RF TECHNIQUES FOR IMPROVED LUMINOSITY IN RHIC*

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Abstract

The luminosity of the Relativistic Heavy Ion Collider has improved significantly [1] over the first three physics runs. A number of special rf techniques have been developed to facilitate higher luminosity. The techniques described herein include: an ultra low-noise rf source for the 197 MHz storage rf system, a frequency shift switch-on technique for transferring bunches from the acceleration to the storage system, synchronizing the rings during the energy ramp (including crossing the transition energy) to avoid incidental collisions, installation of dedicated 200 MHz cavities to provide longitudinal Landau damping on the ramp, and the development of a bunch merging scheme in the Booster to increase the available bunch intensity from the injectors.

LOW-NOISE RF SOURCE

When the beam is stored in the 197 MHz rf system during physics data taking it is vulnerable to emittance growth driven by either Intra-Beam Scattering or rf noise. The rf buckets are full so that any longitudinal emittance growth causes debunching which is one of the main determinates of the luminosity lifetime. IBS is inevitable but rf noise can be minimized to a negligible level. A new Direct Digital Synthesizer operating at 197 MHz was built to obtain the lowest possible noise at the rf source.[2] The basic clock is a 300 MHz crystal oscillator (Wenzel). A master DDS generates 2048 times the revolution frequency ($2048F_{rev}$=160 MHz). This clocks a second DDS, which is set to $472F_{rev}$. The second alias, which appears at the output frequency plus the clock frequency, is filtered to derive $2520F_{rev}$, the operating frequency of the storage system. The clock achieves an average noise floor of better than -85 dBc in a 1 Hz bandwidth at 10 Hz from the carrier, and –103 dBc at 100 Hz. Furthermore, special active filtering techniques are applied to the DC power supplies to reduce narrowband noise lines at harmonics of the mains frequency (60Hz). The synchrotron frequency in the storage system is ~230 Hz. With the previous source we have seen problems at 180 Hz. During the store the 28 MHz cavities are left on to capture beam that escapes the 197 MHz bucket, and prevent it drifting into the abort gap. Because the bucket is full we do not see emittance growth, only beam populating the adjacent “satellite” buckets. The signal of trouble at 180 Hz is very narrow lines at this frequency in the high frequency (2.7 GHz) longitudinal Schottky spectrum.

FREQUENCY-SHIFT REBUCKETING

Rebucketing is a term coined [3] for the process of passing the RHIC bunches from the 28 MHz accelerating system to the 197 MHz storage system. A bunch shortening gymnastic is required because the matched bunch length in the 28 MHz buckets is ~10 ns. A jump to the unstable fixed point for bunch stretching and jump back to the stable fixed point for 3/8 of a synchrotron period (~20 ms) is used. The gymnastic is time critical and the 197 MHz cavities must switch on abruptly to high voltage in the presence of beam loading. Several steps must be executed; the fundamental mode damper is mechanically removed, the tuning servo moves the mechanical tuner to resonance, the voltage passes through the region of vulnerability to multipactoring, and vacuum in the cavity is perturbed. In previous runs we found that often at least one of the 10 cavities did not switch on successfully.

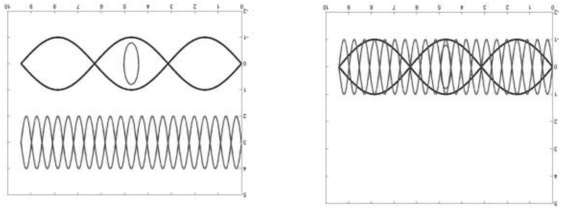

Figure 1. The principle of frequency-shift rebucketing. The frequency of the storage cavities jump to capture the bunch when the bunch length is shortest.

The technique of frequency-shift rebucketing was developed to allow the cavities to turn on slowly without interacting with the beam until the precise moment of the gymnastic. Moreover, if a cavity does not come on then there is opportunity to correct the situation before the gymnastic is executed. The principle is illustrated in figure 1. When the cavities are turned on and brought up to voltage, the drive frequency is offset from the exact harmonic of the revolution frequency. The size of the offset frequency (-3 kHz) is chosen such they do not interact with beam as it is maintained in the buckets of the accelerating system. At the precise moment of the bunch shortening gymnastic the drive frequency of the storage system is jumped to the exact harmonic, and the bunches are captured in the high frequency buckets. Before the jump the relative phase of the two rf systems is changing at the offset frequency. To realize the correct phase at time of the frequency jump a trigger is issued by the low-level circuitry that is synchronized with the beat frequency. This trigger initiates the gymnastic. Figure 2 is a mountain range display of the bunch during the process.

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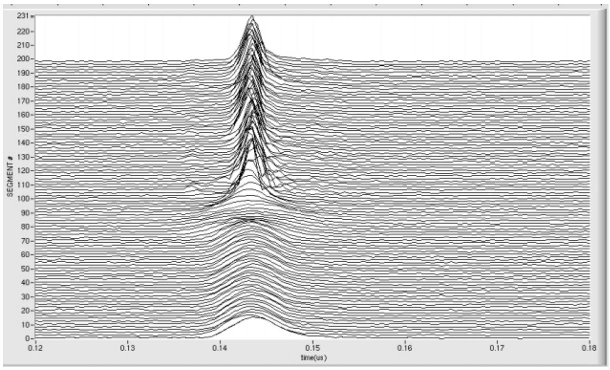

Figure 2. Mountain range display of rebucketing. The horizontal axis is 60 ns full scale. The total time is 100ms.

Pre-tuning of the tuning servos

To effectively compensate a cavity for beam loading it is tuned with its resonance frequency different from the operating frequency. It is tuned properly when the reactive part of the beam current is completely shunted by the susceptance of the cavity. Two benefits follow: 1. the loading angle of power amplifier is zero (real load), 2. the cavity is tuned on the correct side of the resonance curve for Robinson stability. The sign and magnitude of frequency offset are chosen such that when the cavity is started with the shifted frequency its tuning servo anticipates the proper resonance frequency to compensate the cavity. In figure 3, when the cavity is brought on at the frequency of the dotted line the tuning servo makes it resonant at that frequency and the power amplifier generates $I_{generator.}$ When the drive frequency is shifted up to solid line the cavity suddenly feels the beam current. At this frequency the impedance angle is 63^o and the vector diagram on the right shows that the cavity is now compensated for the beam loading and the tuning servo and generator current to not change.

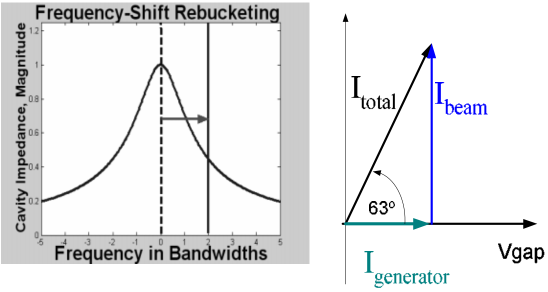

Figure 3. Left, the cavity resonance curve, showing the size and direction of the frequency shift. Right, the beam current and generator current when the cavity is compensated. The drive frequency changes but the cavity resonance frequency does not. It is tuned on the correct side of resonance for beam above transition to obtain Robinson stability.

LANDAU CAVITIES

RHIC beams have exhibited longitudinal instabilities that have all been of single-bunch in nature. For example, after crossing the transition energy gold bunches develop strong bunch shape oscillations that damp very slowly, if at all. There is no correlation between adjacent bunches. By the end of the energy ramp these oscillation cause unacceptable longitudinal emittance growth. Protons are injected just above transition in RHIC and these instabilities are very pronounced. They have been characterized as solitons [4] and have been observed to persist indefinitely. The instabilities have been prevented by a dedicated Landau damping cavity at 200 MHz in each ring. They function by increasing the synchrotron tune spread within the bunch and enhancing Landau damping.

Hardware

The cavities are decommissioned Standing Wave Cavities from the SPS, [5] supplied gratis to Brookhaven. The voltage needed for Landau damping is less than 200 kV so the cavities are powered with the 2 kW solid state amplifiers that serves as the tetrode driver for the storage cavities. The cavities have high impedance (8 MΩ) since they were designed to produce 1 MV. In this application they operate at much less voltage and furthermore, they must be turned on and off adiabatically. However, since the wavelength at 200 MHz is longer than the bunch length there is no preferred phase relationship between the Landau cavity and the bunches. This enables us to operate the Landau cavities at a harmonic of the revolution frequency that is not a harmonic of the bunch frequency, thus avoiding any beam loading. We use harmonic number 2563, which is not a multiple of any of the bunch patterns used in RHIC. The range of the mechanical tuner allows operation from transition to store energy.

RING-TO-RING PHASE LOCKING

Synchronization on the ramp

The rf systems of RHIC’s two rings operate independently on the energy ramp. Different rf frequencies cause the beam to drift in and out of collision. The resulting modulation of the beam-beam tune shift leads to transverse emittance growth and particle loss. To prevent the spurious collisions the two rings are synchronized by detecting the phase difference between the revolution marker clocks, and feeding back to the frequency control of the Yellow ring in a master/slave configuration. The dynamics is similar to the conventional synchronization loop but with the added complication that the rings must pass through the transition energy, where the tolerance to frequency error vanishes. The feedback equation of the master ring is;

$$\begin{aligned}\delta\omega_{rf} &= k_{\varphi}\left(\varphi_{b2b} - \varphi_{s}\right)\\ &+ k_{R}\left(R_{beam} - R_{steer}\right)\\ &+ k_{Int}\int\left(R_{beam} - R_{steer}\right)dt\end{aligned}$$

While the equation for the slave ring is changed to;

$$\begin{aligned}\delta\omega_{rf} &= k_{\varphi}\left(\varphi_{b2b} - \varphi_{s}\right)\\ &+ k_{R}\left(R_{beam} - R_{steer}\right)\\ &+ k_{sync}\int\left(\omega_{yellow} - \omega_{blue}\right)dt\end{aligned}$$

Where: φ is phase (bunch-to-bucket and synchronous), ω is frequency (Yellow or Blue rings), and R_{steer} is the radial steering reference function.

Measuring the relative phase at the revolution frequency accomplishes two things: 1. the natural gain of the synchronization term, k_{sync}, is low, and 2. a phase error of several rf buckets can accumulate without phase detector ambiguity. As the beam approaches transition the second term gains weight because of the beam response, $\delta R / R = \left(\gamma^2/\gamma_t^2 - \gamma^2\right)\delta\omega/\omega$, a temporary frequency difference occurs between the rings as the value of the third term changes.

Bρ loop

The rf frequency is determined by the radial loop. Normally the dynamical value of the position of the average orbit in the arcs is measured by standard RHIC Beam Position Monitors whose signals are split off to dedicated electronic modules. Two BPMs which are separated by ½ betatron wavelength are averaged to reject closed orbit distortions. The rejection is not 100%, resulting in some variation of ~40 Hz in the rf frequency when the beam reaches store energy. To remove this variation an additional correction loop compares the actual rf frequency to a value calculated from the set point for Bρ for the dipole magnets and the known circumference of the rings. The value of the rf frequency is sensed, not the beam frequency. The gain of the correction is approximately 0.5 Hz/second.

BUNCH MERGE IN THE BOOSTER

An rf gymnastic was developed in the AGS Booster to provide gold bunches for RHIC with more than 10^9 ions. The intrinsic longitudinal emittance of beam from the Tandem Van de Graaff is very low. In the standard mode the AGS is filled with 24 bunches in four loads from the Booster, then debunched and captured into four RHIC bunches. A new technique was developed to merge the six bunches of the Booster into three before transferring to the AGS. The process takes place on an intermediate flattop and adds 50 ms to the cycle length. In figure 4 one sees six bunches merging into three and then the harmonic number of the rf system is adiabatically changed (by blending cavities at different frequencies) from three to six, filling only ½ the ring with bunches. The three bunches are then transferred to the AGS and captured in harmonic 24 buckets. The process is repeated eight times to fill all buckets and the process in the AGS is unchanged. The extra emittance generated in the process is small compared to the growth cause by energy straggling on the stripper foil in the transfer line. The technique produced bunches of 1.7×10^9 ions, and in a test, six bunches were injected into RHIC and accelerated.

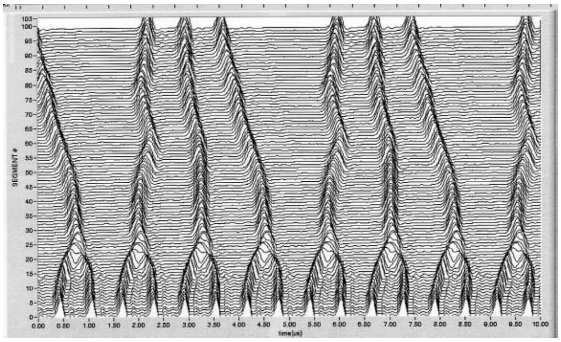

Figure 4. Mountain range of bunch merge and harmonic change in the Booster. Two & 2/3 turns are shown and the total time is 50 ms. Three bunches go to the AGS 8 times.

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