SUCCESSFUL BUNCHED BEAM STOCHASTIC COOLING IN RHIC*

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Abstract

We report on a successful test of bunch-beam stochastic cooling in RHIC at 100 GeV. The cooling system is designed for heavy ions but was tested in the recent RHIC run which operated only with polarized protons. To make an analog of the ion beam a special bunch was prepared with very low intensity. This bunch had ~1.5 x 10^9 protons, while the other 100 bunches contained ~1.2 x 10^{11} protons each. With this bunch a cooling time on the order 1 hour was observed through shortening of the bunch length and increase in the peak bunch current, together with a narrowing of the spectral line width of the Scottky power at 4 GHz. The low level signal processing electronics and the isolated-frequency kicker cavities are described.

INTRODUCTION

The prospects for stochastic cooling of heavy ions in RHIC have been under study since the beginning of its operation[1]. Cooling is the only remedy for the effects of Intra-Beam Scattering and both electron cooling[2] and stochastic cooling are envisioned. Indeed, both cooling techniques face requirements well beyond the state of the art because of the parameters of the RHIC.

For stochastic cooling the challenges come from: the high beam energy, 100 GeV/nucleon; the high effective particle number, due to bunched beam, and the coherent components in the high frequency Schottky spectra, which tend to saturate low-noise electronics. The key components of cooling system that have been designed to address these challenges have been tested with beam in previous RHIC runs with ions[3]. In the Cu-Cu run of FY05 signal suppression over a limited bandwidth was observed but not actually cooling of the beam. In the most recent RHIC run (FY06) with polarized protons successful bunched beam cooling was achieved on a proton bunch which served as an analog to the intended heavy ion beam. Results of the experiment and details of the system hardware and operational techniques are given here.

THE TEST BUNCH

The main determinates of the cooling time for a bunched beam stochastic cooling system are the effective particle number, the system electronic bandwidth, and the value of the optimal gain.

For a bunched beam the effective number of particles is the equivalent number of particles that would occupy the ring with coasting beam whose constant line density equals the peak density of the bunched beam. For heavy ions $N_{eff.}$~2.5 x 10^{12} particles and for achievable bandwidth and optimal gain this implies a cooling time of approximately one hour, which will effectively counteract IBS. Proton bunches in RHIC, however, have 100 times the particle number of heavy ions.

To enable testing the cooling system with protons we prepared a very low intensity bunch (1%) to be included among the 100 bunches of productions stores. The intensity of this particular bunch was reduced by kicking it transversally with the tune meter kicker. The tune meter was left on after the energy ramp until the desired intensity was obtained. A fast PIN diode switch after the first low-noise amplifier (gain=30 dB, NF=1.5 dB) at the pickup gated the signal, for the low intensity bunch only, into the low level electronics.

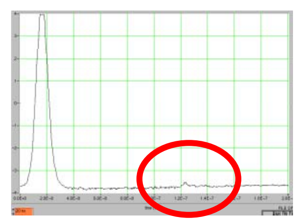

Figure 1: Low intensity bunch (in red circle) used for cooling tests and a nominal bunch (106 ns separation).

SYSTEM DESCRIPTION

Pickup

The pickup is the planar loop array that was built for the Tevatron [4] and donated to RHIC for this project. It consists of 2x16 loops that are combined in the sum mode for a longitudinal pickup with transfer impedance ~50 Ohm at 4 GHz. The signal to noise ratio was 20 dB at 4 GHz for the test bunch, but 5 dB at 8 GHz. For highly charged ions the SN ratio is much higher. The signal is transmitted to the kicker via a 10 GHz analog fiber optic link with delay of ⅓ turn.[5]

Kicker

The voltage required from the kicker is high (1.5 kV) because of the beam energy and charge to mass ratio (for ions). A broadband kicker would require high power and be very expensive. Because the beam is bunched a truly broadband kicker is not necessary. Following the principle envisioned for processing low level signals for

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stochastic cooling in the Spp(bar)S [6] the kicker is segmented into 16 narrowband cavities [3] that span the system bandwidth of 5-8 GHz at intervals equal to the reciprocal of bunch length (200 MHz). Because the information is redundant in all the revolution frequency harmonics within these intervals there is no need to apply kick to all the frequencies. One may think of the kick as being synthesized from a truncated Fourier series spanning the operational bandwidth. The benefit of this design is that the power needed for the kickers is much smaller (20 W) than for a broadband kicker because their high Q effectively makes the peak power close to the average. The Q is limited only by the bunch spacing (100 ns » 10 MHz bandwidth) and is set by 50 ohm loads that are external to the vacuum.

Low-level Electronics

The major components of low level circuits are; the notch filter, the traversal filter, and the I/Q modulators. Figure 2 shows the basic block diagram.

Stochastic Cooling Low Level Block Diagram

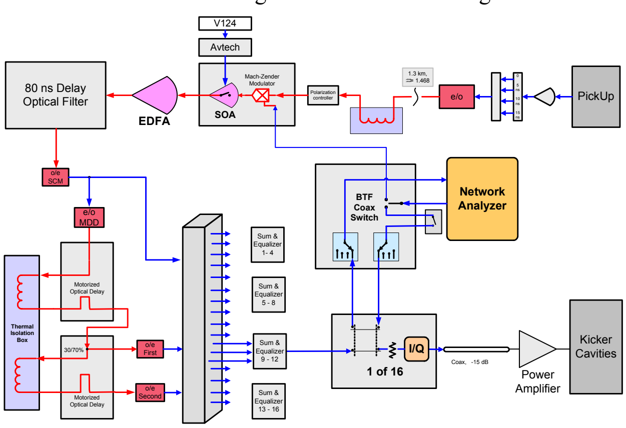

Figure 2: Block diagram of the low level electronics. Red indicates fiber optic, blue is coax. EDFA=erbium doped fiber amplifier, SOA=semiconductor optical amplifier.

The two-turn version of the notch filter[5] was not used for the test with protons. The 6-tap traversal filter was realized in two sections. The first is made with coax cables (5,10,15 ns) with 100 ps trombone adjusters, and is situated before the fiber optic transmitter. This reduces the peak voltage into the transmitter by a factor of 6 and was the key development for overcoming the saturation and inter-modulation distortion caused by the coherent components of the pickup signal. The second section was realized with fiber optic delays in order to avoid dispersion. Because the light signal is AM modulated and the delay paths are combined optically it is necessary to gate off the carrier light between the 20 ns pulses in order to avoid coherent optical interference. This is accomplished with the switched Semiconductor Optical Amplifier. A Mach-Zender optical modulator allows the network analyzer to monitor the notch filter periodically.

The I/Q modulators were built from mixers (Minicircuits ZMX-106) used as DC modulators. We found that in order for the RF path to provide a linear response the input level must be kept below -10 dBm. The response to the DC values applied to the IF ports are then very non-linear. Look-up tables are used to orthogonalize and linearize the I/Q transfer functions.

OPERATION

The network analyzer plays an active role in the operation of the system. After the initial delays, gains, and phases are set for each cavity we expect the parameters to drift slowly compared to the time it takes to make new measurements, but fast compared to the overall cooling time. The Agilent PNA E8362B contains an imbedded Windows 2000 operating system with Ethernet connection. In this environment we have written code that operates the network analyzer and controls the stochastic cooling low level electronics. Each cavity is taken off line periodically, via the transfer switch in the I/Q modulators, and the notch filter and cooling loop transfer functions are measured. Corrections are calculated and sent to the motorized optical delays and the I and Q set points in order to compensate for parameter variations.

Timing

The pickup to kicker delay is obtained by observing the beam induced signal on the kickers and the signal created from the cooling loop. Figure 3 shows diode detected signals from the cavity pickup port. The signal from the 1% test bunch cannot be seen but the timing with respect to the nominal bunches is know precisely.

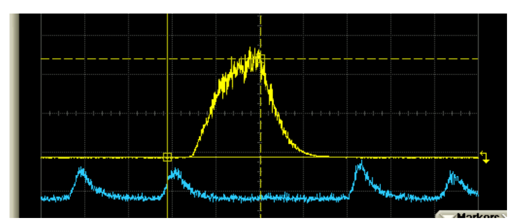

Figure 3: Beam induced signal on kicker cavity (blue). Signal induced on the cavity from cooling system (yellow). Beam induced signal is amplified by 30 dB.

Cooling Loop Transfer Function

Once the pickup to kicker delay is set, the precise phase and amplitude of each cavity is obtained by measuring the open-loop system transfer function. To get the correct magnitude of the transfer function the network analyzer is calibrated through a switch that imposes the duty factor of the bunched beam. The phase is inferred from the measurement result plotted in polar format as shown in figure 4. The settings are then checked by observing signal suppression on the Schottky lines at the center of the cavity bandwidth, see figure 5.

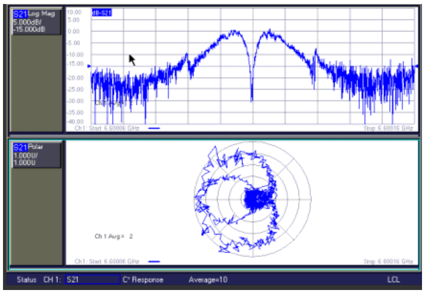

Figure 4: Cooling system open-loop transfer function, used for phasing the cavity. Polar plot has magnitude 1 at phase of 180 degrees for optimal gain.

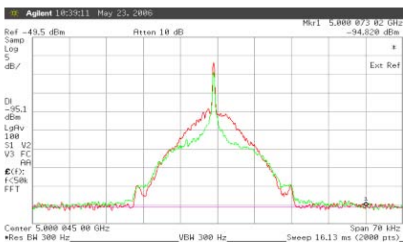

Figure 5: Signal suppression of the Schottky spectrum when the cooling loop is phased correctly. Red is open loop, green is closed.

RESULTS FROM COOLING TEST BUNCH

The RHIC stochastic cooling system is designed to operate with bunches stored in the 197 MHz rf system with essentially full buckets. It has been shown that the beam transfer function in this case is basically that of coasting beam.[7] This affects the behavior of the cooling system by enhancing the good mixing. For these tests the good mixing situation was provided by 50 kV at 197 MHz in conjunction with the 300 kV at 28 MHz which provided the main bucket during the stores. The natural momentum spread in the test bunch was nevertheless quite small compared to the intended ion bunches. To increase the momentum spread we heated the test bunch for about 10 minutes by reversing the phases of the cooling system. After that the system was switched back to the cooling mode and operated for from one to two hours.

Narrowing of Schottky Spectrum

The Schottky spectrum from the pickup signal at 4 GHz was recorded before the cooling runs started. The lowest frequency cavity of the system was 5 GHz but the signal suppression at 4 GHz was conspicuous, verifying that the narrowband kickers were in fact affecting the broadband spectrum of beam. The cooling system was switched off at about ½ hour intervals and the modified Schottky spectrum was compared to initial condition. Figure 6 shows that the Schottky line at 4 GHz had narrowed, implying a reduced momentum spread in the bunch.

Bunch Shortening

The test bunch was observed with the wall current monitor detector throughout the cooling test.

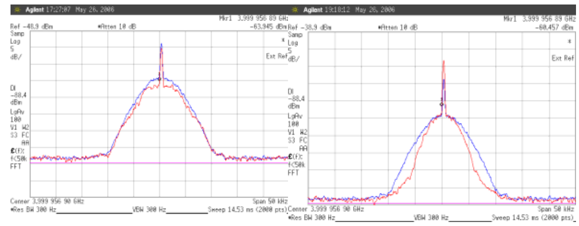

Figure 6: Schottky spectra at 4 GHz before and after cooling. Left: blue is reference spectrum before, red is signal-suppressed spectrum during cooling. Right: blue is reference, red is narrowed spectrum after cooling (system off).

The area under the curve was integrated in the oscilloscope and confirmed no particle loss from the test bunch during cooling. Figure 7 shows that the bunch became shorter and the peak current increased.

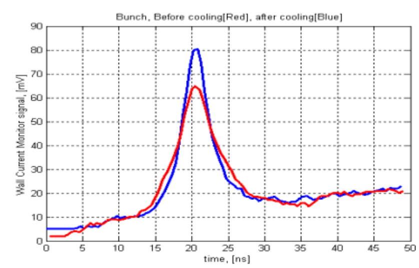

Figure 7: Test bunch, before (red) and after (blue) cooling.

CONCLUSION

By cooling a test proton bunch in RHIC the principle of bunched beam stochastic cooling for high frequency and high energy beam has been demonstrated with equipment that will be used to counteract IBS and increase the integrated luminosity for heavy ions.

ACKNOWLEDGEMENTS

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