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MICROWAVE TRANSMISSION MEASUREMENT OF THE ELECTRON CLOUD DENSITY IN THE POSITRON RING OF PEP-II*

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Abstract

Clouds of electrons in the vacuum chambers 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 applied a novel technique to directly measure the electron cloud density via the phase shift induced in a TE wave which is independently excited and transmitted over a straight section of the accelerator. The modulation in the wave transmission which appear to increase in depth when the clearing solenoids are switched off, seem to be directly correlated to the electron cloud density in the section. Furthermore, we expect a larger phase shift of a wave transmitted through magnetic dipole field regions if the transmitted wave couples with the gyration motion of the electrons. We have used this technique to measure the average electron cloud density (ECD) specifically for the first time in magnetic field regions of a new 4-dipole chicane in the positron ring of the PEP-II collider at SLAC. In this paper we present and discuss the measurements taken in the Low Energy Ring (LER) between 2006 and 2008.

INTRODUCTION

Evaluating the electron cloud density based on microwave transmission measurements was first suggested by F. Caspers and T. Kroyer in 2003 [1,2]. In an effort to better understand their results on the SPS, we performed similar measurements in the LER of the PEP-II collider at SLAC.
In the next section we first calculate an estimate of the effect on the microwave propagation based on the theoretical analysis and computer simulations.
In the following section we describe our experimental setups at SLAC. We finally show the results obtained up to now and discuss how we could improve the setup for our upcoming experiments planned at other accelerator beam lines.

THEORETICAL EVALUATION OF MICROWAVE PROPAGATION IN A BEAM PIPE WITH AN ELECTRON CLOUD

The derivation of the wave dispersion relationship for propagation of an electromagnetic wave through an electron plasma has been described in [3, 4] and is limited to first order perturbation, so that the model does not anticipate any amplitude variation of the transmitted wave. The phase shift of a wave of angular frequency ω caused by a homogeneous density of cold electrons over a length of propagation L is given by:

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

where ω_c is the beam pipe cut-off frequency, ω_p is the plasma frequency $\omega_p = 56.4[rad/s]\sqrt{n_e[m^{-3}]}$ (in SI Units) and n_e is the electron density per cubic meter. It is clear that the phase shift is proportional to the electron cloud density and increases as the carrier frequency approaches the vacuum chamber cut-off. Figure 1 shows the theoretical phase shifts for a few different electron cloud densities from the LER beam pipe cut-off of 2 GHz. Numerical simulations using VORPAL agree very well with the above estimates [5].
Furthermore, in a dipole field the electrons are spiraling along the magnetic field lines with a gyration (cyclotron) frequency $f = eB/2\pi m_e$ where m_e is the electron mass, e the electric charge, B the magnetic field induction and assuming non-relativistic electrons. If the transmitted radiofrequency wave signal couples with the gyration motion of the electrons, the phase shift is more pronounced.

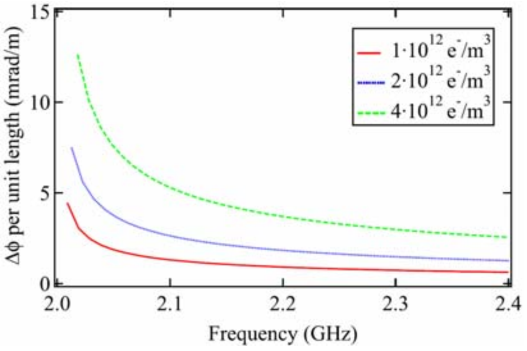

Figure 1. Calculated phase shift per unit length in a magnetic-free region for a uniform cold electron plasma in a waveguide with 2 GHz cutoff frequency.

Figure 2 shows the calculated phase shift in a dipole. The phase shift is larger as the electron gyration frequency approaches the transmitted wave frequency. The vertical lines correspond to the electron gyration frequency equal to the wave frequency.
In the case of the dipole field region, an estimate for the electron cloud density in PEP-II chicane is underway by

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simulations. A theoretical model for the phase shift in dipole regions with electron cloud is actually under study. In case of a magnetic-free region, an estimate for the electron cloud density in PEP-II straight is reported in [6]. Scaling from this estimate, at a typical beam current 2.1 A and ~ 1700 bunches during our measurements, assuming a chamber secondary electron yield 1.4 in the LER stainless steel sections an ECD of $1.2{\cdot}10^{12}$ e^{-}/m^{3} is expected, giving a plasma frequency of 9 MHz and a phase shift of 1.1 mrad/m calculated from Eq.(1) for a frequency 2.15 GHz.

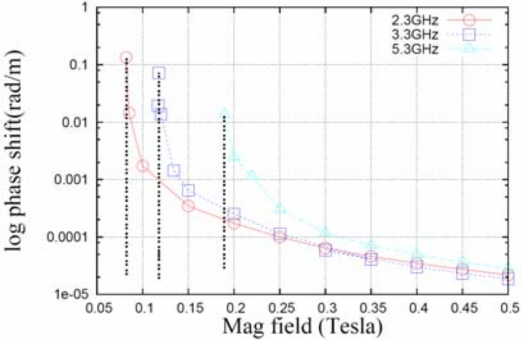

Figure 2. Calculated phase shift per unit length in a dipole region for a uniform cold electron plasma in a waveguide with 2 GHz cutoff frequency, the cloud density is assumed to be $1{\cdot}10^{12}$ e/m^{-3}. The vertical lines correspond to an electron gyration frequency equal to the wave frequency.

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 Figure 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 Comitech 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.

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

In the second experimental region, we connected cables to a couple of BPMs located upstream and downstream of a new 4-dipole chicane recently installed, see Figure 4, 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 3dB 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.

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.

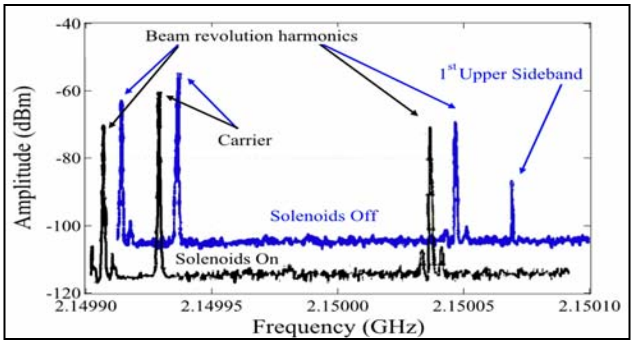

Figure 5. Spectrum analyzer traces showing microwave carrier and beam signals. A phase modulation sideband appears when the solenoid field is turned off (blue), allowing the electron plasma to fill the pipe.

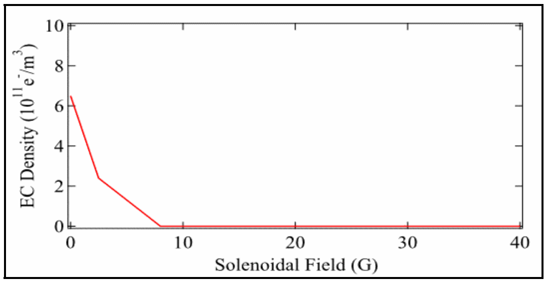

Figure 6. Average electron cloud density derived from the first modulation sideband as a function of the solenoid field strength.

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 Eq. (1).

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 [7] growth and decay time of the electron cloud.

We have also characterized the effectiveness of the solenoid field in controlling the ECD. Shown in Figure 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.

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 Figure 7 (~ 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.

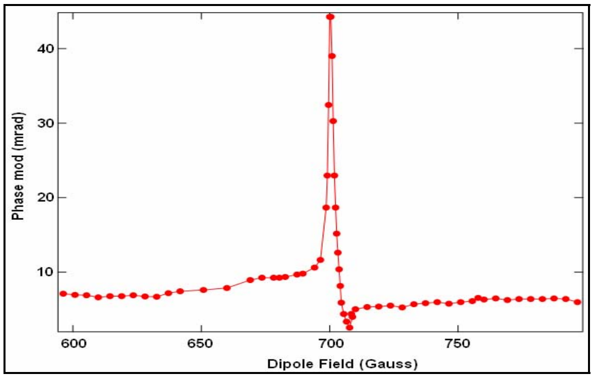

Figure 7. Phase delay as a function of the dipole field strength for a TE mode propagating in the chicane at 2.015 GHz.

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. In a dipole field, when the dipole is set so that its corresponding cyclotron frequency is equal to the microwave frequency, we measured a largely increased total phase delay. In this configuration, the method promises to yield a powerful tool for measuring even small electron densities.

We are planning further measurements at CesrTA Cornell and at the SPS at CERN.

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