BEAM INDUCED MULTIPACTING

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Abstract

Beam induced multipacting driven by the electric field of successive bunches, as first observed in the ISR proton-proton storage ring [1] may arise from a resonance motion of a cloud of secondary electrons bouncing back and forth between opposite walls of the vacuum chamber. Under conditions where the average secondary electron yield of this process exceeds unity, the electron cloud may increase exponentially. A consequence for the vacuum system is strong electron stimulated gas desorption and the associated pressure increase which may affect the beam lifetime. A simple criterion for the onset of multipacting and an estimate of the average secondary electron yield is derived and will be applied to typical vacuum chambers and to the specific conditions found in the LHC.

1 INTRODUCTION

Electrons from ionisation of the residual gas which are accelerated by the electric field of the successive proton bunches and which can build up to a cloud of electrons due to the generation of secondary electrons at the vacuum chamber, have first been observed at the ISR [1]. The most striking detrimental effect for the operation of the machine has been the very fast pressure rise due to electron stimulated gas desorption from the wall of the vacuum chamber. The particular condition under which this electron multipacting effect was observed involved a beam pipe made of aluminium alloy instead of the conventional stainless steel used elsewhere in the machine. Due to its much larger secondary electron coefficient (seec) as compared to stainless steel, the Al_2O_3 surface exhibited - under specific beam conditions - a strong multipacting effect. In LHC, the dominant source of electrons will be photo-electrons from synchrotron radiation. The effects of an electron cloud on the stability of the beam has been studied recently [2].

2 MODEL

A set of basic equations can be derived which applies to locations in the machine without magnetic field. The electric field of a circular beam in a concentric, circular beam pipe can be expressed as

$E(r) = \dfrac{\lambda}{2\pi \varepsilon_O r}$ where λ is the line charge of the bunch

$\lambda = \dfrac{e N_b}{c \tau}$ with τ the bunch duration, N_b the particles per bunch, c the velocity of light and e the electron charge. The momentum transfer by one bunch to a stationary electron at a radial position r, is

$$\Delta p = e E(r) \tau = \frac{e^2 N_b}{2\pi \varepsilon_O c r}$$

and hence independent of the bunch length. From this follows the velocity increment

$$\Delta v = \frac{\Delta p}{m} = \frac{e^2 N_b}{2\pi \varepsilon_O m c r} = 2 c r_e \frac{N_b}{r}$$

introducing the classical electron radius r_e. The electrons must cross the vacuum pipe, with radius r_p, in synchronism with the bunches to be able to multipactor. This condition requires that the transit time must be less than or equal to the time between successive bunches $\dfrac{2 r_p}{\Delta v} \leq t_{bb}$. Introducing the bunch distance $L_{bb} = c\ t_{bb}$ the wall-to-wall transit time condition, determining the threshold beam intensity becomes

$$N_b = \frac{r_p^2}{r_e L_{bb}}.$$

A further, necessary condition to be met is that the energy of the electrons when they hit the vacuum chamber wall is sufficiently large to produce, on average, more then 1 secondary electron. This energy, corresponding to the kick by a bunch, can be obtained from

$$\Delta W = \frac{\Delta p^2}{2 m} = 2 \frac{m c^2}{e} r_e^2 \left(\frac{N_b}{r}\right)^2 (eV)$$

Compared with this simple, stationary electron model, more realistic results can be obtained by introducing the following two generalisations:

i) the radial distribution of the beam charge is assumed gaussian, with the parameter r_b, thus giving

$$E(r) = \frac{\lambda}{2\pi \varepsilon_O} \frac{1 - e^{-\left(r/r_b\right)^2}}{r}$$

ii) the electrons are not stationary but move during the passage of the bunch. This requires the integration of the equation of motion $m \ddot{r} = e E(r)$ from which the velocity $\dot{r}(\tau)$ after the passage of the bunch can be computed. The corresponding energy is

$$\Delta W = \frac{m\ \dot{r}(\tau)^2}{2}.$$

In a strong magnetic field, the net momentum transfer will be confined along the field lines. For a concentric, circular geometry, it can be shown that the transit time condition is unchanged [3].

3 APPLICATION TO THE LHC

Typical parameters for the LHC are [4]:
$N_b = 1 \; 10^{11}$ p/bunch, $\tau = 0.25$ ns, $t_{bb} = 25$ ns or $L_{bb} = 7.5$ m. The beam radius in the arcs is typically 1.1 mm and the vacuum chamber (the beam screen) radius is 22 mm. In LHC, the threshold for multipacting corresponds to an intensity of only $2.3 \; 10^{10}$ p/bunch and at the nominal intensity the transit time condition for wall-to-wall multipacting is met for vacuum chamber radii less than 47 mm.

A comparison between the energy gain of a stationary (dotted curve) and of a moving electron for the nominal bunch length of 0.25 ns as well as for 0.1 and 0.5 ns is shown in Figure 1 where it can be seen that apart from the central region, close to the beam, the approximation for a stationary electron is quite satisfactory. In the LHC an electron created at the wall receives an energy of about 190 eV and electrons which have drifted closer to the beam may gain several keV up to a maximum of about 13 keV.
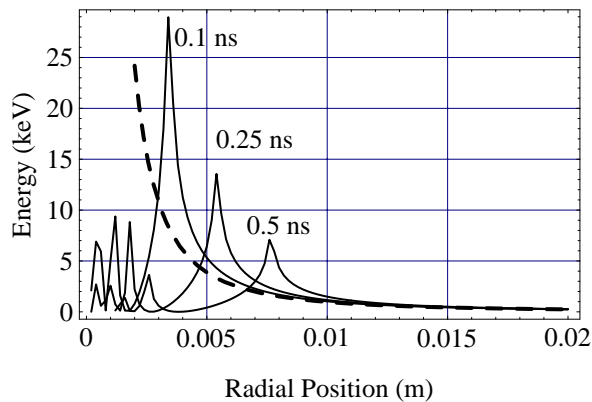

Figure: 1 Electron energy after the passage of a bunch in LHC versus the initial radial position for 0.1, 0.25 and 0.5 ns bunch length. The dotted curve is calculated for the stationary electron approximation.

The secondary electron coefficient (seec) as a function of incident electron energy and for different materials and surface treatments applicable to typical vacuum chambers has been studied extensively by N. Hilleret and co-workers [4]. Figure 2 shows data for technical surfaces at perpendicular electron incidence for aluminium (Al_2O_3), copper plated stainless steel (LHC beam screen), stainless steel and titanium. The important result of these measurements is that, apart from Ti, a seec of unity is exceeded at energies well below the energy range in the LHC and that the seec remains above unity up to many keV. Therefore, the basic conditions for the multiplication of the secondary electron cloud are met.
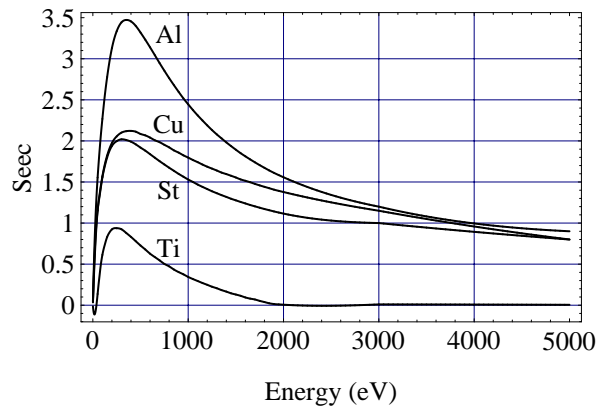

Figure: 2 Secondary electron yield (seec) as a function of primary electron energy for perpendicular incidence and for technical surfaces representative for vacuum chambers (provided by N. Hilleret, extrapolated for energies >2 keV)

Combining the energy dependence on the radial position and the dependence of the seec on incident electron energy gives the secondary electron coefficient as a function of the radial position in the vacuum chamber shown in Figure 3.
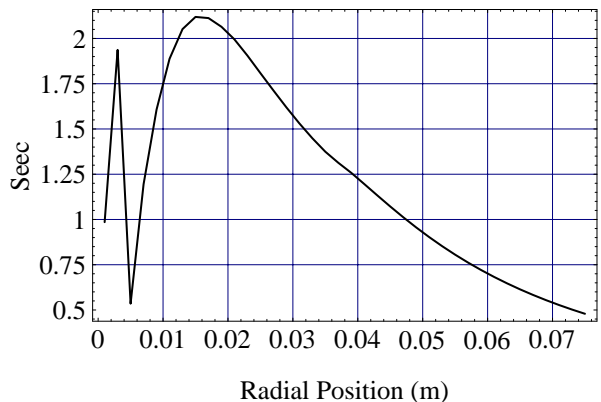

Figure: 3 Seec versus radial position for nominal LHC parameters and for copper plated stainless steel.

Whether an electron cloud remains limited or will grow exponentially, depends on the secondary electron coefficient averaged over the cloud <seec>. To compute this average the following simplifying assumptions have been made :
i) electrons which are kicked by the bunch must meet the transit time condition, i.e. they must reach the opposite side of the vacuum chamber before the next bunch arrives.
ii) secondary electrons drift with a given energy (e.g. 5 eV) and are lost when they reach the opposite wall before the next bunch arrives.
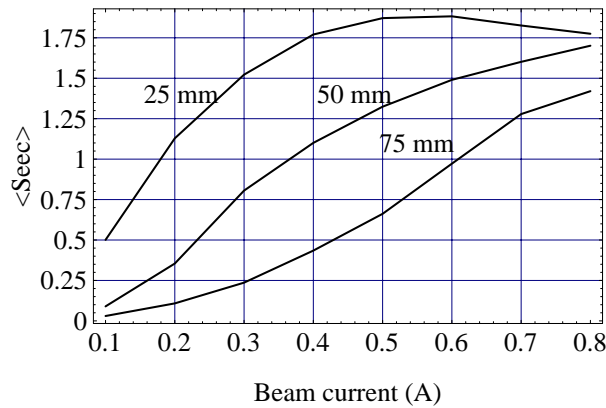iii) under steady state conditions, the electron cloud is uniformly distributed over the vacuum chamber aperture.

Figure: 4 < seec> versus beam current for different beam pipe dimensions and for copper plated stainless steel.

From Figure 4 it can be seen that the average yield of unity can be exceeded at beam currents below the nominal value in LHC for small beam pipes. The validity of the assumptions in this model has been cross-checked with results from the ISR. From this comparison one may conclude that the multipacting threshold corresponds to a computed <seec> of 1.3 rather than unity. Figure 5 illustartes the importance to use a vacuum chamber material with a low secondary electron coefficient.
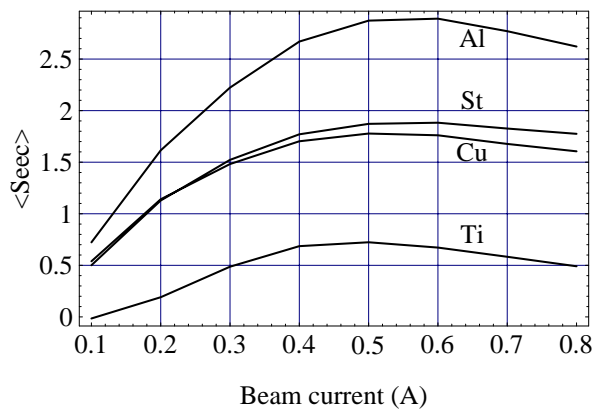

Figure: 5   <seec> for different materials versus beam current for a 25 mm beam pipe

4. HEAT LOAD DUE TO PHOTO-ELECTRONS

For LHC where the dominant source of electrons are photo-electrons from synchrotron radiation, an additional aspect is the power dissipated on the beam screen and thus the heat load to the cryogenic system which results from the energy transfer to the electron cloud. The average energy transfer to the uniformly distributed electron cloud by a single bunch passage can be calculated from Figure 1 as 700 eV. The photo-yield as a function of the critical photon energy has been measured with a copper plated test chamber in the EPA synchrotron radiation beam line at CERN [5]. When these data are converted to LHC conditions one finds that up to 4 TeV the photo-yield is negligible but it increases to 0.02 at 7 TeV. The specific linear photon flux as a function of the beam current I(A)

and beam energy E(GeV) is $2.65.10^{13}$ I E photons/s/m. The production of photo-electrons is shown in Figure 6.
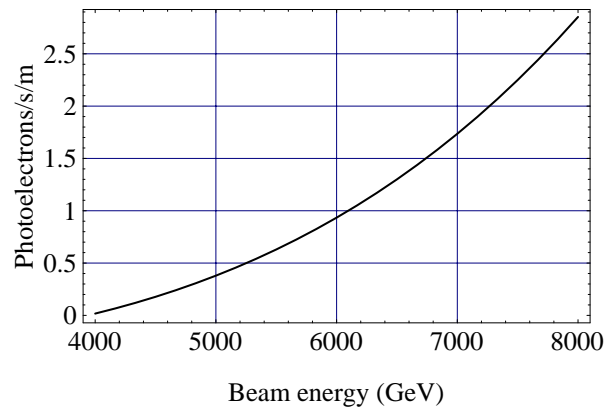

Figure: 6 Production of photo-electrons in LHC (units of 10^{15}) versus beam energy for 0.53 A beam current.

Assuming that each photo-electron in the cloud receives just one kick with an average energy transfer, computed from Figure 1 as 700 eV, this would give a linear power dissipation -on the beam screen- of approx. 0.2 W/m.

5 CONCLUSIONS

Bunch induced multipacting is a potential problem for LHC but may be avoided by constructing the vacuum chambers and the beam screen from materials with low secondary electron coefficient (seec). The influence of the magnetic field has still to be studied in more detail but first estimates tend to show that its effect is small. Wherever possible, beam pipes with sufficiently large size should be chosen to avoid wall-to-wall multipacting. The power dissipation by photo-electrons represents a significant and, so far, not included contribution to the thermal budget.

6 ACKNOWLEDGMENTS

7 REFERENCES

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