

Electron cloud observations in the LHC during the 2023 run for copper and amorphous carbon

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17/05/2024

Outline

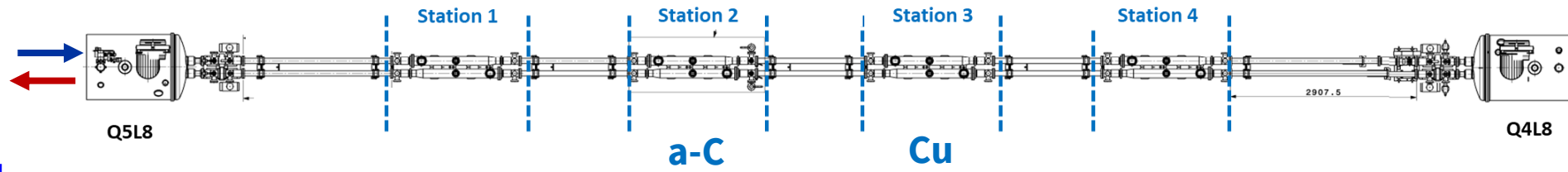
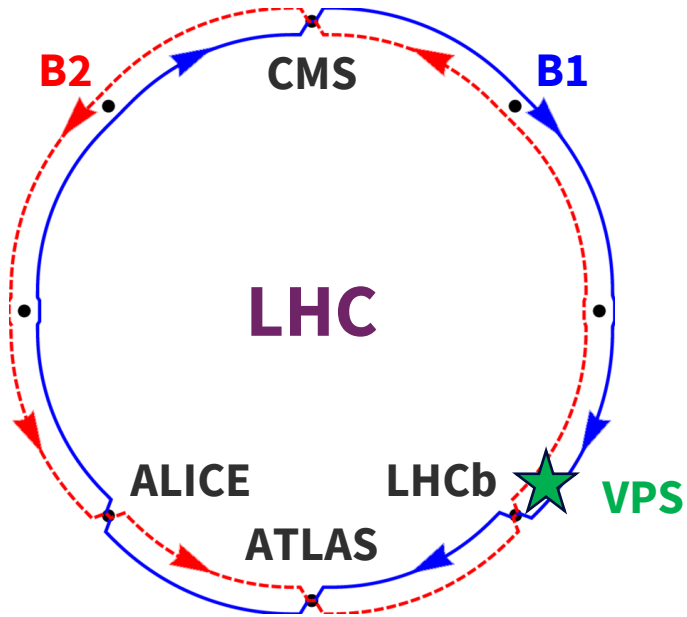
- I. Description & Physics principles**
- II. LHC physics fill's lifetime**
- III. 72b and hybrid fills at 450 GeV**
- IV. Hybrid physics fill at 6.8 TeV**
- V. Electron energy distribution for bulk Copper**

Disclaimer

- **I present the observations performed on some of the 2023 fills**
- **Results are therefore preliminary**

I. Description & Physics principles

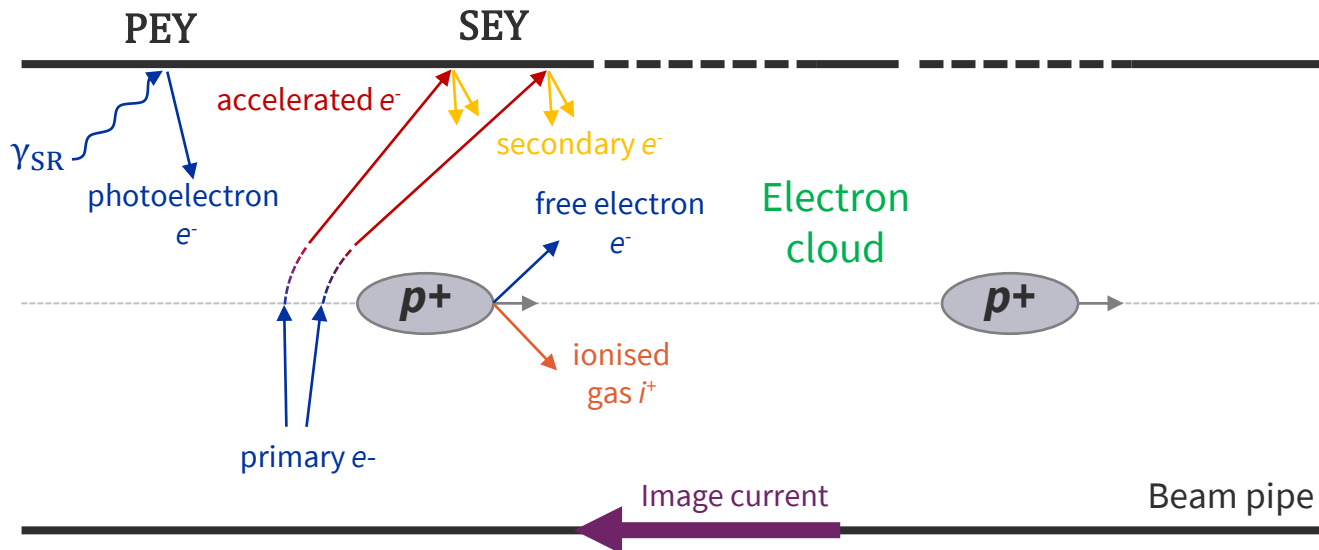
Layout



Vacuum Pilot Sector (VPS)

- **Location:** close to LHCb
- **2 beamlines**
- **Installed in 2015:**
 - 1.4m-long thick a-C coating ~500nm
 - 1.4m-long bulk Cu

Electron cloud build-up



Electron cloud = Primary + Secondary electrons

- **Primary electrons:**
 - Photoelectrons induced by photoelectric effect
 - Free electrons induced by bunch ionising the residual gas
- **Secondary electrons:** induced by primary electrons, accelerated by successive bunches, hitting the surface

Two main material properties for ecloud:

- **Photoelectron Yield (PEY)**
- **Secondary Electron Yield (SEY)**

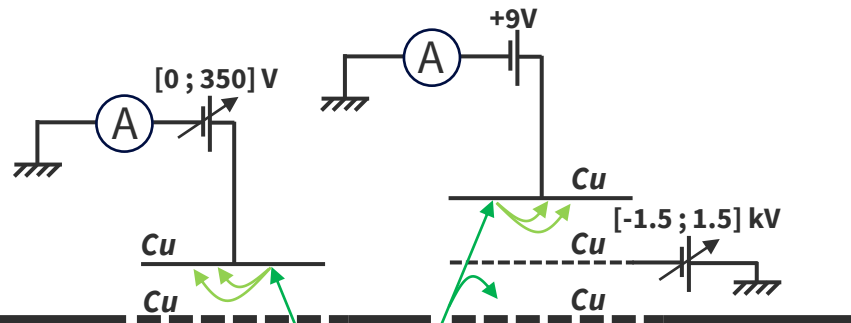
$$PEY = \frac{N_{photo\ e^-}}{N_{\gamma}}$$

$$SEY = \frac{N_{sec\ e^-}}{N_{incident\ e^-}}$$

Electron current and energy detection

Electron pickups

Energy Analyser



Electron cloud

p^+

p^+

Image current

Beam pipe

Electron pickups

- Electromagnetic shield: 7%-transparency
- Geometrical surface: 11.4cm^2
- Bulk copper collector
- Positively biased: $[0 ; +350] \text{ V}$
- Measurement: « electron cloud current »

Energy Analyser (only copper station)

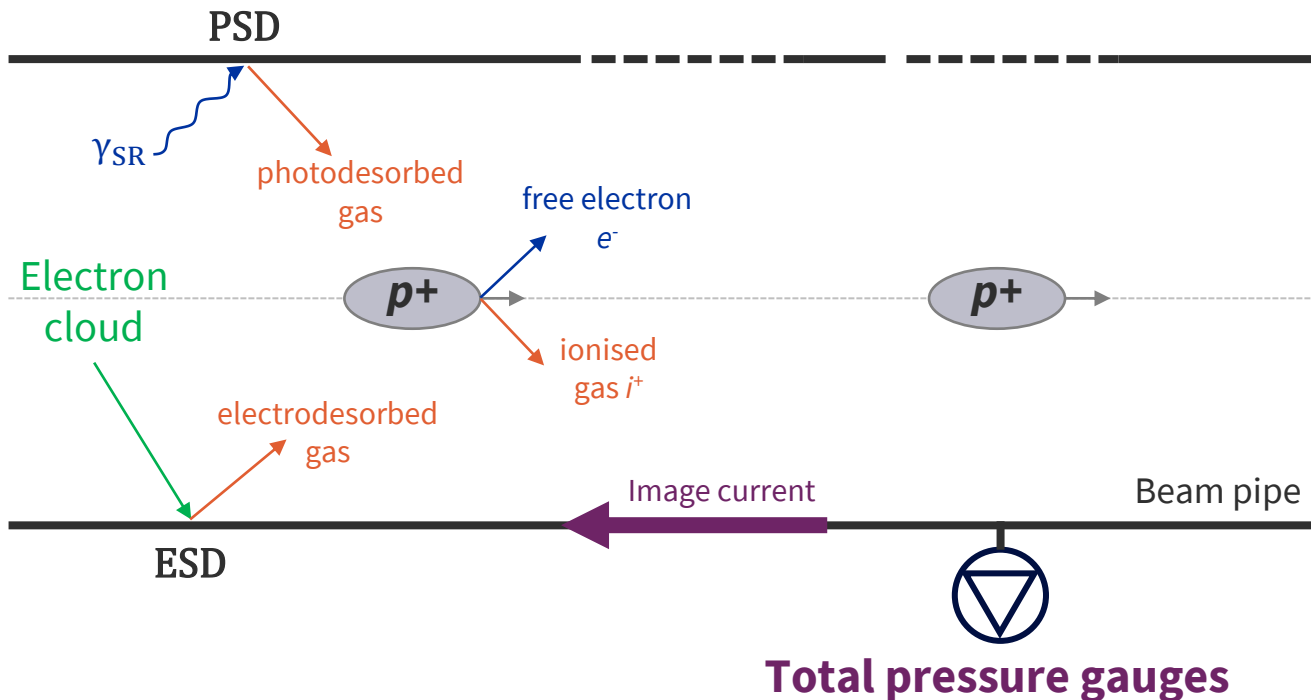
- « Retarding Field Analyser (RFA) »
- Electron pickup: with +9V bias
- Biased filtering grid: 75%-transparency
- Biased filtering grid: $u \in [-1500 ; +1500] \text{ V}$
- Measurement:

« electron cloud current below u [eV] »

Total pressure detection

Pressure elevation during LHC functioning

- **Photodesorbed gas:** induced by photons hitting the surface
- **Electrodesorbed gas:** induced by electrons hitting the surface



Total pressure gauges

- Bayard-Alpert gauges « VGI »
- Measurement: « desorbed gas pressure »

Two main material properties for gas increase:

- **Photodesorption**
- **Electrodesorption**

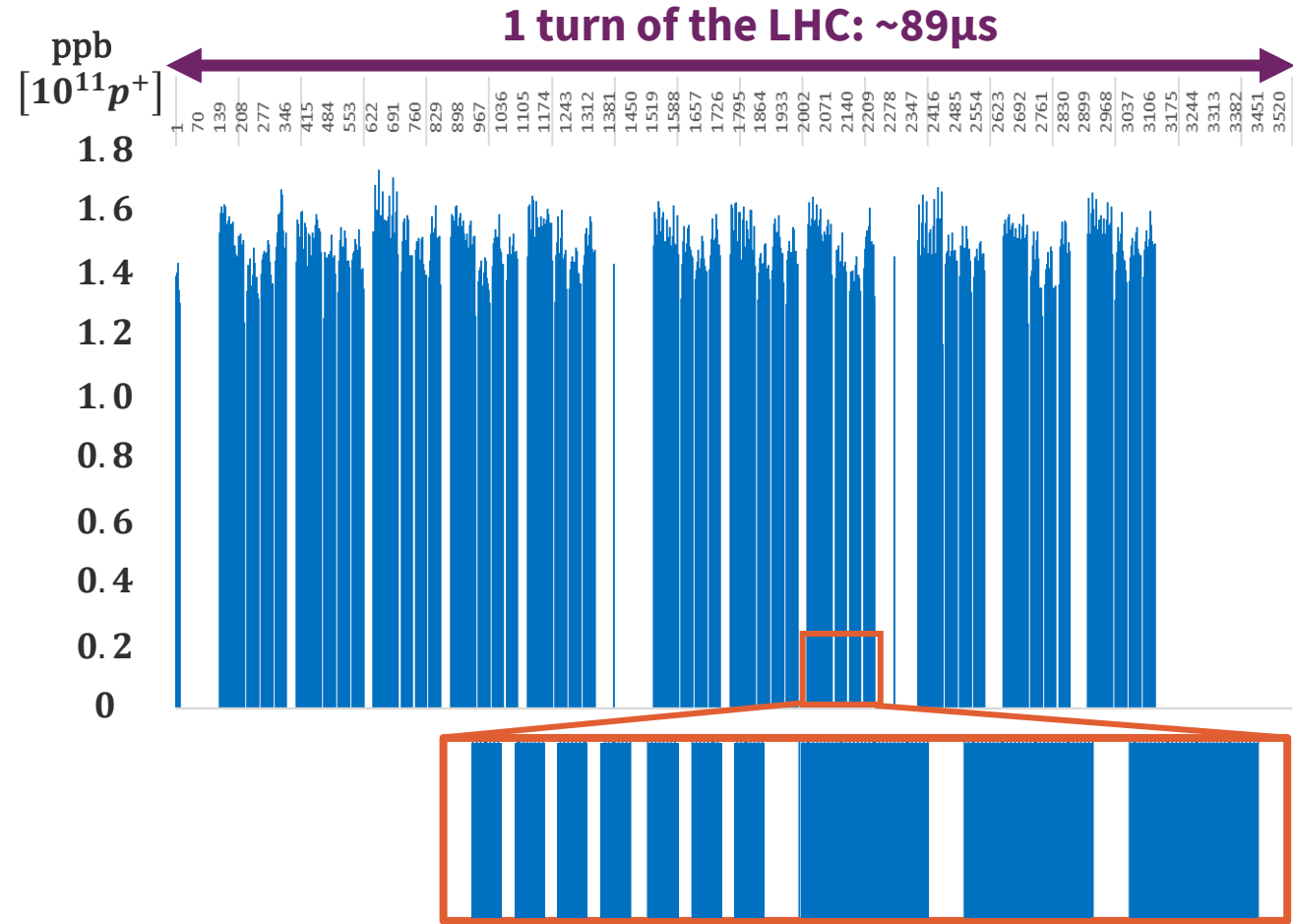
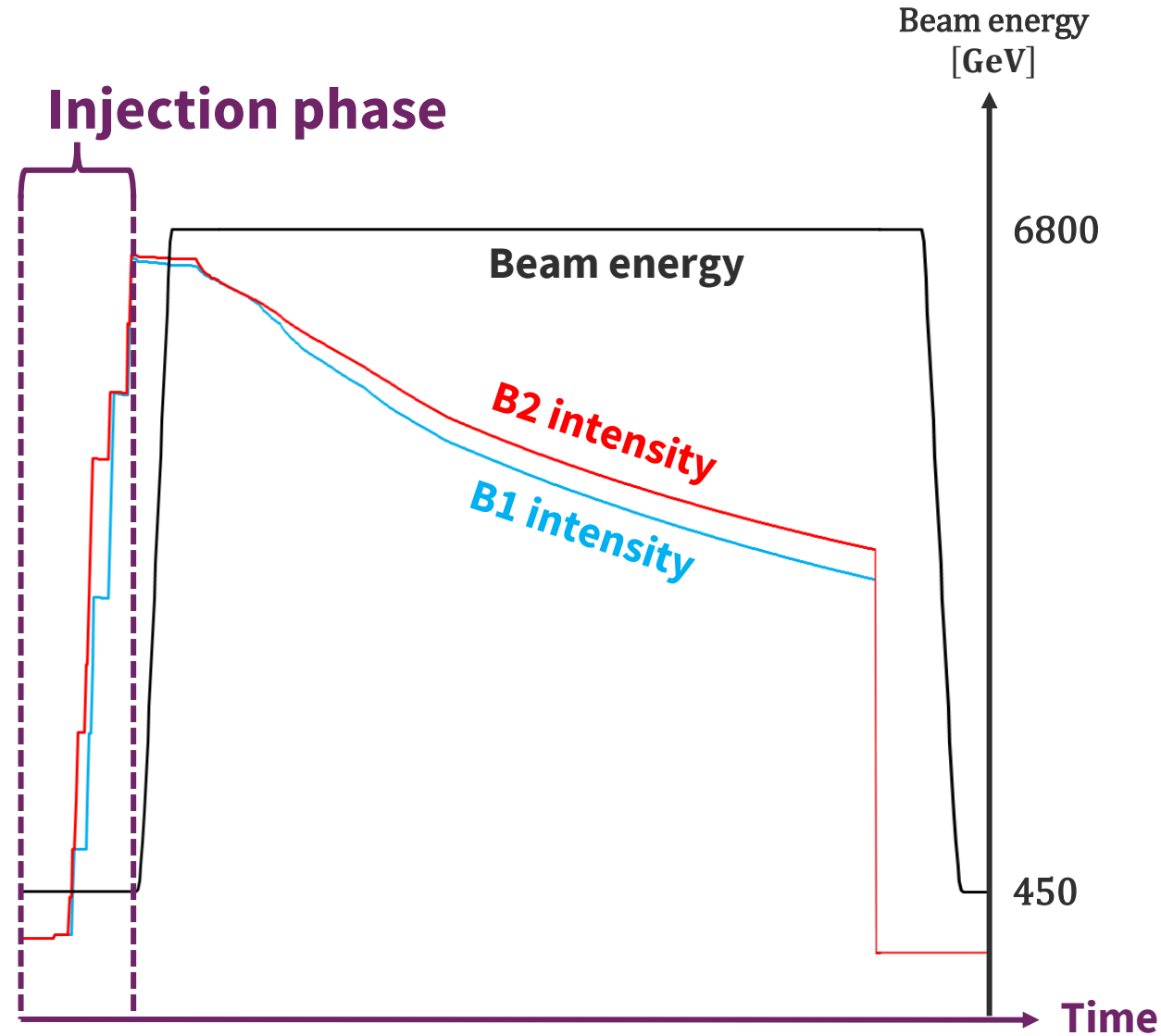
$$PSD_{gas} \propto \frac{\Delta P_{gas}}{N_{\gamma}}$$

$$ESD_{gas} \propto \frac{\Delta P_{gas}}{N_{e^-}}$$

II. LHC physics fill's lifetime

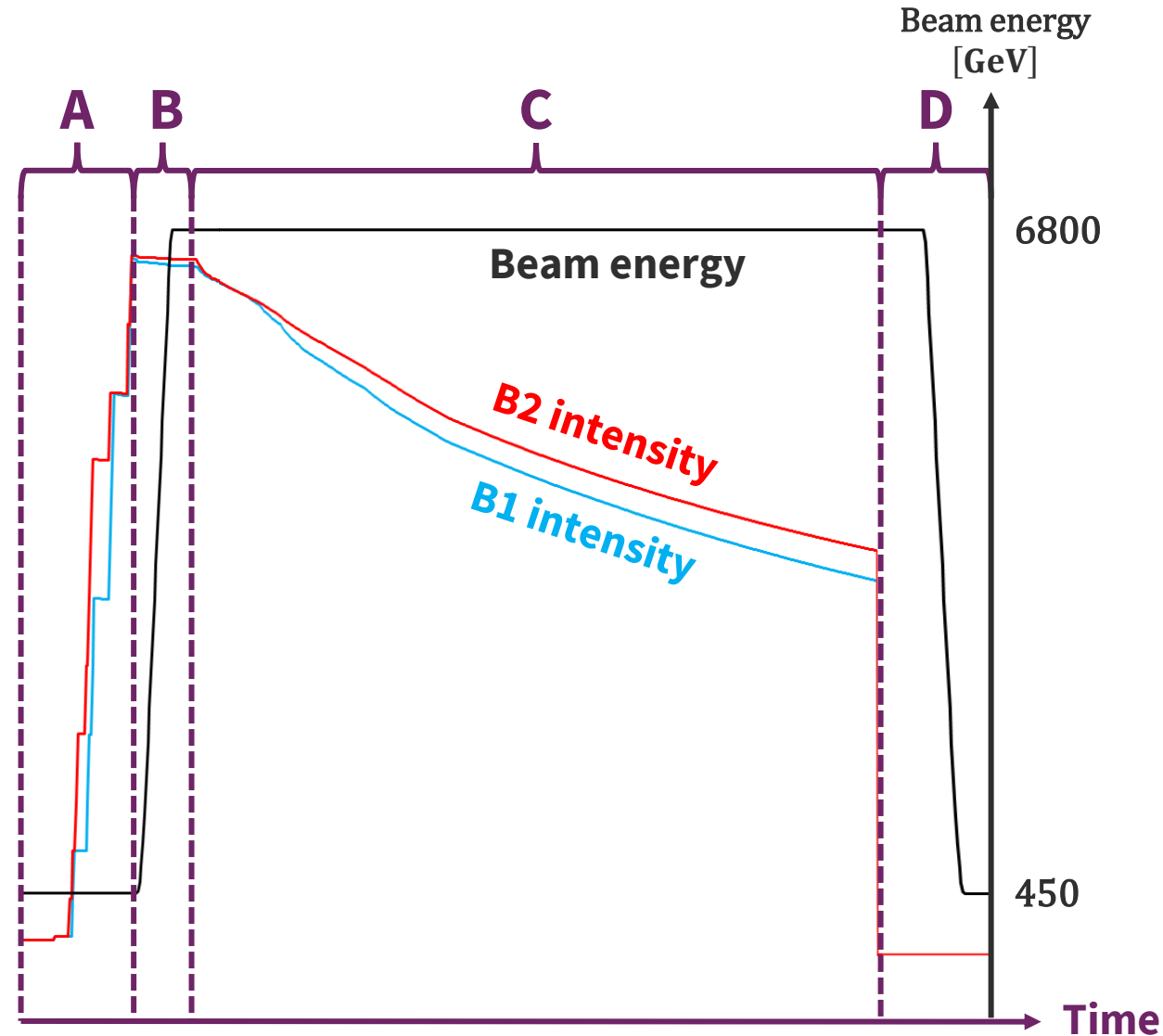
Hybrid scheme injection

Injection phase



« hybrid »
 $7*(8b4e) + 3*(36b)$

Fill lifetime overview



Orders of magnitude of typical beam parameters

N_{bunch}	\overline{ppb} [$10^{11} p^+$]	I_{beam} [$10^{14} p^+$]	I_{beam} [A]
2000	1.5	3	0.5

ppb: proton per bunch

Phases

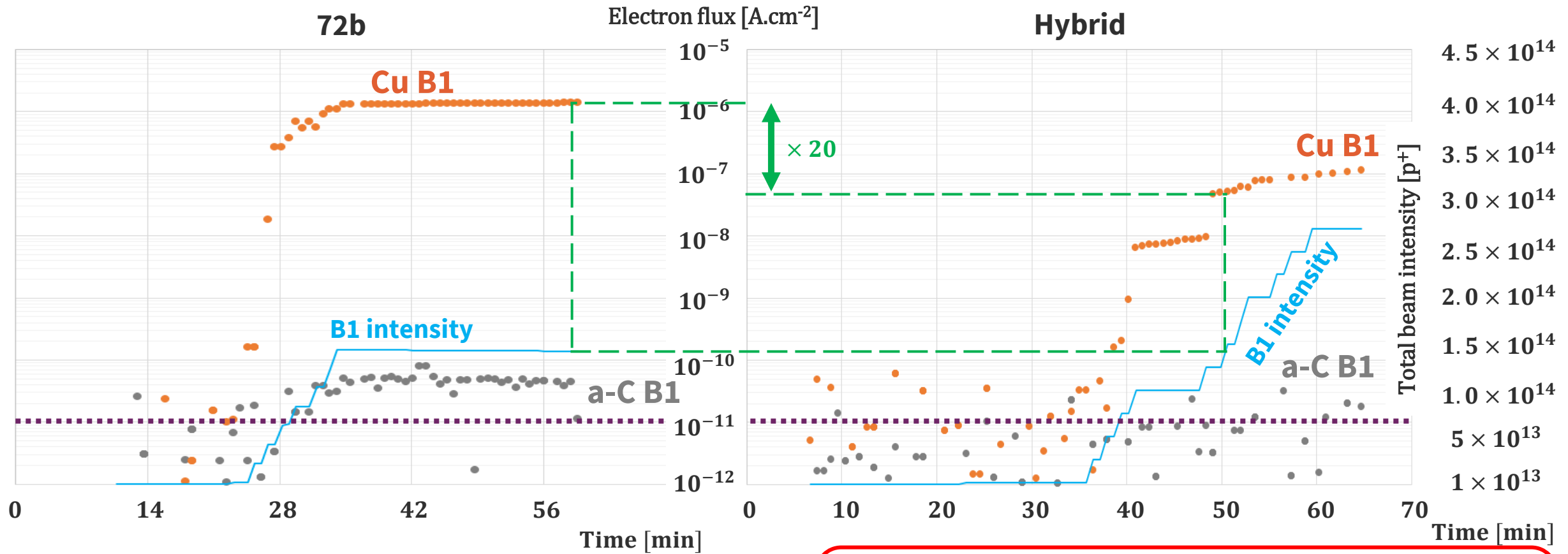
- **Injection (A):** batch injections at 450GeV
- **Energy ramp-up (B):** beam accelerated until 6800GeV
- **Stable beam (C):** bunch collisions for the experiments
- **Ramp-down (D):** beam dumped and RF ramp-down

III. 72b and hybrid fills at 450 GeV

72b: fills 8673

Hybrid (7*8b4e+3*36b): fill 8736

Electron cloud comparisons for 72b and hybrid fills



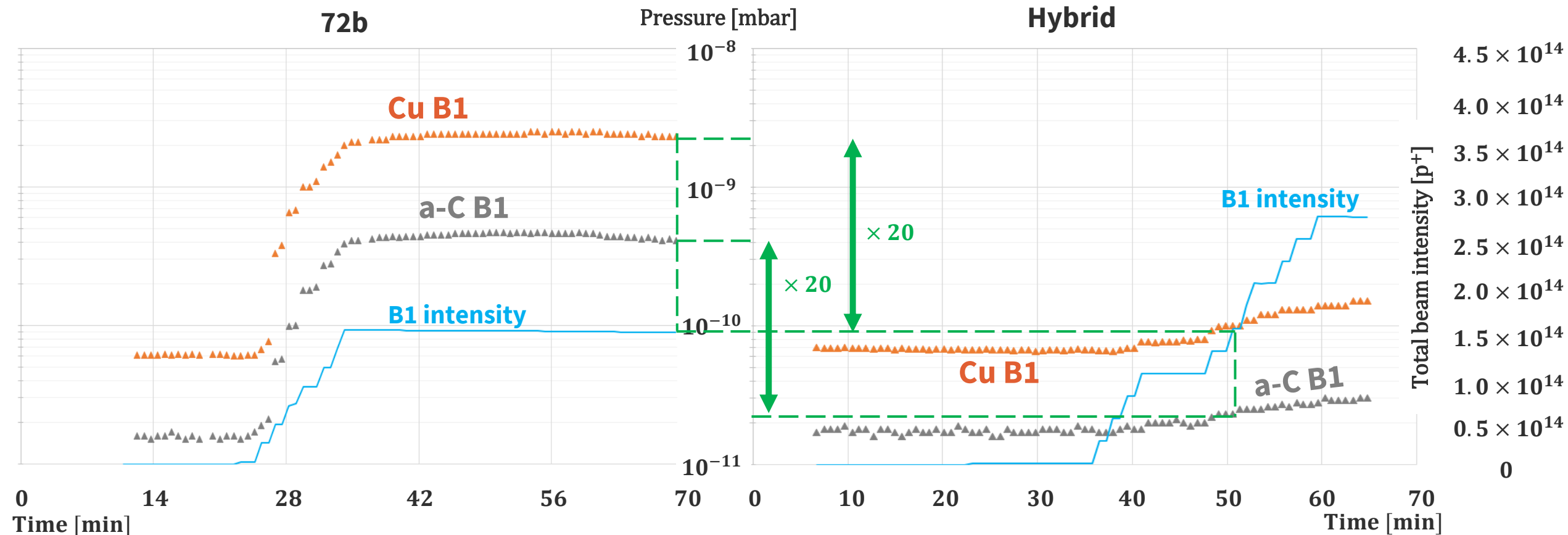
Detection limit: $I_{e^-} \sim 10$ [pA]

(Corresponds to the mean baseline plus 1σ of its gaussian distribution.)

**Copper is 4 orders of magnitude above carbon.
Carbon below detection limit for 8b4e.**

For copper: $I_{72b} \approx 20 \times I_{hybrid}$

Pressure comparisons for 72b and hybrid fills



At equal beam intensity for copper:

$$\Delta P_{72b} \approx 20 \times \Delta P_{\text{hybrid}}$$

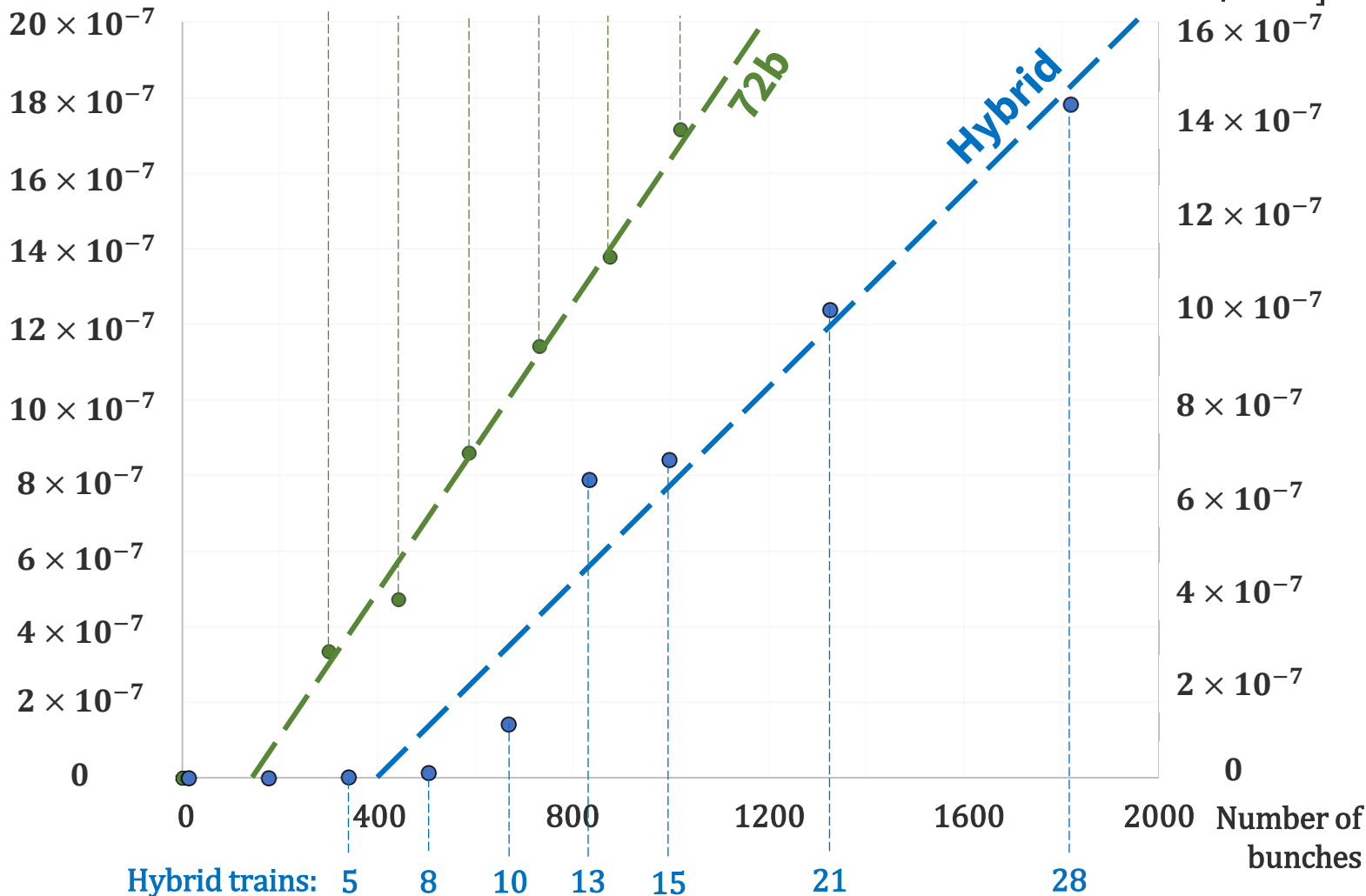
Pressure in carbon station possibly induced by RF bridge.

Thus, pressure rise cannot always be considered as equivalent to electron presence.

Electron cloud response of copper during injection

Electron flux 72b
[A.cm⁻²]

Electron flux hybrid
[A.cm⁻²]



Hybrid train: $7 \times (8b4e) + 3 \times (36b)$

$$I_{72b} [\text{nA}] \approx 20 \times (N_{\text{bunch}} - 160)$$

$$I_{\text{hybrid}} [\text{nA}] \approx 1 \times (N_{\text{bunch}} - 400)$$

More bunches needed for hybrid fill to reach linear behaviour

For high number of bunches:

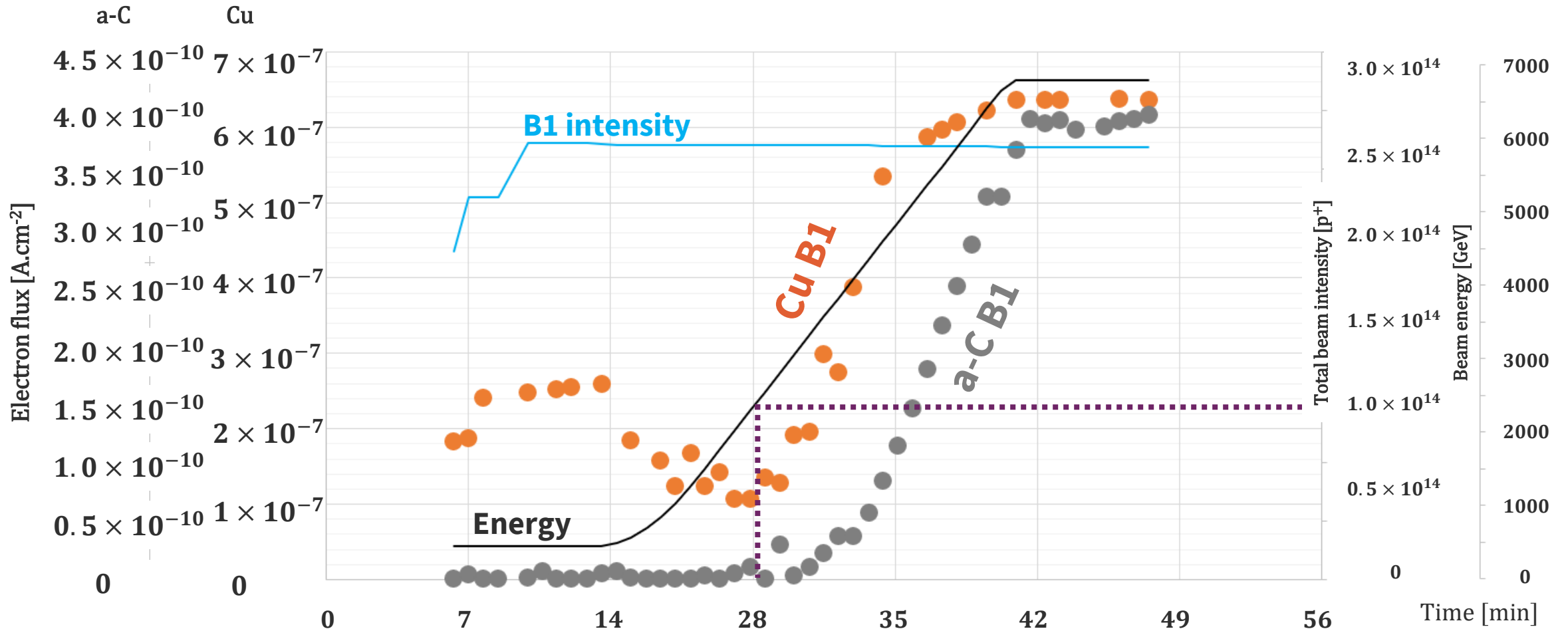
$$I_{e^-} \propto N_{\text{bunch}}$$

$$I_{72b} \approx 20 \times I_{\text{hybrid}}$$

IV. Hybrid physics fill at 6.8 TeV

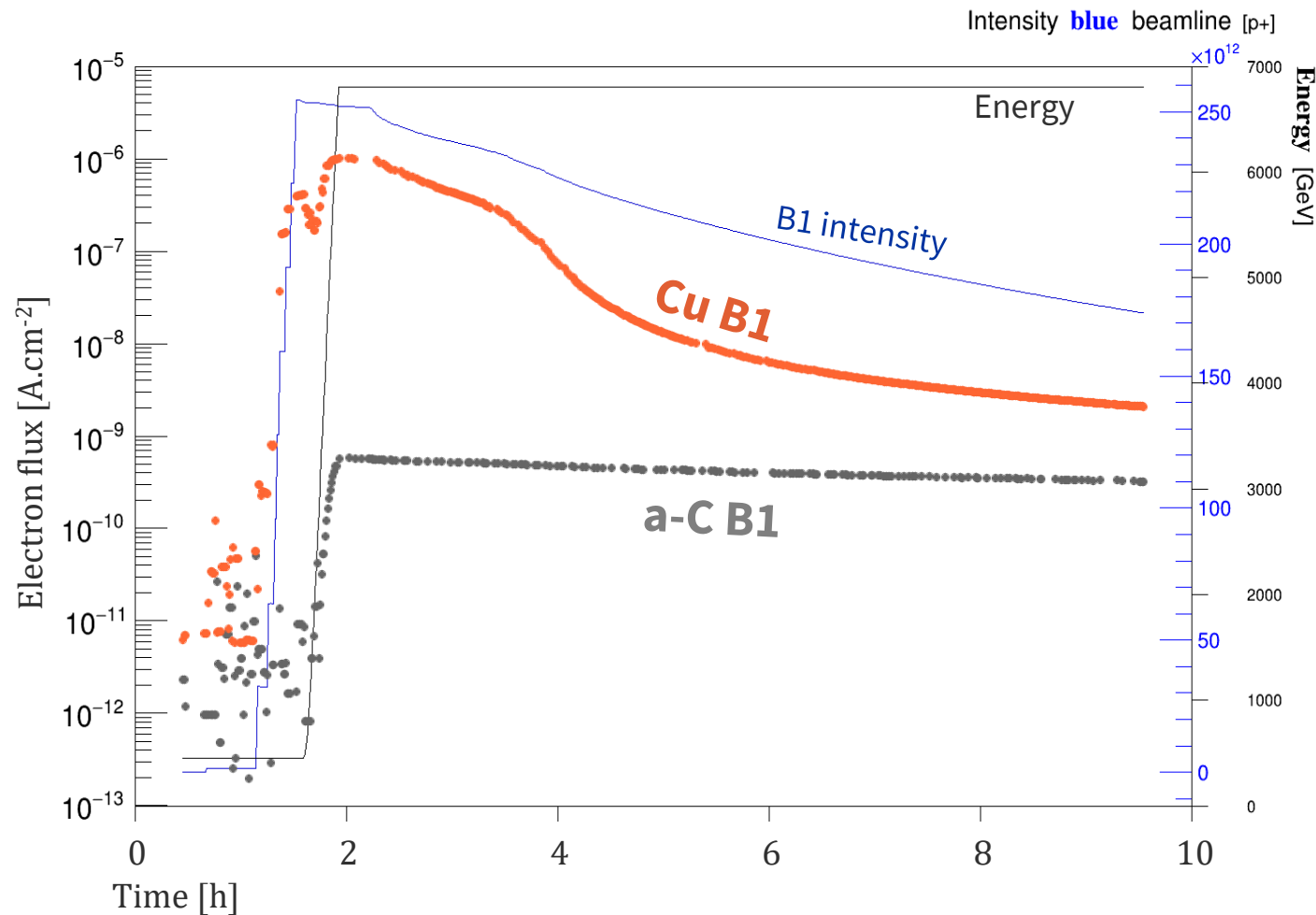
Hybrid (7*8b4e+5*36b): 8741

Photoelectrons during energy ramp-up



Photoelectrons detected by electron pickup at ~2500GeV which corresponds to a synchrotron radiation critical energy of 2 eV, matching the work function of copper or carbon (~ 4-5 eV)

Electron cloud current evolution during a fill



Multipacting occurring only for copper

- Bumped curve for copper
- Flat curve for carbon

Only photoelectrons at the end of the fill

- Both signals scale with beam intensity
- $I_{Cu} \approx 6 \times I_{aC}$

Provided the knowledge of the number of photons absorbed in the stations, one can compute their Photo Electron Yield

V. Electron energy distribution for bulk Copper

Hybrid (7*8b4e+5*36b): 9072

During energy ramp-up

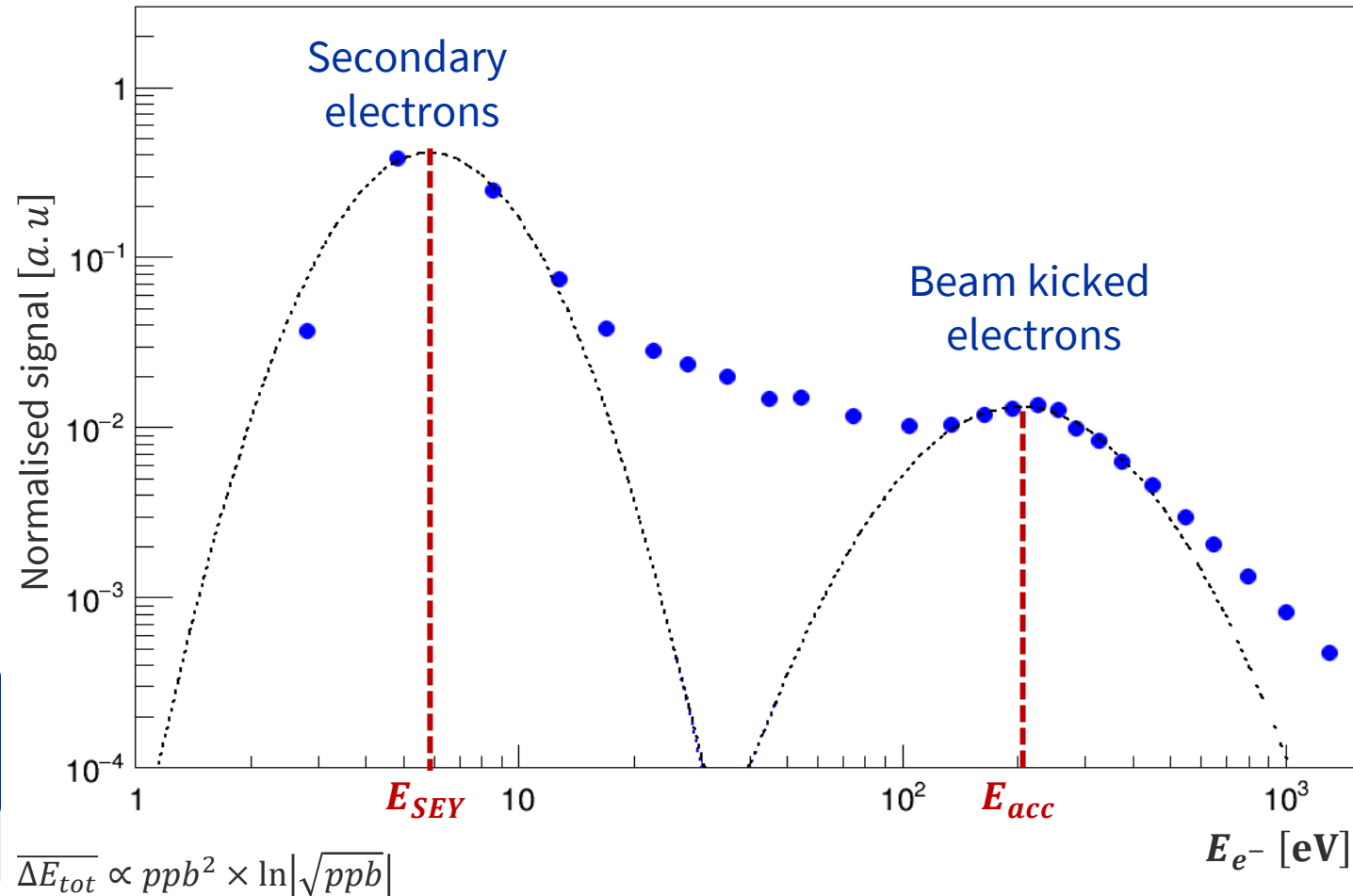
Double lognormal fit

- Assess the energy peaks of secondary and accelerated electrons
 - Measurement step around E_{SEY} : 3-5 eV
 - Measurement step around E_{acc} : 30 eV
- Cannot describe measurements in-between peaks and above accelerated one

E_{B1} [GeV]	ppb [$\times 10^{11}$]	E_{SEY} [eV]	E_{acc} [eV]	$\overline{\Delta E_{tot}}$ [*] [eV]
620	1.60	6.0	203	269
2674	1.60	5.8	202	266
6799	1.59	5.9	203	263

^{*}J. Scott Berg. CERN LHC Project Note 97, July 1997.

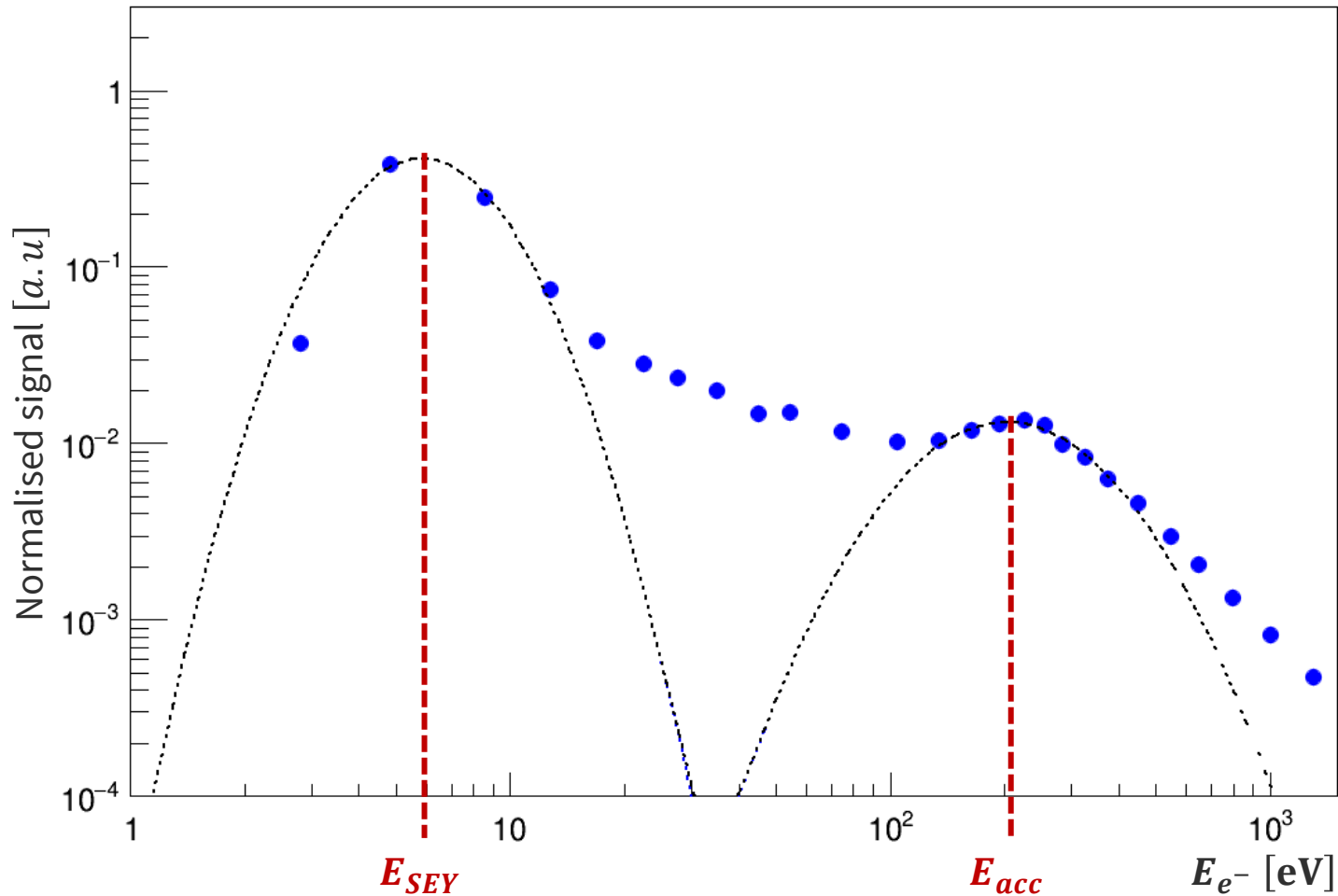
Electron energy spectrum: Fill 9072



No significant impact of the beam energy ramp-up on the electron energy distribution.

At Stable Beam: t = 0h

Electron energy spectrum: Fill 9072



Beam parameters

- **Energy:** $E_{B1} = 6799$ [GeV]
- **Bunch intensity:**

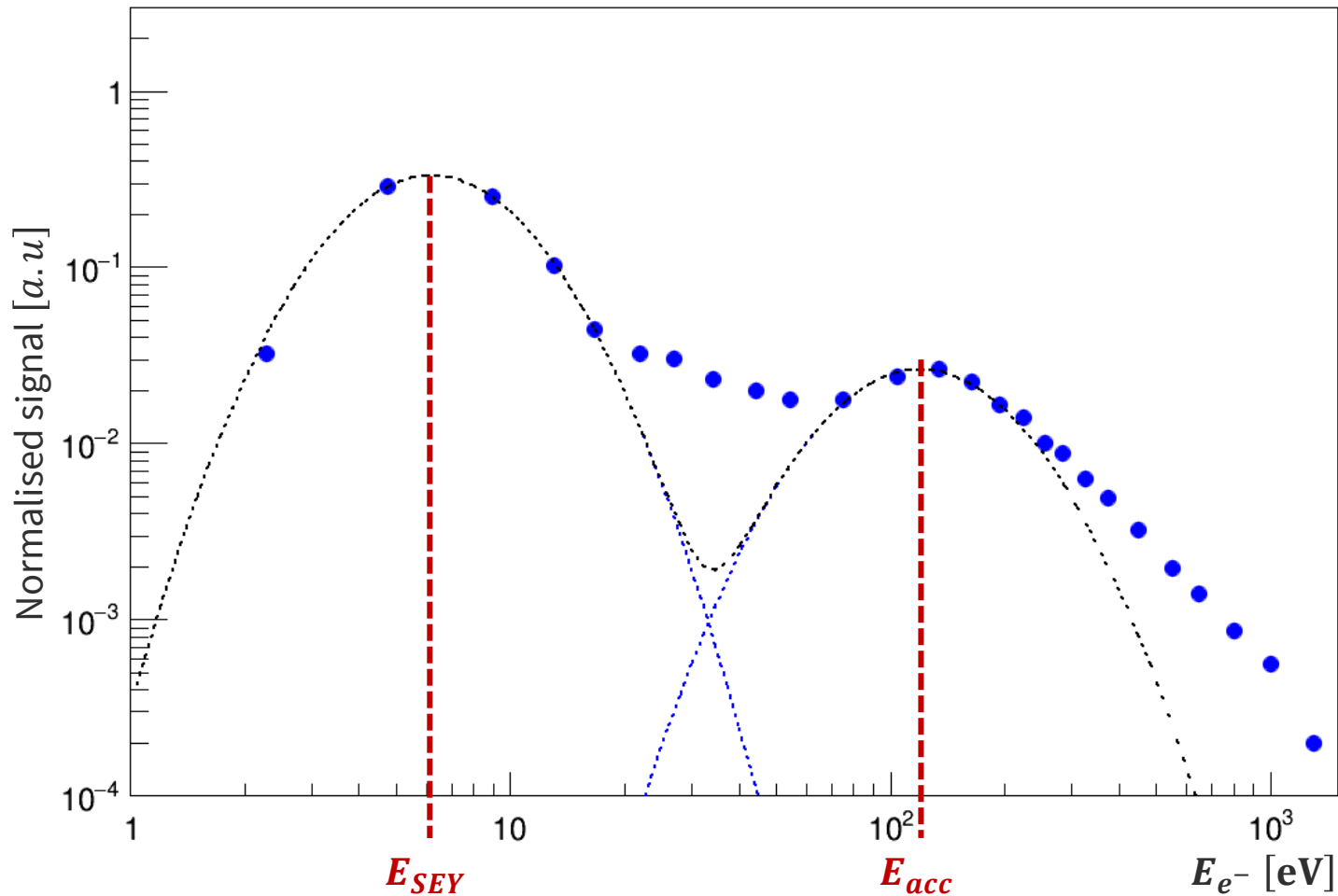
$$ppb_{B1} = 1.59 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$$

Fit results

- **Low energy:** $E_{SEY} = 6$ [eV]
- **High energy:** $E_{acc} = 203$ [eV]

At Stable Beam: t = 6h

Electron energy spectrum: Fill 9072



Beam parameters

- **Energy:** $E_{B1} = 6799$ [GeV]
- **Bunch intensity:**

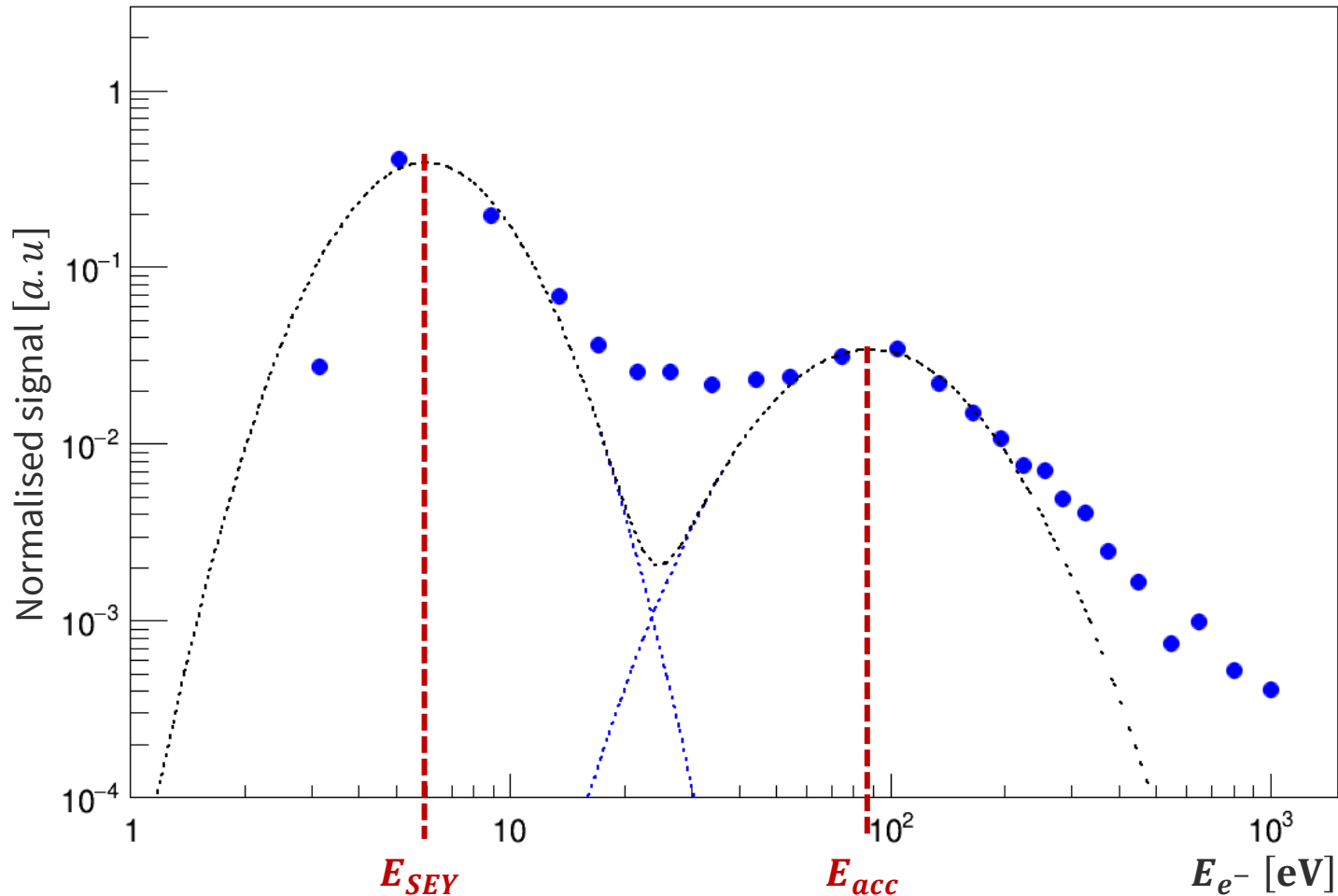
$$ppb_{B1} = 1.23 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$$

Fit results

- **Low energy:** $E_{SEY} = 6$ [eV]
- **High energy:** $E_{acc} = 120$ [eV]

At Stable Beam: t = 11h

Electron energy spectrum: Fill 9072



Beam parameters

- **Energy:** $E_{B1} = 6799$ [GeV]
- **Bunch intensity:**

$$ppb_{B1} = 0.99 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$$

Fit results

- **Low energy:** $E_{SEY} = 6$ [eV]
- **High energy:** $E_{acc} = 89$ [eV]

Impact of the beam intensity at 6800GeV

$$\overline{\Delta E_{tot}} \propto ppb^2 \times \ln|\sqrt{ppb}|$$

Stable Beam +	ppb [$\times 10^{11}$]	E_{SEY} [eV]	E_{acc} [eV]	$\overline{\Delta E_{tot}}$ * [eV]
0H	1.59	6	203	263
6H	1.23	6	120	166
11H	0.99	6	89	114

*J. Scott Berg. CERN LHC Project Note 97, July 1997.

No impact of the bunch intensity on the energy of the secondary electrons.
Decrease of the energy gained by accelerated electrons with bunch intensity.
Kick energy formulae gives a reasonable energy assessment at 30%

Summary

At 450GeV:

- Electron cloud responses for copper are orders of magnitude above carbon ones
- For copper, $I_{72b} \approx 20 \times I_{hybrid}$
- At a certain number of bunches, $I_{e^-} \propto N_{bunch}$
- Pressure rise is not equivalent to local electron cloud presence

During a hybrid physics fill lifetime:

- Photoelectrons detected for $E_{beam} > 2500$ [GeV]
- Multipacting only in copper

Electron energy distribution:

- No significant impact of the energy ramp-up on the electron energy distribution
- Decrease of the accelerated energy peak with ppb
- Kick energy formula is a reasonable first approximation

Perspectives for run 2024

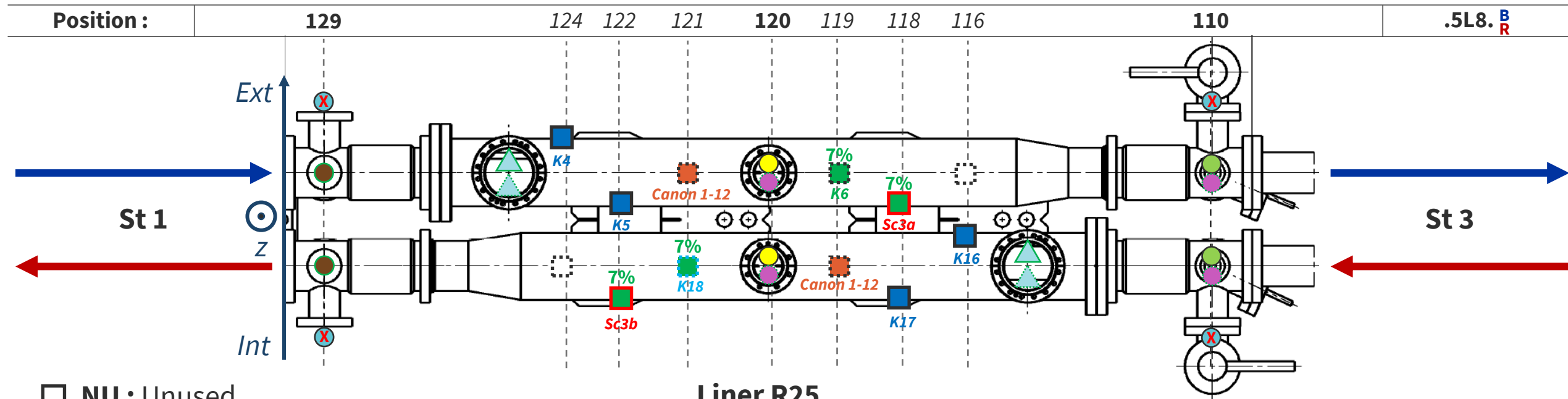
- **Electrostimulated and Photostimulated Desorption** (ESD, PSD) computations with Residual Gas Analyser
- **Photoelectron Yield** (PY) estimations
- **Secondary Electrons Yield** (SEY) evaluation with RFA by refining measurements around electron peaks
- Measurements of the electron cloud bunch by bunch with a scope
- Heat load evaluation with calorimeters
- Confrontation of measurements and parameter evaluations against simulations (PyEcloud, Vasco, Molflow, Synrad...)

Backups

Station 2 – Amorphous carbon

- △ ○ □ Dash line : Downer side
- Red line : Scope
- Blue line : Keithley with variable bias

Liner B23



Liner R25

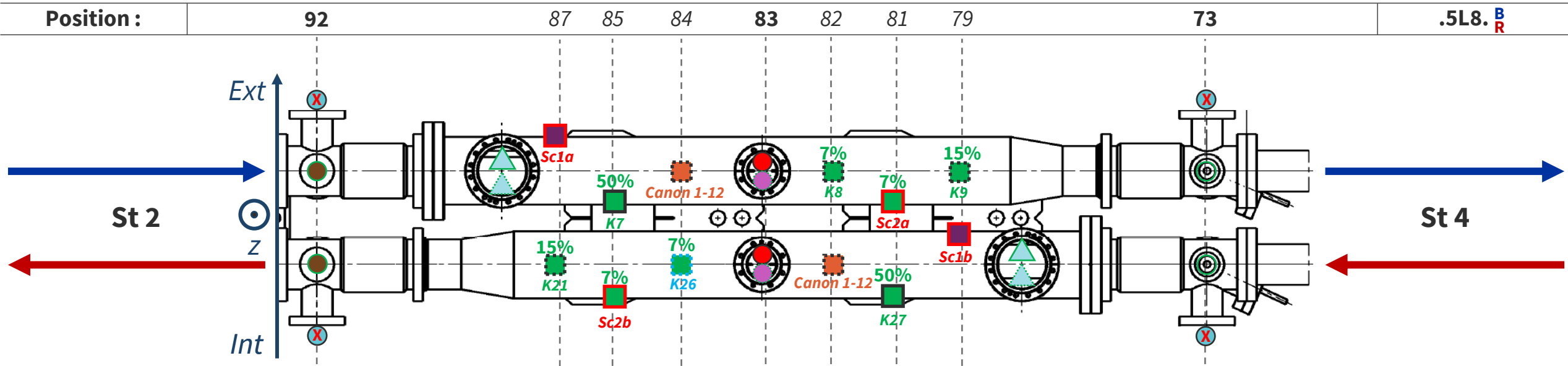
- NU : Unused
- cal : calorimeter
- xx % : pickup with a xx%-transparent grid
- ph : photodetector
- Trig : trigger
- kick : kicker (Electron Kicker Detector)
- RFA : Retarding Field Analyser

- Unused
- VGPB : Penning Gauge
- VGI : Bayard-Alpert Gauge (BAG)
- VQM : Vacuum Quality Monitor
- RGA : Residual Gas Analyser
- VGRB : Pirani gauge
- VPIA : Vacuum Pump
- △ VF : Vacuum Flange
- x N : NEG cartridge

Station 3 – New unbaked copper

- Dash line** : Downer side
- Red line** : Scope
- Blue line** : Keithley with variable bias

Liner B26



- NU** : Unused
- cal** : calorimeter
- xx %** : pickup with a xx%-transparent grid
- ph** : photodetector
- Trig** : trigger
- kick** : kicker (Electron Kicker Detector)
- RFA** : Retarding Field Analyser

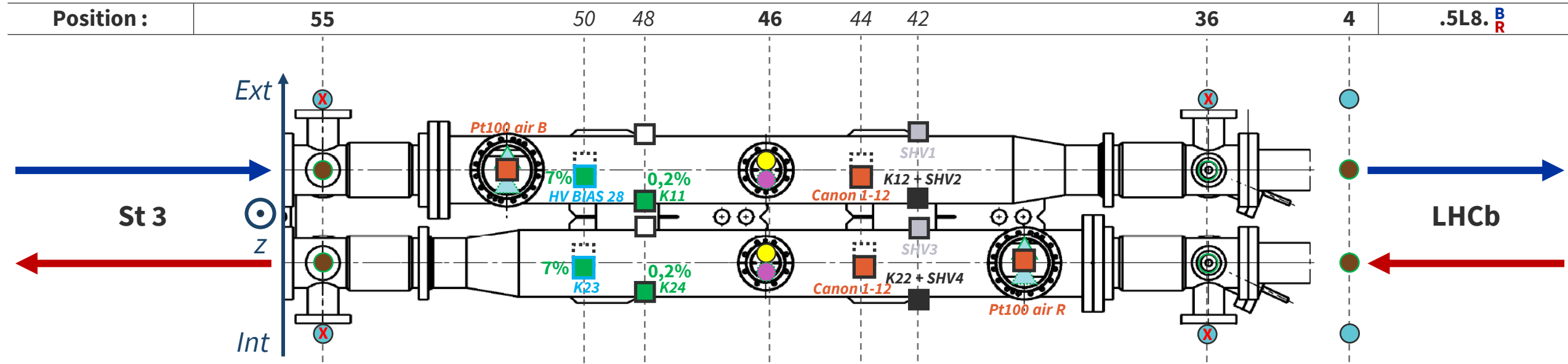
Liner R27

- Unused
- VGPB** : Penning Gauge
- VGI** : Bayard-Alpert Gauge (**BAG**)
- VQM** : Vacuum Quality Monitor
- RGA** : Residual Gas Analyser
- VGRB** : Pirani gauge
- VPIA** : Vacuum Pump
- ▲ **VF** : Vacuum Flange
- x **N** : NEG cartridge

Station 4 – Old unbaked copper

- Dash line** : Downer side
- Red line** : Scope
- Blue line** : Keithley with variable bias

Liner 7

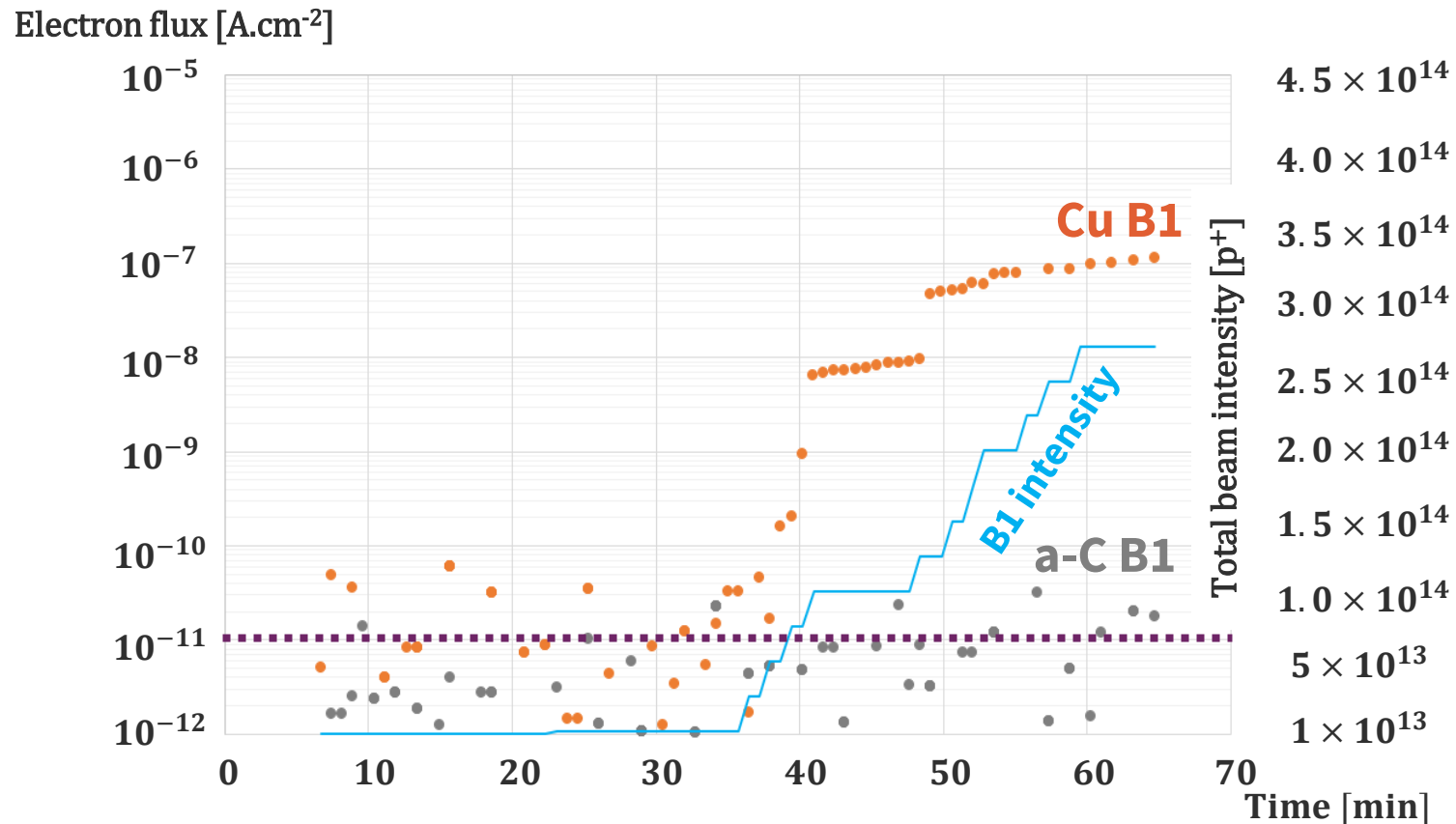


- NU** : Unused
- cal** : calorimeter
- xx %** : pickup with a xx%-transparent grid
- ph** : photodetector
- Trig** : trigger
- kick** : kicker (Electron Kicker Detector)
- RFA** : Retarding Field Analyser

Liner 8

- Unused
- VGPB** : Penning Gauge
- VGI** : Bayard-Alpert Gauge (**BAG**)
- VQM** : Vacuum Quality Monitor
- RGA** : Residual Gas Analyser
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Electron cloud for hybrid fills



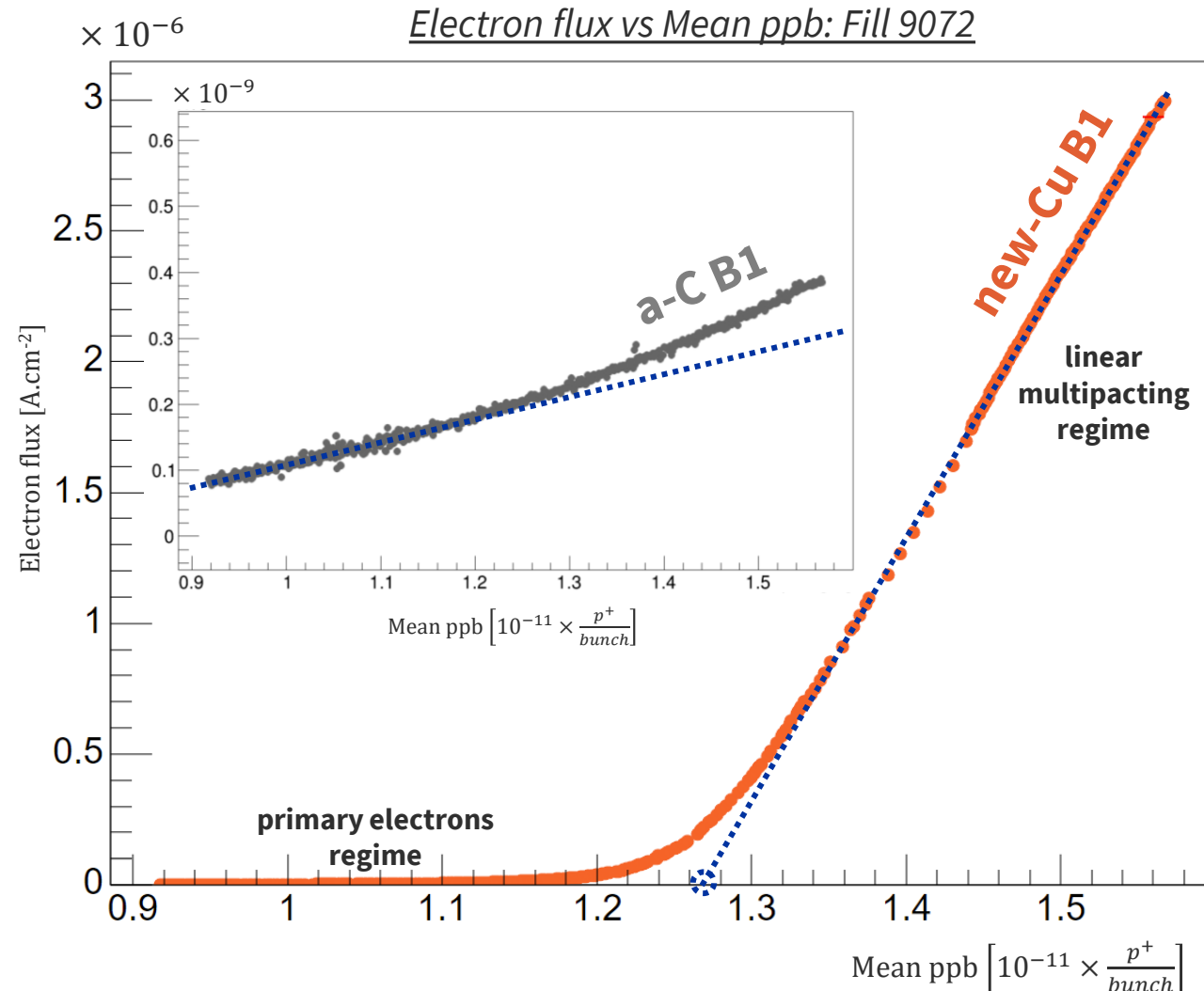
Detection limit: $I_{e^-} \sim 10$ [pA]

(Corresponds to the mean baseline plus 1σ of its gaussian distribution.)

**Copper is 4 orders of magnitude above carbon.
Carbon below detection limit for 8b4e.**

For copper: $I_{72b} \approx 20 \times I_{hybrid}$

Ecloud as a function of beam mean ppb



Multipacting presence

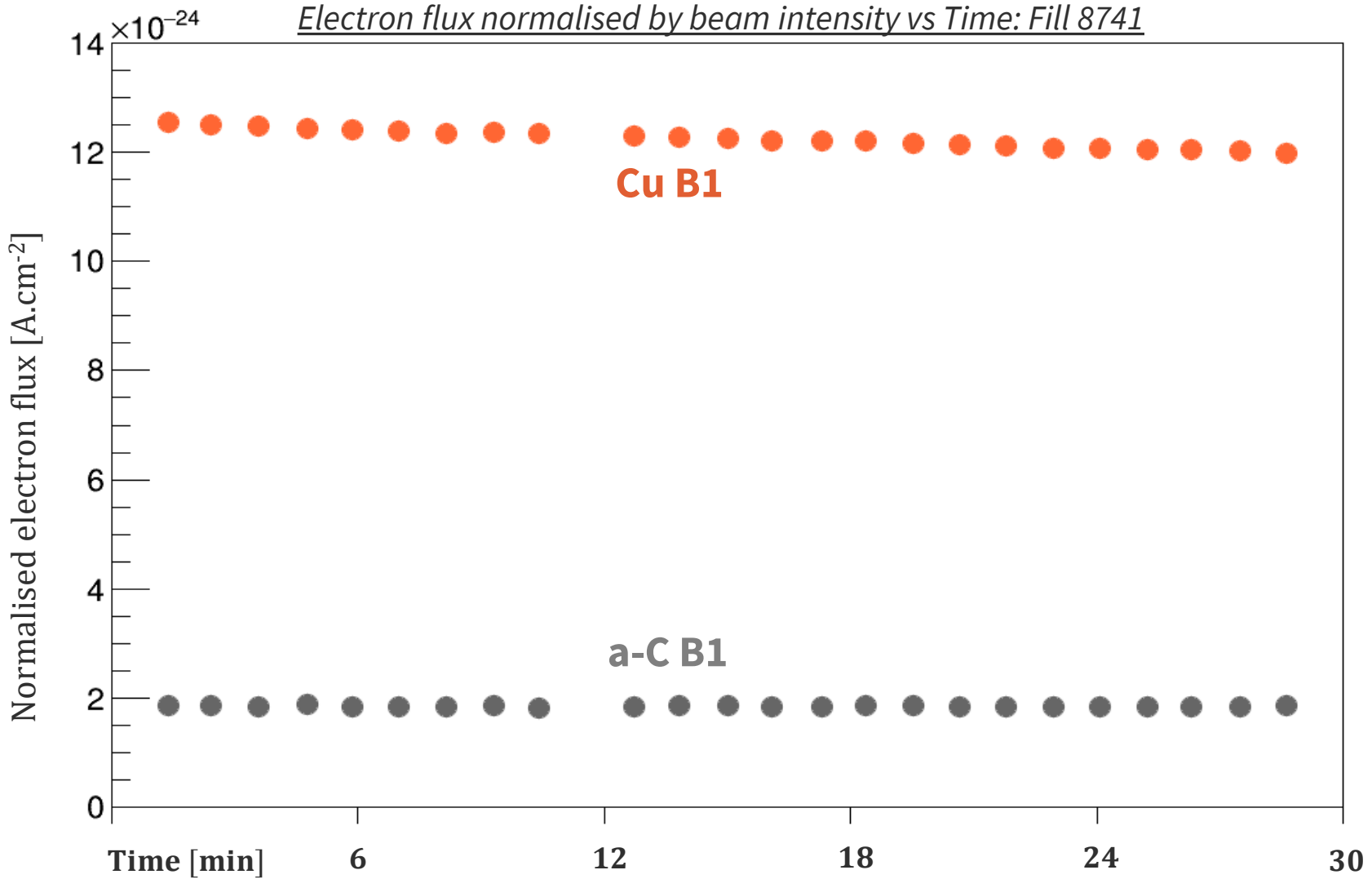
- **Barely present for carbon:** ecloud mainly dominated by photoelectrons
- **Huge contribution for copper**

Asymptotic root method

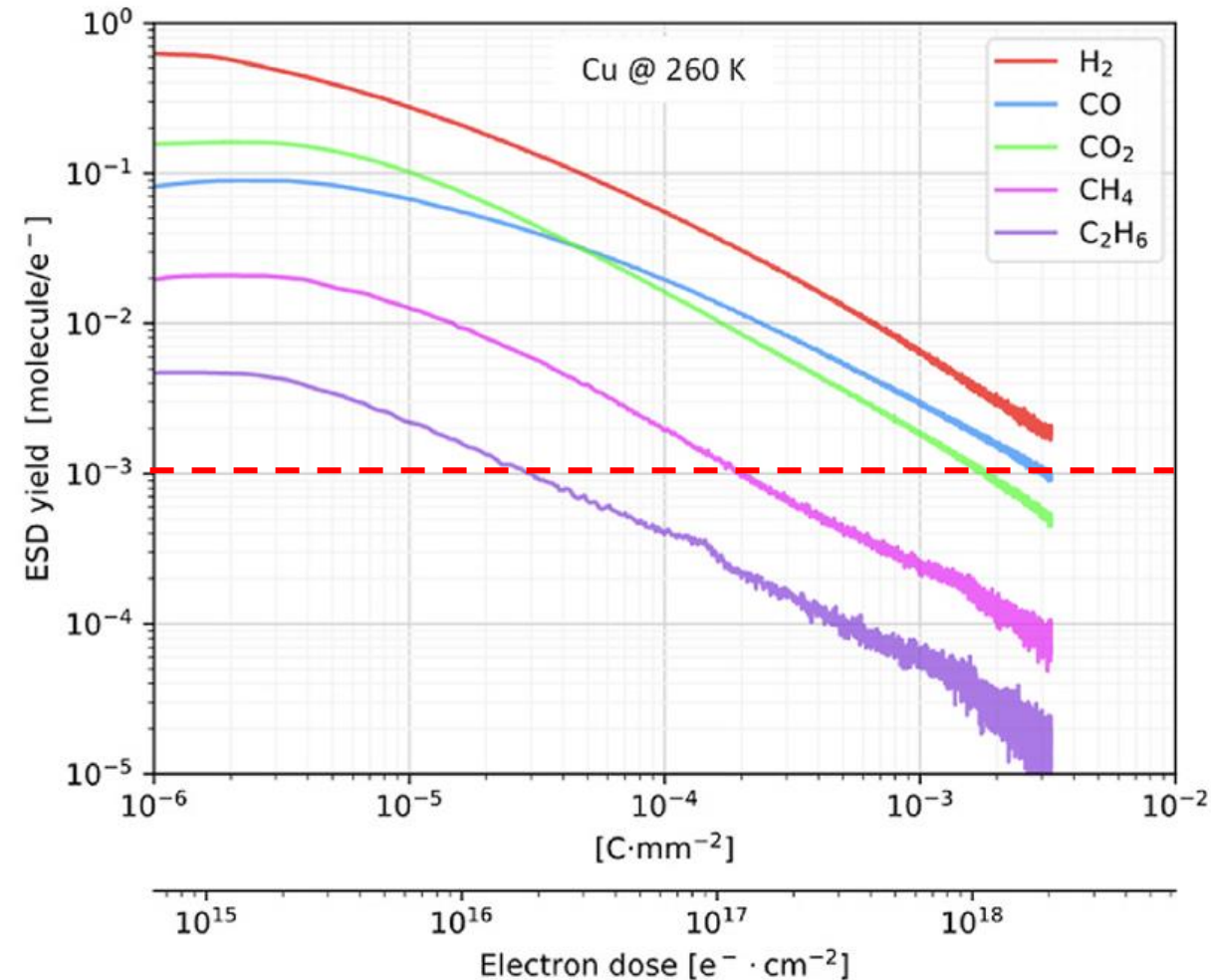
- **Root of linear asymptotic behaviour for high ppb**
- **Method to assess the variations of multipacting with time**

Asymptotic root method is NOT aimed at giving a multipacting threshold as ecloud effect has been identified for lower ppb.

Electron flux scaling with beam intensity at end of fill



Cu ESD for 72b and hybrid fills



M. Haubner et al. Vacuum 207 (2023) 111656

Pressure rise assumed to be induced only by H₂

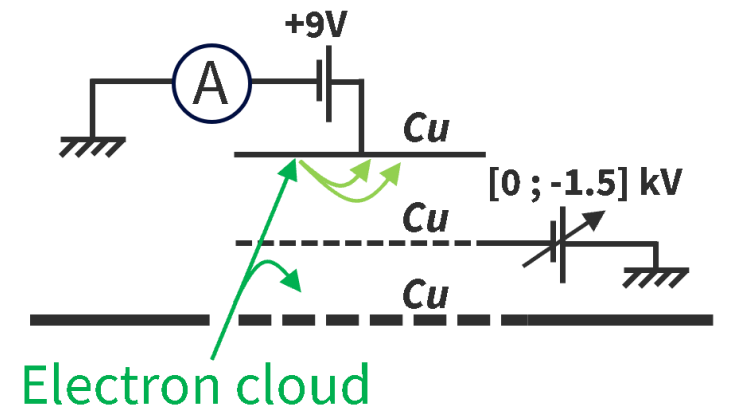
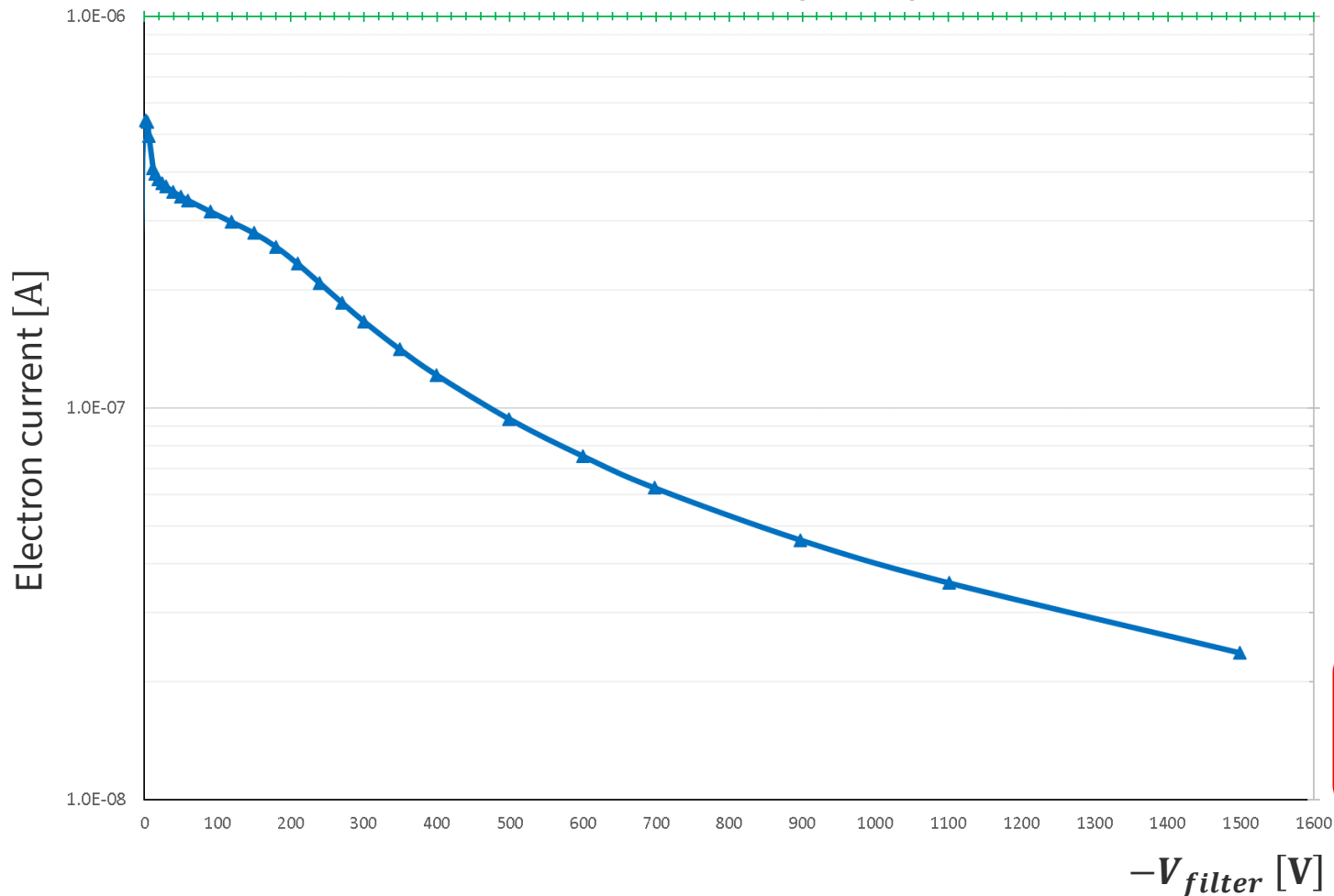
Electrostimulated desorption η computation for copper station

Filling scheme	$\frac{\Delta P}{I} \left[\frac{\text{mbar}}{\text{A} \cdot \text{cm}^{-2}} \right]$	$\eta \left[\frac{\text{molecule}}{e^{-}} \right]$
72b	1.8	1.3×10^{-3}
Hybrid	1.4	1.0×10^{-3}

Measured ESD correspond to a copper surface at a dose of a few $10^{18} \text{ [e}^{-} \cdot \text{cm}^{-2}]$

RFA raw data

Electron current vs Filtering voltage: Fill 9072



RFA scan

- **Scanning time:** ~ 3 [min]
- **Filtering voltage:** $[0 ; -1.5]$ kV
- **Current at a set voltage U [V]:**
current of electrons with an energy under eU [eV]

The energy spectrum of the electrons can be obtained by derivating this curve.

During energy ramp-up

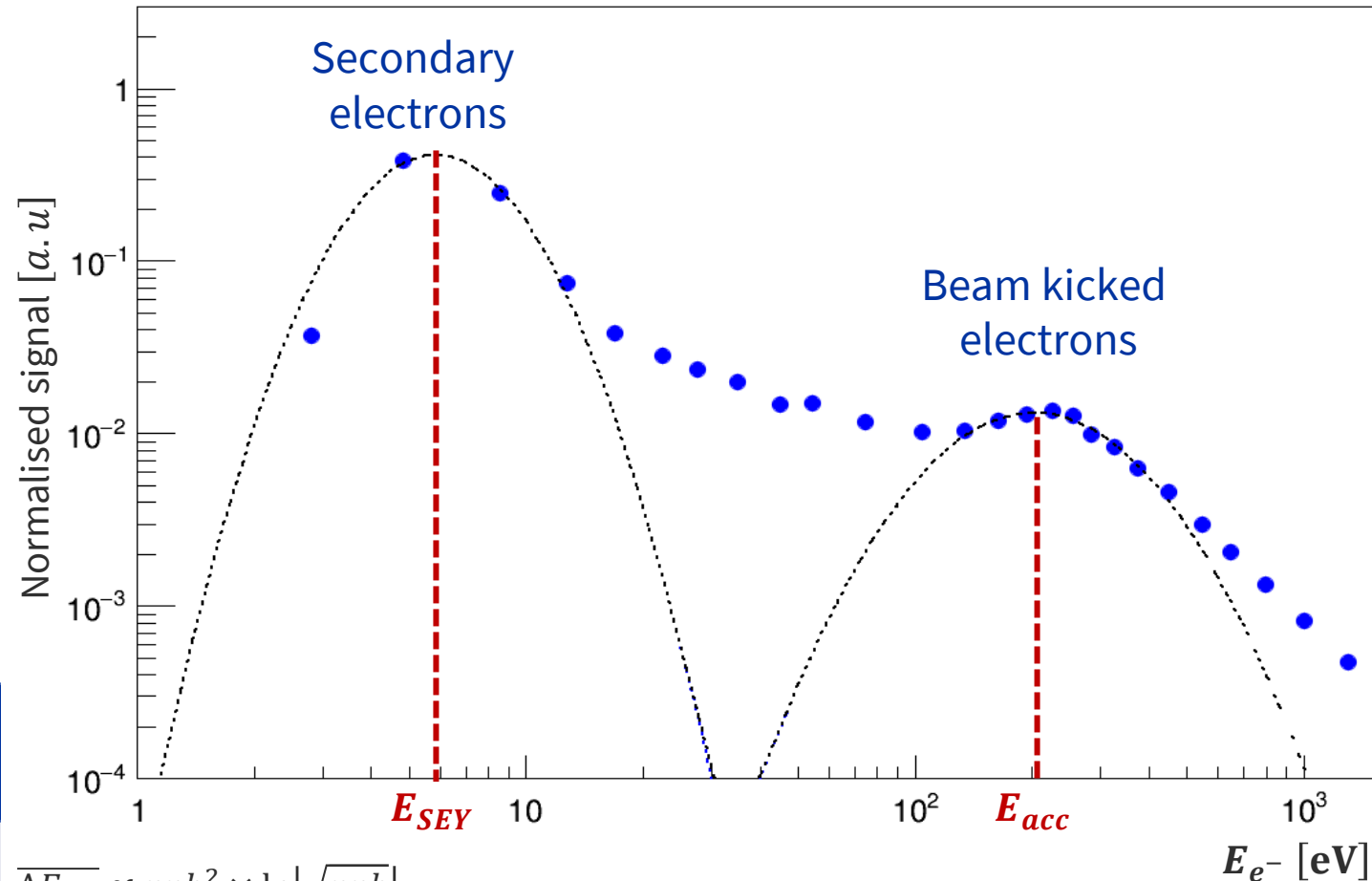
Double lognormal fit

- Assess the energy peaks of secondary and accelerated electrons
 - Measurement step around E_{SEY} : 3-5 eV
 - Measurement step around E_{acc} : 30 eV
- Cannot describe measurements in-between peaks and above accelerated one

E_{B1} [GeV]	ppb [$\times 10^{11}$]	E_{SEY} [eV]	E_{acc} [eV]	$\overline{\Delta E_{tot}}$ [*] [eV]
620	1.60	6.0	203	269
2674	1.60	5.8	202	266
6799	1.59	5.9	203	263

^{*}J. Scott Berg. CERN LHC Project Note 97, July 1997.

Electron energy spectrum: Fill 9072

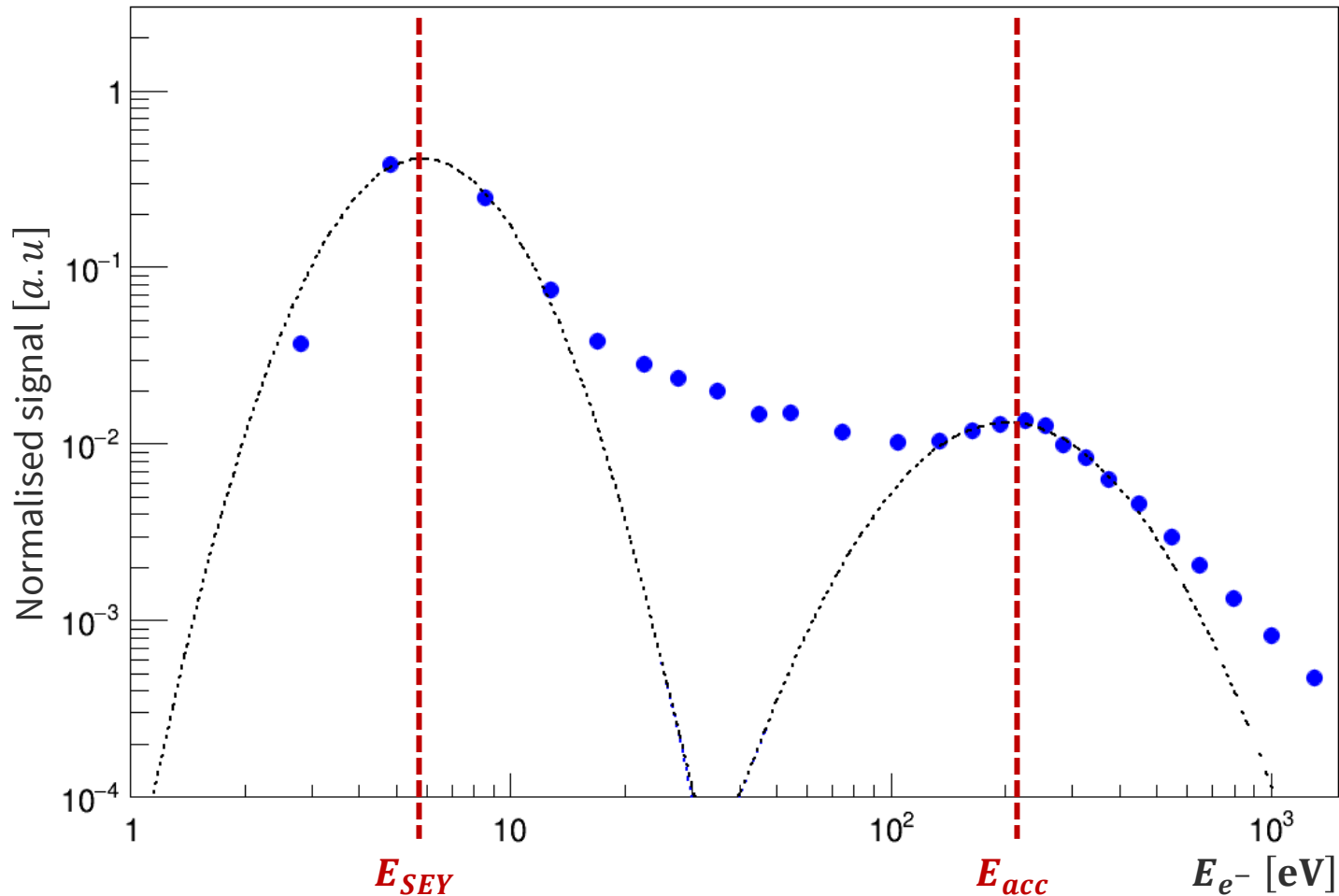


$$\overline{\Delta E_{tot}} \propto ppb^2 \times \ln|\sqrt{ppb}|$$

No significant impact of the beam energy ramp-up on the electron energy distribution.

Energy spectrum double lognormal fit

Electron energy spectrum: Fill 9072



$$f_{\text{lognormal}}(E)_{K,\mu,\sigma} = \frac{K}{E\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(E/\mu)}{\sigma}\right)^2\right]$$

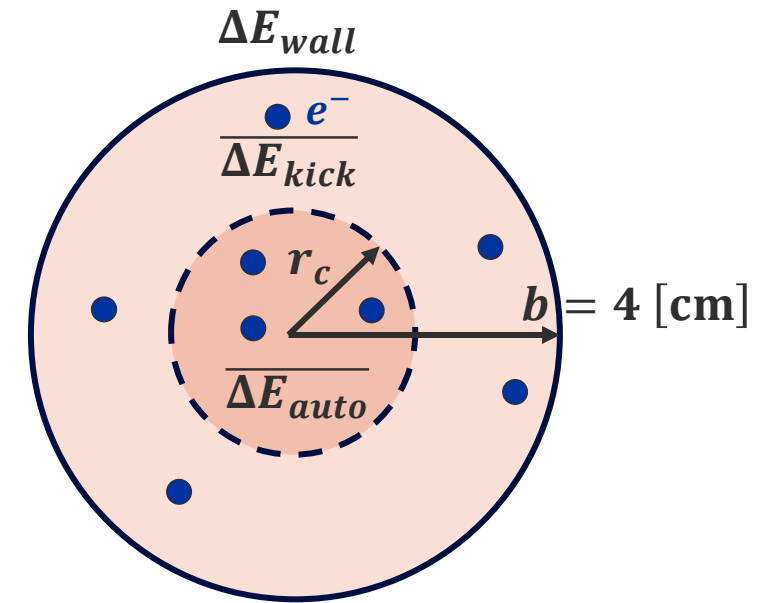
Spectrum properties

- **Peak at:** $E_{peak} = e^{\mu - \sigma^2}$
- **Low peak:** Energy of secondary electrons
- **High peak:** Energy of accelerated electrons
- **Limit of the fit:** within [20eV ; 100eV] and above 600eV

Kick approximation principle

Two different types of motions during the passage of a bunch:

- **Autonomous approximation:** The electrons are strongly pulled by the bunch and begin to oscillate around it.
- **Kick approximation:** The electrons haven't started to move very much before.
- **Deciding which approximation to use:**
 - consists of comparing the oscillation period with respect to the time for the bunch to pass
 - is equivalent to introducing a transition radius to delimit the domains of validity of both approximations



Introduction of the critical radius r_c above which the kick approximation is used, and below which the autonomous approximation is used.

Mean energy kick within these regions:

$$\overline{\Delta E_{auto}}$$

$$\overline{\Delta E_{kick}}$$

Energy kick for an electron on the wall:

$$\Delta E_{wall}$$

Total mean energy gain:

$$\overline{\Delta E_{tot}} = \frac{r_c}{b} \overline{\Delta E_{auto}} + \frac{b - r_c}{b} \overline{\Delta E_{kick}}$$

Ref: "Energy Gain in an Electron Cloud During the Passage of a Bunch" – J. Scott Berg

Kick approximation formulae

Transverse and longitudinal bunch distributions assumed Gaussian

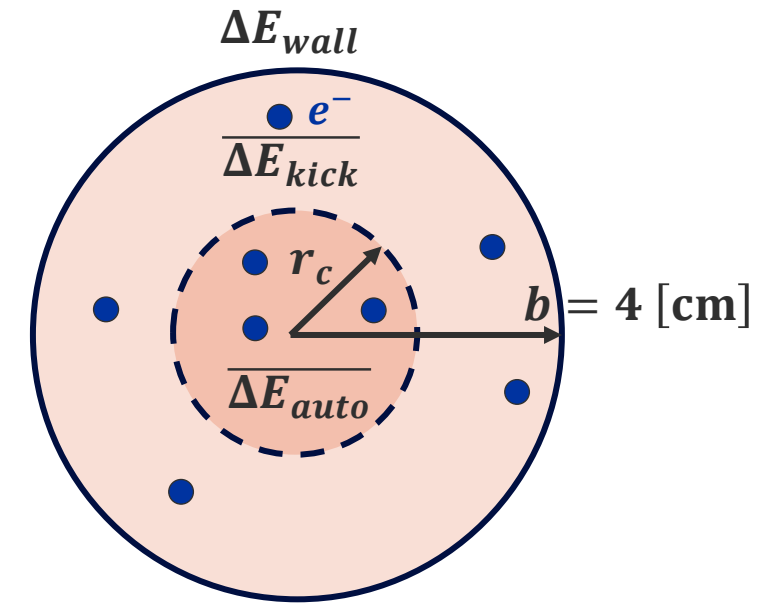
$$c_0 \approx 1.05968 \quad \lambda_{half\ max} = \frac{1}{2\sqrt{2\pi}}$$

Beam parameters

- Relativistic beta: $\beta \approx 1$
- RMS bunch length: $\sigma_l \approx 8$ [cm]
- RMS beam radius: $\sigma_{\perp} \approx 0.2$ [mm]

Electron properties

- Radius: $r_e \approx 2.81$ [fm]
- Rest mass: $m_e \approx 511$ [keV/c²]



$$r_c = 2 \sqrt{\frac{ppb \times r_e \times \sigma_l}{\pi \beta^2 \lambda_{half\ max}}}$$

$$\Delta E_{wall} = 2m_e c^2 \left(\frac{ppb \times r_e}{\beta b} \right)^2$$

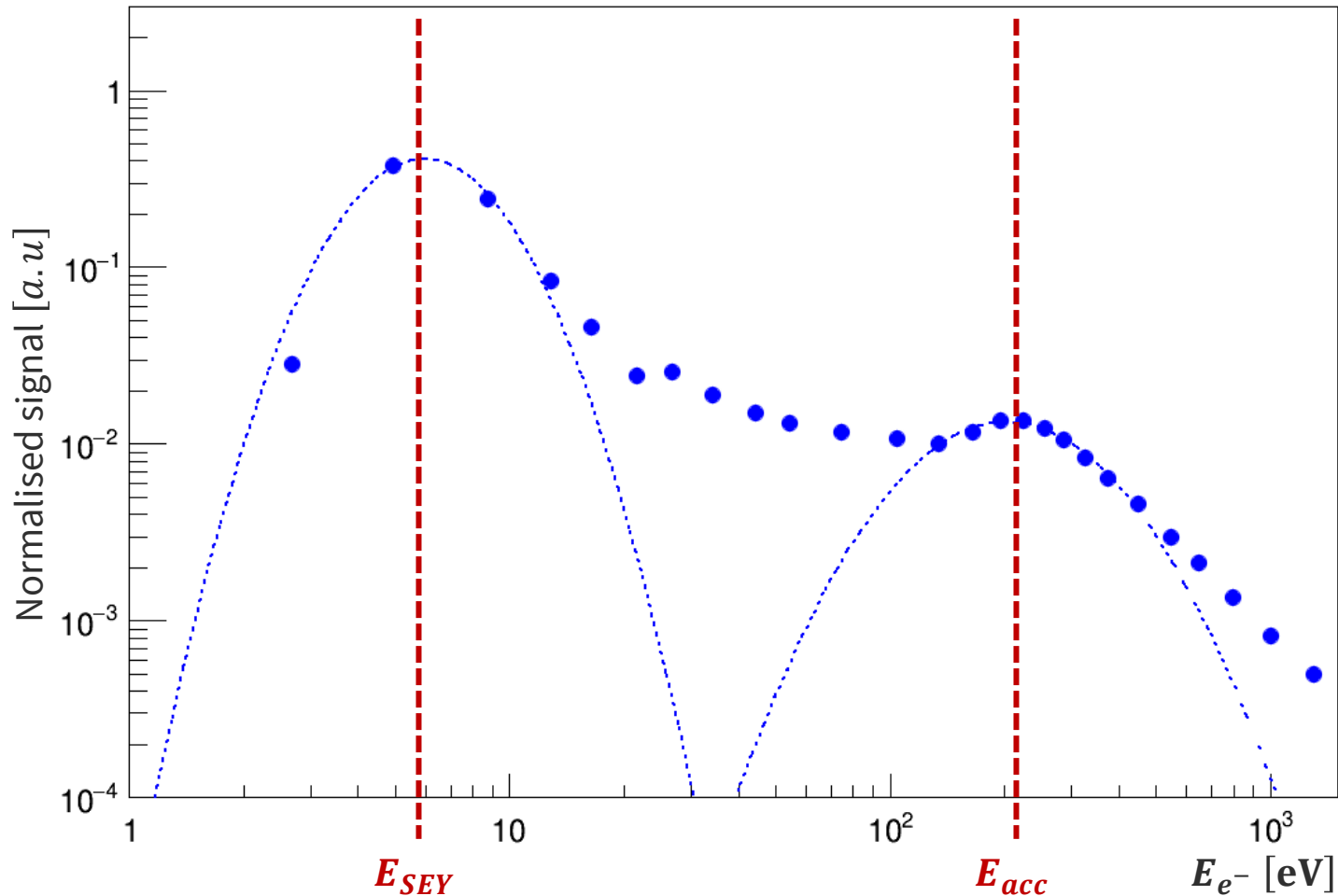
$$\overline{\Delta E_{auto}} = \frac{2}{\pi} \times \Delta E_{wall} \left[\ln \left(\frac{r_c}{c_0 \sigma_{\perp}} \right) - \frac{1}{2} \right]$$

$$\overline{\Delta E_{kick}} = 2 \times \Delta E_{wall} \ln \left(\frac{b}{r_c} \right)$$

Ref: "Energy Gain in an Electron Cloud During the Passage of a Bunch" – J. Scott Berg

Energy ramp-up at 620GeV

Electron energy spectrum: Fill 9072



Beam parameters

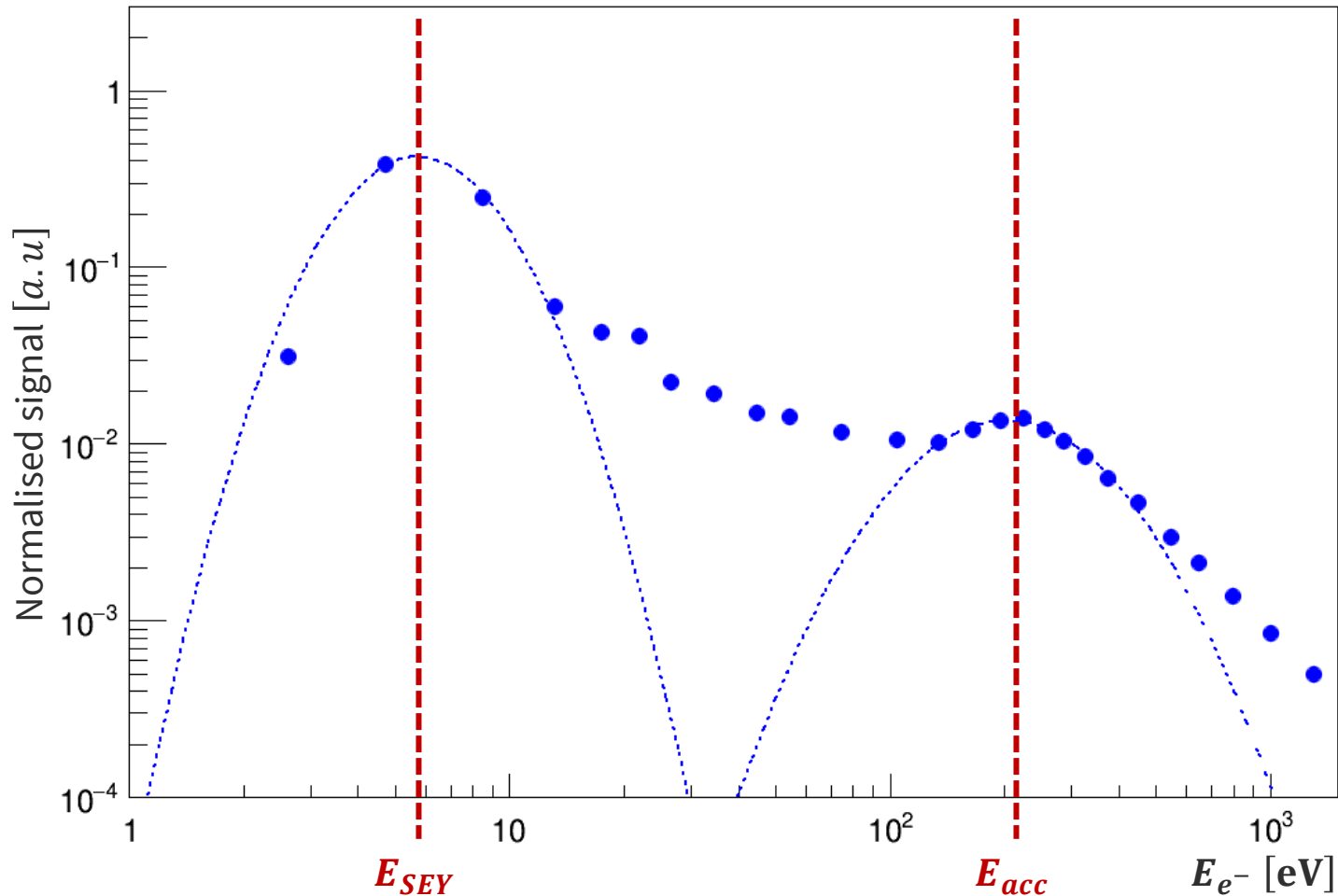
- **Energy:** $E_{B1} = 620$ [GeV]
- **Intensity:** $ppb_{B1} = 1.60 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$

Fit results

- **Low energy:** $E_{SEY} = 6.0$ [eV]
- **High energy:** $E_{acc} = 203$ [eV]

Energy ramp-up at 2074GeV

Electron energy spectrum: Fill 9072



Beam parameters

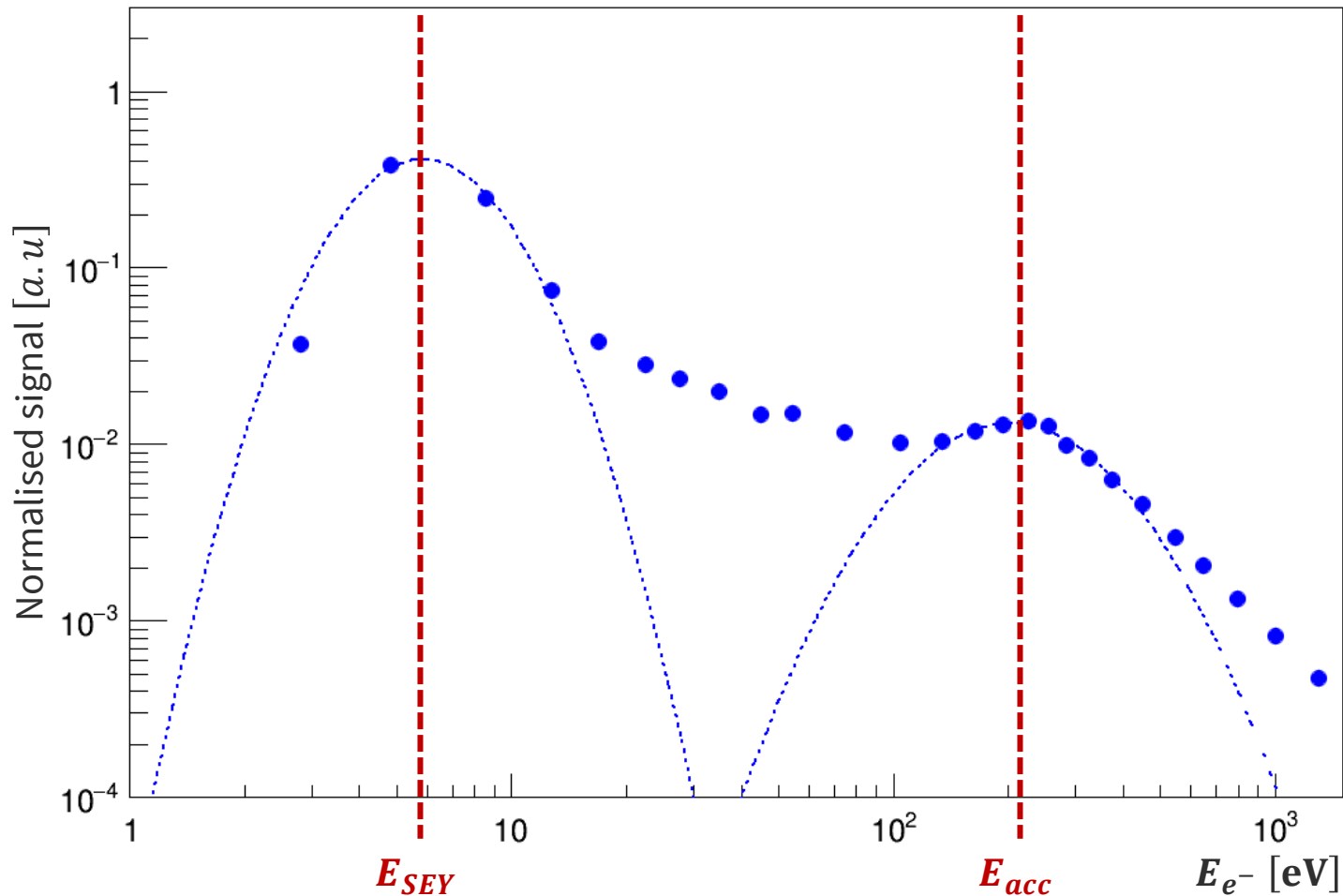
- **Energy:** $E_{B1} = 2074$ [GeV]
- **Intensity:** $ppb_{B1} = 1.60 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$

Fit results

- **Low energy:** $E_{SEY} = 5.8$ [eV]
- **High energy:** $E_{acc} = 202$ [eV]

Energy ramp-up at 6799GeV

Electron energy spectrum: Fill 9072

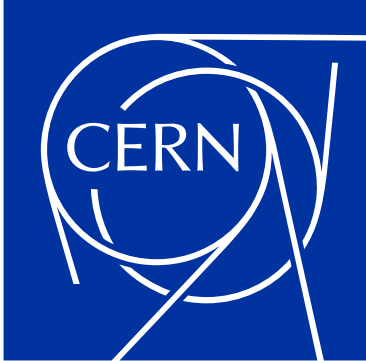


Beam parameters

- **Energy:** $E_{B1} = 6799$ [GeV]
- **Intensity:** $ppb_{B1} = 1.59 \times 10^{11} \left[\frac{p^+}{\text{bunch}} \right]$

Fit results

- **Low energy:** $E_{SEY} = 5.9$ [eV]
- **High energy:** $E_{acc} = 203$ [eV]



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