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MEASUREMENT OF MOMENTUM COOLING RATES WITH ELECTRON COOLING AT NAP-M

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A b s t r a c t

It has been possible, for the first time, to measure momentum cooling at NAP-M. The results of the measurements and the techniques used are shown in this paper. The cooling rate has been measured versus the velocity spreads of both beams. The agreement with the previous measurement of the frictional force[1] is fairly good.

The debunching time of a proton beam with a gap has also been measured versus intensity, with and without electron cooling. The debunching time has then been compared to the cooling rate to infer the equilibrium momentum spread.

Finally, the "sweeping" technique, namely the method which moves the electron velocity across the proton distribution, has been tested. This method is very important for speeding up the cooling of beams with large spreads. The results are in agreement with the expectation.

1. Introduction

In this paper we report the measurements of the damping rates for the momentum spread of a proton beam by means of electron cooling[2] at NAP-M. Until recently, a systematic investigation of cooling of betatron oscillations was carried out[1,3]; but, in the longitudinal plane, it had been possible to measure only the behaviour of the longitudinal drag force $F_{\parallel}$. Indirectly, it is possible to derive the momentum cooling rate $\lambda_{\parallel}$ from the measurements of $F_{\parallel}$, but it is obvious that a direct observation of $\lambda_{\parallel}$ would be more significant and useful.

Recently, schemes[4] to produce and collect antiprotons for $p\bar{p}$ - colliding beam experiments have been proposed, where momentum damping by electron cooling is mainly used. Indeed momentum cooling seems to be more advantageous than betatron cooling, because it could be combined with RF stacking to store antiprotons pulse after pulse. Furthermore, because of the large emittance with which antiprotons are produced, stacking in the betatron phase space does not seem convenient since one would then require very large aperture magnets. Following this line of thoughts, experiments on electron cooling are planned, relatively soon, at Fermilab, where momentum cooling and momentum stacking techniques are combined together[4]. Moreover, the momentum spreads involved at Fermilab are typically in the range of $\Delta P/p = 10^{-3}$, whereas at NAP-M they are around 10^{-5}, and the question arises of the dependence of the cooling rates on the beam spreads.

Also, it has been proposed[5] to exploit electron cooling to accumulate antiprotons produced with energies of few GeV. In fact the yields from protons to antiprotons could be greatly improved if the antiprotons are cooled and stored at the same energy they are produced. In this case, nevertheless, the beam momentum spread can be quite large, possibly around few percents. Then, the cooling rates could be very low, since they are expected, for large spreads, to decrease with the second or third power of the beam spread. The rates could be greatly improved, nevertheless, by "sweeping" the velocity of a coul electron beam[1] through the spectrum of the proton beam.

The purpose of the measurements of the momentum cooling rates at NAP-M is mainly to anticipate the answers to some of the problems we have mentioned above. We measured the following: momentum cooling rate $\lambda_{\parallel}$ versus

a) proton beam longitudinal spread $\theta_{\parallel p}$,

b) electron beam Larmor velocity spread θ_L ,

c) electron beam transverse velocity spread $\theta_{\perp e}$, and

d) electron beam longitudinal spread $\theta_{\parallel e}$.

We repeated some of the experiments, already performed earlier[1], where we measure the proton beam momentum spread before and after cooling and versus the beam intensity. The method used is the usual one where one makes a gap in the beam and observes the debunching time τ ; but now it is possible to compare τ with the cooling rate $\lambda_{\parallel}$ and infer more precisely the dependence of the momentum spread with the beam current.

Finally, we measured the cooling rate, after sweeping the electron beam through the proton beam spread, and compared the result with those obtained with the standard technique to observe any improvement.

All measurements have been made at an energy of 65 MeV and with a typical electron beam density of 0.38 A/cm^2.

2. Measurement of the Momentum Cooling Rates

As it will be shown in Section 4, the proton beam momentum spread is very small, around 10^{-5}, either with or without electron cooling; therefore it is practically impossible to observe directly the momentum cooling of such a beam. One has to devise a way to widen the spread to the range 10^{-4} - 10^{-3} to make the cooling observable. The enlargement can be easily detected by measuring directly the beam size with the magnesium jet[3]; in fact the beam size of a cooled beam is only a fraction of a millimeter, whereas a momentum spread of 10^{-3} would correspond to about six millimeters because of the large dispersion at the location of the magnesium jet (as well as in the cooling region). A fast way to estimate the momentum spread enlargement would be to measure the reduction of the peak signal from the jet and assume it is directly proportional to the enlargement of the distribution. Yet, we needed a way to increase the momentum spread by one or two orders of magnitude.

At the beginning, we thought to apply some RF noise ac -

ross the accelerating gap. In order to apply some RF noise across the accelerating gap. In order to maximize the effect, we narrowed the spectrum of the noise to a range of few KHz around either the first or the second harmonic frequency (2.2 and 4.4 MHz). The noise was applied for 0.1 second in presence of the electron beam. We were not sure about the simultaneous effects of the RF noise and cooling; the beam behaviour was quite erratic and the results not quite reliable. Starting from the end of the noise application, the narrowing of the beam was measured versus time; namely we observed the time the peak signal from the magnesium jet required to return to the level corresponding to a beam completely cooled. This time was made to correspond to the cooling rate $\lambda_{\parallel}$. We could observe a strange linear dependence of $\lambda_{\parallel}^{-1}$ with the beam momentum spread. We now do not assign much credibility to these measurements, especially because we suspect, that, being the cavity also in a location of large dispersion, betatron oscillations too were enhanced by the RF noise.

Next, we found two more reliable methods to enlarge the beam spread. In the first we simply fastly turn on the RF voltage, over a period of time which corresponds to about a quarter of the phase oscillation period, a couple of milliseconds. The beam has tendency to bunch initially and then debunches again under the effect of the cooling. This method works for small spreads, up to 0.2×10^{-3}. For larger spreads we used the second method. A pair of clearing electrodes, which cover the entire cooling region and that are used to control the neutralization of the beam, are both set to a voltage ranging from zero to 100 V. This will create a longitudinal field at both ends which has the effect to change the energy of the electron beam but not that of the proton beam. The amount of the energy separation is measured again with the magnesium jet. One waits several seconds to allow the proton beam to adjust its velocity to that of the electron beam. Then the voltage is suddenly turned off, the electron beam acquires its original energy and the proton beam will

begin to move to readjust its energy again. The time $\tau_{\parallel}$ required for this is recorded. The results are shown in Fig. 1 where $\tau_{\parallel}$ is plotted versus $\theta_{\parallel}$. The dependence is quadtaric and in agreement with the empirical formula for the longitudinal drag force[6]

$$\overline{F_{\parallel}} = - \frac{12\pi r_e^2 n m c^2 \eta}{\beta^2\gamma^3 \sqrt{(\alpha/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}\,\sqrt{(\theta_\perp/2)^2 + \theta_\perp^2 + \theta_\parallel^2/\gamma^2}} \cdot \qquad (1)$$

In this formula, which has relativistic form, the symbols have the usual meaning:

- r_e - electron classical radius = 2.82×10^{-13} cm
- n - volum density of electrons = 2×10^{8} cm^{-3}
- m - electron mass at rest = 0.511 MeV
- c - light velocity = 3×10^{10} cm$\cdot$s^{-1}
- η - fraction of accelerator taken by cooling region = 2%
- β, γ - usual relativistic parameters = ~ 0.3 and ~ 1

During our experiment the transverse spreads were negligible and $\theta_{\parallel}$ smaller than $\theta_\perp$ ($\simeq 4 \times 10^{-3}$), so that one could write

$$\overline{F_{\parallel}}(\theta) = - \frac{A}{\sqrt{(\alpha/2)^2 + \theta_\perp^2 + \theta_\parallel^2}} \,. \qquad (2)$$

Actually, the drag force $F_{\parallel}$ depends on the difference between the proton and average electron velocities $\theta_{\parallel} = \theta_{\parallel p} - \theta_{\parallel e}$. Also, quite generally, $\theta_{\parallel e}$ depends on the proton position X inside the electron beam; therefore it is convenient to express explicitely the dependence of $F_{\parallel}$ on the local electron velocity, that is

$$\overline{F_{\parallel}}(\theta) = - \frac{A}{\sqrt{(\alpha/2)^2 + \theta_\perp^2 + \left(1 - \frac{R_0\psi}{v_s}\frac{dv_{\parallel e}}{dX}\right)^2 \theta_\parallel^2}} \,, \qquad (2.a)$$

where $R_0\psi = 6\,m$ is the dispersion function and v_s the reference velocity. The variation of the longitudinal electron velocity $dv_{\parallel e}/dX$ depends on the space charge potentiall well, on the amount of neutralization and other factors, and it can be determined experimentally, for instance, by measuring the radial displacement of the proton beam versus a change of the electron velocity. One can write

$$\Delta X = R_o \psi \frac{\Delta P}{P} = R_o \psi \gamma^2 \left(\frac{\Delta v_e}{v_s} - \frac{\Delta X}{v_s} \frac{d v_{\parallel e}}{dX} \right) ,$$

from which

$$\frac{R_o \psi}{v_s} \frac{d v_{\parallel e}}{dX} = \frac{R_o \psi}{\Delta X} \frac{\Delta v_e}{v_s} - \frac{1}{\gamma^2} ,$$

where Δv_e is the electron velocity change. The measurement of the radial position of the proton beam versus the electron velocity is shown in Fig. 6 and will be discussed later. The cooling time can be calculated from this according to

$$\tilde{\tau}_{\parallel} = - P_s \int_0^{\theta_{\parallel}} \frac{d\theta}{F_{\parallel}(\theta)} , \qquad (3)$$

where P_s is the nominal value of the proton momentum.

The continuous curve in Fig. 1 is calculated according to (2) and (3). There is good agreement if $\alpha = 0.4 \times 10^{-3}$ and $\theta_L = 4 \times 10^{-3}$ which are the expected values according to previous observations[6].

For very small values of $\theta_{\parallel}$ ($\lesssim \alpha$) one would expect a linear increase of $\tilde{\tau}_{\parallel}$ with $\theta_{\parallel}$; that has not been possible to measure in our experiment because of not sufficient accuracy in this range, but it is shown by the computed curve.

3. Dependence of Momentum Cooling Rate with other Beam Parameters

Once we learned how to measure momentum cooling rates with the technique of energy separation we explained above, we initiated to explore the dependence of $\lambda_{\parallel}$ on such other parameters as θ_L , $\theta_{\perp e}$ and $\theta_{\parallel e}$. These were varyed with the usual techniques[1]: by exciting a capacitor next to the anode with the length of a quarter of Larmor length, by tilting the direction of the solenoid field and hence of the electron stream around the main proton velocity, and, finally, by modulating the electron beam energy by applying an oscillatory voltage of 1 KHz between anode and cathode. The results are shown in Fig.s 2,3 and 4. The continuous curves are calculated by combining (1) and (3) with a proper choice of the remaining parameters. One can see there is good agreement with the previous measurement of the longitudinal frictional force[6]. This would then lead to the following empirical formula for the momentum cooling rate

$$\lambda_{\parallel}^{-1} = \tilde{\tau}_{\parallel} = \frac{P_s A \theta_{\parallel}}{2} \sqrt{(\alpha/2)^2 + \theta_{\perp e}^2 + \left(1 - \frac{R_o \psi}{v_s} \frac{d v_{\parallel e}}{dX}\right)^2 \theta_{\parallel}^2}$$
$$\simeq 5 \cdot 10^7 \theta_{\parallel} \sqrt{4 \cdot 10^{-8} + \theta_{\perp e}^2 + 6 \cdot \theta_{\parallel}^2} \sqrt{1.6 \cdot 10^{-5} + \Delta\theta_L^2} . \qquad (4)$$

The fitting parameter α is about 4×10^{-4}, namely the same than the similar one in previous determinations and therefore, probably, of the same origin.

Estimates of the cooling rate for the Fermilab experiment, using our experimental findings, gave most 8 s^{-1}, half the Booster cycling rate.

4. Intensity Dependence of the Proton Beam Momentum Spread

One concern in cooling intense charged beams, as it could be required in a scheme to collect antiprotons, is the effect, coherent and incoherent, of the space charge forces on the beam dimensions in the phase space. Recently[1], the debunching time of a proton beam with a gap was measured versus the beam intensity, with and without electron cooling. At that time, nevertheless, the cooling time was not known, and a direct comparison of the debunching time to the cooling time was not then possible. This comparison is important[7] to estimate the relation of the beam momentum spread to the debunching time in presence of electron cooling.

We repeated the measurements of the time required to debunch using the method of knocking out a fraction ($\simeq$ 10%)

of the beam, because now we felt we had the other term of comparison: the momentum cooling rate. First we observed the debunching of a proton beam without cooling. The intensity was varied up to $\simeq$ 40 μA, and the beam was few millimeters wide. We did not observe any variation of the debunching time τ, which was constant around 15 msec. Without cooling, the formula that should be used to estimate the momentum spread is the following

$$\tau^{-1} = \left| \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \right| \omega_o \frac{\Delta P}{P} \qquad (5)$$

where $\omega_o = 2\pi \times 2.2$ MHz is the angular revolution frequency, and γ_t is related to the transition energy of the NAP-M lattice. From eq. (5) one derives then $\Delta P/P \simeq 4 \times 10^{-5}$(rms). The fact that the momentum spread does not change with the beam intensity is an indication that, for currents up to 40 μA, there are no significant coherent space charge effects and that the intra-beam scattering effects are negligible over periods of time of at least several minutes. On the other side, we like to remind that an uncooled beam has also a considerably large transverse size.

The results of the measurements of the debunching rate versus intensity, in the presence of electron cooling, are shown in Fig. 5. They confirm previous observations[1] in similar conditions. Since we expect the equilibrium momentum spread to be quite small, around 10^{-5}, by inspecting the two curves in Fig.s 1 and 5, we can now definitely state that:

debunching time $\gg$ momentum cooling time.

In this situation, it seems that the relation between debunching rate τ^{-1} and beam spread is[7]

$$\tau^{-1} = \frac{1}{\lambda_{\parallel}} \left(\left| \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \right| \omega_o \frac{\Delta P}{P} \right)^2 \qquad (6)$$

From the lower part of the continuous curve in Fig. 1 we have

$$\lambda_{\parallel} = \left(160 \frac{\Delta P}{P} \text{ seconds}\right)^{-1}$$

therefore the debunching rate increases with the cube power

of $\Delta P/P$, or conversely

$$\Delta P/P \sim (\text{beam intensity})^{1/3} \qquad (7)$$

For instance, at an intensity of about 20 μA, we have τ = 100 msec and the rms value of the momentum spread is about 3×10^{-5}.

We have nevertheless few reservations about the use of eq. (6).

In our experiment the gap in the beam was created by putting a short pulse of voltage across the deflecting plates. Because of the finite duration of the edges of this pulse, particles at both sides of the gap have quite large betatron oscillation amplitude. These particles are therefore not cooled, either transversely or longitudinally, at least not at the usual fast rate. It derives that one should not use eq. (6) but eq. (5) for these particles. Even if so, though, the large majority of particles should be fastly cooled and for them are should make use of (6). Anyway, for sake of comparison, we can considere the other extreme and calculate the momentum spread for the same example shown above by using the relation (5); we obtain for the rms value 0.8×10^{-5}, quite a smaller value. Moreover, now the dependence of the spread with the current would be linear.

The dependence (7) can hardly be explained with some sort of longitudinal coherent instability. Moreover, this should not depend appretiably on the transverse dimensions of the beam, and we have seen before that, for about the same spread, there were no instabilities in the case without electron cooling. But if one assumes (5) and therefore a linear dependence of the spread with the current one could find a resonable explanation because of the very small value of the spread. In this case, nevertheless, the intra-beam scattering seems to be a better explanation[8]: the dependence with the current would be right and there is also a fair numerical agreement.

5. Enhancement of the Momentum Cooling with the Sweeping Technique

As we have said at the end of Section 2, the extrapola - tion of our empirical findings to the Fermilab experiments indicates a larger cooling time than it was previously anti- cipated[4]. Moreover, the simple and straightforth application of the electron cooling, to collect antiprotons at larger energies, would be associated to rather low cooling rates, not just simply because of the larger energy, but, most im - portant, because of the large momentum spread of the beam to be cooled. In this situation it is necessary to sweep the electron beam energy through the proton beam distribution[1].

It has been possible to simulate these conditions at NAP-M, by separating the velocities of the two beams with the same technique we explained in Section 2. The difference now is that the voltage was turned off, after the usual few se - conds application, not suddenly, but over a period of time t. We could vary this time t and measure the time required for the proton beam to adjust its velocity to that of the electron beam. What we were expecting from these measurements was the following. For sudden change of the clearing electro- des voltage (very small t), the proton velocity would shift toward the electron velocity in a time which is just the momentum cooling time. We have measured this before and shown the results in Fig. 1. But if the voltage is varied slowly (very long time t), the electron velocity would also change slowly, and the proton beam would adiabatically adjust its velocity accordingly. In this case the time required for the proton beam to reset its velocity to the initial value is, then, just t . There must be some intermediate values of t , namely an optimum variation of the electron beam velocity (we can call it the "sweeping" speed), which correspond to a mi - nimum of the consequent variation of the proton velocity, na- mely to a minimum of the momentum coolings time.

In carrying out our experiment we found that the beam position (momentum) was sensitive to the charge neutraliza - tion in the cooling region, activated by the clearing elec - trode themselves. We had then to apply also a voltage diffe- rence between the two plates to sweep the ions away. We show this effect in Fig. 6 where the beam displacement (which in a way is the momentum displacement) is plotted ver- sus the voltage common to both plates, with and without a voltage difference ΔV. The results of our measurements, with this adjustment, are shown in Fig. 7 for two different initial momentum deviations ($\Delta P/p$).

The optimum cooling time so obtained, with the sweeping method, is also plotted in Fig. 1 (dashed line). As one can see, as it was expected, now the dependence with the spread is linear and not just quadratic. The optimum cooling rate and the required speed of change of the electron velocity depend on the other spreads involved. It is obvious that, for instance, it is required to have a reasonably small transverse emittance of both beams for a significant, posi - tive effect. An exact calculation can be easily performed by integrating eq. (3) combined to (1) and letting expli - citely the electron velocity to vary with time.

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Figure captions

Fig. 1. Dependence of the momentum cooling time τ on the total proton momentum spread $\Delta P/P$. • ... with RF excitation of the momentum spread. XXX with velocity separation by beams of clearing field electrodes.

↓ : optimised momentum cooling time with the sweeping technique.

Fig. 2. Dependence of the momentum cooling time τ on the capacitor voltage V which excites the Larmor velocity of electrons. In these measurements the total momentum spread was $\Delta P/P = .8 \cdot 10^{-3}$.

Fig. 3. Dependence of the momentum cooling time τ on the transverse electron velocity spread $\theta_{\perp e}$. In this measurements $\Delta P/P = 3 \cdot 10^{-4}$. On the abscissa the correction coil current is shown.

Fig. 4. Dependence of the momentum cooling time τ on the amplitude of sinusoidal modulation of electron energy. $\Delta P/P = .7 \cdot 10^{-3}$.

Fig. 5. Dependence of the debunching rate τ^{-1} versus proton beam intensity J_p .

Fig. 6. Dependence of the variation of the proton beam position the clearing field electrode potential.
... without clearing
XXX voltage between the plates ΔV = 150 V.

Fig. 7. Dependence of the momentum cooling time τ on the electron energy sweeping time
1. $\Delta P/P = 1.1 \cdot 10^{-3}$
2. $\Delta P/P = 1.5 \cdot 10^{-3}$

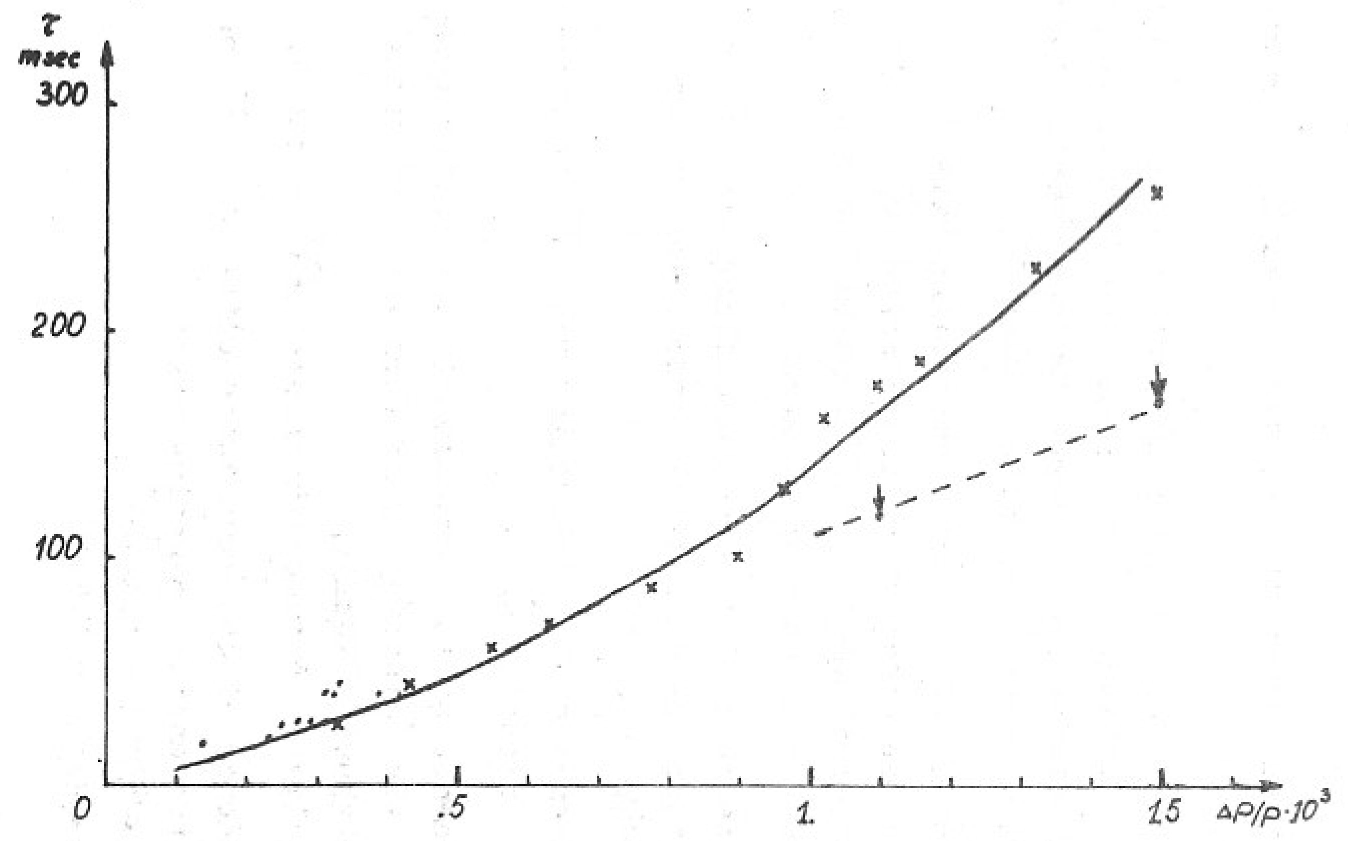

τ
msec
300
200
100
0
.5
1.
1.5
ΔP/P·10³

Fig. 1.

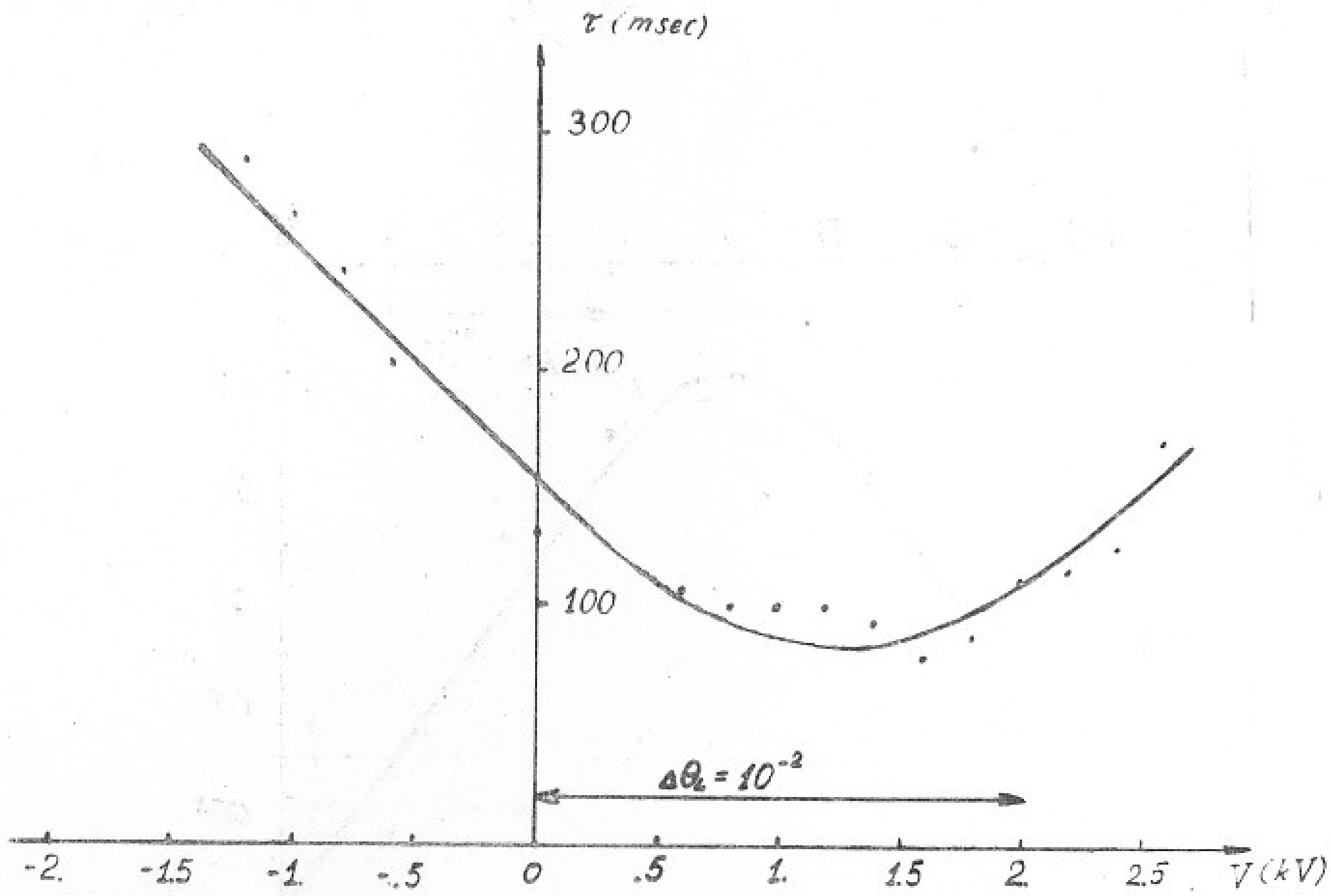
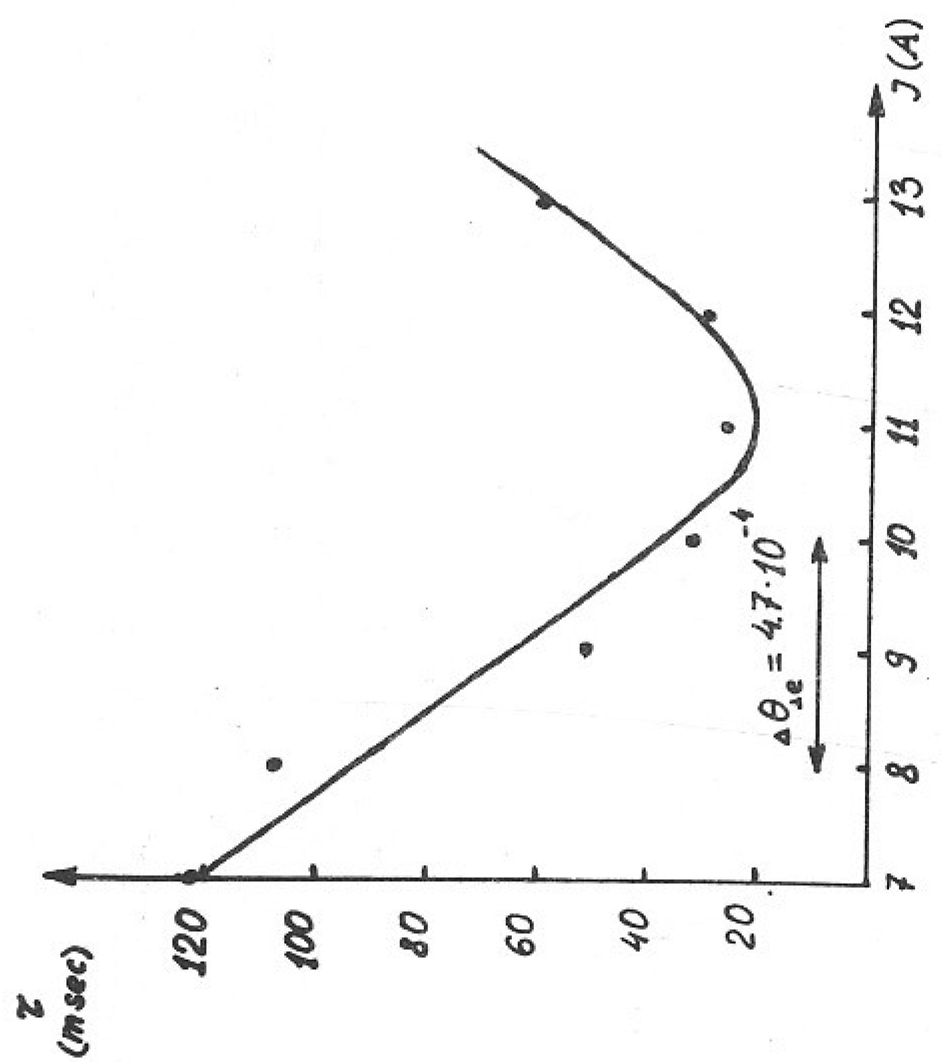
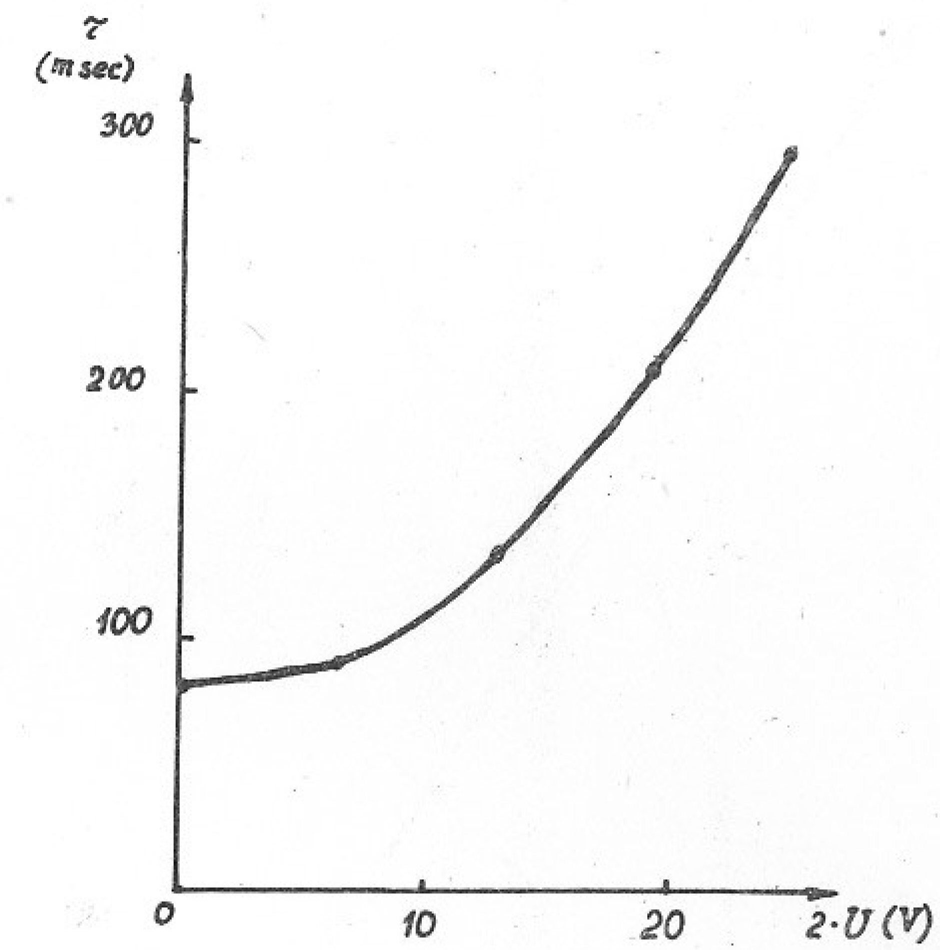

τ (msec)
300
200
100
Δθ = 10⁻²
-2.
-1.5
-1.
-.5
0
.5
1.
1.5
2.
2.5
V (kV)

Fig. 2.



τ
(msec)
120
100
80
60
40
20
7
8
9
10
11
12
13
J (A)
Δθ1e = 4.7·10-4

Fig. 3.



τ
(m sec)
300
200
100
0
10
20
2·U (V)

Fig. 4.

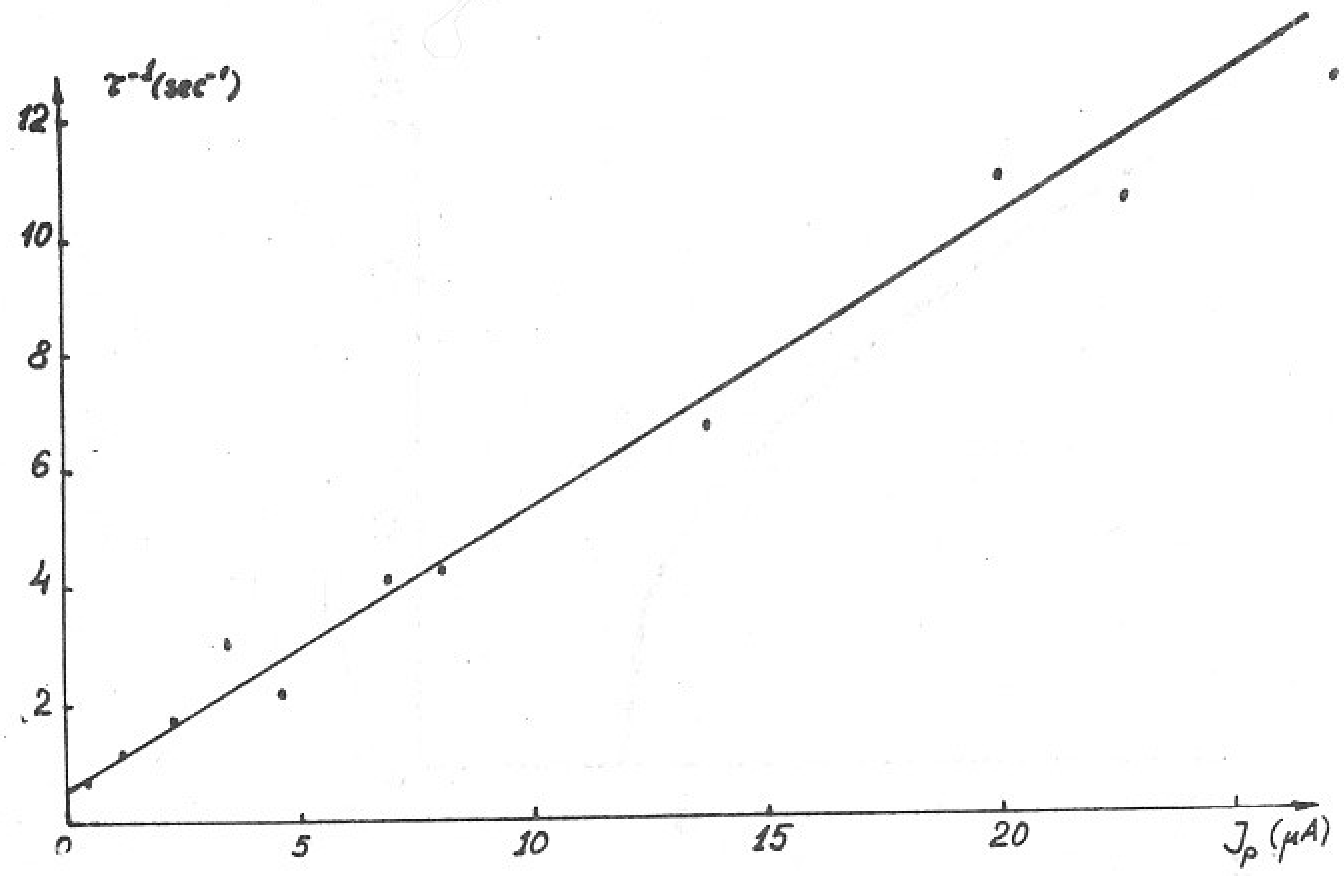

$\tau^{-1}(sec^{-1})$
12
10
8
6
4
2
0
5
10
15
20
$J_p\,(\mu A)$

Fig. 5.

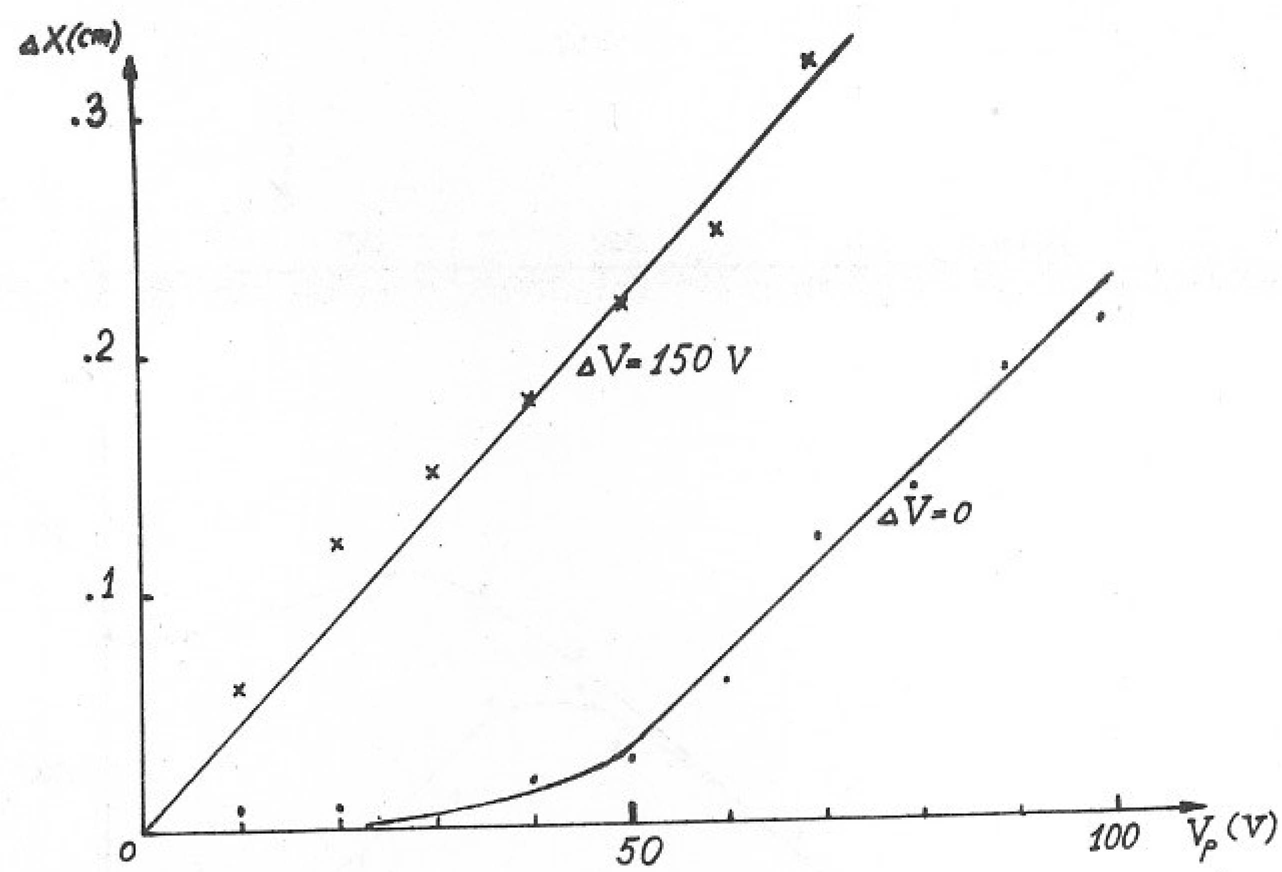

$\Delta X(cm)$
.3
.2
.1
0
50
100
$V_p\,(V)$
$\Delta V = 150\ V$
$\Delta V = 0$

Fig. 6.

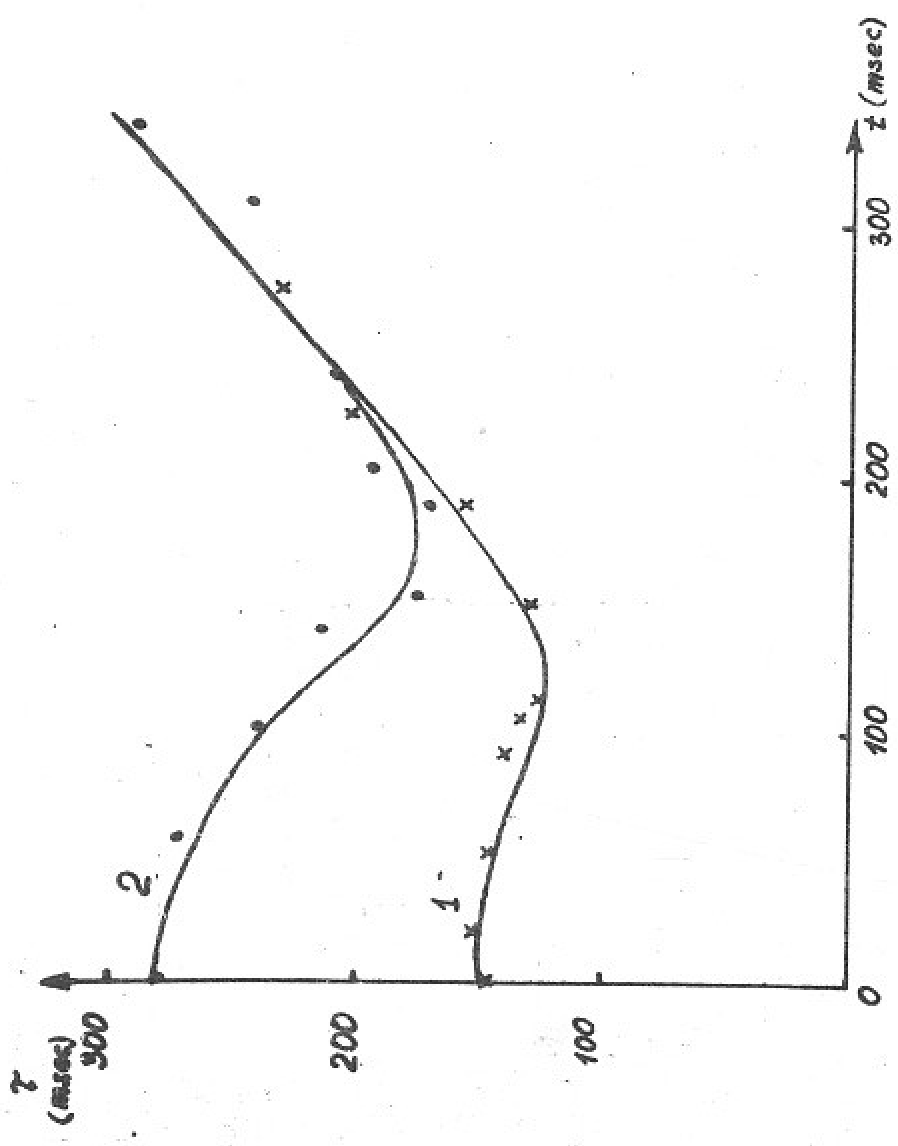


Fig. 7.

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