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

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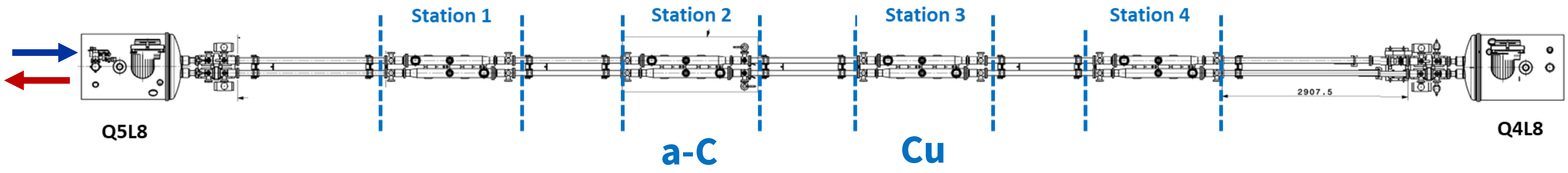
Outline

Disclaimer

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

I. Description

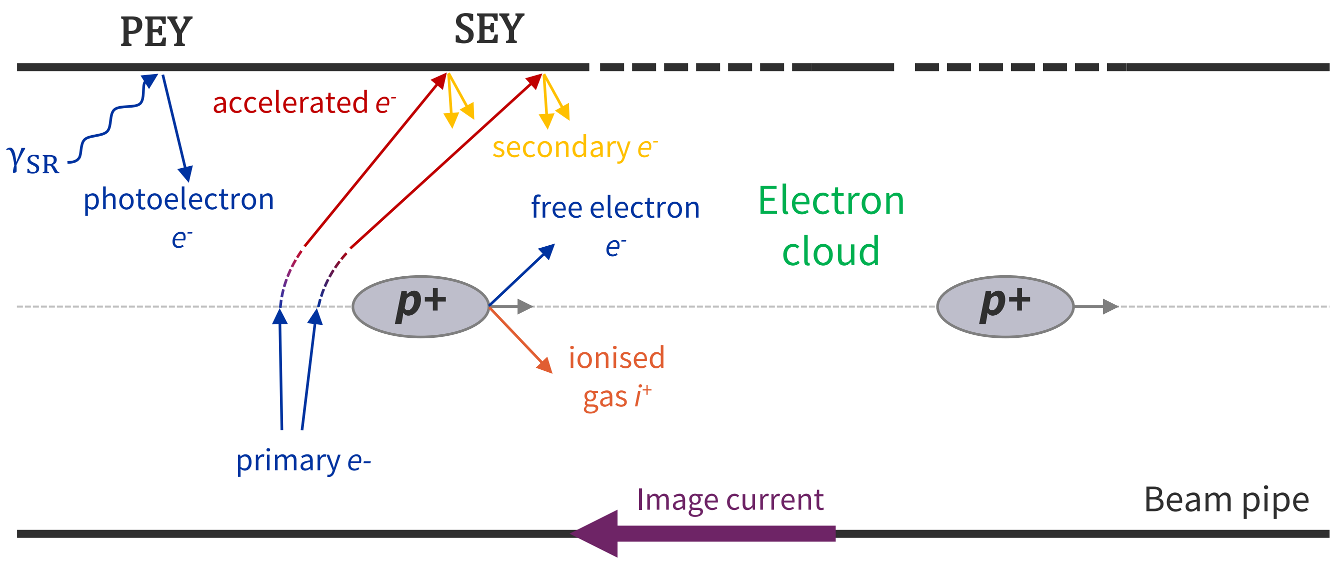
Layout



Vacuum Pilot Sector (VPS)

- **Location:** between Q4L8 and Q5L8
- **2 beamlines :**
  - **External:** B1 (Blue beamline)
  - **Internal:** B2 (Red beamline)
- **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

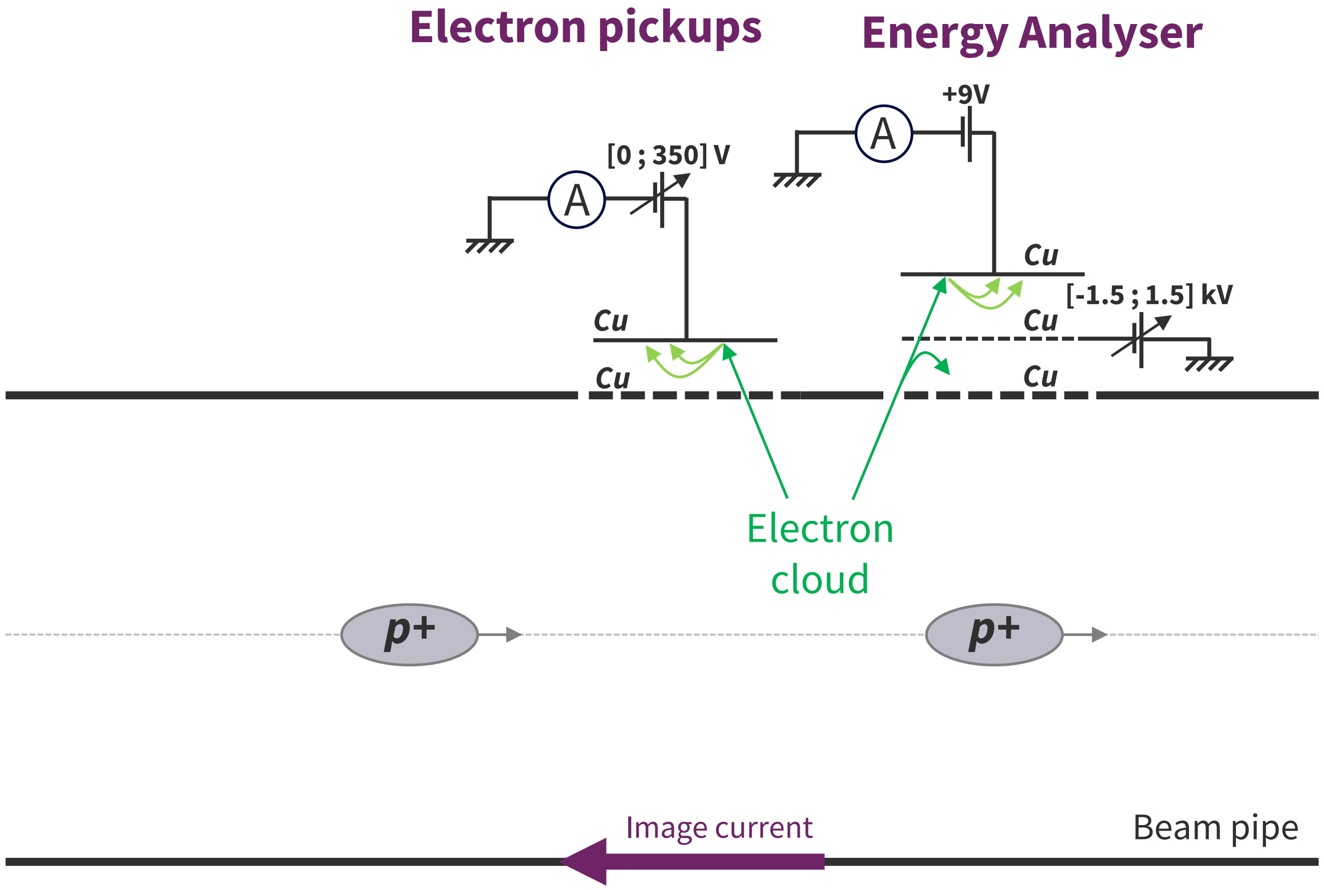
- **Primary electrons:**
  - Photoelectrons induced by photoelectric effect
  - Free electrons induced by bunch ionising the residual gas
- **Secondary electrons:** induced by primary electrons, accelerated by successive bunches, hitting the surface

Two main material properties for ecloud:

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

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

Electron current and energy detection



Electron pickups

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

Energy Analyser (only copper station)

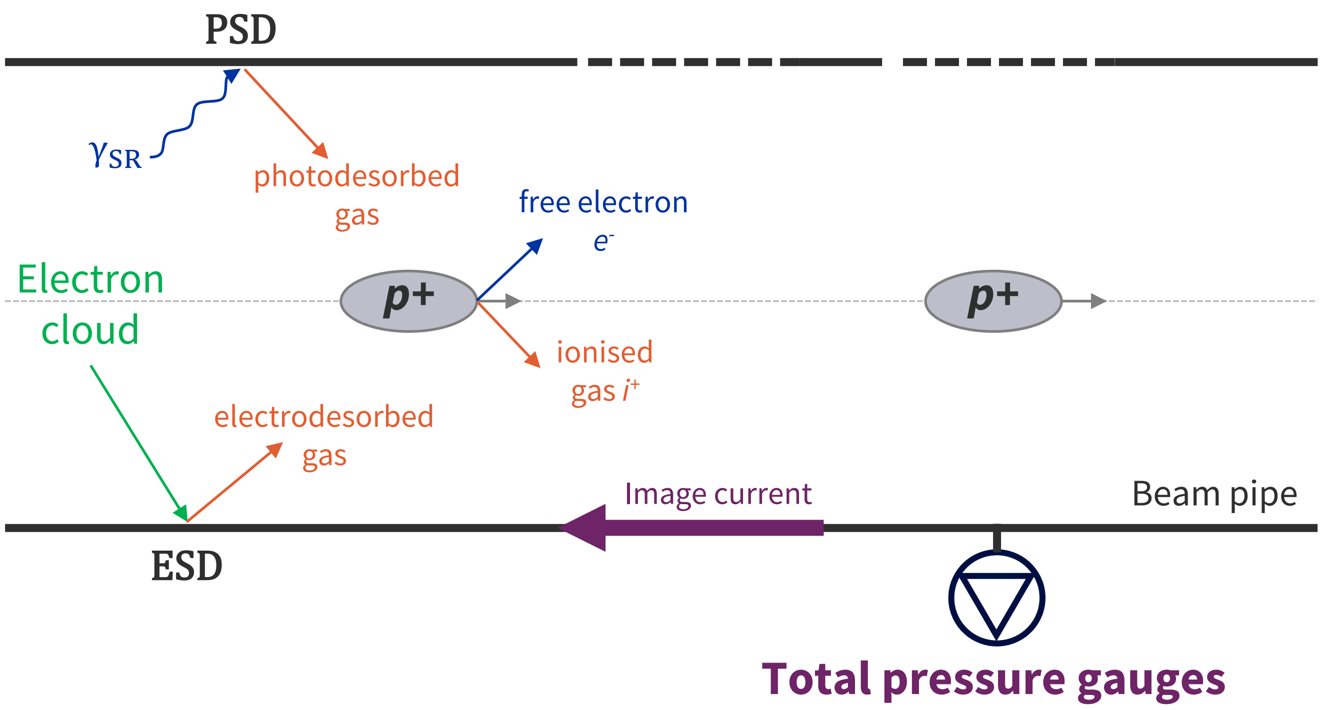
- « Retarding Field Analyser (RFA) »
- Electron pickup: with $+9$V bias
- Biased filtering grid: 75%−transparency
- Biased filtering grid: $u \in [-1500\ ;+1500]$ V
- Measurement:

« 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:

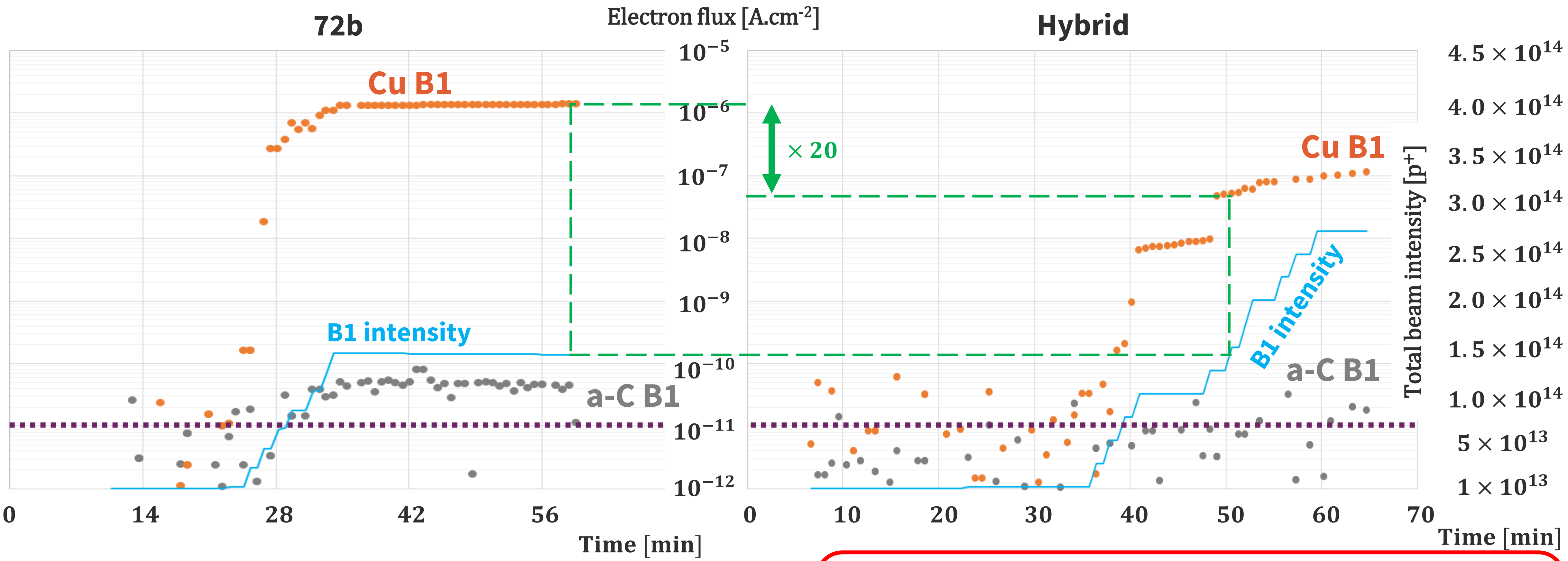
- **Photodesorption**
- **Electrodesorption**

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

II. 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

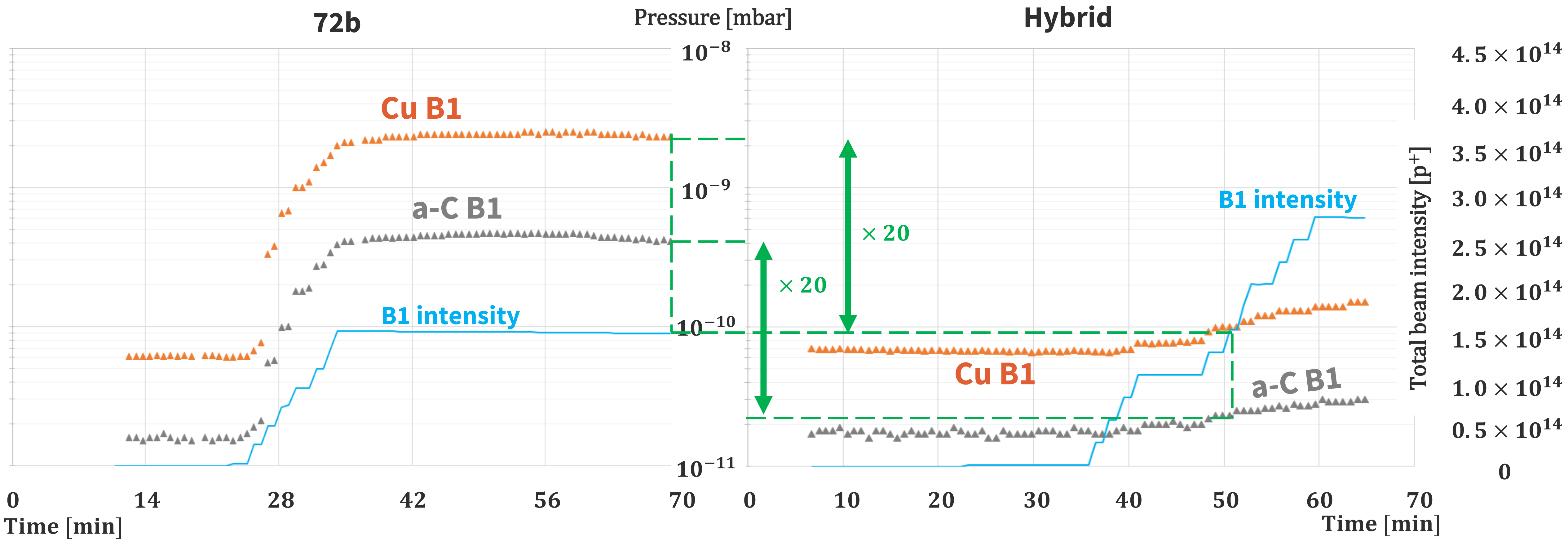


Detection limit: $I_{e^-} \sim 10$ [pA]

(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

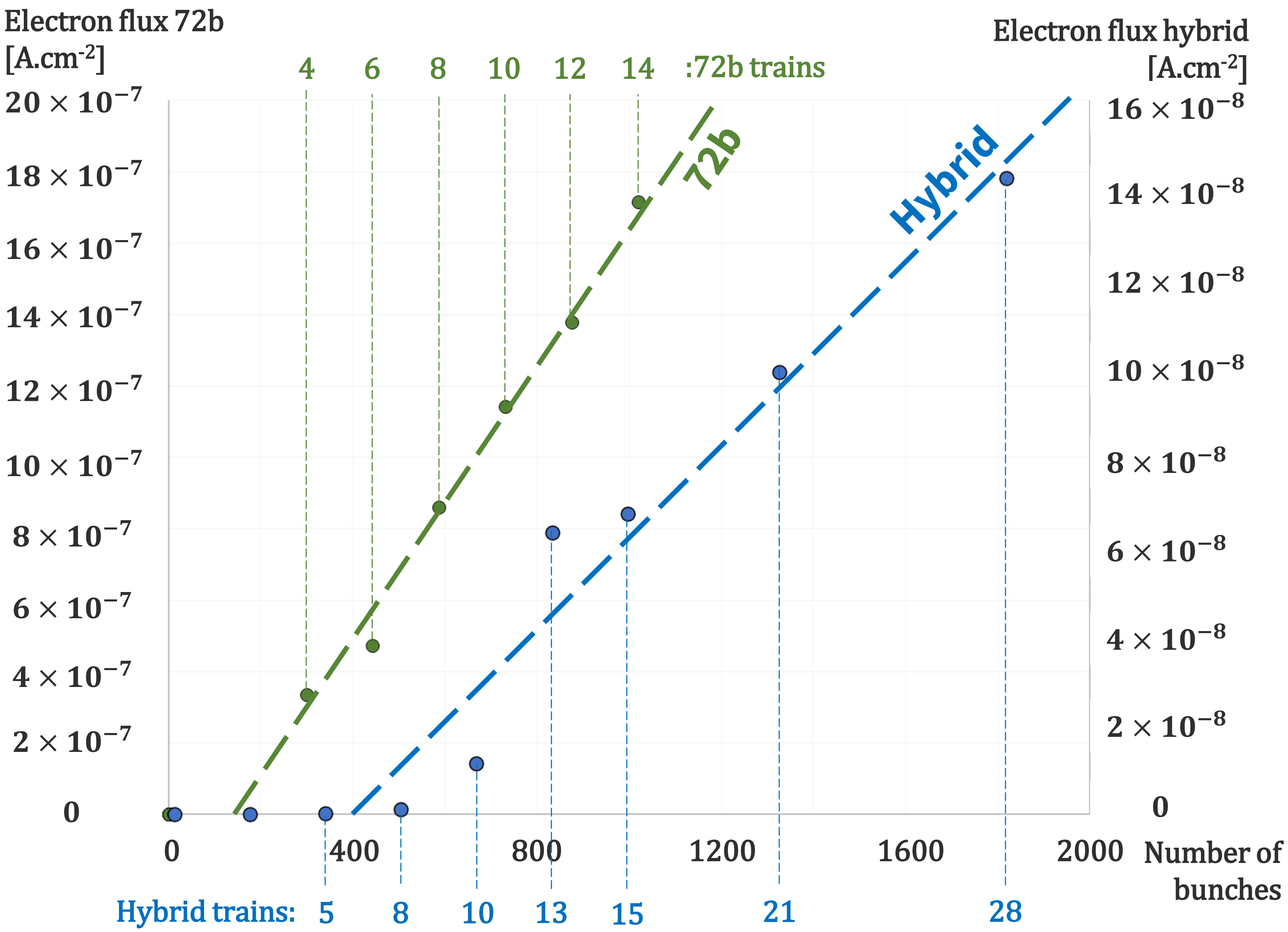


At equal beam intensity for copper: $\Delta P_{72b} \approx 20 \times \Delta P_{hybrid}$

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



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

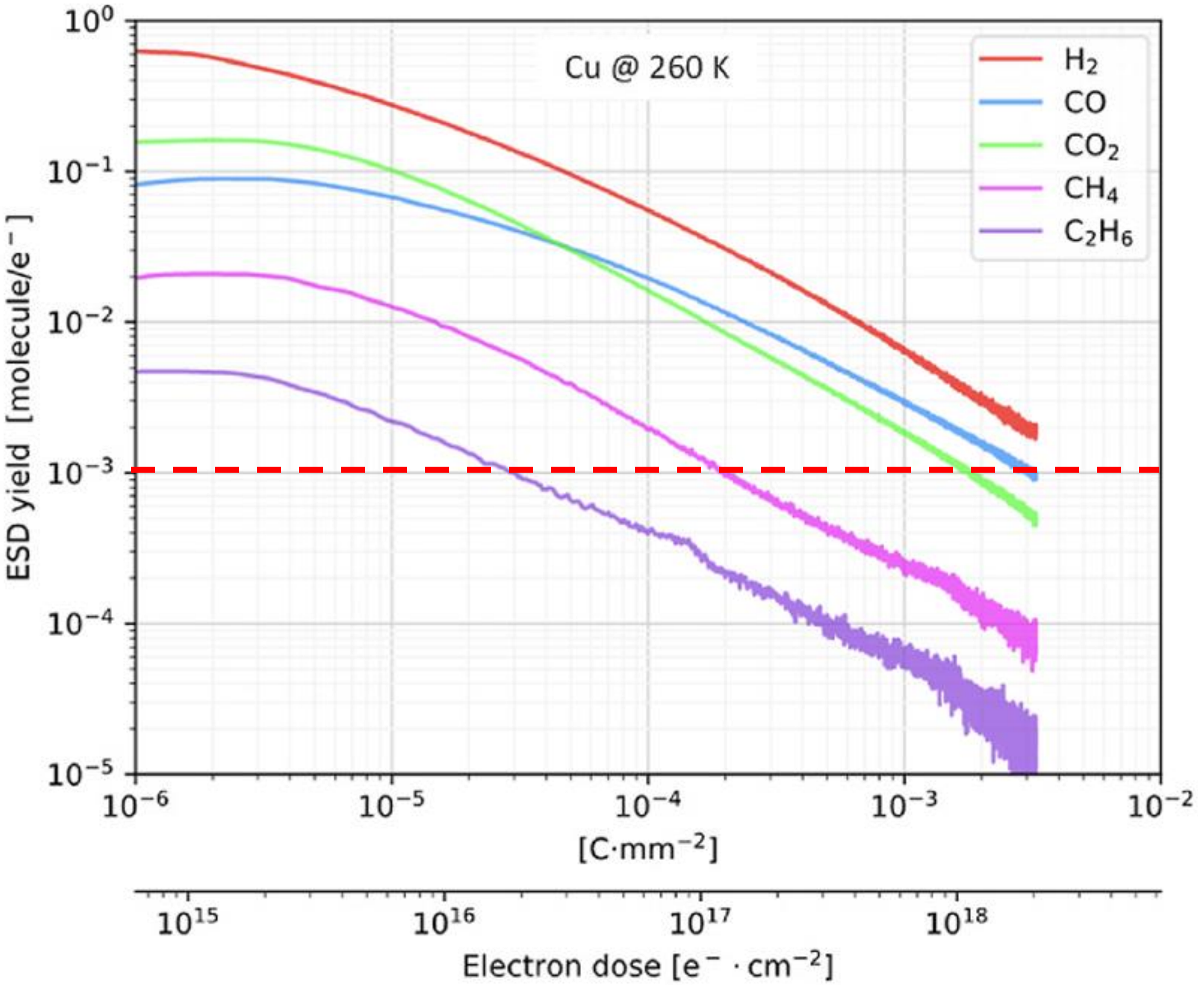
$$I_{72b}[\mathrm{nA.\,cm^{-2}}] \approx 2 \times (N_{bunch} - 160)$$
$$I_{hybrid}[\mathrm{nA.\,cm^{-2}}] \approx 0.1 \times (N_{bunch} - 400)$$

More bunches needed for hybrid fill to reach linear behaviour

For high number of bunches:

$$I_{e^-} \propto N_{bunch}$$
$$I_{72b} \approx 20 \times I_{hybrid}$$

Cu ESD for 72b and hybrid fills



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

Pressure rise assumed to be induced only by H_2

Electrostimulated desorption η computation for copper station

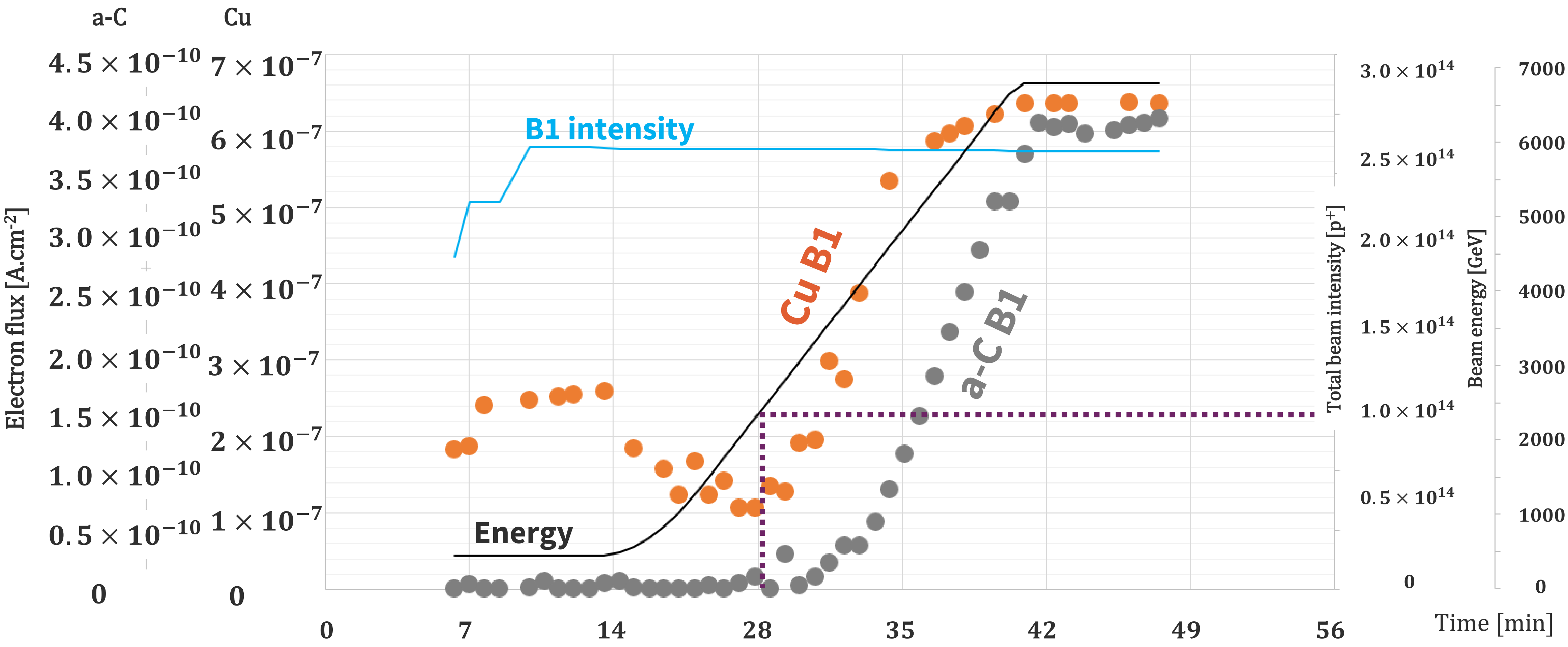
Filling scheme	$\frac{\Delta P}{I}\left[\frac{\text{mbar}}{\text{A.cm}^{-2}}\right]$	$\eta\left[\frac{\text{molecule}}{\text{e}^-}\right]$
72b	1.8	1.3×10^{-3}
Hybrid	1.4	1.0×10^{-3}

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

III. Hybrid physics fill at 6.8 TeV

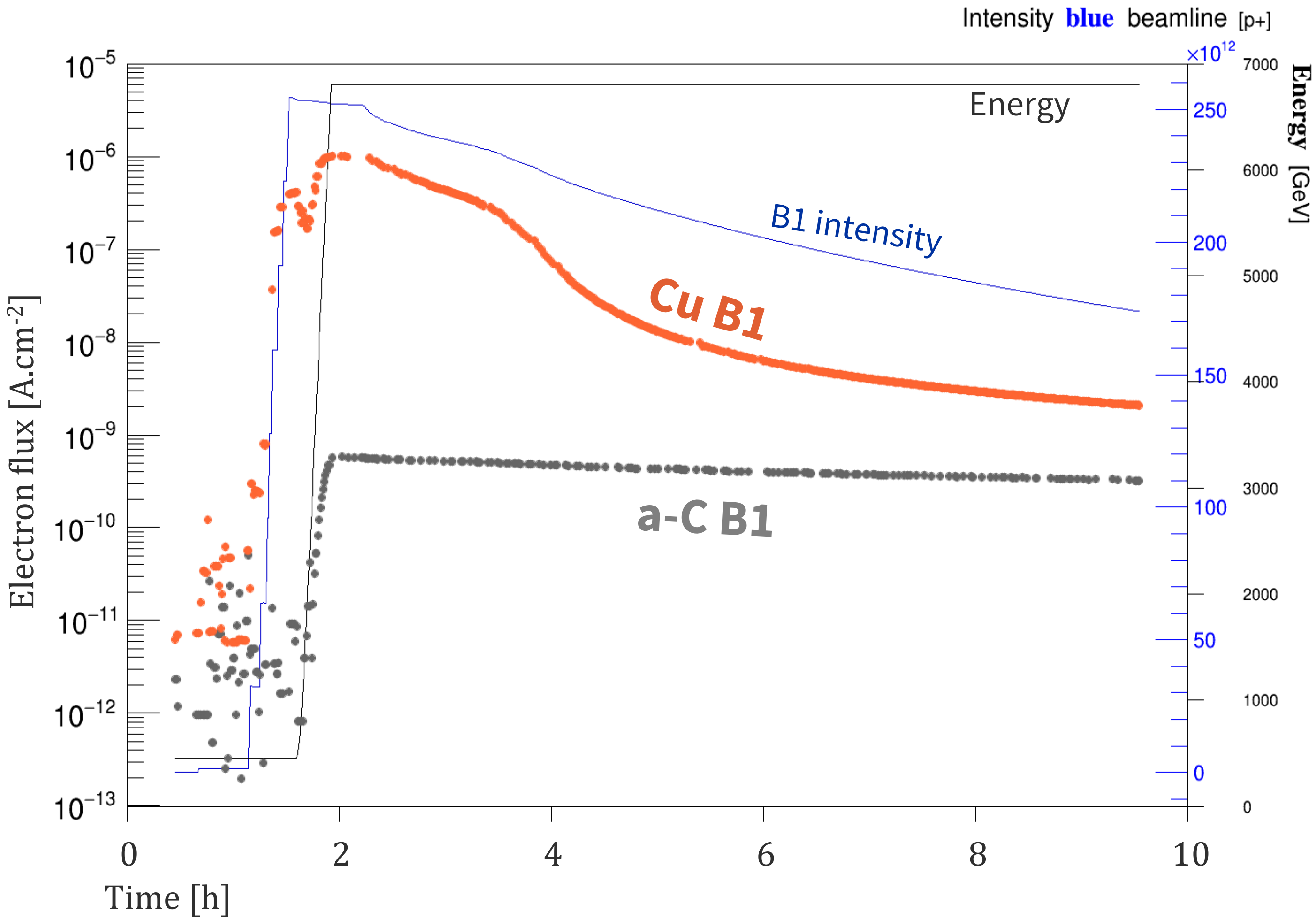
Hybrid (7*8b4e+5*36b): 8741

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 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
- $I_{Cu} \approx 6 \times I_{aC}$

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

IV. Electron energy distribution for bulk Copper

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

During energy ramp-up

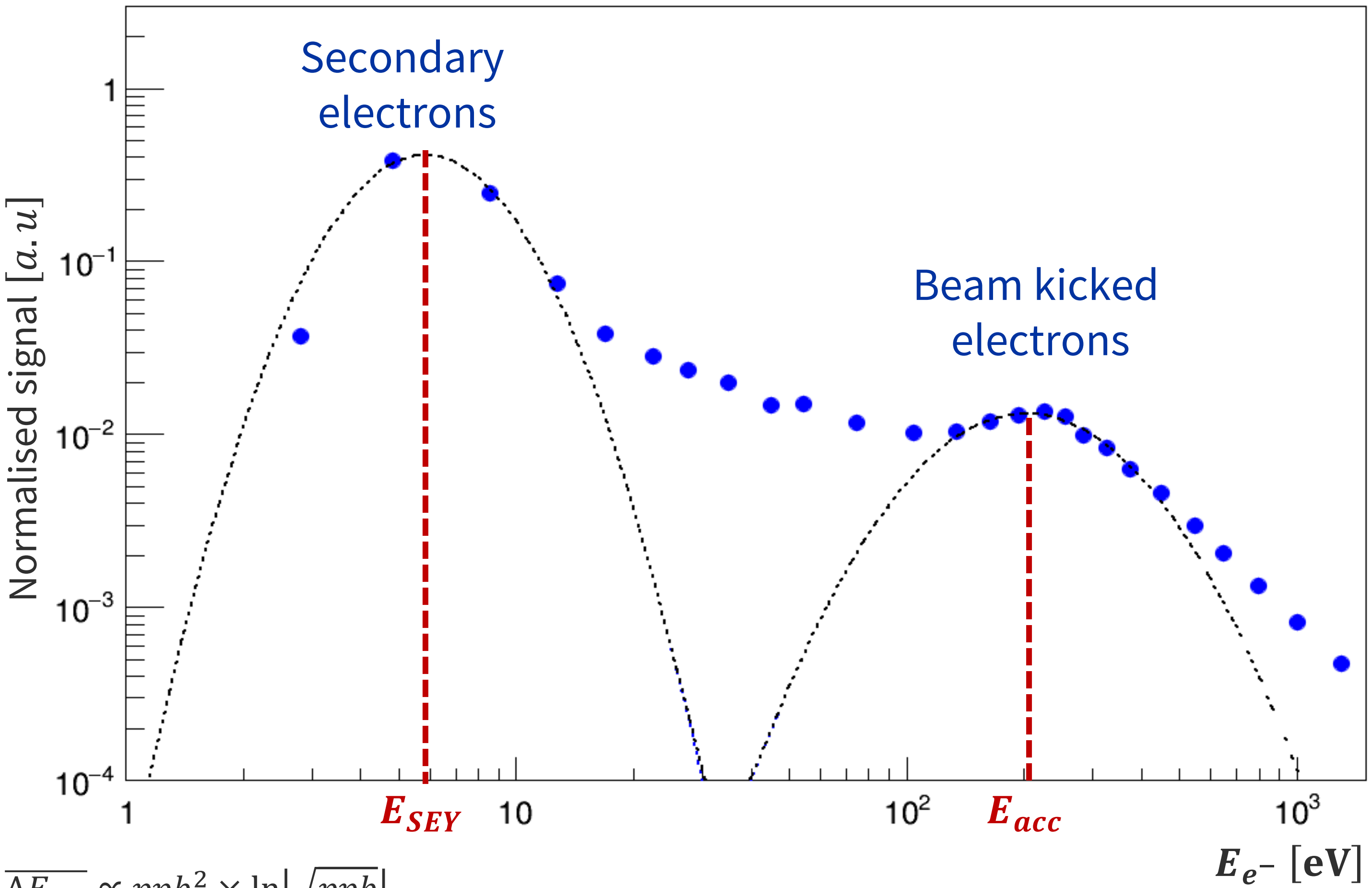
Double lognormal fit

- **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.

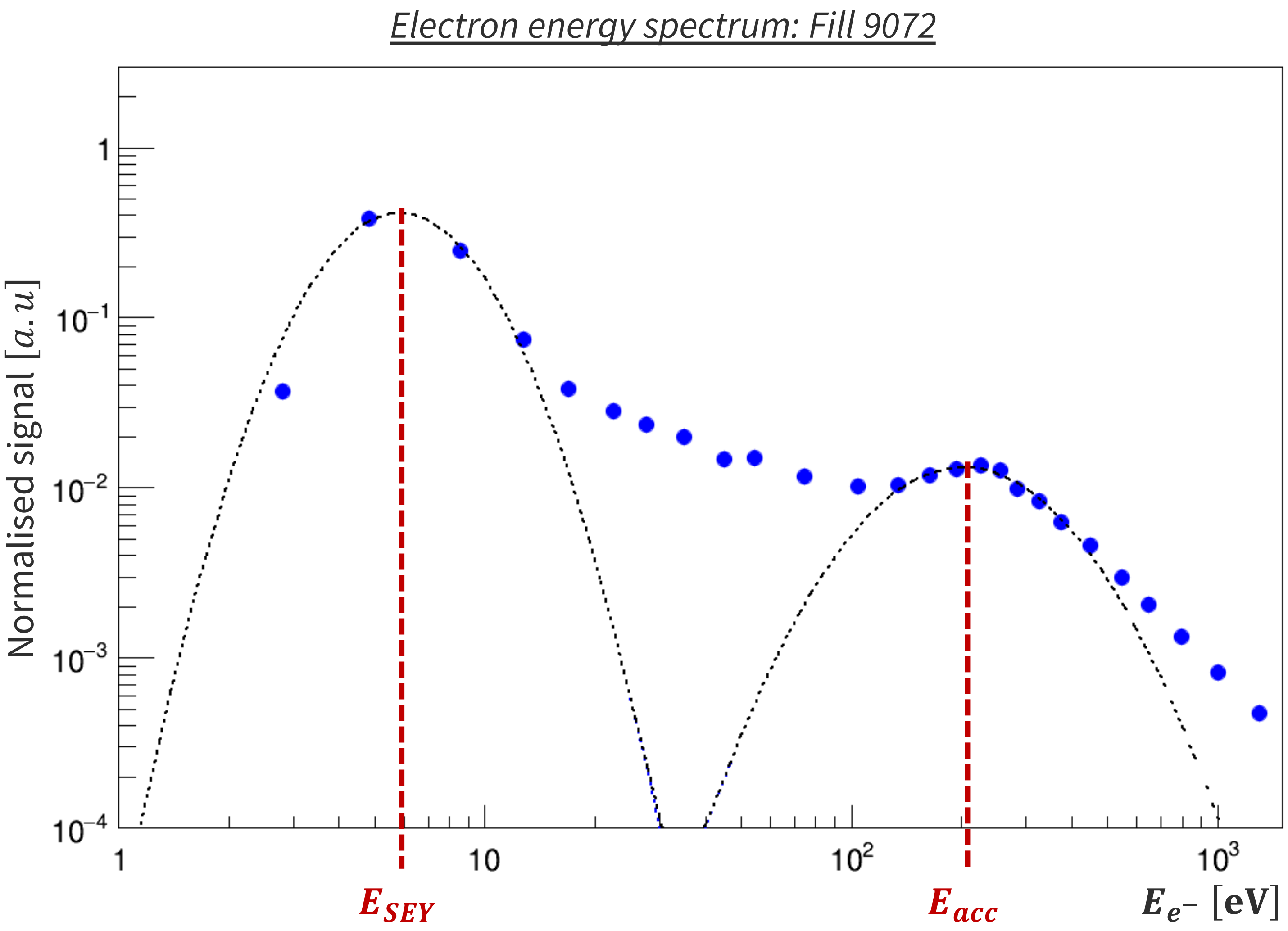
Electron energy spectrum: Fill 9072



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

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

At Stable Beam: t = 0h



Beam parameters

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

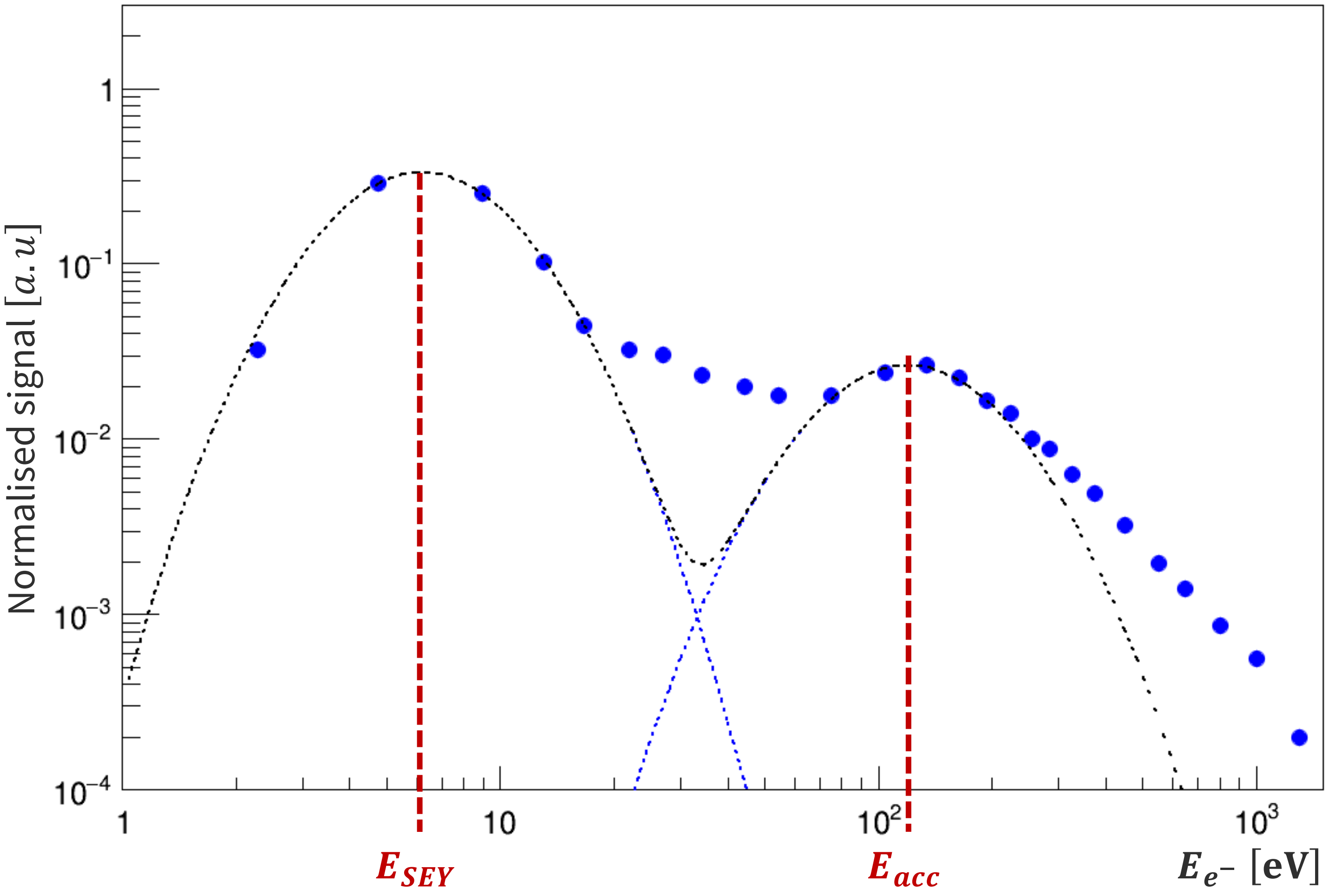
$$ppb_{B1} = 1.59 \times 10^{11} \left[\frac{p^+}{bunch}\right]$$

Fit results

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

At Stable Beam: t = 6h

<u>*Electron energy spectrum: Fill 9072*</u>



Beam parameters

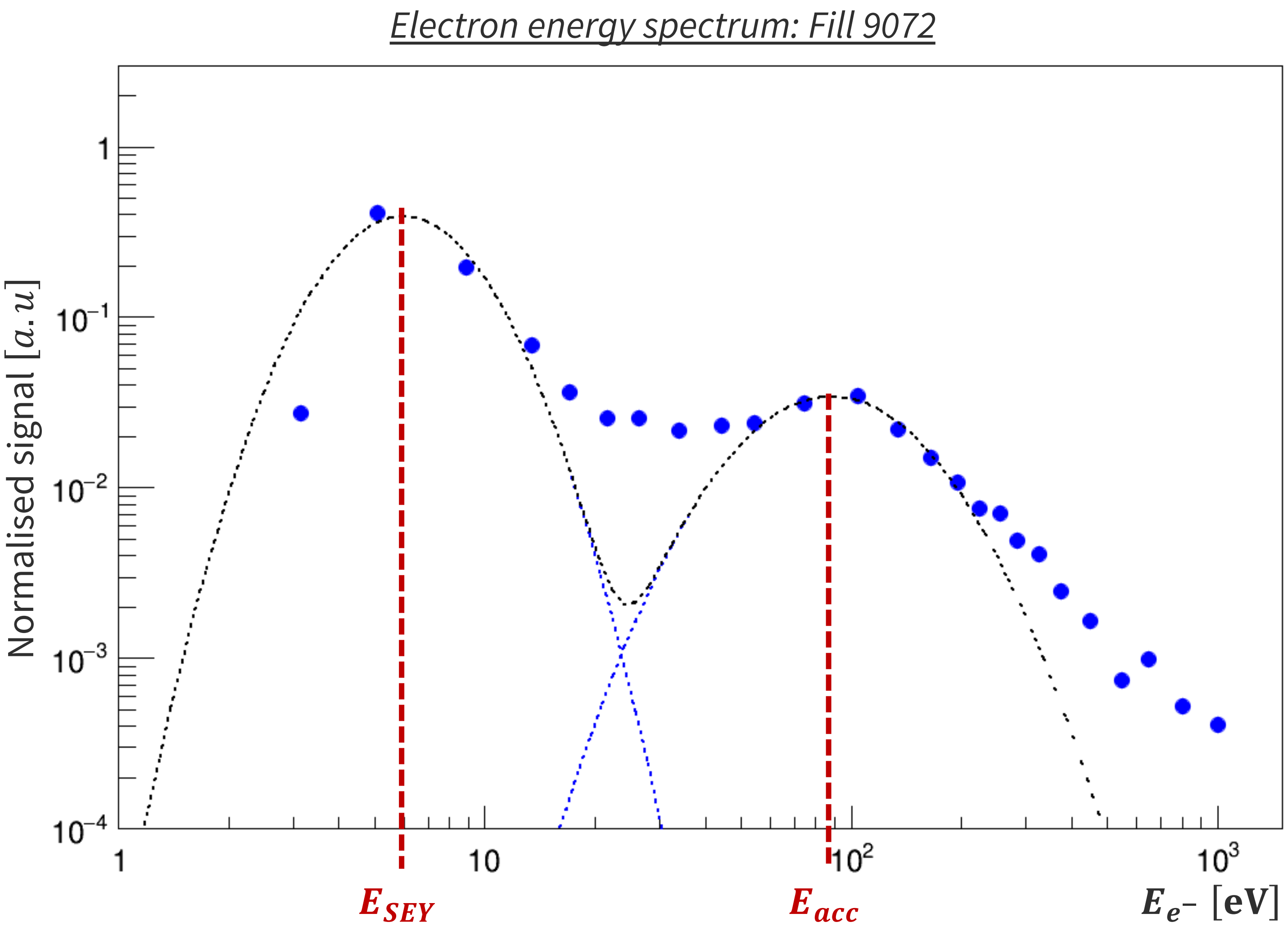
- **Energy:** $E_{B1} = 6799$ [GeV]
- **Bunch intensity:**

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

Fit results

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

At Stable Beam: t = 11h



Beam parameters

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

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

Fit results

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

Impact of the beam intensity at 6800GeV

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

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 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 $E_{beam} > 2500\ [\mathrm{GeV}]$
- 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

- 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…)

Fill parameters which may help electron cloud parameters assessment:

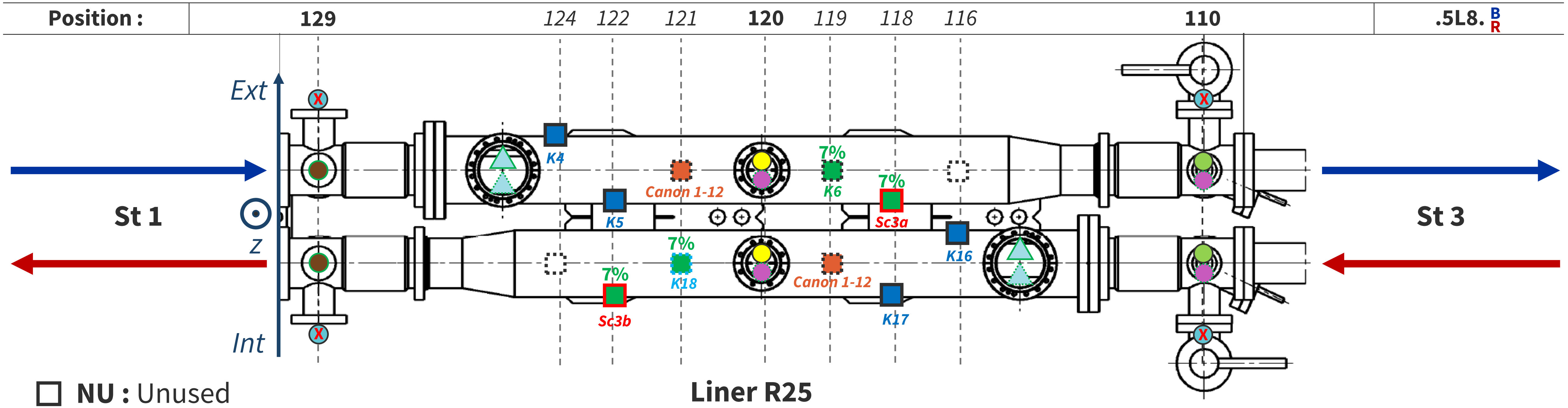
- Long fill (> 10h) at $6800\ [\mathrm{GeV}]$ of hybrid scheme with beam intensity > 10^{14} with **long injection time (> 2h)** to disentangle electrons from photons contributions
- Long fill (> 5h) at $6800\ [\mathrm{GeV}]$ of **spaced trains and 50ns inter-bunch** scheme with $\boldsymbol{ppb \sim 10^{11}}$ and $\boldsymbol{N_b \sim 500}$ to evaluate photons contribution
- Use of a “calibration” fill to assess evolution of the parameters along the year

Backups

Station 2 – Amorphous carbon

△ ○ ⬚ **Dash line :** Downer side
Red line : Scope
Blue line : Keithley with variable bias

Liner B23



Liner R25

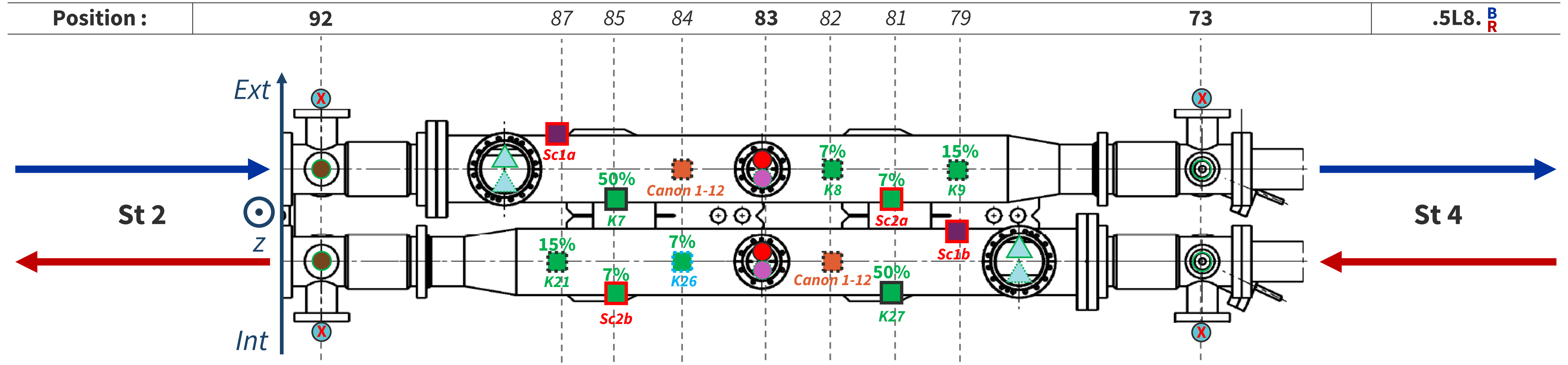
- **NU :** Unused
- **cal :** calorimeter
- ***xx* % :** pickup with a *xx*%-transparent grid
- **ph :** photodetector
- **Trig :** trigger
- **kick :** kicker (Electron Kicker Detector)
- **RFA :** Retarding Field Analyser

- 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 R27

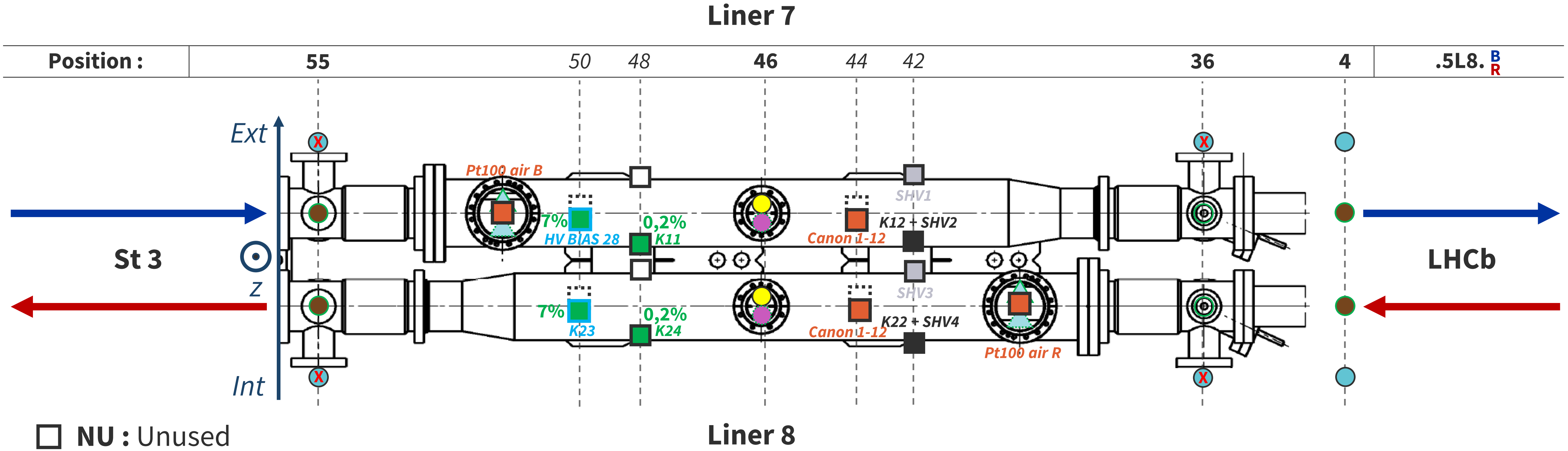
- **NU :** Unused
- **cal :** calorimeter
- ***xx* % :** pickup with a *xx*%-transparent grid
- **ph :** photodetector
- **Trig :** trigger
- **kick :** kicker (Electron Kicker Detector)
- **RFA :** Retarding Field Analyser

- 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 4 – Old unbaked copper

△ ○ ⬚ **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

- Unused
- ***VGPB* :** Penning Gauge
- ***VGI* :** Bayard-Alpert Gauge **(BAG)**
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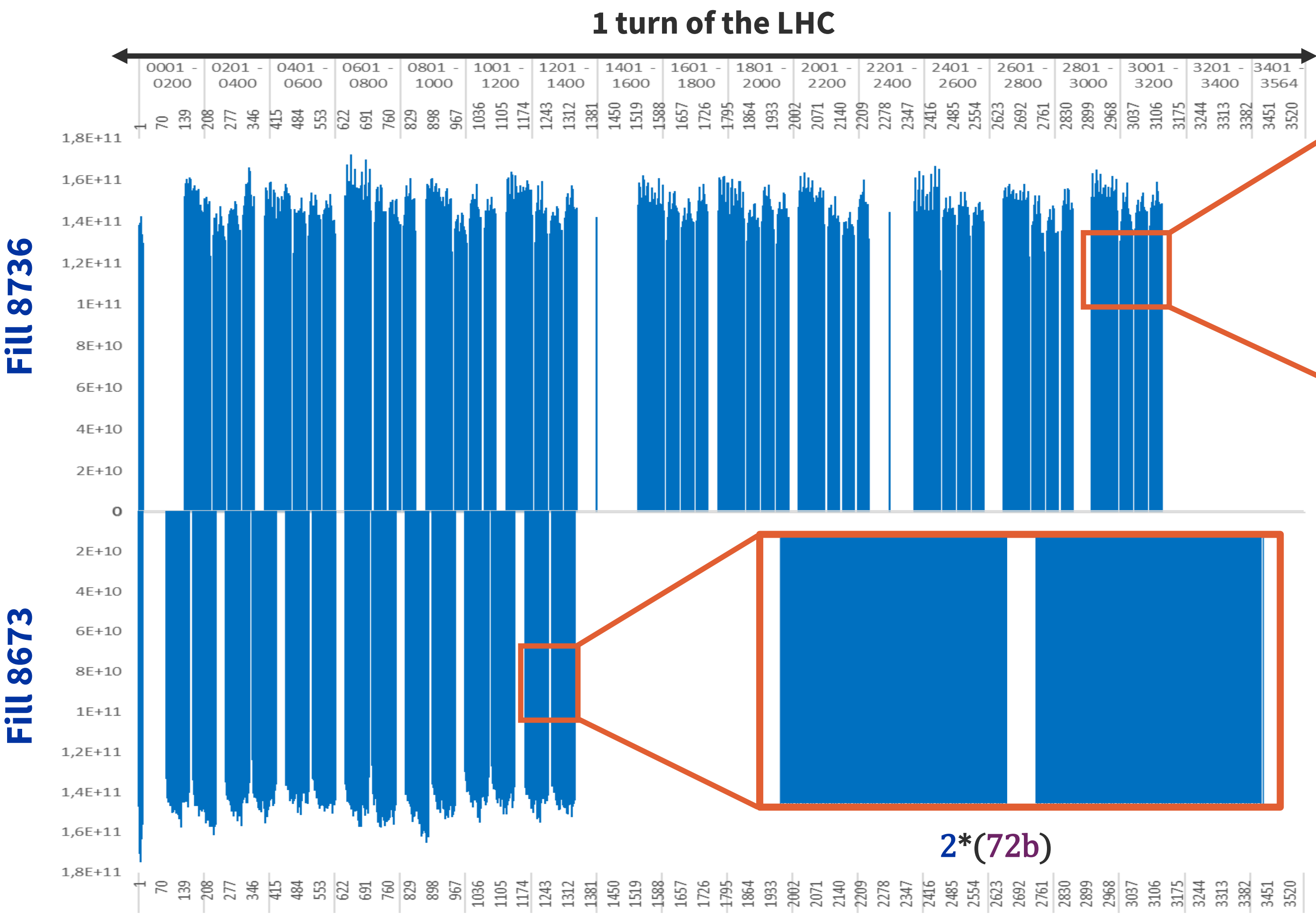
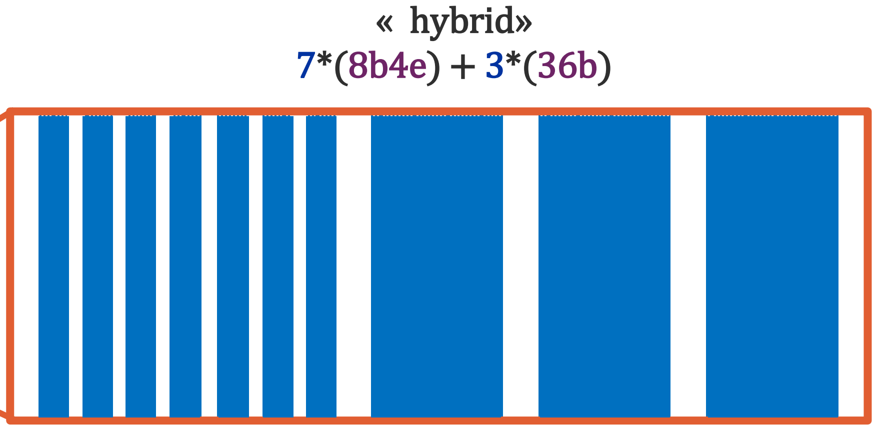
Hybrid and 72b filling schemes





Fill n°	Filling scheme	N_{bunch}	$\overline{ppb}$ $[\times 10^{11}]$	I_{B1} $[\times 10^{14}]$
8736	Hybrid	1818	1.43	2.60
8673	72b	1020	1.42	1.45

Ppb vs Bunch site number for hybrid (top) and 72b (bottom) filling scheme

ESD formula and plots

$$\eta = G S_{eff} \frac{\Delta P}{\dot{\Gamma}_{e^-}} = \frac{e S_{eff} G}{\pi D L} \times \frac{\Delta P}{I} \approx 0.7 \times \frac{\Delta P[\text{mbar}]}{I[\text{A.cm}^{-2}]}$$

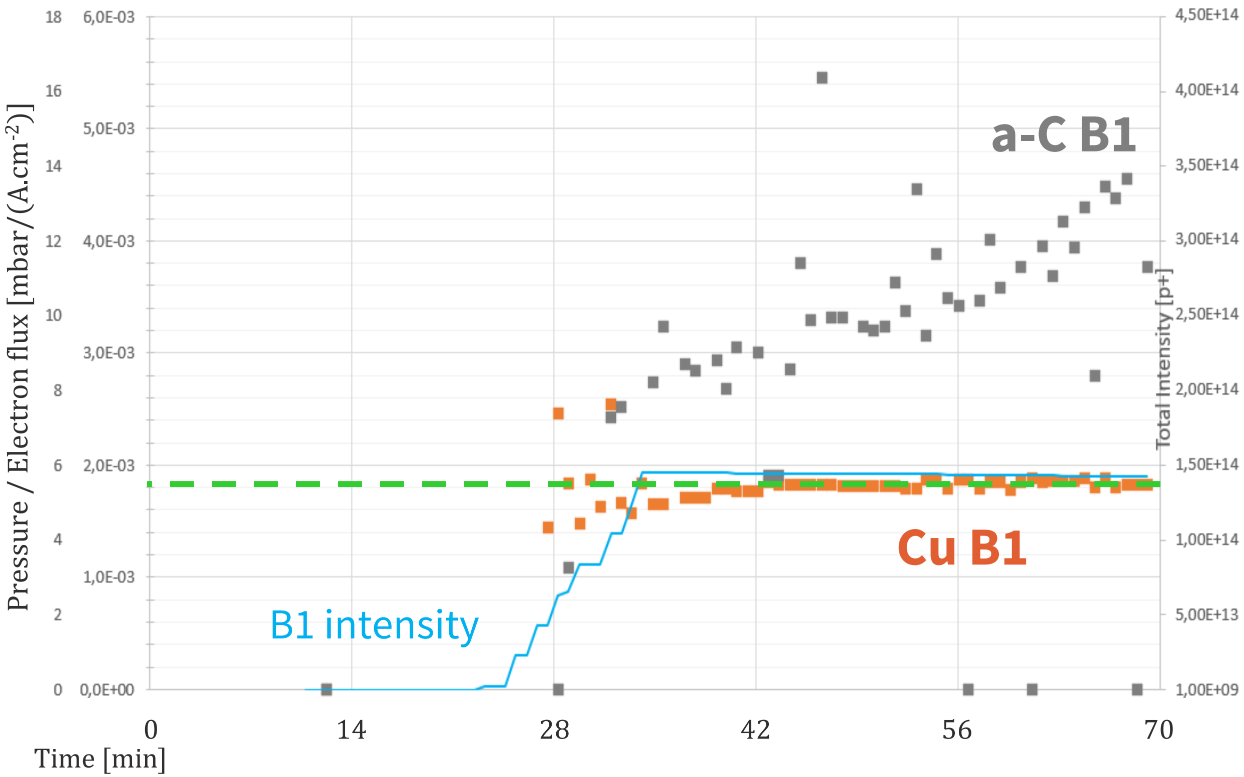
$$G = 2.4 \times 10^{19} \left[\frac{\text{molecule}}{\text{mbar.l}}\right]$$

$$L = 137\ [\text{cm}]$$

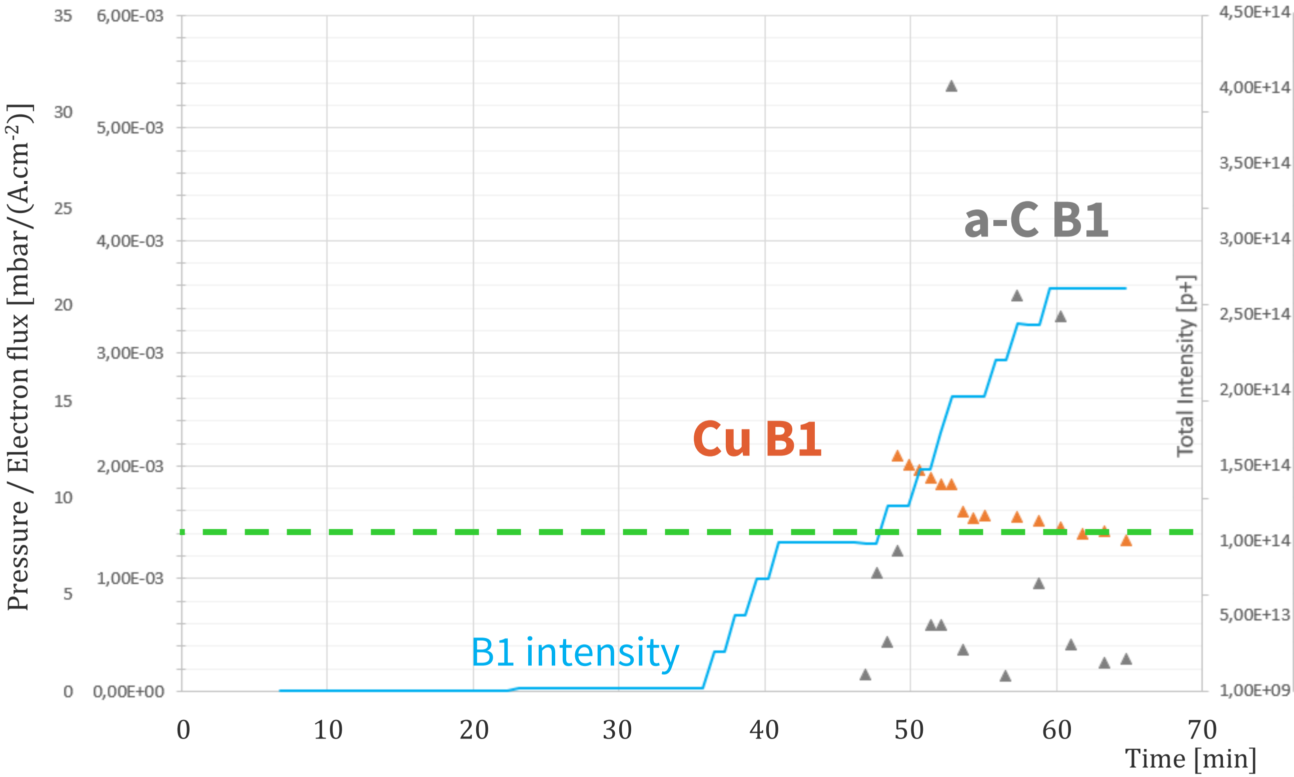
$$D = 8.2\ [\text{cm}]$$

$$S_{eff} \approx 2 \times S_{NEG\ buffer} \approx 600\ \ [\text{l.s}^{-1}]$$

Fill 8673 – 72b

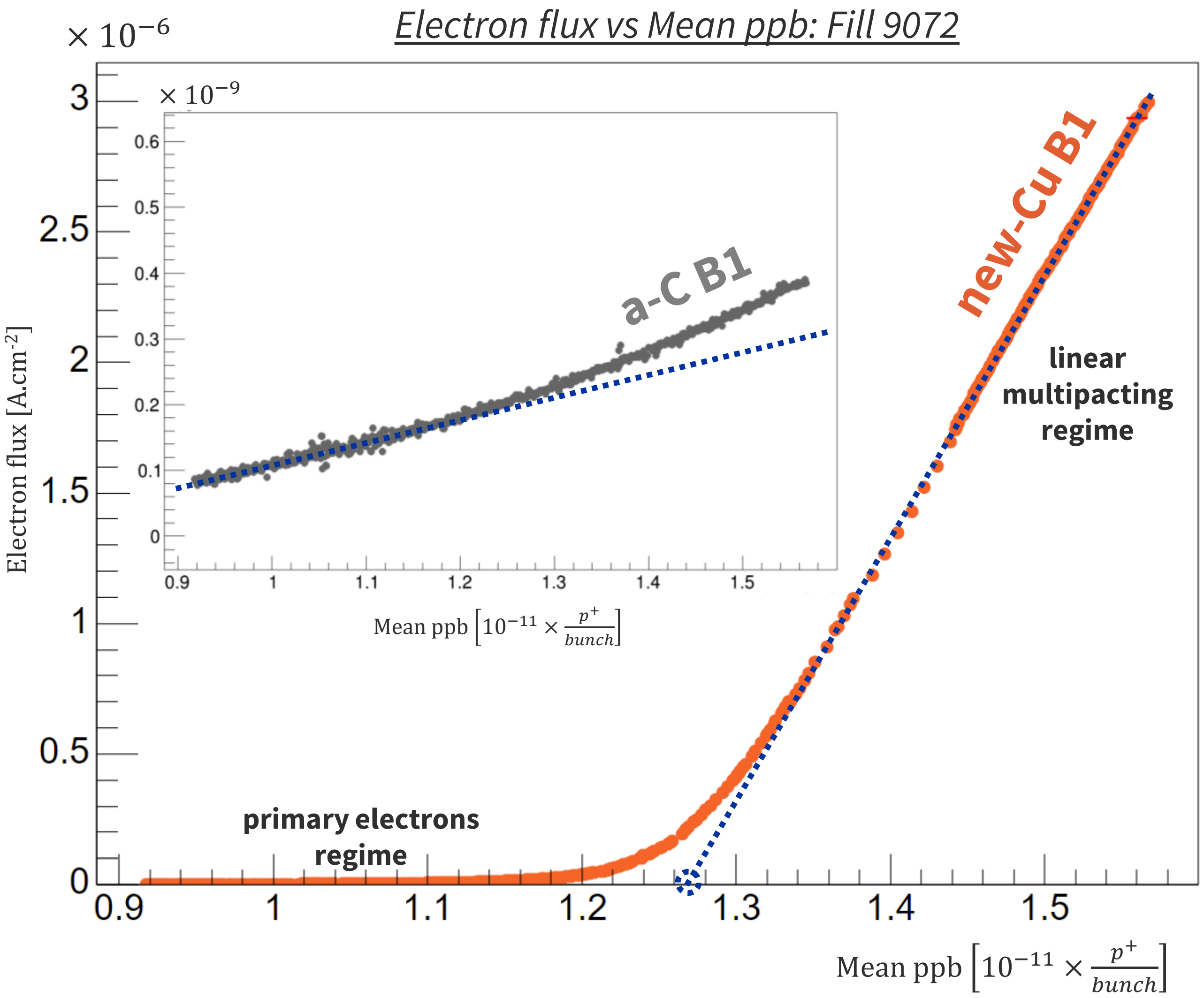


Fill 8736 – hybrid



$L = 137\ [\text{cm}]$

Ecloud as a function of beam mean ppb



Multipacting presence

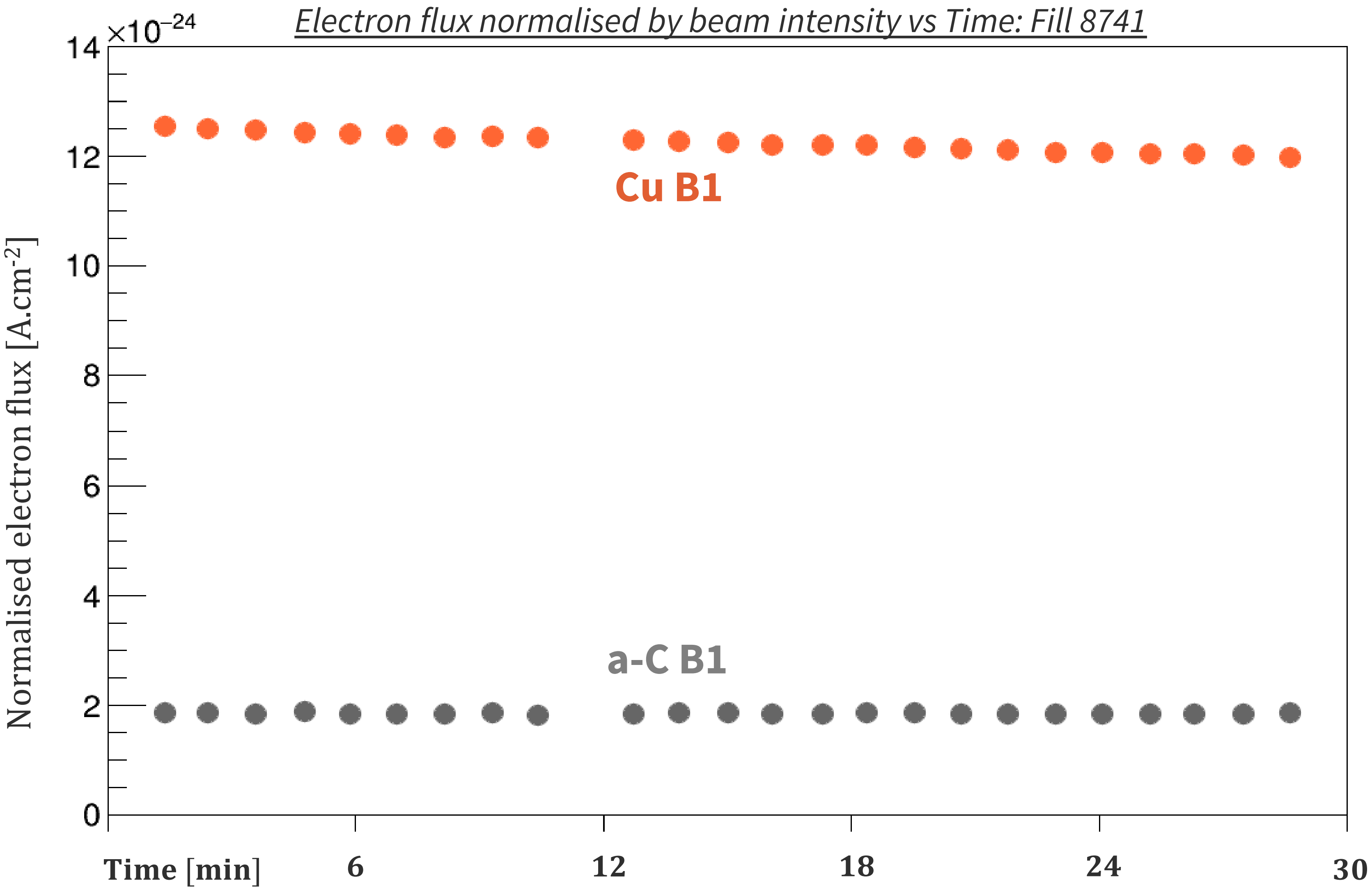
- **Barely present for carbon:** ecloud mainly dominated by photoelectrons
- **Huge contribution for copper**

Assymptotic root method

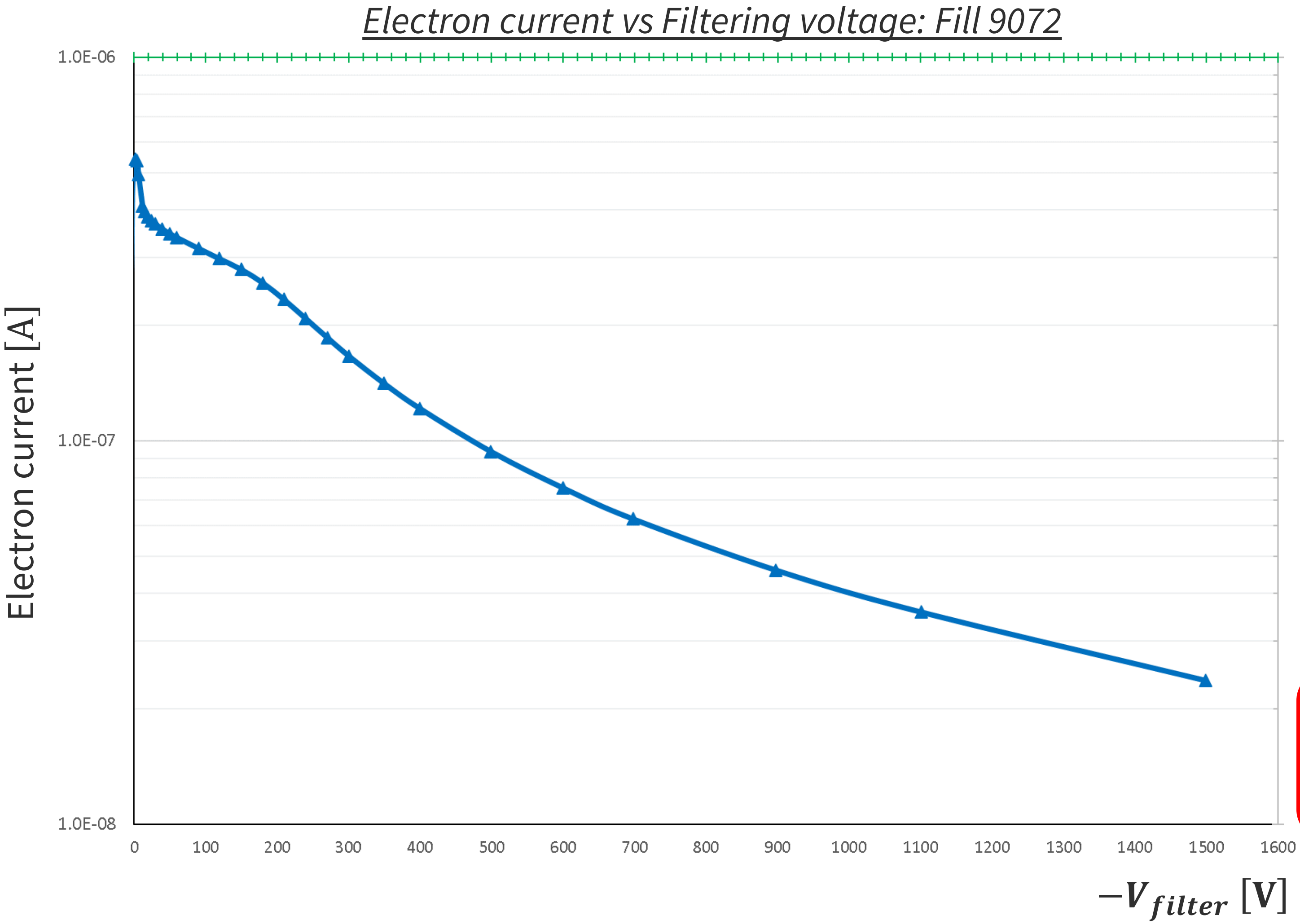
- **Root of linear asymptotic behaviour for high ppb**
- **Method to assess the variations of multipacting with time**

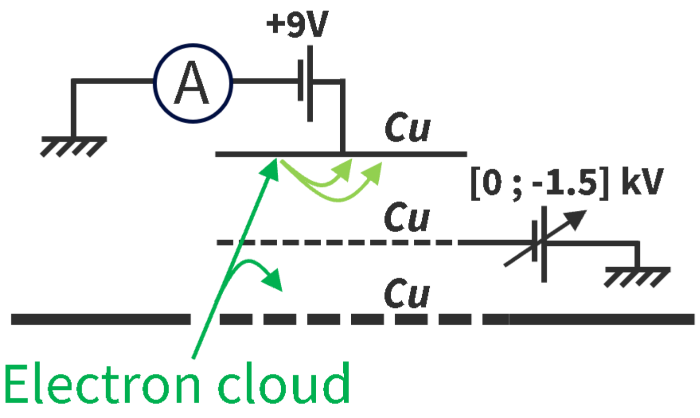
Assymptotic root method is NOT aimed at giving a multipacting threshold as ecloud effect has been identified for lower ppb.

Electron flux scaling with beam intensity at end of fill



RFA raw data





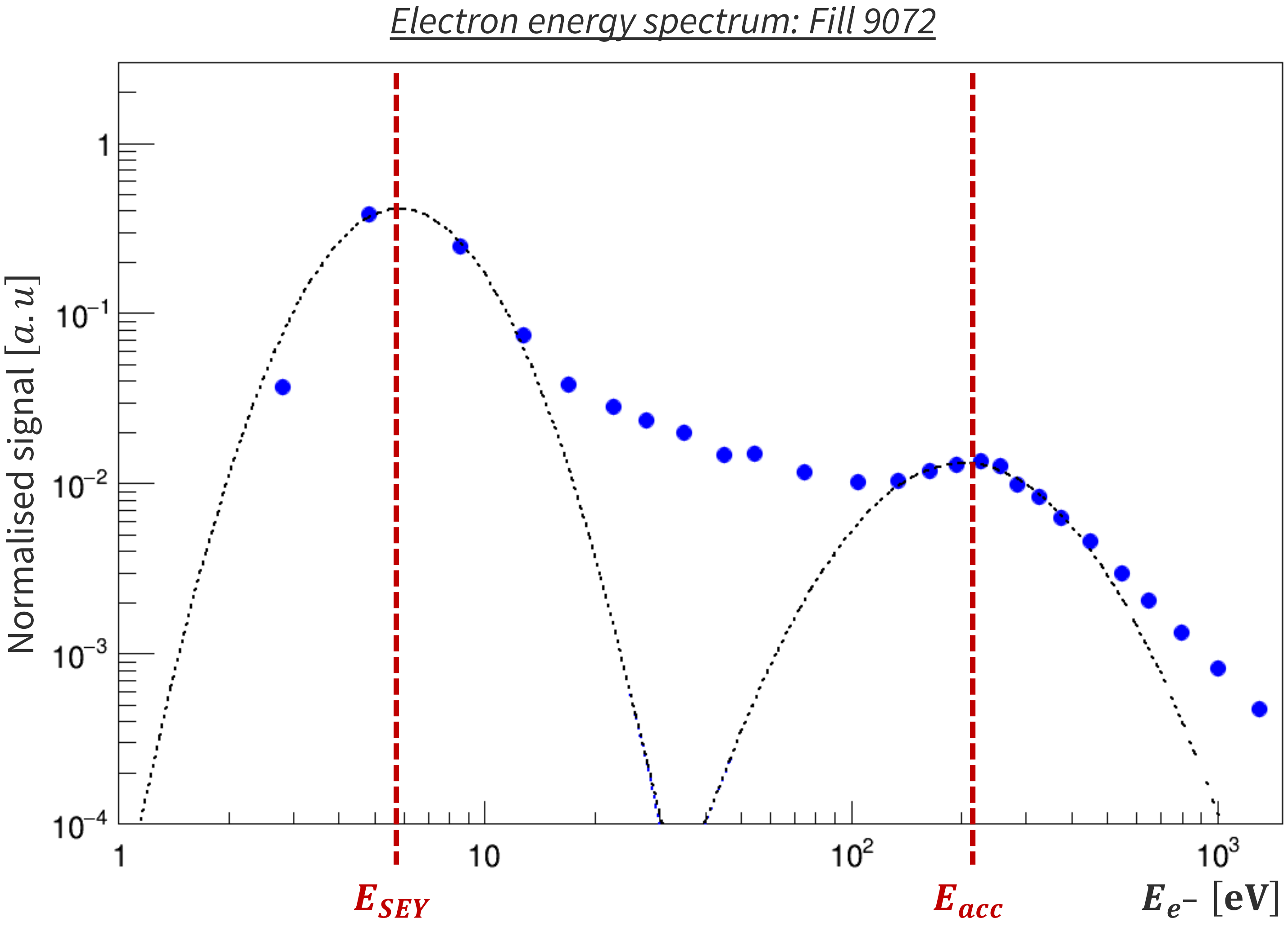
RFA scan

- **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.

Energy spectrum double lognormal fit

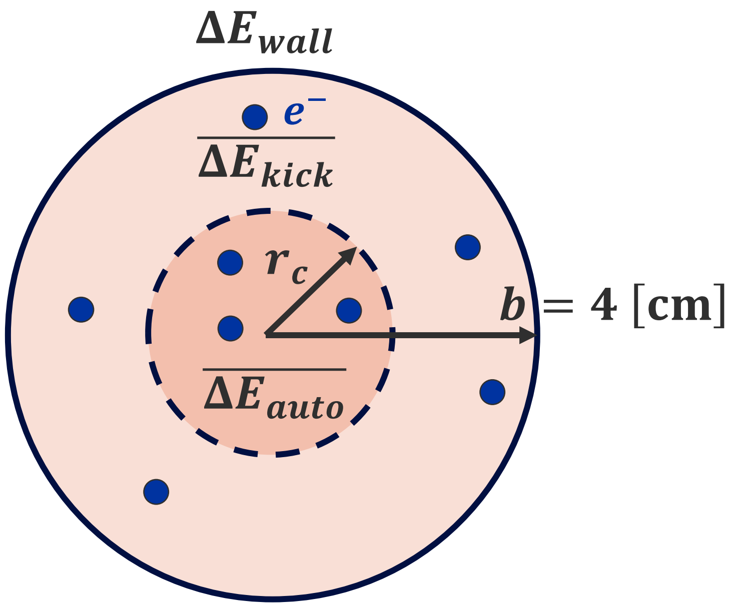


$$f_{lognormal}(E)_{K,\mu,\sigma} = \frac{K}{E\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(E/\mu)}{\sigma}\right)^2\right]$$

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:

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

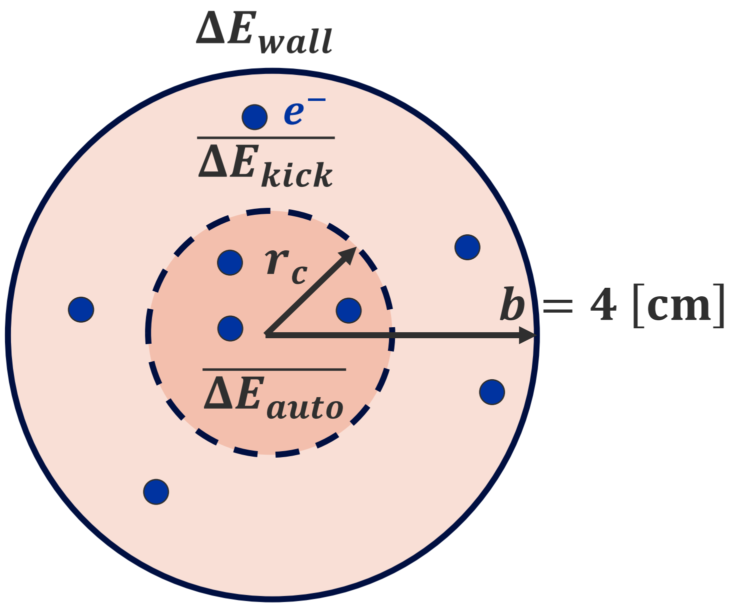
Energy kick for an electron on the wall: ΔE_{wall}

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]

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

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

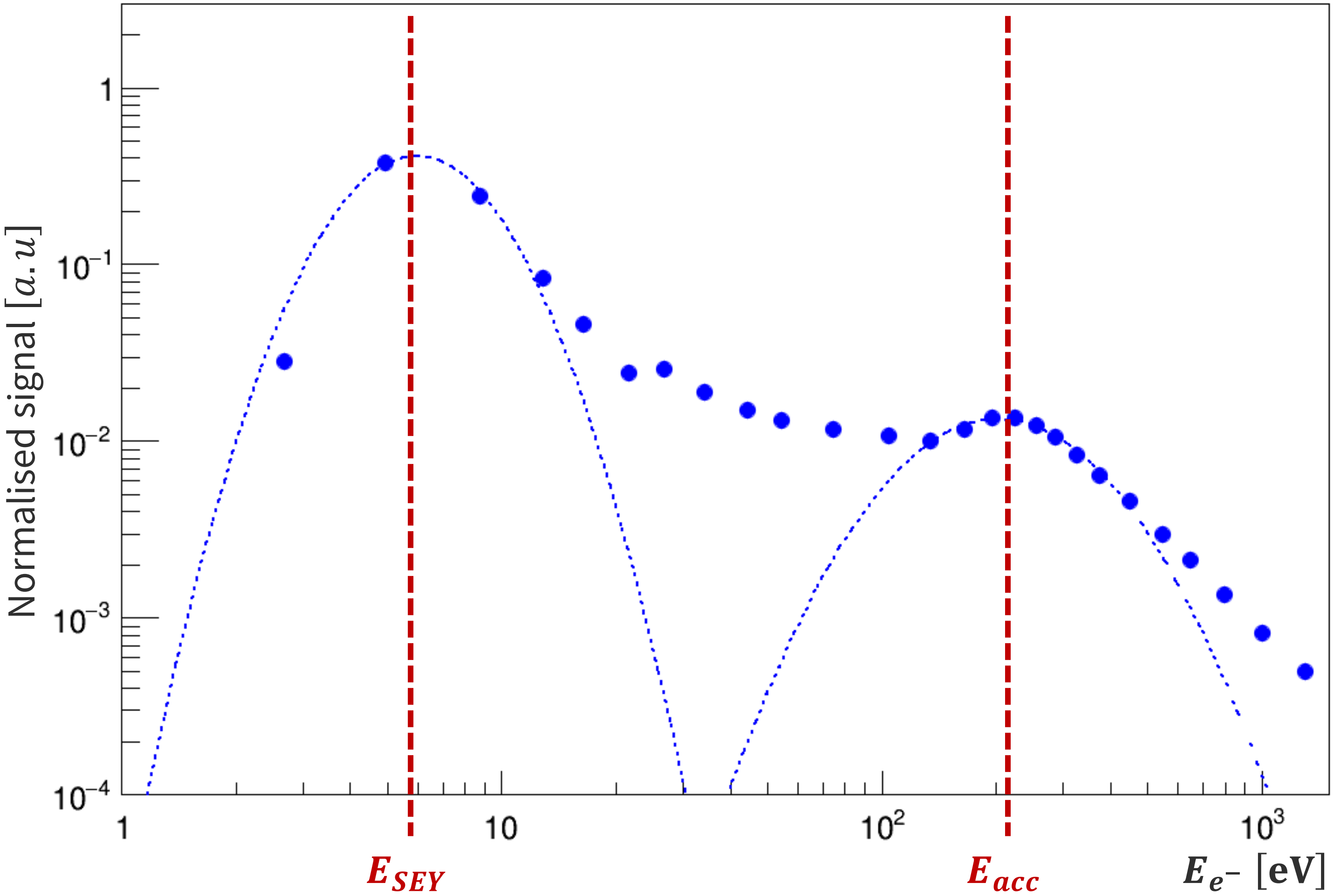
$$\overline{\Delta E_{auto}} = \frac{2}{\pi} \times \Delta E_{wall}\left[\ln\left(\frac{r_c}{c_0\sigma_\perp}\right) - \frac{1}{2}\right]$$

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

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



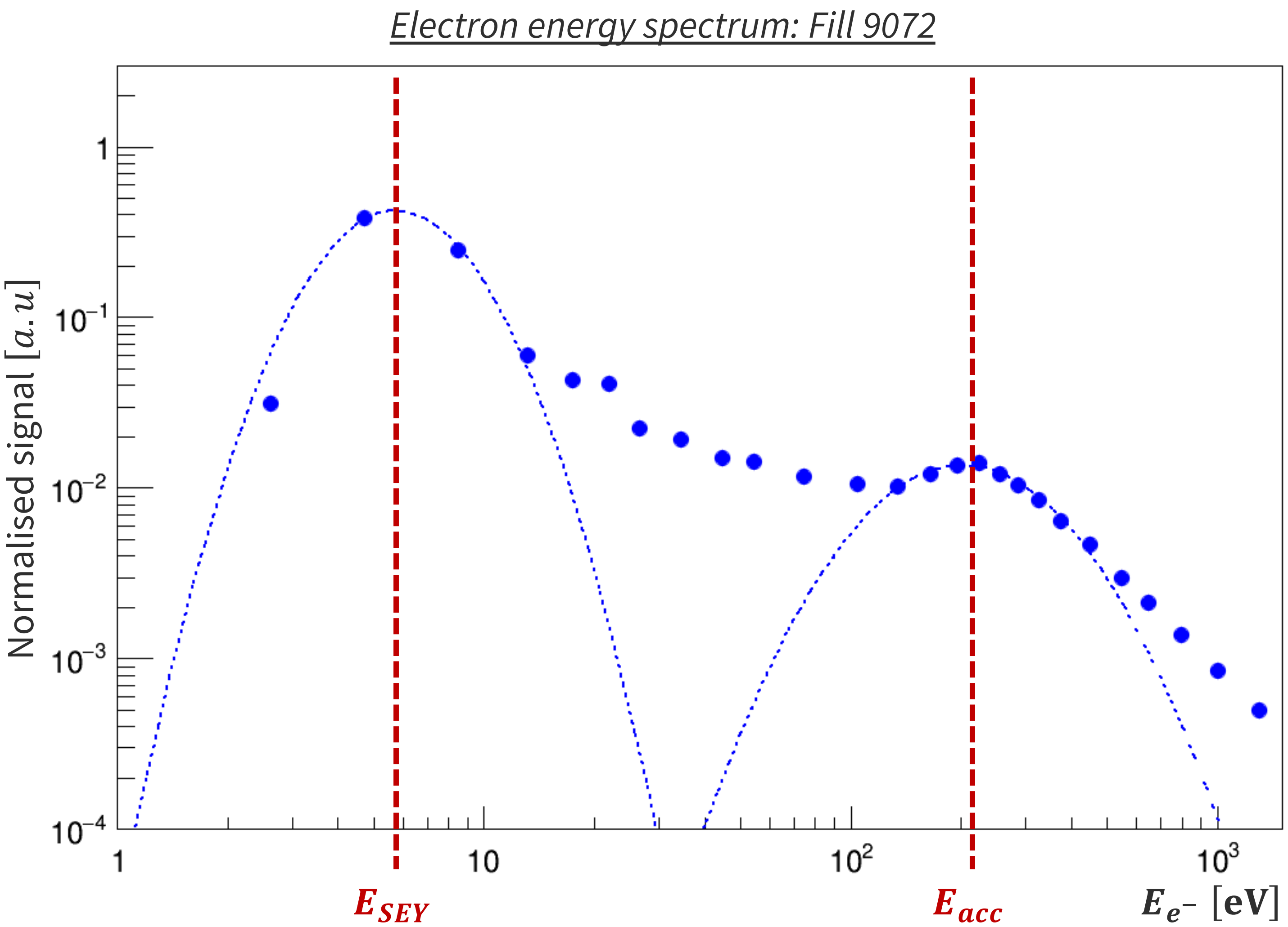
Beam parameters

- **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



Beam parameters

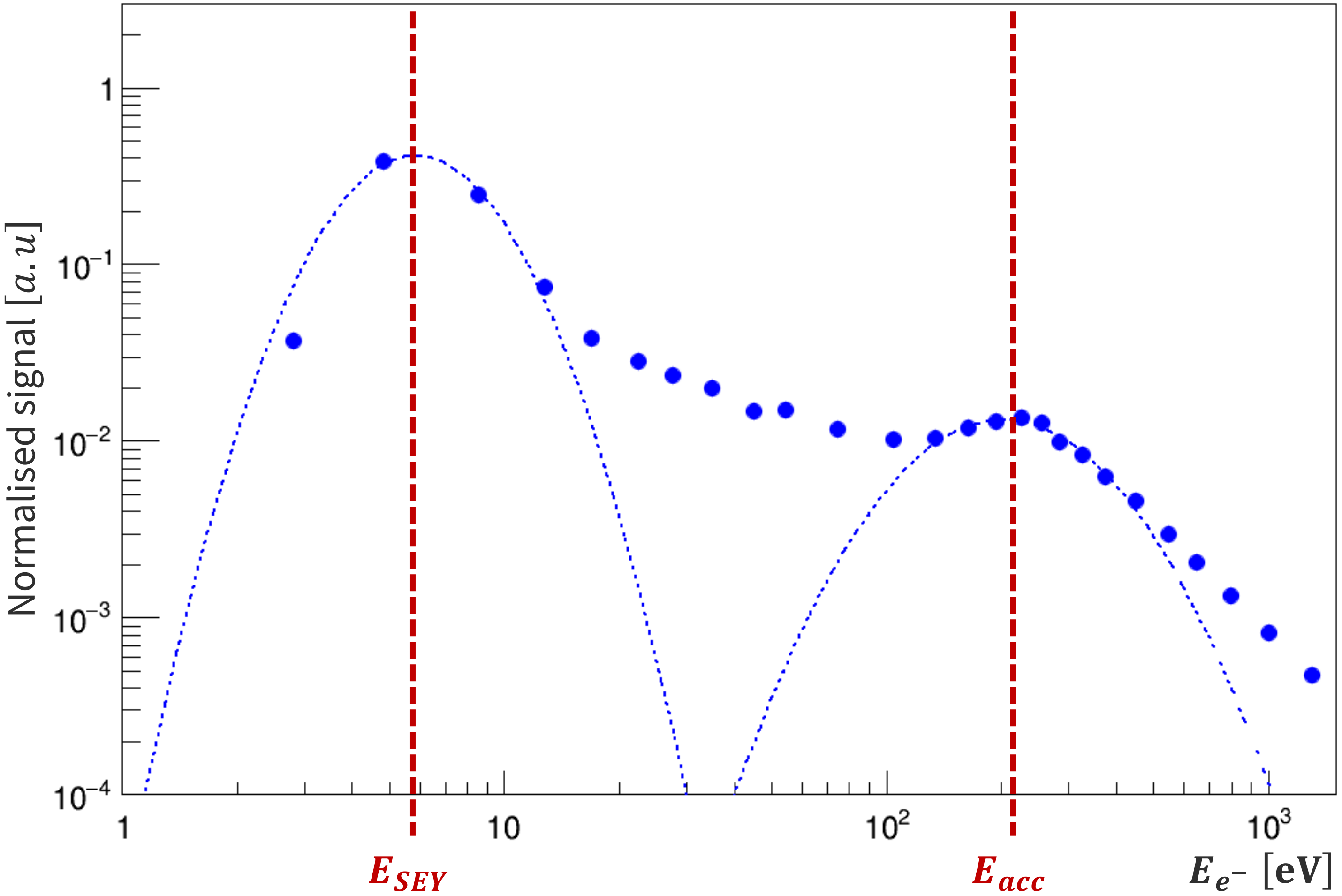
- **Energy:** $E_{B1} = 2074$ [GeV]
- **Intensity:** $ppb_{B1} = 1.60 \times 10^{11} \left[\frac{\mathrm{p}^+}{\mathrm{bunch}}\right]$

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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