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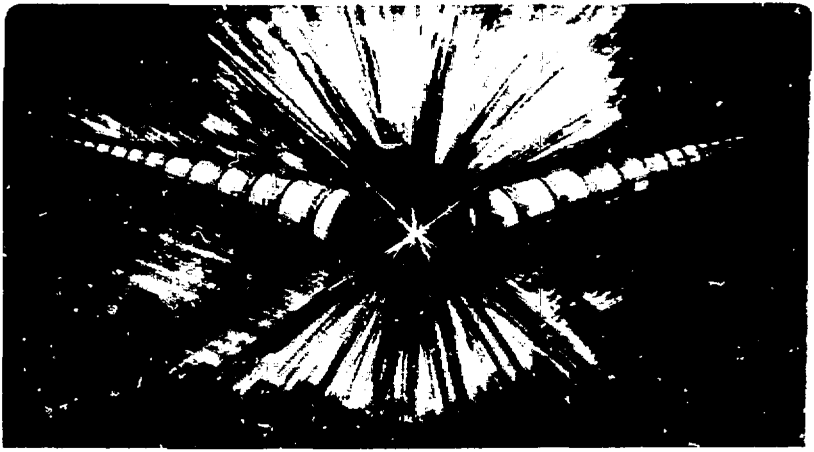

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ABSTRACT

Vertical and longitudinal cooling has been achieved at the FNAL 200 MeV cooling ring. Initial longitudinal cooling times of 20 seconds for 1.5×10^6 circulating protons are in approximate agreement with calculations based on measured system parameters. The cooling systems have an electronic bandwidth of ~ 300 MHz, travelling wave pickups and kickers and a notch filter using flexible cable. The TW structures provide a good signal-to-noise ratio and reduce output power requirements.

Experiments in stochastic cooling of protons have been carried out in the 200 MeV "cooler" ring at Fermilab.[1, 2.] Both the longitudinal momentum spread and the vertical beam emittance have been reduced in experiments intended to develop equipment and expertise in the technique.

The location of beam pickup and kicker electrodes in the ring is shown in Figure 1. The 3.75 m long vertical pickup is in a long straight section and the vertical kicker is downstream $3\pi/4$ radians in betatron phase advance. The longitudinal electrodes are one long dispersion-free straight section. The 200 MeV beam of 1.5×10^6 protons has a revolution frequency of 1.26 MHz, a momentum (frequency) width of 0.22 percent (0.13 percent), and an unnormalized vertical emittance of $2\pi \times 10^{-5}$ rad-m.

PICKUP AND KICKER ELECTRODES

All beam electrodes are traveling-wave structures. As these electrodes must be vacuum bakeable to above 300° C, we chose for reduced complexity and cost, and better performance, the single traveling-wave structure rather than an array of short gaps with external signal-adding networks.

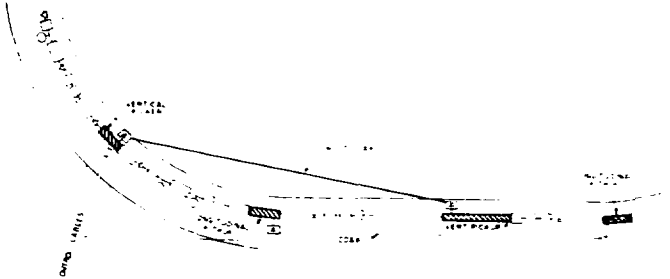

Fig. 1: Layout of cooling systems in the cooling ring.

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The longitudinal pickup is a 1.75 m long trifilar helix wound with 2.7 mm-diameter stainless steel wire. The pitch of the [illegible].6 cm diameter helix is chosen so the wave velocity matches the beam velocity, $\beta = 0.566$. Mounted in a 14.9 cm vacuum pipe, its transmission line impedance Z_L is about 60 ohms. The downstream end is connected directly to the 50-ohm input of a low-noise preamplifier. The upstream termination impedance is a free parameter to the extent that reflections of the small upstream signals are tolerable. We used a 50-ohm resistor, but this could be refrigerated or shorted to improve the ratio of signal to noise.

In the frequency range well below cutoff the voltage response of the pickup of length ℓ to beam current variations $I(\omega)$ is

$$V(\omega) = \frac{j\omega Z \ell I(\omega)}{\gamma^2 \beta c} . \qquad (1)$$

Equation 1 shows the desirable feature of traveling-wave pickups that output power increases as the square of length, without the complexity of adder networks. Also the output is the time derivative of beam current signal, hence output power is proportional to ω^2. Thus the signal-to-noise ratio is poor at low frequency and improves at high frequency. We have not yet optimized the frequency response of our system to take advantage of this fact. With a preamp noise factor, NF, of 2 db and back-terminated pickup, the noise power density $10^{NF/10}\,kT$ is 6.50×10^{-21} watt/Hz. The Schottky signal power density is

$$\frac{dP}{df} = \frac{2NZ}{f_0}\left(\frac{e f_0 \omega \ell}{\gamma^2 \beta c}\right)^2 = 1.50 \times 10^{-38}\, f^2 \ \text{watt/Hz} \qquad (2)$$

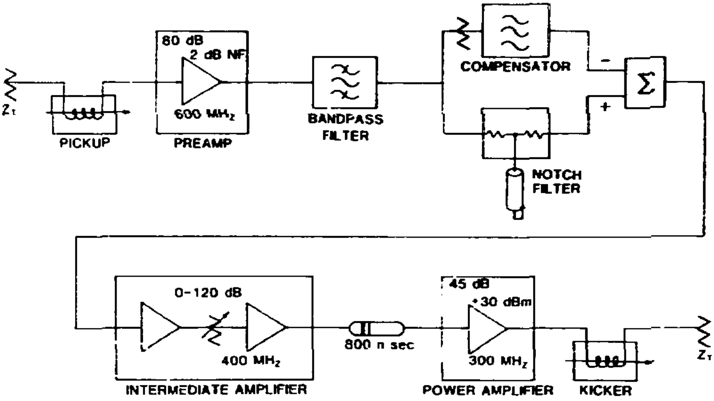

Fig. 2: Electrical configuration of the longitudinal system.

Fig. 3: The vertical pickup partially withdrawn from the vacuum chamber is shown with a temporary central support strut.

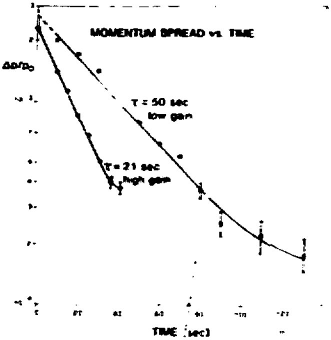

Fig. 4: Relative momentum spread versus time for two values of grain

for beam intensity $N = 2 \times 10^6$ protons in the Fermilab cooler ring. This gives a local signal-to-noise power ratio of 0.14 at 250 MHz, in reasonable agreement with an observed value of 0.13 allowing for uncertainty in the beam intensity.

The 3.75 m long vertical pickup is a traveling-wave structure consisting of two ladder lines placed symmetrically around the beam (Fig 3). Arched cross pieces of 0.13 mm nickel sheet are supported on 0.51 mm dia. tungsten wires. Sag of the lines is limited to 0.3 mm by 40 kG tension in each wire and a single support at center span. The differential signal wave impedance is 100 ohms; this is matched to the 50-ohm preamplifier by a balun transformer. For 2×10^6 protons in the ring the Schottky signal power density should be $4.50 \times 10^{-39} f^2$ watt/MHz, and at 250 MHz the ratio of signal to noise power density should be 0.043. Observed values for these two quantities agree within 30%. This agreement may be partially coincidental as the Schottky power spectrum showed an unexplained modulation with 25 MHz periodicity. Such a periodicity could arise from electrical reflections or from the cell structure of the lines, but electrical measurements have failed to give a quantitative explanation.

The kickers are of similar construction to the pickups but with differences appropriate to the beam dimensions and available space.

ELECTRONICS

The wide-band amplifier system[3] is shown in Figure 2. The vertical and longitudinal systems use commercially available solid state amplifiers and are the same except for paired output amplifiers to drive the vertical kicker, and the addition of a notch filter, band pass filters, and more delay in the longitudinal system. The vertical system time delay from pickup to kicker must be 137 nsec. Of this, 82 nsec is in cables and 55 nsec in circuitry. The 35-watt output amplifier delay is 32 nsec and is flat in gain from 10 MHz to 300 MHz. However, the phase lag is 45° at 250 MHz and increases rapidly above that frequency. The preamplifier responds to 500 MHz and as used with an input coaxial switch has a noise figure of 2 dB. Overall active gain of the system is 239 dB (longitudinal) with typically 120 dB net electrical gain.

The longitudinal notch filter is a shorted 118 m cable of 7/8-inch Andrews air-insulated Heliax wound on a large spool with a remotely-variable delay between the cable and the shorted end. To offset losses of the Heliax a compensation network similar to one devised at CERN[4] is used. This network, supplied by collaborators from Argonne National Laboratory, improves the notch depth at 280 MHz from 18 dB to 32 dB.

EXPERIMENTAL RESULTS

Momentum cooling at high gain produced a best 1/e cooling time of 13 seconds; an example with 21 seconds is shown in Figure 4. The initial momentum spread of 0.22 was reduced to 0.03 with about 4 watts of power into the kicker. With 7 dB less gain, the cooling time increased to 50 seconds and final momentum spread was 0.018 (or 0.011 in frequency) (Fig. 5). We have indications that a primary factor determining the limiting width is ripple in the storage ring guide field magnets caused mainly by line voltage variations from the 8 GeV booster synchrotron operation.

Stochastic acceleration with the notch filter removed provides information on the system time delay, gain, and frequency response. One can also observe acceleration in the complete system by displacing the notch frequency after the beam is cooled. The acceleration rate of the narrowed beam toward the new notch frequency is the noiseless cooling rate. This observed rate agrees well with numerical predictions.

Momentum cooling without a notch filter was also observed. By selecting a time delay at which the stochastic acceleration passes steeply through a null, the beam will cool toward that null (or heat away from it if polarity is reversed). The cooling rates are slower and the data has not yet been analyzed.

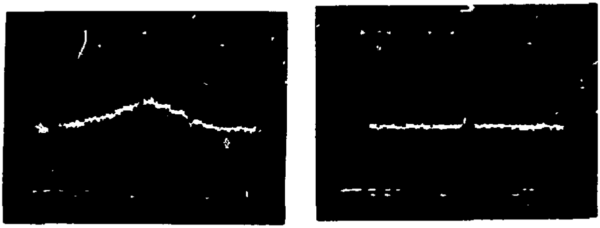

Fig. 5: Longitudinal Schottky scans before and after cooling showing a factor of 13 reduction in momentum width.

Cooling in the vertical direction has just been achieved and observations are very limited. The time to reduce the vertical width by a factor of two (a factor of four in emittance) is approximately 20 seconds. This is observed on a profile monitor[5] detecting the ionization of background gas. The normalized gain function g is about 0.01 in this case and power to the kicker is in the milliwatt range.

An incidental result of vertical cooling is a dramatic increase in the lifetime of the circulating beam. The uncooled beam lifetime, typically of the order of one minute (e-folding time), increased by 1-2 orders of magnitude with cooling. One must note that this occurrs with no direct radial cooling. There is no monitor for radial beam width, but one might conclude that vertical-radial coupling is reducing radial losses.

A computer code using the Fokker-Planck equation has been written at LBL. This code includes many of the frequency-dependent characteristics of the electronic systems used. The code permits the notch filter to be accurately modelled, including the effects of notch frequency dispersion with harmonic number, and losses. Realistic simulation of the system gain and phase errors is included. The code provides numerical predictions and is being used to guide us in understanding and upgrading the systems.

CONCLUSION

It was notable that cooling was obtained with only minor adjustments after installation of the two systems. This was possible even though the apparatus was designed for operation with about ten times greater beam intensity, a circumstance that limited observations and performance. The traveling-wave pickups have provided a signal power many times that possible with an array of discrete pickups occupying the same path length. The electronic systems have been completely reliable. While tests of this cooling apparatus at 200 MeV will continue, the emphasis must shift toward the development and design of cooling systems for the Fermilab Collider project. To this end, a test facility with modulated electron beam is being assembled at LBL to aid in the development of high-β pickups needed for this next project.

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