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Filling patterns in the SSRF storage ring

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Abstract There are various filling patterns in a storage ring for the users' requirements and consideration of the machine performances, such as beam lifetime, instability and chamber heating. These effects have been experimentally studied in the SSRF storage ring for typical filling patterns. Some experiment results and general trends of observations discussed in this paper. The explanations of the results are given.

Key words SSRF, Filling pattern, Lifetime, Ion-trapping, Fast beam-ion insatiability

1 Introduction

The Shanghai Synchrotron Radiation Facility (SSRF), a third-generation light source, has a 3.5 GeV storage ring[1] with a harmonic number of 720, a revolution period of 1.44 μs, and the separation of RF buckets of 2 ns. Table 1 shows their main parameters. The bunch filling patterns of the storage ring should satisfy requirements of different users, which is very import for measuring the ring parameters in different filling patterns.

Table 1 Main parameters of the SSRF storage ring.

Energy / GeV	3.5
Emittance / nm·rad	3.9
Tune (ν_x/ν_y)	22.22 / 11.29
RF voltage / MV	4.5
RF frequency / MHz	499.654
Correcting chromaticity	1.60 / 0.51
Coupling	0.26%

A advanced synchrotron light source has a common filling pattern of a bunch train with a long empty gap of ion cleaning[2,3], and a hybrid filling pattern[4]. A uniform filling pattern of high current beam bunches may produce time structure for special experiments[5]. For instance, the SPring-8 run has complex filling patterns of 1/7-fillling +5 single bunches at 2.8 mA, and the 2/29-filling + 26 single bunches at 1.4 mA[6].

The beam lifetime at the SSRF storage ring is important for investigating the state of single bunch current, bunch volume, and vacuum pressure at different filling patterns, which would affect not only the user experiment but also radiation dose and injection interval.

For a storage ring, the residual gas in the vacuum chamber can be ionized by the Coulomb collisions of the electrons and the synchrotron radiations, and the ions can be trapped in the potential well of the electron beams due to the fast beam-ion instability (FBII) or conventional ion trapping (CIT)[7], which are very sensitive to the filling pattern. To prevent ion trapping, a standard solution corresponds to a gap in the bunch train, i.e. a gap of sufficient width causes a drift of large amplitudes and makes the ions lost. The FBII occurs when the following bunches are perturbed by the ions generated duo to the preceding bunches, and the FBII growth rate is approximately proportional to the square of the bunch number in a bunch train. Therefore, the FBII becomes serious with bunch numbers increasing.

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2 Important issues on filling pattern

2.1 The threshold of transverse mode-coupling instabilities

In the vertical plane of a single bunch filling mode, the threshold of transverse mode-coupling instabilities (TMCI) is a key problem. An increased beam size limits the current to a certain value. The current threshold decreases the injection efficiency and dynamic aperture with increasing the chromaticity. So, the bunch current should be limited by TMCI for a single bunch filling mode or a hybrid filling pattern of high current bunches. Also, the bunch current increases with the bunch length, causing distortion effects of the potential well and threshold of micro-wave instability, and increasing bunch energy divergence and quality-degraded synchrotron radiations.

2.2 The heating effect to the vacuum chamber

In a long bunch train, high-current bunches are filled consecutively. But intensified synchrotron radiations and impedance can cause heating effect in the vacuum chamber, it is a must to have mechanisms for protecting it from over-heating, and this relies strongly on the filling pattern. A defective vacuum chamber is heated by the electromagnetic waves exited by the beam bunches, with an energy losing factor (k) of

$$P = kQ_{\text{bunch}}I \tag{1}$$

where, P is the beam power transported to the chamber, Q_{bunch} is the bunch charge, and I is the total beam current.

2.3 The CIT and FBII

The ion effects of CIT and FBII, which were under-estimated in the past, have become a dominant problem for a modern electron storage ring[8], because they affect the beam performance in high sensitivity for the filling patterns in a long bunch train.

The growth time ($\tau_{\text{asym,e}^-}$) of FBII can be estimated by Eq.(2)[9,10]

$$\tau_{\text{asym,e}}(s) \approx [6pN_b^{3/2}n_b^{2}r_e r_p^{1/2}L_{\text{sep}}^{1/2}c/(\gamma\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2}A^{1/2}\omega_\beta)]^{-1} \tag{2}$$

where, p is the residual gas pressure (torr), which causes the FBII; N_b is the number of particles per bunch; n_b is the number of bunches; r_e and r_p are the classical radius of electron and proton, respectively; L_{sep} is bunch spacing; c is light speed; γ is the relativistic gamma factor; $\sigma_{x,y}$ are the horizontal and vertical beam size; A is the molecule mass of the residual gas; and $\omega_\beta \approx 1/\beta_y$ is the vertical betatron frequency. Eq.(2) shows that the $\tau_{\text{asym,e}^-}$ is small at high current for a light source of low emittance, and is proportional to the square of bunch number (n_b) and vacuum pressure. Then, the stability of the SSRF requests increased $\tau_{\text{asym,e}^-}$, and a prolonged bunch train.

Because there are gaps for the fill pattern fabricated by a number of short bunch trains, the trapping is disturbed. The FBII growth rate is proportional to the ion density[11]. The ion diffusions of the gaps can increase the size of its cloud, and reduces its density.

On introduction of a gap to the bunch train, density of the residual ions can be estimated by the clearing gap [12]

$$\rho_i \approx \frac{\rho_{i0}}{\sqrt{(1+L_{\text{gap}}^2\omega_x^2)(1+L_{\text{gap}}^2\omega_y^2)}} \tag{3}$$

where, ρ_{i0} is the ion density at the end of a bunch train, L_{gap} is the gap length of two adjacent bunch trains, and $\omega_{x,y}$ is the ion oscillation frequency,

$$\omega_{x,y}^2 = \frac{2N_0 r_p}{L_{\text{sep}}A\sigma_{x,y}(\sigma_x+\sigma_y)} \tag{4}$$

Comparing with growth time of a single long train, the experiments in ILC (Instruction Length Code) show that the FBII growth time for gap trains can be enlarged by two orders of magnitude[13].

3 Beam lifetime measurements

The total beam lifetime is the harmonic sum of Touschek, vacuum and quantum lifetimes. In the SSRF storage ring, the cross-section of vacuum chamber is 100 times larger than the beam size, and the ~3.3% RF energy acceptance is much greater than the 0.1% energy spread, so the effect of large quantum lifetime[14] can be neglected. The total beam lifetime (τ) is given by Eq.(5).

$$\frac{1}{\tau} = \frac{1}{\tau_v} + \frac{1}{\tau_T} \tag{5}$$

where, τ_T is the Touschek lifetime and τ_v is the vacuum lifetime. The beam lifetime and vacuum pressure measured with 100- and 200-bunch fillings at 30 mA are shown in Table 2.

Table 2 Beam life-time and vacuum at fillings of different bunches (Collimator size = 20 mm V_{rf} = 4.2MV).

Bunches	Current / mA	Lifetime / h	Vacuum / nTorr
100	29.3	35.6	0.360
200	30.3	56.7	0.347

To avoid the ion trapping, the lifetime difference for low current bunches with a long gap caused by the ions can be neglected. Assuming the Touschek lifetime is inversely proportional to the charge density in a bunch (neglecting the bunch lengthening effect at low bunch current), and the vacuum lifetime is inversely proportional to the vacuum pressure, the Touschek and vacuum lifetimes estimated by Eq.(1) and the data in Table 1 are about 47.3 h at bunch current of 0.293 mA and about 144.0 h at vacuum of 0.360 nTorr, respectively. Comparatively, the former is the dominant in the SSRF storage ring. The beam lifetimes of other filling patterns without the transverse feedback system are shown in Table 3.

Table 3 Beam lifetimes for different filling patterns.

Filling patterns	Current / mA	Vacuum / nTorr	Lifetime / h
2/3-filling	22.6	0.341	96.9
	51.8	0.382	59.8
	82.8	0.416	48.6
	110.24	0.470	42.6
720-bunches	100	0.448	66.5
540-bunches	100	0.448	54.6
480-bunches	100	0.453	51.8
360-bunches	100	0.448	46.3
280-bunches	100	0.448	43.6
360-bunches + 5 mA single-bunch	100	0.449	30.4
48-bunches×10	100	0.448	46.4

For the 2/3-filling pattern, the lifetime decreases with the bunch current and vacuum pressure. This is probably because of the ion-caused bunch elongation and the enlarged beam size. By fixing the total current and changing the gap size, the beam lifetime decreases linearly with bunch current increasing. With the pattern of 360-bunches + 5 mA single-bunch, the short lifetime is mainly attributed to the latter.

4 Observation of the ion effects

The ion trapping and FBII were measured under various beam filling patterns and stored currents. The filling pattern was adjusted by a gap length, that is, continuous empty buckets. The 360-, 480-, and 540-bunches, and full-filling operation mode, were observed to keep the total beam current of 100 mA. Fig.1 shows the vertical betatron tune as a function of the gap length.

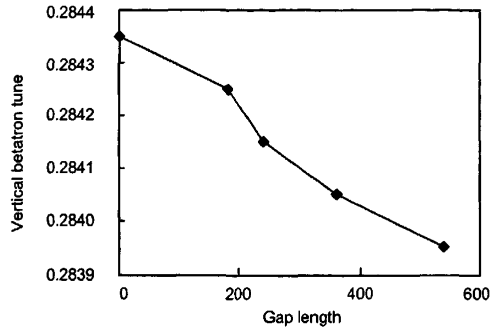

Fig.1 Vertical tune at a stored current of 100 mA as a function of the gap length.

The leading space charge force of the ions on the electron beam is equivalent to a quadrupole lens, and can introduce a tune shift by Eq.(6)[15]

$$\tau_{asym,e}(s)\ \Delta\nu_{x,y} = r_e\, C\beta_{x,y}Q_{iom}\lambda_{ion}/(4\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)) \quad (6)$$

where, r_e is the electron classical radius, C is circumference of the storage ring, $\beta_{x,y}$ is the beta function of horizontal and vertical motion, and Q_{ion} and λ_{ion} are the charge of an ion (in units of the electron charge) and the line density, respectively. Eq.(6) shows the tune shift of coherent betatron is proportional to the ion density. Because of the increased number of trapped ions and effect of the defocusing quadrupole, a large tune shift should be expected. Meanwhile, the beam size is of a horizontal oval, the main ion effect was measured in the vertical plane. Fig.2 shows that the small empty gap in the filling pattern helps to the ions accumulation, which is consistent with the ion trapping theory, that is, the total beam current immobilizing should synchronously lead to instability of the resistive wall, and the uniform filling pattern without gap give rise to severely resistive wall instability due to decreased vertical tune.

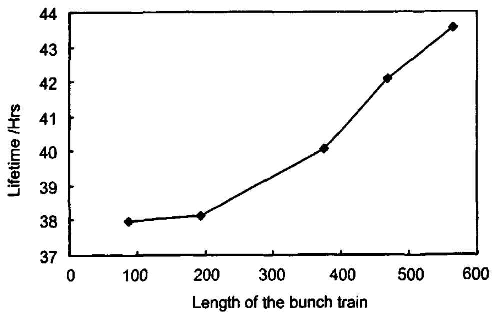

Fig.2 Lifetime as a function of the length of the bunch train.

To obtain the information of different filling patterns, we performed a complex filling pattern, 720-RF-buckets of ten parts, in which every 48-buckets was filled with bunches leaving 24 empty-buckets. In this case, the beam lifetime was 46.4 h at 100 mA, rather than 51.8 h with the 480-consecutive filling mode. Once an ion trapping occurs because of its short gap, the former filling mode traps the ions easily, and has a longer beam lifetime.

The effects are likely caused by the FBII since the generated ion numbers increase with the perturbed coherent beam oscillation along the bunch train. Naturally, the former case will have larger beam size, and have a longer beam lifetime, too.

To validate the FBII, the patterns of 160 consecutive fillings (Case 1) and (8-bunches + 22 empty-buckets)×20 (Case 2) are performed at 100 mA. With the gaps in the bunch train, which is large enough to avoid multiturn ion trapping, the average vertical beam size is measured with an interferometer. The σ_y of Case 1 was 75 μm, while the σ_y of Case 2 was just 35 μm. This is consistent with the FBII theory.

The case 3 to validate the FBII was done in the same bunch current for all the filled buckets, with lengthened bunch train step by step. Since the Touschek lifetime is inversely proportional to the charge density in a bunch, it should not change too much if the bunch volume keeps constant. Neglecting the vacuum lifetime-increasing effect caused by increased total beam current (Section 2), the Touschek lifetime (Fig.2) increases with the length of bunch train, indicating that the FBII causes an enlargement of the beam size.

The relative bunch current can be measured by wall-current-monitor (WCM). By filling a long bunch train and then moving a vertical scraper down close to the beam orbit, a sudden lost of beam current occurrs, and the filling pattern changes. The oscilloscope signals with the relative current along the bunch train are shown in Fig.3. Starting from a uniform current distribution along the train after scrape can be seen in Fig.3(a), and more current loss in tail bunches, which became clearer when scraper gets closer to the beam orbit, can be seen in Fig.3(b).

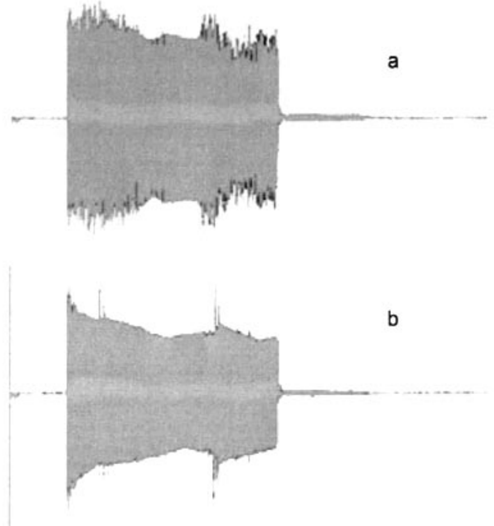

Fig.3 Beam current along a bunch train of 360 bunches. It shows the beam loss at the rear part of the bunch train.

5 Temperature of vacuum chamber

The beam current to avoid vacuum chamber over-heating is measured in different filling patterns (Table 4). The results show the heating effect remarkably limits the total current for uniform filling pattern. This will be further investigated.

Table 4 Machine protection current for different filling patterns.

Filling patterns	Machine protection currents
Bunch train, 600-bunches	>200 mA
Bunch train, 360-bunches	118 mA
32-bunch uniform filling	90 mA
16-bunch uniform filling	68 mA

6 Conclusion

In the 3.5 GeV electron storage ring of SSRF, we obtain different filling patterns and its general trends, enumerate mode-coupling instabilities, protection of machine from over heat, and ion effects on filling pattern. The total beam lifetime estimated by the Touchek lifetime is three times longer than that of the vacuum, and the lifetimes of other filling patterns are also obtained. The CIT is roughly proved by the tune shift. The FBII phenomena in the storage ring are caused by low emittance and many bunch numbers. The heating effect is important for filling patterns with high bunch current.

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