THE FERMILAB ANTIPROTON DEBUNCHER BETATRON COOLING SYSTEM

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Introduction

The primary purpose of the antiproton Debuncher Ring is to reduce the momentum spread of the incoming antiprotons from 3% to about 0.2% by means of RF phase rotation[1-2]. The phase rotation and the adiabatic debunching together require about 12 msec. As the cycle time of the antiproton production process is 2 sec, there is nearly 2 sec available for stochastically cooling the betatron amplitudes before the beam is transferred to the Accumulator Ring. Calculations[3] show that it should be possible to stochastically cool the transverse emittances in both planes from 20π mm-mrad to less than 7π mm-mrad in this period. As the acceptance of the Accumulator Ring is 10π mm-mrad, this is considered sufficient. This paper presents the present design of the proposed betatron cooling systems.

The basic parameters of the Debuncher Ring are outlined in Table I. As the Debuncher was designed primarily for momentum cooling by means of RF phase rotation, its parameters are not optimal for stochastic cooling. In particular, the operating energy is close to the transition energy, which leads to relatively narrow betatron sidebands, adversely affecting the cooling rate. In the present design the transition energy was adjusted slightly to permit both RF phase rotation and betatron cooling. Furthermore, as the Accumulator Ring has a smaller circumference than the Debuncher, a gap in the coasting beam has to be maintained to minimize losses on beam transfer.

Table I Basic Parameters of the Debuncher Ring

Momentum	8.9 GeV/c
Momentum acceptance	4% $\Delta p/p$
Transverse acceptance, x&y	20π mm-mrad
γ	9.53
γ_t	7.65
$\eta = \gamma_t^{-2} - \gamma^{-2}$	.006
Revolution period	1.695 μsec
Tune, x&y	9.75
Periodicity	3
Antiproton flux/cycle time	7×10^7/2 sec
Momentum spread	
before RF rotation	3% $\Delta p/p$
after rotation	0.2% $\Delta p/p$
Transverse emittance	
before stochastic cooling	20π mm-mrad
after cooling	$< 7\pi$ mm-mrad

Stochastic Cooling Layout

Figure 1 shows the overall layout of the Debuncher Ring, including the location of the two betatron cooling systems. As the machine tune is 9.75, and the cooling systems are symmetrically located in the two long straight sections, the betatron phase advance is about 3.25. This is optimal for betatron cooling, as a spacial displacement in the pickups becomes an angular displacement in the kickers. Thus a large position displacement signal creates an angular kick where the position displacement is small. Furthermore, the lattice design is such that there is no momentum dispersion in the long straight sections, so that the beam size is completely determined by the betatron amplitudes, as shown in Figure 2. The betatron lattice functions range from about 7 m to 13 m in the space available for the pickups and kickers, so that the gap in these electrode assemblies ranges from about 25 mm to 30 mm. There are 8 electrode assemblies in each straight section, 4 vertical and 4 horizontal. In order to optimize the spread in betatron phase advance over the array, these are further split into 2 groups of 2 horizontal and 2 vertical arrays, separated by 0.5 betatron wavelengths.

The estimated electronic and cable delays are about 50 nsec less than the beam transit time of 565 nsec, so all of the electronics must be located in the ring enclosure. The cable conduits are buried at beam level, and the electronics is located primarily in stub rooms at the ends of the conduits. Some of the electronics, especially the preamplifiers and the traveling wave tubes, will be located close to the pickups and kickers respectively. The major source of radiation is expected to be from 10^{10} pions and electrons per cycle, which accompany the injected antiprotons, and which will be lost during the first few turns. This does not appear to be a serious radiation problem.

Hardware

The basic hardware design parameters of the betatron cooling system are summarised in Table II. A block diagram of the electronics is shown in Figure 3.

Table II Basic Betatron Cooling System Design Parameters (Each System)

Frequency band	2 to 4 GHz
Gain (maximum, variable)	135 dB
Output power (maximum)	500 watts
Pickup electrode design	loop coupler
pickup electrode pairs	128
characteristic impedance	100 ohms
gap	25 mm-30 mm
effective width	22.5 mm
Back termination temperature	77°K
Preamp equiv noise temp.	80°K
No. of traveling wave tubes	8
Kickers	see pickups
Thermal noise power at input	-83 dbm
Signal power (initial)	-83 dbm.

In order to achieve the large bandwidth required for an effective cooling rate, the operating frequency band was chosen to be the 2 to 4 GHz band. Although we are considering slotted line couplers, our calculations and present design are based on arrays of quarter-wave loop couplers[4]. However, if another coupler design can be shown to offer advantages over loop coupler arrays, we will adopt them. In each electrode assembly there are 32 pairs of loop couplers, connected in the difference mode to provide a signal proportional to betatron amplitude. Four such arrays provide the input signal for each betatron cooling system. The kicker arrays are arranged in a similar fashion.

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*Operated by Universities Research Inc., under contract with the United States Department of Energy.

The output power available in each system is 500 watts, provided by eight 200 watt-rated traveling wave tubes (TWT's). These will require some gain and phase compensation to flatten out their response in the operating band.

Due to the small signals anticipated, thermal electronic noise is expected to be a problem. For this reason, we are cooling the loop pickup assemblies, which include back termination resistors, to liquid nitrogen temperature (77°K). In addition, we have been testing commercially available microwave GaAsFET amplifiers at low temperatures. at -50°C we have achieved equivalent thermal noise temperatures of 100°K, and gain and phase flatness of +1.5 dB and 20 degrees respectively in the operating band. The present performance calculations are based on these values. We are continuing to explore both commercially available and special-design amplifiers cooled to 77°K, and expect to reduce the equivalent thermal noise temperature to about 80°K.

Performance

In the 2 to 4 GHz operating band there are about 3400 Schottky bands, each about 590 KHz wide. Each band contains two betatron sidebands, each about 25 KHz wide. Hence only about 1/10th of the full available bandwidth is being effectively used (i.e. the effective bandwidth is 0.2 rather than 2 GHz). Furthermore, the expected signal-to-noise ratio is expected to be about 1:1 initially (it becomes worse as the betatron amplitudes decrease). Computer simulations of the cooling process indicate that the emittances can be reduced by nearly an order of magnitude in 2 sec.[3]

The present hardware design is output-power limited. The optimal cooling power is of the order of 1500 watts. However, due to signal suppression (reduction of net gain by negative feedback via the beam), the cooling rate is not severely reduced by limiting the total output power to 500 watts, and by raising the system gain as the input power level drops. The final transverse emittances under this operating mode are presented in Figure 4. The presence of sum mode signals (i.e. harmonics of the revolution frequency) was not included in the calculations.

Possible Problem Areas

There are several areas where the overall system performance may be jeopardized. Potentially the most serious one is the excitation of propagating modes in the waveguide-like structure of the beam pipe. Dimensions of the beam pipe are such that the cutoff for the TE_{01} mode is well below the operating band. This mode and its odd harmonics are naturally excited by betatron kickers. As this mode is dispersive, it does not remain in phase with the beam, and can cause beam heating. Furthermore, it can propagate back to the pickups via the beam pipe, and cause electronic instabilities. We are planning to include microwave absorbing strips in the beam pipe to attenuate these modes. Calculations show that an attenuation of 10 db/m is achievable. Furthermore, we plan to place aperture restrictions in the beam pipe in zero dispersion regions to raise the cutoff frequency to at least 5 GHz.

Another potential problem is the presence of harmonics of the revolution frequency appearing between alternate betatron sidebands, due either to pickup misalignment or electronic unbalance. The presence of these sum mode signals will reduce the power available for cooling. For this reason, we will have sufficient magnetic steering elements in the straight sections to minimize this signal. Also under consideration is the possibility of including notch filters (notch spacing = 295 KHz) to block the sum mode signal, and simultaneously to reduce the thermal power by a factor of two.

The group delay must be held constant to within ±25 psec. As amplitude-to-phase (AM/PM) conversion in the TWT's can be of this order, we plan to program the TWT beam voltage to correct this effect. Furthermore, as the group delay drift in cables is about 16 ppm per degree C, long cables must be temperature stabilized.

Due to the fact that the electrode coupler width is narrower than the gap, some loss of sensitivity is expected in the corners where there are large betatron amplitudes in both planes. There is also the possibility that the difference mode sensitivity is less than the calculated value due to interelectrode capacitance. Electrode geometries which minimize these effects are being studied.

References

1. A.G. Ruggiero, "The Fermilab Antiproton Debuncher Ring", IEEE NS-30 #4 p. 2478 (1983).

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3. B. Autin, et. al., "Fast Betatron Cooling in the Debuncher Ring", IBID p. 2593.

4. J. Simpson et. al., "Design and Beam Testing of Microwave Loop Couplers", elesewhere in this publication.

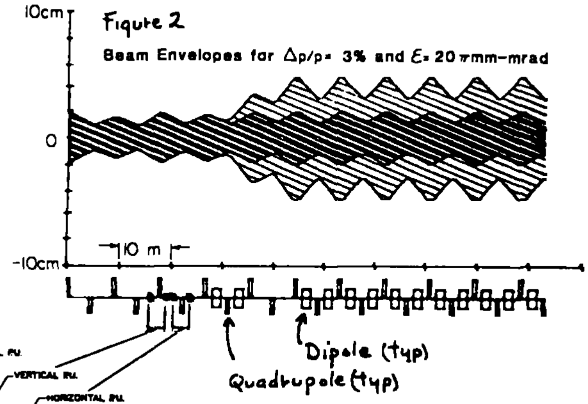

Figure 2
Beam Envelopes for $\Delta p/p = 3\%$ and $\mathcal{E} = 20\,\pi$mm-mrad

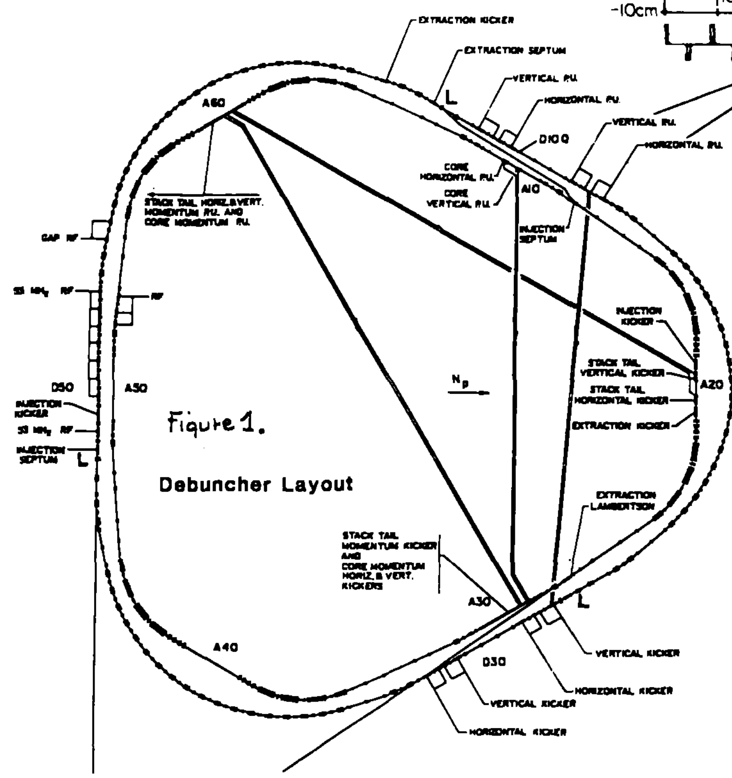

Figure 1.
Debuncher Layout

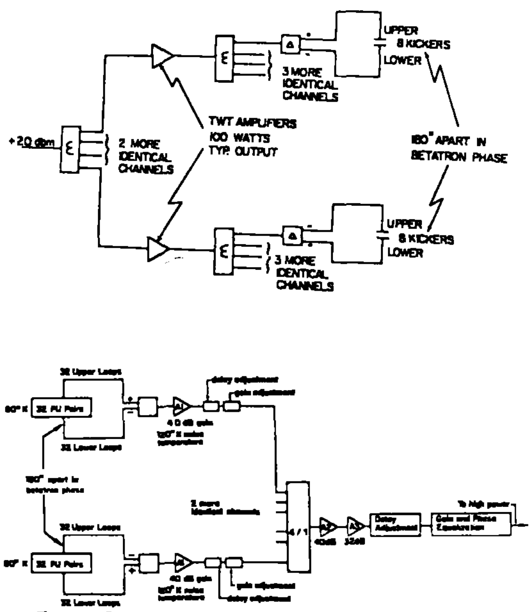

Figure 3.
Debuncher Betatron Cooling Systems
2-4 GHz Horizontal and Vertical Systems are Identical.

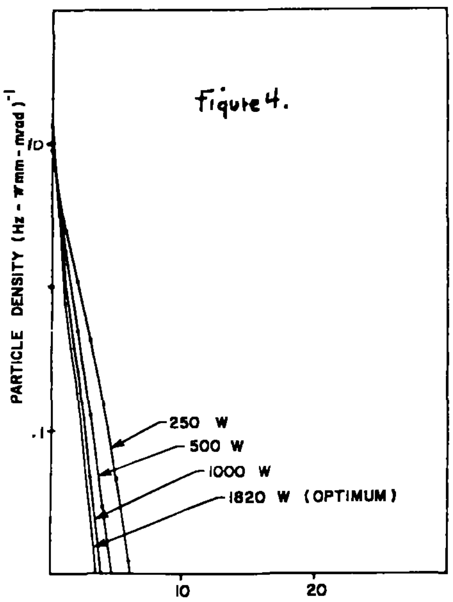

Figure 4.