STOCHASTIC COOLING STUDIES IN RHIC[*]

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Abstract

Emittance growth due to Intra-Beam Scattering significantly reduces the heavy ion luminosity lifetime in RHIC. Stochastic cooling of the stored beam could improve things considerably by counteracting IBS and preventing particles from escaping the rf bucket [1]. High frequency bunched-beam stochastic cooling is especially challenging but observations of Schottky signals in the 4-8 GHz band indicate that conditions are favorable in RHIC [2] . We report here on measurements of the longitudinal beam transfer function carried out with a pickup/kicker pair on loan from FNAL TEVATRON. Results imply that for ions a coasting beam description is applicable and we outline some general features of a viable momentum cooling system for RHIC.

1 INTRODUCTION

When colliding gold (Au) ions in RHIC, the longitudinal emittance grows during the course of a store. The dominant mechanism is intrabeam scattering (IBS), which is the result of small angle Coulomb collisions between the ions in a single bunch. Figure 1 shows the evolution of the total and bunched intensities. The deuteron beam remains in the RF bucket with nearly constant intensity. For the gold beam both the bunched and total intensities decay with time. Figure 2 shows the evolution of the gold longitudinal profile. The traces have been scaled to a peak value of one. The initial peak current was 2.4 amperes and seven hours later it is 0.4 amperes. The net RF voltage per turn is given by[4]

$$V(\phi) = V_A \sin(\phi) + V_S \sin(7\phi) \qquad (1)$$

where ϕ is in units of RF phase for the accelerating cavities with $h = 360$, $V_A \approx 250$ kV is the voltage on the accelerating cavities, $V_S \approx 2.4$ MV is the voltage on the storage cavities, and the stable synchronous phase is $\phi = \pi$ since store is above transition ($\gamma > \gamma_T$). The FNAL pickup and kicker are installed in the yellow ring. During the gold-deuterium run we worked with the gold beam. During the polarized proton run we worked with protons.

2 COHERENT BEAM RESPONSE

Figure 3 compares the coherent response of gold to protons. The FNAL kicker [5] was driven with about 5 Watts of power at single frequencies, 5 GHz for gold, 4 GHz for protons. The longitudinal beam response was detected with the FNAL pickup. The difference in the noise floor is due
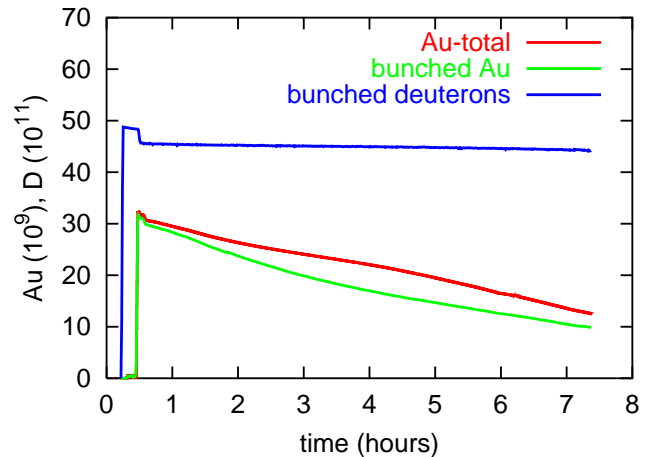

Figure 1: Evolution of the bunched and total intensity in gold (Au) and deuteron (D) beams. There are 55 bunches of each species and the bunched beam data have been smoothed to reduce noise.
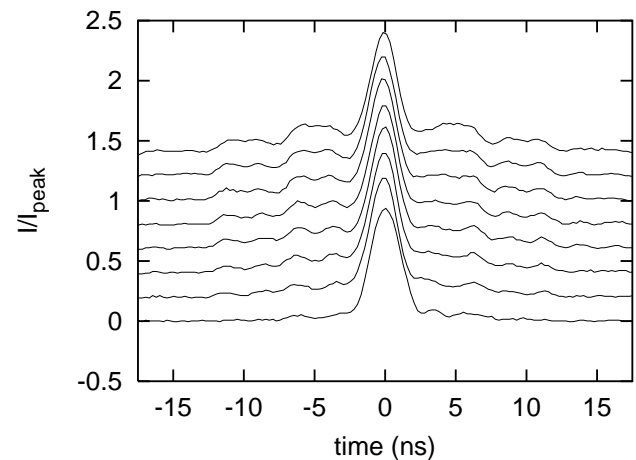

Figure 2: Evolution of the longitudinal profile for an Au bunch. The lowest trace was taken just after rebucketing and each trace above is an hour later.

to different gain in our experimental setups. In both cases the beam was driven at $f_{cent} - \Delta f$ with $\Delta f \approx 5$ kHz. The proton beam spectrum has two narrow lines that are absent in the gold signal. The proton beam shows a strong narrow band signal near the revolution line that was also observed in the Tevatron [3]. We suspect this signal is due to long lived coherent oscillations in the proton beam [6]. Since IBS rates for gold are about 10 times larger than those for protons, we expect gold coherence to diffuse away. The proton signal also shows a narrow line at $f_{cent} + \Delta f$, which is reminiscent of a bunched beam response. This feature

was not always present in the proton spectrum.

To analyze the data consider a coasting beam that has the same number of particles and the same momentum distribution as the bunched beam. The rms Schottky current for both cases satisfies

$$\left|\frac{I_s}{\bar{I}}\right|^2 = \frac{2P(f)\delta f}{N},\qquad(2)$$

where I_s denotes the rms Schottky current, $\bar{I}$ is the DC beam current, δf is the resolution bandwidth of the spectrum analyzer, $P(f)$ is the normalized frequency distribution, and N is the number of particles in the beam.

Now take the same coasting beam and apply a longitudinal voltage kick $\hat{V}\cos(\Omega t)$. Model the beam's frequency distribution as a Lorentzian so that

$$P(f) = \frac{\Delta f}{\pi}\frac{1}{(f-f_{cent})^2 + \Delta f^2}.$$

For drive frequencies near the center of the distribution, and neglecting collective effects, the ratio of the rms beam current at the drive frequency to the coasting beam current is

$$\left|\frac{I_c}{\bar{I}}\right| = \frac{q\hat{V}}{E_T\hat{\epsilon}^2}\frac{1}{2\sqrt{2}\pi f_{cent}T_0|\eta|},\qquad(3)$$

where $E_T = \gamma mc^2$ is the total energy per particle, q is the charge per particle, $T_0 \approx 12.8\mu s$ is the revolution period, and $\hat{\epsilon} = \Delta f/|\eta|f_{cent}$ is the fractional energy spread.
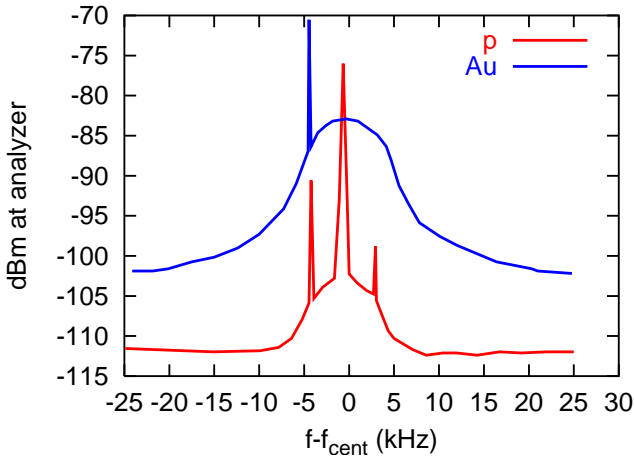
Figure 3: Power spectra of gold and proton beams driven by the FNAL kicker. The resolution bandwidth of the spectrum analyzer was 30 Hz.

Figure 4 shows the beam transfer function for protons taken with an HP8753 network analyzer using a 10 Hz intermediate frequency bandwidth. The curves are very similar to what one expects for coasting beams [8]. Fig 5 was taken during the same store with the same instrumental setup. When the coherent spike near the revolution line in Fig 5 is ignored, the calculated ratio of the coherent power
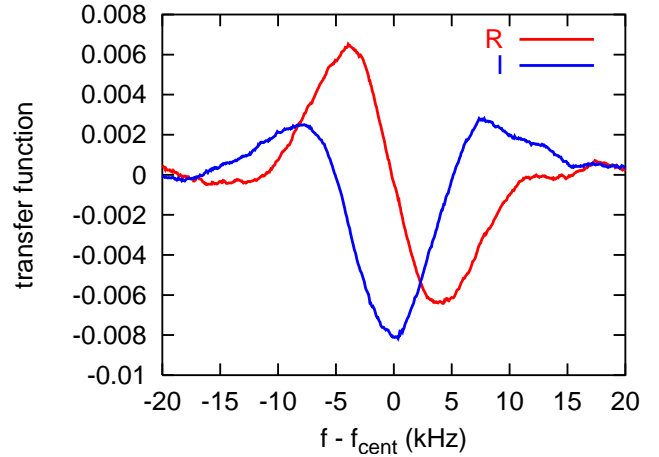
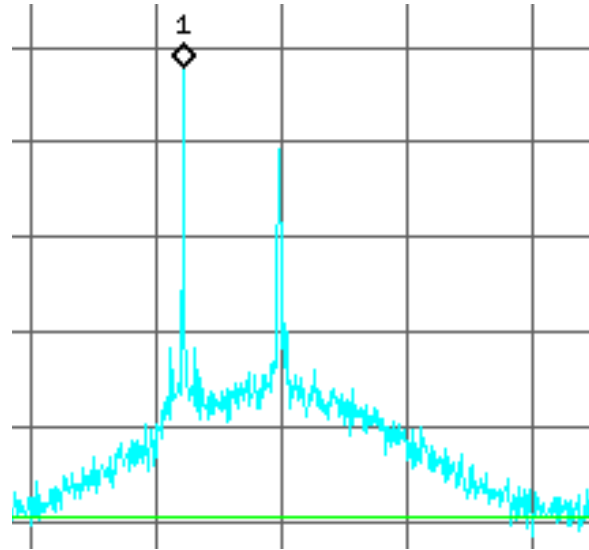Figure 4: Transfer function measurements for protons at 4.8 GHz.

Figure 5: Proton power spectrum when transfer function measurements were made. The center frequency is 4.8 GHz, the horizontal scale is 5 kHz/div, and the vertical scale is 5 dBm/div. There were $N = 10^{12}$ protons and $\gamma = 107$. The noise floor, denoted by the green line, is -86 dBm.

to the Schottky power agrees with the measurement within 1 dB. With both qualitative and quantitative agreement, we have confidence that a coasting beam theory, modified via the bunching factor of the beam, is reasonable for specifying a cooling system.

3 COOLING SYSTEM

Consider a cooling system of bandwidth W. Let N_b be the number of particles per bunch and let τ_b be the bunch length. The number of particles per independent sample of the cooling system is $N_s = N_b/2\tau_b W$ [10]. Consider the

rms energy spread $\sigma_e = E_T\sigma_p/p$; the cooling time is

$$\frac{\sigma_E}{\dot{\sigma}_E} \equiv \tau_E = \frac{N_s M}{f_0}, \tag{4}$$

where M is the mixing factor. For RHIC gold parameters with a 4-8 GHz cooling system and 10^9 particles per bunch we get $N_s M = 2.8 \times 10^8$ which in turn implies $\tau_E \approx 1$ hour. Detailed calculations [7] have shown that this cooling time will significantly improve the integrated luminosity.

Stochastic cooling for RHIC might better be refered to as stochastic confinement. The main goal is to keep particles in the RF bucket, not to reduce the rms momentum spread. Consider a single particle with no RF voltage [8]. In the absence of a cooling system the revolution frequency is constant and the beam current is given by

$$I(\theta, t) = \frac{\omega q}{2\pi} \sum_{k=-\infty}^{\infty} e^{jk[\omega t - \theta]}, \tag{5}$$

where ω is the particle's angular revolution frequency and $\theta = s/R$ is the machine azimuth. Suppose the cooling pickup is at azimuth θ_P and the kicker is at azimuth θ_K. We assume that the change in revolution frequency per turn satisfies $\delta\omega \ll \omega_0/k_{\max}$ where $\omega_0 = 2\pi/T_0$ and $k_{\max}$ is the largest revolution harmonic for which the cooling system has a significant gain. Then, the average rate at which the particle gains or losses energy is given by

$$\frac{dE}{dt} = \left(\frac{\omega q}{2\pi}\right)^2 \sum_{k=-\infty}^{\infty} e^{jk(\theta_K - \theta_P)} Z_T(k\omega)e^{-jk\omega T_d},$$
$$\tag{6}$$
$$= \left(\frac{\omega q}{2\pi}\right)^2 \sum_{k=-\infty}^{\infty} S_k,$$

where Z_T is the transfer impedance between the pickup and kicker and T_d is the delay. We do not plan on cutting a chord across the RHIC ring so the kicker will be placed upstream of the pickup and T_d is chosen so that $\theta_K - \theta_P - \omega_0 T_d = -2\pi$. Then

$$S_k = Z_T(k\omega)e^{-jk\Delta\omega T_d}, \tag{7}$$

where $\Delta\omega = \omega - \omega_0$. For the cooling system to be effective the transfer impedance must cause particles with $\omega > \omega_0$ to be accelerated, and particles with $\omega < \omega_0$ to be decellerated. Therefore, the real part of the transfer impedance must change sign at revolution lines. A natural candidate is a one turn delay notch filter [9] which has a transfer function $T(\Omega) = 1 - \exp(-j\Omega T_0)$. This will be implemented using a fiber optic delay line so there is no loss associated with the delayed signal. We apply one or two such filters in series. Also, we model the net transfer function of the pickup, kicker, and any phase shifters to be $T(\Omega) = jR(\Omega)$ where $R(\Omega)$ is real in the center of the cooling band and has small imaginary parts. Then,

$$S_k = jR(k\omega)\left(1 - e^{-jk\Delta\omega T_0}\right)^n e^{-jk\Delta\omega T_d}. \tag{8}$$

Results for $n = 1, 2$, with $T_d = 2T_0/3$ and $R(\Omega)$ constant between 4 and 8 GHz are shown in Figure 6. The horizontal scale is for fractional moment shifts with $|dp/p| \leq 0.2\%$. The largest voltages available can confine particles with $|dp/p| \leq 0.17\%$, where the filter with $k = 2$ has good gain.
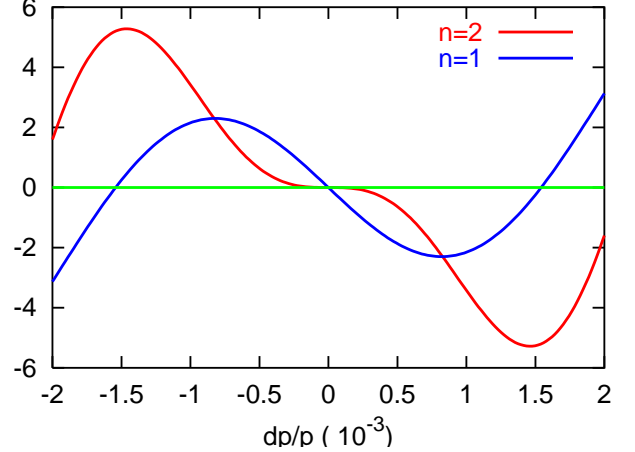

Figure 6: Plot of eq (6) with S_k from eq (8) for RHIC parameters. The vertical scale is in arbitrary units. For the horizontal scale $\Delta\omega/\omega_0 = -\eta dp/p$. For $n = 2$, the filter has good gain at the edge of the bucket.

4 ACKNOWLEDGEMENTS

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