THE STUDIES OF ELECTRON CLOUD INSTABILITY*

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Abstract

The Electron Cloud Instability (ECI) has been studied for years. It may occur in a positive charged particle storage ring when the machine is operated with multi-bunch beam. The phenomena of the ECI are mainly coupled bunch oscillation and transverse beam size blow up. The luminosity of collider may degrade due to the ECI. The progress of the ECI studies is reviewed in this paper firstly, and then we will focus on introducing the recent study results in Beijing Electron Positron Collider (BEPC) in detail, as the machine will be upgraded to be a double-ring collider, BEPCII. The chromaticity effect, the solenoid effect, the octupole effect, and the clearing electrode effect using beam position monitor (BPM) on the ECI have been investigated experimentally in the BEPC. The simulation will be introduced including the electron cloud distribution in the antechamber structure under different conditions, and the beam instability behaviours for multi- and single bunch cases. The potential methods to suppress ECI in a positron storage ring have been issued from the studies, and the meaningful study results are discussed in this paper.

INTRODUCTION

The high energy physics experiment requests the beam current in accelerator stronger and stronger, and the beam performance higher and higher, especially in the particle factory like colliders, where two beams are in separate rings with multi-bunches. The beam intensity and its stability were limited by the single beam instability as the interaction of beam with its environment before people optimize the coupling impedance of the vacuum chamber. Besides the impedance effect on the beam stability, other particles in the vacuum chamber around the beam may also influence the beam performance. The particles may be ions or electrons, which are trapped by the beam with opposite charge. These particles can be as medium similarly like the impedance of vacuum components to make the beam unstable either as single bunch phenomena or coupled bunch oscillation. To distinguish from the beam instability caused by the interaction of beam with the impedance of vacuum components, the above phenomena are called two-steam effects in accelerators. The two-steam effects can be ion effect or electron effect owing to different beams. These effects have been regarded observation since about twenty years in many different machines. There are many special study workshops to be held in the accelerator community. Many papers were published on this subject to report the progress either on experiment, analyses or simulation studies from different laboratories. There are also many review papers to summarize the study on this subject [1]. We want to introduce the study progress on one of the two-steam effects, the electron cloud instability in the BEPC in this paper.

In the multi-bunch positron storage ring, the photons by synchrotron radiation of beam hit the wall of the vacuum chamber. Electrons are emitted and then attracted by the beam moveing to another side of the chamber. Secondary electron may emit too, and when the frequency of the electron movement is resonated with the bunch frequency, the phenomena like multi-pacting will occur. These electrons in the vacuum chamber will be saturated under the space charge effect to form electron cloud (EC) around the positron beam. The instabilities could be raised in the beam either as single bunch phenomena like transverse beam size blown-up, or as a coupled bunch oscillation. It can be understood by the model of wake field of electron cloud. The characteristics of this kind of wake field are: short-ranged propagating along the bunch train longitudinally, varying along transverse direction of the beam tube linearly in the central part of the chamber, following the beam, and treating the wake field in a superposition way.

The electron cloud effects have been observed since early time as PSR in 1965, ISR in 1971. It is paid more attention to be regarded widely since 1989 when the coupled bunch oscillation observed in KEK PF and was explained as beam photoelectron instability (PEI) [2]. Then the phenomena have been repeated in BEPC and studied in detail. Since 1996, with collaboration of KEK, Japan, a series of studies on electron cloud instability has been processing [3]. It was called PEI during the first stage studies because we did not find the secondary electron effect. As it may seriously influence the multi-bunch positron beam performance, it should be considered in one ring of the modern particle factories which under construction like KEKB and PEPII at that time. Subsequently, many studies developed in the different electron machines like BEPC, APS and CESR. Later, the studies also outspreaded in proton machines like SPS, LHC and RHIC, etc.

BEPC is an electron positron storage ring as a collider, and also can run as a synchrotron light source when it is operated in single electron beam. It also can be injected positron beam bunch by bunch, so the ECI can be studied experimentally in BEPC. Now, a plan to upgrade the machine to a double ring collider is progressing to enhance the luminosity for two orders. The ECI may be a limitation to the performance of BEPCII.

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EXPERIMENTS

The main parameters of the BEPC under the typical experimental studies are: beam energy of 1.3 Gev, betatron tune 5.82 and 6.74 in horizontal and vertical direction respectively, natural beam emittance as 134 mmmrad, RF frequency as 200 MHz with a harmonic number of 160, transverse damping time of 86 ms at 1.3 GeV, and minimum bunch spacing of 5 ns. The instrumentations used in the experiments include tune measurement system, BPM system, synchrotron light monitor, beam scraper, spectrum analyzer, and streak camera etc.

First stage observation on ECI phenomena

The first experiment on the ECI was performed in 1996. The typical vertical betatron sidebands as showed in Fig. 1, were observed on the spectrum analyzer when the positron beam was injected to 9.3 mA with 160 uniformly distributed bunches. The vertical coupled bunch oscillation was also detected on the synchrotron light monitor. Any other betatron sidebands caused by HOMs at the corresponding frequency in the RF cavities were not found. The similar phenomena were not found in the electron beam under the same conditions. We then started experimentally on the parameter dependence [4] after the first ECI observation.

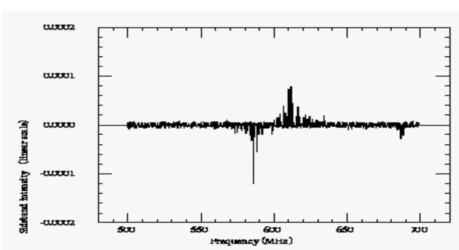

Figure 1: The vertical betatron sidebands.

We can see from the experiment that the instability strongly depends on the bunch spacing, as the threshold current of the instability was higher than 40 mA when the positron bunches were injected every two RF bucket. The experiment of beam emittance effect on the ECI showed that the higher threshold current occurred when the beam has a smaller emittance. For example, with 160 uniformly distributed bunches in the ring, the threshold currents are 16 mA at an emittance of 24 mmmrad and 9 mA at 140 mmmrad respectively.

The chromaticity of the ring can affect the threshold of the instability. At a beam current of 9.6 mA with 160 bunches, the vertical betatron sidebands disappeared when chromaticity was tuned from 4 to 6, and the sidebands reappeared when the chromaticity changed back to 4. The instability can be suppressed by a larger chromaticity. The energy dependence of the instability is not so strong like the instabilities caused by the impedance of the vacuum components. The beam energy was scanned from 1.3 GeV to 2.2 GeV at a beam current of 10 mA with 160 uniformly bunches. The amplitude of the vertical betatron sideband is almost at the same level in the energy range of 1.3 GeV to 1.85 GeV. The observed energy dependence on chromaticity at the threshold of the instability as showed in Fig. 2.

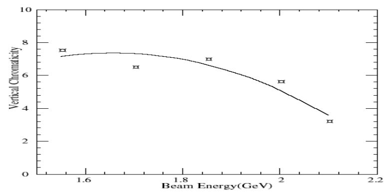

Figure 2: The energy dependence on chromaticity at the threshold of the instability.

The octupole effect on the instability has been tested in experiment preliminary. The instability was suppressed when the octupole was excited to K_3=33m^{-3}, which corresponds to a Landau damping time of 6.2 ms.

A fast beam position system which is supplied by KEK, has been used to observe the bunch oscillation process in the experiment in 1998. The damping time and the oscillation modes can be then issued by fitting and doing FFT to the data. The mode analyses can more clear show that it was definitely different between positron beam and electron beam under the same conditions.

Electron cloud measurement

Electron cloud (EC) detectors were installed in the storage ring since 1999 [5]. The typical structure of the detector is shown in Fig. 3 with the similar structure like what they used in APS [6].

Figure 3: The detector structure for EC measurement.

The detailed EC measurements were carried out using the detectors. The detector current I_c varies linearly with the total beam current I_b, and it did not saturated as the I_b was not yet strong enough. The EC energy distribution was resulted from the bias voltage scan. The dependences of I_c on beam energy, chromaticity, and emittance are not sensitive at the same closed orbit. The couple bunch oscillation caused by ECI dose not influence the yield of EC measurement. The EC measurement is influenced by the distance of the detector to the magnet. The longer distance to bending magnet, the better result is.

The multi-pacting effect has been investigated by injecting positron beam with different bunch spacing, but no clear events to prove that the electron motion was resonated by the bunch train passing in the observation when we used a detector near by the magnet. Another detector which is far away from the magnet was then installed, and the experiment of multi-pacting effect is still under the way in recent study.

Solenoid effect on ECI

It was verified in KEKB [7] and PEPII that solenoid field along the beam can move the electron cloud and then suppress the instability. From the measured I_c by an electron detector which was wound with solenoid, it is different when solenoid was off and on. We understand from the observation that the solenoid can really affect the electron cloud density. This encourages us to wind solenoid on straight sections as much as we can in BEPC.

The total length of the solenoid wound on the vacuum chamber of the straight sections is 42 meters, covering about 18% of the ring circumference. Some examples of solenoid winding are shown in Fig. 4. A current up to 35A in the coils can be offered by a DC power supply, which corresponds to about 30 Gauss magnet field longitudinally.

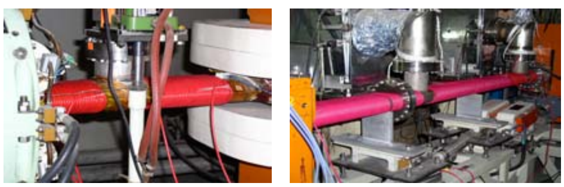

Figure 4: The solenoid wound on the vacuum chamber.

In recent experiments [8], multi-bunch positron beam was injected at the level of the ECI with the chromaticity of 1.5. The betatron sidebands appeared and the vertical bunch size increased by the ECI effect observed on the spectrum analyzer and streak camera, respectively. Then a 15A current was applied on all of the solenoids, the betatron sidebands disappeared and the vertical bunch size reduced by about 15% clearly. These results are shown in Fig. 5 and 6. The same behaviour resulted by the solenoid effect under the different conditions is investigated in the experiment. From the experiments, we also understand that the solenoid effect is more effective in the arc section nearby the magnet than in the long straight section far away from magnet. The polarity of the solenoid is not important.

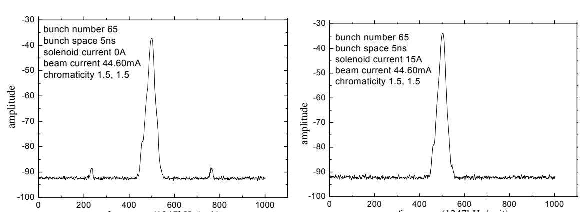

Figure 5: The betatron sidebands observed on spectrum analyzer as the solenoid off (left) and on (right).

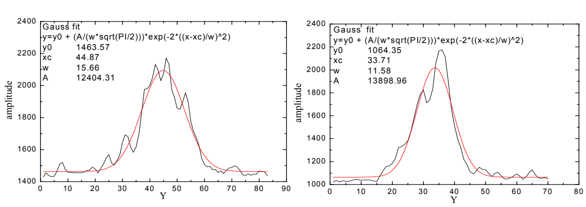

Figure 6: The vertical bunch side observed on streak camera as the solenoid off (left) and on (right).

Clearing electrode to decrease electron cloud

Two kinds of clearing electrode have been tested in the experiment. A special detector as model electrode showed as Fig. 7 was used to clean, and measure the electron cloud first. A DC voltage is applied to the grid inside lower part of detector to clean the electron, and the signal of I_c can be measured from the upper part of the detector. One of the example of the measured electron current I_c as a function of the applied voltage is shown in Fig. 7.

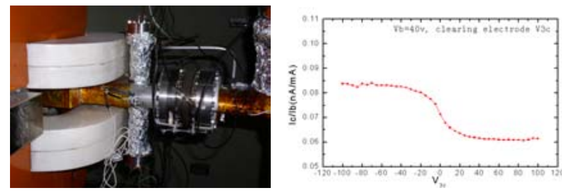

Figure 7: The structure of the detector with a model electrode and the measured I_c vs. the voltage.

We understand from this measurement that an electrode in the beam tube can really wave the electron cloud partially. The density of electron cloud decreases as increase the voltage applied on the electrode increases. The effect is dependent on the structure of the electrode and saturated gradually as the applied voltage is increased. This result encourages us to do more experiment using the buttons of the BPM to be electrodes.

There are 128 buttons in 32 BPM in BEPC ring, 4 buttons in each BPM. A DC voltage from -600V to +600V can be applied to all of the buttons under the different patterns to be connected. At the beam conditions of the ECI, we scanned the applied voltage on the BPM buttons and measured amplitudes of the observed betatron sidebands. The results show that the best voltage applied pattern is +600V on all of the buttons which are on inboard side of the ring, and –600V on all of the buttons which are on outboard side of the ring. In this way, the amplitudes of sidebands and the vertical beam size observed of head bunch and teal bunch vs. the voltages on the BPM buttons are shown in Fig. 8.

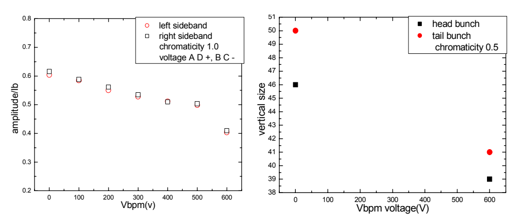

Figure 8: Electrode effect on sideband (left) and bunch size (right) vs. voltage on the BPM buttons.

Chromaticity affect on ECI

The chromaticity effect on ECI is observed again in detail. The amplitudes of sidebands and the vertical beam size observed of head bunch and teal bunch vs. the chromaticity are shown in fig. 9.

We understand by the experiments in BEPC that the chromaticity can change the damping time to suppress the instability, the tune spread can be offered by an octupole to increase the Landau damping, the clearing electrode can partially wave the electron cloud in the beam chamber to decrease its density and then to make the ECI weaker, and the solenoid can modify the electron density distribution to decrease the electron density in the central part of the vacuum chamber where the beam pass though to weaken the ECI.

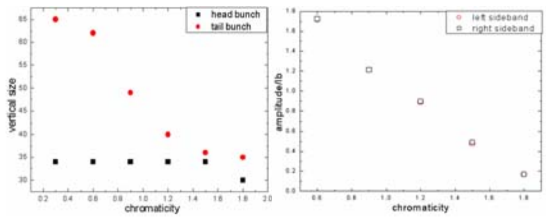

Figure 9: Amplitude of sideband (left) andbunch size (right) vs. chromaticity.

SIMULLATIONS

There are many simulation codes have been developed to study the ECI in the different laboratories, as in KEK [9] and in IHEP. We did a lot of job to simulate the ECI to compare with the observation in the experiments.

In the early simulation studies [10], the electron cloud distribution has been modelled in a vacuum chamber with a round shape of the transverse cross sections, and photoelectrons are involved only. The EC distribution, the raising process of the coupled bunch oscillation and its growth rate and the mode analyses have been resulted from the simulation. The conventional single beam collective theory has been used to analyse the wake field effect by the EC on the beam. The results were comparable with the observation in the experiment qualitatively, and the phenomena can be understood in a clear physics picture.

Later on, a code involving secondary electron emission developed [11] to simulate the EC distribution in a vacuum chamber, and the coupled bunch oscillation. The importance of the secondary electron is analysed. The experimental data recorded by a fast beam position monitor system, which offered by KEK, were analyzed to compare with the simulation. Another code developed in CERN is also used to simulate the dipole effect, the solenoid effect on the ECI in a two dimensional space, and a model electrode is modified in the code.

In recent years, the simulation studies [12] are focused to the BEPC upgrade project BEPCII. The antechamber with absorber is decided to be used in the arc section of each ring, and TiN will be coated inside beam chamber. A new computer code was developed to simulate the EC distribution in the antechamber, the coupled bunch oscillation and the single bunch effect due to the EC.

In the simulation of the electron cloud distribution in the beam tube, the different yield Y, the different reflectivity R, and the different secondary electron yield (SEY) were investigated. The different widths of the antechamber and the electrode in the vacuum chamber are also surveyed. We suppose Y=0.02 and 0.1, R=0.1 and 0.8 with and without photon absorber, respectively, in the antechamber, SEY=1.06 and 1.8 as the TiN coated antechamber and nothing coated respectively.

The EC line density along the chamber and the volume density in the central region (10σ of transverse beam size) of the chamber are issued from the simulation. The electron cloud created along the bunch train is also simulated. All of these EC distribution results are then used to estimate the beam instabilities. The central volume density of electron cloud is much effective to act on the beam in the simulation.

The EC distribution in the different shape of the vacuum chamber, and the comparison with electrode in the chamber are shown in Fig. 10. We can see how the antechamber and the electrode help to reduce the electron density from the pictures, especially in the central region of the chamber where the beam passes though. The electron density decreases as the voltage on the electrode increase, and the effect will be saturated around 600V at the BEPCII parameters.

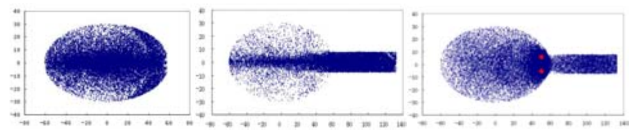

Figure 10: The electron distribution in the elliptical chamber (left), in the antechamber (middle) and in the antechamber with electrode (right).

The electron density accumulated along the bunch train under the different conditions is shown in Fig. 10. We can see that the electron central density may reduce 5 times if the antechamber width is about 5 times to the chamber gap. The electron density will saturate when about 20 to 30 bunches passed, and will dissipate quickly through about 10 empty RF buckets.

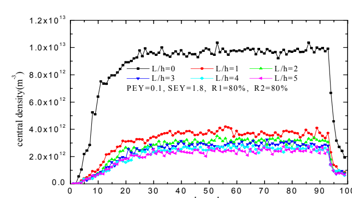

Figure 11: The electron density along the bunch train.

The results of the simulation show that the electron density in the central region of the vacuum chamber can be reduced by about 5 times if the antechamber is adopted, by about 6 time if the TiN is coated only, by about 3 times if the photon absorber is made in the wall of the chamber only, by about 5 times if the electrode is installed in the beam chamber. In recent BEPCII design, the antechamber, the absorber, and the TiN coating have been decided to be used. So the electron density will be decreased about 90 times, i.e., from 1.1×10^{13} m^{-3} to $1.3\times10^{11} m^{-3}$, lower than the case without any special technology to be used in the chamber.

There are two kinds of beam instability may occur due to the EC: the transverse bunch blow-up in a single bunch, and the coupled bunch oscillation along bunch train. For the single bunch effect, the EC is described as macro-particles in transverse direction in the chamber, and the bunch is described as macro-particles in the different slices from the head to the tail of the bunch. The macro-particles move in a 3-dimension space affected by the EC including the movement in the different slices as the particle doing synchrotron oscillation. The short range wake field and the bunch size blow-up can then be issued from the simulation.

The growing process of the vertical bunch size under the different EC density is simulated as shown in Fig. 12. The threshold of the blow-up occurs when the central EC density is about $9.2\times10^{11}m^{-3}$, which corresponds to a wake of $1.47\times10^{6}m^{-2}$. It is comparable to the estimated result from the conventional theory of the strong head tail instability. The chromaticity effect is also involved in the simulation, and the result can be compared with the experimental observation.

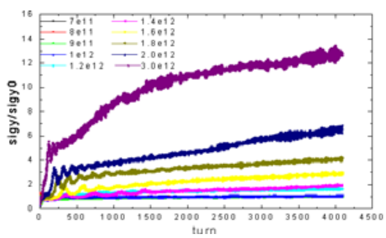

Figure 12: The progress of vertical bunch size increase.

For the simulation of the coupled bunch oscillation, the EC simulated along the build up process in a bunch train is described as macro-particles in transverse direction in the chamber, and each bunch is as one macro-particle to interact with the electron cloud. The vertical coupled bunch oscillation progress in BEPCII conditions and its mode analyse are shown in Fig. 13. The central EC density is taken as $1.0\text{x}10^{13}m^{-3}$, but the damping effect is not involved in the simulation. The growth time fitted from the progress is about 0.08 ms. The mode spectrum is comparable with the observation in the experiment.

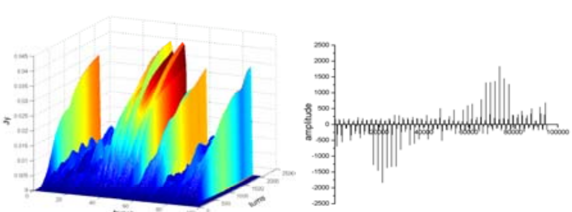

Figure 13: The growth progress of the coupled oscillation and its mode spectrum.

SUPPRESS METHODS

From analyse, simulation and experimental studies, we understand that to avoid or to suppress the potential electron cloud instability in positron storage ring, the following methods can be effective: using antechamber, coating TiN on the inner surface of the beam tuber which lowers the secondary electron yield, making the structure on the vacuum chamber inside as a saw-tooth shape, using photon absorber at the end of each section antechamber, designing lattice with a larger chromaticity by the limit of the dynamic aperture, installing an octupole in the ring at the positron with large betatron function, using clearing electrodes in the vacuum chamber such as BPM buttons or others components, winding solenoids outside of the vacuum chamber on the possible straight section especially nearby the magnet to offer the longitudinal magnet field, using a bunch to bunch feedback system to cure the possible coupled bunch oscillations, etc. The feedback system can only affect the coupled bunch oscillation but not the single bunch effect, say, the transverse beam size blown-up. All of these methods to affect the electron cloud instability have been proved in our studies, and some of these are also proved by the studies in other laboratories.

DISCUSSION

A long term study on the beam electron cloud instability has been progressing in BEPC for years, and quite rich study results have been obtained from the experiments and the simulations. All of these results are very meaningful for understanding the mechanism, for the design and for the operation of storage ring especially the particle factory like colliders. Many of the study results have been adopted in the BEPCII design and construction to guarantee the beam performance to reach the design goal luminosity. Some of the effects related this instability are still need further investigation, and further test in the experiment and machine operation.

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