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Gold beam longitudinal emittance limit at rebucketing

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Abstract

In *RHIC* , rebucketing describes the process of transferring beam from accelerating cavities into storage cavities. Large longitudinal emittance beam loses more particles in the process. This note studies the relationship rebucketing efficiency with gold beam longitudinal emittance, and concludes that at large emittance higher efficiency demands either high voltage on the accelerating cavities or additional higher harmonic cavities to extend the linear region.

1 Introduction

The ultimate task of the *RF* systems is to put the bunches in storage cavities, with as little beam loss as possible, for heavy ion physics experiments. The longitudinal emittance determines how difficult it is to make such a "handoff" between accelerating cavities and storage cavities.

Rebucketing describes the process of transferring the beam from accelerating system to storage system. The storage system provides approximately $5ns$ bucket length, therefore given a margin of 80% for safety, the bunches have to be shorter than $4ns$ in order for the storage system to rebucket them. Away from transition region in which the bunch is naturally short, the bunch length can be shortened (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 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 volts from accelerating cavities.

2 Bunch rotation

The longitudinal emittance, essentially the product of momentum spread and bunch length, is an invariant quantity, under adiabatic conditions. If the momentum spread gets reduced, the bunch length gets increase. Then when the bunch is mismatched (non-adiabatic condition) with the bucket, the bunch as a whole rotates and after a quarter of synchrotron period, the initial momentum spread (small) has become the bunch length (short). The momentum and time are exchanged [1]. This is a non-adiabatic way to shorten a bunch, which lengthens the bunch first. See Figure 1.

The bunch can be lengthened, as a first step of shortening, in two ways. By adiabatically reducing RF voltage, the momentum spread thus is reduced, but the bunch length is increased to maintain the invariant of emittance. The other way is to shift the stable and unstable fixed point of the bucket back and forth to the bunch center (see Figure 2). After a fractional of synchrotron period the bunch has elongated along the sepatrix of the bucket, shift the stable fixed point back to the bunch center again. The bunch being unmatched starts to rotate in the phase space, unlike the previous case, the bunch has to rotate 3/8 of a synchrotron period to reach its minimum bunch length position. See Figure 2.

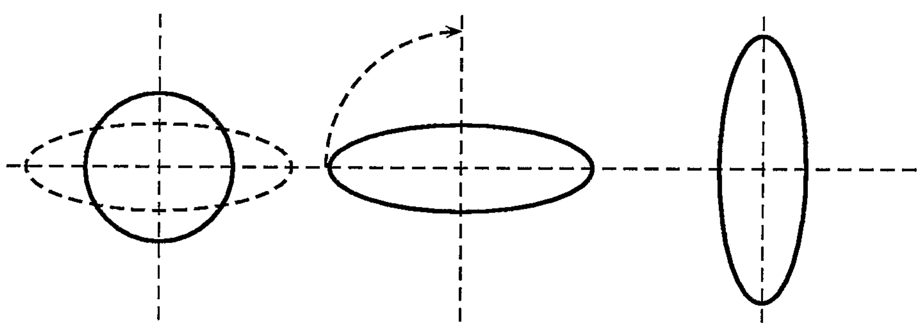

Figure 1: Bunch rotation. Bucket not shown.

3 Beam loss mechanism

The rebucketing occurs when the bunch becomes narrowest, at which the accelerating cavities are switched off and the storage cavities are switched on. If there are particles that are outside of the intended bucket, they either wonder off or are trapped by other buckets. Figure 3 shows mountain range plot of simulation results, where longitudinal emittance $1.0\, eVs/u$ is used. The bunch becomes narrower and narrower; and after the storage cavities is turned on, the bunch stays almost contant but some beam starts to drift away and some beam gets trapped by other buckets. Figure 4 5 6 show the phase space plots at initial point, at rebucketing and the final point corresponding to Figure 3. The initial long bunch is produced by shifting the RF phase back and forth between the stable and unstable fixed points.

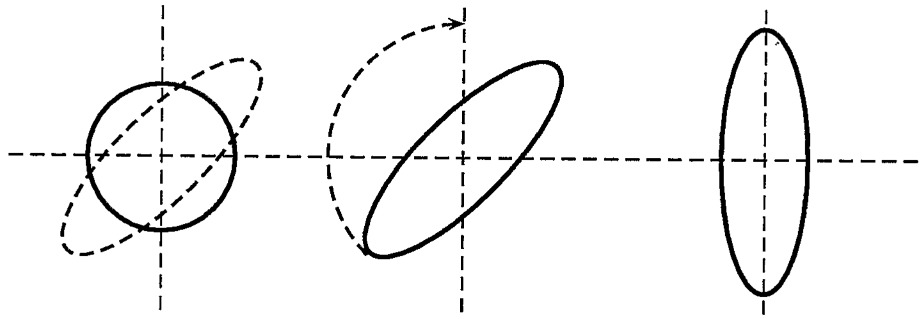

Figure 2: Phase jump back and forth between unstable and stable fixed point. Bucket not shown.

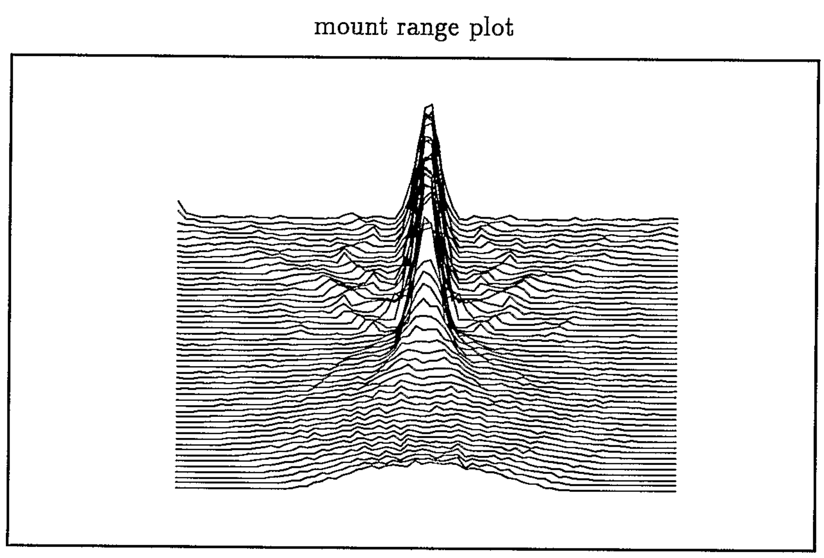

Figure 3: Mountain range plot of a rebucketing process from simulation

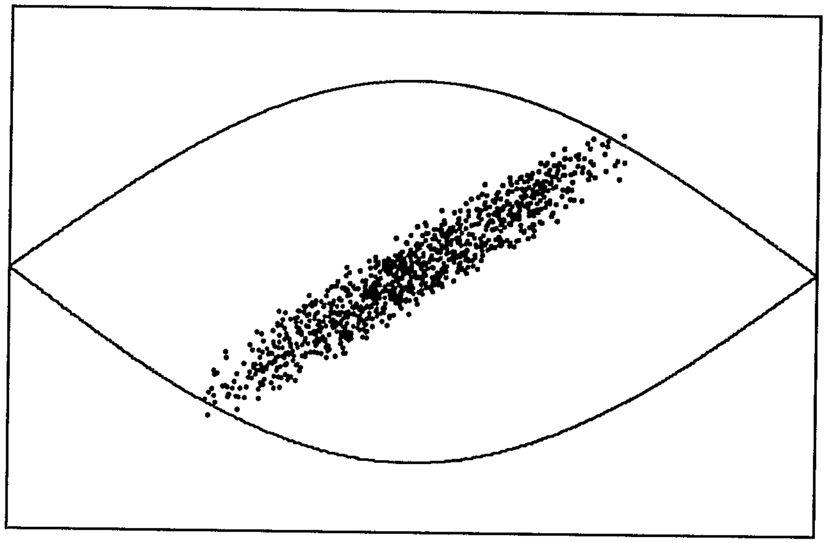

Figure 4: Phase space plot when the bunch is mismatched after shifting the stable fixed point back to the center of the bunch

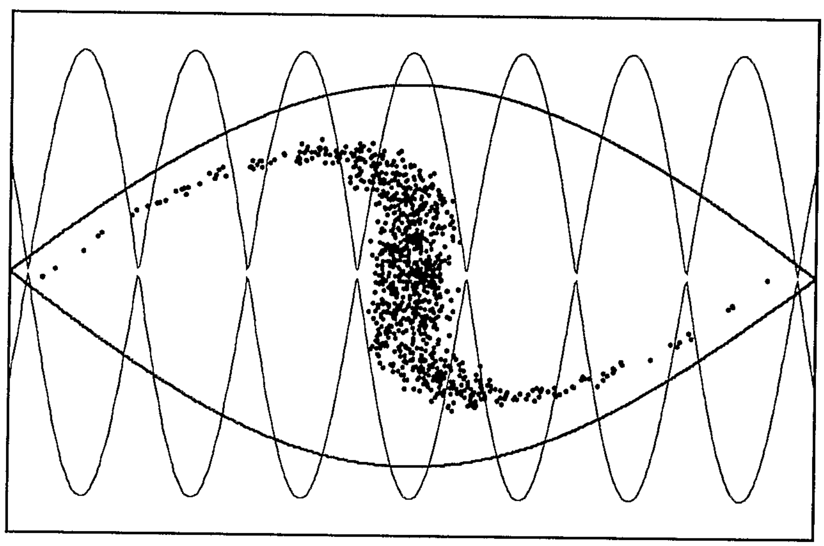

Figure 5: Phase space plot when the bunch is at its narrowest.

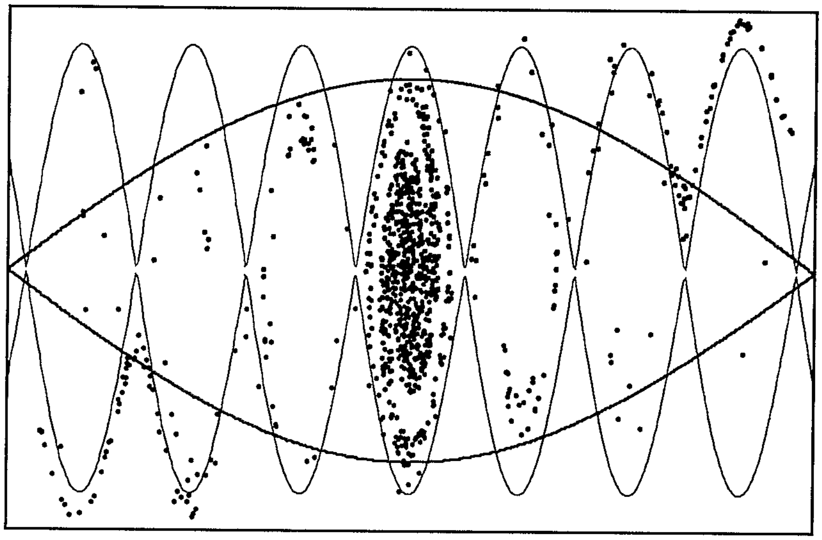

Figure 6: Phase space plot several synchotron periods later after rebucketing.

It's clear that the beam loss is due to the distortion of the bunch from rotation process. The large the longitudinal emittance, the severe the distortion. So is the beam loss.

4 How to reduce the beam loss

It's apparent that in order to reduce the beam loss, we need to reduce or eliminate the distortion from the non-linear region of the bucket. Figure 7 depicts distortion situation in a single accelerating cavity system. Let's look at two points A and B, A is in the linear region whereas B is farther away from it. The synchrotron frequency difference $\delta f_{\nu,AB}$ between points A and B is

$$\delta f_{\nu,AB} \approx \frac{\phi_B^2}{16} f_\nu \tag{1}$$

where ϕ_B is the phase angle at point B. If $\delta f_{\nu,AB}$ is small, the distortion is small. Given ϕ_B, the only way to lower $\delta f_{\nu,AB}$ is to lower f_ν, which means to increase the voltage on the accelerating cavities.

With a second harmonic RF system, the distortion can also be reduced [2]. The combined voltage waveform can be written down as

$$V(t) = V_1(\sin(\omega t) + k\sin(2\omega t - \pi)) \tag{2}$$

where V_1 is the amplitude on the first harmonic system, k is the coefficient to determine the amplitude on the second RF system. The phase difference π is chosen.

What the second harmonic system does is to extend the linear region, see Figure 8 for the more linearized combined waveform. The synchrotron frequency f_ν is proportional to the first derivative

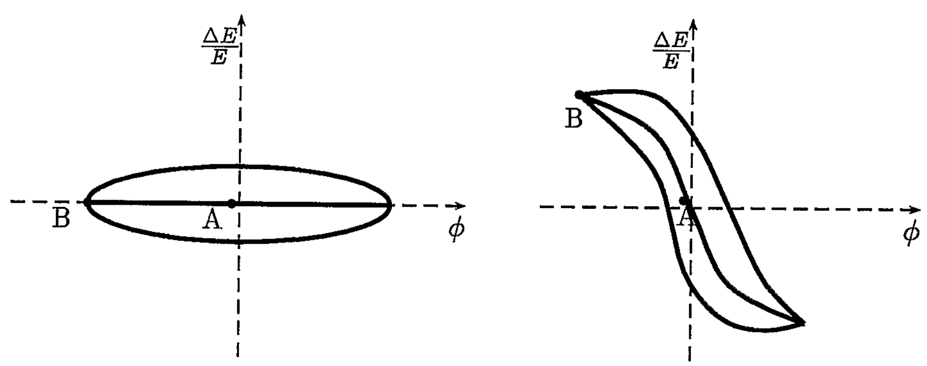

Figure 7: Distortion due to nonlinear effect in the bucket.

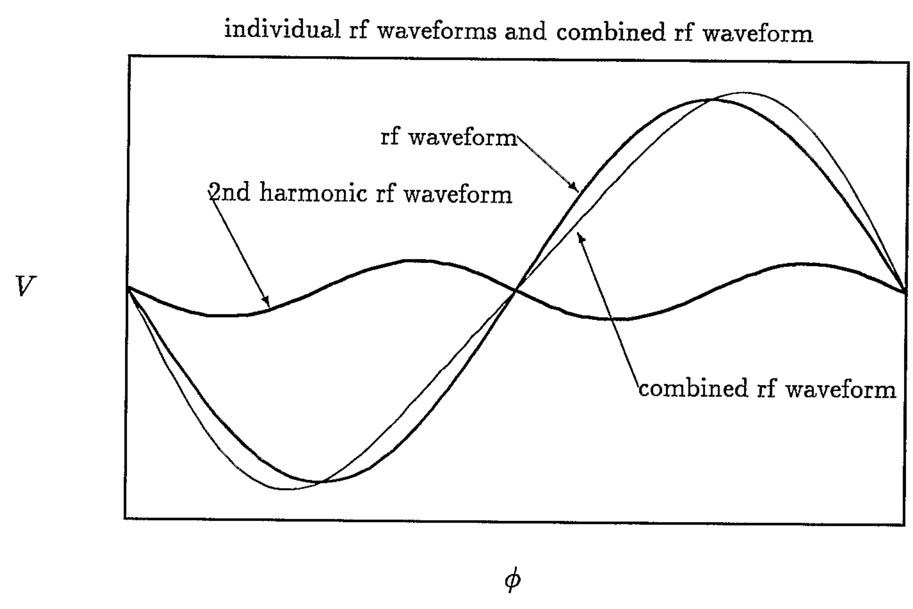

Figure 8: Individual rf waveforms and combined rf waveform.

Variation of synchrotron frequency f_ν away from bucket center.

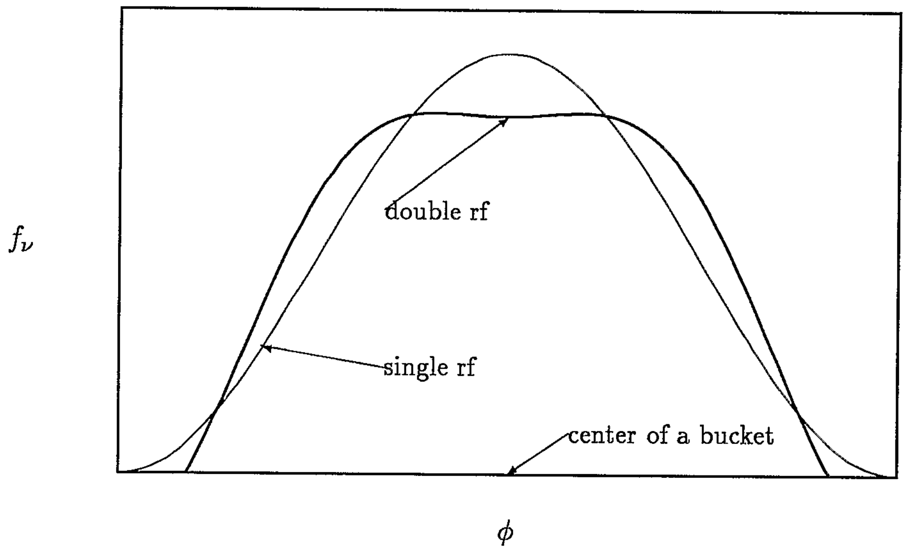

Figure 9: Synchotron frequencies in single and double rf systems.

of the waveform, which reads as

$$V'(\phi) = V_1(\cos(\phi) + 2\,k\cos(2\phi - \pi)) \tag{3}$$

The linear region could be defined as a region that the synchrotron frequency is almost a constant, see Figure 9. The combined RF system has a much wider linear region.

5 Rebucketing efficiency

In this section, we list the results from simulation on the efficiency of rebucketing for gold beam at top energy in various conditions. In the single rf system scenario,

- $V_{acc} = 600\,kV$ and $V_{storage} = 2\,MV$, see Figure 10
- $V_{acc} = 600\,kV$ and $V_{storage} = 6\,MV$, see Figure 11
- $V_{acc} = 800\,kV$ and $V_{storage} = 6\,MV$, see Figure 12

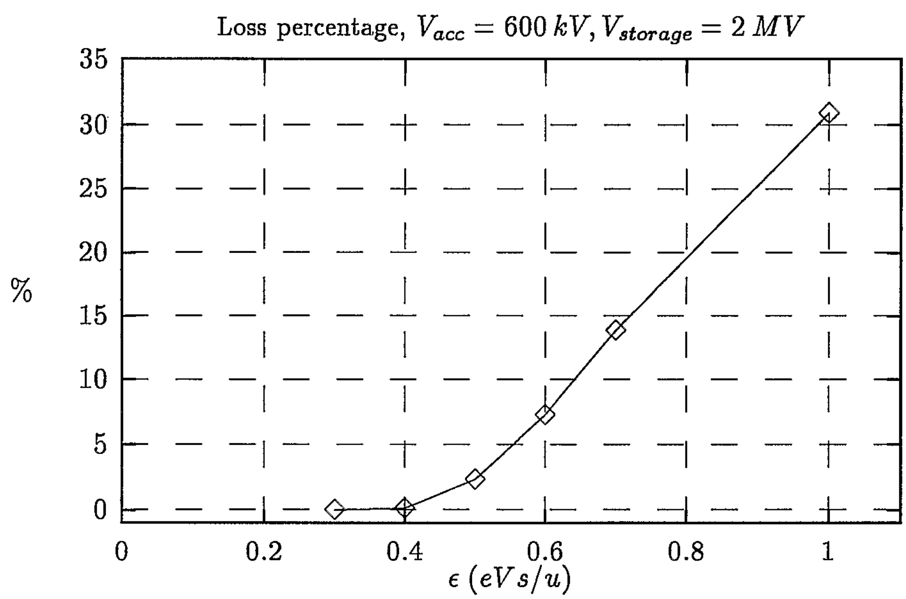

Figure 10: Beam loss *vs.* emittance

The first two cases is to make a point that higher storage voltage improves rebucketing efficiency more at lower emittance, but not so great at higher emittance. The second and third cases show that higher accelerating voltage increase the rebucketing efficiency.

In the scenario of two rf system,

- $V_{1,acc} = 300\,kV, V_{2,acc} = -45\,kV$ and $V_{storage} = 6\,MV$, see Figure 13
- $V_{1,acc} = 600\,kV, V_{2,acc} = -90\,kV$ and $V_{storage} = 6\,MV$, see Figure 14

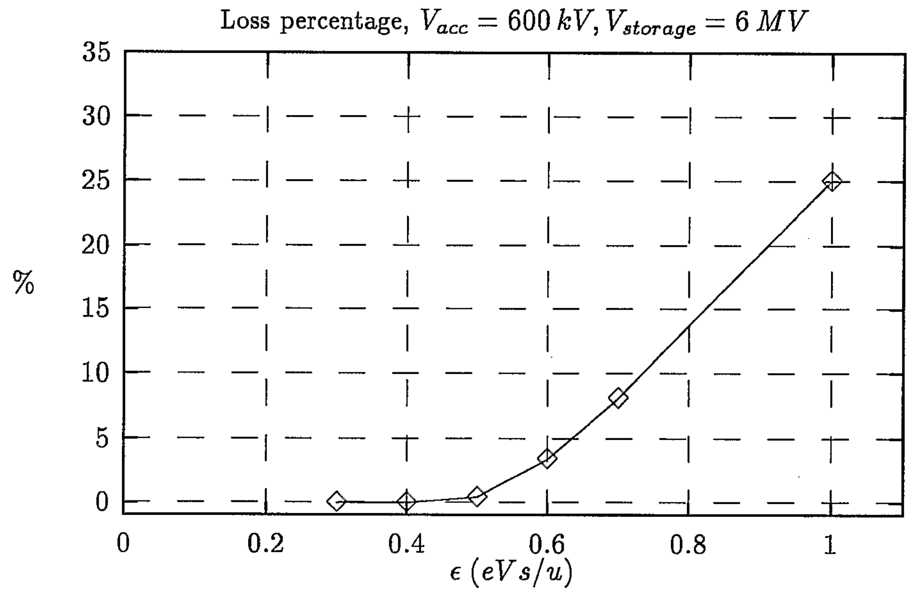

Figure 11: Beam loss *vs.* emittance

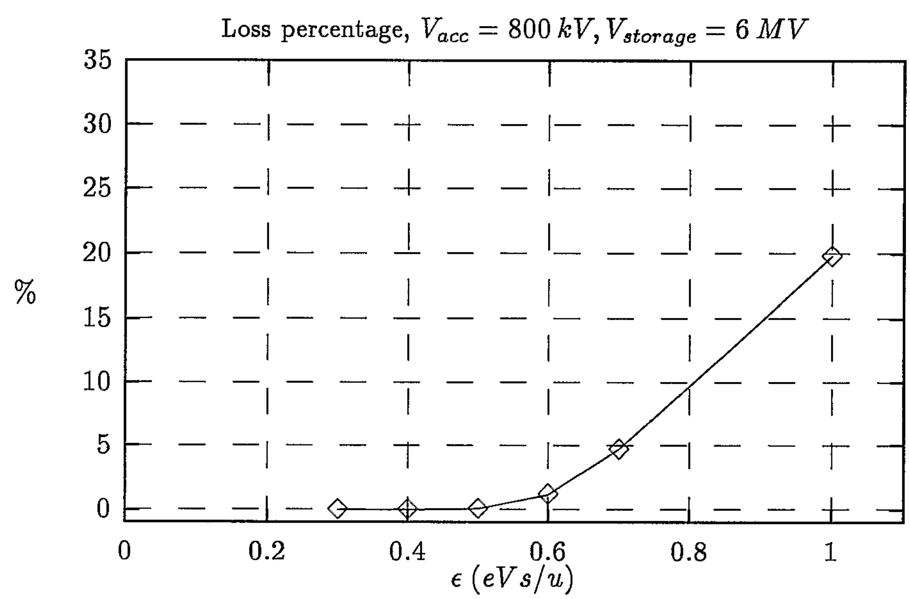

Figure 12: Beam loss *vs.* emittance

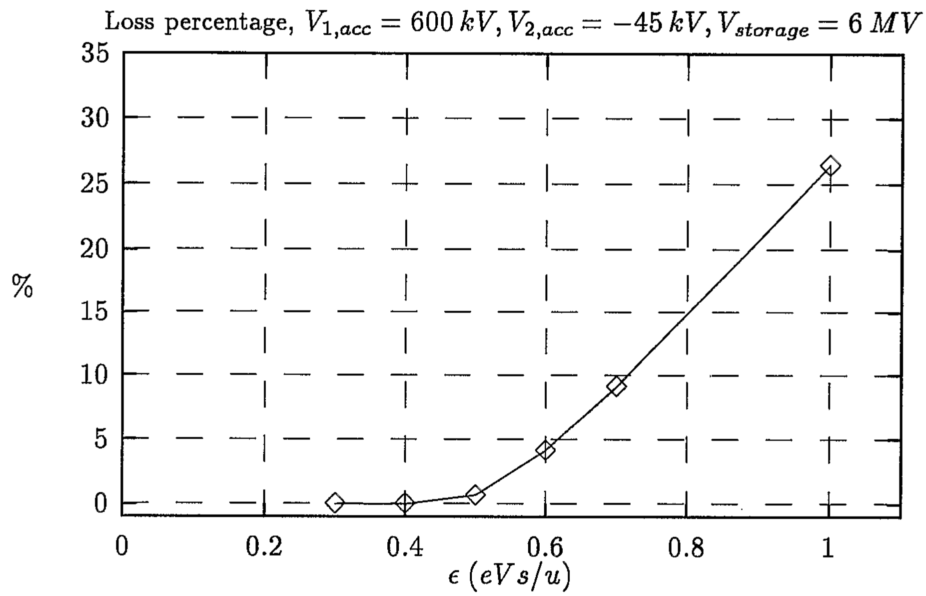

Figure 13: Beam loss *vs.* emittance

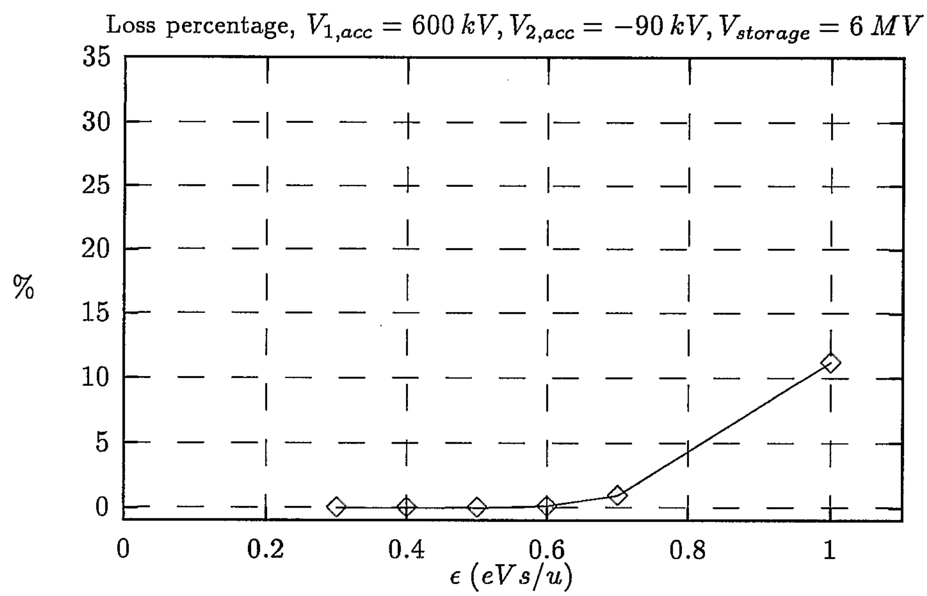

Figure 14: Beam loss *vs.* emittance

In all these studies, the remnant voltage from the storage system, which strongly affects the beam quality through transition, is also considered. Priori to the rebucketing, a $20kV$ voltage from storage system also exerts on the beam, however, the effect of the remnant voltage is negligible at rebucketing.

6 Conclusions

The basic conclusion is that at large longitudinal emittance high rebucketing efficiency has to overcome the nonlinear distortion in the bunch rotation technique, either by raising the voltage on the accelerating cavities or applying an additional second harmonic cavity. The limiting emittance is determined by how much loss is permissible. In the RF configuration that the accelerating cavities can provide up to $600\,kV$. If no loss at all is required, the limiting emittance has to be less than $0.4\,eVs/u$. If 5% loss can be tolerated, the limiting emittance is as high as $0.6\,eVs/u$ (or $0.8\,eVs/u$ in a double RF system.).

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