IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

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

V.V. Parchomchuk,† D.V. Pestrikov,† and A.G. Ruggiero*

Abstract

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 behavior of the longitudinal drag force $F_{/\!/}$. But obviously a direct observation of the momentum cooling rate $\lambda_{/\!/}$ would be more significant. We measured the momentum cooling rate $\lambda_{/\!/}$ versus: (a) proton beam longitudinal spread $\theta_{/\!/p}$, (b) electron beam Larmor velocity spread θ_L, (c) electron beam transverse velocity spread $\theta_{\perp e}$, and (d) electron beam longitudinal spread $\theta_{/\!/e}$. Also 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.

Measurement of the Momentum Cooling Rates

At NAP-M 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]. A fast way to estimate the momentum spread enlargement is to measure the reduction of the peak signal from the jet and assume it is directly proportional to the enlargement of the distribution. We found two realiable 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. The beam has a 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 $\tau_{/\!/}$ required for this is plotted versus $\theta_{/\!/}$ in Figure 1. The dependence is quadratic and in agreement with the empirical formula for the longitudinal drag force[4] in relativistic form

$$F_{/\!/} = -\frac{12\pi\, r_e^2 n\, mc^2 \eta}{\beta^2\gamma^3\sqrt{(\frac{\alpha}{2})^2+\theta_\perp^2+\theta_{/\!/}^2/\gamma^2}\;\sqrt{(\frac{\theta_L}{2})^2+\theta_\perp^2+\theta_{/\!/}^2/\gamma^2}}, \quad (1)$$

where r_e - electron classical radius = 2.82×10^{-13}cm, n - volume density of electrons = 2×10^{8}cm^{-3}, m - electron mass at rest, c - light velocity, η - fraction of accelerator taken by cooling region = 2%, β,γ - usual relativistic parameters. During our experiment the transverse spreads were negligible and $\theta_{/\!/}$ smaller than θ_L (~4×10^{-3}), so that one could write

$$F_{/\!/} = -\frac{A}{\sqrt{(\alpha/2)^2+\theta_\perp^2+\theta_{/\!/}^2}}\,. \quad (2)$$

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

$$F_{/\!/} = -\frac{A}{\sqrt{(\alpha/2)^2+\theta_\perp^2+\theta_{/\!/}^2\left(1-\frac{R\psi}{v_s}\frac{dv_{/\!/e}}{dx}\right)^2}}, \quad (2a)$$

where $R_o\psi$ = 6 m is the dispersion function and v_s the reference velocity. The variation of the longitudinal electron velocity $dv_{/\!/e}/dx$ depends on the space charge potential 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

$$\Delta x = R_o\psi\frac{\Delta p}{p} = R_o\psi\gamma^2\left(\frac{\Delta v_e}{v_s} - \frac{\Delta x}{v_s}\frac{dv_{/\!/e}}{dx}\right)$$

from which

$$\frac{R_o\psi}{v_s}\frac{dv_{/\!/e}}{dx} = \frac{R_o\psi}{\Delta x}\frac{\Delta v_e}{v_s} - \frac{1}{\gamma^2}$$

where Δv_e is the electron velocity change. The cooling time can be calculated from this according to

$$\tau_{/\!/} = -p_s\int_0^{\theta}\frac{d\theta}{F_{/\!/}(\theta)} \quad (3)$$

where p_s is the nominal value of the proton momentum. The continuous curve in Fig. 1 is

†Institute of Nuclear Physics, Novosibirsk 90, USSR

*Fermilab, P.O. Box 500, Batavia, IL U.S.A. Operated by Universities Research Association, Inc., under contract with the Department of Energy.

0018-9499/79/0600-3487$00.75 © 1979 IEEE

calculated according to (2) and (3). There is good agreement if $\alpha = 0.4\times10^{-3}$ and $\theta_L = 4\times10^{-3}$ which are the expected values according to previous observations.[4]

Dependence of Momentum Cooling Rate With Other Beam Parameters

Once we learned 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 $\theta_{\angle}$, $\theta_{\perp e}$, and $\theta_{\parallel e}$. These were varied with the usual techniques[1]. The results are shown in Figs. 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.[4] This would then lead to the following empirical formula for the momentum cooling rate

$$\lambda_{\parallel}^{-1} = \frac{p_s \theta_{\parallel}}{2A} \sqrt{(\alpha/2)^2 + \theta_{\perp e}^2 + \left(1 - \frac{R_o \psi}{v_s} \frac{dv_{\parallel e}}{dx}\right)^2 \theta_{\parallel}^2} \quad (4)$$

$$= 5.10^7\ \theta_{\parallel} \sqrt{4.10^{-8} + \theta_{\perp e}^2 + 6\theta_{\parallel}^2}\ \sqrt{1.6\times10^{-5} + \Delta\theta_{\angle}^2}\ .$$

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.

Intensity Dependence of the Proton Beam Momentum Spread

One concern in cooling intense charged beams 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[5] 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 (~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 ~40 μA, and the beam was a 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

$$\tau^{-1} = \left|\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right| \omega \frac{\Delta p}{p} \quad (5)$$

where $\omega = 2\pi \times 2.2$ MHz in the angular revolution frequency, and γ_t is related to the transition energy of the NAP-M lattice. From Eq. (5) one derives then $\Delta p/p \simeq 4\times10^{-5}$(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.

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 Figs. 1 and 5, we can now definitely state that:

debunching time >> momentum cooling time.

In this situation, it seems that the relation between debunching rate τ^{-1} and beam spread is[5]

$$\tau^{-1} = \frac{1}{\lambda_{\parallel}} \left(|\gamma^{-2} - \gamma_t^{-2}|\, \omega \frac{\Delta p}{p}\right)^2 . \quad (6)$$

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

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

therefore the debunching rate increases with the cube power of $\Delta p/p$, or conversely

$$\frac{\Delta p}{p} \sim (\text{beam intensity})^{1/3}. \quad (7)$$

The dependence (7) can hardly be explained with some sort of longitudinal coherent instability. Moreover, this should not depend appreciably 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 reasonable explanation because of the very small value of the spread. In this case, nevertheless, the intra-beam scattering seems to be a better explanation.[6]

Enhancement of the Momentum Cooling with the Sweeping Technique

Small damping rates are expected to cool beams with initial large momentum spreads. 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 above. The difference now is that the voltage was turned off, after the usual few seconds of 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. For sudden change of the clearing electrode voltage, the proton velocity would shift toward the electron velocity in a time which is just the momentum cooling time. When the voltage is changed slowly the electron velocity would also change slowly, and the proton beam would adiabatically adjust its velocity accordingly. In carrying out our experiment we found that the beam position (momentum) was sensitive to the charge neutralization in the cooling region, activated by the clearing electrodes themselves. We had then to apply also a voltage difference between the two plates to sweep the ions away. The results of our measurements, with this adjustment, are shown in Fig. 6 for two different initial momentum deviations ($\Delta p/p$). 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 effect. An exact calculation can be easily performed by integrating Eq. (3) combined to (1) and letting explicitely the electron velocity to vary with time.

References

1. G.I. Budker, N.S. Dikansky et al., Proc. of X Intern. Conf. on High Energy Accel., Protvino 1977, v. 1, p. 498
2. G.I. Budker, Atomnaja Energia, 22, 346, 1967
3. G.I. Budker, N.S. Dikansky et al., Part. Accel., v. 7, No. 4, 1976
4. N.S. Dikansky, V.I. Kononov et al., Study of the fast electron cooling. Report of the VI USSR National Conf. on High Energy Accel., Dubna 1978
5. N.S. Dikansky and D.B. Pestrikov, Longitudinal Stability of the Coasting Beam in the Storage Ring with Electron Cooling Report to the VI USSR National Conf. on High Energy Accel., Dubna 1978, Preprint INP 78-31, Novosibirsk 1978
6. V.V. Parkhomchuk and D.V. Pestrikov, Preprint INP 77-37, Novosibirsk, 1977

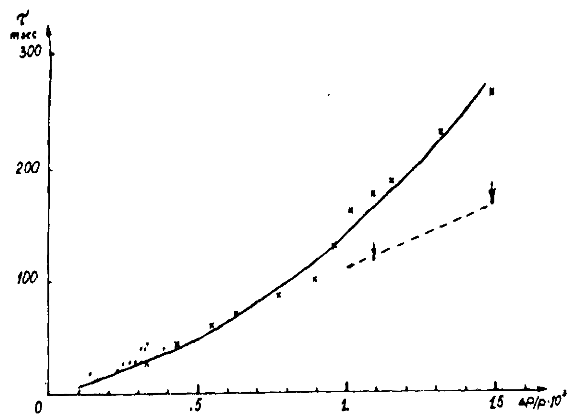

Figure 1. Momentum Cooling Time vs. Proton Momentum Spread, with (dashed line) and without Sweeping Technique.

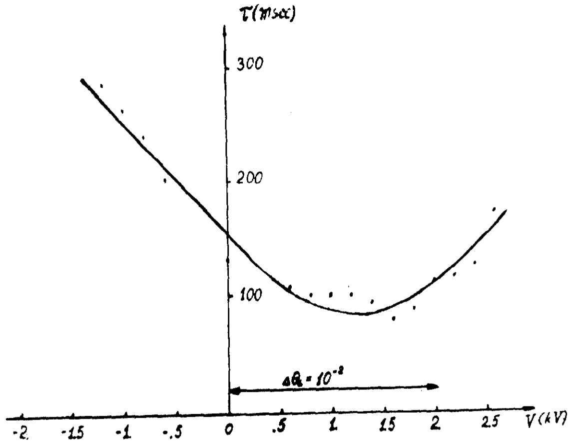

Figure 2. Momentum Cooling Time vs. Capacitor Voltage to Excite Larmor Velocity.

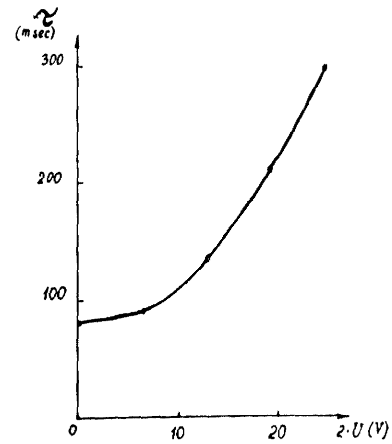

Figure 3 Momentum Cooling Time vs. Modulation of Electron Energy.

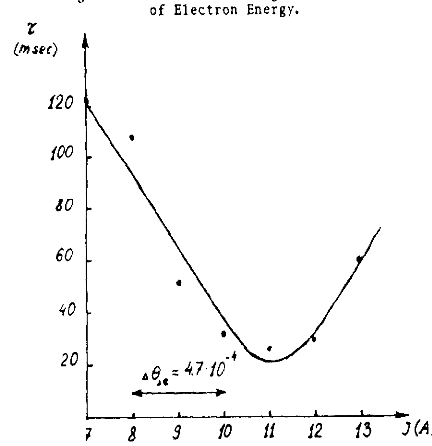

Figure 4 Momentum Cooling Time vs. Transverse Electron Velocity $\Delta\theta_{\perp e}$.

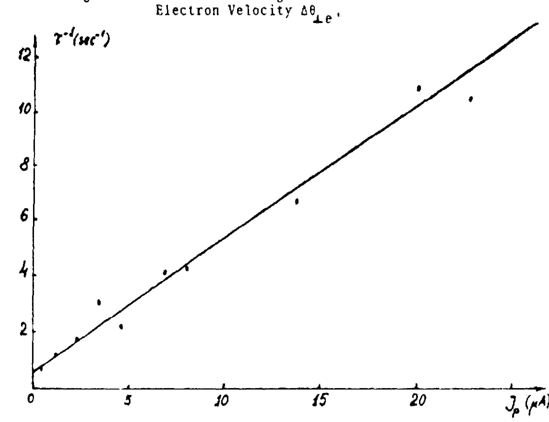

Figure 5. Debunching Rate vs. Proton Beam Intensity during Cooling.

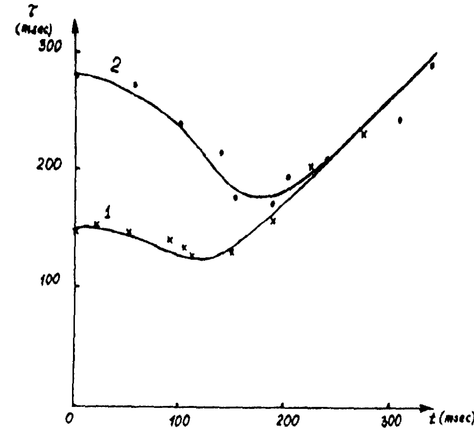

Figure 6. Momentum Cooling Time vs. Sweeping Time. 1. $\Delta p/p = 1.1\times10^{-3}$ and 2. $\Delta p/p = 1.5\times10^{-3}$.