Operational Stochastic Cooling in the Relativistic Heavy-Ion Collider

M. Blaskiewicz,* J. M. Brennan, and F. Severino

BNL 911B, Upton, New York 11973, USA

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Operational stochastic cooling of 100 GeV/nucleon gold beams has been achieved in the BNL Relativistic Heavy-Ion Collider. We discuss the physics and technology of the longitudinal cooling system and present results with the beams. A simulation algorithm is described and shown to accurately model the system.

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The Relativistic Heavy-Ion Collider (RHIC) consists of two synchrotrons called blue and yellow, which share a common tunnel. The beam in yellow travels counterclockwise when viewed from above. There are 6 straight sections (without large dipole magnets) where the beams share a common vacuum chamber. The 6 o'clock and 8 o'clock straight sections are occupied by the two existing experiments, STAR and PHENIX, respectively. In these experiments, along with BRAHMS and PHOBOS, the quark-gluon plasma was detected by colliding beams of gold ions [1]. During operations with these heavy ions the event rates in the detectors decay as the beams diffuse. A primary cause for this beam diffusion is small angle Coulomb scattering of the particles within the bunch. This intrabeam scattering (IBS) is particularly problematic at high energy because the negative mass effect removes the possibility of even approximate thermal equilibrium [2,3].

Stochastic cooling [4,5] is a proven technology for fighting diffusion in low energy, coasting beams [6]. A coasting beam is one for which no accelerating radio frequency (rf) voltage is applied. Figure 1 shows a schematic layout. The beam generates a signal at the pickup. The beam and signal propagate from the pickup to the kicker. After processing and amplification the signal is applied to the beam as a kick. Consider a longitudinal cooling system, which is designed to reduce the energy spread of the beam. The process is easiest to envision for a Palmer cooling system where a horizontal beam pickup is used to directly measure the energy error via the dependence of closed orbit on momentum [4,5]. For a pickup bandwidth W the decay time for the impulse response is $\tau \approx 1/2W$. For a coasting beam of particles with charge q and average current I the pickup signal at a given time is the linear superposition of $N_s \approx I\tau/q$ individual particle signals. Let $\epsilon_k = E_k - E_0$ denote the energy error of particle k from the ideal energy E_0. The kicker updates the particle energies according to

$$\bar{\epsilon}_k = \epsilon_k - \frac{g}{N_s}\sum_{m=1}^{N_s}\epsilon_m, \tag{1}$$

where $\bar{\epsilon}_k$ is the energy error after the kicker and g is the gain. Taking an ensemble average, and setting all cross correlations to zero, one finds that the mean square energy spread changes by

$$\langle\bar{\epsilon}^2\rangle - \langle\epsilon^2\rangle = (-2g + g^2)\langle\epsilon^2\rangle/N_s, \tag{2}$$

where the angular brackets denote an ensemble average. Setting $g = 1$ results in optimal cooling. The inclusion of cross correlations reduces the optimal cooling rate by the mixing factor, which is roughly the number of turns it takes for the beam signal to decay after being kicked by sinusoidal pulse with its frequency centered in the cooling band.

Transverse pickups and kickers are used to reduce the transverse emittance (beam size), and systems of both types are essential in the operation of existing antiproton sources and several low energy ion rings [6]. The rough theory outlined above can be formalized using damped, diffusion equations. The inclusion of mixing is straightforward, as is the effect of signal suppression. The latter is important operationally. When a beam is kicked, it responds. For optimal cooling the response tends to cancel the signal at the pickup. The observed signal suppression is a primary diagnostic for adjusting the cooling system.

In bunched beams the rf voltage complicates the dynamics considerably. For cooling in RHIC we can limit the discussion to a fixed ideal revolution period T_0. The longitudinal motion, neglecting cooling and multiparticle effects, is well modeled by

$$\frac{d\tau}{dn} = T_0\eta\epsilon/E_0\beta^2 \tag{3}$$

$$\frac{d\epsilon}{dn} = -q\hat{V}_1\sin(h_1\omega_0\tau) - q\hat{V}_2\sin(h_2\omega_0\tau), \tag{4}$$

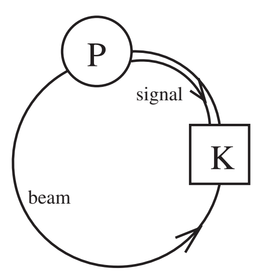

FIG. 1. Physical schematic of the cooling system.

where η is the frequency slip factor, $\beta = v/c$, $\hat{V}_1$ and $\hat{V}_2$ are the rf voltage amplitudes, $\omega_0 = 2\pi/T_0$ is the ideal, angular revolution frequency, $E_0 = \gamma mc^2$ is the ideal energy, h_1 and h_2 are the harmonic numbers, n is the time measured in turns, and τ is the relative arrival time with respect to a stable particle with $\epsilon \equiv 0$. Numerical values are given in Table I. For small τ the motion is well approximated by

$$\tau(n) = \hat{\tau}\sin[\omega_s(\hat{\tau})nT_0 + \psi_0], \tag{5}$$

where ψ_0 is the initial phase, $\hat{\tau}$ is the amplitude, and $\omega_s(\hat{\tau})$ is the amplitude dependent synchrotron frequency. In this approximation a significant amount of analytical progress can be made [7–10]. The damping and diffusion coefficients cannot be obtained in closed form, but certain parameter regimes allow for good analytic estimates.

Some time ago, bunched beam stochastic cooling was observed in the initial cooling experiment at CERN [11] and, more recently, in the recycler ring at Fermilab [12]. In both these machines the bunches were quite long and cooling systems designed for coasting beams worked well. Cooling for short, high energy bunches in the Super proton-antiproton Synchrotron at CERN [8,13] and the Tevatron at Fermilab [8,14] were also considered. Early on [14–18] it was found that "rf activity" extending up to very high frequencies made cooling these kinds of beams very difficult, though promising preliminary results were obtained at Fermilab [19]. The possibility of cooling heavy ions in RHIC was apparent during the design stage [20–22].

We have installed a longitudinal, filter cooling system in the yellow RHIC ring [23]. The Palmer cooling system mentioned earlier used a transverse pickup. Our system uses a longitudinal pickup and can be understood by considering a single particle with revolution frequency ω. Its beam current as a function of azimuth (θ) and time is

$$I(\theta, t) = \frac{\omega q}{2\pi}\sum_{m=-\infty}^{\infty} e^{im(\theta-\omega t-\theta_0)}, \tag{6}$$

with θ_0 the azimuthal position at $t = 0$. The voltage out of the pickup is

TABLE I. Machine and beam parameters for gold.

Parameter	Value
Revolution frequency	$f_0 = 78.2$ kHz
Harmonic numbers	$h_1 = 360$, $h_2 = 2520$
rf frequencies	$f_1 = 28$ MHz, $f_2 = 197$ MHz
rf voltage amplitudes	$\hat{V}_1 = 300$ kV, $\hat{V}_2 = 3$ MV
Initial FWHM bunch length	3 ns
Particles/bunch	10^9
Lorentz factor	$\gamma = 107$
Circumference	3834 m
Frequency slip factor	$\eta = 1.82 \times 10^{-3}$

$$V_p(t) = \frac{\omega q}{2\pi}\sum_{m=-\infty}^{\infty} Z(m\omega)e^{im(\theta_p-\omega t-\theta_0)}, \tag{7}$$

where $Z(\omega)$ is the pickup impedance and θ_p its location. The pickup is a planar loop array that was built for the Tevatron [19,24] and donated to the RHIC project. It consists of 2 arrays with 16 planar loops apiece. The signals from the two arrays are combined in sum mode resulting in a net transfer impedance of 50 Ω at 4 GHz.

This pickup signal is processed through a 16 branch traversal filter giving

$$V_t(t) = \sum_{n=0}^{15} V_p(t - n\tau_0), \tag{8}$$

with $\tau_0 = 5.00$ ns. The filter is constructed from coaxial cables, splitters, and combiners. The signal is amplified and sent to the kicker via a 10 GHz analog fiber optic link.

The travel time between pickup and kicker for a particle with ideal frequency ω_0 is $T_d = 8.5$ μs. We use data from three consecutive turns to construct the kicker signal

$$V_k(t) = K * \{V_t(t - T_d) - 2V_t(t - T_d - T_0) + V_t(t - T_d - 2T_0)\}, \tag{9}$$

where the $*$ denotes convolution with the kicker transfer function K. With this filter the cooling force has the correct sign for $|\Delta f| = m|\omega - \omega_0|/2\pi \leq 23.4$ kHz, corresponding to an upper cooling frequency of 8.3 GHz. We use an upper frequency of 8 GHz and a lower frequency of 5 GHz.

The kicker is a set of 16 rf cavities with resonant frequencies $5, 5.2, \ldots, 7.8, 8.0$ GHz. Additional filters of 100 MHz bandwidth for each cavity remove unwanted frequencies, and a full width half-power bandwidth of 10 MHz allows the cavities to change amplitude and phase between bunch passages. The cavities are driven by 40 W solid state amplifiers and each can produce a rms voltage of 1.5 kV.

The minimum full aperture of the kicker cavities is 2 cm. To reduce aperture limitations during injection and acceleration the kicker cavities are split along the beam axis and open to 60 mm. They are closed only after reaching top energy. The vacuum vessels and motors were supplied by Fermilab and retrofitted for our application.

The gain and phase of the system transfer functions are optimized periodically. This is done by first measuring the open loop system transfer function $B(f)$. A target transfer function $B_0(f)$ is stored in the memory of a microwave network analyzer. The gain and phase settings are updated to restore the reference transfer function. The system loops through all the cavities. The one turn delay filters [the T_0's in Eq. (9)] undergo periodic adjustment. This is done by using the network analyzer to modulate a Mach-Zender interferometer inserted in the optical path and adjusting the minimum of the notch frequency via computer controlled optical delays. More details of the system as well as the results of an experiment using a low energy proton bunch

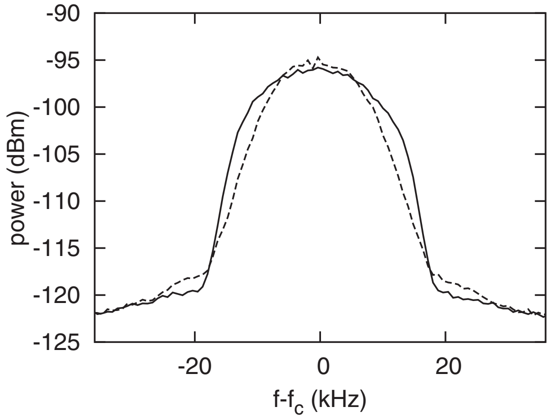

FIG. 2. Unsuppressed (solid line) and suppressed (dashed line) pickup signals at 6 GHz with a 300 Hz resolution bandwidth.

can be found in [25,26]. Comparison with simulations and plans for a transverse cooling system can be found in [27,28]

Pickup signals with the cooling system on and off are shown in Fig. 2. The signal suppression is symmetric and of appropriate amplitude for optimal cooling. Over the 3 GHz bandwidth the root mean square kicker voltage was about 2 kV.

Average bunch profiles for uncooled and cooled beams are shown in Fig. 3. Each of the frames corresponds to a duration of 40 ns and the frames are spaced by an hour. The top panel in Fig. 3 shows uncooled beam. IBS causes significant longitudinal diffusion, reducing both the peak current and the total charge in the bunch. The cooled beam is shown in the bottom panel and exhibits a more complex behavior. The rf kick on the right-hand side of Eq. (4) has

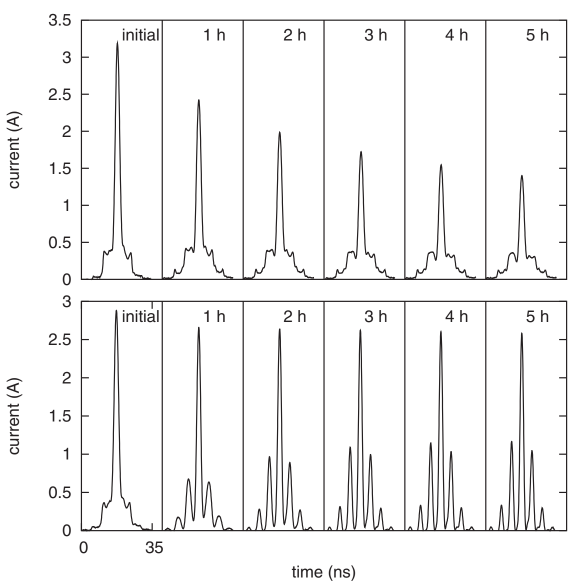

FIG. 3. Evolution of the average uncooled (top) and cooled (bottom) bunch profiles over a 5 h RHIC store with gold beam. Initial conditions are shown on the left and each trace to the right is 1 h later.

seven negative going zero crossings within a single 28 MHz bucket, and the cooling system causes the beam to coalesce around each of these stable fixed points. The peak current is slightly reduced over the 5 h shown, but losses are far smaller than in the uncooled beam. After the first hour, the total charge outside the central 5 ns of the profile was constant to within 5%.

The RHIC beam current in blue and yellow for two physics runs (stores) is shown in Fig. 4. The store shown on the left had no cooling, while the one on the right had cooling. With cooling the yellow loss rates are close to what is expected from luminosity production alone. The improved lifetime led to higher, average event rates in the detectors and increased the total number of collisions by about 15%.

The behavior of the cooling system has been analyzed using simulations. The simulation algorithm exploits the fact that, for fixed gain and bandwidth, the cooling time is proportional to the number of particles [4,5,7,9,10,29].

In a simulation we are free to reduce the number of particles below the value in the actual beam by a factor R. This reduces both the number of macroparticles and the number of turns needed to simulate one cooling time by R. The IBS is handled by using handbook formulas [2] to calculate the growth rates for the rms bunch parameters. The longitudinal profiles in Fig. 3 are decidedly non-Gaussian so the diffusion rates are scaled in proportion to the local line density. Random IBS kicks are applied to the macroparticles each turn. One transverse dimension is tracked and the other is assumed to evolve at the same rate, as appropriate for the strong betatron coupling usually present in RHIC. The stochastic cooling feedback loop is treated using a Green's function approach and implemented via a fast Fourier transform. The convergence of the simulations with the number of macroparticles has

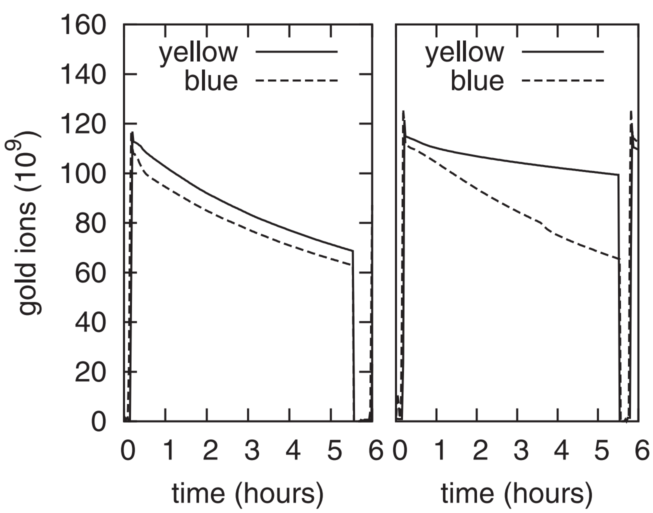

FIG. 4. Evolution of the total beam intensity in RHIC for two physics stores in the yellow (solid line) and blue (dashed line) rings. The store on the left had no stochastic cooling while the one on the right had stochastic cooling on in the yellow ring.

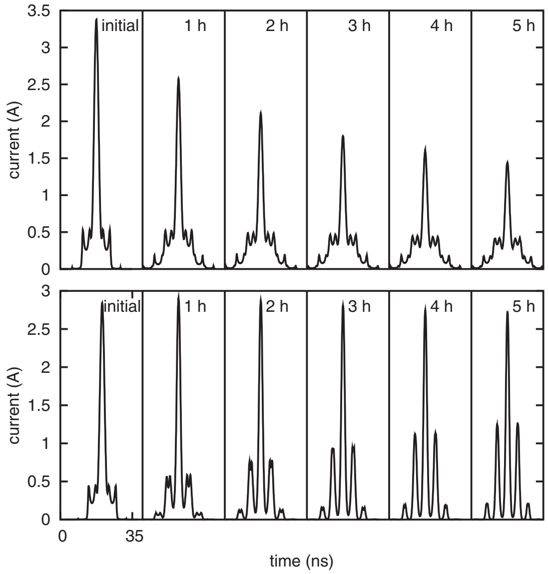

FIG. 5. Simulated evolution of the average bunch profile for uncooled (top) and cooled (bottom) gold beams over a 5 h RHIC store. Initial conditions are shown on the left and each trace to the right is 1 h later. The simulations agree well with the data of Fig. 3. There are no free parameters.

been checked. For RHIC parameters, varying the macroparticle number from 5000 to 500 000 changed the cooling rate by only a few percent [28]. Figure 5 shows simulation results with 50 000 macroparticles for uncooled and cooled beams with the same parameters as in Fig. 3. The simulations did not include losses due to luminosity production, which is of order the discrepancy between the data and simulations. We conclude that our simulation procedure is adequate and we are currently using similar algorithms to design transverse stochastic cooling systems for RHIC. With transverse and longitudinal cooling in both rings we expect a fourfold luminosity increase.

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*blaskiewicz@bnl.gov

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