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Creating and using of superdense micro-beams of relativistic electrons

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Abstract

The problem of creation and the results of experimental investigation of superdense subrelativistic electrons micro-beams with current density $10^{10}\,A/cm^2 \leqslant j \leqslant 10^{14}\,A/cm^2$, duration $\Delta t = 1$–10 ns and energy about 0.01–1 MeV are discussed. The interaction of these micro-beams with condensed target and ions beams are investigated. The problems of isomers excitation and active medium for both X-ray laser and gamma-laser creation by use of super-dense electrons micro-beams are also studied. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The problem of generation of relativistic and subrelativistic electrons is among most challenging ones. Using such beams, it would be possible to develop both X-ray and gamma lasers and to excite short-lived nuclear isomers. As shown by estimates, electron beams of a density not less than $j = 10^{10}$–$10^{14}\,A/cm^2$ are needed for this purpose. Accordingly, a current density $j = 10^{14}$–$10^{16}\,A/cm^2$ is needed for excitation of long-lived isomers. A critical current density $j = 10^{8}$–$10^{10}\,A/cm^2$ is required for an X-ray laser based on the phenomenon of stimulated emission of radiation at channeling of relativistic positrons in single crystals.

Obtaining such current densities with the use of traditional linear and ring-type accelerators is impossible. Some models of microaccelerators and optimized macro accelerators, providing for achievement of required current densities will be discussed below. Some fields of their application will also be considered.

2. Creation of traveling inversion for an X-ray laser in plasma environment with the aid of an annular pulse of femtosecond laser

The problem of generation of a superdense electron beam for exiting a traveling pumping in an X-ray laser can be solved by the use of an annular

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femtosecond laser pulse with a total intensity J_0. The energy of interaction

$$V = V_1 + V_2 = (q/2mc)\boldsymbol{A}(\boldsymbol{r},t)\boldsymbol{p} + (q^2/2mc^2)|\boldsymbol{A}(\boldsymbol{r},t)|^2 \quad (1)$$

of an electromagnetic field characterized by the vector-potential $\boldsymbol{A}(\boldsymbol{r},t)$ with a particle having charge q, pulse $\boldsymbol{p}$ and mass m can be determined from the general expression for the energy of the particle in a non-relativistic approximation

$$\varepsilon = mc^2 + [\boldsymbol{p} - (q/c)\boldsymbol{A}(\boldsymbol{r},t)]^2/2m. \quad (2)$$

The first term in (1), V_1, represents the periodic motion of charge q in the harmonic wave field $\boldsymbol{A}(\boldsymbol{r},t)$ (during every period of oscillations the electron twice draws energy from the field and twice returns it); the second term in (1), V_2, characterizes the process of constant-sign interaction with the field and determines the average force $\boldsymbol{F} = -\nabla\langle V_2\rangle$ which permanently acts on the charge q.

With account of the relation between the vector-potential $\boldsymbol{A}(\boldsymbol{r},t)$ and vector of the wave field intensity

$$\boldsymbol{E}(\boldsymbol{r},t) = -(1/c)\,\mathrm{d}\boldsymbol{A}(\boldsymbol{r},t)/\mathrm{d}t = (\omega/c)\boldsymbol{A}(\boldsymbol{r},t)$$

and also taking into consideration a periodic character of the time dependence of $\boldsymbol{A}(\boldsymbol{r},t)$ and $\boldsymbol{E}(\boldsymbol{r},t)$, we find the final expression for the period-averaged laser wave of the ponderomotive interaction energy:

$$W_{\mathrm{L}}(\boldsymbol{r}) \equiv \langle V_2\rangle = (e^2/2m\omega^2)\langle|\boldsymbol{E}(\boldsymbol{r},t)|^2\rangle = (\pi e^2/mc\omega^2)J(\boldsymbol{r}). \quad (3)$$

Consider the longitudinal action on a slow gas (plasma) jet having a radial density $n(r) = n_0 \exp(-r^2/r_0^2)$ of an annular laser pulse, coaxial with the jet, of an intensity J_0, outer radius R_0, and thickness $\delta R \ll R_0$.

At irradiation of a medium where the density n of electrons and ions is less than the critical density $n_{\mathrm{cr}} = m\omega^2/4\pi e^2$ with an annular laser pulse there occurs a radial acceleration of electrons to the center of the beam. During the action of a femtosecond pulse, ions remain stationary (because of a large difference in masses).

The acceleration of a tubular current of electrons towards the center of the laser pulse in single-ionized plasma increases the intensity $E_q(r) = 4\pi R_0\delta R\, n(R_0)e/r$ of the field acting from stationary ions on each of the electrons being accelerated. The existence of this field of separated charges results in braking of electrons and decrease in the energy of each of the electrons by a value of

$$W_q(r) = \int_r^{R_0} F_q(r)\,\mathrm{d}r = 4\pi R_0\delta R\, n(R_0)e^2\ln(R_0/r), \quad F_q(r) = eE_q(r). \quad (4)$$

The total energy of each of the electrons being accelerated by the laser pulse in the region $r \leqslant R_0$ is

$$W(r) = W_{\mathrm{L}}(r) - W_q(r) = (\pi e^2/mc\omega^2)J_0 - 4\pi R_0\delta R n(R_0)e^2\ln(R_0/r). \quad (5)$$

Consider the action of a laser pulse with an intensity $J_0 = 10^{18}\,\mathrm{W/cm^2}$, frequency $\omega = 2\times 10^{15}\,\mathrm{s^{-1}}$, and focal dimensions $R_0 = 5\,\mu\mathrm{m}$, $\delta R = 1\,\mu\mathrm{m}$ on a plasma jet with an effective radius $r_0 = 2.3\,\mu\mathrm{m}$ and maximum density on the axis $n_0 = 10^{20}\,\mathrm{cm^{-3}}$. The energy of each of the electrons being accelerated by the laser in a region with a radius R_1 $(R_0 > R_1 > R^0/10^3)$ is $W(R_1) \approx 10\,\mathrm{keV}$, which corresponds to their velocity $v \approx 5\times 10^9\,\mathrm{cm/s}$. Accelerated electrons leave the region of action of the annular laser pulse in time

$$\Delta t \approx mw\delta R(2c\pi e^2 J_0)^S \approx 3\times 10^{-14}\,\mathrm{s} \quad (6)$$

which is several orders of magnitude less than the duration of the laser pulse.

The motion of the tubular current converging towards the center increases the volumetric density of moving electrons from the initial value $n_{\mathrm{e}}(R_0) \equiv n(R_0)$ to $n_{\mathrm{e}}(R) \equiv n(R_0)R_0/R$ on a ring of radius R (see Fig. 1).

In the small-radius plasma jet under consideration with a density $n < n_{\mathrm{cr}}$, a linear braking of the current of fast electrons on their path in the jet from the edge to the center of the laser pulse can be ignored. The main mechanism of braking of the converging current of electrons, characterized by velocity $v(R)$ and density $j(R) = v(R)n_{\mathrm{e}}(R)$, at interaction with the plasma target is a collective interaction (two-beam plasma instability), characterized by the development increment $\delta\omega \approx \omega_{\mathrm{p}}[n_{\mathrm{e}}(R)/n(R)]$.

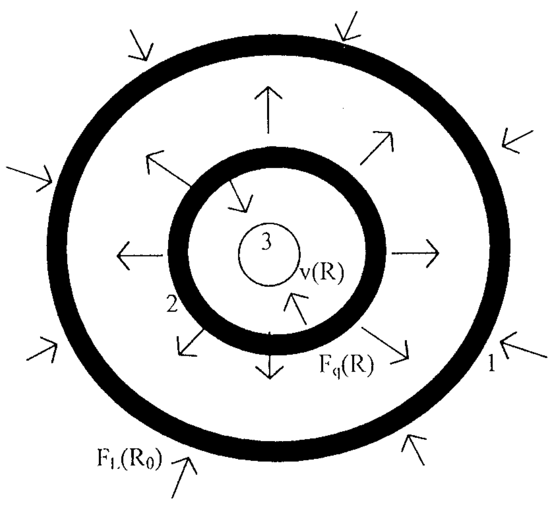

Fig. 1. The structure of electron beam 2 motion to the center of laser pulse 3 with velocity $v(R)$ and action of laser force $F_L(R_0)$ and Coulomb force $F_q(R)$ of separated charges of electron beam 2 and ions 1.

Here $\omega_p = [4\pi \ n(R)e^2/m]^{1/2}$ is the plasma frequency of the jet in a region with a radius R; $n_e(R)$ is the volumetric density of electrons moving towards the center of the beam; and $n(R)$ is the volumetric density of electrons of the plasma target (jet).

The condition of "triggering" of such a collective interaction mechanism is $n_e(R) \leqslant n(R)$. With electronic beams of a low volumetric density, $n_e(R) \ll n(R)$, the difference between the phase velocity of plasma oscillations of the target and the velocity of the beam being braked is small, which results in a low efficiency of the energy transfer from beam particles to the plasma target. The equality of electronic densities, $n_e(R) \approx n(R)$ is optimal for an effective energy transfer from the electron beam to plasma.

On account of the relation $n(r)$, the radius R_1 of the beginning of an effective collective braking of electrons accelerated by the laser can be found from the equation

$$\exp[-(R_0^2 - R_1^2)/r_0] = R_1/R_0 \tag{7}$$

and at the condition $R_1 \ll R_0$ is equal to $R_1 \approx R_0 \exp[-R_0^2/r_0^2]$.

The length of the full braking path of accelerated electrons in the plasma target is equal to

$$L \approx v(R_1)\delta\omega \approx v(R_1)/\omega_p(R_1).$$

When the condition $L < 2R_1$ is met, all the accelerated electrons will be braked within the volume of a plasma filament of a radius R. The braking time δt is equal to $1/\delta\omega$. Such a braking will raise the temperature of the filament to

$$KT \approx R_0 \delta R\, n(R_0) W(R_1)/\{\textstyle\int_0^{R_1} n(r) r\, dr + R_0 \delta R\, n(R_0)\}. \tag{8}$$

At the above-presented parameters of the laser pulse and characteristics of the plasma target, we have $R_1 \approx 0.05\,\mu m$; $\omega_p(R_1) \approx 5 \times 10^{14} s^{-1}$; and $L \approx 0.1\,\mu m$. The density of current of accelerated electrons on the surface of a region of radius R_1 is $j \approx n_0 v(R_1) \approx 10^{11}\,A/cm^2$. The resulting temperature of the central region of the plasma jet of a radius R, corresponding to these values is $KT \approx W(R_1) \approx 10\,keV$.

At such a temperature (after an adiabatic cooling of the plasma filament) threshold conditions are met for the triggering of an X-ray laser with a generation wavelength right down to the minimal value of $\lambda_x \approx 0.15\,nm$, based on transitions between inner electronic shells of atoms with $Z \leqslant 30$.

Advantages of the above-considered method of a longitudinal pumping (generation of a plasma filament and active medium for an X-ray laser in the direction of motion of an optical laser pulse) are associated with an automatic generation of a region of inversion of the active medium traveling along the plasma jet at the velocity of light at the rear front of the laser pulse.

In addition, the method of generation of a high-temperature plasma filament with the use of ponderomotive forces makes it possible to create a region of high-temperature heating of plasma, traveling at the velocity of light, with the minimum possible cross-section $S_0 = \pi R_1^2 \approx 10^{-10}\,cm^2$. This value is 10^2 times as small as the diffraction limit

$$S_{min} \approx \lambda^2 = (2\pi c/\omega)^2 \approx 10^{-8}\,cm^2$$

at the traditional method of generation of high-temperature laser plasma in the region of the linear focus, transverse to the direction of the laser pulse.

3. Generation and use of a superdense beam of relativistic electrons, based on a high-current vacuum diode

A high-current vacuum diode is one of the promising systems for generation of superdense beams of subrelativistic electrons (e.g. [1]). Main advantages of such a system are associated with the possibility of generation of a short high-voltage ($U = 0.01$–1 MV) pulse of a duration $\Delta t = 1$–10 ns with rise fronts less than 1 ns.

We have studied the problem of obtaining the maximally high density of current of subrelativistic electrons with an energy $W = \gamma mc^2 = 0.01$–1 MeV and a full current $i = 3$–100 kA. Results of preliminary theoretical investigations [2] demonstrated the importance and efficiency of the mechanism of autofocusing of the electron beam being accelerated through its interaction with the ionic component of plasma in the inter-electrode gap and in the region near the cathode surface. The mechanism of the autofocusing is associated with the self-contraction of the high-current beam, neutralized by the ionic component of plasma ($\eta \approx 1$), by its own magnetic field $H_r = (ie/Rv)[\eta - 1/\gamma^2]$. A substantial influence of the state of the anode surface and the presence of an impurity on the current density increase process, has been found.

The experiments used needle cathodes with the autoelectronic and explosive emission and the minimum possible rounding-off radius $R \leqslant 0.01$ μm as well as flat and needle anodes. Optimal parameters of plasma as well as optimal configurations of the cathode and anode and the optimal distance between them, $L \approx 0.1$–1 mm, have been determined.

In the experiments, a record-breaking current density $j \approx 10^{11}$–10^{12} A/cm^2 has been attained and conditions for achieving $j \approx 10^{13}$–10^{14} A/cm^2 have been determined. A phenomenon of a stable transportation of this superdense current in copper and tungsten anodes with self-stabilization of the resulting minimal beam radius $R = 1$–5 μm was also discovered.

Based on the obtained results of generation of superdense beams of relativistic electrons, the possibility of excitation of nuclei with the aid of inverted electronic conversion (Nuclear Excitation by Inverted Electronic Conversion, NEIEC) in ions of the target plasma under the action of such beams has been considered.

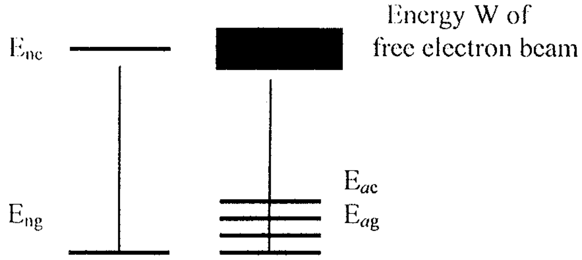

Fig. 2. The structure of transitions at nuclear excitation $E_{ng} \to E_{ne}$ by inverted electron conversion $W \to E_{ag}$ in the case $|E_{ae} - E_{ag}| \ll |E_{ne} - E_{ng}|$.

The basic concept of NEIEC consists of the formation of a vacancy in one of the inner shells of an atom (by a preliminary heating or action of the beam) and a subsequent capture of a free electron from the beam of accelerated particles to this atom's shell with a concurrent excitation of the nucleus (Fig. 2). NEIEC differs fundamentally from the well-known mechanism NEET (Nuclear Excitation by Electron Transition) [3], which consists of a synchronized transition of an electron from the excited state of an atom, E_{ae}, to the ground state, $E_{ag} = E_{ae} - \hbar\omega_{ae,ag}$, and of the nucleus, accordingly, from the ground state, E_{ng}, to an excited isomeric state, $E_{ne} = E_{ng} + \hbar\omega_{ng,ne}$ (see Fig. 3). The NEET method requires excitation of an atom to an energy $W = \hbar\omega_{ng,ne}$ (or its heating to $KT \geqslant \hbar\omega_{ng,ne}$).

The above-considered mechanism acts for beams of accelerated electrons with a free electron energy of about $W = \hbar\omega_{ng,ne}$ and does not require coincidence of the frequency of the transition being excited in the nucleus, $\omega_{ng,ne}$, with one of the frequencies of possible electronic transitions in the atom. NEIEC can also be used in the case of extremely light atoms with a low K-shell ionization energy $W_K = mZ^2e^2/2\hbar^2$, which makes it possible to form a vacancy in the K-shell of atoms at a low temperature, $KT \ll \hbar\omega_{ng,ne}$.

The probability of the process of inverted electronic conversion at excitation of a particular nuclear level with a lifetime τ and electronic conversion coefficient α is determined by the expression

$$P_{\alpha^*} = \eta\alpha/(1+\alpha)\tau, \eta = [\rho(\hbar\omega_{ng,ne})/\rho_e(\hbar\omega_{ng,ne})].$$

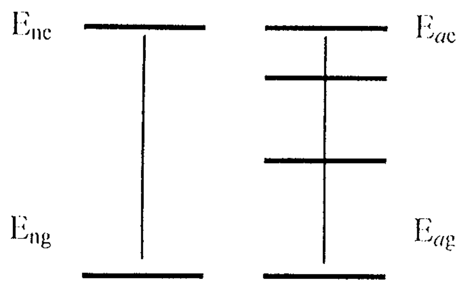

Fig. 3. The structure of transitions at nuclear excitation $E_{ng} \to E_{ne}$ by electron transition $E_{ae} \to E_{ag}$ in atom.

It differs from the probability $P_\alpha = \alpha/(1+\alpha)\tau$ of a forward electronic conversion, accompanying a spontaneous decay of the nucleus, only by the parameter η, which is equal to the ratio of the volume energy density

$$\rho(\hbar\omega_{ng,ne}) = (j/ev)f(\hbar\omega_{ng,ne})$$

of an electronic beam with a density j and distribution function $f(\hbar\omega_{ng,ne})$, accelerated to an energy $W = mv^2/2 = \hbar\omega_{ng,ne}$, to a similar density of the possible states of electrons in a free space,

$$\rho_e(\hbar\omega_{ng,ne}) = m^2 v/2\pi^2\hbar^3,$$

within the same energy range of around $\hbar\omega_{ng,ne}$.

At the use of an electronic beam with a current density $j \approx 10^{14}\,\mathrm{A/cm^2}$, a pulse duration $\Delta t \approx 1$ ns, an average energy $W = \hbar\omega_{ng,ne} = 10$ keV, and a monochromaticity $\Delta W/W = 10^{-3}$, we have $\rho(\hbar\omega_{ng,ne})/\rho_e(\hbar\omega_{ng,ne}) = 0.03$, which corresponds to a probability $P_{\alpha^e} \approx 10^{-3}$ of excitation of nuclei with $\tau = 1$ ns and $\alpha \gg 1$. At the use of the non-inverted gamma amplification [4,5], such a probability of excitation is sufficient for triggering a gamma laser based on such nuclei as Dy^{161} ($\hbar\omega_{ng,ne} = 24.4$ keV), Sn^{119} ($\hbar\omega_{ng,ne} = 24.4$ keV), and Fe^{57} ($\hbar\omega_{ng,ne} = 14.4$ keV).

4. Conclusion

Theoretical results and analysis of conducted experiments evidence the feasibility of generation of superdense beams of fast electrons in laser fields also at the use of high-voltage diodes as well as the feasibility of development of X-ray laser systems and gamma laser pumping systems on the basis of the existing technology.

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