SIMULATION STUDY OF FAST BEAM-ION INSTABILITY

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Abstract

A new type of an ion related instability which was named Fast Beam-ion Instability is suggested harmful to the machines such as B-factories and future linear collider. To study this kind of instability, a computer code was developed and employed during the experimental studies in TRISTAN AR of KEK. In this paper, the simulation study of this instability are presented.

1 INTRODUCTION

The Fast Beam-Ion Instability (FBII)[1,2,3] occurs when a bunch train pass through and interact with the ions which are produced by ionizing of the residual gas molecules in the vacuum chamber of an accelerator. The initial perturbation of the head bunch is coupled resonantly by the ions to the subsequent bunches in transverse direction and amplified, but the first bunch of the bunch train is assumed not to meet any ion. According to the linear theory[1,2], the oscillation amplitude of the n-th bunch (which is numbered from train-head) grows as

$$a_n(t) \propto e^{\sqrt{t/t_c}}, \; t_c \propto 1/n^2 , \quad (1)$$

where the t is the time, t_c the characteristic time of the FBII and $a_n(t)$ the amplitude of the n-th bunch at time t. From the formula (1), we can expect that the tail of the bunches will have a very fast growth of the oscillation amplitude.

The FBII is kind of transient phenomena. When there is an external damping and without any excitation, the oscillation of the each bunch will be damped out one by one from the head of the bunch train to the tail. Unfortunately, the beam is constantly excited by various noise effects in an accelerator. The net result is that each bunch in the bunch train will reach a certain rms oscillation amplitude which is determined by an equilibrium between the damping effect and the noise excitation. Therefore, the oscillation amplitude will be saturated at some level[4,5]. As the FBII is predicted very harmful to the accelerators with high-current, low-emittance and long bunch train such as B-factories and future linear collider, a few experimental studies were carried out at KEK AR, PLS and ALS[6,7,8] and the existence of the FBII was proved.

Because the growth of the instability is very fast, what we observed in the experiments is the saturated oscillation of FBII. Therefore, it is important to study this instability by systematic simulation to help us understand it fully. Moreover, the simulation will help us to know how to minimize or avoid the harm of FBII for real machine such as KEKB. In this paper, we will show some of the simulations on the effects that could affect the saturated oscillation amplitude of FBII.

2 SIMULATION METHOD

2.1 Model and Assumptions

The following assumption and interaction model was used in the simulation code. (1) The electron bunch was treated as the strong one, i.e. a rigid Gaussian bunch. Therefore only its center-of-mass movement was considered. (2) We assumed the bunch length was much larger than bunch transverse size and the bunch spacing was much larger than the bunch length, so only the transverse distribution was taken into consideration in the ionization process. Neither electron bunch length nor synchrotron oscillation was taken into account. (3) We took linear lattice transformation for electron bunches except for the beam-ion interaction. (4) For ions, we assumed there were limited number of ionization points in the ring and the ion motion was non-relativistic without longitudinal drift. It was assumed that the ion distribution at the creation time was the same as that of the parent electron bunch and their initial momentum were thermal motion at 300*K. (5) Ions were assumed to move freely in the bunch interval. (6) Only collision ionization process was considered.

2.2 Beam-Ion Force

For an ion with electric charge $+e$ in the field of the Gaussian bunch, the Coulomb force exerted on it can be calculated by applying Bassetti-Erskine formula[9] to get following equation:

$$F(x,y) = -2N_b r_e m_e c^2 f(x,y) \quad (2)$$

Where, (x,y) are the horizontal and vertical position respect to the bunch center, N_b the number of electrons in a bunch. m_e the electron mass, c the speed of light classic and r_e the electron radius. $f(x,y)$ is a function composed by complex error function W as:

$$f(x,y) = -\frac{\sqrt{\pi}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\left[W\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)W\left(\frac{\frac{x\sigma_y}{\sigma_x}+i\frac{y\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right] \quad (3)$$

where (σ_x, σ_y) are the beam size respectively.

So we can write the kick to the rigid electron bunch by an ion with distance of (x_{ie}, y_{ie}) and sum together for all of the ions as

$$\Delta y'_e + i\Delta x'_e = \frac{2N_b r_e}{\gamma}\sum_i f(x_{ie}, y_{ie}) \quad (4)$$

and similarly, due to the reaction force, the kick to a ion with mass M_A is

$$\Delta y'_i + i\Delta x'_i = -2N_b r_e c \frac{m_e}{M_A} f(x_{ie}, y_{ie}) \quad (5)$$

where γ is the ratio of the electron energy to its rest energy, and $(\Delta x_e^{'}, \Delta y_e^{'})$ and $(\Delta x_i^{'}, \Delta y_i^{'})$ is the transverse angle kick to the center-of-mass of electron bunch and ions respectively.

There is also a similar simulation code which was developed independently by K. Ohmi[10]. It can be employed for same simulation purpose and gives the similar results.

2.3 Effect of the Beam Feedback System

Assuming a feedback system with the proportional kick and the electronic system gain which can be adjusted to 1, then the damping rate $1/\tau$ can be written as[10]

$$\frac{1}{\tau} \approx \frac{\Delta y'}{\Delta y}\sqrt{\beta_p \beta_k}\,\frac{f_0}{2}\sin\varphi_{pk} \quad (6)$$

where $\Delta y'$ is kick angle, Δy the measured beam displacement, $\beta_{p,k}$ the beta function at pickup BPM and feedback kicker respectively, f_0 the revolution frequency, and φ_{pk} the phase advance from monitor to kicker.

The errors of the beam feedback system come from two major sources: error of the BPM and error of the kick strength. The former can be simulated by a uniformly distributed random number in the range of resolution. And the latter is also as a uniformly distributed random number in the range of the maximum error of the kick power. So if we know the damping time of the feedback system, we can simulated the effect of feedback damping and the noise on the instability.

3 SIMULATION RESULTS

The simulation is done based on the linear lattice of KEK Accumulating Ring (AR). The nominal parameters of AR is shown in Table 1. And the collision ionization cross section of 1.8 Mbarn for N_2 and CO was assumed.

In the simulation, the emittance ratio of vertical to horizontal is assumed as 5%. Mainly a 500-bunch train with 2 ns bunch space is used in the simulation. And our default assumptions are that the electrons per bunch are 1.34×10^{10}, the partial vacuum pressure of N_2 and CO is 100 nTorr and the damping time of the feedback system is 100 μs with 20 μm resolution of the BPM and 1% kick error. The radiation damping effect is neglected.

Table 1 Machine parameters of AR

Circumference	C	377.2 m
RF frequency	f_{RF}	508.58 MHz
Beam energy	E	2.5 GeV
Radiation damping time	τ_x, τ_y	42 ms
	τ_ε	21 ms
Emittance	ε_x	4.46×10^{-8} m
Averaged beta function	$\bar\beta_x/\bar\beta_y$	5.95 m/5.87 m
Beta function at the BPM	β_{xm}/β_{ym}	13.6 m/10.2 m
Natural bunch length	σ_l	1.1 cm

3.1 Effect of Feedback Damping Strength

Since usually the damping supplied by the feedback system to the dipole oscillation is much stronger than the radiation damping and the damping effect of the non-linear field of the Gaussian bunch, the saturated oscillation amplitude of the FBII is mainly determined by the damping time of the feedback system. Fig. 1 shows the saturated oscillation amplitude versus feedback damping time.

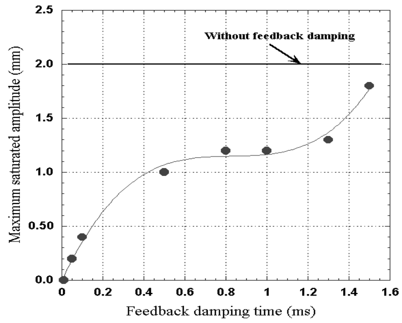

Fig. 1 Maximum amplitude vs. feedback damping time

In case of the simulation without the beam feedback, the damping is supplied by the nonlinear effect of the large oscillation amplitude, whose damping time is longer than that of the beam feedback. Comparing with the case of without feedback damping in the Fig. 1, you can find the saturated oscillation amplitude can be suppressed largely with the a fast beam feedback system.

In simulation without the beam feedback, we find that it takes about 40 turns for the amplitude of the 500-th bunch growing e times. And we also observed that the stronger the beam feedback is, the more bunches in head part of the bunch train will be stabilized.

3.2 Effect of the Noise

The saturation of FBII is driven by the noise which is always existing. In simulation, the noise is simulated by the white noise mainly due to the error of the position pickup and kick strength of the beam feedback system.

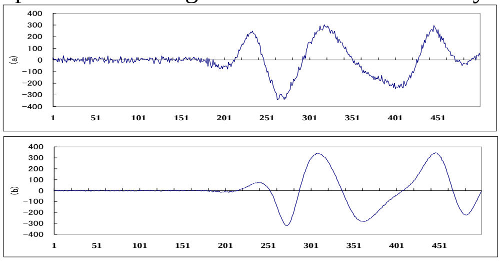

Fig. 2 Oscillation pattern of the bunch train

As an example, Fig. 2 shows the oscillation pattern for the cases of different feedback noise. Vertical axes is the beam position in unit of μm observed at fixed position and the horizontal axes are the bunch id. The rms noise of (a) is 5 times that of (b). You can find the maximum oscillation amplitude is almost unchanged. The effect of noise with large rms amplitude is only superposing the noise on the saturated oscillations. In our simulation, we observed that the maximum saturated oscillation amplitude is almost independent of the noise level. But for the bunches with small oscillation amplitude (in the linear region), the higher the noise level, the lager the oscillation amplitude.

3.3 Effect of the Bunch Gap

The bunch gap is usually employed to let the ions drift away. By introducing a bunch gap in the bunch train, we expected that the instability can be made weaker. In the simulation, the ions drift freely in this gap. For a 500-bunch train, we find the saturated oscillation amplitude of the bunch train, which has a bunch gap of 50 bunches in the middle of train, is only half of that of the bunch train without gap. So we can expect to suppress FBII by introducing the proper gaps and also using the fastest beam feedback system.

3.4 Effect of Bunch Current

The Fig. 3 shows the maximum saturated amplitude and

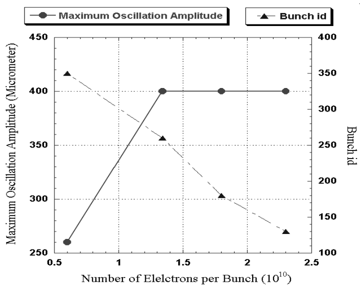

Fig. 3 Effect of the number of electrons per bunch

the bunch id where the obvious oscillation is observed for the trains with different bunch current. We can find the saturated amplitude is almost not changed for the number of electrons per bunch current varied between (1.3~2.3)10^{10}. The difference is that the instability begins earlier in the bunch train if the bunch current is larger. Because of our assumption of the rigid Gaussian bunch, we don't know whether the emittance growth exists or not in case of the large bunch current. These effects should be studied later by the Strong-Strong interaction model[11].

3.5 Effect of Vacuum Pressure

The Fig. 4 shows the relationship between the saturated oscillation amplitude and the partial vacuum pressure of N_2 and CO. The saturated amplitude increases almost linearly with the vacuum pressure. So the good vacuum is still essential for avoiding the FBII.

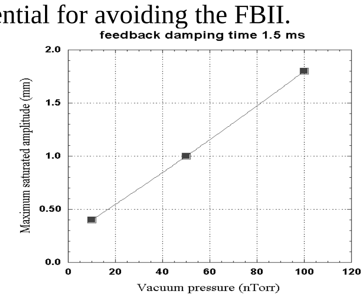

Fig. 4 Saturated amplitude vs. vacuum pressure

4 DISCUSSIONS

We have studied many effects that may affect the behavior of the FBII by simulation. We find out that the saturated oscillation amplitude is independent of the noise level and within a certain range of the bunch current, it is even not affected by the bunch current as well. But the saturated oscillation amplitude is limited by the damping time of the beam feedback system and the bunch gap. As the oscillation amplitude increases linearly with the vacuum pressure in our simulation, the good vacuum is needed to minimize the effect of the instability.

5 ACKNOWLEDGMENTS

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