Controlled Channeling of Atom Electrons and Accompanying Nuclear Processes During the Orientational Action of a Polarized Laser Pulse on a Crystal

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Introduction

The traditional description of electron channeling assumes that the source of moving particles is an external accelerator.

On the one hand, this method allows you to control the energy of particles and the direction of their movement. This method allows for the implementation of long-term cumulative experiments.

On the other hand, this method of external acceleration has several very significant drawbacks:

- It can be implemented only with special complex accelerating equipment;

- With this method, it is very hard or impossible to form pulsed particle beams with high-density and high energy, which is necessary when studying and using threshold fast nuclear and atomic processes such as controlled nuclear transmutation or the formation of a active medium for an X-ray laser etc.

An alternative method for implementing the process of non-stationary channeling is the use of own electrons (both quasi-free and bound) , which can be formed and accelerated by external laser irradiation of crystal target.

The paper considers the dynamics of electron channeling periodically changing in direction and action on crystal atoms and nuclei of superdense flow of quasi-relativistic electrons produced and controlled in the the volume of near-surface crystal layer by the action of a polarized short ($\Delta t \leq 10^{-12}$ s) powerful laser pulse with energy W_L, intensity $J = W_L/\Delta t \Delta S$ and cross section $\Delta S \leq 10^{-4}$ cm^2.

The electric field of laser pulse

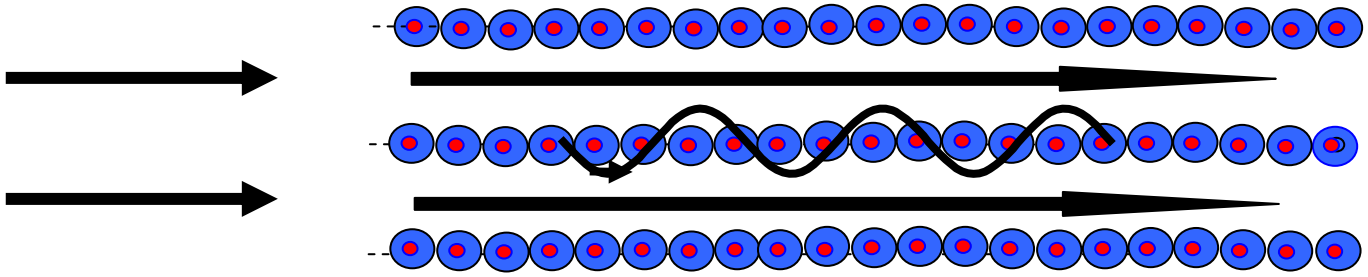
$$\vec{E}(t) = \vec{e}_z E_0 \cos(\Omega t - kz),\ E_0 = (4\pi W_L / \Delta S c \Delta t)^{1/2}$$

can significantly exceed the ionization threshold $E_i = Ze / r_B^2$ of crystal atoms. In this case, the produced electrons will move periodically in crystal layer synchronously with the electric field strength . During the action of such short pulse, the spatial structure of the crystal lattice remains “frozen” and unchanged. This is due to the fact that the electron system thermalizes at , $t \geq \delta t_e \approx 10^{-11} s$ while the nuclear crystal lattice remains quasi-cold up to .

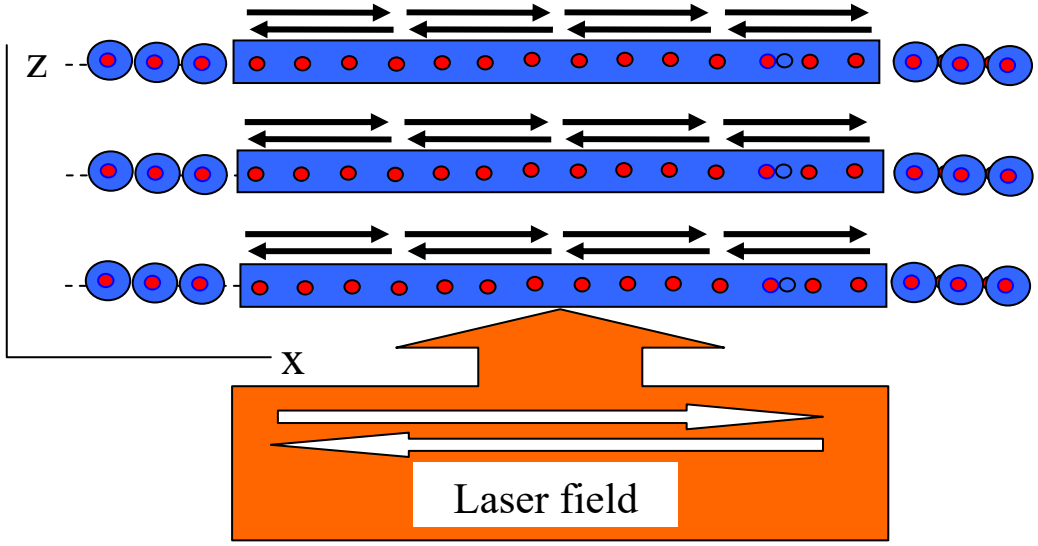
$t \leq \delta t_2 \approx 10^{-8} - 10^{-9} s$

This mode is fundamentally different from standard channeling involving particles accelerated by an external source.

Standard channeling of selected individual electrons accelerated by an external source



Collective controlled spatially oscillating channeling of all electrons of those crystal atoms that are in the zone of action of a powerful polarized laser beam



The motion of an electron under the action of a strong laser field can be described by the Klein-Gordon or Dirac equation with the Hamiltonian

$$\hat{H} = \{\hat{\vec{p}} + e\vec{A}(r,t)/c\}^2 / 2\gamma m_e = \frac{\hat{\vec{p}}^2}{2\gamma m_e} + \frac{e}{\gamma m_e c}\vec{A}\hat{\vec{p}} + \frac{e^2\vec{A}^2}{2\gamma m_e c^2}$$

or relativistic ponderomotive Hamilton-Jacobi equation

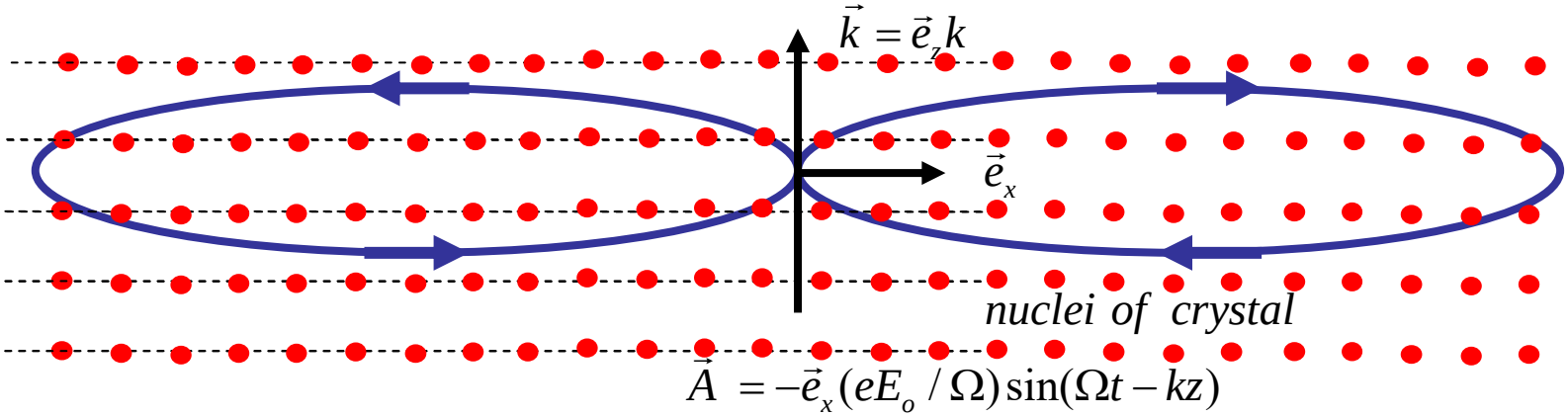
$$g^{ik}(\partial S/\partial x^i + eA_i/c)(\partial S/\partial x^k + eA_i/c) = m_e^2 c^2$$

for the electron action function *S* in the presence of a laser field.
Here g^{ik} - contravariant metric tensor,
$\vec{A} = \{A_x, 0, 0\};\ A_x = -(eE_o/\Omega)\sin(\Omega t - kz)$ - vector potential of laser field,

$\gamma = (1 + 2\pi J e^2 / m_e^2 c^3 \Omega^2)^{1/2}$ - Lorentz factor of the moving electron.

The classical trajectory of motion of each electron in such a field is determined by oscillations in two directions and corresponds to the number "eight" $x = \Delta x \cos(\Omega t - kz),\ y = 0,\ z = \Delta z \sin\{2(\Omega t - kz)\},\ \vec{k} = \vec{e}_z k$

$$\Delta x = 2e(\pi J/c)^{1/2} / \gamma m_e \Omega^2,\ \Delta z = \pi J e^2 / 2\gamma^2 m_e^2 c^2 \Omega^3$$



The trajectory of each electron in the region of action of a powerful polarized laser pulse along the ionized crystal planes xz consisting of "pure" fixed nuclei of crystal

In the case of CO_2-laser ($\lambda = 10.6\mu m, J = 2 \cdot 10^{15} W / cm^2$)

$$\Delta x \approx 3000 \text{ A}, \Delta z \approx 300 \text{ A}, <T_e.> \approx 100keV$$

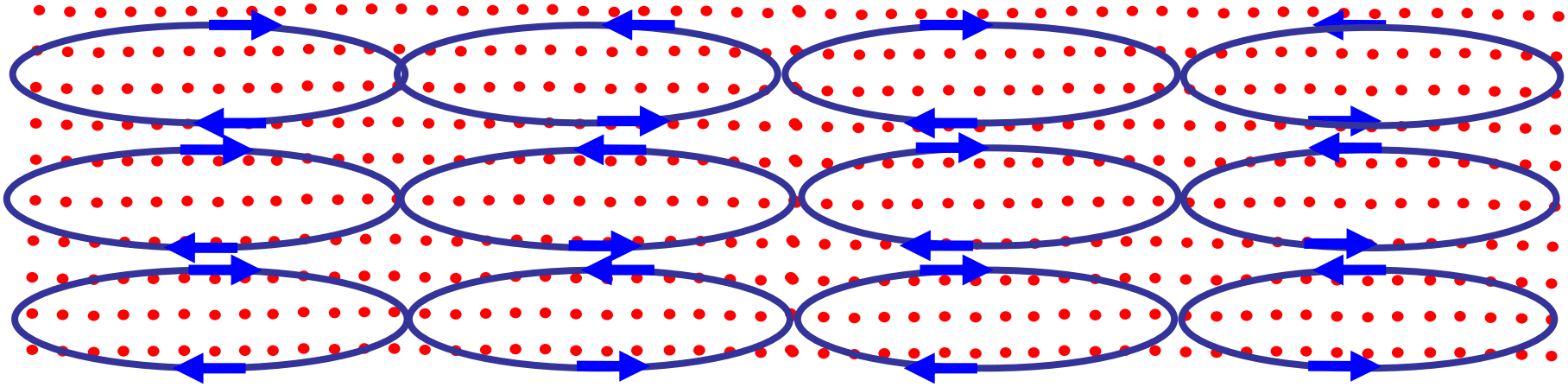
In the case of optical laser ($\lambda = 0.6\mu m, J = 10^{19} W / cm^2$)

$$\Delta x \approx 10000 \text{ A}, \Delta z \approx 4000 \text{ A}, <T_e> \approx 1.2 \, MeV$$

To provide individual relativistic channeled electrons it is necessary to use laser pulses with an intensity

$$J \gg J_{rel} \equiv m_e^2 c^3 \Omega^2 / 2\pi e^2$$

Synchronous motion of all electrons in the region of action of a powerful polarized laser field in a crystal



All free produced electrons will move in a channeling mode in **electric potential of frozen crystal nuclei** if the laser wave polarisation is parallel to the crystal planes.

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In fact this system can be considered as a **periodic high-current subrelativistic self-focusing microaccelerator.**

The energy loss of electron, accelerated and ruled by laser field on each spatial period of its oscillation is small

$$\Delta T = \frac{\pi e^3 n_e}{E_0} \ln\left\{1 - \frac{eZ^{2/3} m_e \Omega}{16 E_0 \hbar}\right\} << 1 keV$$

The motion of electrons remains quasi-harmonic during $N \approx \Omega\Delta t/2\pi \approx 10^3$ oscillations with total path

$$l_{\max} \approx 2N\sqrt{(\Delta x)^2 + (\Delta z)^2} \approx 10^6 A$$

Electrons accelerated by the laser field will move in a planar potential well consisting of an **ordered system of frozen nuclei** and other electrons that are also present in this volume and move under the action of the same laser field. During the relatively short time of each directed acceleration cycle, the electrons will not have time to form a stable distribution of energy levels in this potential well. **With a high probability, the distribution of electrons over the cross section after the start of the laser pulse will be close to uniform.**

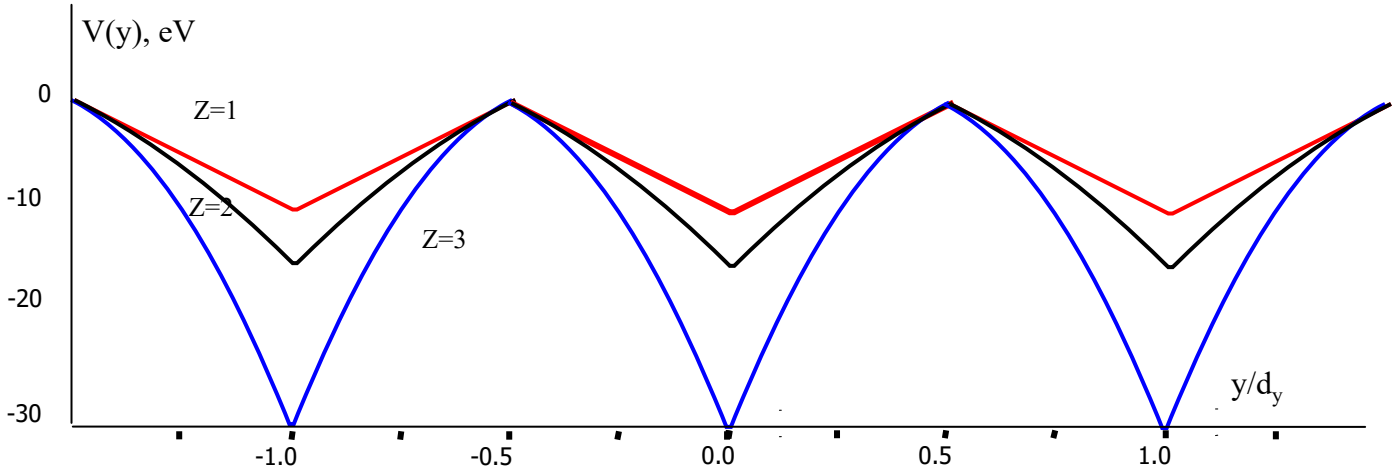
In this case, the structure of the transverse electric field and the corresponding structure of the potential energy of the plane potential well for each electron in a homogeneous crystal lattice will be characterized by the following expressions (here S_0 is the surface of the unit cell in xz plane of the crystal)

$$E_y = -\frac{\pi Ze}{S_0}\frac{y}{|y|} + \frac{2\pi(Z-1)e}{S_0 d_y}y, \quad -\frac{d_y}{2} \le y \le \frac{d_y}{2};$$

.

$$V(y) = \frac{\pi Ze^2}{S_0}|y| - \frac{\pi(Z-1)e^2}{S_0 d_y}y^2$$

Approximate structure of the plane potential for a specific electron, taking into account screening due to distributed other Z-1 moving electrons (at $d_y = 2*10^{16}\ cm$, $S_0 = 4*10^{16}$) has the following form



Because of the distributed electron shielding throughout the space between the planes, the influence of the initial small-sized thermal fluctuations of the nuclei will be very weak.

The main difference between the structure of the potential with such collective movement of all electrons and standard channeling is the very large width of the potential well for moving electrons.

Such a superdense flow of quasi-relativistic electrons can be used to solve many applied problems related to short-lived quantum systems.

1. Excitation of pulsed gamma radiation sources

It is well known that the main result of high-power unoriented pulsed laser irradiation of a target is usually the formation of short-lived plasma with temperature $KT/2 \approx 0.5 \div 3$ KeV and the generation of soft X-ray radiation.

On the other hand for the regime of coherent electron motion in laser field the average $\langle E_{coh} \rangle$ and maximal $E_{max}=2\langle E_{coh} \rangle$ **electron energy exceeds the equilibrium plasma electron energy 0.5 ÷3 KeV with the same power $W/\Delta t$ by 100-1000 times.**

This result allows using fast electrons to form gamma-radioactive nuclei using Coulomb excitation.

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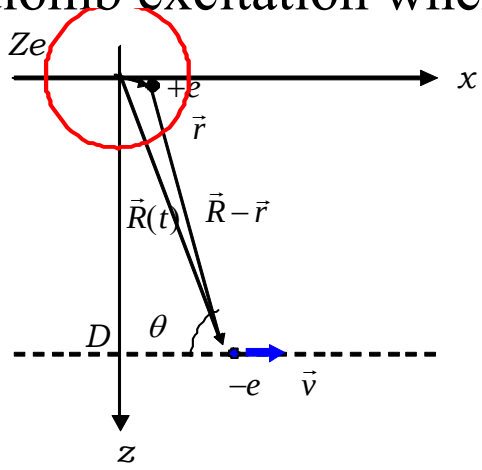
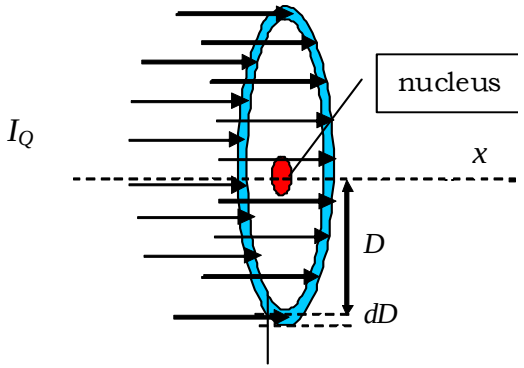


$$W_{nm}(t)=\frac{1}{\hbar^2}\left|\int_{-\infty}^{\infty}V_{nm}(t)e^{i\omega_{nm}t}dt\right|^2;$$

$$V(\vec{R}(t),\vec{r})=-\frac{e^2}{|\vec{R}(t)-\vec{r}|}=-\frac{e^2}{\sqrt{(vt-x)^2+(D-z)^2+y^2}}\approx$$

$$-\frac{e^2}{\sqrt{D^2+v^2t^2}}\frac{vtx+Dz}{D^2+v^2t^2}\ \textit{in dipole approximation}$$

$$W_{nm}(t)\approx\frac{4e^2|z_{nm}|^2}{\hbar^2v^2D^2}\ \ at\ \ D<v/\omega_{nm},\quad W_{nm}(v)_{\Sigma}=W_{nm}(t)J_e(v)$$



$$P_{nm}(v)=\frac{dW_{\Sigma}(v)}{dt}=n_e v\int_{D_{\min}}^{D_{\max}}<W_{nm}(t)>_{\varphi}2\pi DdD\approx$$

$$\frac{4\pi n_e e^4|z_{nm}|^2}{\hbar^2 v}\ln\left(\frac{D_{\max}}{D_{\min}}\right)=\frac{4\pi n_e e^4|z_{nm}|^2}{\hbar^2v^2}\ln\left(\frac{r_0A^{1/3}\omega_{nm}}{v}\right)$$

The size of direct Coulomb excitation region satisfied the condition for targeting distances. Here

$D_{min} = r_0 A^{1/3}$ ($r_0 = 1{,}2.10^{-13}$ cm); $D_{max} = v/\omega_{sk}$ - adiabatic limit.

For gamma-transitions of higher muontipole (quadrupole, octupole, etc.), we have the following expression for the interaction energy of moving electrons with a specific proton in the nucleus

$$P_{nm}(t)=\frac{4e^2Z^2n_e}{3\hbar^2}\int_{v_{\min}}^{\sqrt{\Delta x^2+\Delta z^2}\,\Omega}\left\{[<|Q_{nm}^{(1)}|^2>\ln\frac{m_e v^2}{\hbar\omega}]+\right.$$

$$\left.+[<|Q_{nm}^{(2)}|^2>\frac{1}{10}\left(\frac{m_e v}{\hbar}\right)^2+[<|Q_{nm}^{(3)}|^2>\left(\frac{m_e v}{\hbar}\right)^4+[<|Q_{nm}^{(3)}|^2>\left(\frac{m_e v}{\hbar}\right)^6\right\}f(v)dv$$

$$v_{\min}=\sqrt{2\hbar\omega_{nm}/m_e}$$

The probabilities of spontaneous transition with frequency ω_{nm} between levels E_n and E_m are related to the nuclear muontipole moments $Q_{nm}^{(L)}$ by the relation

$$1/\tau_\alpha=1/\tau_\alpha(1+\alpha)=8\pi(L+1)(c/\omega_{nm})^{2L+1}<|Q_{nm}^{(L)}|>/L\{(2L+1)!!\}^2\hbar$$

Taking into account this replacement, we have a formula for the probability of excitation of a nucleus per unit time for dipole transitions

$$P_{nm}^{(L=1)}=\frac{3Z^2e^2n_ec^3\sqrt{m_e/\hbar\omega_{nm}}}{2\hbar\omega_{nm}^3\tau(1+\alpha_0)}\ln\frac{\sqrt{\Delta x^2+\Delta z^2}\,\Omega}{\sqrt{m_e/\hbar\omega_{nm}}}$$

The probability of similar Coulomb excitation of the same nuclei $P_{nm}^{(uncoher)}$ during their interaction with isotropic uncoherent laser plasma at a specific temperature KT_e will be many times

$$P_{nm}^{(coher)} / P_{nm}^{(uncoher)} = \sqrt{KT_e / \hbar\omega_{nm}} \exp\left\{\hbar\omega_{nm} / KT_e\right\} >> 1$$

less than the probability of coherent ordered excitation $P_{nm}^{(coher)}$ due to rapidly coherent oscillating electrons.

For example, for the isotope Dy^{161} ($\tau \approx 2{,}8\cdot10^{-8}$ c, $h\omega_{nm}$=25,6 КэВ, α_0=1.6) the probability of direct Coulomb thermal excitation at KT= 1 keV is equal to P_{nm}= 0.02 s^{-1}. For a long laser pulse duration of $\Delta t=10^{-8}$ s, this probability corresponds to a concentration of $n^* = nP_{nm}\,\Delta t=10^{-8}$ cm^{-3} excited nuclei Dy^{161m} with an initial induced activity of 10^4 Curie.

When using the ordered excitation mode in a polarized laser field with the same parameters and at $\Delta t=10^{-13}$ s, we have $P_{nm}= 3*10^7$ s^{-1}. This case corresponds to a concentration of $n^* =nP_{nm}\,\Delta t=10^{17}$ cm^{-3} excited nuclei $Dy1^{61m}$ with an initial induced activity of 10^8 Curie.

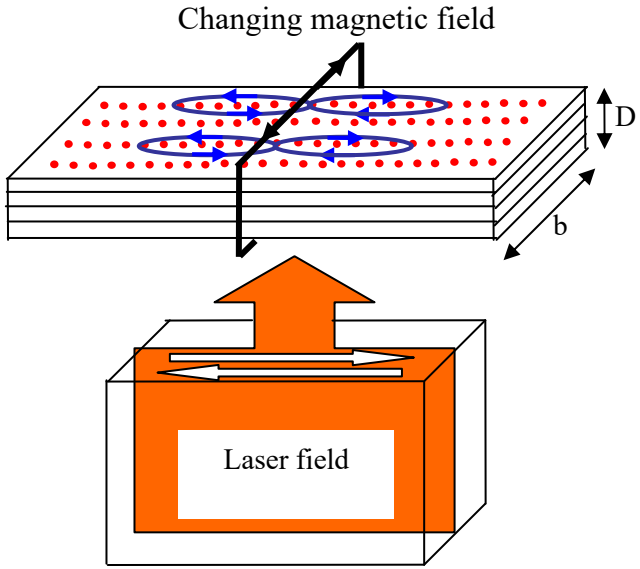
The reason for such a sharp increase in the induced activity is associated with a very significant increase in the concentration of fast electrons, the energy of which is sufficient for direct Coulomb excitation of nuclei.

2. Mechanism of self-compression of ordered thin crystalline target under irradiation with a short powerful polarized laser pulse

The traditional description of the processes that occur when external beams of charged particles are channeled completely **ignores the magnetic fields that form around these beams**. This is due to the fact that the current density of these external particle beams **is very small**. The particle density in these beams is many orders of magnitude less than the density of atoms and electrons in the targets. This leads to neglect of the influence of this magnetic field on the channeling mode.

A fundamentally different situation corresponds to the laser regime of formation of moving intracrystalline beams, which include all (or almost all) atomic electrons.

In the case of o optimal crystal orientation and optimal laser polarization, such electron flows move synchronously along xz crystal planes.This very strong current changes its direction synchronously with the periodic change in the polarization of the laser field.



The flow of a periodically changing strong electric current, synchronous throughout the entire volume of action of the polarized laser radiation, leads to the generation of a strong changing magnetic field synchronous with the changing current.

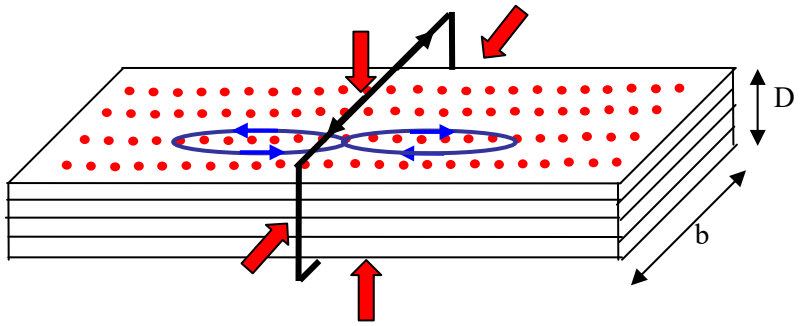
$$\oint \vec{H}(t)d\vec{l} = \frac{4\pi}{c}J(t) \;\Rightarrow\; H(t)(2b+2D) = \frac{4\pi}{c}bDj(t), \quad j(t) = n_e ev(t);$$

$$H(t) \approx \frac{2\pi}{c}\frac{bD}{b+D}j(t) = H_{\max}\cos\Omega t,$$

$$H_{\max} \approx \frac{2\pi}{c}\frac{bD}{b+D}n_e ev_{\max}$$

The presence of such a strong magnetic field results in strong external changing pressure on the front and back surfaces of the irradiated area

$$P(t) = \{H(t)\}^2 / 8\pi = P_{\max} \cos^2 \Omega t$$



This phenomenon corresponds to Lorentz force and the well-known **pinch effect** in thermonuclear fusion, but exceeds it due to the very large current of channeled electrons accelerated by the laser field.

The average pressure on both surfaces of the target during the entire duration of the laser pulse $\langle P \rangle = P_{max}/2$ is also very high.

A distinctive feature of such mechanical action is the very short duration $\delta t=2\pi/\Omega \approx 10^{-15}$-$10^{-14}$ sec of each of the alternating pulses of super-strong pressure and a very large number $\Delta t/\delta t \geq 10^{3}$-$10^{4}$ of such pulses. The action of such short pulses leads to the excitation of **intense shock waves** and to the **general compression of the target.**

The action of these shock waves can leads to the implementation of nuclear fusion reactions involving these nuclei. Also in such processes the probability of the reverse reaction of beta decay

$$X(A,Z)+\beta^{-}=Y(A,Z-1)+\nu$$

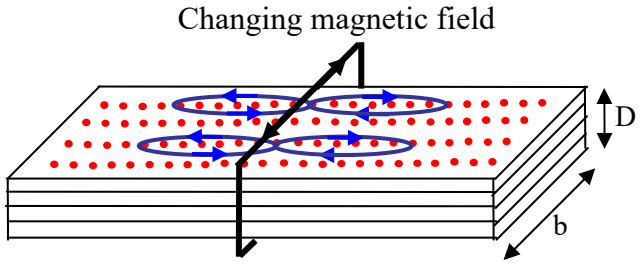
with the participation of a compressed flow of moving electrons increases very much.

It can be pointed out that in pulse processes occurring under such super-strong compression, with a certain composition of the target (iron lattice and the presence of embedded helium atoms), the formation of critical molecules *FeHe* and $FeHe_2$ is possible, the formation of which requires very high pressure

[B.Montserrat,M.Martinez-Canales,J.Needs,C.J.Pickerd. Helium-Iron compaunds at terapascal pressure. Phys.Re.Lett., 121, 015301, 2018]

3. **Electrodynamic limitations on the maximum current density of channeled electrons under laser irradiation**

All discussed data are in good agreement (**but partially limited**) with the estimates that characterize the inverse influence of the generated magnetic field on the electron current in the target due to the action of the general laws of electrodynamics. .



The motion of electrons along the planes of the crystal corresponds to the electric current that flows along the conductor and is controlled by the electric field strength vector $\vec{E}$ of the laser beam.

The parameters of such a conductor can be described by taking into account its **inductance** L. It is well known that inductance is an essential characteristic of any conductor system. The inductance of a conductor in the form of a flat plate with longitudinal length $l = \sqrt{\Delta x^2 + \Delta z^2}$, width b and thickness D is described by the formula

$$L = \frac{\mu_0 l}{2}\{\ln(2l/b) + 0.5)\} Henry,$$

$$\mu_0 = 4\pi 10^{-7}\, Henry/meter \; - \; magnetic\ constant$$

When an alternating current with a frequency Ω, which is equal to the frequency of the laser beam, flows along such an inductance, the reactance (reactive resistance) of this inductance is equal to the value

$R \equiv X_L = (\Omega/2\pi)L.$

From this estimate, we can find expressions for the electrical conductivity

$$\sigma = \frac{l}{RbD} = \frac{4\pi}{\Omega\mu_0 bD\{\ln(2l/b) + 0.5)\}},$$

which corresponds to the movement of electrons under the action of the laser field, as well as for the corresponding current density of these electrons

$$j(t) = \sigma E(t) \approx \sigma\sqrt{2J(t)/c}$$

For the same optical laser pulse

$$(\lambda = 0.6\mu m, J = 10^{19} W/cm^2 = 10^{24} W/m^2, \Delta t = 10^{-13} s, \Omega/2\pi = 5 \bullet 10^{14} s^{-1})$$

and at $bD=10^{-12}$m^2 we have $j_{max} = 10^7$Amper/cm^2.

It is interesting that the maximum current density depends only on the parameters of the laser beam (on the spatial geometry of the laser beam's area of action, on the intensity of this beam and on the frequency of the radiation). In crystals consisting of light atoms, such a condition corresponds to a significantly higher speed of electron movement than in heavier crystals.

Thank you for the attention