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A VERY Informal Note on Cooling pbars from the main injector

I. Cooling in the Debuncher

For the Accelerator Upgrade (Phase I), we have chosen to upgrade the cooling in the following ways:

- A. Increasing the existing 800 W system to 1600 W.
- B. Adding momentum cooling (2x reduction in Δp).
- C. Increasing the electrode gap by $\sqrt{(30/20)}$. The electrode gap increase makes the yield greater at the price of reducing the cooling efficiency.

The performance of the cooling system has been calculated in the approximation that the cooling process can be described by a Fokker-Planck equation. Relevant assumptions follow:

PU noise temperature	80 °K
Preamp noise temperature	50 °K
Pickup/kicker sensitivity	.74
Pickup/kicker impedance	83 Ω
Number of pickups	128
Number of kickers	128
PU losses	2.3-3.1 dB
Kicker losses	2.5-3.7 dB
Optical Filter	Ideal
Gain vrs frequency	Flat
Total power	1600 W

Before discussing the results, it is worth comparing the calculation with current system performance. This is shown in figures 1 and 2. Figure 1 compares the calculated transfer efficiency with the amount of beam on the accumulator injection orbit as a function of cooling time. Figure 2 compares the calculation with the production efficiency (A:PRDCTN). One observes semi-quantitative agreement given rather imprecise data. Attempts to measure the transfer efficiency directly yield numbers which are typically much less than the program prediction of 95%. The discrepancy is not well understood.

Given that the model perhaps has some connection with reality, the expected performance of the "upgraded" system is shown in figure 3. During the Main Injector era one expects a pulse of $.67 \times 10^8$ per pulse every 1.5 sec or about 16×10^{10} anti-protons per hour. For the 1.5 sec cycle time, one expects to see about 75% or 12×10^{10} per hour delivered to the accumulator. For a 2.0 sec cycle the efficiency increases to 86%, but the flux decreases to 10×10^{10} per hour. From this calculation, I think that one can conclude: 1) there should be some significant losses in transferring beam into the accumulator, and 2) the 1.5 sec cycle time is worthwhile if the system performs well (i.e., as well as the simulation).

For figure 3 the effective Accumulator acceptance was chosen to be 7π mm-mrad. After the accumulator aperture studies, the machine aperture was measured to be $9 \times 12 \pi$ mm-mrad. Why the discrepancy? The main reason is probably historical: the TEV I design assumed that the Debuncher beam had to be cooled to 7π mm-mrad in order to fit into the 10π mm-mrad Accumulator acceptance. The difference allowed for emittance growth of 3π mm-mrad due to injection mismatch. The figure also serves as a fudge factor for the following:

1. Imperfections in the cooling systems coming from phase and amplitude errors in the gain function (not included in the simulation).
2. Imperfections in the cooling system filter (the filter was assumed to be ideal in the simulation).
3. Degradation of the ideal accumulator aperture over time. When measured in December 1988 the aperture had decreased to $8\pi \times 7\pi$ mm-mrad (HxV) compared to $10\pi \times 9\pi$ mm-mrad (HxV) measured in March 1988 during the studies.

It should be mentioned that there are opportunities to do better as well as potential problems that might leave us worse off than expected. In particular, we may be able to rebuild the pickup and kicker electrodes to get better sensitivity and have smaller losses, and gain in that way. However, the biggest stumbling block to better performance is bandwidth: with this flux we are approaching the fundamental limitation which comes from bandwidth.

II. Stacking in the Accumulator

The TEV I stacking simulation has been used to see what might happen to the stack stail with main injector type fluxes. An incoming flux of 7×10^7 per 1.5 second cycle was simulated with the existing stack tail system. A stacking rate of 3.9×10^7 was achieved (about 83% efficiency). Stacking rate and stack size vrs time are shown in figure 4.

The simulation was repeated for a 2-4 GHz stack tail system. The system was realized by leaving all parameters fixed except for doubling the frequency and changing η from 0.02 to 0.01 ($\Delta f/f = \eta \Delta p/p$). A stacking rate of 4.5×10^{11} sec⁻¹ was achieved (about 95% efficiency). The stability of the system was considerably improved at large stack sizes due to the reduced gain. Stacking rate and stack size vrs time are shown in figure 5.

Is there any reason to believe that the simulation has something to do with reality? When we stacked secondary protons (Mar 1989), we observed a peak stacking rate of $5-6 \times 10^{10}$ per hour. The system appeared to be stacking efficiently in the longitudinal coordinate (no apparent losses at the shutter or the inside aperture of the machine). The expected stacking rate was in the range $7-8 \times 10^{10}$ per hour. With large stacks, however, the stacking rate dipped to 2×10^{10} per hour. This appeared to be due to large betatron heating of the core beam by the stack tail. The major conclusions of the study are:

1. We achieved about 50% of the theoretical maximum stacking rate.
2. Betatron heating of the core is a more serious problem at high fluxes.

The problem of betatron heating of the core has been an annoyance for a long time. A calculation of the loss rate vrs core emittance is shown in figure 6. The calculation suggests that beam loss will be negligible (compared to the 300-400 hour life time from nuclear and single coulomb scattering) if the core stays at 2π mm-mrad. The antiproton beam size in the accumulator can be gauged by the flying wire measurement at injection into the main ring. This data is shown in figure 7. The beam is smaller than 2π mm-mrad (19 normalized) up to stacks of 10^{12} . In order, for stacking to be sucessful at 10^{12} , however, the stacktail system must not be an appreciable source of core heating. Currently, this is not the case. There is no theoretical reason that demands that the heating be present; it is a

question of how symmetrically the kickers (and the surrounding structures) are built. We currently plan to rebuild the existing stack tail system to alleviate this problem by emphasizing the following:

1. Reduction of kicker mechanical tolerances from .03" to .003" using precision circuit board layouts instead of the bent loop design.
2. Individual alignment of each kicker module (remotely tuneable). This represents a 2x expansion of the current system movement capability.
3. Built-in system to electrically balance (remotely tuneable) the electrodes.
4. Microwave dampers to absorb undesired modes.

We also plan to install a 4-8 GHz core cooling system. This system will help to keep the emittances small when the intensity is high. The 4-8 GHz cooling has a disadvantage in that it cools only half the momentum spread that is cooled by the 2-4 GHz system (because of bad mixing). It is not known how serious a problem the bad mixing might be. The only plan to alleviate beam heating of off-momentum particles is to bring up the stack tail betatron systems.

Resonances can also lead to beam growth - especially when the beam tune spread is large as it would be when collective effects are operating. It is not known how serious these might be although there is no evidence that they represent a fundamental limit.

III. Accumulator instabilities

The longitudinal stability limit is proportional to Ψ^2/N where Ψ is the density (pbars/eV) and N is the total number of pbars. This quantity appears to actually decrease slightly as stacking progresses (i.e., core gets wider faster than it gets more dense). So one does not necessarily expect a problem. However, one can also tune the width of the core - it can be left wide enough for stability to be achieved.

The devices which might drive an instability are discussed in some detail in pbar note 422. The main result is that the stability limit seems to be determined by the high Q devices, i.e., the r.f. cavities. An instability at 100 mA has been observed and is believed to have been driven by the $h=2$ cavity. The two accumulator resonant cavities have been resistively loaded to reduce the shunt impedance.

The loading can be increased further. However, the peak voltage will be reduced unless the rf power is also increased. In any event, the longitudinal stability is not expected to be a fundamental problem.

Resistive wall (transverse) instabilities are currently controlled by the damper. We expect that the damper will continue to be effective with high intensity stacks and that no further measures will be required.

Ion instabilities (transverse) are a fundamental limitation at the CERN anti-proton collider. Ion instabilities have been observed also at FNAL at the $(n-Q)=1.4$ sideband. The instability is cured with beam shaking. The beam shaking has also been observed to improve stacking by 10-20%. The threshold for the onset of various ion instabilities have not been calculated and probably should be. However, the problem is extremely complicated by the fact that the distribution of ions around the machine is very poorly known. It is believed - though hardly guaranteed - that one will be able to control the instabilities either by modifying the ion distribution or by applying appropriate feedback.

Conclusion:

It appears that the existing anti-proton source can do fairly well with the anti-proton flux which is expected from the main injector. The Debuncher cooling will be noticeably inefficient, but probably acceptable. Improvements can be made by changing the Debuncher bandwidth to 4-8 GHz (perhaps several M\$) or by increasing the accumulator aperture (15π would be ambitious, but maybe not crazy).

The existing 1-2 GHz stack tail system performs surprisingly well on paper - capable of fluxes up to 1.4×10^{11} per hour. However, it is not clear that our "as built" stack tail system is really that good - having achieved a maximum of 0.6×10^{11} to date. Furthermore, there are noticeable problems with stability and roll-off of the stacking rate at high intensities (beyond 200 mA!). In order to increase the stacking rate beyond 1.4×10^{11} per hour, one must consider a higher bandwidth system. The simplest way to implement the system would be to change γ_t such that $\gamma_t = .01$ (half its current value of 0.02). Clearly changing γ_t and upgrading the cooling system would also run in the multi-M\$ range.

Debuncher Betatron Cooling

2-4 GHz. 800W + filter

Figure 1

Debuncher Betatron Cooling

2-4 GHz. 800W + filter

Figure 2

Debuncher Betatron Cooling

2-4 GHz. 1600W + filter

Starting emittance is 30π mm-mrad.

Momentum spread reduced from $\Delta p/p = 0.2\%$ to 0.1% by stochastic cooling

Figure 3

Accumulator Stacking Rate with Phase II flux

Current 1-2 GHz Cooling System

Figure 4

Accumulator Stacking Rate with Phase II flux

Stack Tail Upgraded to 2-4 GHz

Figure 5

Core Loss Rate

for a 10 pi-mm-mrad Accumulator

Figure 6