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ION INSTABILITY SIMULATION IN THE HEPS STORAGE RING

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Abstract

The Ionisation of residual gases in the vacuum chamber of an accelerator will create positively charged ions. For the diffraction limit storage ring, the ion effect has been recognized as one of the very high priorities of the R&D for the High Energy Photon Source (HEPS), due to the ultra-low beam emittance and very high intensity beam. In this paper, we have performed a simulation based on the weak-strong model to investigate characteristic phenomena of the fast beam-ion instability.

INTRODUCTION

This ionization of the residual gas in the vacuum pipe by the circulating electron beam will create positive ions. These ions could be trapped in the potential well of the stored beam under certain conditions [1].The accumulation depends on several factors, e.g. the filling pattern (the number of bunches, bunch spacing, beam current), transvers beam sizes (beam emittances, the storage ring optics) and the property of the ions (the mass, the charge).

Generally speaking, ion effects can be divided into two categories. One is called conventional ion trapping instability and the other is called fast beam-ion instability (FBII) [2] [3]. The former occurs mainly in the storage rings when bunches are uniformly filled. If some conditions are satisfied, the ions are accumulated over many turns and trapped by the beam potential all the time. These ions mutually couple to the motion of beam particles and lead to a beam instability in the ring. This instability can be partially suppressed by intentionally leaving a gap after the bunch train. These gaps will make the ions over focused and eventually lost to the vacuum chamber wall [4]. However, the diffraction limit storage ring light source feature an extremely small beam emittance (nanometre scale) and many bunches (a few hundreds) operation. The bunch spacing is therefore not very long enough, single passage ion instability, which is called fast beam-ion instability, is dominant. In this case, ions created by the head of the train via ionization of the residual gas perturb the tail during the passage of a single electron bunch train.

The High Energy Photon Source (HEPS), a kilometre scale quasi-diffraction limited storage ring light source with the beam energy of 6 GeV, is to be built in Beijing area and now is under extensive design. Extensive efforts have been made on the lattice design and relevant studies of this project. A hybrid 7BA design for the HEPS has been made. The design beam current is 200 mA, and basically two filling patterns are under consideration. One is the high brightness mode with 680 bunches (1.3nC, 0.3mA), followed by a 10% gap; the other one is the high bunch charge mode, with 63 bunches (14.4nC, 3.2mA) of equal bunch charges uniformly distributed around the ring. The main parameters were listed in Table 1.

Table 1: HEPS Lattice Design Parameters

Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1360.4 m
Natural emittance ε_{x0}	34.2 pm.rad
Working point υ_x/υ_y	114.14/106.23
Natural chromaticity (H/V)	-215.9/-292.2
No. of super-periods	24
ID section length L_{ID}	6.00/6.07m
RMS energy spread	1.061×10^{-3}
Momentum compaction	1.561×10^{-5}
Energy loss per turn	2.888 MeV

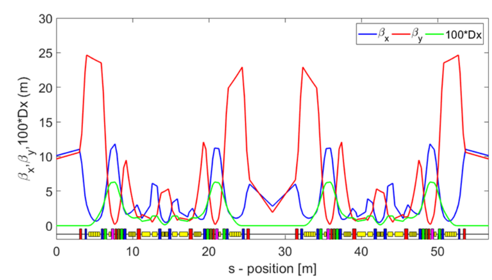

Figure 1: Optical functions and lattice structure for one cell of the HEPS storage ring.

ION TRAPPING

The ions generated by beam-gas ionization will experience a force from the passing electron bunch, which can be regarded as a thin lens focusing element followed by a drift space before the next bunch passes. Based on the linear theory of ion trapping [5], the ions with a relative molecular mass greater than $A_{x,y}$ will be trapped horizontally (vertically) in the potential well of the beam. The $A_{x,y}$ in units of amu is given by:

$$A_{x,y}(s)=\frac{N_e r_p L_{sep}}{2\left(\sigma_x(s)+\sigma_y(s)\right)\sigma_{x,y}}, \quad (1)$$

Where N_e is the number of particles per bunch, r_p ($\sim1.535\times10^{-18}$m) is the classical proton radius, L_{ess} is the bunch separation in meters, $\sigma_x(s)$, is the local horizontal rms beam size, and $\sigma_y(s)$ is the local vertical rms beam size.

The ions should be trapped both in x and y directions simultaneously, so the critical mass in units of amu is given by:

$$A_{crit}(s)=\frac{N_e r_p L_{sep}}{2\min\left(\sigma_x(s),\sigma_y(s)\right)\left(\sigma_x(s)+\sigma_y(s)\right)}. \quad (2)$$

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Any singly-ionized species with atomic mass greater than A_{crit} will be trapped. Using the beam parameters of Table 1 with the emittance coupling factor κ=10% and the optical functions shown in Figure 1, the critical mass for the high brightness mode with 680 bunches was shown in Figure 2.

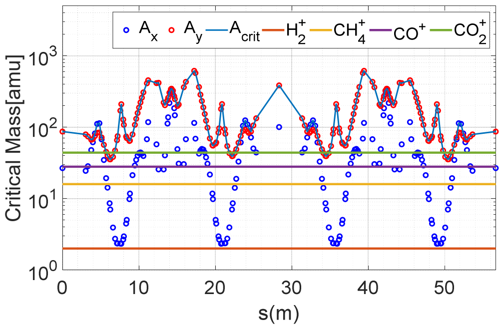

Figure 2: Calculated critical mass along the ring.

The critical mass will vary along the ring. A given ion may be trapped in some parts of the lattice, but not in others. The minimum value of critical mass is about 35.4(amu), so that only CO2+ can be trapped, the trapped fraction is about 6.7%.

FAST BEAM-ION INSTABILITY

Simulation Model and Assumptions

We employ a weak-strong code to simulate the interactions between the electrons and ions [6]. 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 consideration. The electron bunch was treated as the strong one, i.e. a rigid Gaussian bunch. Only its barycentre motion is taken into account. The ions are treated as macro particles which are ionized by the previous electron bunch, its distribution is the same as the electron bunch. The motion of ions is non-relativistic without longitudinal drift and they are assumed to move freely in the bunch interval. The number of ions is increased with respect to the bunch index in the bunch train, the ion line density per bunch is given by $\lambda_{ion} = N_b\, \sigma_{ion}\, d_{gas}$. We assume that the first bunch in the train only produces the ions and it does not interact with the ions, while the trailing bunches in the train will produce the ions and interact with the ions created by the preceding bunches. After one turn interaction, we assume that the ions are cleared away from the beam vicinity. The new ions will be produced by the beam in the second revolution turn. The adjacent beam ion interaction points are connected through the linear transfer matrix.

The major species of the residual gas in the vacuum chamber are Carbon Monoxide (CO) and Hydrogen (H_2). Since the cross section of collision ionization for CO is about 6 times higher than that for H_2 in this beam energy regime. Therefore in the simulation, CO^+ ions are regarded as the dominant instability source and its pressure sets to be 1.0 nTorr.

Beam-Ion Force

The interaction between ions and electron beam is based on the Bassetti–Erskine formula, for an ion with electric charge +e in the in the field of the Gaussian bunch, the Coulomb force exerted on it can be calculated [7]:

$$F(x,y) = -2N_e r_e m_e c^2 f(x,y) \tag{3}$$

where (x, y) are the horizontal and vertical position with respect to the bunch center, m_e the electron mass. $f(x, y)$ is well known Bassetti–Erskine formula as:

$$f(x,y) = -\sqrt{\frac{\pi}{2(\sigma_x^2-\sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right) w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right], \tag{4}$$

here

$$w(z) = \exp\left(-z^2\right)\left[1-erf(-iz)\right], \tag{5}$$

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-x^2\right)dx \tag{6}$$

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:

$$\Delta y_e' + i\Delta x_e' = \frac{2N_e r_e}{\gamma}\sum_i f(x_{ie}, y_{ie}) \tag{7}$$

Similarly, due to the reaction force, the kick to an ion with mass M_i is given by:

$$\Delta y_i' + i\Delta x_i' = -2N_e r_e c\frac{m_e}{M_i} f(x_{ie}, y_{ie}) \tag{8}$$

Where $(\Delta x_e', \Delta y_e')$ and $(\Delta x_i', \Delta y_i')$ are the transverse angle kick to the centre-of-mass of electron bunch and ion respectively.

Simulation Results

In the simulations, the time evolution of the growth of beam dipole amplitude is computed and recorded in every turn. The transverse oscillation amplitude of the bunch centroid is half of the Courant-Synder invariant and given by:

$$J_z = \frac{1}{2}\left[\gamma_z z^2 + 2\alpha_z z z' + \beta_z z'\right], z \in (x,y) \tag{9}$$

Where α_z, β_z, γ_z are the Twiss parameters of the ring lattice. We compare the square root of J_z with the beam size which is represented by the square root of transverse emittance ε_z. Both of these quantities are in units of $m^{1/2}$.

We perform simulations on the fast beam-ion instability for the average beta function (β_{x_ave} = 4.5m, β_{y_ave} = 8.1m). The growth time of FBII could be estimated from the time duration of maximum amplitude growth of beam from 0.1σ to 1.0σ, shown in Figure 3, by exponential fitting [8]. The estimated growth time for the high brightness mode is 3.9ms.

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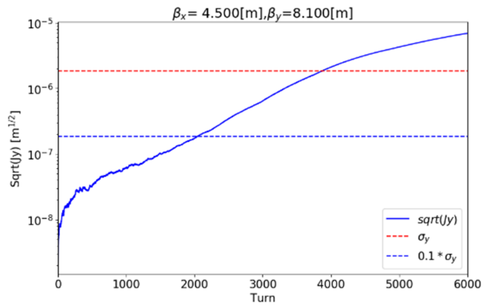

Figure 3: Maximum vertical amplitude of bunches with respect to number of turns for high brightness mode.

We also predicted fast beam-ion instability rise times analytically, the results are shown in Table 2. The detailed process of analytical estimation can be found in reference [9].

Table 2: Analytical Estimation of FBII Growth Time

Parameters, Unit	High brightness mode	High charge mode
Beam energy, GeV	6	
Circumference, m	1360.4	
RF frequency, MHz	166.6	
Beta function β_x/β_y, m	4.5/8.1	
Bunch number	680	63
Bunch spacing, m	1.8	21.6
$\rho_{i,\ eff}$, 10^{11}m^{-3}	7.3	5.0
f_i, MHz	4.8	3.8
$4L_{sep}f_i/c$	0.1	1.1
τ_c, µs	19.3	31.9
τ_e, ms	1.9	2.8
τ_H, ms	61.7	27.2

CONCLUSION

We have investigated simulation studies to estimate the fast beam-ion instabilities for the HEPS storage ring. The growth time was obtained by using a weak-strong simulation method. The simulation results showed that the bunch by bunch feedback of about hundreds of turns is required to cure the fast beam-ion instabilities.

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