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Abstract

The velocity distribution of electrons in the intense beam, which is produced by an electrostatic accelerating device, possesses a substantial anisotropy: the spread of electrons over longitudinal velocities is much less than that over transverse velocities. When such a beam moves through the drift chamber, the longitudinal and transverse temperatures equalize. This process becomes much slower if the beam is generated and transported in the devices with longitudinal magnetic field. The present paper deals with a study of this effect.

The intense electron beams with low temperature of particles are of interest for a great variety of applications, for example, low-noise electronics and so on. In recent time the charged particle accelerator physics has also interested in such beams in connection with the development of the electron cooling method /1/. The efficiency of this method - the time decrements of emittance of the cooled heavy particles and their momentum spread - depends substantially on the temperature of particles in the cooling electron flux.

In the study of the properties of the electron cooling, it has been found out a characteristic feature of the distribution function of electron velocities in the intense beam which is accelerated in an electrostatic device (the gun): after acceleration the longitudinal-velocity spread of electrons is much less than the transverse-velocity one /2/. Indeed, neglecting the electron interaction and using the energy conservation law and the conditions for transformation of the longitudinal component of momentum, we find

$$T_{\parallel} = \frac{\Delta p_{\parallel}^2}{2m} = \frac{T_{\perp}^2}{2\beta^2\gamma^2 mc^2} \xrightarrow{\beta \ll 1} \frac{T_{\perp}^2}{4W} \qquad (1)$$

where $\Delta p_{\parallel}$ is the electron momentum spread in the system wherein the average velocity v is equal to zero, m is the electron mass, $T_{\perp}$ is the kinetic energy of electrons prior to acceleration; $\beta = v/c$, $\gamma = (1-\beta^2)^{1/2}$ and $W = mv^2/2$ at $v \ll c$. This result is none other than the consequence of the Liuville theorem: conservation of the longitudinal phase volume of the beam during acceleration results in reducing, proportionally to the decreasing particle density, the spread of the longitudinal component of the momentum. In the nonrelativistic case, to which we confine ourselves in the following, this gives

$$v \Delta v = Inv \quad \text{or} \quad W T_{\parallel} = Inv \quad . \tag{2}$$

The effect of such a "flatness" of the velocity distribution function of electrons is very strong; so, for thermo-emission sources, when accelerating the electrons up to an energy of the order of 30 keV, we obtain, correspondingly:

$$T_{\perp} \approx 0.1 \text{ eV}, \; T_{\parallel} \approx 10^{-7} \text{ eV} \approx 10^{-3} \text{ K}^{\circ}.$$

However, at so low longitudinal temperatures it is already impossible to ignore the electron interactions, that imposes the limitation on a minimally possible longitudinal temperature of the beam after acceleration /3/.

It has turned out that this characteristic feature of the distribution function enables one to increase substantially the efficiency of electron cooling by an electron beam which travels in a strong magnetic field (magnetized flux) /3/.

The efficiency of electron cooling grows linearly with lengthening the cooling section if the properties of the electron flux remain unchangeable. In connection with this, the natural question arises: how long the "flatness" of the distribution function is conserved while travelling the electron beam through the long drift section.

In Ref./4/ an attempt is made to obtain, in terms of the thermodynamic approach, a variation of the transverse emittance of the beam (transverse temperature) in an ideal Pierce gun, which is caused by the (electrostatic) electron interaction. As is shown in that paper, this variation is rather weak. Unfortunately, the author was not concerned with the variations in longitudinal temperature, whereas for the problem of electron cooling (the cited paper deals with just this problem) the longitudinal temperature plays a dominant role /1/.

In the present paper the experiments on temperature relaxation in a magnetized electron flux are described. The experiments have been performed with the beam of electrons whose energy has varied from 200 eV to 1000 eV. The electron density has ranged from 10^{7} cm^{-3} to 10^{9}cm^{-3}, that has corresponded to the beam current from 50 μA to 10 mA.

1. Basic ideas

Let us discuss the basic ideas underlying our experiments. They have mainly been formed as a result of the electron cooling method development and are described in more details in the review article /3/ and in the literature cited there. When the electron beam travels through the vacuum chamber, its longitudinal temperature grows because of the internal electron scattering and the energy transfer from the transverse to longitudinal velocities will occur until the longitudinal and transverse temperatures become equal. In the case of a weak magnetic field (non-magnetized beam), such a relaxation is readily calculable /5/:

$$\frac{dT_{\parallel}}{dz} = \frac{\pi e^{3} j L k}{W} \cdot \sqrt{\frac{m}{T_{\perp}}} \quad , \tag{3}$$

where $z = vt$ is the longitudinal coordinate, j is the current density, L is the Coulomb logarithm, k is a numerical coefficient of the order of unity, which depends on the character of the velocity distribution function of electrons. For the Maxwellian distribution function and $T_{\parallel} \ll T_{\perp}$ this coefficient is equal to 0.87. In this case, the longitudinal temperature increases rather rapidly: so, the electron beam with an energy of 400 eV is almost completely thermalized at a current density of 0.5 A/cm^2 on the 3-m length (characteristic parameters of the experiment under discussion).

In the longitudinal magnetic field the energy transfer from the transverse phase space to the longitudinal one is somewhat complicated because of the limited character of the transverse displacement of electrons, and sharply decreases if

$$\rho_\perp \lesssim r_{min} , \qquad (4)$$

where $\rho_\perp = (2T_\perp mc^2)^{1/2}/eH$ is the Larmor radius of transverse rotation of electrons in a magnetic field H; r_{min} is the shortest distance between the scattered particles. In the case of a strong magnetic field, the electron motion is representable as the motion of Larmor circles with low longitudinal velocity and the energy transfer from the transverse motion to a longitudinal one occurs due to the violation of adiabatic collisions of the Larmor circles. At a low electron density the minimum distance between electrons is determined by the longitudinal temperature, $r_{min} \approx e^2/T_\parallel$. With this condition substituted into eq.(4), we obtain

$$\rho_\perp \lesssim \frac{e^2}{T_\parallel} \qquad (5)$$

In the case of a low longitudinal temperature and a high electron density, the minimum distance between the electrons is dictated by the inter-particle distance and the condition (4) yields

$$\rho_\perp \lesssim n_e^{-1/3} \qquad (6)$$

The use of both equations, (5) and (6), determines the necessary conditions to suppress the transversely-longitudinal relaxation. For the beam with the same parameters as in the

preceding example and at 0.1 eV these conditions require that H $\gtrsim$ 1 kGs and $T_\parallel <$ 10^{-4} eV. Therefore, for the beam relaxation to be depressed as low temperature as possible is needed after acceleration. Near the cathode the electrons have a high density, low average velocity, and a high longitudinal temperature $T_\parallel$. In this case, the conditions (5) and (6) violate and the relaxation can proceed fastly.

The other effect which leads to increasing the longitudinal temperature of the beam is a longitudinally-longitudinal relaxation. If the acceleration proceeds fastly compared to the period of plasma oscillations of electrons, then the relative distances between electrons do not change during acceleration and the initial state with chaotic location of circles, which slowly move, one respect to another, is conserved. This state then relaxes to that with the longitudinal velocity distribution, which corresponds to an approximate equality

$$T_\parallel \approx \frac{T_\perp^2}{4W} + e^2 n^{1/3} . \qquad (7)$$

The relaxation time is short and is equal, in order of magnitude, to the plasma oscillation period. For $T_\perp \approx$ 0.1 eV (cathode temperature) and W = 400 eV both terms in (7) have the same value already at $n_e \approx 10^5$ cm^{-3} ($j \approx$ 15 µA/cm^2). With a further growth of the current density the contribution from the second term becomes dominant.

In the case of a slow acceleration of electrons, plasma oscillations succeed in intermixing the density fluctuations and the longitudinal temperature after acceleration is determined by the expression (1). The condition for adiabaticity of acceleration relative to plasma oscillations is of the form

$$\lambda \equiv \frac{1}{\omega_p(z)\cdot T_\parallel}\cdot\frac{dT_\parallel}{dt} \ll 1 \quad , \qquad (8)$$

where $\omega_p(z)$ is the plasma frequency at the point z. It seems to be interesting that even during acceleration of the electrons in the gun, which operates in the "law 3/2" (space charge limited emittance), the adiabaticity condition is not satisfied. Indeed, if the electron interaction is neglected, it follows from (2) that

$$\frac{1}{T_\parallel}\cdot\frac{dT_\parallel}{dz} = -\frac{1}{W}\cdot\frac{dW}{dz} \quad . \qquad (9)$$

Substituting this relation into (7) and taking into account the dependence of W and $\omega_p(z)$ on z for the Pierce gun (the "law 3/2"), we find that $\lambda_{Pierce} = 2\sqrt{2}$. Inparticular, only one half of the plasma oscillation period will occur during acceleration up to 400 eV.

The variation in longitudinal temperature during acceleration is described by the equation

$$\frac{dT_\parallel}{dz} = -\frac{T_\parallel}{W}\cdot\frac{dW}{dz} + \frac{\pi e^3 j L k}{W}\cdot\sqrt{\frac{m}{T_\perp}} \quad , \qquad (10)$$

if the internal electron scattering (3) is taken into account and the influence of a magnetic field is ignored. The solution of the above equation is the following:

$$T_\parallel(z) = \frac{T_c^2}{4W} + \pi e^3 j L k\sqrt{\frac{m}{T_\perp}}\cdot\frac{z}{W} \quad , \qquad (11)$$

where $T_c = T_\parallel(0)$ is the cathode temperature.

For j = 0.5 A/cm^2, W = 400 eV and z = 0.5 cm, the second term in eq.(11) equals $1.2\cdot10^{-4}$ eV, and exceeds the first by a factor of about 10. A magnetic field is capable to change

substantially this relation if the magnetization conditions (5) and (6) are satisfied. However, the very conditions, represented as rough inequalities, allow one to evaluate the situation rather approximately, in particular near the cathode, where the density and longitudinal temperature of the beam are high. Thus, the question on the achievability of a low longitudinal temperature of the beam after acceleration should be studied experimentally.

2. Description of the experiments

The experiments have been carried out at an electron cooling device /6/, in which the electron beam produced by a three-electrode gun, is transported in a longitudinal magnetic field with a strength up to 1.4 kGs. Having passed through the 3-m-long drift section, this beam enters an analyzer (Fig.1). The pressure of residual gas in a vacuum chamber 4 was lower than 10^{-8} Torr.

The gun cathode was thermoemissive, oxide and had 2 mm in diameter. Its negative potential U_c dictated the energy of the beam. It was possible to change the potential of the first anode from U_c to +3 kV, that allowed the regulation of the beam current. The second anode had the zero potential (it was grounded).

The strength of longitudinal magnetic field in the gun region can be varied relative to the field level in the remaining part of trajectory within 0.5÷4.5 kGs with an additional short solenoid 2. At the entrance of the analyzer (Fig.2) the beam 1 hit a collimating diaphragm 3 whose central hole was 0.1 mm in diameter. The diaphragm had a positive potential of the order of 30 V. First, this enabled one to suppress the secondary elec-

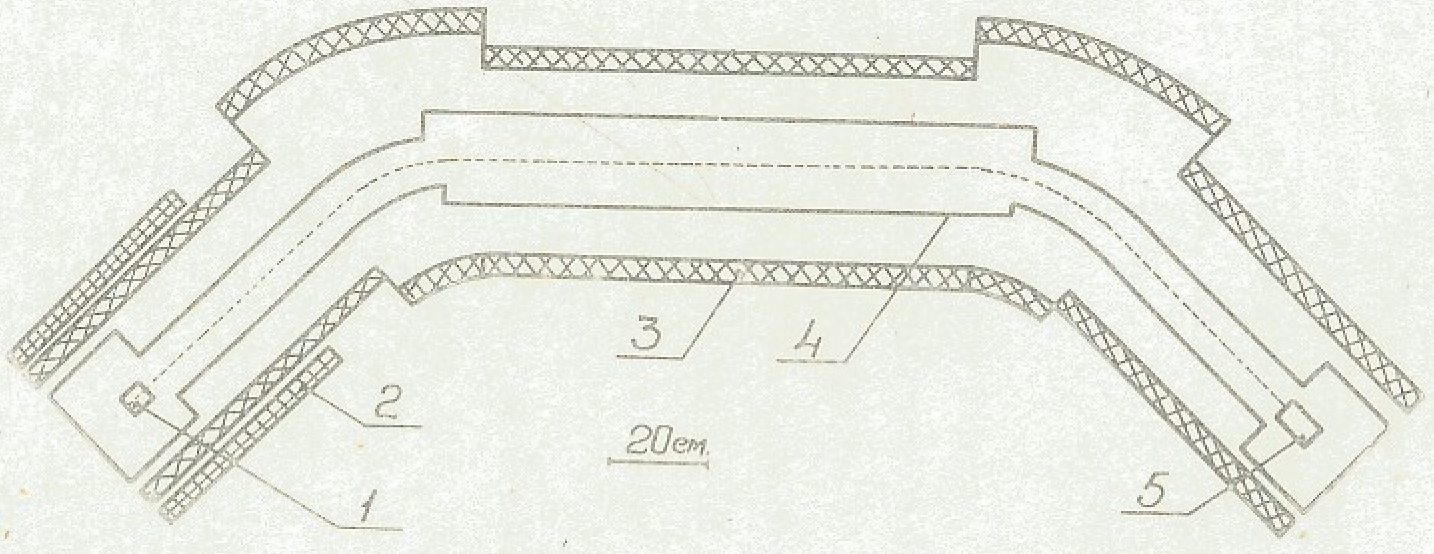

Fig.1 Layout of the experimental device: 1 - gun, 2 - solenoid of the additional magnetic field in the gun region; 3 - basic solenoid; 4 - vacuum chamber; 5 - analyzer.

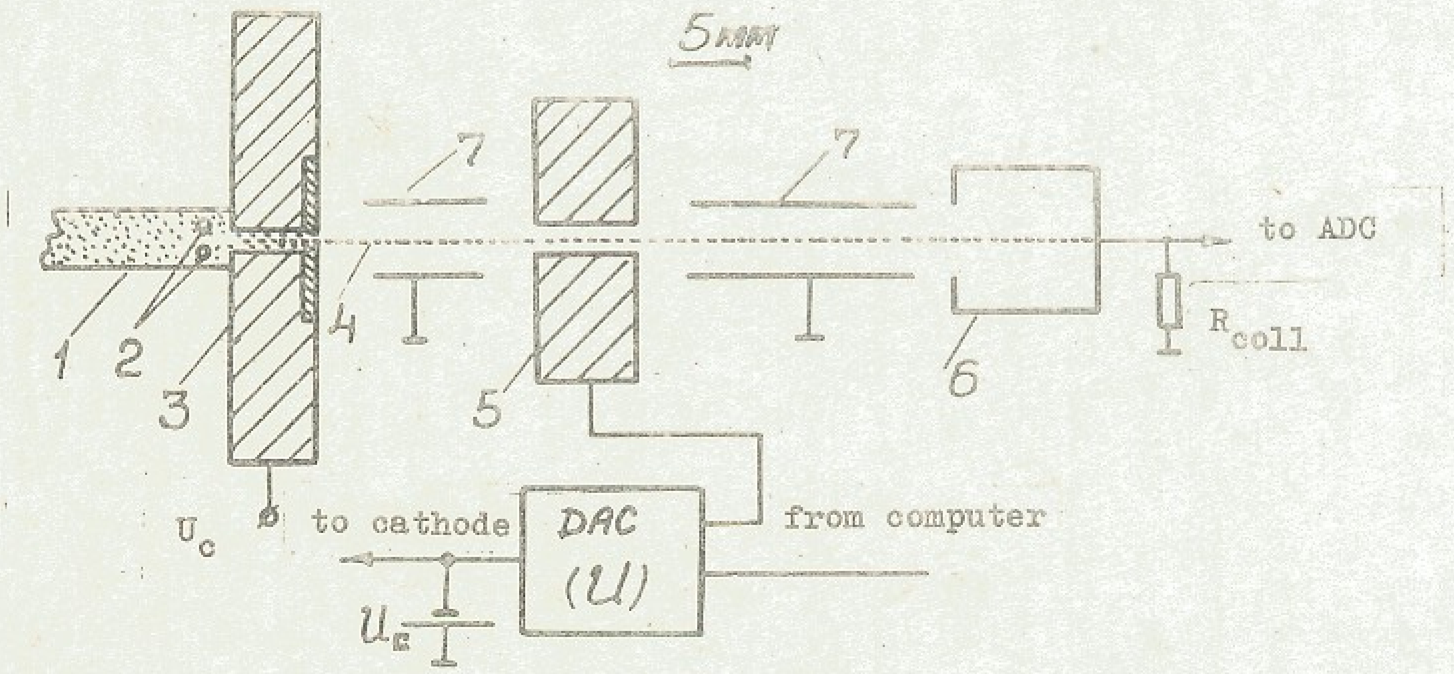

Fig.2. Layout of the analyzer: 1 - electron beam; 2 - beam-position indicators; 3 - collimating diaphragm; 4 - the beam to be analysed; 5 - analyzing diaphragm; 6 - collector; 7 - screening plates.

tron emission and, second, to lock the residual gas ions in the beam (see below). The beam position at the analyzer entrance was controlled by the current signal of two pairs of parallel wires 2 of 0.3 mm in diameter. This device had a small design defect: when the beam came to the wires, they were heated and deformed, partially closing the diaphragm hole. This defect was noticeable at currents higher than 1 mA. It is the effect that caused the spread in the measurements when the beam was scanned over the collector (Fig.3, below). However, this defect did not influence the results of longitudinal temperature measurements carried out in stationary conditions but, most likely, improved the situation on the space charge in the collimated beam (usually, the current to the collector did not exceed 3 μA). The collimated beam was decelerated in the longitudinal electric field of an analyzing diaphragm 5 and came to a collector 6 connected to the zero potential ("earth") via a resistor $R_{coll} = 10$ kO ÷ 10 MO. The voltage on this resistor enabled the beam current to be measured. The potential of diaphragm 5 could be ranged within given limits , from -30 to +30 V relative to the cathode potential, that made it possible to analyse the energy of the collimated beam. The change in the potential of the diaphragm was performed by the computer with a digital-to-analog converter with the cathode potential. The measured dependence of the collector current $I_{coll}(\mathcal{U})$ on the potential $\mathcal{U}$ of the analyzing diaphragm was processed by a computer. It computed, based on the integral spectrum measured, the differential spectrum $dI_{coll}/d\mathcal{U}$, its width $\delta\mathcal{U}$, and the voltage of analyzing diaphragm $\Delta\mathcal{U}$, which corresponds to the half of the intensity of the collimated beam.

The systematic errors, which occur with such a method of

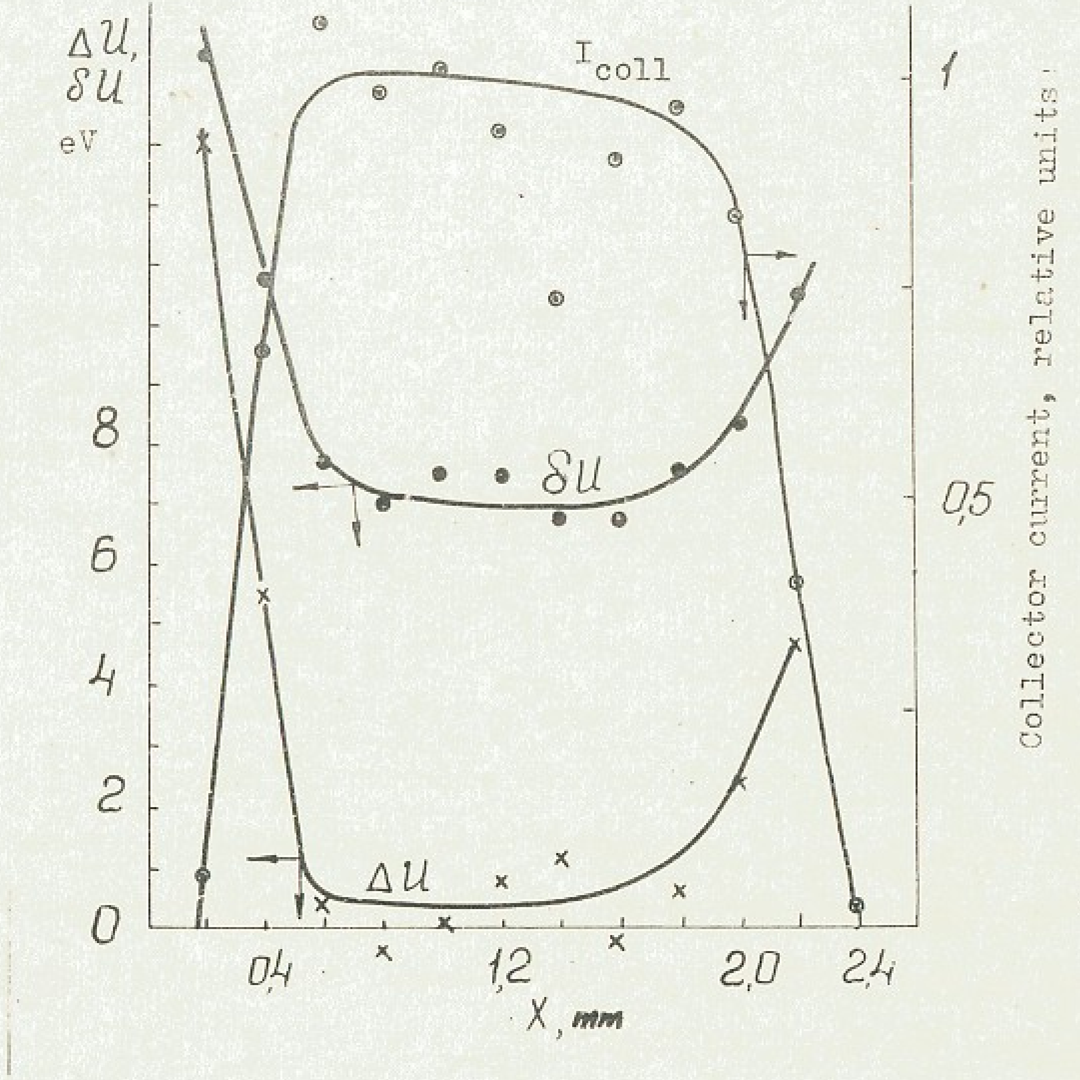

Fig.3. The results of scanning over the entrance hole of the analyzer by the beam: the dependence of the currents in the collector (current density of the beam), the width ofdifferential spectrum $\delta\mathcal{U}$ and of the value of its centre of gravity $\Delta\mathcal{U}$ on the transverse shift of the beam at the entrance of the analyzer.

analysis of a longitudinal temperature of the beam, are mainly connected with the variation of the potential inside the analyzing diaphragm and also with the shift of electron energy in the collimated beam because of its space charge. Both errors in the experiments under description are negligibly small. In addition, there can exist, in the beam, the longitudinal velocity spread associated with "optic" perturbations of the beam in the gun (the influence of anode aperture holes) and bearing no relation to the effect under study. This spread is of "aperture" character (increases with moving off from the system axis) and can be significant for the diode and triode guns with no accompanying magnetic field. In the guns with the strong magnetic field guidance such a spread is strongly suppressed /7/. For a complete elimination of the errors associated with this spread, a control scanning of the beam over the entrance hole of the analyzer (Fig.3) was performed in each series of measurements and for temperature measurements the "unperturbed" region near the beam axis was chosen. The scanning was carried out by introducing a transverse magnetic field into the drift section.

Fig.4 shows the typical curves of the functions of I_{coll} (U). Fig.5 is an original demonstration of the sensitivity of the longitudinal temperature analysis described above, in which two differential spectra are presented. These spectra were obtained for the beam with the same current, I = 90 μA, but produced by the gun, which operates, in one case, in the limited emission regime and, in the other case, in the "law 3/2". In the second case, the mean electron energy in the beam is higher because of the formation, near the cathode, a minimum potential which reflects an "extra" current from the cathode and is equal to /8/

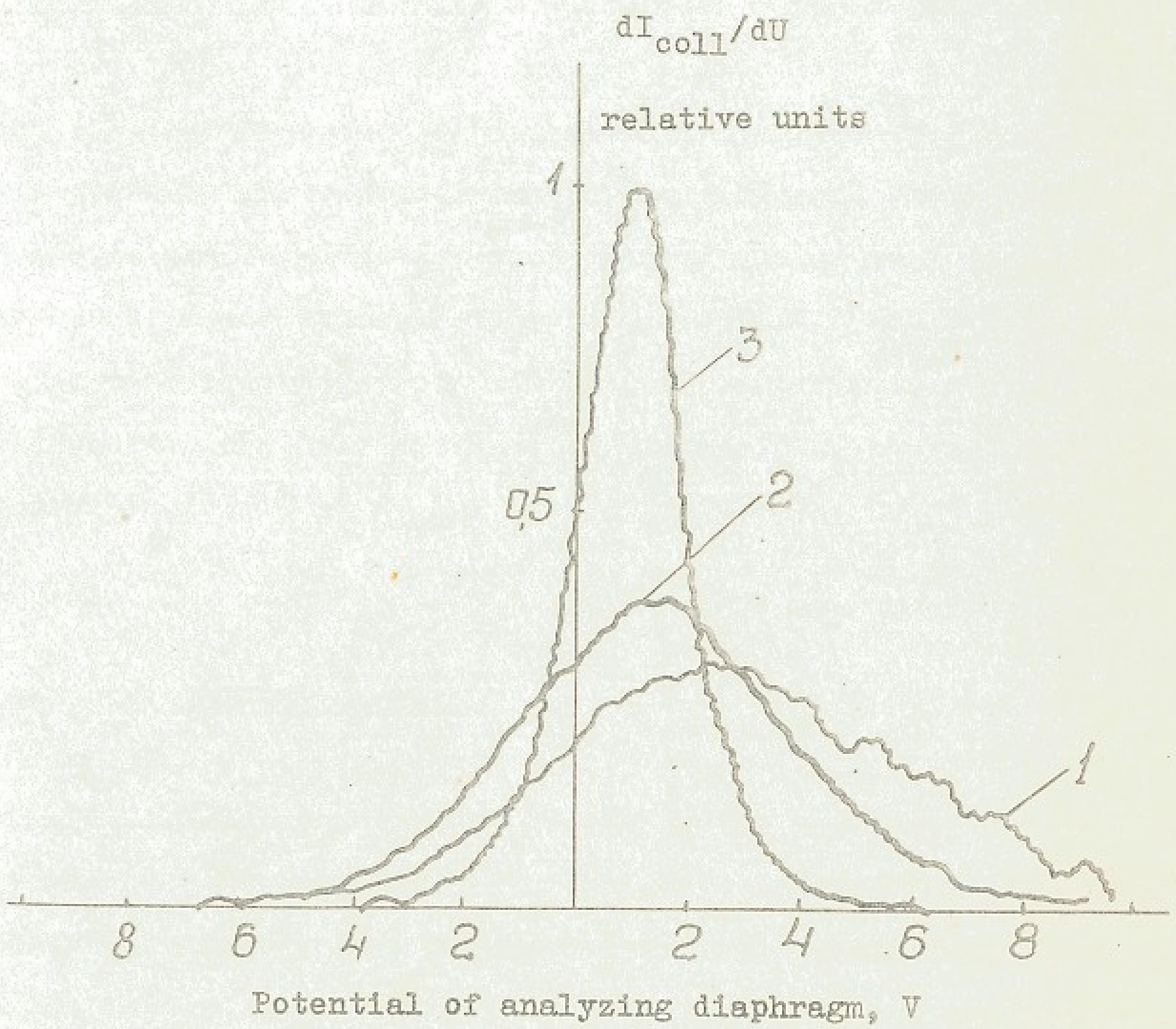

Fig.4. The dependence of dI_{coll}/dU on the potential of the analyzing diaphragm for various values of the system's magnetic fields:

Number of curve	Magnetic field, kGs		
	on the drift section	in the gun region	spectrum width, eV
1	1	0.6	4.3
2	1	1	3.1
3	1	3.4	1.3

The current beam is 2.4 mA, the electron energy is 400 eV.

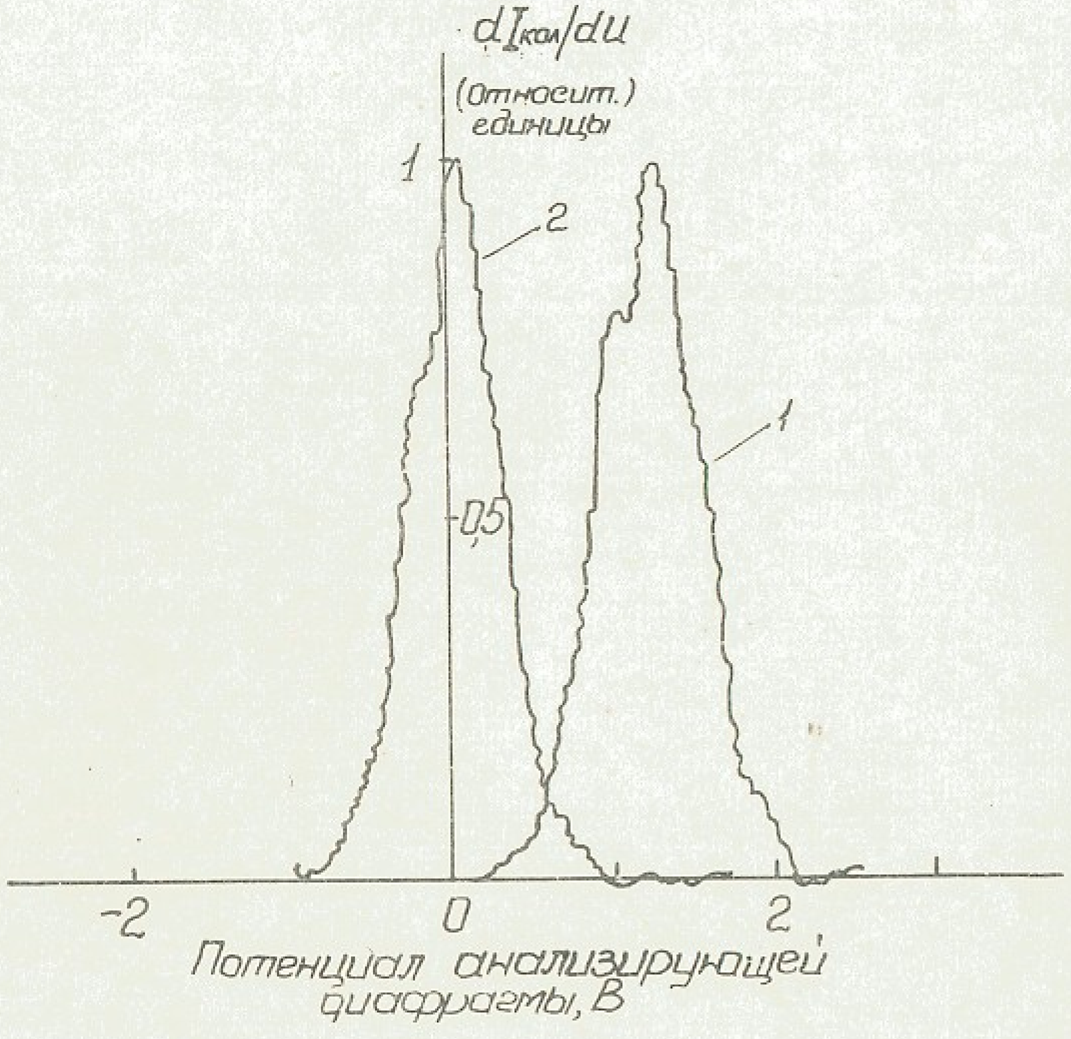

Fig.5. The influence of the gun regime on the longitudinal velocity distribution of electrons: 1 - regime of limited emission; 2 - regime of current limitation by a space charge ("regime 3/2"). The current beam is 90 μA, the energy is 400 eV, the magnetic field is 1 kGs throughout.

$$U_{min} = \frac{T_c}{e}\cdot \ln\frac{I_{max}}{I} \quad . \qquad (12)$$

Here I_{max} is the saturation current of the cathode, I is the beam current. Calculated from (12) on the basis of the results in Fig.5, the longitudinal temperature of electrons near the cathode is equal approximately to 0.2 eV.

The differential spectrum width is connected to a longitudinal temperature at the entrance of the analyzer by the relation inverse to (1):

$$e\cdot\delta U = 2\sqrt{W T_\parallel} \quad . \qquad (13)$$

3. Experimental results

1. The first and major result of the experiment is a strong dependence of the longitudinal temperature of the beam after its passage through the drift chamber on the value of magnetic fields in the device. The considerations mentioned in the preceding part of the paper allow the assumption to be made that in the non-magnetized beam the value of spectral width δU should grow with current density as $j^{1/2}$. This follows from the comparison of formulas (11) and (13); curve 1 in Fig.6 is constructed basing on these formulas. The experimental curves presented in Fig.6 are of characteristic form: in the region of low currents there exist a plateau whose length depends on the magnitudes of fields. At high enough currents the curve reaches the asymptotic $I^{1/2}$, that corresponds to beam heating in the gun in the drift section (3,11). The existence of the plateau on the experimental curves points to a strong influence of the longitudinal magnetic field which suppresses the process of transversely-longitudinal tem-

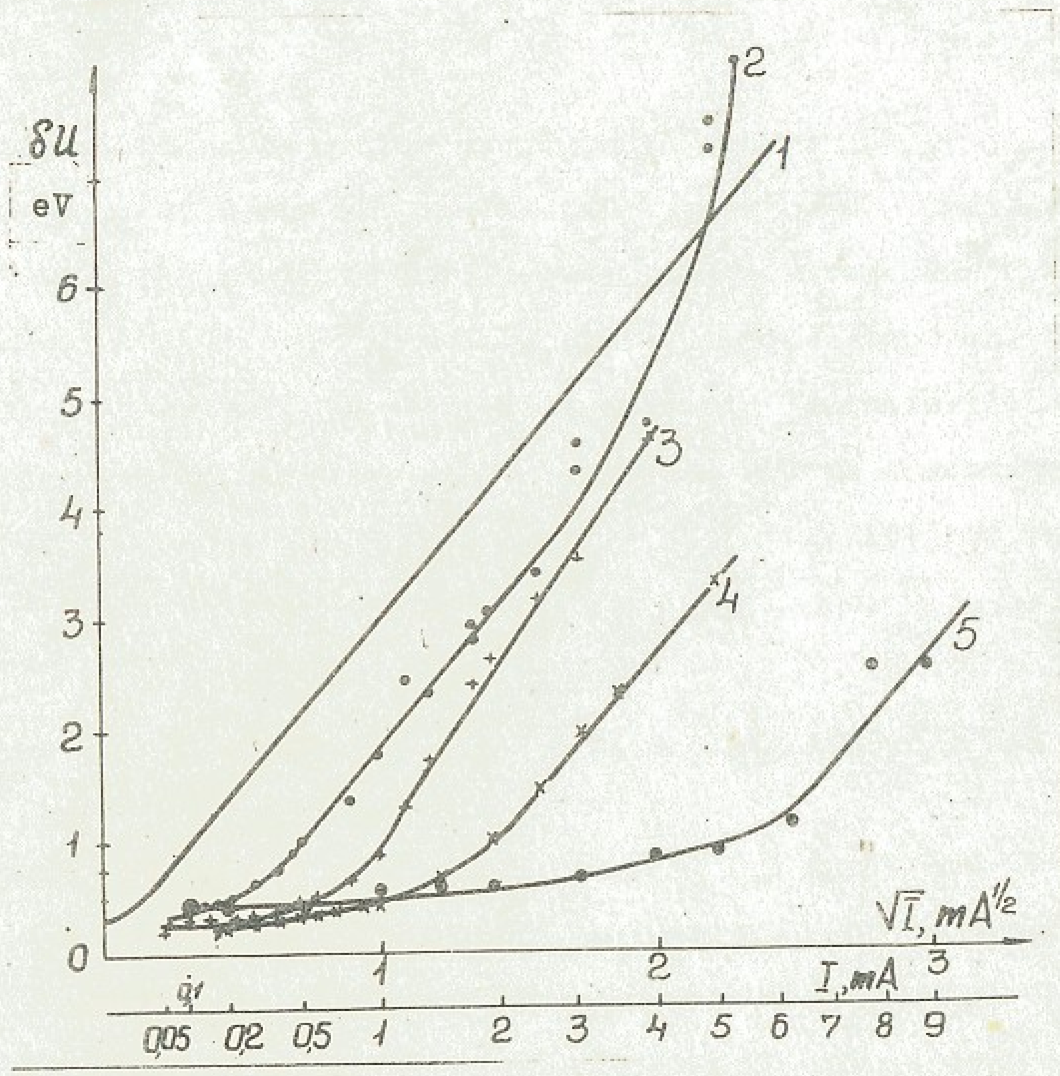

Fig.6. The dependence of the specrtum width δu on the parameters of the electron beam and of the device.

Number of curve	Magnetic field, kGs		Electron energy, eV
	on the drift section	in the gun region	
1	Calculated curve (formula (11))		400
2	1	1	400
3	1.4	1.4	400
4	1.2	3.85	400
5	1	3.2	1200

perature relaxation. Its length grows with increasing the field (curves 2 and 3). The minimum values of the spectrum width, in the experiments were 0.2 V, that was close to T_c/e.

2. The possibility for independent tuning of magnetic fields in the gun region and in the drift section has made it possible to reveal a strong influence of the gun magnetic field on the relaxation process. The results in Fig.4 and curves 4 and 5 in Fig.6 clearly show an important role of the magnetic field H_c in the gun. The plateau length in such cases is much large compared to that on curves 2 and 3. Such a lengthening of the plateau with a growth of the magnetic field in the gun is accounted for by the influence of the two effects, whose relative contribution is difficult to separate. The first effect is a suppression of the internal electron scattering during the period of acceleration: in the gun region the conditions for satisfaction of inequalities (5) and (6) are extremely severe, but as the magnetic field in the gun grows, they "begin working". The second effect is an adiabatic expansion of the beam during its transport from the region of strong magnetic field H_c in the gun (on the cathode) to the region of increased field H in the drift section. In this case, the beam density decreases proportionally to H/H_c and $\rho_\perp$ increases proportionally to $(H_c/H)^{1/2}$ As a result, the condition (6) is satisfied in the drift section only up to

$$I = I_{threshold} \approx \frac{\pi e^4 r_c^2}{2m^2c^3} \cdot \sqrt{\frac{W \cdot H \cdot H_c^5}{T_c^3}} \qquad (14)$$

If the first effect "does not work" for any reason, the value of $I_{threshold}$ in (14) limits the length of the plateau on the curves in Fig.6. Here r_c and T_c is the beam radius and tempera-

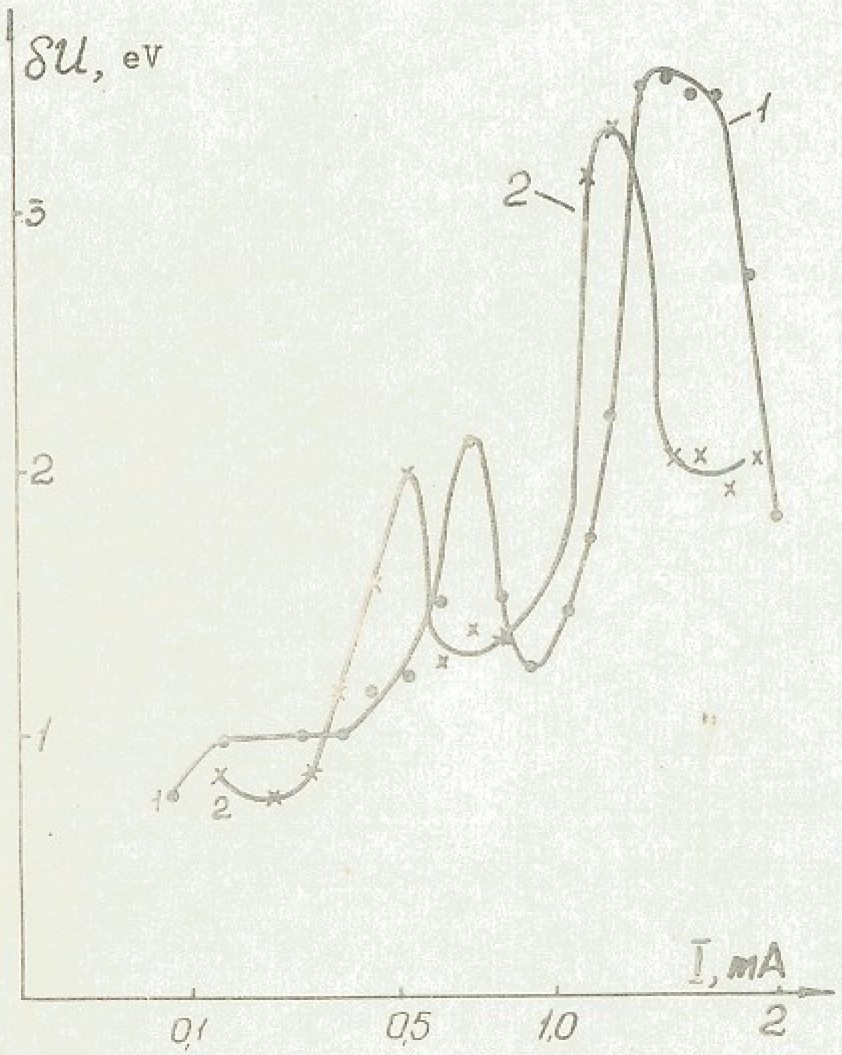

Fig.7. The dependence of the spectrum width on the electron beam current at a decreased value of the magnetic field in the gun region. Curves 1 and 2 differs from each other by the beam position on the analyzing diaphragm. The field is 0.8 kGs in the gun region and 1.2 kGs on the drift section. The electron energy is 400 eV.

ture on the cathode.

3. With a decrease of the field in the gun below 1 kGs it has been revealed that the dependence $\delta U(I)$ becomes non-monotonous. On the curve there appear the maxima and minima whose position varies during the scanning over the transverse cross section of the beam and the depth increases with increasing the current (Fig.7). These oscillations do not disappear when increasing the field in the drift section if the gun field remains small. Occurring of these oscillations is probably connected with large transverse velocities of electrons caused by the aberrations of the gun optics. Note that as the magnetic field in the gun falls off, these aberrations influence stronger and stronger./7/.

4. Applying a positive potential, relative to the walls of the vacuum chamber, to the collimating diaphragm and to a specialized electrode at the exit of the gun, one can lock, in the beam, the ions produced during the residual gas ionization by the electron beam. Then, both the electric field of space charge of the beam and the change of longitudinal velocity with radius , which is caused by this field, disappear, as a result. In this case, as the experiments have shown, the width of the spectrum somewhat decreases at high currents. This can be accounted for by the fact that, as the beam is compensated, the radial gradient of longitudinal velocities decreases.

5. A very striking illustration of the influence of a magnetic field on the relaxation process is the obtained dependence of spectral width on particle energy (Fig.6). For a classic diffusion, the spectrum width, according to (13) and (11), is energy-independent, and is only determined by the current density in the beam and also by the drift section length. The ex-

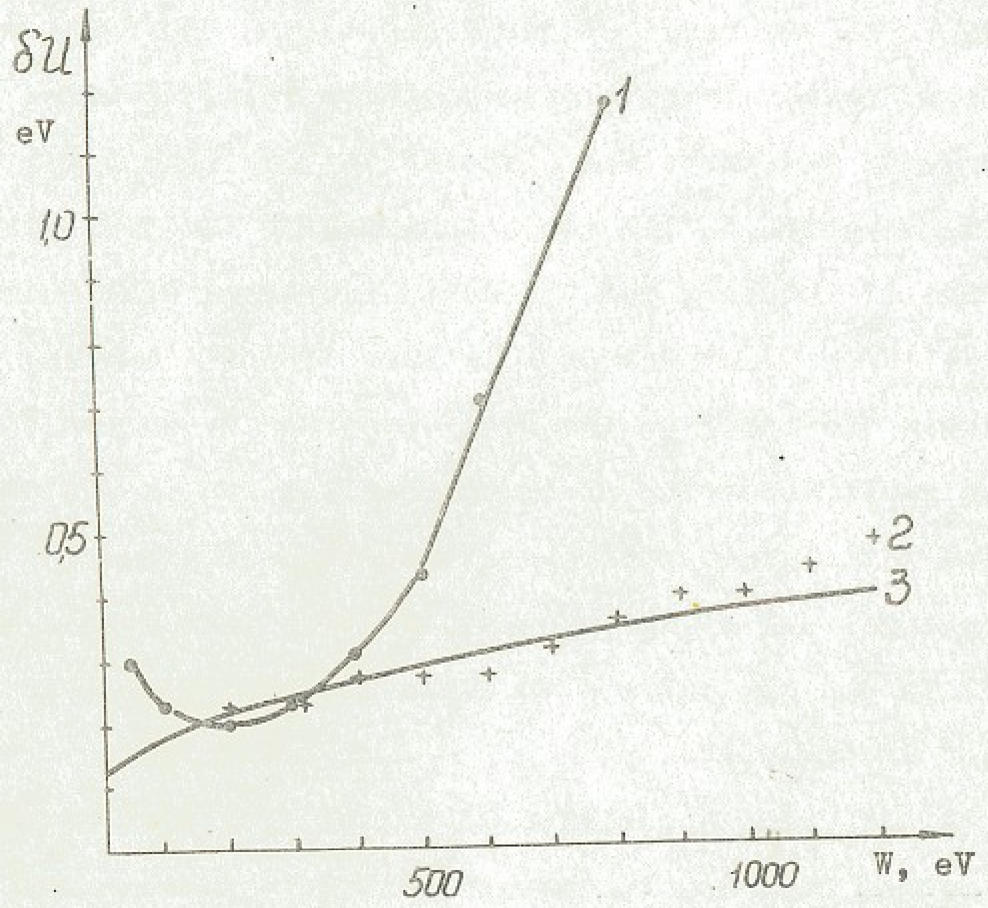

Fig.8. The dependence of the spectrum width on the electron energy at low currents of the beam.

Number of curve	Magnetic field, kGs		Beam current (μA)
	on the drift section	in the gun region	
1	1	1	50
2	1	4.3	100
3	Calculated curve (formula (6))		

periments show that with the same magnetic field in the device the length of the plateau on the curves in Fig.6 increases as the electron energy increases (curves 4 and 5), that is connected with lowering the longitudinal temperature and density during acceleration up to a higher energy.

At a low current in the beam and a strong magnetic field the relaxation process is strongly depressed and the longitudinal temperature in the electron beam is determined by the longitudinally-longitudinal relaxation. Fig.8 gives the energy dependence of the spectrum width at different magnetic fields in the device. Curve 2 corresponds to a strong magnetic field, and well coincidences with the calculated curve 3, constructed according to formulas (7) and (13). Curve 1 corresponds to a small magnetic field in the device. In this case, the electrons acquire high transverse velocities in the gun, that leads to increasing the differential spectrum width because of the finiteness of the analyzer input hole. The minimum on curve 1 is associated with decreasing transverse velocities as a result of the "resonance optics" effect /7/.

Conclusion

The performed experiments have shown that a longitudinal magnetic field in electron beam devices strongly suppress the process of longitudinally-transverse temperature relaxation. This makes it possible to produce the intense electron beams with a very small spread of longitudinal velocities and, correspondingly, with a high degree of order of the particles in the beam. Such beams can be transported in a longitudinal magnetic field without the variation of their characteristics. Th value of its longitudinal temperature at the exit from the source (gun) plays a dominent role in the process of longitudinally-transverse relaxation of the beam in the drift section.

Below we formulate some recommendations concerning the generation of such beams:

- the distribution of an electric field in the near-cathode region of the gun should obey the "law 3/2" (Pierce gun) and particle acceleration behind this region should be adiabatically slow with respect to the frequency of plasma oscillations of electrons;
- a strong enough lomgitudinal magnetic field which satisfies inequality (4), should be applied to the whole track; for a given field in the drift section, the critical current density, to which the beam magnetization "works", increases with growing the field in the gun region.

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ТЕМПЕРАТУРНАЯ РЕЛАКСАЦИЯ В ЗАМАГНИЧЕННОМ ЭЛЕКТРОННОМ ПОТОКЕ

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