LONGITUDINAL DYNAMICS SIMULATION AT TRANSITION CROSSING IN RHIC WITH NEW LANDAU CAVITY*

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Abstract

At the Relativistic Heavy Ion Collider (RHIC), heavy ion beams cross transition energy during acceleration to energies required by the physics programs. In the past, to battle longitudinal instabilities, a Landau cavity was turned on just after acceleration through transition energy. The Landau cavity with modified frequency will be implemented before beam crosses transition in Run-14. Longitudinal dynamics with this new configuration have been simulated to optimize the phase and amplitude of the Landau cavity. We will present simulation results in the report.

INTRODUCTION

At RHIC, heavy ion beams cross transition energy during acceleration to full energies. For example, Au beam is injected into RHIC with $\gamma = 10.5$. It crosses the transition energy ($\gamma = 23$) at ~85 s after the start of the acceleration. The heavy ion beams are accelerated by the 28 MHz cavities, whose harmonic number is 360. In the past, the Landau cavity (~197 MHz) was turned on after transition. For Run-14, it was proposed by J.M. Brennan to turn on the Landau cavity before transition crossing for better beam transmission efficiency. In addition, the frequency of the Landau cavity was slightly modified (harmonic number from 2640 to 2580) to better control coupled bunch instability [1]. There were several questions associated with the mentioned changes: what is the impact on the beam emittance if we turn on the Landau cavity before transition? what to do with the phase of the Landau cavity at transition? and what is the optimal configuration for the voltage of the Landau cavity? The simulations will be presented in this report were carried out to answer these questions.

The simulation was performed with a tracking program, ESME [2], which calculates the evolution of a distribution of particles in energy and azimuth as it is acted upon by the radio frequency system of a synchrotron or storage ring. The basis of the program is the pair of single particle difference equations

$$\begin{aligned} \vartheta_{i,n} &= [\tfrac{\tau_{s,n-1}}{\tau_{s,n}}\vartheta_{i,n-1} + 2\pi(\tfrac{\tau_{i,n}}{\tau_{s,n}} - 1)]_{mod(\pi)} \\ E_{i,n} &= E_{i,n-1} + eV(\phi_{s,n} + h\vartheta_{i,n}) - eV(\phi_{s,n}) \end{aligned} \tag{1}$$

where ϑ is the particle azimuth, in the range of $(-\pi, \pi)$. $E_{i,n}$ is the beam energy of the ith particle at the nth turn, relative to that of the synchronous particle. $\tau_{i,n}$ is the revolution period of the ith particle at the nth turn. $\phi_{i,n}$ is the synchronous phase at the nth turn.

As one of the inputs to the program, the revolution period is correlated with the machine lattice design. According to Ref. [3], the revolution period is expanded as follows

$$\frac{\tau}{\tau_0} = 1 + (\alpha_0 - \frac{1}{\gamma_0^2})\delta + (\alpha_0\alpha_1 - \frac{\alpha_0}{\gamma_0^2} + \frac{3}{2\gamma_0^2} - \frac{1}{2\gamma_0^4})\delta^2 + O(\delta^3) \tag{2}$$

where the γ_0 is the Lorentz factor of the beam. δ is the beam energy spread. The first and second order compaction factors, α_0 and α_1, can be obtained from the optics model or measurement. It was showed in Ref. [3] that the agreement between measured and the model α_1 was within 10%. The measurement ($\alpha_1 = -1.15$) was used in the simulation.

HEAVY ION BEAM ACCELERATION AT RHIC

The γ_t jump scheme [4], changing the γ_t by quickly switching the polarity of a group of designated quadrupoles, has been implemented at transition crossing for the heavy ion beams. It takes 35 ms to change the γ_t by 1 unit at RHIC.

The voltage of the 28 MHz cavity during acceleration is shown in Fig. 1. The initial RF voltage was set to the maximum value to reduce intra-beam scatterring contribution to longitudinal emittance by sacrificing momentum spread. The voltage is halved around transition to reduce the bucket height.

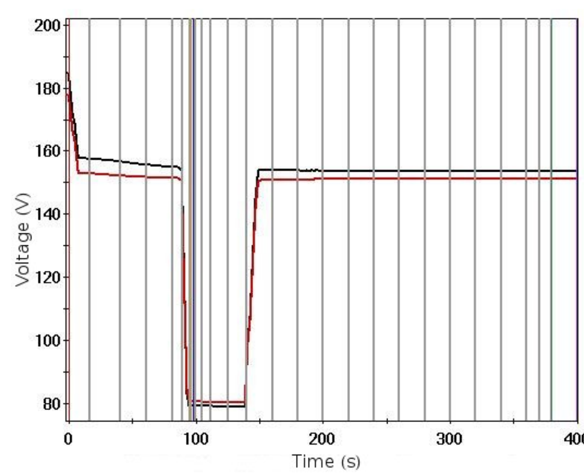

Figure 1: The voltage of the two 28 MHz cavities during acceleration in 2011 Au-Au physics program.

The synchronous phase is determined by the voltage evolution and the beam energy on the ramp. The beam rigidity and its derivatives are shown in Fig. 2.

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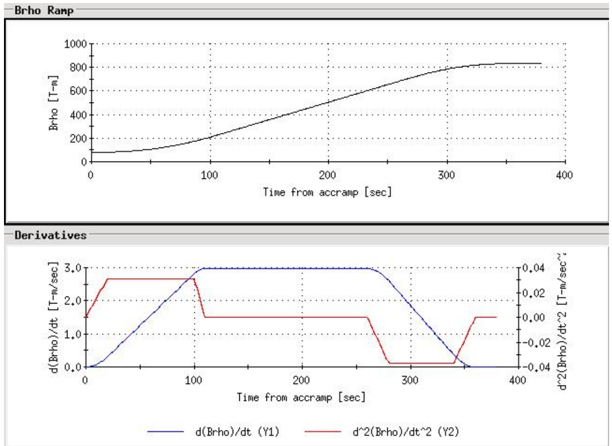

Figure 2: The beam rigidity during acceleration (the upper plot) and the first (the blue curve in the lower plot) and second derivatives (the red curve in the lower plot).

SIMULATION OF THE LONGITUDINAL DYNAMICS WHILE CROSSING TRANSITION

The simulation was performed for the first 150 s of the acceleration cycle. The initial longitudinal emittance was 0.1 eV·s. There were 10,000 particle in the tracking. The longitudinal phase space distribution of the bunch can be displayed at any turn. However, it is more practical to view other derived quantities for monitoring the dynamics.

The beam energy during the first half of the acceleration cycle is shown in Fig. 3. It agrees with the design value. The

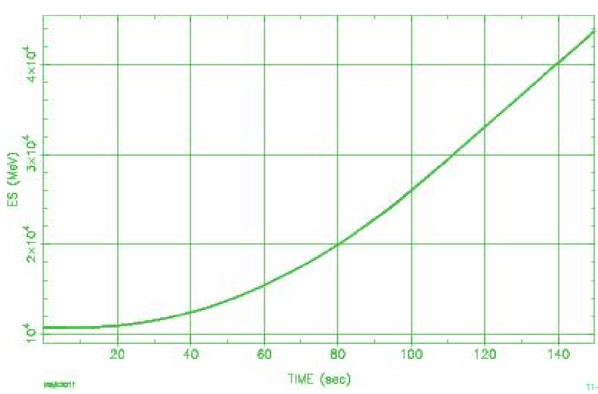

Figure 3: The beam rigidity during acceleration (the upper plot) and the first (the blue curve in the lower plot) and second derivatives (the red curve in the lower plot).

slip factor (η) during the first half of the acceleration cycle is shown in Fig. 4.

We studied the beam emittance behavior at transition without Landau cavity as a baseline. The emittance evolution during the first half of the acceleration cycle is shown in Fig. 5. The emittance increase due to transition crossing is $\sim 3\%$.

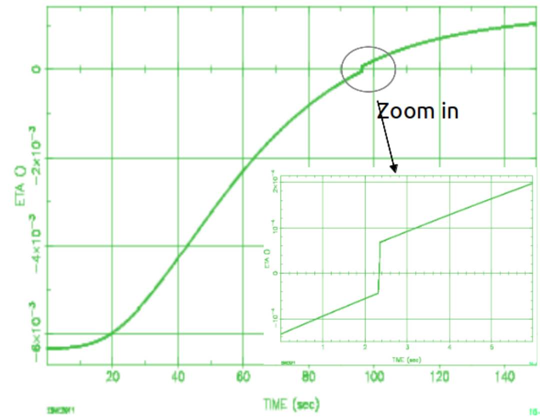

Figure 4: The slip factor (η) during the first half of the acceleration cycle. The transition crossing was zoomed in and shown in the lower right. The slip factor crossing zero fast was enabled by the γ_t jump scheme.

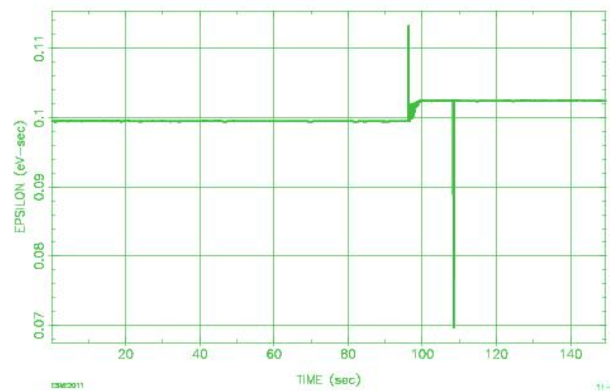

Figure 5: The emittance evolution during the first half of the acceleration cycle without Landau cavity. The γ_t jump scheme was implemented.

Then, we studied the case that beam crosses transition with Landau cavity, and the phase of the Landau cavity was kept constant. The emittance evolution during the first half of the acceleration cycle for this case is shown in Fig 6. Apparently, the emittance blowup at transition was unacceptable.

After that, we studied the case that beam crosses transition with Landau cavity, and the phase of the Landau cavity was switched from 0 *deg* to 180 *deg*. The emittance evolution during the first half of the acceleration cycle for this case is shown in Fig. 7. The emittance increased by $\sim 10\%$, which is slightly worse than that in Fig. 6., but still acceptable. This implies that it is feasible to turn on the Landau cavity before transition for better transmission.

There is one bunch every three 28 MHz RF buckets, every 21.5 Landau RF buckets with its modified frequency. Therefore, the second bunch sits on 180 deg phase of the Landau when the first bunch on 0 *deg* phase of the Landau cavity (see Fig. 8).

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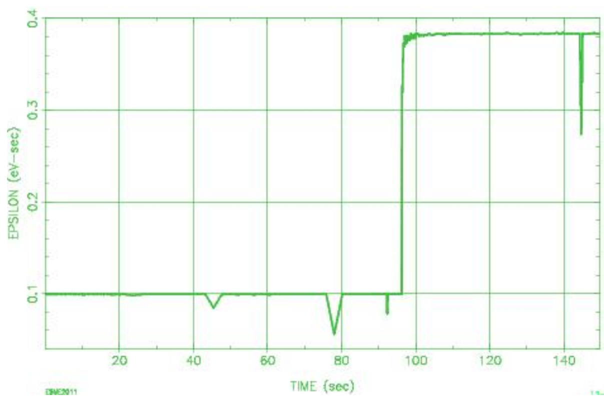

Figure 6: The emittance evolution during the first half of the acceleration cycle with Landau cavity kept on a constant phase. The γ_t jump scheme was implemented.

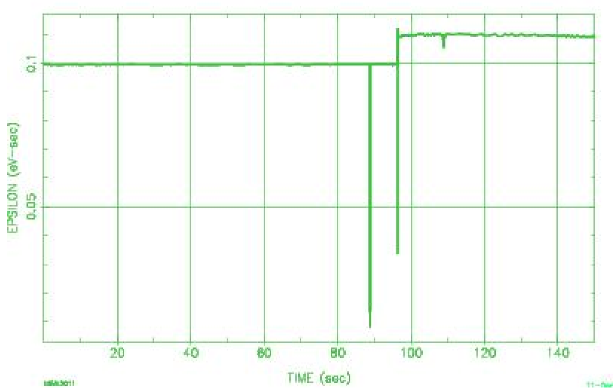

Figure 7: The emittance evolution during the first half of the acceleration cycle, with Landau cavity phase jumps from 0 *deg* to 180 *deg*. The γ_t jump scheme was implemented.

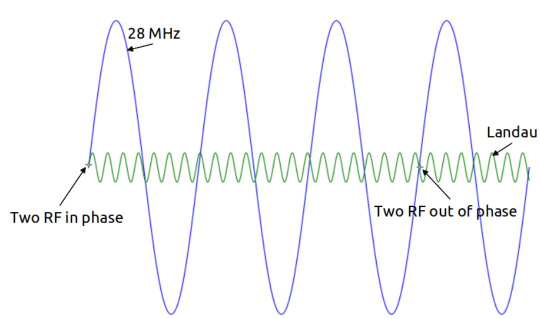

Figure 8: The phase of the 28 MHz and Landau cavity at two nearby bunches (stars) in RHIC. The phase of the Landau cavity is 0 deg at the first bunch, 180 deg at the second bunch.

This means the Landau cavity phase switches back and forth between 0 *deg* and 180 *deg* at the bunches in the bunch train. Also, when the phase of the Landau jumps from 0 *deg* to 180 *deg* for half of the bunches, the phase of the Landau cavity would jump from 180 *deg* to 0 *deg* for the other half. The emittance evolution of those bunches crossing transition is shown in Fig. 9. The emittance increase was ~ 5%.

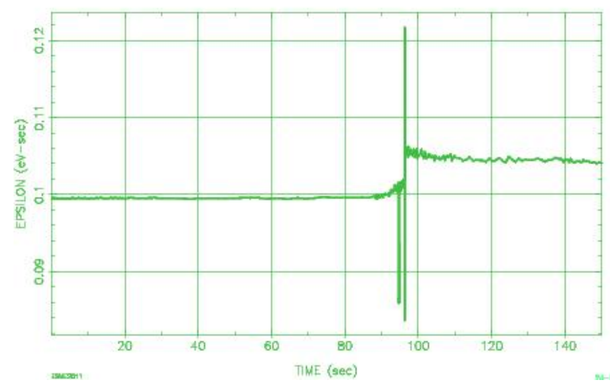

Figure 9: The emittance evolution during the first half of the acceleration cycle, with Landau cavity phase jumps from 180 *deg* to 0 *deg*. The γ_t jump scheme was implemented.

SUMMARY

The longitudinal dynamics simulation was performed with code ESME, to answer questions related to utilizing Landau cavity for transition crossing. The beam emittance evolution through transition, with turning on Landau before transition, was studied in the simulation. It was shown that the beam emittance would blow up if the Landau cavity phase was held constant. The beam emittance would be preserved if the phase of Landau cavity was changed from 0 to 180 *deg* for half of the bunches and 180 to 0 *deg* for the other bunches at transition in RHIC. The configuration of the Landau cavity in Run-14 was guided by the simulation results. The longitudinal beam emittance was well preserved during the transition crossing in the operation.

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