STOCHASTIC COOLING STUDIES IN RHIC, II*

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Abstract

Intra-beam scattering (IBS) is unavoidable for highly charged heavy ions and causes emittance growth during the store for collision physics. A longitudinal bunched beam stochastic cooling system will confine the bunch within the RF bucket increasing the useful luminosity. We describe a series of measurements in RHIC that have been used to verify our understanding of the relevant physics and the cooling system architecture that is being prototyped.

INTRODUCTION

Over the course of several hours the longitudinal emittance of gold beams in RHIC grows due to IBS. A natural candidate to combat this growth is stochastic cooling [1, 2, 3]. With the relatively small number of ions per bunch ($\sim 10^9$), the number of degrees of freedom is manageable. Also, the coherent longitudinal structures, which have been problematic for proton bunch cooling [4, 5], quickly diffuse away [6]. There are still technical challenges, but they all appear solvable, and a longitudinal stochastic cooling system is under construction. In this note we present data which support the viability of cooling gold beams and outline some of the novel aspects of the cooling system design.

SCHOTTKY SIGNALS AND BEAM TRANSFER FUNCTIONS

Stochastic cooling requires information about the fine grained phase space distribution, and this information is contained within the Schottky signals. For longitudinal cooling the system must supply kicks which cause off momentum particles to diffuse toward the stable fixed point of the RF. With a longitudinal (as opposed to transverse) pickup, signals from more than one turn are required to encode the information with regard to particle momentum. Figure 1 shows the bunched beam Schottky spectra for gold beams. The dashed line shows the spectrum of the raw, longitudinal Schottky signal $S_0(t)$ measured with the FNAL planar array in sum mode [7]. Notice the strong peak at the revolution line near $f - f_0 = 143$ kHz. The resolution bandwidth of the analyzer was 1kHz and this peak is 25 dB above the Schottky band. There is about 4 times more power in this single line than in the rest of the data plotted. The revolution line near $f - f_0 = 65$ kHz shows no such enhancement, suggesting that the strong peak is an artifact of the filling pattern. We have verified that this is the case, as shown in Figure 2. A spectrum with a span of 29 MHz, a lower frequency of $f_0 = 1$ MHz, and a resolution bandwidth of 100 kHz, looks very similar to a spectrum starting at $f_0 = 5$ GHz with the same span and resolution bandwidth. This implies that the individual bunches all have the same shape, and that this shape contains sharp features. We conjecture that the sharp features are due to the rebucketing process, where we transfer the bunch from the accelerating RF system with harmonic number $h = 360$, into the storage RF system with $h = 2520 = 7 \times 360$. The accelerating system is left on after the process and there is always a little beam that spills out of the central storage bucket. Since these peaks occur at revolution lines they are, in principle, able to be removed using a one turn delay notch filter. The solid line in figure 1 shows the Schottky spectrum for such a signal. The processed signal is simply $S_1(t) = S_0(t) - S_0(t - T_0)$, where $T_0 \approx 12.8$ μs is the synchronous revolution period. The strong peak near $f - f_0 = 143$ kHz is suppressed by more than 30 dB and the power contained within it is less than 10% of the power in the frequency band 100 kHz $< f - f_0 < 200$ kHz.

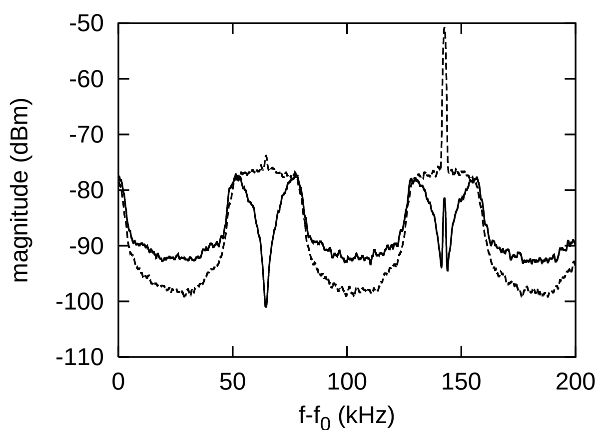

Figure 1: Gold Schottky spectra with (solid) and without (dashed) the one turn delay notch filter, $f_0 = 4.77$ GHz.

A high resolution spectrum for protons is shown in Figure 3. The FNAL kicker was driven at a constant frequency, offset by $+1$ kHz from the central revolution line. The direct response and the image response, 1 kHz below the revolution line, are visible. The smooth backround is the Schottky spectrum and a dense forest of narrow lines near the revolution line is present. We believe that the forest of lines in Figure 3 is due to small coherent structures [6]. Similar structures are apparent in gold beams just after rebucketing, but these dissipate after a few minutes.

The ability to suppress coherent lines is the first require-

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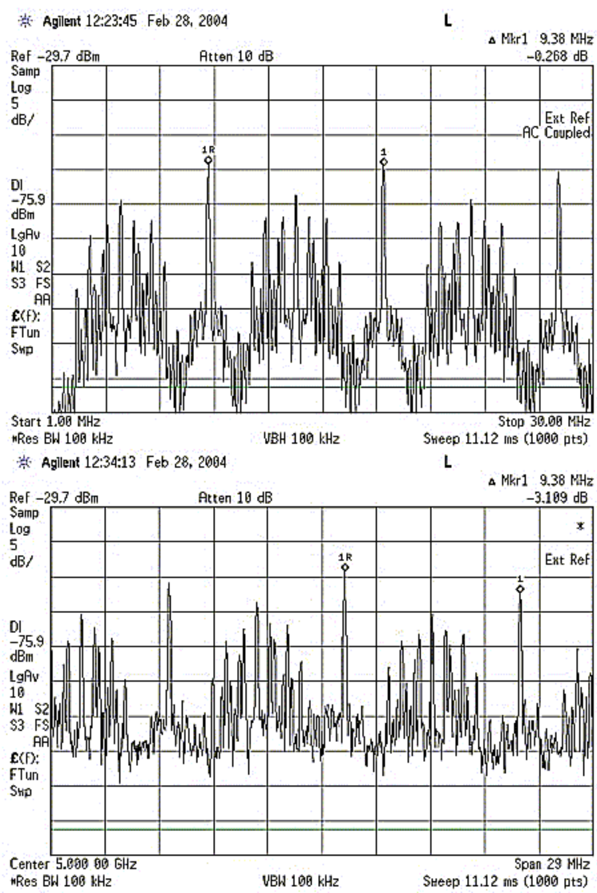

Figure 2: High and low frequency gold spectra with a span 29 MHz and a resolution bandwidth of 100 kHz. The generic features of the spectrum do not change between baseband and 5 GHz.

ment for the cooling system. For optimal cooling it is necessary that the feedback loop be stable for the optimal gain. For coasting beams this is described in [8]. The stability of bunched beam cooling was developed in [9]. Since these references are somewhat difficult to obtain, we will present an overview.

We use time t as measured in the lab frame as the evolutionary variable, ω is the angular revolution frequency for a given particle, ω_0 is the central value, and θ is the azimuth. The phase space distribution function for the beam is decomposed as

$$F(\theta,\omega,t) = F_0(\omega,t) + F_1(\omega,\theta,t) + F_s(\omega,\theta,t), \quad (1)$$

Where $F_0(\omega,t)$ is the average coarse grained phase space distribution, which evolves over the cooling time scale. The fine grained Schottky distribution corresponding to F_0 is F_s, and F_1 is a coarse grained perturbation.

Over short time scales we neglect the time dependence of F_0. Consider a coasting beam with average current I_0. The linearize Vlasov equation for F_1 is,

$$\frac{\partial F_1}{\partial t} + \omega\frac{\partial F_1}{\partial \theta} + \frac{q\eta\omega_0^2}{\beta^2 E_T} V_K(t)\delta_p(\theta-\theta_K)\frac{dF_0}{d\omega} = 0, \quad (2)$$

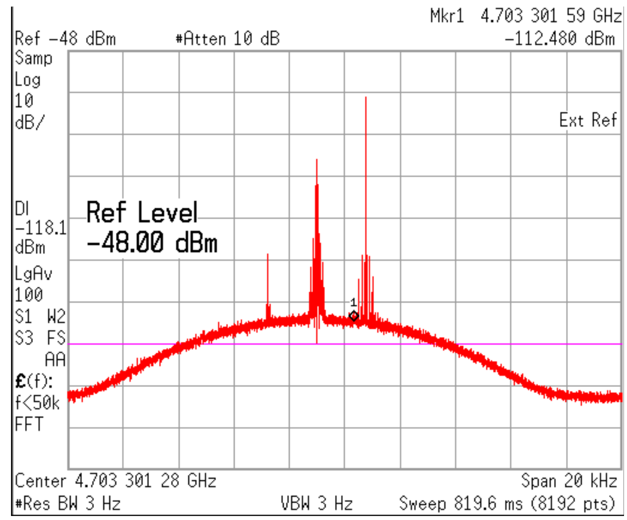

Figure 3: High resolution proton Schottky spectrum.

where the stochastic cooling kicker is located at azimuth θ_K, the *total* voltage across is the kicker is $V_K(t)$, $E_T = \gamma mc^2$ is the total energy of a synchronous particle, q is the charge per particle, $\delta_p(\theta)$ is the periodic delta function, η is the frequency slip factor, and $\beta = v/c$.

The kicker voltage depends on the current at the pickup, located at θ_P. Consider the response of a filter cooling system at a single frequency $\tilde{\omega}$ so that $V_K(t) = \hat{V}\exp(-i\tilde{\omega}t)$. Then

$$\hat{V} = Z^0(\tilde{\omega})[I_s(\tilde{\omega},\theta_P) + I_1(\tilde{\omega},\theta_P)], \quad (3)$$

where $Z^0(\omega)$ is the transfer impedance of the cooling system, $I_1(\tilde{\omega},\theta_P)$ is the perturbation current at the pickup, and similarly for $I_s(\tilde{\omega},\theta_P)$. Using

$$\delta_p(\theta) = \sum_{k=-\infty}^{\infty} \exp(ik\theta)/2\pi,$$

we may set $F_1(\tilde{\omega},\theta) = \sum_k f_k \exp(ik\theta)$, and solve for each f_k. Setting $Y_b = I_0 q\eta/(2\pi\beta^2 E_T)$, the perubation current is

$$\begin{aligned} I_1(\tilde{\omega},\theta) &= Y_b\hat{V}\sum_k \omega_0^2 \int d\omega \frac{e^{ik(\theta-\theta_K)}}{0^+ + i(k\omega-\tilde{\omega})}\frac{dF_0}{d\omega} \quad (4) \\ &= Y_b\hat{V}\mathrm{BTF}(\theta,\omega) \quad (5) \end{aligned}$$

where $\int d\omega F_0 = 1$ is the normalization for the unperturbed distribution and 0^+ is the limit through positive values. The total voltage is related to the Schottky current by

$$\hat{V} = V_s^0/[1 - Z^0(\tilde{\omega})Y_b\mathrm{BTF}(\theta_P,\tilde{\omega})], \quad (6)$$

where $V_s^0 = Z^0(\tilde{\omega})I_s(\tilde{\omega},\theta_P)$ is the Schottky voltage one would obtain without including the coherent response. If one breaks the cooling feedback loop and inserts a spectrum analyzer, the measured value of the output to input scattering parameter is given by $S_{21} = Z^0(\tilde{\omega})Y_b\mathrm{BTF}(\theta_P,\tilde{\omega})$.

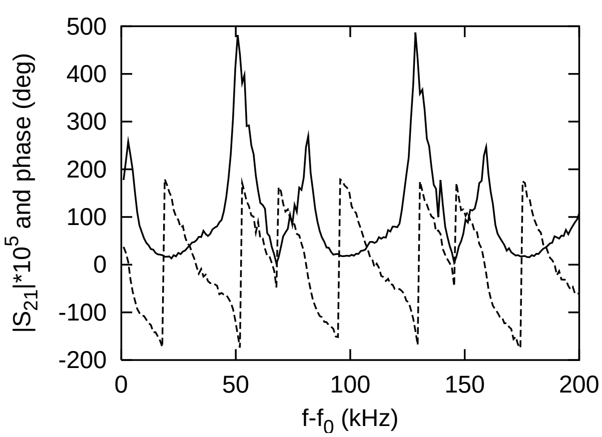

Figure 4: Gold beam scattering parameter with the one turn delay filter, $f_0 = 4.76$ GHz. S_{21} has been multiplied by 10^5.

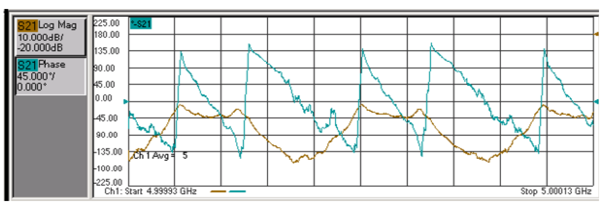

Figure 5: Gold beam scattering parameter without the one turn delay filter, $f_0 = 5.00$ GHz. The magnitude satisfies $|S_{21}| < 10^{-3}$

Measured scattering parameters with and without the one turn delay notch filter are shown in Figures 4 and 5, respectively. The pickup and kicker were both planar arrays in sum mode, supplied by FNAL. The total gain in the feedback loop was quite small with $|S_{21}| < 5 \times 10^{-3}$. For optimal cooling in coasting beams one requires $|S_{21}| \sim 1$ within the Schottky band, and gain as a function of frequency can be severely distorted. The practical implications of this are under study.

COOLING SYSTEM

The cooling system is designed to operate between 4 and 8 GHz and a few kV, rms are needed for optimal cooling [10]. Systems based on traveling wave tube amplifiers and wide band kickers would be quite expensive, so we have taken an alernate approach that makes use of the bunched structure of the beam [11]. At store, the RHIC bunches are $\tau_b = 5$ ns long and are spaced by 100 ns for a 120 bunch fill pattern. The voltage needs to have a prescribed value only when the bunch is traversing the kicker. When there is no beam in the kicker the voltage can have any value. Therefore we can take a kicker voltage of the form

$$V_K(t) = \sum_{k=20}^{40} A_k(t)\cos(k\omega_b t) + B_k(t)\sin(k\omega_b t), \quad (7)$$

where $\omega_b = 2\pi/\tau_b$. The amplitudes $A_k(t)$ and $B_k(t)$ vary smoothly between bunches. Using appropriate timing, each of the terms in the sum can be generated at a different physical location. Therefore, we may consider a system of 21 cavities with resonant frequencies $4.0, 4.2, 4.4, \ldots 8.0$ GHz. Since A_k is uncorrelated from one bunch to the next, the amplitude filling time of the cavity needs to be smaller that 100 ns. A prototype 4 cell cavity with $R/Q \approx 100\Omega$, $Q = 1000$ amd $f_r = 8$ GHz has been constructed and tested to a voltage of 1.6 kV with no evidence of multi-pacting or other problems.

To create the low level drive we start with the notch filtered signal $S_1(t)$. This signal is composed of noise like bursts of duration τ_b, separated by 100 ns. Consider the signal

$$S_2(t) = \sum_{k=0}^{19} S_1(t - k\tau_b).$$

The spectrum of S_2 is composed of bands spaced by 200 MHz and the width of each band is ≈ 20 MHz. An additional filter of width 100 MHz rejects the out of band signals for a given cavity.

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