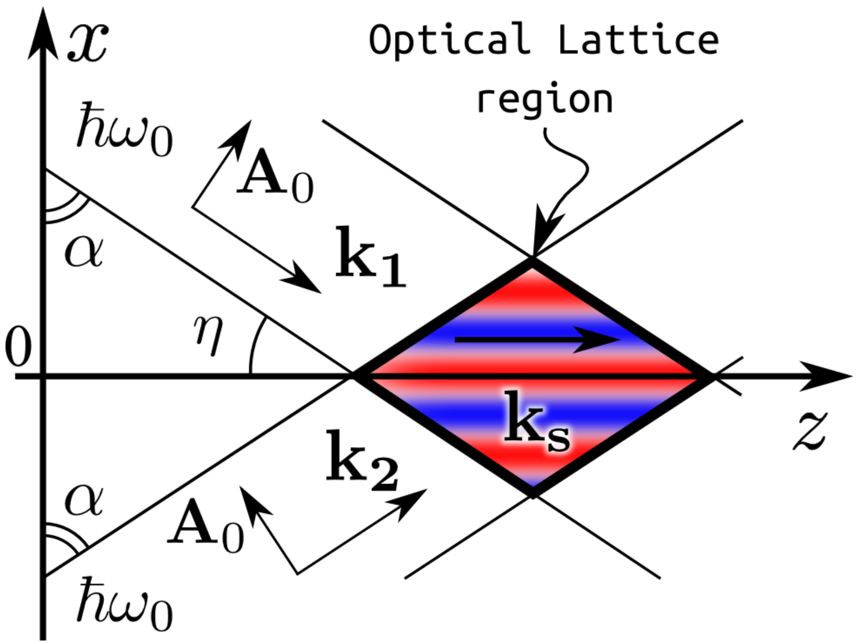
Muon Beam Channeling in Laser Standing Wave

A.A. Babaev[1], S.B. Dabagov[2]

1) Tomsk Polytechnic University
2) INFN Laboratory Nazionali di Frascati
RAS P.N. Lebedev Physical Institute
NR Nuclear University MePhI

Presented at Channeling-2016, Sirmione-del-Garda, September 25-30, 2016

1. Channeling in a standing electromagnetic wave [1]



Main points:

- 2 crossing laser waves form the standing wave (optical lattice).
- Particle penetrates into the field at small angle to nodes (antinodes) planes (XY-planes).
- The ponderomotive potential could be applied to describe the motion.
- The ponderomotive potential forms channels along Z direction.
- In X-direction the cos-like periodic potential structure is formed.
- **The ponderomotive potential defines the smooth oscillationg trajectory similar to the particle trajectory at crystal channeling.**

[1] S.B. Dabagov et al, Phys. Rev. ST Accel Beams **18**, 064002 (2015).

2. Why the standing wave channeling of muons could be interesting?

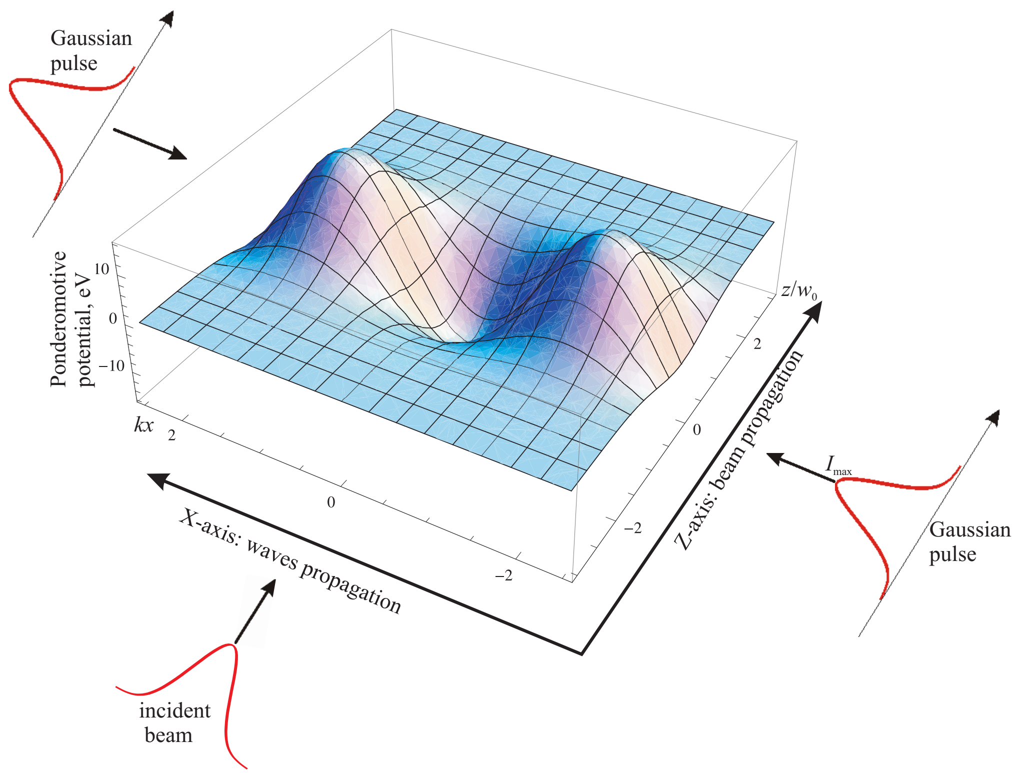
A) In principle, the system of standing wave channels could be used instead of crystal channeling in all possible applications.
Advantages:
- scattering of the beam by a crystal matter as well as the nuclear interactions between particles of the beam and crystal nuclei are absent.
- channel width is about half of laser wave length, hence, the beam management at the scale 100 nm – 1 um is possible

B) Especially, the use of the laser standing wave could be attractive for muon beams.
Advantages:
- The radiation of muons in the electromagnetic field is insignificant.

The aim of the work – is to simulate the channeling of muons in the standing wave formed by Gaussian laser pulses that are widespread. The channeling in plane wave was considered earlier [1,2].

[1] S.B. Dabagov et al, Phys. Rev. ST Accel Beams **18**, 064002 (2015).
[2] A.A. Babaev, S.B. Dabagov, , J. Phys.: Conf. Ser. **732** (2016) 012001.

3. Potential formed by Gaussian pulses



The aim of the work – to simulate the channeling in the standing wave formed by Gaussian laser pulses.

Intensity of initial Gaussian wave:

$$I = I_{\max} \exp\left(-\left(y^2 + z^2\right) / w_0^2\right)$$

w_0 - caustic

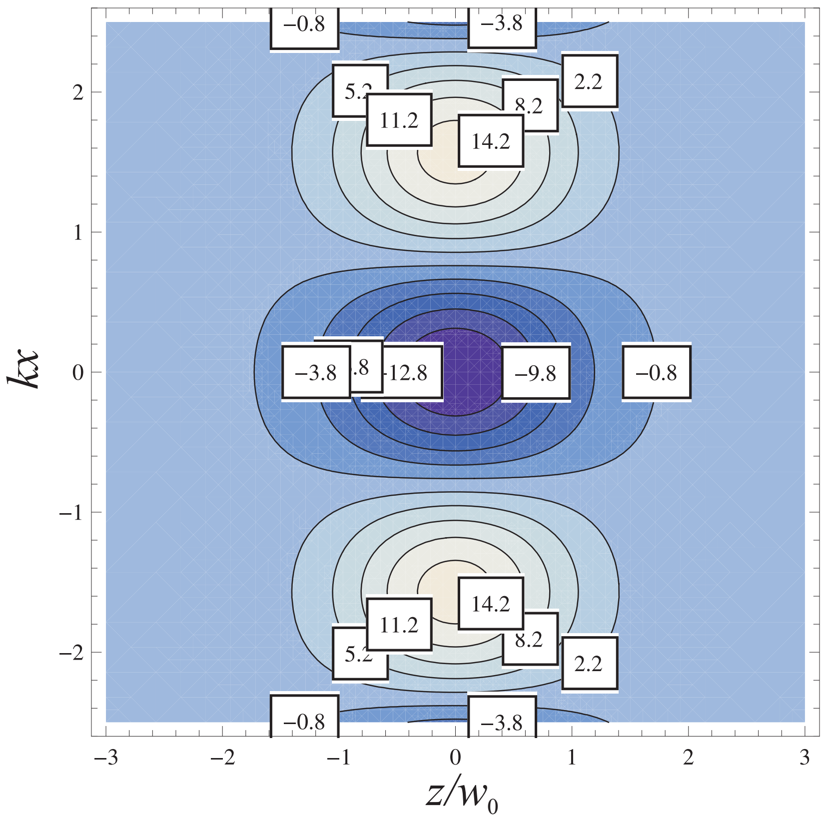
Ponderomotive potential if $w_0 \gg L_{osc}$ (*):

$$U(x, y, z) = -U_{am}(y, z)\cos\left(2kx\right)$$

(*) Characteristic parameter of channeling:
L_{osc} – the distance along the channel while a projectile make during one transverse oscillation.
L_{osc} is estimated near the channel center at y=z=0.

4. Parameters of channeling

Contour map of ponderomotive potential at y=0.
Numbers are $U(x,y,z)$ [eV].



[1] S.B. Dabagov et al, Phys. Rev. ST Accel Beams **18**, 064002 (2015).
[3] C. Choubey et al, *International Design Study for the Neutrino Factory*, Interim Design Report IDS-NF-020 (2011).

If w_0>>L_{osc} theory [1] can be applied:

$$U_{am}(y,z) = \frac{4\pi\alpha\hbar I_{max}}{\omega^2\gamma_z m}\left(2\beta_z^2 - 1\right)\exp\left(-\frac{y^2+z^2}{w_0^2}\right)$$

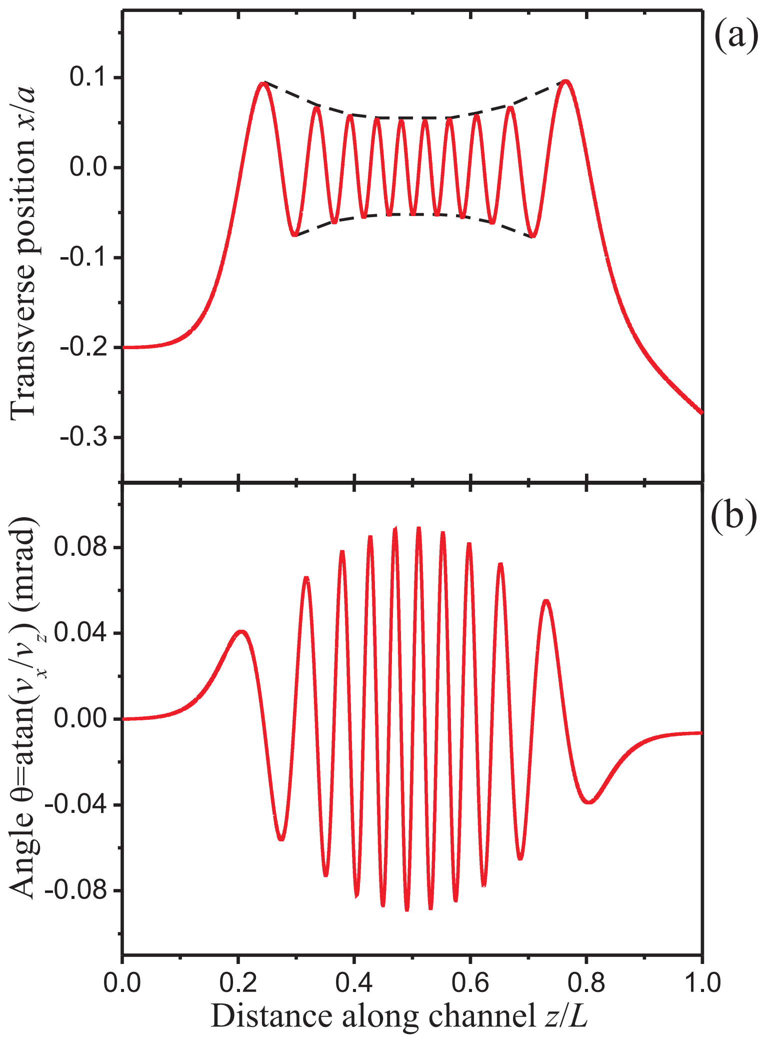
$\alpha\hbar$ – fine structure*Planck constant;
ω – laser angular frequency;
k=2π/λ; λ – laser wave length
γm – relativistic mass of the projectile;
$v_z=\beta_z c$=const – longitudinal velocity of projectile; c – speed of light

$$\gamma_z = \left(1-\beta_z^2\right)^{-1/2}$$

In simulations:

230 MeV/c muons (neutrino factory project [3])
$I_{max}=10^{17}$ W/cm^2 (to obtain potential as at the crystal channeling)
w_0=6 mm
$\omega=2\pi c/\lambda$; λ=800 nm
$a=\lambda/2$ – channel width
L_{osc}=1.46 mm; U_{am}=15.7 eV

5. Trajectories of channeled particles



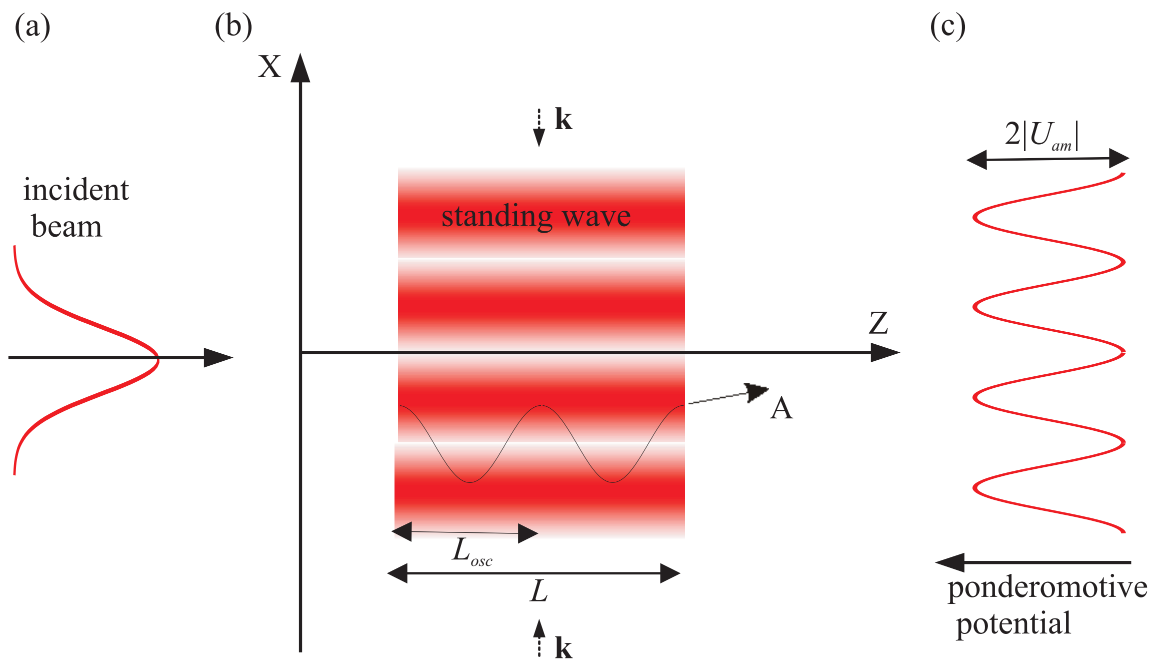
(a) The trajectory of channeled particle and

(b) the corresponding change of the angle $\theta = \mathrm{atan}(v_x/v_z)$ between Z axis and particle's velocity. The particle initially moves along Z axis, initial distance from the channel center is $-0.2a$. The trajectory is evaluated for y=0. The channel length $L=6w_0$.

The dash lines in the panel (a) connect turn points and represent unipotential surfaces, see in slide 3. **Projectile oscillates between curved unipotential surfaces.**

In comparison with crystal channeling and with the plane wave channeling:
The potential wall $2|U_{am}|\neq$const => **there are not definite crytical channeling angle, channeling and quasichanneling fractions.**

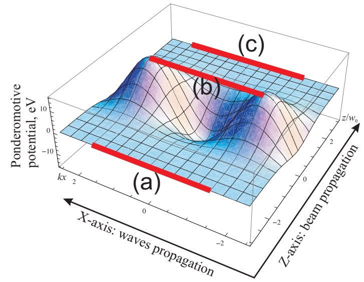
Remark 1: trajectories at plane wave channeling



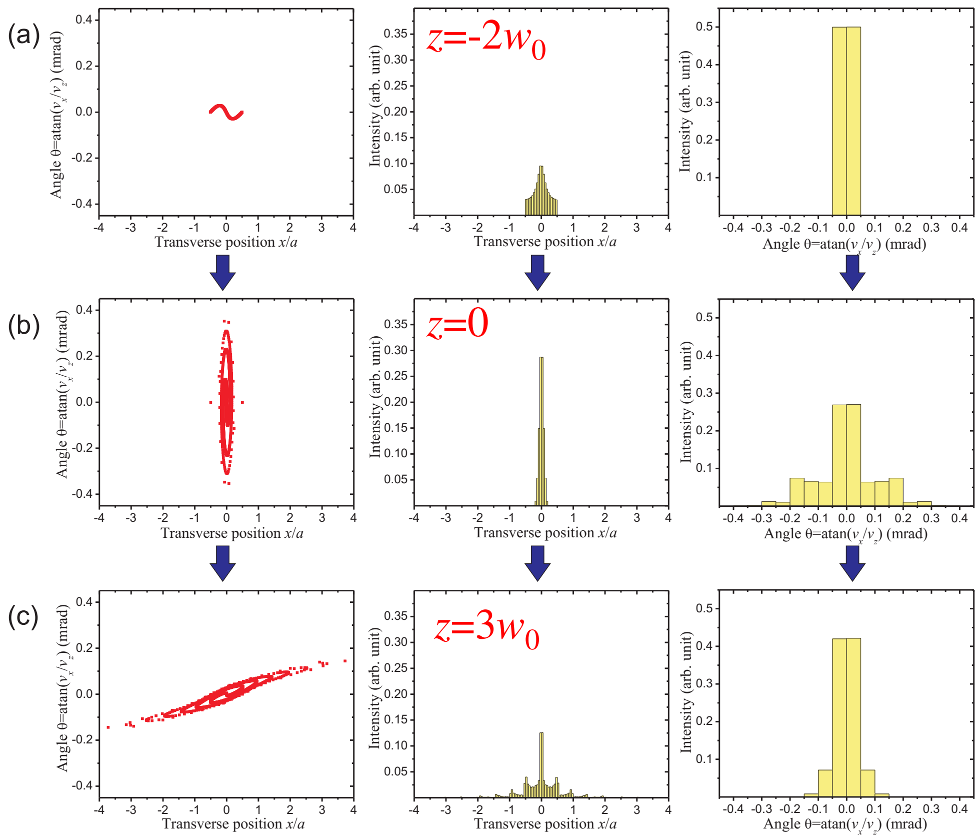
The potential wall $2|U_{am}|$=const => **the channeled projectile makes regular oscillations while it moves along the channel.**

The scheme of plane wave channeling. The standing wave (b) is formed by two counter-propagating plane waves. The propagation direction is shown by **k**. The bunch of particles (a) penetrates into the field along Z axis and particles enter the field at small glancing angle θ to node planes (that are along Z axis and orthogonal to the plane of figure). The ponderomotive potential (c) forms cos-like structure in transverse X direction with the wall $2|U_{am}|$. The trajectory of channeled particle is shown by A — oscillations within single channel between plane unipotential surfaces.

6. Phase space evolution



Initially non-divergent beam enters the channel along Z-axis. The transverse beam direction is the channel width *a*.



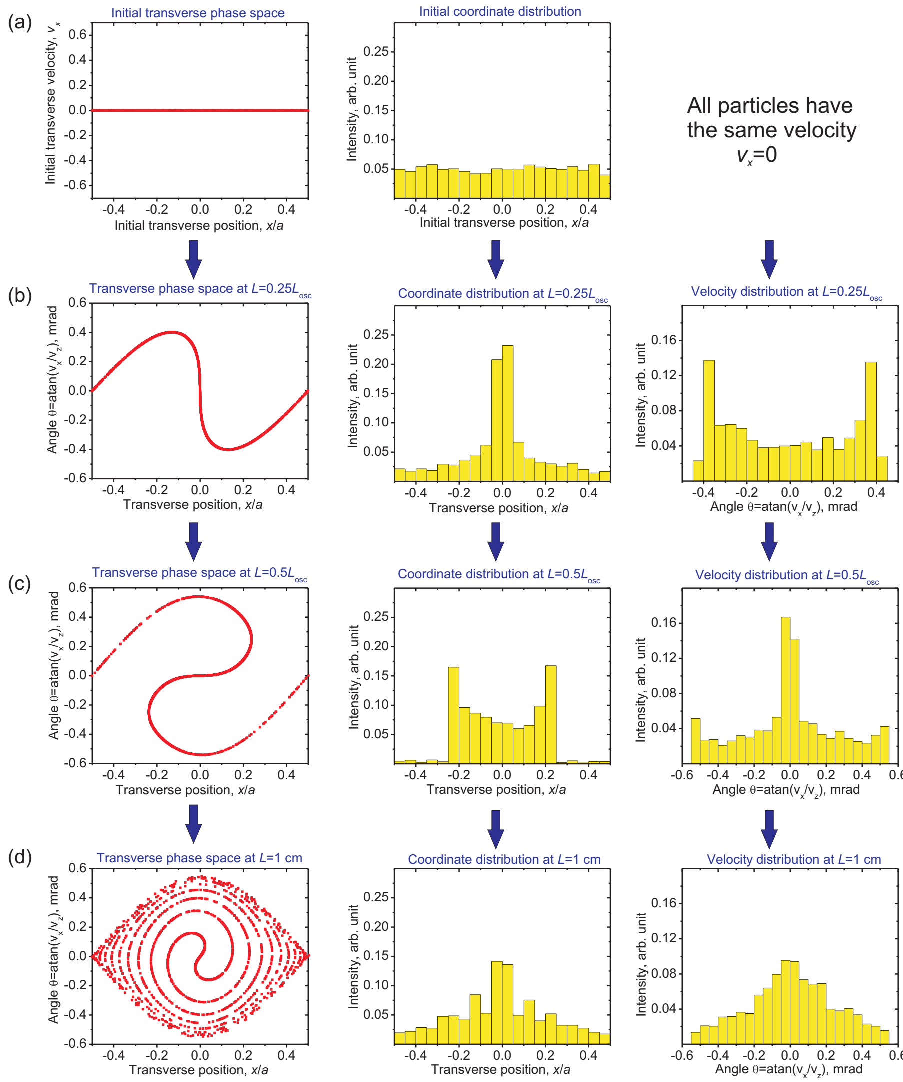
Left – transverse phase space, ***center*** – transverse coordinate distribution, ***right*** – transverse velocity distribution.

(a) At the channel beginning. The averaged potential is weak. The beam phase space changes insignificantly.

(b) At the central area of the field. The averaged field is maximal. The beam is focused, its transverse dimension is minimal. The focusing is due to curved unipotential surfaces.

(c) At the channel end. The beam transverse dimension is significantly bigger than the initial dimension *a*.

Remark 2: phase space evolution at plane wave channeling

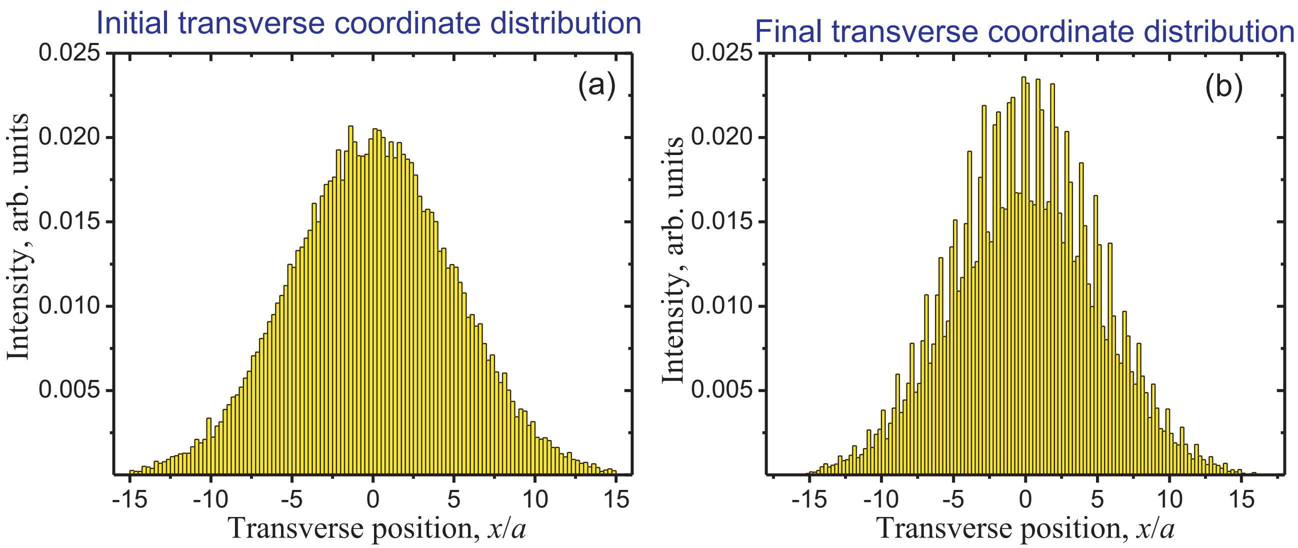


Simulations are based on [2] A.A. Babaev, S.B. Dabagov, , J. Phys.: Conf. Ser. **732** (2016) 012001.

- (a) The initial beam is space uniform and all particles have the same, zero, transverse velocity.
- During the beam motion the phase space line is whirling around the channel center, it forms two branch helix.
- For both the space and transverse velocity distributions this leads to the forming of peak in the center of distribution with the periodicity $L=0.5L_{\text{osc}}$.
- In general, when the beam is mostly focused (b), it demonstrates the maximal divergence, and vice versa, when the beam obtains the minimal divergence (c) its transverse space tends to become uniform.
- (d) The central peaks are smeared while the beam propagates. At $L \gg L_{\text{osc}}$ the beam shape does not depend on L.

7. Micro-structures in the beam cross-section

The sample on beam flux redistribution at 100-nm scale:



Beam in simulations:

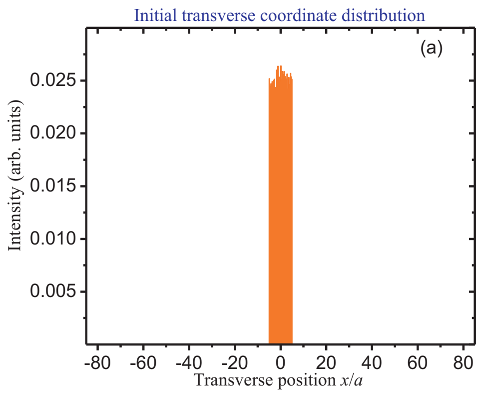
- 230 MeV/c muons
- Gaussian shaped beam in XZ-plane
- RMS width $\sigma_x=5a$
- y=0 for all particles
- non-divergent beam directed along Z

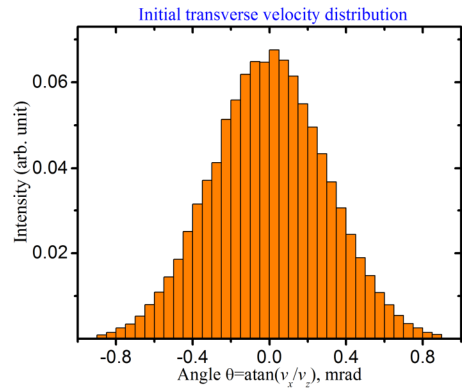
- The beam is compressed in the central part of the every channel. The compression is not disappear completely behind the field.
- (a) For wide beam (the beam transverse dimension >> channel width *a*) one can find (b) thin peaks in transverse distribution with the periodicity *a*. (*)

(*) The modulated transverse beam distribution can be transformed to the microbunched longitudinal distribution [4].

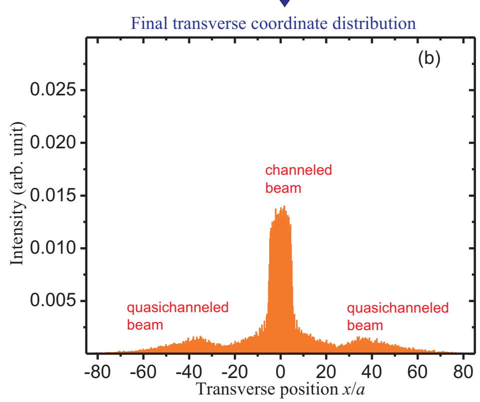
[4] Y.-E. Sun, et. al, Phys. Rev. Lett. **105**, 234801 (2010).

8. Beam splitting

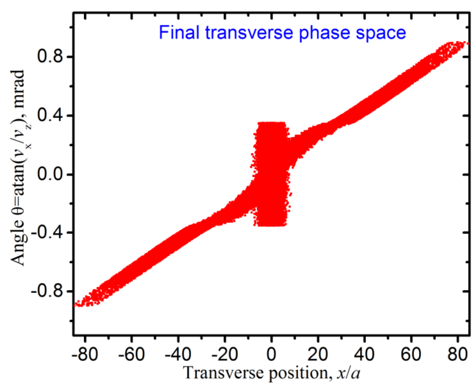




- (a) Initial beam of 230 MeV/c muons:
wide (the beam transverse dimension 10a) and divergent in XZ-plane (Gaussian, RMS σ_{vx}=0.6 mrad).



- Initial beam contains particles with high transverse velocities v_x;
- In the field of standing wave particles with large v_x move almost straight-line (above-barrier motion, quasichanneling);
- In the field of standing wave particles with low v_x move along channels;
- (b) Hence, one can divide particles with low v_x from particles with high v_x.



- (c) Right and left wings and corresponding peaks in (b) contain particles with high transverse velocities.

9. Standing wave channeling feasibility

Limiting conditions:

A) The less the laser intensity I_{max} => the less the channeled fraction in divergent beam => the possibilities to manipulate the beam are reduced.

B) The less the intensity I_{max} => the bigger the parameter L_{osc} => the bigger the channel length $L \approx 6w_0$ to see the channeling => the higher pulse power $W = \pi w_0^2 I_{max}$

C) The higher beam energy => the less potential well $2|U_{am}|$ => the less the channeled fraction in divergent beam.

Beam parameters and laser requirements (#):

	momentum, MeV/c	I_{max}, W/cm^2	w_0, cm	W, TW	l_b, cm	E_{min}, J
considered case	230	1E17	0.6	1.1E5	10	5.0E7
low laser intensity	230	**1E16**	1.8	1.0E4	10	6.9E6
high beam energy	**1000**	1E17	2.1	1.4E6	0.1	5.9E8
short muon bunch	230	1E17	0.6	1.1E5	**0.1**	1.4E7

- At present lasers with required pulse energy do not exist.

(#) in estimations $w_0=4L_{osc}$, $L=6w_0$, L_{osc} are estimated for maximum $|U_{am}|$ (at λ=800 nm), $E_{min} \approx W(L+l_b)/c$ – pulse energy, l_b – bunch length.

10. Conclusion

Concerning crystal channeling and standing wave channeling:

A) The laser standing wave channeling could be effective such as the crystal channeling (i.e. comparable potential walls).

B) The scattering of particles by the solid target is absent in the case of the standing wave lattice.

C) The channeling in the standing wave opens several possibilities for the beam shaping that are inaccessible for the case of crystal channeling.

D) The using of the tunable laser sources enables the ”dynamic” beam shaping.

Concerning Gaussian and plane waves:

A) Gaussian laser beams produce the standing waves where both channel width and wall change while beam propagates along a channel.

B) Projectiles dynamics is more complicated in comparison with plane standing wave channeling.

C) Nevertheless, all features founded in plane standing wave channeling exist in the case of Gaussian standing wave channeling.

Concerning muons and light leptons:

A) Results presented here are valid not only for muon beams but also for another particles.

B) For light particles the channeling in standing electromagnetic wave can be observed at existing lasers.

C) But for light particles the radiation energy loss is significant.