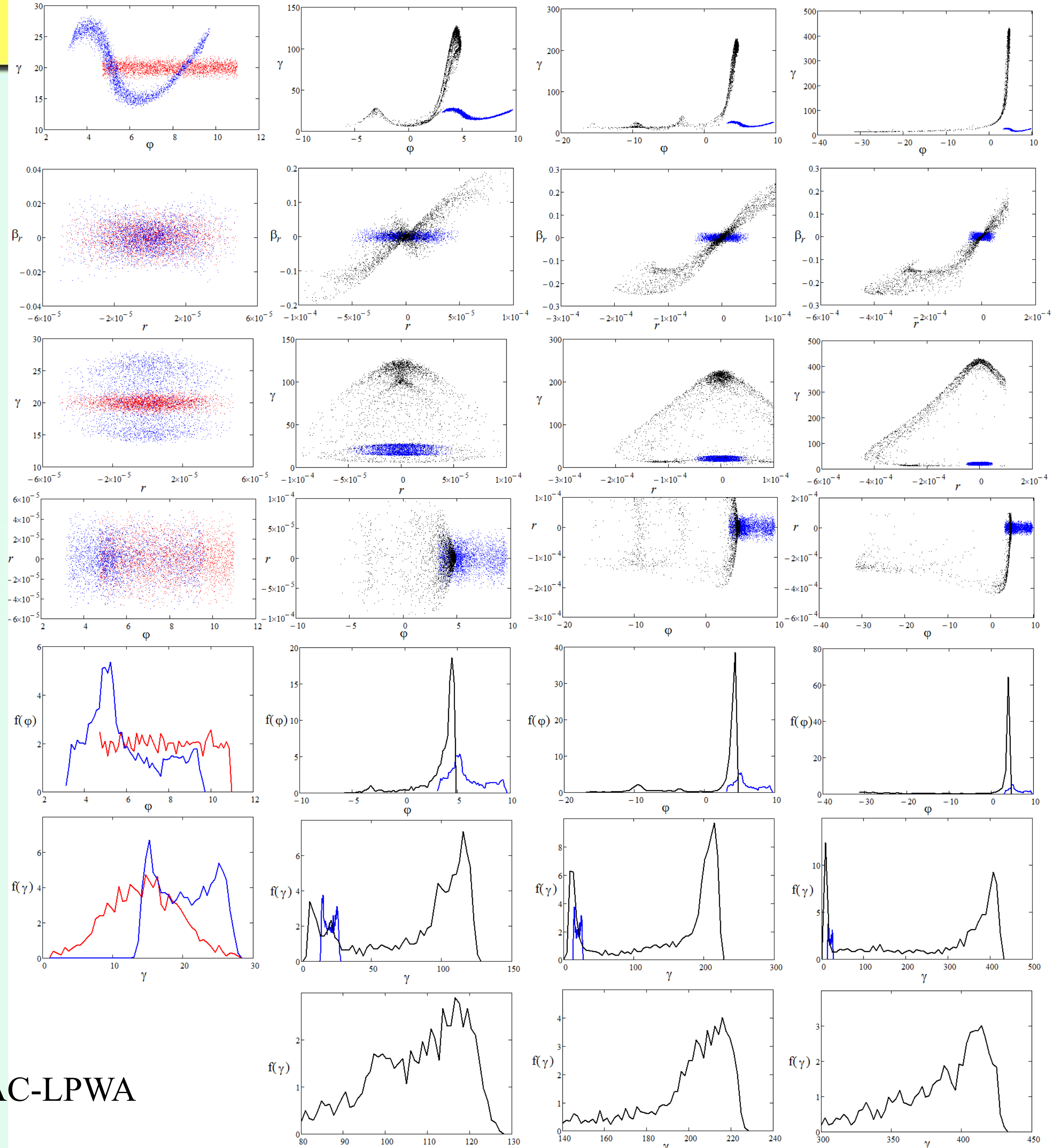
The following assumptions are made: the beam is injected externally, the amplitude of the electric field does not vary on the scale of the time of flight, the plasma is cold, linear and collisionless, the space charge field of the injected electrons is much lower than the plasma.

Results: 200 MeV± 4-5 %, K_T ? 40-45 % (for the second stage ? 70 %). This results are closer to the classic RF linac, but not enough yet for main applications.

The idea # 2:

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_1 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.



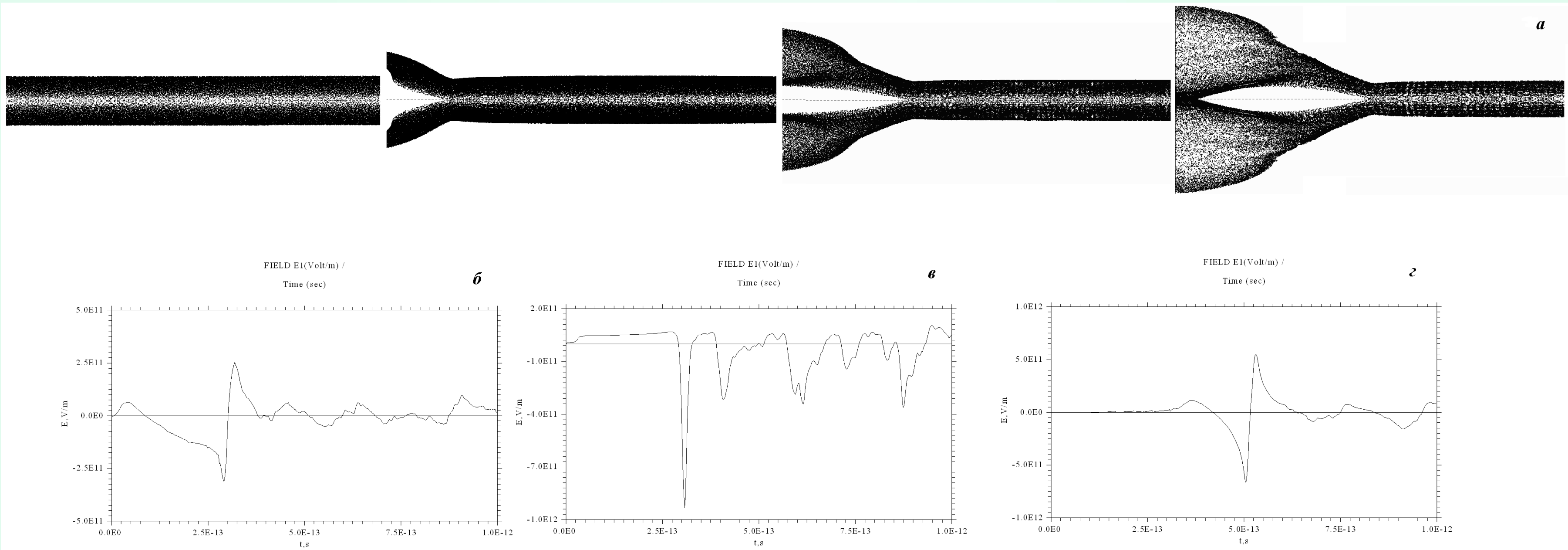


BEAMDULAC-LPWA simulations

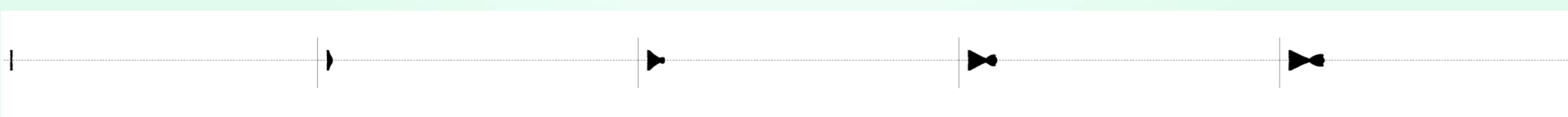
It is clear that the electrons are effectively bunched and captured into acceleration in the main stage. The spectrum is lower than 3 % and decreases with energy. The part of electrons are decapturing of acceleration and part of electrons having maximal energy decreases from 70 % for 120 MeV to 40-45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

- Problem of the longitudinal instability

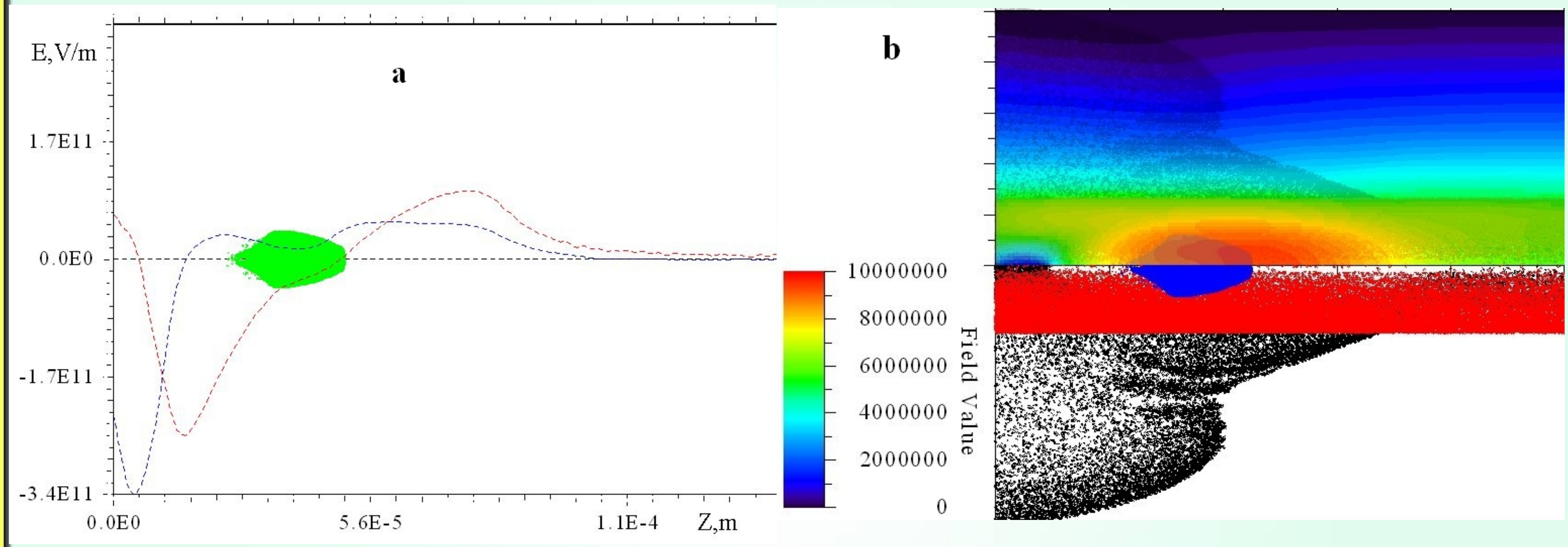
CHANNEL WITH RAMPED PLASMA DENSITY DISTRIBUTION



Time depended longitudinal(a) and transverse (b) fields on the axis at the beginning and at the middle (c) of the buncher



Time depended electrons injection to buncher

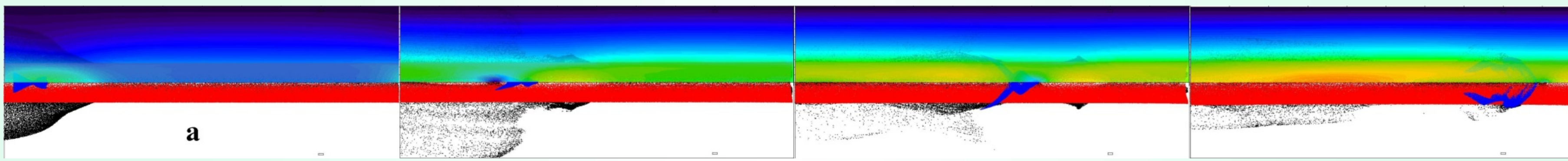


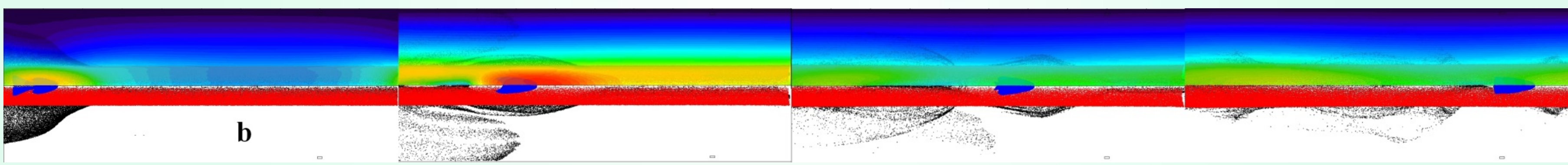
(a) Longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution in buncher at the mean beam radius,

(b) The upper part shows plasma self field potentials distribution and lower - charge particles distribution. Black and red points correspond to plasma electrons and ions accordingly. Injected electrons are presented at the lower part of the figure by blue points near the potential maximum.

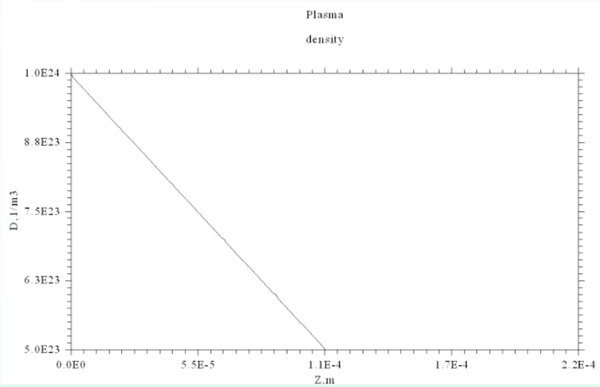
Simulations were done by SUMA electrodynamics + PIC code

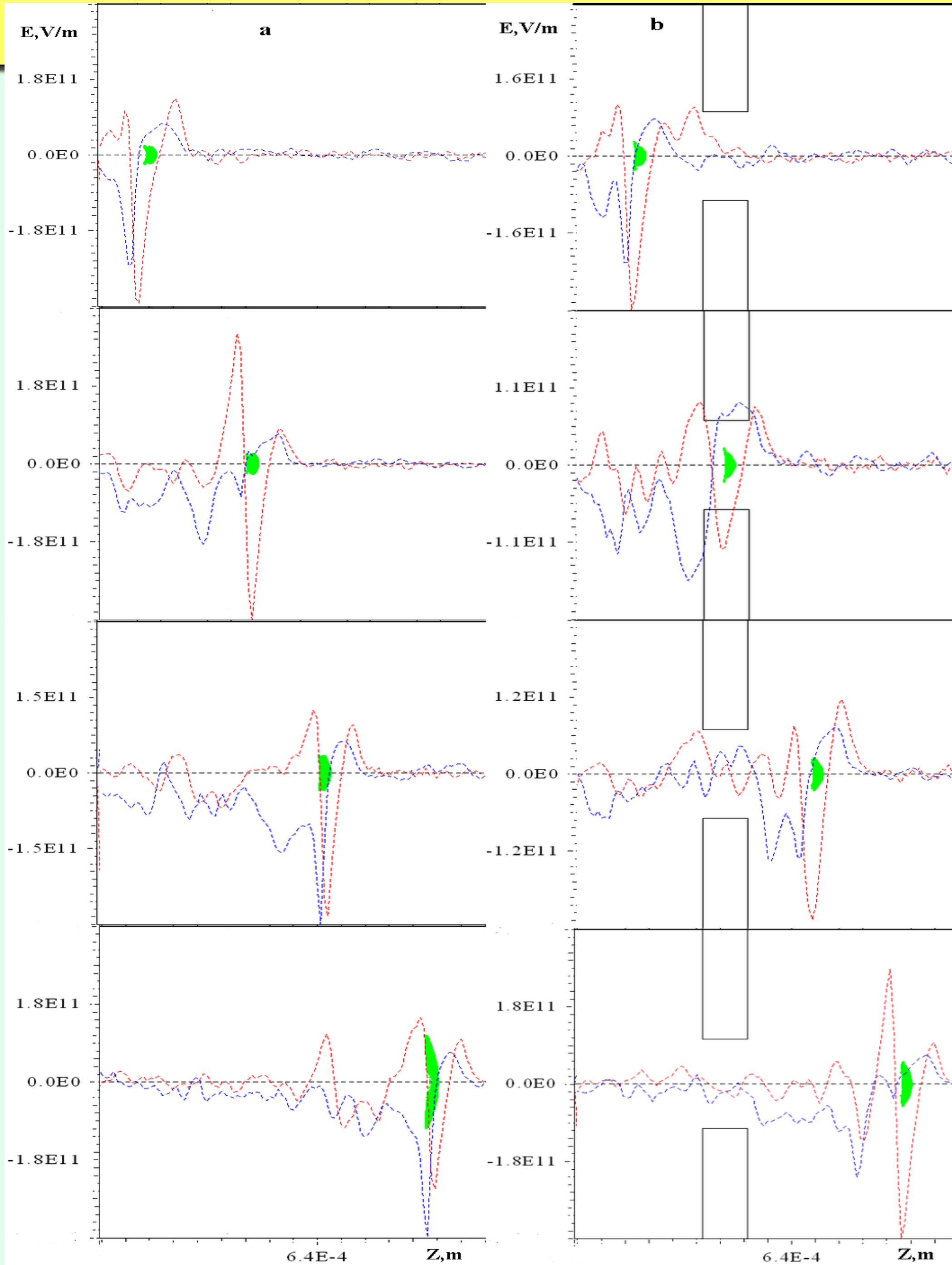
Time depended (time step 100 fs) potential and charged particles distributions (lower part) in the channel with constant plasma density 10^{24} m^{3} (Fig. a).





Time depended potential and charged particles distributions in the channel with ramped plasma density (Fig. b).





Time depended (time step 400 fs) electron bunch (green dots), longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution in channel at the mean beam radius with (b) and without (a) iris.

Conclusions:

- The basic idea of klystron-like beam pre-modulation for linear mode laser plasma wake-field acceleration was discussed.
- 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 %.
- The interesting effect defines the longitudinal electron motion instability inside of the LPWA channel was observed, investigated and explaned.

Thank You for attention !