A COMPARISON OF ELECTRON CLOUD DENSITY MEASUREMENTS USING SHIELDED PICKUPS AND TE WAVES AT CesrTA*

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Abstract

The Cornell Electron Storage Ring has been reconfigured as a test accelerator (CESRTA) with beam energies ranging from 2 GeV to 5 GeV. Measurements of electron cloud (EC) densities have been made using a number of techniques, including Shielded Pickups (SPU) and Resonant TE Waves. These measurements include different bunch configurations, from single bunches of positrons and electrons to multibunch trains. The comparison of those results, obtained in the same portion of the vacuum chamber, highlights the characteristics of the two techniques and helps identify their relative merits for ascertaining various properties of the electron cloud. In many respects, the techniques are complementary. For example, TE Wave measurements are most sensitive to cloud electrons near the horizontal center of the beampipe, while the SPU is sensitive to cloud electrons with velocities that are normal to the inner surface of the beampipe. The SPU measures the time evolution of the cloud, while the Resonant TE Wave technique measures the overall cloud density. We present an outline of our current understanding of these two techniques and a comparison of recent measurements.

INTRODUCTION

Electron clouds consist of relatively low energy electrons in accelerators that are an unwanted by-product of the beam. They can be initiated by synchrotron radiation and photoemission from the beampipe inner wall or by ionization of the residual gas. An electron cloud density of 10^{11} m^{-3} or higher can result in significant beam instabilities and emittance growth among other effects. One of the goals of the CESRTA program is to study the growth and decay of electron clouds as well as the effectiveness of mitigation techniques. This paper will focus on two techniques for measuring the properties of electron clouds at CESRTA.

SHIELDED PICKUPS

Shielded pickups have been used at other accelerators [1] to characterize electron clouds. The electrode of a shielded pickup is in the vacuum space of the beampipe, but is isolated from the electromagnetic field of the passing bunches by a pattern of small holes in the beampipe wall as shown in Fig. 1. This design uses a pattern of 169 holes of 0.76 mm diameter with a depth of about 2 mm for each pickup. Electrons with nearly vertical trajectories can pass freely through the holes and be collected by the electrode - typically biased at $+50\ V$ to reduce secondary emission. The direct beam signal is suppressed both by the small hole diameter and the depth of the holes [2]. A voltage gain of 100 is applied to the signal before being sent to an oscilloscope with a bandwidth of 500 MHz. The system time resolution is less than 1 ns.

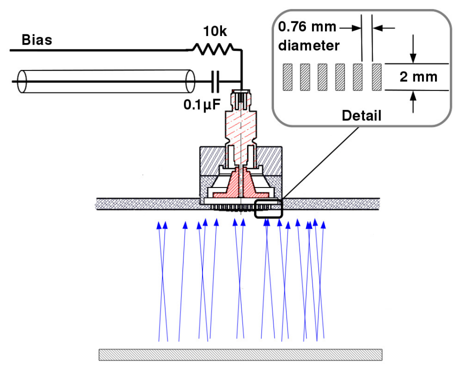

Figure 1: Sketch of Shielded Pickup (SPU)

The signal from two positron bunches is shown in Fig. 2. There is a small but detectable direct beam signal, that provides a convenient marker for the time of the bunch passage. The electron cloud signal from the second bunch is much larger than that of the first, since the electrons that were generated by the first bunch are accelerated into the detector by the second bunch. This effect has been used to measure the decay of the electron cloud by using pairs of bunches with different spacings [3].

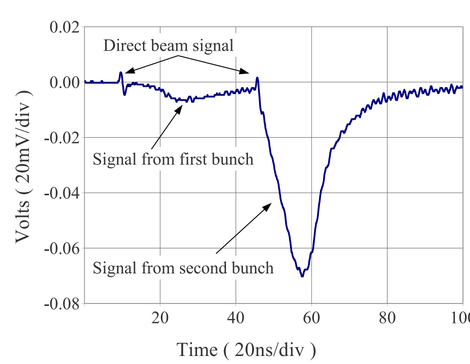

Figure 2: SPU signal with 2 bunches of 4.8×10^{10} positrons each with bunches 36 ns apart. The beam energy is 2.1 GeV

* This work is supported by the US National Science Foundation PHY-0734867, PHY-1002467 and the US Department of Energy DE-FC02-08ER41538.
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ISBN 978-3-95450-121-2

The SPU samples the flux of electrons that hit the beampipe walls, providing an indirect determination of the EC density at the position of the beam. A model that includes evolution of the cloud and the effect of the beam on the cloud electrons is used to simulate the response of the SPU to various beam configurations. Comparisons of simulation with the SPU measurements are used to constrain the physics parameters of the model, including quantum yield, photoemission energy spectrum, and secondary emission coefficients. We have used this technique to compare the properties of various vacuum chamber surface treatments with those of bare aluminum, including carbon coated and titanium nitride coated aluminum [4].

TE WAVE RESONANCES

The technique of using the transmission of microwaves through the beampipe in order to measure the EC density was proposed at CERN [5]. The electrodes of beam position monitors (BPMs) can be used to couple TE waves in/out of the beampipe and the electron cloud will produce a phase shift in the transmitted signal. Since the EC density varies with the pattern of bunches, the result is phase modulation sidebands of the carrier frequency. Sidebands have been observed with amplitudes that scale with the expected EC density.

At CESRTA, while it was possible to transmit TE waves through the beampipe, the response vs. frequency indicated that there were a large number of resonances. Also, the largest response was generally found by coupling microwaves in/out at the same detector. It was clear that there were significant reflections in the beampipe, produced by longitudinal slots for vacuum pumps, sliding joints and other alterations in the shape of the beampipe. This made quantitative measurements difficult, as the calculation of the phase shift becomes unwieldy if all of the relevant discontinuities are properly included. The multiple reflections led to an uncertainty in the effective path length of transmission.

We are now using a different approach for the analysis of signals that takes advantage of these reflections - treating the beampipe as a resonant cavity [6]. The resonant frequency ω of a cavity will be changed by the presence of an electron cloud inside it. The magnitude of the shift is proportional to the integral of the local electron density n_e weighted by the square of the electric field within its volume V (see Eq. 1).

$$\frac{\Delta\omega}{\omega} = \frac{e^2}{2\varepsilon_0 m_e \omega^2} \frac{\int_V n_e E_0^2 \, dV}{\int_V E_0^2 \, dV} \tag{1}$$

For rapid changes in the EC density, the cavity damping time will limit its phase response. However, if the change in EC density is slow compared to the damping time of the cavity, the change in resonant frequency will result in a phase shift across the cavity. This will give phase modulation sidebands as with the transmission method, but with a different interpretation. The EC density can be calculated from the ratio of the sideband to the carrier amplitudes and the cavity Q (about 3000). For a cw phase modulation of $\Delta\phi$, the ratio of voltage amplitudes of the first sideband to the carrier is $\approx \frac{1}{2}\Delta\phi$. So after some approximations [6],

$$n_e \approx S_{ratio} \cdot \frac{\omega^2}{Q \cdot 1.59 \times 10^3} = S_{ratio} \cdot 2.5 \times 10^{13} \tag{2}$$

where ω is the cavity frequency. The calculation above would be for sinusoidal modulation of the cloud. An additional factor is needed to correct for the time profile of the cloud using its Fourier transform.

The distribution of the electric field within the cavity volume determines the local sensitivity to the electron cloud density n_e as shown in Eq. 1. We generally excite the fundamental TE mode of the beampipe, so the transverse field maximum is at the horizontal center, going to zero as $cos(\frac{\pi x}{2a})$ when approaching either side wall at $x = \pm a$. The electric field along the length of the beampipe will be determined by reflections and standing waves. A common source of reflections is the longitudinal slots that connect ion pumps to the beam vacuum space as show in Fig. 3. Standing waves can be confined to the region between the pumps. Depending upon the geometry near the drive point, it is also possible for the lowest resonance to be a cutoff mode, where the field decreases exponentially with distance from the drive point [6].

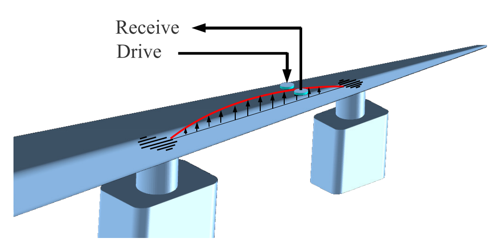

Figure 3: Standing waves are set up between ion pumps with longitudinal slots. Microwaves are coupled in/out of the beampipe using the electrodes of a beam position monitor. The resonances will be multiples of a half-wavelength.

COMPARISION OF MEASUREMENTS

As outlined above, the two devices measure different parameters - the SPU samples the electron current hitting the inner surface of the beampipe, while TE Wave resonances measure the EC density mostly near the center of the beampipe. On the other hand, the SPU is well suited to time domain measurements while the time response of the TE Wave resonance is limited by the beampipe cavity Q.

Fig. 4 shows a particular location at CESRTA where both TE Wave and SPU measurements have been made. While most of the beampipe at CESRTA is bare aluminum, the SPU is installed in a short test section coated with diamond-like carbon. The sensitivity of the TE Wave measurement extends over the region between the pumps, so it samples

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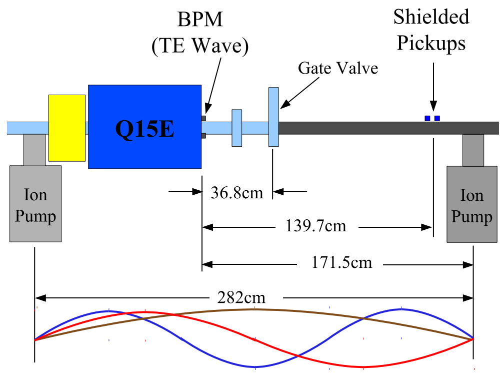

Figure 4: The SPU is located in a short test section of chamber where the vacuum surface has been coated with diamond-like carbon (the darker section in the sketch). The TE Wave region spans both the coated and uncoated sections of beampipe.

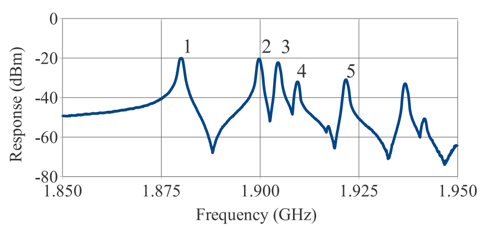

Figure 5: Above is the TE Wave response at 15E when resonantly excited. The sideband amplitudes of first five major peaks were used to generate Fig. 6 .

both the coated and the bare aluminum sections. This complicates the comparison of the two methods since the aluminum section will have a much higher EC density than the coated section.

Fig. 6 is an example of the response of these two devices as a function of beam current, using a 20 bunch train of positrons at 5.3 GeV with a bunch spacing of 14 ns (train length 266 ns) and a revolution time of 2563 ns. For TE Wave data, the duration of the cloud was taken to be the roughly the length of the bunch train. The first Fourier component gave a correction of 4.7 to the density calculated by Eq. 2, giving the peak EC densities shown. For the SPU data, the voltage gain of 100 was removed and the charge deposited on the electrode for each turn is plotted.

In the TE wave plots, the data for first three resonances are close to each other, but resonances 4 and 5 have a lower signal. According to Eq. 1, if the EC density n_e were uniform the frequency shift - and therefore the signal - would be independent of the details of the electric field distribution and all of the TE Wave curves should be the same. The fact that the curves differ suggests that the EC density is non-uniform.

SPU signal is very non-linear at low bunch currents as might be expected. At low bunch currents, the SPU signal can be increased both by a larger EC density and increasing bunch charge. With increased bunch charge, the electron cloud is more effectively kicked into the detector by the beam. So in this low bunch charge region, the SPU signal for a train of bunches should be roughly quadratic with current.

Simulation indicates an approximately linear increase in EC density with beam current as suggested by the TE Wave plots. The full simulation of EC density plus SPU sensitivity is in reasonable agreement with the SPU signal at the location of that detector. A comparison with the EC density given by the TE Wave measurement is complicated by the fact that the resonances span both the aluminum and carbon coated sections of beampipe and the flux of synchrotron radiation photons hitting the wall varies by a factor of three over this region. At 100 mA, the simulation predicts average EC densities of 1.0×10^{13} for the aluminum and 0.58×10^{12} for the diamond-like carbon section. This corresponds to an average value of 5.3×10^{12}, in reasonable agreement with the measurements. Further work is required in order to complete the comparison of TE Wave and SPU data. The results can be used to provide experimental verification of the simulations.

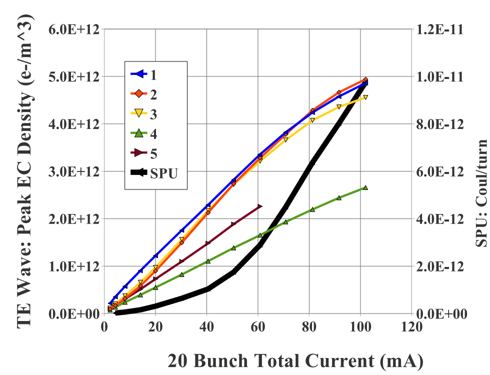

Figure 6: Comparison of SPU and TE Wave measurements for a 20 bunch train of positrons. The thick curve is the total charge deposited in the SPU in a single turn; the thinner, numbered curves are based on the TE Wave sidebands of five different resonances shown in Fig. 5.

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ISBN 978-3-95450-121-2