INSTITUTE FOR HIGH ENERGY DENSITIES
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# On the structure of accelerating wakefields generated by laser pulses and charged particle bunches

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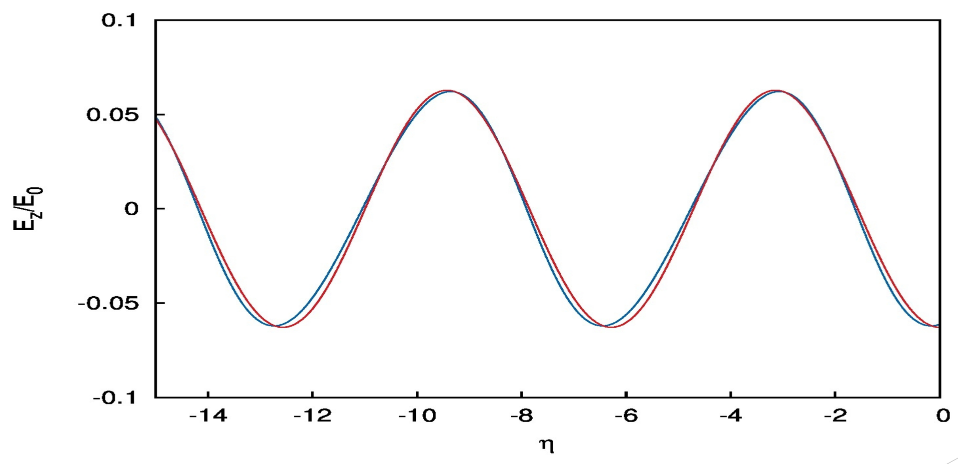
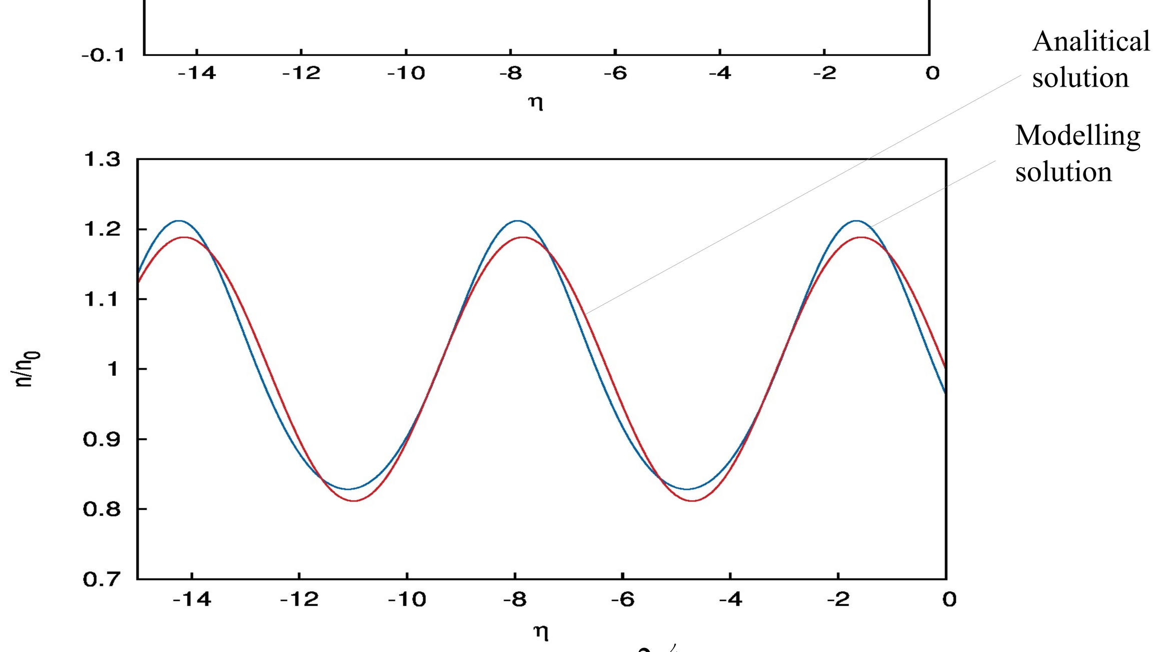
The structure of plasma waves excited by intense laser pulses or beams of charged particles is investigated on the base of cold hydrodynamic model. The laser wakefield is analyzed in homogeneous plasma and also in wide and narrow (compared with the plasma wavelength) plasma channels. Analytical solutions in the linear approximation are supplemented by numerical simulations of the nonlinear wakefields generated by intense laser pulses and charged particle beams. In view of the planned AWAKE experiment at CERN, acceleration of externally injected electrons in proton driven plasma wake-field is modeled using elaborated numerical code.

## Laser wakefield in homogeneous plasma



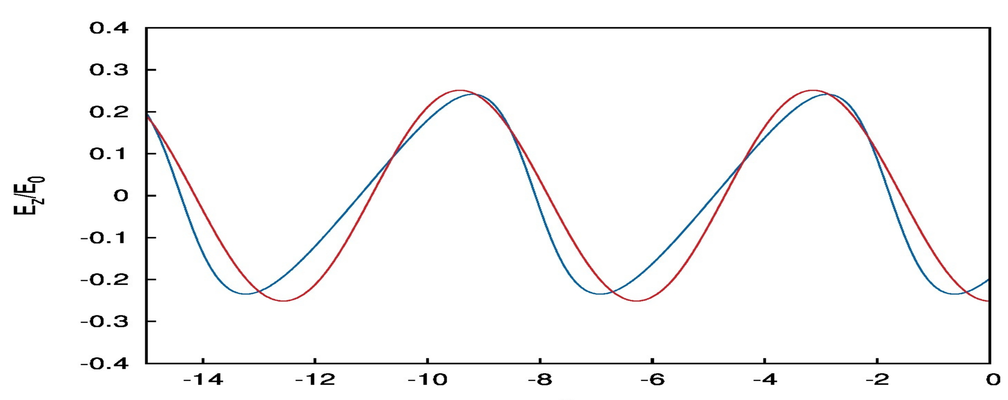


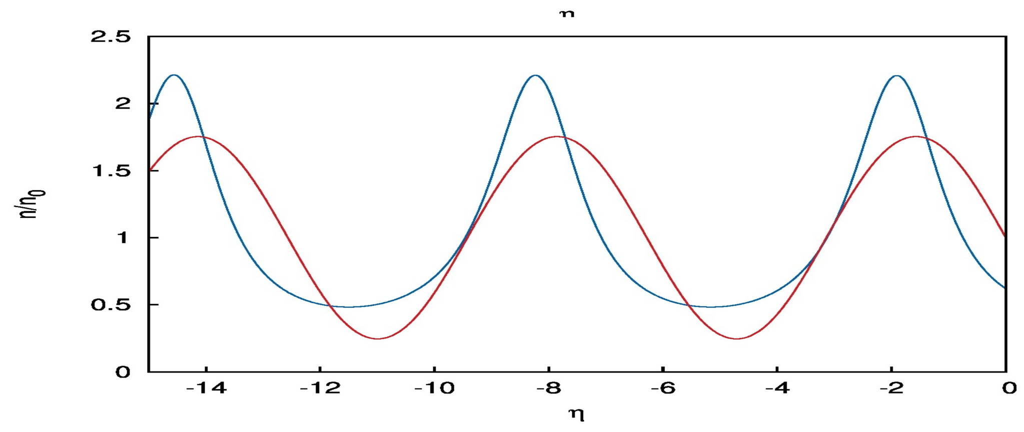

Impulse configuration is $a^2=a_0^2\exp(-\frac{2r^2}{r_0^2})\sin^2(\pi\eta/k_pL), 0<\eta<L$
$a_0=0.4,\ k_{pL}=2\pi,\ k_pr_0=2$

Analytical linear approximation is given by following equations:

$$\frac{E_z}{E_0}=-\frac{\pi}{8}a_0^2\exp\left(-\frac{2r^2}{r_0^2}\right)\cos(\eta)$$

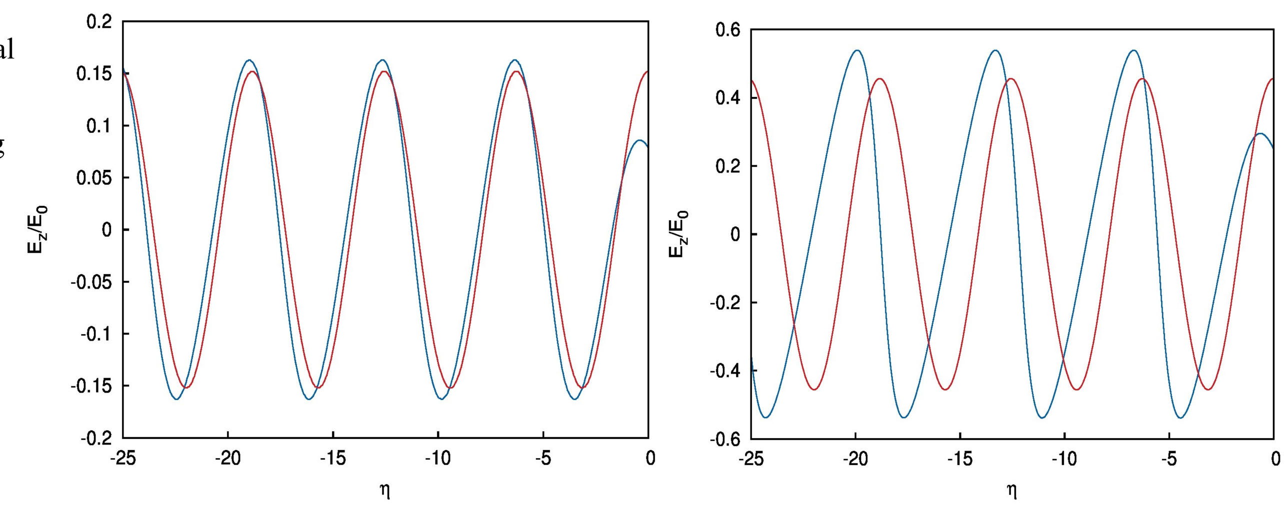
$$\frac{\delta n}{n_0}=-\frac{\pi}{8}a_0^2\left[1+\frac{8}{k_p^2r_0^2}\left(1-\frac{2r^2}{r_0^2}\right)\right]\exp\left(-\frac{2r^2}{r_0^2}\right)\cos(\eta)$$





Plasma wave in non-linear regime. Impulse configuration is $a_0=0.8,\ k_{pL}=2\pi,\ k_pr_0=2$

## *Wave excited by charge beam in homogeneous plasma*



Wave excited by ion beams. Beams shape is given by :

$$\rho(r,\eta)=\begin{cases} n_b\exp(-\eta^2/(k_pL)^2) & if\ r<r_0\\ 0 & if\ r>r_0\end{cases}$$

Analytical linear approximation is given by following equation:

$$E_z/E_0=(2\pi)^2(n_b/n_0)k_pL\exp(-k_p^2L^2/2)H_R$$

Where

$$H_R(r)=\begin{cases}1-k_pr_0K_1(k_pr_0)I_0(k_pr) & if\ \ r<r_0\\ k_pr_0I_1(k_pr_0)K_0(k_pr) & if\ \ r>r_0\end{cases}$$

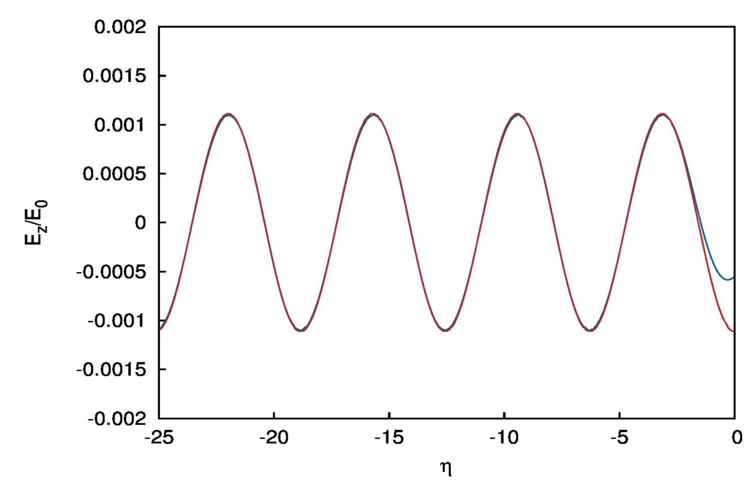
In case of narrow beam ( $k_pr_0\ll 1$ ) : $H_R(0)=k_p^2r_0^2/2(0{,}62-\ln(k_pr_0))$

In case of wide beam ( $k_pr_0\gg 1$ ) : $H_R(0)=1$

Parameters of ion bunch are $k_pL=1,\ k_pr_0=10$

$n_b/n_0=0.1$ -on the left image

$n_b/n_0=0.3$ -on the right image



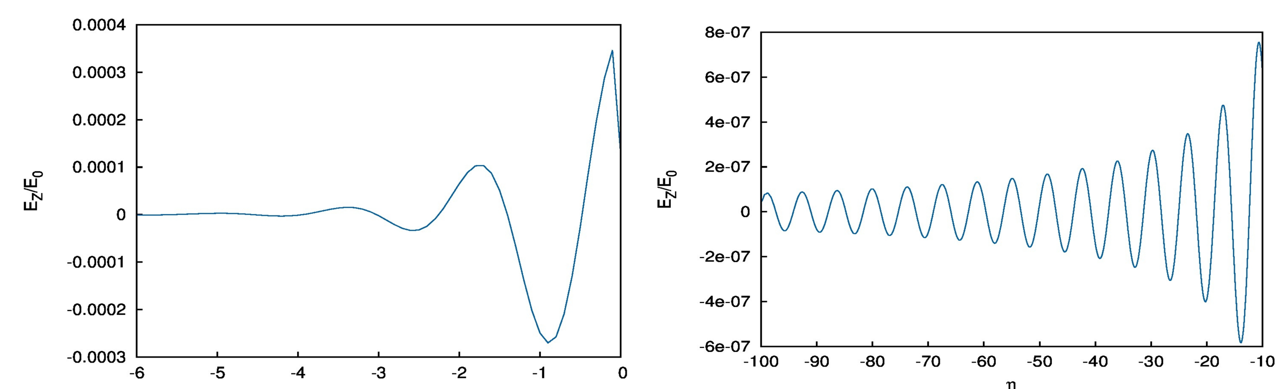
Wave excited by electron bunch.

Parameters of electron bunch are : $k_pL=1,\ k_pr_0=0.1,\ n_b/n_0=0.05$

Designations:
$n_0$-electron density on the axis in the beginning
$\omega_0$-laser frequency
$k_{p0}=\omega_{p0}/c=(4\pi ne^2/m_e)^{1/2}/c$

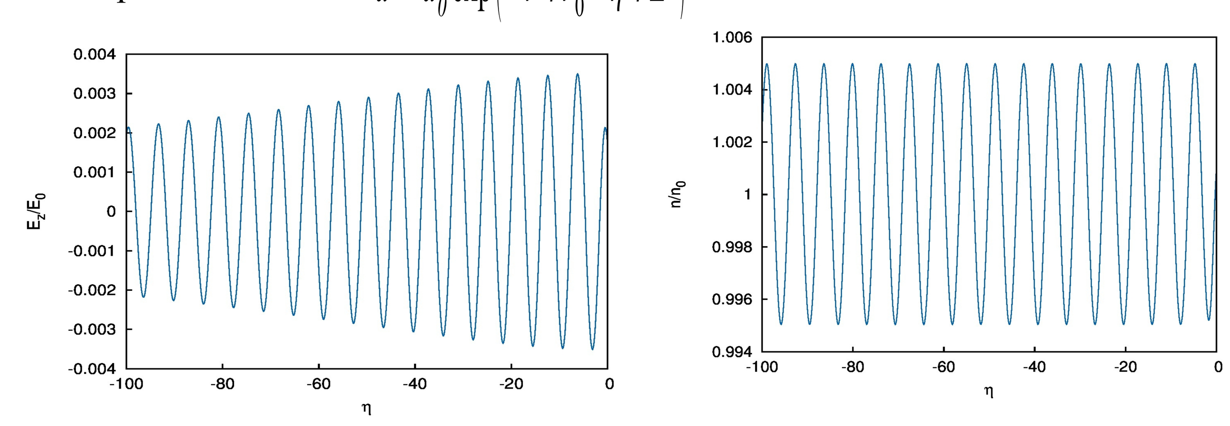
Plasma density for channels is given by $n=n_0(1+r^2/R_{ch}^2)$
$\vec{a}=e\vec{E}/mc\,\omega_0$ -laser envelope
$\varphi$ -wakefield potential
$\eta=k_p(z-ct)$

## Laser wakefield acceleration in plasma channels



Parameters of laser are $a_0=0{,}1,\ k_{p0}L=0{,}01,\ k_{p0}r_0=0{,}3,\ k_{p0}R_{ch}=0.09$

Shape of laser beam: $a^2=a_0^2\exp(-r^2/r_0^2-\eta^2/L^2)$



Parameters of laser are $a_0=0{,}1,\ k_{p0}L=1,\ k_{p0}r_0=3,\ k_{p0}R_{ch}=9$

Field in narrow plasma channel rapidly decrease. This solution is in agreement with analytical solution of field for short laser beam in narrow plasma channel:

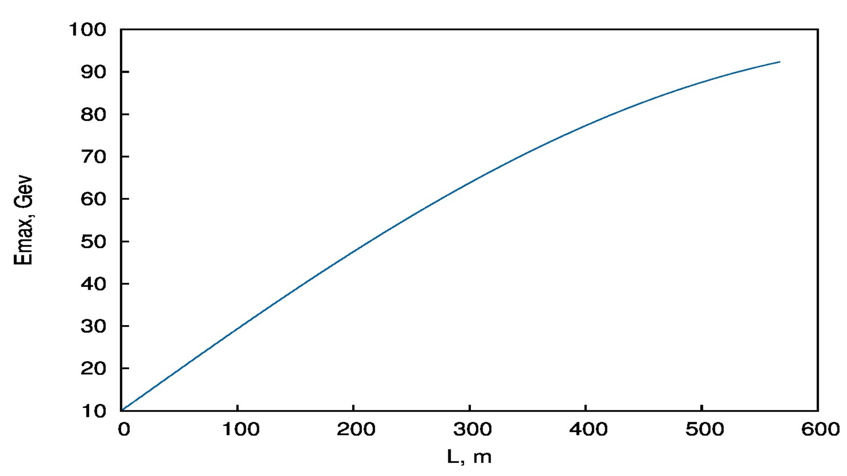
$$E_z(r=0,\eta)/E_0=\frac{1}{4}|a_0|^2Lr_0^2k_{p0}^2\frac{\sin(\eta)}{\eta}$$

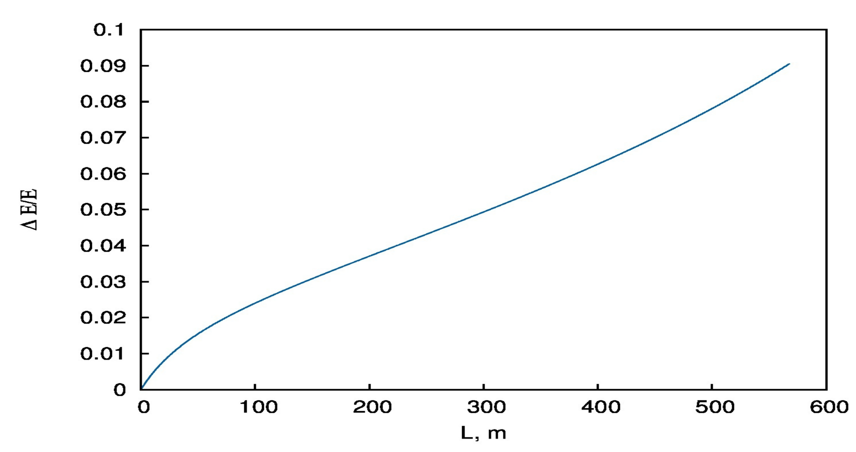
But field in wide plasma channel decrease slowly. That is in agreement with analytical solution of potential for laser beam in wide plasma channel:

$$\delta\varphi(r=0)=A_0[1-\frac{2}{k_p^4R_{ch}^4}\eta^2]\sin(\eta)$$

## CERN experiment

Experiment parameters:
$n_0=6\,10^{14}\ cm^{-3}$
$r_0=0.43\ mm$
$L=0.1\ mm$
$\lambda_p=1.35\ mm$
$n_b/n_0=0.57$
$\rho(r,\eta)=n_b\exp\left(-\frac{r^2}{2r_0^2}-\frac{\eta^2}{2(k_pL)^2}\right),$

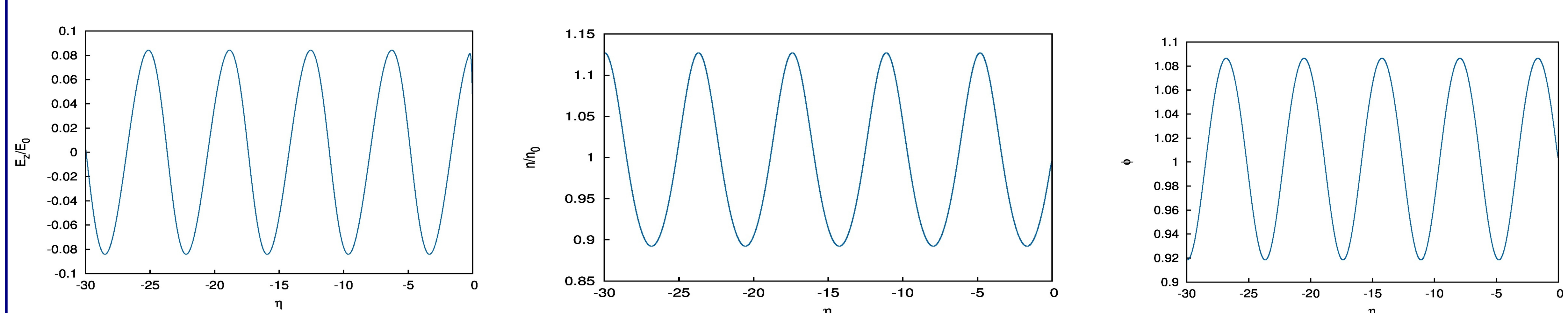




Wake was excited by ion bunch. Energy of ion bunch was $E_i=1\ \ TeV$.

After that electron bunch was injected behind ion bunch in the minimum of wakefield potential. Energy of injected electrons was $E_e=10\ \ GeV$. Numerical simulations continued until maximum of potential were achieved.

Parameters of electron beam are $k_p\sigma_L=0.1,\ k_p\sigma_r=0.1$



## Conclusions

- Structure of laser and charged particles wakefield analyzed for homogeneous plasma. Numerical simulations of the nonlinear wakefields and Analytical solutions in the linear approximation were shown
- Fast field decrease in narrow plama channel and slow decrease in wield plasma channel were shown
- Parameters of CERN experiment were used for prediction energy gain of electrons injected after ion bunch propagation in plasma.