STUDIES ON THE DUST EFFECT IN THE BEPC STORAGE RING

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1 INTRODUCTION

The Beijing Electron Positron Collider (BEPC) has been running for more than 12 years since 1989, not only as a collider, but also a synchrotron radiation (SR) facility. Every year, BEPC provides beam to users of synchrotron radiation for 2 or 3 months with a dedicated mode. Table 1 lists some main parameter of the BEPC dedicated mode for synchrotron radiation.

Table 1 Main parameters of BEPC dedicated SR mode

Beam energy	2.2 GeV
Circumference	240.4 m
Horizontal emittance	80 nm
Energy spread	6.2×10^{-4}
Momentum compaction	0.016
Betatron tunes	8.72/4.75 (H/V)
RF frequency	199.533 MHz
RF voltage	0.8 ~ 1 MV
Harmonic number	160
Bunch number	1~100
Beam current (Multi-bunch)	~140 mA
Beam current (Single bunch)	~80 mA

In the routine dedicated synchrotron radiation operation, the normal beam lifetime is 8~10 hours at I_b ~ 80 mA for the single bunch case, and 20~25 hours for multi-bunch case with the total beam current of ~140 mA. A beam lifetime reduction was observed very often in operation for both single and multi-bunch cases. The beam lifetime can degrade to 2 hours or several minutes in the single bunch case, and 5~6 hours or less in the multi-bunch case. Such a lifetime reduction has the following characteristics:

- It happens at any beam current.
- Only in electron beam operation, in single or multi-bunch cases.
- When it happens, dump and re-fill the beam again, this phenomenon does not repeat in the same beam and machine parameters. It may appear again at any other current in any time.
- Such a phenomenon happens more frequently year-by-year.
- The reduced beam lifetime can be recovered itself, or by using a kick to the beam. Sometimes, none is effective to rescue the beam.
- This phenomenon is never observed in electron and positron beam collision.

Fig. 1 gives an example of the beam lifetime reduction. Some theoretical analyses on the beam lifetime reduction will be given in the following section. Studies on the effect of vacuum pump will be shown in section 3. Section 4 will focus on the possible cures on this problem.

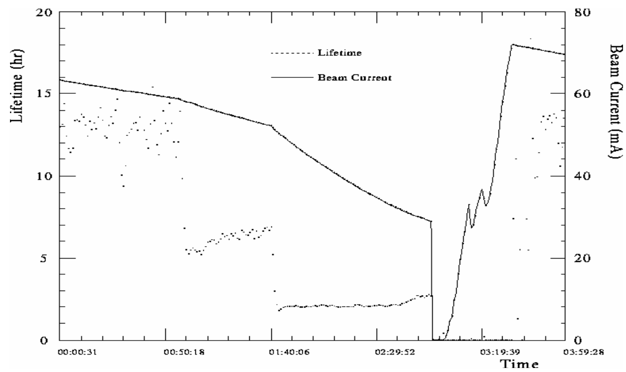

Fig. 1 A typical beam lifetime reduction (Dec. 6, 1998).

2 THEORETICAL ANALYSES

According to the characteristics of the beam lifetime reduction, the phenomenon is concluded as the effect of beam-dust interaction, i.e., dust effect, which was also observed in other machines like HERA[1], CESR[2], etc.

As the increase of running time, some kinds of metallic oxide particle, such as Al_2O_3, SiO, SiO_2, are gradually accumulated in the vacuum chamber. Operating some hardware, e.g., vacuum pumps, masks, scrapers, profiles, valves, will cause the macro-particles to drop from the pumps or chamber wall. When they meet electron beam, these macro-particles may be ionized. In the same time, distributed ion pumps (DIP) around the ring also spray some positively ionized macro-particle into the chamber. These ionized particles can be trapped by the beam, and cause the dust effect.

2.1 Source of Dust Particle in BEPC Chamber

The main material of the BEPC vacuum chamber is aluminum. RF cavity is made from copper. Titanium is contained in the material of DIP. Quartz particles exist on the surface of DIPs' polar plates. Among these particles, SiO_2 is easiest to be ionized and trapped by electron beam.

The electric field at the place of 1σ far away from the center of the bunch can be written as

$$E_{x,y}(\sigma_{x,y}) \approx \frac{eN_e}{2\pi\varepsilon_0(\sigma_x+\sigma_y)C}, \tag{1}$$

where e is the electron charge, N_e the total number of electron in beam, ε_0 the dielectric coefficient in vacuum, C the circumference of storage ring and $\sigma_{x,y}$ the bunch transverse sizes. The field on the chamber wall can be expressed as

$$E(b) \approx \frac{eN_e}{2\pi\varepsilon_0 bC}. \tag{2}$$

Here, b is the effective half size of the vacuum chamber. From eq. (2), we can get the forces act on the SiO_2^+, if it lies on the bottom of the vacuum chamber. There are three kinds of force: gravitation, attraction from electron beam and image charge force, shown as Fig. 2.

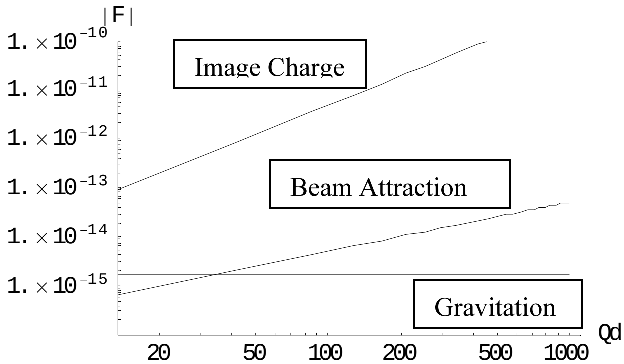

Fig. 2 Forces on the dust particles lying on the bottom of vacuum chamber. (F in unit of Newton, Q_d in unit of e)

Among these, the force from image charge is much stronger than the other two. So the dust particles lying on the bottom of vacuum chamber cannot be trapped by electron beam. Thus the trapped dust particle should be from the upper wall of chamber or sprayed from the DIPs in the bends. Fig. 3 shows the structure of the DIP and its electric field in a bend.

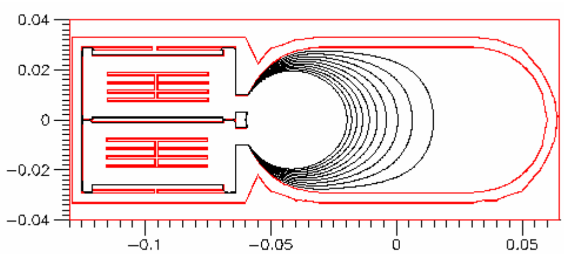

Fig. 3 Structure and Electric field of DIPs in BEPC.

2.2 Beam lifetime due to Bremsstrahlung

The beam lifetime due to inelastic scattering between the electron in beam and the nuclei of dust particle can be expressed as[3]

$$\frac{1}{\tau} \approx -\frac{cAZ^2_{azom}}{2\pi\sigma_x\sigma_y CA_{atom}}\left(\frac{16r_e^2\alpha}{3}\ln\frac{\Delta E}{E}\ln\frac{183}{Z^{1/3}_{atom}}\right), \quad (3)$$

where c is the speed of light, A the mass number of dust particle, Z_{atom} and A_{atom} the atom number and atom mass number of particle nuclei, respectively, r_e the classical radius of electron, α the fine structure factor and $\Delta E/E$ the energy acceptance of machine. With the parameters of BEPC SR mode, for SiO_2^+ particle, A = 4.9×10^{11} when the beam lifetime reduces to 2 hours and A = 8.2×10^{10} for the normal beam lifetime in the single bunch case, i.e., ~12 hours. Thus, we will have

$$8.2\times10^{10} \le A \le 4.9\times10^{11}. \quad (4)$$

Another kind of Bremmstrahlung happens in the electric field of the ionized dust particle as a whole, and may be called "duststrahlung". It can be treated similar to the treatment in linear collider[4], with a dimensionless parameter Γ, expressed as

$$\Gamma \equiv \frac{\hbar c\gamma^3}{\rho E} \approx \frac{\hbar c e^2 Q_d \gamma^3}{2\pi\varepsilon_0 b^2 E^2}, \quad (5)$$

where $\hbar$ is the Plank constant, Q_d the charge of dust particle, γ the relative beam energy, E the beam energy, ρ the bending radius and b the impact factor, normally 1μm ≤ b ≤ 2μm. The average number of photons emitted from each electron per turn is

$$N_\gamma \approx \frac{5}{2\sqrt{3}}\frac{b\alpha\Gamma}{\lambda_e\gamma}\frac{1}{\sqrt{1+\Gamma^{2/3}}}. \quad (6)$$

where λ_e the electron Compton wavelength. Thus, the effective cross-section of bremsstrahlung is

$$\sigma_{eff} = \pi\int_{b_{min}}^{b_{max}} N_\gamma b db. \quad (7)$$

The beam lifetime due to bremsstrahlung will be

$$\frac{1}{\tau} = \frac{c\sigma_{eff}}{2\pi\sigma_x\sigma_y C}. \quad (8)$$

With the parameters of BEPC SR mode, and the reduced beam lifetime from normal value, i.e., 2 hrs ≤ τ ≤ 12 hrs, we can have

$$2.4\times10^5 \le Q_d \le 1.4\times10^6. \quad (9)$$

Together with eq. (4), we can find the region of A/Q_d for trapped dust particles in the BEPC SR operation:

$$5.7\times10^4 \le \frac{A}{Q_d} \le 2.0\times10^6. \quad (10)$$

2.3 Dynamic stability of trapped dust particles

Adopting the linear model for the interaction between beam and dust particles, and with the method of transfer matrix, we have the equation describing the interaction:

$$\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_1 = M\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_0, \quad (11)$$

where z and $\dot{z}$ represent the displacements and velocities in transverse direction, and M can be expressed as

$$M = \begin{pmatrix} 1 & \Delta t \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ k_{x,y} & 1 \end{pmatrix}. \quad (12)$$

Here, Δt is the time interval between two bunch passages, and $k_{x,y}$ the strength, written as

$$k_{x,y} = -\frac{2N_b r_p c Q_d}{\sigma_{x,y}(\sigma_x+\sigma_y)A}, \quad (13)$$

where N_b is the electron population per bunch and r_p the proton classical radius. If the dust particles are trapped by electron beam, i.e., dust particles are stable, there will be

$$\frac{1}{2}\left|\mathrm{Tr}(M)\right| \le 1. \quad (14)$$

Then, we can get the critical bunch current for trapped dust particles:

$$N_b \le N_{b,crit} = \frac{2\sigma_{x,y}(\sigma_x+\sigma_y)}{r_p c\Delta t}\frac{A}{Q_d}. \quad (15)$$

If the peak bunch current in the BEPC SR operation is 150 mA, considering the vertical direction, we will have

$$\frac{A}{Q_d} \geq 2.1\times10^3 \,. \qquad (16)$$

For a typical value $A/Q_d = 1\times10^5$, we can get $I_{b,crit} = 7.3$A, which means for $I_b \leq I_{b,crit}$, dust ions will be trapped by the electron beam. The oscillation frequency of trapped dust ions can also be obtained as

$$(f_d)_{x,y} = \frac{1}{2\pi}\left(\frac{2c^2 r_p N_b Q_d}{C\sigma_{x,y}(\sigma_x+\sigma_y)A}\right)^{1/2} . \qquad (17)$$

For the peak bunch current I_b =150 mA, we will have

$$(f_d)_x = \frac{5.85\times10^6}{\sqrt{\frac{A}{Q_d}}}, \qquad (f_d)_y = \frac{1.80\times10^7}{\sqrt{\frac{A}{Q_d}}} . \qquad (18)$$

3 EXPERIMENTAL STUDY

Experiments on vacuum pumps, which are considered one source of dust particles, were carried out on the BEPC. Switching off and on all or part of the DIPs and lumped pumps (LPs) give the following results.

1) The amount of beam lifetime reduction may decrease when DIPs are switched off.
2) The process of switching on DIPs makes the beam lifetime reduce suddenly.
3) The normal beam lifetime is not seriously affected when DIPs are off.
4) When LPs are off, the vacuum pressure and normal beam lifetime degrade. But LPs' on and off don't cause the beam lifetime reduction.

Additionally, the change of horizontal beam orbit seems to affect beam lifetime very little. Switching on the injection kickers when the beam lifetime decreases, can stabilize the beam. A kick from the shaker of the betatron tune measurement system, also make the beam stable from the lifetime reduction. Sometimes, external kick to the beam cannot rescue the beam lifetime. The reason why the external kick can stabilize the beam is that the local dust particles are also kicked along with the beam. If the dust particles oscillate with the same frequency as that given by eq. (18), resonance will happen to the dust ions. Ions will fly to the wall of chamber and the beam will stabilize.

Experiment on positron beam results that no any dust effect happens with the same optics as electron beam.

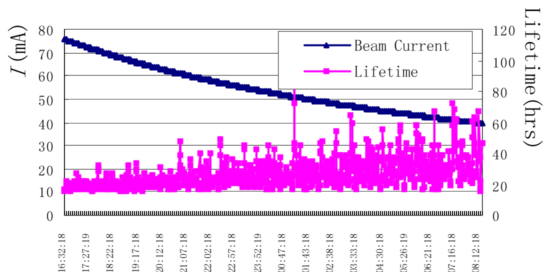

Fig. 4 Positron beam current and lifetime in 16 hrs.

Fig. 4 shows the positron beam current and lifetime change with the running time. More than 70 hours were spent on observing the behavior of positron beam, no any beam lifetime reduction happened.

4 POSSIBLE CURES

Based on the experimental study, three methods can be used to cure the dust effect in the BEPC SR operation. First is switching off all or part of the DIPs around the ring. Calculations also show that only with the LPs, the vacuum pressure can still maintain of 2 nTorr. If the beam current is 100 mA, the pressure reduction due to the gas desorption caused by synchrotron radiation will be 4.1 nTorr. So the vacuum pressure without DIPs will be 6 ~ 7 nTorr, which can maintain a good beam lifetime.

The second method is to excite beam and dust particles with the shaker of tune measurement when the lifetime reduction happens. The present shaker on the BEPC is a strip-line exciter, acts on beam in both horizontal and vertical planes. But due to the insufficient power of the exciter, the efficiency of rescuing beam is not so good. In the routine operation, we found that varying RF voltage up and down with a small fraction, can sometimes make beam stable as well, when the lifetime reduction happens. The reason is not known.

Finally, the thorough way to eliminate the dust effect is to use positron beam to run the dedicated SR mode in the routine operation, if the filling rate is fast enough.

5 CONCLUSIONS

Beam lifetime reduction in the BEPC dedicated SR operation is observed frequently, which severely degrades the beam performance. This phenomenon is ascribed to the dust effect, according to the theoretical analyses. The experiments on vacuum pump show the main source of dust ions is the DIPs around the ring. Partially switching off the DIPs can weaken the dust effect. Transverse kick to the beam is applied in routine operation when the beam lifetime reduces. RF voltage variation in a small amount can also rescue the beam, but beyond understanding. To fully avoid the dust effect, running with positron beam is the best way. Further studies on simulation are under way.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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