ON THE POSSIBILITY OF CREATION OF ULTRA-HIGH-CURRENT PERIODICAL MICRO-ACCELERATOR OF SUBRELATIVISTIC OSCILLATING ELECTRON BEAM PRODUCED AND CONTROLLED INSIDE ORIENTED CRYSTAL BY POWERFUL SHORT POLARIZED LASER PULSE

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The paper considers the dynamics and action on the resonant nuclei of fast electrons produced in crystal by short powerful laser pulse[1,2].

The solution of relativistic ponderomotive equation for electron

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

in this case has the parametric form

$$x = -g\cos\eta;\ y = 0;\ z = -\Delta z\sin 2\eta;$$
$$p_x=(eE_0/\Omega)\sin\eta,\ \ p_y=0,\ \ p_z= -(e^2E_0^2/4\gamma\Omega^2)\cos 2\eta;$$
$$g = eE_0c/\gamma\Omega^2 = 2e(\pi qc)^{1/2}/\gamma\Omega^2;\ \eta = (\Omega t\text{-}kz);$$
$$\Delta z = e^2E_0^2c/8\gamma^2\Omega^3 = \pi qe^2/2\gamma^2\Omega^3;$$
$$t= (\eta/\Omega) - (e^2E_0^2/8\gamma^2\Omega^3)\sin 2\eta;$$
$$\gamma^2 = m^2c^2+e^2E_0^2/2\Omega^2 = m^2c^2+2\pi qe^2/c\Omega^2;$$

Here g^{ik} is contravariant metric tensor,

$$\mathbf{A}=\{A_x,0,0\};\ A_x= -(eE_0/\Omega)\sin(\Omega t\text{-}kz)$$

is the vector potential of laser field.

If the short (duration $\Delta t \le 10^{-12}$ s) and focused (area of laser beam $\Delta S \le 10^{-4}$ cm^2) optical laser pulse with energy W acts upon the crystal, its electric field with maximal value

$$E_{max}= E_0 \equiv (4\pi W/\Delta Sc\Delta t)^{1/2}$$

can exceed the threshold ionization field $E_i \approx e/r_b^2$ of the atom in the crystal.

For the case of laser field $E_0 << \Omega mc/e$ (e.g. , at Ω=2.10^{15} s^{-1}, λ=1micron and at

$$q \equiv W/\Delta S\ \Delta t << q_0 \equiv \Omega^2m^2c^3/2\pi e^2 \approx 10^{19}\ \text{Wt/cm}^2\ \text{s})$$

we have

$$g \equiv \Delta x = eE_0/m\Omega^2 = (4\pi e^2q/m^2c\Omega^4)^{1/2},$$
$$\Delta z = e^2E_0^2/8\Omega^3m^2c = e^2\pi q/2m^2c^2\Omega^3.$$

In this case

$$\Delta z/g = eE_0/8\Omega^2mc <<1.$$

E.g.,at q = 10^{16} Wt/cm^{2}s we have

$$g\equiv\Delta x \approx 100\text{A},\ \Delta z \approx 0{,}7\text{A}.$$

In this case the produced electrons will move synchronously with the laser field **E** , i.e., periodically with subrelativistic velocity

$$v = dx/dt \approx (eE_0/m\Omega)\sin(\Omega t - kz).$$

During the action of short laser pulse the electron system and ion lattise of crystal stays quasi-cold (the electron system thermalizes only at $t \ge \delta t_1 \approx 10^{-11}$ s, while the lattice stays cold until $t \ge \delta t_2 \approx 10^{-8}$ s).

The following items are important for this consideration:.

1) Both free and ionization (ΔZ electrons per atom) atom electrons (with total concentration $n^* \ge 10^{23} - 10^{24}$cm^{-3}) are oscillating. The amplitude of electron oscillations along laser field $\mathbf{E_0}$ polarization equals

$$\Delta x \approx (4\pi e^2W/m^2\Delta Sc\Omega^4\Delta t)^{1/2}.$$

In case of powerful laser pulse ($\lambda\approx$1 mkm, 10^{19} Wt/cm^2 s >> q $\ge 10^{12}$ Wt/cm^2 s) this amplitude reaches the values $\Delta x \approx$ 500 -1000 A and exceeds the interatomic distance d $\approx$ 2 A by several orders of magnitude.

2) For such regime of coherent electron motion the kinetic energy of periodically moving electron averaged by period of oscillation $2\pi/\Omega$ equals

$$<T_{coh}> \approx \pi e^2W/m\Delta Sc\Omega^2\Delta t \ge 50 \div 100\ \text{KeV}.$$

For this case the maximal velocity of electrons equals

$$v_{max} = eE_0/m\omega = (4\pi e^2W/m^2\Delta Sc\Omega^2\Delta t)^{1/2} \approx (0{,}5 - 0{,}8)c.$$

This allows to consider the averaged plane and axis potentials of crystal lattice instead of system of discrete atoms of crystal. Such simplification make it necessary to consider the influence of mutual orientation of laser field $\mathbf{E_0}$ polarisation and crystallographic direction of quasi-cold crystal (at $t \le \Delta t << \delta t_2$) upon the motion of fast electrons and leads to the model (regime) of laser produced electron beam channeling with self-focusing

$\phi(\rho)$ of moving electrons to plane (axis) of crystal and increasing of moving electron density (beam density) in the volume of localization of nuclei and inside atomic electrons by $F \approx 3 - 10$ times. If the laser wave polarisation $\mathbf{e}_x=\mathbf{E_0}/E_0$ is parallel to the crystal axes or planes, the density of current of laser generated fast electrons inside atoms equals

$$j_{max} \approx n^* v_{max} F \approx 10^{15}\ \text{A/cm}^2.$$

In fact this system can be considered as a unique ultra-high-current subrelativistic periodical micro-accelerator.

3) For this regime of coherent electron motion the average $<T_{coh}>$ and maximal $T_{max}=2<T_{coh}>$ electron energy exceeds the equilibrium plasma electron energy

$$<T_{eq}> = 3KT/2 \approx 0.5 \div 3\ \text{KeV}$$

with the same power $W/\Delta t$ (for longer pulses $\Delta t \gg \delta t_1$) by several orders of magnitude. Also it is possible using this regime to excite nuclear states (direct Coulomb excitation) with superthermal energy

$$\hbar\omega_{sk}^{(max)} \approx <T_{coh}> \gg KT.$$

4) The energy loss of moving electron (accelerated and ruled by laser field $\mathbf{E}$) on each spatial period of its oscillation

$$\Delta E = \oint dT(v(x))/dx \approx$$

$$(\pi e^3 n_e / E_0)\ |\ ln\{1-(eZ^{2/3}m\Omega/16E_0\hbar)^2\}| << 1\ \text{KeV};$$

is small and $<T_{coh}> \gg \Delta E$.

Here for $v \geq e^2Z^{2/3}/\hbar$ (inelastic regime of electron motion)

$$dT/dx = dT_1/dx \equiv -2\pi e^4 n_e\{ln[(m^2v^2c^2)/(2J^2(1-v^2/c^2)^{3/2})] - ln2(2(1-v^2/c^2)^{1/2}) -1+v^2/c^2+1-v^2/c^2\}/mv^2,$$

and for $v \leq e^2Z^{2/3}/\hbar$ (elastic regime of electron motion)

$$dT/dx << dT_1/dx;$$

J - averaged potential of atom ionization,

$$v(x) = v_{max}\,[1-(x/\Delta x)^2]^{1/2}.$$

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

$$x \approx 2N\Delta x \approx 10^6\ \text{Å}$$

5) The angular divergence of the electron beam accelerated by laser equals

$$<\theta^2> = n_0\,\Delta x \int_{v_{min}}^{v_{max}} f(v)dv \int_0^{\pi} \theta^2\,\{d\sigma(v,\theta)/d\theta\}\,\sin\theta\, d\theta \approx$$

$$(16\,Z^2e^4\,n_0\,\Delta x/m^2\pi v_{max}) \int_{v_{min}}^{v_{max}} \sqrt{1-(v/v_{max})^2}\ dv/v^4 <$$

$$16\,Z^2e^4\,n_0\,\Delta x/3m^2\pi v_{max}\,v^3_{min}$$

Here

$$d\sigma(v,\theta)/d\theta =$$

$$(2em/\hbar^2K^2)^2\,|\int_0^{\infty} |\sin Kr/Kr|[\rho_n(r) - \rho_e(r)]4\pi r^2dr|^2 =$$

$$(e^4/4m^2v^2)\{\exp(-3K^2u^2) - (1 - K^2R^2/4)^{-2}\}^2\,\mathrm{cosec}^4\theta/2$$

is the differential scattering cross-section for moving electron in crystal lattice[3] ,

$$K = (2mv/\hbar)\sin\theta/2,\ \rho_n(r) = Ze|\Psi_{n0}|^2,\ |\Psi_{n0}|^2 =$$
$$(2\pi u_0^3)^{-3/2}\exp(-r^2/2u_0^2),\ u_0=\sqrt{3}\,u;$$
$$\rho_e(r) = Ze|\Psi_e|^2 = (Ze/\pi R_0^3)\exp(-2Zr/R_0),$$

u is 1-dimentional averaged amplitude of thermal atom oscillation in lattice in ground state.

According to the result of $<\theta^2>$ calculation

$$[<\theta^2>]^{1/2} \leq \theta_{chan}$$

for a crystal with not very heavy atoms) the motion of fast electrons remains quasi-channeling within each spatial period of laser induced oscillation Δx.

These fast electrons interact with Mossbauer-type nuclei which are non-excited in their initial state. The low energy transitions in nuclei are known to be the result, in most cases, of single-nucleon processes.

Assuming $\mathbf{r}$ to be the radius of a proton related to Mossbauer transition, one can easily deduce an expression for non-stationary energy of the interaction of a moving electron with a nucleus

$$V(\mathbf{R},t)= \int\rho_e(r)\,\varphi(\mathbf{r},\mathbf{R},t)d\mathbf{r} = -Ze^2\exp(-R(t)/R_0)/|\mathbf{R}(t) - \mathbf{r}|,$$

where $R_0 = 1{,}4\,\hbar^2/me^2\,(Z - \Delta Z)^{1/3}$ is parameter of electronic shielding,

$$\rho_e(r) = e\sum_{k=1}^{Z}\delta(\mathbf{r} - \mathbf{r_k}),\ \varphi(\mathbf{r},\mathbf{R},t) =$$
$$e\exp(-R(t)/R_o)/\,|\mathbf{R}(t) - \mathbf{r}|$$

is Coloumb potential,

$\mathbf{R}=\{vt, \rho, 0\}$, ρ.- targeting distances.

The above interaction can induce excitation of the nucleus. The probability of the excitation can be calculated according to equation

$$P_{sk}= n^* \int_{\rho_{min}}^{\rho_{max}} \int_{v_{min}}^{v_{max}} W_{sk}(\rho,v)\,f(v)v\phi(\rho)2\pi\rho d\rho dv.$$

Here

$$W_{sk}(\rho,v) = h^{-2} \left| \int_{-\infty}^{\infty} V_{sk}(\rho,v,t) \exp(i\omega_{sk}t)\, dt \right|^2,$$

$$f(v)= [1-(v/g\Omega)^2]^{1/2}/\pi g\Omega \ -$$

the function of velocity distribution for harmonic motion of electron, $g = eE_0 /m\Omega^2$.

The motion of fast electrons can be approximated by the laws of classical kinetics.

Expanding now the expression for $V(\mathbf{r},t)$ into a series of the parameter $r/(\rho^2 + v^2t^2)^{1/2}$

$$V(r,t) \approx - Ze^2\{1/R + [\rho y - (x^2 +y^2 +z^2) /2]/R^3+3[(\rho y)^2 + x^2 +y^2 +z^2)^2 /4 - \rho y(x^2 +y^2 +z^2) + (vtx)^2 /2]/2R^5 + 5[(y\rho)^3 \rho^2 y^2 (x^2 +y^2 +z^2)/2 +3\rho y(vtx)^2 \ 3v^2 t^2 (x^2 +y^2 + z^2)^2 /2]/2R^7 + 35[(\rho y)^4/2 +(vt)^4 x^4 /2 +3(vt\rho xy)^2]/4R^9 \}$$

and calculating the matrix elements of the operator of the nucleon coordinate **r** we have

$$W_{sk} \approx (Ze /v\rho\hbar)^2|2Q^{(1)}_{sk}+Q^{(2)}_{sk} /\rho +6Q^{(3)}_{sk}/\rho^2+Q^{(4)}_{sk}/2\rho^3 |^2.$$

Here

$Q^{(1)} \equiv d = ey$, $Q^{(2)} = e(y^2-z^2)$, $Q^{(3)} = e(y^3-y^2z/3)$,
$Q^{(4)}=e(y^4+z^4-6y^2 z^2)$ -

are correspondingly matrix elements of the dipole moment (l=1), quadrupole one (L=2), octupole moment (L=3) and so on.

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

$$\rho_{min} \geq \rho \geq \rho_{max}.$$

Here

$$\rho_{min} \geq R_n = r_n A^{1/3} \ (r_n =1,2.10^{-13} \text{ cm});$$
$$\rho_{min} \geq \rho_{min}^{(1)} = Ze^2/mv^2 \ \text{- quasiclassical limit;}$$
$$\rho_{min} \geq \rho_{min}^{(2)} \approx \hbar/mv \ \text{- quantum limit}$$

and

$$\rho_{max} \leq R_o= 1,4\, \hbar^2/me^2 (Z - \Delta Z)^{1/3};$$
$$\rho_{max} \leq v/\omega_{sk} \ \text{- adiabatic limit.}$$

After averaging by v

$$(v_{min} \leq v \leq v_{max},$$
$$v_{min} \approx (2\, \hbar\omega_{sk}/m)^{1/2} ,$$
$$v_{max} = 4\pi eW/\Delta Sc\Delta t)^{1/2}/m\Omega)$$

and targeting distances ρ one can derive the result for total probability of direct excitation of the nucleus[1,2].

The total probability of Coulomb excitation of nuclei (or excitation of atomic electron to upper X-level) in dipole approximation equals

$$P_{sk} \approx [3Z^2e^2n^*c^3/2\hbar\omega_{sk}{}^3](m/\hbar\omega_{sk})^{1/2} ln[eE_0/\Omega(m^3/\hbar\omega)^{1/2}]\, FG_\tau.$$

Here
$G_\tau = \Delta t/\tau$ for the case $\tau \geq \Delta t$ and
$G_\tau =1$ for the other case $\tau \leq \Delta t$,
τ is time of life of excited nucleus state E_k for dipole transition $E_s \rightarrow E_k$ with excitation frequency of nucleus ω_{sk}.

For octupole transitions

$$P_{sk} \approx 9Z^2e^2n^*c^7m^4(eE_0\Omega/m)^3/28\pi\hbar^7\, FG_\tau$$

The probability of Coulomb excitation of nuclei by laser produced subrelativistic oscillating electrons during action of short powerful polarized optical laser pulse on perfect oriented crystal exceeds the probability of Coulomb excitation by thermalized electrons (at same laser power $W/\Delta t$) by the coefficient

$$C \approx (KT/\hbar\omega_{sk})^{1/2}\exp(\hbar\omega_{sk}/KT),$$

which equals several orders of magnitude for case $\hbar\omega_{sk} >> KT$. As a result the probability of Coulomb excitation of lattice nuclei reaches 10-50% (for laser with $q \approx 10^{17}$ Wt/cm^2 and for nuclei with $\tau /\Delta t \approx 10^{-3}$) .

Such nonthermal mechanism of obtaining excited nuclei (or atomic electron) state proves by many orders more effective, than traditional methods of thermal **(**at $\Delta t >> \delta t_1$) or photo (by equilibrium X-rays) excitation **(**at $\Delta t >> \delta t_1$) of nuclear or atomic levels for gamma-laser in quasi-equilibrium laser electron or ion plasma.

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