CROSSING TRANSITION AT RHIC*

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Abstract

Operational experience on RHIC transition crossing as well as observed beam dynamics effects are described. The techniques to provide the successful transition crossing without beam losses and deterioration of the beam quality are reviewed. Presently the ion beam intensity is limited by the transverse instability happening at the transition region. It was observed that the threshold of the instability was significantly affected by the presence of the electron cloud. The results of recent studies of the intensity limiting instability are presented.

INTRODUCTION

Except protons, all species accelerated in RHIC have to cross the transition energy, when the revolution frequency becomes independent on particle momentum (in first order approximation). From the experience of previous machines it is well known that the transition crossing brings up the range of specific problems, which have to be addressed in order to prevent beam losses and beam emittance blow up. Usually the longitudinal dynamics issues are of a primary importance at the transition area [1,2,3]. Vanishing dependence of revolution frequency on the momentum and, consequently, small synchrotron tune create a good basis for the longitudinal microwave instability. The things may be complicated further if considerable higher order terms of the dependence of the revolution frequency on the momentum are present. In this case the transition crossing happens at different time for different particles depending on their momentum. In order to eliminate the harmful influence of the mentioned effects the transition has to be crossed at fastest possible rate. For superconducting RHIC machine speeding up the transition crossing rate is especially crucial, since the acceleration rate is quite low (see Table 1). A standard way to realize fast crossing rate is the application of γ_t jump scheme. A specific variety of γ_t-jump scheme, the first order matched scheme has been developed and successfully realized at RHIC[4,5].

Another kind of the longitudinal dynamic effect which has been observed and addressed at RHIC is the longitudinal quadrupole oscillations happening right after the transition. A dedicated damper has been developed and applied to reduce the longitudinal emittance increase due to these oscillations [6].

In addition, RF system control loops are used to prevent a mean horizontal orbit excursion near the transition energy, as well as to keep the beams of two RHIC rings separated well in longitudinal phase in the interaction regions.

The transverse beam dynamics at RHIC is also strongly affected in the vicinity of the transition energy. Main problem is the transverse instability happening near the transition when the number of bunches becomes large. The instability has a stronger effect on later bunches in the bunch train, the electron cloud is suspected to cause reduced instability thresholds for the later bunches [7,10]. Presently this instability limits maximum ion beam intensity that can be accelerated in RHIC without deterioration of the beam quality.

RHIC TRANSITION PARAMETERS

Table 1 presents most important parameters relevant to the transition crossing.

Table 1: Transition parameters at RHIC

Transition gamma γ_t	22.91
Acceleration rate dγ/dt, s-1	0.4
Gold ions per bunch, 10^9	1.1
Peak RF voltage, kV	150
Stable phase, rad	0.08
RF frequency, MHz	28.124
Harmonic number h	360
Long. bunch area (95%), eV-s/u	0.4
Nonlinear compaction α_1 (β*=5m)	-0.3
Max momentum spread δ_{max}, 10^{-3}	5.2
Nonadiabatic time T_c, ms	73
Nonlinear time T_{nl}, ms	355

Sufficiently low ramping rate of RHIC superconducting magnets leads to low acceleration rate in a comparison with other machines where the transition crossing has been done. The low acceleration rate defines large values of two time parameters characterizing different features of the transition crossing [2,3]. Nonadiabatic time, T_c, present the time interval around the transition when the adiabatic description of the synchrotron motion breaks out. On the other hand, the nonlinear time T_{nl} characterizes the chromatic effect due to α_1, higher order part of the momentum compaction factor. T_{nl} serves as a measure of the spread of the time of the transition crossing for particles with different momentum. During that time there are particles in the beam which undergo an unstable motion.

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$$T_{nl} = \left(\alpha_1 + \tfrac{3}{2}\beta_t^2\right)\frac{\gamma_t}{\dot{\gamma}}\delta_{\max} \qquad (1)$$

where $\beta_t = v_t/c$ and γ_t are taken at the transition energy, and δ_{max} presents the maximum relative momentum spread in the beam. And α_1 is defined as:

$$\frac{\Delta L}{L_0} = \alpha_0 \delta \left(1 + \alpha_1 \delta + \ldots\right) \qquad (2)$$

where $\Delta L/L_0$ presents relative orbit lengthening for a particle with relative momentum deviation δ.

Importance of the chromatic effect at the RHIC transition is stressed by the large value of T_{nl} compared with other machines, where typical values did not exceed few milliseconds. Due to larger value of T_{nl} compared with T_c the chromatic effect was expected to be potentially more dangerous and harmful than possible longitudinal microwave instability.

The α_1 parameter depends on the lattice of the machine and on the chromaticity. From (1) the optimal value of the α_1 is equal to -1.5. The lattice required to achieve this value of α_1 has β^*=3m at all six interaction points. Unfortunately, because of the aperture limitation in the IR triplets such lattice was considered not realistic at the transition energy. As compromise solution the lattice with β^*=5m is used at the transition which has α_1=-0.3. Corresponding beta-squeeze is done on the ramp, since the injection lattice has β^*=10m. Measurements of the α_1 were done and showed a good agreement with design values [8].

GAMMAT JUMP

To drastically reduce times T_{nl} and T_c, which beam spends in nonlinear and nonadiabatic areas of the synchrotron motion, a γ_t-jump scheme has been implemented at RHIC [4,5]. The γ_t-jump was designed as first order matched scheme. In such scheme γ_t changes approximately linearly with the gradient of γ_t-quadrupoles and distortions of the lattice functions are kept minimal. Each sextant of RHIC rings contains two families of the jump quadrupoles. One of them, placed in the dispersive section in an arc, is responsible for controlled fast change of the dispersion function and, therefore, γ_t parameter. Using four quadrupoles in such scheme allows to keep both dispersion function and beta-function distortions local, if the phase advance between quadrupoles is close to 90°. In the real machine lattice the phase advance is about 82°, the optical function distortions are not local but still are at the acceptable level. Another family of jump quadrupoles is placed in a low dispersion region, its purpose to compensate the betatron tune excursion caused by the first family. As result the tune excursion during the jump does not exceed 0.003.

In order to overcome the chromatic effect, related with α_1, the amplitude of the γ_t -jump has to be at least:

$$\Delta\gamma_t = 4\dot{\gamma}T_{nl} \approx 0.6 \qquad (3)$$

The polarity of the jump quadrupoles are changed in 40 ms time, causing the change of γ_t by one unit (Figure 1). That increases the rate of the transition crossing by factor 60 and reduce both nonlinear and adiabatic time to below 20 ms.

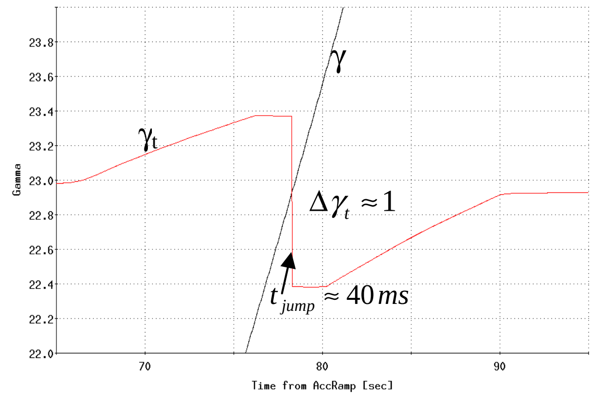

Figure 1: The schematic of γ_t and γ changes trough the transition region with 40 ms long γ_t -jump.

Another parameter which experience fast changes during the jump is the chromaticity. This is due to both the dispersion function changes at the locations of sextupoles and the beta-function changes at the quadrupoles. It was observed that the chromaticity jump can be either directions (positive or negative), depending both on the choice of the design lattice and on the lattice errors. Because of the problems with the transverse instability at the transition, the improvement of chromaticity measurement and control through the transition area has been recognized as a priority task. Corresponding tools to realize this task are under development.

As result of the successful γ_t-jump application and fine tuning of betatron tunes and chromaticities the beam losses through the transition region can be diminished to less than 1%. Also, no problems have been observed with longitudinal microwave instability.

FEEDBACK OF QUADRUPOLE OSCILLATIONS

Even with optimally timed γ_t jump just after transition a bunch length starts oscillations (Figure 2). This leads to a longitudinal emittance increase which causes the rebucketing process (at the storage energy) to be less effective .

Possible reasons for these quadrupole mode oscillations include beam self-induced field (with space charge or other source of reactive impedance) as well as remaining value of chromatic non-linearity α_1. Both those effects can cause a mismatch of the bunch area right after the transition crossing. The decision was made to develop a damper to address this problem and minimize the longitudinal emittance growth.

As the input for the damper system the amplitude of 4th RF harmonic of the wall current monitor signal is used.

The RF voltages of 28 MHz cavities are adjusted to provide better matching and gradual damping of the quadrupole oscillations.

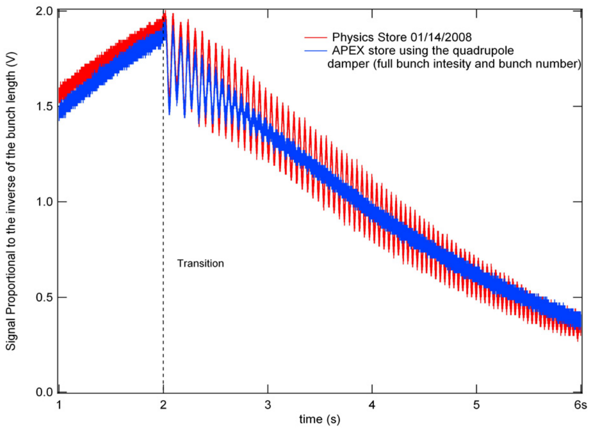

Figure 2: The comparison of the bunch length oscillations after the transition with the feedback on and off. Plotted signal is proportional to the inverse of the bunch length.

The feedback system was developed before the last RHIC run (Run-8). As shown in Figure 2, first tests of the system were very successful, with oscillations effectively damped on the scale of few synchrotron periods [6]. Following initial tests, the feedback system was used in the Run-8 machine operation making reduction of the resulting longitudinal emittance by 10%.

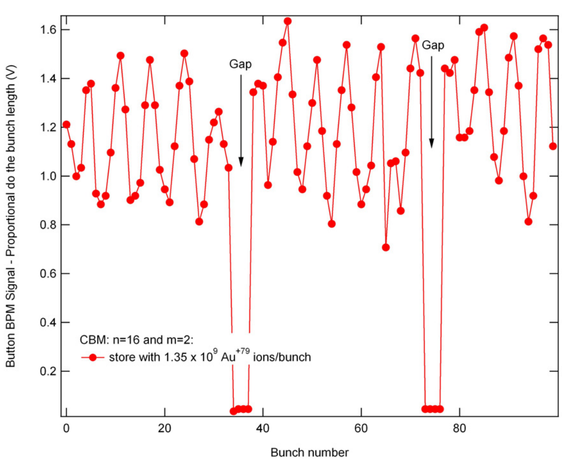

Figure 3: The signal proportional to bunch length is shown at some short time after the transition for all bunches of the beam. The oscillation phase varies with the bunch position in the train. The bunch pattern had two small gaps.

The described feedback system works in the same way for all bunches. So far, this approach has been well justified for the machine operation. However, during dedicated beam experiments with high intensity beam clear signs of a coupled bunch oscillation mode were observed, with the phase of quadrupole oscillations varying along the bunch train (Figure 3). The effect was seen at gold ion bunch intensities above 1.2 10^9 Au/bunch. These coupled bunch oscillations can not be damped effectively with the present feedback system. Thus another feedback system development may be needed to for higher bunch intensities.

MEAN ORBIT CONTROL

One issue that arises during the transition crossing is the control of the mean horizontal orbit, since very small bending field error can cause a significant mean orbit distortion:

$$\frac{dR}{R} = \frac{1}{\gamma_t^2 - \gamma^2}\left(\gamma^2 \frac{df}{f} - \frac{dB}{B}\right) \qquad (4)$$

where R presents the average radius of the closed orbit, f is the revolution frequency and B is the average dipole field on the orbit.

At RHIC the mean horizontal orbit stability is provided by a radial loop running in the RF control system. The radial loop dominates the RF frequency control of one of RHIC rings (Blue ring) in the transition area. The RF frequency control of another RHIC ring (Yellow ring) is dominated by a synchronization loop which aims to maintain the same longitudinal phase separation between Blue and Yellow beams at the interaction points (to prevent a possible harmful effect of parasitic collisions). At this control setup the presence of a small bending field integral error between Blue and Yellow rings causes the mean orbit excursions of Yellow beam near the transition. To evaluate the orbit error one can use the expression (4) assuming dB is the average bending field error between two rings and df is zero. The relative bending field error between two rings varies for a ramp to ramp at few units of 10^{-5} level, which leads to considerable orbit excursions (Figure 4). In order to enhance the mean horizontal orbit stability at the transition region an additional feedback loop is under the design and development for the Yellow ring. The loop will make adjustments of the Yellow main bending field on the basis of the orbit data from selected BPMs. The dipole field feedback should be tested in next RHIC heavy ion run.

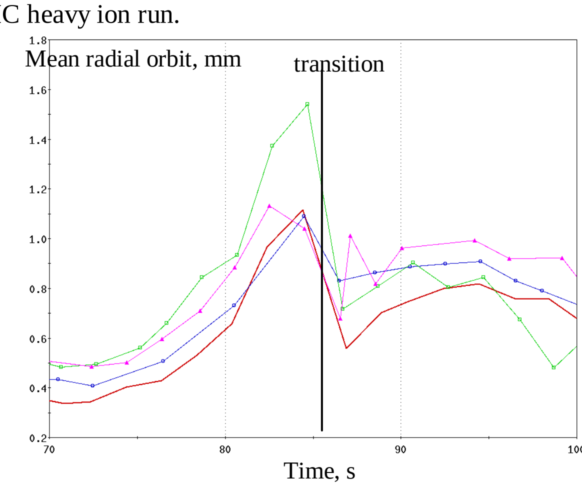

Figure 4: The Yellow mean radial orbit through the transition area on several consecutive ramps.

TRANSVERSE INSTABILITY

The transverse instability, happening in the transition area, limits the ion beam intensity to about 1.1 10^9 gold ions per bunch, when large number of bunches (more than 90) are accelerated. Presently it is a major limiting factor for the achievable luminosity of ion collisions at RHIC.

The instability growth is very fast, on the scale on tens of milliseconds, which is considerably shorter than the synchrotron period near the transition (which is about 130 ms just outside the γ_t-jump area). Thus the mechanism may be similar to the beam break up mechanism in linacs.

In early RHIC runs the fast transverse instability was observed at much lower bunch intensity values with small number of bunches in the machine, so it was essentially the single bunch instability [8,9]. At that time the instability was cured by introducing the betatron tune spread into the beam, first by allowing the beam-beam collisions, and, then, in more controllable way, by powering the octupole corrector families. From that time the octupoles have been used routinely to keep the instability under control.

However, in recent runs, when the number of bunches had been gradually increased to above 100, the fast transverse instability became a major factor again, even with strong octupoles. A major observed feature is the dependence of the strength of the instability on the bunch position in the train. The Figure 5 demonstrates the bunch train affected by the instability near the transition. The train consists of 103 bunches arranged in three mini-trains. The bunches at the latter half of the mini-trains are affected by the instability. The degree of intensity losses and the transverse emittance blow up also had the dependence on the bunch position at the train (Figure 6).

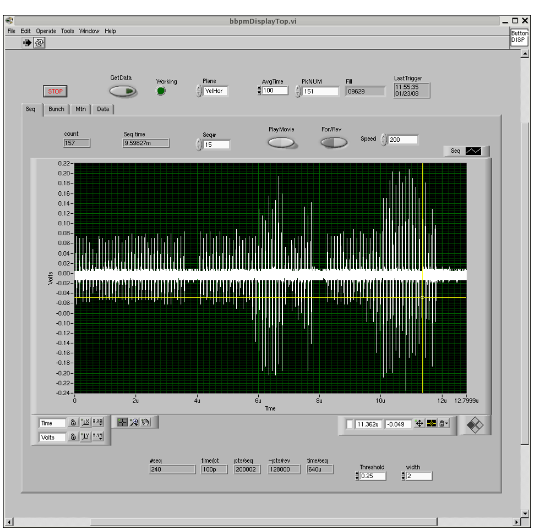

Figure 5: The instability, as measured by a button BPM, affects bunches at the end of the mini-trains.

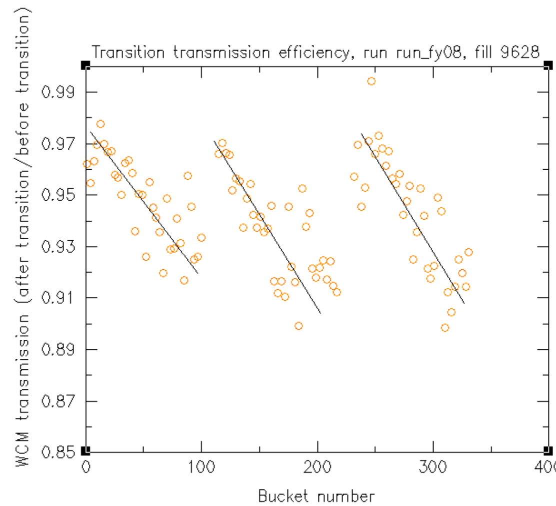

Figure 6: The efficiency of bunch intensity transmission through the transition area versus bunch position in the train. The bunch pattern shown contains two mini-gaps.

Since it was observed that with large number of bunches the electron cloud density increased drastically in the vicinity of the RHIC transition energy due to shortening of the bunch length [7,10], the explanation of the instability threshold reduction because of the impedance introduced by the electron cloud is presently considered as most realistic. The increase of the electron density along the bunch train results in lower single bunch instability threshold for later bunches. To make bunches longer and reduce the e-cloud density, the RF cavity voltage decrease to total of 150kV at the transition area is presently used in the RHIC operation. This helped to improve the instability threshold and achieve higher beam intensities. However, further reduction of the RF cavity voltage in controlled way is not possible. Though the single bunch instability picture involving the electron cloud seems very feasible, the possibility of the multi-bunch instability due to other sources of the machine impedance should not be completely discarded yet. Possible effect of the chromaticity on the instability development is yet to be understood. Although there were indications that the instability happens when the chromaticity crosses zero, on its way from the negative value below the transition to the positive value above the transition, better chromaticity measurement tools as well as the improved chromaticity control at the transition area are needed to effectively study a possible effect of the chromaticity on the instability.

In the recent RHIC run the detailed data on the instability development were collected using a button BPM. Figure 6 and 7 show selected results of the measurements done with the button BPM. As seen in Figure 6 the tail of the bunch is most strongly affected, although for later traces the oscillations gradually propagate closer to the bunch head. The development of the instability spectrum is shown in the Figure 7. The instability grows happens at about 300 MHz frequency.

At later stages the spectrum peak gradually shifts to higher and higher frequencies.

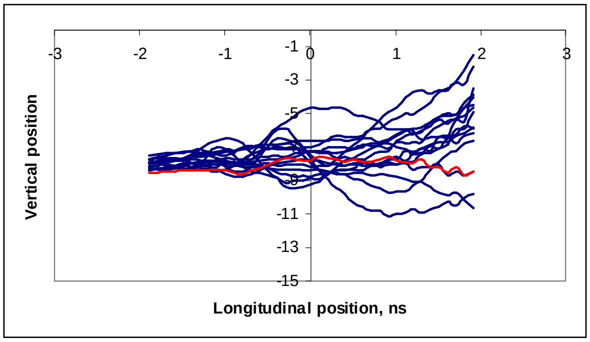

Figure 6: The transverse instability development. The traces are taken with 4ms interval. The head of the bunch is on the left side of the plot. The vertical axis shows the vertical position in arbitrary units.

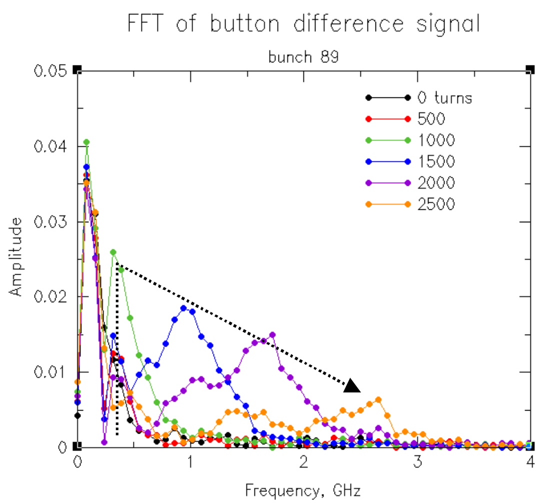

Figure 7: The evolution of the transverse instability spectrum with the time. The traces are taken with 6.4 ms interval.

On the way to better understanding the instability detailed simulations are planned, which should include machine impedances, the effect of electron cloud and the octupoles. Possible measures that can be tried to improve the instability threshold by the reduction of the electron cloud density include the beam scrubbing and the RF counter-phasing technique. The latter aims to decrease the total RF voltage at a fixed voltage of individual cavities by a proper selection of RF phases in each cavity [11]. The possibility of high bandwith feedback system against the instability is also under consideration

CONCLUSIONS

The transition is crossed in RHIC with all ion species except protons. The successfully implemented gammaT jump provides the transition crossing almost without beam intensity loss and the longitudinal emittance deterioration.

The bunch length oscillations excited at the transition are effectively damped by recently implemented feedback. Although higher beam intensity will require the development of more dedicated feedback against multibunch effects.

The dipole field feedback is under development to provide better stability of the mean horizontal orbit at the transition.

The transverse instability at the transition region presently limits achievable ion beam intensities. The instability is stronger for later bunches in the bunch train. The electron cloud is suspected to decrease the instability threshold. The measurements of the details of the instability development were done in the latest RHIC run.

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