Fast Betatron Cooling in the Debuncher Ring
for the Fermilab Tevatron I Project

B. Autin, CERN Geneva, Switzerland
J. Marriner, A. Buggi, K. Takayama
Fermilab*, P.O. Box 500, Batavia, Illinois 60510

Introduction

Originally, the only function of the Fermilab antiproton debuncher was to compress the momentum spread of the injected antiproton beam using a bunch rotation technique. This operation is actually very fast and almost all the time between two injections can be used to cool the beam transverse emittance. The cooling is based on the stochastic method and designed to reduce the initial emittance of 20NWmm-mrad by an order of magnitude in two seconds. Thus, the beam transmitted to the accumulator has a small transverse size and is easily handled by the high frequency systems of the accumulator.

To achieve this performance, the betatron cooling is handicapped by the low value of η, the dispersion in revolution frequency with the particle momentum; η has indeed to be maintained small in order to keep the radio frequency voltage required for the bunch rotation within a reasonable limit; moreover, the momentum spread is small, (0.01), therefore, a very broad bandwidth (2-4 GHz) is required to have an efficient sampling of the beam. Betatron cooling of low intensity beams (10⁸ particles) is usually limited by the thermal noise since the signal is naturally weak; here it is taken advantage of the ample space left between the areas of the ring to dispose a great number of pick-up electrodes; furthermore, a low noise temperature of the pick-up and of the preamplifier is obtained using cryogenic techniques. Fast cooling requires a high output power for the power amplifiers. The conjunction of high power and broad bandwidths may be exceedingly uneconomical. It is possible to get a reasonable power (500 watts) by using a large number of kickers and by optimizing the gain during cooling. A discussion of the system parameters and computer simulations are presented below.

System Parameters

The cooling of a beam of particles is obtained by correcting at a "kicker" the position of the center of gravity of a beam sample observed at a "pick-up". Superimposed to the signal of the center of gravity are the Schottky noise and the thermal noise which do nothing but a beam heating.

Schottky Signal, Frequency Range and Pick-Up Geometry

The Schottky signal is created by the fluctuations in particle motion inside a beam sample. It depends on the pick-up geometry which in turn is defined by the beam size. The pickup electrodes consist of n pairs of direction loop couplers. The pairs function in the difference mode and the individual signal add up in the microstrip lines of a combiner board. Each pair is optimized to have the maximum sensitivity η and loop impedance Z within an octave bandwidth W. The electronic frequencies f are as high as possible but they are limited by the condition of non-propagation of the wave guide modes; thus, the width w, the length l of a loop and the gap 2h between the loop of a pair are smaller than the shortest half wavelength. The only mode which propagates is the TEM mode of wave number k = 2πf/c (c, light velocity). Loop characteristics are given in Figure 1. The expression of the Schottky power is

\[ S = \frac{1}{4} NW f_0 \sin^2(kl) Z \left( \frac{\omega}{n} \right)^2 n_p \]

where \( n \) is the number of particles (10⁸), \( f_0 \) the revolution frequency (.565 MHz). The mean value of \( \sin^2(kl) \) over one octave (π/3 < k < 2π/3) is 0.13 and \( n \) has been chosen equal to 128 so that \( S = 4 W \). The sensitivity for so many pick-ups may be reduced by the variation of the beta-function and of the betatron phase advance over the length of the pick-up station. Therefore, the system has been split into two subsystems of 64 pick-ups each, separated by half a betatron wavelength; in each subsystem, the variation of the betatron characteristics have a negligible influence in practice. A block diagram of the pick-up system is drawn in Figure 2.

Thermal Power

The finite temperature of the terminating resistors of the loop and of the preamplifiers creates at the input to the preamplifier a signal or power

\[ P_D = K(T_A + T_s) W \]

where K is the Boltzman's constant, \( T_A \) the equivalent temperature of the amplifier and \( T_s \) the temperature of the resistors. By cooling resistors and gallium arsenide field effect transistors at liquid nitrogen temperatures, \( P_D \) is equal to 4.4 pW so that the initial Schottky signal to thermal power ratio is about 1.

Cooling Rate and Electronic Power

The variation of the emittance \( \epsilon \) with time obeys an exponential law

\[ \epsilon(t) = (\epsilon_0 - \epsilon_\infty)e^{-t/\tau} + \epsilon_\infty \]

where \( \epsilon_\infty \) is the initial emittance, \( \epsilon_\infty \) the asymptotic emittance determined by the level of thermal noise and \( (1/\tau) \) the cooling rate which is uniquely determined by the Schottky signal:

\[ \tau = \frac{\hbar^2\eta(\delta p/p)}{N\epsilon_0} \]

That expression \( (1) \) is valid when the Schottky bands do not overlap, the parameter \( \eta \) does not depend on electronic frequency and for a uniform particle distribution in momentum space. \( F(u) \) is plotted in Figure 3, \( \eta \) is a property of the lattice; its value

© 1983 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

0018-9499/83/0800-2593$01.00 © 1983 IEEE

0018-9499/83/0800-2593$01.00 © 1983 IEEE
C.006) results from a compromise between bunch rotation and betatron cooling requirements. In the definition of the parameter $u$:

$$u = \frac{NG}{W_{10/100}}$$

$G$ is the transfer function of the chain, pick-up amplifier, kicker

$$G = \frac{1}{d^2} \left( \frac{\alpha}{\beta} \right) \left( \frac{\beta}{\beta} \right)$$

Kickers and pick-ups have the same structure and they are an odd multiple of a quarter betatron wavelength apart. $\beta$ is the relative particle velocity $v/c$. $g$ is the gain of the amplifier, it has to be limited in order to keep the power

$$p = g^2 (S + P)$$

at a reasonable value; this is the reason why the number of kickers $n$ has been chosen as high as possible (124). The block diagram of the kicker system is shown in Figure 4. For a power of 500 W, and a particle momentum $P$ of 8.89 GeV/c the amplifier gain is 138 db and the cooling rate is 1.6 s$^{-1}$.

Asymptotic Emittance

In the determination of the cooling rate, it is only the relative change of emittance which matters. For the asymptotic emittance, an absolute definition is needed. An estimate for the asymptotic emittance which encompasses 95% of the particle is given by

$$\varepsilon_{00} = \frac{K}{\kappa} \frac{(T_\theta + T_\phi)}{e} \frac{1 + \beta}{\beta (pc/e)}$$

Its value is 67 mm-mrad and the emittance after 2 seconds is below 27 mm-mrad.

Computer Simulation

A simulation of the betatron cooling in the Debuncher was made to calulate the expected system performance. Included in the simulation were the pickup and kicker response functions, transit-time differences of the electrical signal and particles between pickup and kicker, and signal suppression. The amplifier was modeled as a physically unrealizable ideal amplifier having a gain $g$, from 2 to 4 GHz and zero elsewhere. It was assumed that $g$ is purely real. While the amplifier model was not realistic, measurements of the TWT tube amplifiers in the 1-2 GHz range show that, when externally phase compensated, the tubes can provide gain and phase characteristics that lead to cooling rates equal to or better than the 1-2 GHz "ideal" amplifier. It was assumed that the Debuncher had an emittance of 25 mm-mrad but that the transport line had already limited the beam size of 20 mm-mrad. The total output power was limited to 500 W. The gain was continually adjusted to provide the best cooling within the 500 W limit.

Figure 5 shows the initial and final beam distributions for particles at the central momentum. Ninety-nine percent of the particles fall within an emittance of 77 mm-mrad. Also shown is the final curve for particles with a momentum offset of 0.075%, or halfway to the edge of the distribution. The cooling of these particles is somewhat better since they have a somewhat lower density, i.e., less than Schottky noise. Since the noise figure assumed is somewhat optimistic. Figure 6 compares the final spectrum for design case $\theta_0 = \theta_0 = 100^\circ$ and noise figures 2x and 3x worse. If the noise figures were worse because of the pick-up sensitivity being less than supposed, the kickers would presumably be less sensitive in the same ratio. In this case, the total dissipated power would be larger than the design case of 500 W. Figure 7 is a comparison of the final distribution for different power levels assuming the design case noise figure $\theta_0 = \theta_0 = 80^\circ$. There is little advantage in running at power levels corresponding to optimum gain.

Conclusion

The stochastic cooling system for the debuncher as designed will cool the beam emittance by about an order of magnitude. If the system fails to perform as designed, there is a substantial margin of safety in getting the beam to 77 mm-mrad for transfer into the accumulator.

References

2. Lars Thorndahl. Private Communication.