BEAM INSTABILITY STUDIES IN THE BEPC*

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Abstract

The Beijing Electron Positron Collider (BEPC) has been operated since 1987 for the experiment of high energy physics and synchrotron radiation application. About 25mA of a single bunch per beam for colliding is obtained at the energy of 1.55GeV, and over 120mA multi-bunch electron beam is reached at the energy of 2.2GeV in routine operation. Many current dependent phenomena have been observed and analysed during operation and machine studies for years. The bunch lengthening effect, the beam photoelectron instability, the dust effect and the beam ion instability are intensively studied in recent years.

1 INTRODUCTION

Since the BEPC performs as a collider, and a light source as well, it has different beam patterns for routine operation, including single electron and positron beam, multi-bunch for both electron and positron beam, etc. As a result, a wide aspect for the different beam phenomenon observations and studies[1] was done in the BEPC, such as bunch lengthening, tune shift, energy spread widening, transverse beam size blow-up, head-tail instability, beam cavity interaction, longitudinal coherent oscillation, multi-bunch instabilities, dust effect, beam ion interaction and beam photoelectron instability (PEI). The coupling impedance of the BEPC has been estimated from these studies. The performance of the machine has been improved gradually, and also the beam instability studies are very meaningful for machine upgrade and are very interesting in understanding the accelerator physics.

2 CURRENT DEPENDENT PHENOMENA

The coupling impedance is studied in different ways, including the bench measurement via the pulse method, beam measurement with tune shift dependence and the bunch lengthening effect. It shows that the longitudinal coupling impedance of the BEPC storage ring is about 4Ω at low frequency.

As the bunch lengthening may influence the luminosity when two beams collide, it remains very important in the BEPC. A scaling law of bunch lengthening has been obtained from the measurement, and the relation with the impedance has been studied which are introduced in details in the following section.

The energy spread increase above a threshold of 8 to 10mA has been observed with the method of limiting the longitudinal acceptance via decreasing the RF voltage until quantum lifetime becomes dominant. The energy widening is about 30% at the beam current of 30mA.

The transverse beam blow-up with beam current has been observed with the scraper monitor. About 20% increment of the horizontal emittance occurs at the beam current of 50mA, but much less increment in the vertical direction.

The tune shift as a function of beam current has been measured accurately with a strip-line monitor. The result shows that the vertical tune decreases with a slope of –0.00025/mA at the lower beam current.

The head-tail instability is observed with a threshold current less than 1mA, and can be eliminated when the chromaticity is corrected to above 0.5 in the machine routine operation.

The beam stability is quite influenced by the HOM when the temperature of the RF cavities is not well controlled. Such an effect can be suppressed by setting the tuners of the cavities to suitable positions. The longitudinal Robinson effect is controlled by the tuning loop in normal operation. The longitudinal coherent oscillation could be excited by the noises of the RF system occasionally, the oscillation signals can be observed clearly either on the wall current monitor or on the spectrum analyser. The longitudinal coherent oscillation may lead to a reduction of the luminosity when it happens in the colliding beam mode.

The multi-bunch mode of electron beam is operated for the dedicated synchrotron radiation. There are 160 RF buckets in BEPC. We use different filling patterns to avoid the potential multi-bunch instability. The bunch train with a long gap, or sinusoidal distribution of the bunch current along bunches without any gap in the beam may be used to avoid the ion effect, and to avoid the harmonic resonance with the HOM of the RF cavities.

3 BUNCH LENGTHENING AND COUPLING IMPEDANCE

Bunch lengthening due to potential well distortion in low beam current and microwave instability at a medium current is measured with a system of streak camera. Substantial data obtained above the microwave instability threshold give us a scaling law for bunch lengthening[2], which can be written as

* Work supported by Natural Foundation of National Science No. 19875063-A050501 and 19975056-A050501.

$$\sigma_l\,(cm) = 0.651 \times \left(\frac{\alpha_p I_b\,(mA)}{\nu_s^2 E(GeV)} \right)^{1/3.49}, \qquad (1)$$

where α_p is the momentum compaction, I_b the bunch current, ν_s the synchrotron tune, and E the beam energy.

Because of serious bunch lengthening, we can't reduce the vertical β function at the interaction point further to enhance the luminosity. The essential way to decrease the bunch lengthening is to improve the coupling impedance. Partially shielding the bellows in the storage ring and removing the idle kickers for injection help a little on the impedance improvement. The impedance of whole storage ring is considered to be inductive, which leads to the bunch lengthening, and it happens at very low current. When a purely inductive impedance is assumed, the Haissinski equation, given in eq. (2), can be solved numerically for a positive momentum compaction[3].

$$\frac{dy}{dx} = -\frac{xy}{1+y}, \qquad (2)$$

where $x = t/\sigma_{t0}$, $y(x) = LI(x)/\sigma_{t0}\dot{V}_{rf}$, L the inductance, V_{rf} the RF voltage, I the bunch current and σ_{t0} the natural bunch length in time. By finding the integral of $y(x)$, which is a dimensionless normalized charge per bunch, for the increasing beam current, we can obtain the inductance L finally. The inductance of the whole storage ring got in this way is around 520nH, which corresponds to 4.1Ω for the low frequency impedance $|Z/n|_0$.

For further shortening the bunch length, we plan to change the frequency of the RF system from 200 MHz to 500 MHz, and to modify the beam tube to reduce the coupling impedance during the next machine upgrades.

4 BEAM LIFETIME AND DUST EFFECT

The beam lifetime is one of the important issues in an accelerator especially in the machine operated as a light source. It is mainly influenced by the Touschek effect, quantum fluctuation and beam gas interaction. The beam lifetime of BEPC, quite stable in collision mode, is nearly 10 hours in routine operation at the energy of 1.55GeV and the current of 40mA. It depends on the vacuum pressure, the beam-beam interaction, and some kinds of beam instability. The beam lifetime of BEPC in dedicated synchrotron radiation operation is normally longer than 20 hours at the energy of 2.2GeV and the current of 100mA.

The dust effect has been observed in recent years. It happens frequently, and plays a crucial role in the routine synchrotron radiation operation with a suddenly reduction for the beam lifetime during the operation. It appears with the following features: it may happen at any beam current in single bunch or in multi-bunch pattern; beam life time may be recovered spontaneously, or by transverse shaking the beam with an oscillator; it could not be controlled by changing any beam dynamic parameters; it is not repeatable when the beam is injected again at the same machine conditions. It happens neither in the case of colliding beams, nor the positron beam. A typical record of dust effect in BEPC is shown in Fig. 1.

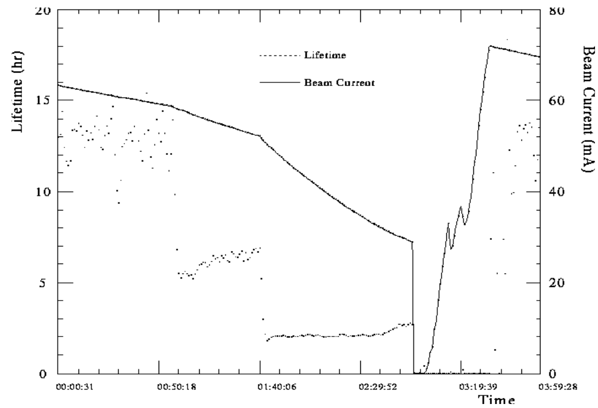

Figure 1: A record of beam lifetime acted by the dust effect in BEPC.

The dust may come from the wall of the vacuum components of the beam tube[4]. Under the following effects: the gravity, the electromagnet field of the beam, the image charge on the vacuum chamber, the photo-electron from the wall, the ion evaporation of the dust itself, etc., the dust may be ionised by electron beam, and the ionisation of the dust reaches equilibrium, then they are trapped by the beam. The beam lifetime may be decreased seriously due to bremsstrahlung between the dust and electrons of the beam. The main parts of the dust in BEPC may be Al_2O_3, SiO and SiO_2, which mostly come from the vacuum bumps, especially from the distributed ion bumps (DIP).

In linear approximation, the frequency of the dust particle at 1σ of beam size is:

$$f_{x,y} = \frac{1}{2\pi}\left[\frac{2c^2 r_p m_p N_e Q_d}{eCm_d \sigma_{x,y}(\sigma_x + \sigma_y)}\right]^{1/2}$$

(3) where m_d and Q_d are the mass and charge of the dust, C the circumference of the ring, c the speed of light, N_e the number of electron in the bunch, and r_p the classical radius of proton, m_d the mass of proton, and e the electron charge.

We tried the following methods to overcome the dust effect in BEPC recently. The DIP was partially switched off along the ring, keeping the vacuum pressure not decreased obviously in quite a long time, the dust effect is clearly reduced. The effect of the different distance between the closed orbit and DIP was tested. When the lumped vacuum bumps have been switched off for a short period, the influence has also been observed. It indicates that the main source of the dust in BEPC comes from the vacuum bumps. Sometimes the trapped dusts may be waved out by means of shaking the beam with a frequency scanner. The positron beam has also been suggested for the synchrotron radiation experiment.

5 BEAM PHOTOELECTRON INSTABILITY

A multi-bunch instability in positron beam has been studied in BEPC, which is known as beam photoelectron instability (PEI), under the cooperation with KEK colleagues in recent years[5]. The mechanism of the instability is understood as follows: the photoelectrons are produced at the inner surface of the vacuum chamber by synchrotron radiation, and propagated as the effect of positron beam, then the electron cloud can be equilibrium and plays a medium to cause a coupled bunch instability in the multi-bunch positron beam.

This coupled bunch instability arose at a low threshold of the beam current about 9.4mA with a fully filling of 160 bunches uniformly in BEPC. The broad distribution of the betatron sidebands by each oscillation frequency is observed on the spectrum analyser. The threshold of the instability is much higher when the bunch space increases, while the amplitude of the sidebands slightly decreases when the energy gets higher. The instability can be controlled by tune spread offered by increasing chromaticty, or by octupole powered on. This instability does not occur for the electron beam, and can not be suppressed by any gap in the bunch train.

We analyse the mechanism of the instability in the following two ways. First, the coherent interaction between bunches and the electron cloud was evaluated by means of a wake force. In the conventional beam instability theory, the growth rate can be estimated by the calculation of dispersion relation. The distribution of the sideband can be explained qualitatively in this way. Second, a computer code are applied to simulate the interaction between bunches and electron cloud. The photoelectrons are described by micro-particle, and the beam is depicted as a series of Gaussian bunches in the code. The nonlinear force between electron cloud and bunches are involved in the simulation, but there are still not any damping mechanism to be taken into account. From the simulation results, the growth behavior of the coupled bunch instability can be illustrated clearly; the dependence of the instability on the bunch spacing, the beam current, and the beam energy are coincided semi-quantitatively with the observation. The growth rate of the photoelectron instability in BEPC is estimated as about 3ms at 1.3GeV, which is almost the same as the experimental observation.

In the simulation of the instability, one of the important factors is the photoelectron conversion rate, which plays a very sensitive role to the quantitative results. We took 0.1 on average in the simulation. To prove the physical model, and to well understand the mechanism of the instability, it would be very meaningful to measure the yield of the photoelectron directly in the beam tube. In order to characterize the electron cloud, a special detector has been fabricated, and will be installed on a sensitive position of the vacuum chamber in the ring during the machine shut down. The detector consists of two mesh grids, a graphite-coated collector and an electronics system. We expect to get the measurement result of this experiment later this year.

6 BEAM ION INSTABILITY

Ion trapping effect in BEPC has been observed and studied for years, as there are about two months dedicated synchrotron radiation operation every year. In particular, since 1998, bunch train has been adopted as the filling pattern in the SR mode. Recently we investigated the coupled bunch oscillation sidebands in detail under different multi-bunch filling patterns with a 1.5GHz spectrum analyser. Meanwhile, we developed a simulation code for ion trapping and fast beam-ion instability based on “weak strong” interaction model[6].

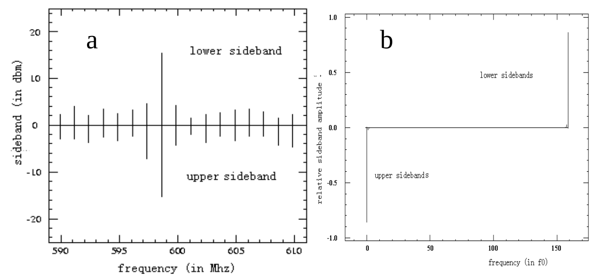

Figure 2: a) observed spectrum, b) simulated spectrum

Figure 2a shows the coupled bunch oscillation sidebands observed with the spectrum analyser under the condition of 160 bunches filled uniformly with total beam current of 17mA. It can be seen that there was just one upper sideband centred at 598.83MHz (about $3\times160 f_0 + 0.25 f_0$) where the relative amplitude was much larger than the others. The linear ion trapping theory can qualitatively explain that this sideband was induced by beam ion coherent interaction, but failed to give the full span sidebands and the growth time of the instability. Our simulation code successfully reproduced this sideband and gave growth time of the instability was about 33ms which was comparable with the synchrotron radiation damping time of 86ms. Fig. 2b is a full-span sidebands given by simulation under the experimental condition.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to all BEPC staff for the perfect collaboration in machine operation and machine studies.

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