STOCHASTIC COOLING IN RHIC*

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INTRODUCTION

The full 6-dimensional [x,x′; y,y′; z,z′] stochastic cooling system for RHIC was completed and operational for the FY12 Uranium-Uranium collider run. Cooling enhances the integrated luminosity of the Uranium collisions by a factor of 5, primarily by reducing the transverse emittances but also by cooling in the longitudinal plane to preserve the bunch length. The components have been deployed incrementally over the past several runs [1,2,3], beginning with longitudinal cooling, then cooling in the vertical planes but multiplexed between the Yellow and Blue rings, next cooling both rings simultaneously in vertical (the horizontal plane was cooled by betatron coupling) [4], and now simultaneous horizontal cooling has been commissioned. The system operated between 5 and 9 GHz and with 3 x 10^8 Uranium ions per bunch and produces a cooling half-time of approximately 20 minutes. The ultimate emittance is determined by the balance between cooling and emittance growth from Intra-Beam Scattering. Specific details of the apparatus and mathematical techniques for calculating its performance have been published elsewhere [5,6]. Here we report on: the method of operation, results with beam, and comparison of results to simulations.

SYSTEM DESCRIPTION

A unique feature of the RHIC cooling system is that the kickers are high Q resonant cavities. This type of kicker works here because the beam is bunched with 10 MHz bunch frequency and ~5 ns bunch length. The benefit of high Q is that the drive power is reduced drastically. The cavity Q is set so that the filling time matches the bunch spacing and bunch-by-bunch control of the kicks is possible. The drive is provided by 40 W solid state amplifiers. The kickers for each cooling plane comprise 16 cavities of frequencies separated by 200 MHz (1/bunch length). The kicks are a Fourier synthesis from these components. Transverse kickers in the Yellow ring span 4.8,5.0,…7.8 GHz, while in the Blue the frequencies are offset to 4.7,4.9,…7.7 GHz. The offset eliminates cross talk between the rings that results from microwave propagation in the common beam pipe of interaction regions. The longitudinal systems operate from 6.0,6.2,…9.0 GHz. The higher frequency gives more cooling power to combat bunch length growth due to IBS.

Another special feature is that pickup-to-kicker signals for longitudinal are delivered via a free-space microwave link at 70 GHz. The link travels 700 m on the chord of the arc of a sector. This gives 200 ns for signal processing and cable delay. Minimum delay of the pickup-to-kicker signal is crucial because a one-turn delay filter is used for longitudinal cooling. For the transverse systems the signal is sent on fiber optic cable inside the tunnel, giving a 2/3 turn delay.

The key component that creates drive for the kickers is a traversal filter that repeats the 5 ns bunch 16 times with resolution of 1 ps. The filter is realized with coaxial cables. There are no active components that could saturate and cause inter-modulation distortion. This reduces dynamic range of the pickup signal before it is used to modulate the light for the fiber links or the carrier of the microwave link.

OPERATION OF THE SYSTEM

With 96 independent cavity kickers, automated switch-on and tune up are essential. The heart of the low level electronics is the microwave network analyzers that automatically measure the transfer functions of the cooling loop for each kicker. A mechanical relay transfer switch is installed in the low level signal path for each kicker. The transfer switch allows the injection of a signal toward the kicker and the measurement of the subsequent response from the pickup. The switch also allows all insertion attenuation and delays to be absorbed into the network analyzer calibration. Inevitable drifts of system delays on the picosecond time scale are compensated by phase changes in kicker drive signal. Since the kickers are resonant cavities, phase is the relevant quantity. The absolute pickup to kicker timing is only sensitive on the scale of the filling time of the cavities, 80 ns. The gains of the transfer functions are set and stabilized by amplitude adjustment of the kicker drive signal. When the system is cooling this measure/correct cycle is automatically repeated about every 15 minutes. The resulting degradation of cooling strength is minimal since only one frequency is switched off for tune up at a time.

The reference values for these gain and phase settings are found at the beginning of the run by first observing the transfer functions with a polar plot. The gain and phase are adjusted for magnitude on the order of one and the phase with the orientation as seen in Fig. 1. Second, refinements are made by observing the amount and the symmetry of signal suppression [7] in the Schottky

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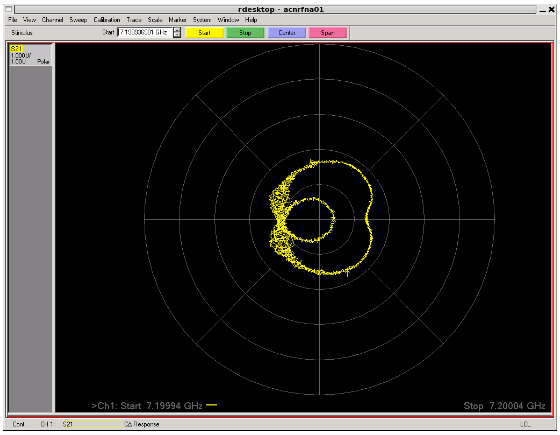

Figure 1: System transfer function of horizontal cooling in polar coordinates at 7.2 GHz. Magnitude=1 is full scale.

spectrum of the pickup signal. See Fig. 2. The number of particles per bunch of the Uranium beam was considerably less than the Gold beam for which the system was designed (1 x 10^9). This meant that the system was kicker strength limited and optimal cooling with a gain of one could not be achieved. Nevertheless, the cooling rate was high enough to enhance the luminosity greatly, see below.

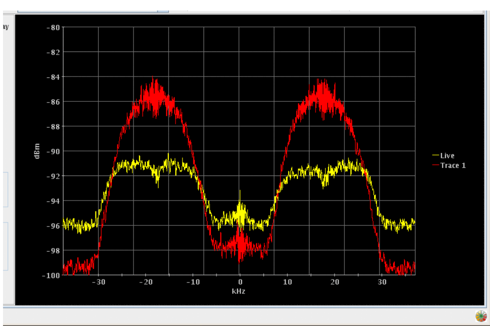

Figure 2: Betatron sidebands from pickup at 5.8 GHz Red, cooling off. Yellow, 6 dB signal suppression.

Beginning with this run all the transverse pickups are moved with high precision linear translation stages with < 5 micron resolution. The pickup devices are planar arrays produced by Fermilab [8] and retrofitted into ultrahigh vacuum vessels wherein the motion of the translation stage are transmitted into the vessel with vacuum balanced welded bellows. The signal from each array is brought out of the vacuum and delivered to the 180^O combiner via motorized coaxial trombones. One array of each pair has a longitudinal axis adjustment of ± 1 mm. These features allows precision phase balance of the array signals so that the common mode Schottky signal is minimized compared to the betatron signal. Some frequency dependence remains in the common mode rejection so that the rejection cannot be simultaneously maximized at all frequencies. In a typical compromise the power averaged over frequencies in the common mode is 3 dB less that the power in the sum of betatron sidebands. See Fig. 3.

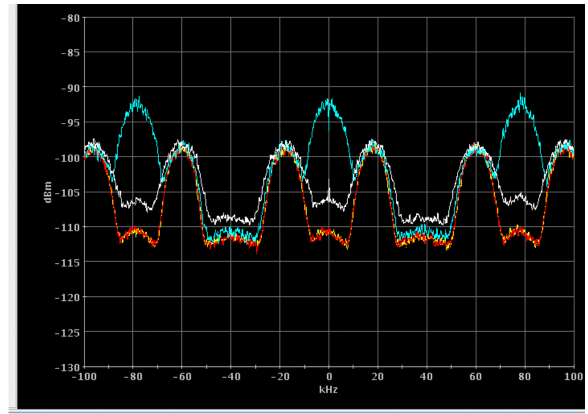

Figure 3: Common mode rejection from transverse pickup at 3 frequencies. Best, worst, and typical.

RESULTS WITH BEAM

The FY12 RHIC heavy ion run began in mid-April with Uranium on Uranium collisions. This is the first Uranium run in RHIC, so several important beam parameters are different than in past runs where stochastic cooling has operated on Gold beams.

The number of particles per bunch is significantly reduced from previous Gold runs, a factor which was expected to lead to improved performance of the cooling system. The addition of the horizontal cooling system was also expected to improve performance.

Table 1: RHIC Machine Parameters

Parameter	2011 Au-Au	2012 U-U
Particles per Bunch	1 – 1.5 x 10^9	2 – 3 x 10^8
Particle Charge	79	92
Lorentz factor, γ	107	103

The luminosity improvement achieved with stochastic cooling is illustrated in Fig. 4. In the 2011 Gold run, stochastic cooling improved the integrated luminosity by a factor of 2[4], with longitudinal and vertical cooling in both rings. In the current run, the same configuration yields an improvement of a factor of 3.75. For the first time at RHIC, the peak luminosity of a store exceeds the initial luminosity.

Adding the horizontal cooling systems in both rings gives an additional increase in integrated luminosity of approximately 35%, which raises the improvement to a factor of 5.

The transverse emittance at the beginning of a store is approximately 15 π mm-mrad in both planes. In stores with no cooling, the emittance grows to about 20 π mm-mrad after six hours. The change in emittance with transverse cooling is shown in Fig. 5. On stores with the vertical and longitudinal cooling systems running, the emittance was reduced by a factor of 4 from the initial value. With all three planes running, the emittance reaches 2 π mm-mrad. Measurements of the transverse

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emittances from Ionization Profile Monitors [9] and calculations of the emittance based on the collision rates at the STAR and PHENIX experiments generally agree on the effectiveness of the stochastic cooling systems and rate of cooling, but there is some discrepancy in the absolute emittances. The values above are based on the calculated emittances.

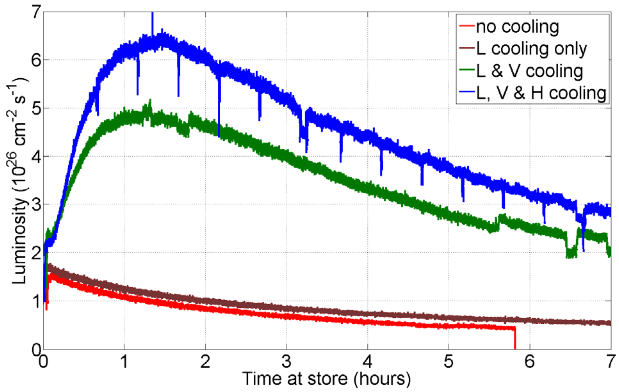

Figure 4: Effect of different cooling configurations on the luminosity. No cooling is shown in red, longitudinal only in brown, longitudinal and vertical in green, and all 3 systems in blue. The initial luminosity for these stores varies slightly due to other improvements in RHIC and the injectors.

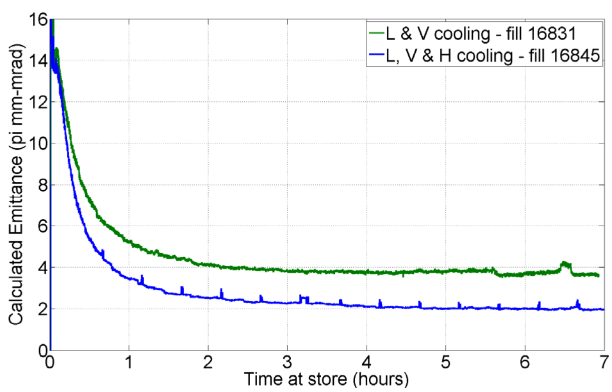

Figure 5: Effect of cooling on the transverse emittance. The average of the horizontal and vertical emittances in both rings, calculated based on the collision rates at the STAR and PHENIX experiments, is shown for a store with longitudinal and vertical cooling (green) and with all 3 planes (blue).

COMPARISON WITH SIMULATION

To confirm that the cooling system is performing as expected the measured results are compared with a simulation that calculates the evolution of beam emittances from first principles. The simulation algorithm exploits the fact that for fixed gain and bandwidth the cooling time is proportional to the number of particles, and so one can trace a small number of macro-particles and the scale up the cooling time by the same factor as the reduction of particle number. [7,10] IBS is handled by using handbook formulae[11] to calculate the growth rates for the rms bunch parameters. The longitudinal profiles are decidedly non-gaussian so the diffusion rates are scaled in proportion to the local line density. Random IBS kicks are applied to the macro-particles each turn of the simulation. Both transverse planes are cooled. Each stochastic cooling feedback loop is treated using a Green's function approach and implemented via a Fourier transform. The convergence of the simulations with the number of macro-particles has been checked. For RHIC parameters varying the macro-particle number from 5,000 to 500,000 changed the predicted cooling rate by only few percent. The calculation results are shown in Fig. 6. The agreement between the simulation and the measured results shows that the cooling system is understood and is functioning as designed.

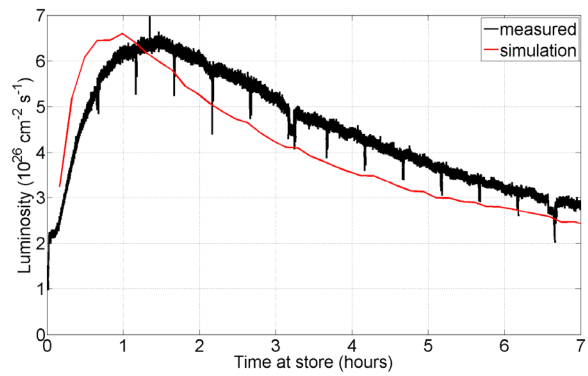

Figure 6: Simulated luminosity, red, compared to measured luminosity in a 7 hour store.

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