REDUCTION OF FEEDBACK-DRIVEN TRANSVERSE HEATING IN THE ANTIPROTON ACCUMULATOR

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1. Introduction

Transverse heating has been identified as a problem in the stacktail momentum cooling system of the Antiproton Accumulator for some time. A number of basic, open-loop heating mechanisms exist and have been identified [1]. These mechanisms result in emittance growth which is independent of beam current. It has long been seen that emittance growth *is* dependent on current in the core, which suggests the existence of a closed loop feedback mechanism.

2. Feedback Mechanism

The Palmer cooling scheme used in the Antiproton Accumulator stacktail momentum cooling system deduces beam momentum from beam position in a high dispersion region. Hence, the momentum pickups are inherently not very pure; they will pick up betatron oscillations in addition to momentum variations. Betatron oscillations in the beam (especially in the core) will be misinterpreted as energy variations, and will generate signals which will propagate through the amplifier chain to the stacktail momentum kickers. In parasitic studies done with a large stack (about 200 mA) in 1994, suggestions of such betatron sidebands were seen in spectrum analyzer scans of the pickup signal in the amplifier chain. Thus, a mechanism exists for closed-loop feedback and current-dependent beam heating.

Notch filters in the amplifier chain are set to the revolution frequency of the core, thus will eliminate longitudinal signals from the core. But the notch filters will not affect these betatron signals, because they are offset from the notch positions by nearly half of a Schottky band (because the fractional tune is about 0.5). In fact, it is virtually impossible to eliminate these betatron signals with electronic filters in the amplification chain. This is because 1) the frequencies to be filtered out are not simply harmonics of one another, so a recursive notch filter is not sufficient, and 2) a filter would greatly disturb the amplitude and phase characteristics of the desired longitudinal signal. In principle, the Antiproton

Accumulator could be re-designed with a slip factor about half as large as at present, so the longitudinal frequencies never overlap the betatron sidebands, and perhaps an exotic high-order filter could be realized which would have flat frequency and phase characteristics across the Schottky band. However, this reduction of the slip factor would reduce the cooling rate, and the necessary filter would be very difficult, if not impossible, to realize.

As long as the beam is well centered between the kicker plates, the kickers should not be able to excite the beam on betatron lines, even if core betatron signal is picked up, amplified, and delivered to the kickers. (The beam can be excited by quadrupole resonances, but not by betatron resonances if the beam is centered between perfect kickers.) However, because of imperfections in the kickers and miscentering of the beam, there will generally be some response at the betatron frequencies.

This response should still be canceled if the delta kickers are properly adjusted. Then these betatron signals should not couple back into the beam, and the feedback chain should be broken. However, there will likely be some misadjustment or some response variations between the main kickers and the delta kickers across the microwave band, and these will allow a non-zero excitation of the beam.

It may be possible to address this closed-loop feedback by better centering of the beam, by better construction of kicker plates, or by better tuning of delta kickers, but it is doubtful that large gains can be made in these areas. A more promising approach is to try to eliminate this closed-loop feedback by attacking the problem at its source, attempting to reduce the pickup of betatron signals before they pass through the amplification chain or reach the kickers. This is a much cleaner way to solve the problem, as it does not allow large unwanted signals to be amplified, wasting amplifier power and potentially generating intermodulation products through nonlinearities in the amplifiers.

3. Pickup Response

The pickups used in the stacktail system of the Antiproton Accumulator have an amplitude response which is given by [2, equation 5.22]:

$$H = \frac{1}{\pi}\left[\tan^{-1}\left(\sinh\left[\frac{\pi}{h}\left(x+\frac{w}{2}\right)\right]\right) - \tan^{-1}\left(\sinh\left[\frac{\pi}{h}\left(x-\frac{w}{2}\right)\right]\right)\right] \qquad 1)$$

where h is the full height of the pickup (distance between pickup plates, about 3 cm in the Antiproton Accumulator), w is the width of the pickup plates (about 4 cm in the Antiproton Accumulator), and x is the horizontal distance of the beam from the center of the pickup.

The phase response will be flat for a relativistic beam. (No matter where a particle is in x, as soon as it crosses the plane of the pickup its electromagnetic fields will immediately induce a signal in the pickup.)

For large distances from the pickups, the amplitude response falls off roughly exponentially [2, § 5.11]:

$$H \approx \frac{4}{\pi} \sinh\left(\frac{\pi w}{2h}\right) e^{-\pi x/h} \tag{2}$$

Pickups are located at +27 MeV (formerly +16 MeV) and -1 MeV, and the core is at -60 MeV. The dispersion and momentum are such that 1 mm corresponds roughly to 1 MeV. Because of the pickup response function, signal from the core should be reduced by about 65 dB at the +16 MeV pickup and about 40 dB at the -1 MeV pickup. With a 200 mA stack, the amount of beam in the core is typically about 40 dB higher than the amount of beam under the -1 MeV pickup, and about 50 dB higher than the amount of beam under the +27 MeV pickup. Thus, though the core attenuation is large, there is still significant signal with a large antiproton stack in the core.

The above pertains to the pickup response to longitudinal signal. For a betatron signal, the response function will be proportional to the *derivative* of equation 1. (If beam is directly below a pickup plate, its betatron motion will not produce a signal.) This becomes:

$$H_{betatron} \propto \frac{1}{h}\left[\operatorname{sech}\left[\frac{\pi}{h}\left(x+\frac{w}{2}\right)\right] - \operatorname{sech}\left[\frac{\pi}{h}\left(x-\frac{w}{2}\right)\right]\right] \tag{3}$$

For large x, it is proportional to the longitudinal response:

$$H_{betatron} \propto \frac{1}{h} \sinh\left(\frac{\pi w}{2h}\right) e^{-\pi x/h} \tag{4}$$

4. Pickup Manipulations

How can the pickups be modified to reduce response to betatron motion of the core? It may be possible to accomplish this by changing the physical size and shape of the pickup electrodes, but this is a major endeavor with doubtful prospects for success. It is preferable to accomplish this by forming a composite pickup from a number of standard pickups with known properties.

Two different approaches may be considered for such a composite pickup. Perhaps the simplest conceptually is to split the pickup tanks into two sets, separated by 180° in betatron phase. Then a simple summation of the signals from both sets of tanks will cancel betatron signals. This would imply a major modification to the Antiproton Accumulator, and would likely not even be possible with the present lattice. In addition, there would be some bad mixing of beam as it traverses the distance between the two sets of tanks, so that the cancellation of betatron signals would not be complete across the Schottky band.

Another approach is to use a number of pickups separated in x, and to sum their responses with the proper amplitudes and phases to form a null for betatron motion at the position of the core. This approach of manipulating signals in "pickup space" has some significant advantages over manipulating signals in "frequency space" in the amplifier chain. As shown above, a pickup naturally has a flat phase response across a Schottky band. By properly summing the responses of a number of pickups at different x locations, this phase response can be forced to remain flat while the amplitude response can be tailored quite flexibly. Thus, filter functions may be realized in "pickup space" which would be quite impractical (and perhaps impossible) to realize in "frequency space" at microwave frequencies.

Conceptually, one could think of mirroring all of the +16 MeV and -1 MeV pickups on the opposite side of the core and simply adding their signals in phase with the existing pickups. This is not practical, however, as it would double the number of pickups, which would be a very expensive proposition.

A modification can be made to this approach, however, which should be nearly as good and much more practical. By positioning a second set of pickups near the core, one can greatly reduce the number of pickups needed. A single pair of pickups at -15 MeV would have about the same sensitivity to core signal as the existing 16 pickup pairs at -1 MeV. It should be possible to sum the signal from only one or two pairs of pickups located near the core to cancel core betatron signal. Because of the difference in numbers and in longitudinal position, there will need to be a separate gain and time delay adjustment for these pickups, thus it is simplest to sum the signals after a first stage of amplification rather than summing the pickup outputs directly.

For greatest flexibility, a set of four pickups with a geometry similar to the core pickups (which are at -30 and -90 MeV) would be best. The inner and outer pairs can be subtracted to give a pure betatron signal, which can be added to the pickups to cancel betatron signals. The inner and outer pairs of pickups could also be summed to give a signal with no betatron component, which could be added to the pickup signals to help tailor their longitudinal gain profile, if desired.

The core pickups themselves cannot be used for this purpose, because they cover a different frequency range in the microwave band. It would have been ideal to build a new set of pickups for this purpose, but this would have been a costly endeavor and would have taken a significant amount of time. In addition, it was not clear how much performance gain would be seen by reducing the pickup of betatron signal. Thus, a simpler and faster method of testing this idea was needed.

5. The -23 MeV Pickup

It turns out that there were a pair of unused pickups in the stacktail system at -23 MeV. These pickups were originally intended to be used in a very similar way, setting a null for pickup of longitudinal signal from the core [2, § 5.9]. There had been abortive attempts to use these in the past, but these had been abandoned because no one could find a useful way to tune them which did not increase noise [3]. (It is possible that a low level amplifier, found to be broken when this pickup was re-connected, had been broken since its initial installation.) It seemed that it may be feasible to use the output of this pickup pair to set a null for betatron motion at the core.

On October 5, 1994, I proposed in a memo to Mike Church that we connect the -23 MeV pickups in this manner. This was accomplished over the next few months, with the help of many people, and the pickups were commissioned during January, 1995. The -23 MeV pickups were timed, phased, and gain-adjusted to subtract from the -1 pickup, creating a null at the core for betatron signals. This was done by putting cooled beam in the core, driving stacktail betatron kickers on betatron sidebands with a network analyzer, and looking at signals from the stacktail momentum pickups with the network analyzer. The result was that this new "composite pickup" had 10 to 20 dB less sensitivity to core betatron signal across the 1 to 2 GHz band than did the -1 MeV pickup alone (figure 1). A similar adjustment was done for the +27 MeV pickup leg, using the -1 MeV pickups to null out core betatron signal on the +27 MeV pickups, with a similar reduction in sensitivity to core betatron motion.

Because of the slight change in the longitudinal gain profile due to the addition of the -23 MeV pickup (gain under the -23 MeV pickup drops by about 1.5 dB) and the changes in the other compensation leg, the time delays and gains of the +27 MeV and -1 MeV legs needed to be changed significantly. With only one pickup pair, on only one side of the core, care must be taken not to create a null in the longitudinal gain profile which is in the stacktail region, since this would inhibit beam cooling into the core. A spreadsheet was used to analytically change time delays and phases of the measured responses of these pickups, and a solution was found which produced a very similar longitudinal gain profile to the one measured with the old settings.

After a few weeks of tweaking on the various parameters to improve performance, during which time some new stacking records were set, the system was left to the operators for a number of months. They set more new stacking records and developed some very different ways of tuning the -23 MeV leg, based on reduction of transient power peaks immediately following beam injection into the Antiproton Accumulator [4]. However, network analyzer measurements showed that their tuning procedure still maintains the -23 MeV signal at an equal and opposite level to the -1 MeV signal, and that there is still a 10 to 20 dB reduction in core betatron pickup (figure 2).

Plots of maximum stacking rate as a function of stack size show a significant gain for February, 1995, just after the -23 MeV leg was commissioned (figure 3) [5]. A number of other modifications were made to the accelerator simultaneously (including increasing Main Ring intensity), so these stacking gains are not all due to the -23 MeV leg. However, none of the other modifications should have changed the slope of the curves (and none of the earlier increases in Main Ring intensity had changed the slopes). I am convinced that the slope change (hence, the increase in stacking rate for large stacks) is a result of this reduction in core betatron pickup which was achieved by the use of the -23 MeV pickups. It is possible that better reduction of betatron signals (e.g. by using a pickup geometry similar to the core pickups) would flatten this slope even more.

6. Conclusions

A feedback mechanism exists which couples core betatron oscillations back to the core through a Palmer-type momentum cooling system. This causes a significant reduction in stacking rate for large stacks. This feedback signal can be greatly reduced by the formation of a "composite pickup" which has a response null for betatron motion of the core.

These results suggest that it is essential to incorporate such compensation pickup schemes in the design of new Palmer-type cooling systems if high stacking rates for large stacks are desired. Ideally, these additional pickups would have the geometry of a core pickup system, with a pair of pickups on each side of the core. This would take very little additional space, and the benefits far outweigh the loss of a small amount of real estate.

In addition, the unique characteristics of manipulating response functions in "pickup space" rather than in "frequency space" should not be overlooked. Such "pickup space" manipulations can easily produce response functions with flat phase characteristics. In addition, response functions formed in this way will inherently tend to be identical for each Schottky band.

REFERENCES

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2. Design Report Tevatron 1 Project, September, 1984.

3. Ralph Pasquinelli, private communication, 1994.

4. Dave Vander Meulen, private communication, 1995.

5. Jim Morgan, private communication, 1995.

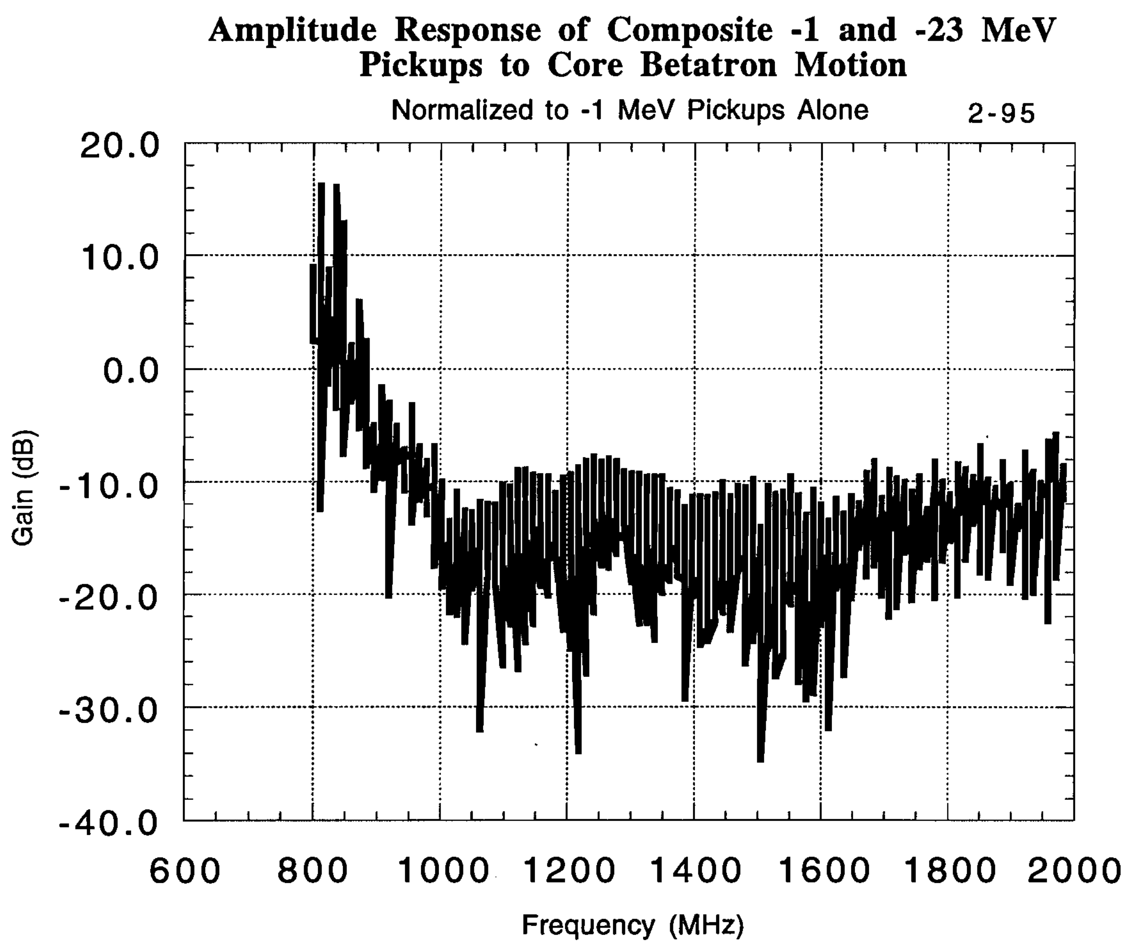

Fig. 1. Reduction in sensitivity to core betatron motion upon commissioning -23 MeV pickups.

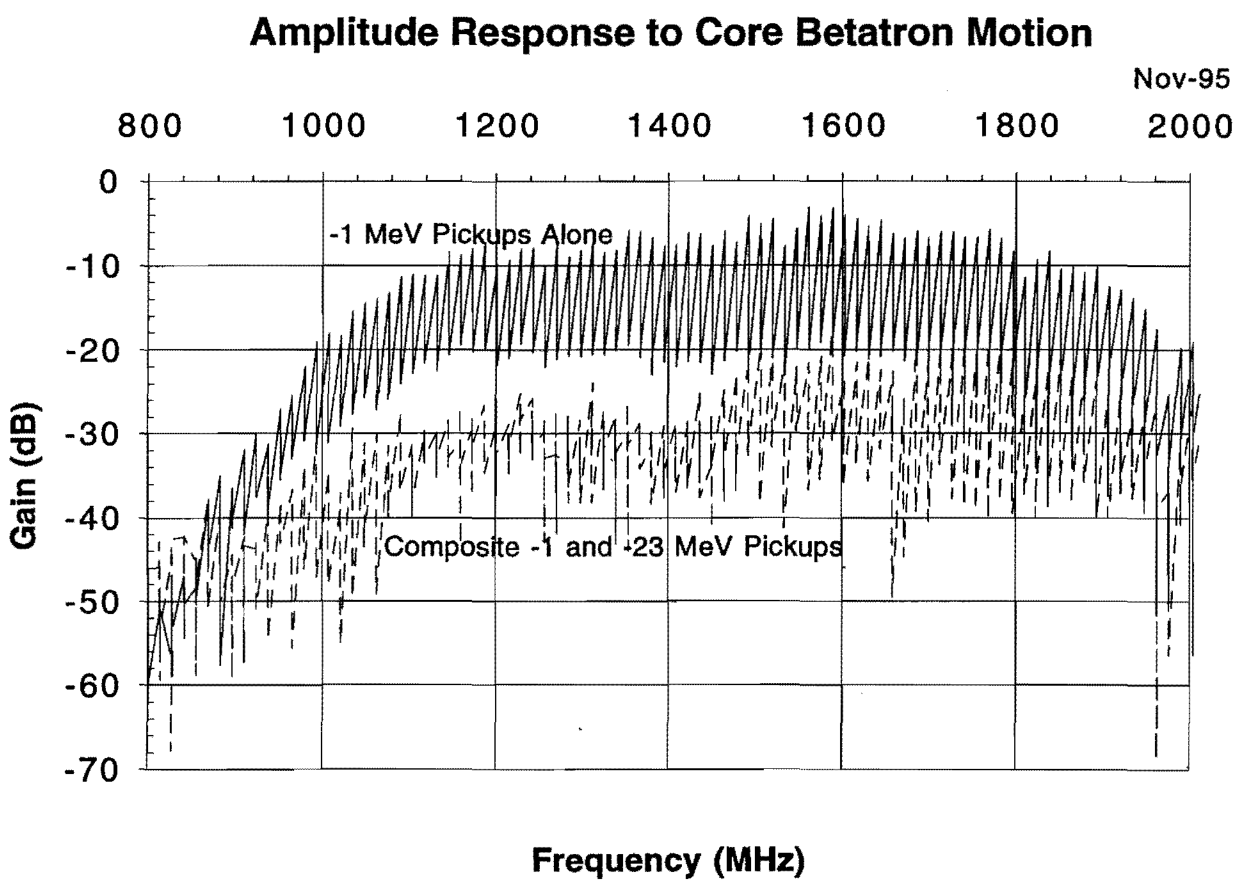

Fig. 2. Performance of -23 MeV pickups, measured 9 months after commissioning.

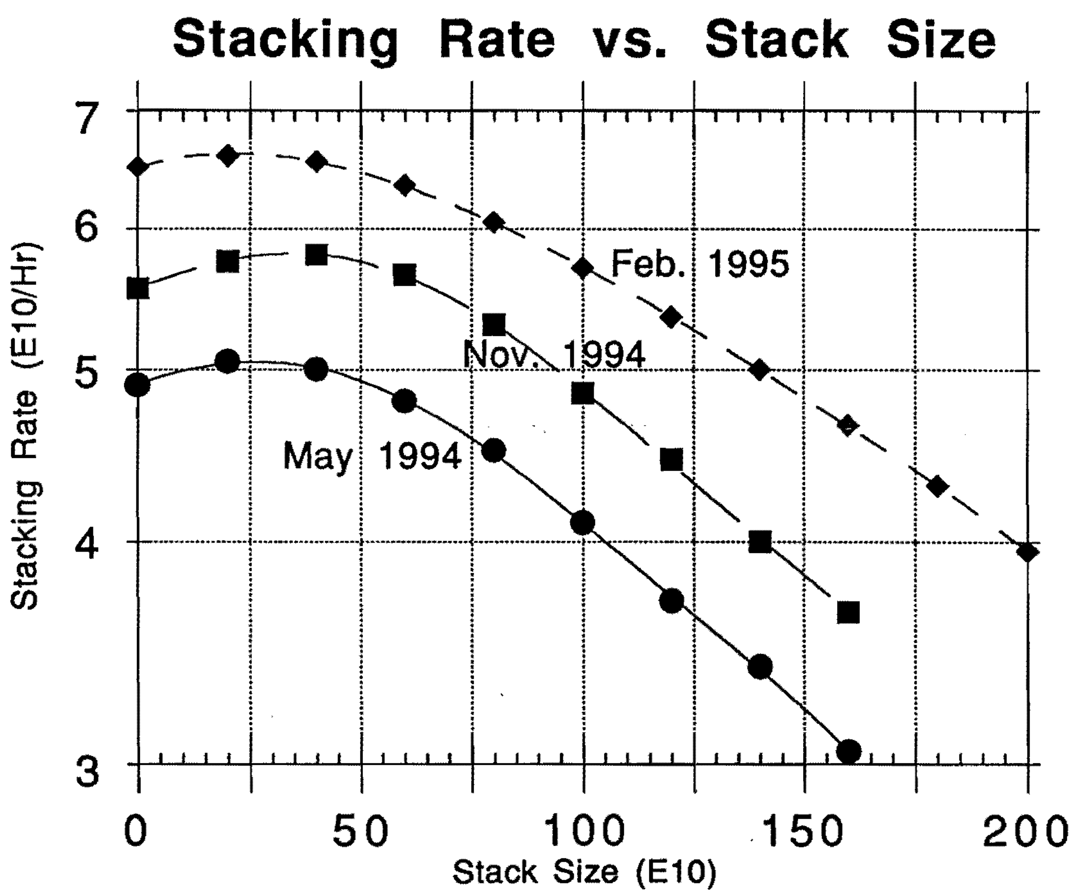

Fig. 3. Maximum stacking rates *vs* stack size. The −23 MeV pickups were commissioned in January, 1995.