A Barrier Bucket Experiment for Accumulating De-bunched Beam in the AGS*

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Abstract

The AGS accumulates four batches of two bunches from the $1.5\mathrm{GeV}$ Booster at $7.5\mathrm{Hz}$. At an intensity of 6×10^{13} protons per AGS cycle, slow beam loss during the $400\mathrm{ms}$ accumulation time is important. The experiment demonstrated the principle of accumulating beam and storing it in an essentially debunched state by using barrier cavities. When the beam is de-bunched the peak-to-average current ratio drops by an order of magnitude. By using two barriers with time varying relative phase, any number of injections is possible, limited only by the momentum acceptance of the ring. In a test with beam, six injections of one bunch yielded 3×10^{13} protons in the AGS. The benefits of reduced space charge tune shift from lower peak current suggest that barrier cavities may be a path to higher AGS intensities.

1 PRINCIPLE OF OPERATION

A gap in an otherwise dc beam can be maintained with a barrier cavity [1, 2]. The cavity provides an impulse of longitudinal voltage to the beam, phased so as to repel beam as opposed to capturing it. If the duration of the impulse is much shorter than the revolution period the beam will be essentially debunched, but for the gap. The voltage impulse used here was a single sinewave of $2\mathrm{MHz}$ triggered at the revolution frequency of $345\mathrm{kHz}$. A peak voltage of $12\mathrm{kV}$ per cavity allowed for a momentum deviation $(p_{max}-p_{avg})/p_{avg} = 0.3\%$ in the stored beam.

Using two barriers opens the possibility of some useful manipulations with the beam, such as changing the size of the gap in the beam by rotating the phase of the trigger of one cavity with respect to the other. Processes of this sort place additional constraints on the required cavity voltage, much in the way that the bucket area of an acclerating bucket in a normal rf system depends on both the cavity voltage and the synchronous phase. More specifically, let f_0 be the ideal revolution frequency. Suppose that the phase at which a barrier is fired varies as $\phi_n = \pm n\delta f T_0$ where each barrier moves to compress the stored beam. Consider a particle with a frequency deviation with respect to the ring $f - f_0 \equiv \Delta f_r > 0$. This particle will move forward through the bunch and encounter a barrier moving toward it with frequency deviation $-\delta f < 0$. With respect to the moving barrier the particle has a frequency deviation of $\Delta f_b = \Delta f_r + \delta f > \Delta f_r$. For this particle to be reflected by the barrier, the height of the barrier must be such that it would reflect particles with a frequency deviation of Δf_b if it were stationary. After reflecting off the moving barrier the particle has a frequency deviation of $-\Delta f_r - 2\delta f$ which is larger in magnitude than Δf_r, consistent with adiabatic compression. For our experiment, the initial frequency spread was $|\Delta f_r| \lesssim 60\mathrm{Hz}$, corresponding to $2\sigma(p)/p \approx 0.14\%$ and the barrier velocity was $|\delta f| \lesssim 7.5\mathrm{Hz}$.

Even if the voltage is large enough to trap the beam, changing the relative phase of the two barriers creates the possibility of emittance growth. An integrable model of this process exists and can be used to obtain a general rule of thumb. Consider the one-dimensional motion of a particle trapped between two perfectly reflecting walls. The particle coordinate is given by x and the conjugate momentum is $p = \dot{x}$. One wall is fixed at $x = 0$ and the other is located at $x = \lambda(t)$. The Hamiltonian is $H = p^2/2 + U(x,\lambda)$ where $U(x,\lambda)$ is the potential due to the reflecting walls at $x = 0$ and $x = \lambda$. The action is given by $J = \lambda|p|/\pi$ and the angle θ is defined implicitly by $x = \lambda\hat{s}(\theta)$, where $\hat{s}(\theta)$ is periodic with period 2π and $\hat{s}(\theta) = |\theta|/\pi$ for $|\theta| < \pi$. A generator of Goldstein's third type [3, pg 384] $F_3(p,\theta,t) = -\lambda(t)p\hat{s}(\theta)$ connects the new and old coordinates. For time varying λ the Hamiltonian in the new coordinates is given by

$$H(J,\theta,t) = \frac{\pi^2}{2\lambda^2}\left(J^2 - 2Jf(\theta)\lambda\dot{\lambda}/\pi\right), \quad (1)$$

$$= \frac{\pi^2}{2\lambda^2}h(J,\theta,\lambda\dot{\lambda}), \quad (2)$$

where $f(\theta)$ is periodic with period 2π and $f(\theta) = \theta/\pi$ for $|\theta| < \pi$. If $\lambda\dot{\lambda}/\pi = \hat{J} = \mathrm{constant}$ then, since $dH/dt = \partial H/\partial t$, $h(J,\theta,\lambda\dot{\lambda}) = J^2 - 2J\hat{J}f(\theta)$ is a constant of the motion. To obtain an adiabaticity parameter consider an initial distribution of particles with $J = \bar{J}$ and distributed uniformly in θ. For this distribution $|h - \bar{J}^2| \le |2\bar{J}\hat{J}|$, and the particles are uniformly distributed in h. Let this distribution of particles evolve. In the worst case, complete phase mixing occurs and the particles fill out a uniform distribution in both h and θ. For $\bar{J} \ge |2\hat{J}|$ the final action distribution satisfies $|J - \bar{J}| \le |2\hat{J}|$, and the fractional emittance increase will be $\sim |\hat{J}|/\bar{J}$. For our experiment $|\hat{J}|/\bar{J} \sim |\delta f/\Delta f| \sim 0.1$.

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2 RF CONSIDERATIONS

Our experiment used two of the ten rf cavities in the AGS, configured for dedicated barrier cavity operation. The loading capacitors at the four gaps were reduced from 600 to $300\mathrm{pF}$.The rf feedback system was replaced with a broadband matching network at the grid of the $300\mathrm{kW}$ tetrode. The network matched a $50\mathrm{m}$ coax line to a $1\mathrm{kW}$ broadband power amplifier at the surface. The tetrode acts like a current source and cavity current is programmed to generate the barrier sinewave with a minimum of residual voltage between pulses. Approximately $100\mathrm{A}$ were needed to attain $3\mathrm{kV}$ on each of the 4 cavity gaps. To optimize the quality of the waveform, empirical fine tuning of the grid drive voltage pulse shape was used to compensate for nonlinearities at high power and spurious structure resonances. The basic shape of the current pulse can be found by modeling the cavity as a parallel RLC circuit [4]. The voltage across each circuit element is the same, and the total current through the cavity is the sum of the currents in each element,

$$I(t) = \frac{V(t)}{R} + \frac{1}{L}\int_0^t V(t')dt' + C\frac{dV(t)}{dt}. \qquad (3)$$

For the isolated sinewave used here

$$V(t) = \begin{cases} V_0 \sin(\omega t) & 0 < \omega t < 2\pi \\ 0 & \text{otherwise,} \end{cases} \qquad (4)$$

the required current is

$$I(t) = \frac{V_0 \sin(\omega t)}{R} + \frac{V_0}{\omega L} + V_0 \cos(\omega t)\left(\omega C - \frac{1}{\omega L}\right), \quad (5)$$

when $0 < \omega t < 2\pi$ and vanishes otherwise. Figure 1 shows the current and voltage waveforms from equation (5) for $Q = 5$ on resonance.

Some remarks on equation (5):

1. when the cavity is on resonance the current is in phase with the voltage,
2. when R is large (high Q), and the cavity is on resonance the current is just a square pulse,
3. the initial value of the current does not depend on R and the notion that one needs a low Q cavity capable of *resistively* supporting many Fourier modes does not apply.

Figure 2 shows a mountain range plot of a composite signal made by summing the gap voltage monitors from the two barrier cavities. One cavity remains fixed in phase while the other moves once around the entire revolution period and then moves out by $90°$ in $133\mathrm{ms}$, four times, to clear a fresh gap in the beam for subsequent injections.

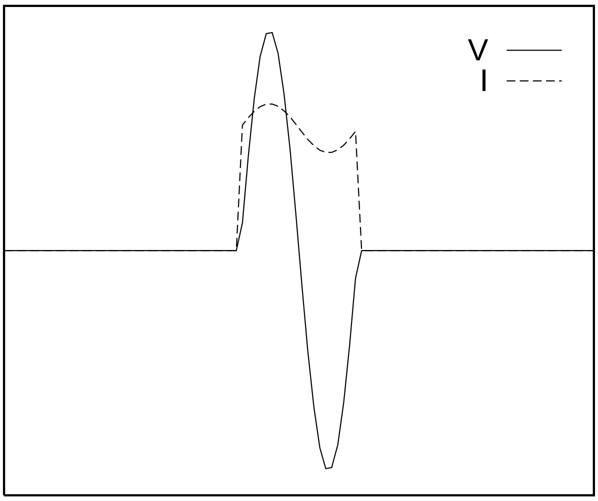

Figure 1: Barrier cavity voltage and current for one turn.

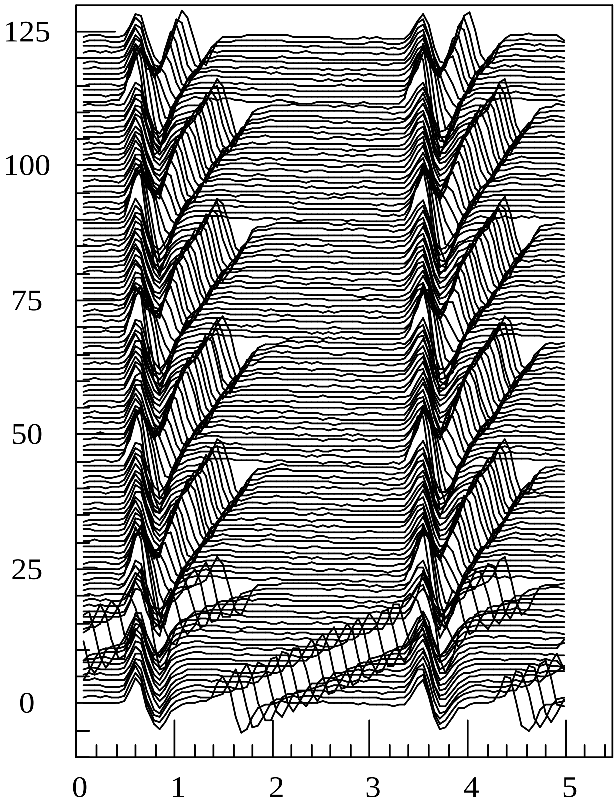

Figure 2: Mountain range display of the sum of the rf voltage from the two barrier cavities for 6 transfers. There are $6.0\mathrm{ms} = 2048\,\mathrm{turns}$ between traces and the horizontal axis is in μs, ($2.9\mu\mathrm{s}$ per turn).

3 RESULTS WITH BEAM

Barrier cavities enable two capabilities valuable for high intensity beams. Where space charge is important, the low peak current of the quasi-debunched beam can be advantageous. For accumulating beam, the ability to open space on the ring for multiple injections eliminates constraints on the

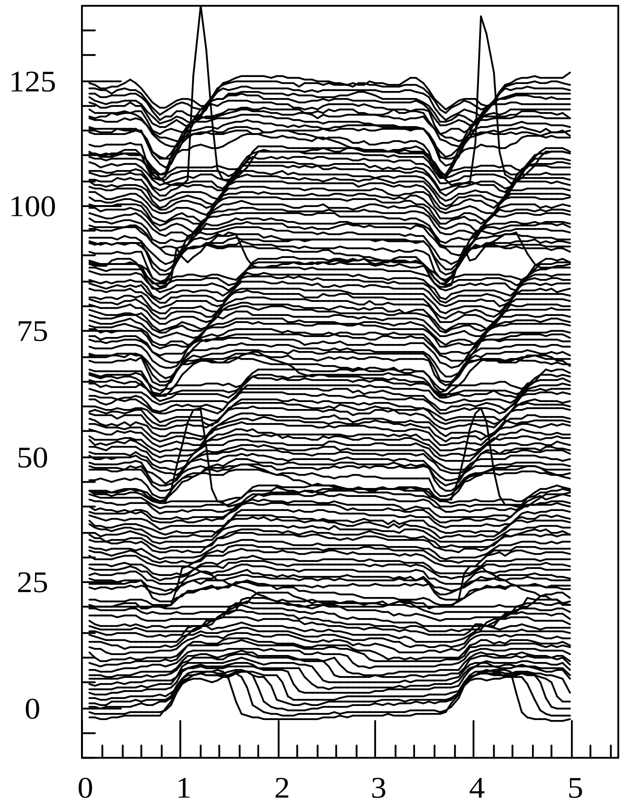

Figure 3: Mountain range display of beam current for 6 transfers. There are $6.0\mathrm{ms} = 2048$ turns between traces and the horizontal axis is in μs.

number of injections. Conservation of longitudinal emittance is possible but intentional emittance blow up is also an option. We have carried out three different operations with the two barrier cavities in the AGS. In the first run, we tested the adiabaticity condition by injecting one bunch of about $200\mathrm{ns}$ length with $2\sigma(p)/p = 0.14\%$ and stretching it out to $2.5\mu s$ in $200\mathrm{ms}$. The bunch was then compressed to close its original length in the same time. No quantitative measurement of emittance growth was made but because the beam remained trapped between the barriers, the momentum height of the barrier implies that the emittance no more than doubled.

In the second test, aimed at preserving emittance, multiple injections of one bunch were carried out. The first bunch was debunched as above. For subsequent bunches the movable cavity was rotated by $90°$ to compress the stored bunch and make space on the ring for the next bunch. After the next bunch was injected the second barrier was rotated further, in about $50\mathrm{ms}$, to equalize the momentum spread of the stored and freshly injected beam. The movable cavity was then switched off. A slow turn-off capability for the second cavity is planned. The injection process was repeated until a total of six Booster bunches were accumulated. During this process we encountered a fast instability occuring during the debunch of the first injection. The instability was characterized by large high frequency horizontal signal. During normal operations only vertical transverse instabilities are seen and the machine lattice was essentially the same as for normal operations. We suspect that the large high frequency horizontal signal was due to the longitudinal microwave instability coupling to transverse motion via dispersion. This conclusion is further supported by the fact that thresholds for fast longitudinal instabilities scale as $I_{peak}Z/n \propto \delta p^2$ while fast transverse instabilities scale as $I_{peak}Z_\perp \propto \delta p$. During adiabatic debunch $I_{peak} \propto \delta p$ so the threshold impedance for transverse instabilities does not change while the threshold impedance for longitudinal instabilities decreases linearly with δp. In any case, the instability was cured by increasing the momentum spread using a $20\mathrm{kV}$ high frequency cavity running at $h \approx 270$.

For the third mode of operation the emittance was intentionally allowed to grow with each injection. A controlled emittance blow up by a factor ot two to three is standard operation for the AGS at high intensity. The phasing program of the cavities is shown in Figure 2. No attempt was made to match momentum spread of the new and stored beam. A mountain range display of the resistive wall current monitor is shown in Figure 3. Six injections accumulated 3×10^{13} protons.

4 CONCLUSIONS

The barrier bucket experiment has demonstrated the capability of accumulating debunched beam and of repeatedly opening space on the ring for multiple injections, by using isolated sinewave voltages. By manipulating the relative phase between the two barrier cavitities the momentum spread and the peak current were controlled so as to preserve longitudinal emittance and, alternatively, to increase emittance. These capabilities could be exploited to increase the intensity of the AGS.

5 ACKNOWLEDGMENTS

The successful completion of these experiments required some rather nifty last-minute solutions to some rather formidable last-minute technical obstacles. The staff of the AGS rf group is commended for not taking "impossible" as a reason to give up trying.

6 REFERENCES

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