Some bulk Cu and aC coating preliminary results obtained with the Vacuum Pilot Sector during 2023 run

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Outline

I. Set-up description & physics principles

II. LHC physics fill's lifetime

III. Electron cloud of a hybrid physics fill

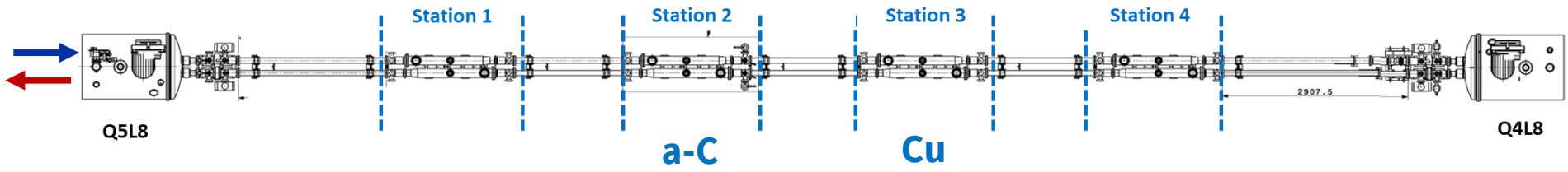
IV. Electron energy distribution for bulk Copper

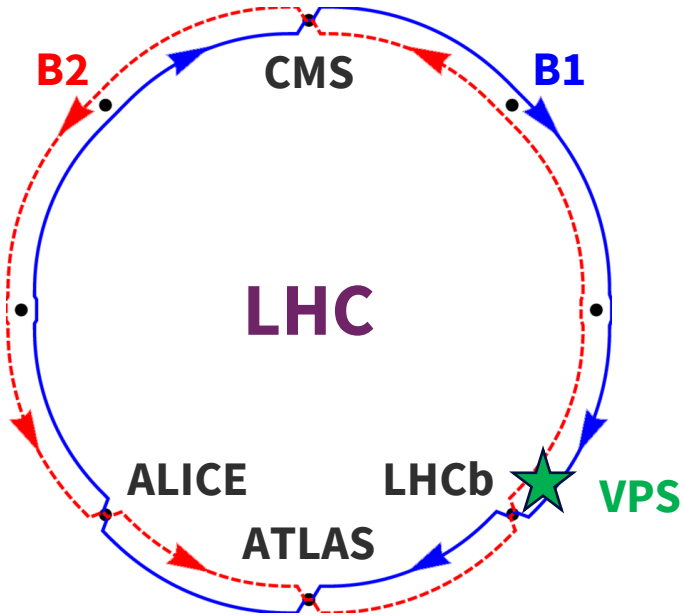
Disclaimer

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

I. Set-up description & physics principles

Layout

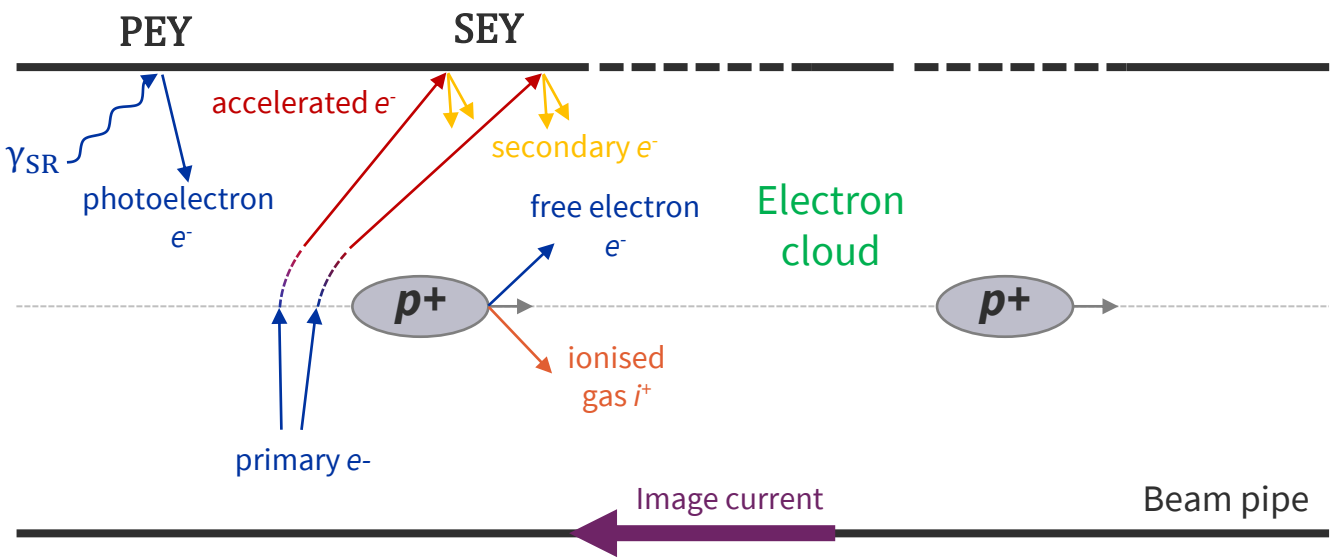




Vacuum Pilot Sector (VPS)

- **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

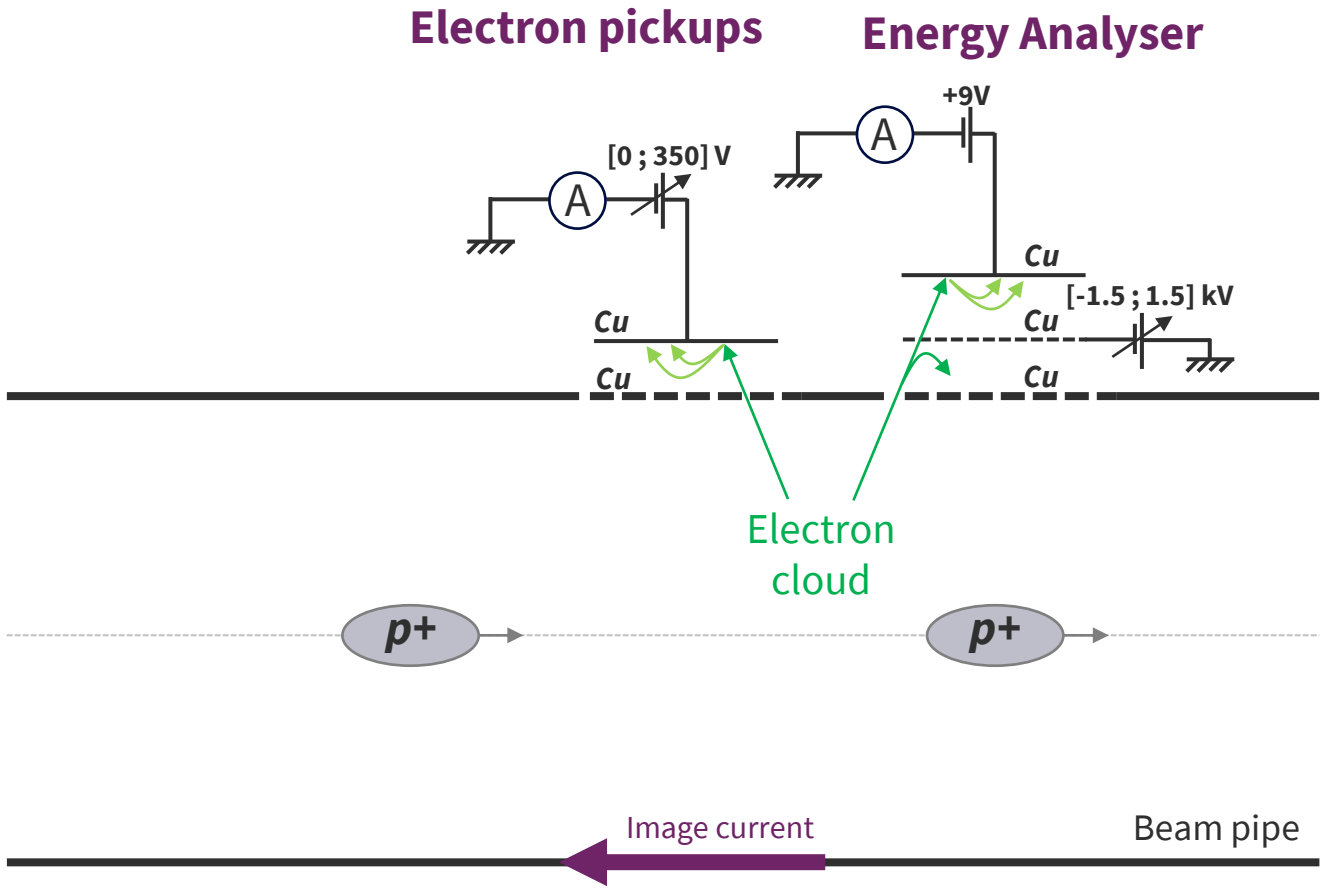
- **Primary electrons:**
  - Photoelectrons induced by photoelectric effect
  - Free electrons induced by bunch ionising the residual gas
- **Secondary electrons:** induced by primary electrons, accelerated by successive bunches, hitting the surface

Two main material properties for ecloud:

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

$$\mathbf{PEY} = \frac{N_{photo\ e^-}}{N_\gamma} \qquad \mathbf{SEY} = \frac{N_{sec\ e^-}}{N_{incident\ e^-}}$$

Electron current and energy detection



Electron pickups

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

Energy Analyser (only copper station)

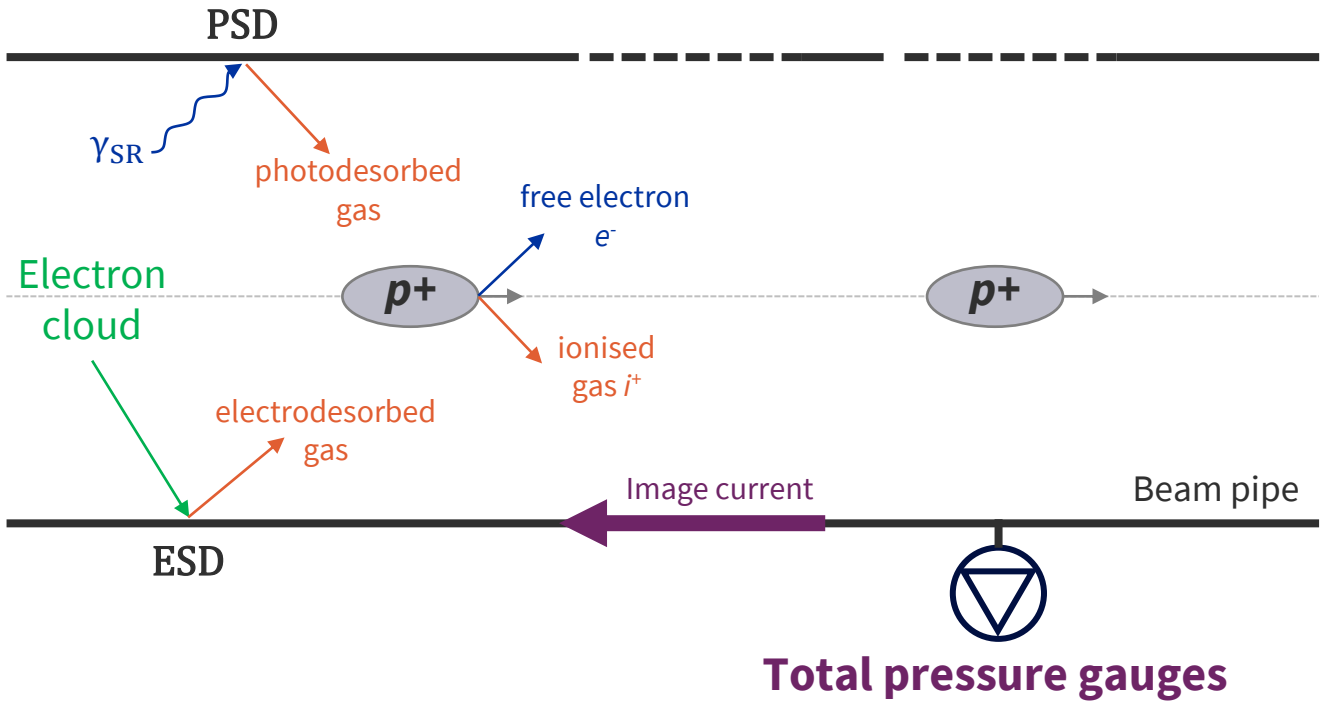
- « Retarding Field Analyser (RFA) »
- Electron pickup: with $+9$V bias
- Biased filtering grid: 75%−transparency
- Biased filtering grid: $u \in [-1500\,;+1500]$ V
- Measurement:

« electron cloud current below u [eV] »

Total pressure detection

Pressure elevation during LHC functionning

- **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 »

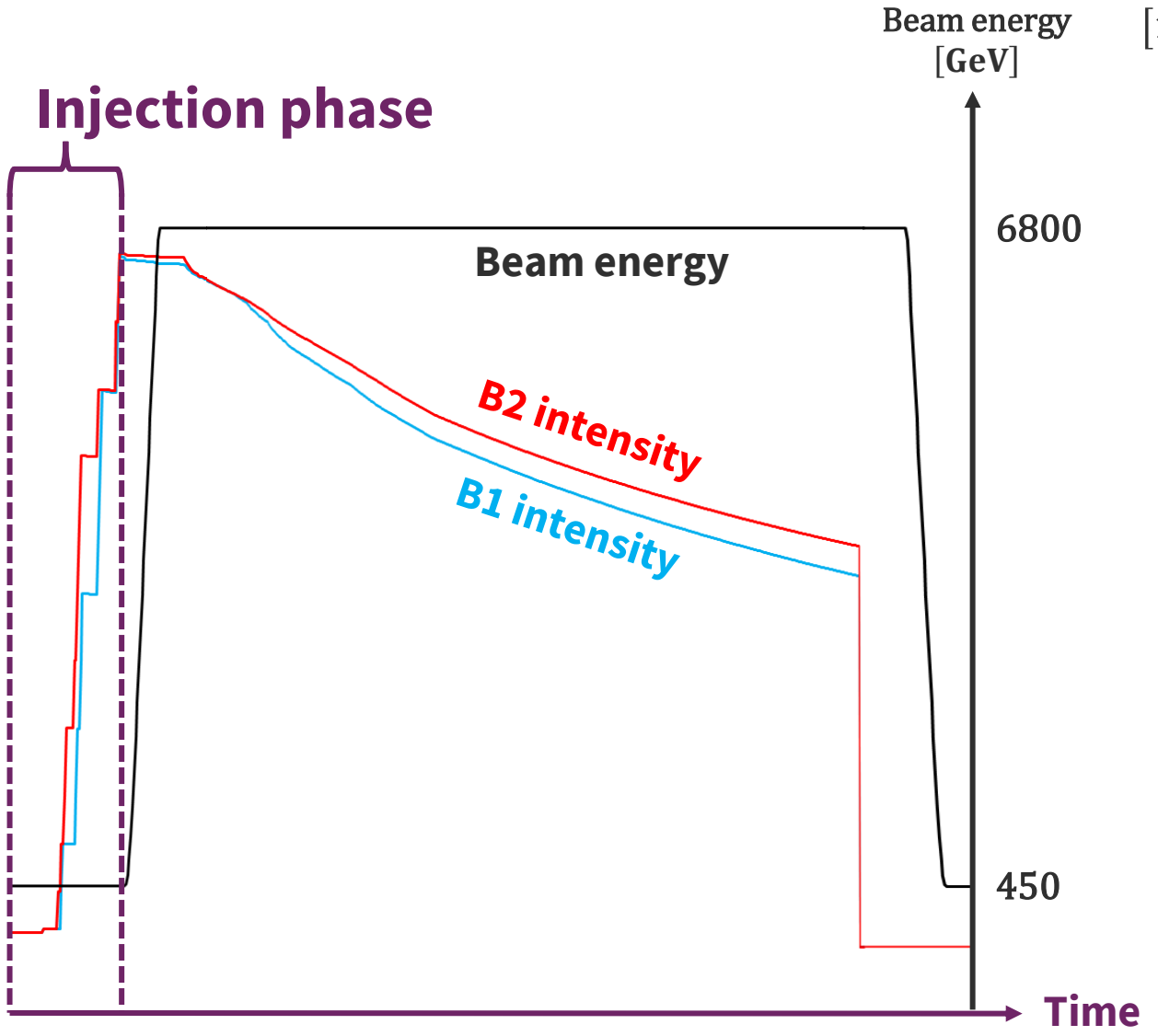
Two main material properties for gas increase:

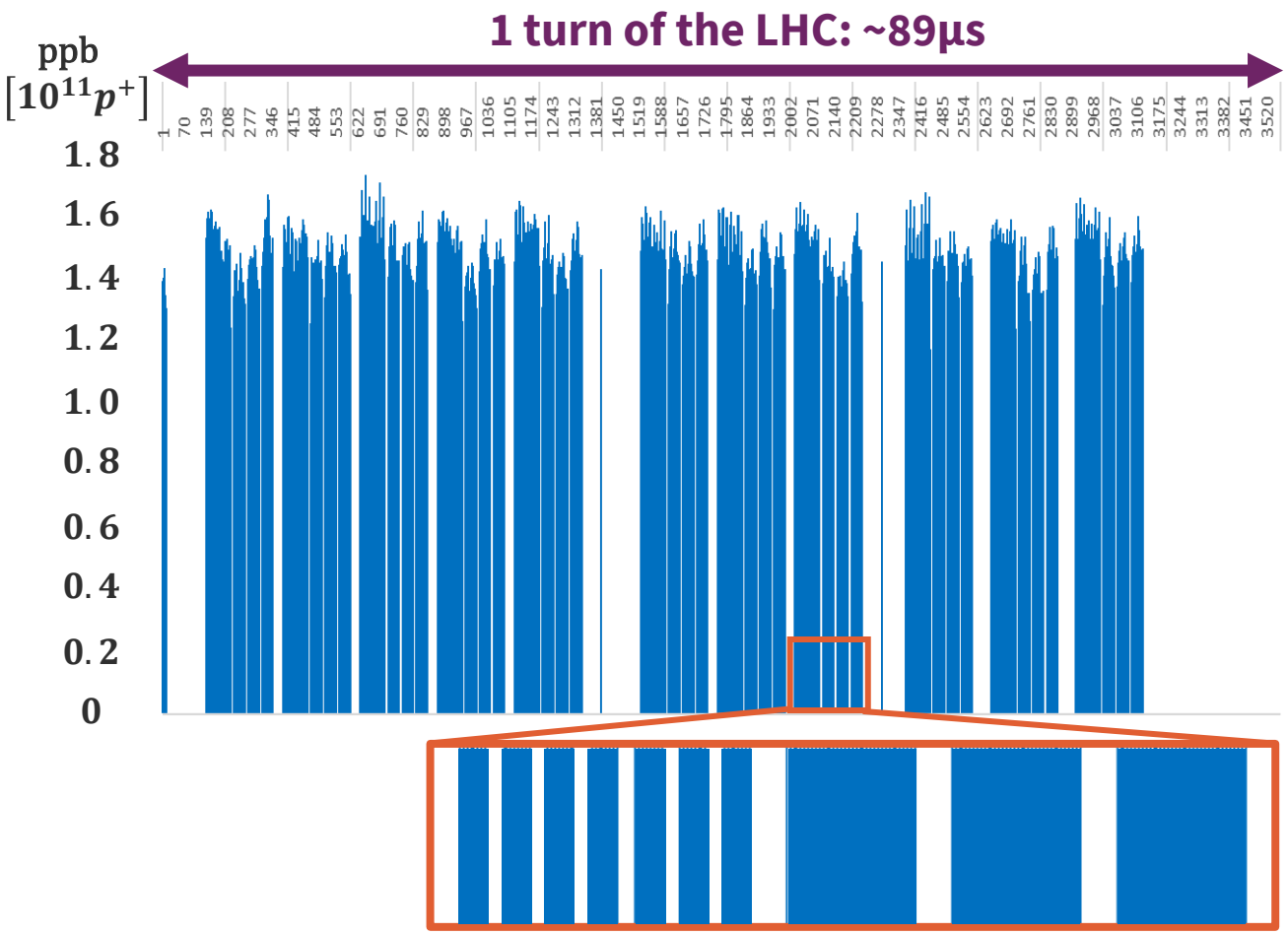
- **Photodesorption**
- **Electrodesorption**

$$\mathrm{PSD}_{gas} \propto \frac{\Delta P_{gas}}{N_\gamma} \qquad \mathrm{ESD}_{gas} \propto \frac{\Delta P_{gas}}{N_{e^-}}$$

II. LHC physics fill’s lifetime

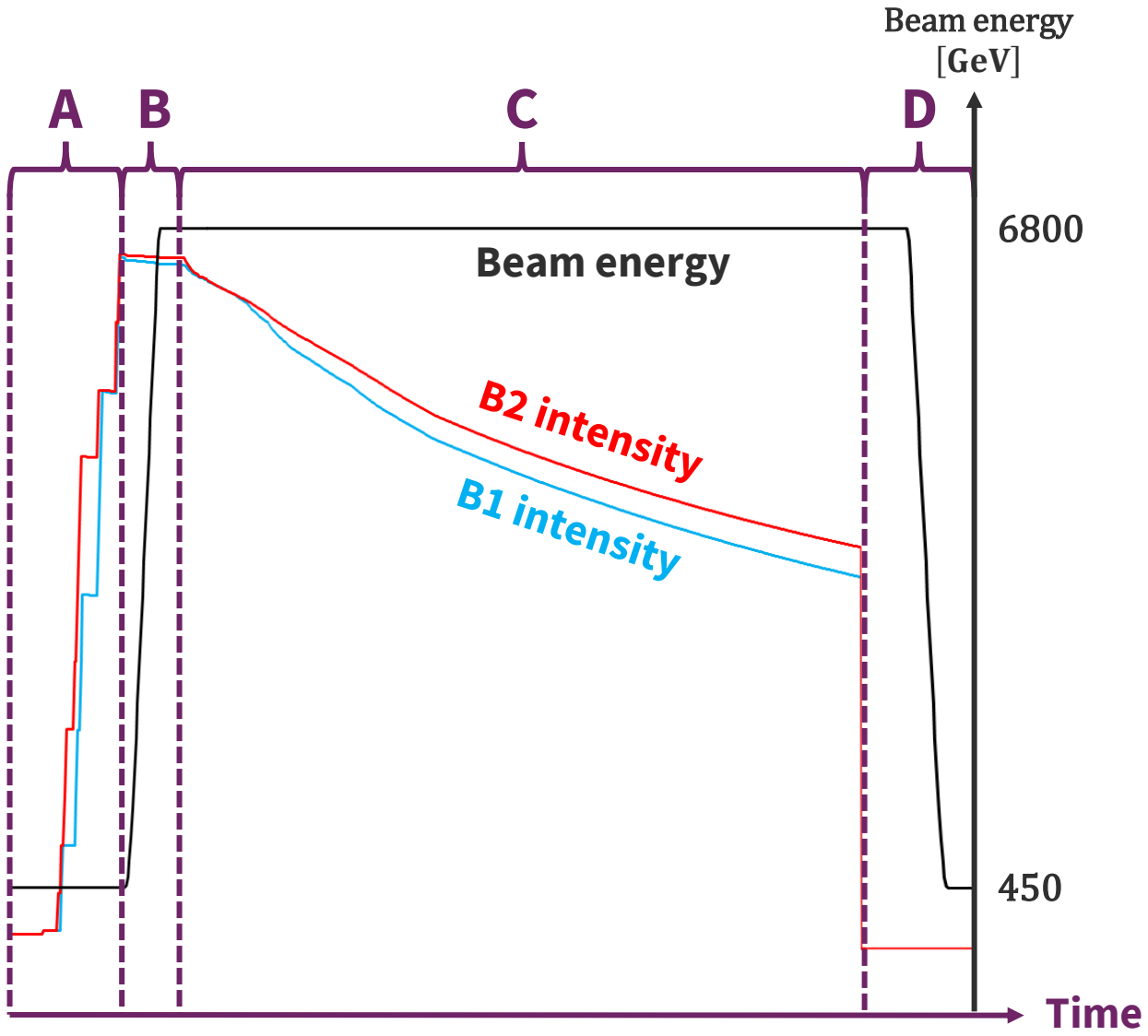
Hybrid scheme injection





« 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

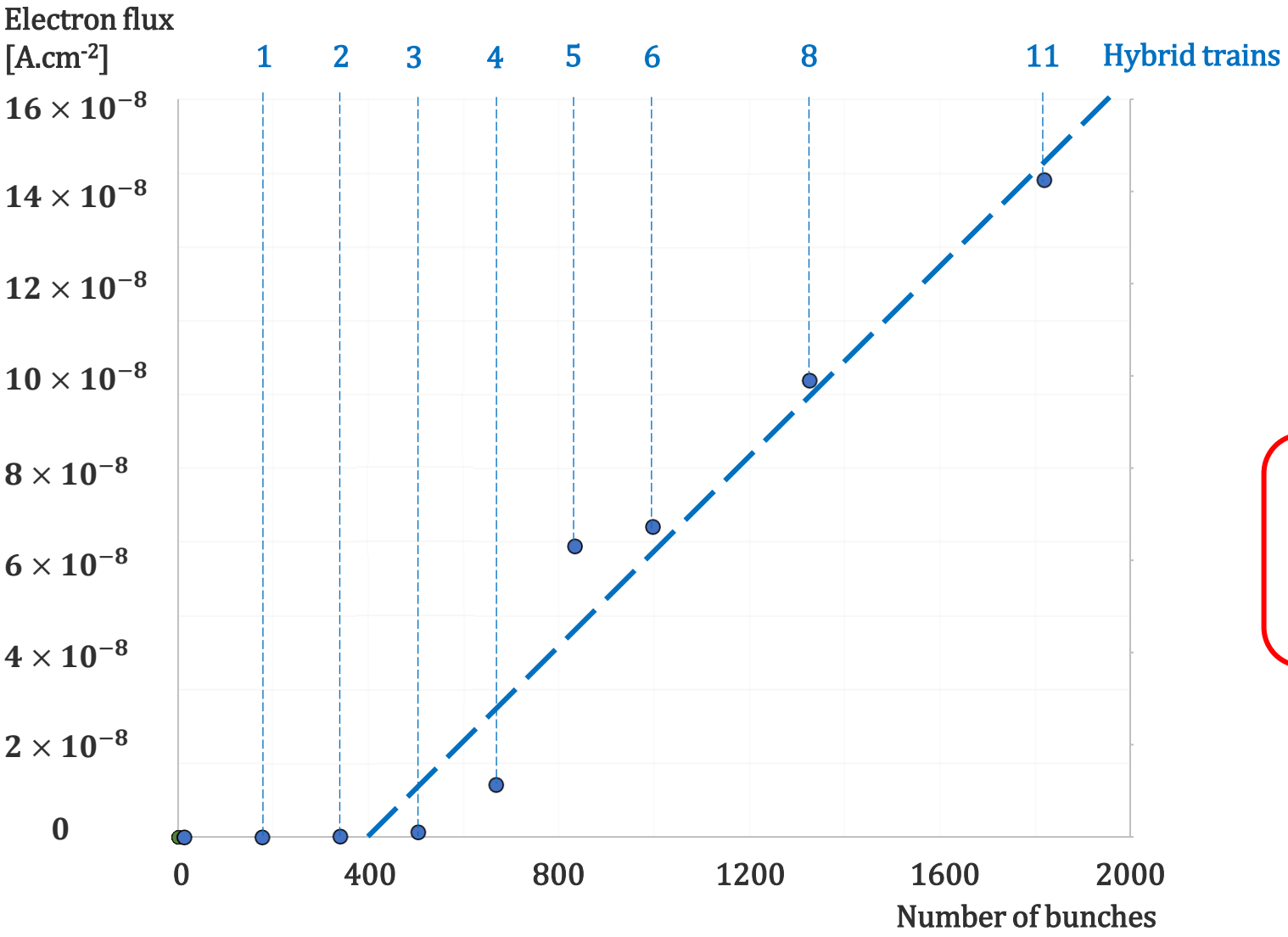
ppb: proton per bunch

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. Electron cloud of a hybrid physics fill

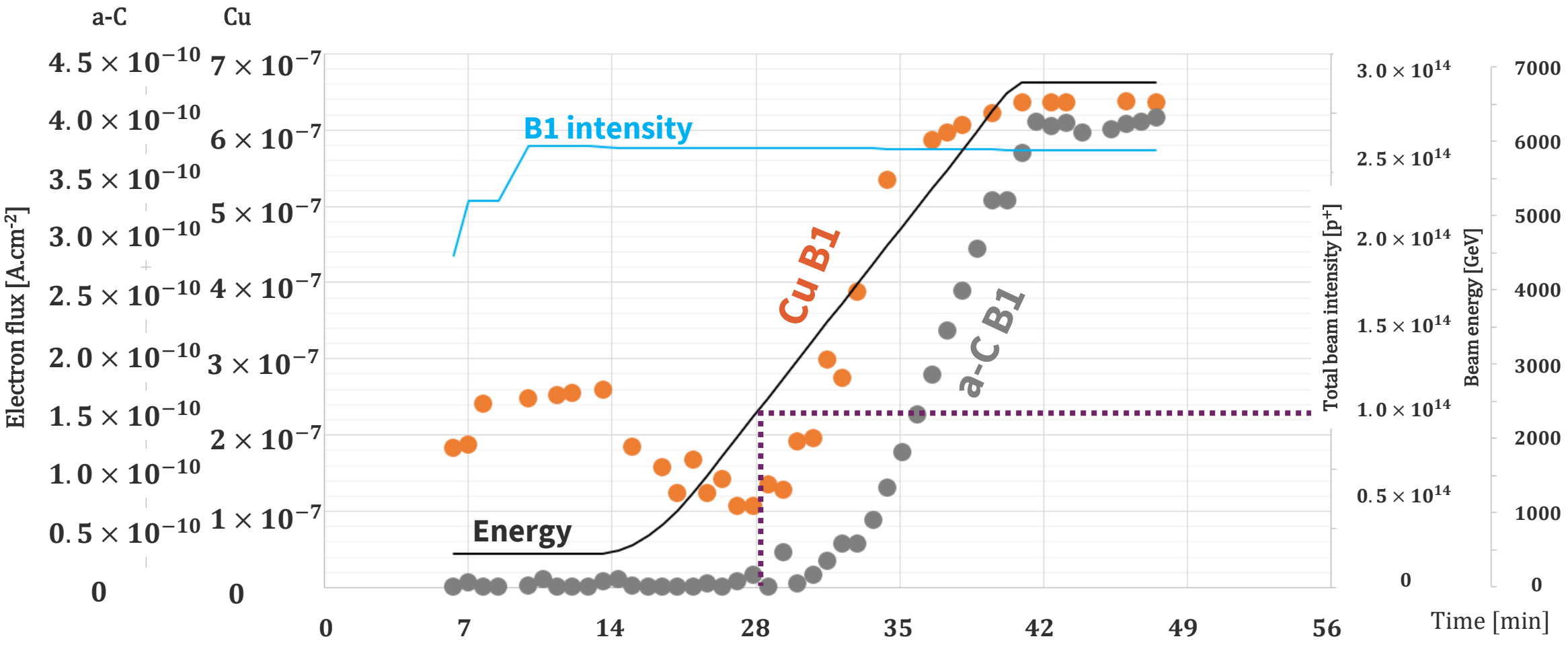
Electron cloud response of copper during injection



$$I_{hybrid}[\mathrm{nA.\,cm^{-2}}] \approx 0.1 \times (N_{bunch} - 400)$$

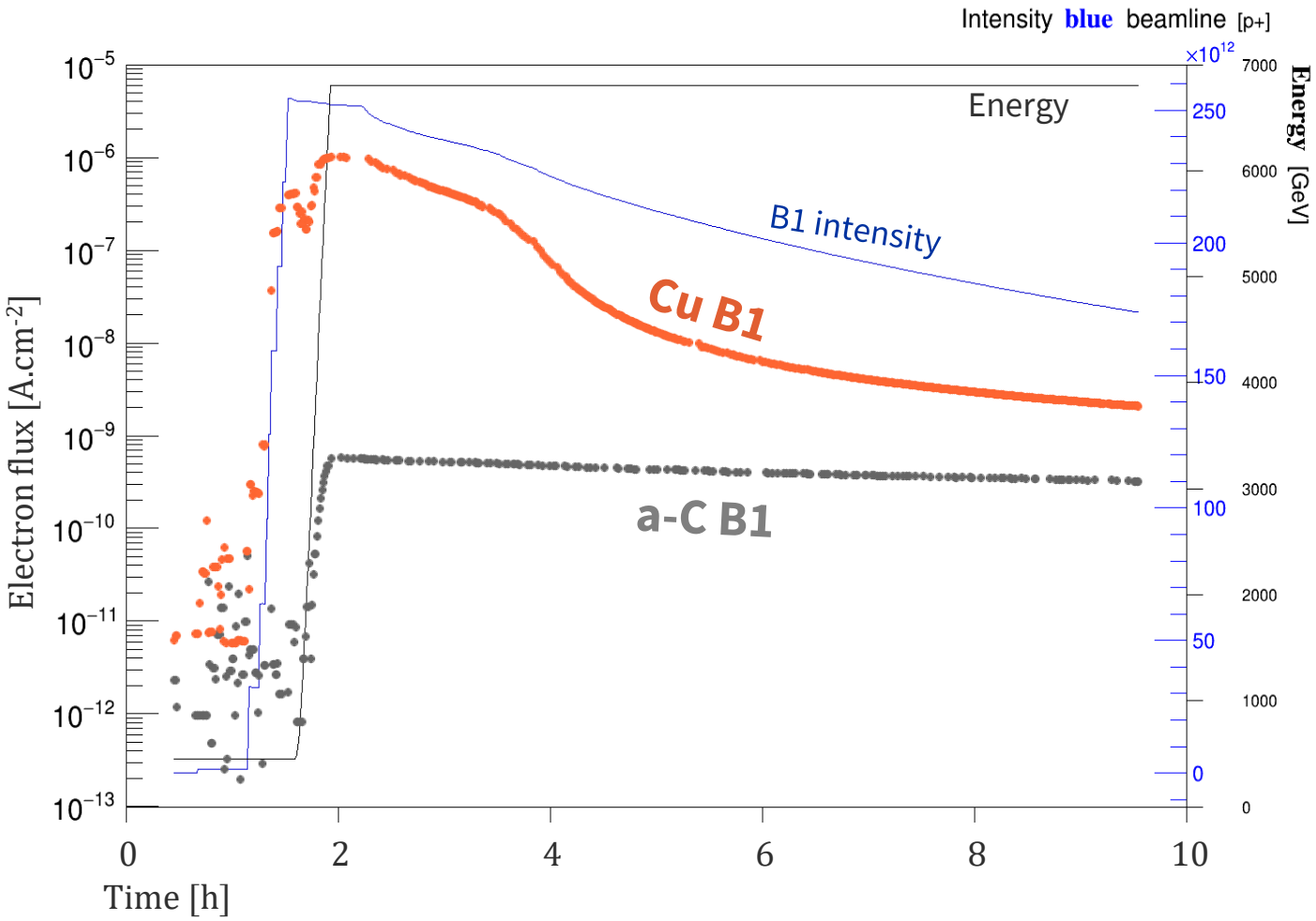
Electron cloud's linear behaviour after a certain number of bunches injected

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 occuring only for copper

- Bumbed curve for copper
- Flat curve for carbon

Only photoelectrons at the end of the fill

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

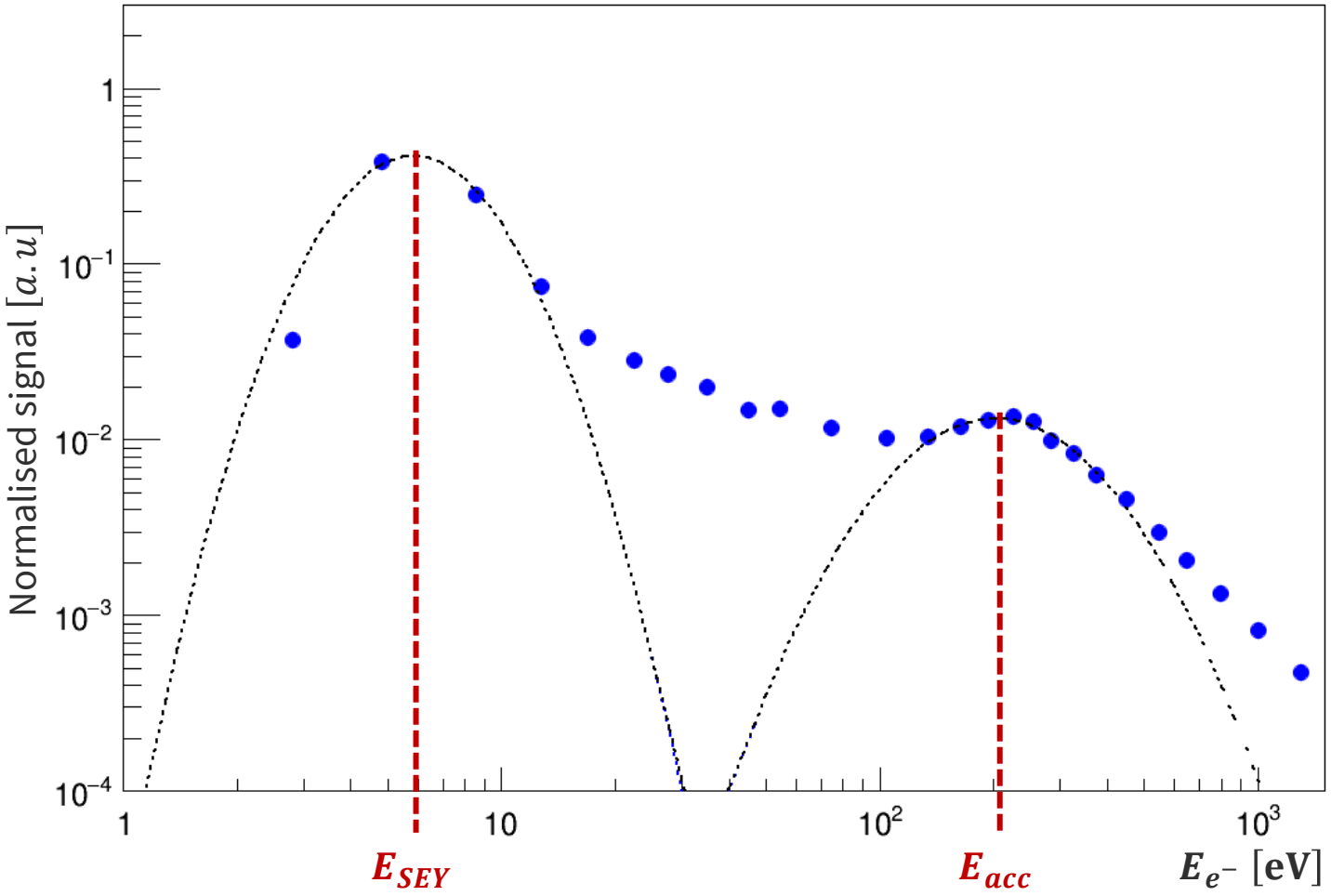
Multipacting induces orders of magnitude of difference between copper and carbon electron cloud signals.

IV. Electron energy distribution for bulk Copper

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

At Stable Beam: t = 0h

Electron energy spectrum: Fill 9072



Beam parameters

- **Energy:** $E_{B1} = 6799\ [\mathrm{GeV}]$
- **Mean bunch intensity:**

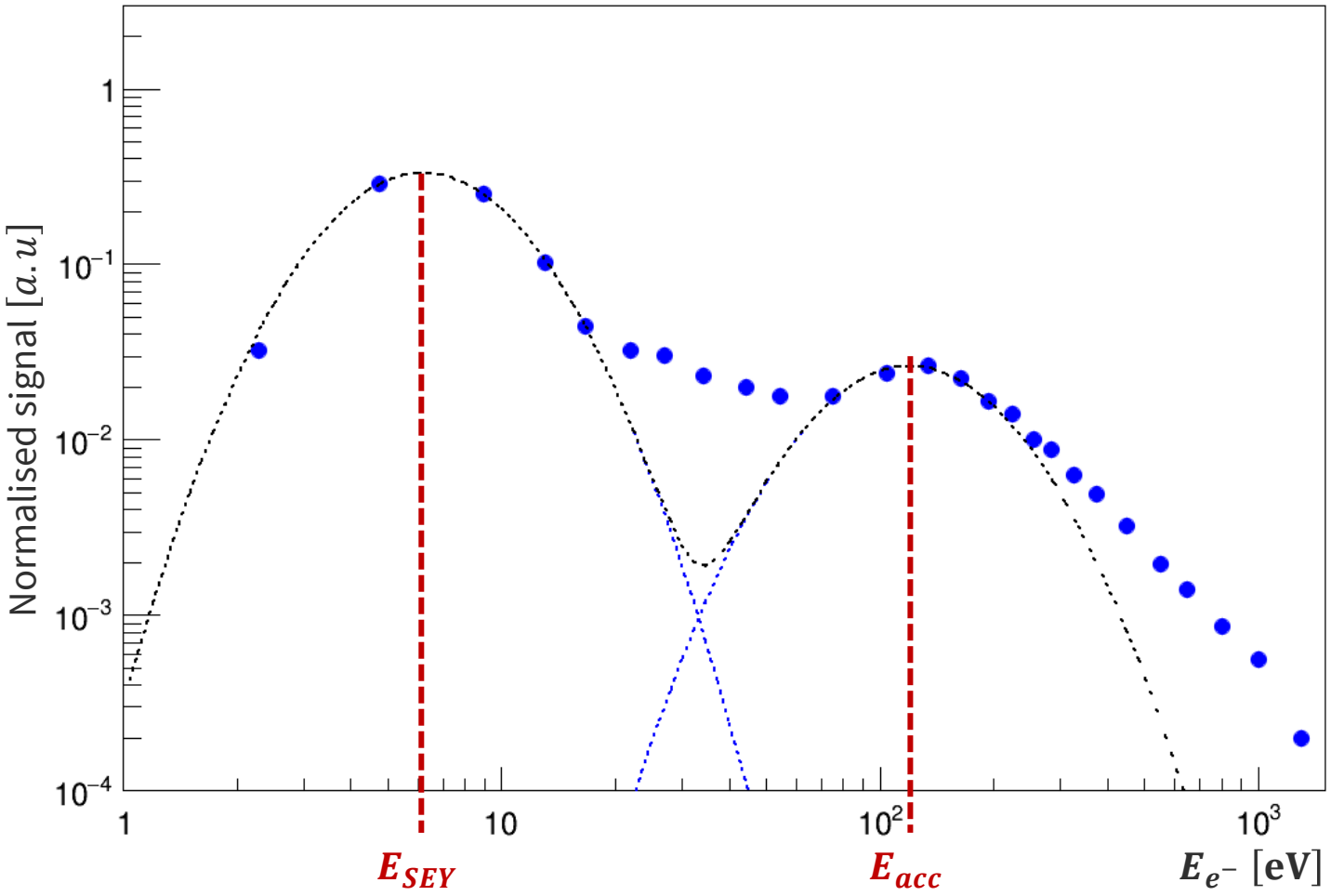
$$\overline{ppb}_{B1} = 1.59 \times 10^{11} \left[\frac{\mathrm{p}^+}{\mathrm{bunch}}\right]$$

Fit results

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

At Stable Beam: t = 6h

Electron energy spectrum: Fill 9072



Beam parameters

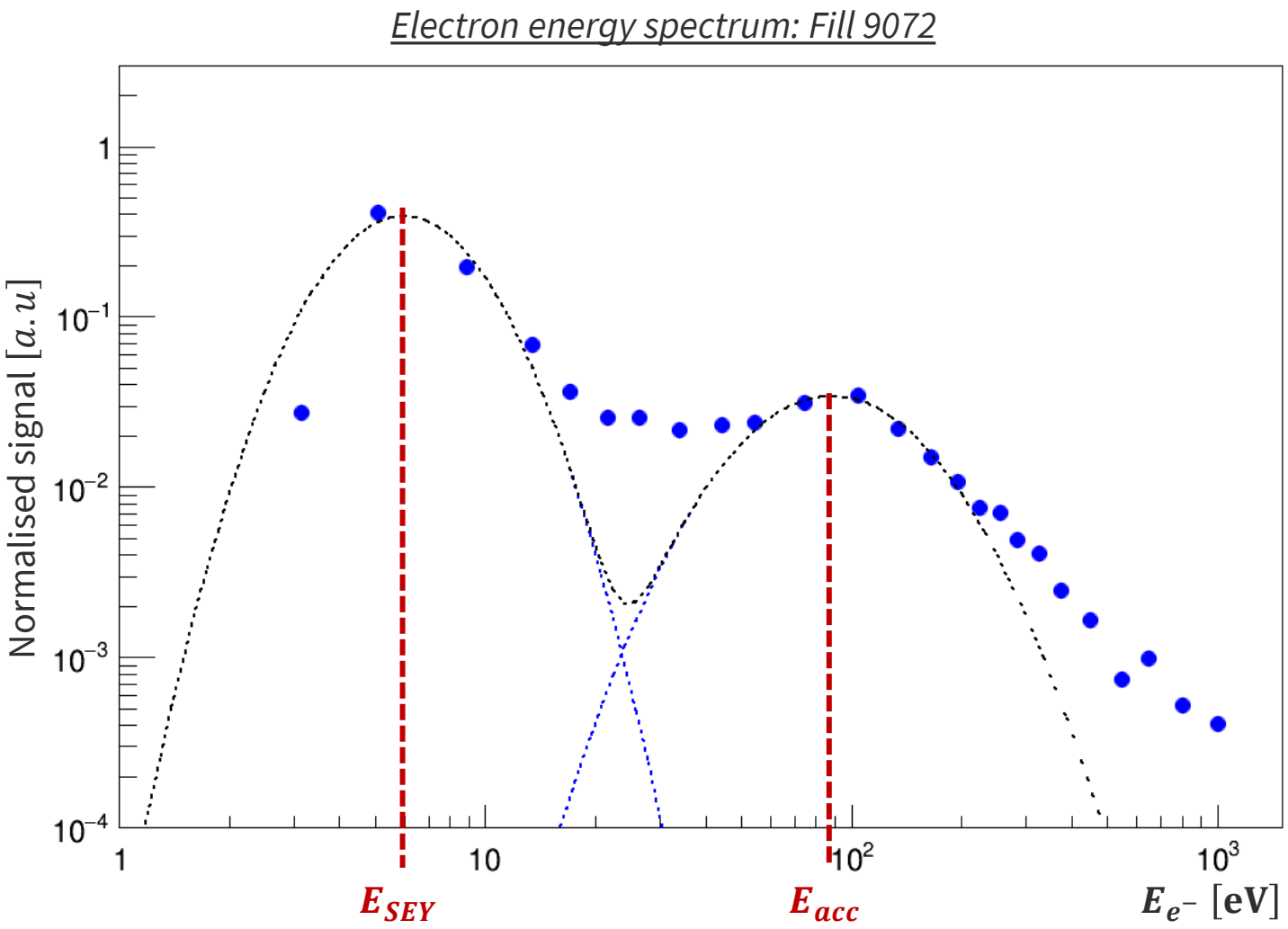
- **Energy:** $E_{B1} = 6799\ [\mathrm{GeV}]$
- **Mean bunch intensity:**

$$\overline{ppb}_{B1} = 1.23 \times 10^{11} \left[\frac{\mathrm{p}^+}{\mathrm{bunch}}\right]$$

Fit results

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

At Stable Beam: t = 11h



Beam parameters

- **Energy:** $E_{B1} = 6799\ [\mathrm{GeV}]$
- **Mean bunch intensity:**

$$\overline{ppb}_{B1} = 0.99 \times 10^{11} \left[\frac{\mathrm{p}^+}{\mathrm{bunch}}\right]$$

Fit results

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

Impact of the beam intensity at 6800GeV

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

Stable Beam +	$\overline{ppb}$ $[\times 10^{11}]$	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

Electron cloud current:

- At a certain number of bunches, $I_{e^-} \propto N_{bunch}$
- Photoelectrons detected for $E_{beam} > 2500\ [\mathrm{GeV}]$
- Electron cloud responses for copper orders of magnitude above carbon ones
- Multipacting only in copper

Electron energy distribution:

- Decrease of the accelerated energy peak with ppb
- Kick energy formula is a reasonable first approximation

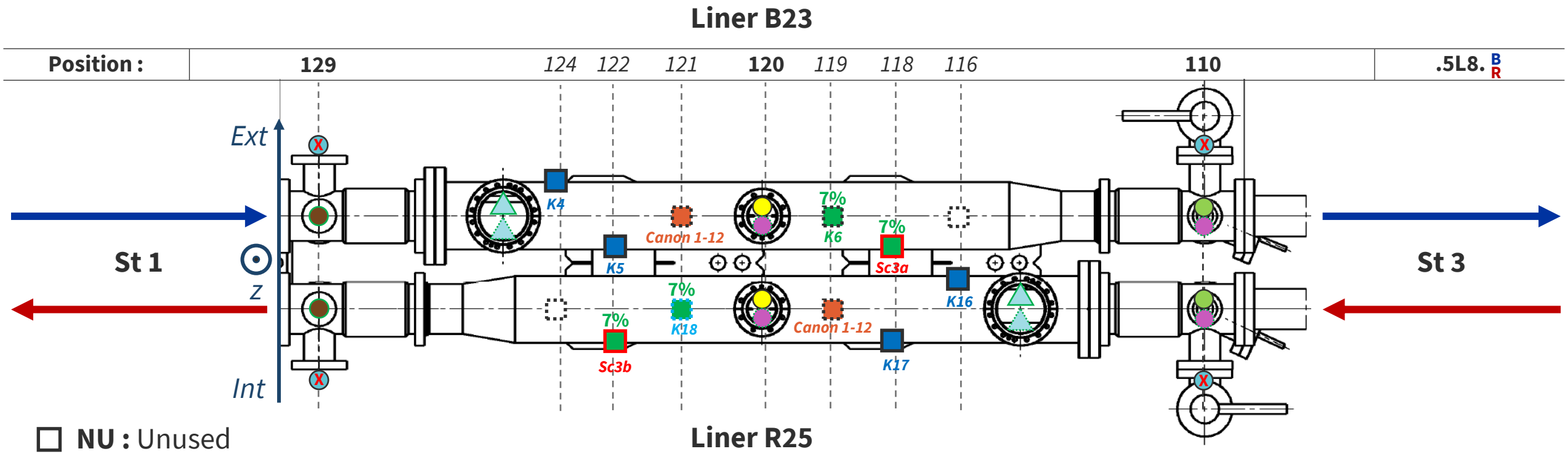
Perspective

- 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

Backups

Station 2 – Amorphous carbon

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



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 R25

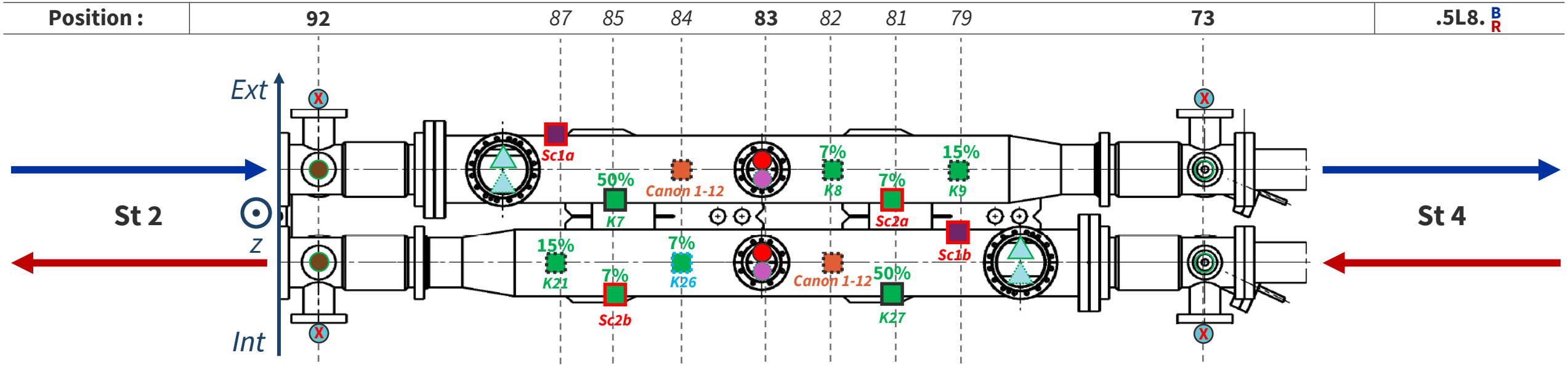
Unused
***VGPB* :** Penning Gauge
***VGI* :** Bayard-Alpert Gauge **(BAG)**
VQM : Vacuum Quality Monitor
RGA : Residual Gas Analyser
***VGRB* :** Pirani gauge
***VPIA* :** Vacuum Pump

***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

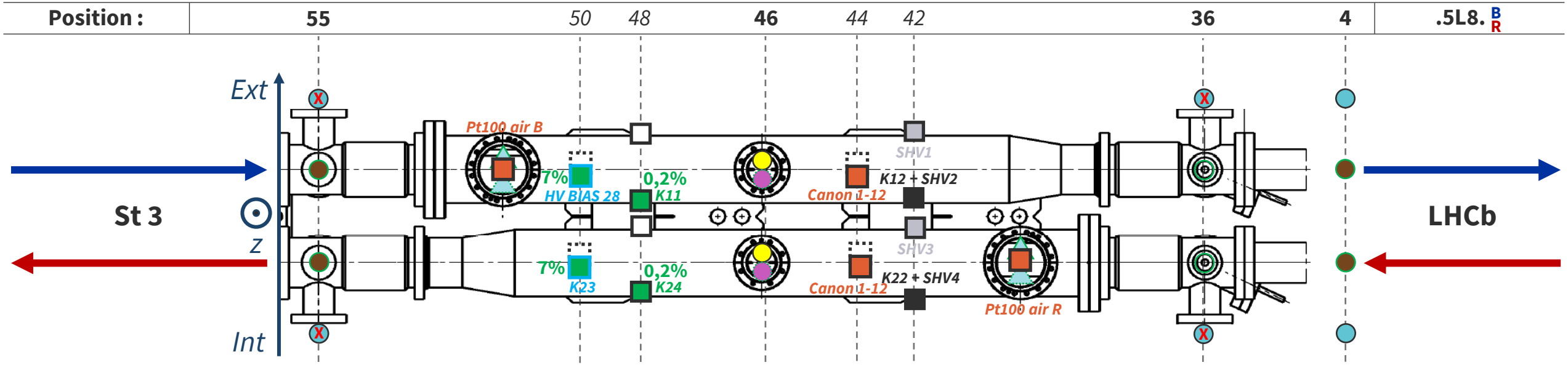
Unused
***VGPB* :** Penning Gauge
***VGI* :** Bayard-Alpert Gauge **(BAG)**
VQM : Vacuum Quality Monitor
RGA : Residual Gas Analyser
***VGRB* :** Pirani gauge
***VPIA* :** Vacuum Pump

***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



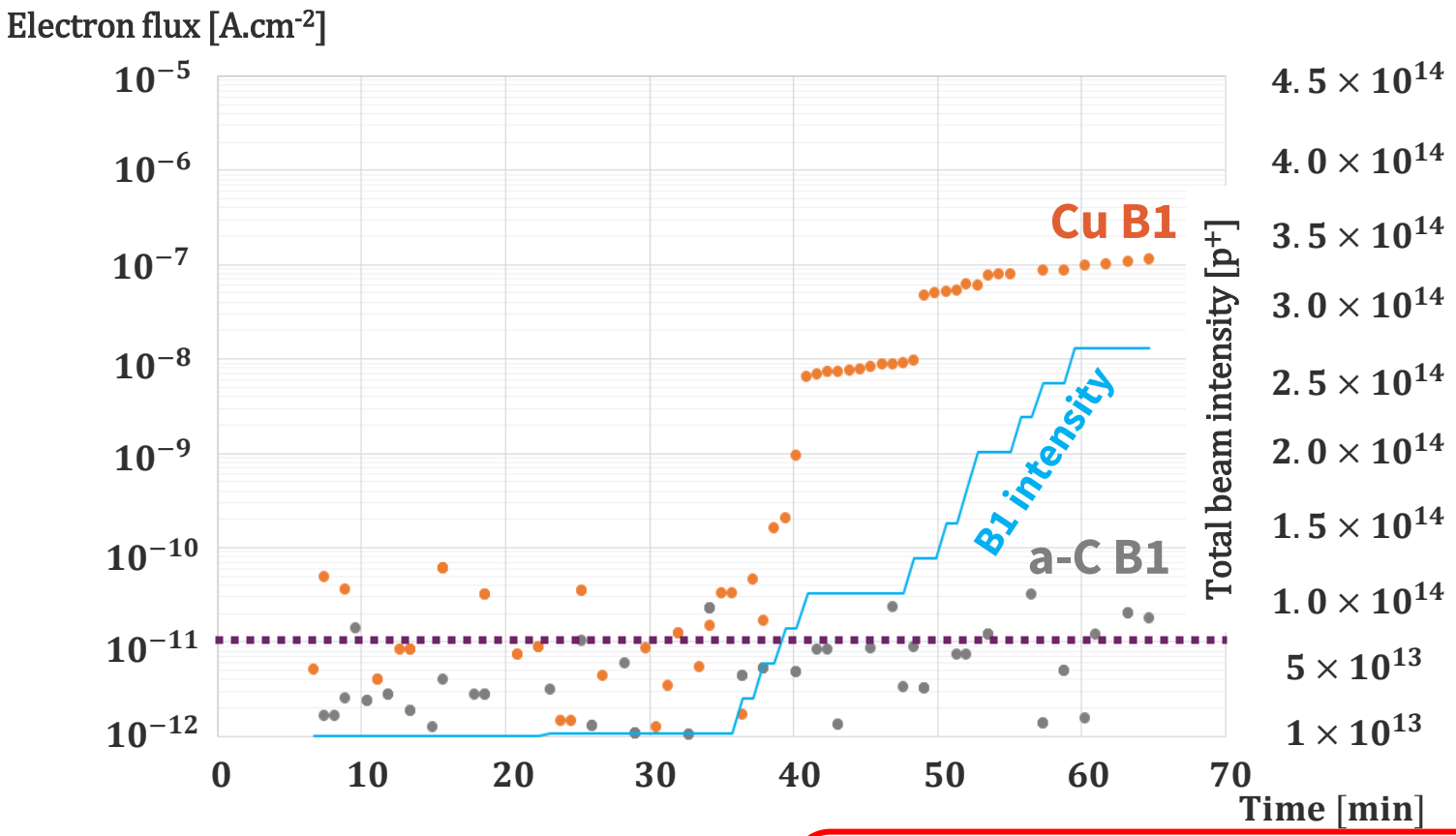
NU : Unused
cal : calorimeter
***xx* % :** pickup with a *xx*%-transparent grid
ph : photodetector
Trig : trigger
kick : kicker (Electron Kicker Detector)
RFA : Retarding Field Analyser

Liner 8

Unused
***VGPB* :** Penning Gauge
***VGI* :** Bayard-Alpert Gauge **(BAG)**
VQM : Vacuum Quality Monitor
RGA : Residual Gas Analyser
***VGRB* :** Pirani gauge
***VPIA* :** Vacuum Pump

***VF* :** Vacuum Flange
x ***N* :** NEG cartridge

Electron cloud for hybrid fills

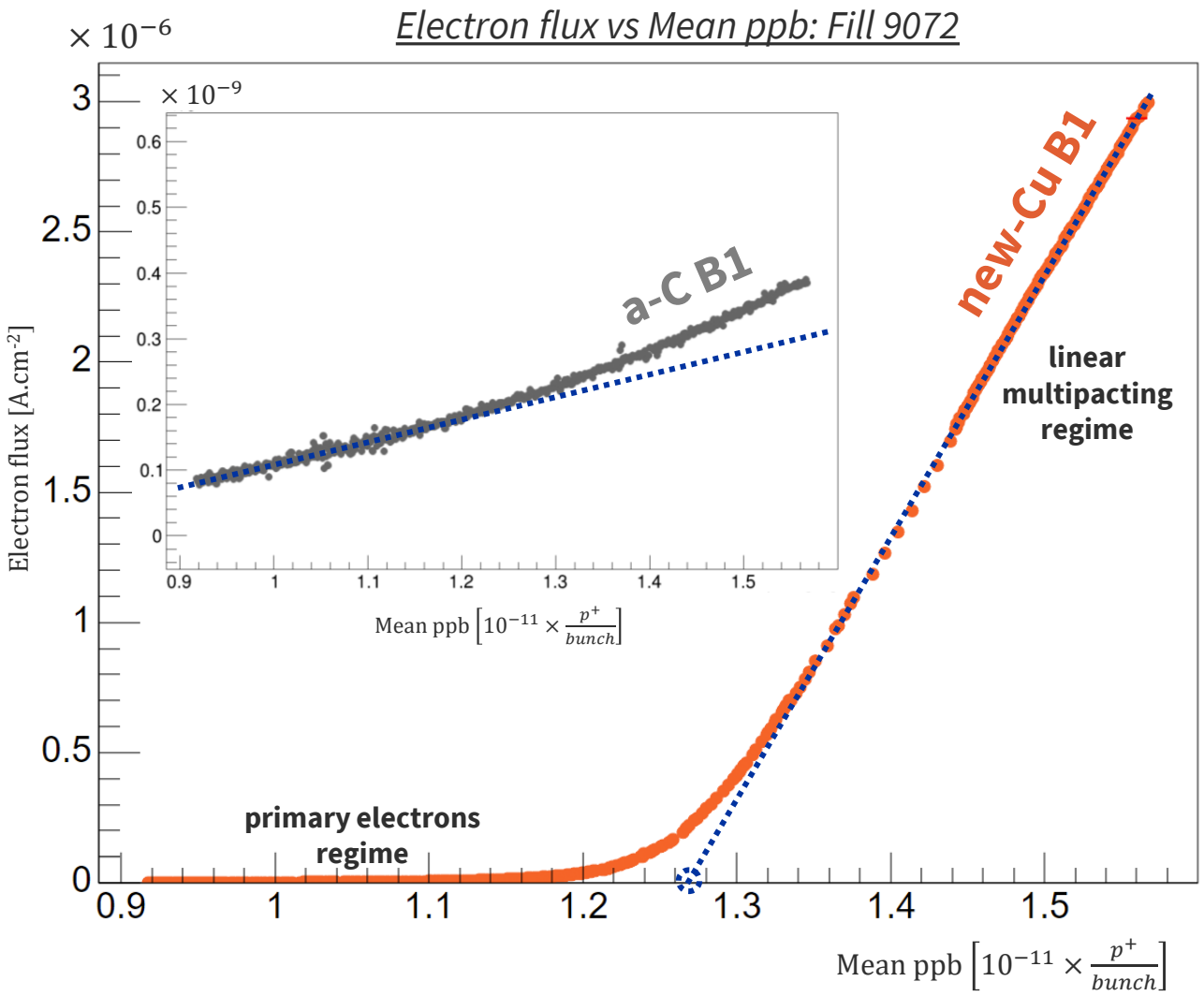


Detection limit: $I_{e^-} \sim 10$ [pA]

(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

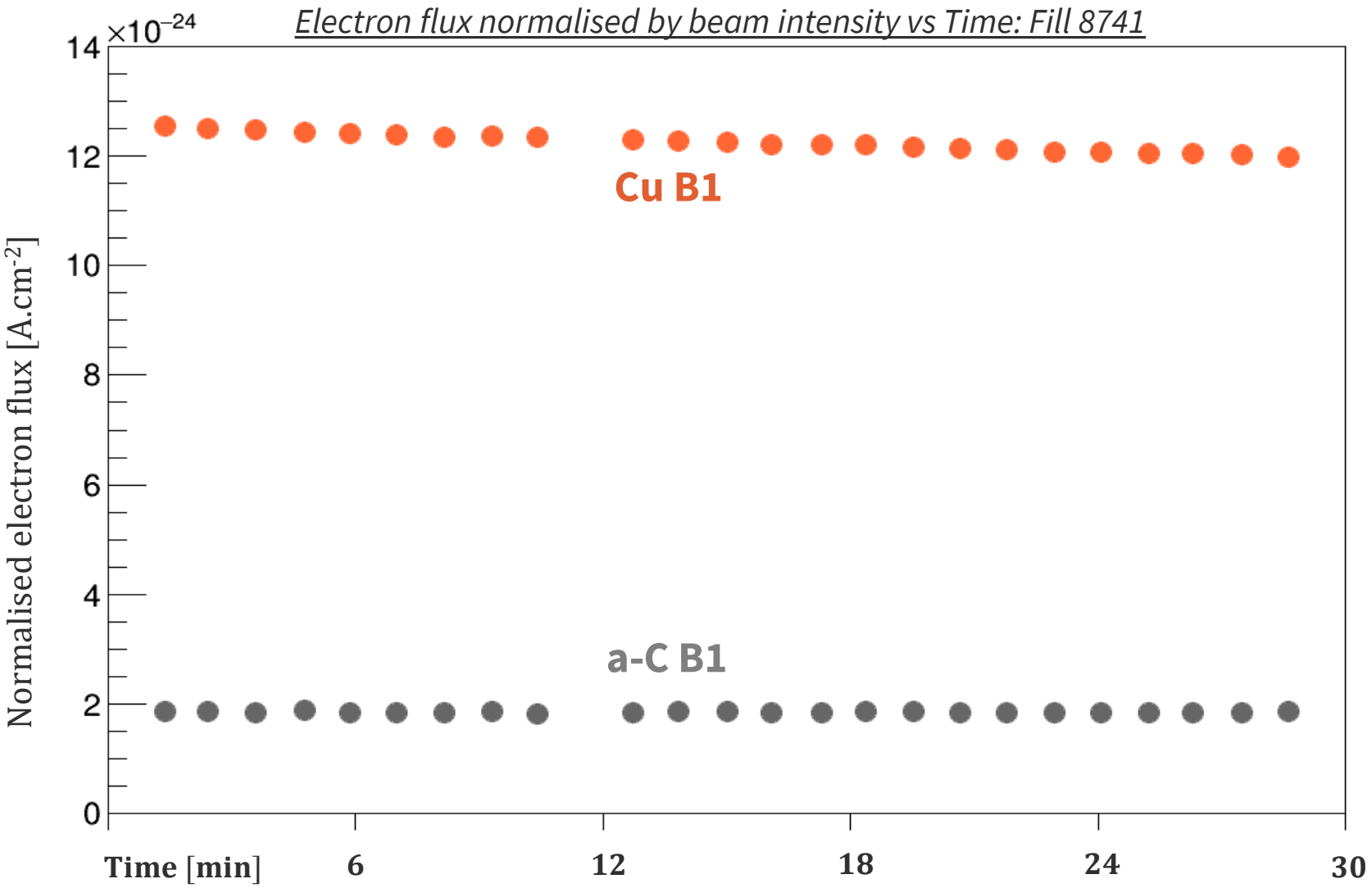
- **Barely present for carbon:** ecloud mainly dominated by photoelectrons
- **Huge contribution for copper**

Assymptotic root method

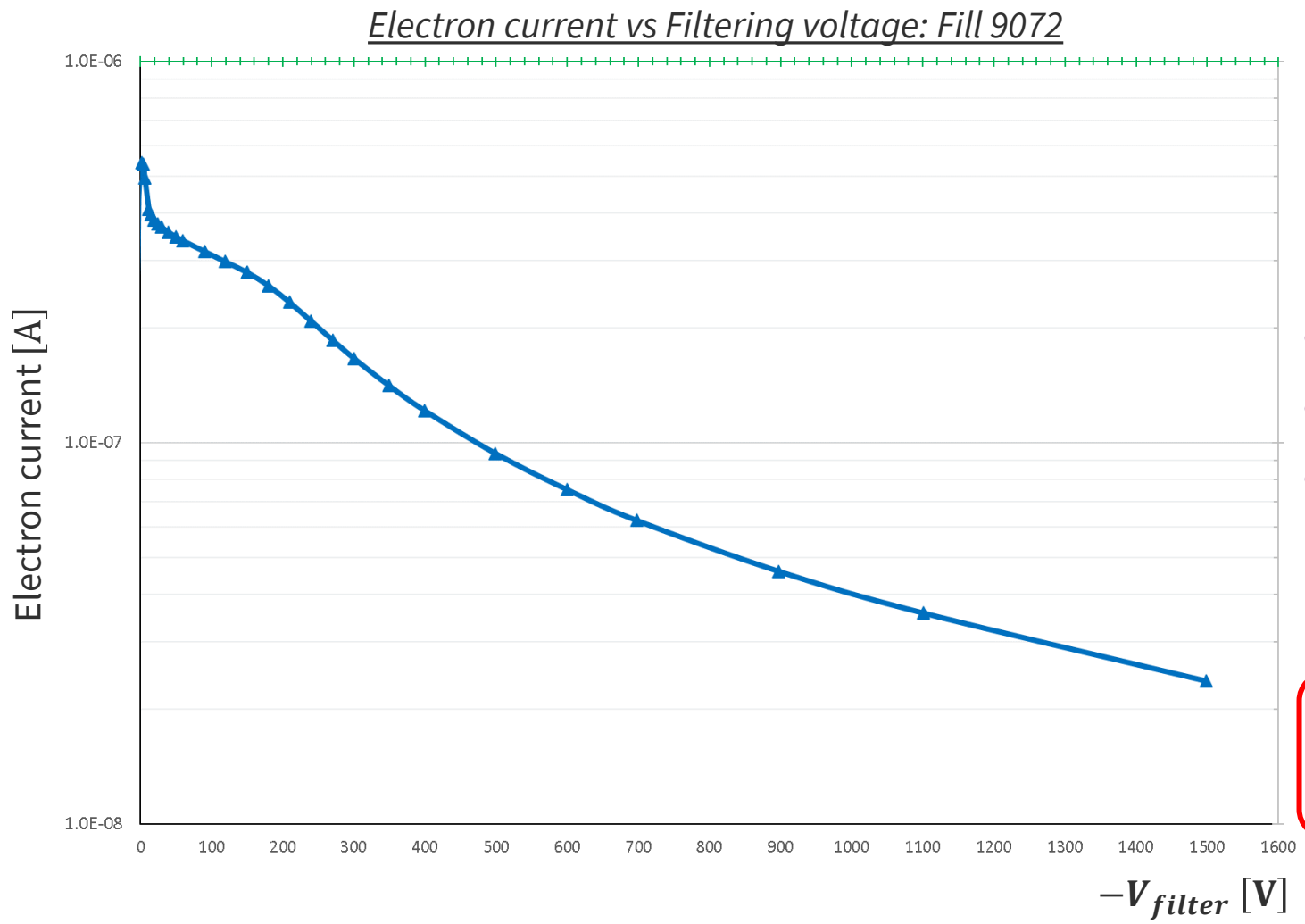
- **Root of linear asymptotic behaviour for high ppb**
- **Method to assess the variations of multipacting with time**

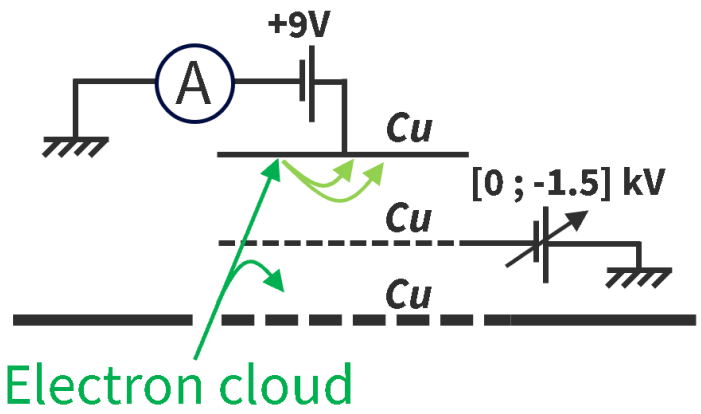
Assymptotic root method is NOT aimed at giving a multipacting threshold as ecloud effect has been identified for lower ppb.

Electron flux scaling with beam intensity at end of fill



RFA raw data





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

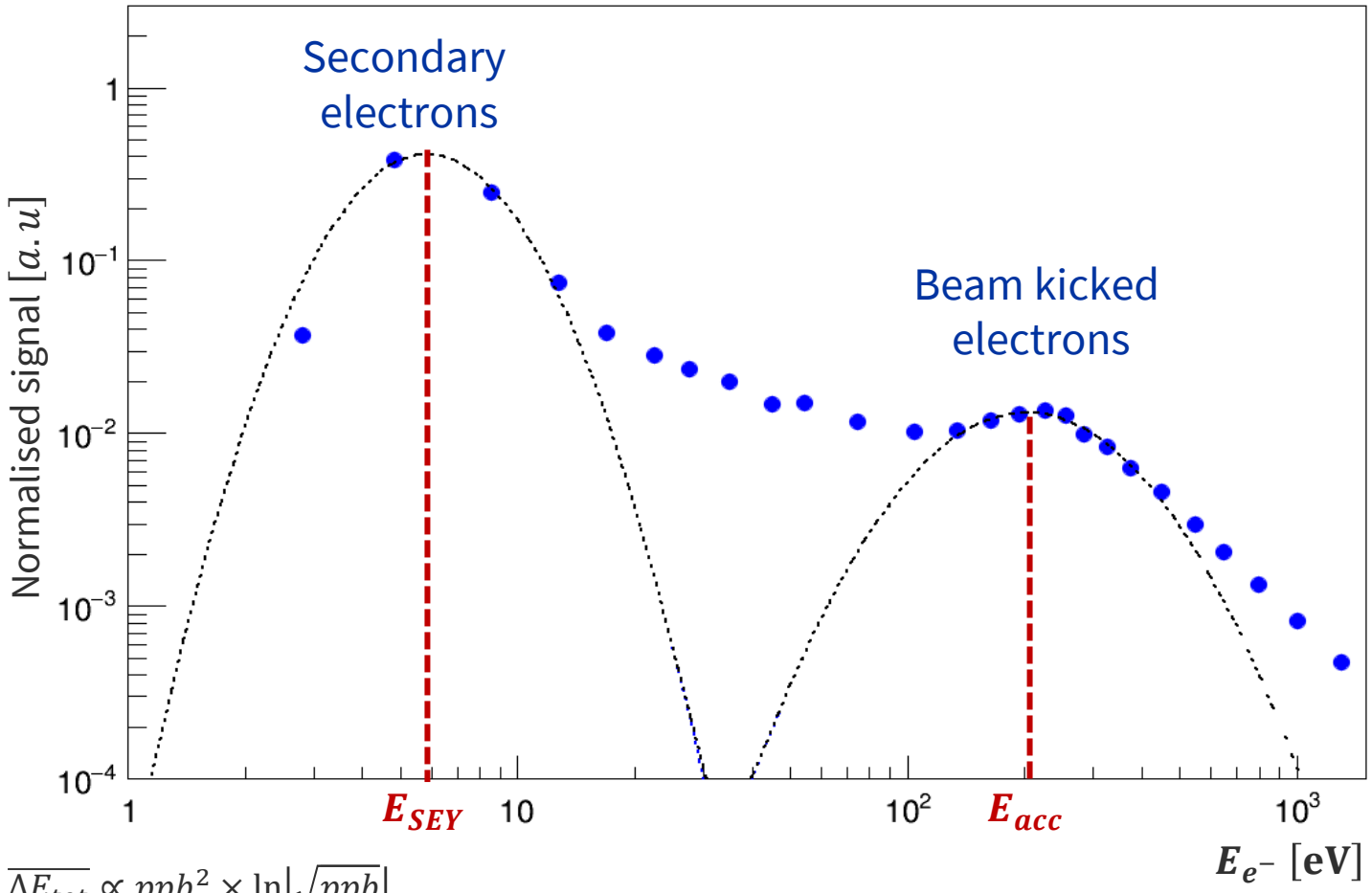
Double lognormal fit

- **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]	$\overline{ppb}$ [$\times 10^{11}$]	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.

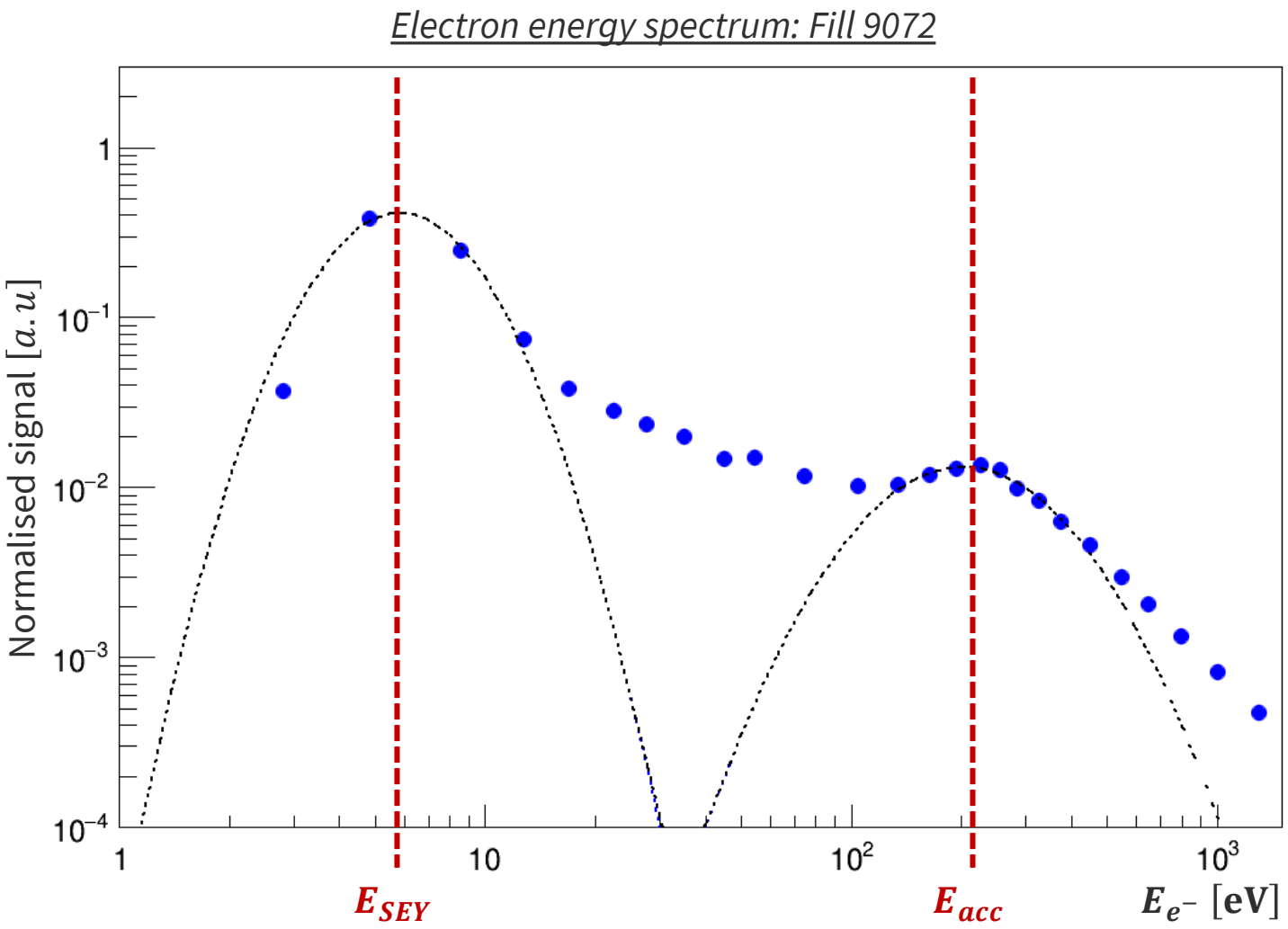
Electron energy spectrum: Fill 9072



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

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

Energy spectrum double lognormal fit

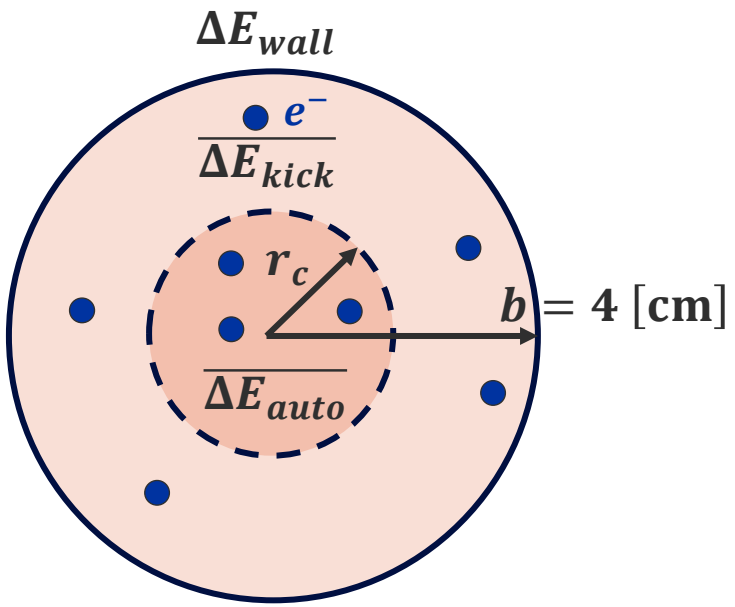


$$f_{lognormal}(E)_{K,\mu,\sigma} = \frac{K}{E\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(E/\mu)}{\sigma}\right)^2\right]$$

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:

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

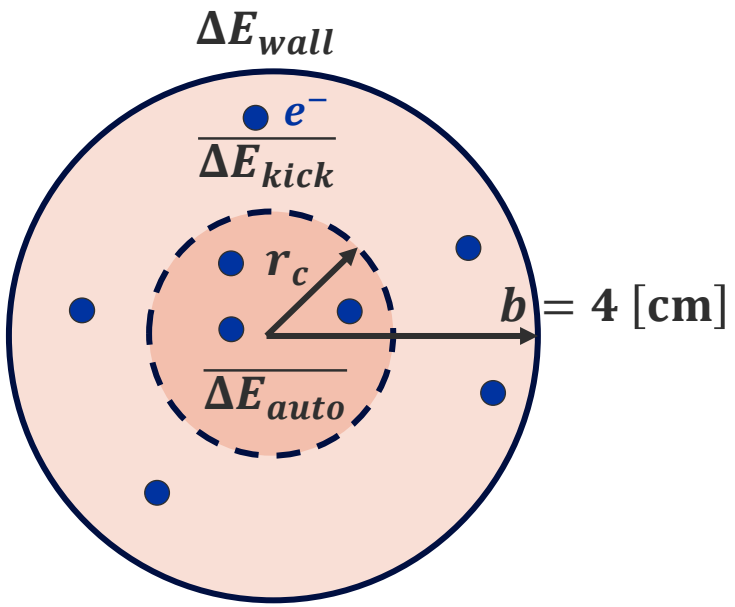
Energy kick for an electron on the wall: ΔE_{wall}

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

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

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/c^2]

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

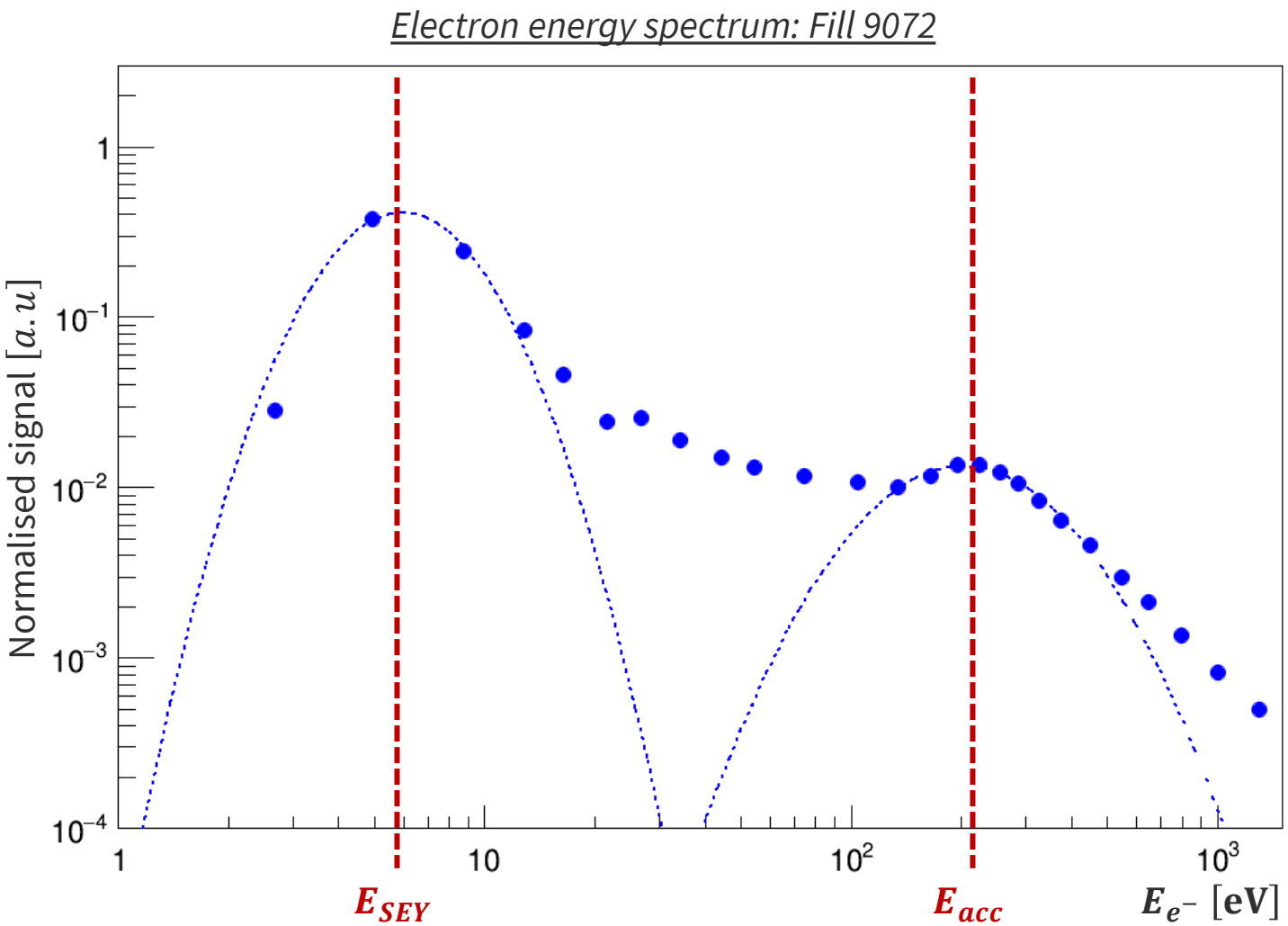
$$\Delta E_{wall} = 2 m_e c^2 \left(\frac{ppb \times r_e}{\beta b}\right)^2$$

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

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

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

Energy ramp-up at 620GeV



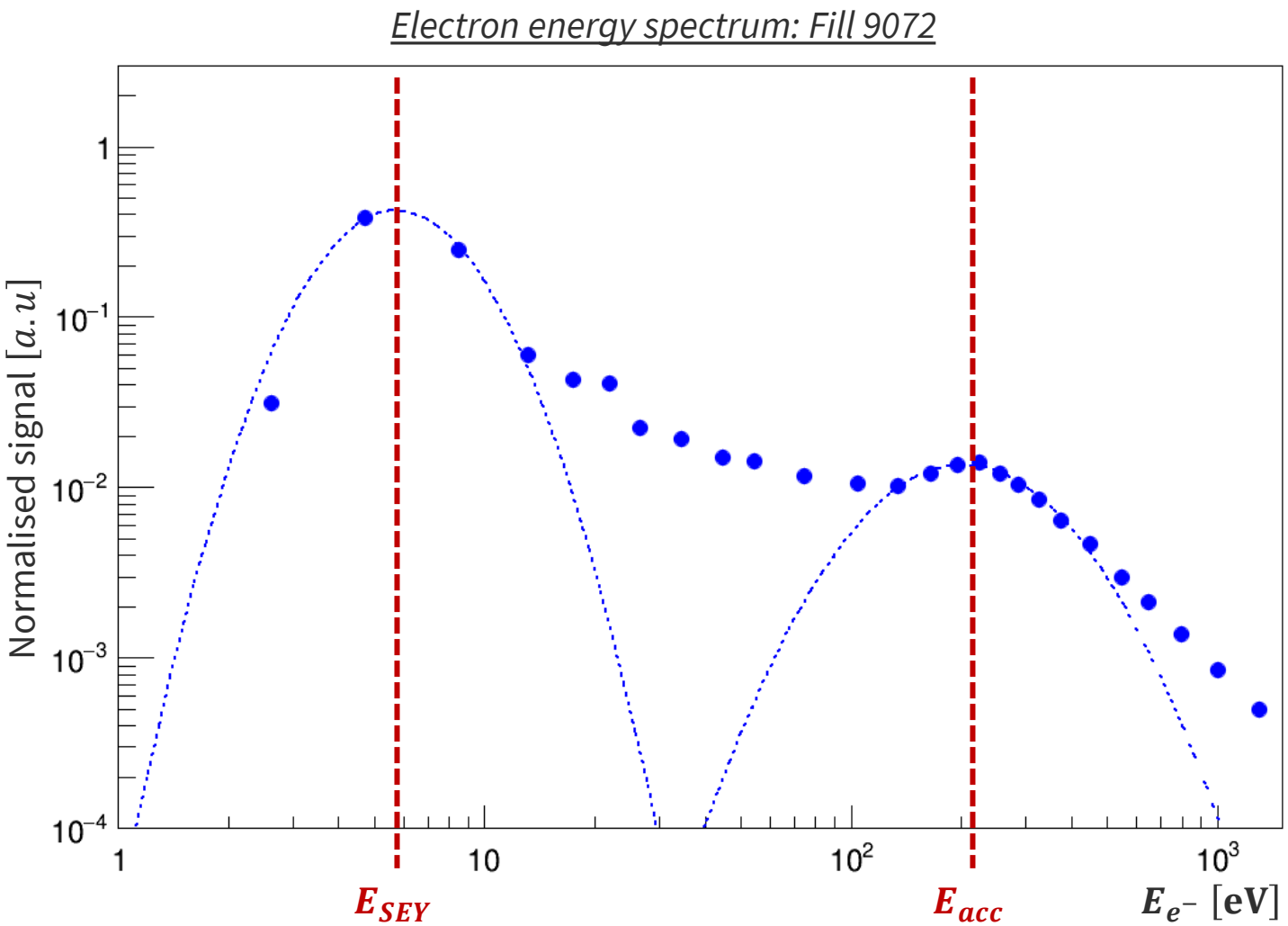
Beam parameters

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

Fit results

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

Energy ramp-up at 2074GeV



Beam parameters

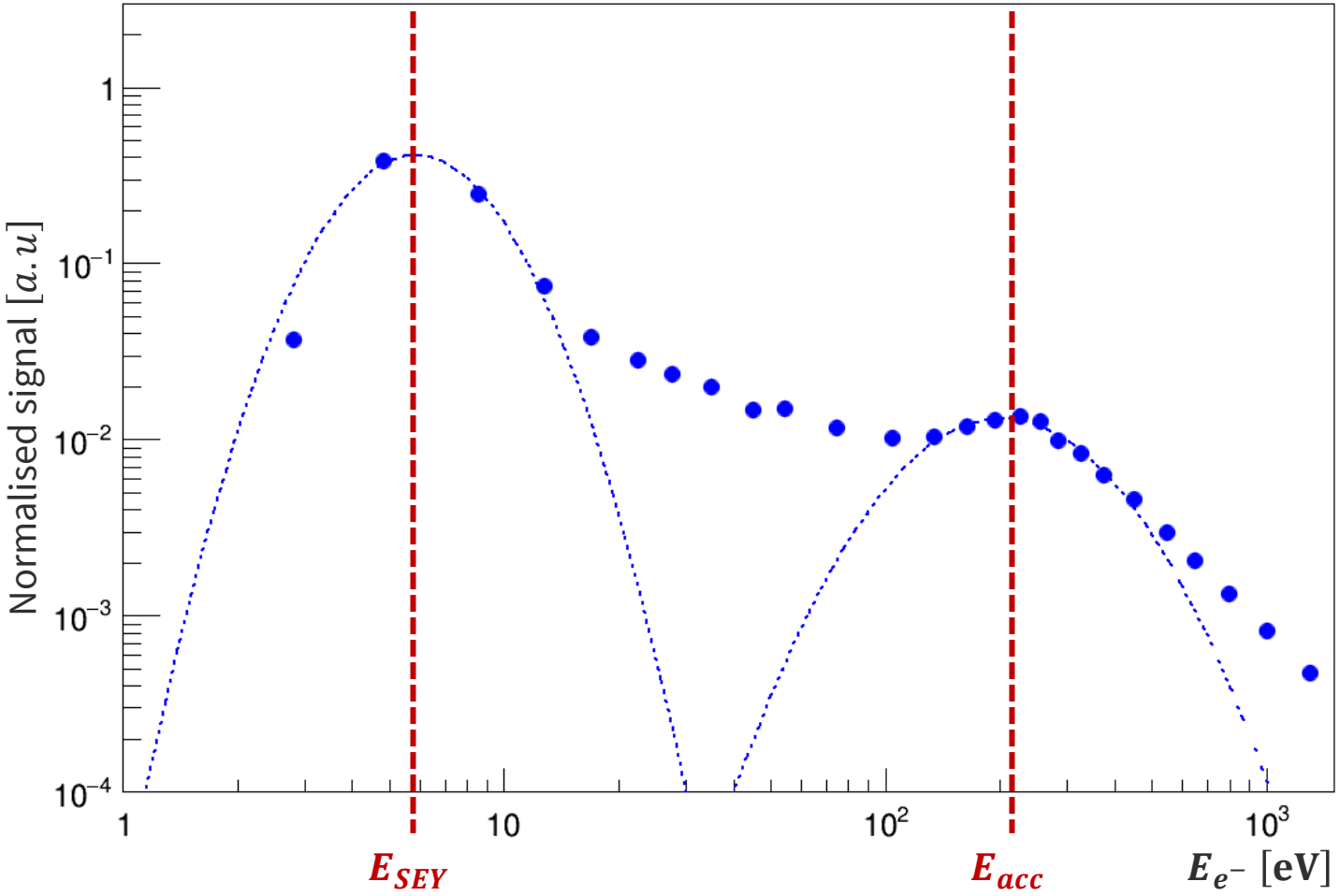
- **Energy:** $E_{B1} = 2074\ [\mathrm{GeV}]$
- **Intensity:** $ppb_{B1} = 1.60 \times 10^{11} \left[\frac{\mathrm{p}^+}{\mathrm{bunch}}\right]$

Fit results

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

Energy ramp-up at 6799GeV

Electron energy spectrum: Fill 9072



Beam parameters

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

Fit results

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

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