MEASUREMENTS OF THE PROPAGATION OF EM WAVES THROUGH THE VACUUM CHAMBER OF THE PEP-II LOW ENERGY RING FOR BEAM DIAGNOSTICS*

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Abstract

We present the results of our measurements of the electron cloud density in the PEP-II low energy ring (LER) by propagating a TE wave into the beam pipe. By connecting a signal generator to a beam position monitor button we can excite a signal above the vacuum chamber cut-off frequency and measure its propagation through the beam pipe with a spectrum analyzer connected to another button about 50 meters away. The measurement can be performed with different beam conditions and also at different settings of the solenoids used to reduce the build up of electrons. The presence of a modulation in the TE wave transmission, synchronous with the beam revolution frequency, which appear to increase in depth when the solenoids are switched off, seem to be directly correlated to the electron cloud density in the region between the two BPM's. In this paper we present and discuss the measurements taken in the Interaction Region 12 straight of the LER during 2006 and the first part of 2007.

INTRODUCTION

Evaluating the electron cloud density based on microwave transmission measurements was first suggested by F. Caspers and T. Kroyer in 2003 [1]. In an effort to better understand their results on the SPS, we performed similar measurements on the Low Energy Ring (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 setup at SLAC.

We finally show the results obtained up to now and discuss how we could improve our setup and preferred beam conditions for our upcoming experiments.

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 [2] 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 ω caused by an homogeneous density of cold electrons per unit propagation length is given by:

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

where ω_c is the beampipe cut-off frequency and ω_p is 2π times the plasma frequency, which is approximately equal to 9 times the square root of the electron density per cubic meter.

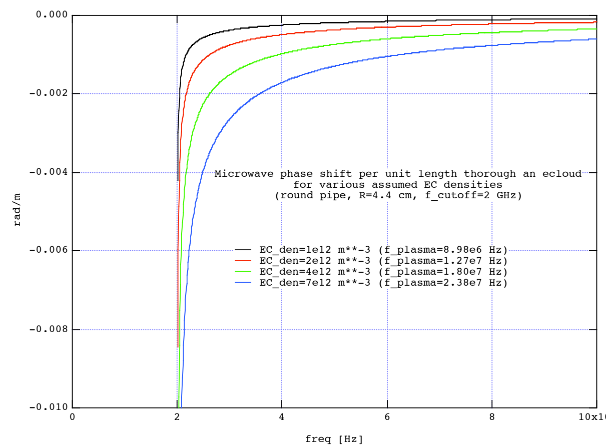

Figure 1: Phase shift per unit length for different electron densities. The cut-off frequency is 2 GHz.

Figure 1 shows the theoretical phase shifts for a few different electron cloud densities from the LER beam pipe cut-off of 2 GHz to 3 GHz.

Numerical simulations using VORPAL agree very well with the above estimates [3].

An estimate for the electron cloud density in PEP-II is reported in [3]: assuming a bunch population of $9{\bullet}10^{10}$ positrons and a chamber surface secondary electron yield of 1.4 in the LER stainless steel straight sections, an electron density of $2{\bullet}10^{12}$ e^-/m^3 is expected.

At the nominal beam current of 2.1 A with ~1700 bunches circulating in the machine, the number of positrons per bunch is rather $5.5{\bullet}10^{10}$, so that the expected electron cloud density, which scales linearly, is around $1.2{\bullet}10^{12}$ e^-/m^3. Under these conditions the plasma frequency is therefore 9.86 MHz and from Eq.(1) we can derive the phase shift per unit length at 2.3 GHz, which is the frequency used for our experiment as we will explain later on. We calculate a phase shift of around 0.89 mrad/m. This means that the total phase shift due to the electron cloud over 50 meters (see later) would be around 2.5°. Rather than making two separate measurements with

*Work supported by the U.S. Department of Energy under Contract No. DE-AC0-05CH11231.
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beam and without beam, we make use of the presence of a ~1.4% gap in the LER fill pattern. Assuming that this gap is long enough to clear the electron cloud, its effect on a CW signal transmitted through the beam pipe would correspond to a phase modulation at the 136 kHz LER revolution frequency. From the theory of phase modulation one can easily recognize that the amplitude of the modulation sidebands relative to the carrier would be related to the electron cloud induced frequency shift and precisely equal to $\Delta\varphi/2$. In our case that would correspond to a –33 dB level.

EXPERIMENTAL SETUP ON THE PEP-II LER

A couple of beam position monitor buttons located in the long straight 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.

Figure 2: Detail of the LER vacuum chamber in IR12 (upper beam pipe). The inner clearing solenoid can be seen.

The beam pipe in the LER is surrounded by electrical cables generating a solenoidal 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 is a long solenoid, covering the entire distance, plus six shorter solenoids, which increase the field locally. Each solenoid family generates a magnetic field of about 20 Gauss.

Since we performed measurements in different sessions from May 2006 to June 2007, we didn't have a permanent setup. Figure 3 shows the situation in our initial experiments. 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. For our latest measurements we added a Comitech PST solid state 5W amplifier. This amplifier is rated up to 2 GHz, but we verified it could still give a +30 dB amplification at 2.3 GHz.

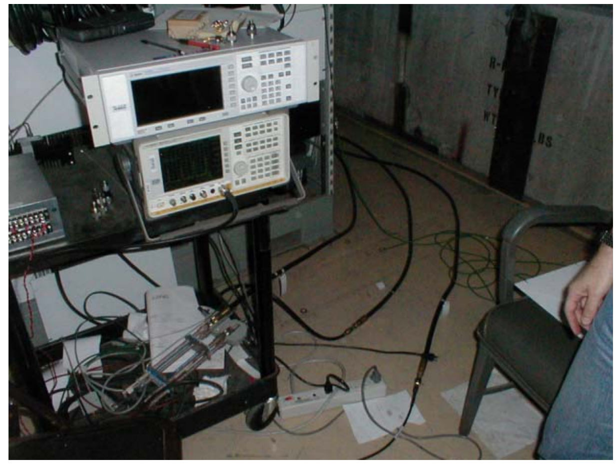

Figure 3: Instruments setup in the IR12 experimental hall. The RF cables from the BPM are visible on the floor.

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. All of these are rated for a maximum 1 W average input power.

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 2.1 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), as stated earlier.

EXPERIMENTAL RESULTS

Our first experiments in May 2006 were aimed at establishing a transmitted signal from one BPM to the other (we had seen learned at the ALS how this could present difficulties) and measure the signal attenuation in the band 2 to 3 GHz. One can see from Fig. 1 how one would like to be as close to the cut-off as possible in order to maximize the electron cloud effect. Of course, near the cut-ff the attenuation also increases, so that one has to find a compromise. We found that generally our signal was attenuated around 90 dB, with a marginally better transmission around 2.3 GHz. At that point, given the sensitivity of our spectrum analyzer and the signal generator maximum output power, the signal on the receiving end was only about 30 dB above the noise level, so that we couldn't hope to see the modulation sidebands. In April 2007, after adding a 5 W amplifier , we were able to improve the level of our received signal (or carrier) to 50+ dB above the noise floor. Figure 4 shows a picture of the spectrum analyzer screen: on the left, under the marker, one can see our carrier signal at 2.295 GHz. The other large signal in the center, also about 50 dB above noise, is a beam rotational harmonic. The marker to the right points to the upper modulation sideband 136 kHz above the carrier. This is more than 40 dB below the carrier level, but one has to keep in mind that the clearing solenoids were on, thus reducing the effective electron density.

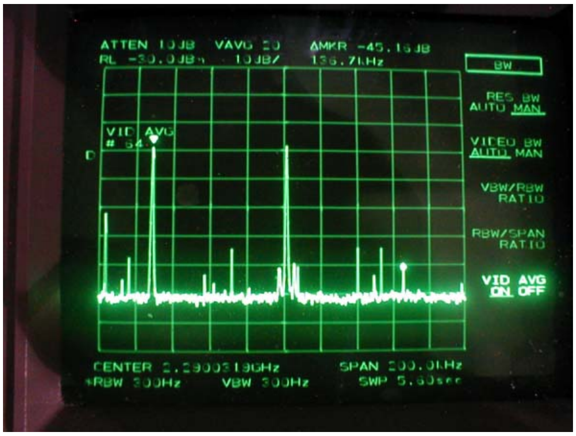

Figure 4: Carrier and upper modulation sideband at 2.295 GHz with a beam rotational harmonic.

Whenever the beam is lost, all the signals would disappear, except for the carrier.

It is worth mentioning that observing the signals while the LER is being filled, one cannot detect any modulation sidebands until the beam current reaches approximately 1.7 A.

We repeated the measurement after switching off all the solenoids between the two buttons. While we could simultaneously see all the vacuum gauges in the region registering a pressure increase, we could see the modulation sideband increasing its level as shown in Fig. 5.

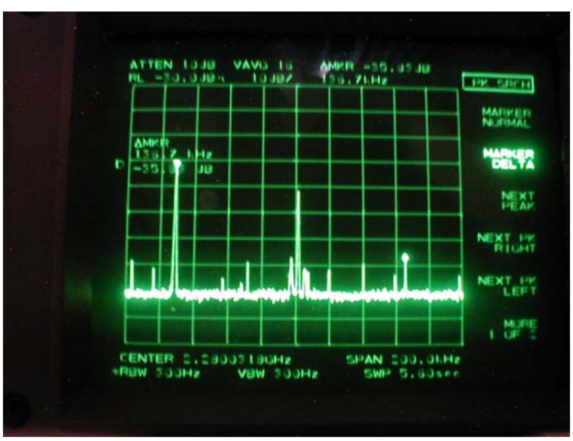

Figure 5: Received signals after clearing solenoids are switched off. Sideband level is increased ~8 dB.

We can see how the sideband relative level is increased up to –36 dB, which is reasonably close to the –33 dB theoretical estimate. The beam signal appears reduced by more than 10 dB because we switched the solenoids off rapidly, without correcting the orbit.

Since the total signal power was uncomfortably close to the maximum input for our spectrum analyzer, we repeated the measurements with a variety of attenuators on the output port. Figure 6 shows the same measurement as taken in Fig. 5, but with a –10 dB external attenuator on the spectrum analyzer input.

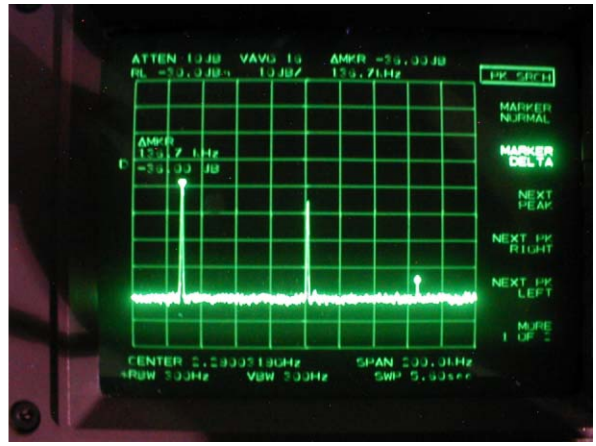

Figure 6: Received signals with a –10 dB external attenuator (solenoids off).

Figure 6 shows the measurement with the 10 dB attenuator. The sideband-to-carrier amplitude ratio is still –36 dB. One can notice how all the small amplitude signals present in Figs. 4–5 have disappeared. We measured an average power of about 11 dBm, well below the 30 dBm maximum input.

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 are planning further measurements to assess unequivocally the nature of the signal we have detected, with improved electronics and with different machine conditions.

ACKNOWLEDGEMENTS

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

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