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Summary

In the work presented here experimental results on proton cooling are given. At electron current 600 mA and proton energy 65 MeV cooling time was 40 ms. The decrement and longitudinal friction force dependences on parameters of electron and proton beams are presented. Possible limitations of electron cooling efficiency are also discussed.

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The study of elecrton cooling carried out at the Institute of Nuclear Physics, Novosibirsk during last five years allowed to gather a reach experimental material and substantially advanced the primary theoretical concepts based on the model of the isotropic and homogeneous electron-ion plasma with the Maxwellian distribution over the velocities /1/. It was understood the existence of the sharp anisotrope function of electron distribution over the velocities in the beam under electrostatic acceleration /2,3/, the role of a strong magnetic field in the installation with electron beam /4/, the effects of a space charge in electron cooling /5/.

Corresponding theoretical descriptions based on the detailed account of microscopic structure of beam particles collisions enable one to understand the physics of certain events when some effects or parameters are crucial. In practice, we usually deal with superposition of a number of effects, so the attempts to use similar calculations for descriptions of experimental data encounter considerable difficulties because of too much calculations needed. In this connection, it seems reasonable to represent the obtained experimental results in the form of empirical formulae which on one hand, should correspond to the main features of collisions in magnetic field and, on the other hand, should be simple and convenient enough for practical estimations of various characteristics of cooling process.

By now, experimental data are obtained on electron cooling for protons at energies 65, 35 and 1.5 MeV with electron current within the range 500-2 mA. The experimental method was described in references /2,3,5/.

1. Efficiency of proton electron collisions at cooling essentially depends on electron beam density and on the difference in the proton and electron velocities. When analysing the latter dependence one should differ longitudinal velocity of Larmor rotation of electrons in accompanying longitudinal magnetic field (in the installation with electron beam /2/) from the difference of the proton and electron average velocities $\Delta\vec{v} = \vec{v}_p - \langle\vec{v}_e\rangle$. Symbol $\langle\ \rangle$ denotes an operation of averaging over the Larmor rotation.

The difference in transverse average velocities $\Delta v_\perp$ in experiments was introduced by the shock excitation of betatron oscillations or by variation of the angle between electron and proton beams (Δv_p or Δv_e) /7/.

All the data obtained for the decrement of betatron oscillations over the whole energy range can be combined with the common dependence (Fig.1):

$$\lambda / n_e = 10^6 / \Delta v_\perp^2 \ \ cm^3/sec$$

In these measurements $\Delta v_\perp$ was within the range $\Delta v_\parallel \ll \Delta v_\perp \ll v_L$. In addition, v_L did not change at energy variation. At normal conditions the value is determined by the velocity spread on the electron gun cathode. Application field for this dependence are discussed in p.5 in more detail.

2. Decrement λ falls down rapidly with an increase in the electron longitudinal velocity spread $\Delta v_\parallel$ (Fig.2), this decrease being already commenced at $\Delta v_\parallel \simeq 10^{-4} v_0$ (v_0 is an average velocity of protons and elecetrons) which substantially less than the difference in longitudinal velocities $\Delta v_p \simeq 4 \cdot 10^{-4} v_0$ at which the measurements were performed.

Electron longitudinal velocity spread was excited in these experiments with an energy modulation for electrons with frequency $f \simeq 200$ Hz $\gg \lambda$.

3. When measuring dependence of the decrement λ on the velocity of Larmor rotation the value v_L was controlled by constant voltage applied to the short plates with length of 1/4-th period of electron Larmor helix/6/. Results of measurements are given in Fig.3 as the dependence $\lambda \Delta v_p^2$ on the Larmor circle radius ρ_L. This form is convenient for comparison of results at energies 65 MeV and 1.5 MeV, as, in this case, it is excluded a trivial contribution of velocity dependence Δv_p, which is introduced, as mentioned above, while measuring decrement.

4. Damping rate for the energy spread is determined by longitudinal friction force $F_\parallel$. Its dependence on relative velocities of beams and Larmor velocities of electrons was measured at an energy 65 MeV (Fig.4,5). Like decrement, $F_\parallel$ depends weakly on the velocity of Larmor rotation v_L. Nevertheless, unlike decrement λ, $F_\parallel$ approximately equally depends on difference in both the longitudinal and transverse velocities.

5. Experimental data described in points 1-4 can be combined with two empirical formulae:

$$\lambda = \frac{66\, r_p r_e n'_e c^4 \eta}{[(\alpha v_0)^2 + \Delta v_\perp^2 + 11\Delta v_\parallel^2]\sqrt{v_L^2 + \Delta v_\perp^2 + \Delta v_\parallel^2}}\,, \qquad (1)$$

$$\bar{F}_\parallel = \frac{12\pi r_e^2 n'_e m c^2 \eta}{\sqrt{(\alpha v_0/2)^2 + (\Delta v_\perp)^2 + \Delta v_\parallel^2}\,\sqrt{(v_L/2)^2 + \Delta v_\perp^2 + \Delta v_\parallel^2}}\,, \qquad (2)$$

where n'_e is electron density in the particle system; η is a fraction of the proton orbit occipied by cooling section; α - is a factor which takes into account the distortion of force lines of longitudinal magnetic field (in the experiments at proton energy 65 MeV we had $\alpha \simeq 4\cdot10^{-4}$); r_p, r_e are classical radii of proton and electron respectively; c is the velocity of light.

Let us emphasize that empirical formulae (1) and (2) given above are experimentally proved only in the range of parameter values which was studied in the experiments on NAP-M installation. So, the velocity spread and electron beam density were limited by the range of values given below:

$$10^5 \text{ cm/sec} < \Delta v_\parallel < 7\cdot10^6 \text{ cm/sec}$$
$$4\cdot10^5 \text{ cm/sec} < \Delta v_\perp < 2\cdot10^7 \text{ cm/sec}$$
$$4\cdot10^7 \text{ cm/sec} < \Delta v_L < 10^8 \text{ cm/sec}$$
$$10^7 \text{ 1/cm}^3 < n'_e < 4.8\cdot10^8 \text{ 1/cm}^3$$

Extrapolation of these formulae to the extended range of parameter values should be done with some care. Agreement of (1) and (2) with experimental results is no less than 20% in the mentioned range of parameter values.

For relative velocities $\Delta v_\perp$ in the region $\alpha v_0 < \Delta v_\perp < v_L$ decrement is proportional to $(\Delta v_\perp^2 v_L)^{-1}$. This result is principally different from the concepts which did not take into account an effect of longitudinal magnetic field where λ is

proportional to $v_\perp^{-3}$ /1,7/. In experiments on NAP-M, magnetic field of the installation with electron beam is 10^3 Gs , so, at an energy 35 keV at the electron section of 1 m length one can put about 25 periods of Larmor helix.

The fact that experimental data are described with formulae (1,2) apparently proves the strong effect of longitudinal magnetic field on the transition processes in particle collisions /4/. This effect is characterized by the number of Larmor cycles $\Omega_L T$ during collision time T. If $\Omega_L T \ll 1$, an effect of magnetic field is negligibly small and it is hard to expect that formulae (1) and (2) will remain valid. Maximum collision time T may be determined either by the path time through collision section $\frac{\ell}{v}$ or by the time necessary for establishing Debay shielding $T \sim \omega_p^{-1}$, where ω_p is a plasma oscillation frequency of electrons. With increase in density n'_e frequency ω_p increases and relation Ω_L/ω_p decreases that can also violate the validity of (1) and (2).

6. Natural wish to intensify electron cooling effect with increasing density of electron beam is limited by electron space charge effects. Two of these effects are most essential:

1) Potential reduction inside electron beam /2/ leads to appearance of transverse gradient of lomgitudinal electron velocities $dv_\parallel^e/dr$. For the stability of longitudinal motion of protons it is necessary that /7/

$$\frac{dv_\parallel^e}{dr} < \frac{v_0}{R_0 \psi \gamma^2}$$

or $\qquad (3)$

$$n_e < \frac{1}{R_0 \psi}\cdot\frac{\beta^2\gamma}{2\pi r_e \chi}$$

where $R_0\Psi$ is the value of dispersion function of storage ring at cooling section, R_0 is an average radius of proton orbit, X is displacement of a proton beam with respect to electron beam axis. This limit for electron density can be decreased in several ways:

- by decreasing Ψ (in special structures one can have $\Psi = 0$),

- by introducing at cooling section the transverse electrostatic fields of quadrupole type which compensate for radial component of a field of electron space charge and corresponding component $dv_\parallel^e/dr$,

- by neutralization of the electron space charge with ions. Only the latter method was studied experimentally.

2) Space charge of electrons effects by its fields on protons like axial lens, which leads to perturbation in focusing system of storage ring. Correspondingly, an admissible shift of betatron oscillation frequencies determines the limit in electron density:

$$\eta n_e \leq \frac{\nu_\Delta \nu_e \gamma^3 \beta^2}{\pi r_p R_0^2} \qquad (4)$$

where $\beta = v_0/c$, $\gamma = (1-\beta^2)^{-1/2}$. This limit is rather relates to space inhomogeneous electron beam when admissible value $\Delta\nu_e$ is given by a distance to the nearest resonance and by nonlinearity $\partial\nu/\partial a^2$ which determines the shift of betatron oscillation frequencies on the size of electron beam $\overline{a^2}$.

Of course, the reaching of electron beam space charge itself is connected, in its turn, with some difficulties which were studied in detail in /8/.

7. Neutralization of electron beam space charge was studied in view of enhancement of electron cooling process. In the experiments described the compensation achieved by applying positive potential to the cut circular pick-up electrodes encircling electron beam at the input and output of cooling section. In this case, though, in electrostatic plugs the electrons and negative ions are stacked which resulted in generation of strong oscillations of potential causing the ion drop from electron beam. For obtaining stable compensation, the plugs required to be cleaned by transverse electric field. To this end, potential was applied to the half-rings of pick-up electrodes. Compensation level of the electron beam was measured using effect of variation of the average energy of protons /2/: if electron energy is varied (potential of electron gun cathode U_e) proton velocity (under cooling effect) is tuned to velocity of electrons and proton beam orbit shrinks or expanded, the beam is shifted in radial direction. Similarly, at compensation for space charge of electrons: potential inside electron beam and, correspondingly, electron energy increases. In the experiments, the dependence was removed between locking potential of plugs U and the cathode potential variation ΔU_e (when equilibrium orbit does not expand (proton beam maintains its position). At electron current 300 mA (proton energy 65 MeV) compensation commenced when potential U achieved the value +450 V (Fig.6), from this very moment the proton beam did not change its position with increase in locking potential.

While cooling protons with compensated electron beam the proton beam sise variation are observed which accompanied with partial drop of ions from electron beam. A slight excitation of the ion oscillations by transverse electric field with frequency of an order of 1 MHz cancelled this instability. In this case, damping decrements were in coincidence with those measured in the absence of compensation. It is worth mentioning that during compensation for space charge by ions it is impossible to compensate simultaneously for electric and magnetic fields of electron beam especially for relativistic energies. In addition, in this method of compensation some additional efforts are required for ensuring collective stability of heavy particle beam in the presence of ions and electrons.

8. Empirical formulae (1) and (2) are, in fact, expressed through parameters of beams in an accompanying system. Therefore, experimental data described by these formulae can be also used for other energies if the beam parameters in an accompanying system are within the region experimentally studied.

Effects of electrons on the proton motion stability in a storage ring is convenient to be characterized by frequency shift $\Delta\nu_e$. As experiments have shown, ultimate electron current at energy 1.5 MeV was 2 mA and at energy 65 MeV - 600 mA which corresponds approximately the same value $\Delta\nu \simeq 10^{-2}$ at $\nu_x \simeq 1.15$, $\nu_z \simeq 1.35$.

In this connection, it is useful to rewrite relations (1,2) through an admissible value of betatron oscillation shift $\Delta\nu_e$. Using symbols accepted earlier:

$$\theta_\perp = \Delta p_\perp / p_0 , \quad \theta_\parallel = \Delta p_\parallel / p_0 , \quad \theta_L = p_L / p_0 \qquad (5)$$

taking into account transformation into laboratory system one can have from (1,2) the following:

$$\lambda = \frac{21 r_e c \nu \Delta\nu_e}{\beta\gamma^2 R_0^2 \left[\alpha^2 + \theta_\perp^2 + 11\theta_\parallel^2/\gamma^2\right]\sqrt{\theta_L^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}} , \qquad (6)$$

$$\bar{F}_\parallel = \frac{12 M c^2 r_e \nu \Delta\nu_e}{R_0^2 \sqrt{(\alpha/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}\sqrt{(\theta_L/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}} \qquad (7)$$

where M is a proton mass.

From (7) write the expression for damping time of energy spread:

$$\tau^{-1} = \frac{\bar{F}_\parallel}{\Delta P_\parallel} = \frac{12 r_e c \nu \Delta\nu_e}{\beta\gamma R_0^2 \theta_\parallel \sqrt{(\alpha/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}\sqrt{(\theta_L/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}} \qquad (8)$$

This formula gives the upper estimation of τ, as force $F_\parallel$ increases in the process of cooling.

Relations (6)-(8) allow extrapolation of experimental data obtained in the work presented here into the region of high energies and also to answer to the question of cooling efficiency dependence of particle energy. Note also that Larmor velocity of electrons is mainly determined by a constant spread of thermal velocities of electrons on cathode[1], so that during acceleration θ_L falls down as $1/\beta\gamma$ with increase in energy. Therefore, if velocity difference $|\Delta\vec{v}|$ is small compared to $v_L(\theta_\parallel, \theta_\perp \ll \theta_L)$ (which is, in particular, realized on NAP-M), cooling time for betatron oscillations (λ^{-1}) rises with energy only as γ but cooling time for energy spread is not changed. So, in the experiments on NAP-M damping decrements obtained are about the same for energies 1.5 MeV and 65 MeV with equal angles $\theta_\perp$.

Obtained results show the feasibility of obtaining sufficiently high cooling efficiency for a wide energy region of cooling particles. One should note, though, that for obtaining minimum cooling times it is required electron current increase as $\gamma^3\beta^3$. Therefore, in the region of high energies the current value can be limited by technological possibilities. In this case, in (6) and (8) instead of $\Delta\vartheta_e$ one should put the value corresponding to electron current achieved which means the faster decrease of decrement with energy increase.

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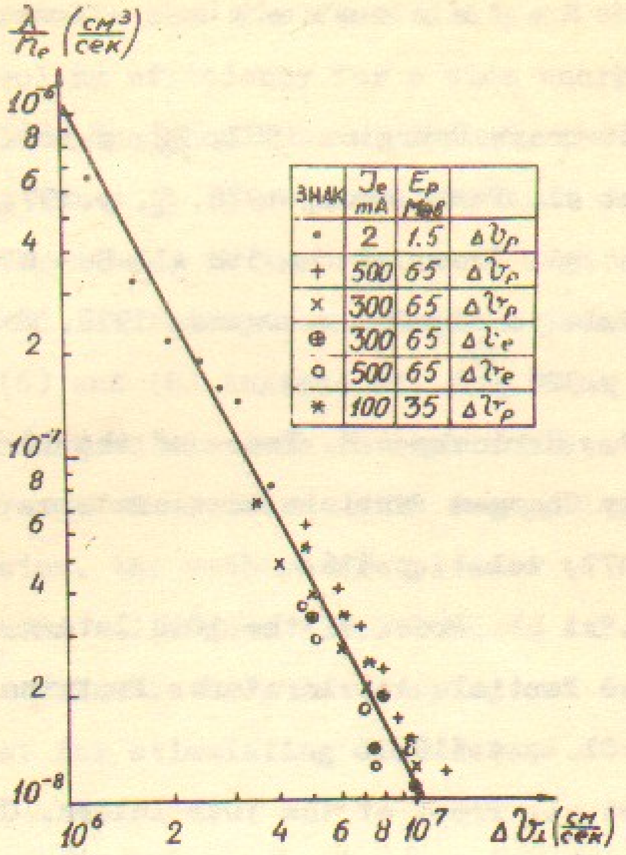

Fig.1 Damping decrement of transverse oscillations (λ) as a function of relative velocity of protons and electrons at various proton energies. Relative transverse velocity was created by excitation of betatron oscillations of protons (Δv_p) either by bending electron beam with respect to proton trajectory Δv_e (n_e - density of electrons).

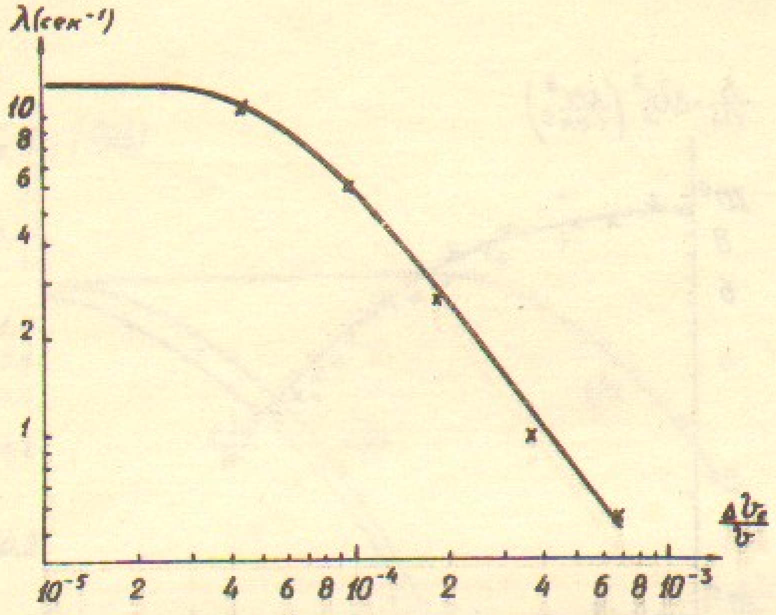

Fig.2 Damping decrement of transverse oscillations of protons as a function of modulation amplitude of electron longitudinal velocities (electron current 300 mA, proton energy 65 MeV).

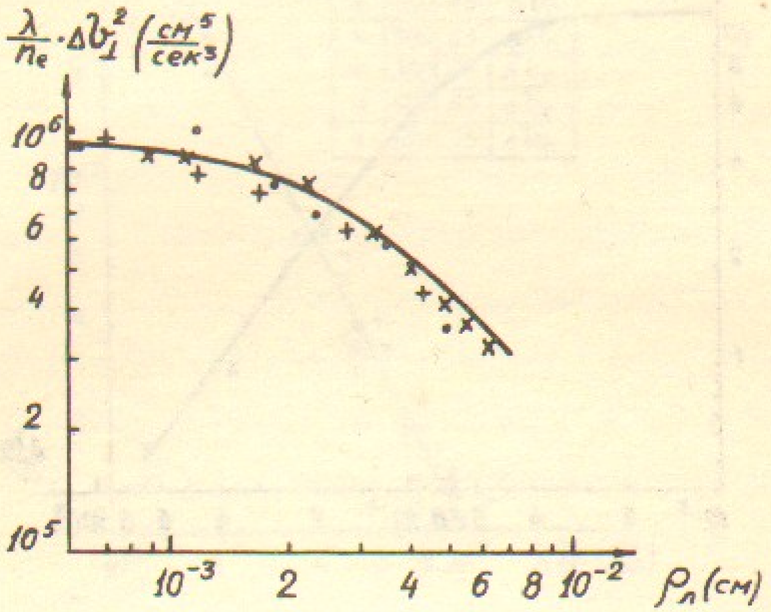

Fig.3 Effect of Larmor rotation of electrons on the value of damping decrement of transverse oscillations (current values are the same as given in Fig.1).

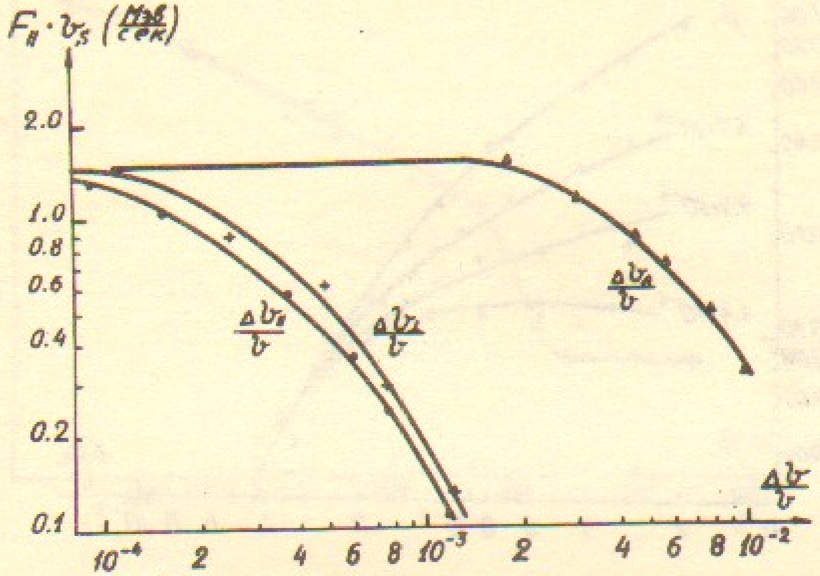

Fig.4 Longitudinal friction force dependence on proton velocity detuning from average velocity of electrons (Δ) at various relative transverse velocities $(\Delta v_\perp/v_o)$. Electron current is 300 mA, proton energy is 65 MeV).

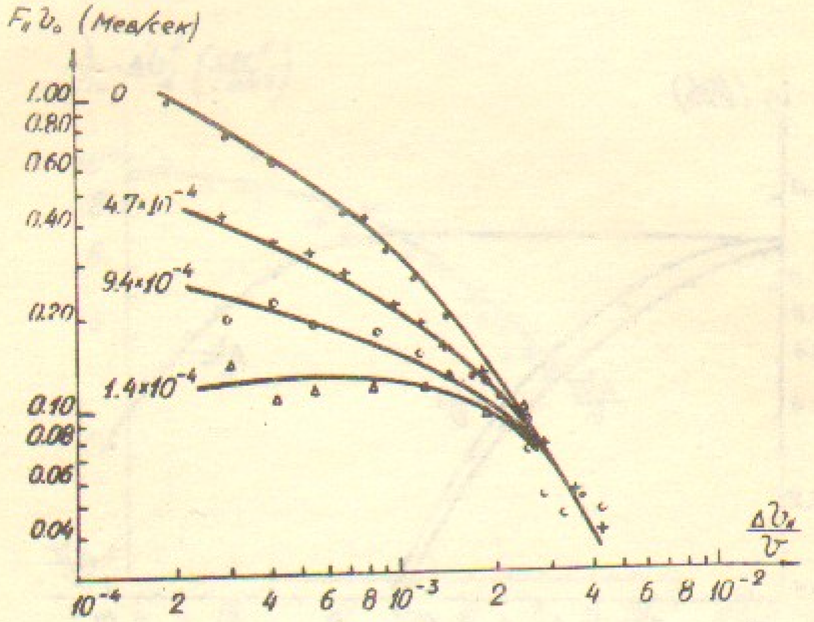

Fig.5 Longitudinal friction force dependence on detuning longitudinal velocities $\Delta v_{\parallel}$, transverse velocities $\Delta v_{\perp}$ and velocity of Larmor rotation Δv_{L} (electron current is 300 mA, proton energy is 65 MeV).

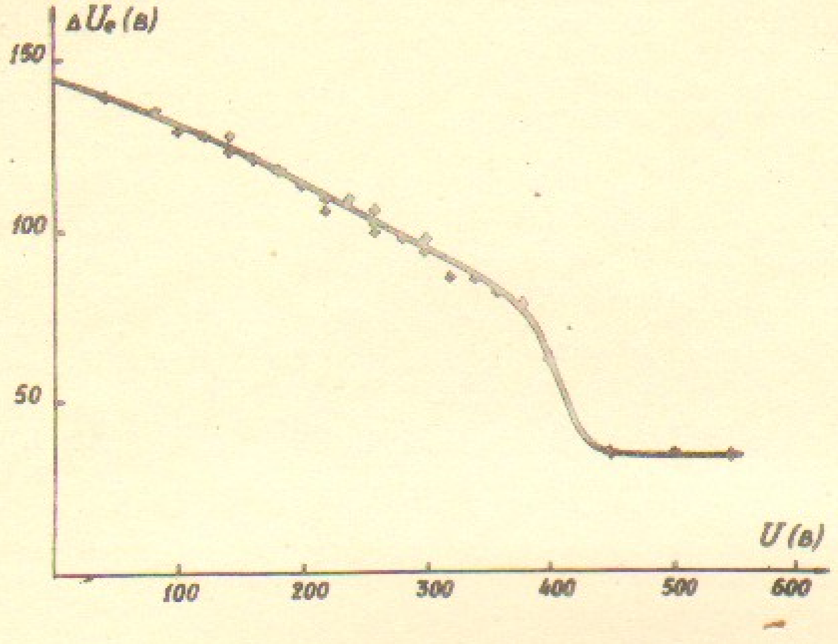

Fig.6 The gun potential variation as a function of locking potential.