BNL-105991-2014-NE

New stochastic cooling kickers for RHIC

J.M. Brennan, M. Blaskiewicz, K. Mernick

August 2014

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
Office of Science

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

1.1 New Stochastic Cooling Kickers for RHIC

J. M. Brennan, M. Blaskiewicz, K. Mernick
Mail to: Brennan@bnl.gov
Brookhaven National Laboratory, Upton NY 11973

1.2 Introduction

Stochastic cooling increases the luminosity of RHIC by combating Intra-Beam Scattering and compressing the 6-dimentional phase space of the bunched beam during collisions at 100 GeV/nucleon.[1] Because IBS is strong for highly charged (bare) ions it is essential to simultaneously cool in all three phase space planes because increased density in one plane enhances the IBS-driven emittance growth rate in the others. Implementation of cooling for RHIC has progressed in stages by installing cooling systems plane by plane over several runs.[2,3,4] The first plane was longitudinal. The kickers of that system employed de-commissioned hardware from the Tevatron[5] retrofitted for the narrowband kicker concept of the RHIC cooling system. This report describes the new kickers that replaced the originals. The upgrade follows design concepts developed for the RHIC transverse systems. Some new features are employed to increase reliability, vacuum performance, and kicker voltage.

1.3 System Description and Requirements

1.3.1 Bunched Beam and Narrowband Kickers

A unique feature of cooling in the collider is that the beam is bunched. This implies that; 1. The local particle density is high so that a large system bandwidth is required for practical cooling rate, and 2. The beam effective frequency spectrum is sparse, only harmonics of 1/(bunch length) (10 ns) being non-redundant[6]. The RHIC system exploits this situation by employing narrowband kickers whose resonant frequencies match these harmonics. This approach energy averages the drive power needed to excite the kickers, thereby reducing the power amplifier size requirement by an order of magnitude. The kickers' bandwidth is adjusted such that they fill and empty in the time between bunches. In this way the effective system bandwidth is 3 GHz while the kicker resonant frequencies range between 6 to 9 GHz in 200 MHz intervals.

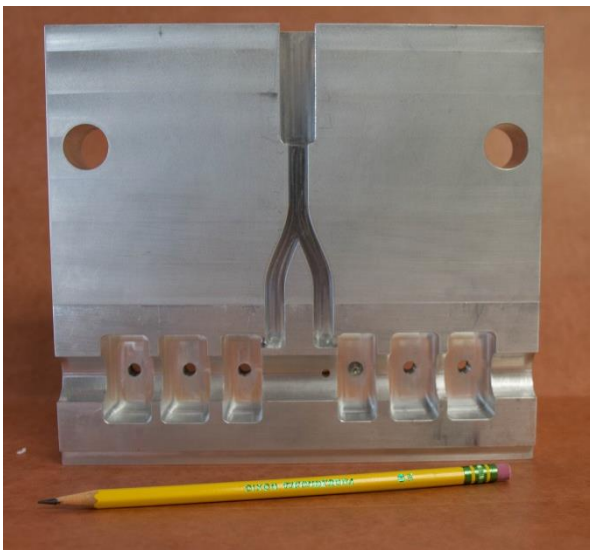


Figure 1. Prototype of 6 GHz 6-cell kicker cavity. One half of the cavity is shown. Waveguide splits to feed the two 3-cells in phase.

Figure 1 shows a prototype kicker cavity. It is essentially six TM_{010} rectangular cells, tuned to one of 16 frequencies, 6.0, 6.2…8.8, 9.0 GHz. It is split into two sections on the vertical median plane. The symmetry of fields in the TM_{010} ensures that no currents cross the median plane. Therefore no ohmic contact between the two halves is necessary. The beam bore diameter is 20 mm when in operation but the two halves separate by ~70 mm during filling and ramping of the collider. Each cavity is driven with a 40 W solid state amplifier and develops ~ 3 kV of kick. More details below. The low-level electronics produces a drive signal that begins 80 ns before the beam arrives. The circuitry is described elsewhere [3] and was not part of this upgrade program.

1.3.2 **Goals of the Upgrade**

The prototype kickers provided barely enough kick as judged by maxim signal suppression being typically less than 6 dB and power level from drive amplifiers running near maximum output. These kickers were 4-cell cavities with R/Q of ~200 Ohms. The new kickers are 6-cell cavities giving 50% more voltage. The voltage can also be limited by precision of frequency of the cavities. The new design improves the precision by better mechanical tolerances and temperature stability. The vacuum performance is improved by eliminating coaxial cables and Teflon connectors from the vacuum vessel. Leaks occurred in the water cooling channels of original kickers. The new design has no cooling channels in the vacuum. Mechanical motion inside the vacuum is necessary to increase cavity's clear aperture for injection and ramping. Metal-to-metal friction is always a problem in high vacuum. The new design provides motion with no sliding parts which improves precision and reliability.

1.2 Cavity Design

1.2.1 RF structure

The 6-cell cavities are actually two 3-cells operating in π-mode and the two 3-cells are separated by one wavelength. They are fed by a TE_{10} waveguide with a 3 dB H-field split. This drives the two innermost cells in phase. See figure 1. The rectangular shape of the cells facilitates the machining. CST Microwave Studio is used to find the dimensions of the cells with the Eigenmode solver. The cells are coupled via the beam bore. Adjustments are made to individual cell dimensions in order to equalize the field strength and thereby maximize the shunt impedance. A typical value for the 6-cell structure is R/Q = 300 Ω. The mode spectrum is generated with the Frequency Domain solver. The operating mode is the highest frequency. See figure 2. Each cell has two fine tuners to achieve frequency accuracy of 1 MHz. Tuners are silver plated ¼-28 screws. The two 3-cells have the same frequencies. The material is copper-plated aluminum. The purpose of copper plating is to reduce the secondary electron yield. The benefit for reduced power dissipation is insignificant.

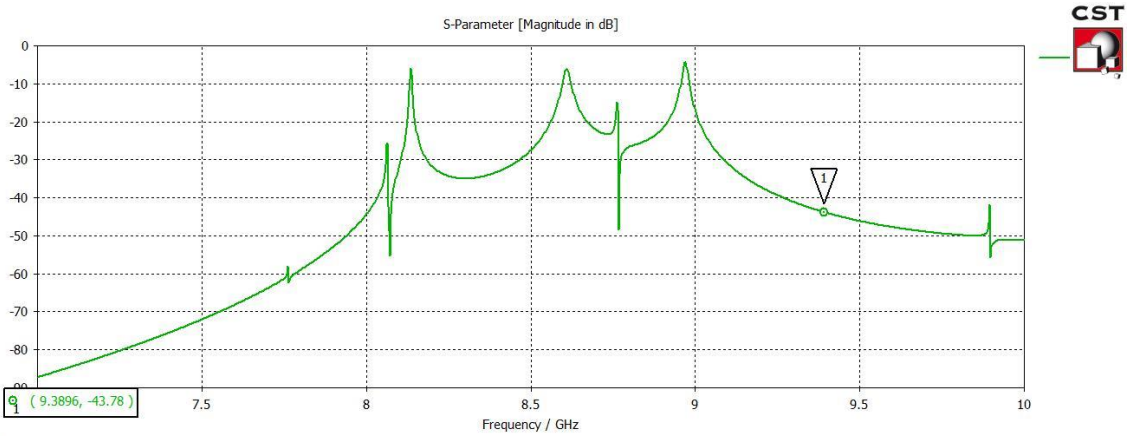


Figure 2 Mode spectrum of 9 GHz 3-cell substructure.

1.2.2 Fill and decay time

Coupling strength to the waveguide sets the $Q_{external}$ to obtain a loaded bandwidth of 10 MHz, matching the cavity fill/decay time to the bunch repetition period. Coupling is determined by the size of the aperture between inner cells and the end of the waveguide where the magnetic fields are parallel. Coupling reduces the resonant frequency of the inner cells which is compensated by refinements to the cell dimensions.

1.2.3 Opening of the cavities

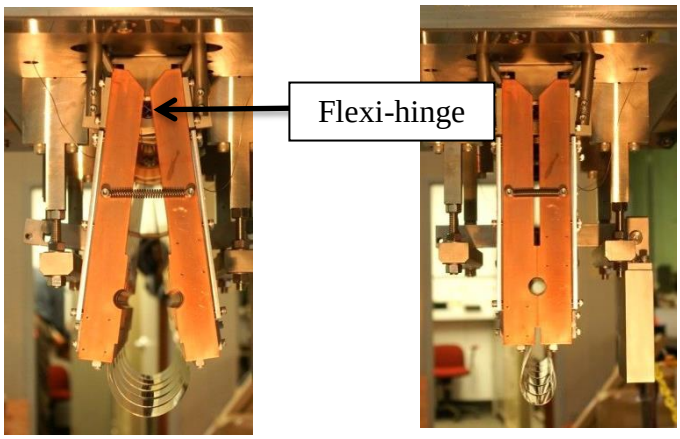


Figure 3. The cavities split on the vertical median plane and open, left, for filling and ramping then close, right, for operation during store.

Figure 3 shows how the cavities open. The two halves of cavities are suspended from the top by a "Flexi-hinge"[7]. This allows for rotation of 10 degrees, by elastic deformation only, of a stainless web structure within the hinge. No sliding metal-to-metal surfaces are employed and therefore problems of binding and galling in vacuum are eliminated. The mechanism achieves the 10^{-4} inch reproducibility needed for 1 MHz frequency precision. The two halves of the cavity are coupled in a master-slave arrangement. The master determines the location of the beam hole with respect to the beam axis and the slave is pulled to the master to ensure reproducibility of the cell dimensions and resonant frequency. The beam hole is referenced to survey targets outside the vacuum with a laser tracker and is not adjustable once the vacuum vessel is closed. Thin (0.010 inch) stainless straps at the bottom of cavity structures make an electrical connection between the two halves to prevent low frequency resonances from being excited by the beam when open. Actuators connect to the internal mechanism via welded bellows. Thin flexible straps of copper-beryllium connect the ends of the cavities to inside wall of the vacuum tank to pass beam image current.

1.2.4 **Waveguide Power Feed**

Each cavity assembly comprises five or six 6-cell cavities, figure 4. RF power is fed to the cavities via waveguides that are rigidly fixed to the top to the vacuum tank. The waveguide dimensions are 1.300 by 0.325 inches for all frequencies. They do not touch the cavity structures which move. A 1 mm gap allows for mechanical tolerance and accommodates relative motion between the aluminum cavities the stainless steel tank when the temperature changes. The largest motion occurs when the assembly is baked at 150 C for vacuum improvement. At the interface between the moving and fix parts a choke joint blocks power from escaping. Two sections of the joint provide coverage over the 6 to 9 GHz range with the same dimensions making the waveguides interchangeable.

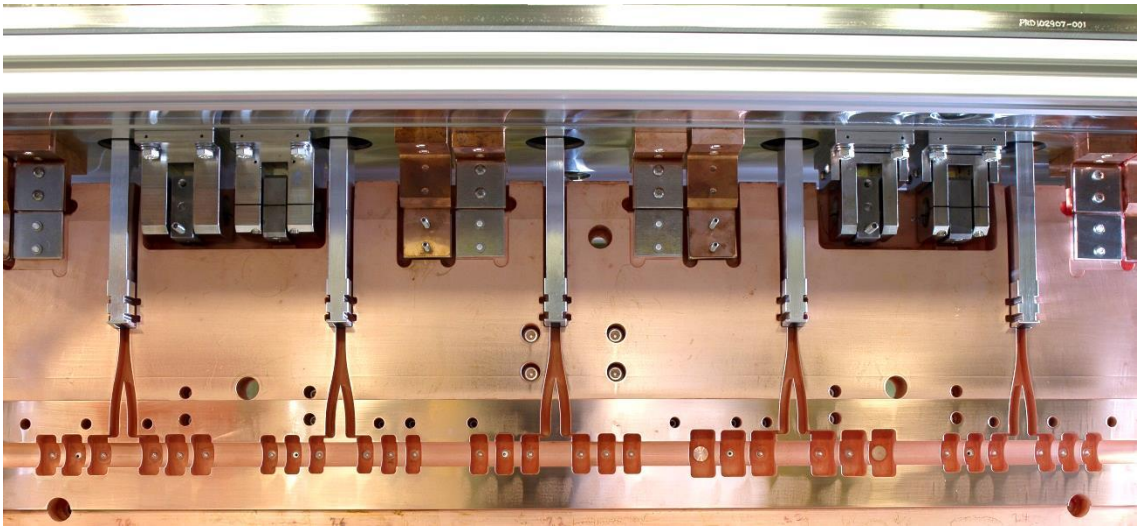
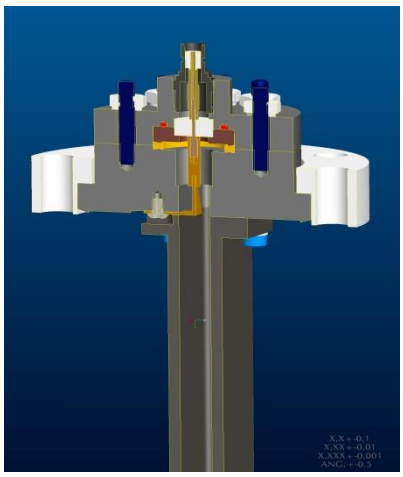


Figure 4. An assembly of 5 6-cell cavities. Waveguides fixed to the top deliver power to the movable assemblies. Flexible copper-beryllium straps conduct heat to the top plate.

At the top of waveguide there is a custom design of coax to waveguide transition and vacuum feedthrough. A loop couples the TEM coax to the dominant TE waveguide mode over the full frequency band. Loop coupling is preferable to probe coupling because the loop is well thermally anchored to the wall. Figure 5, right. In vacuum even a small amount of power can lead to high temperature unless the thermal conduction path is short. The shorted end of the waveguide is roughly ½ guide wavelength from the loop. A short section of 66 Ω coax matched the loop to 50Ω. At the coax end the hermetic seal is realized with an alumina-to-kovar braze assembly. Figure 5, right. The pin is 0.030 inch and the alumina dielectric seal is 0.400 x 0.200 inches. The mini-conflat knife edge is a solid kovar piece. The pin integrates into a 3.5 mm coax connector on the air side. A circulator separates the forward and reflected power. The reflected power is always high because the cavity is over coupled. The circulator improves the reliability of the power amplifiers and also provides a means to observe the emitted power from the cavities. The emitted power can be used to measure the resonant frequency of a cavity. It is sometimes used to see the beam induced signal from a cavity. This is useful for adjusting the pickup to kicker timing of the cooling system.



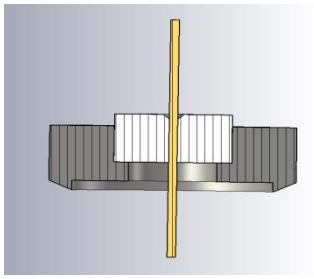


Figure 5. The coax to waveguide transition, left, and vacuum feedthru, right.

1.3 Cavity Fabrication

1.3.1 **Machining**

Cavity assemblies are CNC cut from 6061-T6 aluminum. STEP files containing the cells and the waveguide structures are generated by Microwave Studio and are integrated into assemblies with features for attaching the flexi-hinges and actuator brackets. The arrangement of 6-cell structures is sorted so as to prevent the lower frequency modes of one cavity from overlapping the operating mode of an adjacent cavity. In addition the beam tubes between 6-cells are always a least two diameters in length for further decoupling. A complete kicker consists of three pairs of the assembly shown in figure 4 in three vacuum tanks. The machining of the cavities is done in two stages. The first stage leaves 0.05 inch of material on all the critical dimensions. The piece is then heat treated to relax internal stresses before the finish stage. The plane where the right and left halves meet is flat to ±0.001 inch over the 39 inch length.

1.3.2 **Frequency and Bandwidth Tuning**

The cavity fields are measured with the bead pull technique in the transmission mode. A small loop at the end of 0.085 inch semi-rigid coax is inserted through a hole in one of the tuning screws serves as a pickup for S21 measurement. Each 3-cell is measured independently of the other by either inserting a microwave absorber into the other's waveguide branch or by decoupling the two 3-cells by separating their frequencies with the tuning screws. First, the fields in the three cells are balanced by adjusting the tuners. The bandwidth is measured and corrected by making trim cuts to the size of waveguide-to-cavity aperture. This affects the frequency of the inner cells so the fields need to be balanced again with the tuners. Next, trim cuts are applied to the size of each cell to set the operating frequency. The target frequency anticipates the air-to-vacuum ($\Delta f/ f= +2.8 \times 10^{-4}$) and ambient-to-operating temperature frequency ($\Delta f/f = -2.5 \times 10^{-5}/C$) shifts. The assembly is then copper plated, cleaned in a 10% solution of Citronox at 60 C, and vacuum baked at 150 C for 48 hours. The tuners adjustment is repeated before installing the cavity into the vacuum tank.

1.4 Operation

1.4.1 **Temperature control**

In operation the cavities are cooled by conduction through flexible copper-beryllium straps between the cavity body and top of the vacuum tank. See figure 4. The straps are 0.010 inches thick by 1 inch wide and flex 10 degrees over a length of ¼ inch. This length is kept small by locating the straps on the axis of rotation of the hinge pivot.

There are four stacks of the three strips per cavity half. The thermal conduction of each stack is ~0.7 Watt/C. The vacuum tanks are kept at ambient temperature by heat sinks and fans. The cavities are kept at an elevated temperature of 50 C so that power always flows through the straps. When not in operation all the power is delivered by thermal radiation through glass windows on the vacuum tank. The thermal radiation comes from ordinary 60 W halogen spot lights. Black targets are mounted on the cavities to absorb the power. Black porcelain enamel was chosen for the absorber because of its high emissivity and very low outgassing. Four bulbs per half cavity can deliver ~80 W, which is more than the RF dissipation. When in operation power comes from RF dissipation in the cavities and the lights. The temperature of the cavity is monitored and the power of the bulbs is regulated to maintain a constant temperature of 50 C. See figure 6.

Figure 6. The three vacuum tanks of the new longitudinal kickers for the blue ring. Spot lights shine through glass windows to keep the cavities at 50 C.

1.4.2 **Vacuum**

The vacuum tanks have a rectangular shape. This makes it difficult to make a reliable metal-to-metal demountable seal. Instead the top plates of the tanks are welded to tank bodies. Circular ports with standard conflat flanges at the windows allow access to the tuners if necessary. Major access would require cutting the weld so the joint was designed to accommodate rewelding. The tanks are baked at 150 C for 48 hours after installation. Vacuum levels are ~ 6e-11 Torr at 50 C and <1e-11 Torr at room temperature.

1.4.3 Commissioning

Because of the narrowband nature of the kickers the pickup to kicker delay must be correct to only a small part of the filling time of the cavities (100 ns). Precise timing of the kick is governed by the phase control of cavity drive signal. With the kicker cavities closed and beam in the machine one observes the emitted power from the beam-induced voltage on the cavity via the circulator between the power amplifier and cavity. Then with the same connection one sees the emitted power when the cavity is driven by the power amplifier and low-level system with the pickup as the source. It is not difficult to make this timing coincide at the 1 ns level by adjusting cable delays.

1.4.4 Tune up of the cooling system

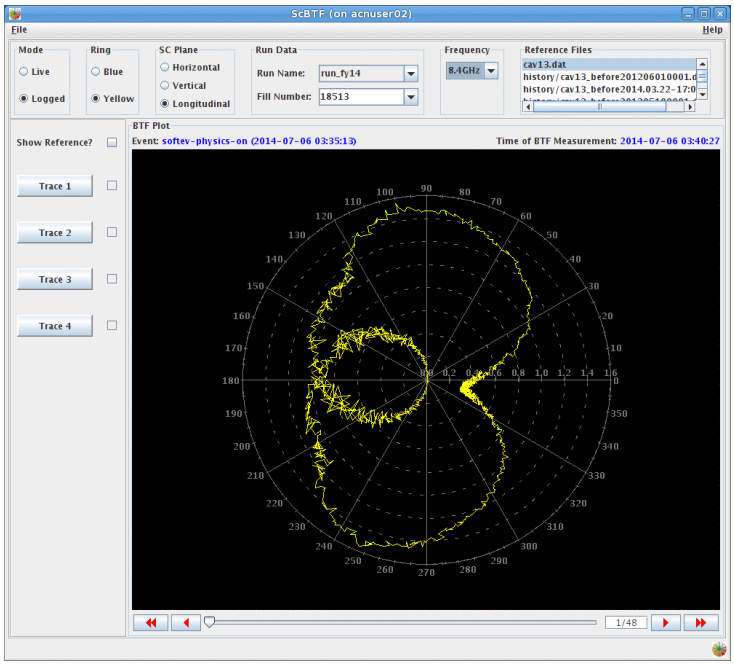


Figure 7. Longitudinal cooling system transfer function at 8.4 GHz. The amplitude is very close to zero at the revolution because of the notch filter. Full scale corresponds to unity gain for optimal cooling

The first step in switching on the cooling system is to make system transfer function measurement with a network analyzer. A transfer switch in the low-level electronics allows interjection of a test signal and connection to the return signal around the entire path of the cooling loop. That includes kicker, beam response, pickup output, signal transmission via the microwave link, revolution frequency notch filter, and low-level gain and phase control. Figure 7 is a polar plot of a typical transfer function measurement over one revolution harmonic. The response shows zero amplitude at the revolution frequency because of the notch filter. The plot is normalized such that full

scale corresponds to optimal system gain and the phase shown is approximately correct. With these setting the cooling loop is closed and signal suppression is checked with the spectrum analyzer. Small corrections are usually made to the phase to balance the signal suppression between the high and low frequency sides of the revolution harmonic. The need for corrections comes from the difference in phase of the kickers when excited by the CW signal from the network analyzer and the pulsed signal from the bunched beam. The transfer function is measured again and saved as the "reference transfer function". When cooling is in operation the transfer function is periodically re-measured and gain and phase setting are updated to replicate the "reference transfer function". The main need for corrections are drifts in cable delays, temperature variation of kickers, and changing emittance of the cooled beam.

1.5 Summary

New kickers have been built and commissioned for the longitudinal stochastic cooling system for RHIC. The new kickers improve reliability, vacuum performance, and provide more kick voltage. Key features of the new design are increased kick voltage from 6-cell cavities, improved vacuum performance by eliminating coaxial cables and cooling pipes in the vacuum and better reliability because of frictionless mechanical design of moving parts. The new kickers were commissioned and operated in the highly successful FY2014 RHIC.

1.6 References

1. Burn-off Dominated uranium and asymmetric copper-gold operation in RHIC, Y. Luo, W. Fischer, M. Blaskiewicz, J. M. Brennan, N. Kling, K. Mernick, and T. Roser, Phus. Rev. ST Accel. Beams, July 2014
2. Three-Dimensional Stochastic Cooling in the Relativistic Heavy Ion Collider, M. Blaskiewicz, J.M. Brennan, and K. Mernick, Phys. Rev. Lett. 105, 094801, 2010
3. Full 3D Stochastic Cooling at RHIC, K. Mernick, M. Blaskiewicz, J.M. Brennan, Proceedings of PAC2013, Pasadena CA USA.
4. Stochastic Cooling in RHIC, J.M. Brennan, M. Blaskiewicz, K. Mernick, Proceeding of IPAC2012, New Orleans, USA
5. Bunched Beam Cooling for the Tevatron, R. Pasquinelli, PAC 1995, p2379
6. D. Boussard, CERN Accelerator School, 87-03, Vol II, p423
7. C-Flex Bearing Co. www.c-flex.com