# DIAGNOSTICS OF ACCELERATOR PERFORMANCE UNDER THE IMPACT OF ELECTRON CLOUD EFFECTS

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*Abstract*

A large number of electrons called electron clouds are observed in many accelerators. The electron clouds produce various effects such as pressure rise, beam induced multipacting, tune shifts, coupled bunch instability, beam size blow-up and so on which often limit performance of the accelerators. Characteristics of the electron clouds are studied not only by direct measurements of the electrons but also by measurements of beam behavior affected by the electron clouds. This paper reviews various diagnostic methods to study the electron clouds with a short summary of the electron cloud effects on the accelerators.


## INTRODUCTION

Many electrons are generated and accumulated in accelerators. Primary electrons can be produced by synchrotron radiation or lost particles hitting a chamber wall, or by ionization of the residual gas. If charge of a beam is positive, the primary electrons receive kicks from the beam toward the center of the beam chamber and hit the opposite wall, then secondary electrons are produced. Under some operational conditions of the accelerators rapid growth of the electrons known as beam induced multipacting can occur. The primary and secondary electrons form a group of the electrons called the electron cloud.

Spatial distribution of the electron cloud is strongly affected by magnetic fields as shown in Figure 1 of Reference[1] as an example. In drift space the electrons concentrate at the center of the chamber. In a dipole magnet several strips of the electrons sometimes appear. In a quadrupole magnet eight spots which have large density of the electrons are seen on the chamber wall. In a solenoid magnet most electrons are confined near the chamber wall.

Energy of the electrons is low, typically less than 100eV [2,3,4]. Owing to a low energy nature of the electrons it is possible to measure the energy distribution by applying a manageable voltage to grids as described later.

The electron cloud is built up along a bunch train [5]. In proton rings with a long bunch the electrons produced on the chamber wall are multiplied toward the tail of the bunch and lead to the trailing edge multipacting. Low energy electrons which stay near the center of the chamber before the bunch comes are trapped in the bunch by the beam potential and released at the tail of the bunch [6]. Due to two mechanisms a large number of electrons are observed at the tail of the bunch. The electrons can be trapped in a quadrupole and a sextupole magnetic fields as shown by a simulation [7]. The survived electrons between train gaps would lead to accumulation of the electrons by the passage of many bunch trains. The measurement of the time evolution of the electron cloud is thus important to study the characteristics of the electron cloud.

It is mentioned that the electron cloud can affect electron beams as well as positron beams [2,5,8].

## ELECTRON CLOUD EFFECTS AND CURES

The electron clouds produce various effects [9] such as 1) nonlinear pressure rise due to gas desorption by the bombardment of the electrons, 2) electrical noise to instrumentations, 3) beam induced multipacting, 4) heat load to a cold chamber wall of superconducting accelerators such as LHC, 5) tune shifts caused by Coulomb force by the electron cloud, 6) transverse coupled bunch instability mediated by the electron cloud and 7) single bunch (strong head-tail) instability due to the short range "wake" by the electron cloud which causes a beam size blowup. A combined phenomenon of the electron cloud and the beam-beam effect is predicted though it is not yet confirmed by experiments [10].

Various cures have been taken to mitigate the electron cloud effects [9]. Ante-chambers are introduced to reduce the number of the primary electrons from synchrotron radiation. In order to reduce the secondary electrons, processed chamber surface by TiN coating and NEG(TiZrV) coating are used and a grooved surface is considered. The reduction of the secondary electron yield by beam scrubbing is observed. In B factories weak solenoids installed almost all drift space around the ring are very effective to moderate the beam size blowup by the electron cloud. Coupled bunch instability by the electron cloud can be cured by bunch-by-bunch feedback system and Landau damping by nonlinear magnetic fields if the growth rate is not large.

## ELCTRON CLOUD DIAGNOSTICS

Many dedicated or standard instrumentations have contributed to understand the electron cloud effects. They also give the data for a benchmark of simulation programs. In this section diagnostics of the electron clouds themselves are reviewed. Diagnostics of the beam behavior under the impact of the electron clouds are discussed in the next section.

### *Pressure gauge*

Pressure rise which is caused by desorption of the gas by the electrons hitting the chamber wall, gives an

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indication of the electron-induced multipacting. At PSR [11] a pulse of the ion pump current was measured with HV probe by looking at the voltage across a resistor during beam accumulation. The ion pump pulse correlates well with a retarding field analyzer signal. In PEPII [12] the ion pump current was measured by removing the permanent magnets from the ion pump in order to measure the electrons entering the pump from the beam chamber. Pressure gauge is useful for getting the electron cloud distribution along the accelerator since many pressure gauges distribute around it.

### *Simple biased electrode*

A simple biased electrode was used in many laboratories for evaluating the flux of the electrons. An interesting example is an electron-collecting electrode installed in the ante-chamber at PEPII LER to gather the electrons in the beam chamber [12]. The electrode installed in the pumping chamber close to the synchrotron radiation fan collects the electrons propagated from the beam chamber. The bias voltage of ~ +100 Volts relative to the vacuum chamber is applied to the electrode.

### *Retarding field analyzer*

A biased electrode is simple to implement. But the measurement would be disturbed by several effects [11,13]. Signal is affected by varying the biased voltage since the secondary emission of the electrons from the electrode is a function of the bombardment energy of the electrons which is changed by varying the biased voltage. An area where the electrons are collected will be dependent on the applied bias voltage to the electrode. And the signal comes both from striking electrons on the electrode and from leaving electrons by secondary emission from the electrode. It is difficult to remove the effect of leaving electrons.

A planar retarding field analyzer (RFA) is developed at APS to overcome the disadvantages of the simple biased electrode [2,13]. The RFA measures the electron intensity at the chamber wall. It consists of a shielding grid, a retarding grid (or a repellar) and a collector. The collector is coated by graphite to minimize the secondary emission. By applying the voltage to the retarding grid the energy distribution of the electrons can be measured. The shielding grid shields the retarding grid from the beam to enable the unperturbed measurement of the electrons. The collector current as a function of the retarding voltage $V_{ret}$ gives an integrated flux of the electrons whose energy is larger than $eV_{ret}$ if the electrons are injected perpendicularly to the RFA. The derivative of the collector current with respect to $V_{ret}$ gives the energy distribution of the electrons. If the incident electrons have an angular distribution the energy resolution is degraded since the transmission curve of the RFA depends on the angular distribution of the incident electrons.

The planar RFA based on that at APS is also installed at PSR [11,14]. Information on the time structure of the electron flux can be obtained by a fast electronics connected to the collector. The chassis is placed below the beam line to reduce radiation damage to solid-state components.

The planar RFAs at KEKB [15] are similar to those at APS. Several RFAs are equipped with a multi-channel plate to measure the time structure of the electron flux. An idea is proposed by K. Kanazawa to measure the electron density near the beam position. Energetic electrons are produced near the bunch due to a strong kick from the beam. The retarding bias voltage defines the observed volume around the beam from which observed electrons come. The cloud density near the beam just before the arrival of the bunch can be estimated from the collector current per bunch and the retarding bias voltage.

The planar RFA similar to that at APS is also installed at BEPC [16].

### *Electron sweeper*

An electron sweeper developed at PSR is a variant of the RFA [9]. It consists of a curved electrode subtending an angle of 150° and a RFA with a large aperture which is placed the opposite side of the electrode. A pulse of ~-500V with rise time of ~15-20 ns is applied to the electrode in order to sweep the electrons into the RFA. Thus the low energy electrons remaining in the chamber after a bunch passing through can be measured. The acceptance region calculated by a numerical simulation corresponds to ~30% of the cross sectional area of the beam chamber. After applying HV pulse at the end of the bunch gap a signal with a very fast rise time (~5ns) and a narrow width (~10 ns) was observed as expected from design calculations. A longer tail of the signal is not completely understood yet. The electron sweeper is also used for measuring the decay time of the electron cloud after the passage of the last bunch. The electron sweeper similar to that at PSR is also installed at KEK-PS [17].

### *Strip detectors*

Strip detectors [4,18,19,20] were developed at CERN to study the spatial and the energy distributions of the electron cloud. A collector placed under a beam chamber is composed of 36 channels copper strips with spatial resolution of 1.25 mm. The strips are separated from the beam by the chamber wall which has hundreds of holes (2mm in diameter) to reduce the perturbations to the electron cloud by an excessive collection of electrons. Three versions of the strip detectors were installed in the SPS; a strip detector to measure the spatial distribution of the electrons, a strip pick-up detector for the measurement of the energy distribution and a retarding field strip detector to study simultaneously the energy and the spatial distributions of the electrons. In the strip pick-up and the retarding field strip detector, filtering grids placed between the beam pipe and the collecting strips allow the measurement of the energy distribution. The signal from each channel is integrated using a current integrator with a integrating time from 2 to 255 ms. One version of the strip detector has a variable vertical aperture and another version is operated at 30 K. A measurement by the strip detector in a bending magnet at SPS clearly showed the appearance of two lateral strips of the electrons which were predicted by a simulation.

Recently a strip detector was installed in a quadrupole magnet to study the spatial distribution of the electrons in a quadrupole field [21]. The result of the measurement shows that two strips appear on a pole of the magnet, which was also predicted by a simulation.

### *Microwave transmission measurement*

The density of the electron cloud would be measured by studying the interaction between the electron cloud and the microwave. A microwave transmission measurement was tried at CERN [22]. TE waves were fed to a wide band button pair then detected by a strip line monitor which was placed 30m downstream of the button pair. The electron cloud in the beam chamber should give a small phase shift of the microwave signal (0.6˚ for the frequency of 2.5GHz and the electron density of $10^{12}m^{-3}$). Since the phase shift is modulated by the bunch revolution frequency, a phase-modulated signal can be observed. Contrary to the expectation an amplitude modulation which couldn't be understood by current electron cloud models was found. Further study is continued.

At PEPII [12], higher order modes (HOMs) generated at collimators in the upstream of a straight section were used as a source of the microwave. A pick-up connected to a spectrum analyzer was located at the end of the straight section. Solenoids of 20 m at the beam chamber between the collimators and the pick-up were switched on and off in order to control the density of the electron cloud. Any noticeable modulation of the HOM amplitudes with the density of the electron cloud was found.

## BEAM DIAGNOSTICS

### *Pickup electrode*

A pickup electrode connected to a spectrum analyzer has been used for measuring oscillation modes of the transverse coupled bunch instability by the electron cloud [23,24]. The mode distribution by the electron cloud instability is wide since the "wake field" by the electron cloud has a medium range (typically several to several ten m). The measurement is simple and useful for quickly identifying the threshold current of the instability. It may take long time to obtain the amplitude distribution of the betatron sideband if the harmonic number is large such that at KEKB.

### *Beam position monitor (BPM)*

A bunch-by-bunch beam position monitor measures the beam position of every bunches in a turn-by-turn manner. Oscillation modes and the growth rate of the coupled bunch instability are obtained from the measurement. The data can be taken in very short time (i.e. less than 1 sec). At KEKB [25] Bunch Oscillation Recorder (BOR) which is made by modifying a filter board in the bunch-by-bunch feedback system is used for A/D conversion of the BPM signal, demultiplexing and storing the data to a memory. The BOR was helpful for measuring the effect of the solenoid field on the oscillation modes and the growth rate of the coupled bunch instability at LER [26]. At DAFNE [27,28] a digital oscilloscope Lecroy LC574A was used for storing the data of the BPM with the sampling rate up to 500MHz to observe the fast horizontal instability at the positron ring which is suspected to be caused by the electron cloud.

Synchrotron sidebands caused by the head-tail instability by the electron cloud also can be measured by the BPM. At SPS [29] the synchrotron sidebands were found by SVD analysis of the oscillation data. At KEKB [30] the oscillation of each bunch was processed by Fourier analysis individually, then the power spectra of each bunches were averaged to enhance the peak of the sidebands. As a result a sideband peak appeared in the spectrum. Both observations at SPS and KEKB could be an indication of the head-tail instability by the electron cloud. In such a case the sideband would be used as a diagnostic tool sensitive for the presence of the electron cloud.

### *Interferometer*

An interferometer using synchrotron light from the beam measures the average beam size over the bunches [31]. The principle of the measurement is based on the van Cittert-Zernike theorem. The resolution of the measurement, typically several μm, is not limited by the diffraction effect. Its operation is not as difficult as a fast gated camera or a streak camera which usually require the operation by experts. It has been used to determine the threshold current of the beam size blowup at KEKB LER [32].

### *Fast gated camera*

A fast gated camera measures the transverse size of each bunch. It consists of a photoelectric surface and a multi-channel plate. A gate pulse changes the voltage between the photoelectric surface and the multi-channel plate in order to gate the light of synchrotron radiation. Minimum gate width is typically 3ns. Simultaneous measurement of successive bunches is difficult since the repetition rate is an order of 10 kHz. Resolution of the measurement is limited by the diffraction effect. The fast gated camera was used at KEKB and PEPII for measuring the transverse bunch size along bunch trains in order to observe the buildup of the electron cloud and to measure the effect of train gap and bunch gap on the beam size [33,34].

### *Streak camera*

A streak camera measures the longitudinal and the transverse distribution of the bunch by detection of synchrotron radiation. Simultaneous measurement of several consecutive bunches is possible. Resolution of the measurement of the transverse distribution is limited by the diffraction effect. Head-tail motion by the electron cloud would be detectable. At KEKB [35] the change of the vertical beam size with and without solenoid field was observed by the streak camera. A tilt of the bunch which indicates head-tail motion was not clearly observed. Increase of the light intensity may be necessary in order to get clearer result. At IHEP the streak camera was used for measuring the effect of solenoids, chromaticity, octupole magnets and clearing electrodes on the vertical beam size [36].

### *Tune meter*

The electron cloud causes betatron tune shifts of the bunches. The tune shifts can be increased along the bunch train due to the buildup of the electron cloud. Comparison between the tunes of the head bunch and those of the tail bunch gives an indirect estimate of the average density of the electron cloud around the ring. At RHIC [37] a beam position monitor in each plane recorded the oscillations of the last incoming bunch at the injection. Typically 1024 turns data were recorded and processed by a fast Fourier transform to obtain the tunes of the coherent beam oscillations. At KEKB [38] another approach was taken to measure the bunch-by-bunch tune shift. A high-speed gate consisted of two GaAs switches was introduced in a standard tracking measurement system. A pair of two switches was used for avoiding a ringing at on/off transition. Results at RHIC and KEKB showed the increase of the tunes along the bunch train.

### *Bunch-by-bunch luminosity monitor*

A bunch-by-bunch luminosity monitor gives an estimate of the transverse size of each bunch because the luminosity is inversely proportional to the cross sectional area of the beam at a collision point. At PEPII [39] gamma rays generated by radiative Bhabha scattering were detected by measuring Cherenkov light which was emitted by the electrons converted from gamma rays. The bunch-by-bunch luminosity monitor was used for determining the optimum filling pattern of the bunches to moderate the electron cloud effect [40]. At KEKB [41] the bunch-by-bunch luminosity monitor called Zero Degree Luminosity Monitor (ZDLM) detects recoil electrons which are emitted by radiative Bhabha scattering at an angle of 0° and then deflected by the quadrupole magnetic field because, after replacement of a vacuum chamber, the intensity of radiative gamma rays largely decreased due to the absorption by the thick chamber wall.

## SUMMARY

The electron clouds give various effects on the accelerators as described in this paper. They often limit the performance of existing accelerators and would be a potential threat to under constructing and future accelerators such as intense neutron sources and damping rings of linear colliders.

Many dedicated or standard instrumentations have contributed to understand the electron cloud effects. The efforts to refine and develop the diagnostics should be continued in order to improve the performance of existing accelerators and to predict the influence of the electron clouds on the future accelerators. For example a challenge for experimentalists is the measurement of the electron cloud at the beam location in the magnetic fields. The measurement of the electrons in the magnetic fields is important because a large fraction of the ring is already occupied by the magnets in some machines such as DAFNE, BEPCII, PSR and SPS and most drift space has been covered by the solenoids in B factories. The measurement of the electrons at the beam location is important because beam instabilities, especially single bunch instability, are largely governed by the electron cloud near the beam. The measurement would be difficult because detectors are usually located on the chamber wall while motion of the electrons is affected by the magnetic fields until they reach at the detectors.

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