Channeling, Dechanneling and Focusing of Charged Particle beams in Hollow Laser Beams

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Abstract

Developing the considerations of [*] the trajectories of high energy electrons channeled or dechanneled in co-propagating and counter-propagating hollow laser beams with radial and azimuthal polarization and Gaussian intensity distribution are calculated. The equations of motion are solved numerically using the expressions for the electric and magnetic fields corresponding to really existing beams. The obtained results can find some applications for handling of moderate energy and high energy electron beams.

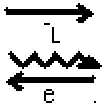
[*]. X. Artru, K.A. Ispirian, M.K. Ispiryan,Particle Refraction, Reflection and Channeling by Laser Beams, Arxive.0707.0148, 2007.

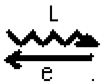
1. Introduction

a) The interaction of strong laser (LB) and electron beams (eB) are used mainly for

i. Particle acceleration (tightly focused & co-propagating, ) [1]

ii. Short *fs* X-pulses (tightly focused & co-propagating, ) [2]

iii. X-, gamma-beam production (counter-propagating,  by ICS) [3]

iiii) Short *as* X=pulses(~plane wave & counter-propagating,  NTS) [4,5]

b) Weak and moderate LBs are used mainly for

i. Microparticle or “atom” trapping and handling (Optical twitters) [6]

And it has been shown experimentally that they can be used for

ii. Trapping low energy electrons (E<1 MeV)[7]

iii. Deflection of low energy electrons [8]

iiii. There are a few proposed applications of such LB which are not ofinterest here

c) After a brief reviews on eB+LB interaction physics, especially in hollow beams (HB) [9], E-M fields of various types and published theor. works on e-channeling, some new results will be discussed.

1. Y.I. Salamin, S.X. Hu, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Rep. 427, 41-155, 2006.
2. S.Y. Chung et al, Phys. Rev STAB 2011.
3. ICS There are many reviews.
4. Y.Y. Lau, F.He, D.P. Umstadter, R. Kowalczyk, Physics of Plasmas, 10, 2155, 2003.
5. K. Lee, S.Y. Chung, D.E. Kim, In Advances in Solid State Lasers, Development and Appl, Ed. M. Grishin, 2010, Croatia, Ch. 22, p. 509.
6. Q. Zhan, Advances in Optics and Photonics, 1, 1-57, 2009.
7. J.L. Chaloupka and D.D. Meyerhofer, Phys. Rev. Lett. 83, 4538, 1999.
8. S. Banerjee et al, Phys, Rev. Lett. 95, 035004, 2004.
9. X. Artru, K.A. Ispirian, M.K. Ispiryan,Particle Refraction, Reflection and Channeling by Laser Beams, Arxive.0707.0148, 2007.

2. Review on eB+LB interaction and e-channeling in LBs and in particular in HBs [9]

One can begin from [10] on diffraction of e on standing waves. After [11] important results have been obtained in [12,13]:Let us note that depending on the value of the normalized LB intensity parameter, $a = eE_0 / m\omega c = eE_0 \lambda / 2\pi mc^2$ **, one can separate three regions in the motion of electrons in a laser beam (see, for instance, [14]): 1) Non-relativistic or ponderomotive, when** $a << 1$ **, 2) relativistic, when** $a \sim 1$ **and 3) ultra-relativistic when** $a >> 1$ **. In the case 1) the electrons make quivering motion associated with the rapid field oscillations. Besides, independent of the polarization they undergo a weak transversal drift motion pushed by the ponderomotive force due to the gradient of the field of the LB. It is often carried out calculations assuming that the longitudinal electric field effects are negligible after averaging over the laser photon wavelength and there is no acceleration of electrons. In the cases 2) and 3) it is always necessary to take into account all the components and oscillations of the field.**

10. P.L. Kapitza and P.A.M. Dirac, Proc. Cambridge Philos. Soc.. 29, 297, 1933.
11. G.A. Askarian, Zh. Eksper. Teor. Fiz , 42, 1567, 1962.
12. T.W.B. Kibble, Phys. Rev. 138, B740, 1965; Phys.Rev. Lett. 16, 1054, 1966; Phys. Rev. 150, 1060, 1966.

13. V.I. Balykin, M.V. Subbotin, V.S. Lethokhov, Opt. Commun. 129, 177, 1996.
14. C. Varin et al, Appl. Sci. 3, 70-93, 2013.

A few words about the physics which takes place in HBs [9]. The following simple formula has been obtained in [12,13] for the effective refractive index $n_e(\omega)$ of electrons passing the interface between laser field and free region

$$n_e(\omega) = (1-\Delta)^{1/2} = (1 - a^2/\gamma\beta^2)^{1/2},$$

where $\gamma = \varepsilon / mc^2 = 1/\sqrt{1-\beta^2}$ is the relativistic factor of the electron. Since $n_e(\omega)$ is less than 1 , as for X-rays, the electron beams can undergo not only refraction and reflection, but also total external reflection and, therefore, channeling on the boundary between vacuum and laser beam with effective critical angle [9]

$$\varphi_{crit} = \arccos(1 - a^2/\gamma\beta^2)^{1/2},$$

or for $\gamma >> 1$ and $a^2/\gamma << 1$,

$$\varphi_{crit} = a/\beta\sqrt{\gamma}.$$

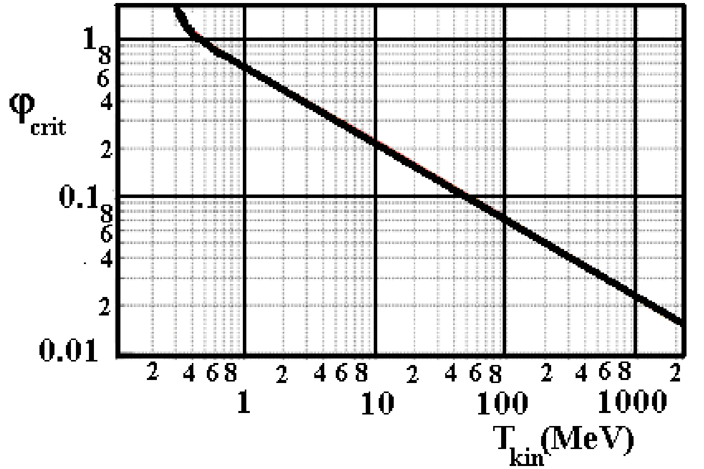


Fig. 1 The dependence of φ_{crit} upon electron kinetic energy Tkin

Therefore, as it is shown in [9] in axially symmetric HB with radially increasing photon density of the types of Fig. 3 of [3] the electrons will be channeled, dechanneled and focused as the photons in optical fibers [15] or as charged particles in carbon nanotubes [16,17]. If these predictions of [9] will be confirmed by numerical calculations in this work one can begin the experimental study of high energy electrons in HB.

15. V.B. Veinberg, D.K. Satarov, Optika Svetovodov, 2-nd Ed. Moscow, Mashinostroenie, 1977 (In Russian).
16. L.A. Gevorgian, K,A, Ispirian, R.K. Ispirian, Nucl. Instr. and Meth. B145, 155, 1998.
17. X. Artru, S.P.Fomin, K.A. Ispirian et al, Phys. Rep. 412, N2-3, 89-189,2005.

3. Correct and Convenient Approximate Expressions for the Electric Field of various types LB and HB and ElectronTrajectory Calculations

a) **Plane wave approximation.** If LB is propagating along axis OZ

$$\vec{E}(r,t) = E_0 \exp(i\eta)\hat{e}, \qquad \textbf{(PW)}$$

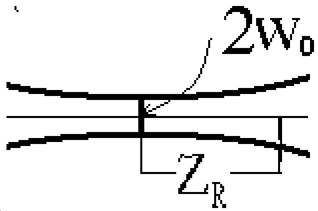
where E_0 is the amplitude, $\eta = \omega t - kz$, $k = \omega / c$ and $\hat{e}$ is a unit vector in the direction of polarization, perpendicular to OZ. There are many publications, [17]-[18], devoted to the calculation of the trajectories with the help of (PW). The magnetic field, $\vec{B}(r,t)$ is perpendicular to $\vec{E}(r,t)$ and $B_0 = E_0 / c$ making a right system with $\vec{E}(r,t)$ and axis OZ. No channeling, i.e. no force directed to the axis of the LB is expected.

There are a few publications [19,20] considering the possibility of channeling in 2 plane waves. In these works it has been shown that the following processes can take place a) channeling of electrons after developing the concepts of potential well and of critical channeling angle, b) collimation (focusing), c) bunching (modulation) and d) radiation of the channeled electron beams.

17. E.S. Saranchik and G.T. Schappert, Phys. Rev. D1, 2738 (1970).
18. E.D. Gazazian et al, Proc. of Intern. Symp. QEDSP, Kharkov, Ukraine. 2006, Problems of Atomic Science and Tchnology, N3(1), 184, 2007.
19. A.V. Andreev and S.A. Akhmanov, Zh. Eksp. Teor. Fiz. 99, 1668, 1991.
20. Dabagov…

b) Gaussian Beams (GB) [21]

For our problems it is of interest only the beams which have axial symmetry, (therefore, the fields do not depend on ϕ of the cylindrical coordinates, (ρ,φ,z),). For zero order GB [21]



$$E^{GB}(\rho,z,t)=E_0\frac{w_0}{w(z)}\exp[-\rho^2/w(z)^2]\exp[i\arctan(z/z_R)]\exp(i\eta), \quad \textbf{(GB)}$$

where w_0 **is the beam waist or the beam radius at the focus,** $w(z)=w_0\sqrt{1+z^2/z_R^2}$ **is the beam spot at z,** $z_R=\pi w_0/\lambda$ **is the Rayleigh range,** $\arctan(z/z_R)$ **is the Gouy phase. GB is focused weakly and tightly for** $w_0>>\lambda$ *and* $w_0\approx\lambda$ **, respectively.**

There are many calulations (see[1]) of the electron trajectories carried out with the help of (GB) which is not hollow. Since we need LB of donut form (dark or hollow inner part) intensity profile, further we consider only higher order axially symmetric GB, namely Lagguere-Gaussian beams (LG), higher order Bessel beams (BB), Airy beams, and cylindrical vector (CV) beams and some other types hollow beams (HG beams are not axially symmetric).

21. E.J. Galves, Gaussian Beams, Department of Physics and Astronomy Colgate University, 2009.

c) Lagguere-Gaussian beams (LG) [6,21]

$$E_{p,l}^{LG}(\rho,\phi,z,t)=E_0\left(\frac{\sqrt{2}\rho}{w(z)}\right)L_p^l\left(\frac{2\rho^2}{w(z)^2}\right)\exp[-\rho^2/w(z)^2]\exp\{ik\rho^2/[2R(z)]\}\exp(il\phi)x\exp[-i\varphi(z)]\exp(i\eta). \quad (LG$$

Here L_p^l(x) is a LG polynom. $R(z)=z+z_R^2/z$ is the radius of the curvature of the wave front at z, and $\varphi(z)=(2p+|l|+1)\arctan(z/z_R)$.For the indices l =0 and p =0 LG becomes GB. There are many calulations (see[??]) of the electron trajectories carried out with the help of (LG) concerning only microparticles and no for electrons.

d) Bessel Beams (BB) [22]

Have the electric field

$$E_l^{BB}(\rho,\phi,z)=A\exp(ik_z z)J_l(k_\rho\rho)\exp(il\phi) \quad \textbf{(BB)}$$

where J_l is a Bessel function of the order l, and k_z , k_ρ are the longitudinal and radial components of the wavevector $k=\sqrt{k_z^2+k_\rho^2}$ .There are many works on microparticles, but only in [23,24] low energy electron trajectories are calculated numerically for l>1, but no word of channeling. The none diffractive theoretical BBs [23,24], which in contrast to the existing GB, and LG beams, have constant intensity profile along OZ cannot be realized in practice, because it is required, for instance, an infinite energy. Approximate BB obtained with conical prisms and axicons [25] still less diffract. Therefore it is necessary to consider other HBs .

22. BB?????
23. I.Bialynicki-Birula, Z. Bialynicki-Birula and B. Chmura, Laser Phys. 15, 1371-1380, 2005.
24. V.H. Mellado, S. Hacyan and R. Jauregui, Laser and Particle Beams, 24, 1-8, 2006.
25. D. Mc-Gloin and K. Dholakia, Contemp. Phys. 46, 15, 2005.

e) Airy Beams (AB) [26]

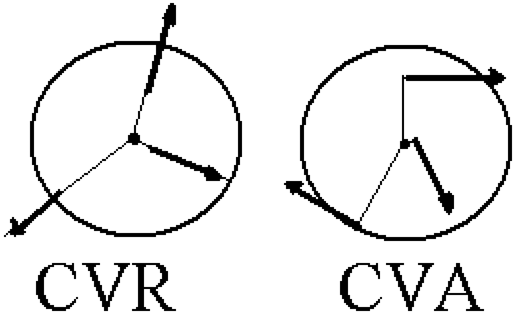
have the following electric field envelope

$$\varphi^{AB}(s,\xi) = Ai\left(s-(\xi/2)^2\right)\exp\left[is\xi/2 - i\xi^3/12\right], \qquad \textbf{(AB)}$$

Where $s = x/x_0$ **and** $\xi = z/kx_0$ **are dimensionless transversal, x, and longitudinal, Z,coordinates,** x_0 **is an arbitrary transverse scale, and Ai(x) is the Airy function. One determines the fields with the help of (AB) and can calculate the trajectories. There are not publication for electrons with ABs. Some hollow ABs experience transversal bending and found wide applications as optical tweezers [26].**

f) Cylindrical Vector Beams (CVB) [6,27]

PW, GB, LG, BB and AB are scalar beams (Sol of scalar Helmholtz eqs). Their polarization does not depend on the point within the beam spot. The CVBs [6,27] (vector Helmholtz eqs) have polarization directed along the radius (radially polarized CVBs, CVR) or along the azimuth (azimuthally polarized CVBs, CVA).



CVA have the following Bessel-Gauss form

$$\vec{E}^{CVA}(r,z,t) = E_0\frac{w_0}{w(z)}J_1\left(\frac{\beta\rho}{1+iz/z_R}\right)\exp\left(\frac{i\beta z/z_R}{1+iz/z_R}\right)\exp[-\rho^2/w(z)^2]\exp[i\arctan(z/z_R)]\exp(i\eta)\hat{e}_i \qquad \textbf{(CVA)}$$

Here $\beta = const$, $\hat{e}_i$ **is a unit vector in azimuthal direction**

26. Y. Hu et al, Self-Accelerating Airy Beams: Generation, Control and Applications, Chapter 1 in Nonlinear…Springer 2012, p.p. 1-46.
27. S.E. Skeleton, Dissertation, Department of Physics and Astronomy, University College, London 2013.

There is a similar expression for CVR. CVBs found wide application in microscopy and vacuum particle acceleration because they provide smaller waist, d $w_0 \le \lambda$ (as left handed materials) and greater E_z . Since the expressions for CV beams have complicated form frequently the following simplified expression is in use

$$\vec{E}(r,z) \approx A\rho \exp(-\rho^2 / w^2)\hat{e}_i . \qquad \textbf{(CVA')}$$

There are many calculation using (CVA') on micromanipulation of microparticles, but no on electron trajectories.

g) Approximate practical expression for HBs

Taking into account that the expressions (LG), (BB), (AB), (CVA) and even (CVA') are complicated in order to write approximate practical expression for HBs in many works it is used the measured profile of the intensity of the HB which usually has the following Gaussian form (see Fig. 5.4 and formula (5,4) of [29])

$$I(\rho) = I_{\max} \exp\left[-\frac{(\rho-\rho_1)^2}{\sigma^2} \right] , \qquad \textbf{(AP)}$$

where $I_{\max}, \rho_1 \, and \, \sigma$ **are respectively the maximum, the distance of the maximal intensity from the center, and the 1/e width of the Gaussian distribution. The field components corresponding to (AP) has the form**

$$E_r(\rho,\varphi,z,t) = E_0 \exp\left[-\frac{(\rho-\rho_1)^2}{2\sigma^2} \right] Cos(\omega t - kz + \psi_0), \quad E_\varphi = 0, \quad E_z = 0 \qquad \textbf{(HB)}$$

$$B_r = 0, \quad B_\varphi = E_0 \exp\left[-\frac{(\rho-\rho_1)^2}{2\sigma^2} \right] Cos(\omega t - kz + \psi_0), \quad B_z = 0$$

29. Y. Song, Dissertation, University of Maryland, College Park, USA, 1999.

where E_0 is the field amplitude, which in Gaussian unit system is connected with the measurable intensity by the relation: $E_0(V/cm) = 19.4\sqrt{I_{max}(W/cm^2)}$, ψ_0 is an arbitrary phase. In the below numerical calculations for motion of electrons in HB it will be used the simplest expression (HB) for CVR, in cylindrical coordinates an. It will be followed the electrons "1" and "2". According to the above discussionone expects that "1" will be channeled, while "2" will be dechanneled (pushed out).

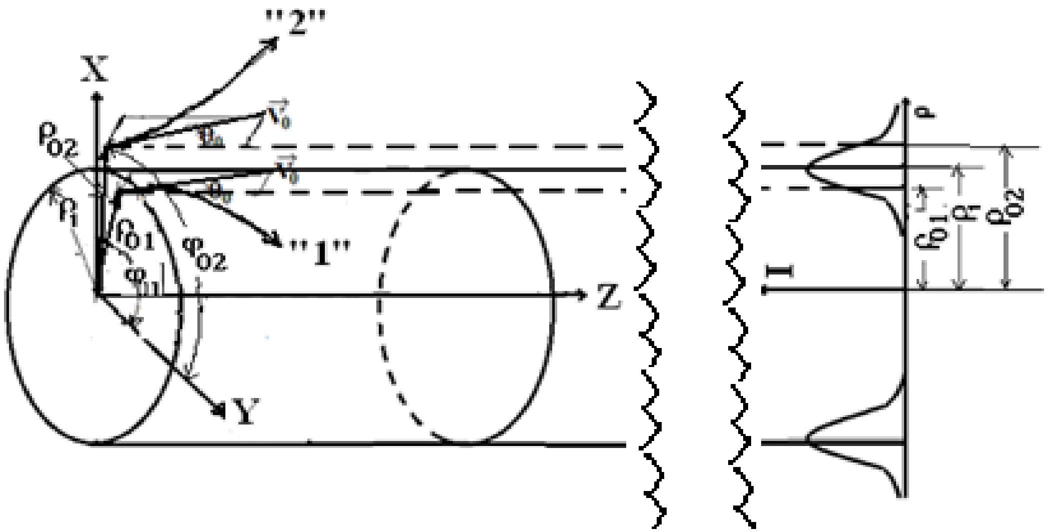


Fig.2 Geometry, EB And HB parameters And intensity profile.

4. Calculation of the Electron Trajectories in HB

To calculate the trajectories one has to solve the following equations of motion [18]

$$\frac{d\vec{r}}{dt} = c^2 \frac{\vec{p}}{\varepsilon}, \quad (1)$$

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + c\frac{\vec{p}\times\vec{H}}{\varepsilon}\right], \quad (2)$$

1) Introducing the dimensionless magnitudes $\tilde{\rho} = \rho/\sigma \quad \tilde{\rho}_1 = \rho_1/\sigma \quad \tilde{z} = z/\sigma \quad \tilde{t} = \omega t$

$$a = \frac{eE_0}{m_0 c\omega} \quad \vec{\tilde{p}} = \frac{\vec{p}}{mc} = \{\tilde{p}_r, \tilde{p}_\varphi, \tilde{p}_z\} \quad \vec{E}' = \{1, \quad 0, \quad 0\} \quad \vec{B}' = \{0, \quad 1, \quad 0\}$$

2)

(1) and (2) take the form in cylindrical coordinate frame

$$\frac{\partial\vec{\tilde{p}}}{\partial\tilde{t}} = -aCos(\tilde{t} - k\sigma\tilde{z} + \psi_0)\exp\left[-\frac{(\tilde{\rho}-\tilde{\rho}_1)^2}{2}\right]\left(\vec{E}' + \frac{\vec{\tilde{p}}}{\sqrt{1+\vec{\tilde{p}}^2}} \times \vec{B}'\right) \qquad \textbf{(1')}$$

$$\frac{\partial\vec{\tilde{r}}}{\partial\tilde{t}} = \frac{\vec{\tilde{p}}}{k\sigma\sqrt{1+\vec{\tilde{p}}^2}} \qquad \textbf{(2')}$$

Going to Cartesian coordinate system in order to avoid confuses at $r = 0$ **using**

$$\tilde{\rho} = \sqrt{\tilde{x}^2 + \tilde{y}^2} \quad \vec{\tilde{p}} = \{\vec{\tilde{p}}_x, \vec{\tilde{p}}_y, \vec{\tilde{p}}_z\} \quad \vec{\tilde{r}} = \{\tilde{x}, \tilde{y}, \tilde{z}\}$$

$$\vec{E}' = \left\{\frac{\tilde{x}}{\tilde{\rho}}, \quad \frac{\tilde{y}}{\tilde{\rho}},, \quad 0\right\} \qquad \vec{B}' = \left\{\frac{\tilde{y}}{\tilde{\rho}}, \quad -\frac{\tilde{x}}{\tilde{\rho}} \quad 0\right\}$$

it will be solved (1') and (2')with the help of MATHEMATICA for 2 initial conditions (IC)

$$\vec{\tilde{r}}_0 = \{\rho_0 - \sigma, \quad 0, \quad 0\} \quad \vec{\tilde{p}} = \{pCos\xi_0, \quad pSin\xi_0, \quad 0\}$$ **(See Fig.2, electrons '1','2')**

$$\vec{\tilde{r}}_0 = \{\rho_0 + n\sigma, \quad 0, \quad 0\} \quad \vec{\tilde{p}} = \{pCos\xi_0, \quad pSin\xi_0, \quad 0\} \qquad n = 1,2,3,\ldots$$

5. Numerical Results

Without discussing the method of HB production [4] it is taken the following
<u>HB parameters:</u> $\lambda = 1.062\ \mu m$ **(Nd-YAG,** $\hbar\omega = 1.183 eV$ **); and various values of *a*.**
<u>EB parameters</u>: Ee=5, 20, 1000 MeV.

Channeled particle trajectory: $\rho_{02} = \rho_0 - \sigma$

Dechanneled particle trajectory: $\rho_{01} = \rho_0 + n\sigma$

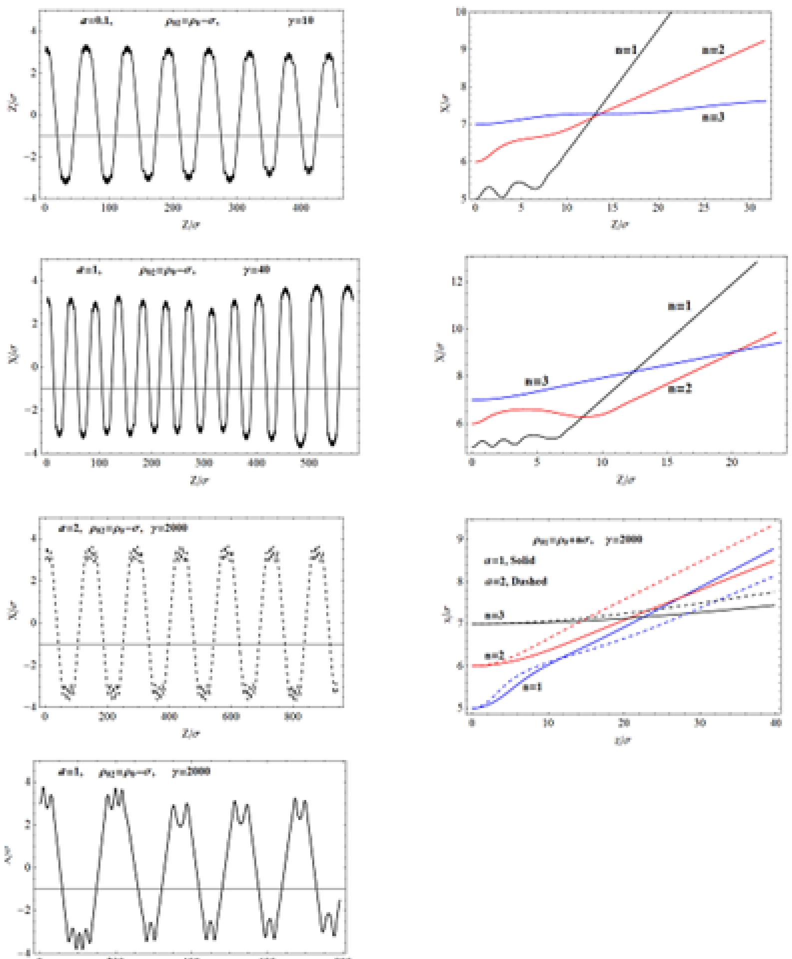


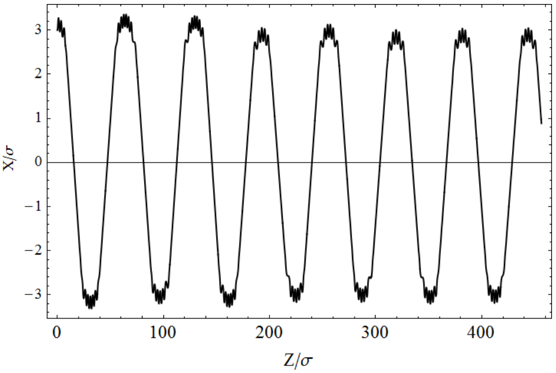
Fig. 4 2D presentation

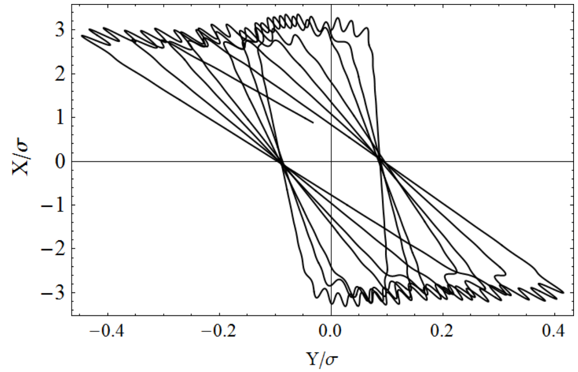
$\xi_0 = 0$

As it is seen……

Channeled particle trajectories

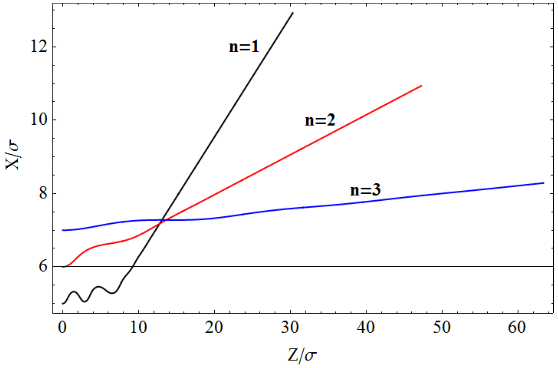
$$\rho_{02} = \rho_0 - \sigma$$





Dechanneled particle trajectories

$$\rho_{01} = \rho_0 + n\sigma$$



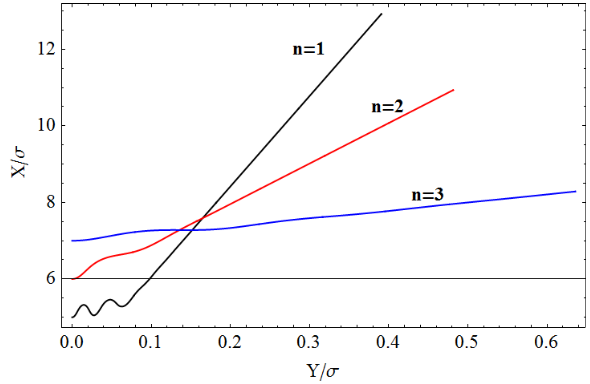
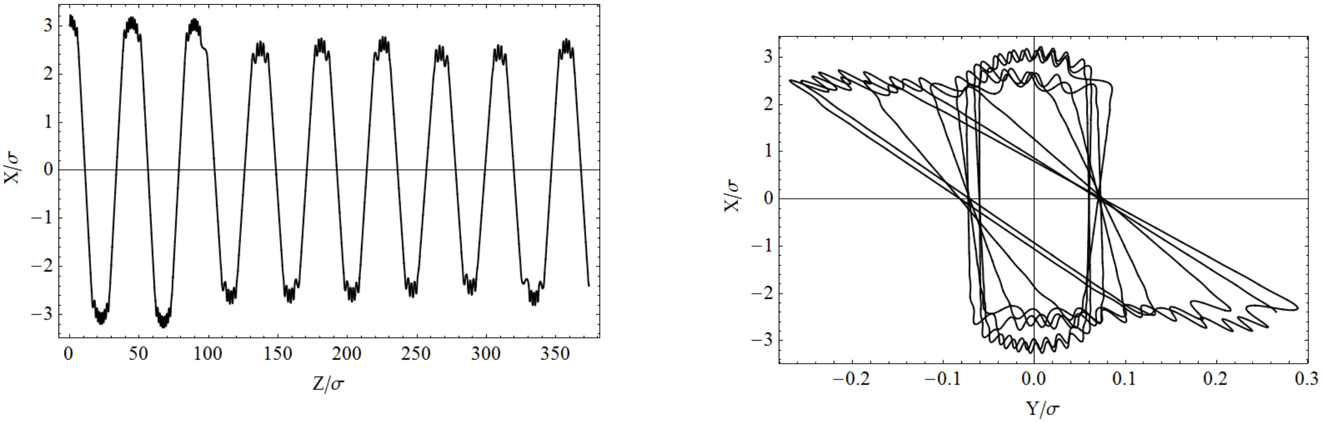


Fig.5 3D presentation $5\ \ MeV,\quad a = 0.1,\quad \xi_0 = 0.01 rad$

As it is seen……

Channeled particle trajectory: $\rho_{02} = \rho_0 - \sigma$



Dechanneled particle trajectory: $\rho_{01} = \rho_0 + n\sigma$

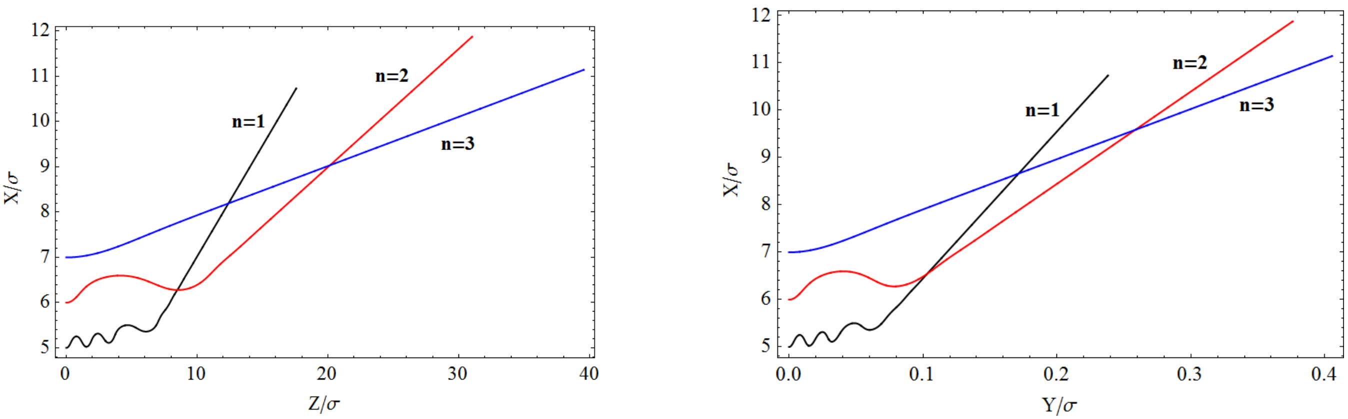
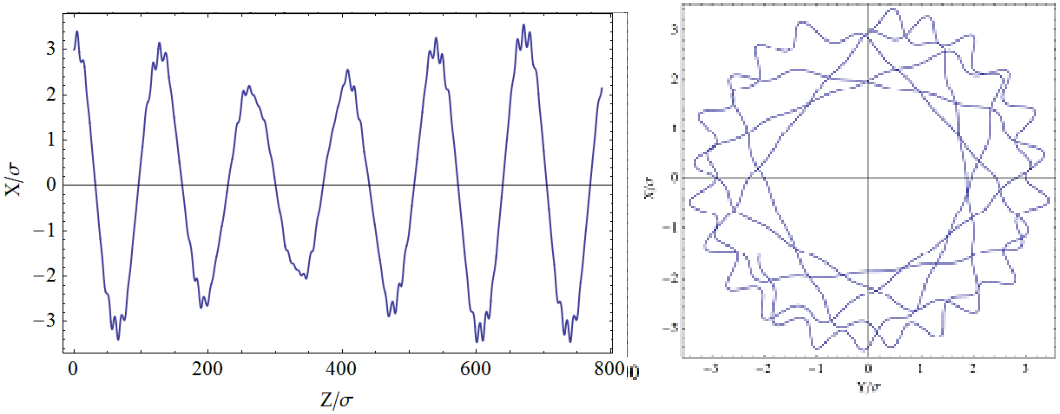


Fig.6 3D presentation $40\ MeV, \quad a = 1, \quad \xi_0 = 0.01 rad$

As it is seen……

Channeled particle trajectory: $\rho_{02} = \rho_0 - \sigma$



Dehanneled particle trajectory: $\rho_{02} = \rho_0 + n\sigma$

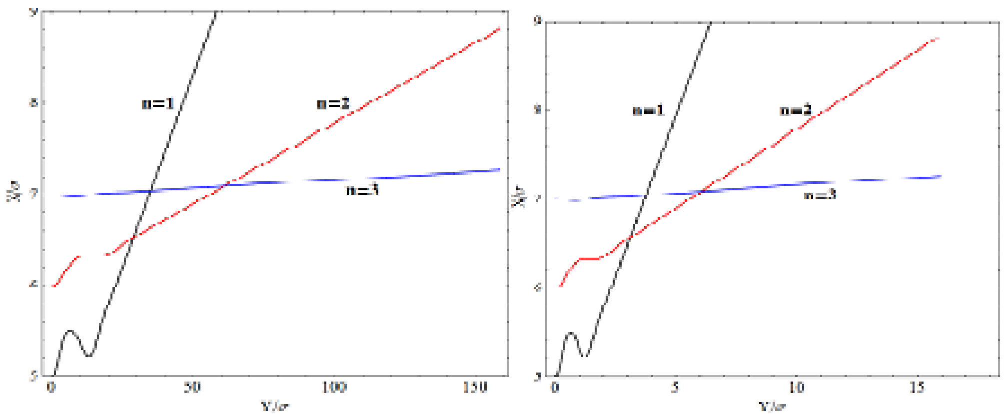


Fig.6 3D presentation $1000 \ \ MeV, \quad a = 2, \quad \xi_0 = 0.1 rad$

As it is seen……

5. Applications and Conclusions

We have not discussed the methods of injection and ejection of particles into channels, of synchronization of e- and L-beams, which must be similar to the same methods applied for the particle acceleration [1,2]. These problems, the calculations with the above discussed other fields (LG)…(CV), as well as applications such as focusing of particle beams (just as focusing of photon beam by graded index optical fibers), joint propagation of eBs- and LBs in cosmos, joint laser and ion nuclear fusion, etc, will be considered in our further publications.

Let us only note that focusing of electron beams can be obtained if the HB radius, will be decreased with the increase of as in conical axially symmetric HBs used in [30] for confinement of atoms and optical twitters or as in the case of optical fibers HB is short .

Nevertheless, it is worthy to discuss a little a possible application of laser dechanneling. The cleaning of beam halo particles in colliders is mandatory because (see […]) these particle can damage, say, the very expensive superconducting magnets. After many methods the extraction of these particles by their channeling in bent crystals seemed the best. However, recently tens of theoretical and experimental works show that a small transversal deflection of these halo particles by volume reflection is more advantageous, but again difficult, since it requires the use of crystals and goniometers. The above considered particle dechanneling after improvement seems can be a concurrent to volume channeling.

30. M. DeAngelis et al, Optics and Lasers in Engineering, 39, 283, 2003.

Thank you in advance for questions and discussion