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ION INSTABILITY IN THE HEPS STORAGE RING *

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Abstract

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 and analytical estimate to investigate characteristic phenomena of the fast-ion instability.

INTRODUCTION

The 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), transverse 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 (nanometer 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 timing 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}	58.4 pm.rad
Working point υ_x/υ_y	107.37/82.43
Natural chromaticity (H/V)	-214/-133
No. of super-periods	48
ID section length L_{ID}	6.15m
RMS energy spread	8.20×10^{-4}
Momentum compaction	3.43×10^{-5}
Energy loss per turn	1.959 MeV

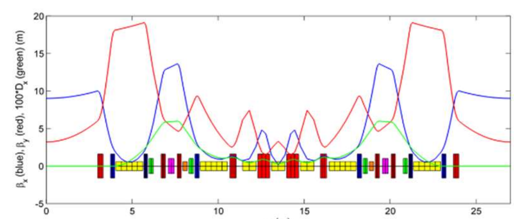

Figure 1: Optical functions and lattice structure for one cell of the HEPS storage ring.

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:

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

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:

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

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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.

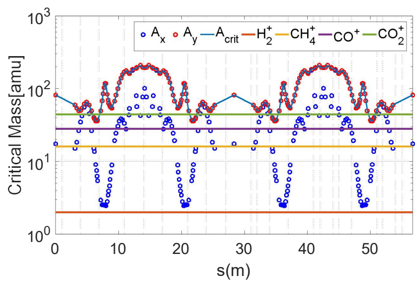

Figure 2: Calculated critical mass along the ring.

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 35.7(amu), so that only CO2+ can be trapped, the trapped fraction is about 5.8%.

FAST BEAM-ION INSTABILITY

Models of the Beam-Ion Interaction

There are several models to investigate the beam-ion interaction. The residual gas ionized ions could be represented by a single macro particle or a continuous distribution along the longitudinal direction in analytic theory. While they are represented by many macro particles in the simulation. The models, which are depicted in Figure 3, are summarized as follows [6]:

1) Electrons and ions are expressed as one macro particle each. The interaction force between the beam and the ion is linear, which is applicable for small amplitudes ($y<<\sigma_y$) [2].
2) Electrons and ions are expressed as one macro particle each. The interaction force between the beam and the ion is linear, the ion decoherence and the variation of the ion frequency along the beam line are included [3].

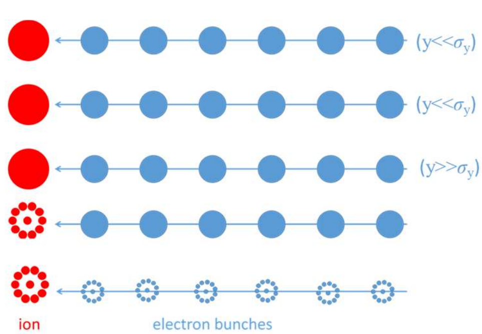

Figure 3: Various models for the beam-ion interaction.

3) Electrons and ions are expressed as one macro particle each. For very large oscillation amplitudes ($y>>\sigma_y$), the beam-ion force becomes very nonlinear [7].
4) A bunch is represented by a macro particle, while the ions are represented using many macro particles. It is called a weak–strong model [8].
5) Both the bunch and the ion cloud are represented by many macro particles. It is called a strong–strong model.

Analytic Theory of the Rise-Time

Analytical expressions for the growth rate at the end of the bunch train have been derived using three different models (Model 1~3 that shown in Figure 3) [9].

Simple linear treatment for small amplitude ($y<<\sigma_y$), the initial vertical perturbation of magnitude increase quasi-exponentially as [2]:

$$y = \hat{y}\frac{1}{2\sqrt{2\pi}(t/\tau_c)^{1/4}}\exp(\sqrt{t/\tau_c}), \tag{3}$$

With a characteristic time:

$$\frac{1}{\tau_c} = \frac{4d_{gas}\sigma_{ion}\beta N_e^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma\sigma_y^{3/2}(\sigma_y+\sigma_x)^{3/2} A^{1/2}}, \tag{4}$$

Where $d_{gas} = p/(kT)$ is the residual gas density (where p is the gas pressure, k Boltzmann constant, and T the absolute temperature), β the average vertical beta function, n_b the number of bunches in the train, γ the beam energy in units of the rest energy, A the ion mass in units of amu, r_e(~2.8×10^{-15}m) the classical electron radius, c the speed of light, and σ_{ion} the ionization cross section.

Take into account the decoherence of ion oscillations due to the ion frequency spread, Eq. (3) is replaced by a purely exponential growth [3]:

$$y \propto \exp(t/\tau_e) \tag{5}$$

With an e-folding time of:

$$\frac{1}{\tau_e} \approx \frac{1}{\tau_c}\frac{c}{4\sqrt{2\pi}L_{sep}n_b a_{bt} f_i} \tag{6}$$

Where

$$f_i = \frac{c}{\pi}\sqrt{\frac{QN_e r_p}{3AL_{sep}\sigma_y(\sigma_x+\sigma_y)}} \tag{7}$$

denotes the coherent ion oscillation frequency, and $2a_{bt}$ the peak-to-peak ion-frequency variation (a_{bt}~0.1-1,for HEPS lattice optics, we set a_{bt}=1). Eq.(5) is also only valid for amplitudes small compared with the beam size.

For very large oscillation amplitudes($y>>\sigma_y$), a linear growth is expected [7]:

$$y \sim \sigma_y \frac{t}{\tau_H} \tag{8}$$

with a time constant:

$$\frac{1}{\tau_H} \approx \frac{1}{\tau_c}\frac{c}{2\pi f_i L_{sep} n_b^{3/2}} \tag{9}$$

The fast beam–ion instability arises when the ions are trapped between bunches. In other words, if the transverse velocity of ions is so small that they stay within the bunch size before the next bunch arrives which pulls them back in, the trapping condition is then fulfilled. The trapping condition can approximately be written as:

$$4L_{sep}f_i/c \le 1 \tag{10}$$

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For a single bunch train consisting of n_b bunches followed by a long gap, the ion line density at the tail of the bunch train is given by:

$$\lambda_i = \sigma_{ion} \frac{P}{kT} N_e n_b \tag{11}$$

The effective ion density is defined as [10]:

$$\rho_{i.eff} = \frac{\lambda_i}{k_y \sigma_y \left(\sigma_x + \sigma_y\right)} \tag{12}$$

k_y represents the ion's distribution, for a flat electron beam, k_y=3/2.

Table 2: Parameters and Predicted Oscillation Growth Rates for HEPS

HEPS	mode1	mode2	mode3	mode4
E [GeV]	6	6	6	6
C [m]	1360.4	1360.4	1360.4	1360.4
β_x/β_y [m]	4.4/5.9	4.4/5.9	4.4/5.9	4.4/5.9
L_{sep} [m]	1.8	21.6	1.8	21.6
n_B	680	63	680	63
N_b[10^{10}]	0.83	9.0	0.83	9.0
σ_x [µm]	15.1	15.1	282.4	334.9
σ_y [µm]	5.9	5.9	100.4	119.1
P [nTorr]	1	1	1	1
$\rho_{i,eff}$[10^{13}m^{-3}]	21.5	21.6	0.063	0.045
f_i [MHz]	82.6	78.5	4.2	3.6
$4L_{sep}f_i/c$	1.98	22.6	0.1	1.0
τ_c [µs]	0.005	0.005	31	51.3
τ_e [ms]	0.031	0.031	10.6	14.8
τ_H [ms]	0.285	0.086	97.5	41.6

In Table 2 we list parameters and predicted instability rise times for the two filling patterns of HEPS. We use the average value of the beta function and the emittance coupling factor κ=10% to get the rms beam size. The projected rise times are are unprecedentedly small: the characteristic time τ_c is of the order of nanoseconds, the e-folding time τ_e and τ_H is a few hundred microseconds or less. From the Table 2, we note that, using Eq.(10), in HEPS the ions are not stably trapped between bunches, it will lead to a reduction of the instability growth rate.

The ion density exhibits exponential decay during the bunch gap with an exponential time constant of the order of the ion's oscillation period. This feature makes the multi bunch train filling pattern a very effective way to reduce the ion density for an electron ring with high beam current and low emittance. In Figure 4, we show the ion density w/ and w/o exponential decay along the ring for brightness mode.The mode 3 and mode 4 in Table 2 show the average ion density with density reduction between bunches for brightness mode and timing mode. We keep the ion line density and the ratio of the transverse beam size to recalculate the transverse beam size with Eq.(12). In such situations, there is a obviously decrease the instability growth rate

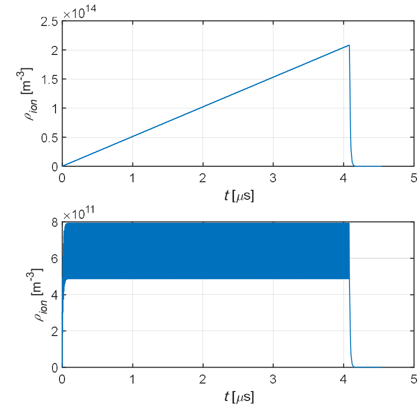

Figure 4: Ion density along the ring. up: without density reduction between bunches; down: consider density reduction between bunches.

Simulation Model and Assumptions

We employ a weak-strong code to simulate the interactions between the electrons and ions [9]. 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 [11]:

$$F\left(x,y\right) = -2N_e r_e m_e c^2 f\left(x,y\right) \tag{13}$$

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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:

$$f(x,y) = -\sqrt{\frac{\pi}{2(\sigma_x^2-\sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right) w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right], \tag{14}$$

here

$$w(z) = \exp\left(-z^2\right)\left[1-erf(-iz)\right], \tag{15}$$

$$erf\,(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-x^2\right)dx \tag{16}$$

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:

$$\Delta y_e' + i\Delta x_e' = \frac{2N_e r_e}{\gamma}\sum_i f(x_{ie}, y_{ie}) \tag{17}$$

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

$$\Delta y_i' + i\Delta x_i' = -2N_e r_e c\frac{m_e}{M_i} f(x_{ie}, y_{ie}) \tag{18}$$

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:

$$J_z = \frac{1}{2}\left[\gamma_z z^2 + 2\alpha_z zz' + \beta_z z'\right], z\in(x,y) \tag{19}$$

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 four different beta function in Table 3.

Table 3: Different β Function Selected for Simulation

Case	β_x[m]	β_y[m]	τ_e[ms]
Case1	4.4	5.9	4.5
Case2	10	15.5	0.77
Case3	3	15.5	1.3
Case4	9	4	6.8

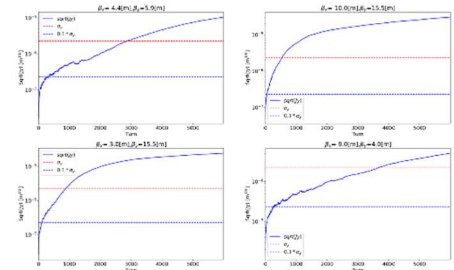

Figure 5: Maximum vertical amplitude of bunches with respect to number of turns.

The growth time of FBII in different β function cases could be estimated from the time duration of maximum amplitude growth of beam from 0.1σ to 1.0σ, shown in Figure 5, by exponential fitting [12]. The estimated growth time is also shown in Table 3.

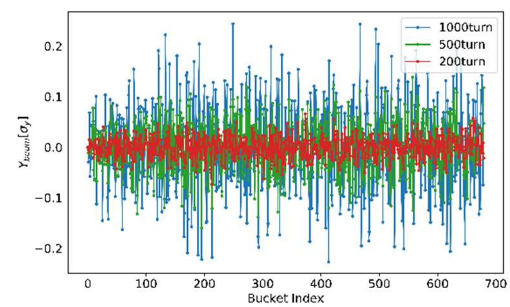

Figure 6: Beam oscillation pattern in different turns.

The amplitude of the beam oscillations due to the interaction with the ions versus the bucket index is shown in Figure 6. It indicates that the beam oscillation grows with respect to the time (number of turns).

CONCLUSION

We have investigated the analytic and simulation studies to investigate the fast-ion instabilities for the HEPS storage ring that showed a rapid growth time. The growth times for various b function cases in the ring were obtained by using a weak-strong simulation method. The simulation results also showed that the bunch by bunch feedback of about 100 turns is required to cure the fast-ion instabilities.

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