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STOCHASTIC COOLING AT FERMILAB *

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Introduction

I will discuss the stochastic cooling systems in use at Fermilab and some of the techniques that have been employed to meet the particular requirements of the anti-proton source. Stochastic cooling at Fermilab became of paramount importance about 5 years ago when the anti-proton source group at Fermilab abandoned the electron cooling ring in favor of a high flux anti-proton source which relied solely on stochastic cooling to achieve the phase space densities necessary for colliding proton and anti-proton beams. The design of the cooling systems was based, to a large extent, on the pioneering work[1] performed at CERN, particularly at the Anti-proton Accumulator (AA). However, the Fermilab systems have constituted a substantial advance in the techniques of cooling including: large pickup arrays operating at microwave frequencies, extensive use of cryogenic techniques to reduce thermal noise, super-conducting notch filters, and the development of tools for controlling and for accurately phasing the system.

Description of the Cooling Systems

The cooling systems for the anti-proton source[2] fall into 3 groups. The first group contains the horizontal and vertical betatron cooling systems in the Debuncher ring. The main purpose of the Debuncher - as its name implies - is to perform an r.f. bunch rotation on the incoming anti-proton beam. While this ring is not optimized for stochastic cooling (the "mixing" is poor), it is possible to reduce the transverse emittance of the beam by a factor of 3 in each plane in 2 sec. The system consists of 4 subgroups of cryogenically cooled pickups (PU's) each with its own cryogenically cooled pre-amplifier, a combining network, medium level amplifiers, a splitting network, and travelling wave tube (TWT) power amplifiers which power the 4 kicker array subgroups. Some of the more important parameters of either of the nearly identical horizontal or vertical systems are given in Table I. The important design considerations for these systems are: fast cooling (high bandwidth), good signal to noise ratio (many pickups with high impedance and low thermal noise), and high gain (many kicker loops with high impedance and high power).

*Operated under contract with the Universities Research Association along with the U.S. Department of Energy.

Table I. Debuncher Cooling Systems

Frequency band	2-4	GHz
Number of pickups	128	
Pickup temperature	80	^{o}K
Pre-amp noise figure	.7	dB
Number of TWT's	8	
Number of Kickers	128	
PU impedance	83	Ω
PU sensitivity	.79	
Total power	1000	W

All the cooling systems, including the Debuncher systems, use 1/4 wavelength pickups and kickers in a parallel plate, strip-line geometry with a nominal impedance of 100 Ω. Table I gives parameters of the pickup, but the parameters apply equally to the kickers since they are electrically identical to the pickups. The pickup sensitivity is defined as the fraction of beam current which is induced on the pickup plates.

One of the important considerations in stochastic cooling systems, particularly in the Debuncher systems, is the need for low thermal noise. In order to reduce the thermal noise the back termination of the pickup loops was cooled to liquid nitrogen temperature. However, it is not sufficient to cool only the back termination since the resistance associated with the ohmic losses in copper can be the dominant source of noise the connecting and combining circuits are not also cooled. The preamplifier noise figure can also benefit from lower temperatures, so the system was designed to be cryogenically cooled from the pickup to the preamplifier.

The next group of cooling systems constitutes the stack tail systems and includes cooling in momentum and both transverse planes. The transverse cooling systems are intended only to protect against growth in the transverse beam size and to add a small measure of flexibility in operation. These systems have not been commissioned; the analogous systems at the CERN AA have been, to the best of my knowledge, largely superfluous.

The momentum cooling or stacking system is probably the most demanding of the stochastic cooling systems. This system has the same requirements as the Debuncher systems for high gain and low noise, but has the additional requirement of linearity over a dynamic range of about 50 dB. In particular, the noise power density at the core must be very low to avoid undesired heating. This latter requirement is met by using notch filters which have a minimum response at harmonics of the revolution frequency. The schematic of the stack tail system that appears on the control system consoles is shown in figure 1. The stack tail pickups are divided into two groups centered on slightly different energies. The second group also provides the signals for the horizontally and vertically cooling systems. A similar schematic is shown in figure 2 for the super-conducting filter. One of the major complications of this device is the need for a phase-locked loop to stabilize the notch frequency. Some parameters which characterize the stack tail systems are given in Table II.

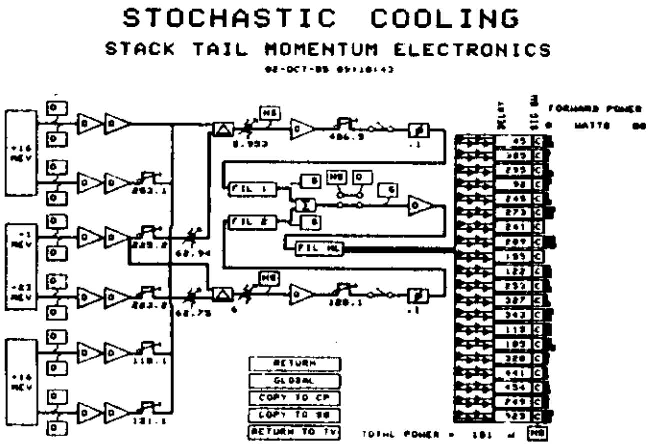

Figure 1. The controls system schematic of the stack tail cooling system.

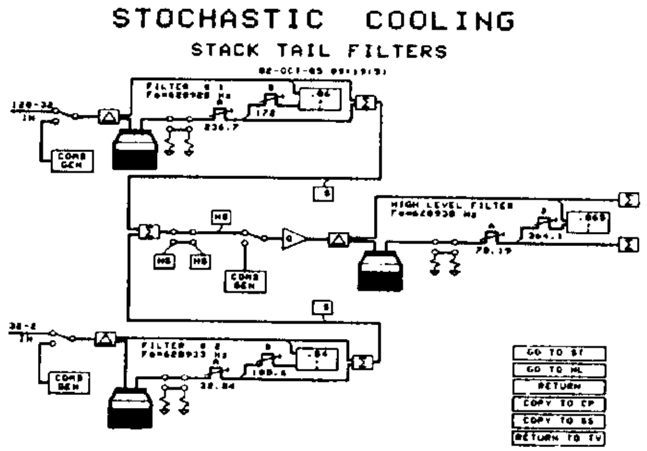

Figure 2. The controls system schematic (expanded view) of the filters in the stack tail cooling system.

Table II. Stack Tail Cooling Systems

	H	V	Δp/p	
Frequency Band	1-2	1-2	1-2	GHz
Number of pickups	32	32	162	
Pickup temperature	80	80	80	°K
Pre-amp noise figure	.4	.4	.4	dB
Number of TWT's	2	1	40	
Number of Kickers	34	32	160	
PU impedance	109	70	109	Ω
PU sensitivity	.06	.96	.85	
Total power	200	10	1500	W

The last group of cooling systems - the core cooling systems - are, by comparison, easy to design and build. The only major consideration for these systems is that they utilize as much bandwidth as possible. These systems must have sufficient cooling to compensate any heating by the stack tail systems. The bandwidth of these systems also determines the ultimate phase space density achieved: the final density should depend on the point of equilibrium between stochastic cooling and heating due to intra-beam scattering. Since the cooling becomes weaker as the momentum spread decreases and since the intra-eam scattering increases with decreasing momentum spread, the final momentum spread is rather well defined. Parameters for the core cooling systems are given in Table III.

The core momentum pickup consists of two arrays of pickups at slightly different radii in a region of high dispersion. A difference signal is obtained which is zero for particles in the core - half way between the two arrays. The core momentum pickup is cooled to about 80 °K because it is in the same straight section as the stack tail pickups. The amplifier, however, operates at room temperature.

Table III. Core Cooling Systems

	Δp/p	H or V	
Frequency band	2-4	2-4	GHz
Number of pickups	32	8	
Pickup temperature	-	300	°K
Pre-amp noise figure	2	2	dB
Number of TWT's	1	1	
Number of Kickers	32	8	
PU impedance	93	83	Ω
Pickup sensitivity	.59	.79	
Total power	20	10	W

Performance of the Cooling Systems

While the control system does not directly affect the performance of the system, it can be a source of convenience or one of frustration. The control program attempts to make a nearly transparent interface between the operator and the cooling system. The interaction is via graphical displays such as are shown in figures 1 and 2. Readback of most of the important parameters is available on this display in a fairly high density format, but with the information organized so that the logical relationship of the devices is readily apparent. The display is very much akin to a conventional circuit diagram except that switch positions, etc., represent the current state of the system. Control is achieved by placing the cursor over the desired device. Devices are controlled via a knob, a button, or typed information depending on the device. This approach has greatly facilitated the operation of the cooling systems and is so much admired that a number of other accelerator systems at Fermilab are borrowing this concept.

During the development of these systems, the pickup sensitivity was measured using low energy electron test beams. These tests generally confirmed our understanding of the behavior of the pickups. The noise figures of the pre-amplifiers were measured in bench tests. The results of measurements on the 2-4 GHz preamplifiers are shown in figure 3.

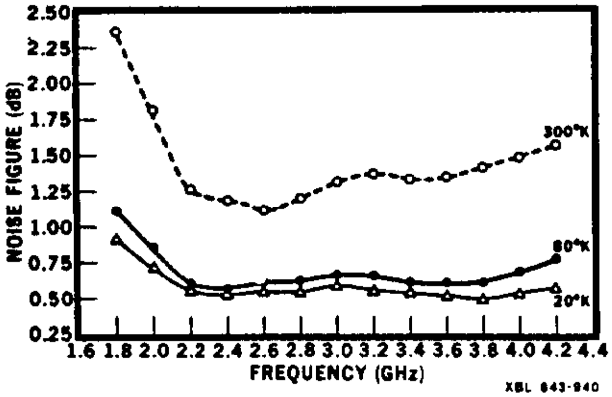

Figure 3. Measured noise figure for the 2-4 GHz band cryogenically cooled amplifiers. The normal operating temperature is 80°K.

The signal to noise ratio for the actual Debuncher pickup and pre-amplifier system was measured with a 8 GeV proton beam. This measurement is made using a relatively high intensity beam (1.5×10^9 particles) and observing the power spectrum with low resolution (3 MHz bandwidth). This technique eliminates uncertainty due to line shape but requires a (small) subtraction of the common mode (momentum) signal. The ratio of power with beam and no beam yields directly the signal plus noise to signal ratio from which the signal to noise ratio can be extracted. The measured signal to noise ratio is shown in figure 4 for the four vertical pickup subsystems. Since the Debuncher systems cool transversely, the sideband power is proportional to the average beam size-about 3π mm-mrad when this data was taken. For a 3π mm-mrad average beam size the design goal was -12 dB. The data are about 1-2 dB higher than the theoretically predicted signal to noise ratios. The discrepancy can be explained if either the losses in the PU combining network were overestimated or if the beam size were taken was underestimated.

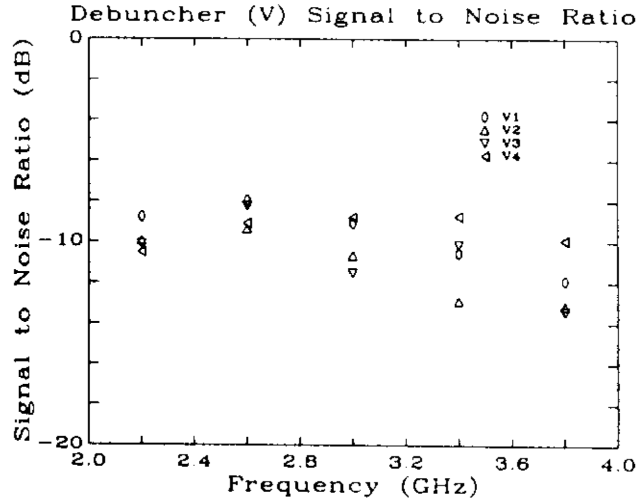

Figure 4. Measured signal to noise ratio for the Debuncher pickups and cryogenic amplifiers. The ratio is plotted for the nominal design current of 10 μa but derived from measurements at high beam intensities.

A less precise, but nonetheless impressive, measurement of the signal to noise ratio is shown in figure 5 where the signal from about 9×10^7 particles stands about 8 dB above the noise floor when all pickups are added together and the resolution bandwidth is set low enough to see the betatron lines. The beam intensity and momentum spread are essentially the design values for the anti-proton beam after bunch rotation.

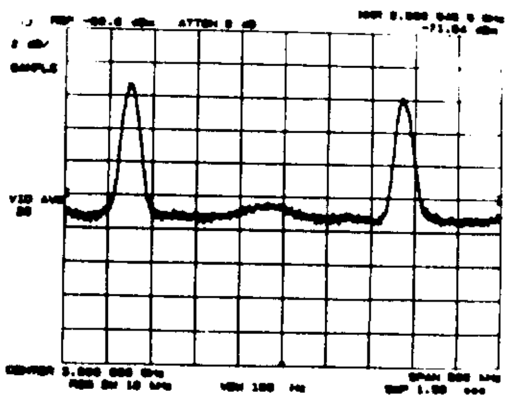

Figure 5. Two betatron sidebands at 3 GHz obtained by summing all the pickups.

A significant problem in achieving good performance in large cooling systems is to properly adjust the gain and phase of the feedback. Measurements are made using the beam transfer function technique[3] and an automatic network analyzer system (Hewlett-Packard model 8409C). In this technique the open loop gain of the cooling system is measured by applying a sine wave excitation to the kicker and observing the excitation (amplitude and phase) of the beam with the pickup through the electronics of the cooling system. A typical measurement of this function between a pickup and kicker array for a schottky band near 3 GHz is shown in figure 6. The two double peak structures correspond to the upper and lower betatron sidebands. The double peak structure results from the fact that the real or resistive part of the beam response comes a small number of particles with oscillation frequencies nearly equal to the applied signal from the network analyzer. These particles do not survive the measurement process because of the very small linewidth of the sweep oscillator, which is a synthesized frequency source run in a continuous wave (c.w.) mode and stepped through a series of discrete frequencies. Exactly in the center of the betatron sideband, the response is entirely resistive - which is not measured due to the demise of the particles which would in other circumstances give the response - hence the appearance of a notch in the response. The fact that the measurement is only sensitive to the imaginary part of the beam response is of no consequence, and the beam distribution is not noticeably affected by the measurement.

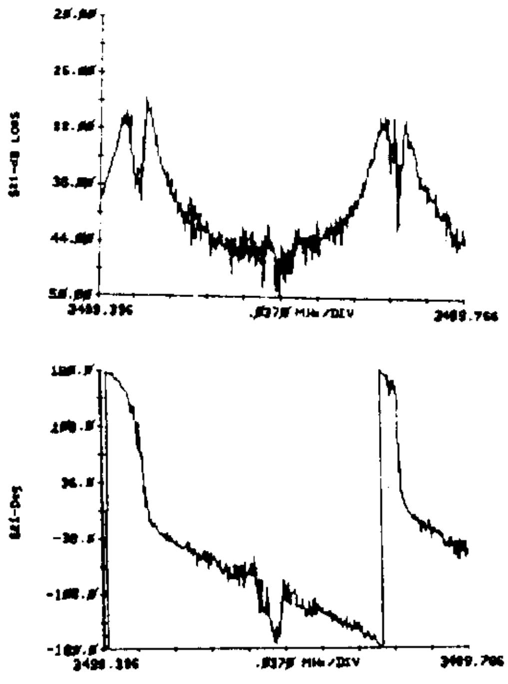

Figure 6. Gain (top) and phase (bottom) response of the open loop Debuncher (V) cooling system at one sideband near 3.4 GHz.

An ideal system would have uniform gain and a phase of 180° at the center of each betatron sideband. The actual gain and phase is easily measured by measuring slightly to either side of the betatron line (near one of the peaks in figure 6). One such measurement of the upper and lower sidebands is shown in figures 7 and 8 for the upper and lower sidebands separately. The measurement shows generally flat phase over the band except at the band edges (where the gain is rolling off). The system delay has not yet been adjusted properly to achieve cooling. It is believed that most of the phase deviation can be compensated with appropriate filtering. The lower sideband is approximately 70° advanced in phase from the upper one. This effect is expected since the betatron phase advance from pickup to kicker is about 36° less than an odd multiple of 90° (2x36=72° is the expected difference). When all pickups and kickers are added together, the difference in phase between upper and lower sidebands is nearly zero. The different betatron phases of the various pickup and kicker arrays causes a non-ideal addition of arrays whose sum is reduced by typically 5% from a perfectly in-phase addition.

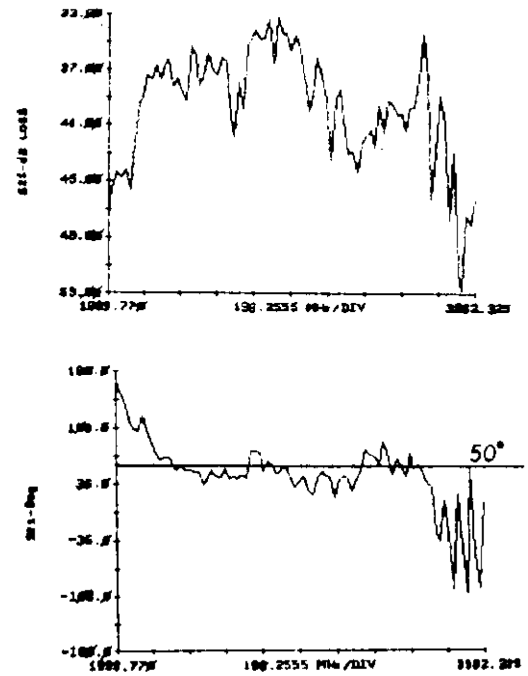

Figure 7. Gain (top) and phase (bottom) response of the open loop Debuncher (V) at the peak of every tenth lower sideband from 2 to 4 GHz.

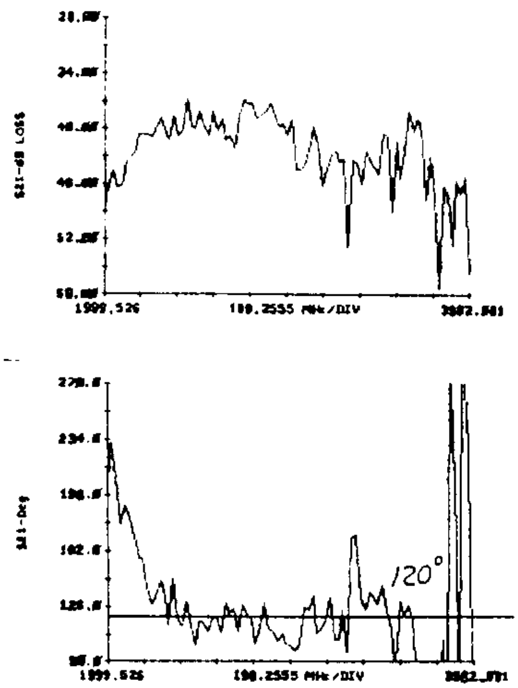

Figure 8. Gain (top) and phase (bottom) response of the open loop Debuncher (V) at the peak of every tenth upper sideband from 2 to 4 GHz.

Network analyzer measurements can be used to define an effective cooling rate of a system relative to an otherwise identical system with an ideal flat gain and phase over the nominal system bandwidth. By this criterion the Debuncher network analyzer measurements indicate that the expected cooling rate of this system is roughly 3/4 of the hypothetical ideal. Of course, the cooling rate can be measured directly also. Figure 9 shows the beam emittance as a function of time with a beam intensity of approximately 10^8 particles in the machine. The emittance was defined as $6\sigma^2/\beta$ where σ was measured by a micro-channel plate profile detector. The observed cooling time of 2.3 seconds is consistent with the expectations from the network analyzer measurements, measured signal to noise ratios, and kicker strength. When this data was taken only 1/2 the kickers were installed; the cooling time under normal conditions should be about 1.4 sec.

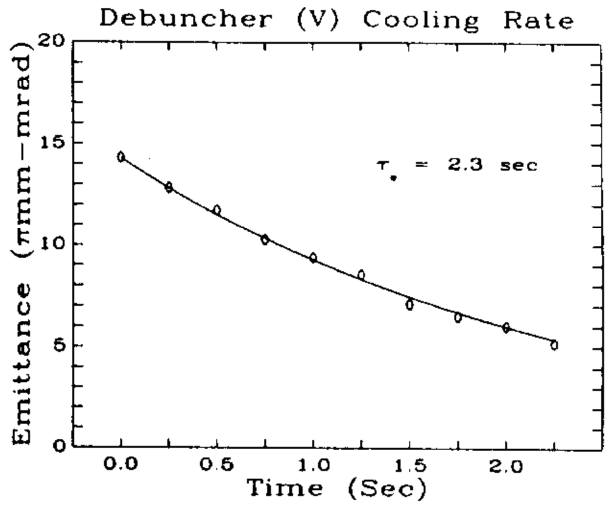

Figure 9. Debuncher emittance as a function of time as measured by the micro-channel plate profile monitor.

While the performance of the Debuncher cooling systems is generally consistent with the expectations from theory, there are some mysteries. The strangest phenomenon so far observed is the relative strengths of the kicker subsystems. The kickers are grouped into 4 arrays, each of which is driven by 2 TWT's. The relative strength of each kicker subgroups was measured by applying approximately 100 W of noise power to each of the TWT's in turn. For each of the 8 TWT's the rate of increase in the beam emittance was measured. It was observed that on each of the 4 arrays the TWT that drove the upstream portion of the array produced a heating rate approximately 2x that of the TWT that drove the downstream portion. At this point it is not possible to say whether this is caused by some trivial error in matching electrical lengths (say, internally in the kicker tank) or whether there is some more subtle feature of kicker behavior which is not understood.

A peculiarity of the momentum cooling in the stack tail is that rather precise filters are required, as was mentioned earlier. The requirements of a minimum notch depth of 25 dB at 1590 harmonics with a rms frequency dispersion of 2 x 10^{-3} for each of three filters were met using super conducting cable. The notch depth across the band is shown in figure 10 and the dispersion is shown in figure 11. These filters have given no significant operational problems so far.

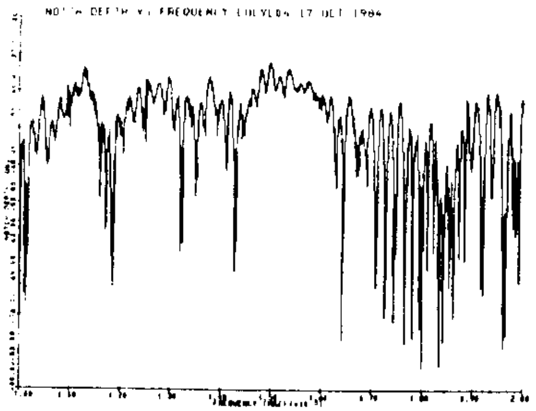

Figure 10. Stack tail filter notch depth as a function of frequency.

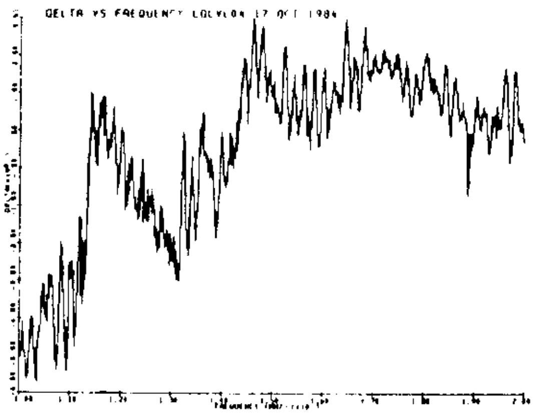

Figure 11. Notch dispersion ($\delta = \Delta f/f$) as a function of frequency.

The performance of the stack tail system has not been as well studied as that of the Debuncher. The system has never stacked at a rate of more than a few per cent of the design rate of 10^{11} particles per hour. The low stacking rates are thought to be due to the lack of a good system test rather than a problem with the system. The maximum anti-proton flux achieved was 10^{9} particles per hour and a good stacking test with protons was not made. However, the gain and phase flatness appear to be good, and the observed stack profile seems to agree well with the design calculations as shown in figure 12. The observed discontinuity in slope half way up the stack tail was probably caused by an interruption in the injected anti-proton flux. During the anti-proton tests more than 50% of the particles deposited at the stack tail (and perhaps 100%) were cooled into the core. Additional tests this fall will tell the story, but if there are problems with this system it is expected that they will be associated with much higher intensities (instabilities or possibly beam heating problems).

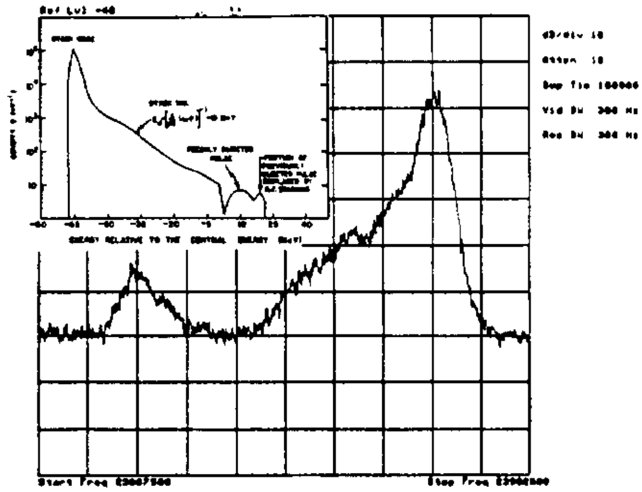

Figure 12. Stack tail profile as a function of frequency. Shown on the inset is the design profile as a function of energy (there is a relative sign between energy and frequency).

Even with the low anti-proton intensities available last year some problems were observed with the stack tail system. One particular problem was betatron heating of particles in the core when the stack tail system was on. The problem was solved by increasing the gain of the core cooling betatron system so that the cooling rate of the core system exceeded the heating of the stack tail system. This solution, however, is not entirely satisfactory since the maximum allowed gain (and available cooling rate) of the core system is inversely proportional to the number of stored particles. The stack tail kickers consist of two loop pairs - half of these pairs are oriented vertically and half are horizontal. Ideally each loop in the pair is excited with equal strength. Mismatches, however, will cause particle deflections - i.e., betatron heating. Each loop is excited by a TWT signal which is split approximately in half by a hybrid coupler. In the initial construction of the system, it was overlooked that these hybrids, have systematic, frequency dependent, amplitude and phase errors between the two output ports. The hybrids were all installed such the polarity of the errors was the same for all kickers. It is clearly a significant improvement to reverse the polarity of half the hybrids leaving only the smaller, residual, random error. It has been calculated that the systematic errors in the hybrids are consistent with the heating rates observed, but it remains to be seen whether the hybrids were the only significant source of betatron heating.

Plans for the future

There is good evidence that the Debuncher systems are working nearly as well as had been expected. The accumulator systems have no known problems, but have been poorly exercised. Clearly, the most important short term goal will be to stack and store high intensity beams in the accumulator.

Looking somewhat further into the future, however, one is naturally led to ask whether a better job can be done. Proton-anti-proton colliders are still in their infancy - can the luminosity be increased? For the anti-proton source increased luminosity means higher anti-proton flux, which requires higher stochastic cooling bandwidths. We are encouraged to think along these lines because of our good experience with microwaves at what now seem like long wavelengths. The design of TeV I was driven by an attempt to build a powerful anti-proton source but, at the same time, not extrapolating too far from the CERN experience. If anything, it seems that we may have been too conservative. One of the striking things about our TeV I experience is that we have encountered no serious technical difficulties (of course we may still have some surprises in store for us!).

Currently we are considering the possibility of an upgrade program for the anti-proton source which will allow a increase in flux to $5\times10_{11}$ anti-protons per hour. This flux would require an increase in the Debuncher cooling bandwidth from 2-4 GHz to 4-8 GHz. A factor of 2 increase in bandwidth in the Debuncher is adequate to handle 4 times the flux because the mixing factor improves by a factor of 2 also with the increase in frequency. In the accumulator, however, the stack tail system will have to increase from 1-2 to 4-8 GHz. A core cooling system bandwidth of 8-16 GHz may be feasible but is not necessarily indispensable.

Conclusion

The stochastic cooling systems for the TeV I project are alive and appear to be healthy. The performance of the Debuncher cooling systems seems to be rather well understood on the basis of experiments and is consistent with the design expectations. The accumulator systems appear to be working adequately but have been tested rather poorly. If our experience continues to be as promising as it seems now, we will be encouraged to investigate improving our source by increasing the bandwidth of the cooling systems.

Acknowledgments

The work reported here was the result of efforts of a large number of people too numerous to mention by name. Much of the credit for the success of the stochastic cooling systems should go to our collaborators at Argonne National Laboratory and Lawrence Berkeley Laboratory. We have also greatly benefited from the generous advice given us by the CERN anti-proton group.

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