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Practical User Guide for ECloud

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Abstract

This note describes the use of the program ECloud for the simulation of the electron cloud build up, which occurs due to photoemission, ionization, and secondary emission inside an accelerator beam pipe during the passage of a narrowly spaced proton or positron bunch train. All input parameters as well as the standard output files are explained. The goal of the note is to facilitate installation and execution of the program with a minimum knowledge of its internal structure.

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1 General

Photoemission, or residual gas ionization, and secondary emission are known to give rise to a quasi-stationary electron cloud inside the beam pipe through a beam-induced multipacting process. The ECLOUD program simulates the build up of the electron cloud. The simulation model and the underlying physical mechanisms have been discussed in Refs. [1, 2, 3, 4]. The code incorporates many features of the programs PEI and POSINST, which were written by K. Ohmi at KEK [5] and by M. Furman and G. Lambertson at LBNL [6], respectively. The ECLOUD simulation includes the electric field of the beam, arbitrary magnetic fields, the electron space charge field, and image charges for both beam and electrons.
As input numbers, the code requires various beam parameters (bunch population, rms bunch length, bunch spacing, filling pattern, ...), surface properties (secondary emission yield, photoemission creation rate, photon reflectivity, etc.), the vacuum chamber geometry (semi-axes, flat vertical cut off), and the type of magnetic field. The program computes the total number of electrons, the central electron density, the energy deposited on the chamber wall, the spatial distribution of the electrons, etc., as a function of time during the passage of a bunch train.
The program can be downloaded via the web address

'http://wwwslap.cern.ch/collective/electron-cloud/'

following the link to ECLOUD, where a 'tarred' file containing the fortran code and an example input is available. The file can be untarred by typing

'tar -xvf ecloud.tar'

which produces the three files 'ecloud', 'ohmilhc.input', and 'Makefile'. consequently produced. Now the 'Makefile' must be edited in order to choose the appropriate Fortran compiler and to set the compiler flags. Then the executable can be created by typing 'make ecloud'.

2 Input Files

The aim of this section is to explain the meaning of all the variables that must be set in the input file 'ecloud.input'. Editing the file will show an alternating sequence of short descriptive lines and lines containing numbers: the numbers set the quantity or the quantities briefly described in the preceding line, and have to be adjusted each time according to the case one intends to simulate. The description lines always contain within brackets the physical dimension of the parameter they refer to (if no dimension is indicated, the parameter is dimensionless): occasionally, they also show in parentheses the name of the variable or variables of the source code to which the following input line assigns a value. We now report and further comment the complete list of input parameters:

- 'Number of seeds (isemax):'
  This parameter lets the simulation be executed 'isemax' times with different random seeds for the photoelectrons and secondary electrons generation. Some results are averaged over the different runs, so that the error introduced by the actual initial distribution is filtered out. The option $isemax > 1$ is primarily used for computing the bunch-to-bunch wake field.
- 'Number of pe-macroparticles/bunch (npepb):'
  It refers to the number of macro-electrons that are generated at each bunch passage in the beam-line section under consideration. These may be photoelectrons or electrons generated by the ionization of the residual gas in the beam pipe. Typical values are between 200 and 2000.
- 'Number of bunches (nbunch):'
  It determines over how many bunches the electron generation and dynamics is studied in a given ring section. Further below, under 'fill pattern', we introduce a second variable connected to the number of bunches over which the simulation extends. The discussion of the role of these two variables is postponed to that point.
- 'Number of intermediate steps per bunch passage (#slices $<$50000) (nbstep):'
  In the simulation two different time steps are chosen for the time of the bunch passage and the inter-bunch 'drift' (gap). T he parameter 'nbstep' gives the number of steps during the bunch passage.
- 'Number of intermediate steps per inter bunch drift (nistep):'
  The parameter 'nistep' sets the number of time steps between two subsequent bunches.
- 'Number of intermediate steps per offset kick (nostep):'
  This parameter sets the number of time steps when the kick from an offset bunch is applied (for the computation of coupled-bunch wake fields).
- 'Number of bunch passage for which the energy distributions is plotted (jebin):'
  It defines for which bunch number the electron energy distribution is written to a file.
- 'Number of bunch slice after which the energy distributions is plotted (iebin):'
  It defines after which bunch slice during the 'jebin'-th bunch passage the electron distribution is written to an external file.
- 'Movie option ($1 \rightarrow$ plotting the particle distribution every slice) (imovie):'
  If this variable is set to 1, it allows the creation of a gnuplot movie to see the evolution of the electron cloud during the bunch passage and in the inter-bunch drift.
- 'The movie pictures are plotted every 'iseq' slice/interbunch step:'
  The variable 'iseq' defines the time-step interval at which the electron distribution is sampled for the movie. Of course, it only comes into play if the previous variable 'imovie' is set to 1.

- 'Number of particles per bunch (ppb):'
  This is the number of protons/positrons contained in one bunch.
- 'Bunch spacing (sb [m]):'
  It defines the distance between two successive bunches.
- 'Bunch length (bl [m]):'
  It defines the bunch length as σ for a Gaussian distribution, in which case the total length of the bunch is $4\sqrt{3}\sigma_z$. For a uniform bunch profile (selected by variable 'idistr' introduced below), 'bl' is equal to the total bunch length.
- 'Length of bending magnet (belen [m]):'
  It sets the length of the section in which we want to simulate the build up of the electron cloud. It must not be necessarily a bending magnet, the kind of section is decided further below through the switch 'ibend'.
- 'Beam particle energy (energy [eV]):'
  Energy of the bunch particles. This is only used for the wake-field computation.
- 'Machine circumference (circum [m]):'
  Length of the ring circumference (only used for bunch-to-bunch wake field calculation).
- 'Primary photoelectron emission yield (peeff):'
  There are three numbers in this line. The first is the primary photoemission yield. The primary photoelectron emission yield, which has to be entered here, must be calculated beforehand by multiplying the number of photons per proton and per meter (which depends on the bunch energy) by the yield Y^* (characteristic of the material of which the inner part of the beam pipe is made) and by the length of the section we intend to study ('belen'). The second number, 'refl', represents the fraction of photoelectrons which are launched distributed all around the chamber azimuth ϕ (ϕ is the angle between a line extending from the center of the chamber to a point on the chamber wall and the horizontally outward direction. It ranges between 0 and 2π.) All other electrons are confined to a narrow outward cone with extent defined by the angle cut for the emitted photons (see below). The third number is an integer, which selects according to which functional dependence the electron fraction 'refl' is distributed, namely

  1 uniform
  2 $\cos\psi$
  3 $\cos^2\psi$
  4 smooth parabolic
  5 $\cos^3\psi$.

  Here $-\pi/2 \leq \psi \leq \pi/2$ describes the angle of reflected photons with respect to the horizontal plane as viewed from the horizontally outward primary impact point of the synchrotron radiation. For example, $\psi = 0$ refers to the horizontally inward point on the inner chamber wall.

- 'Maximum bunch number until which photoelectrons are emitted (nbini):'
  It defines an upper bound for the number of bunches that produce photoemission as they are passing through the section. This option is sometimes used to find a 'critical' secondary emission yield for the onset of multipacting.
- 'Maximum slice number until which photoelectrons are emitted (nsini):'
  It defines an upper bound for the number of bunch slices that produce photoemission as the bunch is passing through the section. (This is used for debugging only.)
- 'Modulo Switch: particles are emitted for every nbini-th bunch (imodo):'
  By setting this variable to 1, photoemission will take place only every 'nbini' bunches and not at every bunch passage. (This is used for debugging only.)
- 'Angle cut for the emitted photons (2.0: normal distribution, < 2.0 limited):'
  The name of this variable in the source code is 'alimit'. The photoelectrons created by unreflected photons are emitted with a Gaussian angular distribution, centered in the horizontal plane, and with rms width alimit $\times \pi/2$. For example, alimit=0.125 corresponds to an rms angular width (standard deviation) of 11.25°.
- 'Energy for photo electrons (position of peak)(epemax [eV]):'
  There are three numbers in this line. The first number represents the peak energy of the photoemitted electrons. The second value represents a second peak energy, and the third the ratio of electrons centered around the second and first peak.
- 'Energy of the photo electrons (sigma of distribution) (epesig [eV]):'
  Width of the distribution of photoemitted electrons. As the distribution is assumed to be Gaussian, the width is given as σ of the distribution. The second number, to be entered here, represents the width of the distribution centered around the second peak.
- 'Energy of the secondary electrons (sigma of distribution) (semax [eV]):'
  It defines the σ of the energy distribution for secondary electrons.
- 'Energy distribution for sec. el. (iseldis): (1: Gauss ,2: Miguel, 3: Exponential, 4: Lorentzian, 5: parametrization by Noel Hilleret [7])'
  This parameter is used to set the type of energy distribution for secondary electrons. It is an integer, and its meaning is clearly explained in the description line.
- 'Energy cut for the 'time.*.data' files (ecut):'
  Not commonly used.
- 'Secondary emission yield (yim):'
  Maximum secondary emission yield (peak value of the secondary emission curve for perpendicular incidence as a function of the energy of the incident electron).
- 'Energy at which maximum secondary emission yield occurs (yemax):'
  It defines the energy of the incident electron (in eV) which corresponds to the maximum secondary emission yield.

- 'Number of times the space charge field is recalculated (interspace):'
  This parameter is an integer which defines how often the space charge force on the electrons is recalculated and is normally set to a common submultiple of 'nbstep' and 'nistep', *e.g.*, to 5 or 10.
- 'Switch for electron image charges (iimage=1 $\rightarrow$ image charges are included):'
  Normally iimage=1.
- 'Switch for beam image charges (iimageb=1 $\rightarrow$ image charges are included):'
  Normally iimageb=1.
- 'Horizontal beam size (sx [m]):'
  Horizontal rms beam size. The horizontal beam distribution is assumed to be Gaussian.
- 'Vertical beam size (sy [m]):'
  Vertical rms beam size. The vertical beam distribution is assumed to be Gaussian.
- 'Horizontal aperture limitation (xbound [m]):'
  This is the horizontal semi-axis of the beam pipe, assumed elliptical or flat (see in the following 'zbound').
- 'Vertical aperture limitation (ybound [m]):'
  This is the vertical semi-axis of the beam pipe, assumed elliptical or flat (see in the following 'zbound').
- 'Vertical aperture limitation at the flat part of the beam pipe (zbound [m]):'
  If this is equal to 'ybound', the chamber boundary is elliptic with previously defined values of the semi-axes. If it is smaller than 'ybound', it defines the half-height of the flat region of the chamber. See Fig. 1, which illustrates the transverse geometry.
- 'Bending field (bfield [T]/[T/m]):8.39; 1.4; 210.0'
  One real value, characterizing either the magnetic field in T (for dipole or solenoid) or the field gradient in T/m (for quadrupole).
- 'Electrostatic field (volt [V])'
  Not commonly used.
- 'Switch for bending field (ibend):'

  0 drift
  1 infinitely strong dipole (only vertical electron motion is considered)
  2 quadrupole with Runge-Kutta (R.-K.)
  3 uniform solenoid with Runge-Kutta
  4 uniform solenoid with piecewise integration
  5 (weak) dipole with piecewise integration
  11 symmetric C yoke quadrupole with z dependence w. R.-K.
  12 asymmetric C yoke quadrupole with z dependence w. R.-K.

13 symmetric C yoke dipole with z dependence w. R.-K.
14 asymmetric C yoke dipole with z dependence w. R.-K.
15 50-G solenoid with z dependence w. R.-K.
16 uniform dipole of 1 T w. R.-K.
17 uniform 50-G solenoid w. R.-K.
18 uniform dipole of strength 'bfield' w. R.-K.
19 two adjacent 50-G solenoids of equal polarity w. R.-K.
20 periodic symmetric solenoid w. R.-K.
21 periodic asymmetric solenoid w. R.-K.
22 symmetric C yoke quadrupole with z dependence (more exact) w. R.-K.
23 asymmetric C yoke quadrupole with z dep. (more exact) w. R.-K.
38 strong dipole with vertical el. field of 20 kV/m (for IPM)
40 dipole with embedded Runge-Kutta integration
41 solenoid with embedded Runge-Kutta integration

Except for options 40 and 41, the Runge-Kutta integration is performed with a NAGLIB (or CERNLIB) library function.

- 'Switch for losing particles (iloss=1: allows particle loss) (iloss):'
  Normally iloss=1.
- 'Switch for space charge (ispace=1 $\rightarrow$ 1-dim mesh, ispace=2 $\rightarrow$ 2-dim mesh):'
  We currently use ispace=2 for a more accurate evaluation of the space charge forces.
- 'Switch for charge distribution (idistr=0 $\rightarrow$ uniform; idistr=1 $\rightarrow$ Gauss)'
  idistr=0 corresponds to simulating a longitudinally flat bunch; idistr=1 (usual case) selects a bunch with a longitudinal Gaussian profile.
- 'Switch for beam-beam kick (ibeam=0: no kick; ibeam=1: beam-beam kick)'
  Normally ibeam=1.
- 'Switch for wave guide mode (iwave=0 $\rightarrow$ bunched beam; iwave=1,2 $\rightarrow$ wave guide)'
  Usually iwave=0. By setting iwave=1,2 it is possible to simulate electron multipacting inside a coaxial cable or in a 6-wire geometry. These options can therefore be used for dedicated simulations of specific experimental set-ups (CERN co-axial chamber and multiple-wire chamber). We will not comment on all the other parameters related to this case, which are listed in the following lines and whose values are important only for iwave$\neq 0$.
- 'Inner radius of the wave guide (rbound [m]):'
  For special purpose.
- 'Length of the wave guide (wgl [m]; for iwave=2: "wavelength"):'
  For special purpose.

- ‘Wave number of the standing wave (wk; for iwave=2:”period/pulsewidth”):’ For special purpose.
- ‘Voltage of the standing wave (vtem [Volt])’
  For special purpose.
- ‘DC Bias for the standing wave (vtem0 [Volt]):’
  For special purpose.
- ‘Wire radius of the 6-wire waveguide(rbound6 [m])’
  For special purpose.
- ‘Number of particles per satellite bunch (ppb1):’
  This number determines the population of a satellite bunch following the main bunch (first satellite).
- ‘Bunch spacing of the satellite bunch (sb1 [m]):’
  Center-to-center displacement of first satellite with respect to main bunch.
- ‘Number of particles per satellite bunch (ppb2):’
  This number determines the population of a second satellite bunch following the main bunch.
- ‘Bunch spacing of the satellite bunch (sb2 [m]):’
  Center-to-center displacement of second satellite with respect to main bunch.
- ‘x,y offsets for main bunch (x1, y1 [m])’
  To offset the beam from the center of the chamber.
- ‘x,y offsets for 1st satellite bunch (x2, y2 [m])’
  To offset the 1st satellite from the center of the chamber. *Note: the offset of the first satellite is defined with opposite sign!* (The satellite can be used to simulate the presence of two beams with different orbits, *e.g.*, in the LHC interaction regions).
- ‘x,y offsets for 2nd satellite bunch (x3, y3 [m])’
  To offset the 2nd satellite from the center of the chamber. The offset of the second satellite is defined with the same sign as the main bunch.
- ‘Switch for gas ionization (icoll)’
  If icoll=0, photoelectrons are emitted from the wall. If icoll=1, the primary electrons are generated inside the beam volume, and not on the chamber wall, but with the same rate. If icoll=2, electrons are generated in the beam volume, but with a different rate, computed from gas pressure and ionization cross section, which for icoll=2 need to be input in the following line:
  ‘pressure [nTorr], cross section [Mbarn]:9,2’
  These two numbers represent the residual gas pressure in nTorr and the cross section of the ionization process in MBarn respectively; they determine how many electrons are generated per bunch passage. The pressure refers to room temperature (300 K).

If icoll=3, electrons are generated on the wall, from lost protons. In this case, a following line must contain two parameters:
'ne_pl, [loss per meter per proton], k [electrons per proton]: 1e-6, 100'
These numbers give the fraction of protons lost per meter and per beam proton, and the conversion efficiency into electrons, respectively.

- 'Switch for elastic reflection (inel)'
  If inel is set to 1, elastically reflected secondary electrons are taken into account according to previous laboratory measurements carried out at CERN [8]. The reflectivity in the lower energy limit varies with $\delta_{\max}$ and typically ranges from 0.3 to 0.5. If inel is set to 2 or 3, a different model of elastic reflection is activated, which predicts that the reflectivity approaches 1 in the limit of zero electron energy.
- 'Fill pattern (1: no of repetitions, 2: full, empty, full, empty buckets)'
  The first line contains four integers, which represent the number (*irep*) of (inner) repetitions of the subsequent pattern described below the number (*iabort*) of empty buckets following at the end of the simulation (for studying the decay of the cloud in a long gap), a number (*igap*) describing the number of empty buckets at the end of each inner repetition, and the number (*irepout*) of outer repetitions, respectively. The second line also has 4 integer numbers, which represent a filling pattern for the inner repetition. Each integer gives a consecutive number of equally intense bunches. The second and fourth group are assumed to be empty. The final row contains 4 real numbers, which represent intensity multiplication factors for the 4 different groups of bunches. These multiply the nominal value of the bunch population 'ppb' (see further above). Only the first and third values are meaningful, since the other two bunch groups are automatically set to zero intensity.
- 'Switch for azimuth'
  An integer. If set to 1, informations about the azimuthal distribution of electrons hitting the chamber wall are printed to various files.
- 'Wake field switch'
  Two lines. The first line contains a logical switch. If set to 1, the multibunch wake field calculation is activated. The second columns contains two real numbers. The first represents a horizontal offset for the bunch exciting the wake field (for the computation of the horizontal wake between bunches), the second number a vertical offset (for the vertical wake). Usually only one of these two numbers at a time is set unequal zero. Offsets of 5–10 mm are typical.
- 'e- monitor'
  Two numbers, which are not active at the moment. This has been used to simulate the performance of a gas ionization profile monitor.
- 'time limit ([s])'
  This is the CPU time limit in seconds. The program loops terminate 300 s before

this limit, in order to guarantee that all output files are written before execution stops. If a large number is selected, this parameter has no effect.

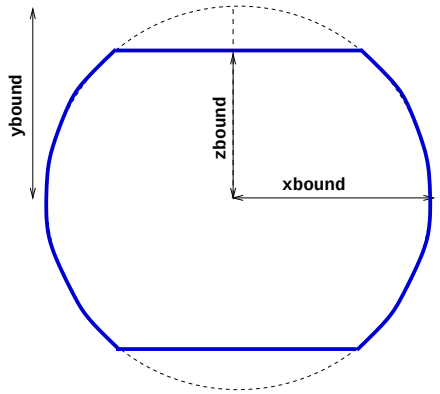

Figure 1: Example of transverse cross section, illustrating the meaning of the variables 'xbound', 'ybound' and 'zbound' which are set in the input file of ECLOUD.

3 Output Files

We only list the commonly used output files:

- 'main.data'; in columns 3 and 5 the time along the bunch train (in seconds) and the total charge of the electron (in meter) are listed. This is used to plot the evolution of the electron build up versus time.
- 'centerdensity.data'; this file lists the time along the bunch train (in seconds) and the electron volume density (in m^{-3}) at the center of the beam pipe. The volume density is used for estimating rise times and thresholds of single-bunch instabilities, and also serves as an input to the separate program HEADTAIL.
- 'eloss.data'; this file lists bunch number and the average heat load in units of W/m for each bunch passage. This is used for the LHC heat load estimates.
- 'qlosswh.data' consists of 4 columns, which list the time, the instantaneous current of electrons bombarding the wall, the accumulated number of electrons hitting the wall, and the accumulated number of electrons with energy larger than 20 eV (*i.e.*, those electrons which participate in surface scrubbing).
- 'onwall.x1.distr.data' lists the average electron charge hitting the wall in $Cm^{-2}s^{-1}$ as a function of horizontal position in the chamber. between 0 and the horizontal half aperture. It is assumed here that the chamber and the beam exhibit a left-right symmetry, which may not always be the case.

- 'onwall.x.distr.data' lists the average electron energy deposited on the wall in units of Wm^{-2} as a function of horizontal position in the chamber. between 0 and the horizontal half aperture. It is assumed that the chamber and beam exhibit a left-right symmetry.
- 'onwall.energy.distr.data contains the normalized energy distribution of electrons hitting the wall, usually in uniform 500 bins extending between 0 and 250 eV.
- 'kick.dat' contains the strength of the bunch-to-bunch wake force. The instability growth time can be estimated using Eq. (11) of Ref. [1].
- 'traj.test.data' lists the time, and the coordinates of the first two macro-electrons over the full length of the simulation. This is used for examining the electron motion and for debugging. Note that the charge of the macro-electrons changes when they hit the wall.
- 'onwall.azimuth.distr.data' lists the average electron energy deposited on the wall in units of Wm^{-2} as a function of the chamber azimuthal angle ϕ.
- 'onwall.azimuth.distr.data' lists the average electron charge deposited on the wall in units of $\mathrm{Cm}^{-2}\mathrm{s}^{-1}$ as a function of the chamber azimuthal angle ϕ.
- 'edistr.movie.data' and 'movie.gnuplot' are used to produce snapshots, and optionally a gnuplot movie, of the electron cloud build up in the transverse plane. The file 'edistr.movie.data' contains 'iseq$\times$nbunch' blocks of data representing the x, y positions of 10% of the macroelectrons at subsequent (but usually unevenly spaced) times over the full simulation time. The file 'movie.gnuplot' can be directly run from a gnuplot prompt by typing the command `load ''movie.gnuplot''` and it produces a 2D animation showing how the cloud evolves in the transverse plane (x, y).

4 Example

The program ECLOUD has for instance been used to predict the electron multipacting inside the LHC experimental areas (ATLAS, ALICE, CMS and LHCb) [9]. One of the main targets of this study was the estimation of the pressure rise due to electron induced desorption in these regions. The number of electrons hitting the inner pipe wall and their energy spectrum are the relevant outputs. For this particular application, many simulation runs for different sets of parameters were required in order to examine a comprehensive set of possible situations in the LHC experimental areas. Specifically, simulations were performed for:

- a well defined set of vacuum chamber radii, from the smallest to the largest diameter in steps of 10 cm for each experimental region. This accounted for the extremely variable geometry in these regions;
- transverse beam sizes at injection and at top energy, both at the interaction points and up to 20 m downstream;

- the cases of two beams reaching the interaction points simultaneously (25 ns bunch spacing and twice the nominal single-bunch intensity) and two beams at half distance (12.5 ns bunch spacing and nominal single-bunch intensity). These represented the two extreme cases for colliding and counter-rotating beams.

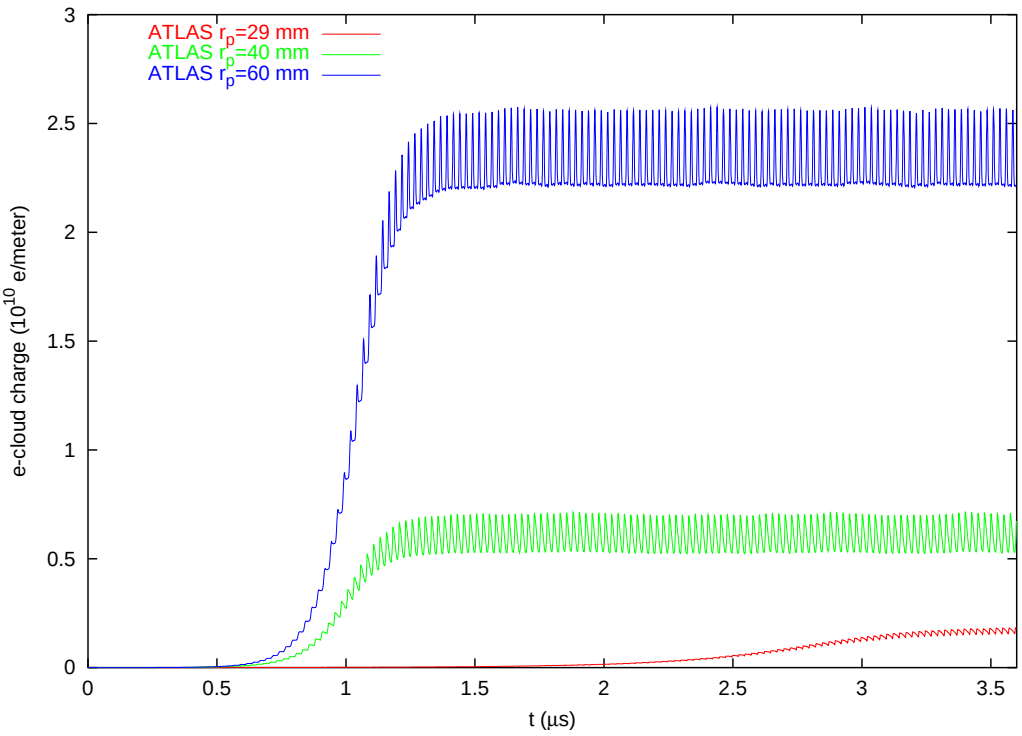

Figure 2: Electron cloud build up in the LHC vacuum chamber for three different radii (29, 40 and 60 mm) and for two bunches arriving simultaneously at the interaction point.

Figure 2 shows the electron cloud build up in ATLAS for three different chamber radii and bunches arriving simultaneously. Each of these plots has been obtained by plotting column 5 versus column 3 from the files 'main.data' generated from input files setting different 'xbound', 'ybound and 'zbound' (but all of them set the bunch spacing 'sb' to 7.48 m). Figure 3 shows the electron cloud build up in ATLAS for three different chamber radii and half-spaced bunches. Again, all plots were generated by plotting column 5 versus column 3 of the file 'main.data' obtained for different values of 'xbound', 'ybound and 'zbound' in the input (but this time the bunch spacing 'sb' was set to 3.74 m).

Figures 4 and 5 show energy spectra of the electrons hitting the pipe wall for two different pipe geometries (29 mm and 158 mm). These diagrams were obtained by plotting column 2 versus column 1 of the file 'onwall.energy.distr.data' generated for different settings of 'xbound', 'ybound and 'zbound'.

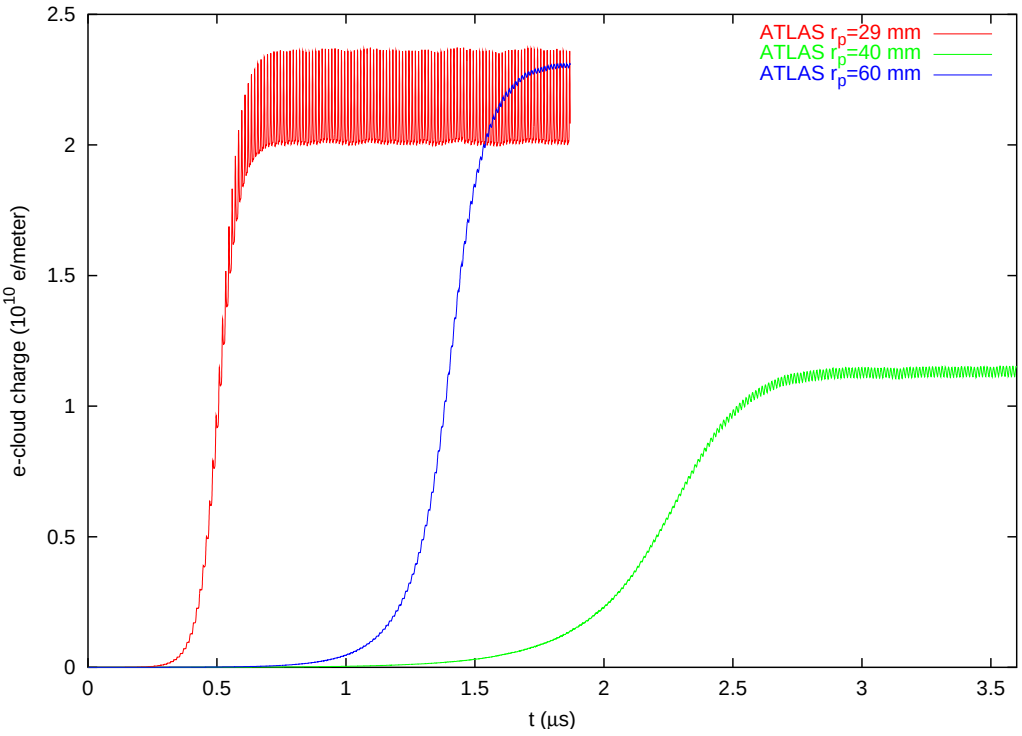

Figure 3: Electron cloud build up in the LHC vacuum chamber for three different radii (29, 40 and 60 mm) and for two bunches arriving at the interaction point with half the nominal spacing.

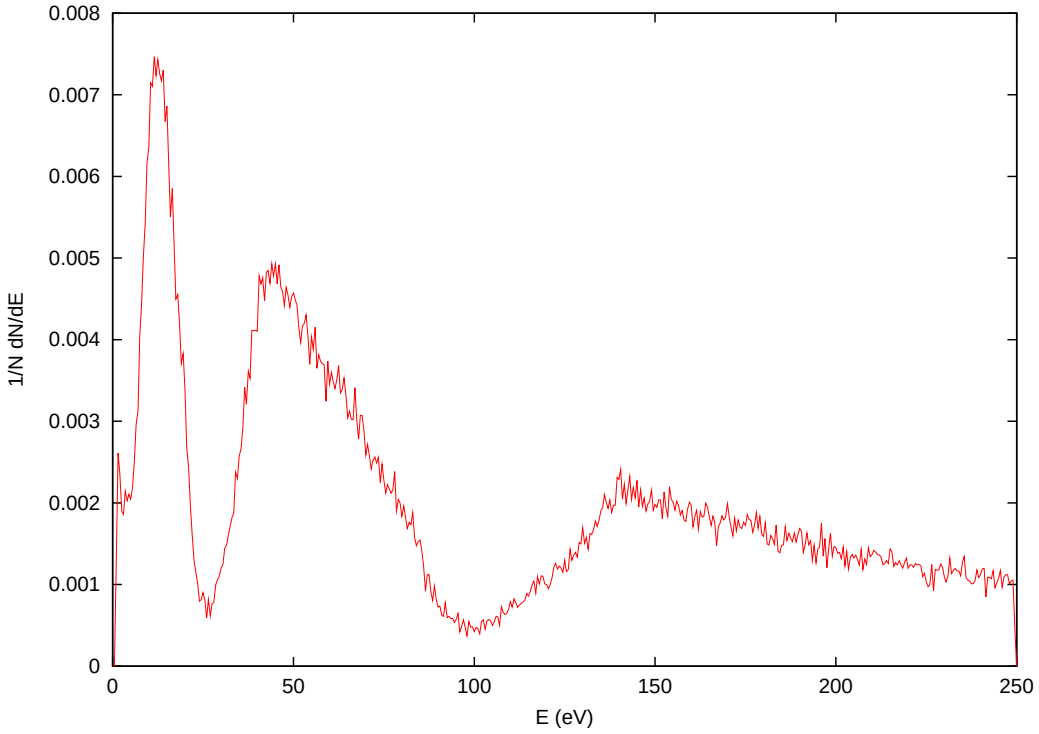

Figure 4: Energy spectrum of the electrons hitting the LHC beam pipe (radius 158 mm).

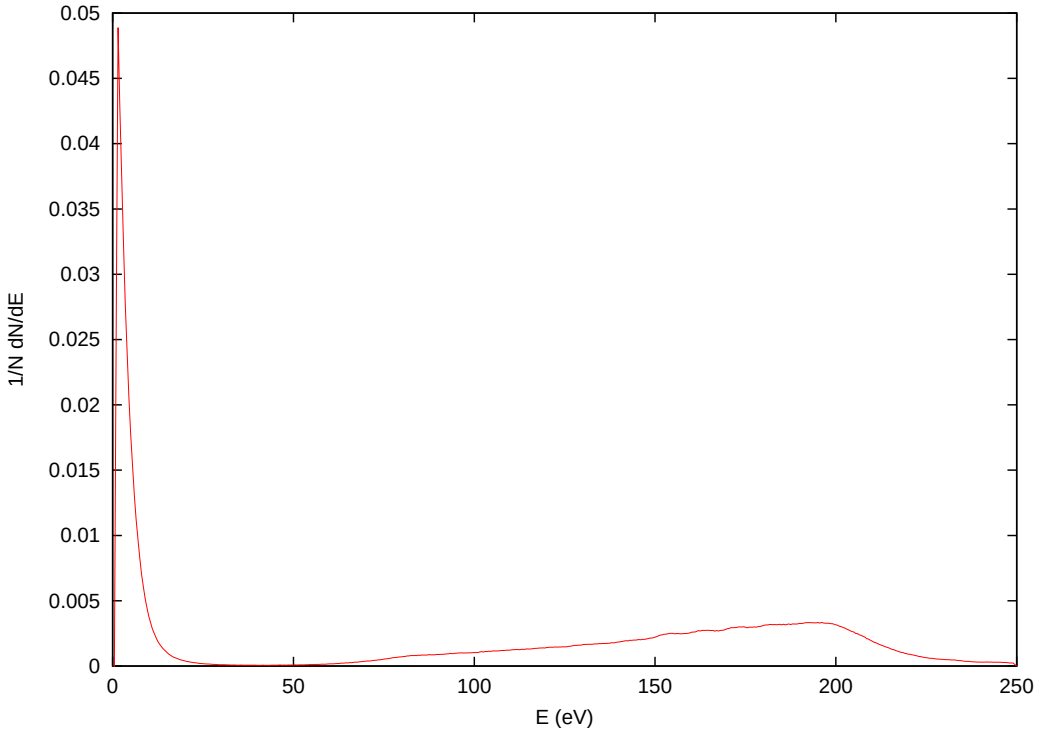

Figure 5: Energy spectrum of the electrons hitting the LHC beam pipe (radius 29 mm).

5 Acknowledgements

The authors would like to thank F. Ruggiero for discussions and for his encouragement to write up this guide. They also would like to acknowledge many earlier contributions to the ECLOUD code development by O. Bruning and X. Zhang. Comments by A. Rossi were helpful in preparing this note. The fruitful collaboration with V. Baglin, I. Collins, and N. Hilleret of the LHC vacuum group was essential for a realistic modelling of photoemission and secondary emission.

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