

ION EFFECT ISSUES IN PETRA III

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Abstract

At DESY the PETRA accelerator has been converted into a new 3rd generation high-brilliance synchrotron radiation facility called PETRA III. For the first commissioning in spring 2009 a positron beam is used. In the future it is also foreseen to operate the synchrotron light source with an electron beam. Ion effects pose a potential problem to the electron beam operation of PETRA III. In this paper, a weak-strong simulation code is employed to study the ion effect issues in detail for different operation scenarios.

INTRODUCTION

The electron beam creates ions by ionizing the residual gas in the vacuum pipe of the storage rings. A coupling between the motion of these ions and the motion of the electrons can cause a two-beam instability which may affect the performance of the accelerator. Depending on the bunch filling pattern the ions with a mass larger than a critical mass may be either lost between two adjacent electron bunches or are trapped in the attractive beam potential, and the number of ions around the beam increases linearly with the number of bunches passing through a certain accelerator section. In circular machines, conventional ion trapping refers to an ion cloud which is accumulated over many turns. In general, this ion instability develops slowly and may be damped with a feedback system or can be avoided with a gap (empty RF buckets) in the bunch train so that the ions become over-focused and too diluted to harm the electron beam upon subsequent passages.

However, even when a beam filling pattern is used with several trains of bunches, separated by long gaps to clear the ions in between the trains, a strong instability can still develop over a single train, which is called fast ion instability (FII) [1,2]. In this scenario, individual ions last only for a single passage of the electron beam and are not trapped during multiple turns. It is like a beam break up instability, which affects only bunches in the rear part of a train, and bunches in the head are not affected. This type of instability has been predicted for accelerators with high current, low emittance and multi bunches operation modes such as the damping rings of the International Linear Collider [3], and storage ring-based light sources, etc.

PETRA III is a new synchrotron light facility with low design horizontal beam emittance of 1 nm on the DESY site in Hamburg [4, 5]. A bird view of the new experimental hall which extends over one octant of the storage ring is shown in Fig. 1. The main parameters of PETRA III are listed in Table 1. The standard bunch

filling pattern consists of a large number of equally spaced bunches with a low bunch population. Additionally a special operation mode is required for time-resolved experiments with a higher single bunch charge in 40 equally spaced bunches. In this year, during the commissioning of PETRA a positron beam is injected. In the future it is also foreseen to operate the synchrotron light source with an electron beam. Since the vertical design emittance of the beam is extremely low (0.01 nm), vertical oscillations of the bunch centroid due to fast ion instability may reach amplitude in the order of the rms beam size. In this paper, the classical ion trapping is discussed and simulation results for the fast ion instability are presented for various operation conditions.

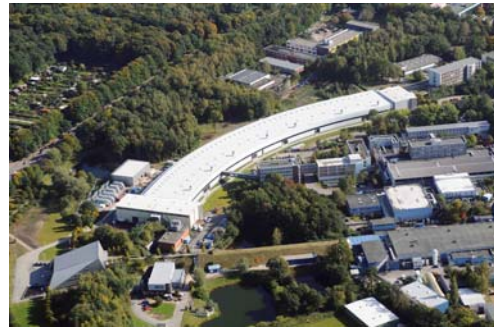


Fig 1: Experimental hall of PETRA III.

Table 1: Beam parameters of PETRA III

Parameters	Value
Circumference [m]	2304
Harmonic number	3840
Energy [GeV]	6
RF frequency [MHz]	499.564
Beam current [mA]	100
Total number of electrons [10^{12}]	4.8
Bunch number (standard mode)	960
Bunch number (time resolved mode)	40
Horizontal / vertical emittance [nm]	1 / 0.01
Horizontal tune	36.12
Vertical tune	30.26
Synchrotron tune	0.049
Momentum compaction factor [10^{-3}]	1.2
Bunch length [mm]	13.2
Energy spread [10^{-3}]	1.27

CRITICAL ION MASS

Based on the linear theory of ion trapping [6], the ions with a relative molecular mass, called critical mass, greater than $A_{x,y}$ will be trapped horizontally (vertically) in the potential well of the beam. The critical mass in units of amu is given by

$$A_{x,y} = \frac{Nr_p L_{sep}}{2\sigma_{x,y}(\sigma_x + \sigma_y)} \quad (1)$$

where N is the number of particles per bunch, r_p is the classical radius of the proton, L_{sep} is the bunch spacing in meter, $\sigma_{x,y}$ is the rms beam size in horizontal and vertical direction, respectively. Using the beam parameters of Table 1 and assuming an average value for the optical functions, the critical mass for 960 and 40 equally spaced bunches are 6 and 3386 respectively. It means for the bunch operation with 960 bunches, that most of ions including CO+ (mass number of 28) are trapped in the beam potential. However, the ions are not trapped in time resolved mode due to large bunch spacing (96 RF buckets). The trapping of CO+ can be avoided if a cleaning gap is introduced. Possible scenarios include one bunch train with 726 bunches and a clearing gap of 936 RF buckets or several filling patterns with several bunch trains, e.g. 8 trains with 85 bunches per train or 32 trains with 29 bunches per train [7].

SIMULATION MODEL

A weak-strong simulation code has been used to study the ion effects in PETRA III [8]. In the simulation, the electron bunch is treated as a rigid Gaussian beam. Only the centroid motion of the bunch is taken into account. The ions are randomly generated according to the collisional cross section for the ionization process and they are modelled as marco-particles. In order to save CPU time, we use a limited number of ionization points along the ring lattice. The motion of ions is non-relativistic without longitudinal drift and it is assumed that the ions drift freely in the time interval between two adjacent bunches. The interaction between the beam and the ions is based on the Bassetti-Erskine formula [9]. To connect the adjacent interaction points, the beam optics is modelled as a linear transport matrix. In this code, the beam size variation due to different values of the beta function and the dispersion function at the interaction points is taken into consideration.

The average ion density λ_{ion} depends on the cross section Σ_{ion} (2 Mbarn for CO), the density of the residual gas molecules λ_{gas} and on the bunch population N :

$$\lambda_{ion} = \Sigma_{ion} \lambda_{gas} N. \quad (2)$$

For residual gas pressure of 1 nTorr and a bunch population of $0.5 \cdot 10^{10}$ electrons one obtains an ion density of about 32 ions/m. In order to save computation time, the simulation uses only a limited number (about 10) of interaction points. The ion density at these points is artificially enhanced to ensure that the average ion density over the storage ring is the same as calculated from Eqn. (2). The motion of the beam and ions is tracked from turn to turn. Since the vertical beam emittance is much smaller than the horizontal one, (for PETRA III, the design emittance coupling ratio is about 1.0 %), the FII is much serious in the vertical plane. Therefore, only the vertical oscillation of the beam is recorded here.

The dipole moment of each bunch is computed and recorded in every turn. The vertical amplitude of the bunch centroid is half of the Courant-Snyder invariant which is given by

$$J_y = \frac{1}{2} \left[\frac{(1+\alpha^2)}{\beta} y^2 + 2\alpha y y' + \beta y'^2 \right] \quad (3)$$

where α and β are the Twiss parameters which depend on the optical design of the ring. We compare the square root of J_y with the beam size which is represented by the square root of vertical emittance ε_y . Both of these quantities are in units of $m^{1/2}$.

SIMULATION RESULTS

The amplitude of the beam oscillations due to the interaction with the ions versus the bunch index is shown in Fig. 2 for different turns using a standard fill mode with 960 bunches and a CO pressure of 1 nTorr. The beam oscillation at the 200th, 400th, 600th, 800th and 1000th turn are shown in the figure respectively. It can be clearly seen that the beam oscillations are growing with respect to the revolution time. The trailing bunches oscillate with larger amplitude than those of the preceding bunches. This is also a typical characteristic of the FII [1].

The evolution of the maximum vertical amplitude for the 960 bunch operation mode at a CO partial pressure of 1.0 nTorr is given in Fig. 3. It shows that the oscillation amplitude is finally larger than the beam size. The growth time of the FII (the time the bunch oscillates from $0.1 \sigma_y$ to $1 \sigma_y$ in amplitude) is also estimated based on the simulation results and noted in the figure. Except that, we also investigate the case that the CO partial pressure is less than 1.0 nTorr. Fig. 4 shows the results at CO pressure of 0.2 nTorr and 0.5 nTorr respectively. The oscillation amplitudes are still beyond the beam size. However, the growth of oscillation amplitude slows down compared to Fig.3 due to low pressure of CO. The growth time is 150 turns and 66 turns for CO pressure of 0.2 nTorr and 0.5 nTorr respectively. It denotes that the growth time of the FII is decreasing with increasing gas pressure. This also agrees to the linear theory of FII [1].

In addition, the fast feedback system is taken into account in the simulation. Fig. 5 shows the evolution of maximum amplitude with respect to number of turns for the 960 bunch mode at CO pressure of 1.0 nTorr with feedback damping time of 100 turns and 50 turns respectively. It can be seen that a feedback with damping time of 100 turns cannot damp the FII totally. However, for a feedback with damping time of 50 turns, it is sufficient to suppress it. Since the design value of the feedback damping time for PETRA III is about 100 turns, a low level CO gas pressure combined with this feedback damping is also investigated. Fig. 6 shows the result for multi bunch mode at CO pressure of 0.2 nTorr with a feedback damping time of 100 turns. It is more or less similar to the real condition of the ring. In this case, the total vacuum pressure is 1.0 nTorr and the CO occupies 20% of it. In this case, a feedback with damping time of 100 turns is enough to suppress the FII. Therefore, a fast

feedback system and a very low level of CO pressure are two critical factors to suppress the FII growth in PETRA III for the 960 bunch operation mode.

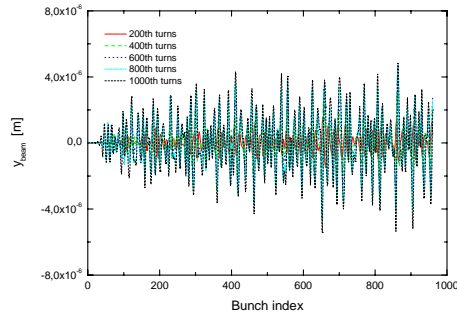


Fig.2: Beam oscillation in different turns for multi bunch mode.

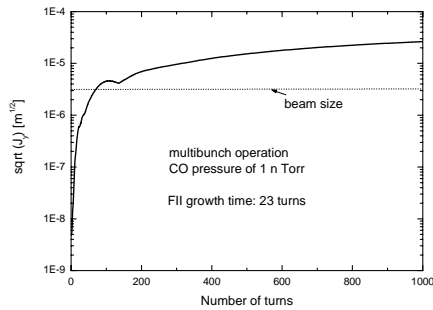


Fig.3: Evolution of maximum amplitude vs. number of turns for the 960 bunch mode at CO pressure of 1 nTorr.

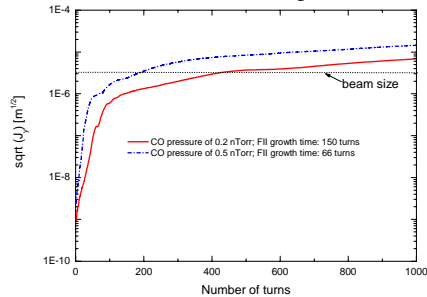


Fig.4: Evolution of maximum amplitude vs. number of turns for the 960 bunch mode at CO pressure of 0.2 nTorr and 0.5 nTorr.

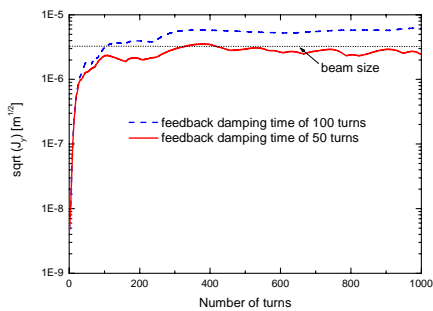


Fig.5: Evolution of maximum amplitude vs. number of turns for the 960 bunch mode at CO pressure of 1.0 nTorr with feedback damping time of 100 turns and 50 turns.

The evolution of maximum amplitude with respect to number of turns for the time resolved mode (40 bunches) at CO pressure of 1.0 nTorr is show in Fig. 7, it can be

seen that the bunch oscillation amplitude is well below the beam size. In this case, most of ions cannot be trapped in the beam potential as shown in Eqn. (1) due to the long bunch to bunch distance. These scattered ions form an ion halo and do not affect the beam motion seriously.

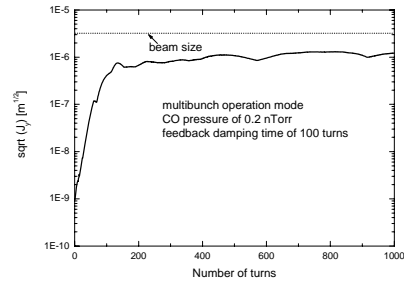


Fig.6: Evolution of maximum amplitude vs. number of turns for the 960 bunch mode at CO pressure of 0.2 nTorr with feedback damping time of 100 turns.

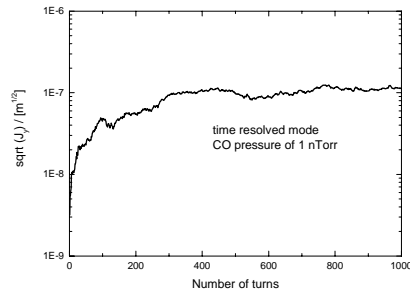


Fig.7: Evolution of maximum amplitude vs. number of turns for the 40 bunch mode at CO pressure of 1.0 nTorr.

CONCLUSIONS

For the PETRA III ring, the FII will not affect the beam seriously in time resolved operation mode (40 bunches). However, for the 960 bunch operation mode, the FII can lead to beam oscillation amplitude as large as the vertical beam size. A fast feedback system with damping time of 50 turns is sufficient to damp the growth of FII. The FII can also be mitigated when a filling pattern with several bunch trains is introduced.

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