STOCHASTIC COOLING IN RHIC

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Abstract

After the success of longitudinal stochastic cooling of bunched heavy ion beam in RHIC, transverse stochastic cooling in the vertical plane of Yellow ring was installed and is being commissioned with proton beam. This report presents the status of the effort and gives an estimate, based on simulation, of the RHIC luminosity with stochastic cooling in all planes.

INTRODUCTION

RHIC heavy ion beams are subject to Intra-Beam Scattering (IBS) that causes an emittance growth in all three phase space planes. With initial emittances about 10π mm-mrad in the transverse planes and 1 eVs/nucleon in the longitudinal plane the growth time during store for physics production at 100 GeV/nucleon is about 60 minutes. Specific luminosity decreases during the store and limits useful luminosity lifetime to about 5 hours. Furthermore, IBS causes de-bunching, and coasting beam must be continuously removed from the abort gap. The only way to increase integrated luminosity is to counteract IBS with cooling during RHIC stores.

We have developed a stochastic cooling system for this purpose. Bunched beam presents a particular challenge for stochastic cooling because of the high particle density and the presence of strong coherent signals that compete with the Schottky signals. Some new technical solutions have been developed for this cooling system to meet these challenges. For example, passive analog filtering is used to reduce the pickup signal electrical dynamic range, and signal processing with linear fiber optics networks realize a system bandwidth of 5-9 GHz. The system cost is reduced by an energy averaging technique that exploits the bunched nature of the beam. Technical details of the system are described here along with results from operating the first plane of cooling gold beam in physics runs of FY07 and FY08. Cooling equipment for the transverse planes is under construction.

COOLING RATE

To effectively counteract IBS the cooling rate must exceed the IBS growth rate, which in RHIC is about 1 hour [1,2]. The stochastic cooling rate is determined by the number of particles in the beam, the system bandwidth, and the process called mixing. The simple coasting beam formula, $\tau = \left({}^{N_{eff}}\!/_{B} \right) M$, gives a correct value of the cooling time for bunched beam[3,4] if N_{eff} is interpreted as the number particles that would be in a coasting beam, that had the same density as the local density in the bunched beam. B is the cooling system bandwidth, and M is the mixing factor, measured in machine turns. Mixing characterizes the process of loss of correlations (called good mixing) in the particle distribution between when correction kicks are applied and when the beam is next sampled. Mixing comes about because of frequency slip driven by momentum spread in the beam. In the general case bunched beam cooling analysis is more complex because synchrotron motion imposes correlations that do not dissipate from simple mixing. However, RHIC beam is stored in full buckets and synchrotron frequency spread provides the equivalent mixing [5]. With 10^9 particles in 5 ns long bunches N_{eff} = 2.5 x10^{12}, and mixing occurs in four turns.

The free parameter is the system bandwidth. It is limited by two major factors: the kicker technology, and the time delay between the pickup and kicker. The cooling system is a feedback loop and the loop will be stable only if the real part of the open-loop gain function is negative. Mixing between the pickup and kicker (called bad mixing) adds phase shift to the loop that is proportional to frequency. We have chosen 5-8 GHz for the transverse cooling systems band and 6-9 GHz for the longitudinal. The resulting cooling time is about 50 minutes to prevent IBS-driven emittance growth.

PICKUPS

The pickups of a stochastic cooling system sense the Schottky signals from the beam. In RHIC the Schottky signals are very strong and signal-to-noise ratio is high. The Schottky spectral power density is the incoherent sum of the power from each particle in the beam, $P = N_{ions} \frac{1}{2} \left(2Qef_0\right)^2 R_{pu}$, where Q is the charges per ion, f_0 is revolution frequency, and R_{pu} is the pickup impedance. Compared to protons with Q = 1, the ion signal delivers Q times the power for the same number of charges in the ring ($QN_{ions}=N_{protons}$). This is 19 dB stronger for gold ions with Q = 79. Heretofore we have used planar array pickup devices built for stochastic cooling tests in the Tevatron[6] which were donated to the RHIC project. These devices have an impedance of ~50 Ohms in the longitudinal mode and yield a Schottky power some 40 dB above the thermal noise floor at room temperature. A much simpler pickup based on commercial double ridge waveguide (WRD-475) –to-coax adapters is being considered for longitudinal pickups in the future.

Coherent Lines in the Schottky Spectra

The main difficulty in bunched beam stochastic cooling is coherent components mixed with the Schottky signals. Fig. 1 shows a spectrum that contains both a Schottky component and a coherent component. The strong coherent components can dominate the power of the signal and would waste kicker power. Moreover, the coherent components drive nonlinearities in the amplifier chain and generate intermodulation distortion (IMD). The

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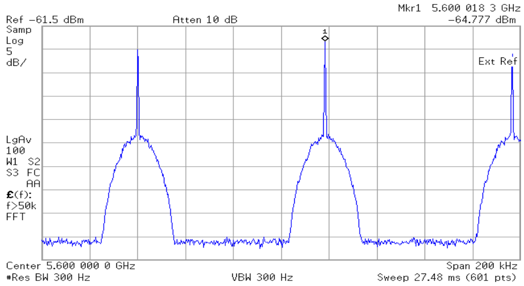

Figure 1: Schottky spectrum with coherent lines.

coherent components drive nonlinearities in the amplifier chain and generate intermodulation distortion (IMD). The most harmful form of IMD is third order products, such as, $2f_1$-f_2. If f_1 and f_2 are from the same or even adjacent Schottky bands then distortion products are also within the band and cannot be removed by downstream filtering.

The strength of the coherent components in the operating frequency range of the cooling system is greater than one would expect from a Gaussian bunch shape with $\sigma = 1$ ns. These components were the main obstacle in previous studies of bunched beam stochastic cooling in proton colliders[7,8]. Although it was recognized early on [9] that stochastic cooling would be beneficial for RHIC the issue of coherent components had to be resolved before construction of a complete system commenced.

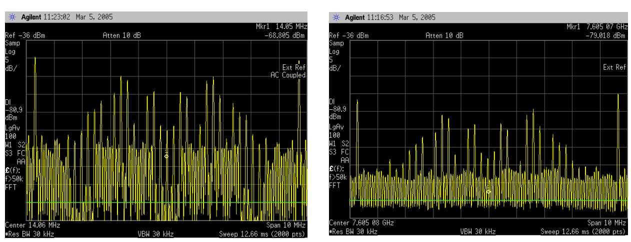

Figure 2: Beam spectra at 10 MHz and 7 GHz. The structure of the spectra are identical.

For ions in RHIC the situation is significantly different from protons. First, IBS provides some “dissipation” within the bunch and acts to dampen hot-spots and soliton-like[10] sub-structures that generate very high frequency Fourier strength. We observe significant diminution of the coherent components during the first half-hour of a store. Second, the RHIC storage rf system uses two frequencies, 28 and 200 MHz, to contain the bunches. This produces a bunch shape with structure that is far from Gaussian and the Fourier strength at 8 GHz is not small compared to the Schottky signal. Fig. 2 compares spectra at 10 MHz and 7.5 GHz. The detailed structure of the spectra reflect the complicated bunch filling pattern, with an abort gap and missing bunches on a basic harmonic 120 pattern. The same structure appears at 7.5 GHz, indicating that the coherent lines are a manifestation of a bunch shape common to all bunches.

To prevent IMD the pickup signal is filtered with a passive traversal filter shown in Fig. 3 and implemented with coax cables. The basic interval of the filter is 5 ns to match the bunch length. Segment lengths are adjusted to sub-ps resolution with mechanical coaxial trombones. The

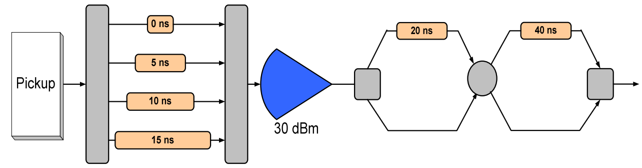

Figure 3: Traversal filter at the pickup, made from coaxial cable

filter reduces the peak voltage before the first high gain stage and again before it is transmitted to the kicker. By repeating the 5 ns bunch 16 times the filter creates an 80 ns pulse to drive the kicker (see below). The frequency domain response is the series of lines separated by 200 MHz (1/5ns) is shown in Fig. 4 with the time domain response.

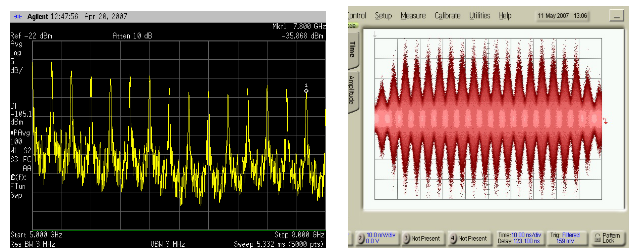

Figure 4: Output of traversal filter. Left is frequency domain, right is time domain

Pickup to Kicker Delay

For the transverse planes the signal is sent from pickup to kicker via an analog fiber optic link; for the longitudinal systems it is sent with a microwave link [11]. The fiber optic link is simpler and less expensive than the microwave link but it produces too much delay for the longitudinal cooling system. Longitudinal cooling requires a cooling filter that reduces the phase margin of the feedback loop. The delay with fiber is long for two reasons. The speed of light in fiber is 0.7c and the route of the fiber stays within the tunnel. With the pickup at the 12 o’clock ring location and the kicker at 4 o’clock, the fiber travels opposite to the beam from 4 o’clock to 12 o’clock for 1/3 the ring circumference while the beam travels 2/3 the ring circumference. Longitudinal cooling that has been done so far has used the fiber approach, but at the cost of cooling performance. To keep the system stable at the highest frequency a special cooling filter [12] was used that reduced the cooling at the center of the bunch in favor of extending the reach to the edge of the bunch. This is an appropriate strategy for preventing IBS-driven de-bunching but is not viable when simultaneous cooling in transverse and longitudinal is desired.

Fiber optic links do not have high dynamic range. The typical noise figure is ≥ 40 dB. We have found a significant difference among the various technologies of optical modulation. Superior performance is given by Electro-Absorption Modulation [13], while direct modulation of the laser diode produces excessive amplitude dependant chirp that leads to signal distortion because of dispersion in the fiber. External modulation with a Mach-Zender interferometer is not appropriate for placement in the tunnel at the pickup.

The microwave link allows us to cut the chord and reduce the pickup to kicker delay from 2/3 turn to 1/6. The link is an adaptation of a commercial product for point-to-point wireless links for Gigabit Ethernet [14]. It operates in the 70 GHz E-band with synchronous up and down conversions at the transmitter and receivers. The local oscillator is distributed to both ends by fiber optics in the tunnel. The transmitters are located at 2 o'clock on the ring and the receiver for the clockwise (Blue) ring is one sector away at 4 o'clock, while for the counterclockwise (Yellow) ring the receiver is at 12 o'clock. Signal arrival precedes beam arrival by 200 ns. Fluctuations and drifts in the signal propagation time must be compensated. An out-of-band CW pilot tone is injected at the transmitter and variations in the phase of the received pilot tone are compensated with a feedback loop. The same corrections that stabilize the pilot tone are applied to the signals sent to the kicker. Fig. 5 is a block diagram of the concept.

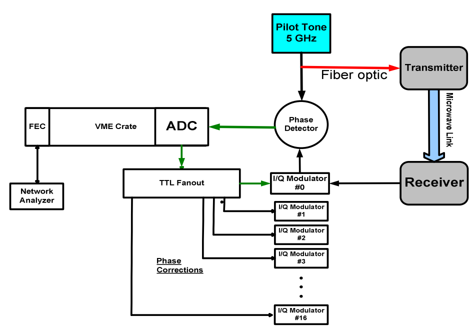

Figure 5: Pilot tone feedback stabilization for the microwave link

SIGNAL PROCESSING

Both longitudinal and transverse cooling systems use filters based on delays of one turn (=12.8 μs), albeit with different topologies and function.

Longitudinal Cooling Filter

For longitudinal the filter extracts the energy error from deviations of the revolution frequency. Fig. 6 shows how the filter is implemented. The signal from the previous turn is subtracted from the present. A particle with exactly the right revolution frequency would get zero kick. The frequencies that correspond to zero kick appear as notches in frequency response of the filter. The notches occur at all the revolution harmonics of the beam, that is, every 78 kHz. The delay must be correct to within a fraction of 1 ps. This is accomplished by periodically (10 minutes) monitoring the notch frequencies and making corrections via the motorized delay. Furthermore, the delay must be the same at all frequencies between 5 and 9 GHz. This is achieved by implementing the filter in fiber optics rendering the dispersion negligible. The amplitude balance is frequency independent because it is controlled by a light attenuator. Finally, balanced PIN photodiodes [15] that are optimized for common mode rejection are used to subtract the signals. Fig. 7 shows a spectrum with the notches.

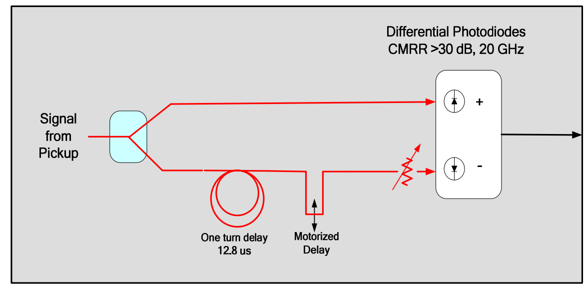

Figure 6: Notch filter for longitudinal cooling

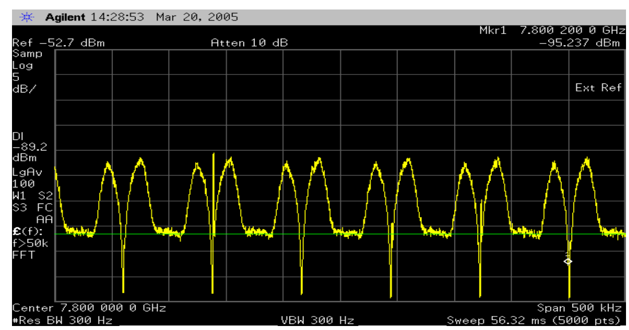

Figure 7: Longitudinal Schottky spectrum filtered by cooling filter with notches

Transverse Common Mode Filter

For transverse cooling the pickup works in the difference mode to detect the position offset of a particle. The kicker is located at a position of 90 degrees betatron phase advance with respect to the kicker. The filter removes the common mode component. The common mode can come from phase imbalance or non-zero closed orbit at the pickup. The realization of this filter is shown in Fig. 8. The delayed branch is replaced with an IIR loop

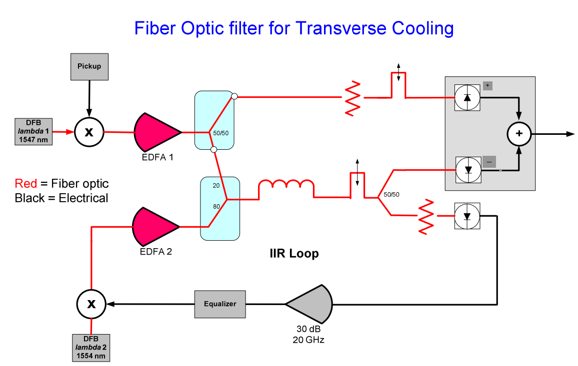

Figure 8: Filter with IIR loop for transverse cooling to remove common mode signal

to increase the Q of its response. This topology was developed at Fermilab for the Tevatron [16]. Here the IIR loop is a hybrid of fiber optic and electrical components. Using electrical gain the IIR loop means that the wavelength of the light in that loop can be different from the direct signal avoiding optical coherent interference. Fig. 9. shows the frequency response. The difference from the longitudinal filter is the phase does not change when switching below and above the revolution frequency.

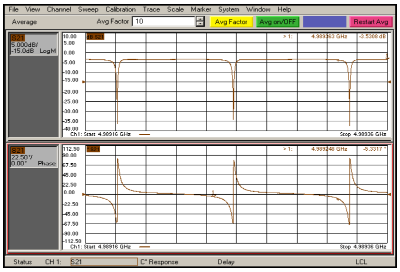

Figure 9: Frequency response of filter for transverse.

I/Q Modulators and BTF

The kicker comprises 16 channels. Each channel is adjusted independently by setting I and Q values in linear modulators. The optimal values are found by switching in a transfer switch and measuring the complete system transfer function, including the beam response (BTF) with an Agilent PNA 8362A. The measured gain is corrected for the duty cycle of the bunched beam. The operating settings are checked by closing the cooling loop on that channel and observing signal suppression in the Schottky spectrum. Fig. 10 shows 5 dB signal suppression at 7.8 GHz. The system is only marginally stable at the edge of Schottky band because the microwave link was not yet in operation. During a store, slow drifts of the optimal settings are periodically corrected. Every 10 minutes the network analyzer cycles through the 16 channels, taking one at a time off line to measure the transfer function and send updates to the I/Q modulators. The main sources of drift are: heating of kicker, ambient temperature affects on the fiber optic delays, and beam response function changes due to cooling.

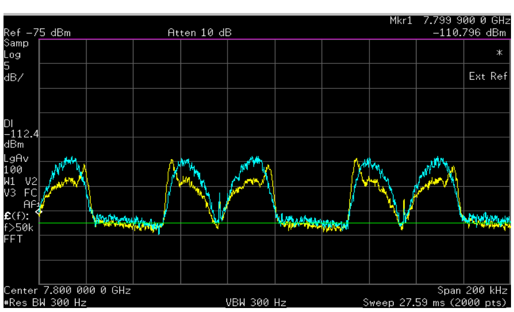

Figure 10: Signal suppression in the longitudinal.

NARROWBAND KICKERS

An optimized cooling system will correct 1/M of the measured error each turn. At 100 GeV/nucleon gold ions with $\Delta P/P = \pm 0.3 \times 10^{-3}$ requires a 3 kV_{peak} kicker voltage across the 6 to 9 GHz band. With a 50 Ohm kicker this would require 90 kW peak power. We take advantage of the bunched beam to implement an energy averaging scheme based on narrowband, high Q kicker cavities. The time between bunches is used to fill the cavities with up to 20 Watts from solid state amplifiers. The traversal filter described above generates drive power that matches the filling time of the cavities. Sixteen cavities span the bandwidth in 200 MHz intervals. Because the bunch length is 5 ns a Fourier series of 200 MHz harmonics is complete [17]. The kickers are two or four-cell TM_{110} and TM_{120} cavities operated in π mode for longitudinal and transverse respectively. The maximum frequency is limited to 9 GHz by the beam bore of 20 mm. The cavities are split on the vertical median plane and open when not in operation to provide greater clear aperture. Each cavity has two ports, one for power input and one for loading, the loading port sets the bandwidth to match the bunch spacing. The loads are external to the vacuum so that the cooling requirement is minimized. The loading ports are also used to observe the beam induced voltage on the kicker which facilitates set up of system timing. Fig. 11 shows a selection of kicker cavities.

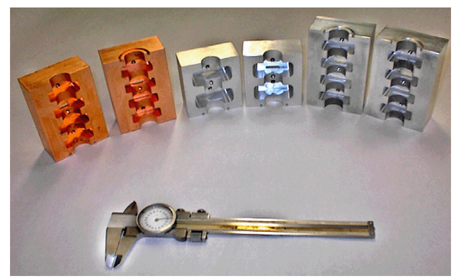

Figure 11: Three kicker cavities. Left is copper plated aluminum.

RESULTS WITH BEAM

Longitudinal cooling was used for gold ions in the Yellow ring in the FY07 and FY08 runs. IBS in the longitudinal plane was overcome by cooling [18,19], and furthermore, the longitudinal emittance was reduced. Fig. 12 shows the results of an initial test where only 50 of the 100 bunches were cooled. The peak current of the cooled bunches became significantly higher than the un-cooled. Cooling also prevented de-bunching so that the dominant loss during the stores was beam burn-off due to collisions. The gain in integrated luminosity for one plane of cooling was approximately 15%. The beam captured in the adjacent buckets of the 200 MHz storage rf system is also cooled. These unwanted satellite bunches will not occur when the RHIC rf system is augmented with a new 56 MHz (h=720) superconducting cavity [20].

LUMINOSITY PROJECTIONS

To gauge the benefit of installing additional cooling in the transverse plans the cooling process has been analyzed with simulations. Complete simulation is only practical if an accurate scaling formulation is applied to keep the number of macroparticles manageable. Recall that the cooling time is proportional to the number of particles in the beam. One can scale down the number of particles for the simulation and scale up the resulting cooling time. IBS kicks are scaled to the local particle density and

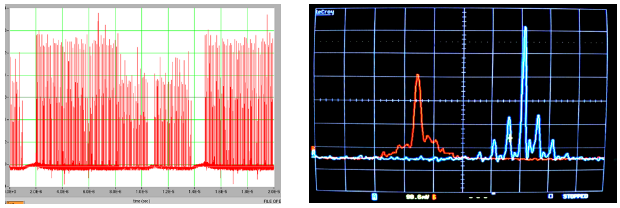

Figure 12: Results of tests of longitudinal cooling. 50 bunches out of 100 were **cooled**. On right, red is un-cooled, blue has been cooled.

applied randomly each to turn to the macroparticles. The approach has been benchmarked by comparing predictions with measured results from longitudinally cooled gold beam [19]. The simulations show that adding cooling in both transverse planes, cutting the chord for reducing pickup to kicker delay in the longitudinal planes, and balancing the cooling rate between longitudinal and transverse all add to the integrated luminosity. Fig. 13. illustrates the result of a simulation comparing no cooling, a complete cooling system, and the addition of the 56 MHz superconducting cavity. An average luminosity of ~3.5 x 10^{27} $cm^{-2}s^{-1}$ is expected.

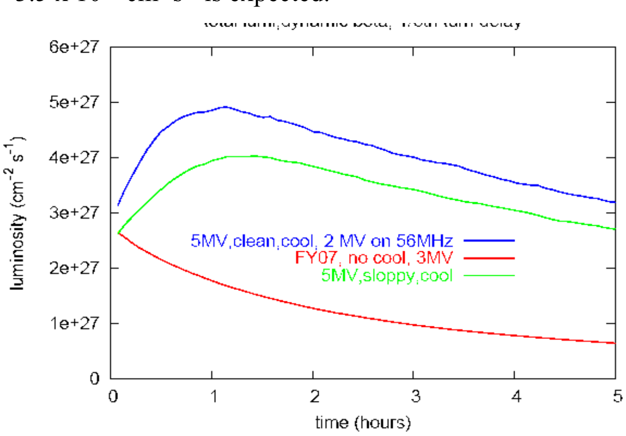

Figure 13: Prediction of luminosity as function time (hours) from simulations of cooling.

CONCLUSIONS

Longitudinal stochastic cooling has been operational with gold beam in RHIC for two runs, demonstrating its ability to counteract IBS during beam stores for collisions. The system has been extended to the transverse plane and the new equipment tested with protons. Simulations show that when the system is complete with cooling in all three phase space planes of both rings we can expect an average luminosity increase of approximately a factor of four.

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