ANTIPROTON AND NEUTRINO PRODUCTION ACCELERATOR TIMELINE ISSUES

Dave McGinnis

August 28, 2005

INTRODUCTION

Most of the accelerator operating period is devoted to making antiprotons for the Collider program and accelerating protons for the NUMI program. While stacking antiprotons, the same Main Injector 120 GeV acceleration cycle is used to accelerate protons bound for the antiproton production target and protons bound for the NUMI neutrino production target. This is designated as Mixed-Mode operations. The minimum cycle time is limited by the time it takes to fill the Main Injector with two Booster batches for antiproton production and five Booster batches for neutrino production (7 x 0.067 seconds) and the Main Injector ramp rate (~ 1.5 seconds). As the antiproton stack size grows, the Accumulator stochastic cooling systems slow down which requires the cycle time to be lengthened. The lengthening of the cycle time unfortunately reduces the NUMI neutrino flux. This paper will use a simple antiproton stacking model to explore some of the tradeoffs between antiproton stacking and neutrino production.

ACCUMULATOR STACKTAIL SYSTEM

After the target, antiprotons are injected into the Debuncher ring where they undergo a bunch rotation and are stochastically pre-cooled for injection into the Accumulator. A fresh beam pulse injected into the Accumulator from the Debuncher is merged with previous beam pulses with the Accumulator StackTail system. This system cools and decelerates the antiprotons until the antiprotons are captured by the core cooling systems as shown in Figure 1. The antiproton flux through the Stacktail system is described by the Fokker –Plank equation

$$\frac{\partial\psi}{\partial t} = -\frac{\partial\phi}{\partial E} \tag{1}$$

where ϕ the flux of particles passing through the energy E and ψ is the particle density of the beam at energy E. The beam signal is detected by the cooling system pickup arrays. Each particle provides its own signal to the pickup which is amplified and applied as a voltage on the kicker. This deceleration can be thought of as a drag (cooling) on the beam distribution.

$$\phi_c = \frac{\Delta E_c}{T_o}\psi = eV_o f_o \psi \sum_n \mathrm{Re}\{G_n(E)\} \tag{2}$$

where G_n is the electronic gain at the revolution harmonic n and f_o ($1/T_o$) is the average revolution frequency of the beam,

$$V_o = 2ef_o\sqrt{R_p R_k} \tag{3}$$

where R_p and R_k is the pickup and kicker impedance. However, other particles will also pass through the pickup at the same time which will act as noise. This noise can be thought of as a diffusion (heating) of the beam distribution.

$$\phi_h = \frac{1}{2}\frac{\Delta E_h{}^2}{T_o}\frac{\partial\psi}{\partial E} = \frac{1}{4}(eV_o f_o)^2\frac{E_o}{\eta f_o}\psi\frac{\partial\psi}{\partial E}\sum_n |G_n(E)|^2 \qquad (4)$$

Where E_o is the average energy of the beam and η is the accelerator slip factor.

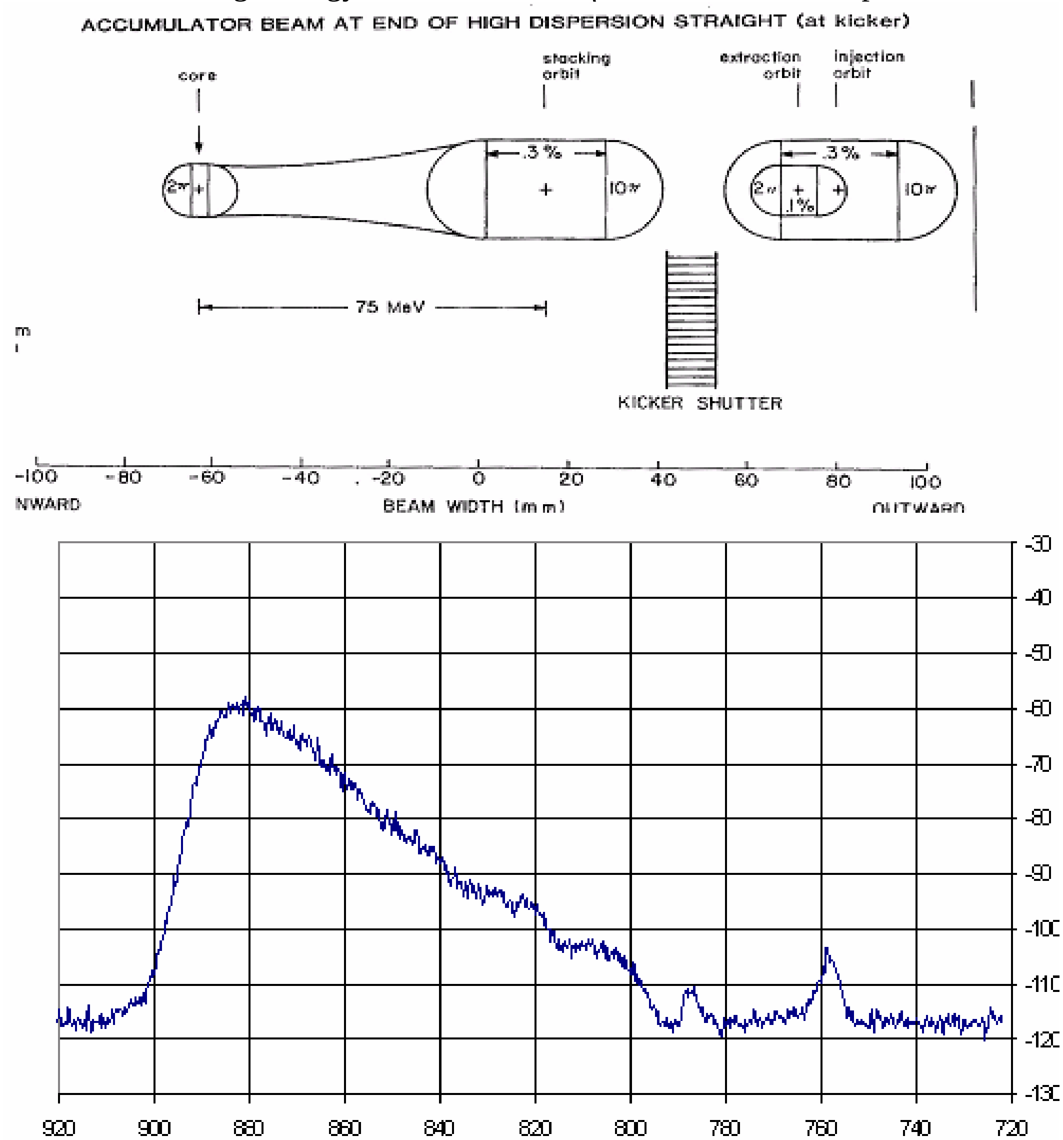

Figure 1. Stacktail Profile

For a constant stacking rate, the flux through the Stacktail system must be a constant:

$$\frac{\partial\psi}{\partial t} = -\frac{\partial\phi}{\partial E} = 0 \qquad (5)$$

This can be accomplished if the energy profile of the electronic gain and the particle density is an exponential:

$$G_n(E) = g_o e^{-E/E_d} \qquad (6)$$

$$\psi(E) = \psi_o e^{E/E_d} \tag{7}$$

The flux through the Stacktail system becomes:

$$\phi = \left(2\frac{g_o}{g_{om}} - \left(\frac{g_o}{g_{om}} \right)^2 \right) \phi_m \tag{8}$$

where:

$$\phi_m = \eta f_o \frac{E_d}{E_o} \frac{\left(W/f_o \right)^2}{\ln\left(f_{max}/f_{min} \right)} \tag{9}$$

$$g_{om} = \frac{2}{eV_o \psi_o} \frac{\phi_m}{W} \tag{10}$$

W is the bandwidth of the cooling system, f_{max} and f_{min} are the maximum and minimum frequencies of the cooling system. The maximum flux that the cooling system can handle is ϕ_m and occurs when $g_o=g_{om}$.

The power density per Schottky band due to the beam at the kicker is:

$$S_n = 2(ef_o)^2 R_p \frac{\psi}{\eta} \frac{E_o}{f_o} \frac{\left| G_n(E) \right|^2}{n} \tag{11}$$

Since

$$\frac{d(nf_r)}{f_o} = n\eta \frac{dE}{E_o} \tag{12}$$

The total power needed by the Stacktail system is:

$$P = g_{om}{}^2 \left(\frac{g_o}{g_{om}} \right)^2 \frac{V_o{}^2}{2R_k} E_d \psi_o \frac{W}{f_o} \tag{13}$$

The initial particle density in the Stacktail is:

$$\psi_o = \frac{N_T P_D}{\Delta E_{bD}} \tag{14}$$

where N_T is the number of protons on target, P_D is the antiproton production per proton on target into the Debuncher (typically ~15×10^{-6}) and ΔE_{bD} is the final energy spread of the Debuncher beam just prior to extraction from the Debuncher. However, not the entire beam that is injected into the Accumulator from the Debuncher needs to be transported from the injection orbit to the Stacktail deposition orbit. The bucket area of the RF system (ARF1) that decelerates the beam from the injection orbit to the Stacktail deposition orbit can be made smaller than the longitudinal emittance of the extracted

Debuncher beam. Beam that is not captured by ARF1 will be left on the injection orbit and be kicked out of the Accumulator when the next Debuncher pulse is injected. The stacking rate into the Accumulator is then:

$$\phi = \frac{N_T P_D}{T_{rep}} \frac{\Delta E_c}{\Delta E_{bD}} = \frac{\psi_o \Delta E_c}{T_{rep}} \qquad (15)$$

where ΔE_c is the momentum spread of the beam that is captured by the ARF1 RF system.

STACKTAIL HEATING

For a constant stacking rate, the power required by the Stacktail system would be constant regardless of stack size. However, because of the design of the Accumulator, the core orbit, in which most of the antiproton stack resides, travels through the Stacktail kicker arrays. Because the Stacktail gain drops off exponentially from the deposition orbit of the Stacktail, most of the Stacktail power will contain harmonic content of the Stacktail deposition revolution frequency. Power at these frequencies cannot affect the core beam longitudinally. However, when the betatron sidebands of the core overlap revolution harmonics of the Stacktail deposition orbit, the power in the Stacktail can excite the core beam transversely giving rise to transverse emittance growth of the core. The frequency where the overlap begins is given as:

$$f_{overlap} = \left(1 - Q_f\right) \frac{f_{o_{core}}}{f_{o_{core}} - f_{o_{dep}}} f_{o_{core}} \qquad (16)$$

where Q_f is the fractional tune. For the Accumulator, the overlap begins around 2.1 GHz, which should be compared to the Stacktail frequency range of 2-4GHz. To excite the beam transversely, the Stacktail kicker arrays would have to give a transverse kick in addition to the longitudinal kick. This transverse kick comes from misalignments or mechanical imperfections of the kicker arrays. In addition, the longitudinal kick could give rise to transverse oscillations if there is non-zero dispersion at the kicker arrays. The lattice of the Accumulator is designed to have no dispersion at the kicker arrays but lattice errors give measurable horizontal and vertical dispersion at the Stacktail kicker location.

The transverse emittance growth due to the Stacktail kickers is compensated by the core transverse stochastic cooling systems. The emittance reduction by transverse stochastic cooling is given as:

$$\frac{d\varepsilon}{dt} = -W_c \left(2g - g^2 N\left(M + U(\varepsilon)\right)\right)\varepsilon + H(N, \varepsilon) \qquad (17)$$

where W_c is the bandwidth of the cooling system, N is the number of particles in the core, M is the revolution frequency divided by the width of the schottky band at microwave frequencies, U is the average noise to signal, and H is the external emittance growth (heating) source. For a system with good signal to noise, the optimum cooling rate occurs when:

$$g = g_{opt} = \frac{1}{NM} \qquad (18)$$

$$\frac{d\varepsilon}{dt} = -\frac{W_c}{NM}\varepsilon + H(N,\varepsilon) \quad (19)$$

Because the strength of the stochastic cooling is inversely proportional to the number of particles in the core, the heating term must fall off as the number of particles if the transverse emittance is to be kept under control. Because the Stacktail is the major source for transverse heating for the core, the Stacktail power must be reduced as the stack size increases. The Stacktail power as a function of stack size for the week of May 15, 2005 through May 21, 2005 is shown in Figure 2. (This time period was chosen because there was no compensation for NUMI cycles at this time.) The power falls off quadratically with a zero Watt intercept when the stack reaches about 240mA.

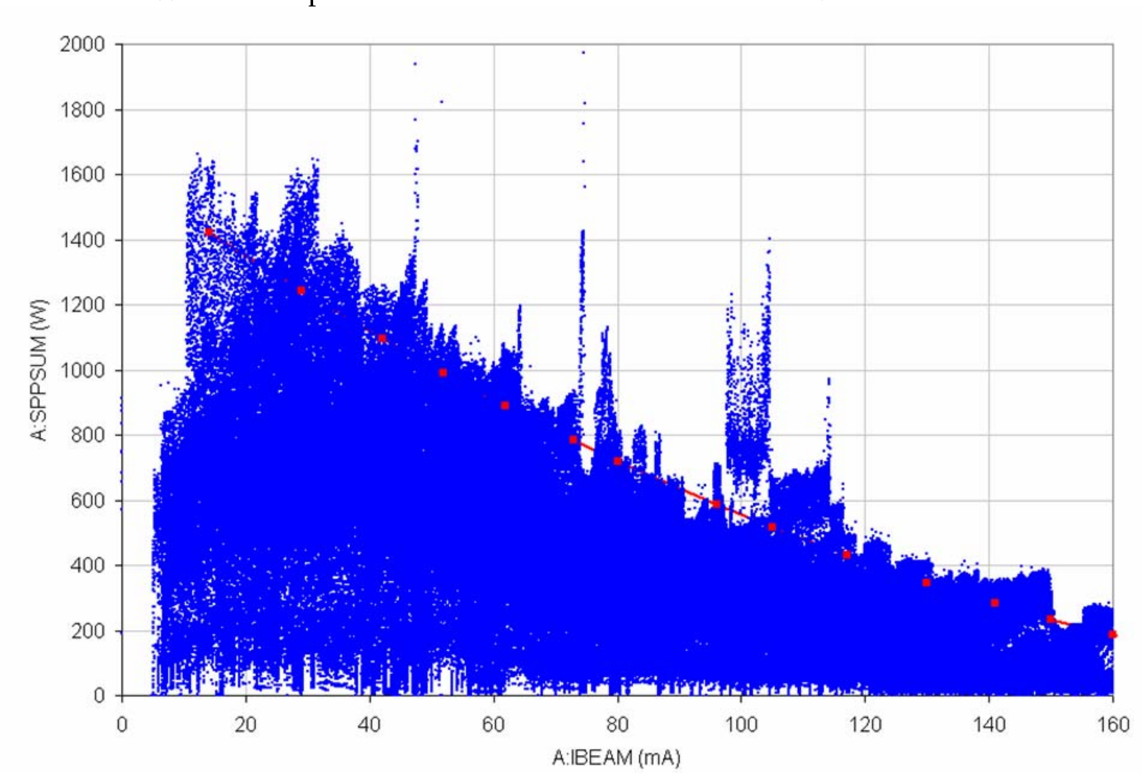

Figure 2. Stacktail Power vs. stack size during May 15, 2005 through May 21, 2005.

<u>EMITTANCE GROWTH IN THE ACCUMULATOR</u>

The Stacktail is not the only source of emittance growth. Because of the large dispersion regions in the Accumulator, intra-beam scattering provides a sizable contribution to the emittance growth. The transverse emittance as a function of stack size for the same time period is shown in Figure 3. Also shown in this figure is a fit to the emittance profile due to the Stacktail heating and intra-beam scattering. The fit for the Stacktail power uses a heating rate of 7.5π-mm-mrad/kW-hour. The fit for intra-beam scattering (IBS) uses a heating rate of 1.4 π-mm-mrad/100mA-hour. The fit indicates that the Stacktail dominates core heating until the stack reaches 120 mA. Intra-beam scattering dominates the heating for stacks above 150mA.

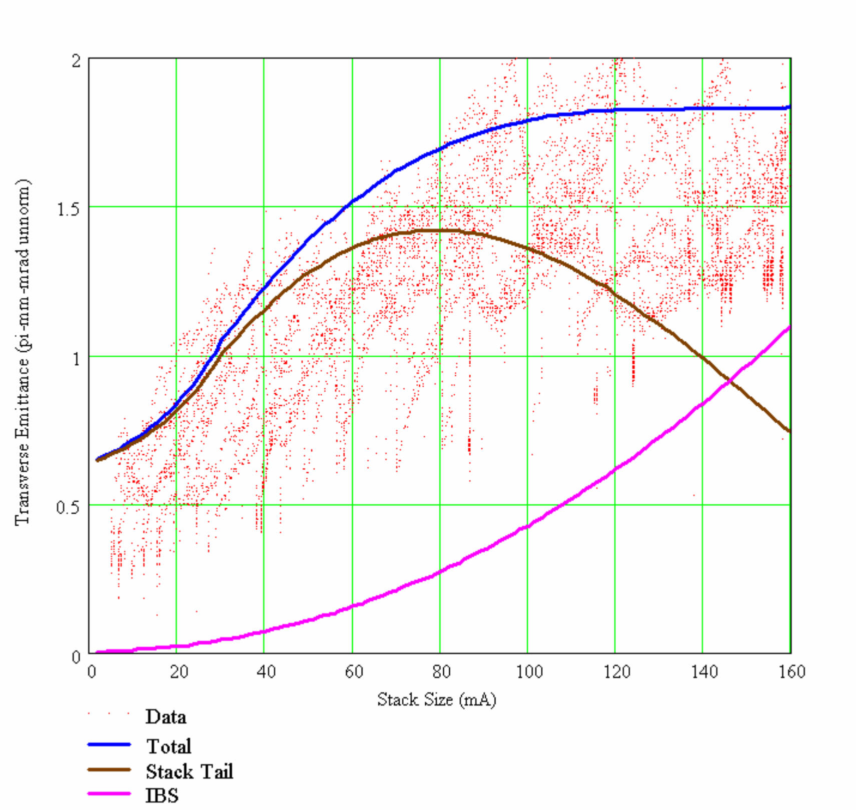

Figure 3. Emittance vs. stack size during May 15, 2005 through May 21, 2005. The fit for the Stacktail power uses a heating rate of 7.5π-mm-mrad/kW-hour. The fit for intra-beam scattering (IBS) uses a heating rate of 1.4 π-mm-mrad/100mA-hour

STACK RATE AS A FUNCTION OF STACK SIZE

A number of options can be used to reduce the Stacktail power as the stack size increases. The technique that has been used for most of Run II thus far is to increase the cycle time. As shown in Equation 15, increasing the cycle time decreases the flux. As shown in Equation 8, reduced flux requires less Stacktail gain, and from Equation 13, less gain results in less Stacktail power. To reduce the power as shown in Figure 2, the cycle time as a function of stack size must increase as shown in Figure 4.

One advantage to going to longer cycle times is that the Debuncher stochastic cooling has a longer time to work which results in a smaller momentum spread:

$$\Delta E_{bd} = \left(\Delta E_{bd_o} - \Delta E_{bd_a}\right) e^{-t/\tau_D} + \Delta E_{bd_a} \qquad (20)$$

where τ_D is the Debuncher momentum cooling time, ΔE_{bdo} is the initial momentum spread before cooling and ΔE_{bda} is the asymptotic momentum spread. A reasonable value for the cooling time is 1 second and reasonable values for the initial spread and the asymptotic spread is about 33 MeV and 6.5 MeV respectively.

As shown in Equation 15, a smaller Debuncher momentum spread results in a higher initial beam density. As shown in Equation 10, a higher initial beam density requires less gain. Because the power needed by the Stacktail is proportional to the gain squared times the beam density as shown in Equation 13, a higher beam density requires less Stacktail power for a given flux.

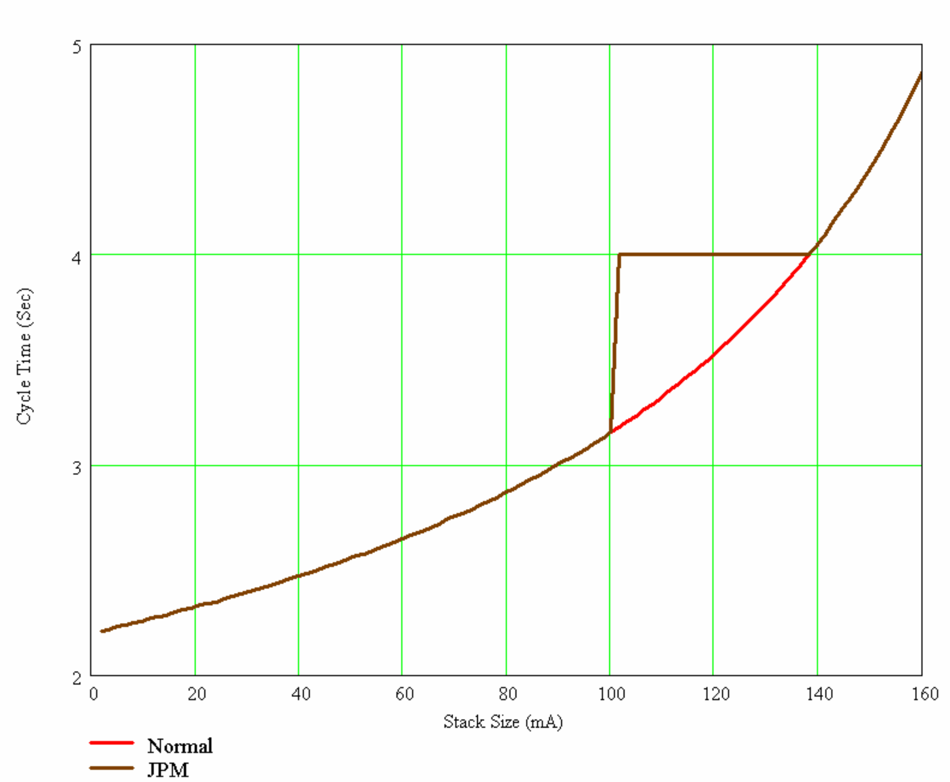

Figure 4. Antiproton production cycle time as a function of stack size for normal operations and for the "4 sec. switchover" where the cycle time is lengthened to 4 seconds at stack sizes greater than 100 mA to permit interleaving of NUMI-only cycles in between the Mixed-Mode cycles.

Once the cycle time is determined, the stacking rate as a function of stack size is given as shown in Figure 5. The normal stacking curve has a slight increase in the mid-stack sizes because of the increase in Debuncher cooling time. The stack rate falls off faster at larger stacks because of the combination intra-beam scattering and Stacktail heating overwhelming the core transverse cooling.

The obvious disadvantage to increasing the cycle time is that the interval between NUMI cycles is also lengthened resulting in a lower neutrino flux. Because it takes about 2 seconds to fill and accelerate the beam in the Main injector for a NUMI-only cycle, NUMI-only cycles can only be interleaved with Mixed-Mode cycles only when the Mixed-mode cycle time exceeds multiples of 2 seconds.

The other technique to reduce power in the Stacktail is to keep the cycle time constant (at ~2.2 seconds) and to decrease the amount of beam that is deposited into the Stacktail system. There are two competing ways of reducing the amount of beam deposited. One technique is to reduce the amount of beam on the antiproton production target. The obvious advantage to this technique is that requires less beam to slip-stack and because slip-stacking in the Main Injector is a fairly lossy process, Main Injector losses will be lower. However, this technique reduces the initial Stacktail beam density.

As shown in Equation 10, less density requires more gain (i.e. more cooling) so that the power is not reduced as quickly as the stacking rate is decreased which can be seen in Figure 5.

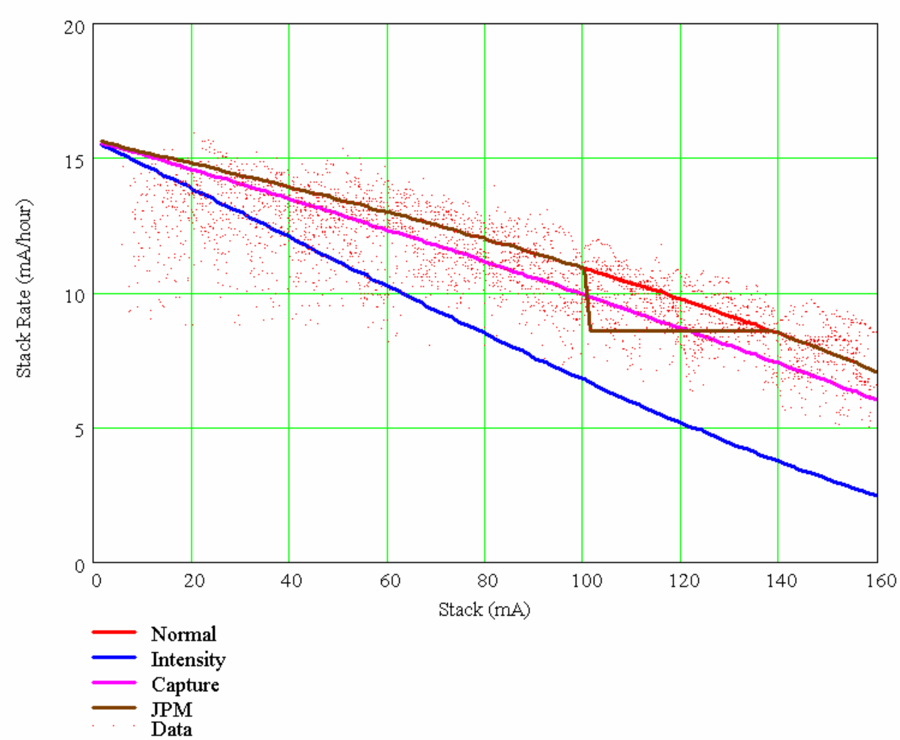

Figure 5. Antiproton Stacking rate as a function of stack size during May 15, 2005 through May 21, 2005. The red curve is with the cycle time lengthened to reduce Stacktail power. The brown curve is the "4 sec. switchover". The blue curve is for a constant 2.2 second cycle time but the intensity on target is reduced as the stack size increases to reduce Stacktail power. The Magenta curve is for a constant 2.2 second cycle time but the ARF1 bucket area is reduced as the stack size increases.

The other technique to reduce the amount of beam deposited on the Stacktail deposition orbit is to reduce the ARF1 bucket size so that some amount of beam will be left on the Accumulator injection orbit. This technique has the advantage to keeping the initial Stacktail beam density high. However, it requires full intensity slip stacked Main Injector cycles even though some of the antiprotons created will be thrown away. Also, the short Main Injector cycles allows for less Debuncher cooling, so this technique is not as efficient in the mid-stack size range as seen in Figure 5.

Stack Size as a Function of Time

The real measure of the different techniques is to examine the stack size as a function of time. The time T it takes to stack to a stack size S is given by:

$$T = \int_0^S \frac{d\sigma}{R(\sigma)} \tag{21}$$

where R(S) is the stacking rate as a function of stack size. The stacking interval as a function of stack size is shown in Figure 6. Below stack sizes of 50 mA, there are no significant differences between any of the techniques. However, the reduced beam on target technique cannot compete at larger stack sizes. It seems somewhat surprising that the ” 4 sec. switchover” in which where the cycle time is lengthened to 4 seconds at stack sizes greater than 100 mA to permit interleaving of NUMI-only cycles in between the Mixed-Mode cycles, is fairly competitive with normal operations and is better than the reduced ARF1 bucket area technique.

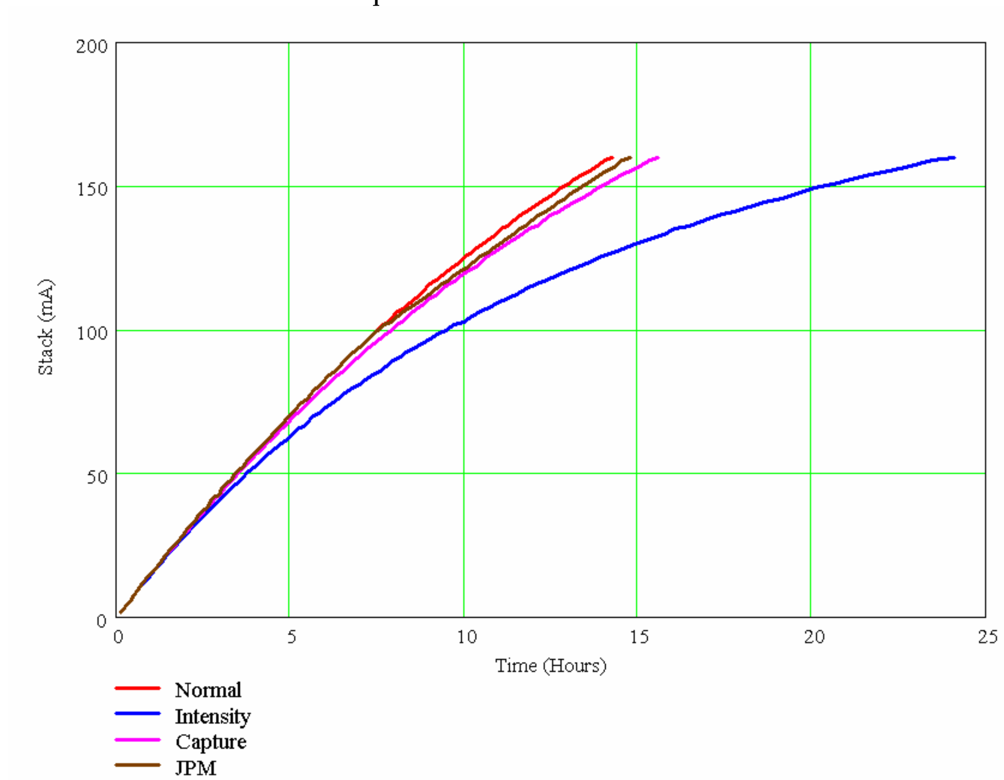

Figure 6. Antiproton stack size as a function of stacking interval. The red curve is with the cycle time lengthened to reduce Stacktail power. The brown curve is the “4 sec. switchover”. The blue curve is for a constant 2.2 second cycle time but the intensity on target is reduced as the stack size increases to reduce Stacktail power. The Magenta curve is for a constant 2.2 second cycle time but the ARF1 bucket area is reduced as the stack size increases.

NUMBER OF NUMI CYCLES

The frequency of cycles for neutrino production is given as:

$$R_{\nu} = \frac{1}{T_{rep}} \mathrm{FLOOR}\left(\frac{T_{rep}}{T_{r\nu}}\right) \qquad (22)$$

Where $T_{r\nu}$ is the minimum Main Injector cycle time needed for neutrino production (~2 seconds). The number of neutrino cycles as a function of stack size is given as:

$$N_\nu = \int_0^S \frac{R_\nu\left(T_{rep}(\sigma)\right)}{R(\sigma)} d\sigma \tag{23}$$

The number of neutrino cycles as a function of stacking interval is shown in Figure 7. The increase in rate for normal operations at a stacking interval of about 12 hours is due to the interleaving of NUMI-only cycles when the Mixed-Mode cycle time exceeds 4 seconds. The "4 sec. switchover" yields a significant increase in cycles as compared to normal running.

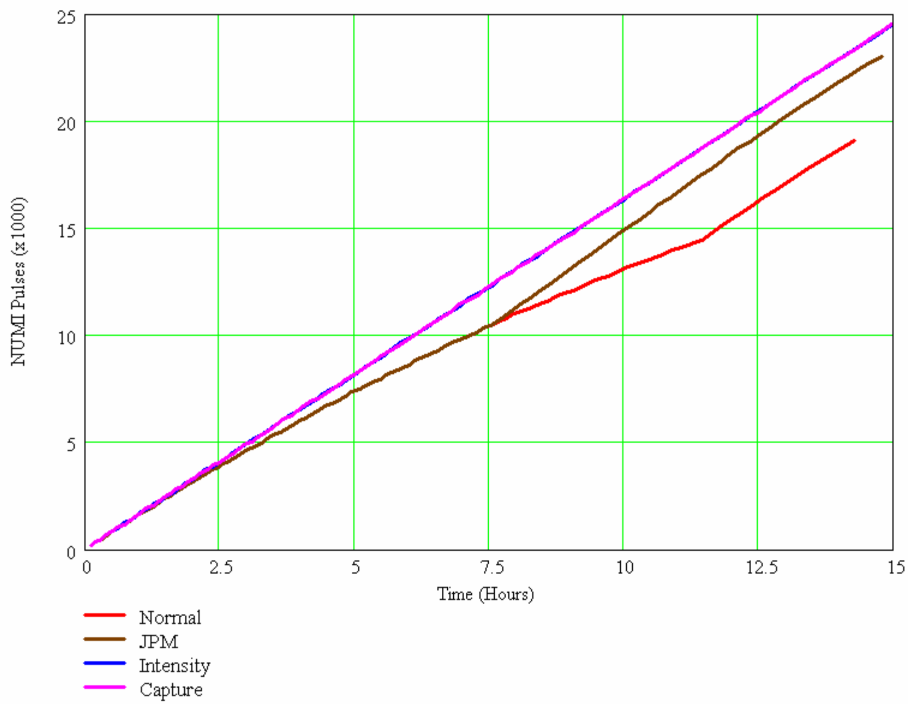

Figure 7. The number of neutrino cycles as a function of stacking interval. The red curve is with the cycle time lengthened to reduce Stacktail power. The brown curve is the "4 sec. switchover". The blue curve is for a constant 2.2 second cycle time but the intensity on target is reduced as the stack size increases to reduce Stacktail power. The Magenta curve is for a constant 2.2 second cycle time but the ARF1 bucket area is reduced as the stack size increases.

SUMMARY

The transverse emittance of the Accumulator core is dominated by Stacktail heating. To keep the emittances of the core under control, the Stacktail power must be decreased as the stack size grows. The normal technique has been to reduce the Stacktail power by increasing the antiproton production cycle time. Reducing the power by reducing the amount of beam on the antiproton production target is not viable at stacks greater than 50 mA. Reducing the ARF1 bucket area as the stack size grows looks promising but suffers from less Debuncher cooling and will also result in higher losses in the Main Injector because of the increased number of high intensity slip-stacked pulses. The "4 sec. switchover" where the cycle time is lengthened to 4 seconds at stack sizes greater than 100 mA to permit interleaving of NUMI-only cycles in between the Mixed-

Mode cycles, increases the number of NUMI cycles significantly and looks to be a reasonable compromise between optimizing the antiproton stack size and increasing the number of neutrino cycles.