FULL 3D STOCHASTIC COOLING AT RHIC*

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Abstract

Over the past several years, the installation of the full 3-dimensional stochastic cooling system in RHIC has been completed. The FY12 U-U and Cu-Au collider runs were the first to benefit from the full installation. In the U-U run, stochastic cooling improved the integrated luminosity by a factor of 5. This presentation provides an overview of the design of the stochastic cooling system and reviews the performance of the system during the FY12 heavy ion runs.

INTRODUCTION

Intra-beam scattering (IBS) is a primary cause of emittance growth of the heavy ion beams in the Relativistic Heavy Ion Collider (RHIC). A 3D bunched beam stochastic cooling system has been implemented to combat IBS and reduce the emittance of the beams. This system has been installed in stages over the past several years. The first operational use of stochastic cooling, in the longitudinal plane of the Yellow ring, began in 2007 [1,2]. The 2010 and 2011 collider runs had longitudinal and vertical cooling in both rings [3,4]. Commissioning of the horizontal cooling system in the 2012 run completed the full system.

SYSTEM DESIGN

The stochastic cooling system is essentially a wideband feedback damper. The momentum error of samples of particles within the bunch is measured and reduced via an applied kick. Longitudinal mixing randomizes the samples on subsequent turns and, over time, the emittance of the bunch is reduced. The time resolution of the samples and the resulting cooling rate are a function of the bandwidth of the system.

The layout of the fundamental components of the RHIC stochastic cooling systems is shown in Fig. 1. The longitudinal cooling pickups are located on either side of the 2 o'clock intersection region. The signals from these pickups are transmitted approximately 700m via microwave link to low-level electronics located near the kickers, which are in sector 4 for the Blue (clockwise) ring and sector 11 for the Yellow (counter-clockwise) ring. The longitudinal microwave links "cut the chord," transmitting the pickup signal across the center of the ring in the same direction the beam travels. This leaves only 200 ns for signal processing and cable delays. To minimize delay, the Blue ring electronics are located in the attic of the RF service building and cables are routed through a dedicated penetration to the tunnel. The Yellow ring electronics are located in a dedicated building on the berm above the tunnel.

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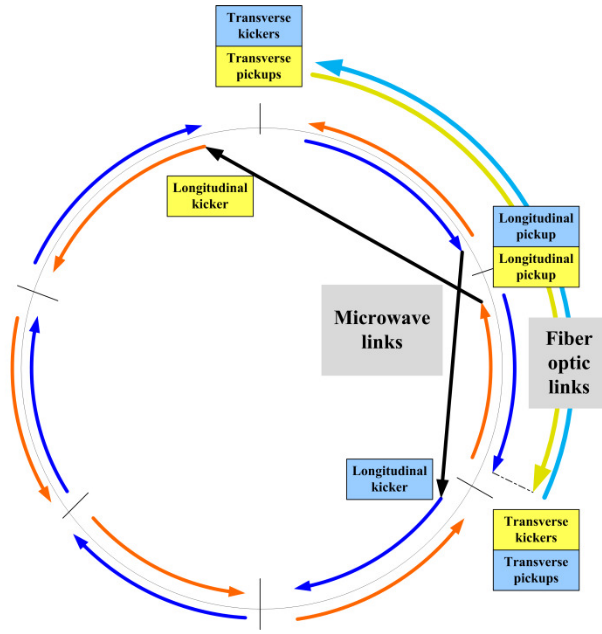

Figure 1: Locations of pickups and kickers (blue and yellow boxes), longitudinal system microwave links (black arrows), and transverse system fiber optic links (light blue and yellow arrows). The dark blue and orange arrows indicate the directions the beams travel.

In the Blue transverse system, signals from pickups in sector 3 are transmitted by fiber optic link to low-level electronics in the 12 o'clock service building, and from the electronics to the kickers in sector 12. The Yellow transverse system is the mirror-image of the Blue, with pickups in sector 12, electronics in a dedicated trailer outside the tunnel, and kickers in sector 3. The fiber optic link travels approximately 1/3 of the ring, while the beam travels 2/3 of the ring in the opposite direction.

Longitudinal Pickups

The longitudinal pickups measure fluctuations in the beam current as a function of the longitudinal position in the bunch. New longitudinal pickups have been designed and installed since the end of the 2012 run. These pickups consist of a keyhole-shaped vacuum chamber, shown in Fig. 2, with a 7 cm aperture round section and a 2 cm high rectangular section. During injection and ramping, the beam circulates in the large round section of the chamber. At top energy, the pickup chamber is moved, with pivoting double bellows on either side, to center the beam in the rectangular section. The small aperture cuts off the propagation of waveguide modes up to 9 GHz. The beam couples to top and bottom WRD-475 double-ridge waveguides parallel to the rectangular section through 8 mm by 6 mm slots. The top and bottom slots are offset in the beam direction, which improves the flatness of the pickup gain across the 6 to 9 GHz operating range.

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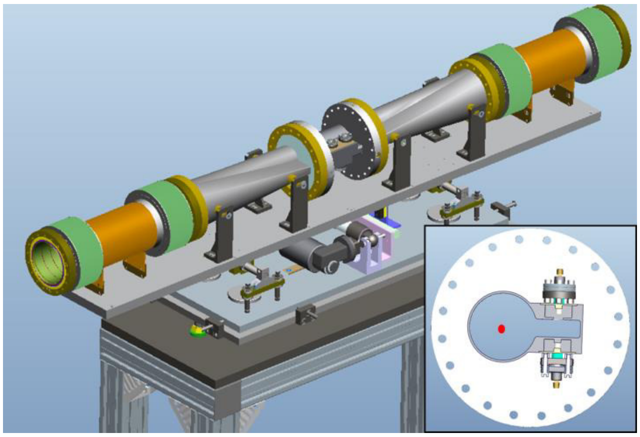

Figure 2: The longitudinal pickup vacuum chamber, drive assembly and stand (main figure) with a cross-sectional view of the active area of the pickup (inset). The red dot in the inset indicates the beam trajectory at injection and while ramping.

The pickup is driven by a DC motor coupled to the vacuum chamber through a gearbox that disengages when it reaches its maximum travel. This determines the in and out positions of the pickup without relying on precise control of the motors. Shape transition pieces provide a smooth transition from the 13 cm RHIC warm bore pipe to the keyhole cross-section. Along with custom RF shields for the welded bellows, these shape transitions minimize the impedance seen by the beam.

The new longitudinal pickup design was tested during the RHIC polarized proton run in 2013. The observed beam spectra are shown in Fig. 3. The response of the pickup across the 6 – 9 GHz band is much flatter than the previous version of the longitudinal pickups, which consisted of waveguides coupled to ceramic windows in a 7 cm round chamber.

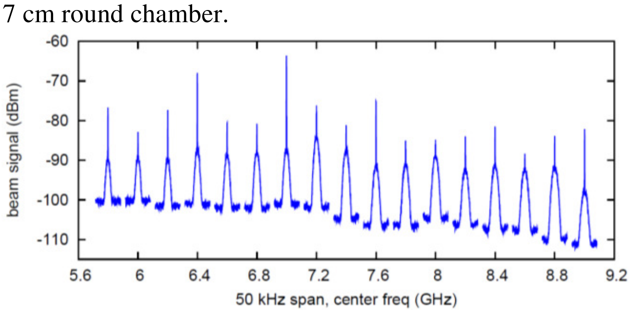

Figure 3: Beam spectra for polarized protons using the keyhole longitudinal pickup. The traces are centered at 5.8, 6.0, …, 9.0 GHz and each have a 50 kHz span.

Transverse Pickups

The transverse pickups measure the fluctuations in transverse position as a function of longitudinal position in the bunch. Each pickup contains two planar loop arrays, originally designed and built at Fermilab for stochastic cooling studies in the Tevatron [5], located above and below (for vertical) or inside and outside (for horizontal) the beam trajectory. The signals from the two pickup arrays must be subtracted with good common-mode rejection. Precision alignment and control of the positions of the two array plates are provided using linear

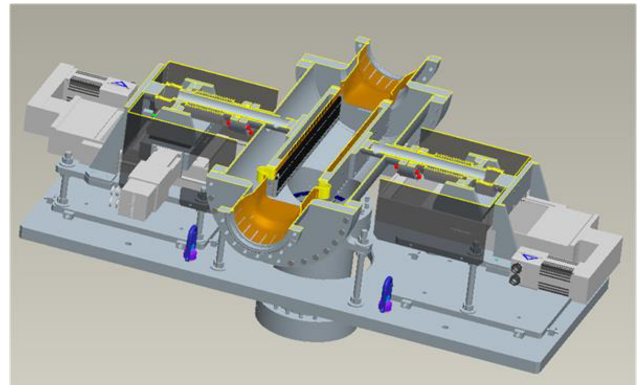

Figure 4: A cross-sectional view of the horizontal pickup vacuum chamber and assembly.

stages from Aerotech. The RF signals from the two plates are routed through matched coaxial cables and vacuum feedthroughs to an external hybrid. For additional fine-tuning of the common-mode rejection, one side has an additional linear stage to adjust the z-axis (beam direction) position of the pickup plate, and remotely adjustable trombones provide adjustable delay matching for the signals before the hybrid.

The design of the pickups, which is described in greater detail elsewhere in these proceedings [6], is nearly identical for the horizontal and vertical planes. The support plates and stands are modified to orient the pickup in the required plane. A cross-sectional view of the horizontally-mounted pickup is shown in Fig. 4.

Kickers

A novel feature of the RHIC stochastic cooling system is that the kickers are composed of an array of high Q resonant cavities. The RHIC beam is bunched with a bunching frequency of approximately 10 MHz and a bunch length of approximately 5 ns. Each kicker consists of 16 cavities, with resonant frequencies spaced by 200 MHz, the reciprocal of the bunch length, and bandwidths of 10 MHz. This allows a Fourier synthesis of the kick waveform to match the broadband signal for the 5 ns length of the bunch, and for the amplitude and phase of the signal to change bunch-by-bunch. This is illustrated schematically in Fig. 5.

In order to match the filling time of the cavities, the bunch signal at the pickup is periodically extended with a traversal filter, whose output is given by

$$y(t) = \sum_{k=0}^{15} u(t - k\tau)$$

with $\tau = 5.0$ ns. This filter is implemented with a series of coaxial cable delay lines, tuned with a resolution of 1 ps. There are no active components in these filters that could saturate and cause distortion. The traversal filter also serves to reduce the dynamic range of the signal before it is sent over either the fiber optic or microwave link.

The Fourier synthesis approach to creating the kick greatly reduces the required drive power. Each cavity is driven with a 40 W solid-state amplifier, and the kicker

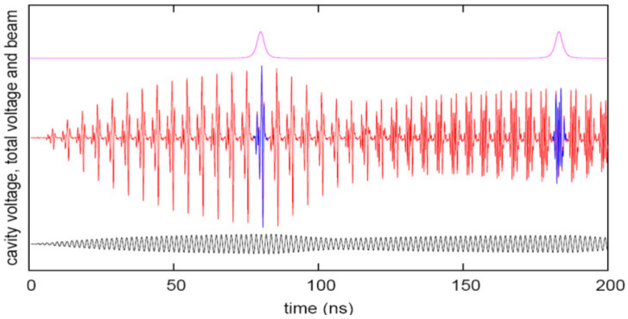

Figure 5: Schematic representation of the synthesis of the kicker waveform. The top trace indicates the time of arrival of two bunches at the kicker. The bottom trace indicates the voltage present on a single kicker cavity, and the middle trace indicates the sum of the voltage on the 16 cavities (red). The blue sections of the middle trace indicate the desired broadband kicker waveform.

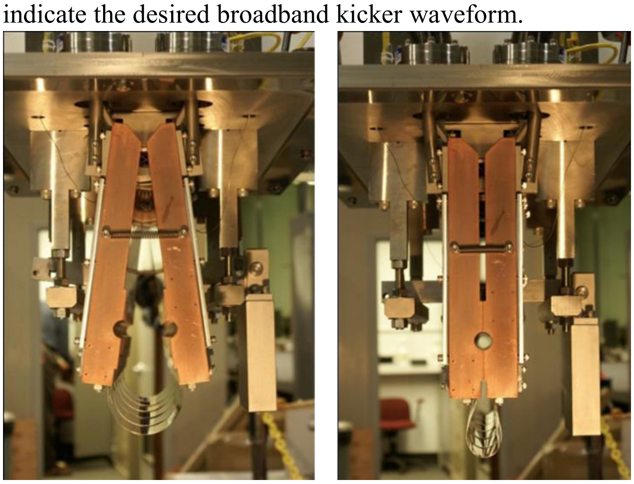
Figure 6: Photographs of the first Blue vertical kicker cavity assembly that used the scissor design, in the open position (left) and the closed position (right). The aperture in the closed position is 2 cm.

generates a kick of several kilovolts. The cost savings due to this method made the RHIC stochastic cooling system possible.

The RHIC stochastic cooling system presently uses three different mechanical designs for the kicker vacuum tanks. The longitudinal kickers are made from retrofitted vacuum tanks originally designed for the Tevatron [7]. Each kicker consists of three vacuum tanks, with either 5 or 6 cavities in each tank. The cavities in this design are split down the middle, allowing them to open to increase the available aperture during injection and acceleration. The cavity bodies are supported on a stainless steel strongback, which is rigidly attached to the drive mechanism. The linear bearings in these tanks have galled and seized on several occasions. Modifications made while refurbishing the kickers prior to the 2011 and 2012 runs have reduced the likelihood of these problems, but it is still a potential failure risk.

The vertical kicker in the Yellow ring was the first to be built in a vacuum vessel designed at BNL. This version of the kicker houses all 16 cavities in a single vacuum tank. This design required very delicate and time-consuming alignment adjustments during assembly, which made it impractical for production. The lessons learned working with this kicker and the Fermilab tanks led to a new design which has been used for all the subsequent kickers.

The vertical kicker in the Blue ring and the horizontal kickers in both rings use a scissor-like pivoting motion on a “flexi-hinge” to allow the cavities to open and close (see Fig. 6). This design has no sliding joints in vacuum. In the closed position, one cavity plate assembly rests against a hard stop and the linkage to the motor goes slack. The other half of the cavity assembly closes against the side supported by the hard stop and its motor linkage goes slack as well. This provides a repeatable closed position, while relaxing the requirements for precise motion control. Further detail on the mechanical design of these kickers is provided elsewhere in these proceedings [8].

During the present shutdown period, new longitudinal kickers are being fabricated using the scissor design. In addition to addressing the reliability concerns mentioned previously, the new longitudinal kickers have several enhancements. The 4-cell cavities in the existing kickers are being replaced by 6-cell cavities in the new kickers. With a higher R/Q, these cavities will provide a larger kick for the same input power. Power is now fed to the cavities through waveguides, rather than coaxial cable, and new coax-to-waveguide transition feedthroughs are used. These changes eliminate the Teflon dielectric in the vacuum chamber, allowing an increased bakeout temperature. The previous kickers all were designed with water cooling of the cavity bodies. The new longitudinal kickers will use radiant heaters to transfer heat to the cavities through glass vacuum windows. A control loop will monitor the cavity temperature and balance the radiant heat input with the RF losses in the cavities and conduction losses to the outside of the vacuum vessel to maintain a constant temperature. These kickers are expected to be completed and installed before the beginning of the 2014 heavy ion run.

Electronics

There are minimal RF electronics located in the RHIC tunnel at the pickups and kickers, but the majority of the electronics are housed outside the tunnel in service buildings. The electronics at the each pickup consist of a digitally-controlled step attenuator, several gain stages, the traversal filter, and low- and high-pass filters to match the system bandwidth and minimize the dynamic range of the signal. At each kicker, there are the 16 power amplifiers that drive the cavities, along with their DC power supplies and monitoring electronics. In addition, some motion control electronics – such as motors, linear potentiometers, limit switches, and resolvers – and PIN diode based beam loss monitors are also located at the pickups and kickers.

The transverse systems use the Photonics Systems PSI-1600 series fiber optic links to transmit the filtered pickup signal to the service buildings. In the longitudinal systems, the filtered pickup signal is used to amplitude

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Figure 7: The microwave link transmitter for the Yellow ring, above the pickup in sector 2, is shown in the foreground. The receiver and dedicated electronics trailer, above the kicker in sector 11, are shown in the distance and the inset.

modulate the carrier of a 70 GHz E-Band microwave link, built by HXI Millimeter Wave Products. The microwave link installation is shown in Fig. 7. A pilot tone is added to the pickup signal, transmitted over the link, and used to correct phase modulation introduced by the link [9].

A block diagram of the electronics for one of the transverse systems is shown in Fig. 8. The optical signal from the pickup is amplified using an Erbium-doped Fiber Amplifier (EDFA), and routed through a delay line to the fiber optic receiver. The length of the delay line is determined to make the signal propagation time from the pickup to kicker match the beam's travel time. The output from the fiber optic receiver is routed through a series of splitters, amplifiers, and band-pass filters with 100 MHz bandwidth to generate the 16 input signals that are sent to the kicker cavities. Each of these 16 signals is connected through an independent I/Q modulator, which is used to optimize the amplitude and phase of the open-loop response. In this way, each cooling system can be tuned as 16 independent feedback systems, and the required precision for matching the pickup to kicker delay is only on the order of a few nanoseconds.

In the longitudinal systems, the microwave link replaces the fiber optic link, and the received signal is filtered with a one-turn delay notch filter prior to the 16-way fanout. The notch filter differentiates the pickup signal, giving an output proportional to the momentum error. A block diagram of the notch filter is shown in Fig. 9. The response of the notch filter is measured by a network analyzer, and the delay is calculated with 0.1 ps resolution. A feedback system regulates the length of the 12.8 μs fiber optic delay line with a piezoelectric line stretcher that provides ±40 ps of adjustment. The entire fiber optic assembly is mounted in a digitally controlled thermal chamber, and a second feedback loop regulates the temperature to keep the delay correction within the range of the line stretcher.

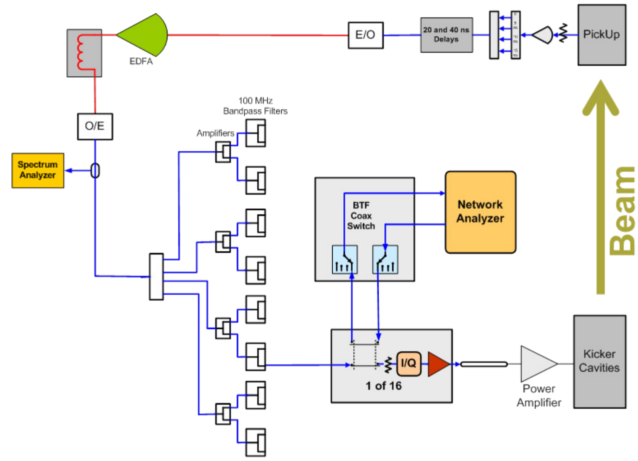

Figure 8: Electronics block diagram for one of the transverse systems. Red lines indicate fiber optic signal paths; blue lines indicate electrical signal paths.

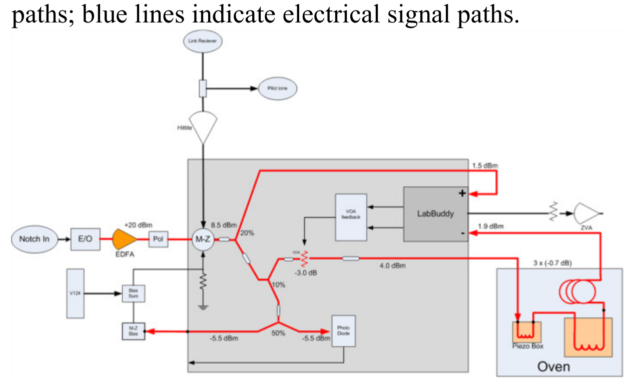

Figure 9: One-turn delay notch filter block diagram. The input from the microwave link is at the top. The block on the left labelled "Notch In" is for the network analyzer measurements. The output at the right of this diagram is connected to the input of the signal fanout.

Control and Operation

Transfer switches in the I/Q modulators and coax relay-based multiplexers allow measurement of the system transfer functions and real-time monitoring of signals while the system is operating. The gain and phase settings of the I/Q modules and the switch settings are sent on a locally broadcast serial "NIM link." This 10 Mbps, bi-phase mark encoded link is electrically identical, and functionally similar, to the RHIC Real Time Data Link [10], allowing common support hardware to be used.

Routine operation of the stochastic cooling systems is fully automated with the "tape" sequencer program. When beam has reached top energy, the sequencer sends commands to control system managers and accelerator device objects (ADOs) to start the cooling system. Several control system managers handle closing and opening of the pickups and kickers, and provide interlocks and alarms if beam loss monitor readings exceed a threshold. Once the pickups and kickers are in the operating positions, the sequencer enables the ADOs that control the low-level electronics.

The low-level software enables the electronics for one cavity at a time and measures the system open-loop

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transfer function. The I/Q modulator gain and phase are modified to minimize the error between the measured and reference transfer functions. The reference transfer function is stored during setup at the beginning of the run after manually optimizing the gain and phase while observing the amount and symmetry of signal suppression [11] in the Schottky spectrum. Once the system is running, the control software continues to automatically measure and correct the transfer functions approximately every 15 minutes. These periodic corrections compensate slow drifts of system delays and changes in the beam conditions.

FY12 RESULTS

In the 2012 heavy ion run, RHIC provided Uranium-Uranium collisions at 96.4 GeV/nucleon and Copper-Gold collisions at 100 GeV/nucleon [12].

Uranium-Uranium

The 2012 Uranium run was the first RHIC run with Uranium, as well as the first to use the EBIS source. The number of ions per bunch was approximately 3 x 10^8, significantly fewer than the 1 – 1.5 x 10^9 Gold ions per bunch in previous runs. This, along with the addition of horizontal cooling, was expected to increase the benefit provided by stochastic cooling.

In the 2011 Gold run, longitudinal and vertical stochastic cooling doubled integrated luminosity. For the 2012 Uranium run, stores with only longitudinal and vertical cooling yielded an improvement by a factor of 3.75. After the horizontal cooling was commissioned, stores with full 3D cooling showed a factor of 5 improvement in integrated luminosity [13]. Peak luminosity was tripled with 3D cooling, the first time in RHIC that the initial luminosity was not also the peak.

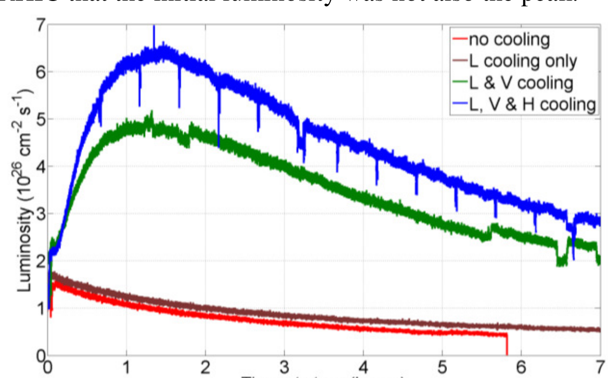

Figure 10: Effect of stochastic cooling on Uranium-Uranium luminosity.

Copper-Gold

The 2012 Copper-Gold run was the first in RHIC with this combination of ions. In addition, it was the first run with different ion species in the two rings with the transverse cooling systems available. Significant improvements in beam intensity were made throughout the run, mostly as a result of improvements at the EBIS source and tuning and introduction of additional bunch merges in the injectors. Ultimately, intensities of 4.0 x 10^9 Copper and 1.3 x 10^9 Gold ions per bunch were reached. Due to changing beam conditions, exact store-to-store comparisons are not possible. However, qualitatively, the benefit from stochastic cooling was clear.

The major operational challenge of the Copper-Gold run was managing the transverse emittance of the Gold beam. Due to the smaller number of ions per bunch, the cooling time for Gold was approximately 1/3 that for Copper. If both beams were cooled with the systems operating at peak performance, the Gold beam emittance was reduced to a much smaller value than the Copper beam. In this circumstance, the beam-beam interaction caused poor lifetime of the Copper beam [14]. To preserve the Copper beam, and maximize integrated luminosity, the transverse cooling for the Gold beam was slowed by turning off the horizontal cooling system and reducing the gain of the vertical system. More detail is available elsewhere in these proceedings [14].

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