A scheme to extract a low intensity slow spill Main Injector beam to the Meson Area without compromising antiproton production rate

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Abstract

We propose a scheme to extract a low intensity beam of 120 GeV Main Injector protons to the Meson Area while simultaneously fast extracting protons for antiproton production such that the total antiproton production rate is unaffected. We achieve this by injecting two booster batches into the Main Injector. At the beginning of flat-top, a single booster batch is extracted to the antiproton source. The remaining batch is used to provide a slow spill to the meson area of low intensity. At the end of the slow spill, the total amount of beam extracted to meson area is less than 10% of the remaining batch which is extracted to the antiproton source providing two batches for anti-proton production in a period of ≈ 3 seconds, thus preserving the rate of antiproton production.

1 Introduction

The current cycle for $\bar{p}$ production (referred to in this document as "pure $\bar{p}$ spill") [1] calls for a 1.466 sec cycle time for extracting a single booster batch of 5×10^{12} protons to the antiproton target. This results in 2455 proton shots to the $\bar{p}$ target (henceforth called $\bar{p}$ shots) and 1.2×10^{16} protons delivered to the $\bar{p}$ target every hour. In the "mixed slow spill mode" as outlined in the Main Injector Design manual [1] and used in calculating rates in the P-907 proposal [2], one runs a 1 sec slow spill combined with $\bar{p}$ production, one has 6 booster batches in the Main Injector, of which the first is extracted to the $\bar{p}$ target and the remaining 5 are resonantly extracted to the switchyard over a period of 1 sec. In this document,we refer to the "mixed slow spill mode" as the "single slow spill", since only a single booster batch is delivered to $\bar{p}$ per spill. The cycle time is 3 sec and results in the delivery of 0.6×10^{16} protons to the $\bar{p}$ target every hour. This is a loss of a factor of 2 in $\bar{p}$ stacking rate and is clearly unacceptable. One option is to run the mixed slow spill cycle after every 10 pure $\bar{p}$ cycles and this will result in a loss of 8.7% in the number of $\bar{p}$'s produced per hour. The $\bar{p}$ stacking rate is a non-linear function of the total amount of $\bar{p}$'s stored, so the full impact of running a mixed cycle after 10 pure $\bar{p}$ cycles may be less than this. The amount of beam delivered to the Meson area will be 17% of what could be achieved if every cycle is a mixed cycle.

The P-907 TPC is expected to take data at a rate of $\approx$ 60Hz. Its dead time is 16 μsec., the time taken for charge to drift across the chamber. During a 1 second flat-top, one expects $\approx10^5$ beam particles to pass through the TPC and 10^3 particles to interact(for the thin target part of the experiment). One booster batch takes 11 μsec to circulate in the Main Injector. This implies that it is possible to generate a secondary beam at the TPC with uniform duty factor from a single circulating booster batch. This permits us to shorten the cycle time of the "single slow spill" from 3 secs to 2.667 seconds, since we need only inject 2 booster batches.

The total amount of beam needed for an experiment such as P-907 is 10^9 - 10^{11} protons per second. For a slow spill of one second duration, this is 2×10^{-4} to 2×10^{-2} of a single booster batch in the main injector. This permits us to attempt to extract a small fraction of a single booster batch during flat-top and then reuse the remainder for $\bar{p}$ production[3]. For this scheme to work, the slow spill resonant extraction has to be adiabatic enough so that at the end of the slow spill, it is still possible to use the remaining booster batch in the main injector for $\bar{p}$ production. In order for $\bar{p}$ production to be efficient, the debuncher has to be cleared of collected $\bar{p}$'s which takes approximately 1.466 seconds. This dictates the length of the flat top. We refer to this new spill mode as the "double slow spill".

2 Simulation results

One needs to establish that the emittance of the batch after slow spill can be made to adiabatically relax to a value suitable for extraction to $\bar{p}$ for this scheme to work. The following section contain details of the results of simulations done by John Johnstone using the Main Injector simulation program. Slow extraction at the Injector is accomplished through excitation of the half-integer resonance. Two orthogonal families of quadrupoles distributed on the 53rd harmonic provide the half-integer driving term. One family alone produces the desired phase-space orientation for extraction, while both families are available to correct the intrinsic half-integer stopband of the machine. A third quadrupole family regulates the actual extraction rate through manipulation of the 0th harmonic (tune shift). The large (non-linear) octupole component of the main quadrupoles drives primarily the 0th harmonic and is sufficient to provide the amplitude dependent tune-shift ($\Delta\mu \propto x^2$) that splits the phase-space into stable and unstable regions.

The numerical simulation of resonantly extracting low intensity beam proceeded as follows:

- Chromaticity was tuned to $\nu_x = \nu_y = +5$. The main quadrupoles were used to move the fractional machine tunes from their nominal (.425, .415) values to (μ_x, μ_y) = (.485, .415), placing the horizontal tune close to the half-integer;
- The transverse co-ordinates of 1000 particles were randomly selected from a 20π mm-mr (95%, normalized) Gaussian distribution, appropriate for describing the launch point at mid-quad #516. Momenta were chosen from a Δ p/p = 0.04% Gaussian distribution. The beam profile can be seen in Figure 1;
- Particles were allowed to circulate unmolested for 200 turns to establish 'steady-state' conditions. This is a necessary step because the non-linear nature of the machine distorts the phase-space from the initially pure Gaussian;
- One family of 53rd harmonic quadrupoles were ramped over the subsequent 300 turns to the point where the 20π mm-mr emittance contour was just marginally stable;
- The 0th harmonic quadrupole circuit was ramped slightly over 1000 turns, causing just 5% of the beam to become unstable, move out along the separatrix, and get extracted. The beam profile can be seen in Figure 2;
- The remaining 95% of the beam circulated for 200 turns to allow time for straggling unstable particles to get extracted;
- Over the next 300 turns the harmonic quads were ramped down to zero;
- The remaining beam was again allowed to circulate unperturbed for 200 turns to re-establish a steady-state distribution, and;
- The emittance of the final circulating beam was measured to be 18.4π mm-mr (95%, normalized). The beam profile can be seen in Figure 3.

3 Main Injector results

We have succeeded in testing the simulations with Main Injector low intensity beams (5E11 protons). We measured the emittance of the beam using flying wires when the Main Injector fractional tunes were 0.425 in the horizontal and 0.415 in the vertical. The results are

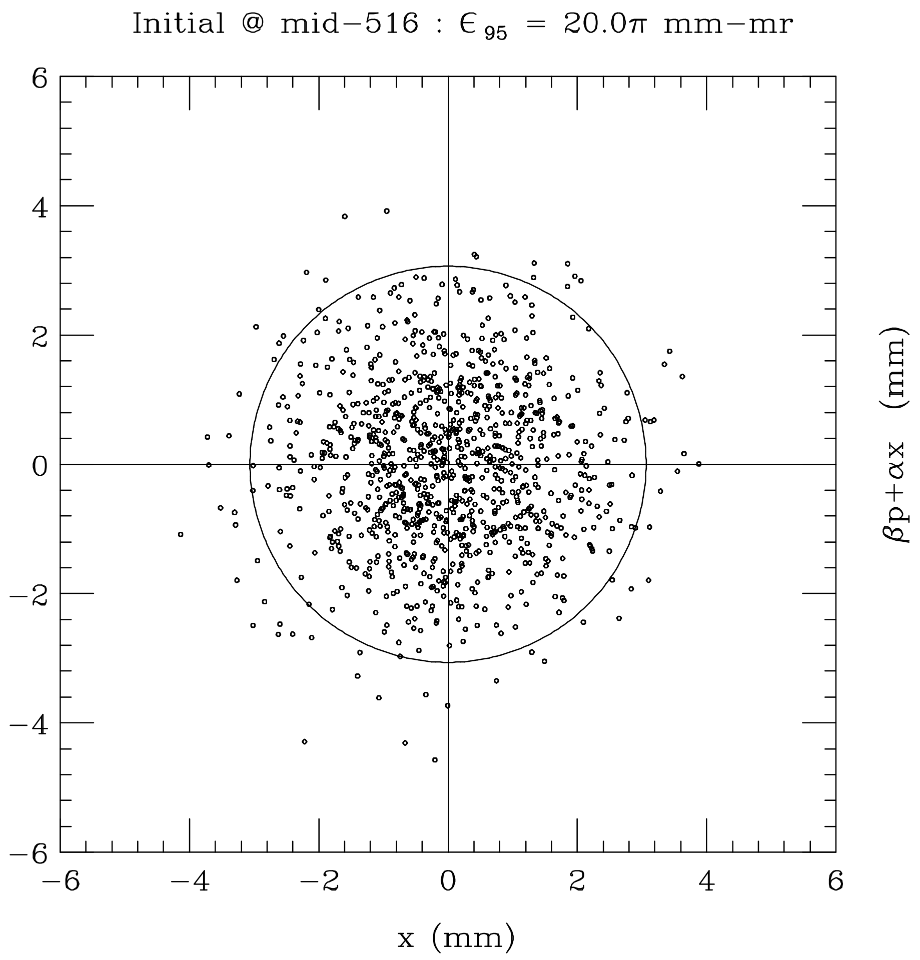

Figure 1: Initial beam profile 20π mm-mr emittance

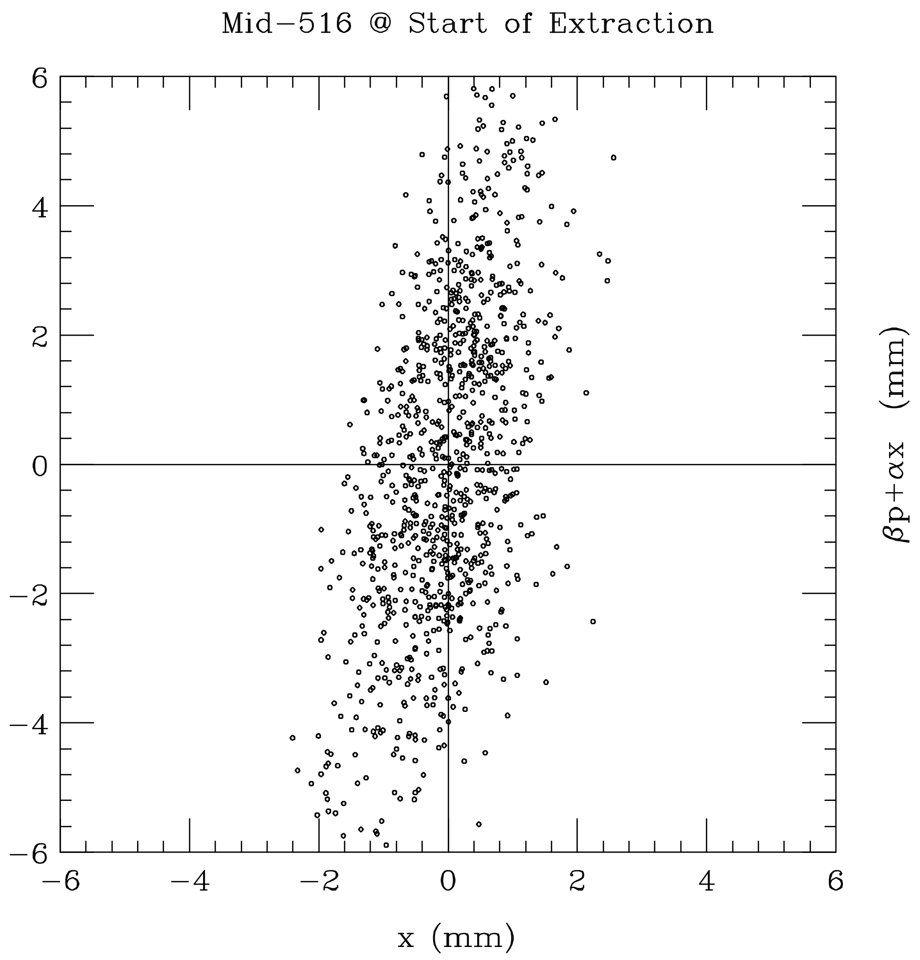

Figure 2: Beam profile during the slow spill extraction

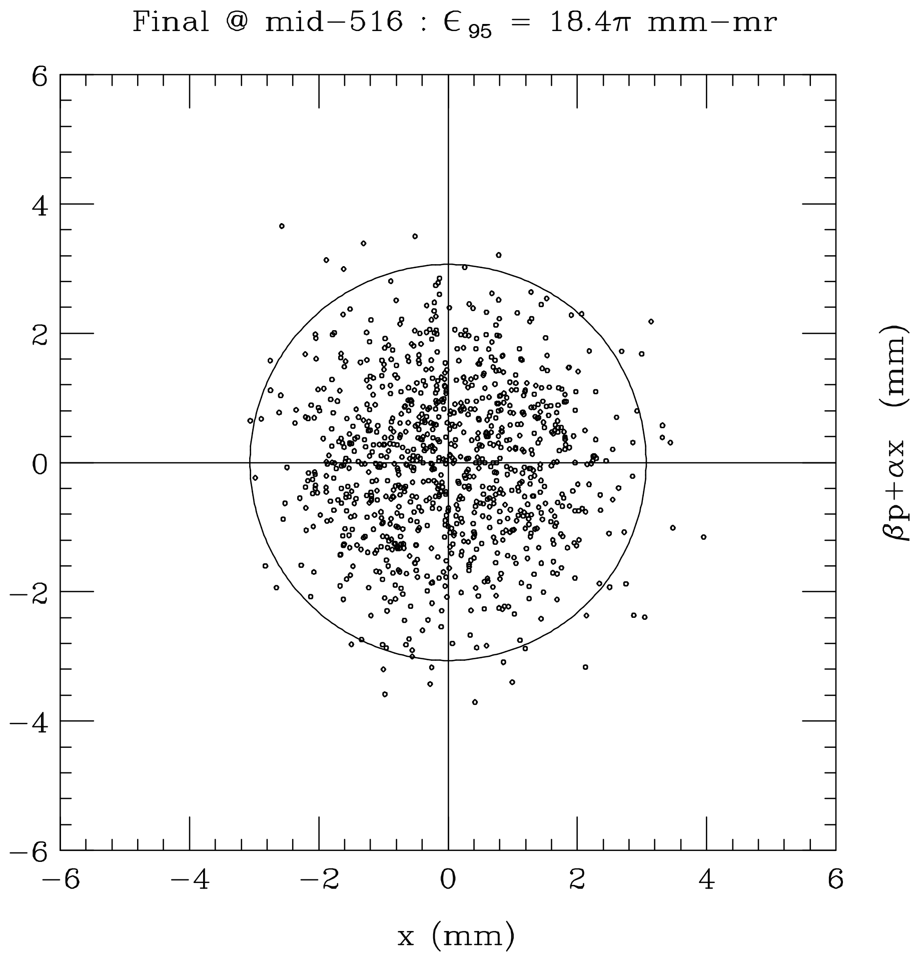

Figure 3: Beam profile after extraction and beam relaxation. Beam emittance is 18.4π mm-mr.

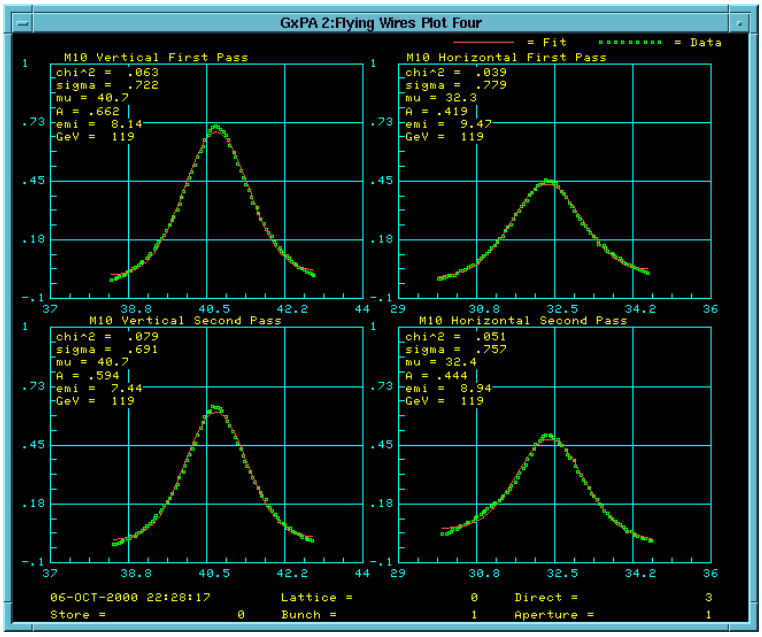

Figure 4: Beam profile before the beam tune is changed, as measured by flying wire.

presented in figure 4 which measures a horizontal emittance of 9.47πmm-mr and a vertical emittance of 8.14πmm-mr, in the first pass of the flying wire. The horizontal tune was then changed by turning on the 53 harmonic quadrupoles and the system was taken very close (within .002) of the half integer resonance. The emittance at this stage is shown in figure 5, where the first pass values of the emittance are 17πmm-mr and 8.76πmm-mr in the horizontal and vertical respectively, i.e,the horizontal emittance has doubled. This is also evident from the beam profile in the figure. After keeping the beam for 300 millisecs at this near resonance condition, the 53 harmonic quadrupoles were ramped down and the emittance measured again. Figure 6 shows the emittance after the machine was set back to its nominal tune. The measured values of the emittance are 10.3πmm-mr and 10.2πmm-mr in the horizontal and vertical, confirming the simulation results. These preliminary results strongly encourage us to proceed further with the "double slow spill" scheme.

4 The Method

Sufficiently encouraged by the simulation results and the Main Injector data, we proceed to work out the ramp structure and cycle rates and power consumption for various spill mixes. Figure 7 shows the proposed ramp structure to implement this scheme. A single booster batch is extracted to $\bar{\text{p}}$ at points C,D, and G,H in the next ramp. The time interval between the points A,B and E,F is 0.141 seconds, the time it takes the booster to input 2 booster batches at 15 Hz into the Main Injector. The up-ramp BC takes 0.6899 secs and the down-ramp DE takes 0.5856 secs. It takes .07 sec for the extraction kicker to fire and another .07 sec for it to reset. It then takes 0.11 sec for the slow spill resonance extraction system to ramp up, produce a slow spill of 1.149 seconds and another 0.11 second for the slow spill

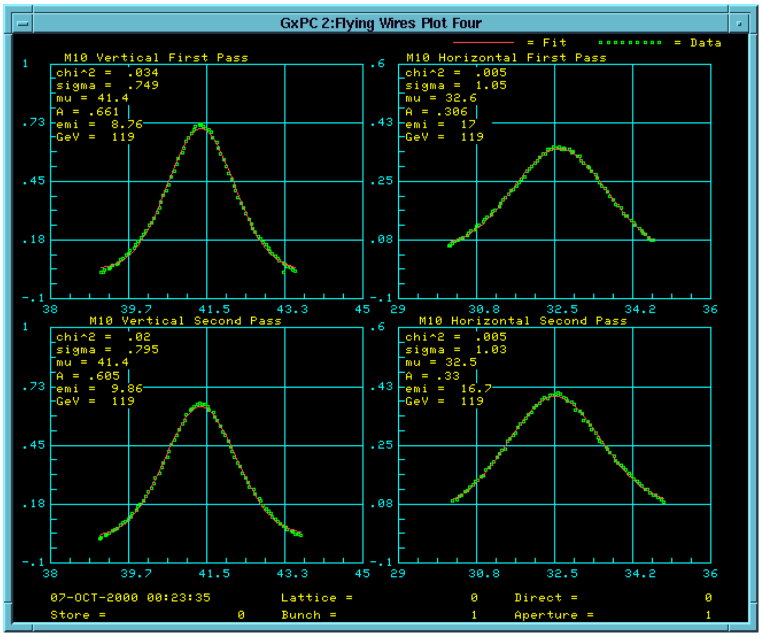

Figure 5: Beam profile with the beam very close to resonance, as measured by flying wire.

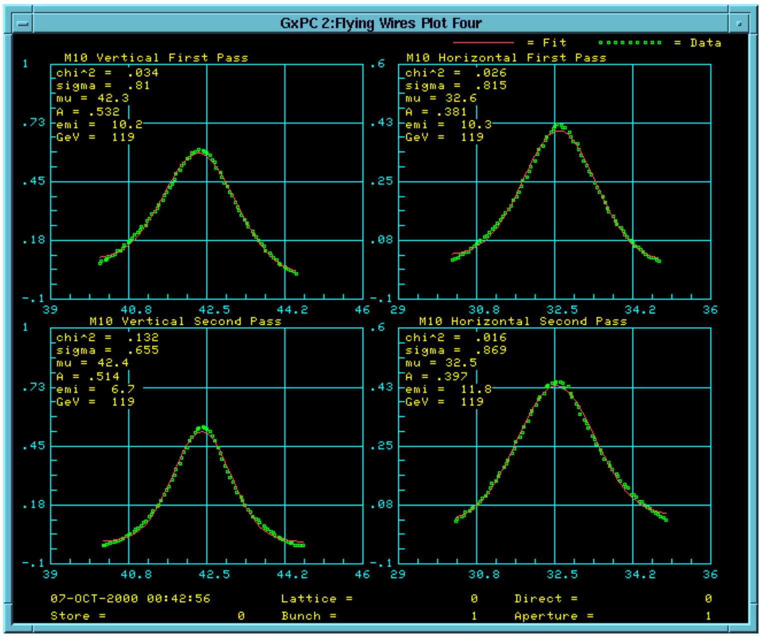

Figure 6: Beam profile after the beam tune is changed back to normal, as measured by flying wire.

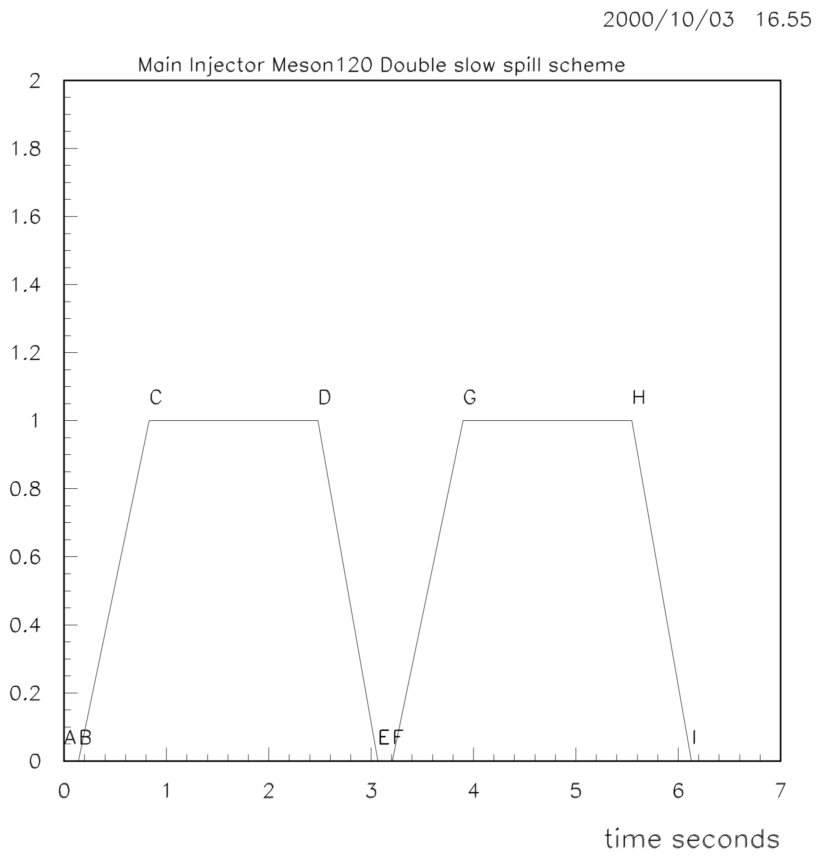

Figure 7: Proposed spill structure.

extraction to ramp down and 0.14 seconds for the extraction kicker to fire and reset at point D for the second proton batch for p̄ resulting in a total flat top length of 1.649 seconds. The time difference between the first booster batch to p̄ and the last booster batch to p̄, i.e. the time difference between the points C,D and G,H is taken to be $\approx$ 1.466 seconds, the time it requires for the debuncher to be emptied. It is the time between extractions to the p̄ under normal antiproton production. The time interval between D and G, the second and third shots to p̄ is $\approx$1.6 seconds. We refer to this new scheme as a "double slow spill". So during a total cycle time of 3.066 seconds, we deliver 2 batches to p̄, resulting in 2349 p̄ shots per hour (as opposed to 2455 p̄ shots per hour in the pure p̄ mode) which is a reduction in p̄ duty factor of 4.3 % from the pure p̄ mode. It results in an increase in duty factor for P-907 of 648% if the double slow spill is run every cycle as opposed to running a single slow spill for every 10 pure p̄ cycles.

4.1 Various ramp mixes

In order to optimize duty factor versus power consumption and p̄ production,we have run various mixes of the pure p̄ spill, single slow spill and double slow spill. The results are to be found in table 1. For example, the case 1 corresponds to running 1 pure p̄ cycle, case 2 a pure single slow spill[4] and case 3 a pure double spill. The cycle time for case 1 is 1.467 secs and the length of the flat top is 0.070 seconds. The number of slow spill seconds per hour to Meson in this mode is zero. The average power consumption per spill is 5200 GeV^2. This is the defined as

$$W = \frac{1}{tspill}\int_0^{tspill} E^2 dt \tag{1}$$

where *tspill* is the time taken by the average ramp cycle and E in GeV is the energy of the main injector ramp. A pure single slow spill run (case 2), which has 1350 slow spill seconds delivered per hour to Meson but only 1350 p̄ shots per hour and has W=9233 GeV^2. The spill cycle time for this slow spill is 2.667 seconds, (as opposed to 3 seconds in the proposal) since we are only using two booster batches in the spill. The Main Injector is designed to handle a power load of $\approx$ 8216 GeV^2. The pure double spill case is illustrated by case 3, which has 2349 p̄ shots per hour, 1349 slow spill seconds to Meson and a W=9906 Gev^2, which may exceed the main injector tolerance in power consumption. A good compromise would be case 11, which has one pure p̄ cycle to 1 double spill resulting in 913 flat top seconds per hour to Meson, 2383 p̄ shots per hour and a W=8383 GeV^2 which may be tolerable. This case delivers 3% fewer p̄ shots per hour than the pure p̄ case and delivers 76% of the amount of beam that we requested in the proposal.

case	pure $\bar{p}$ spills	single slow spills	double slow spills	av. cycle time (secs)	av. power Gev^2	Av. flat-top time sec	slow spill secs per hr	$\bar{p}$ shots per hr
1	1	0	0	1.467	5200.	0.070	0.	2455.
2	0	1	0	2.667	9233.	1.250	1350.	1350.
3	0	0	1	3.066	9906.	1.649	1349.	2349.
4	1	2	0	2.267	8363.	0.857	1059.	1588.
5	1	1	0	2.067	7802.	0.660	871.	1742.
6	10	5	0	1.867	7121.	0.463	643.	1929.
7	10	4	0	1.809	6898.	0.407	568.	1990.
8	10	2	0	1.667	6276.	0.267	360.	2160.
9	10	1	0	1.576	5821.	0.177	208.	2285.
10	1	0	2	2.533	8997.	1.123	1089.	2369.
11	1	0	1	2.266	8383.	0.860	913.	2383.
12	10	0	5	2.000	7605.	0.596	690.	2400.
13	10	0	4	1.923	7343.	0.521	614.	2406.
14	10	0	2	1.733	6587.	0.333	398.	2423.
15	10	0	1	1.612	6014.	0.214	233.	2436.

Table 1: Parameters for various mixes of spills

5 Outstanding questions

- Is there an intensity dependence to the measurements presented here? One should repeat them at high intensity (5E12 protons).

- What is the minimum amount of beam that can be extracted in a controlled fashion?
- Is it possible for $\bar{p}$ to take pulses at two dfferent time intervals, C and D are spaced apart 1.467 seconds and D and G are spaced apart 1.6 seconds.
- What is the minimum spacing between pulses that $\bar{p}$ can tolerate?

6 Slow Spills during MINOS running

The MINOS experiment is expected to start data-taking in late 2003. The MINOS ramp has 6 booster batches one of which is sent to $\bar{p}$ and the other 5 to MINOS using a fast kicker. The length of this cycle is 1.87 sec [5] which results in 1925 $\bar{p}$ shots per hour, a 21.6% reduction in $\bar{p}$ stacking rate. Running MINOS with $\bar{p}$ production results in a more severe reduction in $\bar{p}$ stacking rate than anything we are proposing using the slow spill.

If P907 is approved in November 2000, we expect to setup the experiment in 2001 and start data-taking in 2002. We would then have over 1.5 years to run before MINOS starts up, which is enough to acquire the data we ask for in the proposal. If however, we overlap with the MINOS start-up, it is possible to devise schemes where in we have 5 booster batches injected, one of which is given to $\bar{p}$, the remaining 4 are used in slow spill and 3 given to MINOS and one to $\bar{p}$ at the end of the slow spill. Another possibility is to interleave a MINOS Spill with a double slow spill outlined above. It would be far more economical to have P-907 data taking be completed before MINOS turn on, both for proton economics as well as utilizing the data for MINOS analysis in a timely fashion.

7 Conclusions

The simulation results and the actual Main Injector behavior seem to imply that it is possible to extract a small fraction (5-10%) of the booster batch during a slow spill and still preserve the emittance of the beam so that it can be used for $\bar{p}$ production. The remaining questions have to do with the stability (regulation) of the power supplies driving the extraction system. Are they stable enough such that a small steady fraction of the beam can be extracted during the slow spill, i.e., is the current system of regulation adequate enough to skim off 10% of the intensity in a steady uniform slow spill? Some more development effort will be necssary to achieve the degree of stability in the extraction system.

8 Acknowledgements

We wish to thank John Johnstone for performing the simulations. We wish to acknowledge useful conversations with Jim Hylen, Phil Martin and Peter Prieto.

References

[1] Main Injector Technical Design Handbook, Chapter 2, August 1994.

[2] "P-907 Proposal to measure Particle Production in the Meson area using Main Injector Primary and Secondary Beams", can be found at http://www-ppd.fnal.gov/muscan/meson120/proposal/p907.ps

[3] The "double slow spill idea" was initially proposed by R.Raja to address the duty factor crisis with P-907.

[4] This is a shortened version of the mixed slow spill given in [1] since we only use 2 booster batches. This cycle takes 2.667 secs as opposed to the 3 second cycle used both in the P-907 proposal and the design handbook. The ramp times given in this document are approximate and need to be made into whole number of booster "tics" appropriately.

[5] J.Hylen, Private communication.