EFFECTS OF BEAM FILLING PATTERN ON BEAM ION INSTABILITY AND BEAM LOADING IN PEP-X*

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Abstract

A proposed high-brightness synchrotron light source (PEP-X) is under design at SLAC. The 4.5-GeV PEP-X storage ring has four theoretical minimum emittance (TME) cells to achieve the very low emittance and two double-bend achromat (DBA) cells to provide spaces for IDs. Damping wigglers will be installed in zero-dispersion straights to reduce the emittance below 0.1 *nm*. Ion induced beam instability is one critical issue due to its ultra small emittance. Third harmonic cavity can be used to lengthen the bunch in order to improve the beam's life time. Bunch-train filling pattern is proposed to mitigate both the fast ion instability and beam loading effect. This paper investigates the fast ion instability and beam loading for different beam filling patterns.

INTRODUCTION

In the PEPX design, the emittance is 67 pm [1]. The fast ion instability can be very strong due to this ultra small emittance. There is a short lifetime for such short bunch due to the Intra-Beam Scattering (IBS). Third harmonic cavity is proposed for bunch lengthening. A heavy beam loading can cause large variation of the bunch length. Since both beam-ion instability and beam loading depend on the beam filling pattern, we study these two issues together in this paper.

In most electron rings, one single bunch train with a long gap is often used to remove trapped ions. The ions generated by bunches at the head of bunch-train can cause fast ion instability. To avoid conventional ion trapping, as in the two B-factories and most of the light sources, a long gap is introduced in the electron beam by omitting a number of successive bunches out of a train. However, the beam can still suffer from the beam-ion instability even with gaps in the train [2-5]. In the fast ion instability, individual ions last only for a single passage of the electron beam and are not trapped for multiple turns. In a low emittance ring with a high beam current, multi-bunch-train can significantly reduce the ion density [6]; It also can reduce the beam-loading effect at the same time. Therefore, Multi-bunch-train filling pattern will be very useful for PEP-X.

BEAM-ION INSTABILITY

Without gaps in the beam fill pattern, the ions with a relative molecular mass greater than $A_{x(y)}$ will be trapped horizontally (vertically), where

$$A_{x(y)} = \frac{N r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x(y)}}, \qquad (1)$$

here r_p is the classical radius of the proton, N is the number of electrons per bunch and $\sigma_{x(y)}$ is the *rms* horizontal (vertical) beam size. If the beam size is small enough, the strong beam's force can overfocus ions and causes the ion's motion unstable. Therefore, there is larger $A_{x(y)}$ for a smaller beam size as shown in Eq.(1). Figure 1 shows the critical mass number A_{xy} along quarter of the ring for a beam with 5% coupling. The H_2^+, CH_4^+, H_2O^+ are unstable in most of the regions and CO^+/N_2^+ ions are unstable at partial regions, while CO_2^+ is stable in most of the ring. When the coupling increases, there are more stable regions and more ions can be trapped.

One important damping mechanism is ion oscillation frequency spread $\Delta \omega_i$ along the ring due to the variation of beam size [7]

$$\frac{1}{\tau_{e,FII}} \approx \frac{r_e c \beta_y \lambda_i}{3\gamma \sigma_y(\sigma_y + \sigma_x)} \frac{1}{\Delta \omega_i / \omega_i}, \qquad (2)$$

where β_y is the average betatron function and λ_i is the ion line density. The oscillation frequency of the trapped ions is given by

$$\omega_{i,x(y)} = \left(\frac{4 N r_p c^2}{3 A S_b (\sigma_x + \sigma_y)\sigma_{x,y}} \right)^{1/2}. \qquad (3)$$

The large frequency spread as shown in the Figure 2 provides a significant landau damping of the beam instability. The DBA sections ($s{\sim}500$ *m* in the Figure) have a larger spread than the TME sections ($s{\sim}200$ *m*).
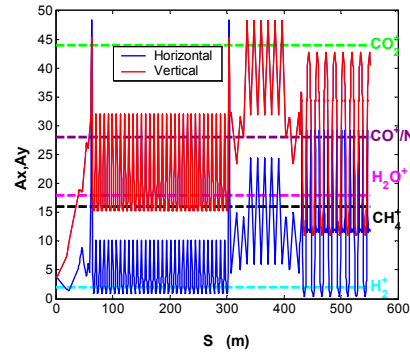

Figure 1: Critical mass number for 5% coupling. The mass number of H_2, CH_4, H_2O, CO and CO_2 is marked in the plot.

A gap between bunch trains can be added to suppress the ion trapping. Our study shows that the ion density exponentially decays during a train gap. With a multi-train beam filling pattern, the ion density can be reduce by a factor of F_{train} [6]

$$F_{train} = \frac{1}{N_{train}} \frac{1}{1 - \exp(-\tau_{gap}/\tau_{ions})}, \qquad (4)$$

here, τ_{ions} is the diffusion time of ion-cloud, which is close to the ion oscillation period. τ_{gap} is the length of bunch train gaps and N_{train} is the number of bunch trains. There is shorter diffusion time for a beam with smaller beam size with higher beam current, such as PEPX beam. This characteristic makes the bunch train filling pattern very effective in PEPX. Figure 3 shows the simulated ion density for various beam filling patterns. The total beam current is 1.5 *A* and the total number of bunches is 3154. The simulation result agrees well with Eq. (4). The trapped ion density can be reduced by a factor of 30 when the beam consists of 50 bunch-trains. With multi-bunch train filling pattern, the beam instability rate is proportional to the ion density near the beam

$$1/\tau \approx r_e c \beta_y \rho_{i,eff} Q / \gamma, \qquad (5)$$

where $\rho_{i,eff}$ is the effective ion density, Q is the Q-value of the wake due to ion cloud. Therefore, the instability growth rate can be reduced by the same amount 30 with a 50 bunch-train filling pattern.
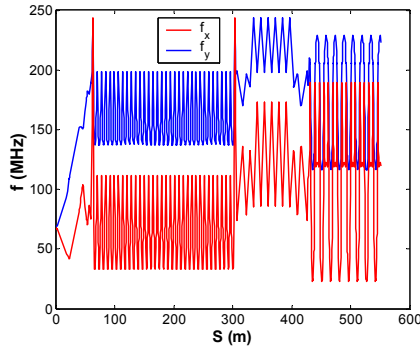

Figure 2: The CO^+ frequency along quarter of the ring, 5% coupling.
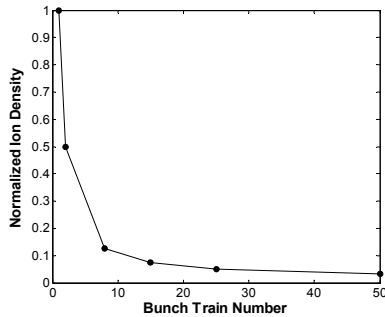

Figure 3: Simulated ion density variation with bunch train number.

The beam instability is simulated with a strong-weak code. Each bunch is represented by one macro-bunch, but the ions are represented by many macro-particles. The electron bunches interact with the ions at each element when they are passing by. Therefore, the effects of trapping condition, train gap and the landau damping are all included in the simulation. The assumed residual gas molecular species in the vacuum chamber are shown in Table 1. We assume a constant pressure of 1.0 *nTorr* along the whole ring. Figure 4 shows one example of simulated beam instability with 4 bunch-train filling

pattern. The fast growth rate at small amplitude is 41.5 μs which is 10 times faster than present feedback damping time used in PEPII. More bunch-train or a better vacuum is required for further mitigation. Simulation shows 83 bunch-trains is a favorite filling pattern, which allows a relative large number of bunches and has a low beam ion instability rate. Beam Position Monitor (BPM) can also work as a clearing electrode additionally to remove the ions. Since there is only small fractional of the ring is occupied by BPMs, the reduction effect is limited. A bunch-by-bunch feedback can finally suppress the instability. When the beam coupling increases, more ions can be trapped. Simulations show there is even a faster instability with a larger coupling.

Table 1: Parameters of the Main Molecular Species used in Simulation

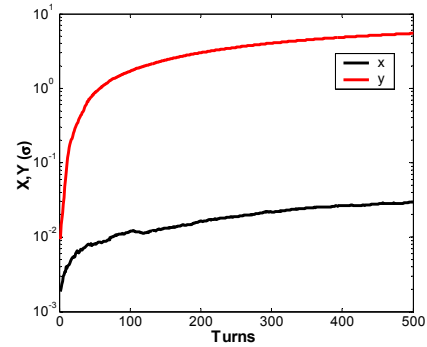|	Cross section (*Mbarn*)	Mass number	Percentage
H_2	0.35	2	75%
CO	2.0	28	14%
CO_2	2.92	44	7%
CH_4	2.1	16	4%

Figure 4: Transverse oscillation amplitude (normalized by beam size). The beam has a total number of bunches of 3154 with 4 bunch-train filling pattern. The total pressure is 1.0 *nTorr*. The vertical growth rate is 42μs.

BEAM LOADING

A particle tracking code has been used in the study of beam-loading effect. The code has been developed to simulate the coupled bunch instability. It can use realistic configuration of the ring, such as RF cavity, Octupole and other elements. We also have a code based on analytical theory. The tracking code has been benchmarked with theory for the coupled bunch instability. It is new to use it for beam loading calculation. A comparison with analytical theory is show in Figure 5, which shows very good agreement.

The major source of beam loading is the cavity's fundamental mode. To minimize generator's power, the cavity detuning frequency is given by

$$\Delta f = -\frac{h f_0 I_b \cos(\phi_s)}{V_c} \frac{R}{Q} \qquad (5)$$

where h is *RF* harmonic number, f_0 is the revolution frequency, I_b is the total beam current and V_c is the cavity

voltage, ϕ_s is the synchrotron phase and R, Q is the shunt impedance and Q-factor of the fundamental mode. The cavity frequency is tuned below the generator frequency. In most cases, there is no instability due to this detuning (Actually it is tuned to the damping direction of the Robinson instability). However, beam can become unstable when the detuning is large enough so that the cavity's frequency is close to the nearby upside-band of the beam spectrum. This can happen for a long storage ring with a low Q of the fundamental mode. In this case a longitudinal feedback is needed to make the beam stable. The beam loading is proportional to the R/Q of mode. Therefore, a cavity with large Q can reduce the beam loading effects, such as synchrotron phase shift and the required detuning of the cavity. Third harmonic cavity can be used to lengthen bunch length. For this purpose, the harmonic cavity should be tuned with a positive frequency shift, which can cause beam instability (Robinson instability).

In this study, we don't consider the beam instability. In order to find the steady status of the system, the beam has to be stable. Figure 6 shows one example of the development of bunches' phase space. When the system reaches steady status, all bunches have zero energy variation as expected.

In order to reduce the beam loading effect, we assume a large Q ($>10^5$) in this study, for example, a superconducting cavity or ARES-type NC cavity [8]. Another advantage of large Q is that there is no coupled bunch instability for this configuration. Figure 7 shows the synchrotron phase variation with different beam filling-patterns: one, two and four bunch-trains. The three straight lines shown in the figure have the same slope. In this case, the variation of the synchrotron phase along the bunch train is proportional to length of the bunch-train. Therefore, a short bunch train can reduce the variation of bunch length when third harmonic cavity is used. There is no such simple relation when low Q ($Q_0 \sim 10^4$) cavities, for instance, NC cavity, are used. In this case, the synchrotron phase along the bunch-train doesn't change linearly for a long bunch train.

SUMMARY

The fast ion beam instability in PEP-X is very fast due to its small emittance and high beam current. The growth time is order of $50\mu s$ with four bunch train filling pattern. More bunch train or a better vacuum is required to further mitigate the instability in order to make the growth time longer than $500\mu s$ (PEPII feedback capability). The instability can be mitigated by a factor of 30 by using 50 multi-train beam filling pattern. A bunch-by-bunch feedback can finally suppress the instability. With SC cavity or ARES-type NC cavity, phase variation along the bunch train is proportional to length of bunch-trains. Therefore, both beam-ion instability and beam loading can significantly benefit from multi-bunch-train beam filling.
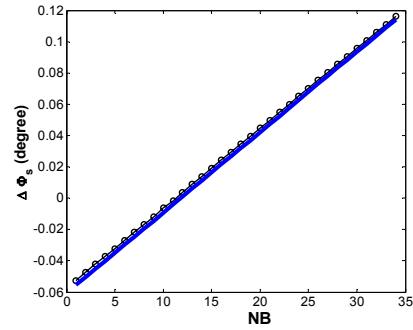

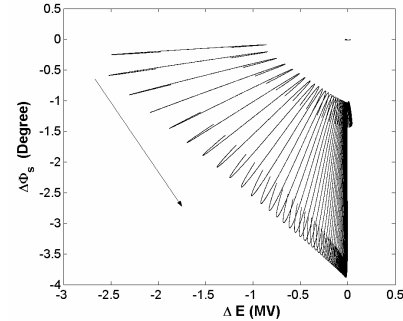Figure 5: Comparison of tracking code with theory.

Figure 6: Example of development of phase space of different bunches. Each bunch is presented by one dot. The line-like shape gives the phase-space of all bunches at different time.
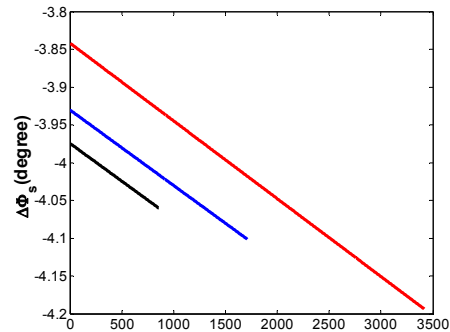

Figure 7: Variation of synchrotron phase along the bunch-train for different beam-filling patterns: One, Two and Four bunch-trains.

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