EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 2002-037 (RF)

IMPACT OF MICROWAVES ON THE ELECTRON CLOUD AND INCOHERENT EFFECTS

F-J Decker, SLAC, Stanford, USA
F. Caspers, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

We consider the use of microwaves for manipulating the electron cloud, describing an exploratory experiment at PEP-II as well as computer simulations of the electron cloud build-up in the presence of a microwave for an LHC dipole. We then show that the incoherent effects of the electron cloud - energy loss and transverse emittance growth due to scattering of the electrons - are negligible. This suggests that the disturbance of the coherent electron motion may be another possible application of microwaves, which could prevent beam emittance growth and beam loss.

ECLOUD'02 Workshop, April 15-18, 2002, CERN, Geneva

Geneva, Switzerland
25 June 2002

Impact of Microwaves on the Electron Cloud and Incoherent Effects

F.-J. Decker, SLAC, Stanford, USA; F. Caspers, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

We consider the use of microwaves for manipulating the electron cloud, describing an exploratory experiment at PEP-II as well as computer simulations of the electron cloud build up in the presence of a microwave for an LHC dipole. We then show that the incoherent effects of the electron cloud — energy loss and transverse emittance growth due to scattering off the electrons — are negligible. This suggests that the disturbance of the coherent electron motion may be another possible application of microwaves, which could prevent beam emittance growth and beam loss.

1 INTRODUCTION

More than 20 years ago the electron cloud was suppressed in the CERN ISR by installing clearing electrodes over 95% of the circumference. An rf field 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 more recently [1].

An rf field could either suppress the electron cloud build up or enhance the surface conditioning. The attenuation of an rf signal could also be used for measuring the density of the cloud [2]. In addition, 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.

The absorption of 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 reduction of the energy deposited by the electron cloud, also taking into account the consequences for beam instabilities.

Compared with conventional clearing electrodes a clear advantage of the approach using microwaves is that the latter can be fed into the beam pipe using existing BPM buttons, or a few special input couplers, spaced at distances of about 100 m. This allows for retrofitting an existing accelerator, and does not at all, or only marginally, affect the impedance budget. On the other hand, dc clearing electrodes, requiring a much narrower spacing on the cm length scale, require extensive additional installations and may represent a significant source of impedance.

A possible choice of rf field mode is a "waveguide" mode, which should not disturb the beam, but might perturb the electrons forming the cloud. In principle, the injection of an rf wave requires an input coupler (maybe BPM button), an rf power source of 10-100 W (possibly more), variable in frequency, phase, maybe chirp, etc.

The waveguide mode chosen could be an H-wave (TE mode) or a E-wave (TM mode). These modes couple either not at all, or only weakly, with the particle beam moving at the speed of light, but strongly with the 'static' electron cloud.

2 EXPERIMENT AT PEP-II

A non-invasive exploratory test was performed at PEP-II. The underlying idea of the experiment was that waveguide modes in the vacuum chamber can be excited by mode converters like the movable collimators. So, the two collimator pairs in PR02 might already be doing this, *i.e.*, they may give rise to trapped rf modes at a certain power level (in this respect it would be interesting to check the bellows temperature in that region). Both H and E-type trapped modes are characterized by a small R/Q and a high Q value. The H mode does not couple to the beam. Also E-modes which resonate over a long distance show virtually no interaction with the beam; indeed their coupling to the beam is zero in the limit of an infinitely long distance.

An electron cloud detector, like the vacuum pump reading, should be able to detect any change in the electron flow. (In the worst case if there is no detectable electron cloud and therefore no reading in the nominal condition, one might have to switch off the electron-cloud suppressing solenoid in the region of interest, which would make the experiment more invasive.)

The experimental procedure was as follows: We moved the collimator jaws inwards or outwards (preferentially those jaws which do not contribute much to background reduction) and watched for *any* change in the pump current in that region. Since the pumps are shielded, they should not be sensitive to changes in the rf fields. The rf signal can only influence the amount of electrons penetrating through the shielding.

Following this procedure, on May 16, 2002, during normal colliding-beam operation the collimators in the PEP-II LER in PR02 (in front of the detector) were moved inwards by about 3 mm, to see if the generated wakefield has an effect on the electron cloud detected by the pump currents in this area. The horizontal collimators are located at positions 3077/3076 and 3044/3043. The pump current readings were observed at VP3044 (single), VP3054 (duplett with 3065) and VP3075 (duplett with 3081); see the diagram of the LER interaction region (IR) in Fig. 1. The base pressure without beam is about 1 ntorr or below. With beam the pressure readings increased to 42, 140, and 4 ntorr for the different pumps. So, the first two pumps recorded a strong electron current from the cloud while the last one might only have detected the real vacuum pressure.

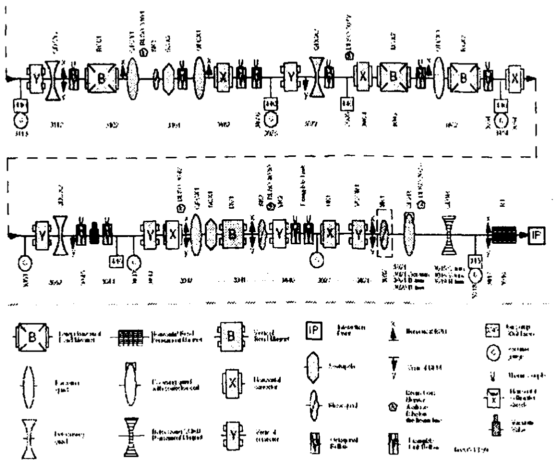

Figure 1: Schematic of PEP-II LER IR.

The observation was only about a 0.5 ntorr effect. The pressure-reading change was especially pronounced in VP3075 (see Fig. 2). At a time of about 1200–1400 s the first collimator jaw was moved inwards (observing backgrounds, lifetime, loss rate), then the second between 1500–1700 s, the third between 1900–2000 s, the last between 2150 and 2300 s. All collimator jaws got restored at once to their original settings at 2500 s. VP3044 sees a little of that restore (Fig. 3), while at 3054 there is no signal (Fig. 4).

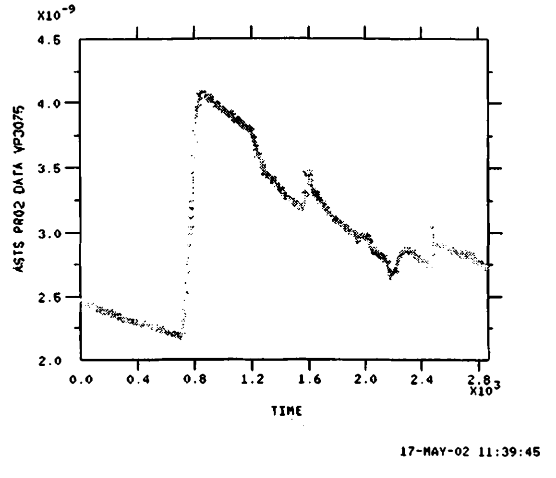

Figure 2: Pump reading VP3075 as a function of time.

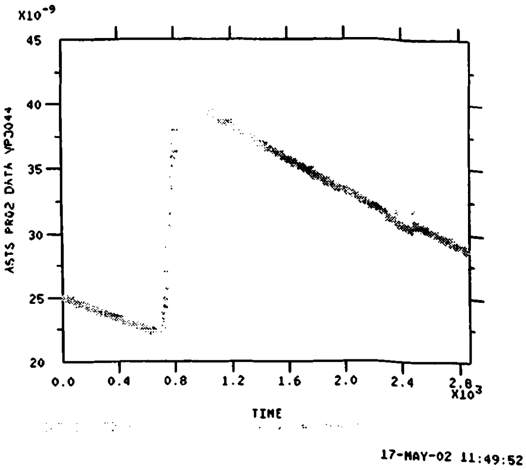

Figure 3: Pump reading VP3044 as a function of time.

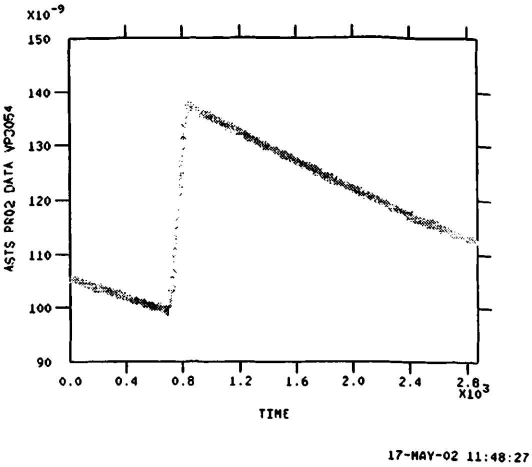

Figure 4: Pump reading VP3054 as a function of time.

The observed effect is small, presumably since the PEP-II collimators are designed with a taper such that they exhibit a smooth slope up and down between the regular beam pipe and the smallest gap, which effectively suppresses the wakefield generation. Nevertheless, we observe about a 0.5-1% change and the vacuum reading is actually reduced, which is the opposite of what is expected due to additional outgassing. We may need to optimize the frequency of the wake field to obtain a clearer effect.

Regardless, this measurement constitutes a first proof of principle that wake fields (microwaves) can influence the electron cloud.

3 SIMULATION FOR THE LHC

At first glance, it appears that the electron motion can only slightly be perturbed by microwaves [1], *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.

As an example, we have simulated the effect of an H_{11}-wave for LHC proton-beam parameters at injection: $N_b = 1.1 \times 10^{11}$ protons per bunch, $\sigma_x = 1.2$ mm, $\sigma_y = 1.2$ mm, $\sigma_z = 13$ cm, $\delta_{\max} = 1.6$, $\epsilon_{\max} = 300$, and $d\lambda_e/ds = 2.5 \times 10^{-7}$ m^{-1}s^{-1}, the creation rate of primary electrons per passing proton; elastic electron reflection on the chamber wall was included. According to the simulation, the rf field strongly increases the multipacting, as is illustrated in Fig. 5. This could be exploited for in-situ surface conditioning (with or without beam, possibly in combination with a gas discharge).

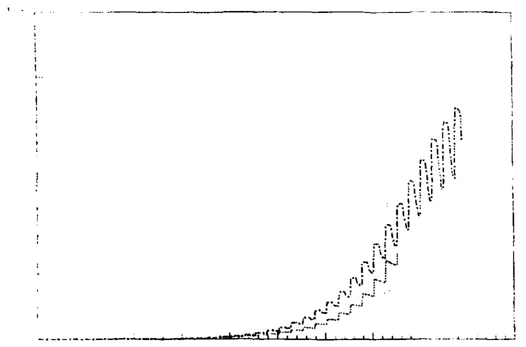

Figure 5: Simulation of electron-cloud build up in an LHC dipole chamber with 2-cm radius with and without an additional 5-GHz H-mode microwave of amplitude 100 kV/m.

In the simulation, the fields for the H_{11}-wave inside a dipole magnet were parametrized as

$$\begin{aligned}
E_x &= A_0(J_1(u) - uJ_1'(u))xy/r^3 && (1)\\
E_y &= A_0(J_1(u)y^2 + uJ_1'(u)x^2)/r^3 && (2)\\
E_z &= 0 && (3)\\
B_x &= (A_0/Z_f)\,\mu_0(uJ_1'(u)x^2 + J_1(u)y^2)/r^3 && (4)\\
B_y &= B + (A_0/Z_f)\,\mu_0(uJ_1'(u) - J_1(u))xy/r^3 && (5)\\
B_z &= (A_z/Z_f)\mu_0 u^2 \lambda_h/(2\pi)J_1(u)y/r^3\,, && (6)
\end{aligned}$$

where $A = E_y 4b/3.7$, $\omega_w = 2\pi f_0$, $\lambda_0 = 2\pi c/\omega_w$, $\lambda_{11} = 1.71 \times 2b$, $\mu_0 = 4\,pi 10^{-7}$ N sA^{-2}, $Z_0 = 377\ \Omega$, $Z_f = Z_0/\sqrt{1-(\lambda_0/\lambda_{11})^2}$, $\lambda_h = \lambda_0/\sqrt{1-(\lambda_0/\lambda_{11})^2}$ $\beta_0 = 2\pi/\lambda_h$, $r = \sqrt{x^2+y^2}$, $u = r3.7/(2b)$, $A_0 = A\cos(\beta_0 z - \omega_w t)$, and $A_z = A\sin(\beta_0 z - \omega_w t)$, $b = 2$ cm the chamber radius, and $B = 0.5$ T the static dipole field. Note that for $b = 2$ cm, the cutoff frequency of the beam pipe is $f_c = c/\lambda_c = c/(3.412b) \approx 4.4$ GHz.

4 INCOHERENT EFFECTS OF THE ELECTRON CLOUD

In this section, we digress from the microwaves, and study whether incoherent effects of the electron cloud may be important. We consider the example of the proton beam in the LHC. However, the formulae equally apply to a positron beam.

Specifically, we compute the average energy loss and the increase in the transverse proton-beam emittance due to scattering off the electron cloud. For the cross sections and integration limits, we mainly use expressions found in Chapter 13 of Ref. [3] or slight modifications thereof.

4.1 Energy Loss

The cross section per unit energy interval for energy loss T follows from the Rutherford formula. It is

$$\frac{d\sigma}{dT} = \frac{2\pi Z^2 mc^2 r_e^2}{\beta^2 T^2}\,. \qquad (7)$$

To compute the total cross section, we integrate this expression from $T_{\min}$ to $T_{\max}$.

Maximum momentum transfer occurs if the electron reverses its direction. This corresponds to the classical limit

$$T_{\max,\text{class}} = \frac{2\gamma^2\beta^2 mc^2}{1 + 2mE/(M^2c^2) + m^2/M^2} \approx 2\gamma^2\beta^2 mc^2 \qquad (8)$$

where m is the electron mass, M the mass of the beam particle, Ze the charge of the beam particle ($Z = 1$ for protons, but the equations also remain valid for heavy ions), and E the beam energy. The above approximation is usually justified except possibly for the LHC at top energy.

There is also a quantum-mechanical limit, given by

$$T_{\max,\text{quant}} = \eta^2 T_{\max,\text{class}} \qquad (9)$$

where

$$\eta = \frac{Zr_e mc^2}{\hbar\beta c}\,. \qquad (10)$$

The smaller of the two values (8) and (9) applies. For $\beta \approx 1$, and $Z = 1$ one has $\eta \approx 0.007$ and we should use the quantum limit.

Concerning the minimum energy transfer, we note that the maximum impact parameter is equal to the radius of the vacuum chamber, a, and from this we obtain the classical and quantum limits

$$T_{\min,\text{class}} = \frac{2Z^2 r_e^2 mc^2}{\beta^2}\frac{1}{a^2} \qquad (11)$$

and

$$T_{\min,\text{quant}} = \frac{2Z^2 r_e^2 mc^2}{\beta^2}\frac{1}{a^2}\frac{1}{\eta^2}\,. \qquad (12)$$

In this case, the larger of the two limits (11) and (12) should be taken, which again is the quantum expression.

The total energy loss per revolution is $\Delta E = C\rho_e \int (d\sigma/dT)T\,dT$, or

$$\Delta E = \rho_e C \frac{2\pi Z^2 r_e^2 mc^2}{\beta^2} \ln\frac{T_{\max}}{T_{\min}}\,. \qquad (13)$$

Assuming a typical electron cloud density $\rho_e = 10^{12}$ m^{-3}, $C \approx 27$ km, $E = 7$ TeV, and $a \approx 2$ cm, we find

$\Delta E \approx 86\ \mu$eV per proton and turn. This appears negligible.

For completeness we note that the total scattering cross section $\sigma_{\rm tot} = \int (d\sigma/dT) dT$ is

$$\sigma_{\rm tot} = \frac{2\pi Z^2 r_e^2 m c^2}{\beta^2} \left(\frac{1}{T_{\rm min}} - \frac{1}{T_{\rm max}} \right) . \qquad (14)$$

Thus the total number of scattering events per proton and per turn is

$$n_{\rm scatt} = \sigma_{\rm tot} \rho_e C \ , \qquad (15)$$

which in our example amounts to about 2×10^9.

4.2 Emittance Growth

For a single scattering event, the mean square scattering angle of an electron in the rest frame of the proton is

$$< \theta^2 > = \theta_{\rm min}^2 \ln \frac{T_{\rm max}}{T_{\rm min}} \ , \qquad (16)$$

where $\theta_{\rm min}$ equals

$$\theta_{\rm min,class} = \frac{Z r_e}{\gamma a} \qquad (17)$$

or

$$\theta_{\rm min,quant} = \frac{Z r_e}{\gamma a \eta} \ , \qquad (18)$$

whichever is larger. The scattering angle of the proton is smaller by a factor m/M (the ratio of electron and proton mass). The emittance growth per turn is

$$\frac{\Delta \epsilon}{\Delta t} = c \beta \rho_e \sigma_{\rm tot} \frac{m^2}{M^2} \theta_{\rm min}^2 \ln \frac{T_{\rm max}}{T_{\rm min}} \ . \qquad (19)$$

Here, β denotes the average beta function.

This amounts to a minuscule growth rate for the normalized transverse emittance ($\epsilon_N = \gamma \epsilon$) of $d\epsilon_N/dt \approx 3 \times 10^{-30}$ m/s.

5 CONCLUSIONS

We have discussed the possibility to use rf microwaves for suppressing the build up of the electron cloud and for reducing its detrimental effects on the beam. The microwave approach offers a number of significant advantages compared with dc clearing electrodes, in particular the retrofitting potential and an insignificant change of the accelerator impedance.

A first experimental test at PEP-II indicates that the elecron cloud can indeed be affected by collimator wake fields or, more generally, microwaves. Earlier peculiar observations with a horizontal collimator and adjacent BPM in LEP have pointed to a similar interference of wake fields and photo-electron motion [4].

In the PEP-II experiment the excited frequency lines were related to the beam harmonics. In future dedicated applications of microwaves this does not need to be the case. In fact, with external excitation it will be safer to choose rf frequencies which do not coincide with harmonic frequencies of the beam, in order to preclude any harmful interaction via E-waves. It might also be interesting to modulate the rf amplitude, frequency, and phase, as well as a simultaneously excitate waves at multiple frequencies.

In electron-cloud simulations for the LHC the inclusion of an rf H-wave above the chamber cutoff frequency enhances the electron cloud build up for all frequencies and field strengths explored. This indicates that microwaves might enhance the surface conditioning.

Another aspect considered is the interaction of the electron cloud with the particle beam. Incoherent scattering off the cloud electrons is estimated to be a negligible effect. This suggests that disturbing the coherent motion of the electrons may prove an efficient means of preventing beam quality degradation. Microwaves sent through the vacuum chamber could as well serve this purpose.

6 REFERENCES

[1] A. Chao, private communication, KEK MBI workshop (1997); F. Caspers, proposal at ECLOUD'02 (2002).

[2] S. Heifets, private communication at ECLOUD'02 (2002).

[3] J.D. Jackson, "Classical Electrodynamics," Third Edition, John Wiley (1999).

[4] G. Vismara, "The QD20 Phenomenon," CERN BI Day 1998.