TEMPERATURE RELAXATION AND ADIABATIC ACCELERATION AT MAGNETIZED ELECTRON FLUX

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Introduction

In the absence of intrabeam scattering the electrons acceleration of in electron gun results in a decreasing of longitudinal temperature [1]. At the same time the transverse temperature (is assumed the absence of the transverse velocities perturbation) does not change. If the accompanying magnetic field is sufficiently strong the transverse movement of electrons is magnetized and their effective temperature is defined by the longitudinal temperature, which value can be extremely small.

The intrabeam scattering leads to an increasing of the longitudinal temperature. We can distinguish two effects: transverse-longitudinal relaxation when the temperature increase due to the transfer of the transverse motion energy into the longitudinal one (Boersch effect) [2], and the longitudinal-longitudinal relaxation when the temperature increase due to the thermodynamic relaxation only in the longitudinal direction [3].

The transverse-longitudinal relaxation is easily suppressed by sufficiently strong magnetic field [3]. At the same time the opportunities of suppressing of the longitudinal-longitudinal relaxation have strong confinements. For sufficiently small electron density the particular suppress can be received by use of more slowly (adiabatic) acceleration than in the Pierce gun [4].

This paper is devoted to the experimental study of the longitudinal temperature relaxation in electron beam and the study of opportunities of the adiabatic acceleration use for the supercooled electron beam preparation.

Longitudinal-longitudinal relaxation

If the transverse-longitudinal relaxation is suppressed by a magnetic field then the main contribution to an increasing longitudinal temperature is given by the longitudinal-longitudinal relaxation.

In an ordinary electron gun the acceleration of electrons proceeds quickly as compared to the period of the plasma oscillations of the electrons. There for, for the time of acceleration the relative location of the electrons in the beam practically does not change and their initial locations with the chaotic distribution is preserved. Since the longitudinal temperature after acceleration is small, the absence of correlations in positions of electrons leads to its increase by the value $\simeq e^2n^{1/3}$ (due to the electrostatic reputing). As a result we get the estimation of the longitudinal temperature [3]:

$$T_{\parallel}=\frac{T_k}{2W}+Ce^2n^{1/3}, \qquad (1)$$

where the constant C is about one.

We can build a simple model to estimate the constant C [6]. We guess $U_0(n, T_{\parallel})$ is the total internal energy of the thermodynamically equilibrium (in the longitudinal degree of freedom) magnetized electron gas. By equaling the internal energy of electrons just after fast acceleration to the one after establishing the thermodynamic equilibrium we get:

$$\frac{T_k^2}{2W}+U'=U_0(n, T_{\parallel}). \qquad (2)$$

where U' is a correlative energy of nonequilibrium state of an electron beam just after fast acceleration

In the high temperature region $T\gg e^2n^{1/3}$ the expression for correlation energy of equilibrium state is well known [5]:

$$U_c=-\frac{e^2}{2r_D}=-\frac{e^2}{2}\sqrt{\frac{4\pi e^2n}{T}}. \qquad (3)$$

where r_D is Debye radius. In the opposite case $T_{\parallel}\ll e^2n^{1/3}$ the electron beam is crystallized and a correlative energy is equal to

$$U_c=T_{\parallel}/2-Ae^2n^{1/3}. \qquad (4)$$

The coefficient 1/2 in the first attend is connected with the magnetization of transverse degrees of freedom. The constant A is determined by the grid type. The state with the minimum energy is achieved for a volume-centered grid for which $A\simeq 1.4$. For other types of grids the constant value A will be somewhat less. Let us choose the dependence of the internal energy in the form [6] satisfying to both asymptotic (3) and (4) in order to simplify further calculations:

$$U_0(n, T_{\parallel})=\frac{T_{\parallel}}{2}+U_c(n, T_{\parallel})=\frac{T_{\parallel}}{2}-e^2(\pi n)^{1/3}\sqrt{\frac{e^2(\pi n)^{1/3}}{T_{\parallel}+e^2(\pi n)^{1/3}}}. \qquad (5)$$

Just after fast acceleration the correlative energy of an electron beam U' is small in comparison with $e^2n^{1/3}$. Really the relative positions of electrons practically do not change during the time of acceleration. Therefore correlative energy expressed in the $e^2n^{1/3}$ units does not change and equals the correlation energy calculated by (3) near a cathode surface where the condition of a weak nonideally of plasma is fulfilled ($T_{\parallel}\gg e^2n^{1/3}$). For the usual cathode temperature $T_k=0.1$ eV, in this case we can neglect in equation (2) by values U' and $T_k^2/2W$ in comparison with $U_0(n, T_{\parallel})\simeq e^2n^{1/3}$ (see (5)). As a result if $T_k^2/2W\ll e^2n^{1/3}$ we have

$$0=\frac{T_{\parallel}}{2}-e^2(\pi n)^{1/3}\sqrt{\frac{e^2(\pi n)^{1/3}}{T_{\parallel}+e^2(\pi n)^{1/3}}}. \qquad (6)$$

The solution of this equation is

$$T_{\parallel}\simeq 1.9\ e^2n^{1/3}. \qquad (7)$$

We carried out the numerical simulations to get a more accurate dependence of the electron gas internal energy upon temperature. The calculated dependence of the electron gas internal energy upon temperature is shown on Fig. 1 for region:

$$0.1\ e^2n^{1/3}<T_{\parallel}<2e^2n^{1/3}.$$

More high value of correlative energy for the random deposition in comparison with the volume-centered grid is explained by

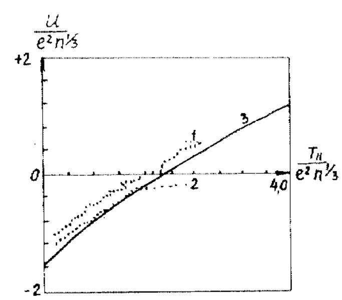


Fig. 1. Dependence of the internal energy of equilibrium electron gas on temperature. ······ is a result of computer simulations (1—for the random initial disposition, 2—for the volume-centered grid), ——— is the result of calculation by formula (5).

«freezing» of the transverse coordinate fluctuations in the longitudinal magnetic field. That gives the sufficient correlation energy increase and hence the additional corrections in (5) and (7). In this case after the end of the longitudinal-longitudinal relaxation the electron temperature in the rest frame is

$$T_{\parallel}\simeq 1.6\,e^2n^{1/3}. \qquad (8)$$

Time of the longitudinal-longitudinal relaxation have the same order as a period of the plasma oscillations. In contradistinction to the transverse-longitudinal relaxation the longitudinal-longitudinal one is not suppressed by a magnetic field, and as a rule it defines the longitudinal temperature. Begun from the electron energy 100 eV and the current density 4 mA/cm^2 the second item in (1) is equal to the first one and $T_{\parallel}\simeq 1.5\cdot 10^{-4}$ eV.

The adiabatic acceleration

We introduce the parameter of adiabaticity of acceleration λ as a relative change of the longitudinal temperature due to acceleration during a plasma oscillation period:

$$\lambda = \frac{1}{T_\parallel}\frac{dT_\parallel}{dt}\frac{1}{\omega_p}. \qquad (9)$$

During the acceleration of electrons in a gun operating in the «mode 3/2» (and more than that in the gun operating in the mode of emission limitation) the adiabaticity criterion $\lambda \ll 1$ is not satisfied. Really for Pearce gun the parameter λ is equal to $2\sqrt{2}$ and does not change during the acceleration [6]. In the case of sufficiently slow acceleration $\lambda \ll 1$ the plasma oscillations have enough time to mix the density fluctuations, and the increasing of the longitudinal velocity spread due to the longitudinal-longitudinal relaxation is suppressed by a following acceleration.

Let us find the change of the longitudinal electron temperature during slow (adiabatic) acceleration. The change of electron internal energy at acceleration on dW is

$$dE = -T_\parallel \frac{dW}{2W} + \frac{1}{3}U\frac{dn}{n} = T_\parallel \frac{dn}{n} + \frac{1}{3}U\frac{dn}{n}. \qquad (10)$$

where $U(T_\parallel, n) = U_c(T_\parallel, n) - U_c(0, n)$. Hence, we have a differential equation describing the temperature variation during acceleration [6]:

$$\left(\frac{1}{2} + \frac{\partial U}{\partial T_\parallel}\right) dT_\parallel = \left(T_\parallel + \frac{1}{3}U\right)\frac{dn}{n}. \qquad (11)$$

Fig. 2 shows dependencies of the longitudinal temperature (according to (11)) upon the current for parameters of ion storage

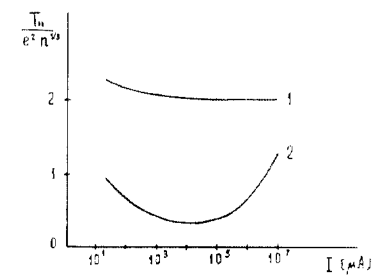


Fig. 2. Calculated dependence of the longitudinal temperature of electron beam on beam current at typical parameters of ion storage rings ($W = 100$ keV, $T_k = 0.3$ eV) for fast (*1*) and slow (*2*) acceleration.

rings with electron cooling (electron energy up to 100 keV, initial electron temperature is of order 0.3 eV). At the same figure are shown corresponding dependencies for the usual (fast) acceleration in the Pierce gun. It is necessary to emphasize, that adiabatic acceleration means the usual acceleration in the Pierce gun up to the energy W_{min} and following much slower acceleration up to full energy, W_{min} is defined by conditions of obtaining of the essential current. Therefore the temperature at Fig. 2 is a function of the full current and does not depend on beam radius.

Description of the installation

The temperature relaxation studying in electron beam was carried out at the modified variant of «Solenoid model» installation

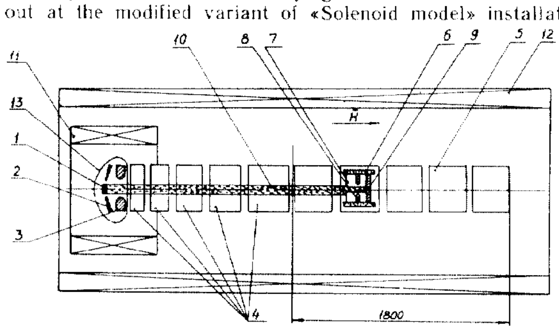


Fig. 3. The scheme of the experimental installation.

[6]. A general scheme of the installation is given on Fig. 3, and main parameters are the following:

Electron energy	50 — 800 eV
Electron beam current	0.01 — 10 mA
Radius of electron beam	1 mm
Magnitude of magnetic field	1 — 4 kG
Solenoid length	2.88 m
Vacuum	$5\cdot10^{-8}$ Torr

The electron gun (13), placed in the magnetic field of the solenoid (12) and electron beam moves along the solenoid axis to the energy analyzer (6), that is an electron collector at the same time. After fast acceleration the electron beam passes through the adiabatic acceleration structure of five pipes with 16 mm diameter.

In order to realize the adiabatic acceleration, the potential of the accelerating structure was distributed along the beam axis in accordance with dependence $\varphi \sim Z^{4/3}$. This one corresponds to the constant value of λ-parameter [6]. The full length of the adiabatic structure was selected to provide more slow acceleration, than in the Pierce gun. It corresponds to condition $\lambda < 1$, which is necessary for damping of the longitudinal-longitudinal relaxation during the acceleration. To simplify the current control, the gun anode and the adiabatic structure have the same high voltage source. The voltage between cathode and anode determines beam current.

At the fast acceleration regime all structure for the adiabatic acceleration has zero potential, that converts it to usual drift space. As in the previous case, the voltage between cathode and anode determines beam current, but the acceleration up to full energy takes place immediately in the gap between the anode and the first pipe of structure.

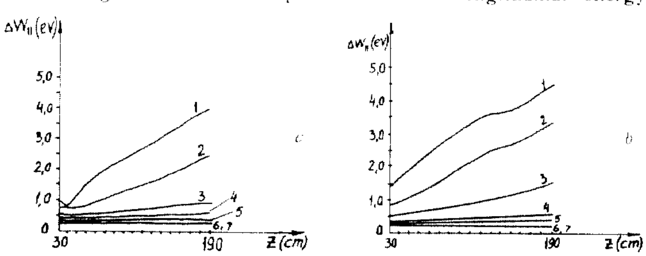
It is necessary to note, that acceleration in this case will be faster than in Pierce gun, and parameter λ will be lager, then Pierce one ($\lambda = 2\sqrt{2}$). For beam current 6 μA and energy 1500 eV $\lambda_{max} \simeq 60$.

After adiabatic structure the beam passes through the drift space (5), which consists of five pipes, with 10 mm radius. The energy analyzer (6) is placed inside these pipes and can move along their axis. All these pipes usually has zero potential, if it is not emphasized especially.

The scheme of measurement of the longitudinal temperature is the same as described in [6]. This method is based on the analysis of the energy spread in a fine electron beam cut from the main beam with small hole (0.025 mm radius). The analysis is performed with decelerating electric field of the analyzer diaphragm.

Experimental results

Transverse-longitudinal relaxation. Data obtained in experiments on the NAP-M and the «Solenoid model» [6] gives only indirect information about dependence of the longitudinal temperature upon coordinate along the beam, because the energy spread is measured in the single point at the end of the drift space. Using of the moving energy analyzer allows to carry out direct observation of the transverse-longitudinal relaxation process in the electron beam. Fig. 4 shows the dependence of the longitudinal energy



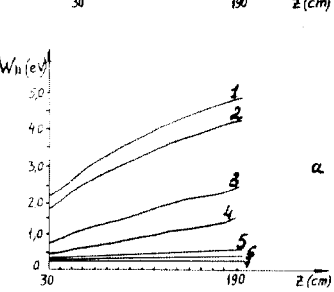


Fig. 4. Dependence of the longitudinal energy spread on coordinate at various beam current: *7* — 100 μA, *6* — 400 μA, *5* — 800 μA, *4* — 1600 μA, *3* — 3200 μA, *2* — 6400 μA, *1* — 9000 μA for various magnetic field: $H = 1$ kG (*a*), $H = 2$ kG (*b*), $H = 3$ kG (*c*).

spread upon the coordinate Z for various magnitudes of magnetic field and beam currents. Slope of the curve directly corresponds to the rate of transverse-longitudinal relaxation. The strong damping of the relaxation by the longitudinal magnetic field is clearly seen. The irregularity of the experimental curves at large currents is connected with the considerable transverse beam displacement due to excitation of ion-electron transverse oscillations [7]. The ionization of residual gas leads to the ion accumulation inside the electron beam right up to the equality of ion and electron densities [7].

To check the dependence (12), at first proposed in Ref. [6], the numerical steering of the constants C_1, C_2, C_3 to experimental data was fulfilled by the least squares method.

$$\frac{dT_\parallel}{dz} = \frac{\pi e^3 j}{W} \sqrt{\frac{m}{T_\perp}}\, C_1 \exp\left\{ - \frac{C_2 e^2}{\rho_\perp (e^2 n^{1/3} + C_3 T_\parallel)} \right\}. \qquad (12)$$

The results show that experimental data is in satisfactory agreement with formula (12) for the following values of constants:

$$C_1 = 7.4^{+2.6}_{-1.7} \quad C_2 = 0.35^{+0.18}_{-0.12} \quad C_3 = 0.35^{+0.18}_{-0.12}.$$

The poor accuracy of $C_1 - C_3$ (up to 50% by χ^2-criteria) is explained by the weak dependence of formula (12) under simultaneous varying of the constants. Let us note, that if it is necessary to estimate the relaxation rate out of the accepted region (magnitude of magnetic field 1—3 kG, the electron density $10^6 - 10^9$ cm^{-3}, $T_\parallel \simeq 0.1$ eV) formula (12) can be used with the certain care. The considerable difference between $C_1 - C_3$ and previous results (see [6]) is connected with the strong dependence of the expression (12) upon initial temperature. In the first experiments the temperature was measured only at the end of the drift space and the initial temperature was unknown. For the calculations of initial temperature was used $T_{\parallel init} = 2e^2 n^{1/3}$ that has led to mistakes [6].

Longitudinal-longitudinal relaxation. For direct observation of the longitudinal-longitudinal relaxation (with damping of the transverse-longitudinal relaxation by strong magnetic field) the electron beam after forming in the electron gun was transported on low energy ($\simeq 50$ eV) to the first gap between pipes attainable for the moving analyzer, (see Fig. 3), where beam was accelerated to the full energy (800 eV). Fig. 5 shows the dependence of the longitudinal temperature upon the time from the moment of fast acceleration in dimensionless variables. It is clearly seen that temperature relaxation occur for the time the same as the plasma oscillation period. For comparison the results of computer simulation of the longitudinal-longitudinal relaxation are shown on the same figure. The effect of the final temperature decreasing for

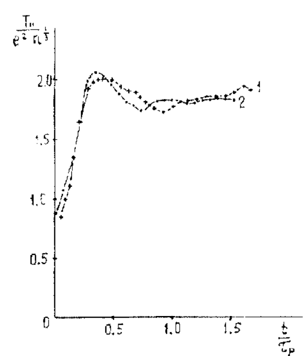


Fig. 5. Dependence of the longitudinal electron temperature on time after fast acceleration. + + + + is a result of computer simulation; · · · · is the experimental plots. $I = 300$ μA, $W = 800$ eV, $n_e = 3.73 \cdot 10^7$ cm^{-3}, $v = 1.6 \cdot 10^9$ cm/c.

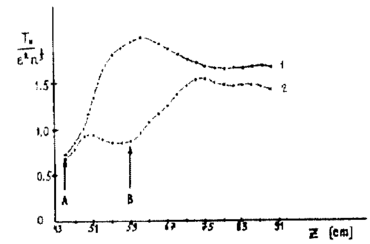


Fig. 6. Dependence of the longitudinal electron temperature on coordinate for fast acceleration (*1*) and acceleration with drift space (*2*). $I = 100$ μA, $W = 800$ eV. *A* is the first acceleration gap, *B* is the second one.

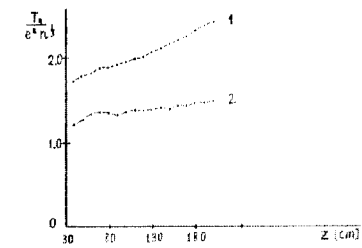


Fig. 7. Dependence of the longitudinal electron temperature on coordinate after fast (*1*) and slow (*2*) acceleration $I = 200$ μA, $W = 470$ eV.

more slowly acceleration is shown on the Fig. 6. The upper curve corresponds to the fast acceleration (at point *A*), the lower one is obtained at two-step acceleration of the beam with the same parameters. At first it is the acceleration up to the intermediate energy 250 eV (at point *A*), then the drift (15 cm), where relaxation of temperature occurs, after that acceleration up to the full energy (at point *B*) and observation of the following relaxation. Fig. 7 shows the dependence of the longitudinal temperature upon distance along the drift space after fast and slow (adiabatic) acceleration in the electron gun. The difference in initial temperatures is connected with damping of longitudinal-longitudinal relaxation by adiabatic acceleration. The regular growth of temperature along coordinate is connected with the transverse-longitudinal relaxation. This figure clearly demonstrates the growth of the **transverse** -longitudinal relaxation rate with the temperature growth.

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