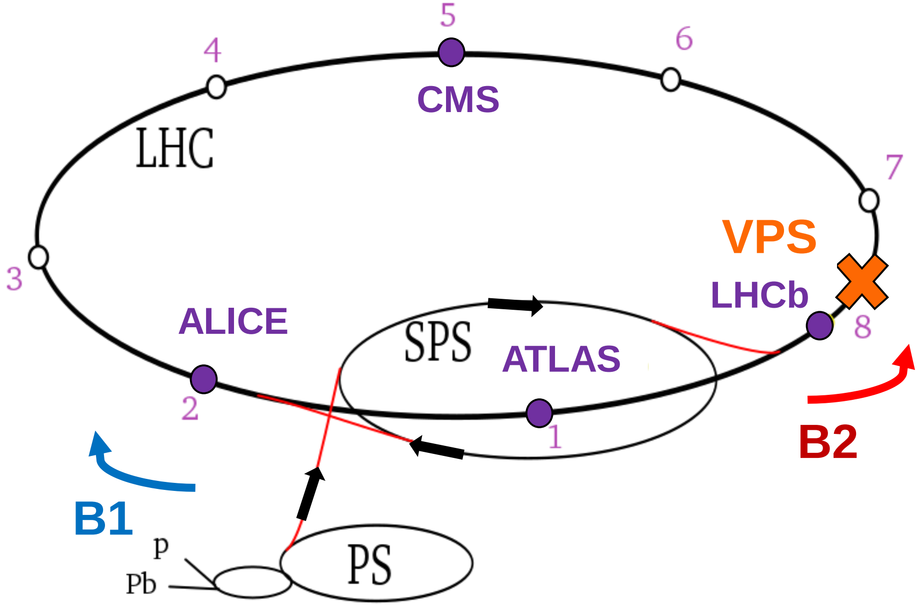
Dynamic Pressure in the LHC

STUDY OF BEAM-SURFACE INTERACTIONS AND DYNAMIC PRESSURE INDUCED BY ELECTRON CLOUDS AND IONS FOR THE LHC, HL-LHC AND FCC-HH

S. Bilgen, G. Sattonnay, B. Mercier, V. Baglin *
LAL, IN2P3-CNRS, Paris-Sud University, Orsay
* CERN, Geneva, Switzerland

LHC RUN II Statement

CERN's accelerator complex



LHC characteristics

- The world's largest and most powerful particle accelerator.
- A P-P collider of 27 km circumference ring.
- Proton beam- PS- SPS- injection in LHC- energy ramp-collision at IP.
- CERN's mission: helps to uncover what the universe is made of and how it works.

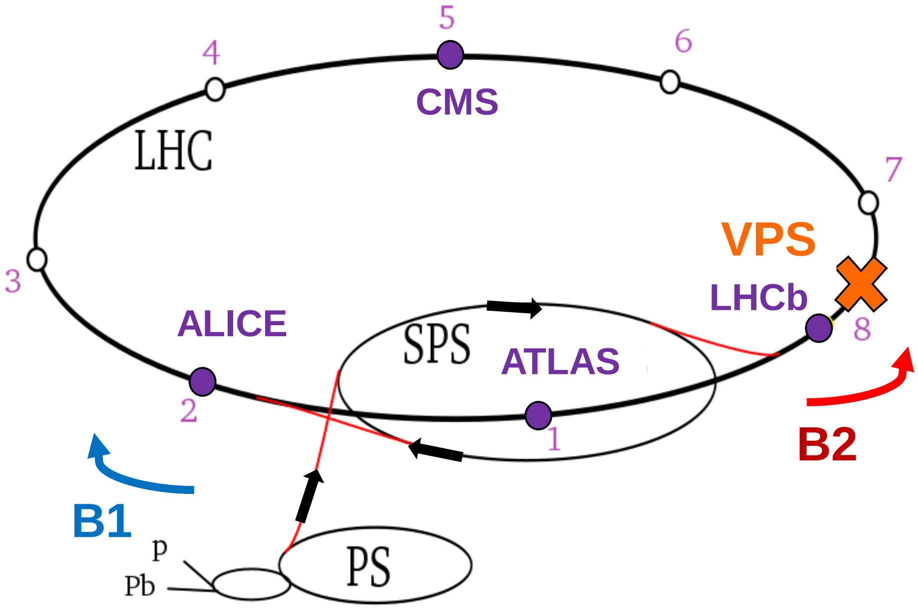
To stay operational during 2018, the LHC was limited to fewer than the nominal number of bunches due to dynamic pressure phenomena

LHC	→	LHC	→	FCC-hh
27 km, 8.33 T		27 km, 8.33 T		80 km, 20 T
13 TeV, 2556 b		14 TeV, 2808 b		100 TeV, 10600 b

These nominal values have never been reached in the LHC!

LHC RUN II Statement

CERN's accelerator complex



LHC characteristics

- The world's largest and most powerful particle accelerator.
- A P-P collider of 27 km circumference ring.
- Proton beam- PS- SPS- injection in LHC- energy ramp-collision at IP.
- CERN's mission: helps to uncover what the universe is made of and how it works.

To stay operational during 2018, the LHC was limited to fewer than the nominal number of bunches due to dynamic pressure phenomena

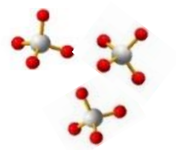
LHC		LHC		FCC-hh
27 km, 8.33 T	→	27 km, 8.33 T	→	80 km, 20 T
13 TeV, 2556 b		14 TeV, 2808 b		100 TeV, 10600 b

Can we reach these nominal parameters for FCC-hh?

DYNAMIC PRESSURE IN THE LHC

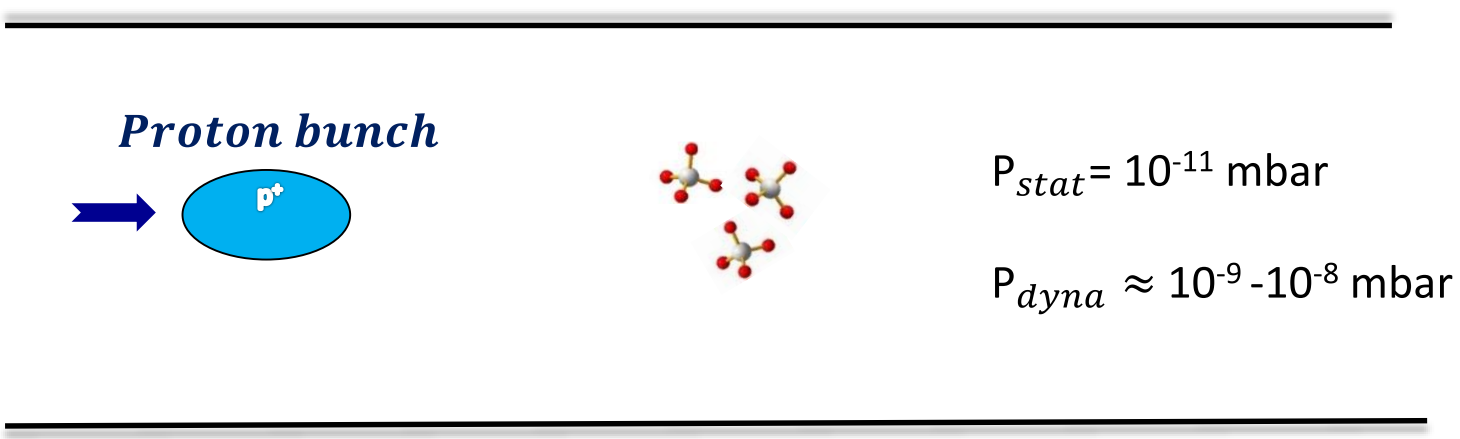
Proton bunch

p^+



$P_{stat} = 10^{-11}$ mbar

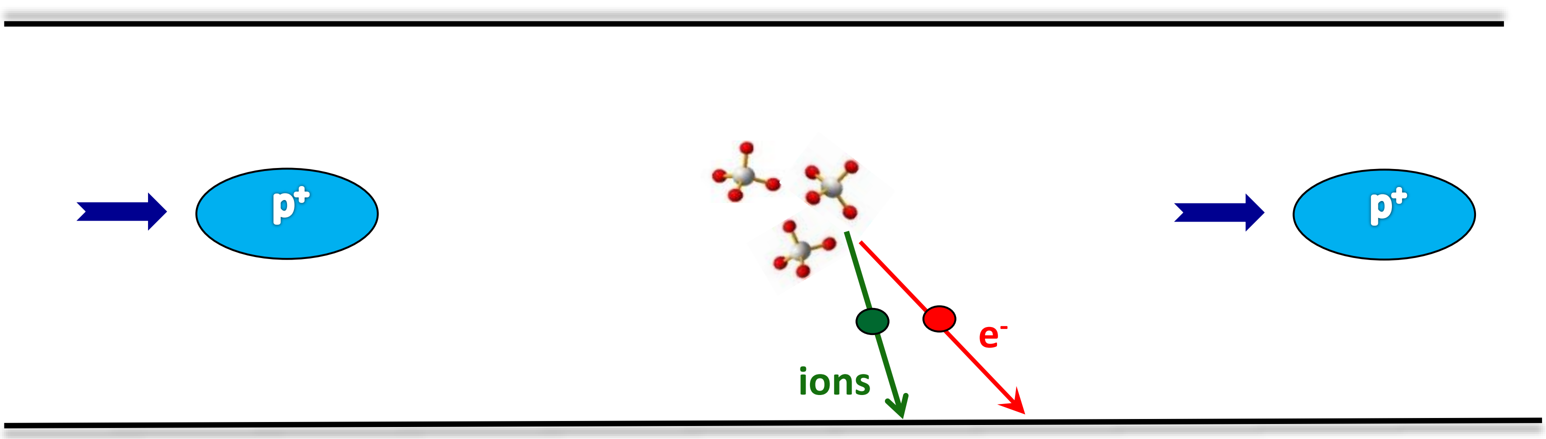
$P_{dyna} \approx 10^{-9}$ - 10^{-8} mbar



How to explain this pressure increase?

bilgen@lal.in2p3.fr

IONIZATION OF RESIDUAL GAS



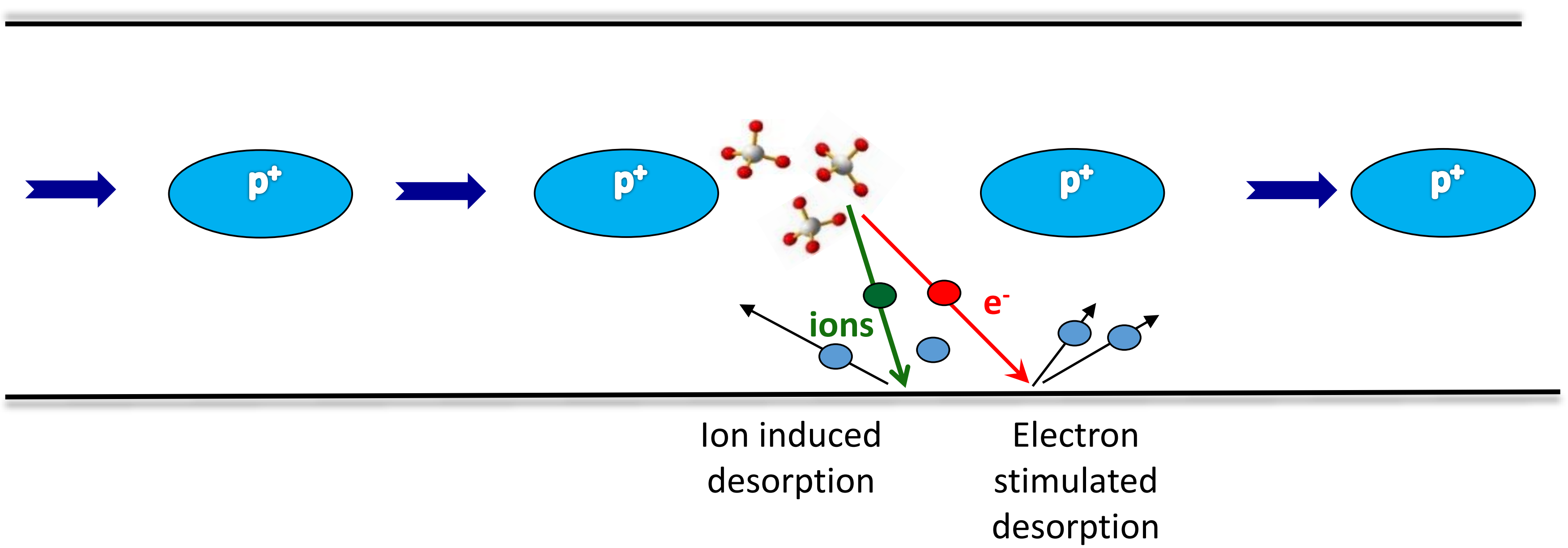
Electrons/ions
- produced by ionization of residual gas
- accelerated by the beam

When the proton beam circulates in the accelerator, it ionizes the residual gas

bilgen@lal.in2p3.fr

DESORPTION

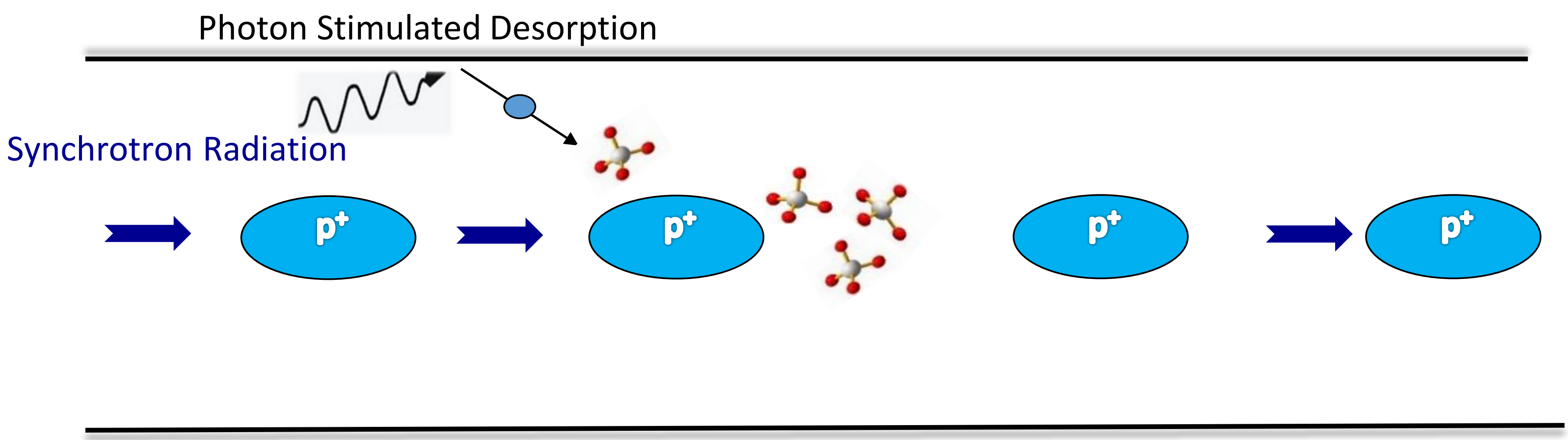
IONIC AND ELECTRONIC DESORPTION



Charged particles are accelerated by the beam.
Desorption →neutral molecules go inside the chamber volume.

DESORPTION

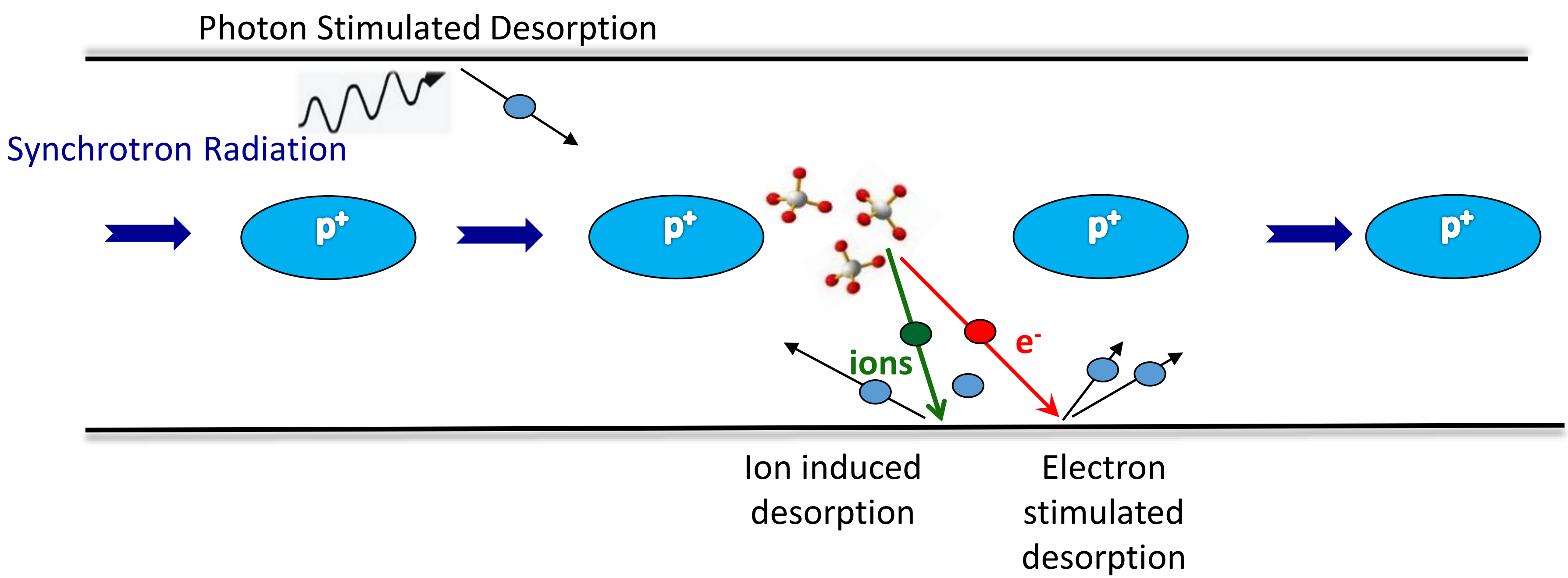
PHOTO-DESORPTION



As the LHC is a ring, protons emit synchrotron radiations which induced also photo - desorption.

DESORPTION

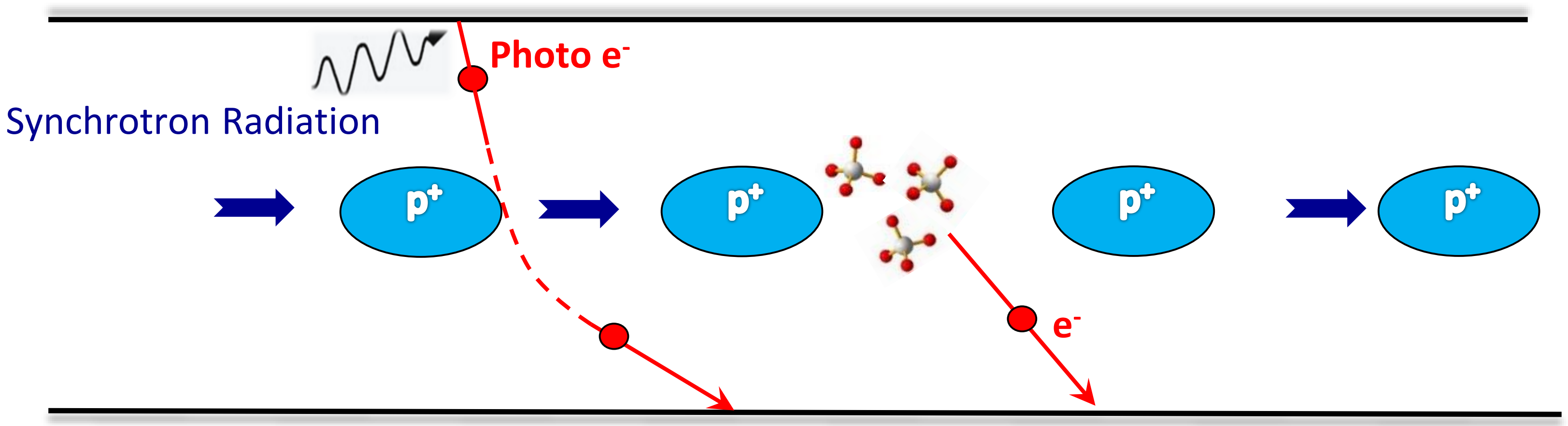
PHOTO-DESORPTION



All of these stimulated desorption induced an increase of the amount of residual gas

PARTICLE CREATION

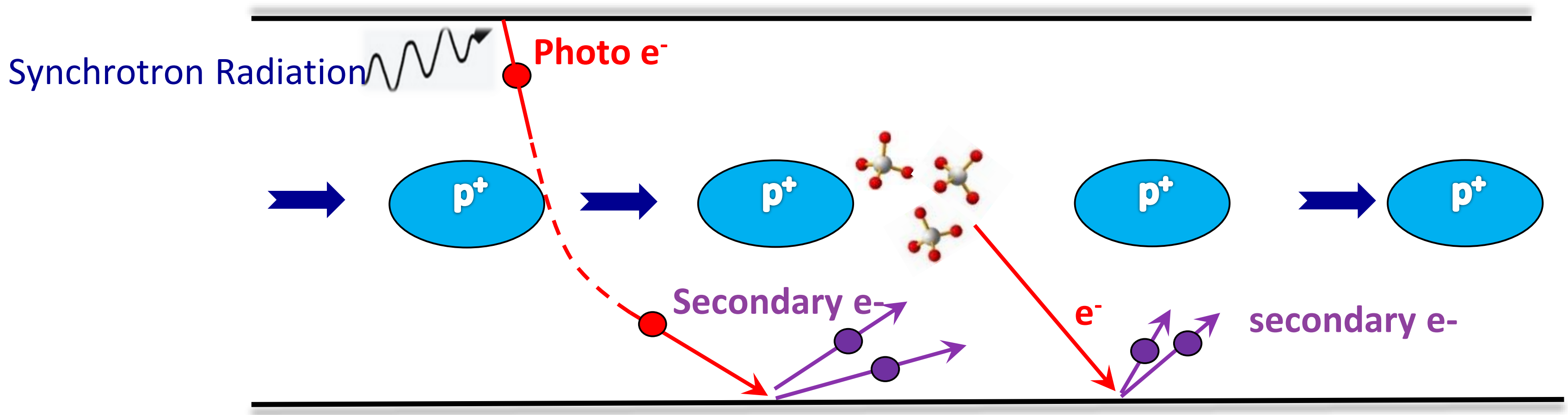
PHOTOELECTRON PRODUCTION



In addition, creation of photoelectrons
(interactions between photons and beam pipe walls)

PARTICLE CREATION

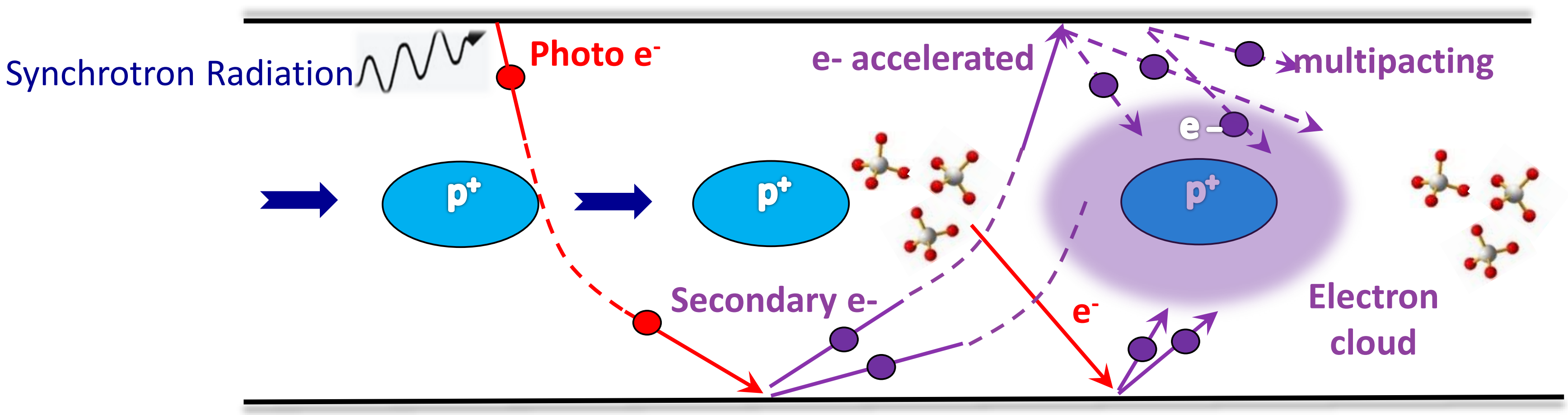
SECONDARY ELECTRON PRODUCTION



Electrons resulting from the ionization of the residual gas as well as the photoelectrons accelerated by the field of the beam interact with the beam pipe wall and create SE.

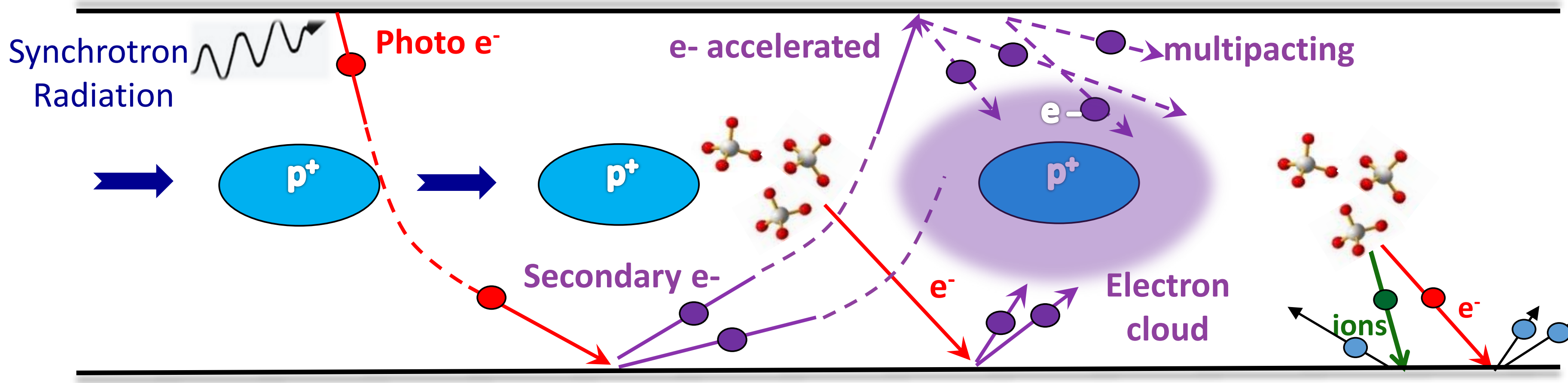
COLLECTIVE EFFECT

ELECTRON CLOUD PRODUCTION



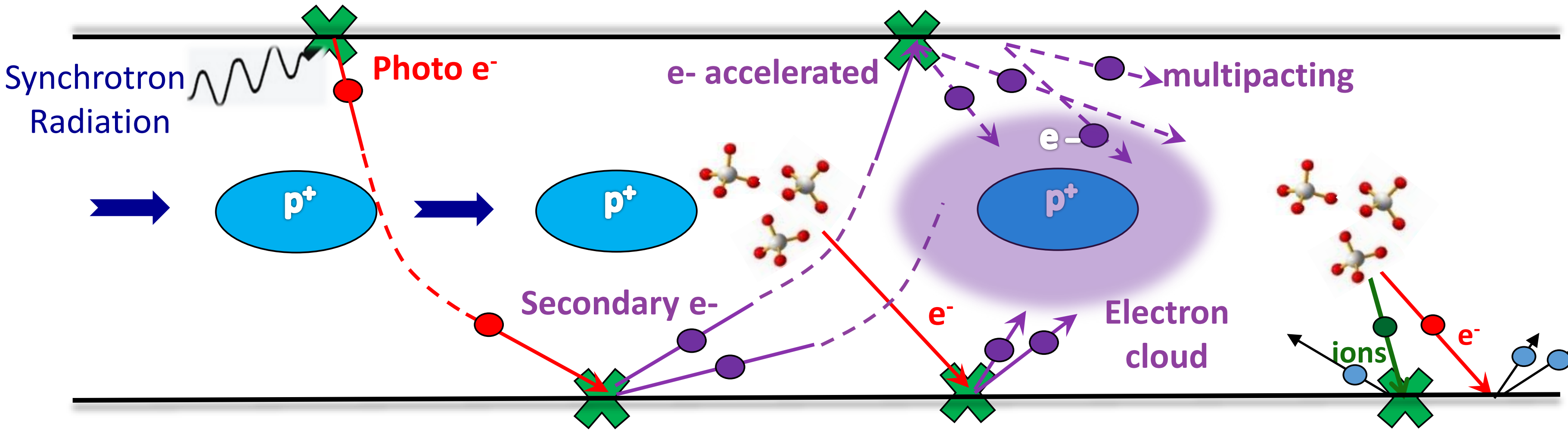
By multipacting effect → electron cloud formation which disturbs the beam

Stimulated desorption, secondary particle creation, and collective effects

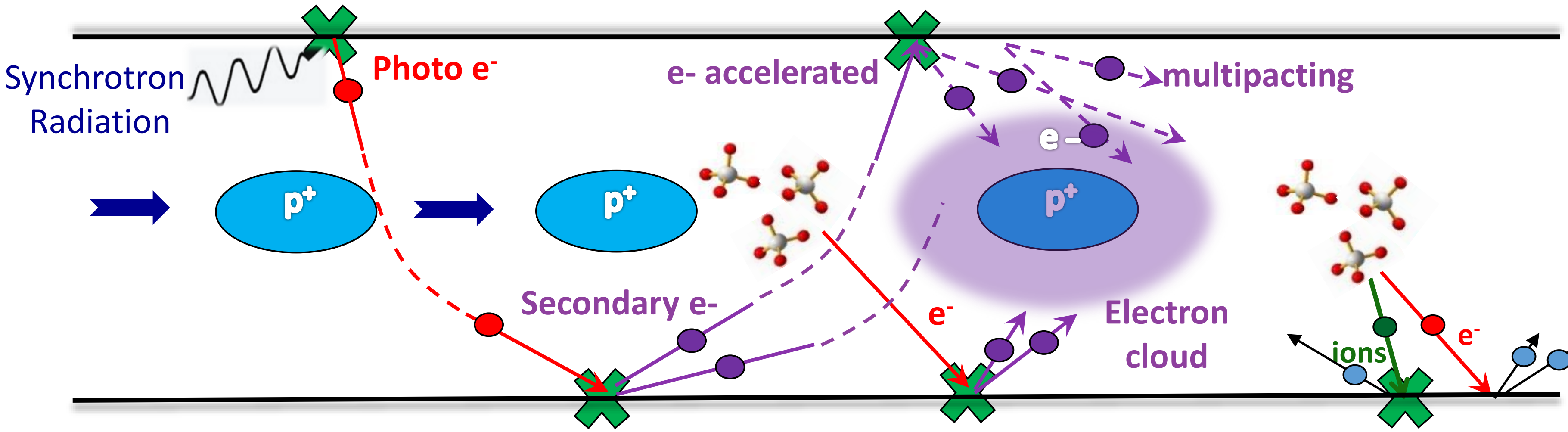


The LHC beam is limited by these phenomena which induce:

- Beam emittance increase →Deterioration of the luminosity factor
- Beam instabilities
- Premature beam dumps occurrence due to the beam divergence



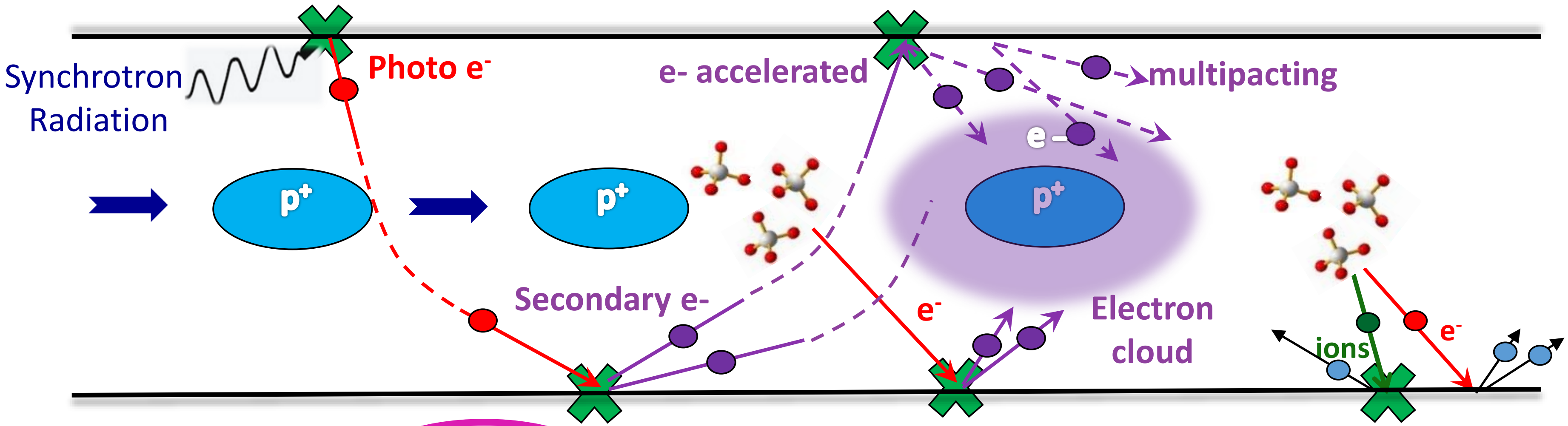
Particle / Surface interactions



Particle / Surface interactions

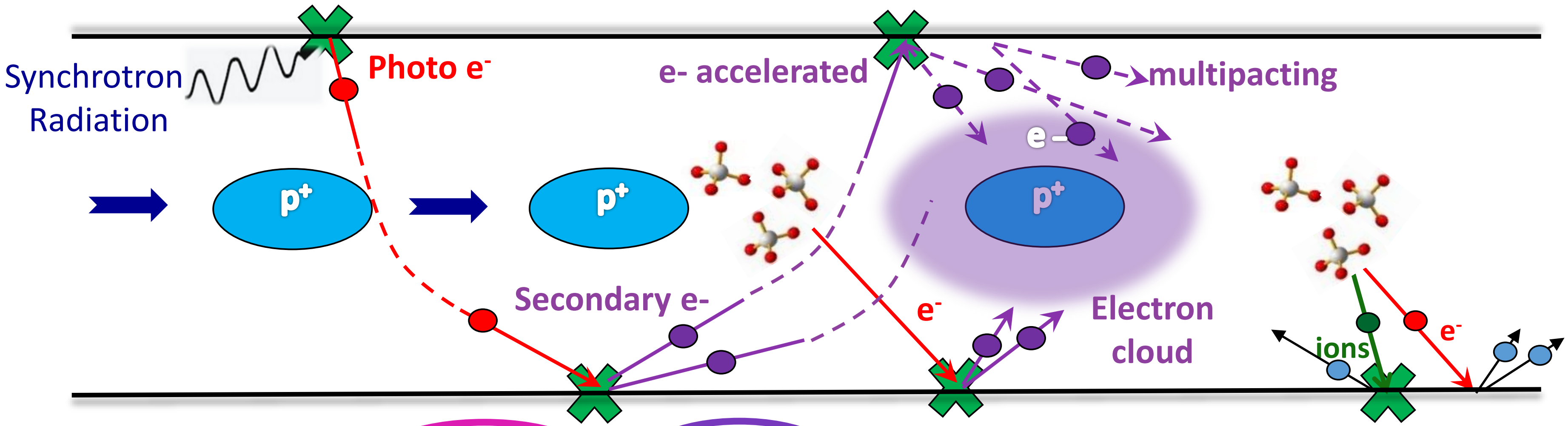
To achieve high performances for the FCC-hh project, it is essential to understand all of these phenomena in order to find solutions to improve beam quality.

DYNAMIC PRESSURE IN THE LHC



Particle / Surface interactions

In situ measurements in the LHC ring



Particle / Surface interactions

In situ measurements in the LHC ring

Surface analysis using TOF-SIMS method and XPS

Objective: Stimulated desorption, secondary particle creation, and collective effects will be amplify for the FCC-hh beam conditions and so have to be managed!

It's necessary to understand all of these particle/surface interactions investigating the LHC

Objective: Stimulated desorption, secondary particle creation, and collective effects will be amplify for the FCC-hh beam conditions and so have to be managed!

It's necessary to understand all of these particle/surface interactions investigating the LHC

I. In-situ measurements in VPS of LHC

II. DYVACS Code - Calculation of the dynamic pressure

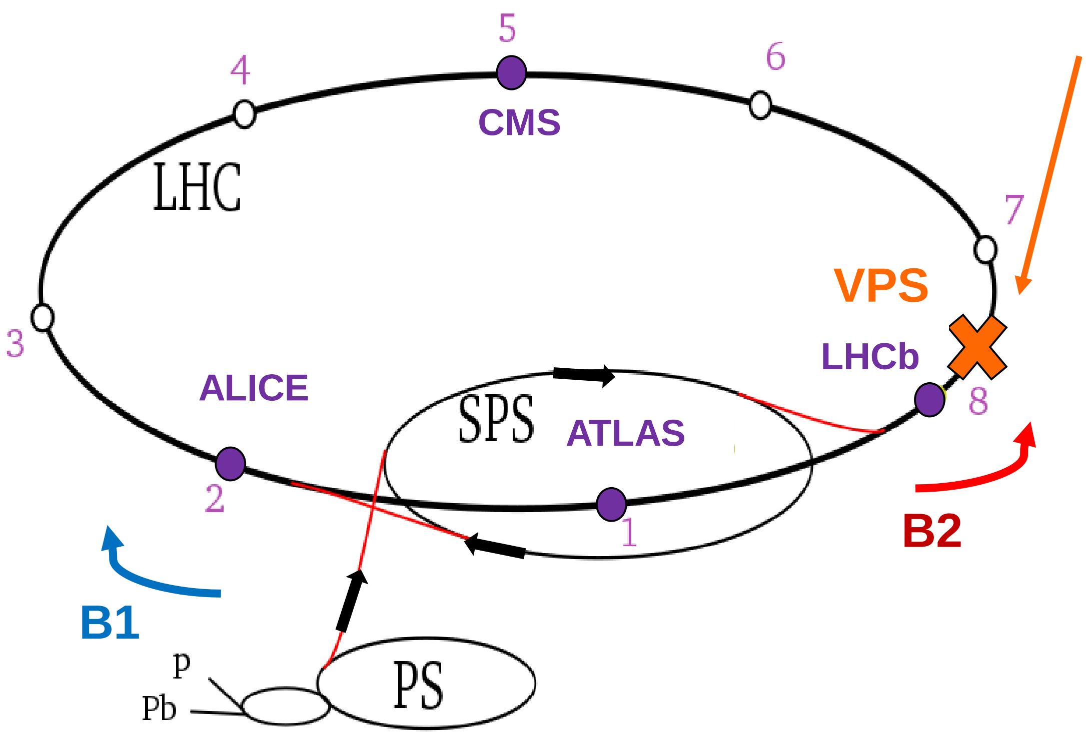
III. LHC beam screen surface analysis

IV. Conclusions & Perspectives

Stimulated desorption, secondary particle creation, and collective effects will be amplify in the FCC-hh

How many charged particles interact with LHC beam screen during the operation?

In-situ measurements in VPS of LHC



VPS – Vacuum Pilot Sector (18m)

The sector study is close to the Interaction point 8.

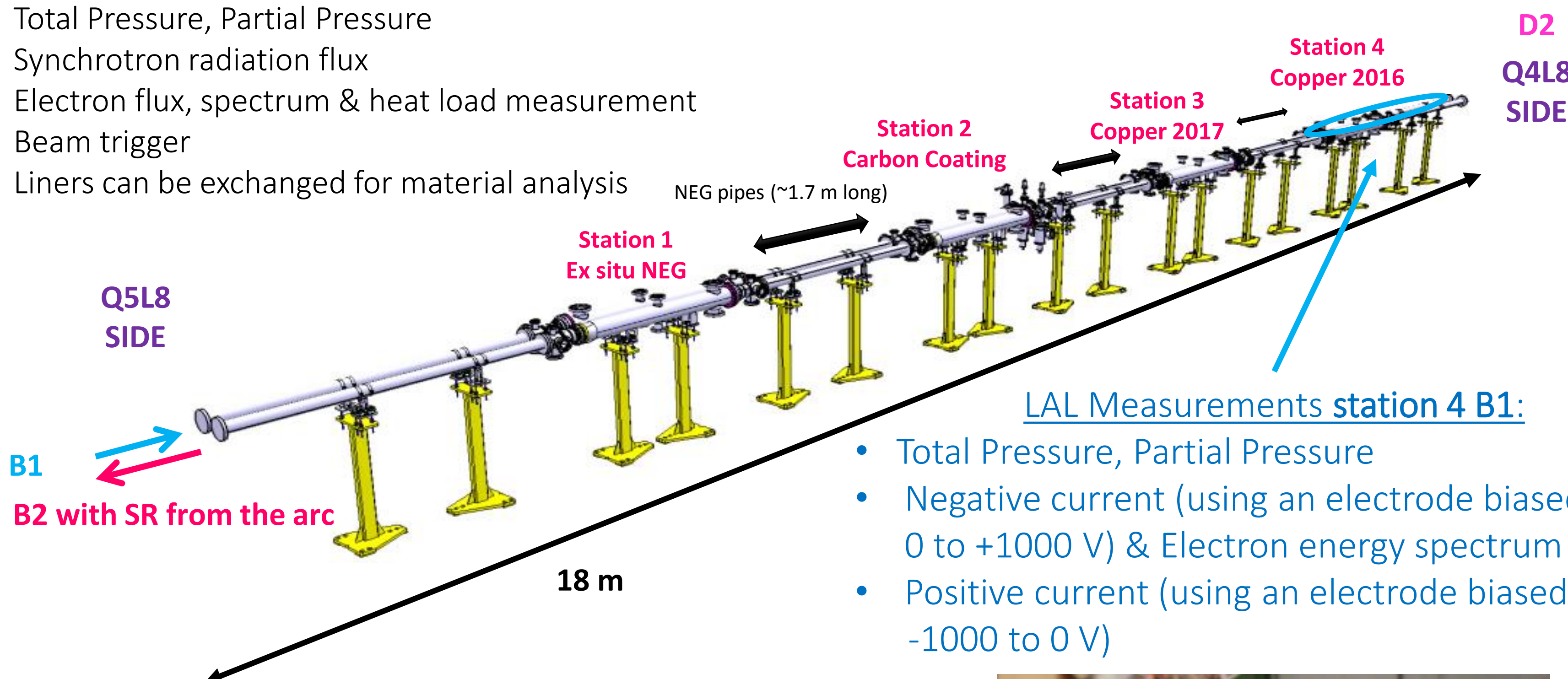
Conditions

- At room temperature
- In a straight section of LHC
- No magnetic field

VPS - VACUUM PILOT SECTOR

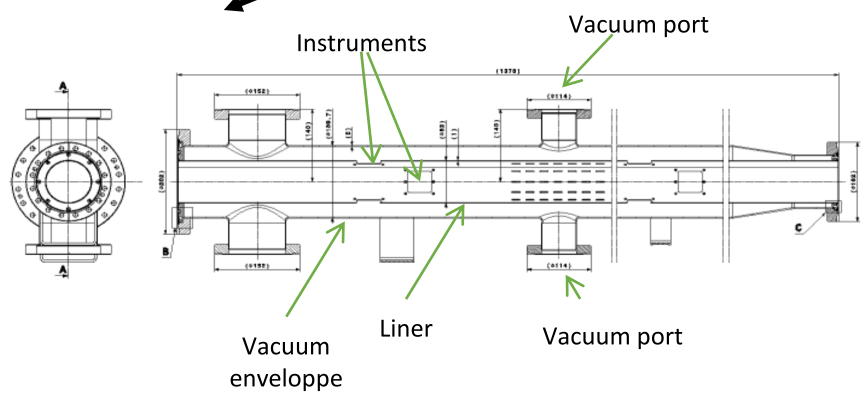
VPS Measurements:

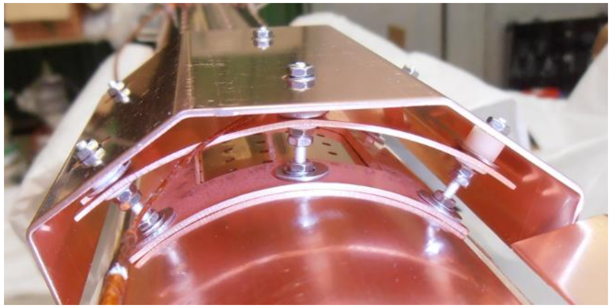
- Total Pressure, Partial Pressure
- Synchrotron radiation flux
- Electron flux, spectrum & heat load measurement
- Beam trigger
- Liners can be exchanged for material analysis



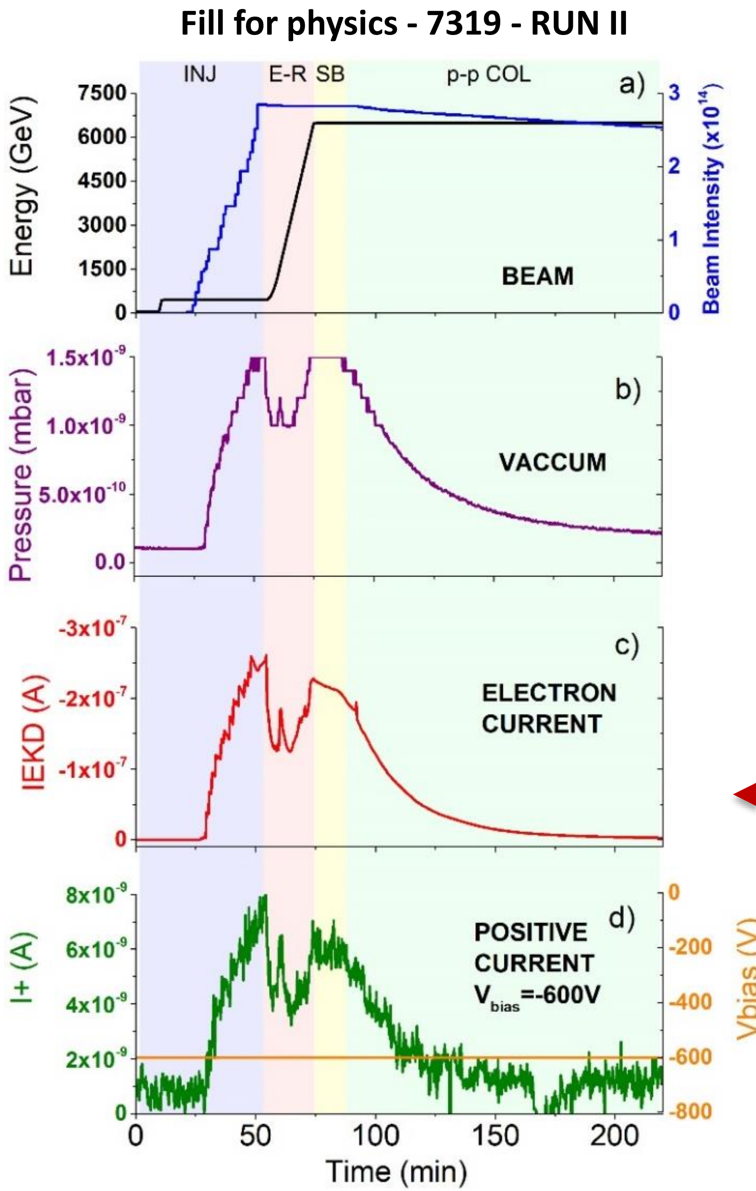
LAL Measurements **station 4 B1**:

- Total Pressure, Partial Pressure
- Negative current (using an electrode biased from 0 to +1000 V) & Electron energy spectrum
- Positive current (using an electrode biased from -1000 to 0 V)

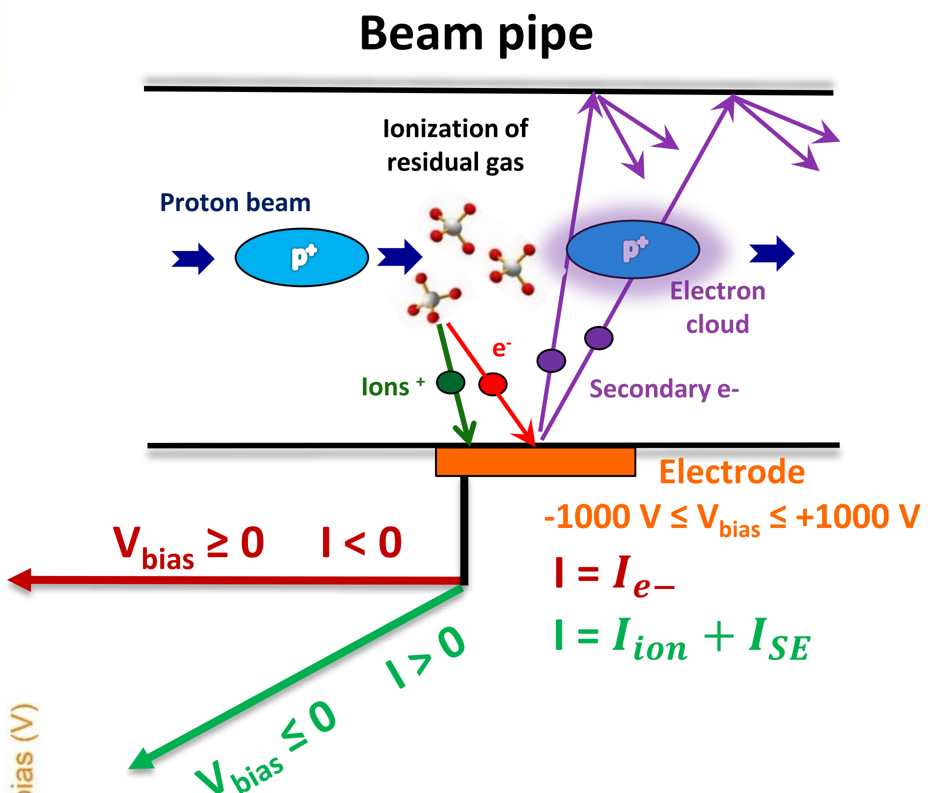




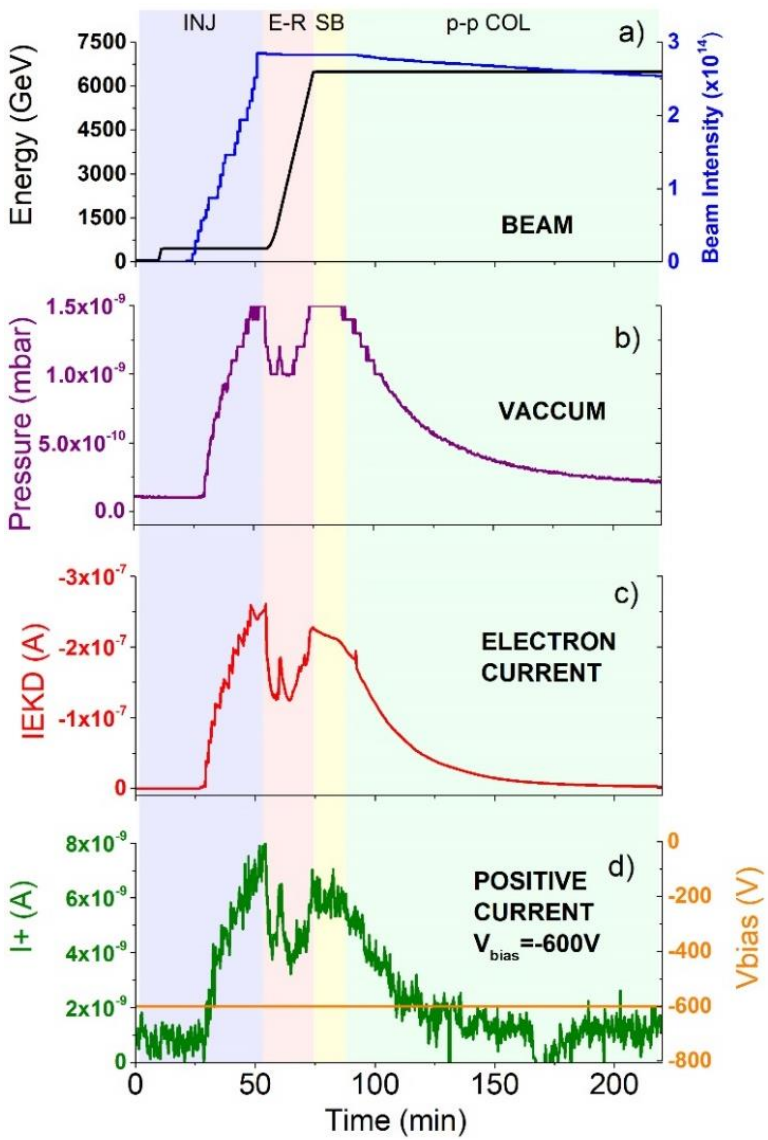
VPS *in situ* MEASUREMENTS



LHC RUN II *in situ* measurements
Vacuum Pilot Sector
Station 4 - blue beam line



Fill for physics - 7319 - RUN II



LHC RUN II *in situ* measurements
Vacuum Pilot Sector
Station 4 - blue beam line

Fill 7319 - 25ns_2556b_144bpi_20inj

I Injection

+ protons circulate, +ionization of residual gas

➢ increase of both pressure and electrical currents

II Energy ramp up

slight decrease of beam intensity due to proton losses

➢ From 2.8 TeV, photoelectrons contribution

III Stable beam

Beam intensity decreases still due to proton losses

IV Proton-proton collision

Electrical signals and pressure decrease due to p-p collisions

I = I_{e-}

I = $I_{ion} + I_{SE}$

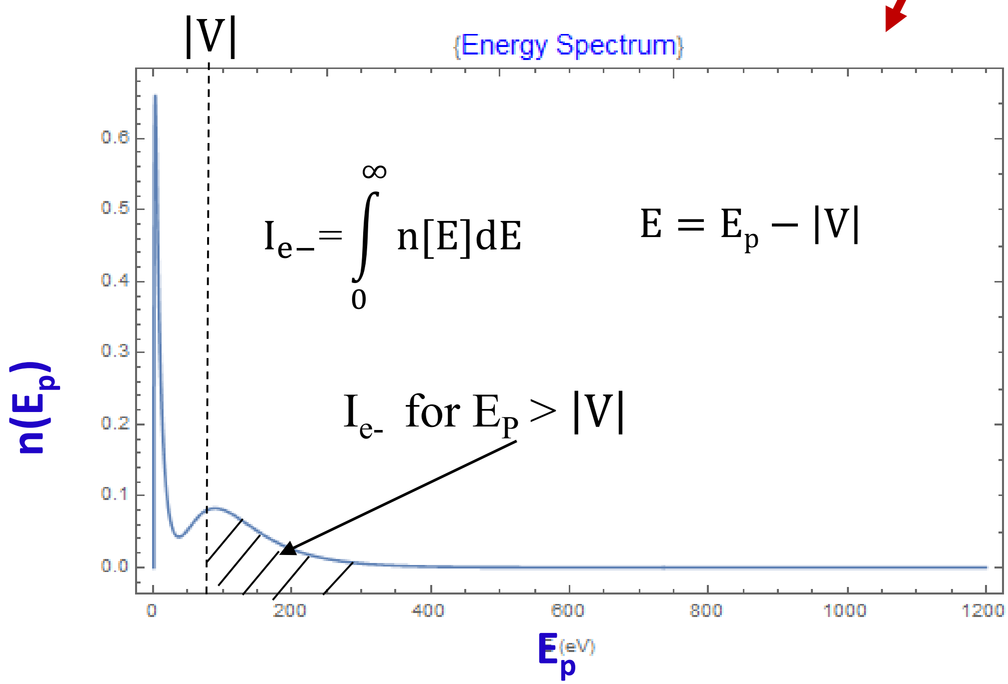
SIMULATION OF THE ELECTRON CONTRIBUTION when $V_{bias} < 0$

To discriminate the contribution of SE to ions → Calculation using experimental data of the e- energy spectrum and calculated Cu SEY

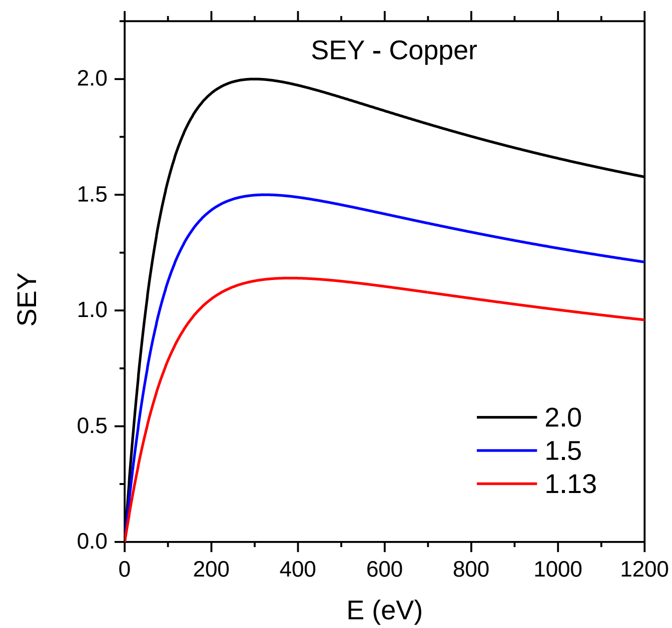
$$I_+ (E, V_{bias}) = I_{e-} + I_{SE} = I_{e-} [1 - SEY]$$

Depends on e- energy spectrum

Depends on SEY=f(E_{e-})

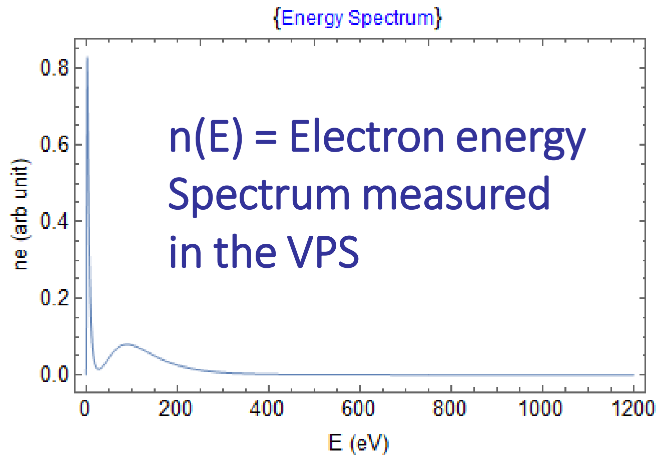


Experimental Data from Elena Buratin, 2015, CERN

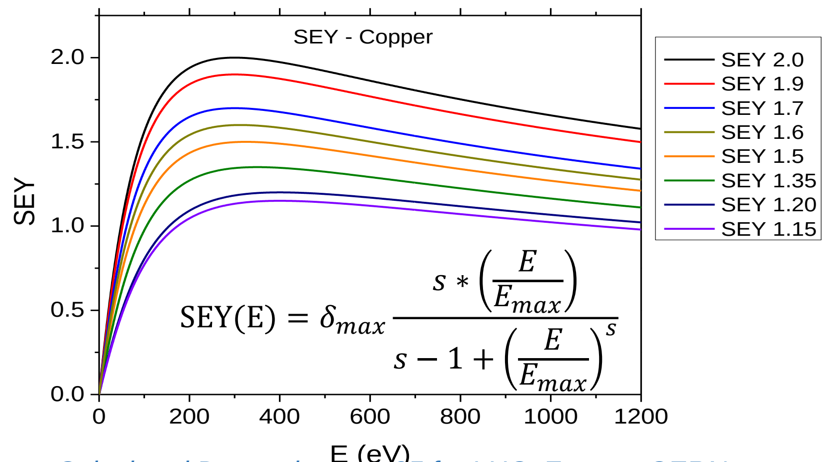


Calculated Data using s=1.35 for LHC Forman CERN

SIMULATION OF THE ELECTRON CONTRIBUTION when $V_{bias} < 0$

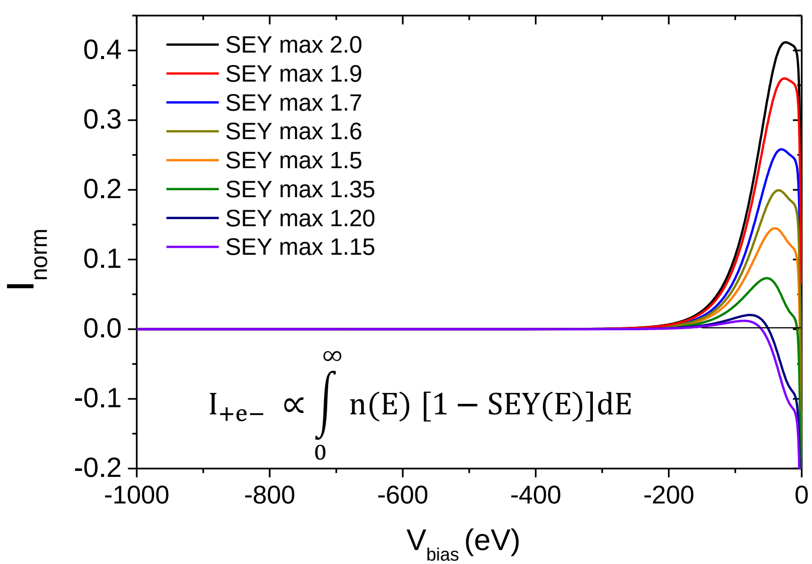


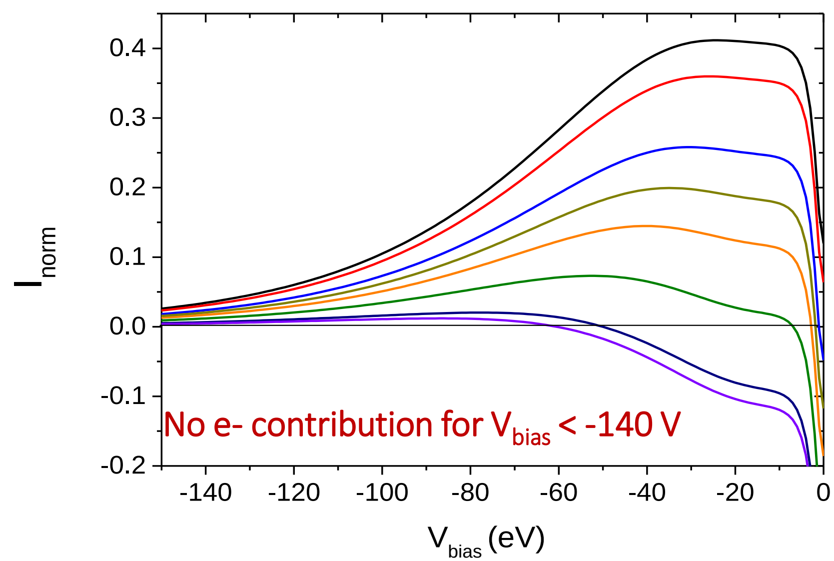
Experimental Data from Elena Buratin, 2015, CERN



Calculated Data using s=1.35 for LHC Forman CERN

We obtain the e^- contribution to I_+ as a function of V_{bias} calculated for several SEY

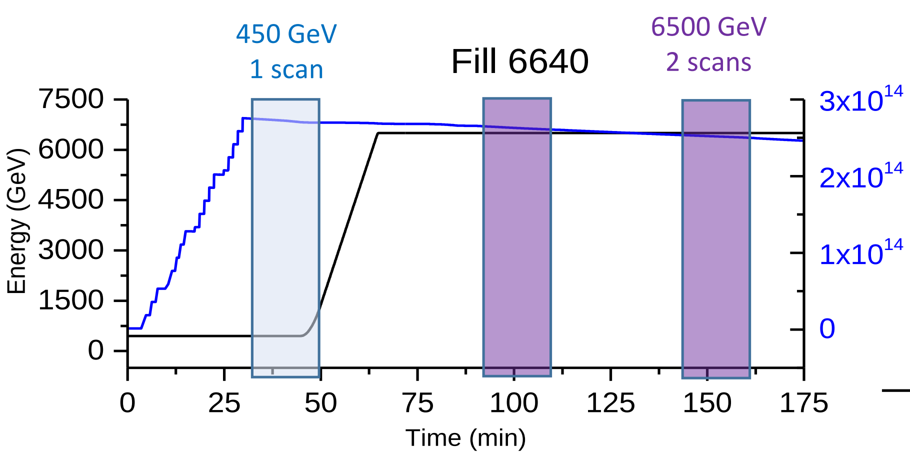




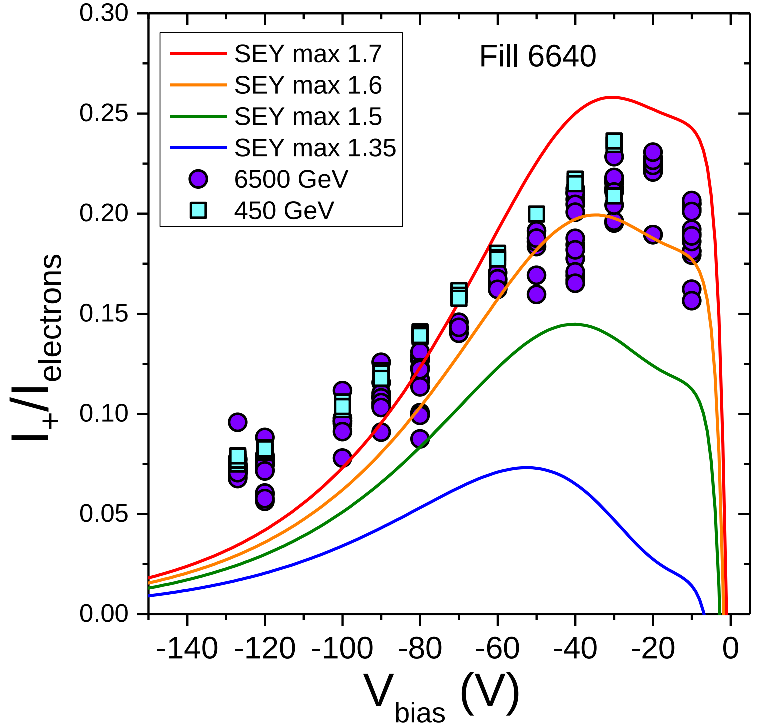
RUN II MEASUREMENTS *vs* SIMULATIONS

Measurements performed during a fill for physics of the LHC Run II, scanning the bias applied to the electrode.

LHC RUN II *in situ* measurements
Vacuum Pilot Sector
Station 4 - blue beam line



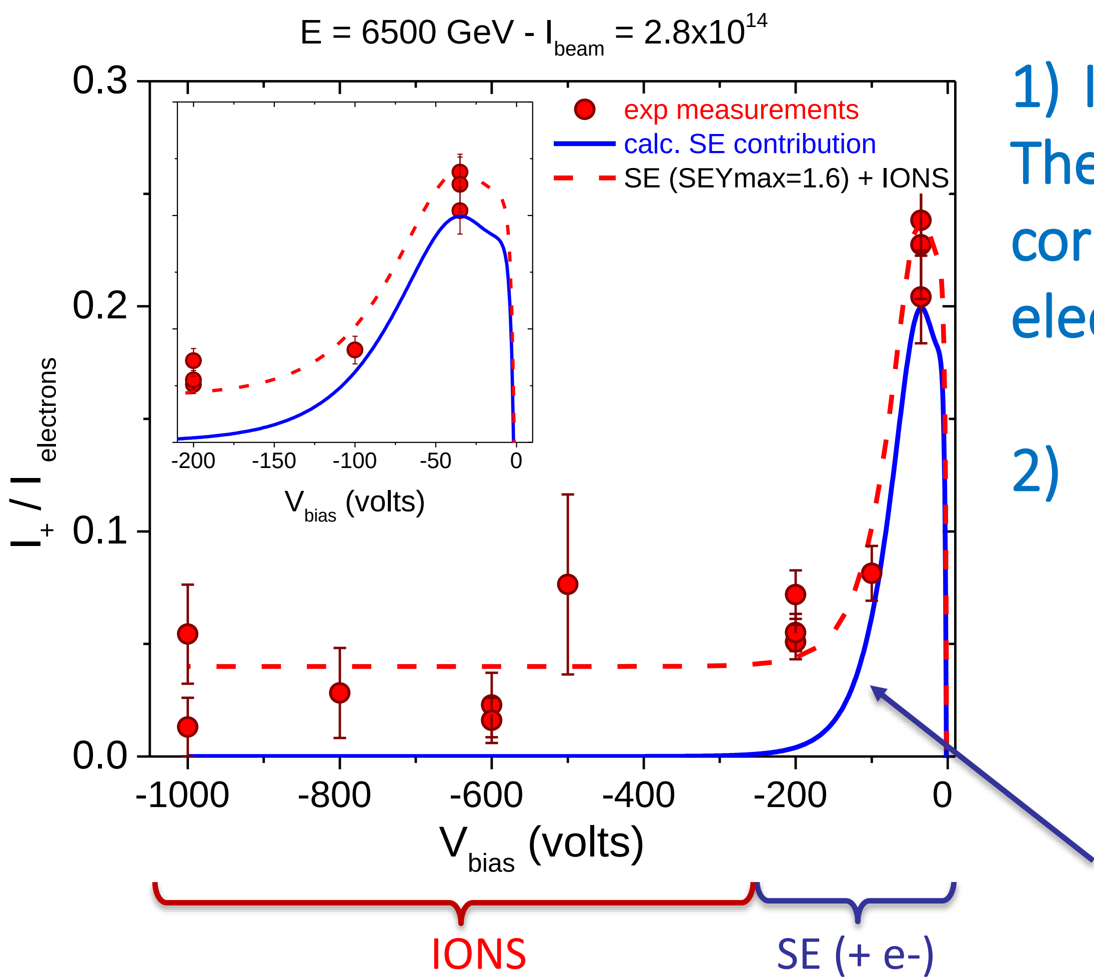
Measurement from VPS
normalized to total electron current



Contribution of SE predominates for the lowest values of $|V|$
But disagreement occurs for the highest $|V|$

Ions or not ions?

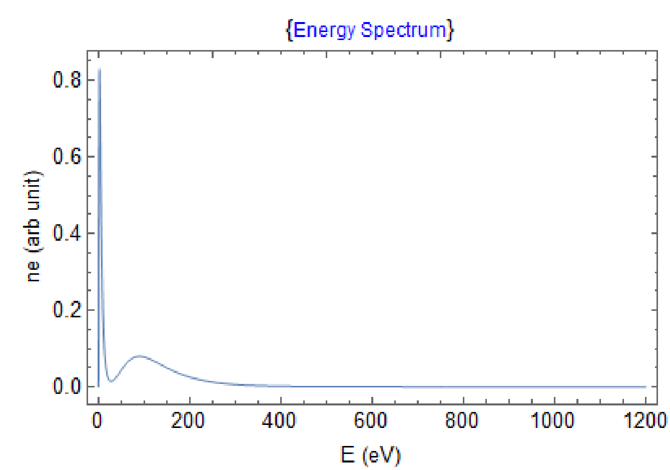
Measurements performed during several Fills using different electrode polarizations from -35 to -1000 V



1) IONS ARE DETECTED !

The positive ion current could correspond to 4% of the electron current.

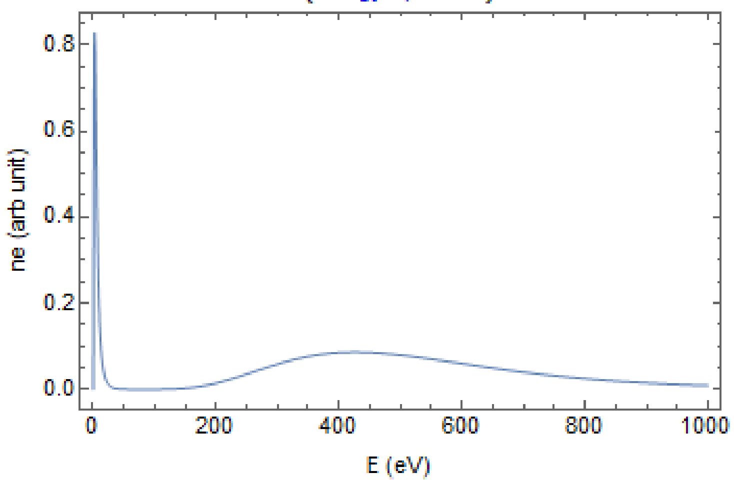
2) SEY was estimated to be around 1.6.



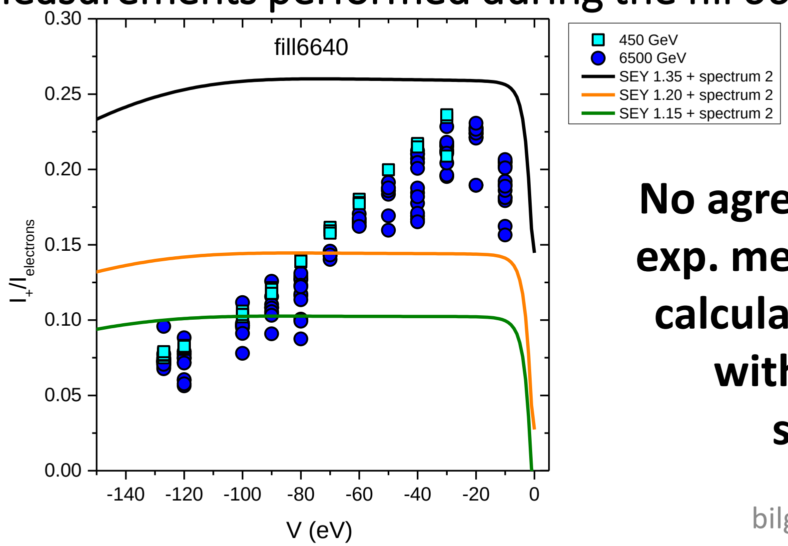
bilgen@lal.in2p3.fr

Ions or not ions?

Influence of electron energy spectra

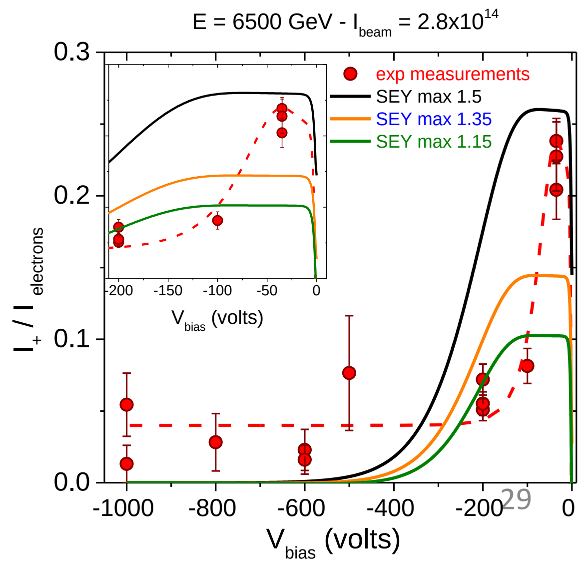


Measurements performed during the fill 6640



No agreement between exp. measurements and calculation performed with this energy spectrum!

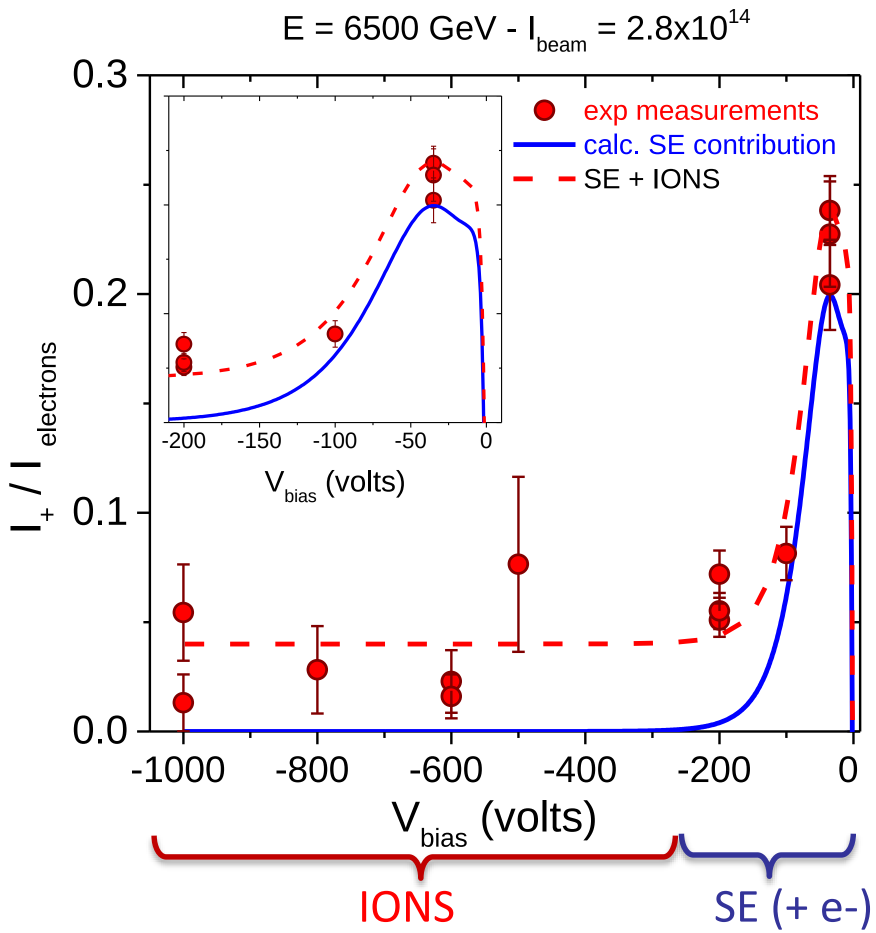
Measurements performed during several fills



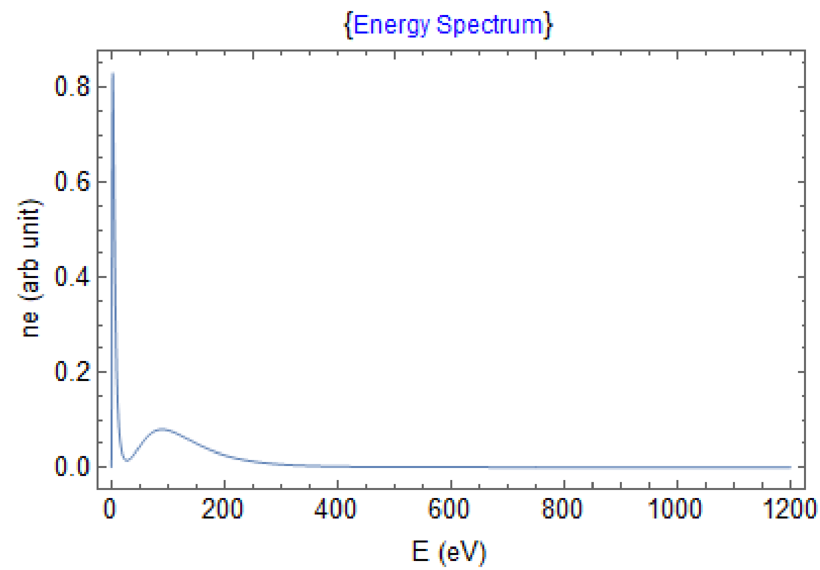
bilgen@lal.in2p3.fr

Ions or not ions?

Measurements performed on several Fills using different electrode polarization from -35 to -1000 V



3) Our measurements validate the electron energy spectrum recorded in the VPS



Can we predict the dynamic pressure in the FCC-hh?

DYVACS Code
Calculation of the dynamic pressure

DYVACS code

DYnamic VACuum Simulation code

Analytical model of the dynamic pressure based on VASCO code (CERN)

n=1D gas density

Residual gas ionization: **by p beam** / **by EC**

thermal desorption

$$C\frac{\partial^2 n}{\partial x^2} + \eta_i\left(\sigma_{i-p}\cdot\frac{I_{beam}}{e} + \sigma_{i-e}\cdot\Gamma_e\cdot L\right)\cdot n + \eta_e\Gamma_e + \eta_{ph}\Gamma_{ph} + a\cdot q_{th,} - S\cdot n = 0$$

Molecular Diffusion

Ionic Desorption

Multi-gas model [1]

For the gas j=H_2, CO_2, CO, CH_4)

Electronic Desorption (e^- Cloud)

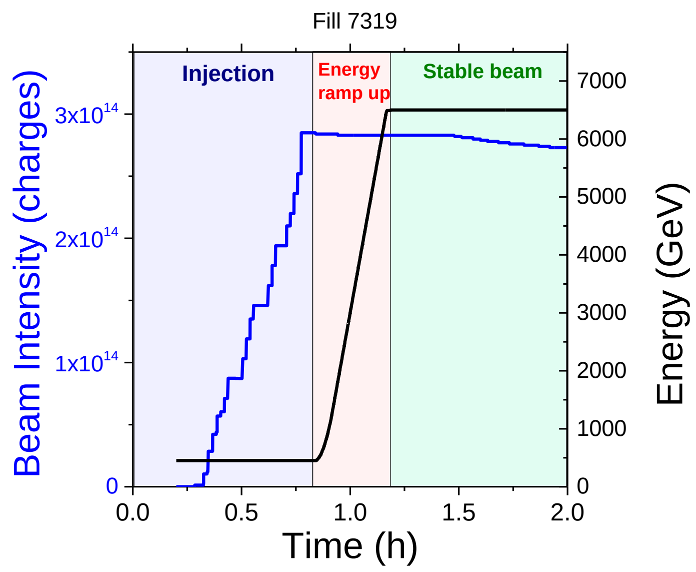
Photon Desorption

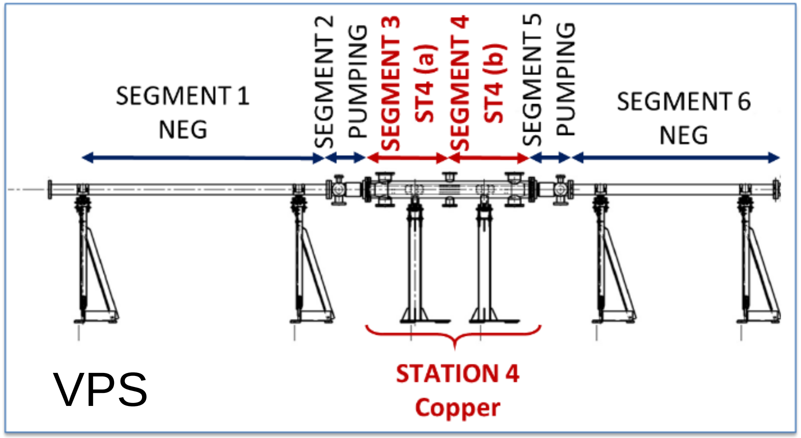
Pumping Flux

$$\Gamma_{ph} = 7.017\times10^{13}\frac{E}{r}I_{beam}$$ **(ph/m/s)**

DYVACS: first results for LHC configuration

Calculation of the dynamic pressure in LHC →DYVACS, first results





Station 4 = Cu @RT

1) **Electron cloud build up**:
   a) Electron density maps

$$\rho_{n+1} = a\rho_n + b\,\rho^2_n + c\,\rho^3_n$$

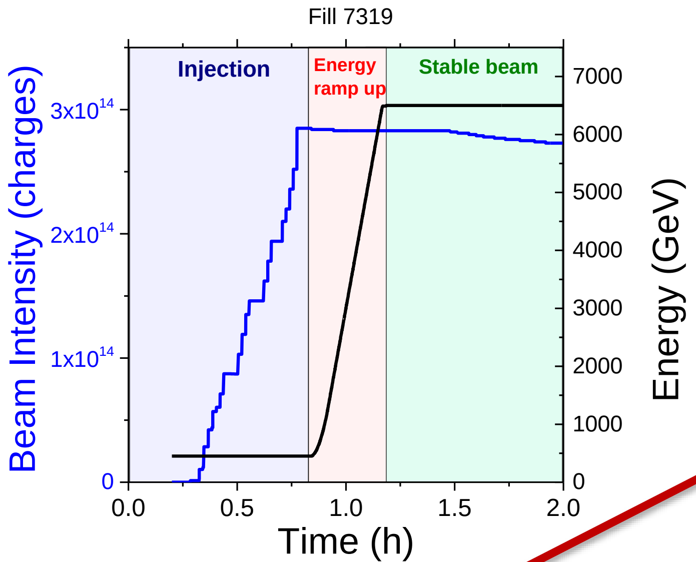
T. Demma *et al.* Model

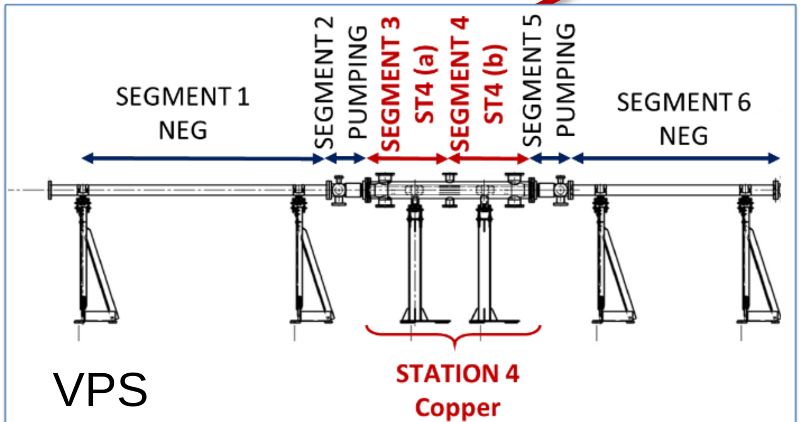
   b) the beam filling pattern

2) **Ionization of the residual gas by this Electron cloud**

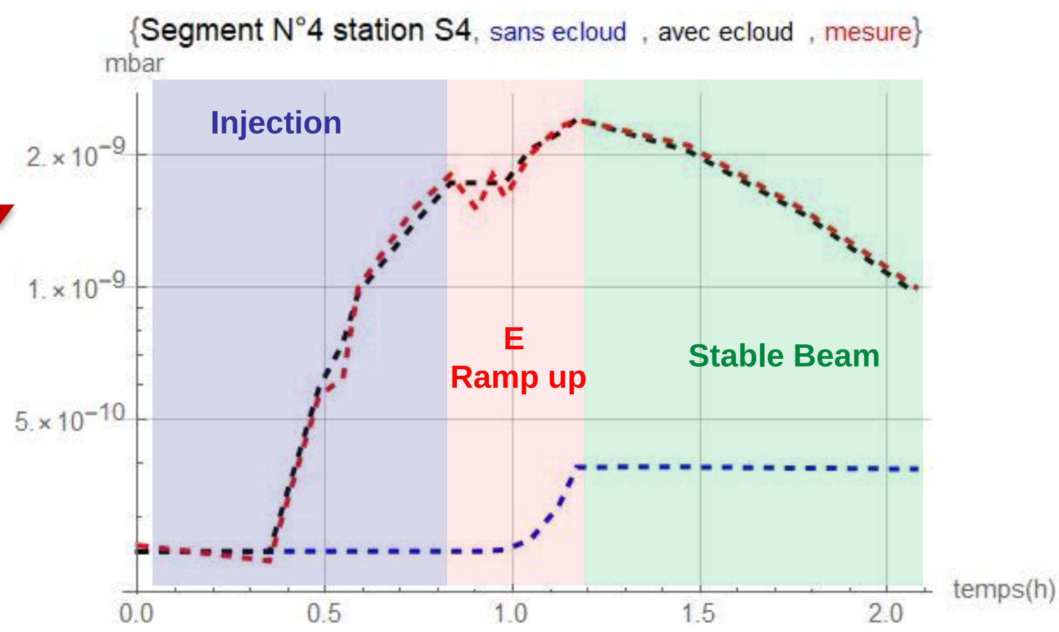
ON GOING WORK…

Calculation of the dynamic pressure in LHC →DYVACS, first results





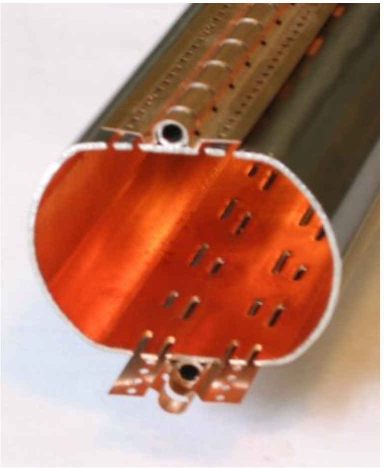
Station 4 = Cu @RT



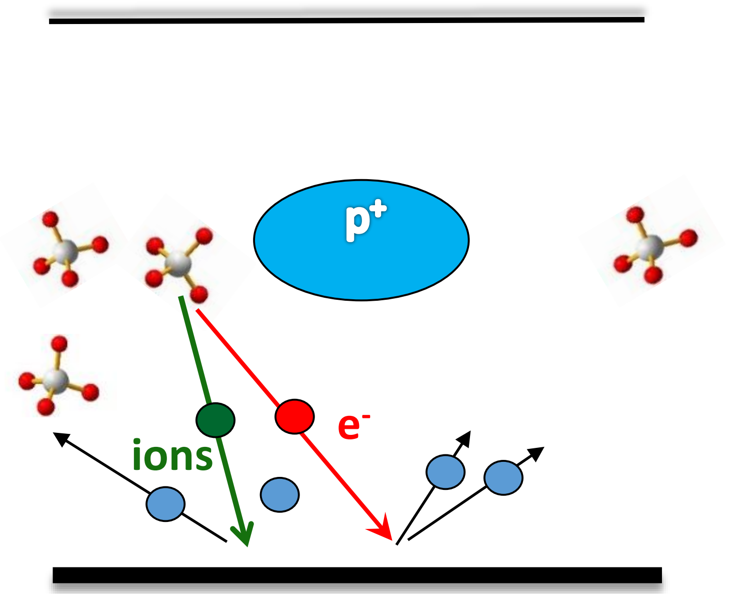
ON GOING WORK…

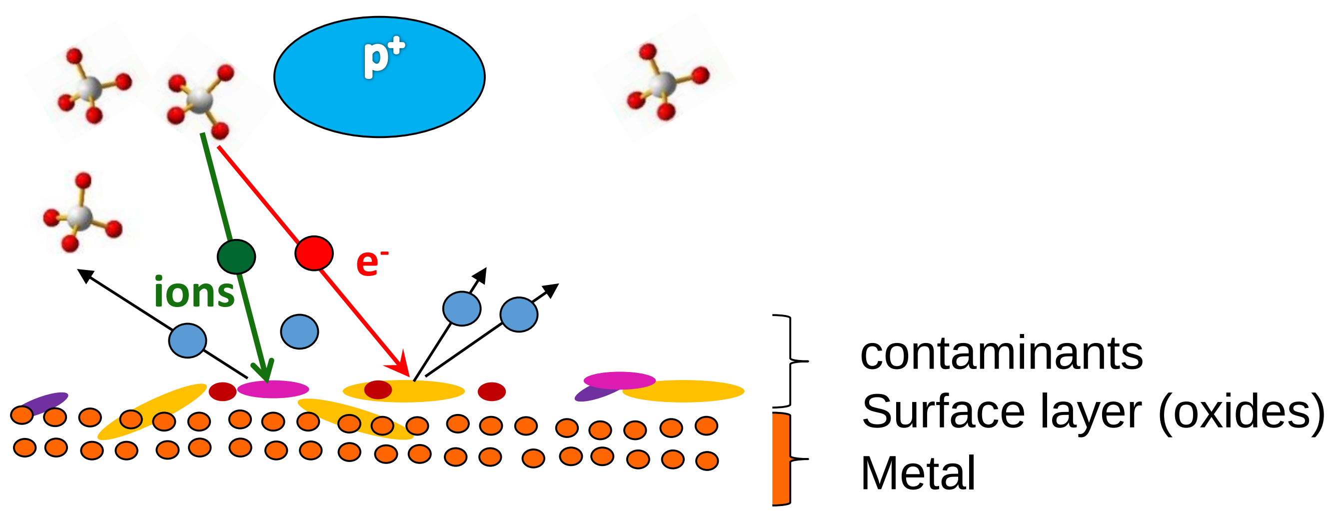
How to better understand the surface phenomena for the FCC-hh?

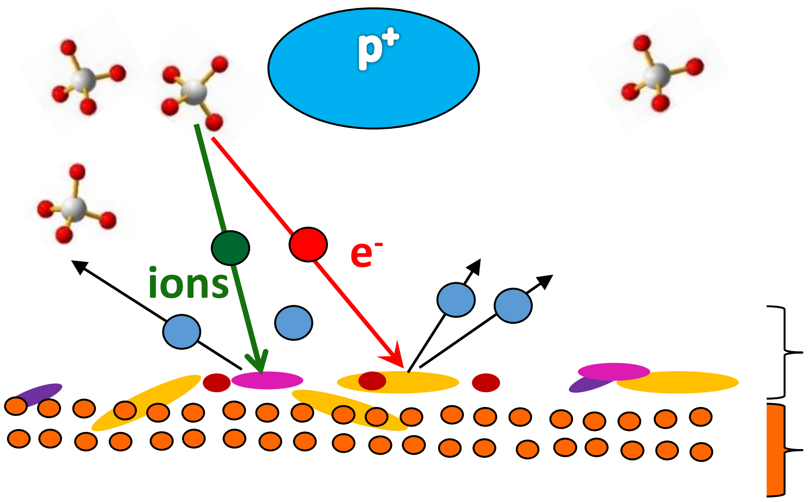
LHC beam screen surface analysis



LHC BEAM SCREEN SURFACE ANALYSIS

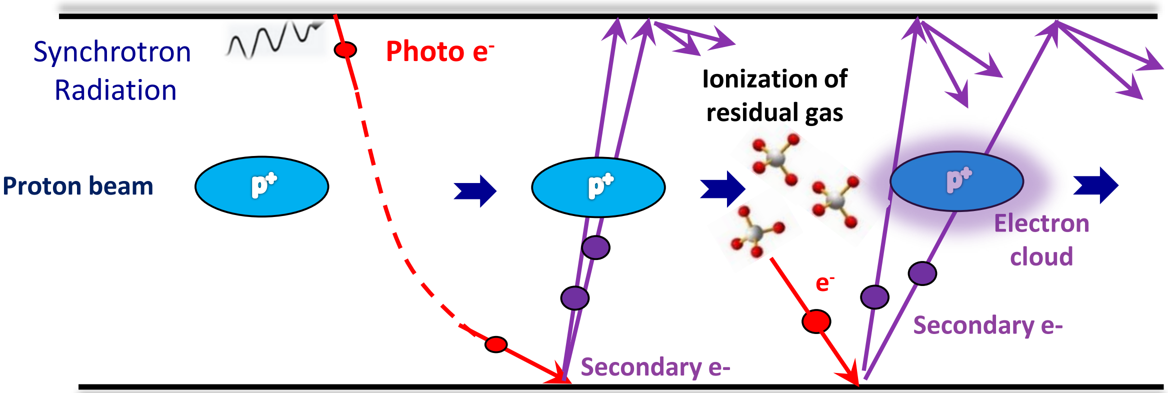



p+
ions
e-
contaminants
Surface layer (oxides)
Metal

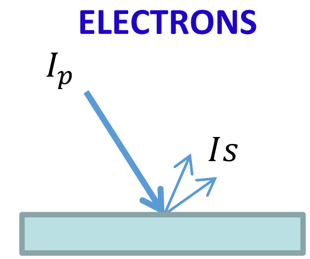


It is necessary to analyze surfaces to understand desorption and conditioning mechanisms.

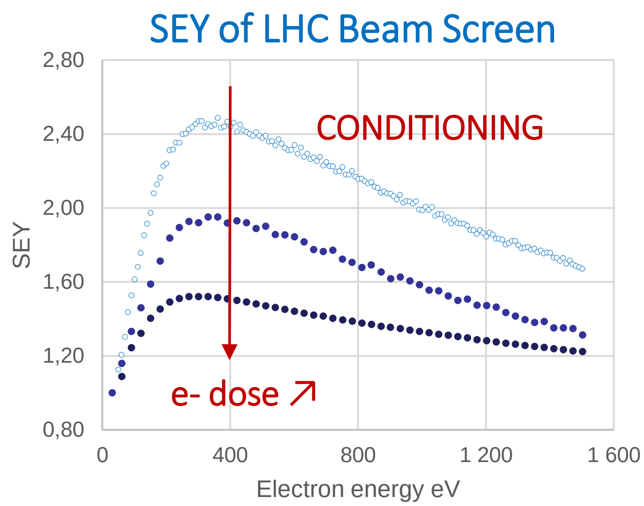
BEAM PIPE CONDITIONING



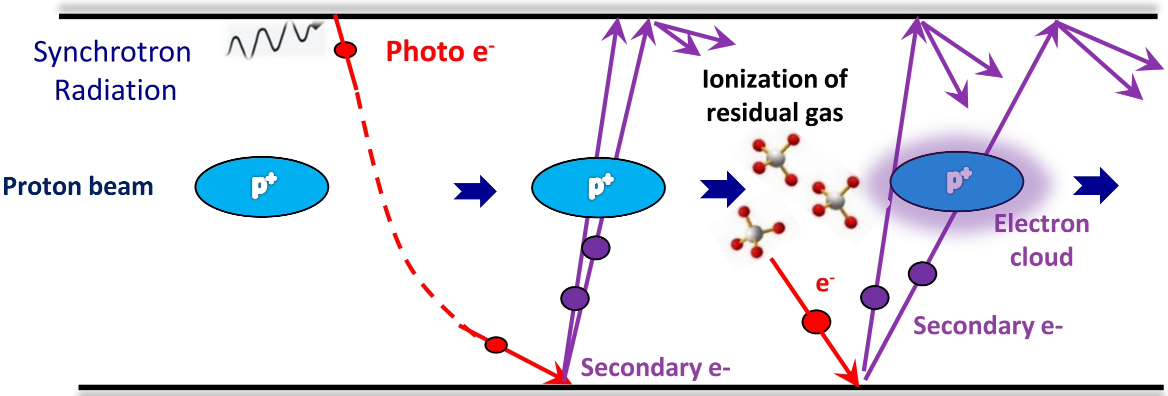
Before LHC operation, Scrubbing Run:
Producing a proton-beam promoting the EC formation, in order to increase the electron dose on beam screen surfaces.



$$\text{SEY} = \frac{I_s}{I_p}$$



BEAM PIPE CONDITIONING

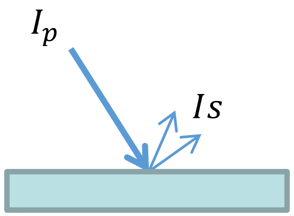


Before LHC operation, Scrubbing Run:

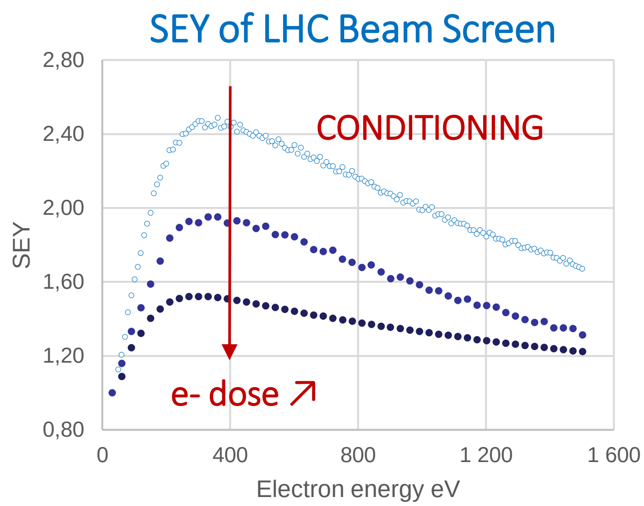
Producing a proton-beam promoting the EC formation, in order to increase the electron dose on beam screen surfaces.

→ Scrubbing run is performed for beam pipe wall conditioning to reduce the EC formation.

ELECTRONS

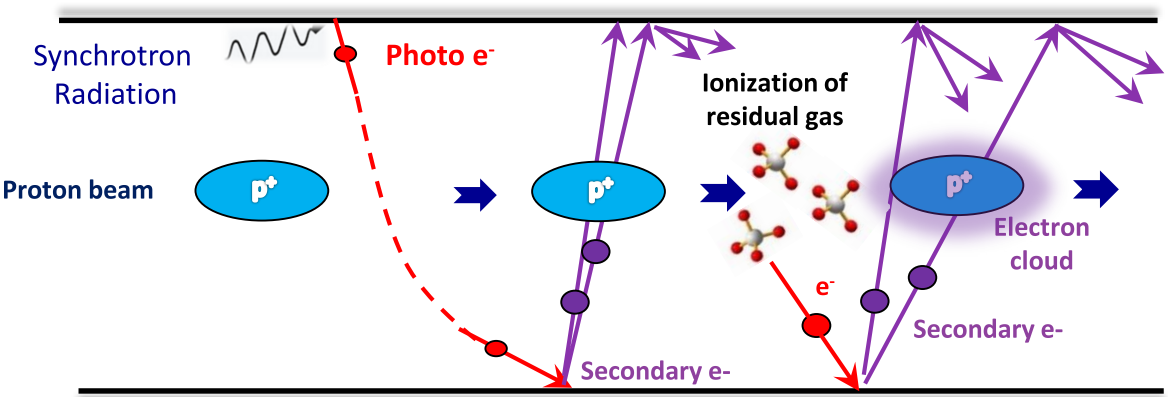


$$\textbf{SEY} = \frac{I_s}{I_p}$$



bilgen@lal.in2p3.fr

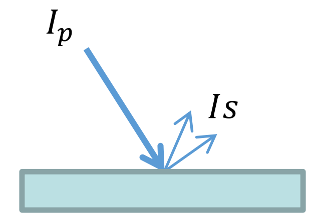
BEAM PIPE CONDITIONING



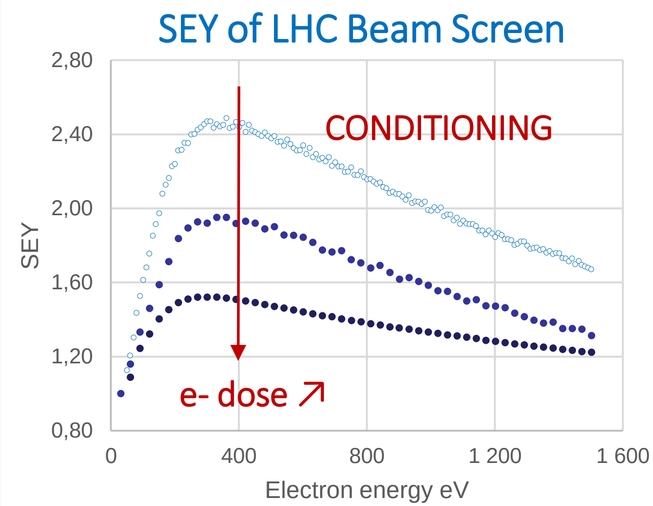
Before LHC operation, Scrubbing Run:
Producing a proton-beam promoting the EC formation, in order to increase the electron dose on beam screen surfaces.
→ Scrubbing run is performed for beam pipe wall conditioning to reduce the EC formation.

Conditioning effect? Surface analysis of LHC beam screen samples using the TOF-SIMS method

ELECTRONS



$$\mathrm{SEY} = \frac{I_s}{I_p}$$



ANDROMEDE FACILITY - ORSAY

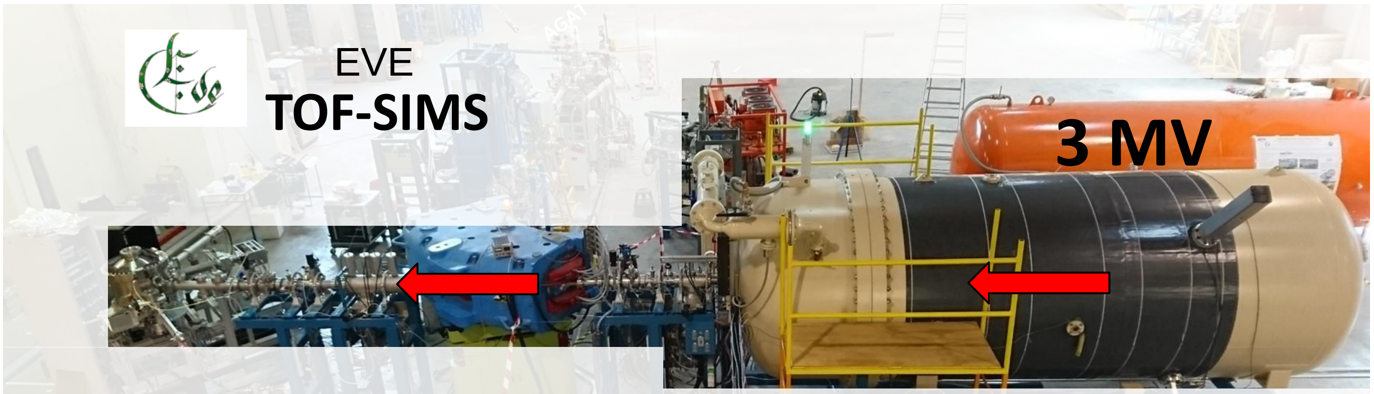
Collaboration with Serge Della Negra - IPNO

Conditioning effect?

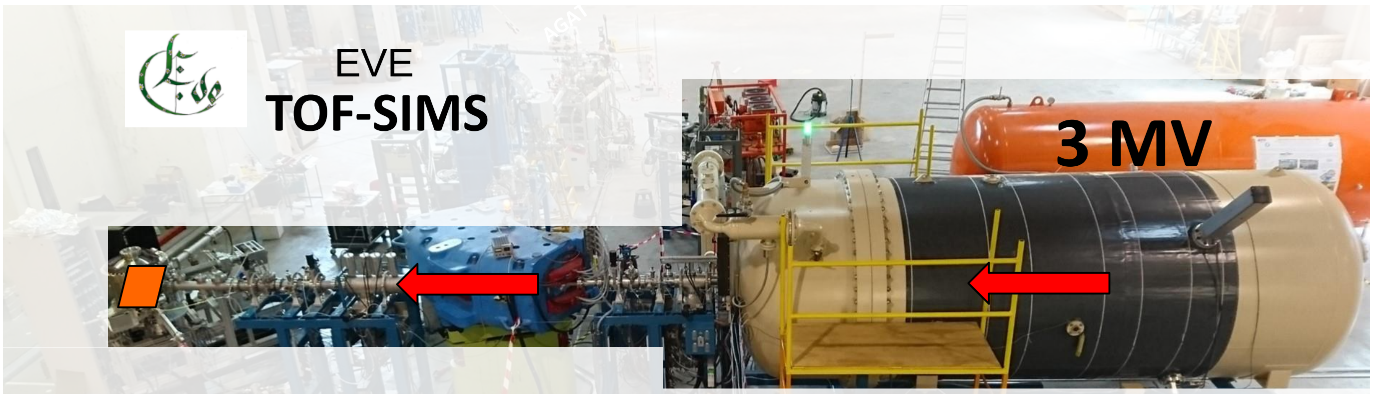
Surface analysis using ANDROMED TOF-SIMS

- Electrostatic Accelerator of 4 MV (Pelletron)
- Ion sources can deliver proton to nanoparticle beams
- Surface analysis using a Time of flight mass spectrometer

https://andromede.in2p3.fr/



12MeV – Au_{400}^{4+} nanoparticle beam



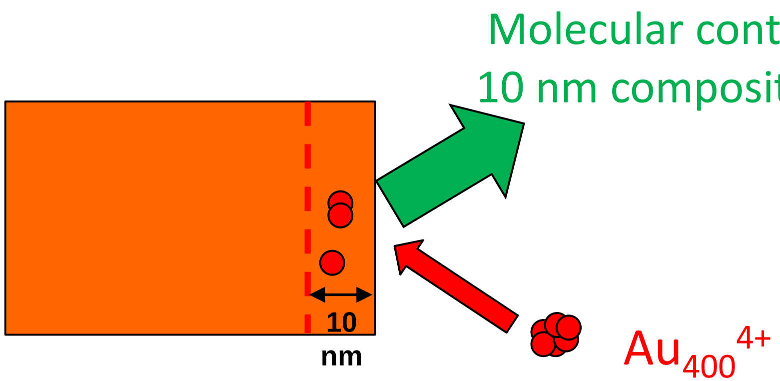
CERN Beam screen

12MeV – Au_{400}^{4+} nanoparticle beam

5 mm

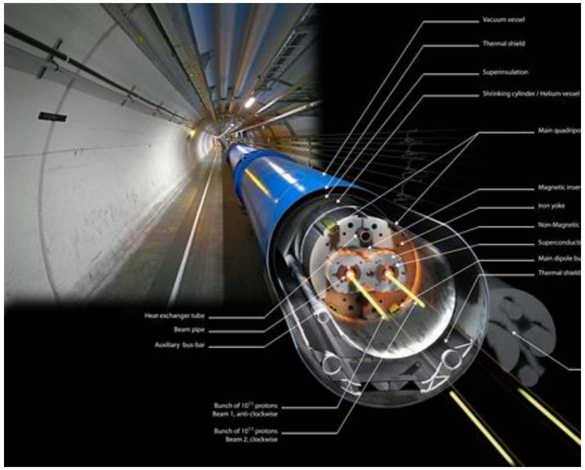
LHC Beam screen

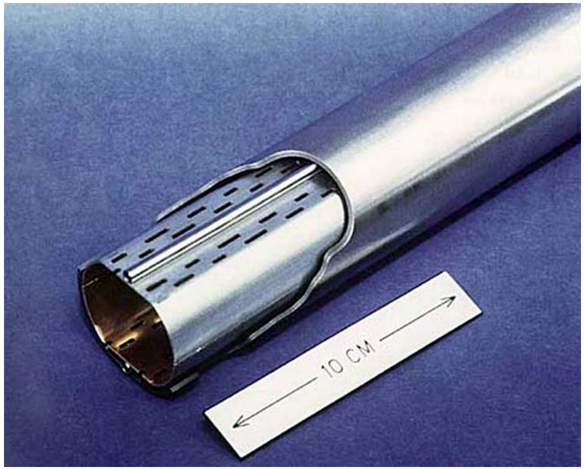
12MeV – Au_{400}^{4+} nanoparticle beam

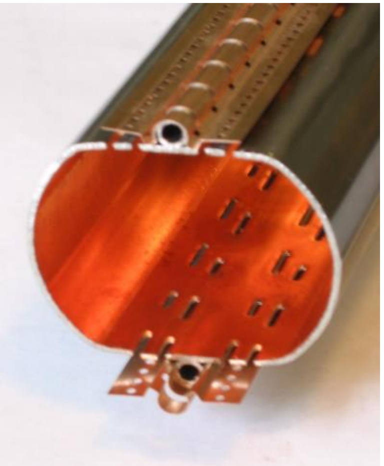


- This probe is sensitive to molecules deposited on the surface.
- Gives the composition of the first 10-20 nm of the solid surface.

LHC BEAM SCREEN





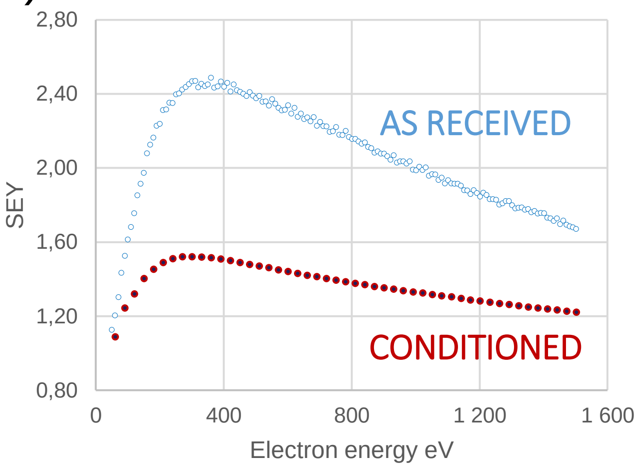


Sample comparisons

1) Cleaning process A *vs* B

	A	B
Detergent	NGL 17.40 P. SP	Simple green
baking	no	no

2) As received *vs* conditioned



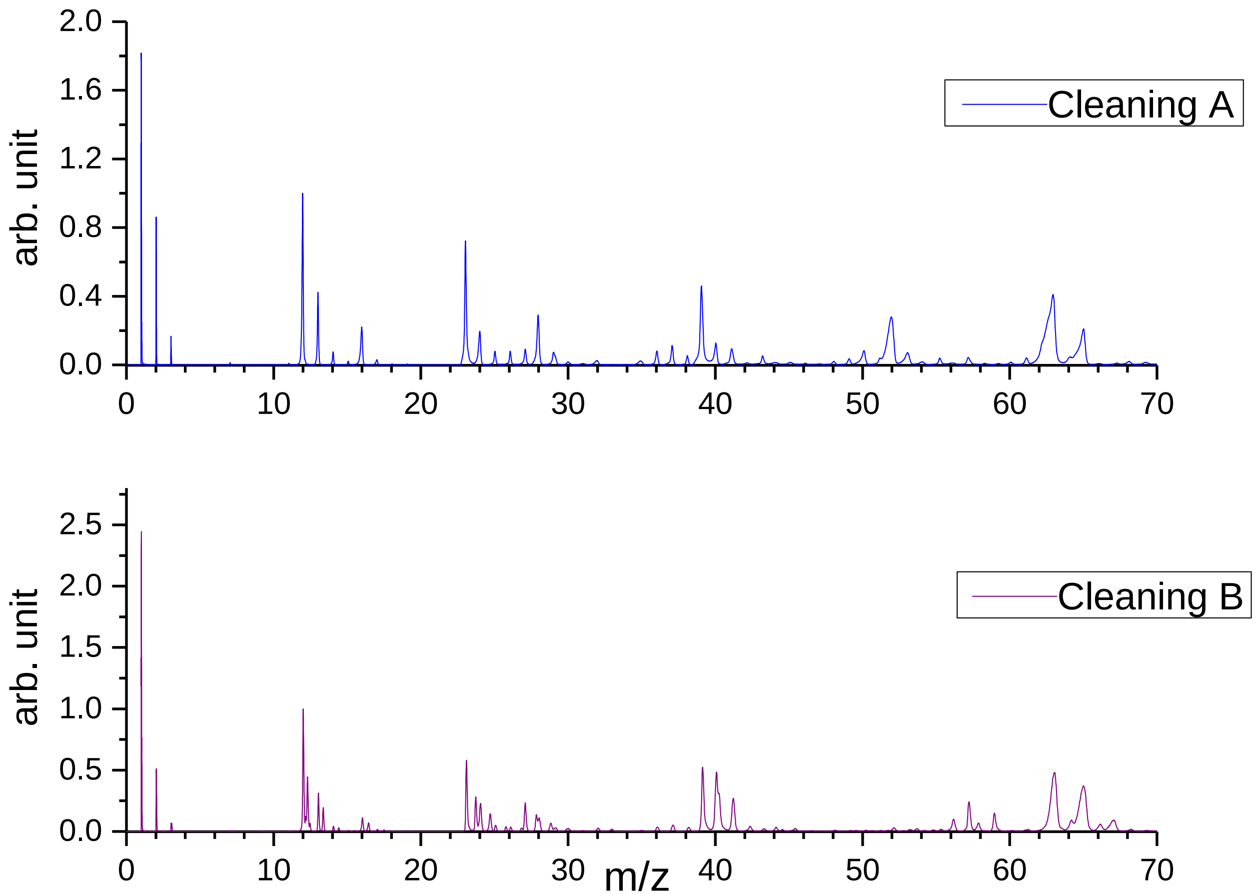
Remember that we study technical surfaces, so the cleaning procedure should be done for 7 m long beam pipes!

Spectra Analyses

Cleaning process

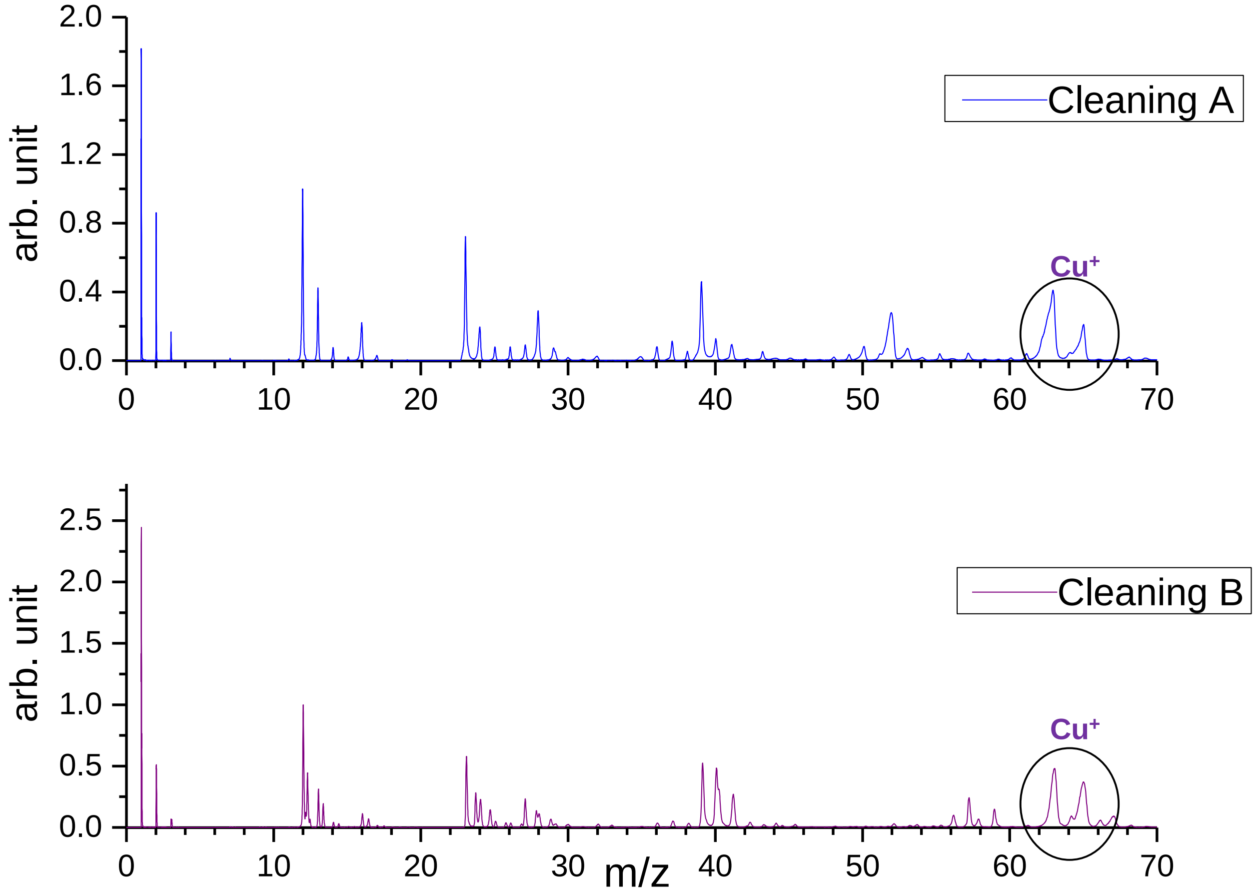
ANDROMEDE TOF-SIMS MEASUREMENTS

LHC beam screen: Cleaning process A *vs* B



Amount of secondary ions emitted from the sample surface due to nanoparticles impact, as a function of m/z.

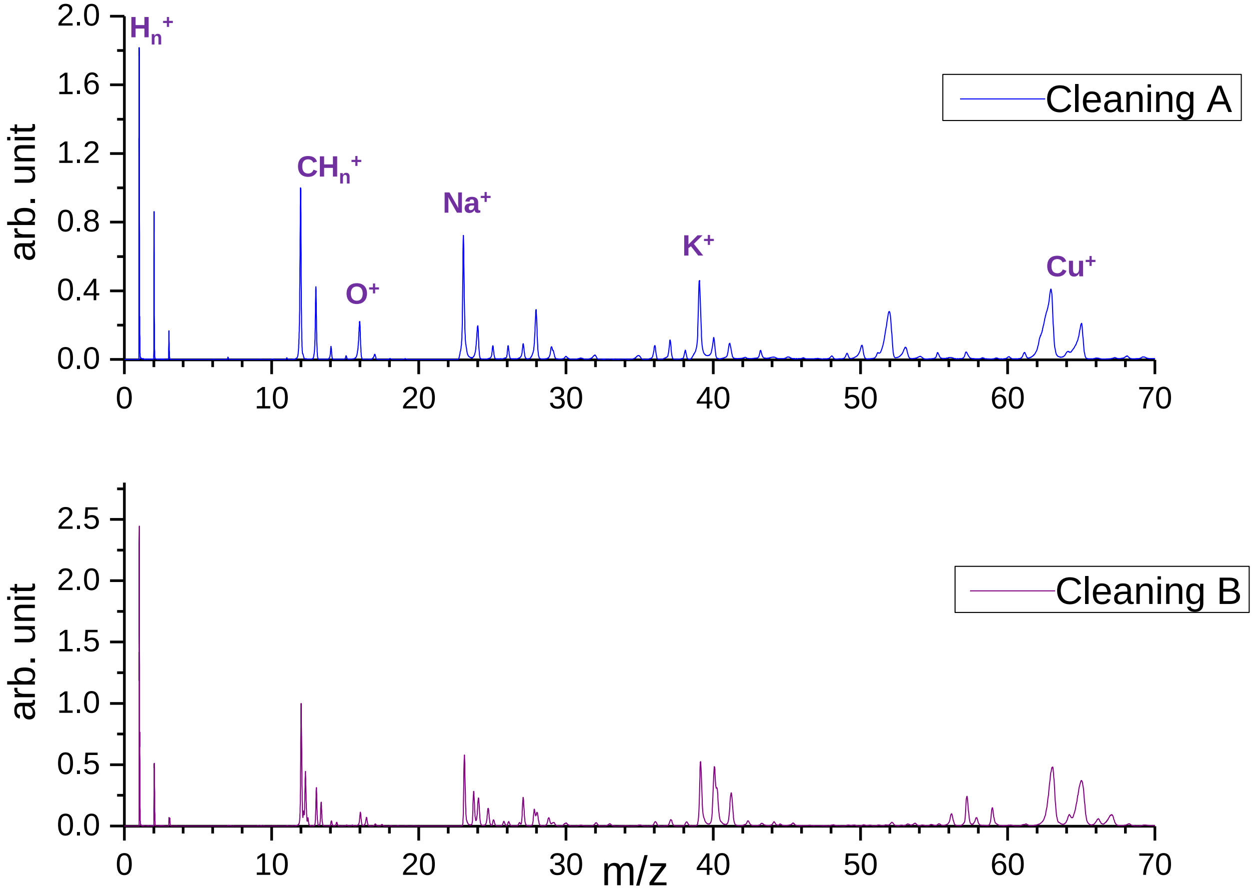
LHC beam screen: Cleaning process A *vs* B



Samples seem to be relatively clean, the Cu signal comes out in the analysis of the 10 first nm.

ANDROMEDE TOF-SIMS MEASUREMENTS

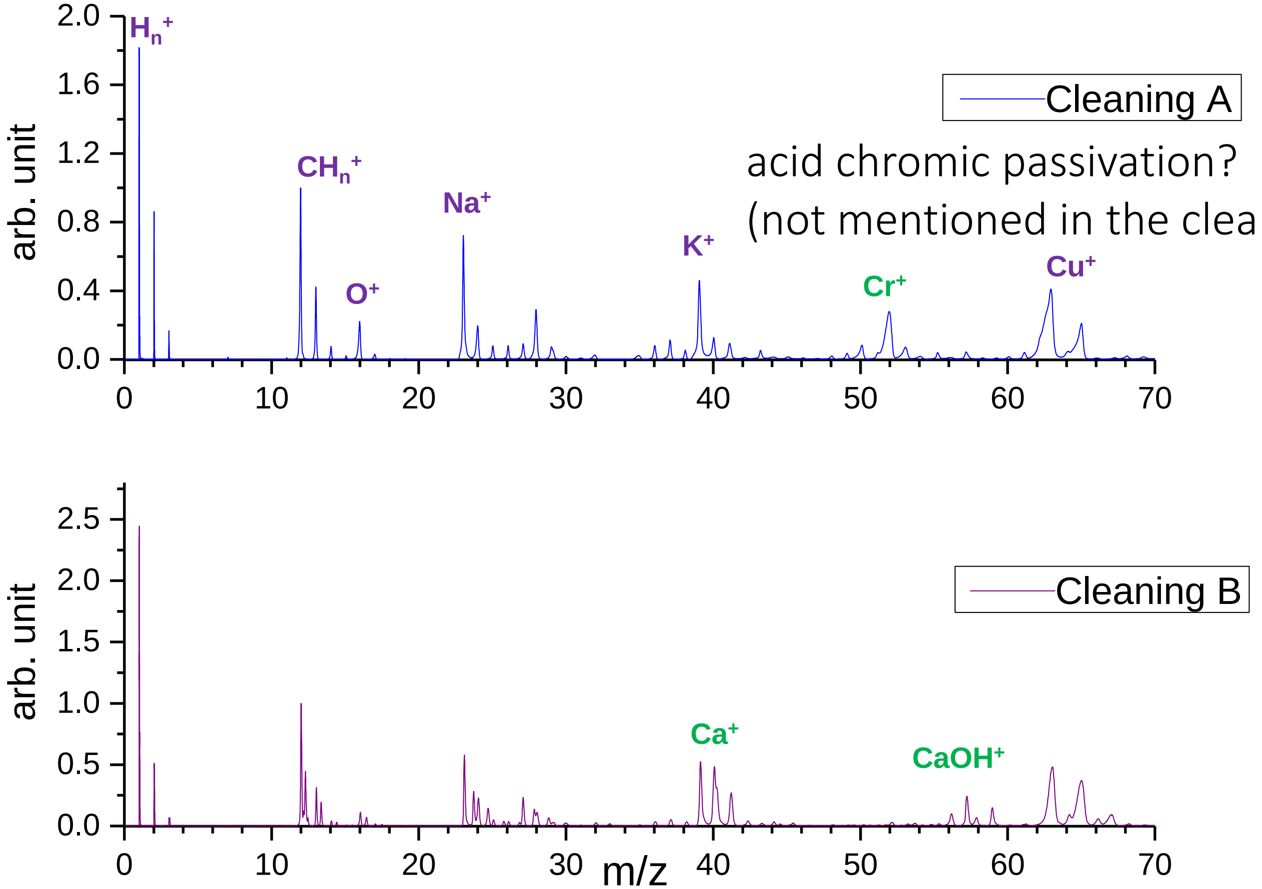
LHC beam screen: Cleaning process A *vs* B



Usual species present due to air exposure and also common elements from the detergent composition like potassium and sodium appear.

ANDROMEDE TOF-SIMS MEASUREMENTS

LHC beam screen: Cleaning process A *vs* B



acid chromic passivation?
(not mentioned in the cleaning process!)

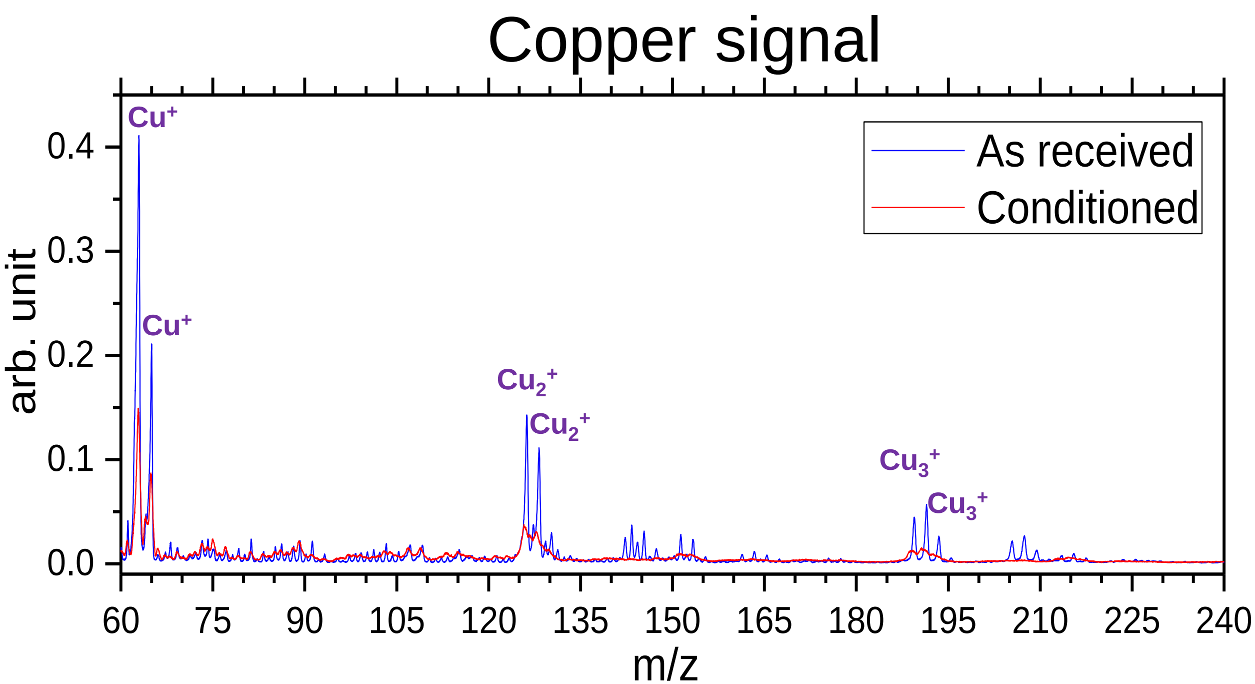
pollution : Ca contaminant

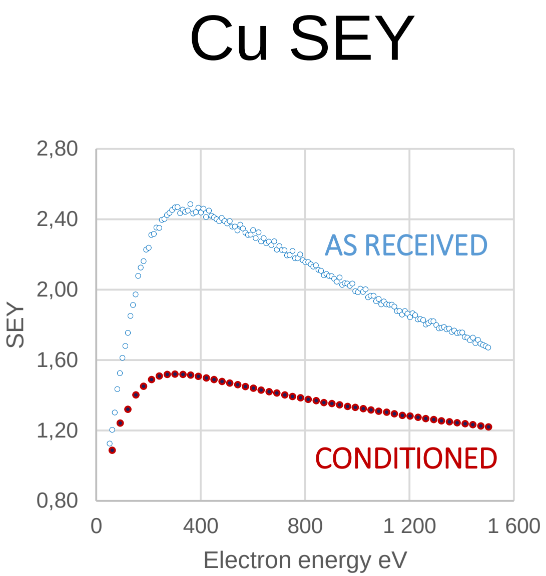
Using this reference, we carry out the study by comparing an as received to an e- conditioned sample.

Spectra Analyses

Conditioning effect

LHC beam screen: As received *vs* conditioned



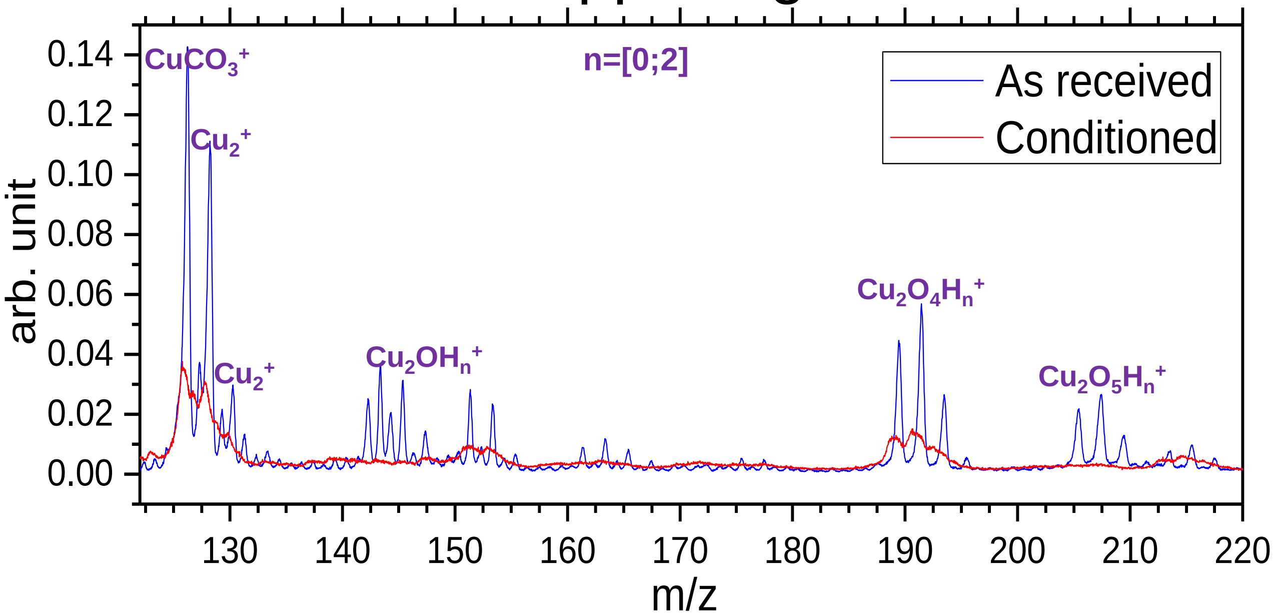


After an electron conditioning, the Cu signal decreases

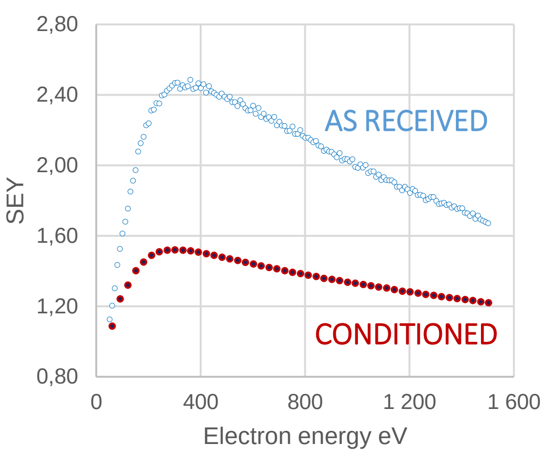
Amount of secondary ions emitted from the sample surface due to nanoparticles impact, as a function of m/z.

LHC beam screen: As received *vs* conditioned

Copper signal



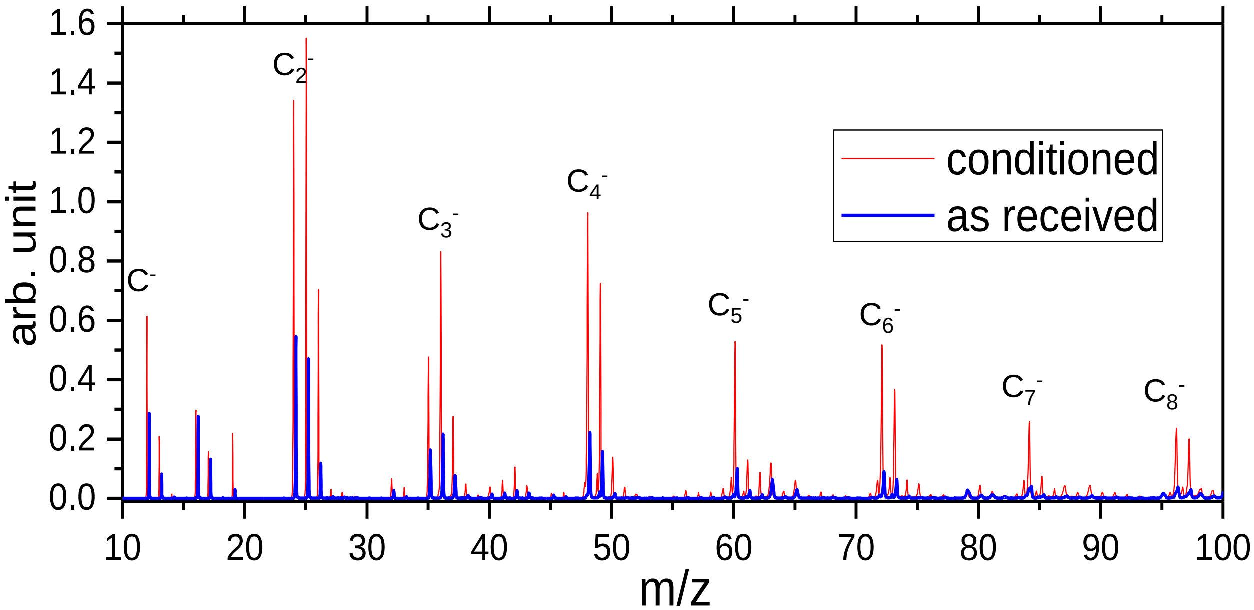
Cu SEY



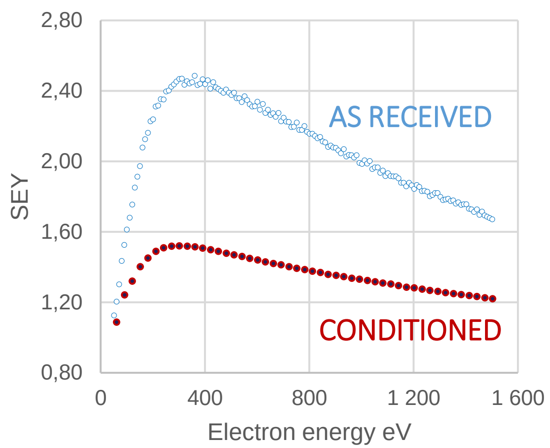
After an electron conditioning, the Cu oxide signal decreases

LHC beam screen: As received *vs* conditioned

C_n^- & $C_nH_m^-$

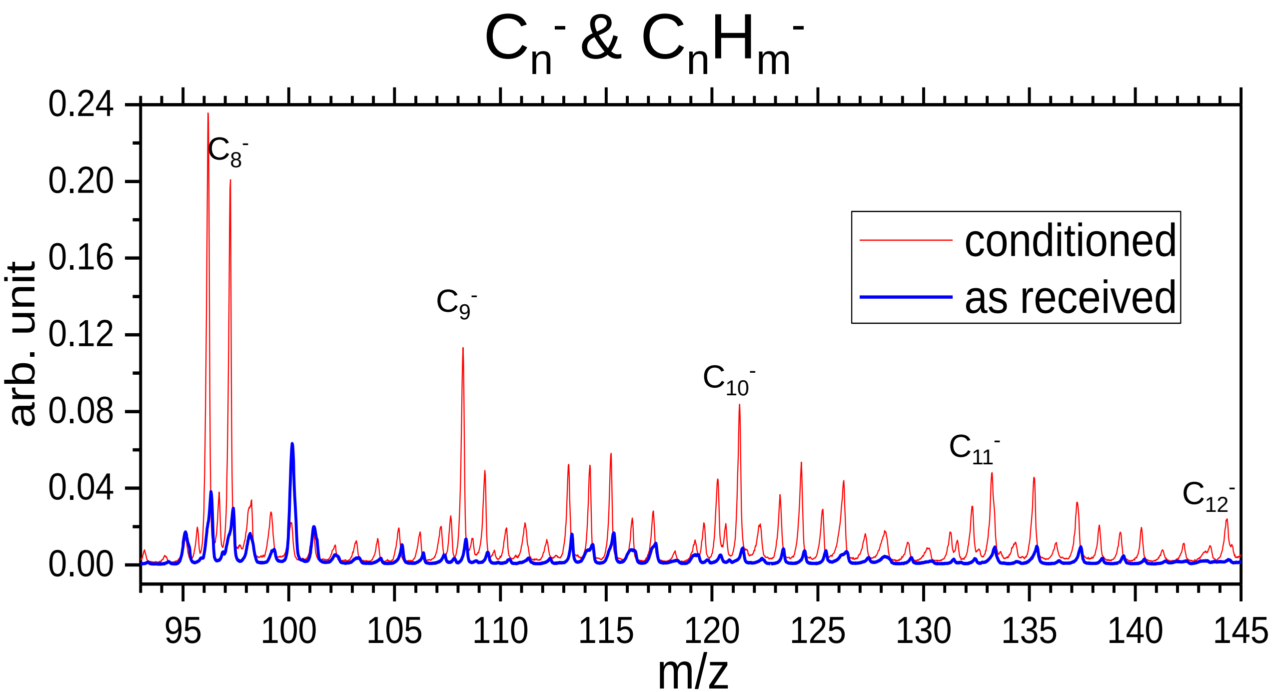


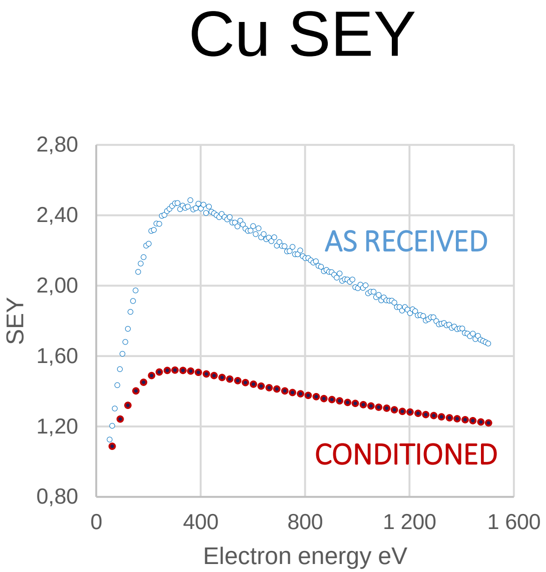
Cu SEY



A huge quantity of carbon and CH clusters is detected from the conditioned surface

LHC beam screen: As received *vs* conditioned

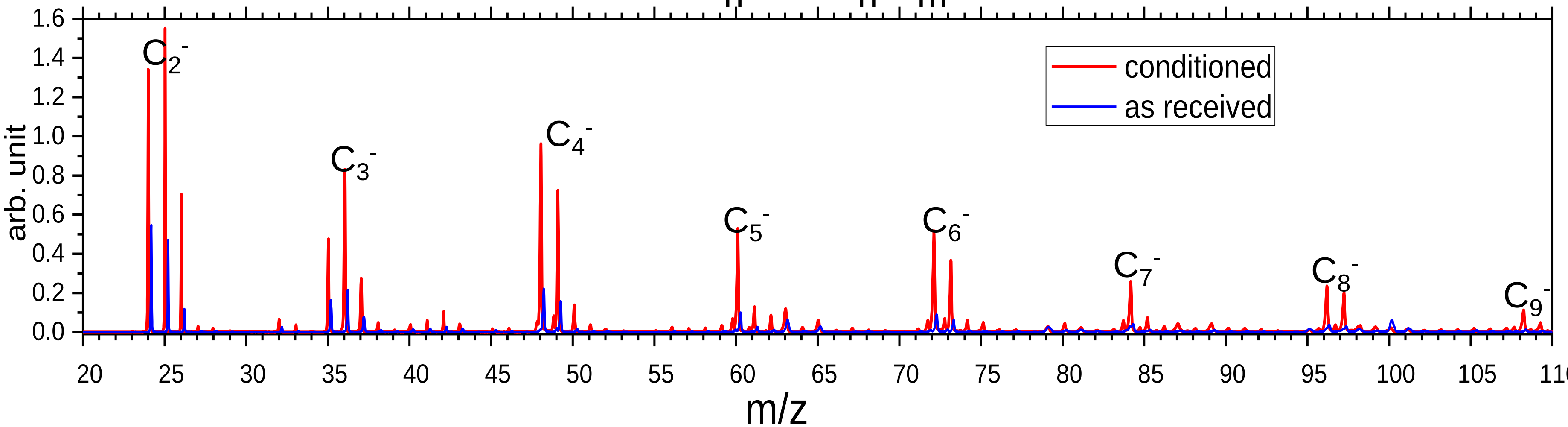


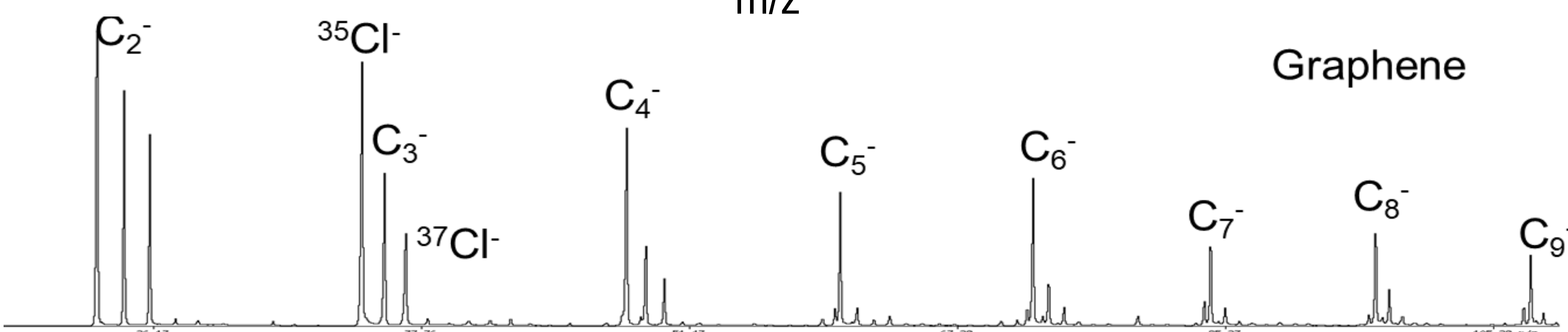


You can easily detected from C to C_{12} clusters

LHC beam screen: As received *vs* conditioned

C_n^- & $C_nH_m^-$

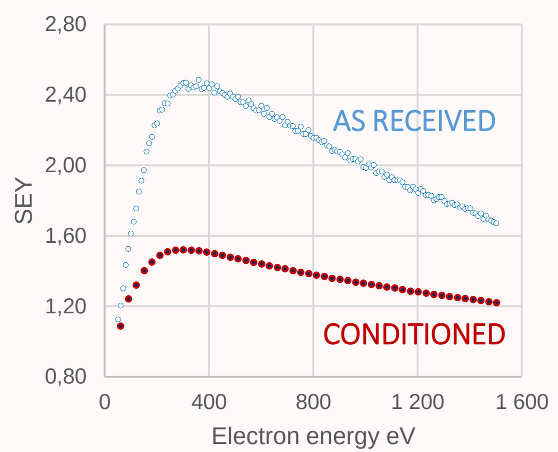




Conditioned sample spectrum looks like a Graphene spectrum recorded in the same conditions

LHC beam screen: As received *vs* conditioned

Cu SEY



After an electron conditioning

① " Something " covers the Cu surface
→ formation of a layer

② The copper oxide signal is modified

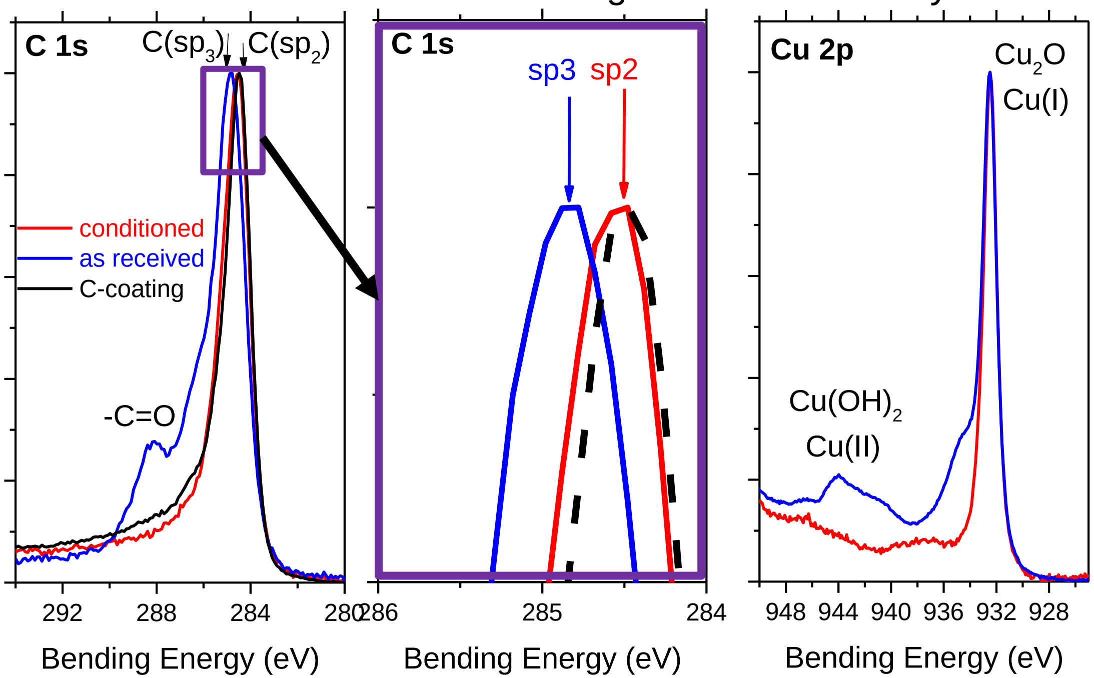
③ A huge quantity of carbon and CH is detected from the conditioned surface.

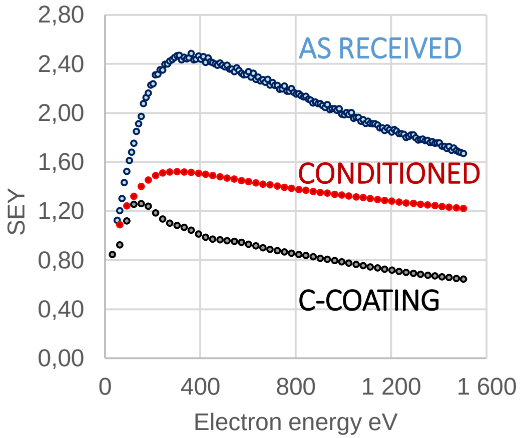
Conditioning = modification of surface contaminants due to an electron irradiation
Organic compounds are transformed into a C-graphite layer

XPS MEASUREMENTS

LHC beam screen: As received *vs* conditioned

Collaboration with Diana Dragoe – ICMMO/Orsay





C (sp3) to C (sp2)
Conditioned spectrum = C-coating spectrum

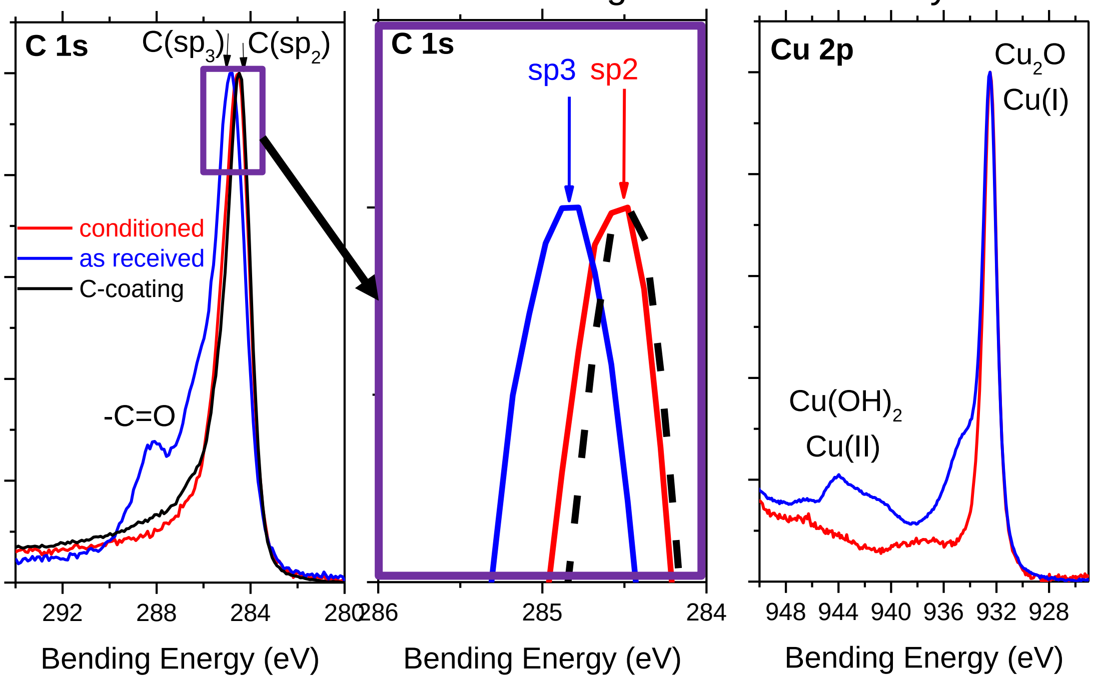
$Cu(OH)_2 \rightarrow Cu_2O$
Copper oxide reduction

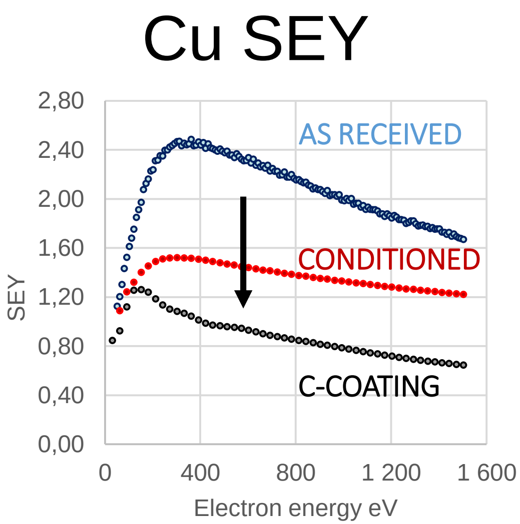
Performing XPS analysis : modification of both C hybridization and Cu oxide modification.
XPS Carbon peak of an e- conditioned surface brings closer to C-Coating one
In agreement with TOF-SIMS results : formation of a graphite-layer induced by e-irradiation

XPS MEASUREMENTS

LHC beam screen: As received *vs* conditioned

Collaboration with Diana Dragoe – ICMMO/Orsay





C (sp3) to C (sp2)

Conditioned spectrum = C-coating spectrum

$Cu(OH)_2 \rightarrow Cu_2O$

Copper oxide reduction

Performing XPS analysis : modification of both C hybridization and Cu oxide modification.

XPS Carbon peak of an e- conditioned surface brings closer to C-Coating one

In agreement with TOF-SIMS results : formation of a graphite-layer induced by e-irradiation

Summarize & Perspectives

SUMMARIZE

- ***In Situ* measurements in LHC** : a significant amount of positive ions have been detected in the VPS
  → What is the impact of these ions on the dynamic pressure in the LHC ?

- **DYVACS code** allows us to simulate the dynamic pressure by taking into account the EC build up and the filling pattern (and all desorption phenomena)
  → Predictive calculations for FCC-hh?

- **Surface analysis** of LHC beam screen : formation of a C-layer on the Cu surface after e-conditioning
  → Impact of contaminants on the surface evolution during operation?

PERSPECTIVES

- Lab. measurement :
  - Further investigations of **conditioning & stimulated desorption** (e- and ions) are necessary: changing many parameters (conditioning energy, current, nature of the surface, incident angle…)
  - **Investigations of new materials** for future accelerators are needed (C-coating, laser structured surface)

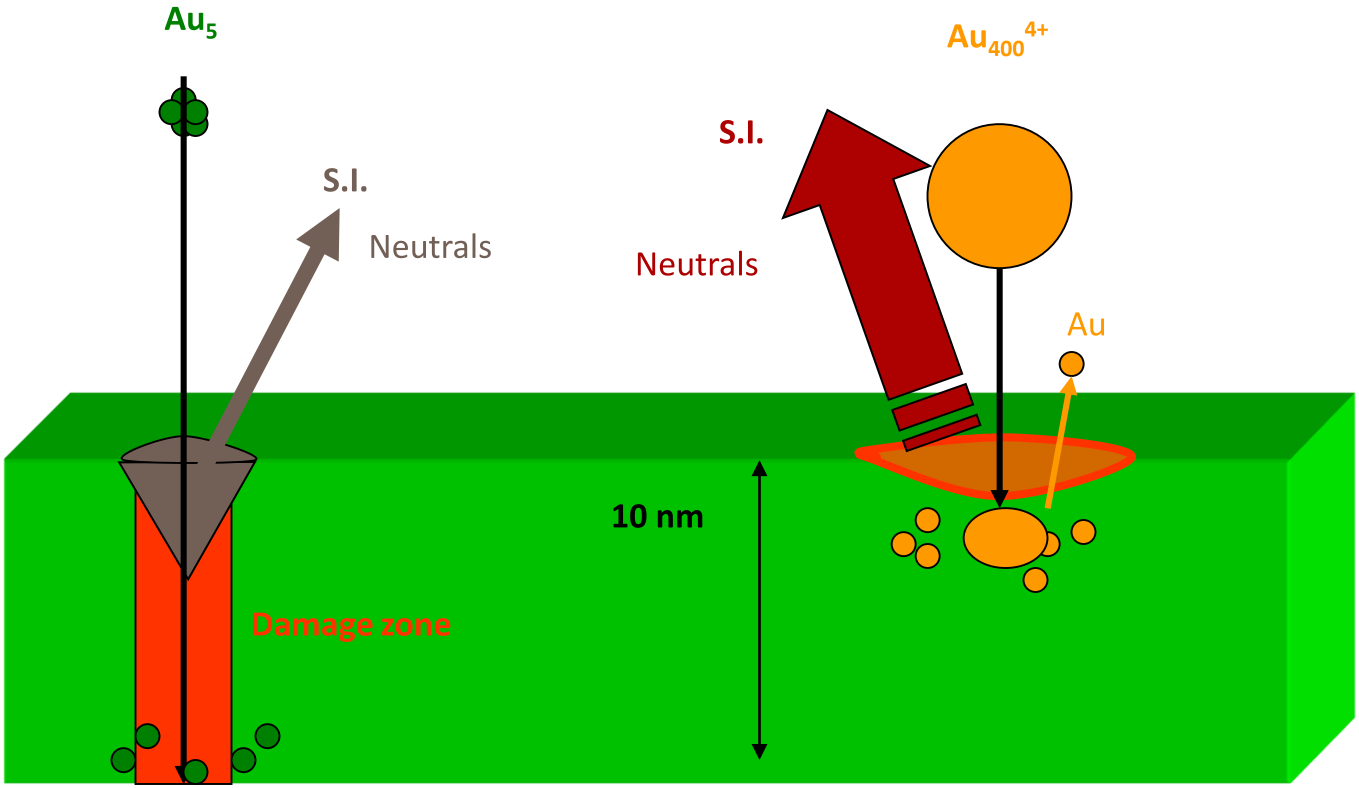
- New ***in situ* measurements in VPS** are necessary during the next LHC RUN III

- **A study of the impact and possible mitigation can be done applying DYVACS code to FCC-hh conditions.**

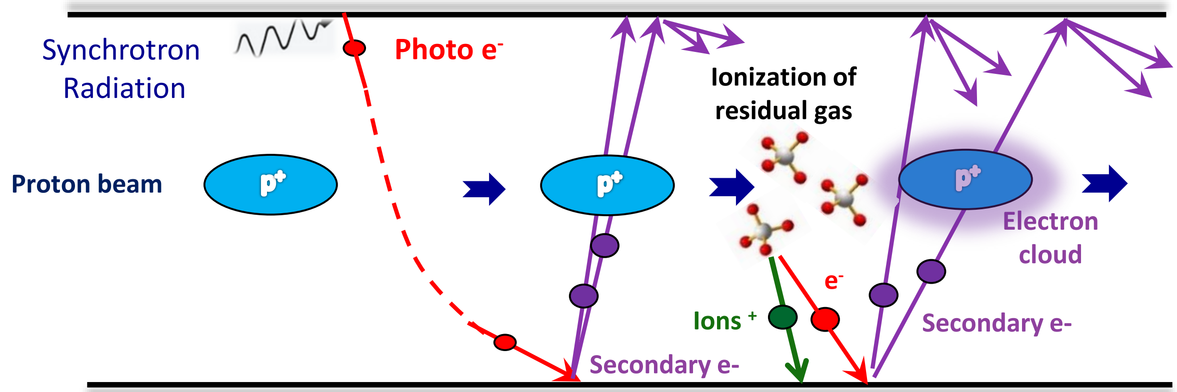
Thank you for your attention !

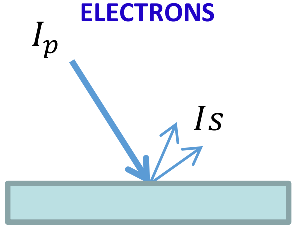
Backslides

Differences between Au_5 and Au_{400}

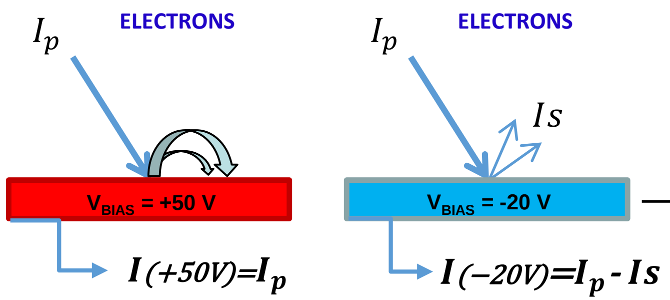


BEAM PIPE CONDITIONING

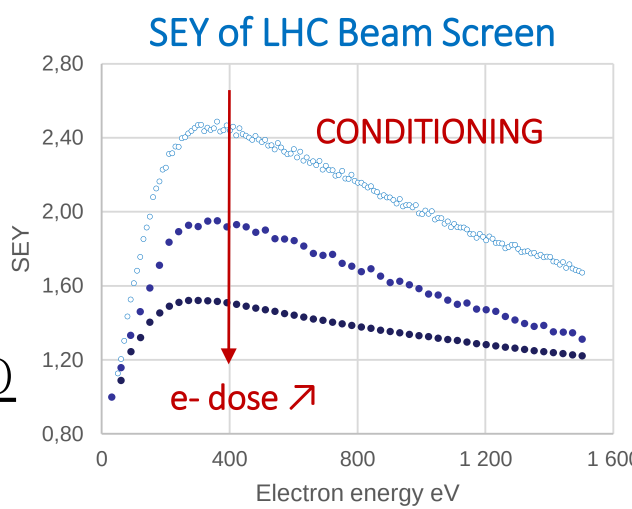




$$\mathbf{SEY} = \frac{I_S}{I_p}$$



$$\mathbf{SEY} = \frac{I_{(-20V)} - I_{(+50V)}}{I_{(+50V)}}$$



Copper Electrodes

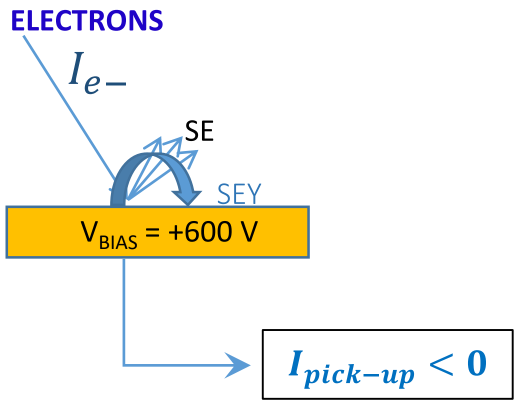
$$I_-(E, V_{bias}) = I_{e-}$$

$$I_+(E, V_{bias}) = I_{e-} + I_{SE} + I_{ion}$$

$I_{e-} < 0$

$I_{SE} = - SEY \cdot I_{e-}$

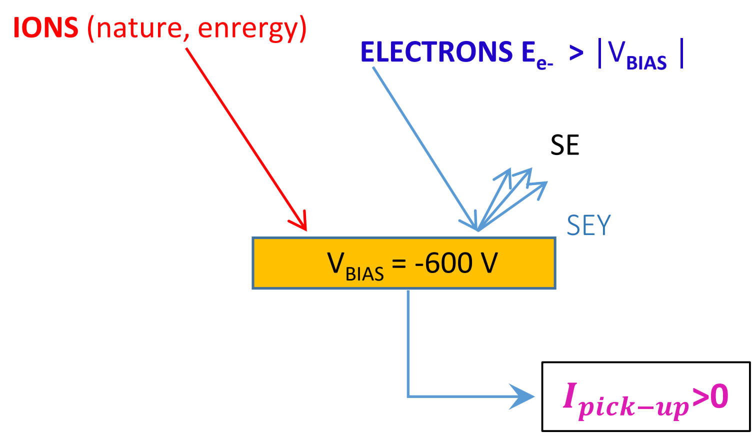
Positively polarized



Considering $I_{ions} \ll I_{e-}$

$$I_{pick-up} = I_{total\ e-}$$

Negatively polarized



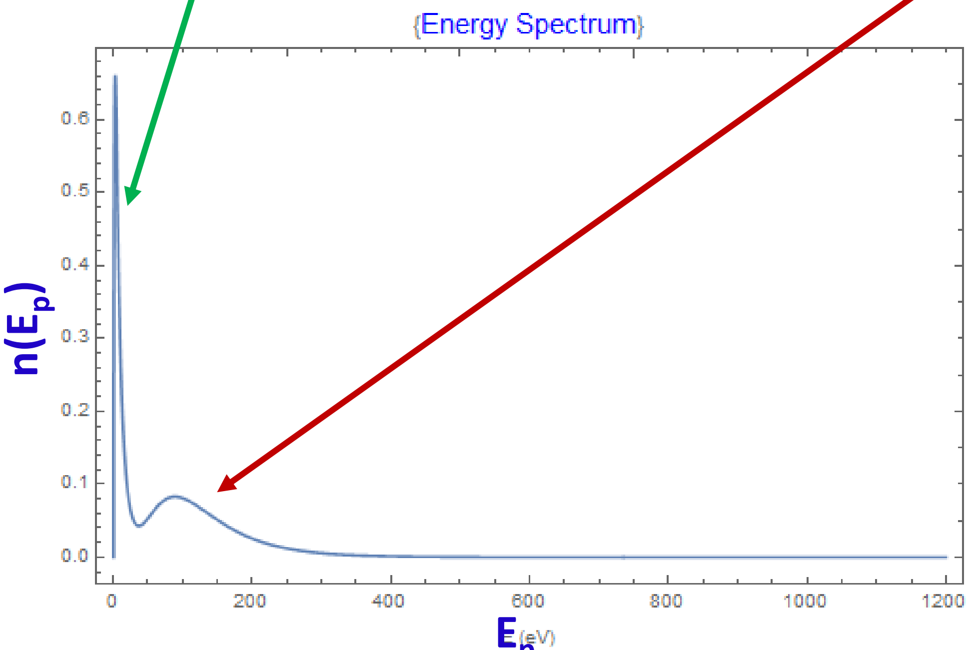
$$I_{pick-up} = \underbrace{I_{ions}}_{\text{Always > 0}} + \underbrace{(1 - SEY)I_{e-}}_{\text{> 0 if SEY > 1}}$$

Electron energy spectrum

$$n(E_p)= \frac{K1}{(\sqrt{2*\pi})*w1*E_p} * e^{\left(-\frac{\left(\mathrm{Log}[\frac{E_p}{\mathrm{Ec1}}]\right)^2}{2*w1^2}\right)} + \frac{K2}{(\sqrt{2*\pi})*w2*E_p} * e^{\left(-\frac{\left(\mathrm{Log}[\frac{E_p}{\mathrm{Ec2}}]\right)^2}{2*w2^2}\right)}$$

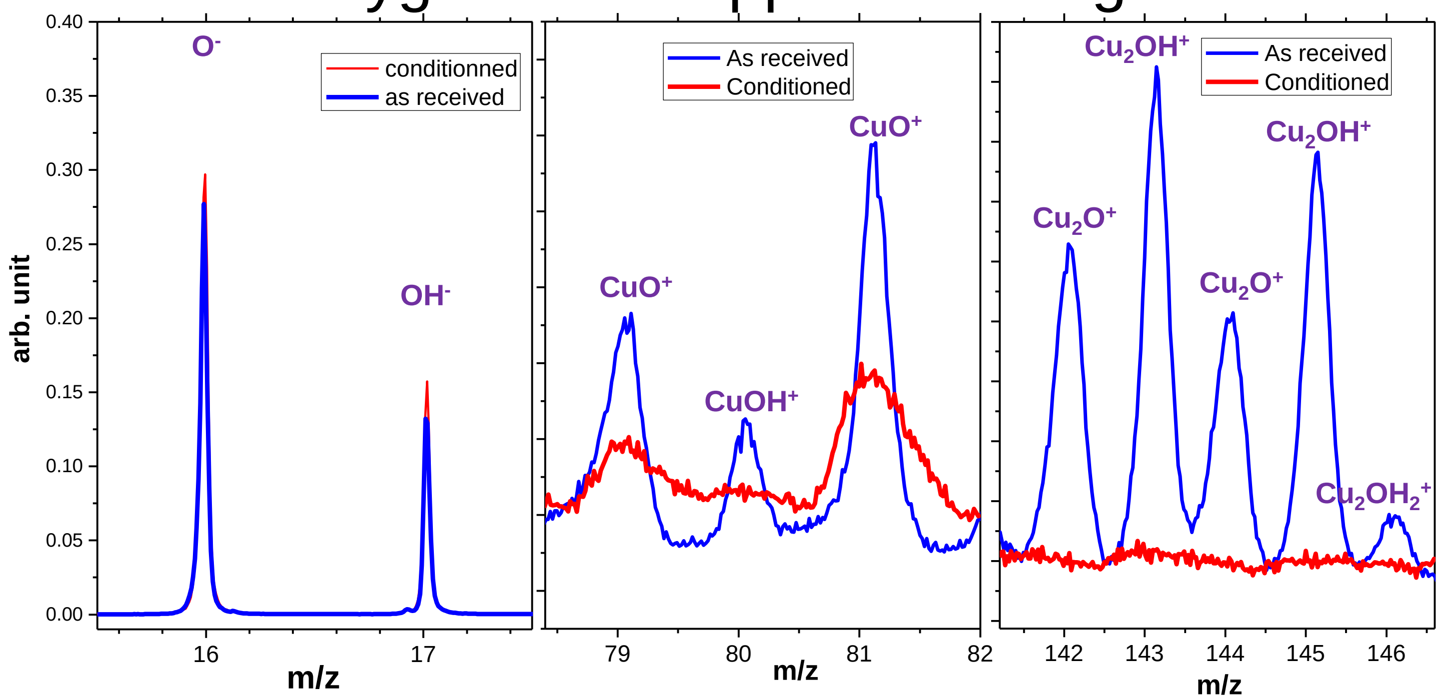
SE produced initially by e- impinging the wall + Photoelectrons

e- submitted to a single kick acceleration by the proton beam



LHC beam screen: As received *vs* conditioned

Oxygen and Copper oxide signals



After an electron conditioning, O^- and OH^- signals don't significantly change whereas some copper oxides completely disappear

→ Modification of the oxide layer