

Electron cloud energy distribution measurement and model in the LHC with the Vacuum Pilot Sector

Quentin Duong^{}* and Vincent Baglin^{}

European Organisation for Nuclear Research (CERN), 1211 Geneva, Switzerland

Gaël Sattonnay^{}

IJCLab, Paris-Saclay University, 91405 Orsay, France



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Electron cloud effects constitute a major performance limitation in high-intensity particle accelerators such as the Large Hadron Collider (LHC). A key ingredient for understanding and modeling these effects is the energy distribution of electrons impinging on the vacuum chamber walls. In this paper, we present direct measurements of electron cloud energy distributions obtained in the LHC Vacuum Pilot Sector (VPS) using retarding field analyzers with a beam pipe diameter of 8 cm, i.e., twice the LHC arc one. The VPS provides a dedicated, fully instrumented test environment for electron cloud studies under real LHC beam conditions. The measured energy spectra systematically exhibit a low-energy component associated with secondary electron emission and a higher-energy component originating from bunch-driven acceleration. To characterize these features, a phenomenological model is developed to reproduce the observed distributions up to 3 keV. Model parameters are extracted from a large dataset of LHC fills, with a representative 2025 physics fill used for detailed illustration. The evolution of the accelerated-electron peak is analyzed throughout the fill cycle and compared with predictions from the analytical kick approximation model. Good agreement is observed—particularly during the stable beam phase in one beamline—confirming that bunch-induced kicks dominate the electron energy gain in the field-free regions, as for the VPS. Discontinuities in the peak energy at operational transitions, as well as the recurrent observation of narrow accelerated peaks in the other beamline, are reported and suggest a dependence of the beam optics on the resulting energy gain. Finally, cumulative energy distribution functions are derived to quantify the fraction of electrons exceeding given energy thresholds. These results establish a quantitative experimental reference for energy-resolved electron cloud modeling in the LHC, providing direct inputs for electron cloud simulation benchmarking, heat load estimates, ESD modeling, and residual electron background assessment in ion diagnostics.

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I. INTRODUCTION

A. General context

First observed in the mid-1960s [1–3] and subsequently termed “bunch-induced multipactoring” at CERN [4], the electron cloud phenomenon has established itself as a major limiting factor for the performance of high-intensity proton and positron accelerators. As thoroughly surveyed by Zimmermann [5], electron cloud effects give rise to a broad spectrum of adverse consequences, ranging

from beam instabilities and losses to vacuum pressure rises and excessive heat deposition in cryogenic superconducting magnets. In the Large Hadron Collider (LHC), the electron cloud builds up through a coupled mechanism involving primary and secondary electrons. Primary electrons are produced predominantly by residual-gas ionization and, above a certain beam energy threshold, by photoemission driven by synchrotron radiation. Accelerated by the electromagnetic fields of the passing bunches, these electrons impinge on the vacuum chamber walls and release secondary electrons. Provided that the effective secondary electron yield—which accounts for both the secondary electron yield (SEY) curve and the energy spectrum of the electron cloud—exceeds unity, the electron population undergoes exponential growth through *multipacting* until saturation is reached. While SEY curve maxima could be determined using an *in situ* method presented in a previous paper [6], the present work is

*Present address: PHENIICS Doctoral School, Paris-Saclay University, 91405 Orsay, France.

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devoted to the characterization of the electron cloud energy distribution.

Direct experimental information on electron cloud energy distributions remains relatively scarce. *In situ* measurements performed at the J-PARC Main Ring [7] and at CESR-TA [8] using retarding field analyzers have shown that low-energy electrons dominate the distributions in field-free regions, while only limited high-energy contributions—typically of the order of 100 eV—could be resolved. These pioneering measurements provided important experimental benchmarks but were obtained under machine-specific conditions, motivating further studies under LHC-relevant beam parameters and vacuum chamber geometries.

First, energy-resolved measurements in the LHC Vacuum Pilot Sector were reported by Buratin [9] and Bilgen [10], who, respectively, demonstrated the feasibility of measuring electron cloud energy distributions in the Vacuum Pilot Sector (VPS) and proposed an initial descriptive model of the observed spectra. Building on this proof of principle, the present study extends and generalizes these early results by analyzing a large sample of LHC physics fills and by providing calibrated, statistically robust energy distributions with quantified uncertainties. A refined phenomenological model is developed to reproduce the measured spectra over the experimentally accessible energy range, and the evolution of the accelerated-electron component is systematically analyzed and compared with predictions from the analytical kick approximation model, using a representative 2025 LHC physics fill as a detailed case study. This comprehensive approach establishes a solid experimental reference for benchmarking electron cloud simulations and for assessing energy-dependent electron cloud effects in the LHC.

B. Kick approximation model

In the LHC, electrons gain energy through repeated electromagnetic interactions with successive proton bunches. At each bunch passage, electrons are attracted toward the center of the vacuum chamber and may reach the chamber wall before the arrival of the next bunch, provided their kinetic energy is sufficiently high. For a bunch spacing of 25 ns and a vacuum chamber diameter of 4 cm, as for LHC arc operating conditions, the minimum kinetic energy required for an electron to travel from wall to wall is approximately 30 eV.

Scott Berg [11] and Gröbner [12] proposed an analytical model to describe the energy gain of electrons as a function of their radial position inside a field-free vacuum chamber. In this framework, the transverse cross section of the vacuum chamber is divided into two distinct regions, separated by a transition radius r_c :

$$r_c = 2\sqrt{\frac{N_{\text{ppb}} r_{e^-} \sigma_z}{\pi \beta_{p^+}^2 \lambda_{\text{max}}}}, \quad (1)$$

where N_{ppb} is the number of protons per bunch, $r_{e^-} = e^2/(4\pi \times \epsilon_0 \times m_{e^-} c^2) \simeq 2.8 \times 10^{-15}$ m is the electron radius, σ_z the bunch length, β_{p^+} is the speed ratio between protons and light, and $\lambda_{\text{max}} = 1/\sqrt{2\pi}$ comes from the Gaussian distribution normalization.

These two regions correspond to distinct interaction regimes: (i) *Autonomous Regime*—a region in direct proximity to the bunch, where electrons have relatively low velocities and undergo oscillatory motion around the bunch center. (ii) *Kick Approximation Regime*—a region sufficiently far from the bunch, where electrons mainly experience a strong impulsive electric attraction during the bunch passage.

Figure 1 illustrates a vacuum chamber of radius b and the associated transition radius r_c . The energy gain ΔE_{wall} of electrons originating from the chamber wall—typically photoelectrons or secondary electrons—is given by:

$$\Delta E_{\text{wall}} = 2E_0^{e^-} \left(\frac{N_{\text{ppb}} r_{e^-}}{\beta_{p^+} b} \right)^2, \quad (2)$$

where $E_0^{e^-} = 511$ keV is the electron rest energy. On average, electrons emitted from the wall gain only one third of this maximum energy, such that $\overline{\Delta E_{\text{wall}}} = \Delta E_{\text{wall}}/3$ [13].

In the kick approximation regime, the average energy gained by electrons is expressed as:

$$\overline{\Delta E_{\text{kick}}} = 2\Delta E_{\text{wall}} \ln \frac{b}{r_c}, \quad (3)$$

while in the autonomous regime, the average energy gain is given by:

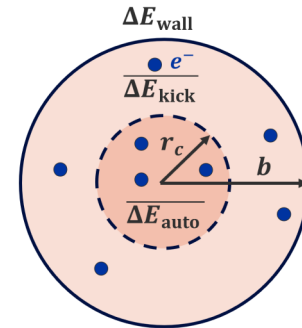


FIG. 1. Sketch of a vacuum chamber transverse section of radius b in the presence of electrons. Two kicking regimes are delimited by the transition radius r_c : the autonomous regime (dark orange) corresponding to a disk of radius r_c , and the kick regime (light orange) corresponding to the complementary area.

$$\overline{\Delta E_{\text{auto}}} = \frac{2\Delta E_{\text{wall}}}{\pi} \left(\ln \frac{r_c}{c_0 \sigma_{\perp}} - \frac{1}{2} \right), \quad (4)$$

where $c_0 \approx 1.05968$ [11] and $\sigma_{\perp}$ is the beam size.

Assuming a homogeneous radial distribution of electrons, which is a fair assumption in a magnetic field-free region, one can define an average energy gain over the whole vacuum chamber section by a simple linear combination:

$$\overline{\Delta E_{\text{tot}}} = \left(\frac{r_c}{b} \right) \overline{\Delta E_{\text{auto}}} + \left(\frac{b - r_c}{b} \right) \overline{\Delta E_{\text{kick}}}. \quad (5)$$

For completeness, the maximum energy gain possible can be estimated with Eq. (6):

$$\Delta E_{\text{max}} = 2E_0^e \frac{N_{\text{ppb}} r_{e^-}}{\sigma_z} \lambda_{\text{max}} \ln \frac{r_c}{c_0 \sigma_{\perp}}. \quad (6)$$

Notably, within the kick approximation regime, the energy gain depends solely on the beam pipe radius, the number of protons per bunch, and the beam size and is independent of both the total beam current and the beam energy.

Table II presents the expected transition radius and energy gain in the different regimes for typical LHC 2025 beam parameters, listed in Table I. Results have been computed for two beam pipe radii: the LHC arc one (2 cm) and the one relevant to this study (4 cm). The critical radius is approximately half that of the LHC arc pipe. In this case, electrons are uniformly accelerated in both the autonomous and kick regimes, reaching a total energy gain of nearly 1 keV. Conversely, for the pipe radius relevant to this study, which is twice that of the standard LHC pipe, the energy gain in the kick regime accounts for about 75% of the total energy acquired by electrons. In this larger pipe scenario, the energy gained in both regimes is

TABLE I. Beam parameters of a typical LHC physics fill for computation in Table II. The beam size taken is the same as the one used by Scott Berg [11].

Beam parameters		
$N_{\text{ppb}}(\text{p}^+)$	σ_z (cm)	$\sigma_{\perp}$ (mm)
1.6×10^{11}	37.5/4	0.2

approximately equal, transferring around 300 eV to the electrons. Finally, the maximum energy, being independent of the beam pipe radius, was expected to reach almost 8 keV in this scenario for both beam pipe radii.

II. EXPERIMENTAL APPARATUS

The VPS is an 18-m-long, fully instrumented test section installed in the LHC to characterize the electron cloud. Its description was extensively detailed in another paper dealing with *in situ* SEY determination [6].

In the present study, the diagnostics measuring electron cloud energy distribution are considered. All results reported here correspond to measurements performed at Station 4, where the beam pipes—called “liners” in the VPS context—were installed in 2014. The two liners correspond to the blue beamline (B1) and red beamline (B2), circulating clockwise and anticlockwise, respectively, when viewed from above.

A. Electron energy analyzer

The measurement principle of the electron energy analyzer is illustrated schematically in Fig. 2. The diagnostic is based on a retarding field analyzer (RFA) geometry, consisting of a copper electron collector positioned behind a grounded copper grid mounted onto the liner surface. The grid has dimensions of 3.45×3.45 cm and a transparency of 7%. A second grid, with a higher transparency of 75%, is installed between the grounded grid and the collector and is biased using a FUG HCB bipolar high-voltage power supply. This grid acts as a high-pass energy filter, allowing only electrons with kinetic energies exceeding a threshold determined by the applied bias voltage to reach the collector. Although the FUG power supply is capable of delivering voltages up to 3.5 kV, measurements are typically limited to a maximum of 1 kV. This choice is motivated by two considerations. First, the measured energy distributions systematically decrease exponentially above approximately 500 eV. Second, scans at higher voltages are time-consuming and provide limited additional information. Since no significant signal has been detected above 3 kV across multiple fills in 2025—even under conditions of pronounced electron cloud activity—the electron energy distribution measurements are restricted

TABLE II. Electron energy gain model results for standard LHC pipe radius (2 cm) and pipe radius relevant to this study (4 cm). Beam parameters listed in Table I.

Pipe radius b [cm]	Energy gain model results					
	r_c [cm]	$\overline{\Delta E_{\text{wall}}}$ [eV]	$\overline{\Delta E_{\text{kick}}}$ [eV]	$\overline{\Delta E_{\text{auto}}}$ [eV]	$\overline{\Delta E_{\text{tot}}}$ [eV]	ΔE_{max} [eV]
2	1.16	173.1	564.9	1158.4	909.4	7855.3
4	1.16	43.3	321.2	289.6	312.0	7855.3

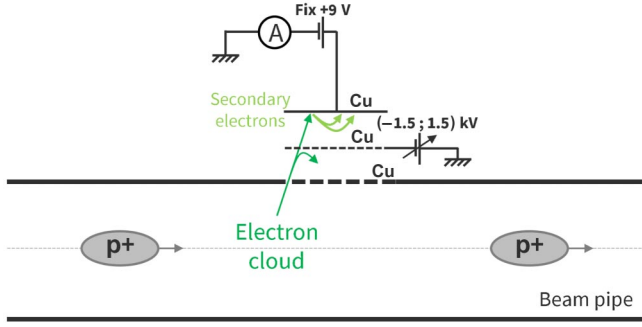


FIG. 2. Electric scheme of the RFA.

to a maximum bias voltage of 1 kV, allowing finer resolution in the sub-keV region.

The electron collector is biased at +9 V to recapture secondary electrons emitted locally from the collector surface. As a high-pass filter, the RFA transmits only electrons with kinetic energies greater than the applied grid bias eU . The electron energy distribution is therefore reconstructed numerically by differentiating the measured collector current with respect to energy. During operation, a systematic voltage offset was observed between the voltage set via the control software U_{FUG} and the actual voltage measured at the station flange. This offset amounts to $U_{\text{loss}} = 5.4$ V and is attributed to voltage drops in the cabling and connectors. In addition, the observed absolute voltage uncertainty of the FUG supply is $\delta U_{\text{FUG}} = 0.1$ V.

These effects are taken into account when computing the effective mean electron energy E_i associated with two consecutive bias steps U_i^{FUG} and U_{i+1}^{FUG} :

$$E_i = e \left| \frac{U_{i+1}^{\text{FUG}} + U_i^{\text{FUG}}}{2} - U_{\text{loss}} \right| \quad \text{and} \quad (7)$$

$$\delta E = E_{i+1} - E_i = e \times \delta U_{\text{FUG}}.$$

The electron energy distribution $f_{\text{RFA}}(E_i)$ is computed from the difference in measured currents at two successive bias points I_i^{meas} and I_{i+1}^{meas} :

$$f_{\text{RFA}}(E_i) = \frac{I_{i+1}^{\text{meas}} \times \alpha_{i+1}^{\text{bias}} - I_i^{\text{meas}} \times \alpha_i^{\text{bias}}}{e(U_{i+1}^{\text{FUG}} - U_i^{\text{FUG}})}, \quad (8)$$

where the α_i^{bias} corrects for secondary electrons escaping the effective collection bias field, as induced by both the collector bias and the negative bias of the energy filtering grid. This one was assumed to follow an exponential trend, as extensively discussed in Appendix A of Ref. [6]:

$$\alpha_i^{\text{bias}} = 2.70 \times \exp(-0.96[9 + |U_i^{\text{FUG}} - U_{\text{loss}}|]^{0.37}) + 1.00. \quad (9)$$

To facilitate comparison between measurements, the distribution is normalized using the trapezoidal rule

(Riemann sum):

$$f_{\text{RFA}}^{\text{norm}}(E_i) = \frac{f_{\text{RFA}}(E_i)}{\sum_j (E_{j+1} - E_j) \frac{f_{\text{RFA}}(E_j) + f_{\text{RFA}}(E_{j+1})}{2}}. \quad (10)$$

Typical values of the relative error δf_i^{norm} range approximately between 7% (high-energy electrons) and 55% (low-energy electrons). Further details on the related propagation of uncertainties for the spectra are discussed in the Appendix.

B. Data acquisition and management

A dedicated data acquisition and processing infrastructure was developed for VPS. A dedicated computer, running a custom voltage-scanning LabVIEW routine, continuously formats energy spectrum data collected over a 5-min scan, triggered on beam presence. Postprocessing includes timestamp alignment with metadata extraction—including LHC beam properties, such as beam energy and intensity, or bunch populations, lengths, and emittances—along with automatic plotting.

The presented results are extracted from a dataset of over 130 formatted physics fills acquired by the VPS in 2025. Particularly, Fill 10866 is taken as a representative one, with beam parameters and results shared by the other fills.

III. METHODOLOGY

Electrons circulating in the LHC exhibit a broad energy distribution. This is expected because primary electrons are generated at different positions and momenta, leading to a variety of subsequent interactions with the bunches. In addition, interactions of electrons with the chamber surface generate both elastic and inelastic emissions, further complicating the overall electron cloud dynamics and its associated energy spectrum. A precise mathematical description of this distribution is therefore extremely challenging.

This paper characterizes typical electron cloud energy distribution as measured at VPS during physics fills, using Fill 10866 results as an illustrative example, following these steps:

- (1) Observation of typical distribution types—Two characteristic patterns are consistently observed:
 - (a) A nearly constant distribution at low energies, attributable to secondary electrons.
 - (b) A high-energy distribution, either broad or narrow in shape, attributable to electrons accelerated by the bunches. Both distribution types have been observed across fills, although the physical origin of the differences between broad and narrow peaks is not yet fully understood.
- (2) Mathematical modeling of the distributions—The distributions are fitted with phenomenological

functions. These functions are not intended to describe underlying physical processes directly but rather to provide convenient inputs for simulation programs.

- (3) Tracking the evolution during the fill—Energy distributions are analyzed at different moments of the fill to monitor how they evolve with beam parameters.
- (4) Determining the proportion of electrons under or above a certain energy—Cumulative distribution functions (CDFs) are computed to provide input for extensive studies.

It is important to note that all distributions discussed here correspond to VPS Station 4 (copper “2014”), averaged over an integration time of 20 ms (i.e., corresponding to 200 LHC turns), and truncated at 3 keV. Any extrapolation to other situations of the presented results should carefully account for modifications of the electron energy gain with beam pipe radius and surface characteristics, at least.

IV. RESULTS AND DISCUSSIONS

A. Electron energy distribution model

Figure 3 presents typical energy distributions measured at Station 4, taken in the middle of the collision phase of Fill 10866. The distributions share several characteristics:

- (i) Maximal values in the low-energy range: from 0 to 1 eV.
- (ii) A decreasing trend, with a small bump—more or less

visible depending on the case—appearing just before the peak located between 100 and 300 eV. (iii) A linear decreasing trend (in log-log scale) beyond the peak.

Low-energy electrons were found to dominate the measured distributions, in agreement with previous *in situ* measurements performed in the J-PARC Main Ring [7] and CESR-TA [8], where only limited high-energy contributions, typically around 100 eV, could be resolved.

The blue beamline systematically exhibited broad peaks around 200 eV, while the red beamline alternated between broad and narrow peaks depending on the fill, or even within the same fill. No correlation could be established so far between the observed peak shape and beam parameters or other electron cloud characteristics. To provide a descriptive framework suitable for numerical simulations, the normalized measured energy distribution $f_{\text{RFA}}^{\text{norm}}$ is decomposed into a secondary electron component and an accelerated-electron component:

$$f_{\text{RFA}}^{\text{norm}} = f_{\text{SE}} + f_{\text{acc}}, \quad (11)$$

where f_{SE} corresponds to the secondary electron distribution and $f_{\text{acc}} = f_{\text{mid}} + f_{\text{peak}} + f_{\text{high}}$ represents the contribution of accelerated electrons.

Relying on the usual description of the true secondary electrons energy spectrum, the secondary electron distribution is assumed to follow a lognormal trend of parameters μ_{SE} and σ_{SE} , weighted by a factor A_{SE} :

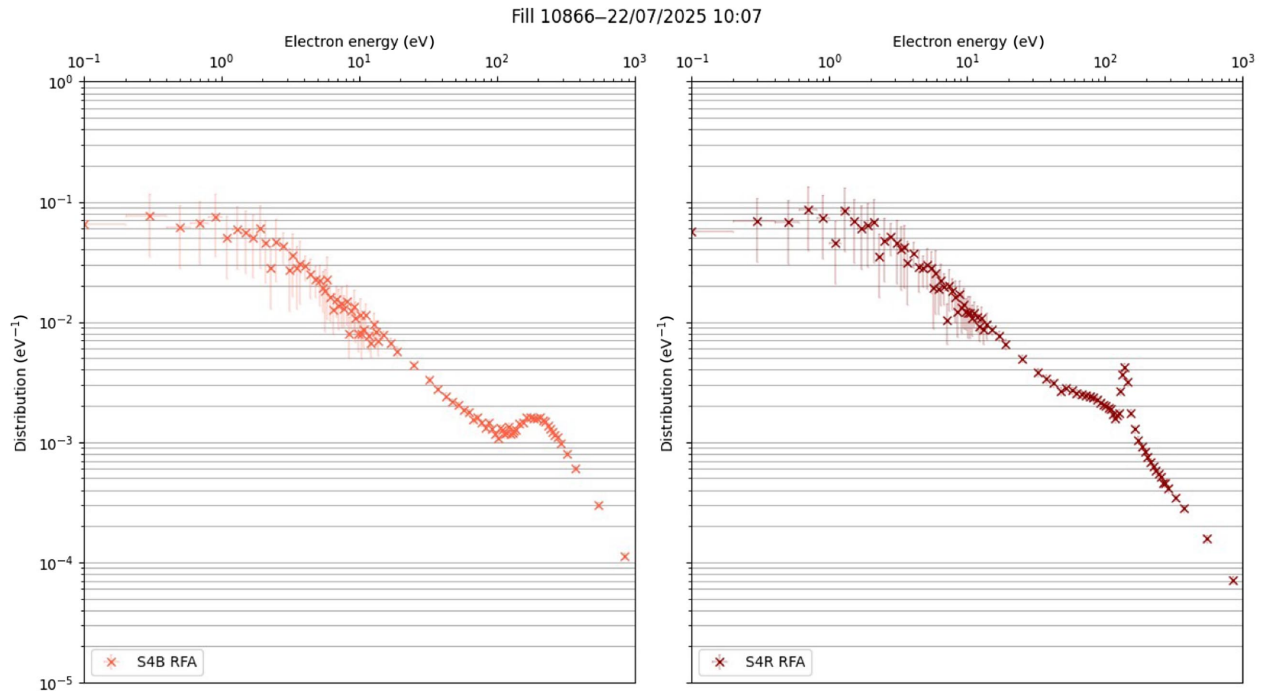


FIG. 3. Typical electron cloud normalized energy spectra in Station 4 of VPS (copper 2014), based on the one obtained in the middle of the stable beam phase of Fill 10866. Blue beamline values are plotted on the left frame (orange) and red beamline values on the right frame (dark red). The distributions are represented on a double logarithmic scale and are cut for energies under 0.1 eV and above 1 keV.

$$f_{\text{SE}}(E) = A_{\text{SE}} \times \mathcal{N}_{\mu_{\text{SE}}, \sigma_{\text{SE}}}^{\text{log}}(E), \quad (12)$$

where

$$\mathcal{N}_{\mu_{\text{SE}}, \sigma_{\text{SE}}}^{\text{log}} = \frac{1}{E \sigma_{\text{SE}} \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\ln(E) - \mu_{\text{SE}}}{\sigma_{\text{SE}}} \right)^2 \right]. \quad (13)$$

The accelerated-electron contribution is broken down into three parts: (i) f_{peak} —describing the peak located at a few hundred eV. (ii) f_{mid} —ensuring the smooth transition between the secondary and accelerated components. (iii) f_{high} —describing the high-energy tail beyond the peak.

The accelerated peak contribution is described by a lognormal function in case of a broad peak, as first modeled by Bilgen [10], or a Gaussian normalized by the error function in case of a narrow peak. In both cases, functions are parametrized by μ_{peak} and σ_{peak} parameters, weighted by A_{peak} one:

$$f_{\text{peak}}(E) = \begin{cases} A_{\text{peak}} \mathcal{N}_{\mu_{\text{peak}}, \sigma_{\text{peak}}}^{\text{log}}(E) & (\text{for broad peak}) \\ A_{\text{peak}} \frac{\mathcal{G}_{\mu_{\text{peak}}, \sigma_{\text{peak}}}(E)}{\text{erf}(E)} & (\text{for narrow peak}) \end{cases}, \quad (14)$$

where

$$\begin{cases} \mathcal{G}_{\mu_{\text{peak}}, \sigma_{\text{peak}}}(E) = \frac{1}{\sigma_{\text{peak}} \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{E - \mu_{\text{peak}}}{\sigma_{\text{peak}}} \right)^2 \right] \\ \text{erf}(E) = \int_0^E \frac{2}{\sqrt{\pi}} \exp(-t^2) dt \end{cases}. \quad (15)$$

The transition f_{mid} and high-energy f_{high} contributions are modeled by exponential functions, which allow a linear behavior in logarithmic scale (given by the parameters R_{mid} and R_{high}), but drop at characteristic energies before the peak central energy (given by the energies E_{mid} and E_{high}), with a sharpness defined by the parameters Q_{mid} and Q_{high} . These distributions are also weighted by the parameters A_{mid} and A_{high} :

$$f_{\text{mid}}(E) = A_{\text{mid}} \times \exp \left[-\left(\frac{E}{E_{\text{mid}}} \right)^{Q_{\text{mid}}} \right] \times \left(1 - \exp \left[-\left(\frac{E}{E_{\text{mid}}} \right)^{R_{\text{mid}}} \right] \right), \quad (16)$$

$$f_{\text{high}}(E) = A_{\text{high}} \times \exp \left[-\left(\frac{E_{\text{high}}}{E} \right)^{Q_{\text{high}}} \right] \times \left(1 - \exp \left[-\left(\frac{E_{\text{high}}}{E} \right)^{R_{\text{high}}} \right] \right). \quad (17)$$

Typical fit parameters are given in Table III. This description is purely phenomenological and only valid over the measured energy range (0.1 eV–1 keV).

TABLE III. List of the typical electron normalized energy spectrum fit parameters observed on several typical fills for Station 4 copper 2014. In case of typical value absence, a typical range is given instead. This is the case of the transition energies E_{mid} , μ_{peak} , and E_{high} , which strongly depend on the beam-induced kick, and thus on the beam parameters. In case of typical range absence, the related parameter was fixed to the typical value for the fits. Data point error bars-induced parameter relative errors are not included in the typical range. They correspond to 40% for A_{SE} , 20% for μ_{SE} , 5% for σ_{SE} , and are negligible for the other parameters. These parameters give the distribution shape, but they may not generate a normalized distribution. Therefore, one should divide A_{SE} , A_{mid} , A_{peak} , and A_{high} by the distribution integration value to obtain a normalized distribution.

Distribution		Parameter		
Type	Part	Symbol	Value	Range
Secondary electrons	f_{SE}	A_{SE}	0.18	[0.15; 0.21]
		μ_{SE}	−0.9	[−1.6; −0.5]
		σ_{SE}	1.6	[1.3; 1.7]
Accelerated (broad peak)	f_{mid}	$A_{\text{mid}} [\times 10^{-3}]$	2.0	[1.0; 3.0]
		E_{mid}	...	[70; 150]
		Q_{mid}	5.0	...
		R_{mid}	...	[0; 0.6]
	f_{peak}	A_{peak}	0.13	[0.11; 0.16]
		μ_{peak}	...	[5.0; 5.6]
		σ_{peak}	0.45	[0.35; 0.55]
	f_{high}	$A_{\text{high}} [\times 10^{-3}]$	0.7	[0.4; 1.0]
		E_{high}	...	[250; 500]
		Q_{high}	5.0	...
		R_{high}	2.0	...
Accelerated (narrow peak)	f_{mid}	$A_{\text{mid}} [\times 10^{-3}]$	3.0	[2.0; 4.0]
		E_{mid}	...	[90; 130]
		Q_{mid}	20.0	...
		R_{mid}	...	[0; 0.4]
	f_{peak}	A_{peak}	0.09	[0.08; 0.10]
		μ_{peak}	...	[110; 140]
		σ_{peak}	8.1	[8.0; 8.2]
	f_{high}	$A_{\text{high}} [\times 10^{-3}]$	2.0	[1.8; 2.2]
		E_{high}	...	[100; 160]
		Q_{high}	40.0	...
		R_{high}	2.0	...

Figure 4 shows an example of such fits compared with the kick approximation model: ΔE_{wall} , ΔE_{auto} , and ΔE_{kick} , respectively, Eqs. (2), (4), and (3). The fits reproduced both the low-energy secondary component and the high-energy peaks, while the analytical model provided a benchmark for bunch-driven acceleration with very good agreement of the energy gain in the kick regime for broad peaks. Overall mean energy was found to be ~ 30 eV below each energy peak mode value.

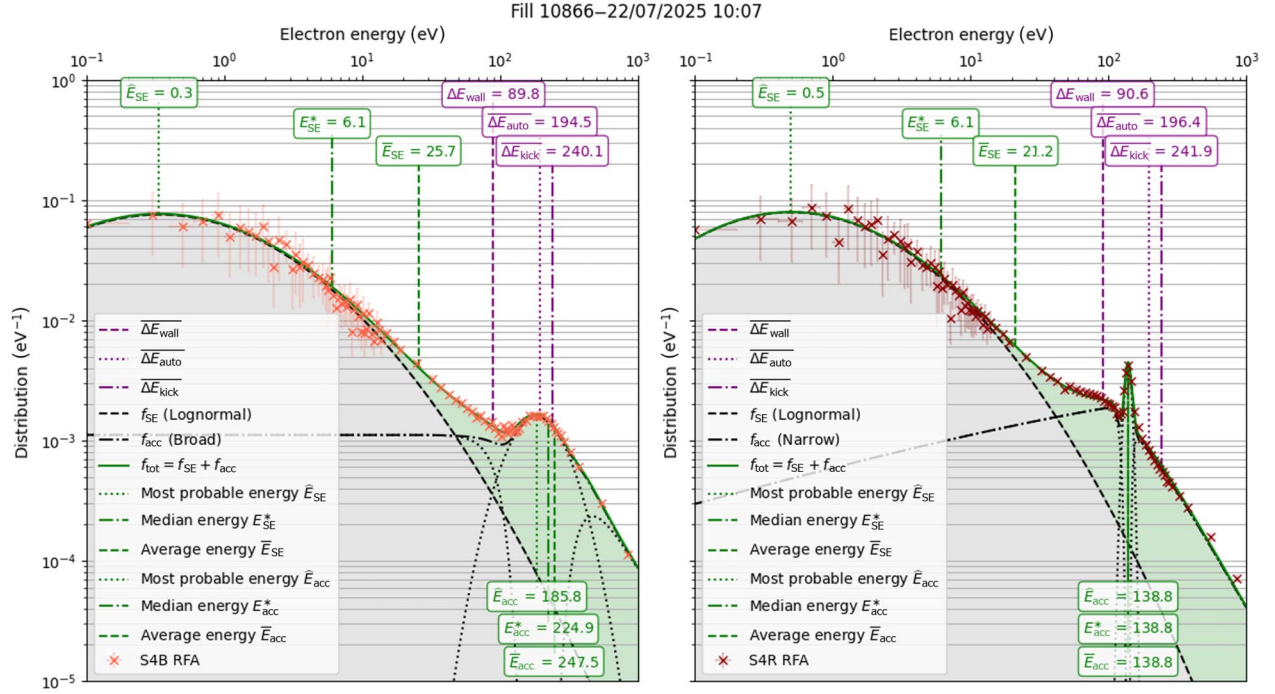


FIG. 4. Model fits of normalized measured distributions (Fig. 3). The global spectrum (green) is fitted as the sum of a secondary component (gray, dashed black lognormal) and three accelerated contributions (green region, dotted lines). The dash-dotted line represents the sum of the three accelerated contributions. Most probable $\hat{E}$, median E^* , and average $\bar{E}$ energies are marked for secondary and accelerated peak distributions. Bunch-driven acceleration models (purple) are shown for comparison, comprising gain electrons coming from the wall ΔE_{wall} and in the autonomous ΔE_{auto} or kick ΔE_{kick} regimes.

The narrow-peak central energy (~ 138.8 eV), when associated with a radial position through Eq. (2) generalized to an arbitrary radius r ($b \rightarrow r$), corresponds to $r \sim 3.2$ cm, i.e., close to the chamber wall ($b = 4$ cm). This is consistent with a population of low-energy electrons residing in the vicinity of the wall prior to bunch passage, receiving only a modest kick due to their proximity to b , and supports the interpretation of the narrow peak as originating from this near-wall electron layer.

B. Accelerated electron peak evolution along fill 10866 lifetime

Figure 5 shows different normalized energy distributions at different stages of Fill 10866: after injection, at flattop, at the beginning of stable beam, and after 3 and 6 h of stable beam. For readability, fits based on measurements are displayed. Overall, all distributions exhibit features consistent with those of Fig. 3. The low-energy portion remained essentially unchanged, as expected for secondary electrons whose spectrum is independent of the primary energy provided it exceeds ~ 50 eV, by convention. Regarding the accelerated peak distributions, their respective peak maxima decreased during the stable beam phase as the beam intensities decreased, even though these trends differ between beamlines, as more explicitly visible on Fig. 6.

Figure 6 traces the mode energy of the accelerated peak, i.e., its central value, regardless of whether it was a broad one or a narrow one, throughout the fill lifetime. Expected kick energy E_{tot} was also computed using the kick approximation formalism for comparison. Both blue and red beamlines followed piecewise evolutions, which were consistently observed in other physics fills as well. (i) Blue beamline—The peak energy remained ~ 230 eV through injection, ramp-up, and flattop, increased suddenly at stable beam and then decreased linearly with the beam intensity during the stable beam phase. This linear trend is consistent with the linear correlation established in the kick approximation model and represented by dashed lines. (ii) Red beamline—The peak increased slightly from ~ 250 to ~ 270 eV during ramp-up, likely due to small variations in bunch length during this phase. At the onset of stable beam, it dropped sharply to ~ 200 eV and continued to decrease to a limit around ~ 160 eV, before abruptly transitioning to a narrow peak centered near 140 eV. Following this step, the peak again decreased linearly, in agreement with the expected bunch-kick trend.

No direct correlation was found between these discontinuities and recorded VPS parameters, but they were systematically observed on electron and photon probes during the beam commissioning, being strongly suspected to be linked to beam orbit or dispersion changes. As the

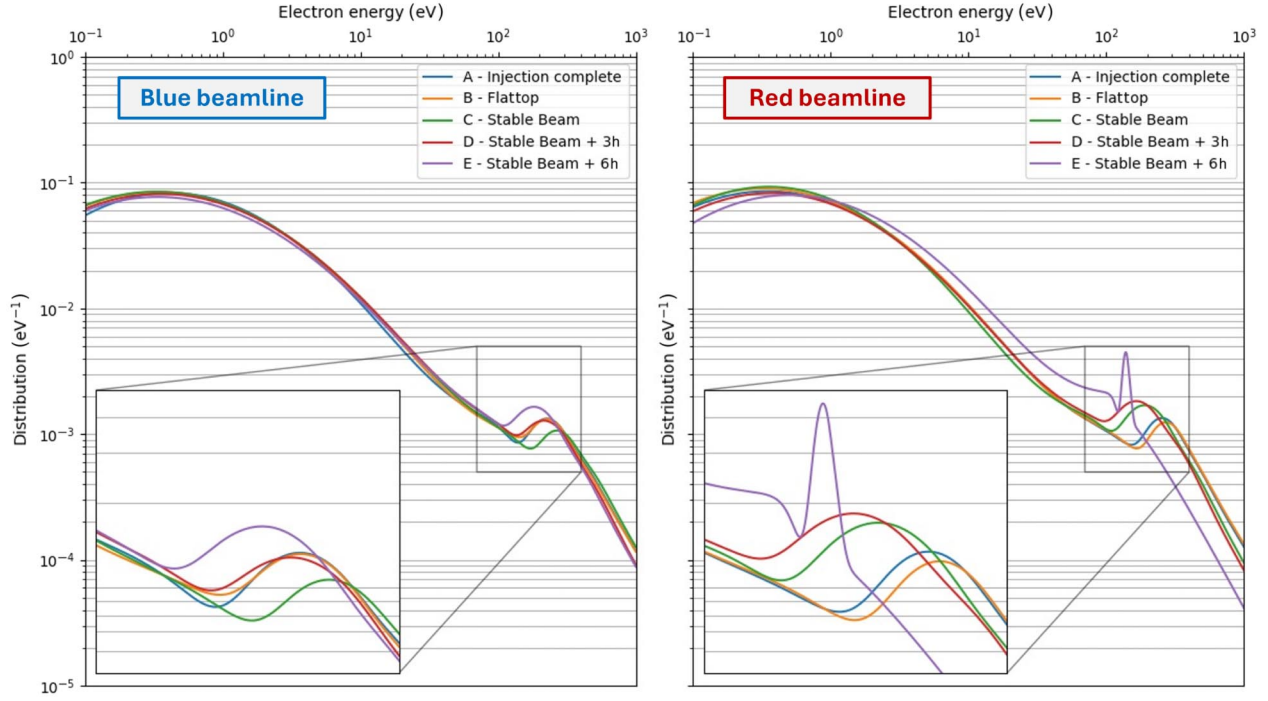


FIG. 5. Fitted electron cloud energy distributions at different moments of Fill 10866 lifetime: injection complete (A, blue), flattop (B, yellow), at the beginning of stable beam (C, green), and after 3 (D, red) and 6 (E, purple) h of stable beam phase. Distributions are displayed for blue (left) and red (right) beamlines of Station 4.

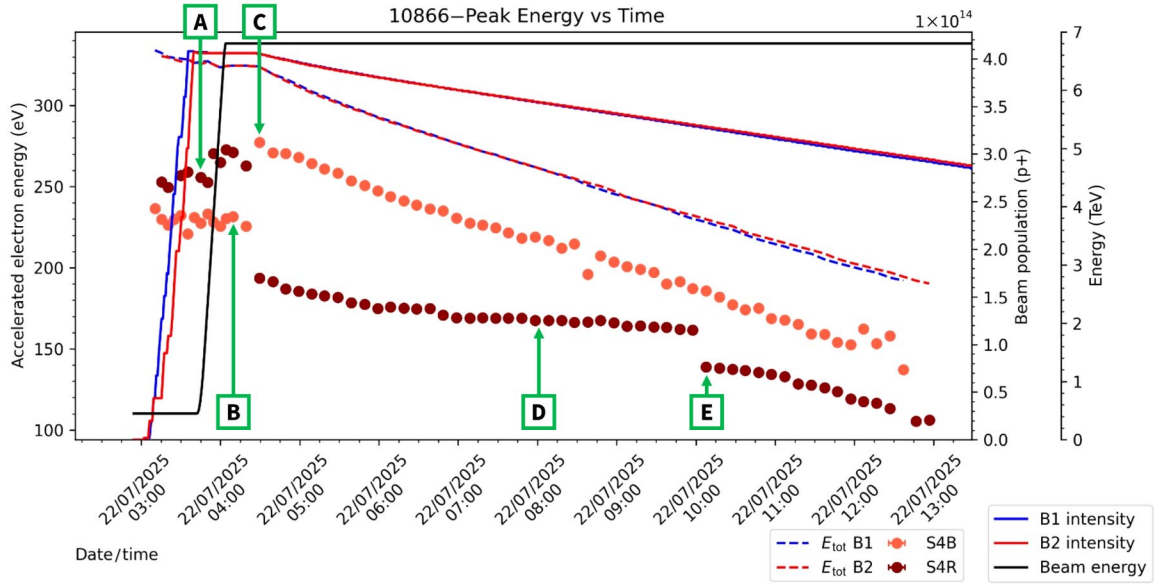


FIG. 6. Peak energy mode value evolution with time of the physics Fill 10866 for Station 4 blue liner (orange) and red liner (dark red). Beam population of the blue and red beams, as well as the beam energy (black), are displayed in plain lines. Average kick energy E_{tot} , expressed by the formalism of Eq. (5), considering a transverse uniform distribution of electrons on average, is displayed in dashed lines. Time markers correspond to the distributions plotted in Fig. 5: injection complete (A), flattop (B), at the beginning of stable beam (C), and after 3 (D) and 6 (E) h of stable beam phase.

RFA samples only a fixed azimuthal location, this could be significant: under nominal, centered orbit, the electron cloud is expected to remain transversally isotropic, consistent with the field-free nature of the VPS—a trend qualitatively supported by a preliminary PyECLOUD check, though the corresponding results are not available for inclusion here—but an orbit or dispersion shift would break this symmetry and could place the RFA in the shadow of the electron dynamics for specific energy ranges, rendering the measured spectrum azimuthally dependent. This hypothesis could, however, not be verified against orbit feedback records and remains to be confirmed by future investigation.

The transition between broad and narrow peaks remains unexplained, with no associated observed discontinuity in electron current or other VPS sensors. As it was found to occur within a single ~ 5 -min voltage scan, its timescale is at most a few seconds—below the resolution of the diagnostic, making a smooth transition inherently unobservable with the present method.

C. Cumulative electron energy distribution function

Figure 7 presents the CDFs derived from the fitted electron energy spectra over the lifetime of Fill 10866, extrapolated up to 3 keV; electrons with energies above this threshold are neglected. All CDFs exhibit a characteristic double-step structure, reflecting the respective contributions of low-energy secondary electrons and of the accelerated-electron population.

As the energy of the accelerated peak decreases with time, the slope of the corresponding CDF becomes steeper. Distributions with narrow peaks exhibited particularly

sharp transitions: typically, 50% of electrons had energies below 140 eV and 95% below 1400 eV.

These findings indicate that particular care must be taken in the choice of collection bias voltage to suppress the residual electron background in any diagnostic device relying on electrostatic filtering to discriminate ion from electron contributions.

V. APPLICATIONS

The electron cloud energy distributions and CDFs presented in this work provide direct quantitative input for several practical applications to interpret extensive data with the VPS or for the LHC and future high-intensity accelerators. The following paragraphs present a sample of such applications [14].

A. Benchmarking of electron cloud simulations and SEY curve parameter refinement

Simulation codes such as PyECLOUD [15,16] predict electron cloud energy distributions that can be directly compared with the measured spectra. Such a comparison first can first serve to validate whether the simulation correctly reproduces the underlying physics—including the relative contributions of secondary and accelerated electrons and the overall shape of the energy spectrum. Where agreement is achieved, the problem can then be inverted: by fitting simulated spectra to the measured reference, the surface electron emission parameters used as inputs might be refined. Combined with the *in situ* $\delta_{\max}$ determination method of Ref. [6], this approach offers a pathway toward a more complete, *in situ* characterization of the SEY curve under operational conditions.

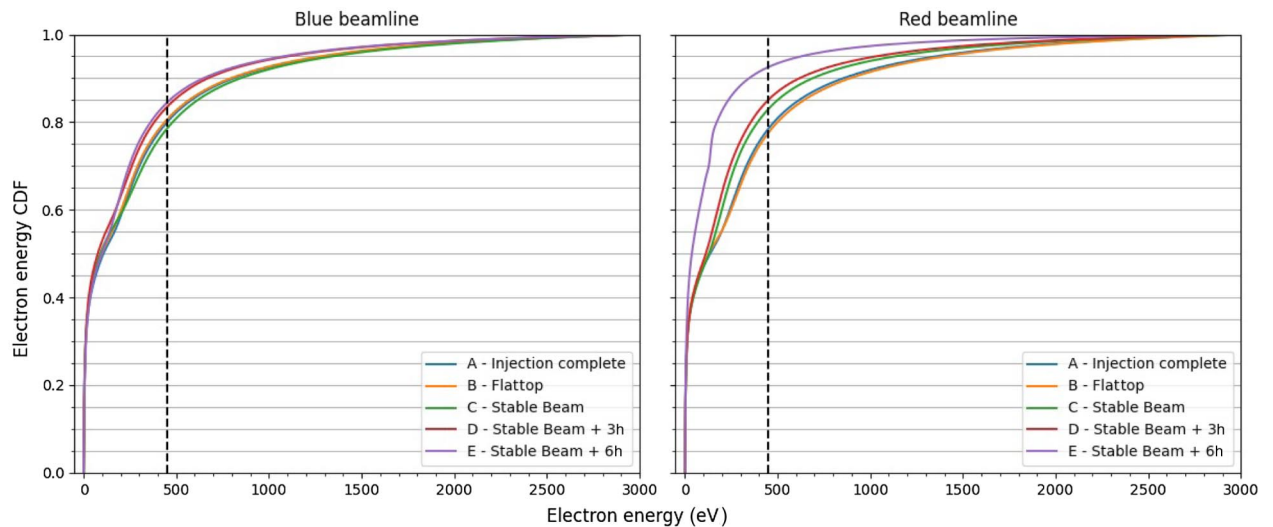


FIG. 7. CDF of both blue (left) and red (right) beamlines of Station 4 during Fill 10866. Time markers correspond to the distributions plotted in Fig. 5: injection complete (A), flattop (B), at the beginning of stable beam (C), and after 3 (D) and 6 (E) h of stable beam phase.

B. Scrubbing run optimization

Surface conditioning efficiency under electron bombardment depends critically on the energy of the impinging electrons, peaking at energies of a few hundred eV [17]. Laboratory conditioning studies are typically performed with monoenergetic electron sources, which do not reflect the broad spectral distributions observed in operational accelerators. The parametric model developed in this work, extracted from a large set of Run 3 physics fills, provides energy spectra that are representative of typical LHC operating conditions. These can serve as direct spectral inputs for laboratory conditioning studies aimed at benchmarking the efficiency of different scrubbing protocols under operationally relevant electron spectra.

C. Electrostimulated desorption and vacuum dynamics

ESD yields depend sensitively on the energy of the impinging electrons and on the cumulative electron dose undergone by the surface [18]. By analogy with SEY conditioning studies using realistic electron spectra, the energy distributions presented here could serve as spectral inputs for laboratory ESD measurements, substantially refining desorption yield predictions for future high-intensity beam operation. In the LHC context, the resulting predictive models could be directly benchmarked against the measurements of the numerous pressure gauges distributed along the machine.

D. Electron cloud-induced heat loads

Electron cloud energy spectra provide direct input for computing the instantaneous power deposited by electrons on the vacuum chamber walls. The measurements presented here constitute an early experimental characterization of these spectra under realistic LHC beam conditions. While a partial correspondence with the kick approximation model has been established, the unexpected features observed—such as energy discontinuities at operational transitions and the systematic blue/red beam-line asymmetry—reveal spectral dependencies that remain unexplained, yet are qualitatively consistent with the unexpected electron-induced heat load heterogeneities reported along the LHC [19]. These findings motivate further investigation of the spectral dependence on additional beam parameters—beam orbit or dispersion in particular are suspected to play a role—which could ultimately lead to a better understanding and prediction of heat load variations along the LHC and in future high-intensity accelerators.

E. *In situ* ion measurement error assessment

The VPS is also equipped with collectors whose bias voltage can be set to negative values, enabling the selective collection of ions while rejecting electrons. In practice, electrons with kinetic energies exceeding the applied bias

magnitude are not fully suppressed and contribute a residual background to the collected signal. The CDFs derived in this work directly quantify this residual electron contribution as a function of the applied collection bias for representative stages of the fill cycle. These figures provide concrete estimates of the electron background contamination in ion measurements and constrain the minimum bias magnitude required to achieve a clean ion signal in future VPS campaigns, while offering useful insights for any analogous diagnostic device capable of discriminating between ion and electron contributions through electrostatic filtering.

VI. CONCLUSIONS AND PERSPECTIVES

The central result of this work is the good agreement between the measured accelerated-electron peak energies and the kick approximation model during the stable beam phase, confirming that bunch-induced kicks dominate electron energy gain in the field-free regions of the VPS. The systematic offset between the most probable and average peak energies underlines the importance of characterizing the full distribution rather than relying on single representative values.

Several features nevertheless remain unexplained: energy discontinuities at operational transitions, the recurrent broad-to-narrow peak transition in the red beamline, and the systematic spectral asymmetry between the two beamlines despite similar geometries. These observations are qualitatively consistent with the unexpected heat load heterogeneities reported along the LHC and suggest that additional beam parameters—possibly beam orbit or dispersion—play a significant role in shaping the electron energy distribution, although this could not be directly verified against orbit feedback records in the present study.

Together, the validated spectral model and the derived cumulative distribution functions provide direct quantitative input for electron cloud simulation benchmarking, heat load estimates, ESD modeling, and residual electron background assessment in ion diagnostics. Establishing correlations between the observed spectral features and beam parameters constitutes the most promising direction for future work, with potential implications for operational tuning during both physics fills and scrubbing campaigns.

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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: RFA PROPAGATION OF UNCERTAINTIES

Let's consider a set of N values of current I_i^{meas} read on a picoammeter and their related values of the filtering grid applied by the voltage supplier U_i^{FUG} .

Considering that the bias on the grid U_i is systematically shifted by a voltage drop U_{loss} compared to the set voltage U_i^{FUG} with an error of δU_{FUG} , the voltage supplied on the collector can be written:

$$U_i = U_i^{\text{FUG}} - U_{\text{loss}} \pm \delta U_{\text{FUG}}. \quad (\text{A1})$$

The real current collected on the collector I_i has to be converted using the bias-induced current loss factor α_i^{bias} for an equivalent collection bias $9 \text{ V} + |U_i|[\text{V}]$. The current is therefore expressed as follows:

$$I_i = \alpha_i^{\text{bias}} \times I_i^{\text{meas}}. \quad (\text{A2})$$

Therefore, one can define $N - 1$ energies E_i as the mean energy associated with two consecutive filtering voltages. The energy E_i and its absolute error are given by:

$$E_i = e \left| \frac{U_{i+1} + U_i}{2} \right| \quad \text{and} \quad \delta E = e \times \delta U_{\text{FUG}}. \quad (\text{A3})$$

As RFA is a high-pass electron energy filter, the derivative of the current I_i with respect to the energy E_i is to be considered to plot an electron energy distribution. Numerically, the derivative f_i and its relative error $\delta f_i/f_i$ are expressed by:

$$f_i = \frac{I_{i+1} - I_i}{e(U_{i+1} - U_i)} \quad \text{and} \quad \frac{\delta f_i}{f_i} = \frac{\delta U_{\text{FUG}}}{U_{i+1} - U_i}. \quad (\text{A4})$$

Plotting f_i versus E_i gives the electron energy distribution graph. However, in some cases, the energy distribution normalized by its integral could be preferred as input for other computations. In this case, the integral S_f over all the points and its absolute error δS_f are given with

the following expressions:

$$\begin{cases} S_f = \frac{1}{2} \sum_{j=0}^{N-2} (f_{j+1} + f_j)(E_{j+1} - E_j) \\ \delta S_f = \frac{1}{2} \sum_{j=0}^{N-2} \sqrt{\xi_j} \end{cases}, \quad (\text{A5})$$

where

$$\begin{aligned} \xi_j &= (E_{j+1} - E_j)^2 (\delta f_{j+1}^2 + \delta f_j^2) \\ &+ (f_{j+1} + f_j)^2 (\delta E_{j+1}^2 + \delta E_j^2). \end{aligned} \quad (\text{A6})$$

Finally, the normalized derivative f_i^{norm} and its relative error δf_i^{norm} can be defined by:

$$f_i^{\text{norm}} = \frac{f_i}{S_f} \quad \text{and} \quad \delta f_i^{\text{norm}} = \frac{\delta f_i}{f_i} + \frac{\delta S_f}{S_f}. \quad (\text{A7})$$

Typical values of the relative error δf_i^{norm} range approximately between 7% (high-energy electrons) and 55% (low-energy electrons).

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