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NUMERICAL CALCULATION AND EXPERIMENT OF ION RELATED PHENOMENON IN SPring-8 STORAGE RING

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Abstract

In the SPring-8 storage ring, we have tried to develop new filling patterns which have equally spaced bunches. In the development, we have found vertical beam instability which strongly depends on the bunch interval; the instability becomes stronger when the bunch interval becomes shorter. From the dependence of the filling pattern, we have speculated that the instability is ion related phenomenon, and performed computer simulation which is based on macro-particle calculation. The agreement between the change in the observed vertical beam size on the bunch interval and the result of the simulation is good.

INTRODUCTION

In an electron storage ring, ultra high vacuum condition is always kept inside the beam ducts to realize enough beam lifetime. In the vacuum condition, however, the high energy electrons circulating in the ring are scattered by the residual gas molecules and lost by the collision. In the scattering process, positive gas ions are created and trapped stably by the negative potential-well around the electron beam orbit. The trapped ion clouds oscillate around the beam orbit due to the successive and periodic passage of the electron beam and disturb the original beam motion. The condition which determines the stability of the trapped ions depends on the filling patterns of the electron bunches; successive bunch train pattern tends to keep the ions stable.

In the SPring-8 storage ring, various kinds of bunch filling patterns are available because of the large harmonic number h of $2436 = 2 \times 2 \times 3 \times 7 \times 29$. We have tried to develop new filling patterns which have equally spaced bunches for synchrotron radiation experiments. In the filling patterns, we have observed vertical betatron sidebands and increase in the vertical beam size; the increase in the beam size tends to be larger when the bunch interval is shorter. From these phenomena, we have speculated that they are from ion related phenomena and performed computer simulation based on the interaction between the ions and the electron beam.

EXPERIMENT AND ANALYSIS

In the experiment, we have tested 6 filling patterns; 203 bunches (12 buckets interval), 406 bunches (6 buckets interval), 609 bunches (4 buckets interval), 812 bunches (3 buckets interval), 1218 bunches (2 buckets interval) and 2436 bunches (full-filling) at the same total beam current of 95mA. To make clear the phenomenon, we have turned off the vertical bunch-by-bunch feedback [1, 2]. Figure 1 shows beam spectrum measured by vertical pick-up electrode. As seen in the figure, at 203 bunches only the integer peaks which correspond to the beam revolution f_{rev} appear; on the other hand, at 406 bunches decimal peaks which correspond to the vertical betatron sidebands appear, and at 2436 bunches the spectral power of the sidebands increases. Figure 2 shows measured vertical beam size by visibility monitor [3]. As seen in the figure, the measured vertical beam size increases when the bunch interval is shorter than 4 buckets interval (609 bunches).

Such phenomena which strongly depend on the bunch filling pattern are supposed to be caused by residual gas ions trapped by the beam. To consider this, we have performed analytical calculation based on the classical theory of ion trapping [4]. From the theory, we have calculated a critical mass which is the minimum ion A/Z to be stably trapped by the beam. Figure 3 shows the change in the critical mass for different bunch interval. The vertical bars in the figure correspond to the variation of the electron beam size around the ring. As seen in the figure, in the 12 buckets interval (203 bunches) the critical mass is about 30 and 7 buckets interval (348 bunches) the critical mass is about 10; in the SPring-8 storage ring the residual gas components are H_2 (60 %) and CO (30 %) [5], namely, in the case the bunch interval is shorter than 7 buckets the CO^+ ions can be trapped stably around the beam. Experiments show that at 12 buckets interval (203 bunches) there is little vertical betatron sideband and at 6 buckets interval (406 bunches) the sidebands appear. That implies the vertical beam oscillation observed in the experiments is caused by the ion related phenomenon.

SIMULATION

To discuss quantitatively, we have performed computer simulation for the ion related phenomenon. The simulation is basically based on macro-particle tracking. To do this, we have applied following assumptions and approximations:

- We assume that the electron beam has a Gaussian distribution in transverse direction and the distribution does not change. We treat the electron beam as single macro-particle without longitudinal structure. We also assume that the electron beam has no energy spread.
- We assume that the residual gas component is CO and the vacuum pressure is 10 nPa which is the typical pressure value in the SPring-8 ring.
- We settle one ionization point in the ring. In the following calculation, we have selected the ionization point in the position where β_y is large. The number

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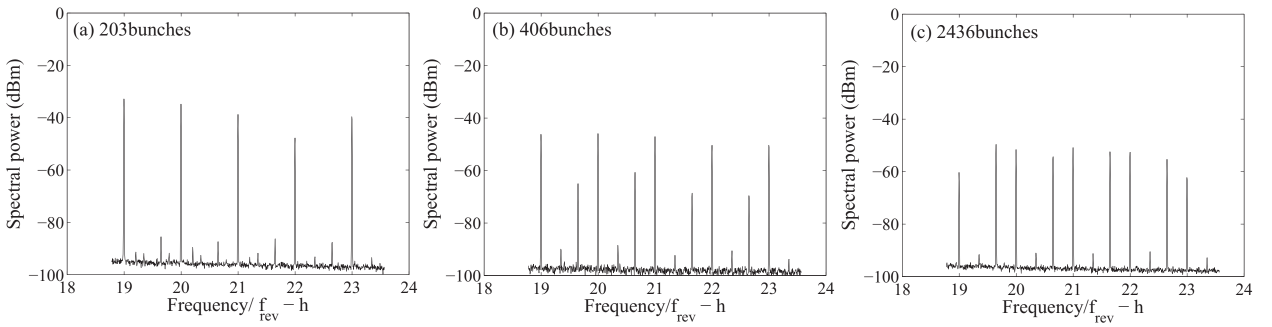

Figure 1: Beam spectrum measured by vertical pickup electrode for (a)203 bunches (12 buckets interval), (b)406 bunches (6 buckets interval) and (c)2436 bunches (full-filling).

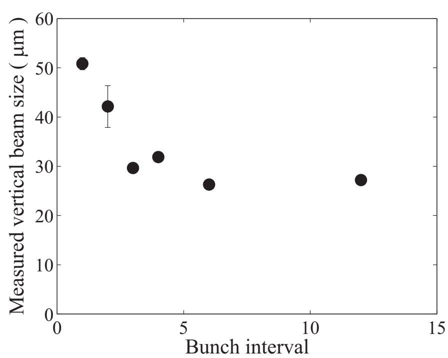

Figure 2: Measured vertical beam size at the bunch interval of 1,2,3,4 and 12 buckets.

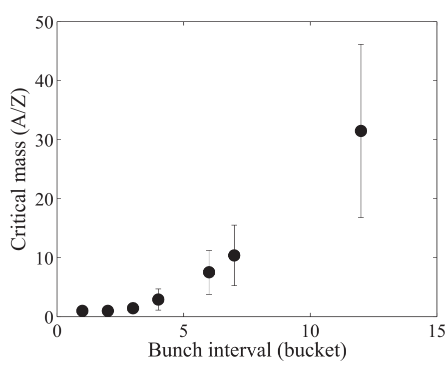

Figure 3: Change in critical mass for equally spaced bunch patterns. Vertical bars correspond to the variation of the beam size around the ring.

of created ions per one revolution of the beam is determined by the ionization time [4]. From this, total number of the created ions for one revolution of 100 mA electron beam is $N_i^{turn} = 2.0 \times 10^6$. We assume that N_i^{turn} ions are created in one revolution of the beam.

- When the electron bunches pass the ionization point, we select one bunch randomly and assume that 10 macro-particle ions are created. We assume that transverse aperture of the ions and the ions which move beyond the aperture are treated to be lost. We also assume that the ions are not affected by the magnetic field and have only transverse motion.

From these assumptions and approximations, the equation of motion of the ion and the electron macro-particle are written as

$$\frac{d^2\boldsymbol{x}_i}{dt^2} = \frac{qN_e}{m_i}\boldsymbol{E}\left(\boldsymbol{x}_i - \boldsymbol{x}_e\right), \quad (1)$$

$$\frac{d^2\boldsymbol{x}_e}{ds^2} = \frac{qN_i}{\gamma m_e c^2}\sum_j \boldsymbol{E}\left(\boldsymbol{x}_e - \boldsymbol{x}_{i,j}\right) \quad (2)$$

where $\boldsymbol{x}_i$ and $\boldsymbol{x}_e$ are the position of the ion and electron bunch, q is the charge of the electron, γ is the Lorentz factor of the electron beam, m_e and m_i are the electron and the ion mass, N_e and N_i are the number of the electrons and ions in one macro-particle. We calculate the electric field $\boldsymbol{E}$ using the Bassetti-Erskine's formula [6]. In the simulation, we have repeated the tracking calculation for 10000 revolution of the beam. Figure 4 shows the change in the number of survived macro-particle ions on the beam revolution. As seen in the figure, the number of the ions increases as the bunch interval becomes shorter. Figure 5 shows change in the rms vertical ion cloud size on the beam revolution. The ion cloud sizes do not change so much as the beam revolution proceeds. The ion cloud distributes in the wide range compared to the average vertical beam size of 12.6 μm. As seen in the figure, the ions tend to concentrate as the bunch interval becomes shorter. Because of the perturbation from the trapped ions to the electron beam, the electron beam distribution in the $y - y'$ phase space diffuses and the beam emittance becomes larger. Figure 6 shows change in the vertical emittance on the beam revolution. The original vertical beam emittance is 9.56 pm rad. The vertical emittance grows in about 5000 revolution and after that the growth tends to saturate. As seen in the figure, the growth of the emittance is prominent in case that the bunch interval is shorter. From the results of Fig. 6 and the optical function of the SPring-8, we have estimated the vertical beam size at the position of the visibility monitor. Figure 7 shows the comparison between the measurement (Fig. 2) and the simulation. Although there are several ambiguities in the simulation such as vacuum pressure value, the simulation

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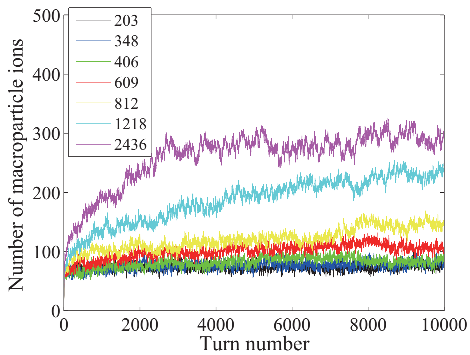

Figure 4: Change in the number of the survived macroparticle ions on the beam revolution. Numbers in the legend correspond to the total number of bunches.

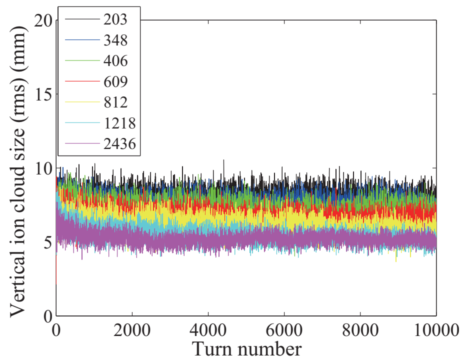

Figure 5: Change in the rms vertical ion cloud size on the beam revolution. Numbers in the legend correspond to the total number of bunches.

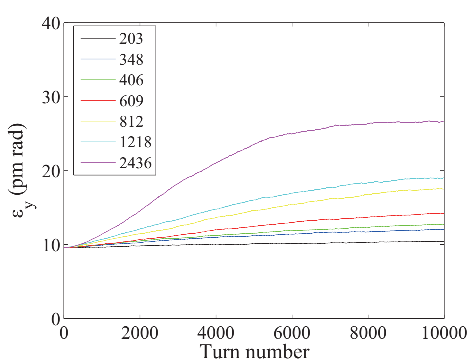

Figure 6: Change in the vertical emittance on the beam revolution. Numbers in the legend correspond to the total number of bunches.

agrees well with the measurement in the factor of the beam size.

SUMMARY

In the SPring-8 storage ring, various kinds of filling patterns are available because of the large harmonic number. In the development of new filling patterns which have equally spaced bunches, we have found a vertical instability which has strong dependence on the bunch interval. We have speculated that the instability is ion related, and performed analysis based on the classical theory of ion trapping. From the discussion of the critical mass, the critical mass for shorter than 7 bucket interval (348 bunches) is smaller than 10; assuming CO^+ ions, the ions are trapped in case that the bunch interval is shorter than 7 buckets. In the measurement, while we have little vertical betatron sidebands in 203 bunches, in 406 bunches we have observed the distinct sidebands. This agreement implies that the vertical instability is ion related, and we have performed the computer simulation based on the macro-particle model. The simulation shows that the number of trapped ions increases and the ion cloud tends to concentrate to the electron beam orbit as the bunch interval becomes shorter. The betatron oscillation amplitude becomes larger in case that the bunch interval is shorter due to the perturbation of the trapped ions. Agreement between the measurement and the simulation of the dependence of the vertical beam size on the bunch interval is good; from the discussion, the vertical instability occurred in the equally spaced bunches filling patterns in the SPring-8 is ion related phenomenon.

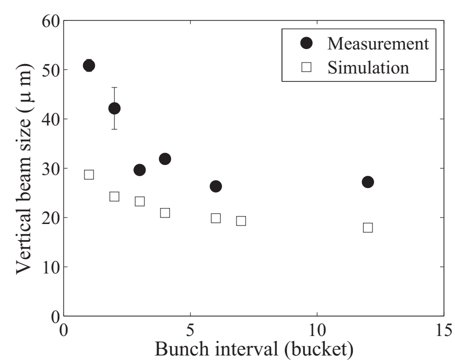

Figure 7: Measured and calculated vertical beam size.

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