ECLOUD'22

Ions in particle accelerators

Their simulations and impact on the ecloud / gas densities of the LHC and future machines

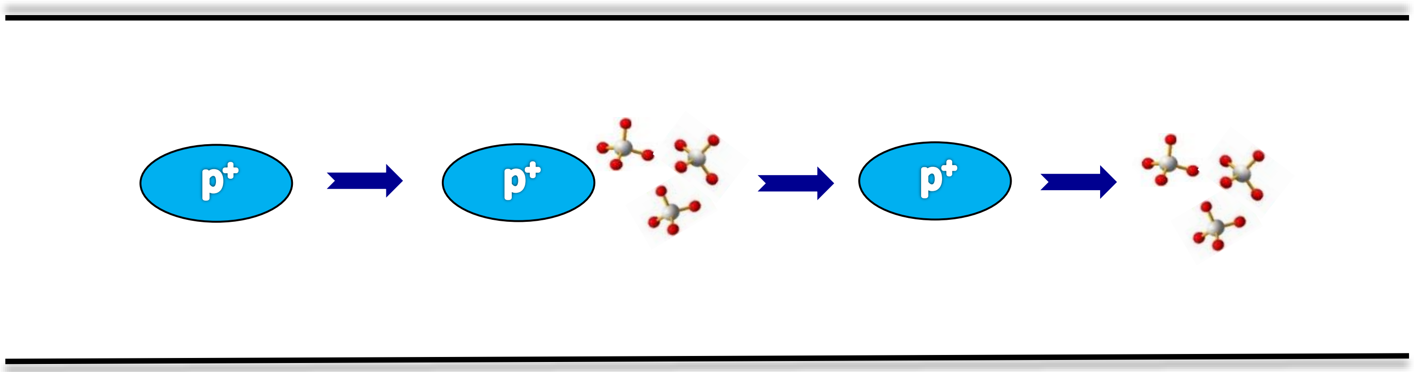
Suheyla BILGEN – Bruno MERCIER – Gaël SATTONNAY – Vincent BAGLIN

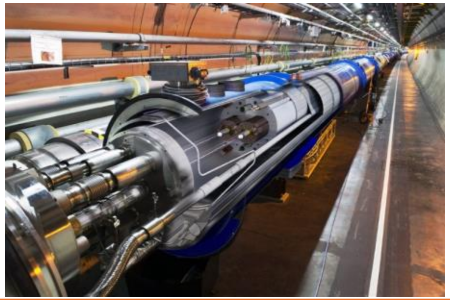
MAVERICS team at IJCLab
CERN TE-VSC collaboration

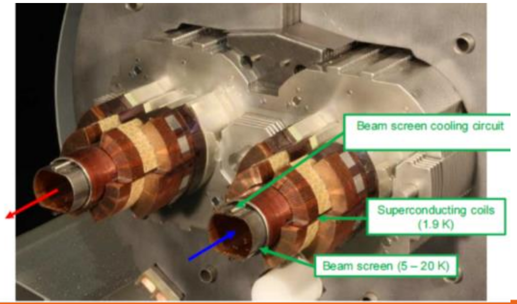
September 26, 2022

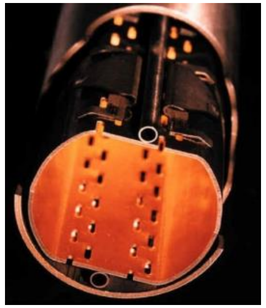
Origin of ion production?

LHC







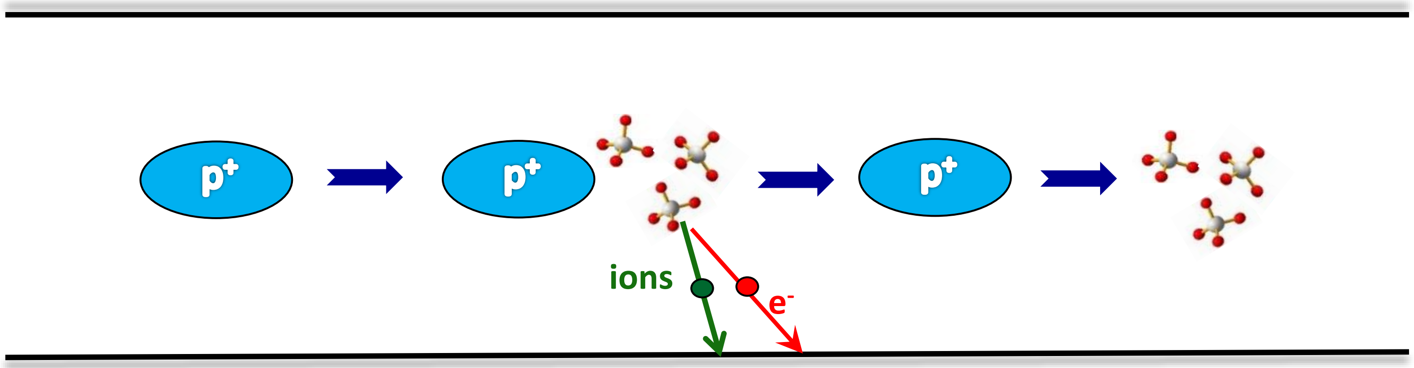


suheyla.bilgen@ijclab.in2p3.fr

Ions in particle accelerators

Origin of ion production?

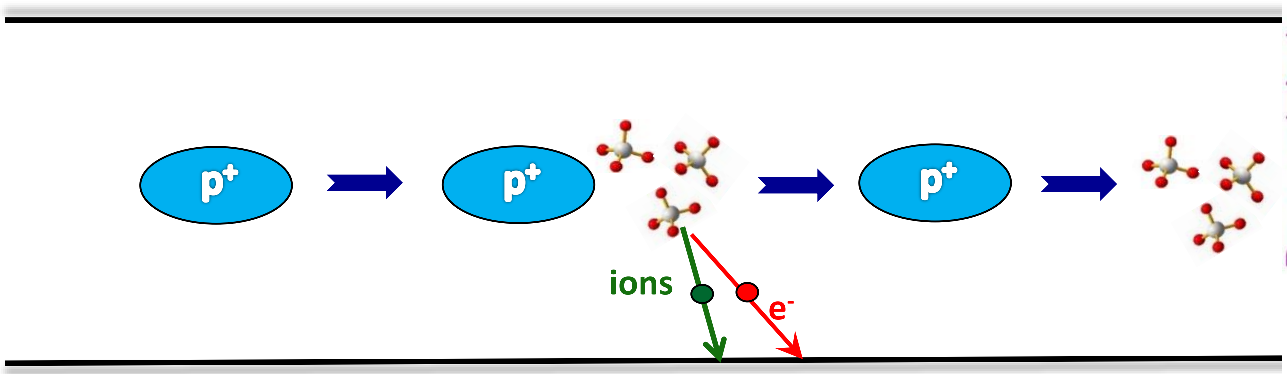
Ionization of residual gas

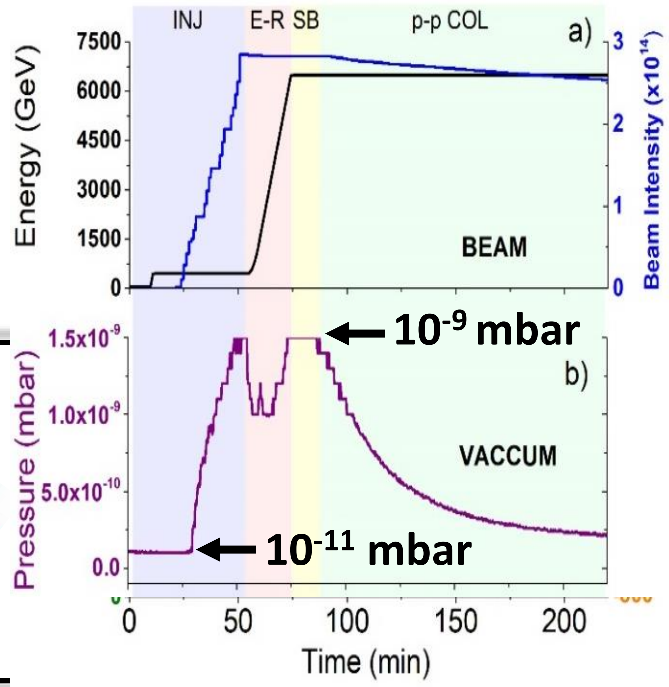


Ions in particle accelerators

Origin of ion production?

Ionization of residual gas





Ions in particle accelerators

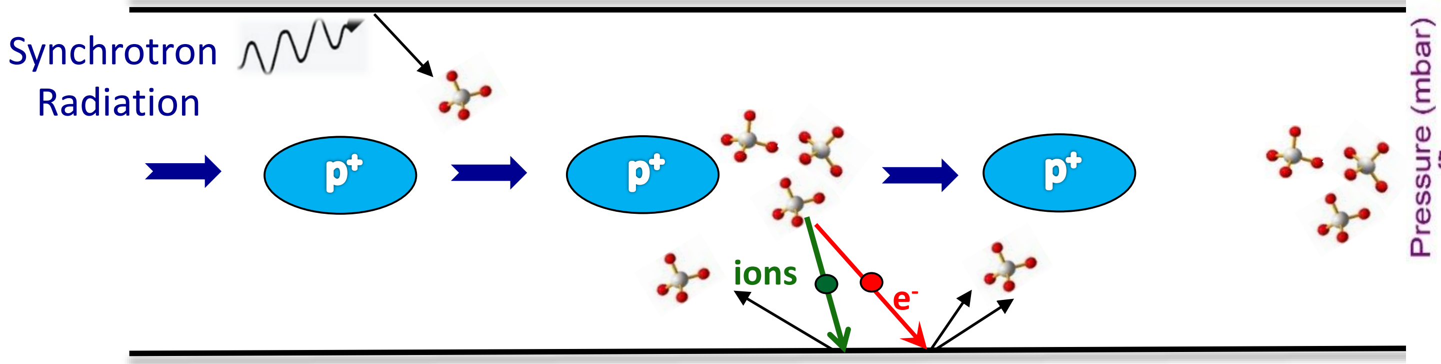
origin of ion production?

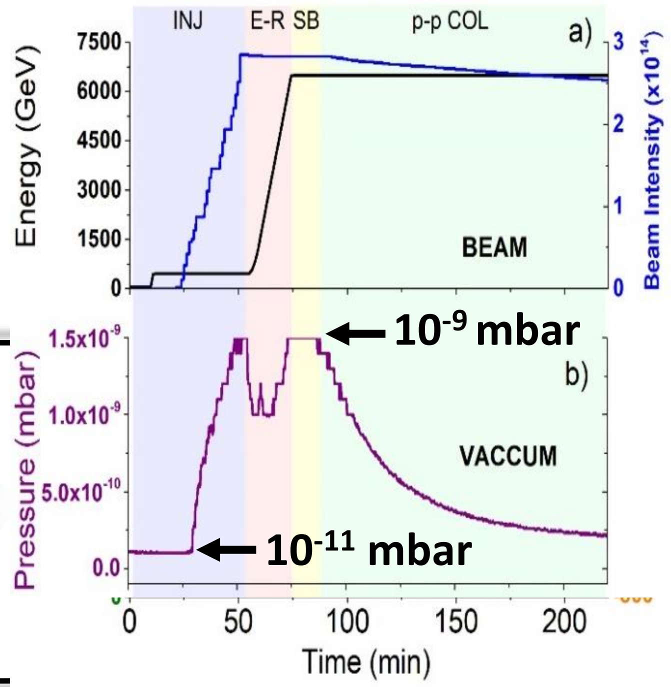
Stimulated Desorption

Ionization of residual gas

Increase of residual gas

Stimulated Desorption



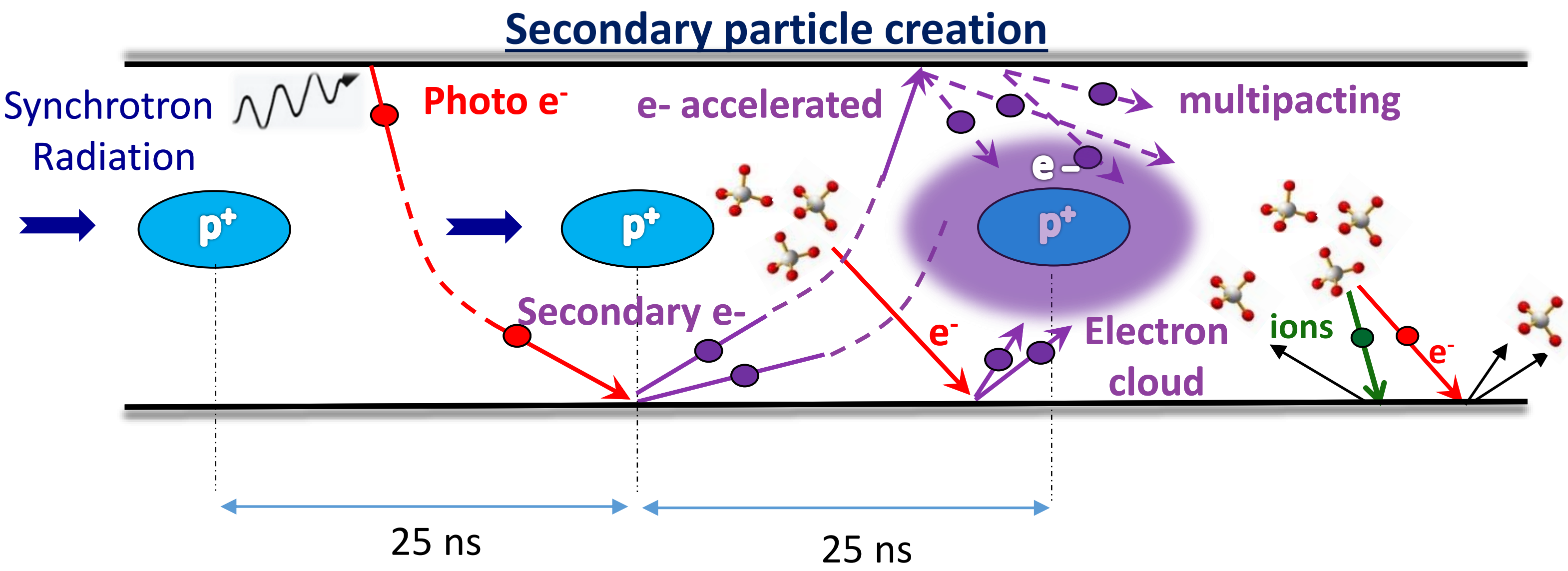


Ions in particle accelerators

origin of ion production?

Stimulated Desorption → e- / i+ production

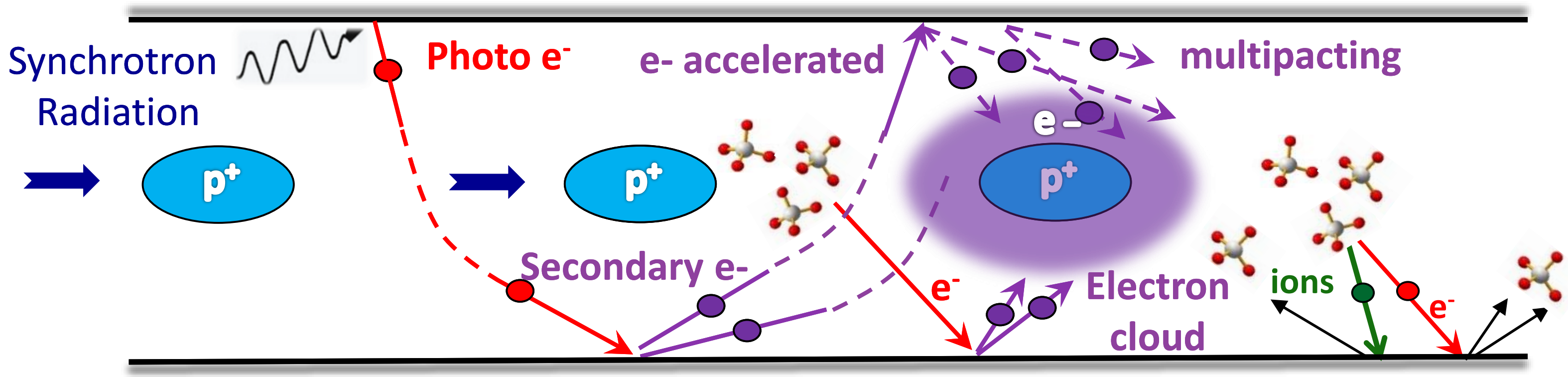
- Ionization of residual gas
- Increase of residual gas
- Increase of Stimulated Desorption + ionization of RG



Ions in particle accelerators

origin of ion production?

Residual gas density evolution + **Secondary particle creation**



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Ions in particle accelerators

origin of ion production?

Residual gas density evolution + **Secondary particle creation**

Pressure evolution

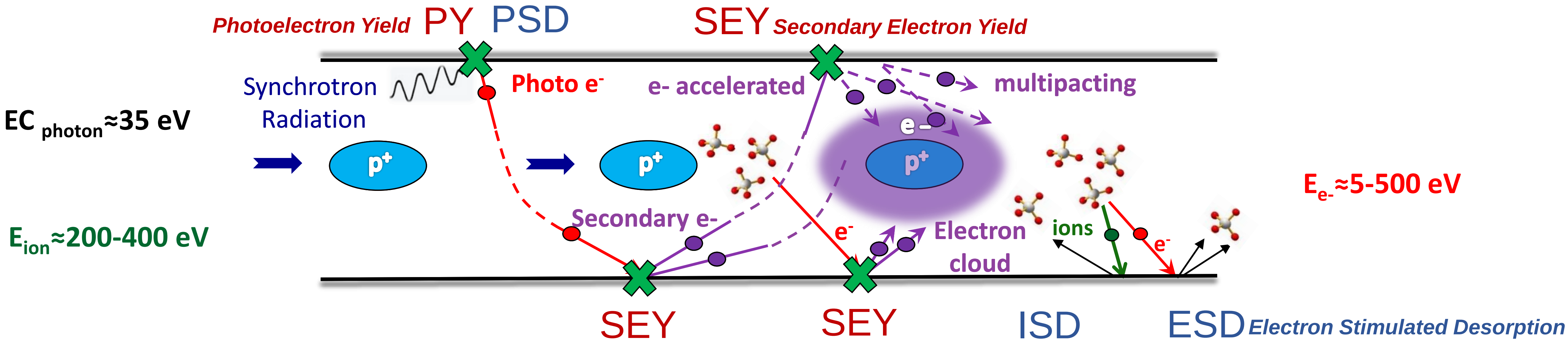
i^+ e^-

Ions in particle accelerators

origin of ion production?

Residual gas density evolution + **Secondary particle creation**

For the LHC



main impact of ions: ISD → $\eta_i > \eta_{e-} > \eta_{ph}$

The goal of this study is to understand the role played by ions on pressure increase

Ions in particle accelerators

origin of ion production?		
Residual gas density evolution	+	Secondary particle creation
Pressure evolution		i^+ e^-

1) In situ measurements during the LHC run II

2) Simulation of dynamic vacuum during the LHC run II

3) Conclusion and perspectives

Ions in particle accelerators

origin of ion production?

Residual gas density evolution + **Secondary particle creation**

Pressure evolution i^+ e^-

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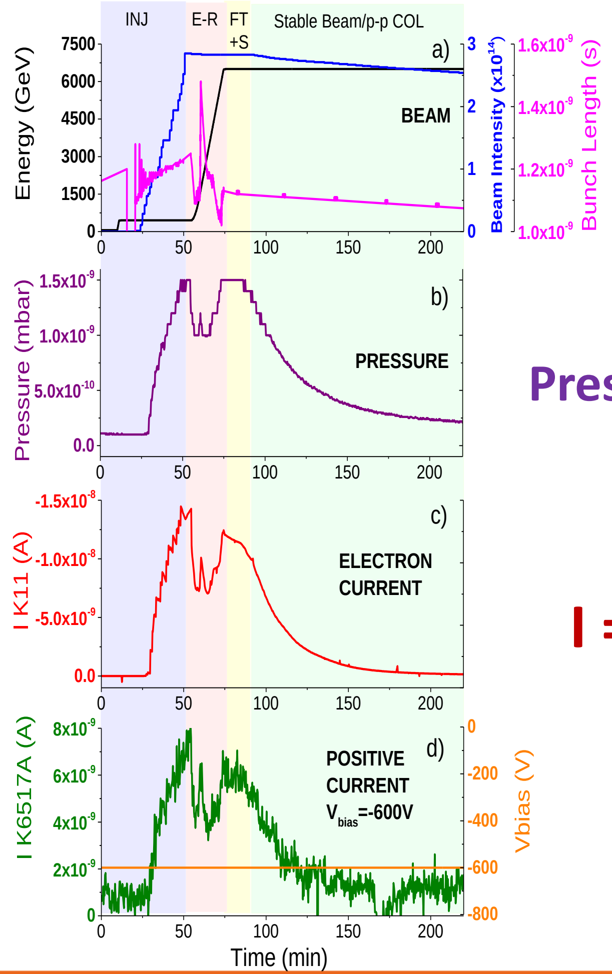
In situ measurement during the LHC run II

origin of ion production?

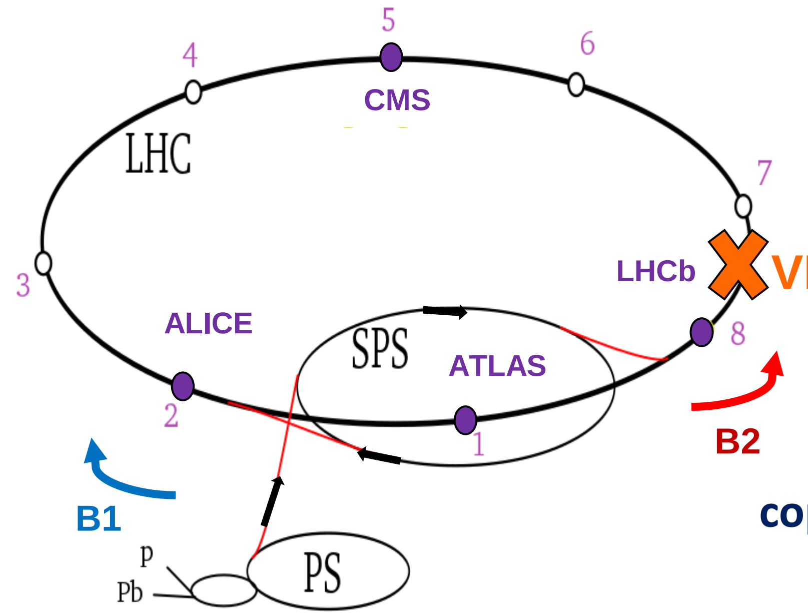
Residual gas density evolution + **Secondary particle creation**



Fill for physics 7319 - RUN II

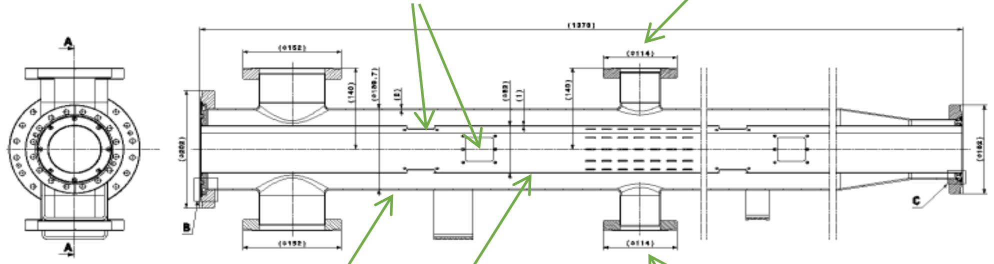
Pressure evolution

$\mathbf{I} = I_{e-}$

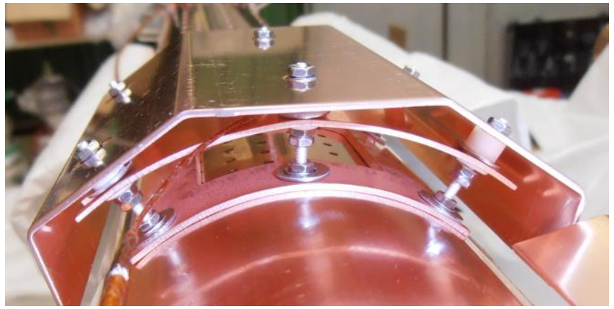


VPS Conditions

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



Measurements performed on **copper beam screen (station 4) B1**

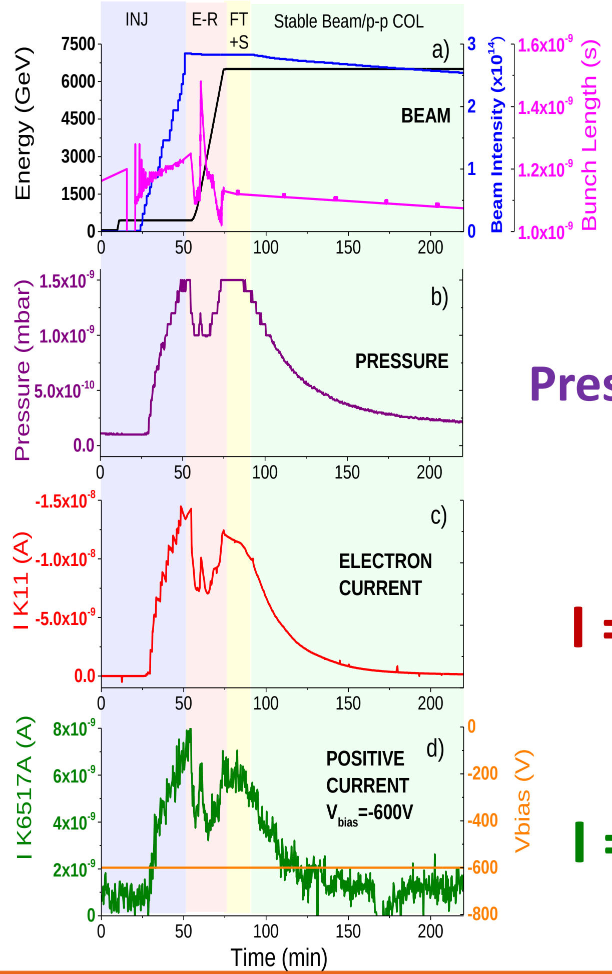


V. BAGLIN, meeting, CERN, 5th Dec. 2017

In situ measurement during the LHC run II

origin of ion production?

Residual gas density evolution + **Secondary particle creation**



Fill for physics 7319 - RUN II

Pressure evolution

$\mathbf{I} = I_{e-}$ $\quad$ $\mathbf{V_{bias} = +9V}$

$\mathbf{I} = I_{ion} + I_{e-(E>V_{bias})} + I_{SE}$ $\quad$ $\mathbf{V_{bias} = -600V}$ $\quad$ $\leftarrow$ *ions?*

In situ measurement during the LHC run II

origin of ion production?

Residual gas density evolution + **Secondary particle creation**

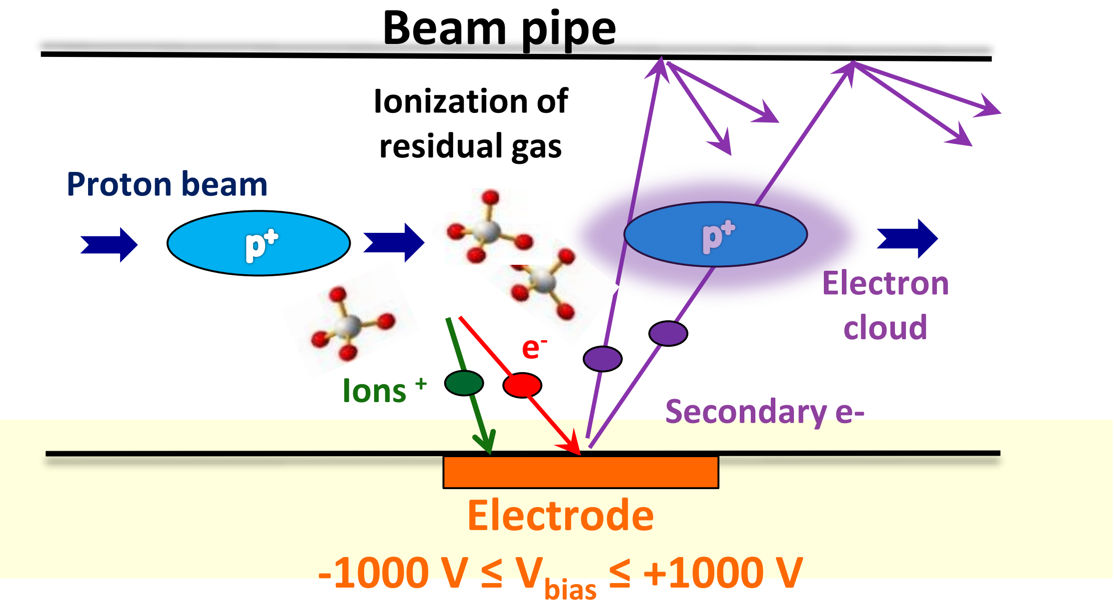
To discriminate the contribution of e- to ions, we compare the exp measurement

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

vs

calculated current only due to an e- contribution for different bias applied to the electrode.

$$I_{+\ \text{due to e-}}(E_{e-}, Vbias) = I_{e-} + I_{SE}$$



origin of ion production?

Residual gas density evolution + **Secondary particle creation**

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$$I_{+\ \text{due to e-}}(E_{e-}, \text{Vbias}) = I_{e-} + I_{SE}$$
$$= I_{e-}\,[1\text{-SEY}]$$

In situ measurement during the LHC run II

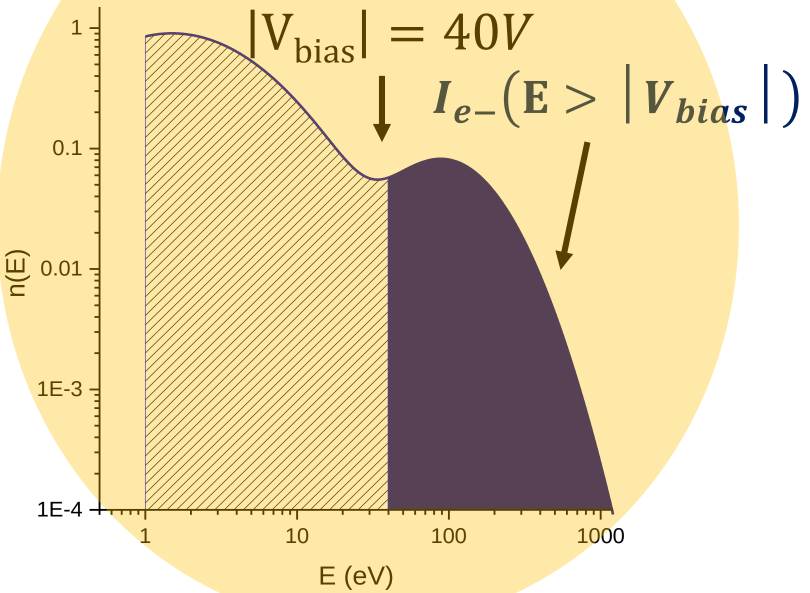
origin of ion production?

Residual gas density evolution + **Secondary particle creation**

To discriminate the contribution of e- to ions, we compare the **exp measurement *vs* calculated current** only due to an e- contribution for different bias applied on the electrode.

I_{e-}

Depends on e- energy spectrum



Experimental Data from Elena Buratin, 2015, CERN

$$I_{+\text{ due to e-}}(E_{e-}, \text{Vbias}) = I_{e-} + I_{SE}$$
$$= I_{e-}\,[1\text{-}\mathbf{SEY}]$$

Calculated current induced by e- = e- contribution using experimental data of the e- energy spectrum and calculated Cu SEY.

In situ measurement during the LHC run II

origin of ion production?

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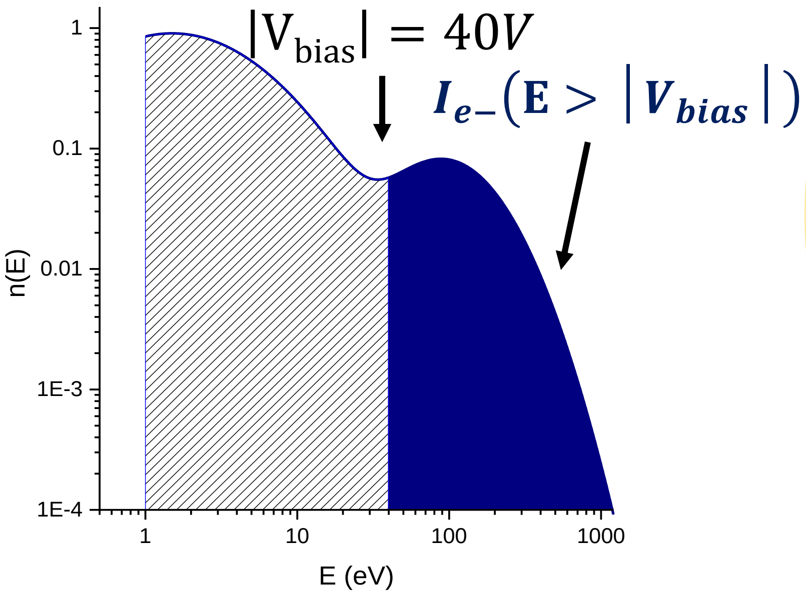
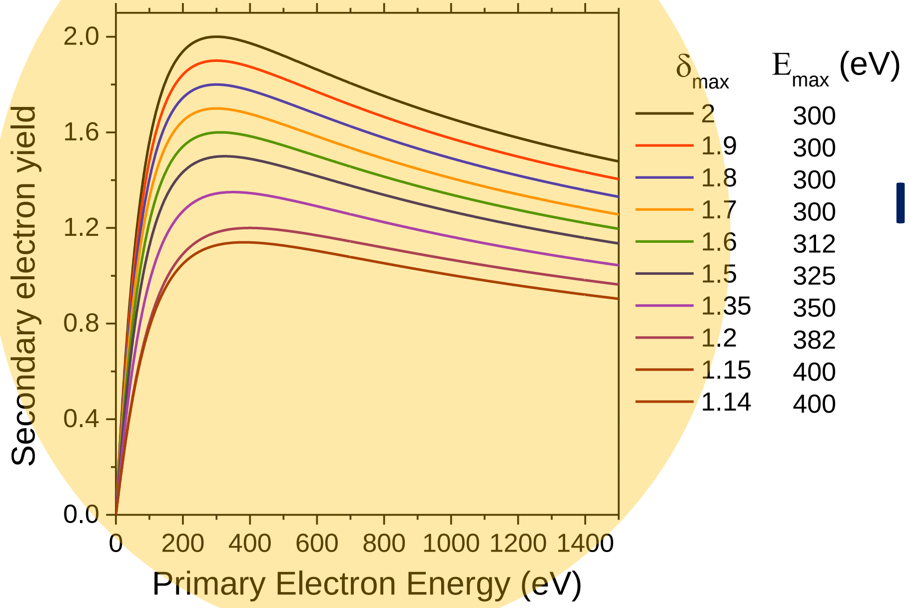


Experimental Data from Elena Buratin, 2015, CERN

SEY

Depends on SEY=f(Ee-)



Calculated Data using s=1.35 for LHC Forman CERN

$$I_{+\ \text{due to e-}}(E_{e-}, \text{Vbias}) = I_{e-} + I_{SE}$$
$$= I_{e-}\,[1-\text{SEY}]$$

In situ measurement during the LHC run II

origin of ion production?

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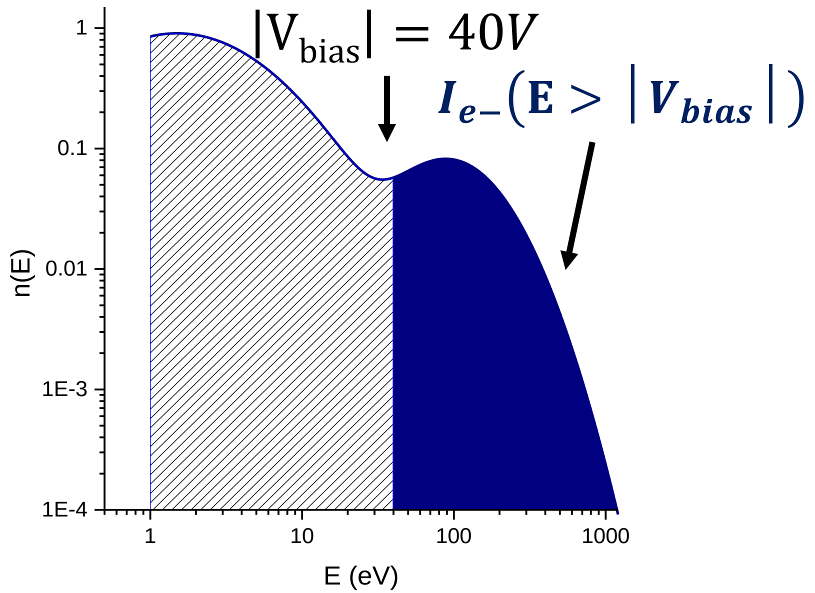
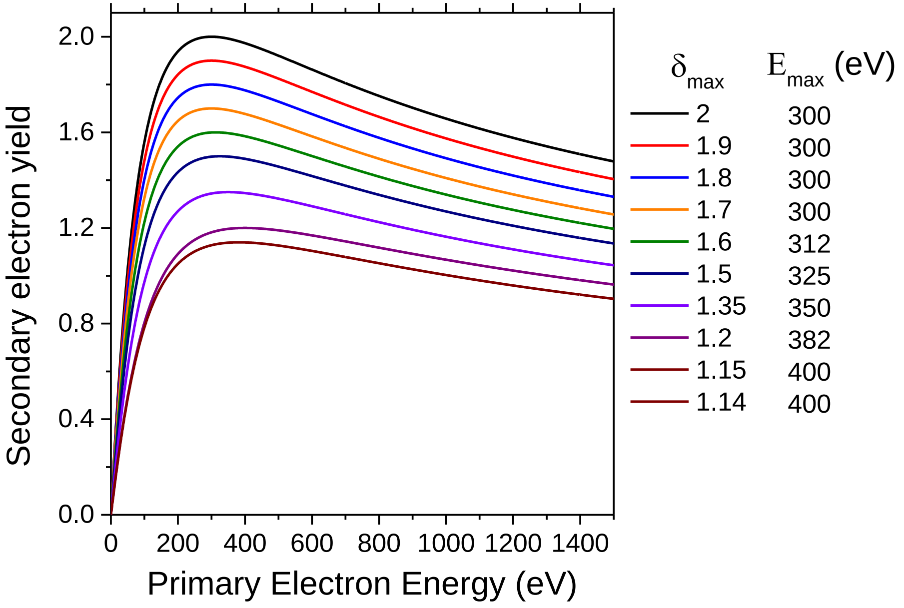


Experimental Data from Elena Buratin, 2015, CERN

SEY
Depends on SEY=f(Ee-)



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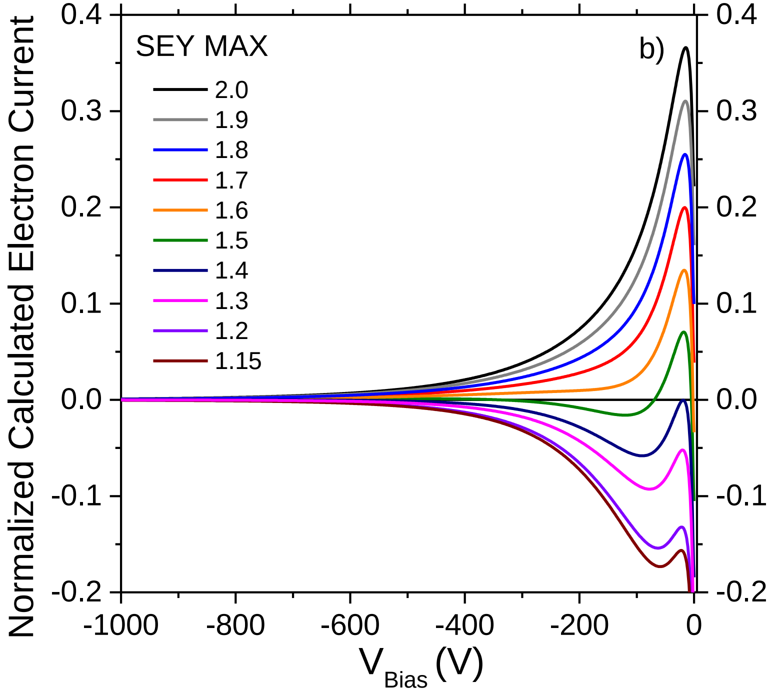

e^- contribution to I_+ as a function of V_{bias} calculated for several SEY

In situ measurement during the LHC run II

origin of ion production?

Residual gas density evolution + **Secondary particle creation**

To discriminate the contribution of e- to ions, we compare the **exp measurement**

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In situ measurement during the LHC run II

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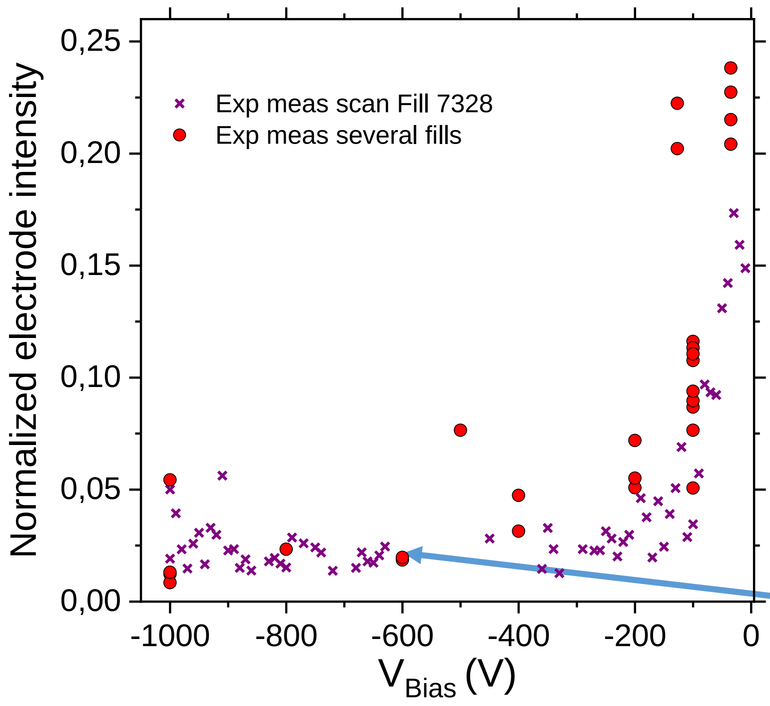

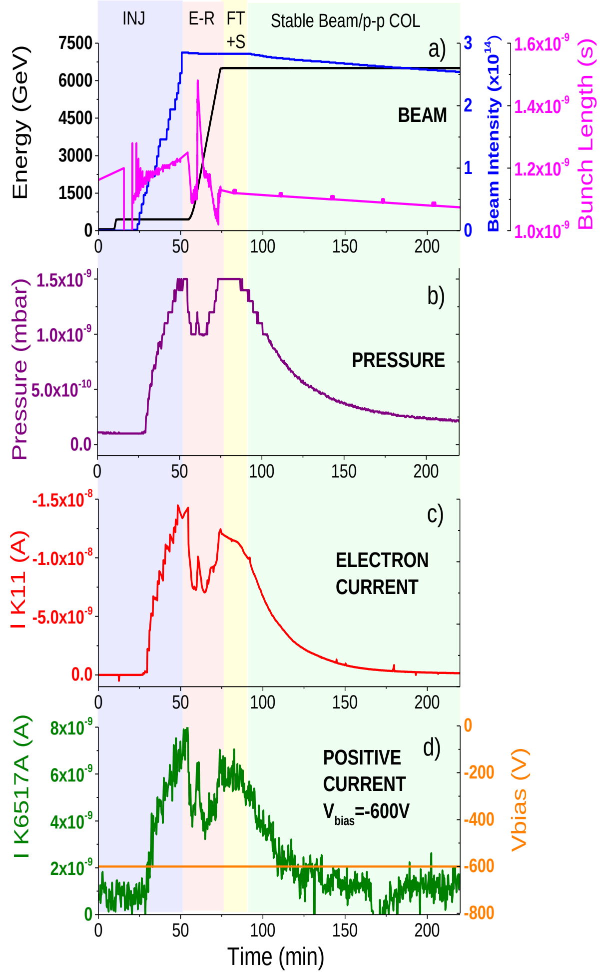

In situ measurement during the LHC run II

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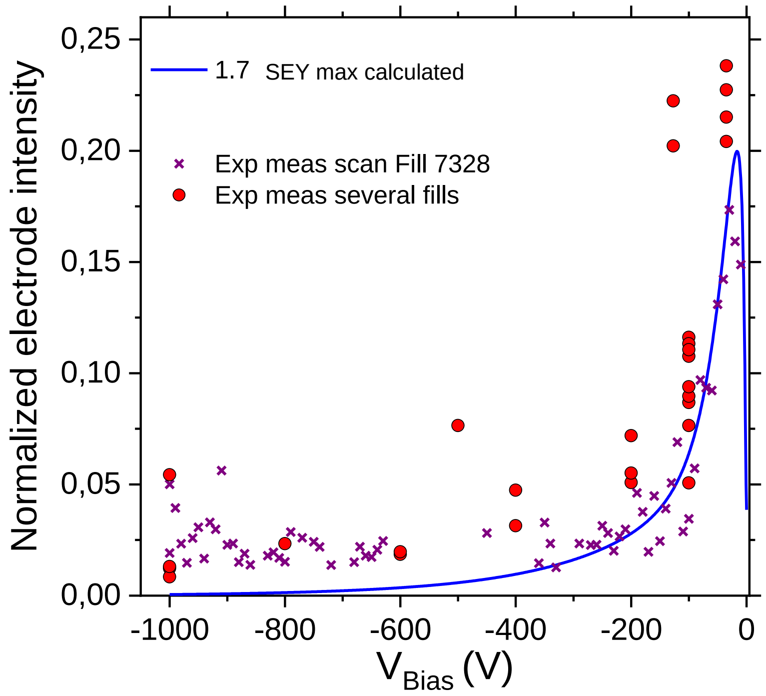
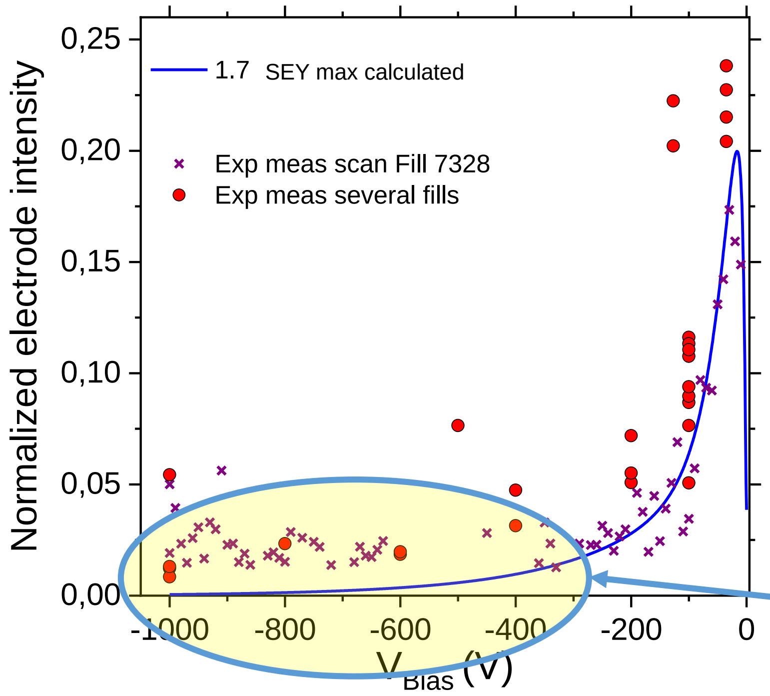


calculated current only due to an e- contribution for different bias applied on the electrode

In situ measurement during the LHC run II

origin of ion production?

Residual gas density evolution + **Secondary particle creation**



calculated current only due to an e- contribution for different bias applied on the electrode

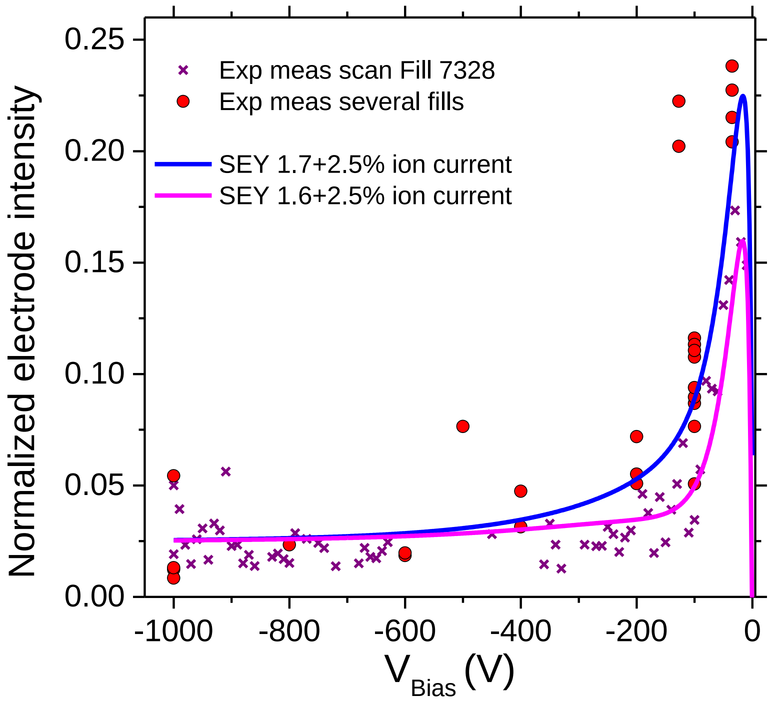
$$I_{+\ \text{due to e-}}(E_{e-}, \text{Vbias}) = I_{e-} + I_{SE}$$

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

In situ measurement during the LHC run II

origin of ion production?

Residual gas density evolution + **Secondary particle creation**



To match experimental data it is necessary to add an ion contribution:

— calculated current due to e- contribution + 2.5 % of ion for an SEY of 1.7

— calculated current due to e- contribution + 2.5 % of ion for an SEY of 1.6

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

Experimental measurements show that the amount of ions represents 2.5% of the electronic current in the VPS

Ions in particle accelerators

origin of ion production?

Residual gas density evolution	+	Secondary particle creation
Pressure evolution		i^+ e^-

1) In situ measurements during the LHC run II

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3) Conclusion and perspectives

DYVACS - Gas density profiles

Analytical model of the dynamic pressure – DYVACS – DYnamic VACuum Simulation code

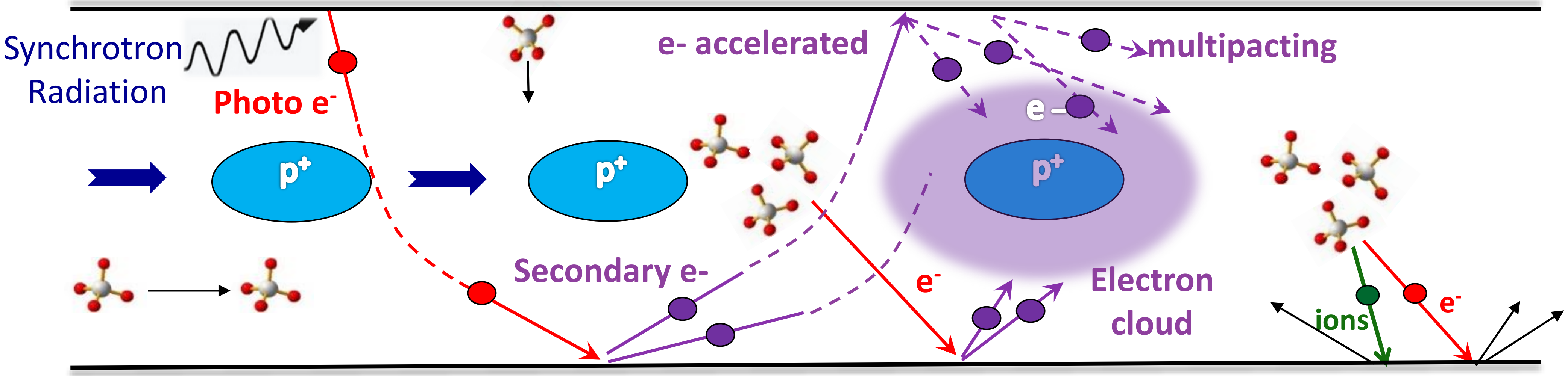
$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

DYVACS is based on the gas balance differential equation (VASCO)

It is used to compute the gas density n_j

for j= H_2, CH_4, CO, CO_2

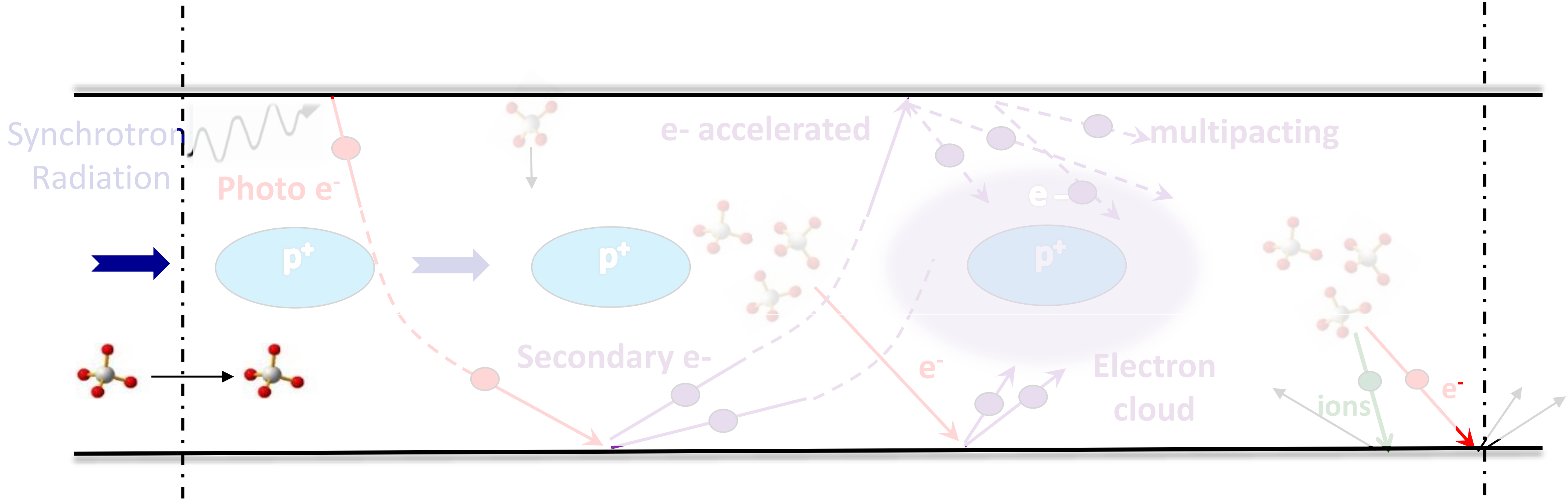
Boundary conditions: continuity of flux and pressure between each segment



Analytical model of the dynamic pressure – DYVACS – DYnamic VACuum Simulation code

$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

C_j is the specific conductance for j gas species



Inputs: C_j,,

DYVACS - Gas density profiles

Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

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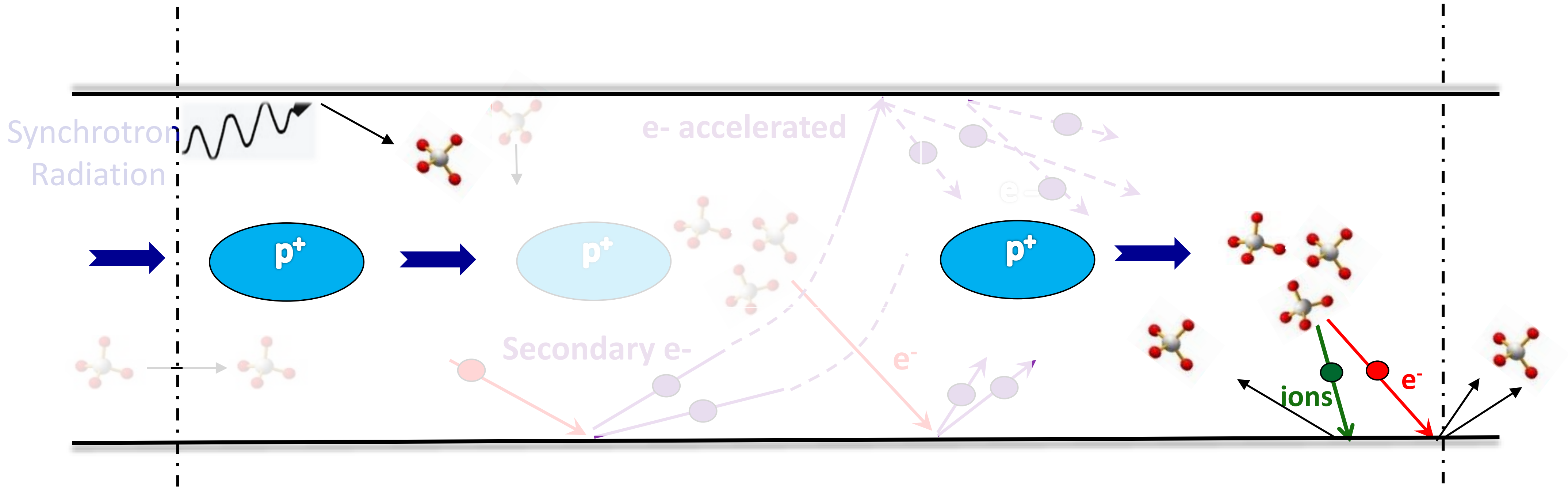

Inputs: C_j,, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph},

Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

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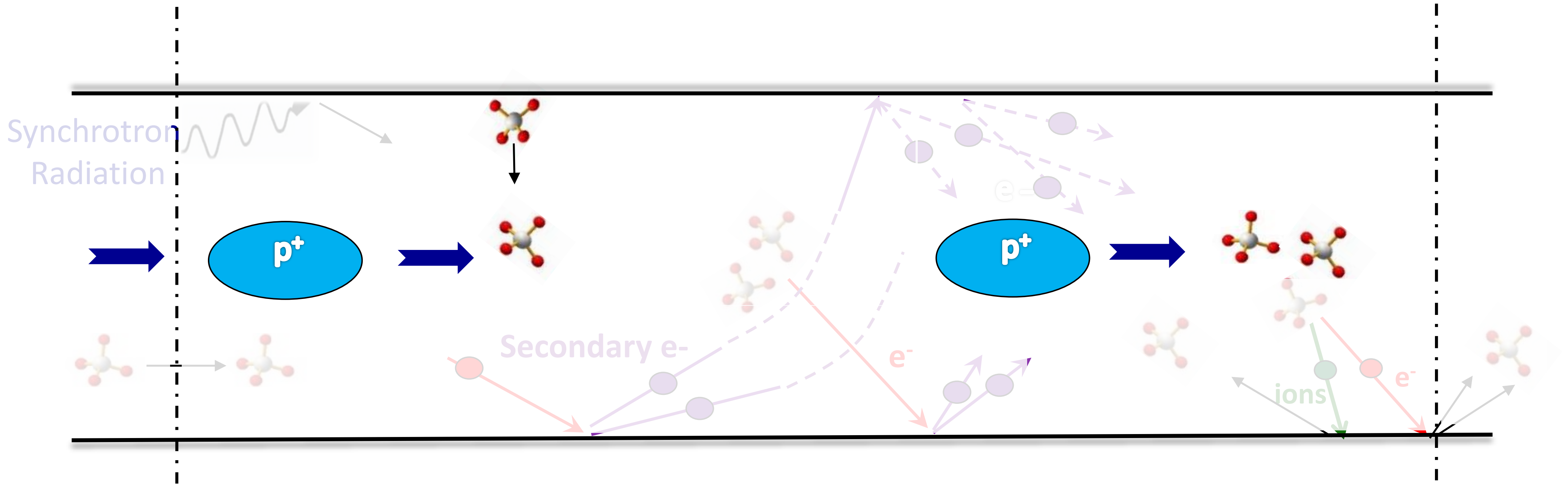
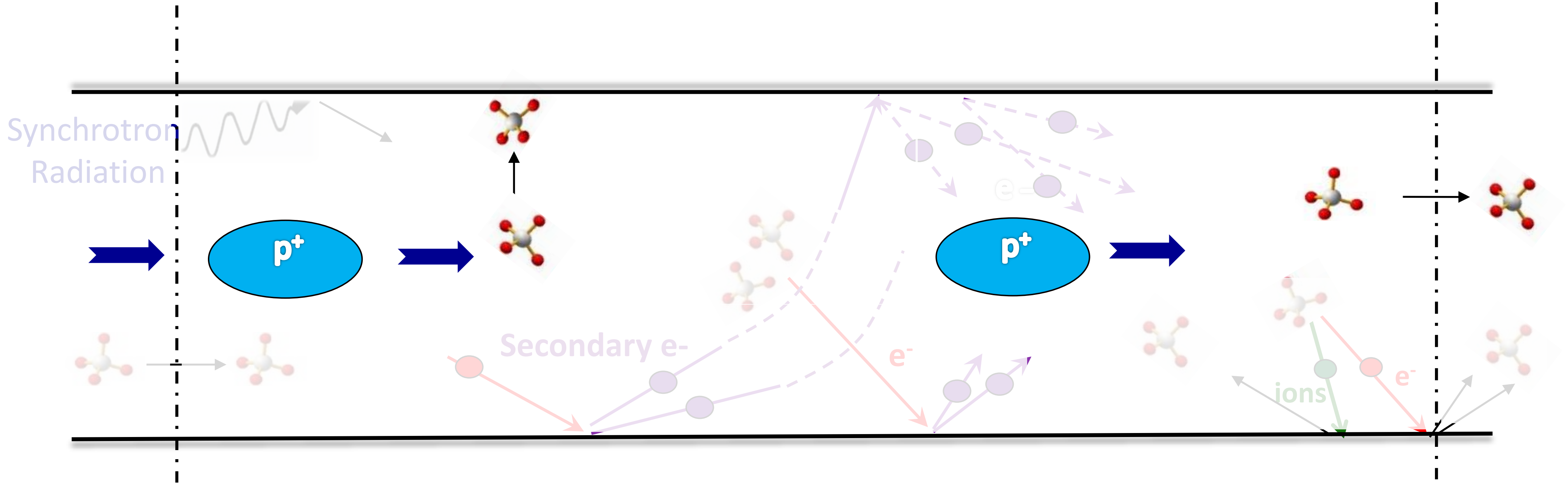


Inputs: C_j,, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$,

Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

S is the wall distributed pumping speed for each gas.



Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j,

DYVACS - Gas density profiles

Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

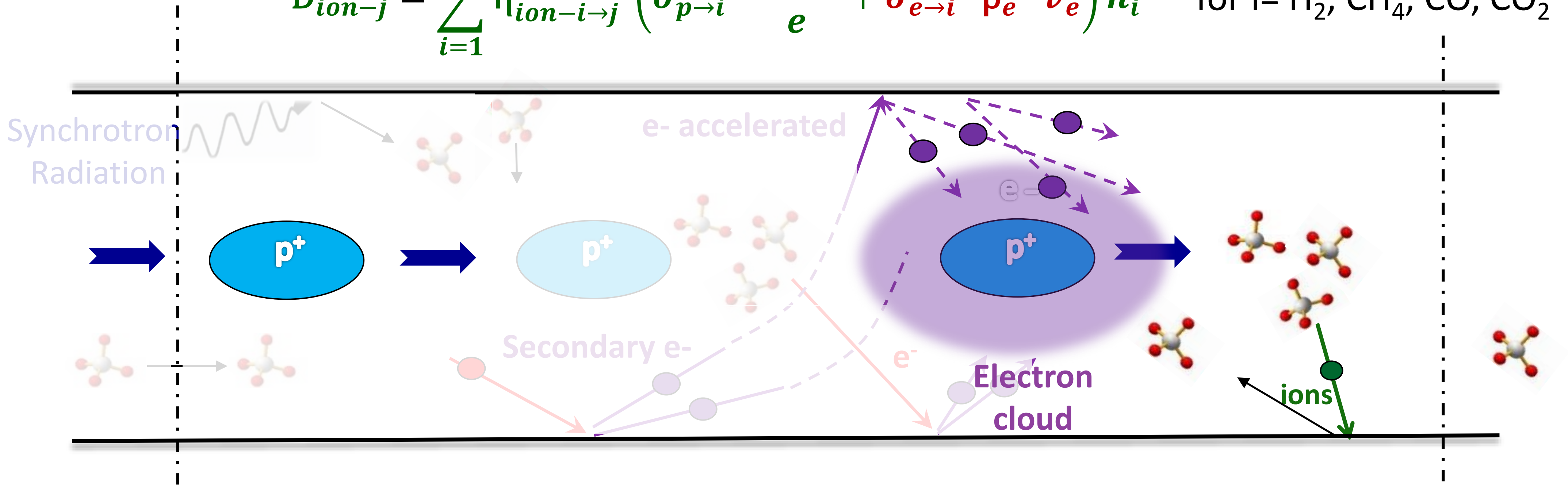
$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

Residual gas ionization

by the p beam — by the EC

$$D_{ion-j} = \sum_{i=1}^{4} \eta_{ion-i\to j} \left(\sigma_{p\to i} \cdot \frac{I_{beam}}{e} + \sigma_{e\to i} \cdot \rho_e \cdot v_e \right) n_i$$

for i= H_2, CH_4, CO, CO_2



Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j, $\sigma_{p\to i}$, $\sigma_{e\to i}$, I_{beam}, ρ_e, v_e,

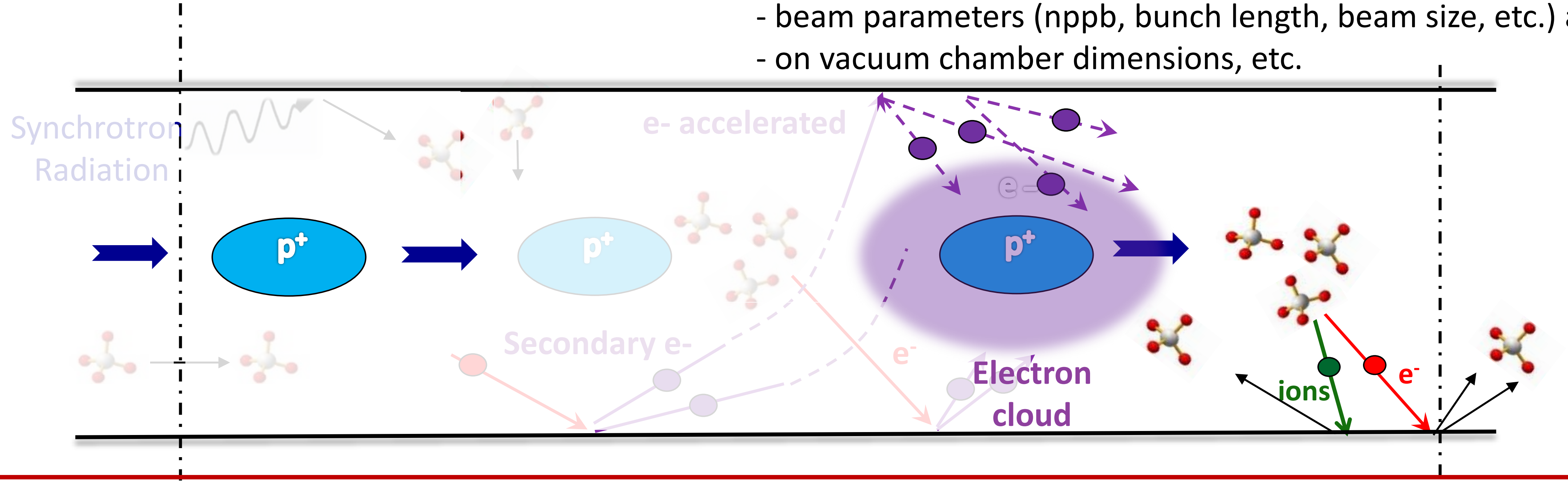
Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

$$D_{e,j} = \eta_{e,j}\Gamma_e \longrightarrow$$ * Γ_e **EC density computed with « the map model »**

T. Demma *et al.* Model

Γ_e depends on : - SEY (surface properties) ,
- beam parameters (nppb, bunch length, beam size, etc.) and
- on vacuum chamber dimensions, etc.



Inputs: C_j,,$\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$,Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j , $\sigma_{p\to i}$, $\sigma_{e\to i}$, I_{beam} , ρ_e, v_e, a, b, c, size of the segment, radius BP, E_{beam}, time of one turn, etc.

DYVACS - Gas density profiles

Analytical model of the dynamic pressure – DYVACS – Dynamic VACuum Simulation code

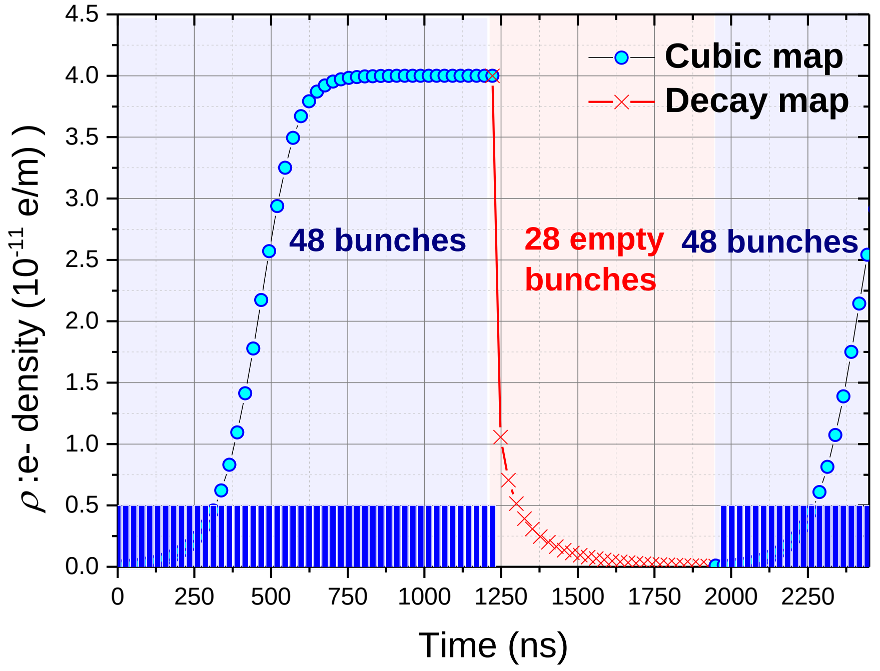
$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

$$\rho_{m+1} = a\rho_m + b{\rho_m}^2 + c{\rho_m}^3$$

$D_{e,j} = \eta_{e,j}\Gamma_e \longrightarrow$ * Γ_e **EC density computed with « the map model »**

T. Demma *et al.* Model

$\rightarrow \rho_m$ (10^{11} e-/m): EC density/meter after the m^{th} passage of bunch



Electron density for a nominal LHC fill using 48 bunches followed by 28 empty bunches for the decay

a: linear coefficient

- used to determine the e- gain from one bunch to another.
- a depends strongly on the SEY.

b: quadratic term

- considers the equilibrium density (plateau) of the EC.
- b depends on beam parameters (nppb, bunch length, beam size, etc.) and on vacuum chamber dimensions.

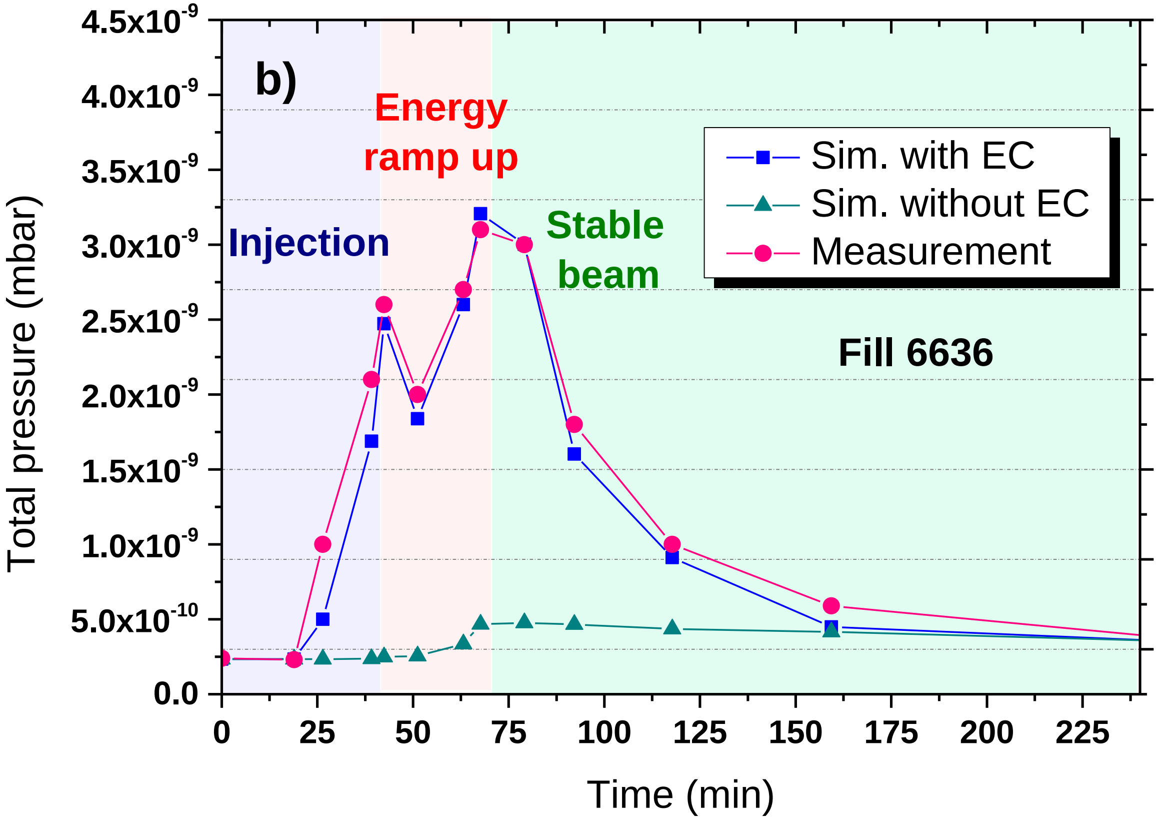
c: cubic term

- corresponds to a minor correction factor and C=0 for our simulations.

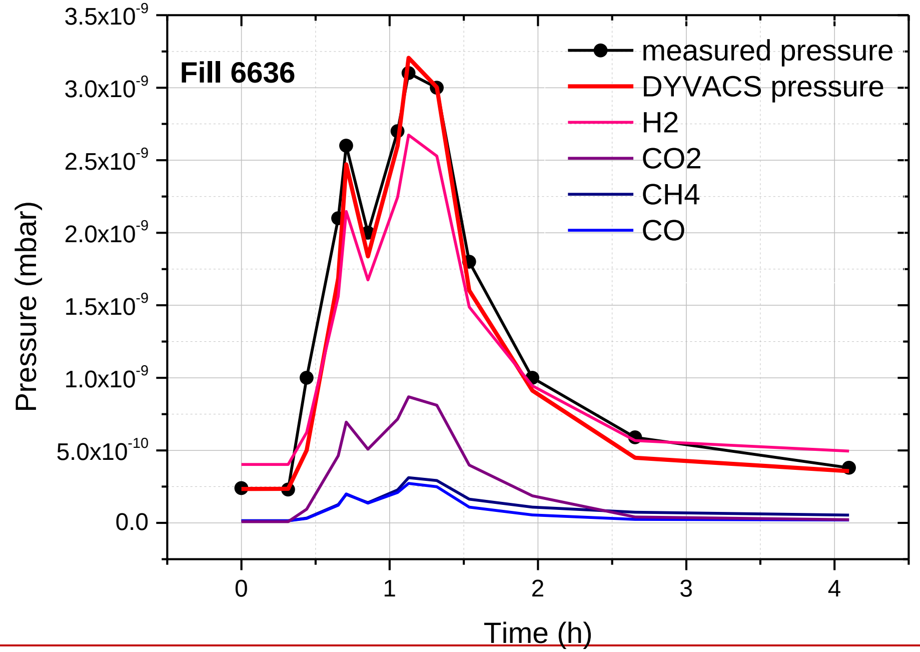
DYVACS - Gas density profiles

Comparison between *in situ* measurements in the LHC and the DYVACS simulation

For a=1,4 (SEY=1,6); b=[0; -5] variation of the b factor by DYVACS; c=0



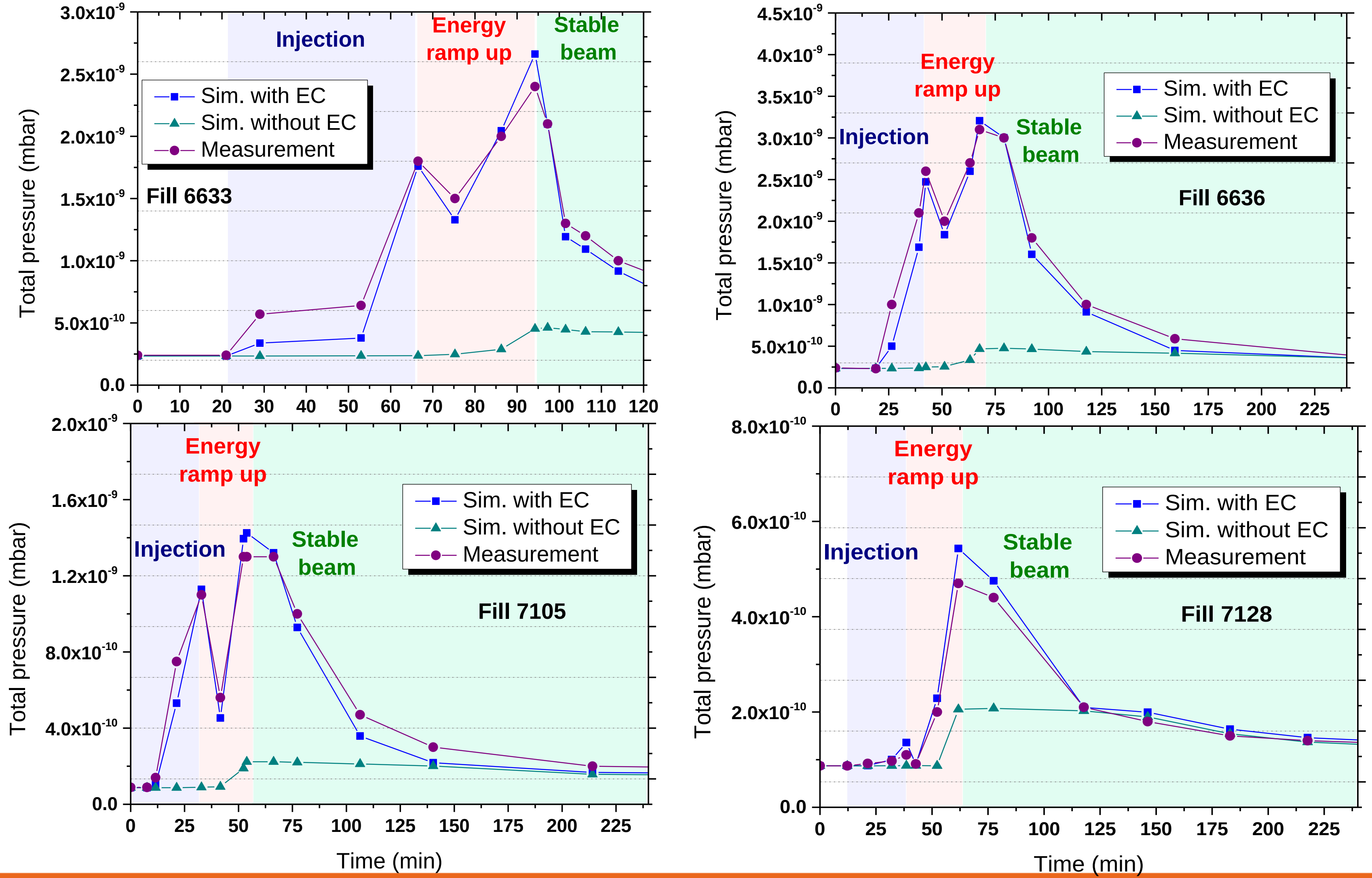
Contribution of each gas to the total pressure



A **good agreement** was observed in a short computation time, between the *in situ* pressure measurements and DYVACS simulation

DYVACS - Gas density profiles

Pressure time evolution measurements vs DYVACS simulations



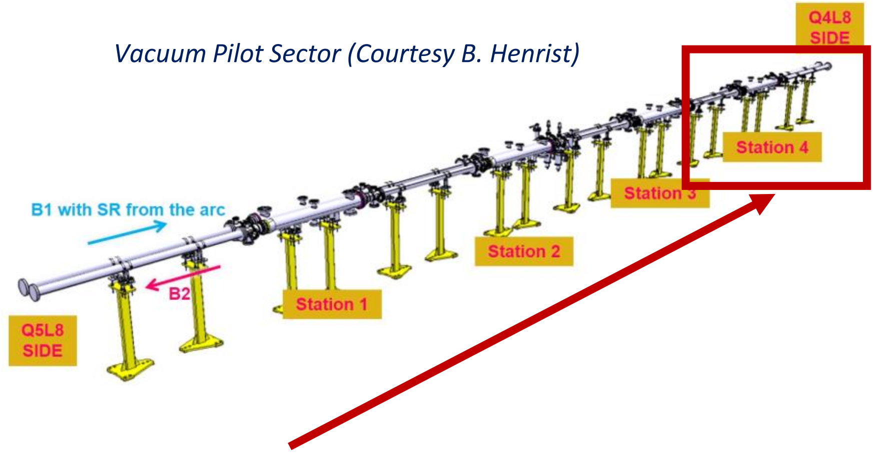
inputs:

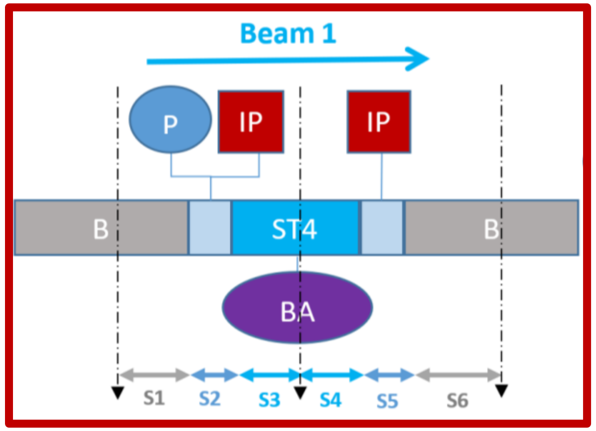
Same ESD,PSD and ISD used.
a fixed for a constant SEY
b is computed as a function of nppb.

All calculations reproduce with a good agreement the in situ pressure evolution measured in station 4 (unbaked copper) of VPS in the LHC.

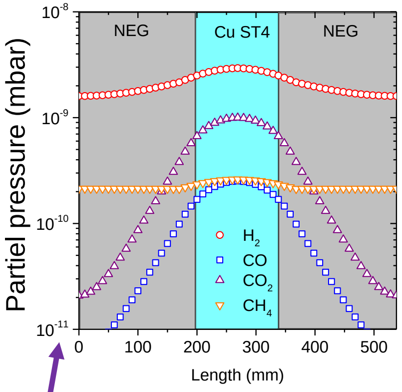
Distribution of partial pressures along the pipe

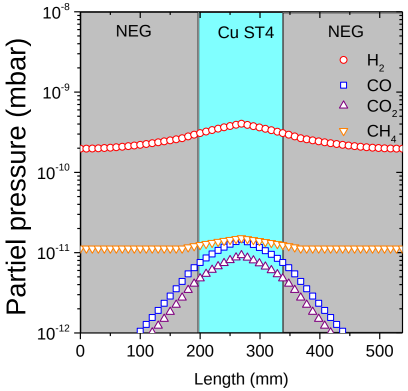
Vacuum Pilot Sector (Courtesy B. Henrist)

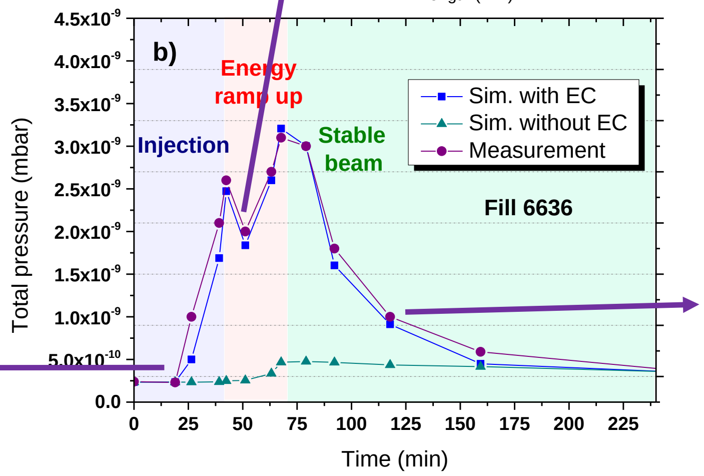


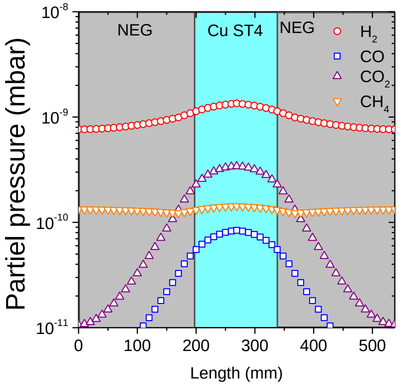


Distribution of partial pressures for H_2, CO_2, CO and CH_4 along the Cu station 4





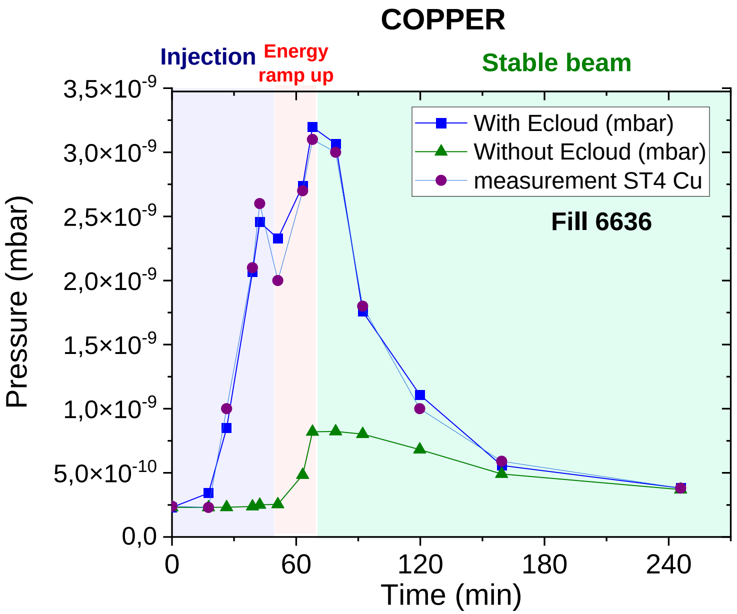


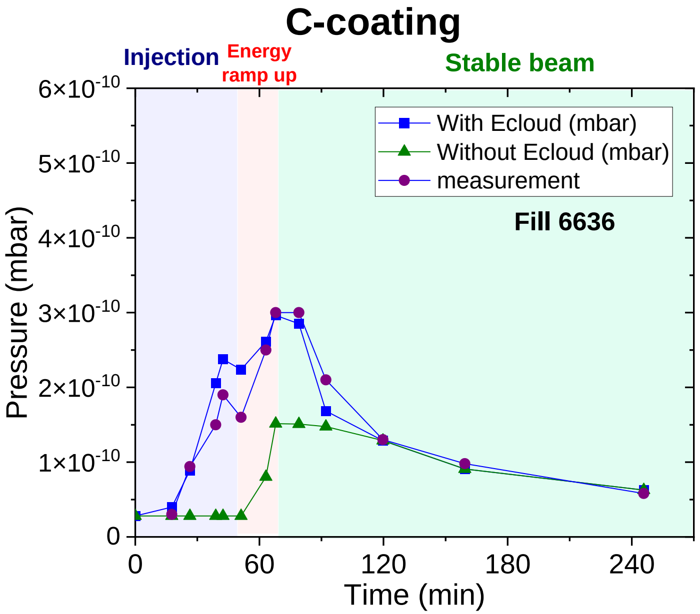


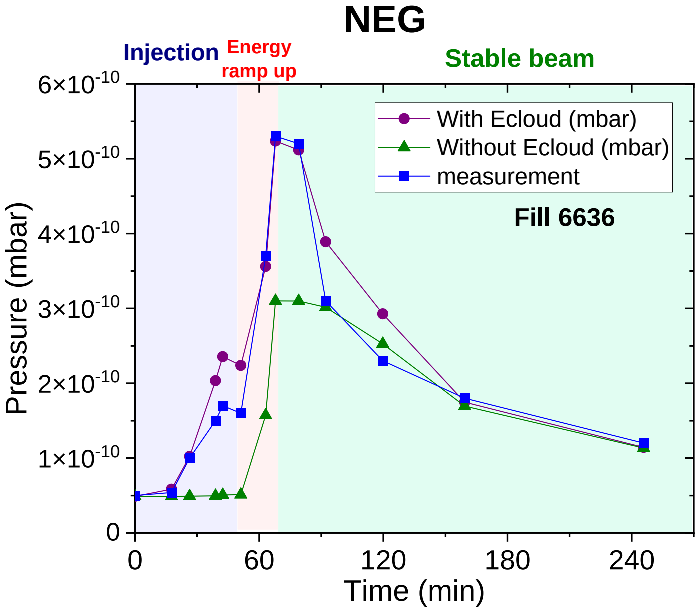
DYVACS reproduces the evolution of the partial pressures for H_2, CO_2, CO and CH_4 during beam operation

H_2 has the highest partial pressure

Pressure time evolution measurements vs DYVACS simulations



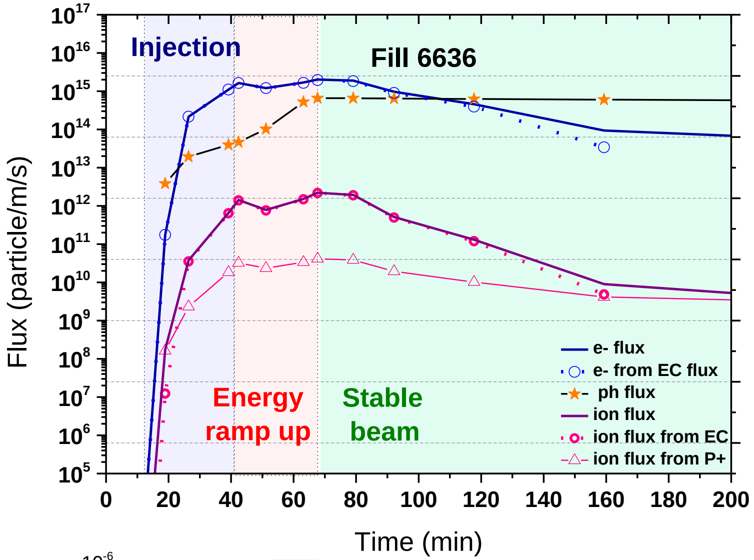


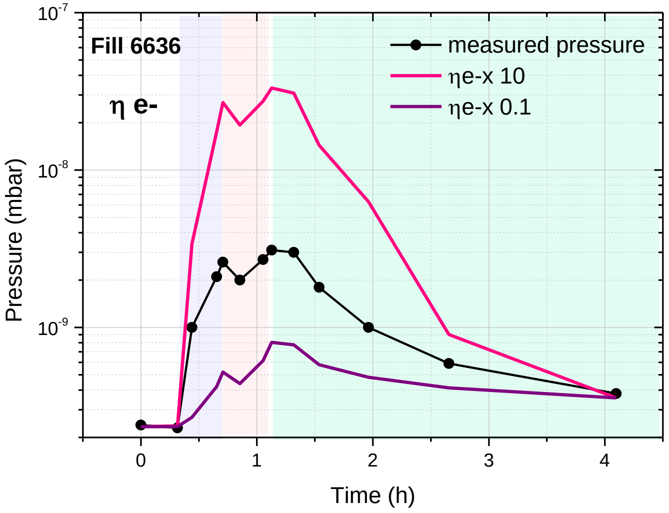


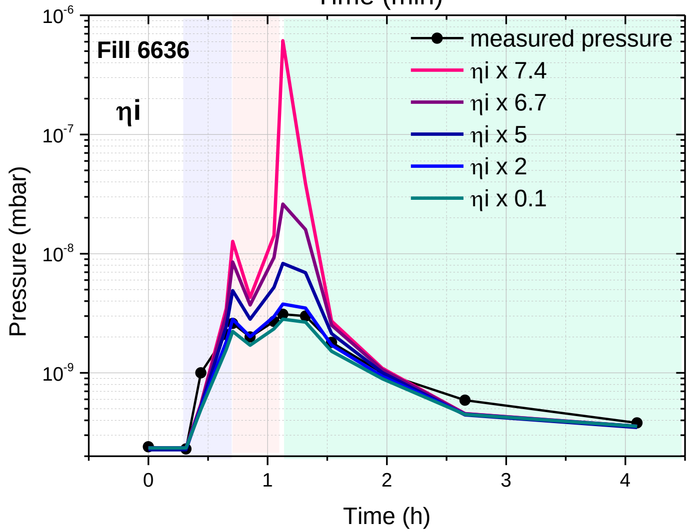
Simulation reproduces with a good agreement the in situ pressure evolution measured in station 4 (unbaked copper), station 2 C-Coating, station 1 NEG of VPS in the LHC.

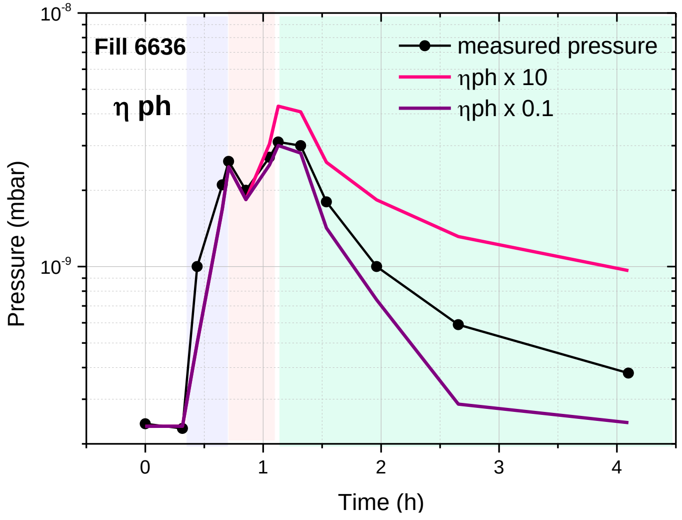
DYVACS - Gas density profiles

Pressure time evolution measurements vs DYVACS simulations









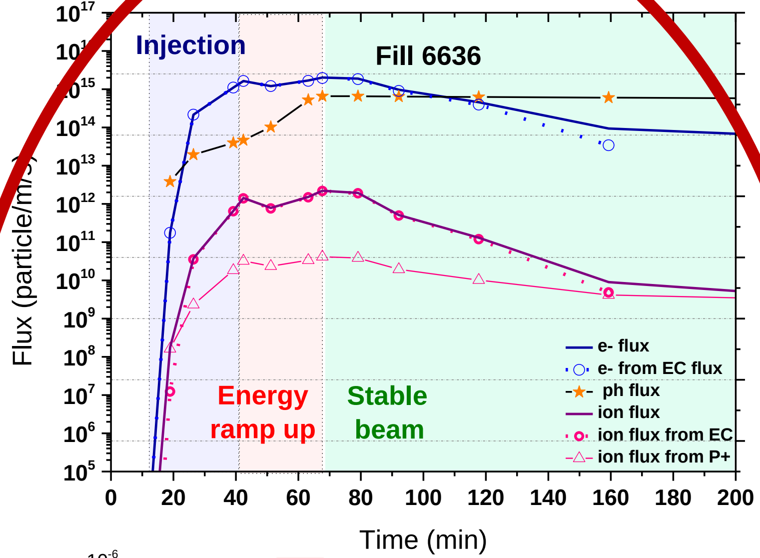
Because the code needs many input data to be run, measurement in laboratory are needed

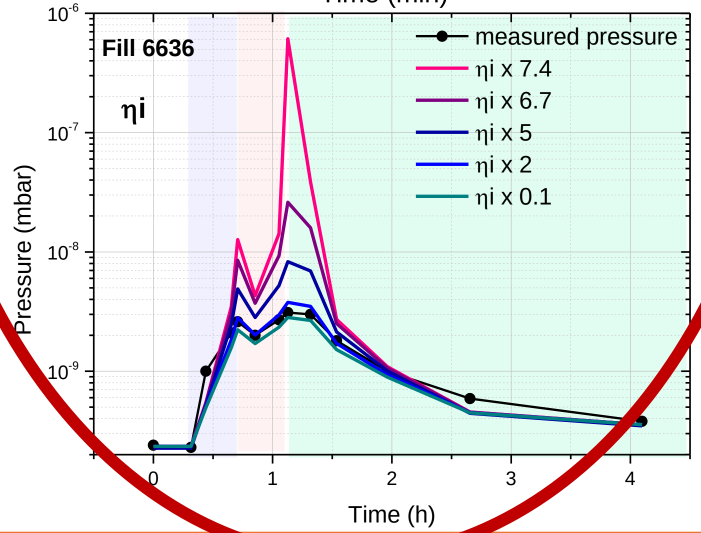
It is possible to play with all phenomena independently

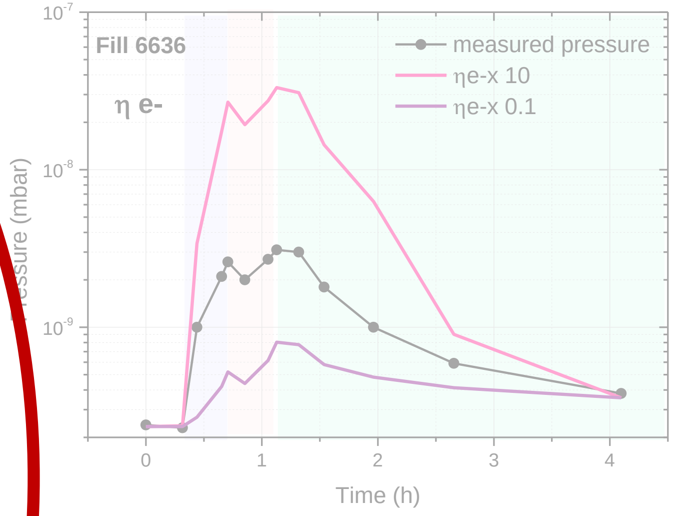
Fill	Yield (molec/ion)	H_2	CH_4	CO	CO_2
6636	$\eta_i - H_2$	0.54	0.54	0.54	0.54
	$\eta_i - CH_4$	0.04	0.05	0.07	0.11
	$\eta_i - CO$	0.25	0.29	0.29	0.33
	$\eta_i - CO_2$	0.14	0.14	0.14	0.14
	η_e	4.2×10^{-3}	8.3×10^{-5}	1.7×10^{-4}	8.3×10^{-4}
	η_{ph}	2.5×10^{-4}	2.3×10^{-5}	1.8×10^{-5}	3.5×10^{-5}

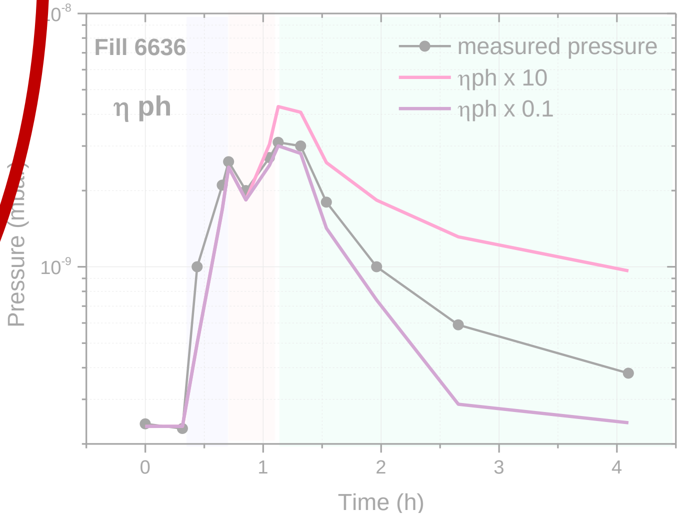
DYVACS - Gas density profiles

Pressure time evolution measurements vs DYVACS simulations









The flux of different particle is essential to determine the dominant parameter driving the pressure evolution,

Because: ISD yield is higher than ESD and PSD yields, a small amount of ions can have a huge impact on pressure evolution

Ions in particle accelerators

origin of ion production?

Residual gas density evolution	+	Secondary particle creation

Pressure evolution

i^+ e^-

1) In situ measurements during the LHC run II

2) Simulation of dynamic vacuum during the LHC run II

3) **Conclusion and perspectives**

suheyla.bilgen@ijclab.in2p3.fr

Conclusion

Goal: Understand the role played by ions and identify dominant parameters which drive the pressure evolution.

- ***In situ* measurements in the LHC** :

1) For the first time, a significant amount of positive ions has been detected in the VPS during the LHC beam operation.

→ *In sit*u measurements in the LHC are essential to improve our understanding of complex phenomena occurring in the LHC beam pipes

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A simulation code called DYVACS was developed and used to successfully compute **the dynamic pressure in the VPS**, by taking into account the influence of the EC density build-up and the ionization of residual gas by the EC.

→ DYVACS needs material parameters (ISD, ESD, PSD, SEY) and EC density parameters (depending on beam parameters and vacuum chamber dimensions).

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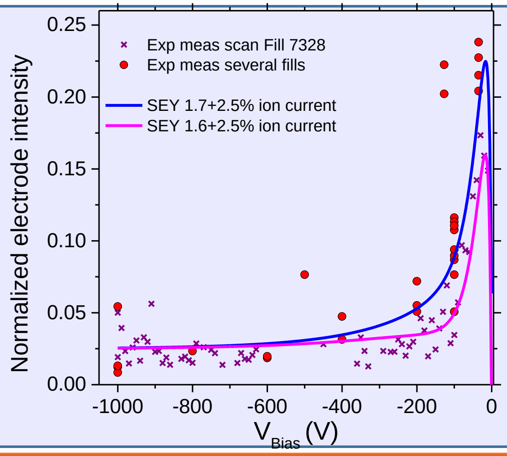
But…

Experimental measurements shows the amount of ions represents 2.5% of the electronic current in the VPS



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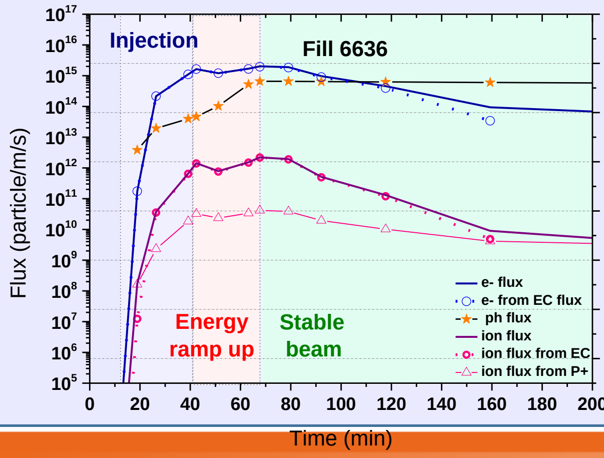

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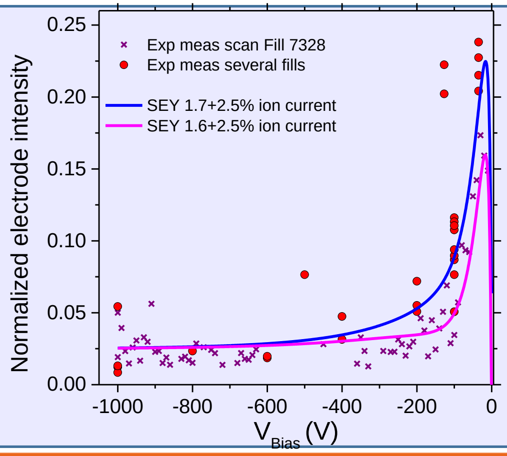

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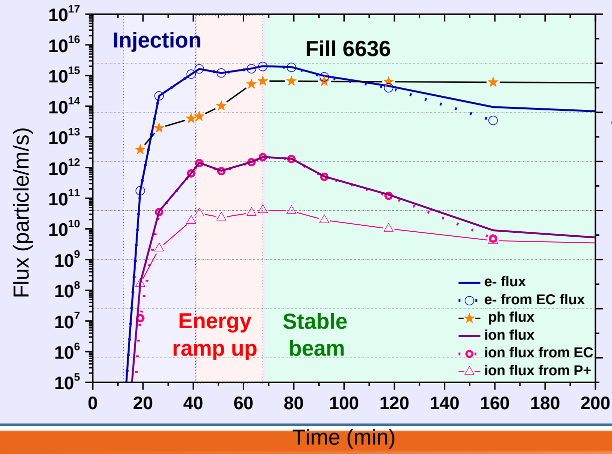

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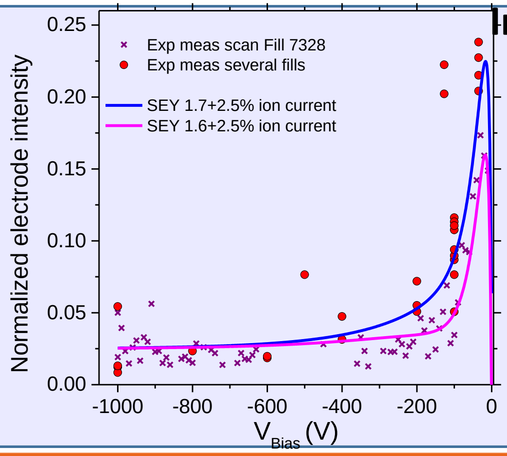
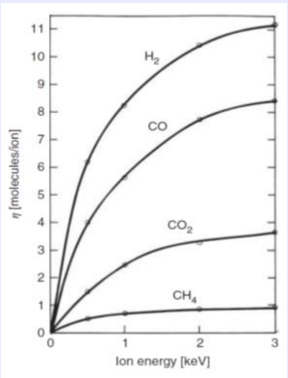
Something is missing → the ion energy spectrum! + ion production

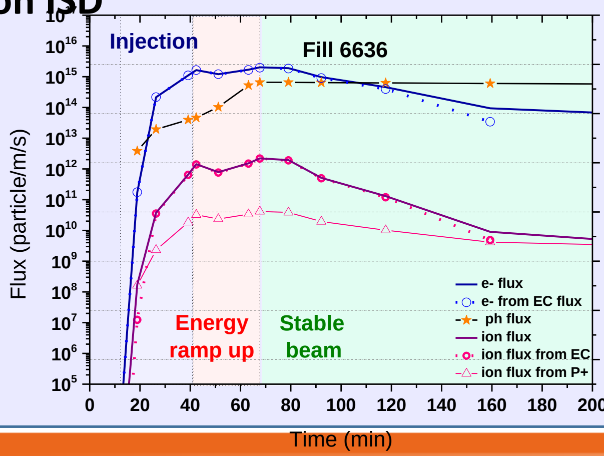
Experimental measurements shows the amount of ions represents 2.5% of the electronic current in the VPS



Influence of ion energy on ISD



(Mathewson, 1976)



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Thank you for your attention !

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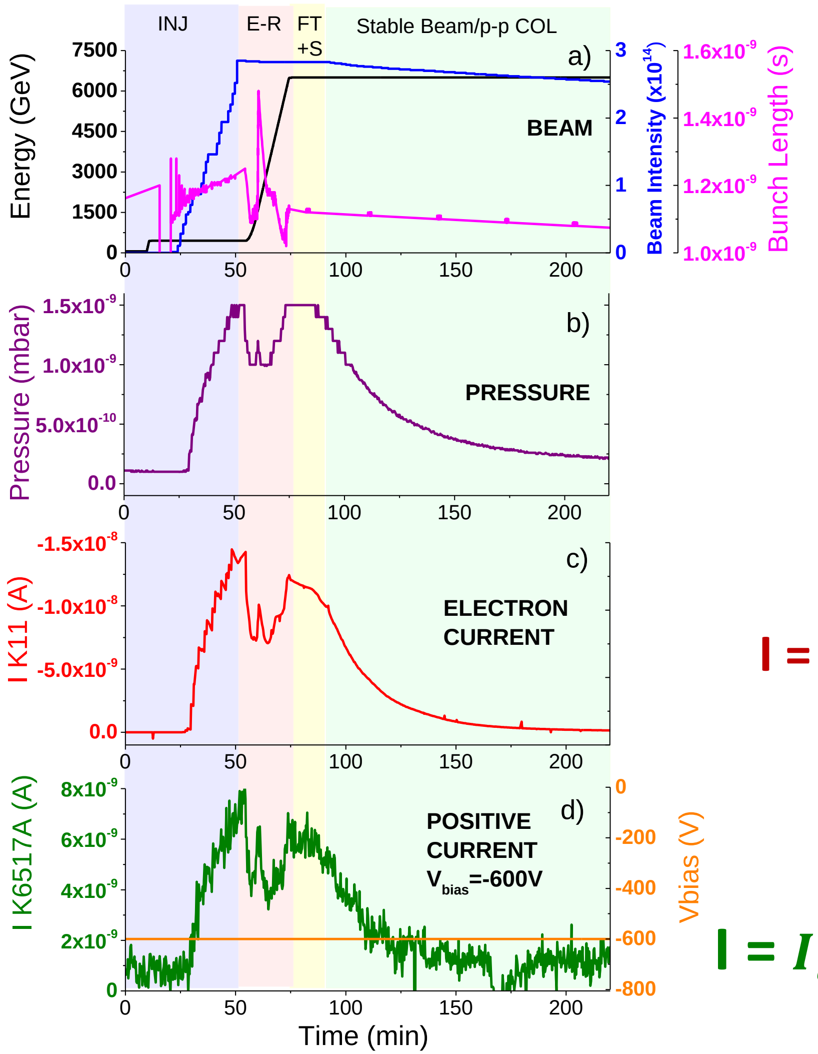
Fill for physics - 7319 - RUN II



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

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

$I = I_{e-}$

$I = I_{ion} + I_{e-(E>V_{bias})} + I_{SE}$ $\leftarrow$ ***ions***?