

INTERACTIONS OF MICROWAVES AND ELECTRON CLOUDS

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Abstract

The modification of microwave signals passing through an electron cloud can be used as a diagnostic tool for detecting its presence and as a measure for its effective density. This observation method was demonstrated in pioneering measurements at the CERN SPS in 2003 with protons and at PEP-II in 2006 with positron beams in the particle accelerator field. Results and applications of this technique are discussed as well as limitations and possible difficulties. A strong enhancement of the electron related signals due to cyclotron resonance is theoretically predicted and has been observed in different machines. The application of this method can also be extended to space applications and to plasma physics where microwave diagnostics is known and used since many years. The dynamics of electron-cloud behavior in strong RF and microwave fields will be addressed. An electron cloud may also emit microwaves itself, either incoherently or coherently, and the intensity of this emission depends on external parameters such as the electrical bias field and resonator frequencies such as trapped modes resonances in a beam-pipe.

INTRODUCTION

Electron multiplication on surfaces exposed to an oscillating electromagnetic field gives rise to the phenomenon of multipacting, which can significantly degrade the performance not only of radio-frequency accelerating cavities but also of storage rings operating with closely spaced positron or proton bunches in particular. For the latter, the secondary electron emission, together with photo-emission or gas ionization, is known to result in a quasi-stationary ‘electron cloud’ inside the beam pipe, which can destructively interact with positively charged particle beams [1-4].

Relatively small amounts of electrons are always present in the vacuum chamber of an accelerator ring due to residual-gas ionization, due to desorption induced by beam particle losses, and possibly photo-emission from synchrotron radiation. The initially low electron population can quickly increase because of elastic reflection and secondary emission of the primary electrons at the chamber walls, or due to abundant production of photoelectrons. When this occurs, an electron cloud is formed in the beam pipe that can seriously affect the storage-ring operation [1-4]. Among the well-known and experimentally observed effects of the electron cloud are pressure rise in the vacuum chamber (CERN SPS [5], BNL RHIC [6]), interference with the beam diagnostics monitors (SPS [5], Los Alamos PSR [7]), coherent beam instabilities [2-5] (KEKB in Japan, CERN PS, CERN SPS), and incoherent particle losses [8] (SPS, RHIC, GSI SIS100). The heat load

deposited by the impinging electrons on the cold chamber wall is expected to be a further important issue for the LHC [2,9-10]. The instability caused by the electron cloud can severely limit the maximum intensity or the luminosity in colliding-beam storage rings due to the induced beam transverse blow up and particle losses. The two B-factories at Stanford (PEP-II) and in Japan (KEKB) were forced to implement various mitigation schemes, like coatings and weak solenoids, to reach and exceed their design performance [11-12].

RADIATION FROM ELECTRON CLOUDS

The properties of the electromagnetic radiation emitted from a non-neutral (electron) plasma provide information about the physical processes occurring in the plasma. The two most important radiation mechanisms are electron bremsstrahlung and cyclotron radiation [13]. The main features of these types of radiation may be calculated by means of classical radiation theory. A common procedure is to first calculate the radiation from a single particle. The radiation for the complete plasma is then obtained by averaging the radiated power over the velocity distribution of the electrons, normally assuming that each electron radiates incoherently with respect to all of the others. For the electron cloud in a storage ring, the possibility of a so-called ‘magnetron effect’ has been conjectured [14] where, under the influence of a beam-induced electromagnetic wake field and for certain values of the external dipole magnetic field, the cloud electrons would start to oscillate and radiate coherently, e.g. causing excessive heating of the liner and cold bore at a certain dipole field during acceleration. Some evidence for an interplay of beam-induced wake fields and electron-cloud build up has been found at PEP-II [15].

MICROWAVE TRANSMISSION MEASUREMENTS

Microwave transmission measurements represent a novel type of diagnostics in the particle accelerator field which is sensitive to the average electron density over a long section of a beam-pipe [16-18]. The underlying idea is that when electromagnetic waves are transmitted through not too dense electron plasmas, they experience a moderate phase shift plus, possibly, a very small attenuation. In 2002 it had been suggested to use this attenuation of an rf signal for measuring the electron-cloud density [19]. It should be noted that microwave plasma diagnostics is basically a very well known tool which has been applied since several decades e.g. in Tokamacs but there usually in the mm wave range due to the higher plasma densities. The phase shift expected for propagation through a uniform electron cloud of low density in free space, after a distance L , is

$$\Delta\phi = -1/2 \omega_p^2 / (\omega_{rf} c) L \quad (1)$$

where ω_{rf} denotes the angular microwave rf frequency and ω_p the plasma frequency, with r_e representing the classical electron radius and c the speed of light. Assuming a typical electron density of 10^{12} m^{-3} , at microwave frequencies between 2 and 3 GHz the expected phase shift over 1 km is of order -20° . In the ionosphere, where the maximum ion density is comparable to the usual electron cloud density in accelerators, the corresponding phase shift limits the accuracy of the Global Positioning System (GPS) [20]. Over 500 km of propagation through the ionosphere, the measured phase delay is of order 1 meter, or equivalently 4 degrees per km in the range of about 2 GHz. If the electrons are not in free space but inside a beam pipe (Figure 1) with a cutoff frequency ω_c the phase shift becomes (2) with $\omega_c =$ cutoff frequency of the waveguide mode considered [18,21].

$$\Delta\phi = -1/2 \omega_p^2 / (\sqrt{\omega_{rf}^2 - \omega_c^2} c) L \quad (2)$$

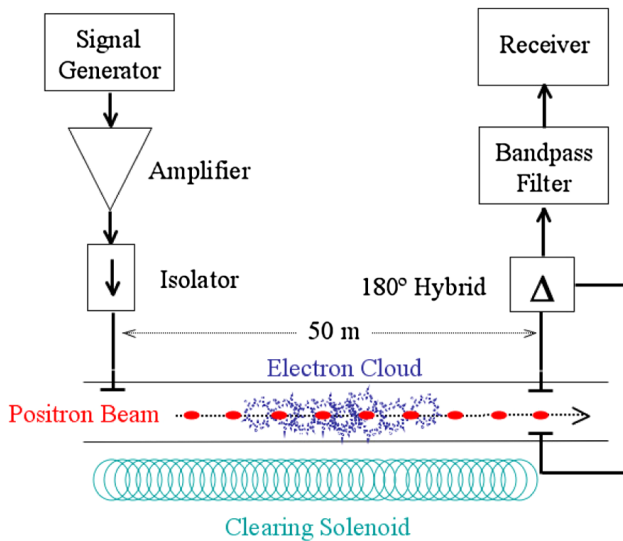


Figure 1: Setup of microwave transmission measurement at the PEP-II B Factory [17,18].

In the presence of a static magnetic field of strength B perpendicular to the beam pipe and to the propagation direction of the microwaves, an enhancement proportional to

$$1 / (1 - (eB / (\omega_{rf} m_e))^2) \quad (2)$$

is expected near the cyclotron resonance. Figure 1 sketches a microwave transmission measurement in the Low Energy positron Ring of the “PEP-II B Factory” at the Stanford Linear Accelerator Center [18]. In this ring, the electron-cloud build up is normally suppressed by a weak solenoid field of about 20 G generated by current-carrying wires wrapped around the beam pipe. If the

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solenoids are turned off, an electron cloud develops, which leads to a faint phase modulation of the transmitted signal that is evident by the appearance of sidebands, separated from the carrier frequency by multiples of the 136 kHz revolution frequency, as is illustrated in Fig. 2. The modulation signal appears since the electron cloud first builds up and then decays to zero in a long “clearing gap” without bunches, on each revolution period. The electron cloud density can be inferred from the amplitude of the sideband with respect to the carrier. Caution is advised to assure that for quantitative analysis only the phase modulation related signals are used and that any amplitude modulation contamination is rejected. Figure 3 shows evidence for a cyclotron resonance in similar measurements at another accelerator, CESR-TA [19]. A potential problem linked to cyclotron resonance related signal enhancement is exact quantification of the electron cloud density as one is operating in the vicinity of a pole. In addition at least partial orthogonality between the static magnetic field and the electric field of the waveguide mode travelling through the beam-pipe must be assured.

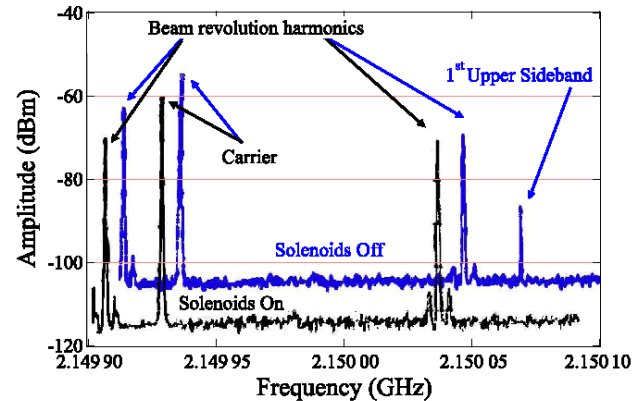


Figure 2: Spectrum analyzer traces showing microwave carrier and beam signals measured in the PEP-II Low Energy Ring over a distance of 50 m with a carrier at 2.15 GHz. A phase modulation sideband appears when the solenoid fields of 20 G covering the entire region is turned off, allowing the electron plasma to fill the beam pipe. Only the upper sideband is shown [18].

During a bunch passage the electrons are subjected to a strong transverse electric field. In a magnetic dipole field, the cyclotron frequency equals 28 GHz/Tesla multiplied with the field strength. With short positron bunches passing through a magnetic dipole field, resonances in the cloud build up have been seen when the bunch spacing equals a multiple of the cyclotron period [22], as first predicted in simulations [23]. In this context the question about measuring the microwave signals caused by the cyclotron motion can be raised. By contrast, at the LHC, the proton bunch length itself extends over many cyclotron periods, so that a sharp resonance between the cyclotron motion and the bunch spacing is not probable.

However for the LHC it has been shown that microwave transmission at cryogenic temperature over a full arc is possible in the frequency range around 7 GHz using coupling structures available at the end of each cold sector. Those coupling structures were originally installed for the in situ microwave reflectometer [24]. This transmission measurement would allow one to see the integral electron cloud over more than 2 km. In addition the variation of transmission loss as a function of the magnetic field and of the beam-screen temperature could be evaluated.

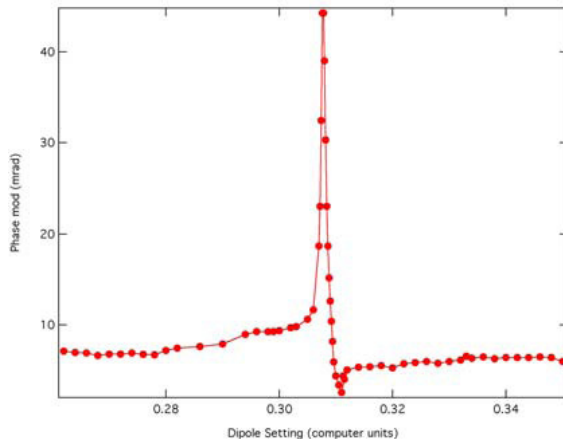


Figure 3: Microwave phase modulation amplitude measured over a length of 4 m in the CESR-TA accelerator with a carrier frequency of 2.015 GHz. The dipole setting at the peak of about 0.307 units corresponds to a field of 0.07 T and to a cyclotron resonance near 2 GHz [18].

However, another resonance effect is possible. If the geometry of the LHC beam pipe allows for some beam-excited trapped modes at suitable frequencies (indeed, due to the fabrication process there are minor mechanical undulations in the beam tube), at a certain value of the magnetic field, during the beam acceleration, one might encounter an accidental “magnetron effect” where the frequency of the trapped modes matches the cyclotron frequency of cloud electrons. This might give rise to a (local) coherent emission at the cyclotron frequency, which could occur at any value between 15GHz and 230 GHz depending on the B field. The 1-mm deep, 1.5-mm wide, and 8-mm long rectangular pumping slots (500 per meter) in the LHC beam pipe, at 5-20 K temperature, will only shield radiation up to about 15 GHz. At higher frequencies, any RF radiation can pass onto the cold bore of the magnets. The bunch potential would act as intermittent anode voltage of this device, similar to pulsed operation of a magnetron. The possibility of such magnetron effect in the LHC was first thought of when in early laboratory measurements using a resonant coaxial structure a substantial decrease of the multipactoring threshold was observed for an external dipole magnetic field (170 Gauss) such that the electron cyclotron frequency was equal to the resonant frequency of the coaxial cavity (480 MHz) [14]. The dip visible in Fig. 4

was caused by the resulting cavity impedance mismatch, related to the refraction index of the electron plasma, leading to a large reflected or absorbed signal.

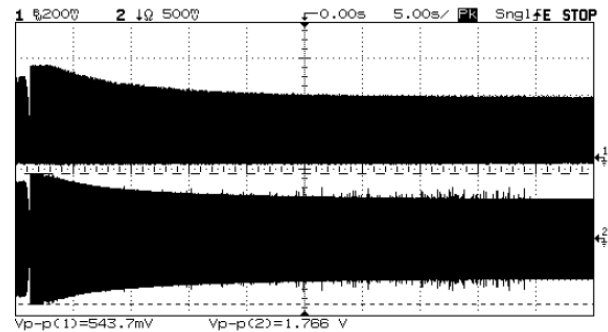


Figure 4: Multipactoring tests in a warm dipole magnet: deposited power (top, 2.5 W peak) and transmitted signal (bottom) measured during a 50 s ramp of the dipole field from 100 up to 7800 Gauss. The dip on the left corresponds to a magnetic field of 170 Gauss, when the cyclotron frequency of the electrons becomes equal to the RF frequency of 480 MHz. AM modulation frequency 20 Hz, DC-bias 100 V, RF forward power 4 W [14].

DYNAMICS OF ELECTRON CLOUD IN STRONG RF AND MICROWAVE FIELDS

It has long been known that microwaves by themselves can give rise to multipacting and electron-cloud generation, e.g. in RF wave guides or RF cavities. A microwave resonator has been developed to reproduce, in the laboratory, a situation similar to the one expected with beam in the LHC [25]. For high-power microwave devices in satellites, multi-carrier operation leads to multipacting phenomena which closely resemble the beam-induced multipacting of the LHC [26]. The combination of beam and microwaves can give rise to more complicated dynamics, for which investigations are only just beginning.

More than 20 years ago, at the CERN ISR the electron cloud was suppressed by installing electrostatic clearing electrodes over more than 95% of the circumference[1]. A dedicated rf field with optimized parameters might have a similar effect. Indeed the use of ac clearing fields (at that time in the MHz range, well below the pipe cutoff frequency) was already proposed for electron-clearing in the ISR by W. Schnell. This idea (but now using microwaves above cutoff) was revived by A. Chao more recently [27]. So far we are not aware of any clear evidence that this suggestion has been verified either in experiments or simulations.

We know of only two experimental indications that RF fields or microwaves can affect the beam-induced electron-cloud build up. In the 1990s some peculiar observations with a horizontal collimator and adjacent BPM in LEP have pointed to a possible interference of wake fields and photo-electron motion [28]. Later, following the E-CLOUD02 workshop, a non-invasive,

more direct exploratory test of the influence of microwaves on electron-cloud behavior was performed at the SLAC PEP-II Factory [15]. The underlying idea of the experiment was that waveguide modes in the vacuum chamber can be excited by mode converters like the movable collimators.

In addition to their possible effect on the build up of electrons, RF fields or microwaves could perturb the electron coherence, thereby weakening the effect of the electron cloud on the beam. Such schemes would work equally for proton or positron storage rings which are afflicted by the electron cloud. However we must remember that in an operating accelerator the beam-pipe is anyway full of RF fields and for lepton machines or hadron machines at very high energy also full of light. A possible interaction of the electron cloud with the synchrotron light was examined for LHC [29].

The absorption of externally added microwaves by the vacuum chamber will generate additional heat load (a concern for the LHC). A trade off must then be made between this added heat and the expected reduction of the energy deposited by the electron cloud, also taking into account the consequences for beam instabilities. In any case, before seriously considering injecting additional microwave power into the beampipe clear and striking evidence for the benefit of such a modification is required. For the moment we have only faint indications.

EARLY SIMULATION OF ELECTRON-MICROWAVE INTERACTION

Various simulation programs are available to model either the electron multipacting under the influence of microwaves, such as FEST3D, or the beam-induced multipacting in accelerators, such as PEI, POSINST, and ECLOUD.

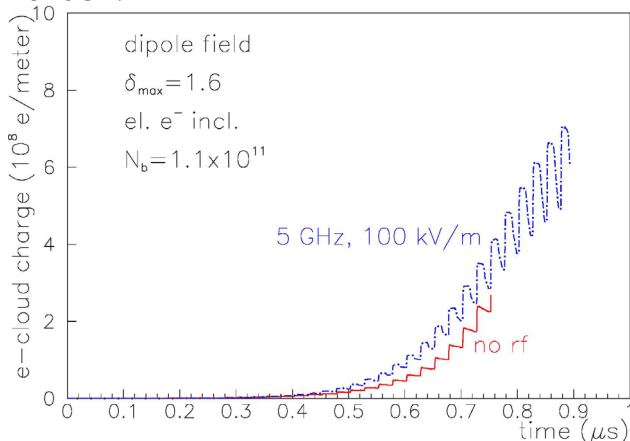


Figure 5: Simulation of electron-cloud build up in an LHC dipole chamber with 2-cm radius with and without an additional 5-GHz *H*-mode microwave of amplitude 100 kV/m (from [15]).

In 2002 a first, rough attempt was made to model the combined effect by adding an RF microwave to the ECLLOUD code [15]. A crude estimate suggested that the electron motion could only slightly be perturbed by

microwaves, e.g. for a field amplitude of 100 kV/m at 5 GHz, the electrons are accelerated to 4×10^5 m/s, which corresponds to a kinetic energy of only 0.44 eV, and to an excursion of +/- 18 μm. Nevertheless we simulated the effect of an H_{11} -wave for LHC proton-beam parameters at injection, assuming a maximum secondary emission yield $\delta_{max}=1.6$, and including elastic electron reflection on the chamber wall. According to the simulation, the RF field could significantly increase the multipacting, as is illustrated in Fig. 5. This feature could be exploited for in-situ surface conditioning to lower the secondary emission yield (with or without beam, and possibly in combination with a gas discharge; however the discussion of microwave gas discharges in the beam-pipe, often applied for sputtering, is beyond the scope of this paper.) More recently the VORPAL code is being used to study certain aspects of electron-cloud microwave interaction [30].

THE MAGNETRON EFFECT

Another physical mechanism not yet included in state-of-the-art electron-cloud simulations is the possible ‘magnetron effect’ (already mentioned above) associated with the electron cyclotron motion in the magnetic field of the bending magnets in the machine. The essential ingredients of a magnetron are a source of electrons, a resonating structure (trapped mode) and some accelerating voltage (beam potential). In order to visualize the similarity between e.g. the LHC beam vacuum chamber and beam screen the simplified drawing of a coaxial magnetron is depicted in Fig 6.

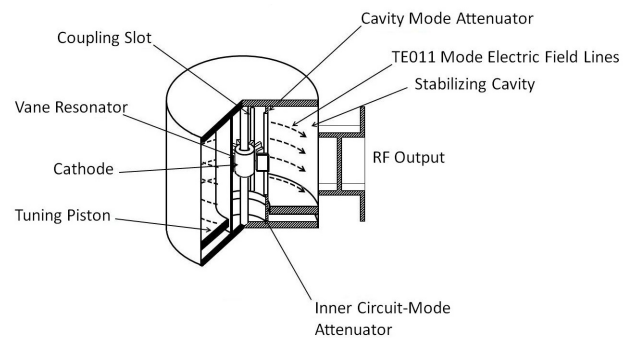


Figure 6: Simplified drawing of a coaxial magnetron [32].

We recognize an analogy between the coupling slots in this structure and the slots in the LHC beam-screen. Obviously, for the LHC case the anode and cathode would be inverted since the electrons come via photoeffect or secondary emission from the inner surface of the beam-screen. A more important difference is the direction of the DC magnetic field which would not be axial in the LHC. However, even in the LHC case we still have ‘cross field’ regions where the direction of the (pulsed - since coming from the beam potential) electric field is orthogonal to the magnetic field. In the frame of rf systems development for kaon factories a magnetron type varactor had been proposed [33] as a tuner for accelerating cavities in synchrotron rings. Such kind of

varactor could be considered a fast capacitive tuning elements over a relatively small tuning range where emphasis is given to the tuning speed. A schematic sketch of the varactor is presented in Fig. 7.

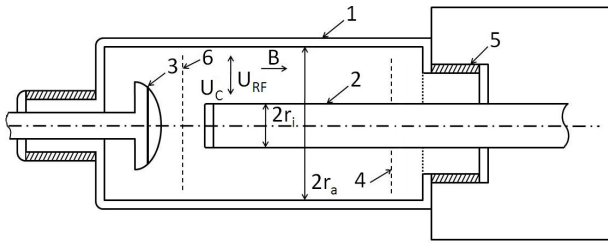


Figure 7: Schematic sketch of the varactor [33]: 1 - outer conductor, 2 - inner conductor, 3 - cathode, 4 - reflector, 5 - insulator, 6 - control grid [33].

This device is essentially a kind of magnetron operated sufficiently below oscillation threshold. Electrons emitted from the cathode form an electron cloud and, due to operation at the cyclotron resonance, the electron scattering cross-section is strongly enhanced compared to the case when operating way from the cyclotron resonance (c.f. Fig. 3). Thus by controlling density, size and position of this electron cloud, essentially via the control grid and reflector potential of the device, a variable capacitor is implemented. The advantage of this solution is a very fast tuning speed as compared to ferrite tuners for RF cavities. A disadvantage is the rather low stored energy which determines the tuning range.

For LHC, the key question is: can the electron cloud meet the coherent oscillation condition, or does it always stay in the incoherent ‘varactor’ regime?

CONCLUSIONS

The interaction of microwaves with electron cloud in a particle accelerator has gained considerable attention over the last few years [16-18,31,34]. The microwave transmission method has proven a useful diagnostics application for electron-cloud density measurement. This technique is already applied in several accelerators and is under construction in others. Strong RF of microwaves fields in the beam pipe may affect the electron-cloud dynamics, but experimental evidence is still scarce, and for the moment related practical applications are not in sight. An important aspect concerns accidentally coherent microwave electron cloud interaction, where the electron cloud would enter a state of coherent emission as in a normal magnetron.

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