# BEAM-INDUCED ELECTRON CLOUD IN THE LHC AND POSSIBLE REMEDIES

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*Abstract*

Synchrotron radiation from proton bunches in the LHC creates photoelectrons at the beam screen wall. These photoelectrons are accelerated towards the positively charged proton bunch and drift across the beam pipe between successive bunches. When they hit the opposite wall, they generate secondary electrons which can in turn be accelerated by the next bunch if they are slow enough to survive. We summarize the results of an intensive research program set up at CERN and discuss recent multipacting tests as well as the importance of several key parameters, such as photon reflectivity, photoelectron and secondary electron yield. Then, based on analytic estimates and simulation results, we discuss possible solutions to avoid the fast build-up of an electron cloud with potential implications for beam stability and heat load on the cryogenic system.

## 1 INTRODUCTION

The linear photon flux due to synchrotron radiation in the LHC is $\Phi_\gamma = \frac{5}{2\sqrt{3}}\,\alpha\gamma\frac{N_{\rm b}}{\rho t_{\rm sep}} \simeq 10^{17}\,\frac{\rm photons}{\rm m\cdot s}$, where $\alpha$ is the fine structure constant, $\gamma \simeq 7000$ the Lorentz factor for protons at 7 TeV, $N_{\rm b} = 10^{11}$ the bunch population, $\rho \simeq 2784$ m the bending radius and $t_{\rm sep} = 25$ ns the time separation between subsequent bunches. The critical energy of these photons is $\varepsilon_{\rm cr} = 3/2\,\gamma^3\hbar c/\rho \simeq 45$ eV, i.e., well above the work function (a few eV); photoelectrons are thus created at the beam screen wall and pulled towards the positively charged proton bunch. A first estimate [3] of the corresponding heat load on the beam screen, based on a photoelectron yield $\delta_{\gamma{\rm e}} \simeq 0.02$ and an average energy gain from the proton bunch $\langle W\rangle \simeq 700$ eV (in the absence of magnetic field and for a uniform electron cloud distribution), gave a linear power $P = \Phi_\gamma\delta_{\gamma{\rm e}}\langle W\rangle \simeq 0.2$ W/m comparable to the heat load due to synchrotron radiation. This estimate does not include a possible electron cloud build-up associated with secondary emission, which can significantly increase the power deposition and, according to earlier simulations [2], can lead to a very fast horizontal multi-bunch instability.

In kick approximation, i.e. neglecting the electron motion during the passage of the proton bunch, the maximum energy gain of an electron initially at rest with radial offset $a$ from the beam axis is independent of the bunch length and given by $\varepsilon_{\rm max} = 2m_{\rm e}c^2{N_{\rm b}}^2r_{\rm e}^2/a^2$, where $c$ is the speed of light, $m_{\rm e}$ the electron mass and $r_{\rm e}$ its classical radius. For a photoelectron starting at the wall $a \simeq 2$ cm of the LHC beam screen, $\varepsilon_{\rm max} \simeq 200$ eV and the corresponding transit time to the opposite wall is about 5 ns, i.e., significantly less than the 25 ns bunch spacing. When the next bunch arrives, there is a relatively uniform distribution of photoelectrons (plus secondary electrons) in the screen cross section: the energy gain can reach a few keV and these fast particles hit very quickly the screen walls, producing low energy secondary electrons. However, for a correct modelling of the electron motion during the bunch passage [6] one has to cut the bunch into several transverse slices (typically 50). This is important for electrons near the beam axis, when the energy gain in kick approximation is largely overestimated, and is a key ingredient in all recent simulations of the LHC electron cloud dynamics [9, 10, 11, 15, 18].

The average number of secondary electrons emitted when a primary electron of energy $W$ hits a metal surface with incidence angle $\theta$ from the normal can be written [20] $\delta_{\rm SEY}(W,\theta) = \frac{\delta_{\rm max}}{\cos\theta}\,h\left(\frac{W}{W_o}\right)$, where the maximum yield $\delta_{\rm max}$, corresponding to a primary electron energy $W_o$ typically around 400 eV, is a characteristic of the metal while $h$ is a universal function having the phenomenological expression $h(\xi) = 1.11\,\xi^{-0.35}\left(1 - e^{-2.3\,\xi^{1.35}}\right)$. In addition to the maximum yield $\delta_{\rm max}$, a key ingredient for the possible build-up of an electron cloud is the energy distribution of the secondary electrons.

The initial estimated surface properties for a copper coated beam screen (by colamination onto stainless steel) were: reflectivity $R \sim 1$, photoelectron yield $\delta_{\gamma{\rm e}} = 0.2$, and maximum secondary electron yield $\delta_{\gamma{\rm max}} = 1.8$. Assuming a half-Gaussian energy distribution of the secondary electrons with characteristic energy $W_{\rm s} = 10$ eV, the corresponding heat load $P = 7$ W/m obtained by simulation for nominal LHC beam parameters exceeds by far the cryogenic budget of about 1 W/m allowed by the cooling capillaries. Therefore an intensive research program has been set up at CERN to measure the relevant physical quantities, to validate analytic estimates and simulation results, and to propose effective remedies: a fairly complete account of the contributions to this 'crash program' can be found in Refs. [1]–[19].

## 2 EPA IRRADIATION TESTS

For high surface reflectivity, the measured photoelectron yield per *incident* photon may differ significantly from the relevant yield per *adsorbed* photon [4] (sooner or later all photons are adsorbed by the beam screen). Therefore both measurements of photoelectron yield and forward scattered reflectivity, at a grazing incidence angle of 11 mrad, have been performed at CERN using synchrotron light from the EPA machine with critical energy of 45 eV. Recent results [7] for copper coatings with different surface preparations indicate a photoelectron yield per adsorbed photon $\delta_{\gamma e} \simeq 0.05 \div 0.11$, however the reflectivity drops from 81% for a smooth colaminated surface with average roughness of 0.2 $\mu$m down to about 5% for an electroplated surface with average roughness of 1.6 $\mu$m and to 2% for a 'ribbed' wall, due to the nearly perpendicular incidence of the photons.

## 3 CRITICAL SECONDARY YIELD

With some simplifying assumption, it is possible to solve analytically the Vlasov equation describing the free drift of secondary electrons along the vertical magnetic field lines in a bending dipole [14]. Combining this with the energy gain from the next bunch in kick approximation and with the secondary yield curve, one gets the 'second generation' electron density: when the latter is larger than the initial density, build-up of the electron cloud will take place.

This defines a critical value $\delta_{\rm cr}$, weakly dependent on the horizontal position along the beam screen cross section, for the maximum secondary electron yield: if $\delta_{\rm max}$ is smaller than the critical value, there is no spontaneous amplification of the electron cloud density. The space charge force weakens the contribution of very slow secondary electrons, with energy below about 1 eV, that are pushed back into the wall. For nominal LHC parameters and assuming a typical secondary electron energy $W_{\rm s} = 10$ eV, one finds a minimum $\delta_{\rm cr}$ of about 1.35, in agreement with simulation results [15, 18]. Such a low value for $\delta_{\rm max}$ may not be easy to achieve, especially in the initial phase of operation until the surface has been exposed to a sufficiently large photoelectron dose. However, $\delta_{\rm cr}$ increases significantly for larger bunch spacings and has a weak dependence on the bunch population.

## 4 MULTIPACTING TESTS

Multipacting tests have been successfully performed at CERN using a coaxial resonator in presence of a solenoid and a dipole magnetic field [13]. We have developed a simple and reliable technique, based on amplitude modulation of the input signal, to detect electronically the onset of multipacting and to monitor the field and power level in the resonator. We observe a negative low-frequency signal superimposed on the 'resistor probe' RF signal from the inner conductor, indicating that the latter acquires a negative electric charge during multipacting: after removing this charge, it is more difficult to start multipacting again. Although the sign of this low-frequency signal becomes positive with a strong magnetic field, the multipacting levels at room temperature are similar to those measured during cold tests, with a dipole magnetic field up to about 7.5 T. This seems to exclude any significant reduction of the secondary electron yield by a strong magnetic field over most of the outer tube surface, away from the region where the field is parallel to the metal surface.

A weak solenoid field of about 50 Gauss (or less, depending on kinematic conditions) is usually sufficient to stop the multipacting, but the same longitudinal field is ineffective in presence of a strong dipole field. Moreover a substantial decrease of the multipacting threshold has been observed when the dipole magnetic field has an intensity such that the electron cyclotron frequency is equal to the resonant frequency of the coaxial cavity.

## 5 POSSIBLE REMEDIES

For a uniform illumination of the beam screen, corresponding to high surface reflectivity, the average energy gain $\langle W \rangle$ in a dipole magnet is half of that in a field-free region, since only the vertical component of the beam force is effective in accelerating the electrons. Indeed they spiral along the vertical magnetic field lines with typical Larmor radii of a few $\mu$m and perform about a hundred cyclotron rotations during a bunch passage. On the other hand, the heat load in a dipole magnet is drastically reduced if the screen reflectivity is much smaller than unity: in this case, photoelectrons and secondary electrons are produced only near the horizontal plane, where the vertical component of the beam force is very small.

Assuming for example that only 10% of the photons are uniformly distributed on the beam screen, the heat load corresponding to a photoelectron yield $\delta_{\gamma e} = 0.2$ and to a maximum secondary yield $\delta_{\rm max} = 1.2$, for a characteristic secondary electron energy of 5 eV, is only 0.2 W/m [15]. However, for a maximum secondary yield $\delta_{\rm max} = 1.8$ above the critical value, the heat load remains 5.2 W/m inspite of the lower reflectivity.

A simple geometrical solution to reduce both the photoelectric yield and the forward scattered reflectivity, is to arrange near perpendicular incidence of the photons. A structure which has been studied is a ribbed, sawtooth shaped Cu surface in the median plane where photons impinge at near perpendicular incidence. A photoelectron yield per adsorbed photon of $\delta_{\gamma e} \simeq 0.05$ and a forward scattered photon reflectivity of about 2% were measured from this surface, corresponding to a heat load of about 10 mW/m assuming a linear scaling with $\delta_{\gamma e}$ and $R$ [7]. The expected suppression of the photoelectrons due to a magnetic field parallel to the surface exposed to the synchrotron radiation has been confirmed by measurements and in order to take full advantage of this effect, it is considered to replace the uniform circular screen shape in the median plane by two flat sections over approximately 10 mm. The corresponding reduction in the horizontal axis will not affect the useful aperture. The beam coupling impedence of such a structure is the subject of theoretical and experimental studies.

The required reduction of the secondary electron yield below the critical value of about 1.3 will be obtained by appropriate surface treatments. A promising method which has been studied is a $350°C$ *ex-situ* bakeout in air for 5 minutes, which produces a thick oxide surface layer [5]. An alternative may be a thin ($\mu$m) film coating, such as TiN or TiZr. To obtain the required low secondary electron yield in a vacuum system which can be baked *in-situ* does not pose a problem. This applies to the room temperature sections in LHC which will have to be baked to guarantee vacuum stability by ion induced desorption. For the cold arcs of the LHC it will, however, not be possible to bake the beam screen. Here, it is proposed to achieve the clean-up of the surface and the lowering of the secondary electron yield by *in-situ* conditioning with beam in the same way as proposed for the PEP2 B-factory vacuum system. Preliminary estimates indicate that it would require less than 200 hours of operation to condition the surface.

As a possible back-up solution, one could envisage to increase the LHC bunch spacing: this would substantially increase the critical secondary yield at the cost of machine performance. Specifically, the critical yield becomes 2.8 for nominal bunch intensity and 50 ns spacing, but the machine luminosity would be reduced by a factor two. Doubling the bunch spacing and increasing the nominal bunch intensity by a factor $\sqrt{2}$ would guarantee the same luminosity and still increase the critical secondary yield to a value around 2. This option is still compatible with the maximum beam-beam tune spread of 0.015 achieved in the CERN S$\bar{p}$pS collider [21], but would increase the number of events per crossing by a factor two.

In addition to solenoid fields (effective only in the drift spaces), another possible remedy is to apply one or a few narrow metallic strips on a thin insulating layer (e.g. Kapton), biased at some $-20$ V relative to the beam screen. These would act as clearing electrodes for the low energy secondary electrons and would reduce the heat load in the bending magnets to about 0.2 W/m [15]. The impedance of such clearing electrodes is currently being estimated.

To improve the predictive power of simulations, a better knowledge of the fraction of photons diffused away from the forward direction and of the secondary electron energy distribution is required. This information should be experimentally accessible in future irradiation and multipacting tests and in further secondary emission studies.

## 6 REFERENCES


[1] F. Ruggiero, World-wide web page on "Electron Cloud in the LHC", `http://wwwslap.cern.ch/collective/electron-cloud/`.

[2] F. Zimmermann, "A simulation study of electron cloud instability and beam induced multipacting in the LHC", CERN LHC Project Report 95 and SLAC-PUB-7425 (February 1997),

[3] O. Gröbner, "Beam induced multipacting", CERN LHC Project Report 127 (July 1997), presented at the IEEE Particle Accelerator Conference (PAC97), Vancouver, May 1997.

[4] J.B. Jeanneret, "Photoemission in LHC–A simple model", CERN SL/Note 97-48 (AP) (June 1997).

[5] I. Bojko, J.-L. Dorier, N. Hilleret and Ch. Scheuerlein, "Lowering the secondary electron yield of thechnical copper surfaces by strong oxidation", CERN LHC Vacuum Technical Note 97-19 (June 1997).

[6] J.S. Berg, "Energy gain in an electron cloud during the passage of a bunch", CERN LHC Project Note 97 (July 1997).

[7] V. Baglin, I.R. Collins, and O. Gröbner, "Photoelectron yield and photon reflectivity from candidate LHC vacuum chamber materials with implications to the vacuum chamber design", contribution to these Proceedings.

[8] A.V. Burov and N.S. Dikansky, "Electron-cloud instabilities", in Proc. International Workshop on Multibunch Instabilities in Future Electron and Positron Accelerators (MBI97), Tsukuba, 1997, edited by Y.H. Chin, KEK Proceedings 97-17 (1997), pp. 200–220.

[9] F. Zimmermann, "Electron-cloud instability and beam-induced multipacting in the LHC and in the VLHC", SLAC-PUB-7664 (October 1997), in Proc. MBI97 (see Ref. [8]), pp. 221–233.

[10] M.A. Furman, "Comments on the electron-cloud effect in the LHC dipole bending magnets", LBNL-40914/CBP Note 241 (October 1997), in Proc. MBI97 (see Ref. [8]), pp. 234–246.

[11] O. Brüning, "Simulations for the beam-induced electron cloud in the LHC liner", CERN LHC Project Note 102 (August 1997).

[12] I.R. Collins, A.G. Mathewson, and R. Cimino, "VUV synchrotron radiation photoemission investigation of proposed materials for the vacuum chambers of the Large Hadron Collider", CERN LHC Vacuum Technical Note 97-24 (September 1997), presented at ECASIA'97, Göteborg, Sweden, 16–20 June 1997.

[13] F. Caspers, J.-M. Laurent, M. Morvillo, and F. Ruggiero, "Multipacting tests with a resonant coaxial setup", CERN LHC Project Note 110 (September 1997) and contribution to these Proceedings.

[14] G. Stupakov, "Photoelectrons and multipacting in the LHC: electron cloud build-up", CERN LHC Project Report 141 (October 1997).

[15] O. Brüning, "Simulations for the beam-induced electron cloud in the LHC beam screen with magnetic field and image charges", CERN LHC Project Report 158 (November 1997) and contribution to these Proceedings.

[16] F. Zimmermann, "Electron cloud effects in high-luminosity colliders", SLAC-PUB-7735 (January 1998), presented at the Advanced ICFA Workshop, Frascati, October 1997.

[17] F. Ruggiero, "Electron cloud in the LHC", CERN LHC Project Report 166, (February 1998), presented at the Advanced ICFA Workshop, Frascati, October 1997.

[18] M.A. Furman, "The electron-cloud effect in the arcs of the LHC", CERN LHC Project Report 180 (May 1998), also published as LBNL-41482/CBP Note 247.

[19] L. Vos, "Electron cloud: an analytic view", to appear as a CERN LHC Project Report (July 1998).

[20] H. Seiler, "Secondary electron emission in the scanning electron microscope", J. Appl. Phys. **54**, 11 (1983).

[21] J. Gareyte, "Requirements of the LHC on its injectors", in Proc. LHC96 Workshop, Montreux, 1996, edited by O. Brüning and E. Keil, Part. Accel. **58**, 53–61 (1997).