

***In situ* estimation of the maximum secondary electron yield in the LHC Vacuum Pilot Sector beam pipe via electron cloud measurements and numerical simulations**

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The maximum secondary electron yield, $\delta_{\max}$, is a key parameter governing electron cloud buildup in high-intensity proton accelerators, yet its direct *in situ* determination under operational conditions remains challenging. This paper presents a novel method to estimate $\delta_{\max}$ in the Large Hadron Collider (LHC) using electron cloud measurements performed in the Vacuum Pilot Sector. The approach exploits the characteristic evolution of electron cloud intensity during beam injection, in particular the transition from an initial build-up regime to a linear scaling of electron flux with the number of injected bunches. Electron cloud currents measured with dedicated electron pickups are compared with PyECLOUD simulations performed for varying $\delta_{\max}$ values. The threshold number of injected bunches required to reach the linear regime provides a robust observable from which $\delta_{\max}$ can be extracted with limited sensitivity to other surface-emission parameters. The method is applied to multiple LHC fills and surface materials. For conditioned copper liners, $\delta_{\max}$ values between approximately 1.16 and 1.30 are obtained, in agreement with independent analyses and literature values. Applying the technique over extended operation periods enables the reconstruction of surface conditioning curves as a function of cumulative electron dose. These curves show a rapid initial decrease in $\delta_{\max}$ before approaching an apparent plateau, which may lie below the detection limit of the method depending on the beam pipe material and location. The method is compatible with routine LHC operation and enables systematic monitoring of vacuum-surface conditioning.

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I. INTRODUCTION

Since its first observation in the mid-1960s [1–3] and later described as “bunch-induced multipactoring” at CERN [4], the electron cloud has rapidly emerged as one of the principal performance limitations in high-intensity proton and positron accelerators. As comprehensively reviewed by Zimmermann [5], electron cloud effects can induce a wide range of detrimental phenomena, including beam instabilities and losses, pressure rises, and excessive heat loads in cryogenic superconducting magnets.

Electron clouds originate from the interplay between primary and secondary electrons. Primary electrons are generated mainly through residual-gas ionization and, at

sufficiently high beam energies, via synchrotron-radiation-induced photoemission. These primary electrons are accelerated by the electromagnetic field of the circulating beam and strike the vacuum chamber walls, generating secondary electrons. When the effective secondary electron yield—accounting for both the SEY curve and the electron cloud energy distribution—exceeds unity, the electron population grows exponentially, following the successive bunch passages, through a process known as *multipacting* until it reaches saturation. This study focuses on the characterization of surface emission properties.

The number of secondary electrons emitted per incident primary electron is described by the secondary electron yield (SEY, denoted δ_{SEY}), which depends on the incident electron kinetic energy and surface material properties [6–9]. As shown in Fig. 1, the total SEY is commonly decomposed into elastic reflection (δ_{elast}) and true secondary electron emission (δ_{true}):

$$\delta_{\text{SEY}} = \delta_{\text{elast}} + \delta_{\text{true}}. \quad (1)$$

(i) Elastic reflection arises when low-energy primary electrons undergo elastic scattering within the material

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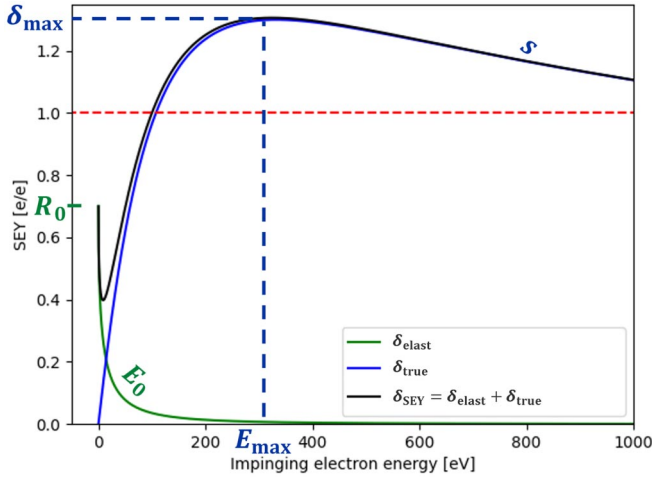


FIG. 1. Empirical model of secondary electron emission curves with respect to the primary electron energy: the total secondary electron yield (δ_{SEY} , black) is composed of elastically reflected electrons (δ_{elast} , green) and true secondary electrons (δ_{true} , blue). The curves represent the analytical functions in Eqs. (2) and (3), with $R_0 = 0.8$, $E_0 = 150$, $\delta_{\text{max}} = 1.3$, $E_{\text{max}} = 332$, and $s = 1.35$. $\delta_{\text{SEY}} = 1$ (red dashed line) corresponds to the limit above which more secondary electrons are expelled from the surface than the number of impinging primary electrons.

and escape without energy loss. This process is particularly relevant at very low incident energies and can be empirically described by [10]:

$$\delta_{\text{elast}} = R_0 \left(\frac{\sqrt{E} - \sqrt{E + E_0}}{\sqrt{E} + \sqrt{E + E_0}} \right)^2, \quad (2)$$

where R_0 represents the reflection probability for zero-energy electrons and E_0 characterizes the skewness of the elastic component. (ii) True secondary emission results from energy transfer from the incident electron to the solid, exciting plasmons or lattice electrons that subsequently decay by emitting so-called true secondary electrons (TSE) [7,8]. This contribution is commonly parametrized by the empirical expression [11,12]:

$$\delta_{\text{true}} = \delta_{\text{max}} \frac{s \frac{E}{E_{\text{max}}}}{s - 1 + \left(\frac{E}{E_{\text{max}}} \right)^s}, \quad (3)$$

where δ_{max} denotes the maximum SEY, occurring at the primary electron energy E_{max} , and the parameter s controls the skewness of the curve.

For completeness, inelastically backscattered electrons may also contribute to the total SEY. However, in the low-energy regime relevant to this work, these electrons cannot be experimentally distinguished from true secondary electrons and are therefore implicitly included in the δ_{true} contribution.

Based on the above-mentioned model, a large set of laboratory studies was conducted to assess these parameters for different technical surfaces and their evolution with electron dose and primary electron incidence angle [13–18]. Complementary to these studies, dedicated *in situ* conditioning experiments have been carried out at EPA [19]—studying photoemission yield evolution with photon dose—PEP-II [20]—where material samples were inserted in the beamline, exposed to beams and tested back in the laboratory on a regular basis—or at CESR-TA [21]—where a manipulator and electron gun were directly mounted onto the chamber to allow direct *in situ* SEY measurements. Such measurements, however, are typically limited to access periods and can only be performed at intervals of several months for PEP-II and approximately one week for CESR-TA. In parallel, detailed electron cloud simulation tools, such as PyECLOUD [22,23], as well as iterative analytical approaches including the cubic map model (MAPS) [24–26], have been developed to reproduce and predict electron cloud buildup under successive bunch passages.

In this paper, we present a novel technique to estimate the *in situ* maximum SEY, δ_{max} , and thereby to monitor the conditioning evolution of accelerator vacuum surfaces. The method is based on measurements performed in the LHC Vacuum Pilot Sector (VPS) combined with PyECLOUD simulations [27]. In contrast to *in situ* SEY measurements carried out at other institutes, the proposed approach relies exclusively on electron cloud intensity measurements and does not require surface sample manipulation or electron-gun irradiation. The technique can be applied during routine accelerator operation, provided that the injected beam parameters are sufficient to induce measurable electron cloud formation during injection.

II. EXPERIMENTAL APPARATUS

A. Overview of the VPS

The VPS is an 18 m-long, fully instrumented test section installed in long straight section 8 (LSS8) of the LHC, between the Q4L8 and Q5L8 quadrupoles. It is specifically designed to investigate electron cloud formation and beam-surface interactions under realistic beam and synchrotron-radiation conditions at room temperature [27,28]. As illustrated in Fig. 2, the VPS comprises four experimental stations equipped with beam pipes made of different materials: an *ex situ* activated nonevaporable getter (NEG) coating—activated at the laboratory, vented with N_2 and installed in the tunnel—and a 500 nm thick amorphous carbon coating (Stations 1 and 2, respectively), as well as two bulk copper liners installed in 2015 (Station 3) and 2014 (Station 4). This configuration enables a direct comparison of surface responses under identical beam conditions. The stations are separated by *in situ* activated NEG-coated buffer sections that provide

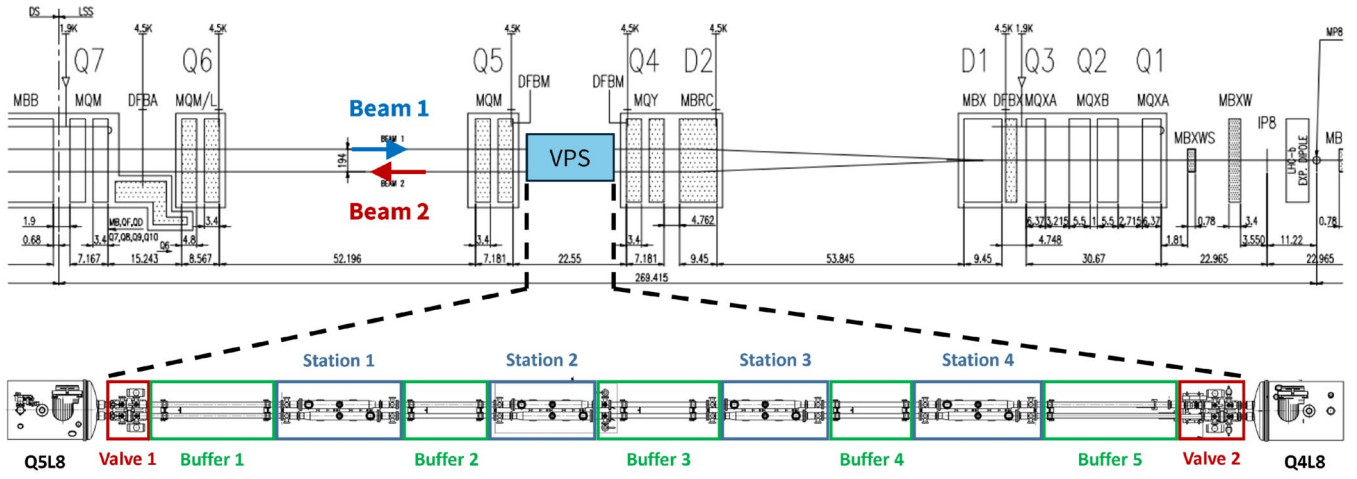


FIG. 2. The VPS setup location within LSS8. VPS consists of four stations—*ex situ* activated NEG coating (1), 500 nm-thick amorphous carbon coating (2), bulk copper (3 and 4)—separated by NEG buffers. Blue and red beams are physically separated, circulating, respectively, toward and from IP8.

pressure decoupling. After installation in the tunnel, a mild bakeout ($\sim 80^\circ\text{C}$) was applied along the VPS, and the buffer was activated at 200°C for 24 h before cooling the entire system to room temperature.

Both LHC beams traverse the VPS: beam 1 (blue) and beam 2 (red), circulating in opposite directions. This layout allows the study of possible asymmetries arising from differences in optical configuration and synchrotron-radiation illumination. For beam 1, synchrotron radiation predominantly originates from the LHC bending dipoles in arc 78, with a critical photon energy of approximately 44 eV at the nominal LHC energy of 7 TeV. For beam 2, the dominant contribution arises from the separation dipole D2, with a lower critical energy of about 20 eV.

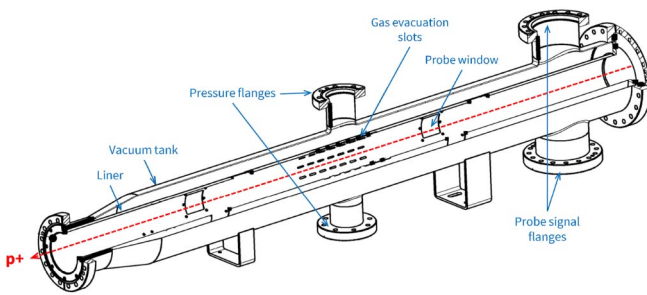


FIG. 3. Schematic of the assembled VPS vacuum chamber. A liner is enclosed in a vacuum tank, releasing pressure rises through gas evacuation slots and providing probing windows for electron cloud characterization or thermal rises assessment. Gas is analyzed via instruments located at pressure flanges, providing partial (top) and total (bottom) pressures. Communication signals between probes and measuring/supplying instruments pass through probe signal flanges. Temperature signals are routed to the top flange while all other signals exit via the bottom flange.

A schematic of the vacuum chamber assembly is shown in Fig. 3. At its core is the beam pipe, called *liner* in the specific case of VPS, the beam-facing component whose surface treatment and coating vary between stations. Each liner is enclosed in a vacuum tank, into which the gas molecules enter through 84 gas slots (1.2 cm long, 3 mm wide). Partial and total pressures are measured by dedicated gauges mounted on the central upper and lower flanges, respectively. Each liner includes several square probe windows to accommodate diagnostics for electron cloud detection and thermal response analysis. Stations 1 to 3 have 6 probe windows, while Station 4 has 8, each

TABLE I. Main technical parameters of VPS stations. Inner/outer values are given for the diameters of the different parts.

Part	Parameter	Value
Liner	Length	1.37 m
	Diameter	80 mm/82 mm
	Volume	6.9 L
	Number of gas evacuation slots	84
	Gas evacuation slot area	0.36 cm ²
	Number of probe windows (Station 1–3/4)	6/8
	Probe window area	18.2 cm ²
	Diameter upstream	135.7 mm/139.7 mm
	Diameter downstream	100 mm/103 mm
	Volume	23.1 L
Vacuum chamber	Pressure and probe exit cylinders length	70 mm
	Pressure exit cylinder diameter	60 mm/63 mm
	Probe exit cylinder diameter	10 mm/10.3 mm

with an area of approximately 18.2 cm^2 . Table I summarizes the key geometric and vacuum specifications of the VPS stations. Notably, the liner's inner diameter is 8 cm, which is twice the standard LHC arc beam screen diameter of approximately 4 cm.

To characterize the electron cloud, the VPS integrates a comprehensive suite of diagnostics: (i) Scopes and electron pickups—electron flux measurements at the nanosecond scale and averaged over 20 ms, respectively. (ii) Retarding-field analyzers—measuring the energy distribution of electrons impinging on the walls. (iii) Photodetectors—quantifying synchrotron-radiation flux and enabling extraction of photoelectron yields. (iv) Calorimeters—monitoring local power deposition from electron cloud heating. (v) Bayard-Alpert gauges and residual gas analyzers—recording, respectively, total and partial pressures for assessing electron-stimulated desorption.

B. Scopes and electron pickups

In the present study, only diagnostics measuring electron cloud currents were used. All results reported here correspond to measurements performed at Station 3, the bulk copper liner installed in 2015.

The measurement setup for scopes and electron pickups is schematically shown in Fig. 4. Both diagnostics rely on copper electron collectors positioned behind a square grounded copper grid of side 3.45 cm and a transparency of 7%. The collector is positively biased at +9 V in order to recapture secondary electrons generated locally at the collector surface. Assuming normal incidence of electrons on the beam-pipe walls—a reasonable approximation in the magnetic field-free region of the VPS—the collected signals can be converted into surface electron fluxes as follows.

(i) Electron pickups provide time-averaged measurements over a 20 ms integration window, corresponding to approximately 200 LHC turns, on a Keithley 6517B picoammeter. The collected surface electron flux I_{e^-} is given by

$$I_{e^-} [\text{A cm}^{-2}] = \frac{\alpha_{\text{bias}} \times I_K [\text{A}]}{A_{\text{eff}} [\text{cm}^2]}, \quad (4)$$

where I_K is the current measured on the collector, and $A_{\text{eff}} \approx 0.83 \text{ cm}^2$ is the effective collection area accounting for both the collector surface and grid transparency. $\alpha_{\text{bias}} \approx 1.30$ corrects for secondary electrons escaping the +9 V bias field, assuming a total collection for +100 V (see Appendix A). Typical measured fluxes range from a few tenths of nA cm^{-2} , corresponding to the lower detection limit, up to several tens of $\mu\text{A cm}^{-2}$.

(ii) Scopes provide time-resolved electron cloud measurements at the nanosecond scale on a Teledyne LeCroy WR620Zi oscilloscope. The collector signal is amplified by an rf module with a bandwidth of 1.5 kHz–57 MHz (at –3 dB) and a gain of $G_{\text{amp}} = 18 \text{ dB}$. The corresponding surface electron flux I_{scope} is obtained from

$$I_{\text{scope}} [\text{A cm}^{-2}] = \frac{\alpha_{\text{bias}} \times U_{\text{scope}} [\text{V}]}{G_{\text{amp}} \times Z_{\text{cable}} [\Omega] \times A_{\text{eff}} [\text{cm}^2]}, \quad (5)$$

where U_{scope} is the voltage measured by the oscilloscope and $Z_{\text{cable}} = 50 \Omega$ is the characteristic impedance of the coaxial cable. In practice, oscilloscope signals are typically of the order of a few tens of millivolts, corresponding to surface electron fluxes of several tens of $\mu\text{A cm}^{-2}$.

C. Data acquisition and management

A dedicated data acquisition and processing infrastructure was developed for VPS. A network of five dedicated computers, running custom LabVIEW and PowerShell-based routines, collects and formats data from dozens of instruments at 1-min intervals. These routines ensure synchronized data acquisition, consistent file management, and reliable identification of operational states (e.g., beam injection, ramp, stable beams). Postprocessing includes timestamp alignment, format normalization, automatic plotting, and metadata extraction—including LHC beam properties and total electron dose estimates.

The presented results are extracted from a dataset of over 7000 formatted fills acquired by the VPS from 2015 to 2025.

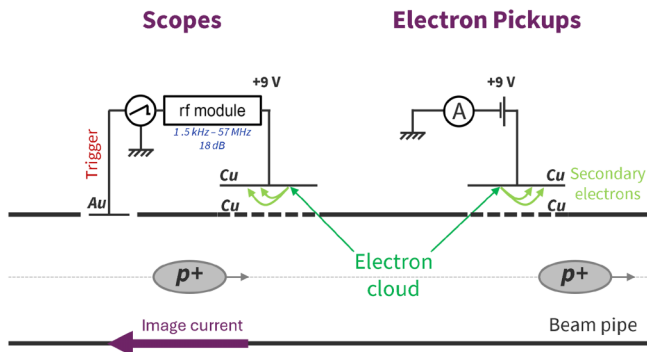


FIG. 4. Electric scheme of scopes and electron pickups.

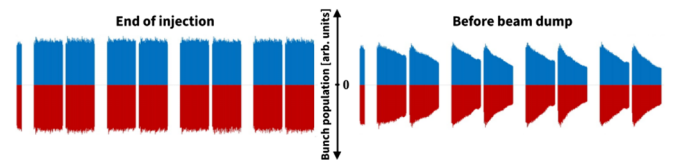


FIG. 5. Evolution of bunch populations during Fill 10621 for the first 588 bunches: one 12b batch + four trains of two 72b batches. Comparison of injection (left) and predump (right) phases. Triangular depletion patterns are characteristic of multipacting-driven proton loss.

III. LINEARITY OF ELECTRON CLOUD FLUXES WITH THE NUMBER OF INJECTED BUNCHES

A. Electron cloud buildup observed bunch by bunch

Figure 5 shows the evolution of the filling scheme during Fill 10621, a scrubbing fill specifically designed to stimulate electron cloud formation. The main beam parameters of reported fills can be found in Appendix B. In addition to the expected uniform proton burn-off, the nonuniform proton-loss pattern visible along the bunch trains is characteristic of the underlying electron cloud density evolution, as routinely observed by beam operators on a bunch-by-bunch basis. This behavior is marked by negligible electron cloud densities for the first injected bunches, followed by a progressive increase in losses along the batches of a train, with intensities rising from the head to the tail of each batch in an approximately increasing triangular trend. Electron cloud densities are further observed to increase from one train to the next until a quasiequilibrium regime is reached, in which the density evolution becomes reproducible across successive trains. In the specific case of Fill 10621, significant electron cloud effects appeared after the injection of the first 12-bunch batch, while a quasiequilibrium was established after the third train, from which electron cloud-induced proton-loss patterns became reproducible across successive trains with comparable intensities, corresponding to a total of approximately 300 injected bunches.

These qualitative expectations, inferred from the proton-loss patterns shown in Fig. 5, were directly confirmed by nanosecond-scale measurements performed with the VPS scopes during fills in which electron cloud was significantly stimulated. As an illustrative example, Fig. 6 presents the electron cloud buildup observed during Fill 11018 at the end of the injection phase. The fill was performed using HL-LHC standard beam parameters and

trains composed of 72-bunch batches. The figure focuses on signals recorded in Station 3 blue beamline, showing both the evolution over the first train, composed of four batches, and a detailed view of its last batch. For reference, the bunch pattern as captured by the oscilloscope is displayed in the upper panel. The timing alignment between the bunch signal and the electron cloud signal was achieved by correcting for differences in cable lengths.

At injection energy (450 GeV), synchrotron radiation is negligible and no photoelectrons are produced. Consequently, the observed electron cloud currents originate exclusively from multipacting initiated by primary electrons generated through residual-gas ionization.

Multipacting was already observed to develop toward the end of the first 72-bunch batch and reached a stationary regime during the second batch. Subsequent batches exhibited similar behavior, characterized by a sigmoidlike rise of the electron cloud current, followed by saturation after approximately 30 bunches within each batch. Notably, similar evolutions could be observed with direct electron cloud measurements in the CERN PS [29]. The beam time structure was found to play a decisive role in the observed multipacting dynamics. The long gap of 1623 empty rf buckets ($40.575 \mu\text{s}$) between the last and first bunch of successive turns efficiently cleared the vacuum chamber of electrons, rendering the build-up process effectively turn-independent. Similar clearing behavior was observed for shorter gaps down to 129 empty rf buckets ($3.225 \mu\text{s}$) [27], which are closer to typical physics filling schemes. In contrast, the much shorter inter-train gap of seven empty rf buckets (175 ns) allowed a stationary electron cloud regime to develop after approximately 144 injected bunches. Once this regime is reached, the resulting electron cloud current scaled linearly with the number of injected batches. This linearity constitutes the physical basis of the *in situ* δ_{max} determination method presented in the following section.

Qualitative validation of the observed bunch-by-bunch buildup was obtained using both the MAPS numerical model and PyECLOUD simulations by adjusting the surface-emission parameters used as inputs. Parameters used in Fig. 6 are listed in Table II. To facilitate visual comparison on the same scale with measured signals, the simulated electron cloud saturation levels were scaled by multiplicative factors of approximately ~ 50 for MAPS and ~ 6 for PyECLOUD. These factors are introduced solely for this purpose; establishing quantitative agreement on absolute amplitudes would require dedicated work beyond the scope of this study. (i) MAPS—The initial electron density was set to 3% of the saturation value. The model successfully reproduced the signal evolution across the batch. The MAPS coefficients a_{map} and b_{map} were then obtained from their relations to the surface parameters, fixing $c_{\text{map}} = 0$, as given in Appendix C. (ii) PyECLOUD—The simulated currents were passed

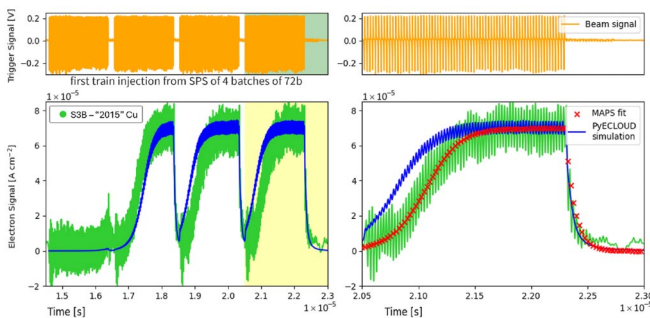


FIG. 6. Close-up of Fill 11018 Station 3 blue beamline scope signals on the first train (left) and its last 72b batch (right). Electron signals (light green) are fitted with PyECLOUD simulations (blue) and MAPS numerical model (red), with additional multiplication by ~ 6 and ~ 50 , respectively, to best match measurements. Fitted surface parameters are listed in Table II.

TABLE II. Surface-emission parameters from MAPS and PyECLOUD fits to Fill 11018 (Station 3, blue beamline). MAPS fits correspond to the last batch of the first 72b train. Saturation was set to the average of the last three bunches; initial density fixed at 3% of saturation. Equivalent MAPS coefficients are: $a_{\text{map}} \approx 1.16$, $b_{\text{map}} \approx -2342$, and $c_{\text{map}} = 0$. The TSE mean energy $\bar{E}_{\text{TSE}}$ is computed considering a lognormal distribution of parameters $\mu_{\text{TSE}} = 1.0828$ and $\sigma_{\text{TSE}} = 1.6636$.

Emission type	Symbol	MAPS	PyECLOUD	Unit
Elastic reflection	R_0	0.5	0.8	e^-/e^-
	E_0	30	50	eV
True secondary	δ_{max}	1.21	1.21	e^-/e^-
	E_{max}	200	210	eV
	s	1.24	1.13	...
	$\bar{E}_{\text{TSE}}$	12	12	eV

through a 40 MHz low-pass filter to reproduce the measurement bandwidth. The model captures reasonably well the signal evolution over the full train, despite minor discrepancies in the saturation timing: saturation is achieved slightly later than observed for the second batch, and slightly earlier for the last two batches.

Both approaches yielded consistent surface parameters, in good agreement with values reported in the literature for copper surfaces, as summarized by Haubner [18]. In particular, the fitted value of $\delta_{\text{max}} \approx 1.2$ is consistent with expectations for conditioned copper [13–16] and agrees with the independent *in situ* δ_{max} determination presented in Sec. IV. The elastic reflection parameters extracted from MAPS, however, deviate from standard reference values, likely reflecting limitations of the model in describing the postbatch decay of the electron cloud.

B. Electron cloud intensity measurements with the electron pickups

Figure 7 shows the electron cloud currents measured by the electron pickups in the Station 3 blue beamline as a function of the number of injected bunches during the injection phase of Fill 8872, a representative LHC physics fill in early Run 3 (2022–2023). In agreement with the nanosecond-scale observations discussed above, electron cloud intensity remained negligible—below the VPS detection threshold of approximately 0.1 nA cm^{-2} , while primary electrons originating from gas ionization were expected to represent less than 0.1 pA cm^{-2} —up to a certain number of injected bunches, here around 200. Beyond this point, the measured current increased sharply before transitioning into a well-defined linear regime.

This linear regime is characterized by a slope α , readily identifiable on a linear-linear scale, and by a threshold number of injected bunches N_{th} , more clearly determined on a logarithmic scale. In the case shown in Fig. 7, α is

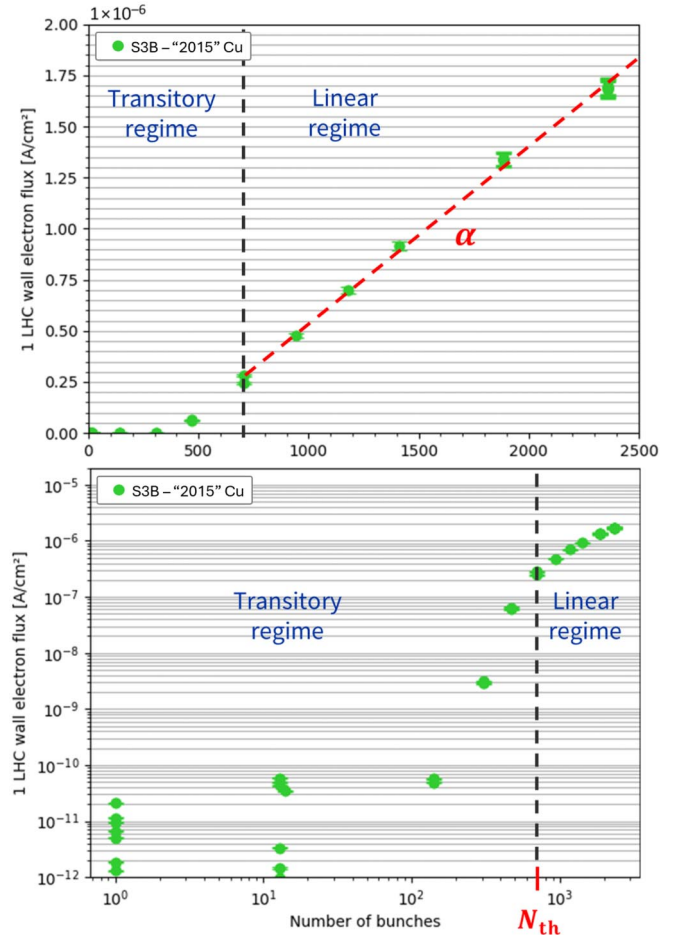


FIG. 7. Electron cloud intensities as a function of the number of injected bunches, measured on Station 3 blue beamline electron pickups during Fill 8872 injection phase. Measurements are displayed in linear-linear (top) and log-log (bottom) scales to exhibit the linear coefficient $\alpha \approx 0.9 \text{ (nA cm}^{-2}\text{)/bunch}$ and the linear regime threshold $N_{\text{th}} \approx 700$ bunches, respectively.

approximately $0.9 \text{ (nA cm}^{-2}\text{)/bunch}$, while N_{th} is close to 700 bunches.

Parametric studies performed with PyECLOUD, detailed in Appendix D, demonstrated that the slope α depends on the full set of surface-emission parameters, whereas the threshold N_{th} is predominantly governed by the value of δ_{max} and is largely insensitive to variations in other model inputs. Consequently, identifying the threshold number of injected bunches provides a direct experimental handle for determining δ_{max} for a given fill.

IV. LHC IN SITU δ_{max} DETERMINATION

The method for determining δ_{max} is based on comparing PyECLOUD simulations with electron pickup measurements during the injection phase of a given fill. The methodology consists of the following steps: (i) PyECLOUD simulations—Simulations are performed for a specific filling scheme, using the beam parameters

corresponding to the fill under investigation. Since simulations are computationally expensive, priority is given to filling schemes and beam parameters frequently used, so that several fills can be analyzed from a single simulation set. Simulations are carried out with injection beam parameters and surface parameters within standard ranges (here $R_0 = 0.7$, $E_0 = 150$ eV, $E_{\max} = 332$ eV, and $s = 1.35$), while only varying the $\delta_{\max}$ parameter. Primary electron generation is assumed to originate solely from proton ionization in pure hydrogen gas at 2 nTorr pressure and 293.15 K, with a cross section of 0.36 Mbarn. (ii) Electron current versus number of injected bunches plot—The electron currents are plotted as a function of the number of injected bunches. For PyECLOUD simulations, the injection currents [I_{inj} , Eq. (6)] are obtained by integrating the simulated current [I_{sim} , Eq. (7)] up to the arrival time of the i th bunch, t_i , and normalizing to the LHC revolution period $\Delta t_{\text{LHC}} \approx 89$ μs :

$$I_{\text{inj}}(t_i) = \frac{1}{\Delta t_{\text{LHC}}} \int_{t_0}^{t_i} I_{\text{sim}}(t) dt, \quad (6)$$

$$I_{\text{sim}}(t) [\text{A m}^{-2}] = \frac{N_{e^-}(t) [\text{e}^- \text{m}^{-1}]}{\Delta t [\text{s}]} \times \frac{e [\text{C}]}{2\pi b [\text{m}]}, \quad (7)$$

where N_{e^-} is the PyECLOUD output linear number of electrons reaching the beam-pipe walls of radius b between $t - \Delta t$ and t , and $\Delta t = 25$ ps corresponds to the simulation time step. This procedure effectively truncates the secondary electron current after the i th bunch, which in principle would be included in a simulation containing only i bunches within one LHC turn. However, the associated error is minimized since the results are analyzed on logarithmic scales. (iii) $\delta_{\max}$ determination—The $\delta_{\max}$ parameter can be retrieved by determining the PyECLOUD curve for which the number of bunches needed to reach the linear regime, N_{th} , approaches most closely the one from the measured curve. As illustrated in Fig. 8, N_{th} monotonically decreased from 1000 to 100 with the $\delta_{\max}$ increase from 1.17 to 1.30. In other words, it takes fewer bunches to reach the electron cloud build-up stationary regime for higher $\delta_{\max}$. Conversely, lower $\delta_{\max}$ values corresponded to higher N_{th} . This imposes a limitation: since the maximum number of bunches that can be injected in the LHC is limited (2556 bunches), very low $\delta_{\max}$ values cannot be resolved without stronger multipacting conditions. This could be achieved by increasing batch sizes, adding more batches per train, or changing the average bunch population to stimulate multipacting and probe lower $\delta_{\max}$.

In the present work, the threshold N_{th} is extracted graphically from the electron current versus injected-bunch curves. Uncertainties on the determined $\delta_{\max}$ values are conservatively estimated as the difference between the two bracketing simulated curves. While this approach has

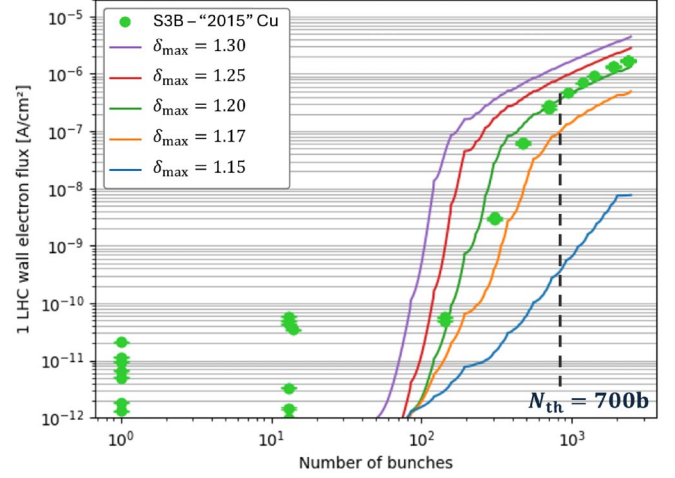


FIG. 8. $\delta_{\max}$ determination of the Station 3 surface (copper “2015,” green dots) during Fill 8872. Plain lines correspond to PyECLOUD-simulated curves for $\delta_{\max}$ varying from 1.15 to 1.30. Linear regime threshold number of injected bunches is displayed in black, $N_{\text{th}} = 700$ bunches.

proven robust, the development of a systematic and mathematically defined procedure for extracting N_{th} would further improve the reliability of the method and the confidence associated with the extracted $\delta_{\max}$ values. Note that no additional factor was used, unlike for Fig. 6, as N_{th} is a feature of the horizontal axis, entirely independent of signal amplitude.

As a representative example, for Fill 8872 the measured threshold $N_{\text{th}} = 700$ bunches for the copper Station 3 blue beamline lies between the simulated curves corresponding to $\delta_{\max} = 1.17$ and $\delta_{\max} = 1.25$. A graphical interpolation yields $\delta_{\max} = 1.21 \pm 0.04$. Notably, simulations performed with $\delta_{\max} = 1.15$ do not exhibit a clear linear regime for this filling scheme, indicating a practical detection limit of approximately $\delta_{\max} = 1.16$ for the present filling pattern and beam parameters. Furthermore, when $\delta_{\max}$ approaches this limit, electron cloud intensities become extremely sensitive to small variations in $\delta_{\max}$, with changes of only a few hundredths leading to variations in current of several orders of magnitude.

Figure 9 shows the evolution of $\delta_{\max}$ as a function of the cumulative electron dose during 2022. The same procedure as above was applied to all liners. The cumulative dose, expressed in C mm^{-2} , was calculated by integrating the electron currents recorded over all fills, setting the origin at the beginning of the year. The year 2022 was chosen as it followed the LHC recommissioning after long shutdown 2 (LS2, from January 2019 to April 2022), when surfaces could undergo significant deconditioning during the shutdown period, thus allowing conditioning effects under beam exposure to be clearly observed.

Conditioning curves revealed strong surface conditioning within the first 2 mC mm^{-2} , approaching saturation thereafter. In the blue beamline, the *ex situ* activated

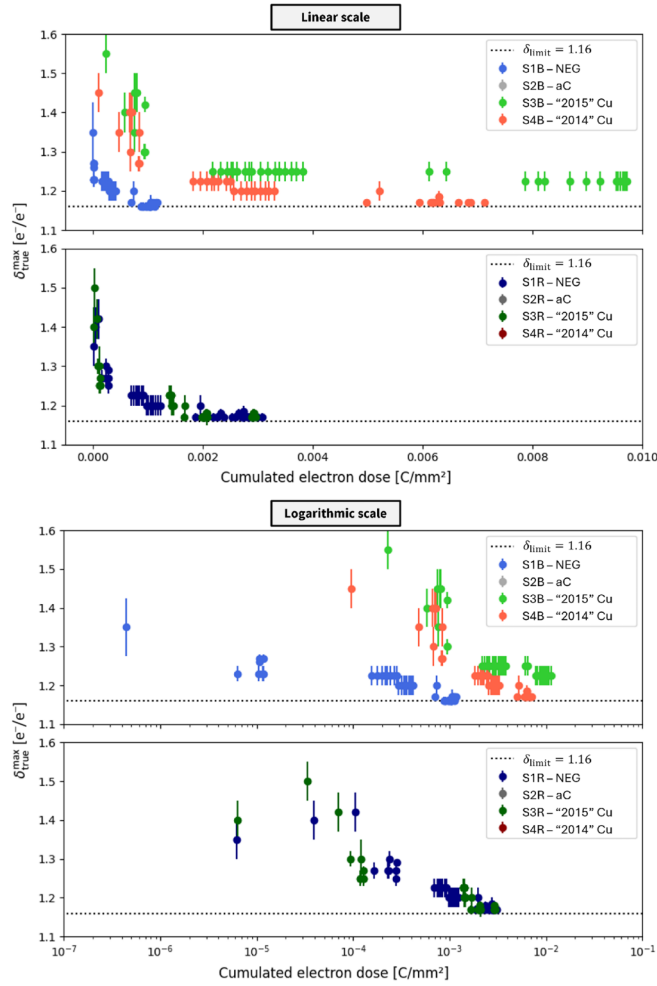


FIG. 9. Evolution of the $\delta_{\max}$ parameter as a function of the cumulative electron dose during year 2022 in linear (top) and logarithmic (bottom) scales. Electron dose origin is set at the beginning of year 2022. Blue beamline liner values are represented in the top frame, and red beamline values in the bottom frame. $\delta_{\max}$ parameter of the amorphous carbon station could not be assessed as it was below the method's determination limit. No data were available for the station 4 (copper "2014") red beamlines.

NEG-coated liner conditioned more rapidly than the copper liners, which displayed slightly different behaviors, converging to higher $\delta_{\max}$ values for Station 3 (~ 1.20) compared to Station 4 (~ 1.16 or below). In the red beamline, both *ex situ* activated NEG and copper "2015" liners exhibited similar conditioning trends, converging below the detection limit of 1.16. Their conditioning was slower than that of the blue NEG liner but faster than that of the blue copper "2015" liner (Station 3). Similar conditioned results were found during years 2023–2025 physics fill campaigns, within variations of a few hundredths. This is particularly the case for Fill 11018, which exhibited a $\delta_{\max} \approx 1.20$ in the blue beamline of copper "2015," consistently with $\delta_{\max}$ derived from MAPS and PyECLOUD fits (cf. Table II).

These results are consistent with conditioning values reported in the literature, ranging from 1.1 to 1.3 for conditioned copper, where variations are attributed to differences in surface cleaning, storage history, or the energy of the conditioning electrons [13–16]. Indeed, differences in electron cloud dynamics among the various copper liners have been observed [27], with both qualitative and quantitative discrepancies in the electron cloud energy distributions, which will be addressed in a forthcoming publication.

Finally, it should be noted that the applicability of the present method requires sufficiently strong multipacting at injection. This condition is often not met immediately after Year-End Technical Stops (YETS) or shorter Technical Stops, during which beam intensities and filling schemes are progressively ramped up. In addition, vacuum surfaces exhibit a memory effect, requiring lower electron doses for reconditioning. As a consequence, by the time the method becomes applicable from the beam parameter perspective, surfaces may already be close to their conditioned $\delta_{\max}$ values, limiting the ability to characterize the early stages of poststop conditioning.

V. CONCLUSIONS AND PERSPECTIVES

This paper has presented a detailed analysis of electron cloud formation during the injection phase of the LHC, combining experimental measurements obtained in the VPS with numerical modeling using PyECLOUD simulations and the MAPS analytical framework. Electron signals recorded by dedicated oscilloscopes and electron cloud pickups reveal a characteristic evolution of the electron cloud over successive injected bunches, following a sigmoidlike buildup and reaching a quasiequilibrium regime after a sufficiently large number of bunches. This behavior has been consistently observed across multiple fills and is corroborated by independent indicators, including nonuniform proton-loss patterns attributed to electron cloud effects.

The experimentally observed build-up dynamics are reproduced qualitatively by both PyECLOUD simulations and the MAPS model when appropriate surface-emission parameters are used. In particular, comparisons between measured oscilloscope signals and simulated electron cloud currents yield fitted values of the maximum secondary electron yield of approximately $\delta_{\max} \approx 1.2$ for conditioned copper surfaces. These values are consistent with expectations based on laboratory measurements and are in agreement with the independent *in situ* $\delta_{\max}$ determination method developed and applied in this work.

The core contribution of this study is the introduction and demonstration of a novel technique for the *in situ* determination of $\delta_{\max}$ under operational accelerator conditions. The method exploits the transition between the initial build-up regime and the linear scaling of electron cloud intensity with the number of injected bunches.

By comparing the experimentally measured threshold number of bunches required to reach this linear regime with PyECLOUD simulations, $\delta_{\max}$ can be extracted in a systematic manner. Applying this technique to VPS data has enabled the construction of conditioning curves, showing the evolution of $\delta_{\max}$ as a function of cumulative electron dose on the vacuum chamber wall.

The resulting conditioning trends reveal a rapid reduction of $\delta_{\max}$ at low accumulated doses, followed by a slower approach to pseudosaturation. In particular, *ex situ* activated NEG-coated surfaces exhibit faster conditioning than copper surfaces, despite the absence of *in situ* activation (i.e., *in situ* bakeout). This observation is of direct relevance for the design of future accelerators, as it suggests that *ex situ* activation of NEG coatings may be sufficient, potentially eliminating the need for complex and costly *in situ* activation systems during commissioning and technical stops.

The conditioning levels obtained for copper surfaces, with $\delta_{\max}$ values ranging between approximately 1.1 and 1.3, are fully consistent with values reported in the literature. Observed variations between different liners are attributed to differences in surface preparation, storage history, and electron cloud dynamics, including differences in electron energy distributions. These aspects will be investigated in greater detail in forthcoming work.

Finally, the automation of the proposed *in situ* $\delta_{\max}$ determination method represents a promising perspective. Implemented as a routine diagnostic, it would enable quasi-real-time monitoring of surface conditioning following each injection, providing accelerator operators with immediate feedback on electron cloud activity and scrubbing efficiency. Given that the method relies solely on electron cloud intensity measurements, it is readily transferable to other accelerators equipped with electron probes. As such, it offers a powerful and versatile tool for the routine monitoring and optimization of electron cloud mitigation strategies in present and future high-intensity accelerators.

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Q. D. contributed to conceptualization, methodology, software, validation, formal analysis, investigation, data

curation, writing—original draft, and visualization. V. B. contributed to conceptualization, methodology, resources, writing—review and editing, supervision, project administration, and funding acquisition. G. S. contributed to conceptualization, methodology, writing—review and editing, and supervision.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX A: IMPACT OF THE ELECTRON PICKUPS BIAS ON THE ELECTRON-CLOUD MEASUREMENT

To quantify the electron flux per unit area, the currents measured on the pickup collectors are normalized by the effective surface area of the grid. This calculation assumes that the applied collector bias satisfies two key conditions: (i) Suppression of TSE emission: The bias must be sufficiently high to prevent underestimation of the collected electron current due to true secondary electrons escaping the collector. (ii) Minimal field perturbation: The bias must not be so high as to significantly distort the electric field inside the beam liner, which would artificially increase the effective collection area and lead to surface current overestimation.

Bilgen [30] suggested that a +100 V bias is a suitable compromise for electron pickups in the VPS, serving as the reference collection bias in this study.

Figure 10 shows a typical response of the electron pickups as a function of the applied bias, normalized to the

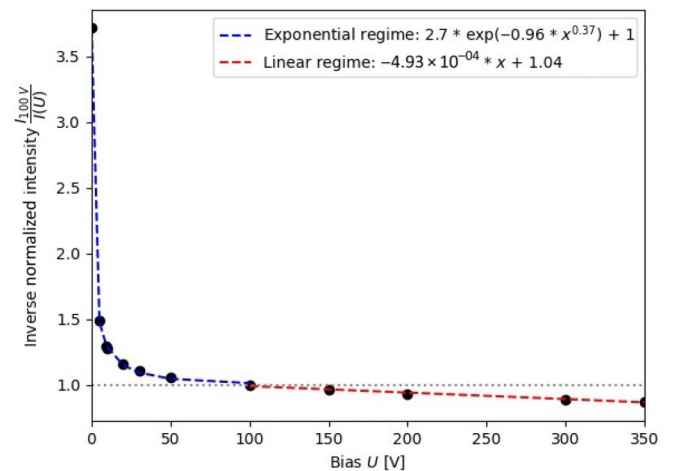


FIG. 10. Typical picoameter responses for different biases. Responses are normalized to the value obtained for a +100 V bias. The inverse of the resulting values are plotted in black. Under 100 V bias responses are fitted by an exponential function (blue dashed line), and over 100 V bias responses by a linear function (red dashed line).

response at +100 V. Inverse values are shown to exhibit the conversion function trend. Two distinct regimes are observed: (i) For biases below +100 V, the response depletes exponentially. (ii) For biases above +100 V, the response decreases linearly.

These trends, transitioning around +100 V, reinforce the idea of using +100 V as the reference bias. All collected electron currents in this study are therefore converted to their +100 V equivalent using the relation:

$$I_{\text{tot}} [\text{A}] = \alpha_{\text{bias}}(U_{\text{bias}}) \times a_K \times I_K [\text{A}], \quad (\text{A1})$$

where a_K is the Keithley calibration coefficient, I_K is the measured electron current at a bias U_{bias} , and α_{bias} is the function returning the equivalent current at +100 V, defined as follows:

For $0 \text{ V} \leq U_{\text{bias}} \leq 100 \text{ V}$:

$$\alpha_{\text{bias}}(U_{\text{bias}}) = 2.70 \times \exp(-0.96 \times U_{\text{bias}}^{0.37}) + 1.00. \quad (\text{A2})$$

For $U_{\text{bias}} > 100 \text{ V}$:

$$\alpha_{\text{bias}}(U_{\text{bias}}) = -4.93 \times 10^{-4} \times U_{\text{bias}} + 1.04. \quad (\text{A3})$$

During the YETS 2024–2025 campaign, effective collector biases have been measured and ranged from +8 to +9.2 V for channels connected to a switch. These batteries were later replaced with new +9.6 V ones. Therefore, for +9 V biases, a correction factor of $\alpha_{\text{bias}} \approx 1.31 \pm 0.03$ is used to account for the bias distribution. In the case of scope collectors, biases stayed constant (+9.5 V) over time, giving a maximum correction factor of $\alpha_{\text{bias}} \approx 1.30$.

APPENDIX B: MAIN BEAM PARAMETERS OF THE FILLS STUDIED IN THIS ARTICLE

Table III lists all fills used in the present work, together with their principal beam parameters. These fills were chosen for the following reasons: (1) Multipacting studies—Fill 10621, part of the 2025 scrubbing campaign, and Fill 11018, HL-LHC standard beam, displayed strong multipacting features. (2) Typical physics fill studies—Fills 8872, 10000, and 10866 represent standard physics fills in early (2022–2023) and mid (2024) Run 3, respectively. Each filling scheme represents one used for more

than 70% of the year’s physics fills, corresponding to more than 100–200 fills. (i) Fill 8872 is used to demonstrate the *in situ* δ_{max} determination method. (ii) Fill 10000 serves as the reference case for PyECLOUD simulations, with several parametric studies reported in this article.

APPENDIX C: CUBIC MAP COEFFICIENTS

The electron cloud density bunch-to-bunch buildup can be described locally (i.e., at an arbitrary set of points along the beam path) by a simple *cubic map* of the form [24–26]:

$$\lambda_{i+1} = a_{\text{map}} \lambda_i + b_{\text{map}} \lambda_i^2 + c_{\text{map}} \lambda_i^3, \quad (\text{C1})$$

where λ_i (respectively, λ_{i+1}) is the electron cloud density after the i th [respectively, $(i+1)$ th] bunch passage, and the coefficients a_{map} , b_{map} , and c_{map} are functions of the vacuum chamber and beam parameters and fitted from simulations.

1. The linear map coefficient

Within the chamber, two distinct electron populations contribute to the electron cloud: primary electrons—including free electrons from the remaining gas ionization and photoelectrons generated by synchrotron radiation if the beam energy is above $\sim 2 \text{ TeV}$ —and secondary electrons, produced via beam-induced multipacting. Electrons in the primary group, generated at the beam-pipe wall, interact with the parent bunch and are subsequently accelerated to a mean velocity v_{pe} [26]:

$$v_{\text{pe}} = c \frac{2\overline{N}_{\text{ppb}} r_{e^-}}{b}, \quad (\text{C2})$$

where c is the speed of light, b is the vacuum chamber radius, r_{e^-} is the electron classical radius, and $\overline{N}_{\text{ppb}}$ is the effective value of bunch population, including the bunch length σ_z and the bunch spacing σ_s [26]:

$$\overline{N}_{\text{ppb}} = N_{\text{ppb}} \frac{\sigma_z}{\sigma_z + \sigma_s}. \quad (\text{C3})$$

Electrons in the secondary group typically miss direct interaction with the parent bunch and instead move away

TABLE III. Main beam characteristics of the fills used for analysis in this chapter. Parameters include fill number, date, maximum beam energy, number of bunches per beam, average bunch population at injection, average bunch length over the fill duration, bunch spacing, and typical batch type.

Fill	Date	$E_{\text{beam}}^{\text{max}}$ (TeV)	N_b	$\overline{N}_{\text{ppb}}$ (10^{11}p^+)	$\overline{\sigma}_z$ (ns)	σ_s (ns)	Typical batch
8872	04/06/2023 13:42	0.45	2358	1.48	1.22/4	25	36b 8b4e
10000	13/08/2024 14:22	6.80	2352	1.57	1.26/4	25	36b
10621	13/05/2025 05:23	0.45	2604	1.64	1.28/4	25	72b
11018	03/09/2025 10:40	0.45	1164	2.23	1.30/4	25	72b

from the beam-pipe wall with a mean velocity v_{sec} until the next bunch arrives, defined as follows:

$$v_{\text{sec}} = c \sqrt{2 \frac{E_{\text{kin}}^{\text{sec}}}{E_0^{\text{e}}}}, \quad (\text{C4})$$

where $E_{\text{kin}}^{\text{sec}}$ is the average kinetic energy of true secondary electrons and E_0^{e} is the electron rest mass energy.

Assuming an electron transverse radial motion perpendicular to the wall, a reasonable approximation in field-free regions, an electron accelerated at a kinetic energy $E_{\text{kin}}^{\text{e-}}$ crosses the transverse radial plane in a time of flight:

$$t_{\text{F}}(E_{\text{kin}}^{\text{e-}}) = \frac{2b}{c \sqrt{2 \frac{E_{\text{kin}}^{\text{e-}}}{E_0^{\text{e}}}}}. \quad (\text{C5})$$

The linear map coefficient a_{map} is given by [24]:

$$a_{\text{map}} = \int_0^\infty \left[f_{\text{e-}} \delta_{\text{elast}}^{N_{\text{col}}} + f_{\text{e-}} \delta_{\text{true}} \delta_{\text{SEY}}^{\eta_{\text{sec}}} \frac{\delta_{\text{SEY}}^{N_{\text{col}} \eta_{\text{sec}}} - \delta_{\text{elast}}^{N_{\text{col}}}}{\delta_{\text{SEY}}^{\eta_{\text{sec}}} - \delta_{\text{elast}}} \right] \times (E_{\text{kin}}^{\text{e-}}) dE_{\text{kin}}^{\text{e-}}, \quad (\text{C6})$$

where $f_{\text{e-}}$ is the electron cloud energy distribution, $\delta_{\text{elast}} \delta_{\text{true}} \delta_{\text{SEY}}$ are, respectively, the elastic, true secondary, and total emission yields, and the notation η_{sec} is defined as follows:

$$\eta_{\text{sec}}(E_{\text{kin}}^{\text{e-}}) = \sqrt{\frac{E_{\text{kin}}^{\text{sec}}}{E_{\text{kin}}^{\text{e-}}}} \quad (\text{C7})$$

and where the number of elastic collisions N_{col} for a kinetic energy $E_{\text{kin}}^{\text{e-}}$ is given by

$$N_{\text{col}}(E_{\text{kin}}^{\text{e-}}) = \frac{2\sigma_{\text{s}} - t_{\text{F}}(E_{\text{kin}}^{\text{e-}})}{2t_{\text{F}}(E_{\text{kin}}^{\text{e-}})}. \quad (\text{C8})$$

From this expression, it is appropriate to define the parameter a_{map} as the effective secondary emission yield of the beam-pipe wall δ_{eff} , which is a function of both the chamber material properties and the beam operational parameters.

2. The quadratic map coefficient

The process of electron cloud buildup depends on two parameters [26]:

$$\kappa_{\text{map}} = \frac{\sigma_z}{b} \frac{v_{\text{pe}}}{c} \quad \text{and} \quad \zeta_{\text{map}} = \frac{\sigma_z}{b} \frac{v_{\text{sec}}}{c}. \quad (\text{C9})$$

The parameters κ_{map} and ζ_{map} characterize the distances (in units of the pipe radius b) traversed by primary and

secondary electrons, respectively, during the bunch transit time. In the regime of low currents, where $\kappa_{\text{map}} < 1$, primary electrons interact with multiple bunches before ultimately reaching the wall. Conversely, when $\kappa_{\text{map}} > 2$, primary electrons traverse the full diameter of the pipe within a single bunch transit time. The transition between these two regimes is anticipated to occur around $\kappa_{\text{map}} \sim 1$.

For $\kappa_{\text{map}} > 1$, secondary electrons are confined to a layer within $\zeta_{\text{map}} < r/b < 1$ near the pipe wall and are expelled from the region $0 < r/b < \zeta_{\text{map}}$ close to the beam by each successive bunch. Operating within the parameter range of $\kappa_{\text{map}} > 1$ and $2 - \kappa_{\text{map}} < \zeta_{\text{map}} < 1$ is highly beneficial for mitigating the adverse effects of the electron cloud on beam dynamics. In this regime, all primary electrons impact the chamber walls after a bunch passage, while the subsequently generated secondary electrons lack sufficient energy to reach the chamber center before the next bunch arrives [25]. For a fixed pipe diameter, adjusting the bunch spacing can help achieve the required condition for secondary electrons, whereas modifying the number of protons per bunch or the bunch length can satisfy the condition for primary electrons. However, it is important to note that such adjustments may not be feasible for the LHC, as the available bunch spaces are restricted to integer multiples of the fundamental 25 ns one. Additionally, altering the bunch intensity or length could lead to excessive heat loads from synchrotron radiation or beam-image currents. In this regime, secondary electrons create a space-charge energy barrier near the chamber wall, effectively trapping them. The saturation condition can be determined by ensuring that the potential barrier exceeds the electron energy at the point $r/b = 1 - \zeta_{\text{map}}$:

$$-eV(1 - \zeta_{\text{map}}) \sim E_{\text{kin}}^{\text{sec}}, \quad (\text{C10})$$

where V is the electric potential generated by the bunch the electron cloud.

This potential can be computed assuming a radial Gaussian distribution of mean and widthlike parameters r_0 and σ_0 for the electron cloud density $\lambda(r) \propto \mathcal{G}_{r_0, \sigma_0}(r)$ [26], and by introducing functions F_{map} and G_{map} :

$$F_{\text{map}}(\tilde{r}) = \tilde{\sigma}_0 \sqrt{2\pi} \int_{\tilde{\sigma}_\perp}^{\tilde{r}} \mathcal{G}_{\tilde{r}_0, \tilde{\sigma}_0}(y) y dy, \quad (\text{C11})$$

$$G_{\text{map}}(\tilde{r}) = \int_{\tilde{r}}^1 \frac{F_{\text{map}}(y)}{y} dy, \quad (\text{C12})$$

where $\tilde{r}$ and $\tilde{\sigma}_\perp$ represent the radius and beam size, respectively, reduced by the vacuum chamber radius. Similarly, $\tilde{r}_0$ and $\tilde{\sigma}_0$ denote the mean radius and the sigma of the Gaussian radial distribution of electrons, also normalized to the vacuum chamber radius.

$$\tilde{r} = \frac{r}{b} \quad \tilde{r}_0 = \frac{r_0}{b} \quad \tilde{\sigma}_0 = \frac{\sigma_0}{b} \quad \tilde{\sigma}_\perp = \frac{\sigma_\perp}{b}.$$

The potential is then given by [26]:

$$V(\tilde{r}) = \frac{e}{2\pi\epsilon_0\sigma_z} N_{\sigma_\perp, b} \left(g_{\text{map}} \ln(\tilde{r}) + \frac{G_{\text{map}}(\tilde{r})}{F_{\text{map}}(1)} \right), \quad (\text{C13})$$

where $N_{\sigma_\perp, b}$ is the total number of electrons in the cylindrical shell with radii $\sigma_\perp$, b , and height σ_z around each bunch; g_{map} is the ratio of the densities of the beam and of the cloud averaged over the beam pipe cross section.

The saturation condition (C10) provides the corresponding critical electron population within the cloud, expressed as

$$N_{\text{sat}} = \frac{F_{\text{map}}(1)}{G_{\text{map}}(1 - \zeta_{\text{map}})} \left[\frac{E_{\text{kin}}^{\text{sec}} \sigma_z}{2E_0^e r_{e^-}} - \overline{N}_{\text{ppb}} \ln(1 - \zeta_{\text{map}}) \right]. \quad (\text{C14})$$

Assuming the electrons are confined within a cylindrical shell, with an inner radius $r_0 - 3\sigma_0$ and an outer radius b , the average saturation density can be formulated as

$$\lambda_{\text{sat}} = \frac{N_{\text{sat}}}{\pi\sigma_z b^2 [1 - (\tilde{r}_0 - 3\tilde{\sigma}_0)^2]}. \quad (\text{C15})$$

Additionally, if the electrons are uniformly distributed in the region $\sigma_\perp \leq r \leq b$ the average saturation density can be written as

$$\lambda_{\text{sat}} = \frac{N_{\text{sat}}}{\pi\sigma_z b^2 [1 - \tilde{\sigma}_\perp^2]}. \quad (\text{C16})$$

Eventually, considering the saturation condition

$$\lambda_{\text{sat}} = a_{\text{map}} \lambda_{\text{sat}} + b_{\text{map}} \lambda_{\text{sat}}^2 \quad (\text{C17})$$

the quadratic coefficient is easily found:

$$b_{\text{map}} = \frac{1 - a_{\text{map}}}{\lambda_{\text{sat}}}. \quad (\text{C18})$$

APPENDIX D: ELECTRON EVOLUTION WITH MAIN SEY PARAMETERS AT INJECTION

Figure 11 shows surface electron cloud currents reaching the beam-pipe walls versus the number of injected bunches, obtained with PyECLOUD during a parametric

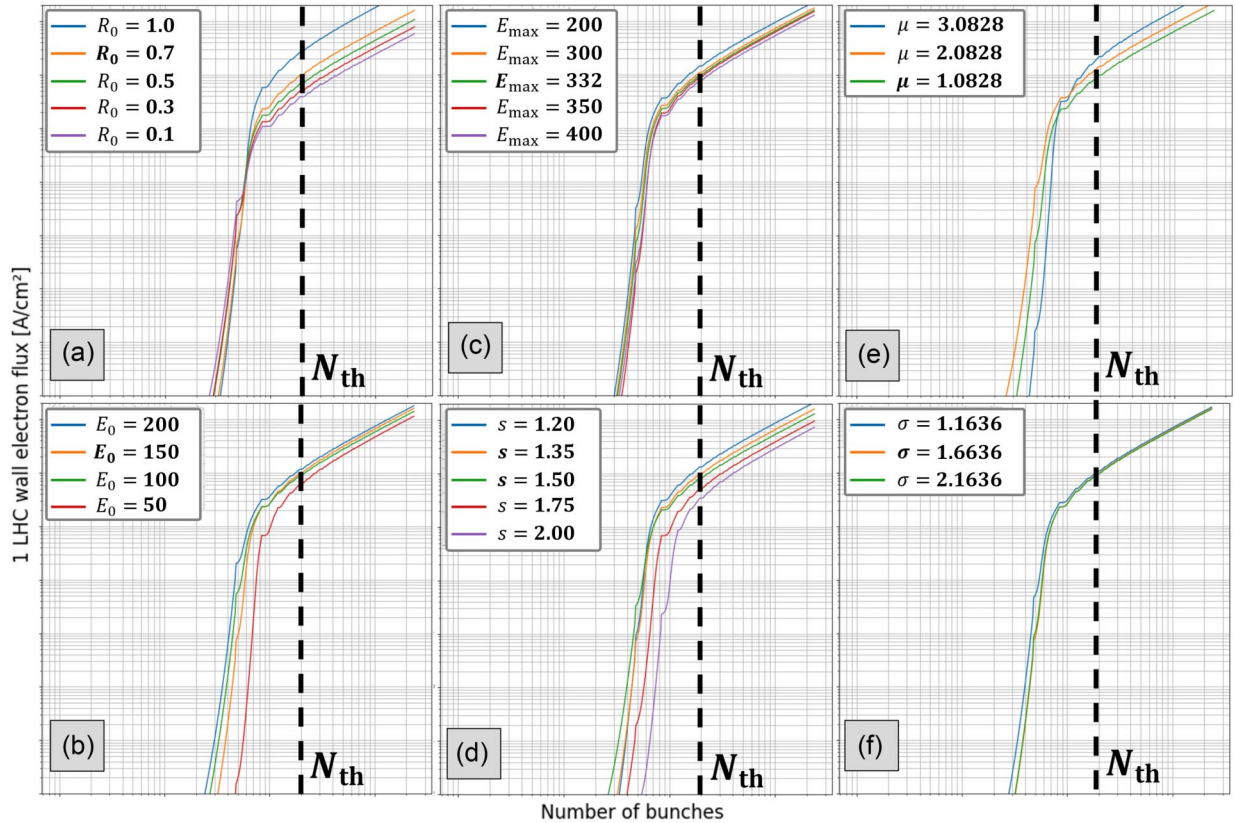


FIG. 11. PyECLOUD-based parametric studies of the surface emission model parameters on the current versus number of injected bunches. Pure-linear regime threshold N_{th} is observed constant while varying R_0 (a), E_0 (b), E_{max} (c), s (d), as well as the lognormal parameters of the secondary electron energy distribution: μ (e) and σ (f). Simulations are based on Fill 10000 and default parameters (bold) are found in Table IV.

TABLE IV. Default surface parameters for simulations on PyECLOUD [22]. R_0 is the reflectivity of electrons of 0 eV kinetic energy on a negative potential step of depth E_0 . $\delta_{\max}$ is the maximum of TSE emission, occurring at energy $\bar{E}_{\text{TSE}}$, s describing the skewness of the true SEY curve. μ and σ are the parameters of the lognormal distribution of TSE energy.

Parameter	R_0	E_0 (eV)	$\delta_{\max}$	$E_{\max}$ (eV)	s	μ	σ
Values	0.7	150	1.6	332	1.35	1.0828	1.6636

study campaign conducted on the surface emission model parameters, $\delta_{\max}$ excluded: R_0 , E_0 , $E_{\max}$, s , μ , and σ . Parameter values set as default, as listed in Table IV, and their ranges used for simulation were chosen to encompass most of the technical materials used for accelerators [18].

The graphical determination of the pure-linear regime threshold N_{th} , as presented in the article, led to the observation of iso- N_{th} for all tested parameter values. In other words, the number of bunches needed to reach the linear regime remained quasi-intensive to all the surface emission model parameters but $\delta_{\max}$. Therefore, the N_{th} determination represents a relevant metric for a good estimate of $\delta_{\max}$. However, it should be noted that quantitative evaluations of the impact of variations in these parameters on the determination of N_{th} —which must be performed together with a mathematically based protocol for estimating N_{th} —are required to provide quantitatively robust estimates of $\delta_{\max}$.

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