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Project for RHIC

J. M. Brennan and M. M. Blaskiewicz

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Collider-Accelerator Department

Brookhaven National Laboratory
P. O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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Bunched Beam Stochastic Cooling Project for RHIC

J.M. Brennan and M.M. Blaskiewicz

Brookhaven National Laboratory, Upton New York, USA

Abstract. The main performance limitation for RHIC is emittance growth caused by IntraBeam Scattering during the store. We have developed a longitudinal bunched-beam stochastic cooling system in the 5-8 GHz band which will be used to counteract IBS longitudinal emittance growth and prevent de-bunching during the store. Solutions to the technical problems of achieving sufficient kicker voltage and overcoming the electronic saturation effects caused by coherent components within the Schottky spectrum are described. Results from tests with copper ions in RHIC during the FY05 physics run, including the observation of signal suppression, are presented.

Keywords: Stochastic cooling, bunched beam cooling, heavy ion collider.
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INTRODUCTION

Intra-Beam scattering causes the beam to jump the separatrix and escape the 200 MHz buckets that store ions bunches during a RHIC physics store. This has two deleterious effects; one, beam is lost from the useful collision vertex at the experiments, and two, the de-bunched beam drifts into the abort gap and can cause excessive losses when the beam is cleared from the machine at the end of a store. Stochastic cooling of momentum can counteract IBS and prevent the de-bunching. Herein we describe the study of the viability of a bunched-beam stochastic cooling system for RHIC and report on results with beam of tests of the key hardware components that have been developed for the special technical problems presented by the 100 GeV/n heavy ion collider.

The main concern as to the viability of such a system stems from the often observed anomalous coherent components of the Schottky spectra of high frequency bunches in collidiers[1]. We believe solutions to the technical problem of filtering these components have been developed. A second technical challenge of such a cooling system is the high voltage that the kicker must produce. By synthesizing the kick with a set of harmonically related high-Q cavities the voltage can be generated with modest microwave power supplied by small solid state amplifiers. The availability of commercial fiber optic components enables realizing much of the broadband signal processing in analog optic networks.
Coherent Components in the Schottky Spectrum

Figure 1 shows a spectrum of a longitudinal pickup at 7.6 GHz from copper ions in RHIC at 100 GeV/n. The two identical broad bands comprise true Schottky signals and the narrow spikes are the coherent components. Although these coherent components are not as severe with ions as they are with protons, they nevertheless can be a serious problem for the signal processing electronics of a cooling system. They can cause saturation in amplifiers that generate non-linearities that can not be removed by further filtering. They are “anomalous” in the sense that one would expect that at 7.6 GHz the bunch Fourier transform would not have strength as great as the Schottky signal. We have learned that this expectation is erroneous. The evidence for this assertion is shown in figure 2. The left and center figures are two spectra with 10 MHz span centered at 15 MHz and 7.6 GHz. The envelopes of the two spectra are identical to one another, and to that shown on the right, which is a calculation of the spectrum in which the bunches are taken as delta functions. The three envelopes then reflect only the bunch filling pattern in the ring, which contains some bunches at harmonic 60 spacing and some at harmonic 120 spacing (9.5 MHz) and three bunches are missing to create an abort gap. The equivalence of these envelopes implies that the current from each bunch contributes coherently to the total current, and that the shape of each bunch is stationary with respect to the rf frequency. One does not need to invoke hot spots or solitons to explain the coherent lines. However, it is clear that the electronics will have to be able to handle the high peak voltages that are generated by these bunch shapes.

Figure 2. Beam spectra with 10 MHz span, left is spectrum from wall current monitor at 14 MHz, center is S.C. pickup at 7.6 GHz, right is delta function calculation of beam bunch fill pattern including abort gap.
Filtering the Coherent Components

The filter shown in figure 3 is very effective in reducing the peak voltages by a factor of eight while reducing the signal strength in its periodic passbands by only 6 dB. Because it is composed of passive components (power splitters and coax cables) which do not saturate it can be situated very early in the amplifier chain. The fact that its passbands are separated by 200 MHz is compatible with the kicker technology described below.

![figure 3](image)

Figure 3. The front-end filter that reduces the peak voltage by a factor of 8. The spectral power at each harmonic of 200 MHz is reduced by only 6 dB.

KICKER VOLTAGE

With an energy spread of $\sigma = 0.3 \times 10^3$, $10^9$ particles in 5 ns bunches and 4 GHz bandwidth, a cooling system requires a kicker voltage of approximately 3 kV for Au$^{+79}$. If this were realized with a conventional 50 $\Omega$ broadband kicker the required power would be prohibitive. We have chosen to synthesize the kick with a set of high-Q cavities, spaced every 200 MHz between 4 and 8 GHz. The spacing is sufficient because the bunch length is 5 ns.[2] The structures are 4-cell and 2-cell (depending on frequency) TM$_{010}$ cavities with 20 mm beam bore and approximately 100 mm length. The loaded Q is constrained by the filling time and the 100 ns bunch spacing. The multi-cell design yields R/Q in order of 120 $\Omega$, so that each cavity can be driven with a dedicated 40 Watt solid state amplifier. The linearity and dynamic range of solid state amplifiers are superior to traveling wave tube amplifiers. The intrinsic Q of the copper-plated aluminum structures is >6000, so that they can be operated CW without water cooling. Loading resistors, which set the cavity bandwidth to 10 MHz, are external to the vacuum. During beam injection and energy ramping the cavities split and open to provide clear aperture.

![figure 4](image)

Figure 4. End view of cavities in vacuum chamber. Closed aperture is 20 mm diameter. Open horizontal aperture is 50mm.
Low-level Drive for the Kickers

The pickup signal is transmitted from the pickup to the low-level room via a fiber optic link. Before the signal is converted back to electrical it is stretched to 80 ns duration with the optical network shown in figure 5. The two delays are set via optical trombones to 20 and 40 ns to within 1 ps. The optical switch (Semiconductor Optical Amplifier) admits light into the network for only 20 ns (see figure 2) to prevent optical interference of the light carrier at the combiners.

![Optical Delay-Line Traversal Filter](image_url)

**Figure 5.** The fiber optic network that stretches the drive signal to the cavities to 80 ns.

Two-turn delay filter for halo cooling

A notch filter is usually used for momentum cooling, but if two notch filters are cascaded a larger momentum spread can be cooled. This is beneficial in the RHIC application where preventing de-bunching is the primary goal. The delays are realized in fiber optics before converting to electrical. Adjustments for drifts in delay are corrected with motorized optical trombones.

RESULTS WITH BEAM

The cooling loop was tested by measuring the open-loop system transfer function, shown in figure 6 with a 200 kHz span. The revolution frequency bands are spaced at 78 kHz. The top traces are the magnitudes, with and without the notch filter. The bottom traces are the real and imaginary parts of the transfer function with the two-turn delay notch filter. The magnitude measurement (after correcting for the bunch duty factor) shows that the kicker provides sufficient voltage and the proper function of the notch filter causes the real part of the transfer function to be anti-symmetric about the revolution frequencies.
Figure 6. Cooling system open-loop transfer function at 7.6 GHz with 200 kHz span. Only one of the high-Q cavity kickers is driven. The top traces are log magnitude, with and without notch filter. Bottom traces are real and imaginary parts with filter. The real part is anti-symmetric about the revolution frequency.

Signal Suppression

When the cooling loop is closed the observed Schottky spectrum is modified by the mechanism known as signal suppression [4]. Figure 7 compares spectra with the loop open and closed, for the cases of a one-turn and two-turn delay notch filters.

Figure 7. Schottky spectra at 7.6 GHz showing signal suppression. The observed spectra are reduced by about 5 dB when the loop is closed. Left is with one-turn delay filter. Right is with two-turn delay filter.

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