DUST EFFECT IN THE BEPC

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1. Motivation

The Beijing Electron Positron Collder (BEPC) runs for users of synchrotron radiation (SR) when it provides beams to high energy physics experiments. Since 1989, the BEPC has been operating with the dedicated SR mode for 2~3 months every year. Electron beam is used in the dedicated SR mode. The main parameters of the SR dedicated mode run on the BEPC storage ring are listed in Table 1.

Table 1 Main parameters of the dedicated SR mode run on the BEPC.

Beam energy	2.2 GeV
Circumference	240.4 m
Revolution frequency	1.247 MHz
Momentum Compaction	0.016
Energy spread	6.2×10^{-4}
Natural horizontal emittance	80 nm
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 ~ 160
Max. current (single bunch)	~ 80 mA
Max. current (multi-bunch)	~ 140 mA

In the routine dedicated synchrotron radiation operation, for single bunch case, the normal beam lifetime is 8~10 hours, and 20 ~25 hours for multi-bunch case at the maximum beam current, respectively. It is very often to observe a beam lifetime reduction in the routine operation for both single and multi-bunch cases or bunch train. If it happens, the beam lifetime will be 2 hours or lower in the single bunch case and 5~6 hours or lower in the multi-bunch case. This phenomenon has the following characteristics:

- It happens at any beam current, but only in electron beam operation, no matter how many bunches are.
- When the beam lifetime reduction happens, dumping and refilling the beam, the phenomenon cannot be repeated in the same machine parameters. But it may happy again at any other beam current in any time.
- It happens more frequently year-by-year.
- The reduced lifetime can be recovered itself sometimes, or by using a kick to the beam. Sometimes, none is effective to rescue the beam.
- It never appears in the electron positron collision.

Fig. 1 shows a typical beam lifetime reduction in the routine SR operation. In the graph, it is very clear to see that the beam lifetime reduction happens two times in 8 hours. Each time, beam lifetime decreases to around 1/3 of previous values.

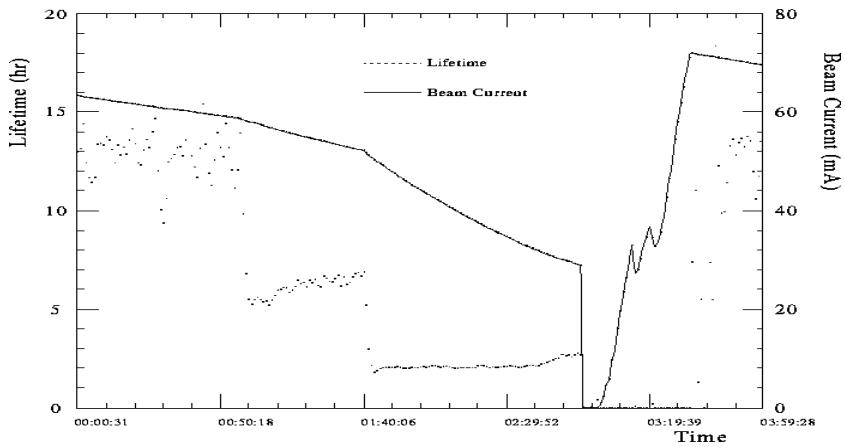

Figure 1. Typical beam lifetime reduction in the routine operation (Dec. 6, 1998).

This phenomenon is ascribed to the effect of beam-dust interaction, i.e., dust effect, which was also observed in other machines like HERA[1], CESR[2], etc. It degrades the performance of BEPC severely when it runs as a light source. In this paper, some theoretical analyses of the dust effect, happened on the BEPC storage ring, are given. Beam experiments related to the effect will then be shown. At last, some possible cures on this problem are set forth.

2. Theoretical Analyses

With the running time increasing, more and more metallic oxide particles, such as Al2O3, SiO, SiO2, etc., are gradually accumulated on the surface of vacuum chamber. On the other hand, manipulating some hardware like vacuum pumps, masks, scrapers, profiles and valves, will also cause these macro-particles to drop from the pumps or the chamber wall. They may be ionized when they meet the electron beam or in the vacuum pumps, such as the distributed ion pumps (DIPs) around the ring. DIPs can then spray the positively ionized macro-particles into vacuum chamber. Trapped by the beam, these ionized particles will finally cause the dust effect and lead to the beam lifetime reduction.

2.1 Source of the dust particles in the BEPC chamber

Aluminum is the main material of the BEPC vacuum chamber. Copper exists in the RF cavity on the storage ring. Titanium is found in the vacuum pumps. In the DIPs, silicon dioxide exists widely. Among these species of macro-particle, SiO_2 is the easiest to be ionized and trapped by electron beam.

From the theory of electric field, it is easily to get the field at the place of 1σ far away from the center of the bunch:

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

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 then can be expressed as

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

Here, b is the effective radius of the vacuum chamber. When an ionized dust particle stays at the bottom of the chamber, the forces act on the particle will be the gravitation, the attraction from the beam and the attraction from the image charge. The gravitation on the dust particle is

$$F_{grav} = m_d g = Am_p g , \tag{3}$$

where g is the acceleration of gravitation, $m_d = Am_p$ is the mass of dust particle, A the mass in unit of m_p and m_p the classical proton mass. The force of the attraction from the beam can be given as

$$F_{beam} = -\frac{2c^2 N_e r_p m_p Q_d}{b_y C} . \tag{4}$$

Here, Q_d is the charge of dust particle in unit of e and b_y the effective vertical half size of the chamber. The force of the image charge can be expressed as

$$F_{image} = \frac{c^2 r_p m_p Q_d^2}{4R_d^2} = \frac{c^2 r_p m_p^{1/3} Q_d^2}{2\times\left(\frac{3A}{2\rho_d}\right)^{2/3}} , \tag{5}$$

where R_d and ρ_d are the radius and density of the dust particle, respectively, if we assume the particle is sphere and the charges distribute on the sphere's surface uniformly.

Taking into account the parameters of BEPC dedicated SR mode with a beam of 150 mA passing the center of the vacuum chamber, the ionized SiO_2 particle, which lies on the bottom of the chamber, will have the forces act on it like Fig. 2.

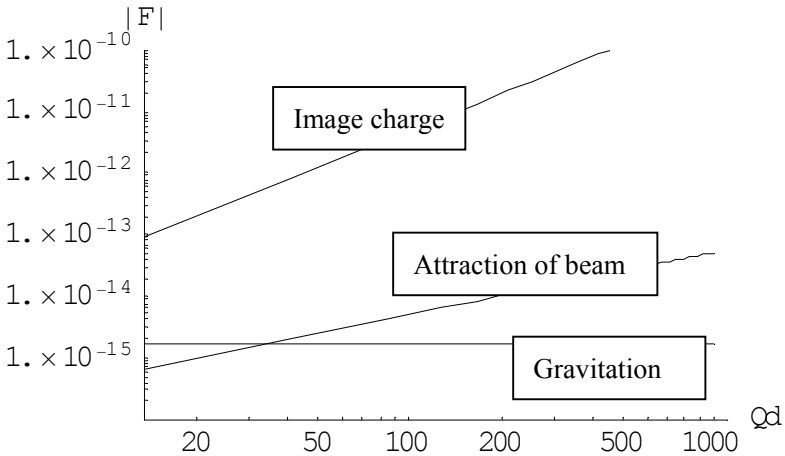

Figure 2. Forces on the dust particles lying on the bottom of vacuum chamber.
(F in unit of Newton, Q_d in unit of e)

From the figure, we can see that the absolute value of the force of the image charge is much bigger than the other two forces, and its direction is opposite to the force of the attraction of beam. So the beam could not trap particles, which lie on the bottom of the vacuum chamber. The dust particles can only come from the other sides of the chamber wall or being sprayed from the DIPs

in the bends. Fig. 3 shows the structure of the DIP on the BEPC storage ring and its electric field.

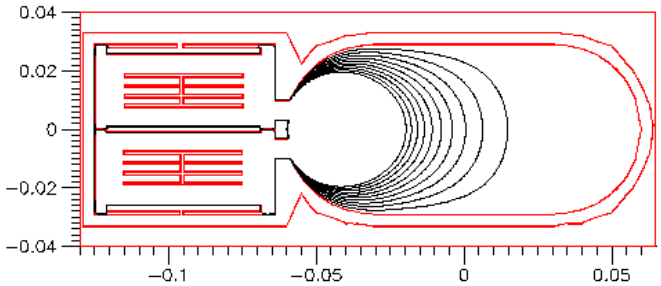

Figure 3. Structure of the DIP on the BEPC storage ring and its electric field.

2.2 Beam lifetime due to bremsstrahlung

When the dust ions are trapped by electron beam, the bremsstrahlung between ions and electron particles will cause the beam lifetime reduction. If the bremsstrahlung happens between the nuclei of beam particles and dust particles, the beam lifetime is determined by[3]

$$\frac{1}{\tau} \approx -\frac{cAZ_{atom}^2}{2\pi\sigma_x\sigma_y CA_{atom}}\left(\frac{16r_e^2\alpha}{3}\ln\frac{\Delta E}{E}\ln\frac{183}{Z_{atom}^{1/3}}\right), \tag{6}$$

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. So, we have

$$8.2\times10^{10} \le A \le 4.9\times10^{11}. \tag{7}$$

From eq. (7), we can see that the beam lifetime determined by such a kind of bremsstrahlung depends on the mass number A of dust ions, but not the charge number Q_d.

Another kind of bremsstrahlung takes place when the dust ions as a whole interact with electrons in beam. It can be treated similar to the treatment in linear collider, with a dimensionless parameter Γ, expressed as[4]

$$\Gamma \equiv \frac{\hbar c\gamma^3}{\rho E} \approx \frac{\hbar c e^2 Q_d \gamma^3}{2\pi\varepsilon_0 b^2 E^2}, \tag{8}$$

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

$$N_\gamma \approx \frac{5}{2\sqrt{3}}\frac{b\alpha\Gamma}{\lambda_e\gamma}\frac{1}{\sqrt{1+\Gamma^{2/3}}}, \tag{9}$$

where λ_e the electron Compton wavelength. Thus, the effective scattering cross-section of the bremsstrahlung happened between the electrons and dust ions with a radius of R_d ($R_d \approx b_{min}$) is

$$\sigma_{eff} = \pi\int_{b_{\min}}^{b_{\max}} N_\gamma b db. \tag{10}$$

The beam lifetime due to such a bremsstrahlung is

$$\frac{1}{\tau} = \frac{c\sigma_{eff}}{2\pi\sigma_x\sigma_y C}. \tag{11}$$

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

$$2.4\times10^5 \le Q_d \le 1.4\times10^6 . \tag{12}$$

We can find that the beam lifetime determined by such a kind of bremsstrahlung, depends on the charge number Q_d of the dust ions, not the mass number A. Combining eqs (7) and (12), we can get the possible value of A/Q_d for the trapped dust ions in the BEPC SR operation:

$$5.7\times10^4 \le \frac{A}{Q_d} \le 2.0\times10^6 . \tag{13}$$

2.3 Dynamic stability of trapped dust ions

When electron bunch meets the dust particles, the linear model assumes the time of the interaction between beam particles and dust ions can be neglected. The dust ions get a kick from the beam and their positions will not be changed when the beam passes the ions. The only change is the angle or speed of the ions. The equation for such a motion can be expressed as a transfer matrix:

$$\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_1 = M \begin{pmatrix} z \\ \dot{z} \end{pmatrix}_0 , \tag{14}$$

where z and $\dot{z}$ represent the displacements and their slopes in transverse, and M can be written as

$$M = \begin{pmatrix} 1 & \Delta t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ k_{x,y} & 1 \end{pmatrix} . \tag{15}$$

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

$$k_{x,y} = -\frac{2N_b r_p c Q_d}{\sigma_{x,y}(\sigma_x + \sigma_y)A} , \tag{16}$$

where N_b is the electron population per bunch and r_p the classical proton radius. If the dust ions are stable, i.e., trapped by electron beam, the stability requires

$$\frac{1}{2}\left|\mathrm{Tr}(M)\right| \le 1 . \tag{17}$$

Then, the critical bunch current for trapped dust ions can be got as

$$N_b \le N_{b,crit} = \frac{2\sigma_{x,y}(\sigma_x + \sigma_y)}{r_p c \Delta t}\frac{A}{Q_d} . \tag{18}$$

Considering the BEPC SR operation again, if a peak bunch current reaches 150 mA, in vertical direction, we will have

$$\frac{A}{Q_d} \ge 2.1\times10^3 . \tag{19}$$

For a typical $A/Q_d = 1\times10^5$, we can get $I_{b,crit} = 7.3$A, which means for $I_b \le I_{b,crit}$, dust ions would be trapped by electron beam in the BEPC SR operation.

Similar to the case of beam-beam interaction, we can get the ions oscillation frequencies in transverse, written as

$$(f_d)_{x,y} = \frac{1}{2\pi}\left(\frac{2c^2 r_p N_b Q_d}{C\sigma_{x,y}(\sigma_x+\sigma_y)A}\right)^{1/2}. \tag{20}$$

For a peak bunch current of I_b = 150mA in the BEPC SR operation, we will have

$$(f_d)_x = \frac{5.85\times10^6}{\sqrt{\frac{A}{Q_d}}}, \qquad (f_d)_y = \frac{1.80\times10^7}{\sqrt{\frac{A}{Q_d}}}. \tag{21}$$

3. Experimental Study

Some experiments related on the beam lifetime reduction were carried out on the BEPC storage ring. When all the DIPs were switched off, but all the lumped pumps (LPs) on, the electron beam lifetime decreased, but not bad. After 5 hours' observation, half of the DIPs were switched on. The beam lifetime then reduced to 5 minutes at once, and didn't recover until the beam lost thoroughly. Re-injected the electron beam, the lifetime became normal. Switching on another half of the DIPs, we found the beam lifetime reduced again, and after several tens of minutes, the beam lost totally. The beam lifetime became normal after the beam was injected again.

With the method of changing the RF frequency, during one hour we didn't observe the beam lifetime degraded.

When all the DIPs were switched on, and the beam lifetime was normal, switching off all the LPs didn't cause the lifetime reduction. After 20 minutes of the LPs' off, the beam lifetime degraded to 5 hours. After 40 minutes, lifetime decreased to 2 hours. This lifetime degradation was considered to come from the vacuum pressure lowered, because during the 4 hours of LPs' off, no sudden beam lifetime reduction happened and re-injected the electron beam, the lifetime kept less than 5 hours.

When the beam lifetime reduction happened, switching on the injection kicker could sometimes make the beam stable. The kick from the shaker of the betatron tune measurement system also rescued the beam from its lifetime reduction, sometimes. Longitudinally, a change of RF voltage, ±20 kV could also make the beam stable, which is still beyond our knowledge.

With the same optics, same RF parameters, no any beam lifetime reduction happened for positron beam, at any beam current or any kinds of filling pattern. More than 70 hours were spent to observe the behavior of the positron beam. Fig. 4 is an example of positron beam performance.

The results of the experimental studies are

- DIPs do influence the beam lifetime when they are switched on.
- After the DIPs are switched off, the vacuum pressure is down from 4×10^{-10} Torr to 9×10^{-9} Torr at the positions of wigglers during 5 hours.
- Without DIPs, beam lifetime degrades a bit, but not much.
- There is no clear effect of beam lifetime due to horizontal beam orbit change.
- Switching on or off LPs does not affect the beam lifetime. The beam lifetime lowered due to the bad vacuum pressure.

- Horizontal external kick can sometimes resume the beam lifetime when it reduces. Periodically change of RF voltage can also sometimes rescue the beam lifetime. It is beyond our understanding.
- With the same optics and other conditions, positron beam has no such a lifetime reduction.

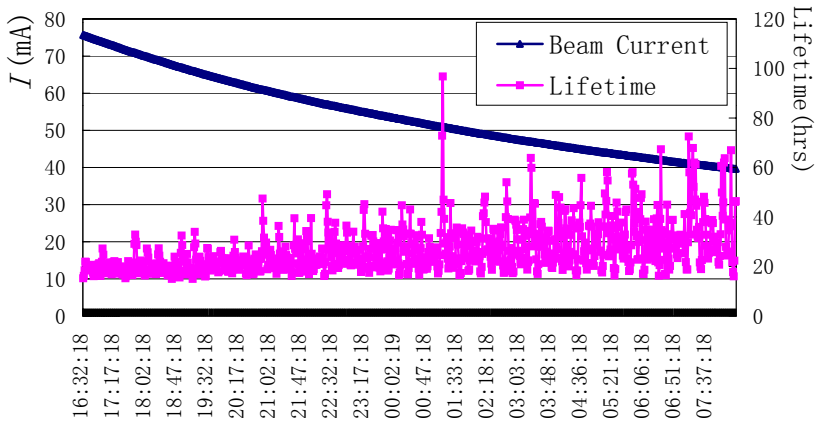

Figure 4. Performance of positron beam. (Recorded from 16:32, Jan. 22 ~ 8:02, Jan. 23, 2001.)

4. Possible cures

Based on the experimental study and theoretical estimation, some measures can bet taken to cure the dust effect or improve the beam performance for the SR operation.

First, switching off all or parts of the DIPs around the storage ring, would be effective on the forming of the "dust cloud". Calculations also show that only with the LPs, the vacuum pressure can still be maintained as 2 nTorr. If the beam current is 100 mA, the pressure reduction due to the gas desorption caused by synchrotron radiation will the 4.1 nTorr. So the vacuum pressure without DIPs will be 6 ~7 nTorr, which can maintain a good beam lifetime.

Second, when the dust effect happens, exciting beam and dust ions with a shaker or the one used for tune measurement, can help to rescue the beam in a certain extent. The present shaker on the BEPC storage ring is a strip-line exciter, acting 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. The longitudinal kick, varying RF voltage up and down with a small fraction, sometimes can make beam stable as well, when the lifetime reduction happens. It is can be applied too, though the reason is not clear.

Finally, eliminating the dust effect thoroughly is using positron beam to run the dedicated SR mode in the routine operation, if the filling rate is fast enough.

5. Conclusions

The phenomenon of beam lifetime reduction in the BEPC dedicated SR operation is observed very often, which lowers the beam performance very seriously. From the observation, this kind of lifetime reduction is ascribed to the dust effect. Theoretical analyses estimate the source of the

dust macro-particles, the region of A/Q_d for the trapped dust ions and the stability criterion of the dust ions.

Experiments on vacuum pumps partially confirm the fact of dust effect and unveil that the main source of dust in the BEPC storage ring is the DIPs around the ring.

Possible cures of the dust effect, such as switching off the DIPs, transversely kicking the beam and longitudinally varying the RF voltage, arise from the experimental and analytical studies, though some of them are not fully understood. Applying positron beam is the best way to eliminate the problem, if the injection rate is fast enough.

Simulation work on the effect is under way.

6. Acknowledgements

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