**Pbar Note 682**

# Stacktail Cooling System Upgrade


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## 1. Motivation

The design choices for the current Accumulator stochastic cooling systems were made under the assumption that the Accumulator is the final repository for the anti-protons, so both flux and momentum density had to be optimized. The upgrade operates under the assumption that the Recycler is the final repository. As electron cooling performance improves as density increases while stochastic cooling performance declines, we can make some tradeoffs in the system design that are optimized for maximizing the flux through the Accumulator. A more complete description of the design requirements and options can be found in reference [1].

It will be necessary to upgrade the longitudinal stochastic cooling systems. The current 2-4 GHz longitudinal cooling system, which moves the injected beam from the deposition orbit to the core, was designed to have a maximum flux of ~35 mA/hour. Changes in the system design will be necessary to handle a flux of 50 mA/hour or greater. A numerical simulation of the Fokker-Planck equation, which includes beam feedback, is used to predict the performance of the upgrade design[2]. The simulation predictions have been compared to measurements of the current hardware and are in reasonable agreement[3]. As there are remaining uncertainties in our understanding of the simulation and hardware performance in the high stacking rate scenarios proposed, the systems are designed to perform at a factor of 2 times the input stacking rate requirement.

In addition to the longitudinal cooling systems, it may be necessary to include additional transverse cooling. The necessity of this transverse upgrade has not been shown and investigations and designs are still in progress. A preliminary cost estimate has been done, using the Tev I design as a template[4]

- **Physics of Stochastic Stacking**

Stochastic stacking with a constant flux is achieved by designing a system with gain as a function of energy that falls exponentially, with characteristic energy $E_d$. The resulting density distribution then rises exponentially with the same characteristic energy[5]. The resulting maximum flux $\Phi$ can be expressed as:

$$\Phi = \frac{W^2 \eta E_d}{f_0 p \ln\left( F_{\min} / F_{\max} \right)}, \qquad (1)$$

where $W$ is the bandwidth of the system, □ is the phase slip factor, $f_0$ is the beam revolution frequency, $p$ is the beam momentum, and $F_{min}$ and $F_{max}$ are the minimum and maximum frequencies in the system bandwidth. Planar pickups have a response that follows $exp(-□x/d)$, where x is the transverse distance from the center of the pickup and d is the vertical aperture. If the pickups are located in a region of high momentum dispersion, a a system can be designed where the gain response falls off exponentially with energy. The region of exponential density increase is called the 'stacktail' and the region where beam accumulates is called the 'core'. As the revolution frequency changes with energy so doesthe flight time between pickup and kicker . The delay time through the electronics is a constant, hence, it is necessary to use multiple sets of pickups with different gains and delays to build the gain slope across the aperture. Correlator notch filters are used to null the signal at the core.

The present Accumulator provides a good example of the basic principles. Figure 1 shows the antiproton density distribution as a function of the beam revolution frequency overlaid in the stacktail region with an exponential fit. The maximum flux this particular stack is calculated from the results of the fit. For the data in question, the fit results in a characteristic energy $E_d$ = 5.7±0.4 MeV and maximum flux of 26.5±1.7 mA/hour. The actual stacking rate at the time this data was taken was 9.7 mA/hour. To achieve the desired rate of 50 mA/hour, the system needs to be upgraded.

- **Design Approach**

Of the parameters appearing in Eq. ( 1), $E_d$, $W$, and □ are the only ones that can reasonably be considered as changeable. The simplest approach to maximize the flux is to increase $E_d$. This approach sacrifices the amount of density compaction achievable, since the density grows as $exp(E/E_d)$, but has fewer implications for other systems in the Accumulator. Increasing the bandwidth clearly increases the maximum flux. Both approaches will be taken in this upgrade. Changes to □ are not being considered at this time.

The stacktail system consists of 2 sets of pickups (see **Figure 2** for schematic), with independent gain and delay control. The pickups are kept at liquid nitrogen temperature to minimize electronic noise. There are 256 pickup loops at 15 MeV (with respect to the central energy of the Accumulator) and 48 pickup loops at -8 MeV. There are 128 kicker loops in 8 tanks, with 4 TWTs per tank. There is approximately 150 dB of gain from pickup to kicker. It is possible to combine the signals from the 2 sets of pickup loops (and a 3rd set, not included in the figure) to fine-tune the gain shape (called 'compensation legs').

A two-stage upgrade is planned to handle increased input flux. In the initial stage, the characteristic energy $E_d$ is increased from ~6 MeV to ~18 MeV. This change can be implemented with a minimal change in hardware through changes to pickup position (moving tanks radially in the Accumulator tunnel) and electronic gain and phase settings. The second stage requires additional pickups, electronics, and kickers; all covering the frequency range 4-6 GHz.

- **Design Constraints and Measurements**

There are drawbacks to increasing $E_d$. The Accumulator has a finite momentum aperture. It is therefore necessary to stop the flux at some point and accumulate it in a 'core'. The gain function will then deviate from a pure exponential and other considerations come to the fore. It is necessary to match the stacktail system gain to the core system gain to have a smooth transition in the gain profile. As the density increases for a given value of the gain, diffusive beam heating from other particles (through the cooling systems) eventually dominates the cooling term and the system no longer is able to effectively increase the density. It is generally true that as the density of the core increases it becomes necessary to decrease the system gain to maintain some margin between the cooling and diffusive terms in the Fokker-Planck equation.

Another limitation is the assumption of constant input flux. The input flux is a transient, with large pulses coming every 2 seconds. It is necessary for the input pulse to move completely into the stacktail region before the next pulse arrives or it will be phase displaced by the RF bucket moving the new pulse onto the deposition orbit. The fraction of the input pulse that moves across the aperture is a function of the gain of the system and the momentum distribution of the input pulse. The larger the gain, the more efficiently the input pulse moves off of the deposition orbit. The large gain necessary for effective stacking of the input pulse is also detrimental (for reasons given above) to accumulating large amounts of beam in the core.

## 2. Performance Parameters

The system will be designed to meet the following input requirements (beam coming from the Debuncher is assumed to meet these requirements):

- Input flux $\geq$ 40 mA/hour
- 2 sec cycle time
- Input pulse 95% full width $\leq$ 6 MeV/c

The output specifications are as follows (the transfer process and the Recycler):

- Transfer 10 eV-sec longitudinal emittance
- $\leq$15 $\pi$ transverse emittance
- Transfer every 30 minutes of stacking

The design goal is to handle $\geq$80 mA/hour input flux to have a factor of 2 design margin with respect to the final performance goal.

## 3. Status of the project

- **Design status**

The simulation designs for stage 1 (2-4 GHz bandwidth, 18 MeV characteristic energy) and stage 2 (2-6 GHz bandwidth, 15 MeV characteristic energy) are complete. For stage 1, the following changes are necessary:

- Move leg 1 tanks ~1 mm radially outward from current location (an energy change of ~1 MeV)
- Move leg 2 tank ~7 mm radially outward from current location (an energy change of ~8 MeV)
- Adjust system gains and delays

With these changes, the stacktail can sustain a stack rate of >60 mA/hour for 30 minutes. With an input flux of 61 mA/hour, the average stacking rate with transfers occurring every 30 minutes and taking 35 seconds to complete is 59.8 mA/hour. **Figure 3** shows the stack size and stack rate for one hour of stacking in this scenario.

For stage 2, the pickup positions for the stacktail are moved. Because of the increased bandwidth of the system, it is necessary to decrease the total energy change in the system to avoid Schottky band overlap. Hence, the core energy is closer to the stacktail. Half the 2-4 GHz pickups and kickers are removed and replaced with 4-6 GHz pickups and kickers. With the increased bandwidth, the characteristic energy is lowered to approximately 15 MeV. The resulting system can sustain ~80 mA/hour for 30 minutes. With an input flux of 82 mA/hour, the average stacking rate with transfers occurring every 30 minutes and taking 35 seconds to complete is 80.9 mA/hour. **Figure 4** shows the stack size and stack rate for one hour of stacking in this scenario.

If we consider alternate scenarios, e.g., more frequent transfers, the average rate can be increased. With transfers occuring every 10 minutes, the system can sustain a flux of greater than 100 mA/hour. For an input flux of 110 mA/hour, the average stacking rate with transfers occurring every 10 minutes and taking 35 seconds to complete is 103.9 mA/hour. **Figure 5** shows the stack size and stack rate for one hour of stacking in this scenario.

The simulations are crucially dependent upon the input pulse moving far enough in the 2 sec available. While the single pulse studies described in reference [3] give good agreement between the data and simulation, the particle densities do not approach what will be present in the future. Stacking of protons (by reversing the polarity of the entire antiproton source downstream of the target) does test the system performance with increased flux. This test, with the stage 1 configuration, should be done as soon as possible.

- **Cost & Resources**

The cost of supporting stage 1 is minimal. Access to the tunnel is required to make the requested tank moves. Some transmission line delay changes will be necessary. A dedicated study period of several shifts initially to commission and characterize the system with protons will be required.

Stage 2 will require significant rework of the hardware. Design of the new 4-6 GHz arrays will be necessary. While the design would follow previous efforts, it is nonetheless new and will require significant engineering. Half of the pickup and kickers would need to be replaced with the new arrays. The vacuum vessels could be retained to save costs. The kicker vacuum vessels were designed to accept arrays of various frequency bands. The pickup vacuum vessels have all the required liquid nitrogen plumbing. If liquid helium is not required, there should be no additional costs for cryogenic improvements.

The cost of modifying the kicker vacuum vessels is basically the cost of new array circuit cards. Sixteen boards are necessary, four per tank, four tanks. The Teflon circuit board material is $500 per board. Setup is typically $5000 for this job. The pickup circuit boards have a similar microwave design, but need to have the termination resistors cryogenically cooled. This will change the board design and require a separate setup charge. The number of pickup loops would increase from 128 to over 200 in the same space due to the increased center frequency of 5 GHz. Pickup circuit boards required are eight with similar cost quoted above.

Much of the microwave hardware could be reused, such as the switches, trombone delay lines, and amplifier power regulators. All frequency dependent devices would need to be replaced. Due to the number and variety of devices, these are lumped in one category of support microwave hardware. New 1/2-inch coax would be required as the installed 7/8-inch coax is not usable in this frequency range. New amplifiers, notch filters, and TWTs and power supplies would need to be purchased. The existing stacktail utilizes the original Logimetrics TWT power supplies, which are incapable of handling the voltages for the higher frequency TWTs.

Table 1 shows an initial cost and labor estimate to implement the stage 2 upgrade. The cost estimate includes spare microwave parts and contingency at 30%.

The stacktail betatron design is still in development. It has not been demonstrated that this system is required. Using the Tev I design as a template, a preliminary cost estimate has been done and is presented in Table 2.

# Stage 2 Stacktail Cooling Upgrade to 4-6 GHz

| Hardware | Quantity | Unit cost | Line total |
|---|---|---|---|
| Cryogenic preamplifiers | 8 | $4,000 | $32,000 |
| Secondary preamps | 8 | $1,000 | $8,000 |
| BAW notch filters | 3 | $10,000 | $30,000 |
| TWT | 20 | $20,000 | $400,000 |
| TWT power supply | 20 | $18,000 | $360,000 |
| Coax cables | 1 | $10,000 | $10,000 |
| Support microwave hardware | 1 | $100,000 | $100,000 |
| Pickup array boards | 8 | $500 | $4,000 |
| Kicker array boards | 16 | $500 | $8,000 |
| Set up charge for array boards | 1 | $10,000 | $10,000 |
| Machine shop | 1000 | $40 | $40,000 |
| Electricians for cables pulls man weeks | 2 | $1,000 | $2,000 |
| subtotal | | | $1,004,000 |
| Contingency @ 30% | | | $301,200 |
| TOTAL | | | $1,305,200 |
| Labor Estimate | | | |
| Array engineering | | man months | 6 |
| Array fabrication | | man months | 6 |
| System engineering | | man months | 2 |
| Installation technicians | | man months | 6 |
| Mechanical engineering | | man months | 3 |

Table 1: Initial cost and labor estimate for stacktail cooling upgrade.

| Stacktail Betatron Cooling | | | |
|---|---|---|---|
| Hardware | Quantity | unit cost | line total |
| Cryogenic preamplifiers | 4 | $4,000 | $16,000 |
| Secondary preamps | 4 | $1,000 | $4,000 |
| TWT | 2 | $20,000 | $40,000 |
| TWT power supply | 2 | $18,000 | $36,000 |
| Coax cables | 2 | $10,000 | $20,000 |
| Support microwave hardware | 1 | $25,000 | $25,000 |
| Kicker array boards | 8 | $500 | $4,000 |
| Machine shop | 500 | $40 | $20,000 |
| Electricians for cables pulls man weeks | 2 | $1,000 | $2,000 |
| subtotal | | | $147,000 |
| Contingency @ 30% | | | $44,100 |
| TOTAL | | | $191,100 |
| Labor Estimate | | | |
| Array fabrication | | man months | 6 |
| System engineering | | man months | 1 |
| Installation technicians | | man months | 2 |
| Mechanical engineering | | man months | 3 |

Table 2: Cost estimate for preliminary stacktail betatron system.

## 4. Issues for the project

There are two important remaining issues for this project design. The first is hardware: the pickup loop design for the 4-6 GHz frequency range. The second is simulation: how well the simulation predicts the performance of the system.

The existing 4-8 GHz pickups have little response above 6 GHz[6]. The simulations used in the design have used the measured pickup response in the range 4-6 GHz. As the existing design has a center frequency of 6 GHz, improvement in the response could be found by designing a new pickup loop with a central frequency of 5 GHz. Such a design has not been started.

Beam studies are part of the project plan for the stacktail momentum system. Characterization of the performance and comparison to models is ongoing. Single pulse evolution measurements and proton stacking measurements (to test the system in high flux conditions) will be done before the system design is finalized.

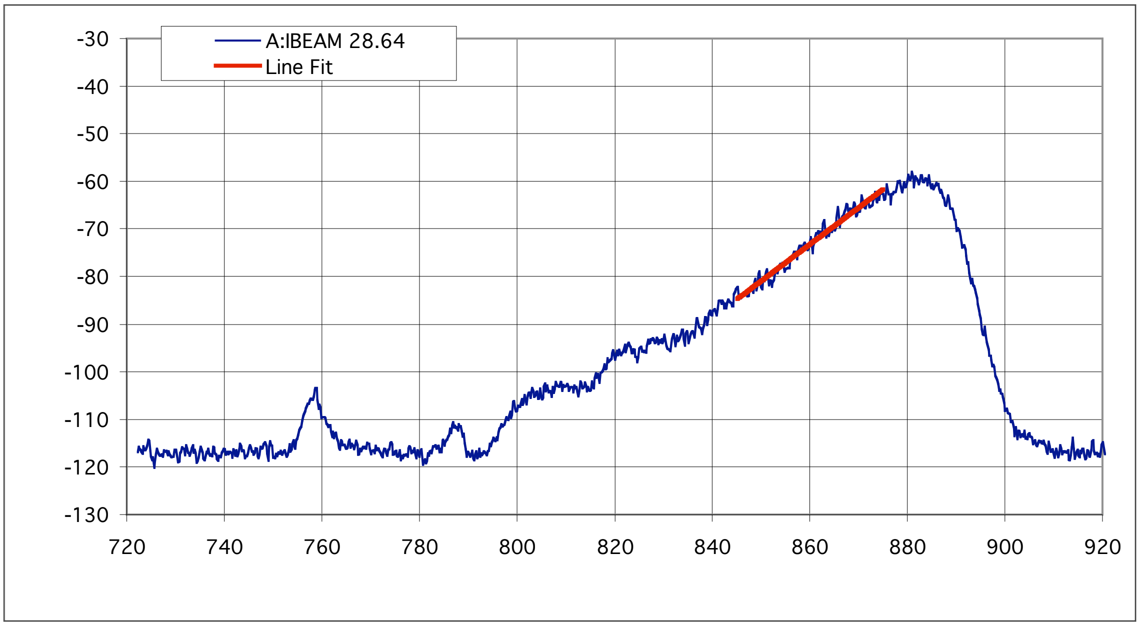


Figure 1: Stacking density distribution overlaid with exponential fit in the stacktail region.

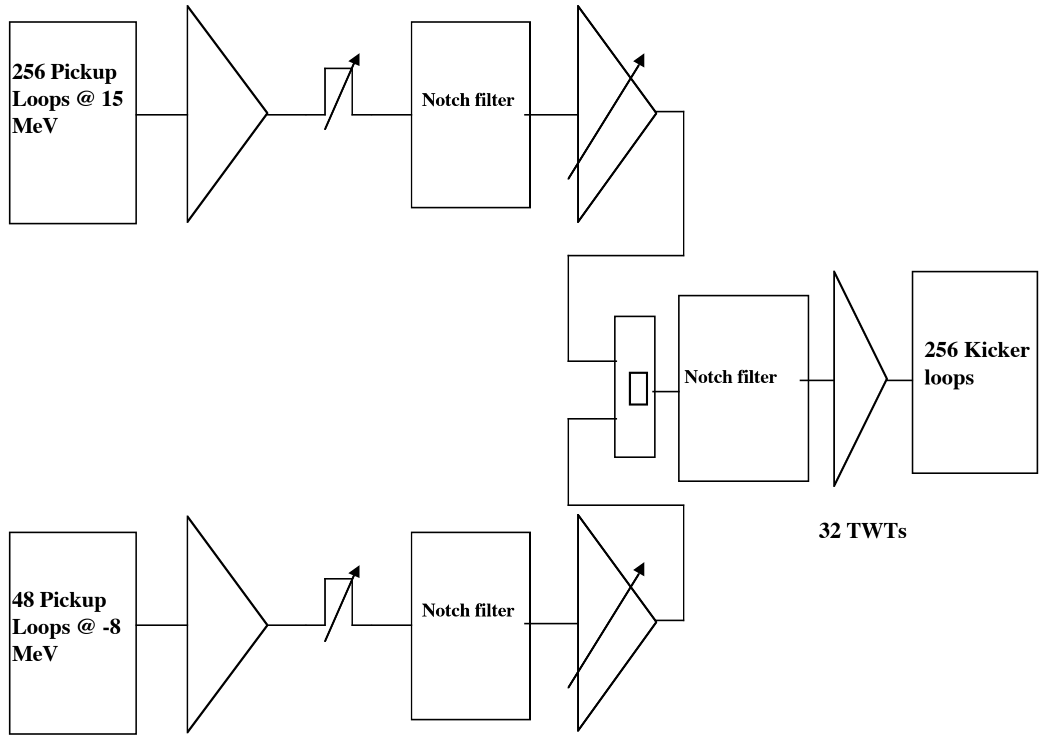


Figure 2: Schematic diagram of the stacktail cooling system. There are two sets of pickups at different energies, with independent gain and delay control. The system electronics has a total gain of 150 dB.

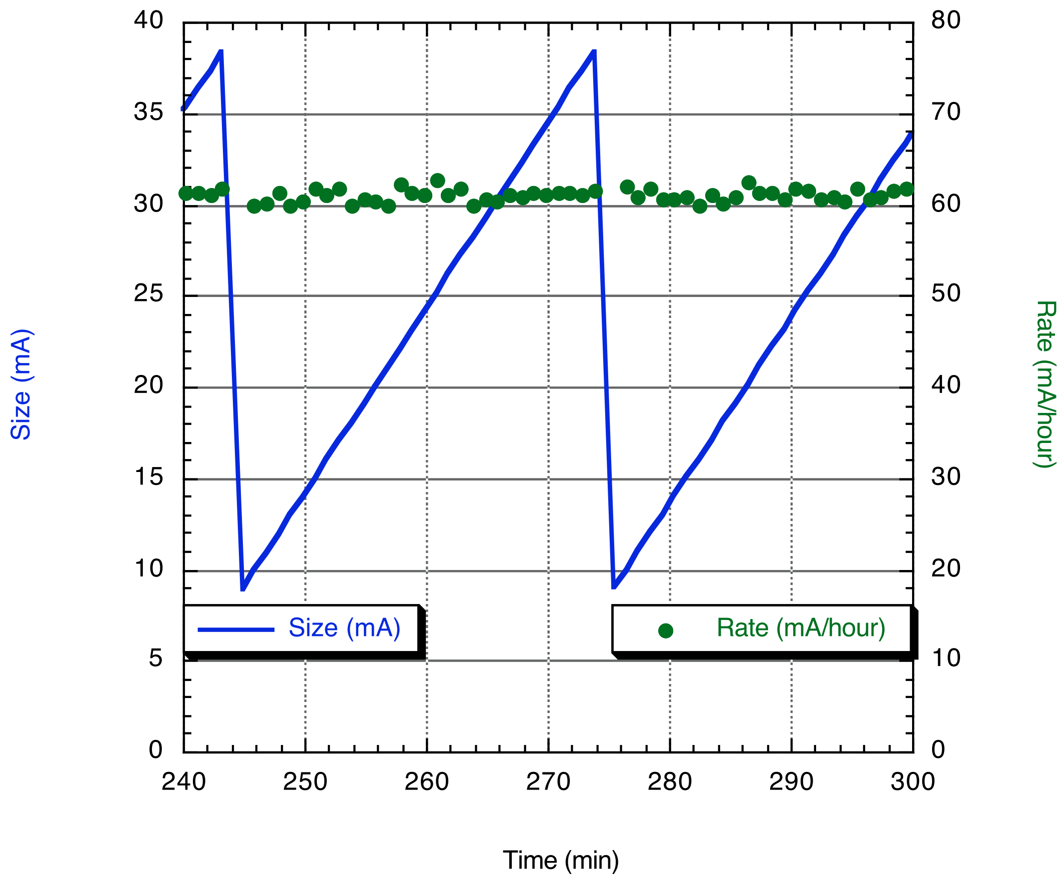


Figure 3: Stage 1 simulation results for one hour of stacking time. The horizontal axis is time (minutes), the left vertical axis has stack size (blue, mA), and the right vertical axis has stack rate (green, mA/hour). Transfers occur every 30 minutes of stacking time and take a total of 35 seconds to complete. On average, 30.5 mA are transferred every 15.583 minutes.

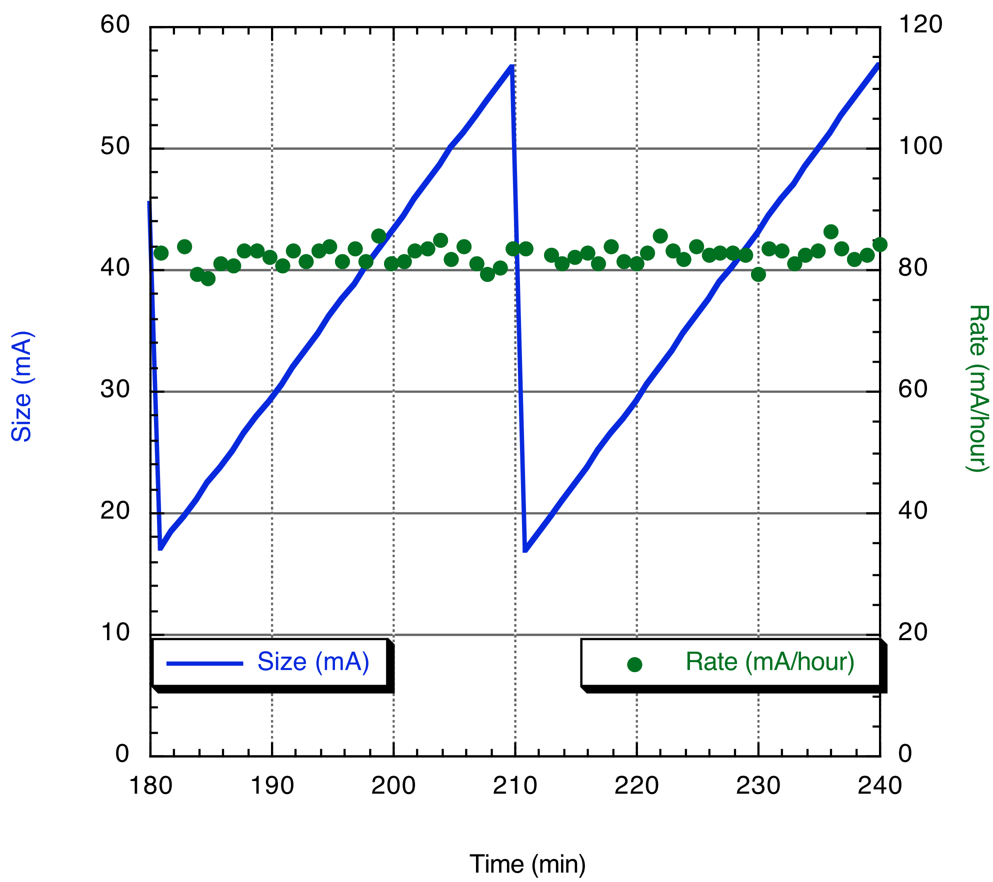


Figure 4: Stage 2 simulation results for one hour of stacking time. The horizontal axis is time (minutes), the left vertical axis has stack size (blue, mA), and the right vertical axis has stack rate (green, mA/hour). Transfers occur every 30 minutes of stacking time and take a total of 35 seconds to complete. On average, 41.2 mA are transferred every 30.583 minutes.

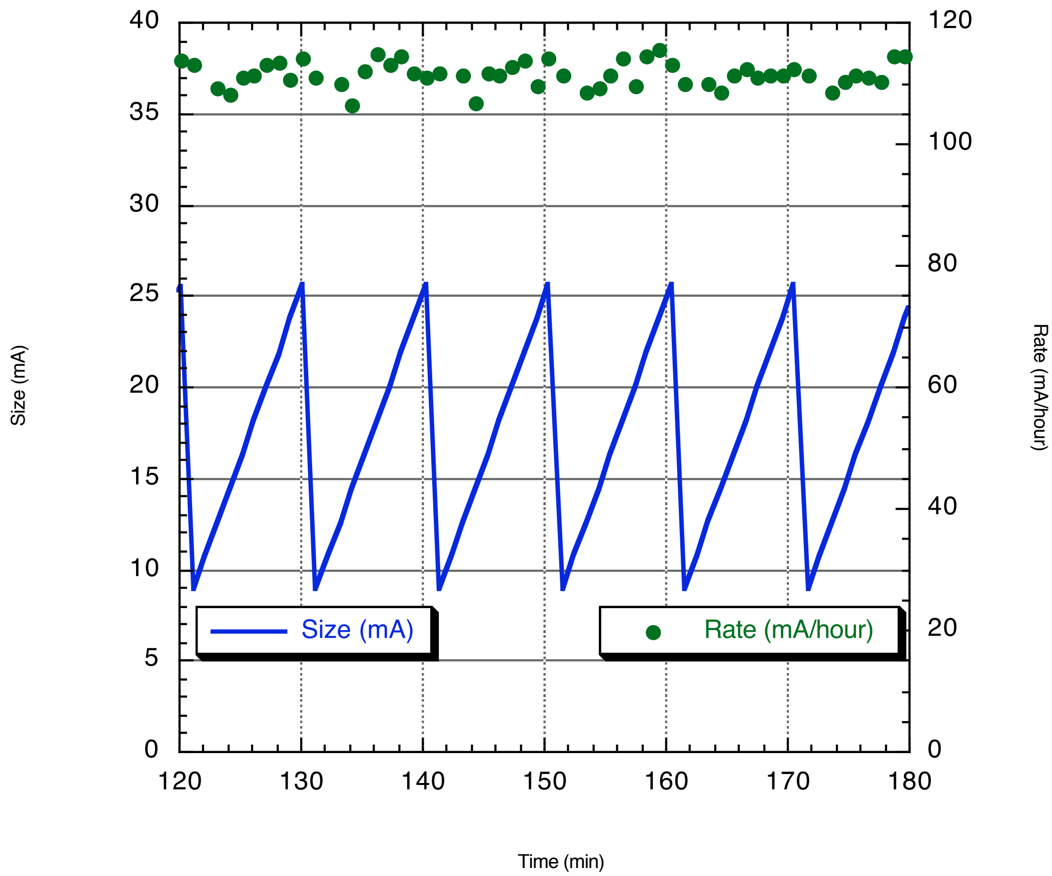


Figure 5: Stage 2 simulation results for one hour of stacking time with more frequent transfers. The horizontal axis is time (minutes), the left vertical axis has stack size (blue, mA), and the right vertical axis has stack rate (green, mA/hour). Transfers occur every 10 minutes of stacking time and take a total of 35 seconds to complete. On average, 18.2 mA are transferred every 10.583 minutes.

[1] D. McGinnis, DAVE'S NOTE ON PBAR PRODUCTION…NEED REFERENCE!
[2] V. Visjnic, "Fermilab Stochastic Cooling Code User's Guide", Pbar Note #498. The Fortran code was rewritten in C++ for these simulations.
[3] P. Derwent, "Pulse Evolution studies in the Accumulator", Pbar Note XXX (unpublished), 2003.
[4] Design Report, Tevatron I Project, September 1984.
[5] Known as the van Der Meer method, a description can be found in D. Edwards and M. Syphers, An Introduction to the Physics of High Energy Accelerators, J. Wiley & Sons, 1993.
[6] P. Derwent, "Accumulator 4-8 GHz Cooling Pickups Impedance Measurements", Pbar Note 624 (unpublished), 1999.