## Title
Measurements of the Electron Cloud Density in the PEP-II Low Energy Ring



**Author**
Byrd, John

**Publication Date**
2009-07-28

# MEASUREMENTS OF THE ELECTRON CLOUD DENSITY IN THE PEP-II LOW ENERGY RING*

J. Byrd, S. De Santis, K. Sonnad, LBNL, Berkeley, CA 94720, U.S.A.
F. Caspers, T. Kroyer, CERN, Geneva, Switzerland
A. Krasnykh, M. Pivi, SLAC, Menlo Park, California.

*Abstract*

Clouds of low energy electrons in the vacuum beam pipes of accelerators of positively charged particle beams present a serious limitation for operation of these machines at high currents. Because of the size of these accelerators, it is difficult to probe the low energy electron clouds over substantial lengths of the beam pipe. We have developed a novel technique to directly measure the electron cloud density via the phase shift induced in a TE wave that is independently excited and transmitted over a section of the accelerator. We infer the absolute phase shift with relatively high accuracy from the phase modulation of the transmission due to the modulation of the electron cloud density from a gap in the positively charged beam. We have used this technique for the first time to measure the average electron cloud density over a 50 m straight section in the positron ring of the PEP-II collider at the Stanford Linear Accelerator Center. We have also measured the variation of the density by using low field solenoid magnets to control the electrons.

## INTRODUCTION

The accumulation of low-energy background electrons in regions of the beampipe of high-energy accelerators of positively charged beams presents one of the most serious challenges to increasing currents in these machines. Depending on bunch repetition rate, beam current and other machine conditions, electrons extracted from the beampipe walls, usually by synchrotron radiation, can be transversally accelerated by the circulating beam and extract even more electrons when they strike the beampipe again. This resonant mechanism leads to a buildup of these electrons, which can negatively affect the accelerator's operation in a variety of ways [1].

Because of its importance for a number of present and future high profile projects, such as the Large Hadron Collider and the International linear Collider, the electron cloud dynamics, its effects on the beam and their cures have been the object of numerous studies in the past few years. From an experimental point of view, electron cloud effects have been observed in various high intensity synchrotrons and storage rings [2-4]. The methods used consist in the analysis of the beam's dynamic behaviour, which can necessarily give only an averaged measurement of the electron cloud density (ECD) around the machine, and local detectors [5], which only measure the energy spectrum of electrons near the beampipe wall at a specific location.

In this paper we present a novel method featuring several positive characteristics, namely the possibility of being applied anywhere a pair of beam position monitors (BPM) are available, without the necessity of any dedicated hardware nor installation, and the ability of probing the electron cloud density directly along the beam path and not only in the vicinity of the beampipe walls.

The method consists in propagating an electromagnetic wave along the beampipe, between two sets of BPM's delimiting the region that one wants to measure.

The propagating wave does not interact with the ultrarelativistic beam, but is affected by the low-energy electron densities it encounters. This interaction essentially translates into a phase delay that can be theoretically evaluated, as shown in the next paragraph.

Besides this basic interaction mechanism it is also possible to obtain a resonant interaction in regions where a local magnetic field is of such strength as to define a cyclotron frequency equal to the frequency of the propagating wave. The theoretical treatment of this case is still object of work. We present nonetheless some preliminary results, with simulations and experimental measurements.

## THEORETICAL EVALUATION OF THE ELECTRON CLOUD EFFECTS ON MICROWAVE PROPAGATION THROUGH THE BEAM PIPE

The derivation of the wave dispersion relationship for propagation of an electromagnetic wave through an electron plasma has been described in [6] and is limited to first order perturbations, so that the model does not anticipate any amplitude variation of the transmitted wave. The phase shift of a wave of angular frequency $\omega$ caused by a homogeneous density of cold electrons per unit propagation length is given by:

$$\Delta\varphi / L = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}} \qquad (1)$$

where $\omega_c$ is the beampipe cut-off frequency and $\omega_p$ is $2\pi$ times the plasma frequency $f_p$, which in turn is approximately equal to 9 times the square root of the electron density per cubic meter $n_e$.

*Work supported by the U.S. Department of Energy Under Contracts Nos. DE-AC0-05CH11231 and DE-AC03-76SF00515

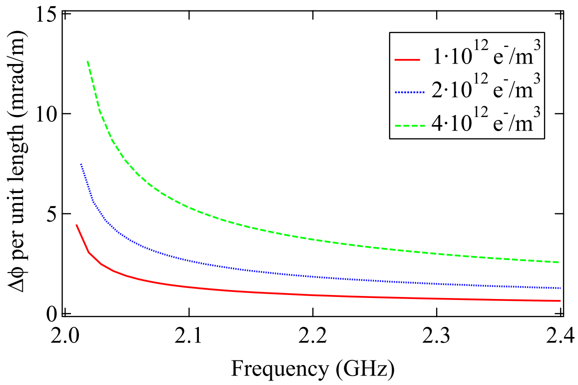


Fig.1. Phase shift per unit length for different electron densities. The cut-off frequency is 2 GHz.

Figure 1 shows the theoretical phase shifts, based on Eq.(1) for a three different electron cloud densities in a beam pipe with a 2 GHz cut-off frequency. Numerical simulations using VORPAL agree very well with the above estimates [7].

It must be noted that as the propagating wave frequency increases the phase shift per unit length tends to zero, while it increases as the propagation frequency gets closer to the pipe cut-off the phase shift increases dramatically. However in the latter case the propagation attenuation increases as well, so that a compromise solution has to be found every time for the optimal frequency to be used in practice.

Based on Eq.(1), one can calculate the plasma frequency from the measured phase shift and obtain the average electron density in the beampipe length where the wave has propagated as:

$$\rho_e \approx \frac{f_p^2}{80} \; (e^- / m^3) \qquad (2)$$

The electron densities present in a vacuum chamber in most cases are below $10^{11}$ $e^-/m^3$ and that the maximum length of the beampipe region used for the measurement is limited by the presence of all those components (vacuum pumps, antechambered sections, ports, etc.) which greatly attenuate the wave propagation. As such, the total phase shift differences one tries to measure when using this method are of the order of a few milliradiants.

Trying to measure directly such a small difference and furthermore trying to do so in a noisy environment characterized by direct beam signals much stronger than the propagating wave, would be a desperate enterprise.

Our method instead takes advantage of the changes in the electron cloud densities introduced by the circulating beam itself: A gap in the fill pattern, if sufficiently long, can reduce the electron density and even eliminate them entirely. In general we can express the wave signal at the receiver in the form

$$s(t) = A\cos[\omega_{car}t + \Delta\varphi(t)] \qquad (3)$$

The modulating signal $\Delta\varphi(t)$ is directly related to the time evolution of the average ECD in the beampipe region between transmitter and receiver. In particular, it can be expressed as a Fourier series at frequencies multiples of the ring revolution frequency $f_{rev}$ and, in the theoretical case of a simple sinusoidal variation of the ECD, the modulated spectrum would consist of just the carrier signal at $f_{car}$, with identical upper and lower sidebands at $f_{car} \pm f_{rev}$. The amplitude of these sidebands, relative to the carrier (one half of the modulation index $\beta$), is equal to one half of the maximum change in phase delay $\Delta\varphi$ and therefore of the ECD [8]. Although it would seem in principle that our method can only measure variations in the ECD and not its absolute value, is of course always possible to introduce a gap long enough to reduce the ECD to zero.

In more realistic cases, with the ECD time evolution encountered in practice, one observes a number of sidebands. Although phase modulation is not a linear process and a full demodulation of the received signal would be required to calculate $\Delta\varphi(t)$, the relative amplitude of the first sideband still gives a reasonably good estimate of the ECD in most cases and the number of observed sidebands (directly linked to the modulating signal bandwidth) offers a guideline on the clearing and build-up times of the ECD.

In the presence of a constant uniform magnetic field $B$, the above results are not valid anymore in the vicinity of the cyclotron frequency $f_{cycl} = eB / 2\pi m_e$. While a complete analytical treatment of the interaction between TE wave and electron in the vicinity of this frequency is currently object of study, simulations are available (Fig.2), which point out to a resonant behaviour, which we believe should result in a combination of amplitude and phase modulation, as the case seems to be also from preliminary experimental results.

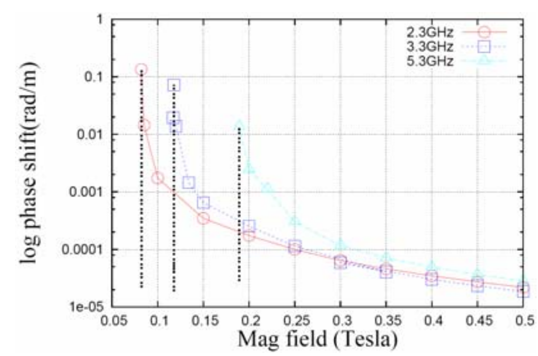


Figure 1. Calculated phase shift per unit length in a dipole region for a uniform cold electron plasma in a waveguide with 2 GHz cutoff frequency, the cloud density is assumed to be $1\cdot10^{12}$ $e/m^{-3}$. The vertical lines correspond to an electron gyration frequency equal to the wave frequency.

## EXPERIMENTAL SETUP IN THE PEP-II LER

We run experiments in two different regions of PEP-II: a 50 m field-free straight and a 5 m magnetic field section.

In the first region shown in Fig.3, a couple of beam position monitor BPM buttons located in the long straight magnetic-free section of the LER Interaction Region 12 (IR12) was available for our measurement. These buttons are about 50 meters apart and long RF cables bring the signal in the experimental hall to our instrumentation. The beam pipe in the LER is surrounded by electrical cables generating a solenoid magnetic field. This field is used to confine the electrons near the beam pipe limiting their interaction with the positron beam and the emission of secondary electrons. In the region of interests, between our two BPM's there are two families of solenoids, each generating a magnetic field of about 20 Gauss. During the two years of measurements, we didn't have a permanent setup. Our instrument suite always included an Agilent E4436B signal generator, capable of generating a CW signal at a fixed frequency up to 3 GHz. The emitted signal power can be selected up to around 15 dBm. We added a Comtech PST solid state 5W amplifier rated up to 2 GHz, but we verified it could still give +30dB amplification at 2.3 GHz.

On the receiver end we initially used an HP/Agilent E4408B and 8561EC spectrum analyzers; later on we also used a Rohde-Schwartz 42 GHz spectrum analyzer. In order to measure the power level at our output port we also used an HP 436A/8545A power meter. We performed measurements with a variety of beam currents, from no beam up to 2.5 A in about 1700 bunches. The PEP-II LER has a 476 MHz main RF frequency and the standard fill pattern is with every other RF bucket filled, except for a gap of 48 buckets (~100 ns long).

Figure 3. LER vacuum chamber in IR12 (upper beam pipe). The outer clearing solenoid can be seen.

In the second experimental region (Fig.4), we connected cables to a couple of BPMs located upstream and downstream of a new 4-dipole chicane recently installed to test the electron cloud effect in magnetic field regions of the future linear colliders. These buttons are about 5 meters apart and long RF cables bring the signal in the experimental hall to our instrumentation. Two cables are used as transmitter and two cables as receivers. A Quadrature Hybrid 3 dB attenuator is connected in series in each receiver cable. The dipoles are 0.435 m long. The magnetic field of the chicane dipoles can be varied between 0 and 1.46 kG. The vacuum chambers at the chicane location are made in aluminum, partially coated with TiN. One magnet is located in the aluminum section and the other three magnets are located in the TiN section. The beam pipe is partially surrounded by electrical cables generating a solenoid magnetic field.

Figure 4. Chicane dipole magnets (Right) installed in the LER (upper beam pipe) for electron cloud tests.

## EXPERIMENTAL RESULTS

We detected electron cloud induced phase modulation in both the experimental setups described in the previous section. A more detailed analysis is reported also in [7].

### *Long straight*

In order to measure a phase modulation in the 50 m-long straight section of the LER the clearing solenoids strength has to be reduced substantially.

Figure 5 shows the power spectrum of the received signal with the clearing solenoid set at the nominal 40 Gauss (black) and turned off (blue). The carrier signal is evident as well as two beam revolution harmonic signals with their small synchrotron sidebands. When the solenoid field is set to zero, the beam pipe fills with electrons, which are then periodically cleared by the 100 ns long gap in the fill pattern originating a phase modulation in the transmitted microwave.

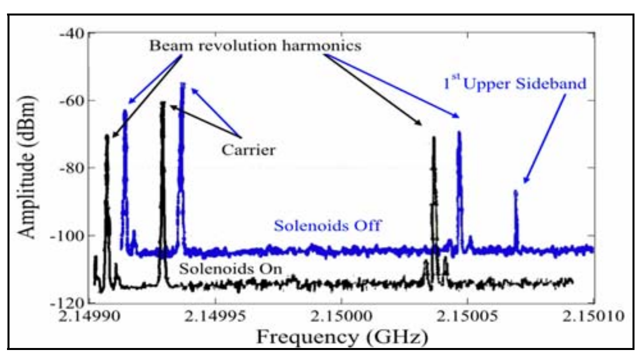


Figure 5. Spectrum analyzer traces showing microwave carrier and beam signals. A phase modulation sideband

appears when the solenoid field is turned off (blue), allowing the electron plasma to fill the pipe.

If we assume for simplicity that this phase modulation is purely sinusoidal and that the ECD reaches zero during the gap, it indicates an average electron density of $6.6{\cdot}10^{11}$ $e^-/m^3$, according to Eqs. (1-2).
In practice, the presence of several other sidebands in the received signal points out to a more complex modulation than the simple sinusoidal one. From the analysis of the modulating signal bandwidth (i.e. the number of visible sidebands) it is already possible to estimate [9] growth and decay time of the electron cloud. We have also characterized the effectiveness of the solenoid field in controlling the ECD. Shown in Fig.6 is an estimate of the ECD derived from the first modulation sideband as a function of the solenoid strength. This measurement indicates that only small solenoid fields are required to confine the electron cloud near the beam pipe walls, thus limiting the ECD.

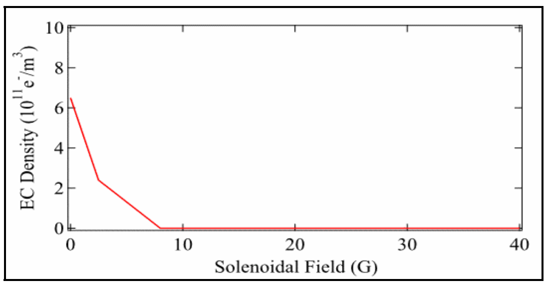


Figure 6. Average electron cloud density derived from the first modulation sideband as a function of the solenoid field strength.

## *Chicane*

Figure 7 shows the phase delay of a TE wave propagating in the chicane at 2.015 GHz. When the dipole field is set so that its corresponding cyclotron frequency is equal to the microwave frequency, the total phase delay is greatly increased. The actual mechanism of this phenomenon is currently the object of investigation. The apparent difference between the propagation frequency of 2.015 GHz and the cyclotron frequency of the maximum phase shift in Fig.6 (~1.96 GHZ) is due to differences between the 700 G set point, the actual field in the four dipoles and its non-uniformity along the magnet length.
In this configuration, the phase shift reaches much higher values, so that it promises to yield a powerful tool for measuring even small electron densities.

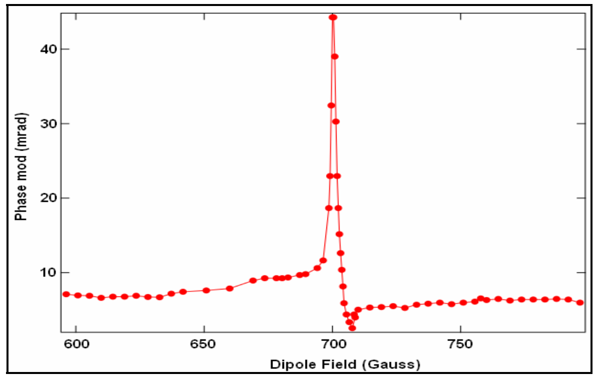


Figure 7. Phase delay as a function of the dipole field strength for a TE mode propagating in the chicane at 2.015 GHz.

## CONCLUSIONS

We have shown the results of our TE wave transmission measurements on the PEP-II LER. We were able to detect modulation sidebands 136 kHz away from our transmitted signal at 2.295 GHz, which is consistent with a phase modulation induced by the presence of an electron cloud. Our results are in reasonably good agreement with theoretical estimates, which in turn have been checked with simulation codes.

We have shown how our method could be easily adapted to most machines as a tool for verifying experimentally the effectiveness of electron cloud clearing methods.

We have also successfully measured the signal in correspondence of a resonance with the electrons' cyclotron frequency in the presence of a fixed dipole field. The analytical study of this phenomenon is currently under investigation.

## ACKNOWLEDGEMENTS

The authors wish to thank U. Wienand, M. Sullivan, F. Decker, F.-J. Decker, S. Hoobler, A. Krasnykh and A. Kulikov for their precious help in realizing the experiments.

## REFERENCES

[1] K. Ohmi, Phys. Rev. Lett **75**, 1526 (1995).
[2] M. Izawa, Y. Sato, and T. Toyomasu, Phys. Rev. Lett. **74**, 5044 (1995).
[3] D. Neuffer, E. Colton, et al. Nucl. Instrum. Methods Phys. Res., Sect. **A 321**, 1 (1992).
[4] G. Arduini, K. Cornelis, et al. In Proc. PAC 2003, Portland, Oregon (2003)
[5] K. Harkay and R. Rosenberg, Phys. Rev. ST-AB **6**, 034402 (2003).
[6] H.S. Uhm, K. T. Nguyen, et al., Journal of Appl. Phys., 64(3), p. 1108-11115, 1988.
[7] K. Sonnad, M. Furman, et al. In Proc. PAC 2007, Albuquerque, New Mexico (2007).

[8] T. Koyer, F. Caspers, et al., in Proc. of the 31st ICFA Advanced Beam Dynamics Workshop, CERN-2005-001, (2005).
[9] J. Carson, Proc. IRE, **10**, 57 (1922).