# DIFFRACTION ACCELERATOR OF CHARGED PARTICLES

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## *Abstract*

We present the results of theoretical and numerical analysis of the physical processes for laser linear accelerator based on two symmetric resonance diffraction gratings with double-sided accelerating field excitation. Structures parameters optimization provides π-mode field amplitude distribution in neighboring diffraction zone. The maximum energy gradient restricted by ablation processes in grating materials is estimated as 1-3 GeV/m. The numerical analyses and analytical approximation of electric and magnetic field structures are done, longitudinal and transverse electron beam dynamics in accelerating systems are considered, wake fields and focusing properties of diffraction gratings are estimated.

## INTRODUCTION

Recently we found the variant of open resonator with diffraction mirror that provides the electron acceleration with energy gradient up to 1 GeV/m [1-3]. The relativistic bunch forming from non-relativistic electron beam at laser frequency was also considered [4].

However the detailed numerical simulation made for this structure demonstrated the excitation of strong longitudinal and transverse wake fields which hardly restrict accelerated bunch charge. Here we investigate different accelerating structure based on diffraction grating disposed upon dielectric slab. In result of field simulation [5] we found a new variant of accelerating structure which essentially differs from the known structures including prototype [6].

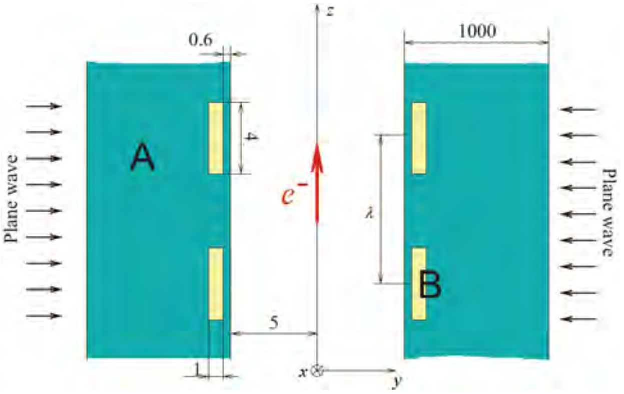

Figure 1: Diffraction accelerating structure. A –dielectric slab (ZnSe, $\varepsilon = 5.773$), B – conducting strip (Al). All dimensions are in μm.

Our accelerating structure, seen in Fig.1, differs from [6] in several respects: (1) it is not resonant, therefore field accumulation time is minimal; (2) the beam channel height is large and is approximately equal to wavelength; (3) the electric field has 100% amplitude modulation within one half period and 180° phase shift between neighboring half periods which provides the high efficiency of particles acceleration; (4) the double sides structure irradiation eliminates the transverse field components in median plane.

## FIELD STRUCTURE

On the base of numerical simulation we obtained the following analytical approximation for field spatial distribution in accelerating metal-dielectric structure beam channel that meets the Maxwell equations (Fig.2):

$$\vec{E} = \left\{ \begin{matrix} 0; 2\pi \dfrac{y}{\lambda} E_{z0} \sin\left(2\pi \dfrac{z}{\lambda}\right) \sin \omega t; \\ E_{z0} \cos\left(2\pi \dfrac{z}{\lambda}\right) \sin \omega t \end{matrix} \right\}, \qquad (1)$$

$$\vec{H} = \left\{ -2\pi \frac{y}{\lambda} \frac{E_{z0}}{Z_0} \cos\left(2\pi \frac{z}{\lambda}\right) \cos \omega t; 0; 0 \right\}. \qquad (2)$$

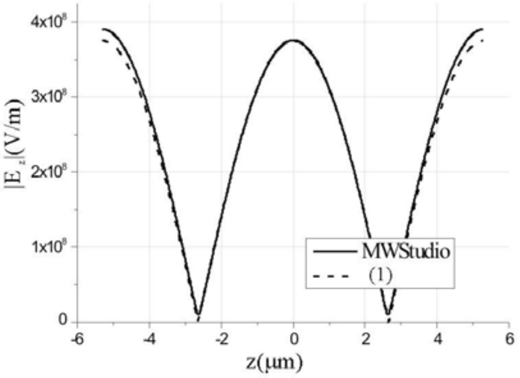

Figure2: Electric field amplitude $|E_z|$ longitudinal distribution for $\omega t = \pi / 2$.

## ELECTRON DYNAMICS

The solution of equation for electron moving along z axis shows that energy gradient for ultra-relativistic particle for this field distribution is $T(eV/m) = E_{z0} (V/m)/2$. For comparison the energy gradient for structure described in [2] is $T = E_{z0}/\pi$. The working region of the beam channel along $y$ axis is approximately one wavelength and along $x$ axis is limited only by laser beam width and may be much grater than wavelength.

In ultra-relativistic case the structure focal power both in $x$- and $y$ directions is zero similar to axially-symmetry accelerating structure. In non-relativistic case the focal power in $y$ direction decreases proportionally to relativistic factor $\gamma$ and in $x$ direction it is always infinite. At Fig.3 the dependence of electron trajectory dip angle $y' = v_y / v_z$ after 100 periods of accelerating structure on the injection phase is shown for the following three initial energies 12, 24 and 60 MeV. Electric field amplitude of incidence wave was $3\cdot10^8$ V/m. In initial moment all electrons had only longitudinal velocity components and 1 μm displacement off the median plane in $y$ direction.

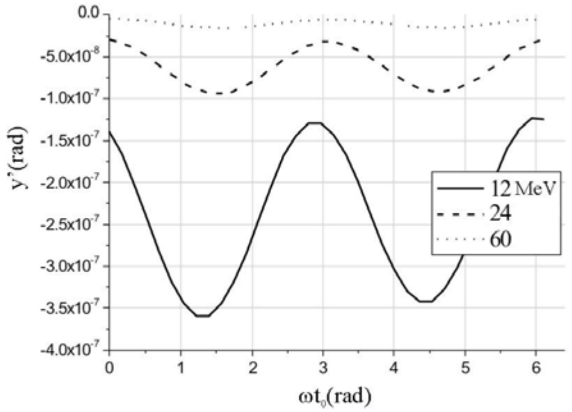

Figure 3: The electron trajectory dip angle after 100 periods.

## METHOD OF FIELD PROBING

For probing the accelerating structure spatial field distribution and amplitude we suggest the method based on the use of low energy (several hundred volts – several kilovolts) flat electron beam passing the structure in $x$ direction. The pattern produced by the beam at luminescent screen installed at the opposite side will depend on the field amplitude and spatial distribution.

If injected electron beam moves along the $x$ axis the field-electron interaction provides transverse particles bunching in *(y,z)* plane. Using theory of particles movement in adiabatic slow inhomogeneous AC fields we write the Hamilton function for averaged coordinates $\bar{\vec r} = (\bar x, \bar y, \bar z)$ and momentum $\bar{\vec p} = (\bar p_x, \bar p_y, \bar p_z)$ :

$$H(\bar{\vec r},\bar{\vec p},t) = m_0c^2 + \frac{1}{2}\frac{\bar{\vec p}^2}{m_0} + \frac{1}{4}\frac{e^2}{\omega^2 m_0}\vec E^2(\bar{\vec r},t) \qquad (3)$$

From (3) for average transverse momentum in *(x,0,z)* plane along $z$ axis for example we obtain Hamilton equations:

$$\frac{d\bar p_z}{dt} = -\frac{16e^2E_{z0}^2}{m_0\omega^2\lambda^2}\bar z, \qquad \frac{d\bar z}{dt} = \frac{\bar p_z}{m_0}, \qquad (4)$$

and pendulum equation:

$$\ddot{\bar z} + \Omega^2\bar z = 0, \qquad \Omega = \frac{2eE_{z0}}{\pi m_0 c}. \qquad (5)$$

In (5) we used following linear approximation for $z$-component of electrical amplitude near field node in accelerating structure:

$$E_z = 4\sqrt{2}\frac{z}{\lambda}E_{z0}. \qquad (6)$$

For $E_{z0} = 10^8$ V/m oscillation period is $2\pi/\Omega = 1.7\cdot10^{-10}$ s. The time of probing electron movement through the structure that has width $2\lambda$ is $\tau = 1.13\cdot10^{-12}s << 2\pi/\Omega$. The structure focal distance in this case is

$$F_{xz} = \frac{\pi^2 m_0 c^2}{2e}\frac{U_0}{d_x E_{z0}^2} \qquad (7)$$

For electron beam potential $U_0 = 1000$ V, laser wave length $\lambda$=10.6 μm, structure width along $x$ axis $d_x=2\lambda$ we obtain $F_{xz}$=1.2 cm.

The estimation of the exit electron velocity shows that maximal transverse velocity at output of the structure having width $2\lambda$ is $5\cdot10^{-5}$ eV. The electrons thermal energy spread for thermocathode with $T$=1000°K is ~0.13 eV. Thus to produce flat probing electron beam special cold field-emission cathode must be used.

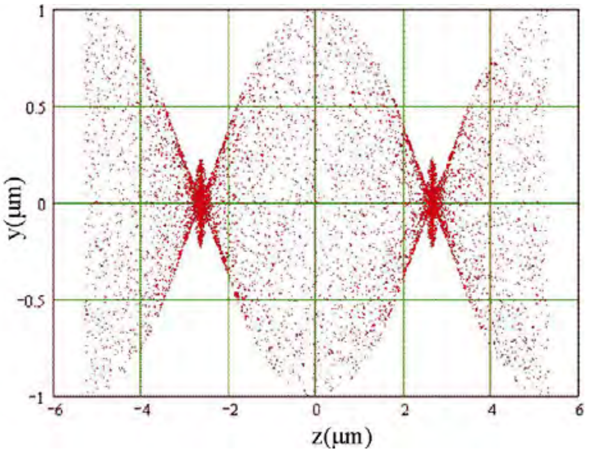

Figure 4: Electron density distribution at plane of maximal bunching.

We made computer simulation of diagnostic electrons movement in the next approximation: (1) field amplitude along the $x$ axis is constant in region with length $d_x = 2\lambda$ and is adiabatically decreasing to zero in edge regions at distance equal to one wavelength; (2) electrons energy is 1 keV; (3) electrons are homogeneously distributed in the spatial region $-10.6\mu m \le x \le 0$, $-1\mu m \le y \le 1\mu m$, $-5.3\mu m \le z \le 5.3\mu m$; (4) electric field amplitude is $E_{z0}$=100 MV/m. In Fig.4 we show the electron distribution in the plane of maximum transverse bunching. As can be seen the field in the beam channel possesses also focusing property in *(x,y)* plane.

In Fig.5 we compare focal power $D_{xz} = 1/F_{xz}$ dependence on the field amplitude in grating estimated with (7) and obtained in numerical simulation, which are in good agreement. Some difference between two curves can be explained by an additional electron beam focusing at edge adiabatic regions which is not taken into account in (7) and by insufficient accuracy of focal distance determination in numerical simulation. From Fig.5 it also follows that using probing electrons and making calculations with formulae (7) we can experimentally determine the electric field amplitude $E_{z0}$ by measuring focal distance $F_{xz}$ for known beam potential $U_0$ and laser beam width $d_x$.

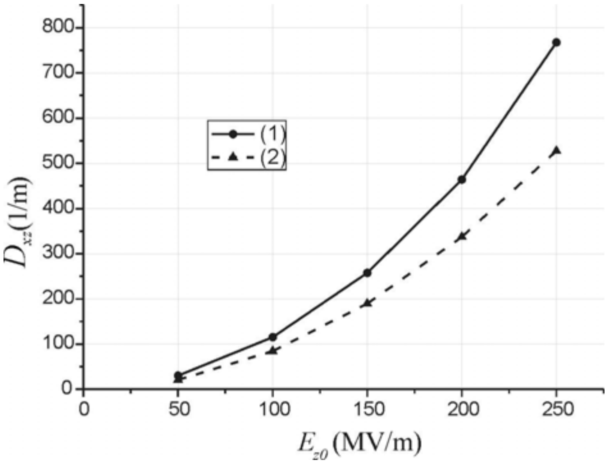

Fig.5. Focal power $D_{xz}$ dependence on field amplitude: (1) – results of numerical simulation, (2) – according (7)

## CONCLUSION

Presented in this paper the double diffraction grating deposited at dielectric slab with period equal to irradiating laser wavelength gives an opportunity to accelerate flat charged particles beam in nearby diffraction zone with energy gradient determined by the radiation strength of grating components and approximately equal to several GeV/m. The analytical approximation for accelerating field was obtained that meet the Maxwell equations. The comparison with results of field numerical simulation showed satisfactorily accordance of field distribution in accelerating channel. The field optimization process was considered and field structure stability analysis with respect to grating geometrical parameters changes was conducted. It was shown that in non-relativistic case the grating has weak focusing property disappearing in ultra-relativistic case.

The flat non-relativistic electron beam moving transversally to accelerating channel can be used as for $\pi$-mode field excitation control with luminescent screen at which the periodic pattern arises with period $\lambda/2$ at distance depending on accelerating structure field amplitude. The important condition for this method realization is producing flat electron beam with very low transverse velocities. The comparison of analytical and numerical results of probing beam dynamics demonstrated acceptable accuracy of analytical approximation.

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