Rebucketing after transition in RHIC*

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Abstract

Rebucketing in the Relativistic Heavy Ion Collider, *RHIC* , describes the process of moving the beam from the 26MHz accelerating system to the 196MHz storage system with as little beam loss as possible. This puts a stringent requirement on the beam longitudinal area done at top energy. The ample bucket space after, but not too close to, transition is explored by computer simulation to relax such stringent conditions.

I. Introduction

The ultimate task of the *RHIC RF* systems, which has one set of accelerating cavities and a set of storage cavities [1], is to put the bunches in storage cavities, with as little beam loss as possible, for physics experiments. The longitudinal emittance determines how difficult it is to make such a "handoff" between accelerating cavities and storage cavities [2].

The storage system buckets are approximately 5 ns long. Therefore, given a margin of 80% for safety, the bunches have to be made no greater than 4 ns long in order for the storage system to rebucket them. The bunch length is defined as containing 95% of the particles in a bunch. The nominal bunch length for gold beam at top energy is greater than 5 ns. Means have to be sought to make shorter bunches. Away from the immediate transition region in which the bunch is naturally short, the bunch length can be shortened (or lengthened) by manipulating the bucket height or the bucket phase relative to the bunch center.

Since the bunch length is inversely proportional to $V^{\frac{1}{4}}$, the adiabatic compression of bunch length has a quartic power law for the voltage required. For instance, a bunch is $6ns$ long, which is typical for gold at top energy, at voltage of $300kV$. To compress it down to $4ns$, the voltage has to increase to $300*(\frac{6}{4})^4 = 1.5MV$, which is excessive in comparison with the maximum available voltage from the accelerating cavities.

The bunch rotation technique is a non-adiabatic way to shorten the bunches. Its main advantages are speed, and lower requirements on the available voltage from the cavities. Its limitation is that it develops long tails if the bunch area is too large. In this note, we explore by means of computer simulation the region after transition where ample bucket area is available to suppress the long tails, and thus eliminate large beam losses.

II. Beam dynamics after transition

The longitudinal particle dynamics are governed by the single particle Hamiltonian

$$H = \frac{1}{2E_0}(\frac{hc}{R_0})^2 \frac{\eta}{\gamma} W^2 + \frac{eV_{rf}}{2\pi h}[\cos\phi - \cos\phi_s + (\phi - \phi_s)\sin\phi_s] + O(W^3) \quad (1)$$

where γ is the Lorenz factor of the beam, E_0 is the particle rest energy, h is the rf harmonic number, R_0 is the average radius of the ring, $W = \frac{E-E_s}{\omega_{rf}}$, E_s is the synchronous energy, ω_{rf} is the angular rf frequency, $\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}$ is the phase slip factor, and ϕ_s is the synchronous phase. In the case of a constant speed magnet ramp ($\dot{B}$) and constant rf gap voltage (V_{rf}), the behavior of a particle is complete determined by the ratio of $\frac{\eta}{\gamma}$. Solving the equation with respect to the top energy ($\gamma = 108$, $\gamma_{tr} = 22.8$)

$$\frac{\eta}{\gamma} = (\frac{\eta}{\gamma})_{top} \quad (2)$$

we find that equivalent point $\gamma \approx 26$, where the particle dynamics behave exactly the same as at top energy.

The bucket size scales inversely proportional to the square root of how close it is to transition, i.e. $A_{bkt} \propto \frac{1}{\sqrt{\gamma - \gamma_{tr}}}$. It's clear that if we move from the equivalent point down close to transition, the bucket size increases dramatically comparing with that of around top energy where the bucket size hardly changes.

III. Simulation Results

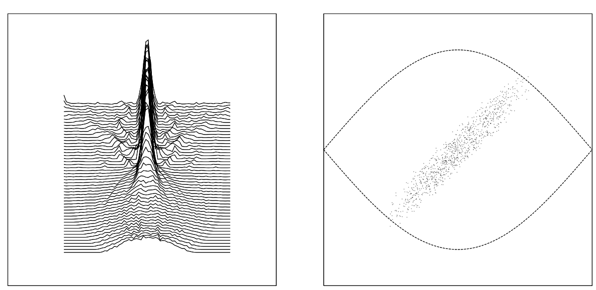

Figure. 1. On the left: mountain range plot of the bunch shape in a rebucketing process from simulation. On the right: phase space plot when the bunch is mismatched after shifting the stable fixed point back to the center of the bunch

The basic idea of bunch rotation is to first lengthen the bunch and then make it mismatched to the bucket. In *RHIC* rebucketing, the procedure goes as follows. First we lengthen the bunch by shifting the unstable fixed point of the bucket to the bunch center. After a fraction of a synchrotron period the bunch has elongated along the separatrix of the bucket. The stable fixed point is then shifted back to the bunch center again. The bunch,

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being mismatched, starts to rotate in the phase space. After the bunch rotates 3/8 of a synchrotron period to reach its minimum bunch length position, the storage cavities are turned on and the accelerating cavities are turned off. Figures 1 and 2 illustrate the rebucketing process, for a particularly large bunch area, to illustrate the beam loss situation.

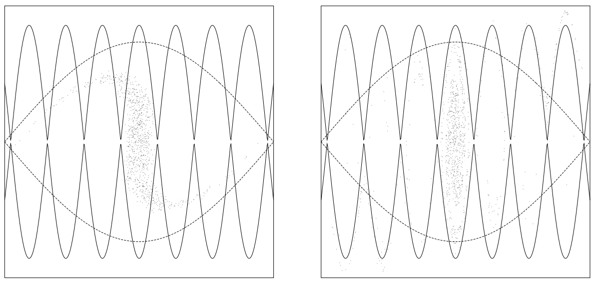

Figure. 2. On the left: phase space plot when the bunch is at its narrowest. On the right: phase space plot several synchrotron periods later after rebucketing.

We simulate the rebucketing process for gold beam in three cases: stationary bucket, stationary bucket with the nonlinear $\alpha_1 = -0.6$ [3] and moving bucket. In each case, we scan for bunch areas of 0.6, 0.7, 0.8 and 1.0 $eV\,s/u$, and for each bunch area we scan at 6 different points away from transition range from $\Delta\gamma = \gamma - \gamma_{tr} = 0.7$ to $\Delta\gamma = 3.2$. In all cases the rf voltage is $600kV$, and $\dot{B} = 0.05T/s$ for the moving bucket, the nominal ramp rate for *RHIC* .

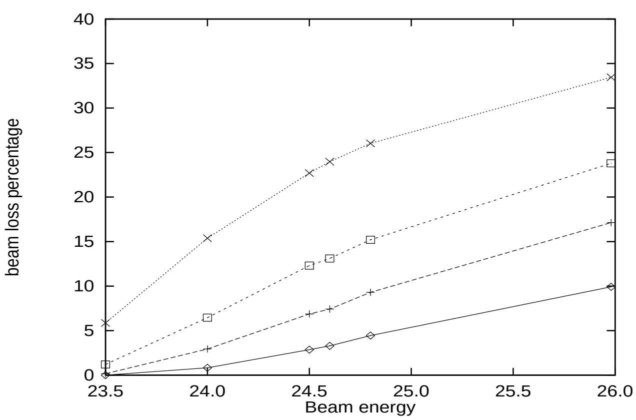

Figure. 3. In a stationary bucket. Percentage of beam loss vs. γ. The curves from top to bottom correspond to bunch area of 1.0, 0.8, 0.7, 0.6 eVs/u.

For case 1, in Figure 3, we plot the beam loss as a function of how far away from transition for various bunch areas. Upon close examination, these curves are united through a reduced variable $\epsilon^x \Delta\gamma^{1-x}$, where ϵ is the bunch area and $x = 0.71$ from data fitting. In Figure 4, we plot the beam loss with respect to the reduced variable. Figures 5 and 6 are for the cases 2 and 3 respectively. As expected, when the non-linear factor is considered, the beam in the phase space distorted more, and thus the beam loss becomes worse. If we use a moving bucket to accomplish the rebucketing, the bucket size is reduced, and the beam loss increases.

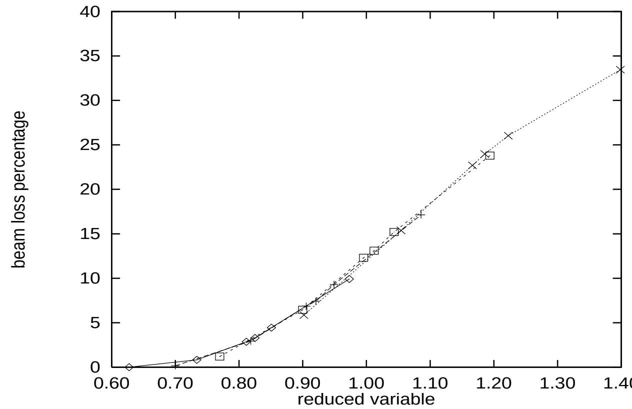

Figure. 4. In a stationary bucket. Percentage of beam loss vs. reduced parameter $\epsilon^x \Delta\gamma^{1-x}$.

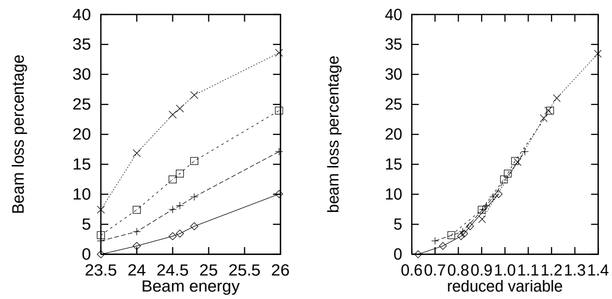

Figure. 5. In a stationary bucket with $\alpha_1 = -0.6$. Left figure:Percentage of beam loss vs. γ. The curves from top to bottom correspond to bunch area of 1.0, 0.8, 0.7, 0.6 eVs/u. Right figure: Percentage of beam loss vs. reduced parameter $\epsilon^x \Delta\gamma^{1-x}$.

From these beam loss curves and the reduced variable, we can plot curves for constant beam loss in the space of bunch area and $\Delta\gamma$. Such a plot allows us to choose where rebucketing should take place. Each point on a curve represents at what energy the rebucketing takes place and the maximum bunch area that will give rise of the amount of beam loss. For example, if we choose to tolerate 5% beam loss while rebucketing at energy $\gamma = 25.5$, following on the 5% curve, the maximum bunch area will then be $0.55eVs/u$. That is, any bunch area greater than $0.55eVs/u$ will result more than 5% beam loss. It's clear from Figure 7 that the closer toward transition ($\gamma_{tr} = 22.8$) the less beam loss will occur, and the larger bunch area that it can tolerate. Of course, we can't arbitrarily get too close to transition, because of other complications associated with transition itself.

IV. Conclusion

Comparing with rebucketing at top energy, rebucketing after transition has some good features. First, it does not require any new hardware investment, it is just a matter performing the same task at a lower energy. Second, since it is performed at low energy, any beam loss has less impact on the performance of the superconducting magnets. Third, it opens up the emittance bottleneck. Depending on what bunch area will result from transition, we can choose many different points to rebucket the beam.

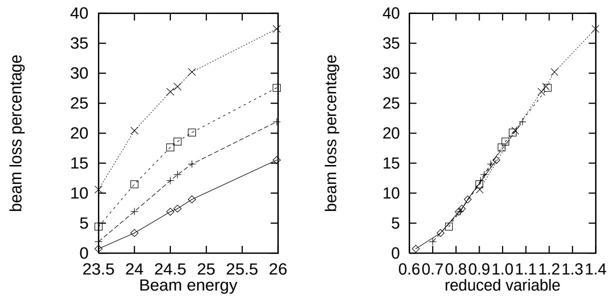

Figure. 6. In a moving bucket. Left figure:Percentage of beam loss vs. γ. The curves from top to bottom correspond to bunch area of 1.0, 0.8, 0.7, 0.6 eVs/u. Right figure: Percentage of beam loss vs. reduced parameter $\epsilon^x \Delta\gamma^{1-x}$.

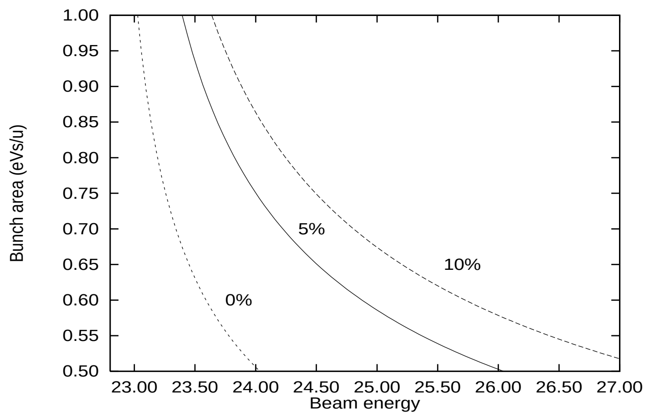

Figure. 7. Constant beam loss curves for rebucketing in a stationary bucket.

Fourth, it can be conducted both with stationary buckets (zero magnet ramp) and moving bucket (nonzero magnet ramp). The subsequent acceleration is done by the storage system.

V. Acknowledgment

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References

[1] The Conceptual RHIC RF design. Tech Note, RHIC/RF-22, 1994.

[2] D. P. Deng Gold Beam Longitudinal Emittance Limit at Rebucketing. Tech Note RHIC/RF-18, 1994

[3] J. Wei *et. al.* in these proceedings for its effects.