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BEAM LOSS IN INITIAL ACCELERATION PROCESS OF KEK BOOSTER

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Summary

Beam intensity in KEK booster decreases within one milli second to about a half of the injected. This loss is explained by the mechanism of the increasing shift of the equilibrium orbits due to the rapid growing of the momentum spread accompanied with the increase of the accelerating RF voltage. The calculation of this loss was made numerically taking into account the beam distribution in the horizontal phase space resulting from the multi turn injection, momentum distribution of the injected beam and the distribution in the RF bucket. An important point in this calculation is that the number of the particles which takes relatively large momentum deviation in the bucket is not so small as expected, for example, from a Gaussian distribution but rather large because of the rotation of the particles in the bucket due to the synchrotron motion. Therefore many particles experience rather large shift of the equilibrium orbit, which results in much loss of the beam as is observed.

Introduction

After the success of the first acceleration of the booster beam, many efforts have been made to increase the intensity and quality of the beam. One of them is the investigation of the loss mechanism in the beginning of the acceleration. As shown in Fig.1, the beam intensity rapidly decreases to about a half within 1 msec after the injection. So far much doubt has been thrown to the RF capture process of the beam. According to the simulation of the process, the capture efficiency 96 % could be obtained.[1] The RF voltage is rapidly increased for the purpose of the adiabatic capture. In spite of many trials of the various schemes of the increasing RF voltage, the transmission of the beam up to 1 msec has been less than 60 %.[2] In this paper we will show that the beam loss can be explained instead of the RF capture process but with another mechanism which is summarized above.[3]

Distribution in the horizontal phase space

The proton beam with the energy 20 MeV is injected into the booster by the multi turn injection method. The horizontal emittance of the injected beam is $22\pi \times 10^{-6}$ rad•m where 80 % of the beam is contained. Beam distribution in the phase space was calculated on the following of the multi turn process. The calculated acceptance is $710\pi \times 10^{-6}$ rad•m. The aparture W is determined by the septum of the septum magnet, which locates at 50 mm apart from the center line. Owing to the betatron oscillation, the particles rotate in the phase space. So it is required for the estimation of the beam loss to know the distribution within the restricted acceptance A_r, which is defined by $A_r = (x_A/W)^2 A$ with the parameter x_A $(0 \leq x_A \leq W)$. Assuming a constant distribution within the emittance $22\pi \times 10^{-6}$ rad•m, we get the distribution y in the restricted acceptance as shown in Fig.2-a. Instead of a square relation as expected first, it follows the linear relation

$$y = \alpha x_A - \beta, \qquad (1)$$

where $\alpha = 2.56$ and $\beta = 28.2$ with arbitrary unit. This is because the beam injected separately and spirally into the phase space.

Distribution in the RF bucket

The momentum distribution of the injected beam is on the average a triangular type as shown with σ_L in Fig.3-a. The maximum width $(\frac{\Delta p}{p})_{max}$ is about ±0.48 %. Next we consider the distribution in the RF bucket.

Figure 4 shows the bucket height $(\Delta p/p)_e$ and the synchronous phase ϕ_s as well as the bucket area A_{RF} and the synchrotron oscillation frequency Ω_s in regard to the usual operation of the RF voltage V during the acceleration. The bucket height is ±0.52 % at injection and rapidly increases to the maximum 1.23 % at 1 msec. The bucket height at injection is settled to nearly the same with the momentum spread of the injected beam because on this condition the beam is more stable longitudinally during the acceleration.[4]

Owing to the synchrotron motion, the beam rotates along the trajectory in the bucket as shown in Fig.3-b, where only a quarter of the bucket is shown, and experiences the maximum momentum deviation $(\Delta p/p)_x$ which belongs to the trajectory shell x (= A ∿ J).[*] Figure 3-c is the distribution of the beam belonging to each trajectory shell at the injection, which is proportional to the summation of the product of the small area a (see Fig.3-b) and the momentum distribution σ_L along the trajectory shell. Note in Fig.3-c that the distribution of the beam which makes larger momentum deviation is more than that of a smaller deviation and that some beams are injected outside the bucket as denoted by $(\Delta p/p)_K$.

With the increase of the RF voltage, the bucket height increases and the phase spread shrinks from 0 ∿ 360° at injection to 8 ∿ 298° at 1 msec. Since the bucket shape at injection and that at 1 msec are not much different , we assume that the beam keeps to belong to the same or corresponding trajectory shell up to 1 msec.

Calculation of the beam loss

The beam injected with the momentum deviation $(\Delta p/p)_i$ takes an equilibrium orbit $\Delta R_i (= x_p (\Delta p/p)_i)$ where x_p is the momentum dispersion. The effective aperture of such a beam is $(W - \Delta R_i)$, so that the distirbution in the phase space is $y_i = \alpha(W - \Delta R_i) - \beta$. In the course of the rotation in the RF bucket, the beam takes until 1 msec several times the maximum momentum deviation $(\Delta p/p)_x$ associated to the trajectory shell, since the synchrotron oscillation frequency is 3 ∿ 8 kHz in the region of this time. The bucket height $(\Delta p/p)_e$ increases rapidly and takes the maximum around 1 msec as shown in Fig.4. Therefore the beam experiences until 1 msec the maximum momentum deviation $(\Delta p/p)_x$ corersponding to the maximum bucket height. Then the distribution is reduced to $y_x = \alpha(W - \Delta R_x) - \beta$, where $\Delta R_x = (\Delta p/p)_x$ (at 1 msec). Since the number of the particles whose momentum is $(\frac{\Delta p}{p})_i$ is proportional to the product $a\sigma_L$ corresponding to the momentum deviation, the number of the particle transmitted up to 1 msec is given by

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$$n_x \propto \frac{(W - \Delta R_x) - \beta}{(W - \Delta R_1) - \beta} a \cdot \sigma_L \qquad (2)$$

This calculation was made for every small area in Fig.3-b. Taking into account that only 76 % of the beam is injected into the bucket, the over all transmission up to 1 msec is 55 %.

In the above calculation we have assumed that the bucket height increases very slowly and that the beam injected outside the bucket is not captured during the acceleration. Really some beams are captured because of a rapid increase of the RF bucket (adiabatic capture).[1] So we have next calculated the transmission of the beam in the other extreme case that the bucket height at injection is the same with that at 1 msec. In this case the transmission is 68 %. The above calculation corresponds to the case with the aperture W = 50 mm. Really there is a closed orbit distortion about ±5 mm, so that the transmission is more reduced. Finally we arrive at the conclusion that the calculated transmission is about 60 %. This agrees with the observation as shown in Fig.1. The beam intensity decreases rapidly until 1 msec which agrees with the rapid increase of the bucket height $(\frac{\Delta p}{p})_e$ as shown in Fig.4. After this time the horizontal beam size decreases slowly due to the adiabatic damping. The gradual decrease of the intensity in Fig.1 from 1 msec to 13 msec is ascribed to the decrease of the bucket area A_{RF} as shown in Fig.4.

Figure 5 represents the beam intensities measured with fast and slow response monitors. The former indicates the build up of the filamentation with the period of a quarter of the synchrotron oscillation. The wavy structure of the latter coincides with the period of the filamentation. This supports that the beam loss is brought about by the shift of the equilibrium orbit as described above.

When a scraper is inserted little by little into the booster ring, the beam intensity decreases gradually. Figure 2-c represents the normalized intensity at 1 msec as a function of the scraper edge position. It reflects the distribution in the phase space and should be compared with Fig.2-a. The agreement is poor. This is because the shift of the equilibirum orbit due to the momentum deviation much contributes to the intensity. By taking into account the momentum distribution σ_x at 1 msec in the RF bucket shown with the shaded area in Fig.3-c, the normalized intensity is given by Fig.2-b. The agreement is very good when we take into account that Figs.2-a and b are obtained on the assumption of the aperture W = 50 mm. The real aperture is around 45 mm due to the closed orbit distortion. Therefore we only need to move the point P to the point Q in the figure.

In conclusion the beam intensity is much affected by the shift of the equilibrium orbit due to the momentum blow up because the beam, which experiences larger momentum deviation in the RF bucket during the synchrotron motion, has larger distribution than those with smaller momentum deviations as shown in Fig.3-c.

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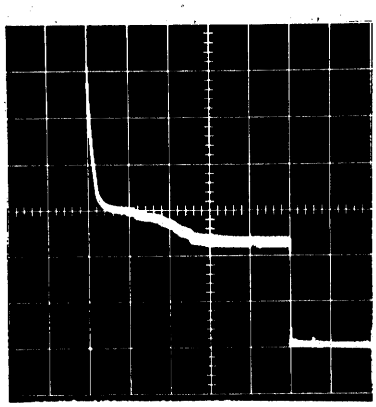

Fig.1 Beam intensity during accelerating period (5 msec/div.).

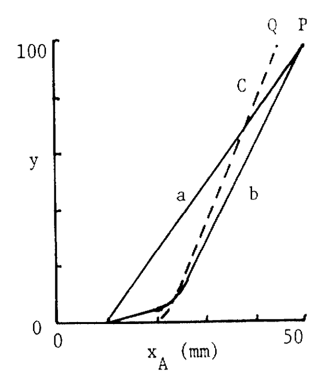

Fig.2 Beam distribution within the restricted acceptance (a), the distribution which takes into account the momentum distribution σ_x (b) and the normalized beam intensity measured with the use of a scraper (c).

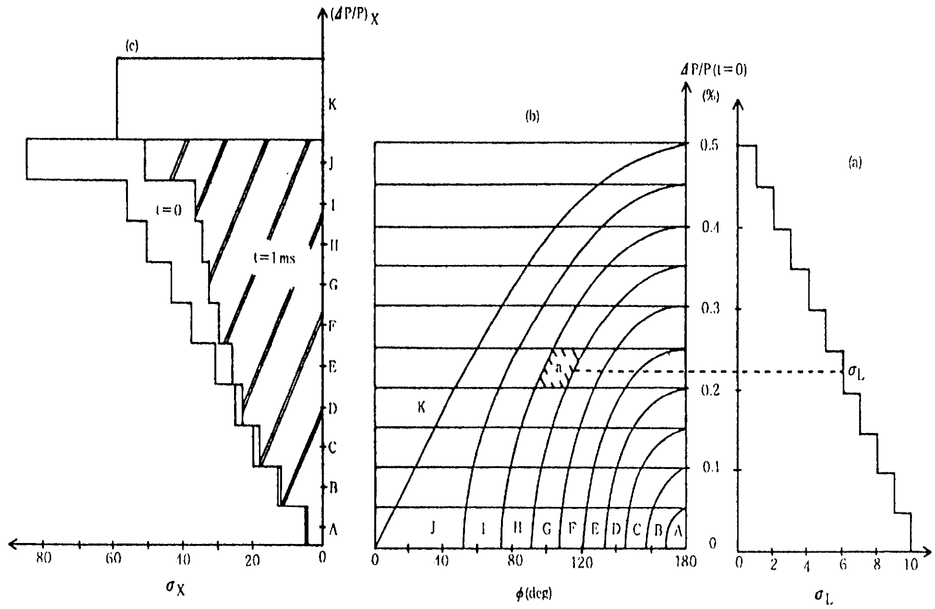

Fig.3 Averaged momentum distribution σ_L from linac (a), a quarter of the RF bucket at injection with the trajectory shells A ∿ J (b) and the distribution σ_x in the trajectory shells at injection and 1 msec (c).

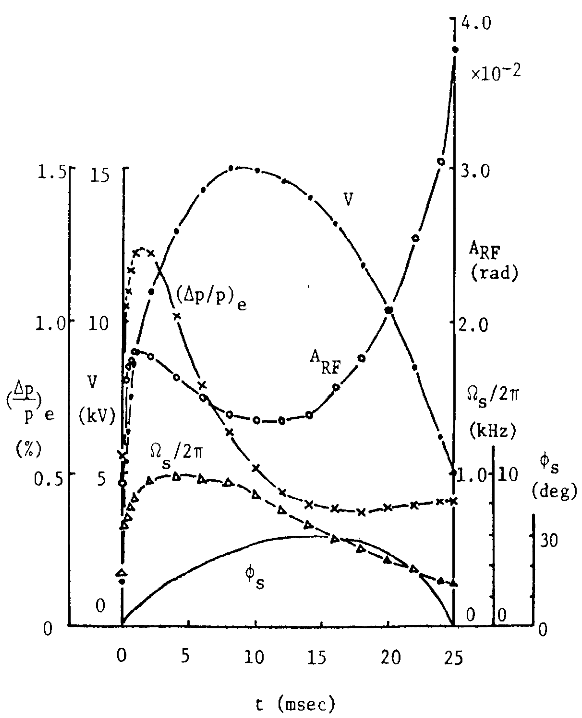

Fig.4 Accelerating RF voltage V, RF bucket height $(\Delta p/p)_e$, bucket area A_{RF}, synchrotron oscillation frequency $\Omega_s/2\pi$ and synchronous phase ϕ_s during the acceleration.

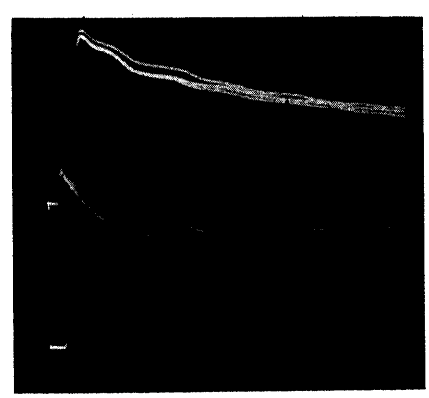

Fig.5 Beam intensity with fast and slow response monitors (50 μsec/div.).