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EXPERIMENTS ON STOCHASTIC COOLING OF 200 MeV PROTONS

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Equipment for the stochastic cooling of 200 MeV protons in the Fermilab cooler ring has been installed and operated. Vertical and longitudinal cooling systems were installed by early 1980 and had successfully operated by May 1980. Traveling-wave structures particularly effective for the sub-relativistic beam velocities were used for the pickup and kicker electrodes.

The longitudinal cooling system, in its nominal configuration, consists of 239 dB of active gain, frequency compensation networks, a notch filter tuned to the revolution frequency of the storage ring, attenuators, and pickup and kicker electrodes. The preamplifier and most of the low-level amplification blocks are Miteq AU-2A-0550, which provide 32 dB gain over a frequency range of 1.5 to 550 MHz with a noise figure of 1.9 dB. The final amplifier, a ENI440LA, provides a peak level of 35 watts over a frequency range of 150 kHz to 310 MHz.

The vertical system is similar, except the notch filter is omitted and the vertical kicker is $3\pi/2$ in betatron phase advance downstream from the pickup. With a transit time of only 137 ns care is taken to reduce all delays, including the use of high-velocity air line wherever possible.

The gain, delay, and notch filter frequency are all remotely adjustable from the control room. The Schottky signal is observed on an HP 8568A spectrum analyzer, which is attached to the FNAL computer control system for data analysis and printout.

Traveling-wave Electrodes

The longitudinal pickup and kicker electrodes are identical trifilar helices wound with 2.7 mm s.s. wire. Each is 1.75 m long and 76 mm diameter, centered in a 15 cm. diameter vacuum pipe by means of alumina posts. Conductor spacing is maintained with circular rings every 22 cm. along the helix. The pitch is adjusted so that signal phase velocity matches the beam velocity ($\beta = .566$). The characteristic impedance is 60 ohm. Vacuum feed-throughs are type "N" connectors which lead directly to the electronics or 50 ohm terminations.

The vertical pickup and kicker electrodes are two-conductor balanced transmission-line structures. Each electrode consists of symmetric upper and lower ladder lines that bracket the beam in the vertical direction and extend axially along its trajectory within a ss vacuum tube; the pickup and kicker are 3.75 and 1.6 m long, respectively. The ladder line rungs are 0.13 mm nickel straps 2.2 cm wide, arched to conform to the beam profile and spot welded to two taut 1 mm tungsten wires 10 cm apart. The geometry was adjusted to match the difference-mode phase velocity to the beam over 50 to 450 MHz. The 100 ohm differential-mode impedance is transformed to 50 ohm by external coaxial baluns. The kicker is driven in push-pull by matched 35 watt power amplifiers. Belville washers provide 40 kg tension to the tungsten wires through alumina-insulating shackles limiting sag to 0.5 mm. The tensioning device allows a 300° C vacuum bake of the entire structure.

The simple helical structure of the longitudinal pickup was analyzed using the Lorentz reciprocity theorem and by direct calculation of the fields in the beam-helix interaction. Well below the 1.2 GHz cutoff the voltage response V to beam current I is

$$V = \frac{j\omega\ell}{2\gamma^2\beta_c} ZI \qquad (1)$$

Where the helical line impedance is approximately

$$Z \approx \frac{\mu_0 c}{2\pi\beta} \ln b/a \qquad (2)$$

For our longitudinal pickup electrode, Z is 60 ohm and V/I is 329 ohm at 250 MHz.

Experimental verification of the pickup coupling impedance was limited by an uncertainty of ±50 percent in beam current. The electrode was used to measure both the signal from beam bunched at 7.6 MHz and Schottky signals from 50 to 450 MHz. Throughout this range, the responses agreed to within ± 10 percent of that calculated from Eq. 1. The noise figure of our preamplifier is 2dB and the ratio of Schottky signal to noise power averaged over a harmonic band at 200 MHz is 0.17 with 1×10^7 protons in the ring.

Analysis of the double ladder line vertical pickup response is less complete. An approximate model gives the difference voltage produced by current I at fraction y/a from the aperture center as

$$V = \frac{j\omega\ell}{2\gamma^2\beta c} \frac{Z_\Delta}{2} I \frac{y}{a} \qquad (3)$$

where Z_Δ is the electrical impedance for the difference mode.

The observed signal from the vertical pickup is larger than predicted by Eq. 3 by a factor of up to 3. The frequency dependence is as expected, however, and linearity with vertical displacement up to quarter aperture is excellent. The S/N power ratio averaged over one band at 250 MHz is 0.07 with 1×10^7 protons and $\sigma/a = 0.18$. We need more detailed analysis of this type of TW pickup to resolve discrepancies and to guide the design of this type of electrode. To measure the electrode characteristics over a wide range of parameters, a test facility using an electron beam modulated at high frequency is being assembled.

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The TW structures used as both pickups and kickers provide relatively large coupling to the beam using simple construction. Used as pickups, the signal power increases with the square of the length and the noise contribution may be reduced by using low-temperature components. However, the response varies as γ^{-2}, which will reduce the efficiency at relativistic velocities compared to an array of loop or gap pickups.

Longitudinal cooling

For these experiments it was sufficient to use commercial semi-flexible cable for the notch filter which consists of 118 m of 7/8-inch Heliax loading a T-network of 540 ohm resistors. The filter exhibits two types of errors: finite notch depth and dispersion of the frequency from precise harmonics of the revolution frequency. The finite attenuation in the notch is well described by resistive losses on the inner and outer conductor. The notch depth ranges from 22 db at 150 MHz to 15 db at 350 MHz. A feed-around compensator, provided by ANL and modeled after the CERN compensator, improved these figures to 27 db at 150 MHz and 24 db at 350 MHz. The dispersion in notch frequencies, due to random dimensional variations in the filter line, and non-ideal terminations at each end of the line, was not significantly changed by the compensator, and remained 2×10^{-4}, measured as a fractional change of the fundamental frequency. Compensation was found to be an essential requirement in achieving a narrow final momentum width of the circulating beam.

Frequency selective networks of various types were tried to reduce the required final amplifier power, increase the overall signal-to-noise, and to reduce the gain near the high frequency cutoff where large phase errors in the final amplifier became significant. The most successful were two 6.7 nsec clipping lines in tandem. These filters have a response characteristic which goes as $\sin(\pi f/f_n)$ and a linear phase characteristic from $\pi/2$ to $-\pi/2$ over $f = 0$ to $f_n = 300$ MHz. This filter reduces the gain at the low frequency end where the signal-to-noise ratio is poor due to the linear frequency sensitivity characteristic of the pickup, and also at the high frequency end where the phase shift of the power amplifier becomes significant.

Cooling tests were carried out on the 200 MeV storage ring in the period from early 1980 through February 1981. The low beam intensity of 10^5 - 10^7 circulating protons was partially compensated for by the high coupling impedance of our pickups and kickers. The sensitivity of the cooling process to variation of several parameters of the cooling system was determined. In our best runs, we were able to reduce the momentum spread of the unbunched circulating beam by a factor of 13, starting with a momentum spread of $\Delta p/p = \pm 0.2$ percent, $\Delta f/f \simeq \pm 0.12$ percent.

We always maintained the normalized gain factor g much less than unity to be within the 35 watt capability of our power amplifier; we therefore did not observe suppression of the Schottky signal.

The results of our best experimental runs were compared to a computer calculation based on the Fokker-Planck equation[1]. The code takes into account detailed properties of the experimental apparatus: the phase and gain errors as a function of frequency, the actual filter response due to dispersion and losses, and the characteristics of the pickup and kicker. Suppression of the Schottky signal due to beam feedback was neglected since that effect would be insignificant in our present parameter range.

Of the several parameters we have observed experimentally, three of the most significant both from the viewpoint of achieving the required cooling conditions and from an understanding of the cooling process are the actual instantaneous cooling rate with a well-compensated filter, the maximum stochastic acceleration rate without a filter, and the acceleration rate of the beam with an off-frequency filter. The latter measurement simulates the single-particle cooling rate and is obtained by first cooling the beam, quickly changing the filter notch frequency, and then noting the instantaneous rate the beam accelerates toward the new notch frequency.

The results of these comparisons are tabulated below.

The numerical simulation assumed an initial gaussian momentum distribution with 350 keV standard deviation ($\Delta f/f \simeq 6 \times 10^{-4}$) and the system frequency and phase characteristic defined by a compensated notch filter, two 6.7 nsec clipping lines in tandem, and the measured phase and amplitude characteristics of the amplifier chain and signal cables.

	Experimental	Numerical
Cooling rate		
power	3.8 W	3.8 W
gain	185.5 db	184.5 db
e-fold time	21.0 sec	15.9 sec
Single-particle cooling rate (notch off frequency, beam cooled to σ_E = 35 keV)		
Δf_{notch}	1000 Hz	1000 Hz
gain	178.5 db	177.5 db
power	0.8 W	0.8 W
dE/dt	14.0 keV/s	13.7 keV/s
Stochastic acceleration (no filter)		
power	0.2 W	0.2 W
dE/dt	24 keV/s	50 keV/s
gain	unrecorded	187.7 db

The agreement of experiment with numerical calculation is excellent, implying adequate knowledge of the equipment parameters, including the coupling impedance of the pickup and kicker to the beam. For our conditions, i.e. non overlapping bands and low gain, the Fokker-Planck approach would be expected to be valid.

Vertical Betatron Cooling

The vertical system gain is primarily controlled by the pickup response, which is proportional to frequency. The noise power presented to the kicker is flat to the 310 MHz amplifier cutoff. This could be favorable in a strong-signal situation where Schottky heating would be a concern. However, in our experiments beam intensities were typically less than 10^7 particles. Furthermore, the pickup electrode aperture was twice the actual beam size, reducing the sensitivity. Therefore, the usable gain is limited by noise at low frequency. A further detrimental factor is the rapid phase change near the cutoff frequency of the power amplifier.

Measurements of open-loop gain are probably the most powerful tool in analyzing cooling system characteristics and finding good initial settings of delays and gain.[2,3] However, this technique was not yet available to us for tune-up when these cooling tests were made. Instead the system timing was obtained by a technique of measuring the stochastic acceleration of the beam when off-axis in the vertical pickup, simulating a longitudinal signal and operating the kicker in common mode. In addition measurements of beam lifetime vs. delay with the vertical cooling system in normal operation were used as aids in setting delays.

Under present conditions the circulating half lifetime is approximately 100 seconds without vertical cooling. With cooling it is strongly dependant on the vertical cooling system signal delay time. At delays corresponding to increased lifetime, settings were further adjusted by maximizing vertical cooling; the vertical Schottky signals disappeared into the noise after several seconds. Since the Schottky signal depends both on the beam current, which decays, and on the vertical beam height, which decreases with cooling, we based our measurements on a vertical profile monitor. This device collects ions from ionized background gas and displays a vertical beam profile, while also serving as a relative current monitor. This monitor provides a beam profile at every 15 to 20 seconds. At all but the lowest gain settings asymptotic beam height was reached before the next profile monitor scan was obtained. So only a lower limit of the initial cooling rate can be given. Despite the beam loss the vertical phase space density, N/ε_V, triples with cooling. Without cooling it is observed to decrease.

Our present data indicates initial cooling times $\tau_0 < 20$ s (in amplitude) where

$$-\frac{1}{\tau_0} = \frac{1}{\sigma}\left.\frac{d\sigma}{dt}\right/_{t=0} \qquad (4)$$

These values are obtained over a range of system gain within which variations of rate were obscured by the 20 secondsintervals between measurements. At 20 dB lower gain, decrease in vertical size over more than one measuring interval was observable, yielding $\tau_0 \approx 70$s.

Asymptotic values of σ_y, although lower at reduced system gain, showed only a weak gain dependence. The presence of diluting mechanisms other than heating by amplifier noise (e.g. multiple scattering) might explain this. The best reduction in beam height was a factor of 2.5.

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References

1. F. Sacherer, Stochastic Cooling Theory, CERN-ISR-TH/78-11 (1978).

2. J. Borer, et.al., Information from Beam Response to Longitudinal and Transverse Excitation, IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, 1979, pp 3405-3408.

3. S. Van der Meer and D. Mohl, Stochastic Cooling of Particle Beams, CERN/PS/AA 79-23 (1979).

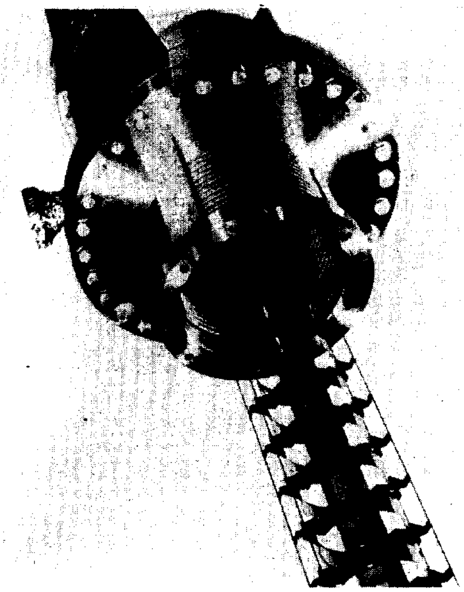

Fig. 1 - The double ladder line of the vertical pick-up is shown. The structure is partially removed from the vacuum enclosure and supported by a temporary fixture running along its center.

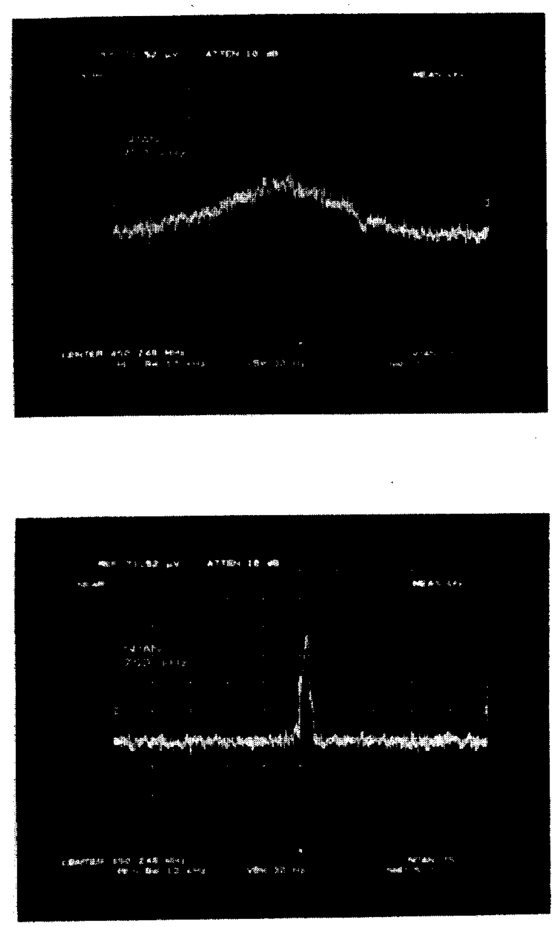

Fig. 2 - Longitudinal Schottky Scans before and after cooling (f_c = 450.24 MHz, h = 357, f_o = 1.2612 MHz). A reduction of $\Delta p/p$ by a factor 13 was observed with an initial time constant of 21 sec.