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ANL STOCHASTIC COOLING EXPERIMENTS USING THE FNAL 200-MeV COOLING RING*

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Summary

Studies of stochastic momentum cooling are being conducted on the FNAL 200-MeV Storage Ring. The specific goal of the activity is to establish confidence in the theory and simulation methods used to describe the cooling process, and to develop techniques and devices suitable for use in the antiproton accumulation scheme now planned for construction at FNAL. A summary of the activity, including hardware design, results of experiments, comparison with theory, and implications for the antiproton accumulator are presented.

Introduction

A collaborative effort between Argonne National Laboratory (ANL) and Fermi National Accelerator Laboratory (FNAL) has been formed to conduct experiments on longitudinal stochastic cooling in the FNAL Electron Cooling Ring (ECR), with an expressed goal of developing improved systems for cooling. This activity is being carried out in conjunction with a larger collaboration to develop an antiproton ($\bar{p}$) source for the colliding beam facility at FNAL.[1] Designs for such a facility are converging on a system that utilizes a precooling ring (4.5 GeV, large momentum acceptance), together with a separate accumulator ring (0.2-1.4 GeV).

The precooler ring will stochastically cool batches of $\bar{p}$ by a factor of more than a hundred and decelerate them to the accumulator ring energy in less than 10 s. The success of the facility is crucially dependent upon adequate, rapid cooling of the produced $\bar{p}$. Parameterization of the cooling sequence has thus far relied upon computer simulations. It is, therefore, important that the equipment models used in this simulation be experimentally verified to develop confidence in predictions of performance and cost estimates. This report will summarize such activities to date and the results presented are to be regarded as preliminary in nature.

General Features of the System

Figure 1 indicates the layout of this system in the ECR. Parameters of the system are summarized in Table 1. The system has been designed to permit parameters to be readily varied. These include system gain, filter length, system time delay, filter in or out, differentiation in or out, and pickup signal or random noise input.

The major components of any stochastic cooling system are the pickup and kickers. Since the general consensus is that the FNAL precooler pickups will consist of a wall current-type device, we have developed a prototype 6-gap, ferrite-loaded structure for the ECR.

Although a traveling wave pickup and kicker[2] already exist and have worked quite well, such devices have limited application to the present precooler scheme. However, these devices have been extremely valuable in establishing the operation of the system now being described.

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Figure 2 shows a close-up photograph of one section of the 6-gap pickup. Signals from each gap are conducted via a pair of diagonally-located 100 Ω striplines to two 100 Ω coax signal cables. The two cables from each gap are matched in length and connected in parallel to one input port of an 8-way, 50 Ω power combiner. The cables from successive gaps are matched in length to phase the signals for $\beta = 0.566$ protons.

The single gap kicker is identical to one gap of the pickup, except that the gap is shunted by an equivalent 50 Ω resistive load. This was achieved by placing 16 resistors, equally spaced, around the circumference of the gap. This kicker can handle up to 25 W of power.

A number of studies of the pickup and kicker have been conducted to determine their characteristics. These include excitation of the gap with signals propagated down a silicone rubber-loaded coaxial transmission line ($Z = 50\ \Omega$, $\beta = 0.566$), narrow band heating of the circulating beam, 2-terminal tests, and Schottky signal strength from the circulating proton beam. These studies yielded a signal bandwidth and coupling impedance consistent with 250 MHz and 35 Ω, respectively.

Figure 3 shows a schematic layout of the filter system and controls developed to provide maximum flexibility in cooling studies. The system bandwidth and gain are large enough to permit studies with higher bandwidth pickups and smaller coupling impedance. The notch filter is easily modified to provide maximum flexibility in studying the effect of differing filters, discrete components, and compensation on the cooling rate.

At present, a shorted half-wave filter has been employed, but sufficient material exists for a full-wave filter. This filter consists of about 400 ft of 1-5/8 in rigid air-dielectric coaxial transmission line. The total length was folded into a 20 ft length, using commercially-available elbow connectors. In order to compensate for the attenuation in the filter,[3] a correction is made to the filtered signal as shown in Fig. 3. The compensation network improves the cooling rate by suppressing the noise in the notches more completely and by removing some of the dispersion in the notch frequency. Figure 4 presents the measured dispersion ($D = f_n/nf_o - 1$) of the minimum of the gain for the compensated filter circuit, where f_n is the measured notch frequency for harmonic number n, and f_o is the fundamental frequency. The measured dispersion, although somewhat larger than expected, should permit cooling to a momentum spread less than $\pm 1 \times 10^{-4}$ ΔP/P and does not appear to be limited by deterioration of the notches by the elbow connectors. These elbows, in fact, appear to reduce the dispersion by the dip near 400 MHz.

To improve the quantitative measurement of cooling rates for different systems, a computer program has been written to record sequences of time-sliced Schottky scans. This program extracts the Schottky signal from the amplifier noise background and determines the rms ΔP/P and mean of the signal as a function of time.

This program will greatly facilitate comparison between measured and calculated performance of various cooling techniques.

Stochastic Cooling Studies

An important consideration in achieving stochastic cooling is the timing of the electrical signal between pickup and kicker to the beam. Precise measurements can be tedious and inaccurate by several ns due to signal propagation delay and connectors. With wide bandwidth systems, these errors become quite critical. One of the simplest ways to realize accurate timing is to apply the unfiltered, amplified beam signal to the kicker and look for acceleration or deceleration of the Schottky signal as a function of total system delay. One such delay curve is shown in Fig. 5(a) and indicates a 0.04% $\Delta P/P$ maximum deceleration of the beam during the measurement period of about 35 s. The width of this curve provides a measure of the bandwidth of the beam signal in the entire system.

By switching in the 10 GHz shorted transmission line to provide a differentiation of the beam signal, a bipolar delay curve is observed with both acceleration and deceleration of the beam. A measured delay curve is presented in Fig. 5(b). The advantage of this curve is that more precise delay timing is achieved with the null effect. In addition, cooling or heating can be observed at the crossover, depending on the sign of the amplifier gain. The rate of cooling is quite slow due to the lack of noise suppression by the notch filter.

With the notch filter switched in, the thermal noise is reduced at the beam revolution frequency and improved cooling rates are achieved. In Fig. 6, the cooling curve for this system is shown. The long cooling time is easily understood from the mismatch of system and signal bandwidth. Large improvements are possible by limiting the system bandwidth and by improving the filter characteristics. Fokker-Planck calculations[4,5] using realistic pickups and one kicker with a similar mismatch of system and signal bandwidth yield an initial e-folding time of 450 s, in good agreement with the measured 500 s cooling time.

In order to improve our confidence in predicting cooling rates for future systems, several tests were performed to test the validity of the computational models. One of these tests involved the study of the incoherent noise heating term in the Fokker-Planck model. This model assumes that the beam particles are equivalent to an array of tuned resonators with large Quality Factor.[4] Consequently, energy is only absorbed by the beam if the frequency of stimulation is conincident with the revolution frequency. This is the basic principle behind the notch filter cooling technique.

Quantitative comparison of the heating rate dependence on the details of the noise spectra have been obtained. After initially cooling the beam, the pickup signal was turned off and thermal noise from a resistor was injected into the system. With constant power applied to the kicker, the rate of heating of the beam was measured for the system with and without the notch filter. This rate increased a factor of 75 with the filter out of the system.

Numerical calculations, using the Fokker-Planck equation with the Schottky terms turned off and for a realistic model of the filter, predict a change in rate by a factor of about 67 times. This rate depends quite strongly on the details of the notch filter and the Schottky spectrum and is in good agreement with the measured rates.

Conclusions and Future Directions

This paper has presented the details behind a stochastic cooling system that is expected to yield improved understanding of realistic cooling systems and the influence of filter characteristics on the rate and momentum spread limit that can be obtained. Considerable work remains to be done on improving the bandwidth of beam pickup devices. Several modifications that promise large improvements in cooling rate will also be studied. In particular, the influence of the amount of compensation and how it is applied could yield significant factors of improvements.

Acknowledgments

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Table 1. Parameters of the ECR and Longitudinal Stochastic Cooling System

ECR Parameters	
Kinetic Energy	200 MeV
Revolution Frequency	1.262 MHz
Average No. Protons	10^6
RMS Momentum Spread	±0.06% ($\Delta P/P$)
Momentum Dispersion	-0.605
Pickup to Kicker Dispersion	-0.303
Cooling System Parameters	
No. Pickups/Coupling Impedance	6/35 Ω
No. Kickers	1
Pickup/Kicker Diameter	15.3 cm
Pickup/Kicker Gap Length	4.5 cm
Pickup/Kicker Gap Separation	8.2 cm
Ferrite Type	4 H
Pickup Bandwidth	50-250 MHz
Pickup Coupling Impedance	35 Ω
Final Amplifier Power	50 W
System Bandwidth	20-400 MHz
Notch Filter Type	1-5/8 in. 50 Ω rigid airline
Filter Length	$\lambda/2 \sim 390$ ft. λ 780 ft.

References

1. D. Young, The Fermilab Proton-Antiproton Collider, invited paper to this conference (1981).
2. G. Lambertson et al., Proc. XIth International Conference on High Energy Accelerators, Geneva, p. 794 (1980).
3. G. Carron and L. Thorndahl, preprint CERN-ISR-RF/17-12 (1978).
4. D. Mohl et al., Physics Reports 58, 73 (1980).
5. F. Sacherer, preprint CERN-ISR-TH/78-11 (1978).

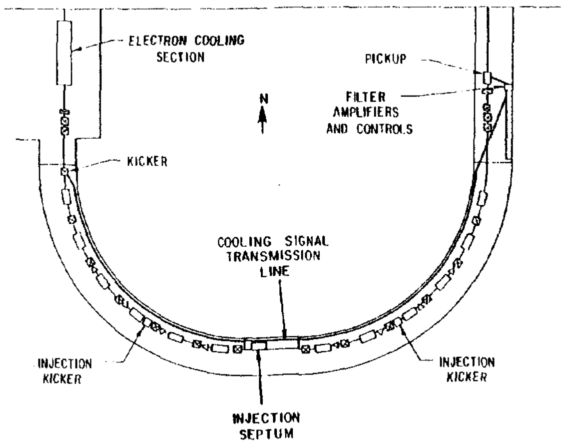

Fig. 1 Schematic layout of the south half of the FNAL Electron Cooling Ring, showing the position of the components of the ANL stochastic cooling system.

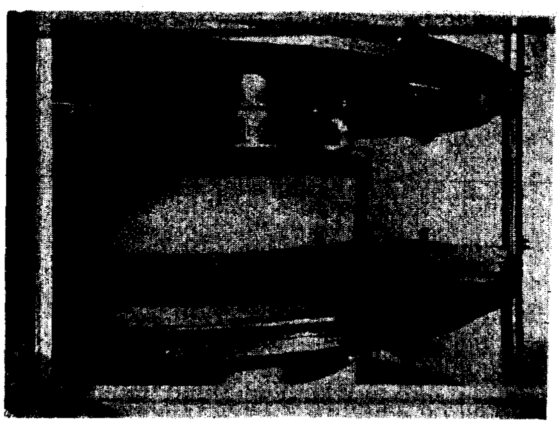

Fig. 2 Photograph of one gap of the 6-gap pickup described in the text.

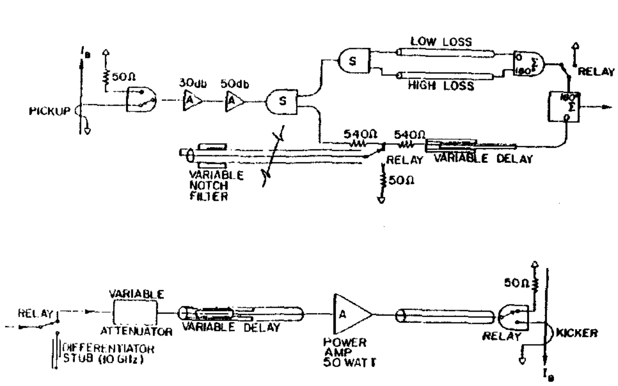

Fig. 3 Schematic layout of the ANL Stochastic Cooling System filter, compensator and amplifier systems. Not all amplifiers are shown.

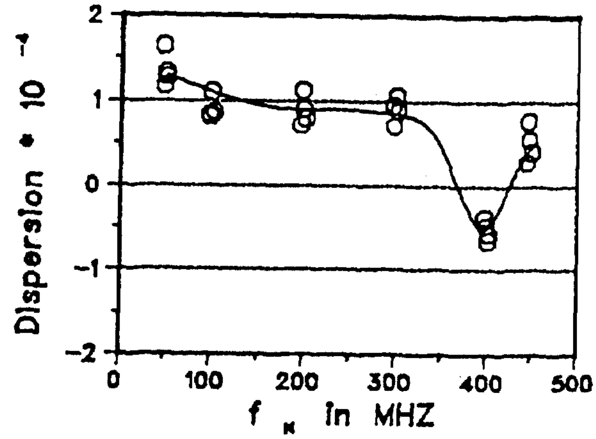

Fig. 4 Measured dispersion ($D = f_n/nf_o - 1$) of the notch frequencies (f_n) as a function frequency for the compensated notch filter.

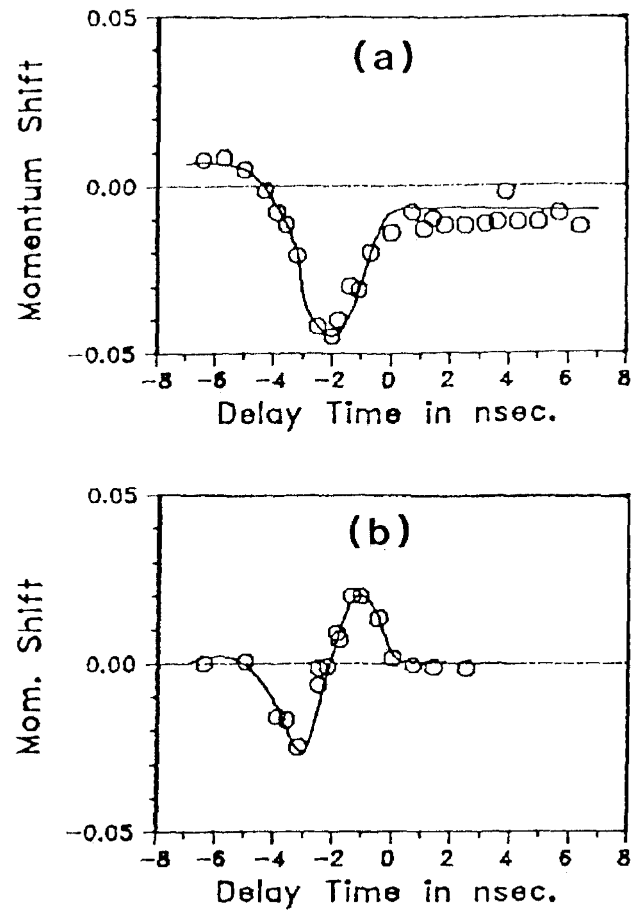

Fig. 5 Measured delay curves for the cooling system as a function of system time delay. The ordinate gives the shift in the mean beam momentum in percent, for a 35 sec measurement period. (a) shows a peak in the deceleration of the beam for the undifferentiated signal, and (b) shows the acceleration and deceleration curve for the differentiated signal.

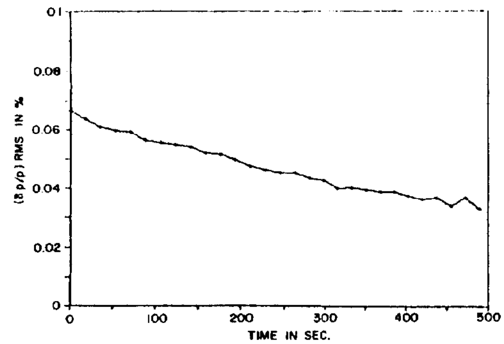

Fig. 6 Measured cooling curve for approximately 5×10^5 protons in the ECR and ≈ 20 watts of power.