Dynamic pressure in particle accelerators
Simulation for the FCC studies

Suheyla BILGEN, Bruno MERCIER, Gaël SATTONNAY, Vincent BAGLIN*, Bernard HENRIST*

IJCLab - MAVERICS team of the Accelerator division
(Materials for Accelerator, dynamic Vacuum studiEs and innovative Research on superconductIng CavitieS)

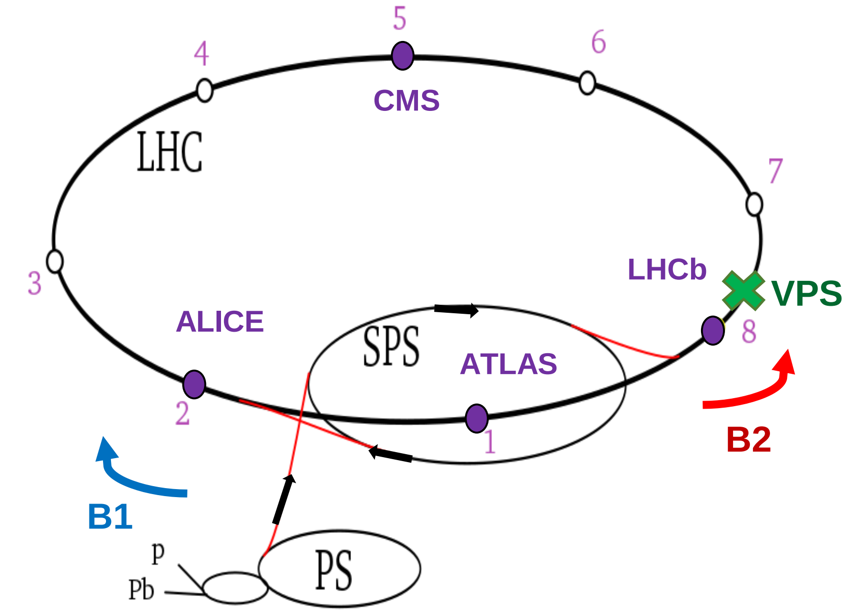
*CERN-TE-VSC team *(Vacuum, Surface and Coating)*

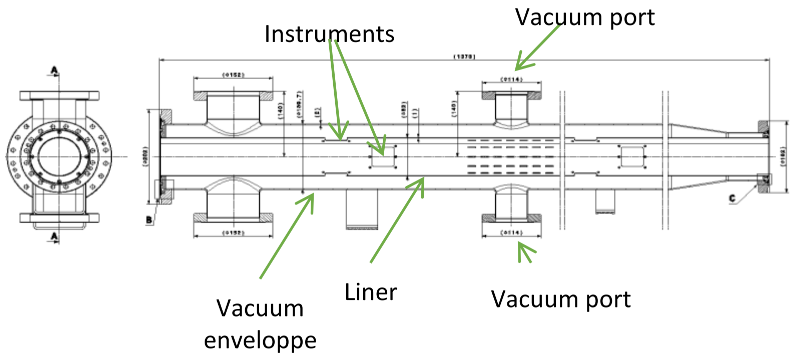
January 20, 2021

2nd FCC-France Workshop

Dynamic pressure in particle accelerators

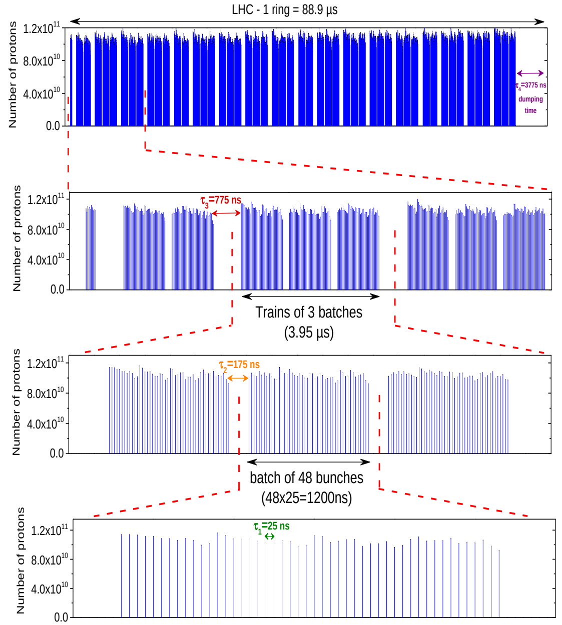
LHC





Bernard Henrist et al., 2014 « The LHC Vacuum Pilot Sectors Project »
doi: 10.18429/JACoW-IPAC2014-WEPME042.

LHC beam pattern

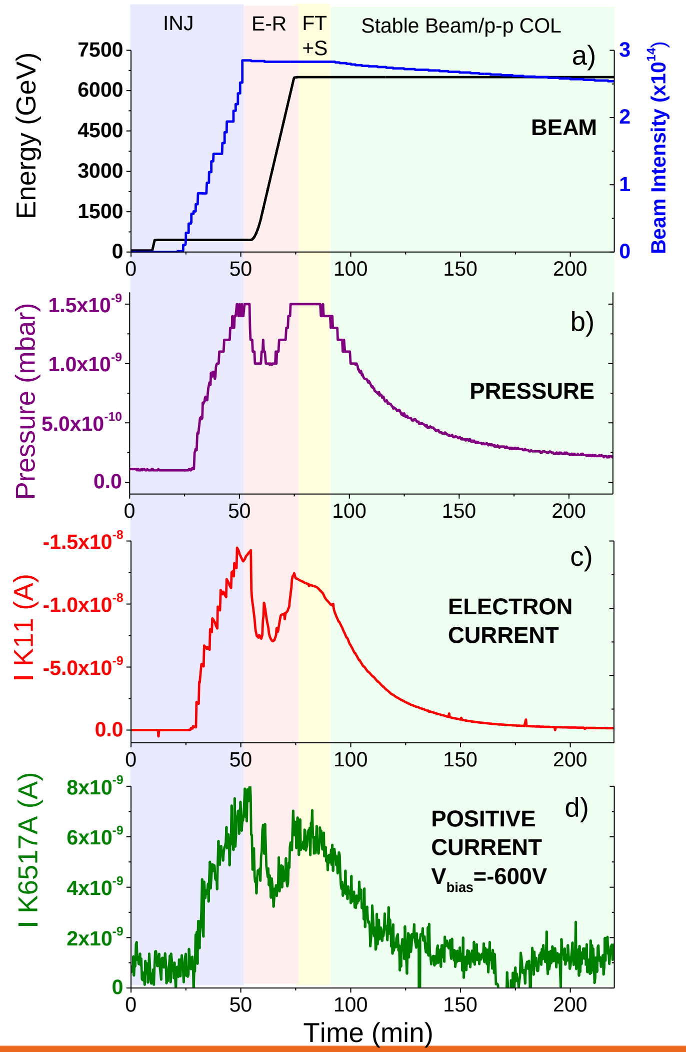


25ns_2556b_144bpi_20inj

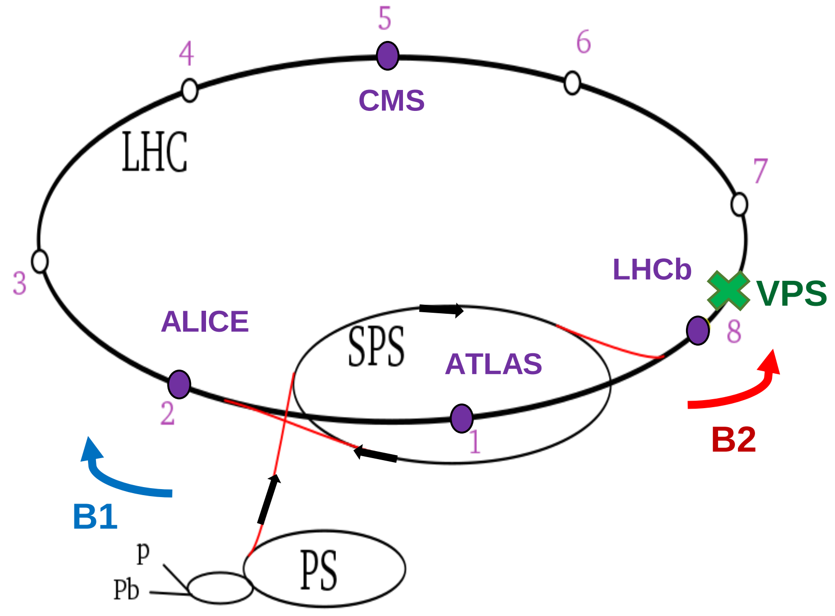
Parameters	Injection	Collision
Proton momentum (GeV/c)	450	6500
Bunch spacing (ns)	25	25
Bunch intensity (10^{11} proton/bunch)	1.3	1.25
Max colliding bunches	2820	2556
Norm transverse emittance (µm)	2.6	2.5

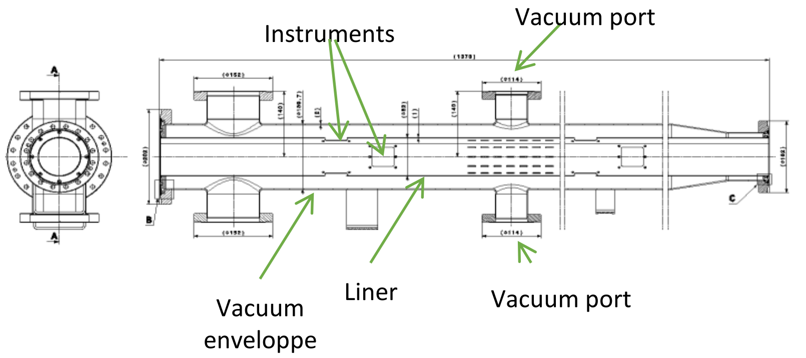
LHC Fill time evolution

Fill for physics - 7319 - RUN II



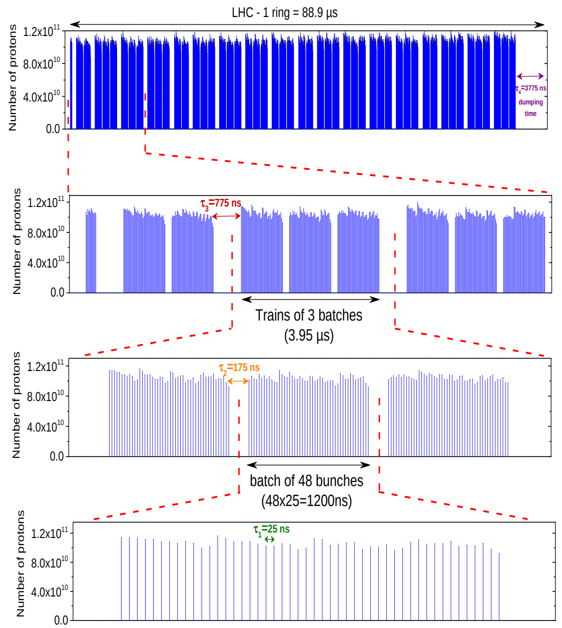
LHC





Bernard Henrist et al., 2014 « The LHC Vacuum Pilot Sectors Project »
doi: 10.18429/JACoW-IPAC2014-WEPME042.

LHC beam pattern

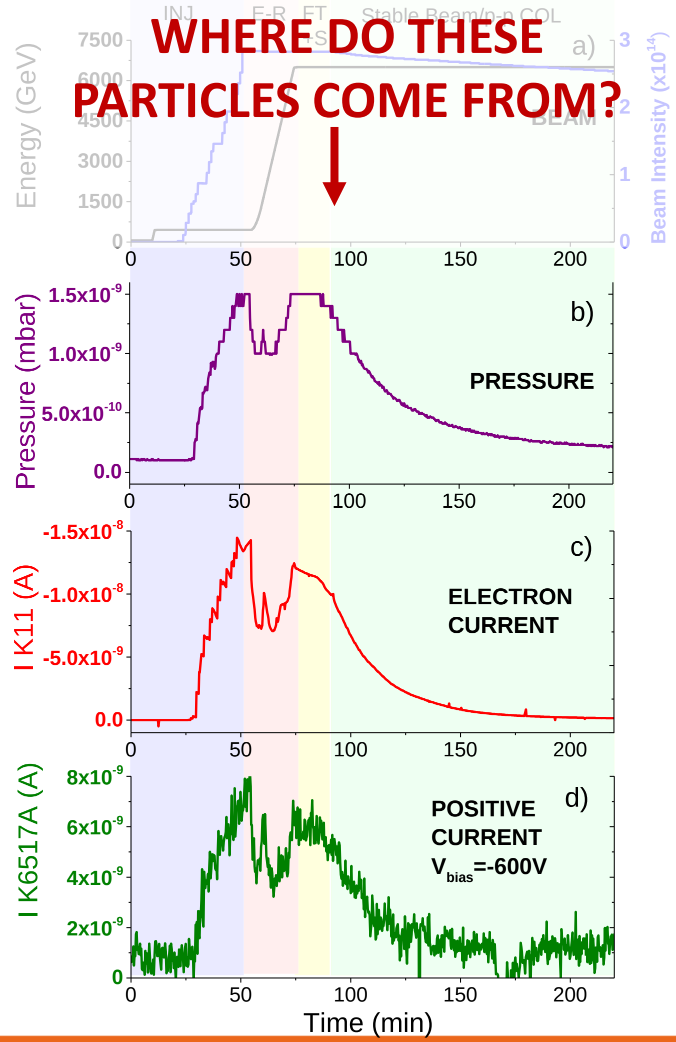


25ns_2556b_144bpi_20inj

Parameters	Injection	Collision
Proton momentum (GeV/c)	450	6500
Bunch spacing (ns)	25	25
Bunch intensity (10^{11} proton/bunch)	1.3	1.25
Max colliding bunches	2820	2556
Norm transverse emittance (µm)	2.6	2.5

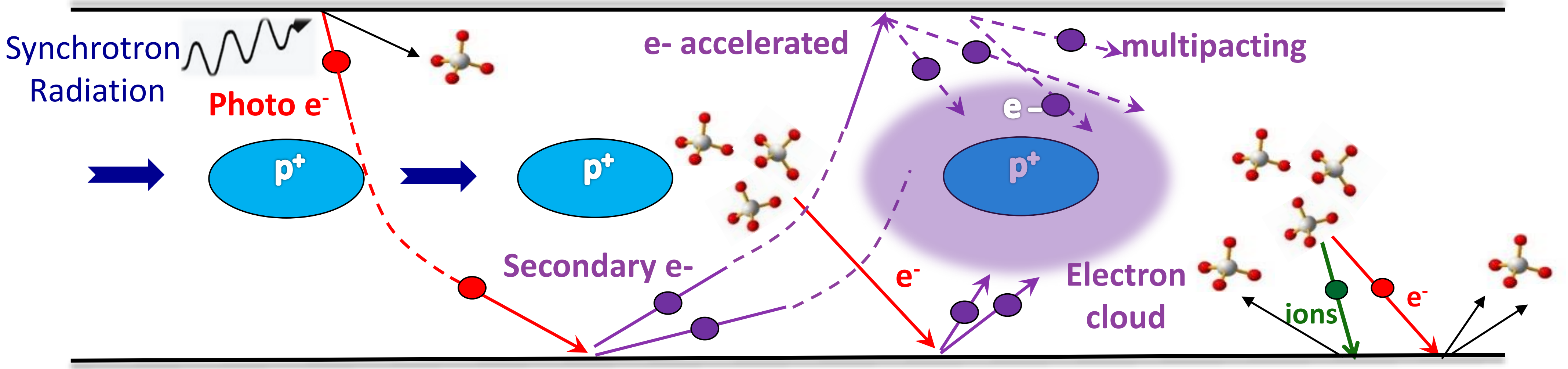
LHC Fill time evolution

Fill for physics - 7319 - RUN II



Stimulated desorption and secondary particle creation

All of these phenomena affect the LHC beam

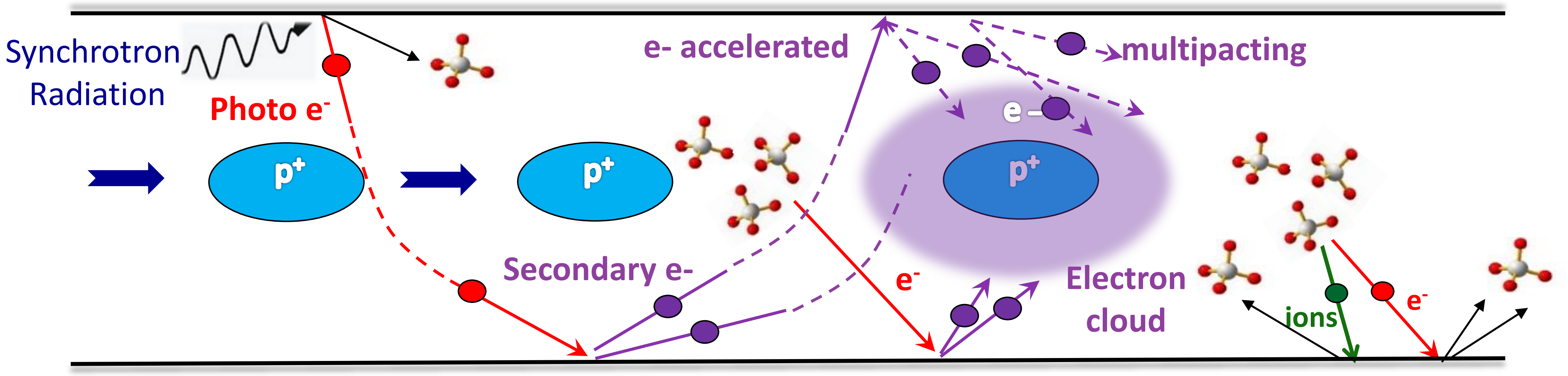


Consequences of these phenomena → Pressure increase and EC formation →

- Increase of beam emittance
- Beam instabilities
- Beam losses ...

Stimulated desorption and secondary particle creation

All of these phenomena affect the LHC beam



To achieve high performances, it is essential to understand accelerator dynamic pressure in order to find solutions to improve beam quality and perform high energy particle physics.

Objectives

Goal: To develop a new simulation code and to compute the dynamic pressure in Future particle accelerators, as FCC, using experimental inputs.

I. DYVACS Code

II. SEY and ISD measurements

III. Simulation *vs* measurements

IV. Conclusion and perspectives

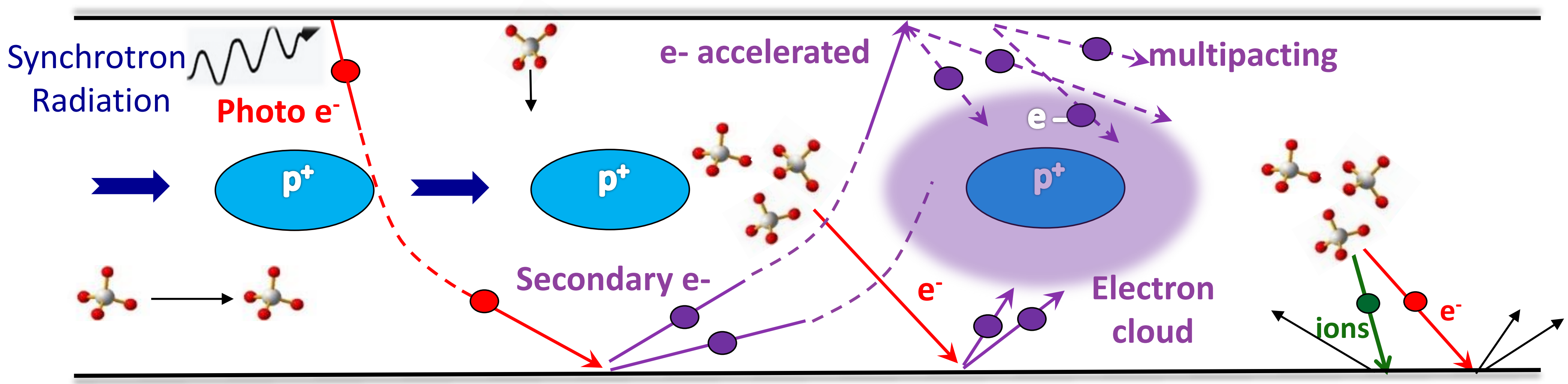
Analytical model of the dynamic pressure – DYVACS – DYnamic VACuum Simulation code

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

DYVACS is based on the gas balance differential equation

It is used to compute the gas density n_j

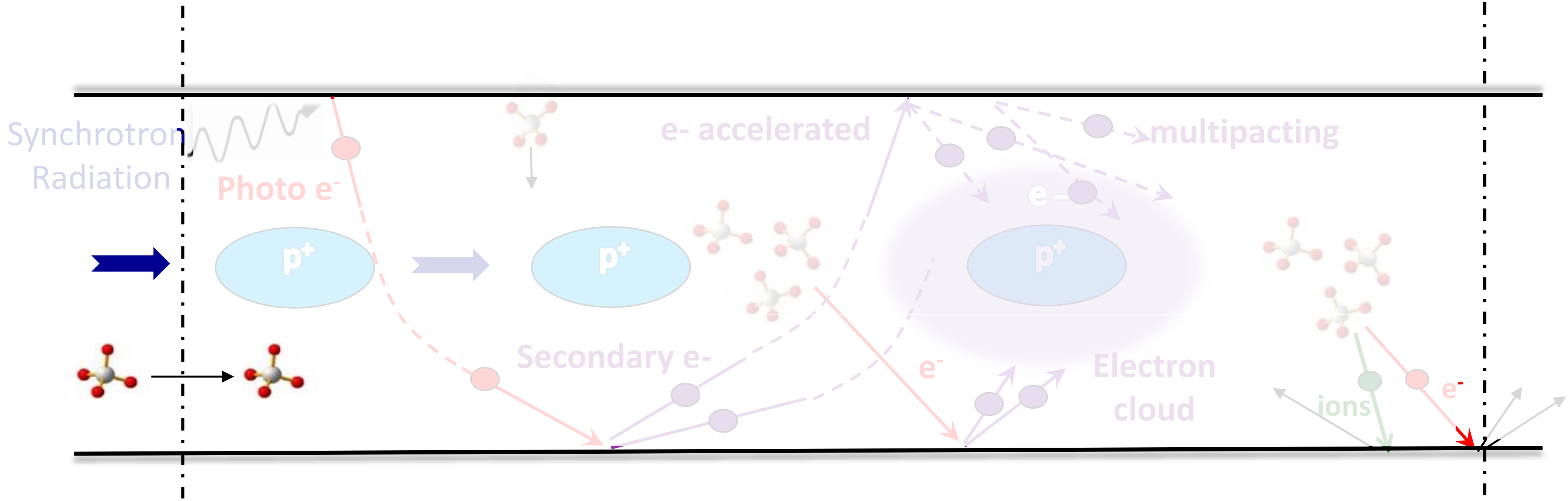
for j= H_2, CH_4, CO, CO_2



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

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

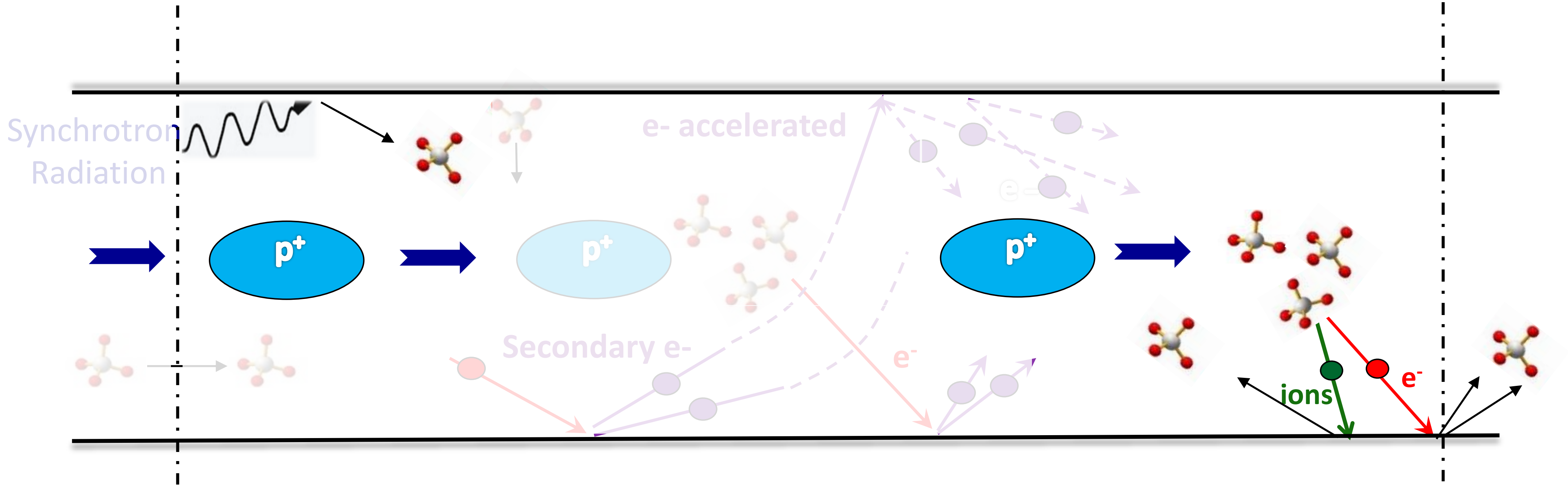
C_j is the specific conductance for j gas species



Inputs: C_j,,

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

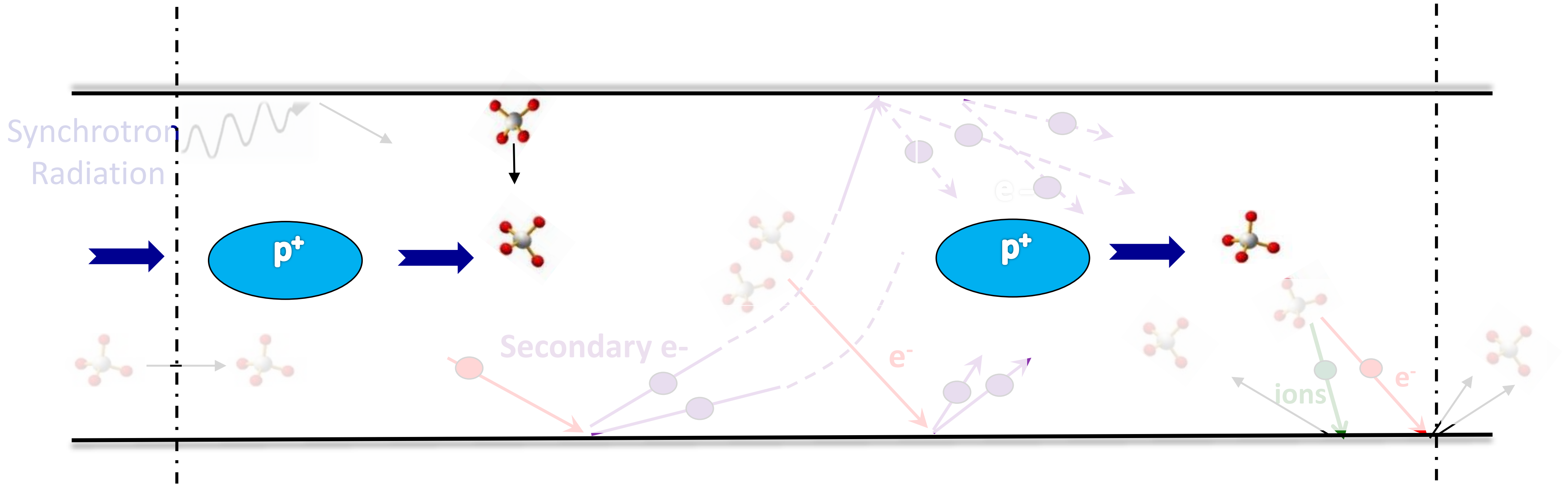
$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$



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

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

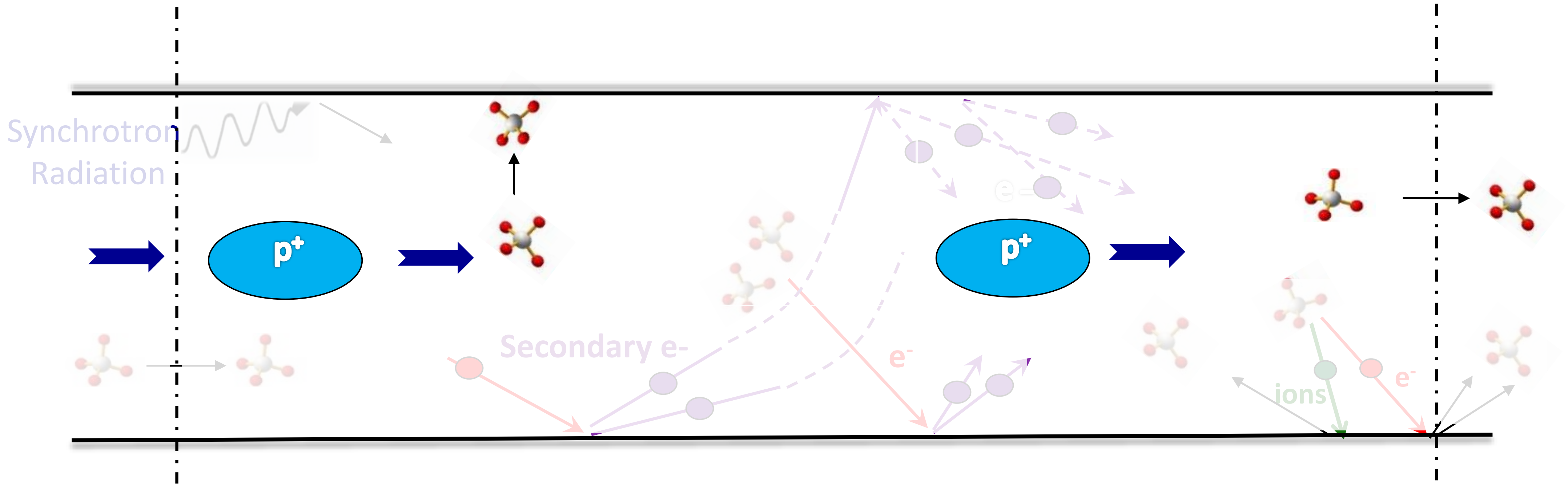


Inputs: C_j,, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$,

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 ,

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

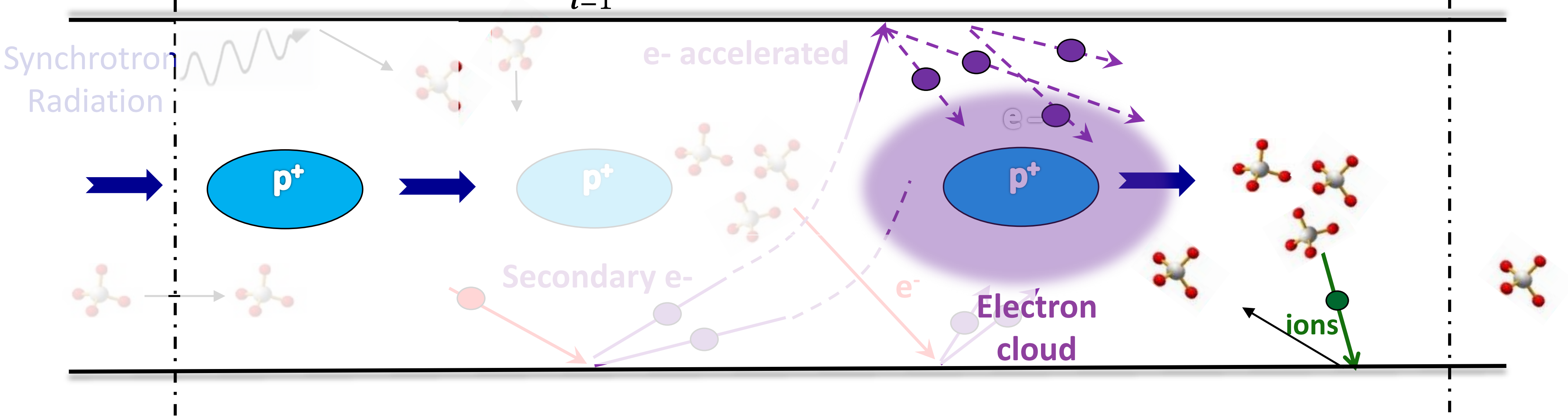
$$C_j \frac{\partial^2 n_j}{\partial x^2} + D_{ion-j} + D_{e-j} + D_{ph-j} + D_{th-j} - S \cdot n_j = 0$$

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

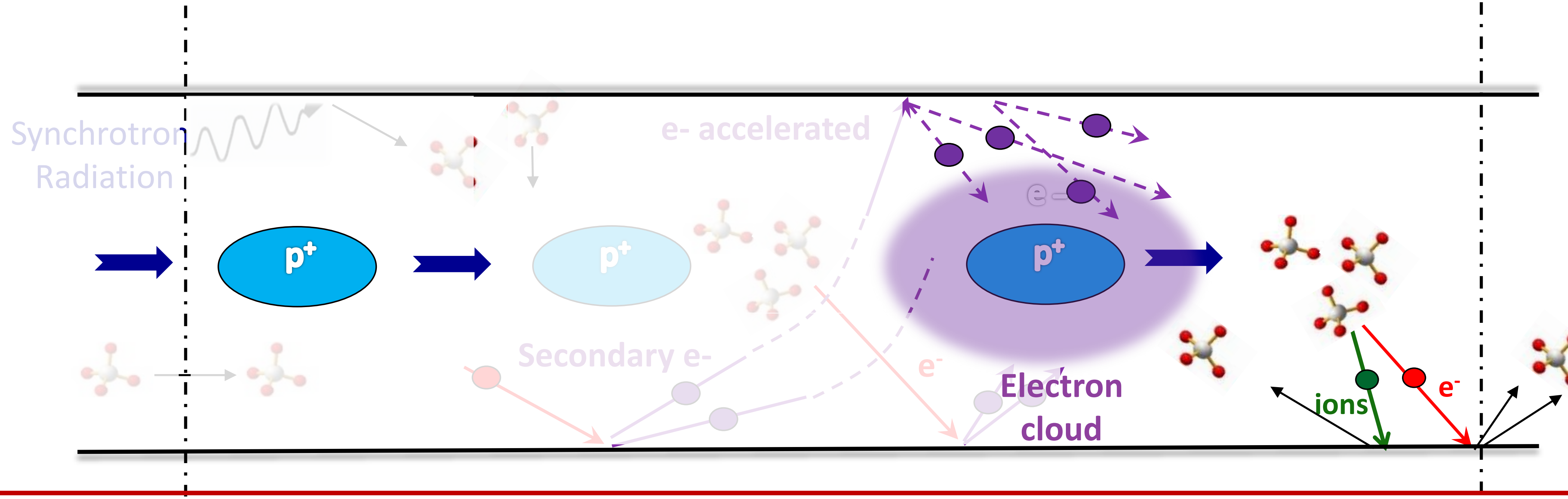


Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j, $\sigma_{p\to i}$, $\sigma_{e\to i}$, I_{beam}, ρ_e, v_e,

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

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

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

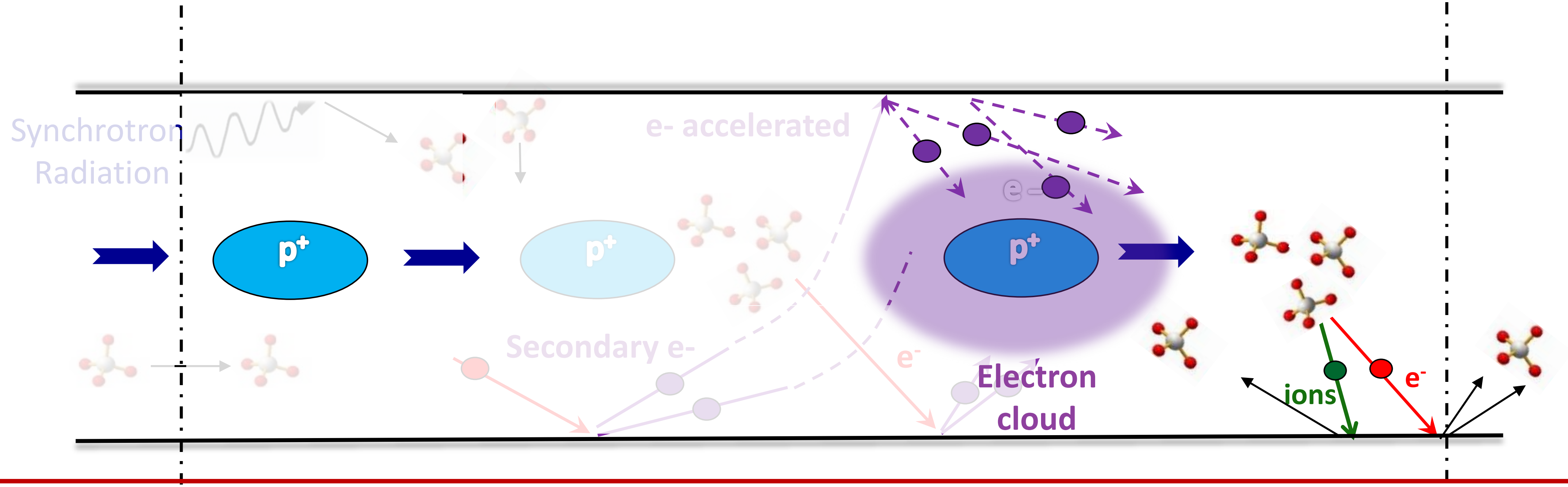


Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j, $\sigma_{p\rightarrow i}$, $\sigma_{e\rightarrow i}$, I_{beam}, ρ_e, v_e, a, b, c, size of the segment, radius BP, E_{beam}, time of one turn, etc.

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

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

Many inputs are necessary → measurements in laboratory are needed!



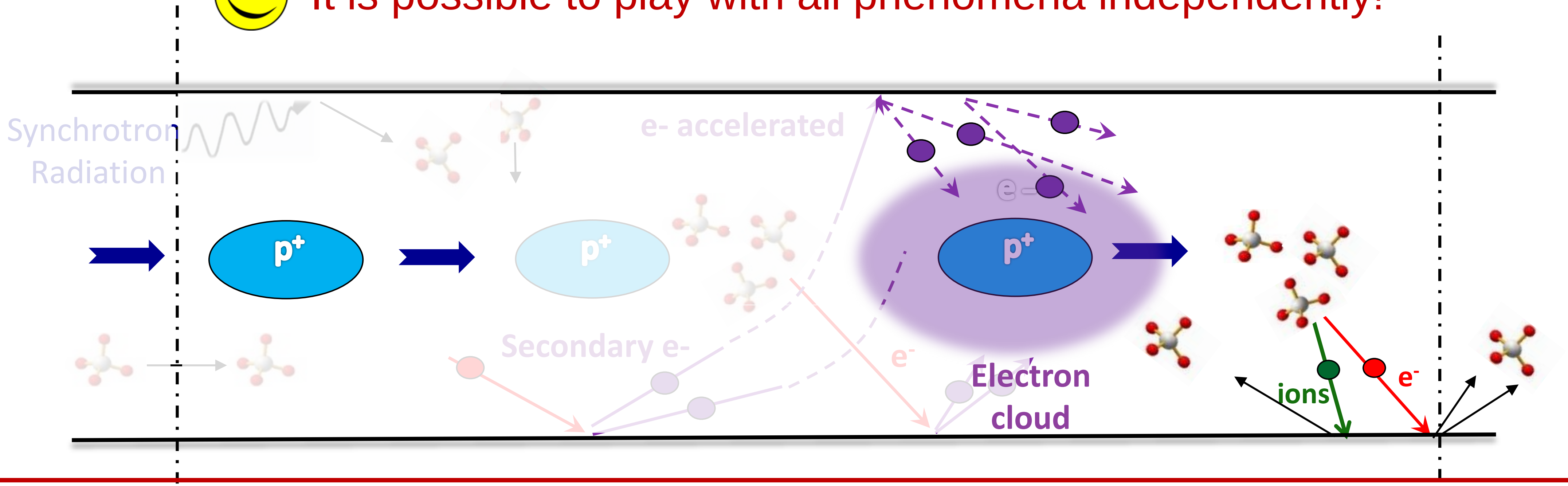
Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j, $\sigma_{p\to i}$, $\sigma_{e\to i}$, I_{beam}, ρ_e, v_e, a, b, c, size of the segment, radius BP, E_{beam}, time of one turn, etc.

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

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

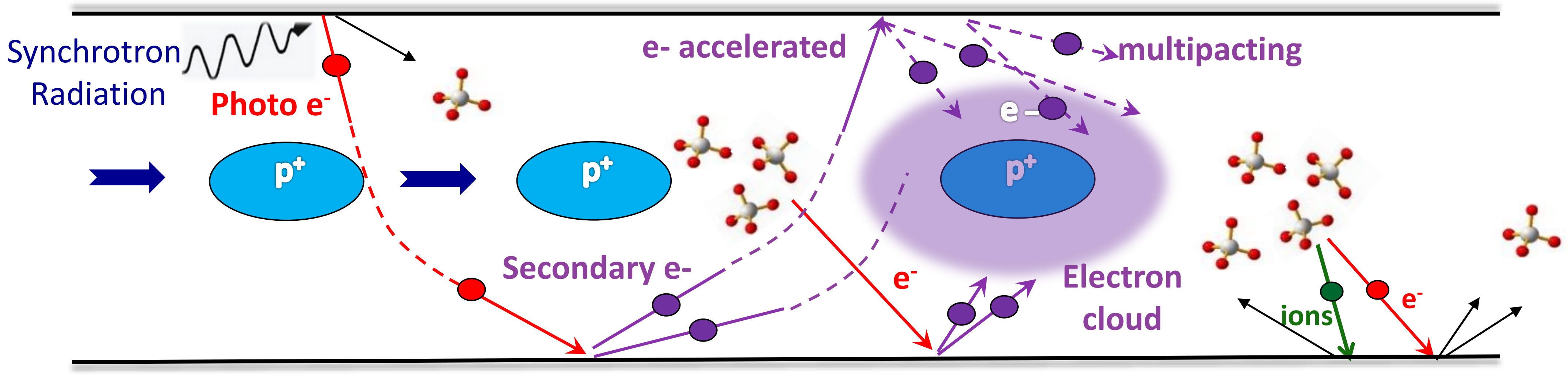
Many inputs are necessary → measurements in laboratory are needed!

It is possible to play with all phenomena independently!

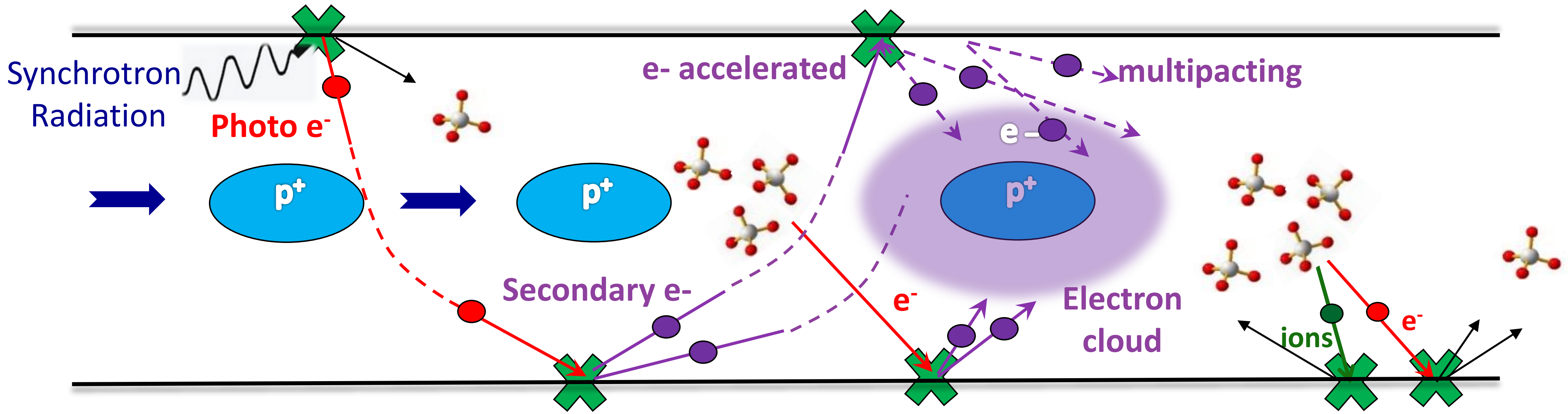


Inputs: C_j, $\eta_{i,j}$, $\eta_{e,j}$, $\eta_{ph,j}$, Γ_i, Γ_e, Γ_{ph}, $q_{th,j}$, S_j, $\sigma_{p\to i}$, $\sigma_{e\to i}$, I_{beam}, ρ_e, v_e, a, b, c, size of the segment, radius BP, E_{beam}, time of one turn, etc.

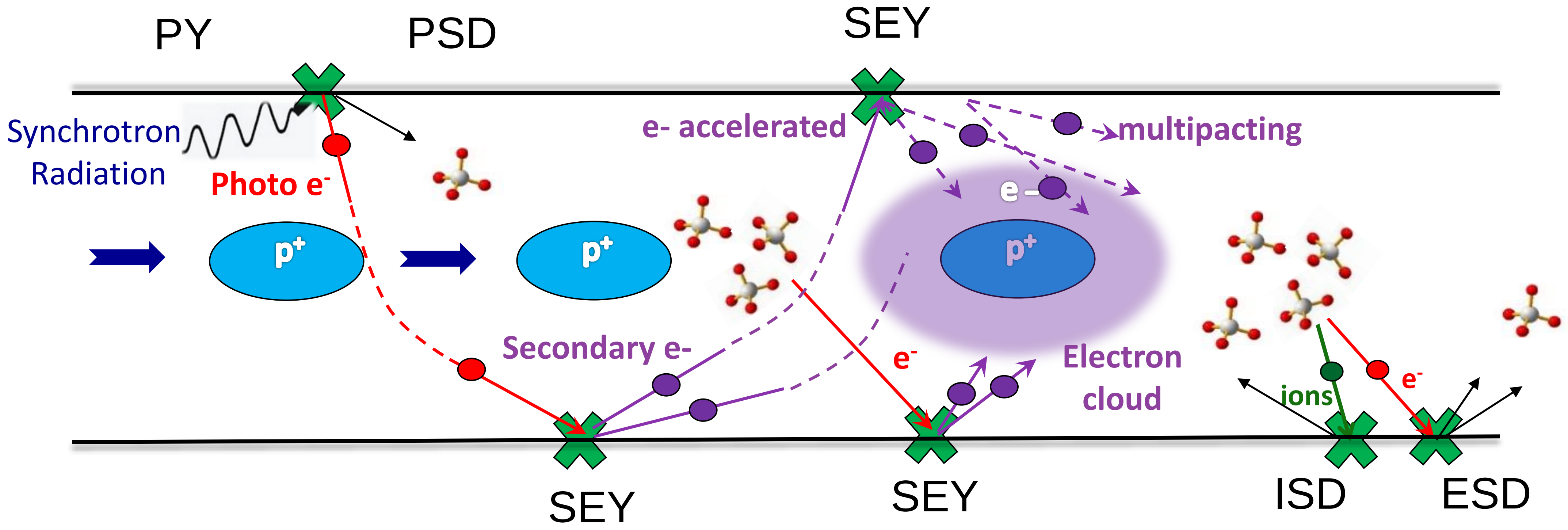
Dynamic pressure in particle accelerators



Particle / Surface interactions

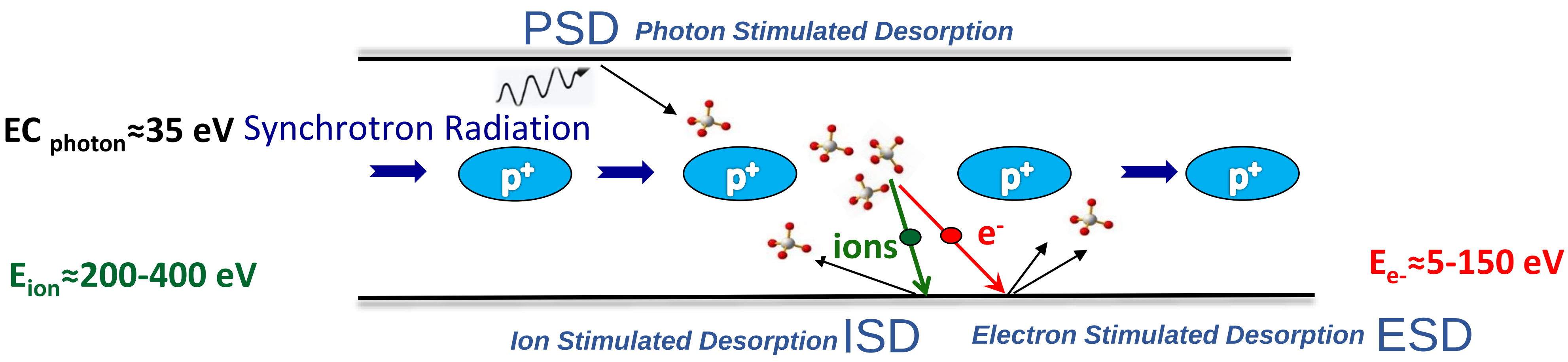


Particle / Surface interactions



Dynamic pressure in particle accelerators

$$\text{ESD, ISD, PSD} \rightarrow yield = \frac{number\ of\ gas\ molecule\ desorbed}{incident\ particle\ (e-, ion\ or\ ph)}$$



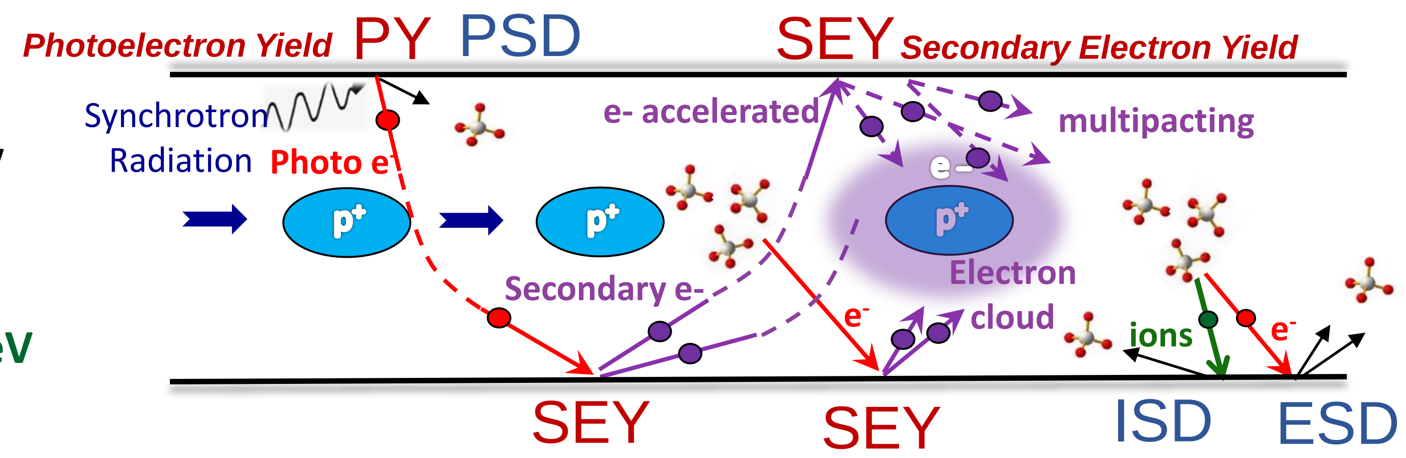
Dynamic pressure in particle accelerators

$$\text{ESD, ISD, PSD} \rightarrow yield = \frac{number\ of\ gas\ molecule\ desorbed}{incident\ particle\ (e-, ion\ or\ ph)}$$

$$\text{PY, SEY} = \frac{number\ of\ electrons\ emitted\ from\ the\ surface}{incident\ particle\ (ph\ or\ e-)}$$

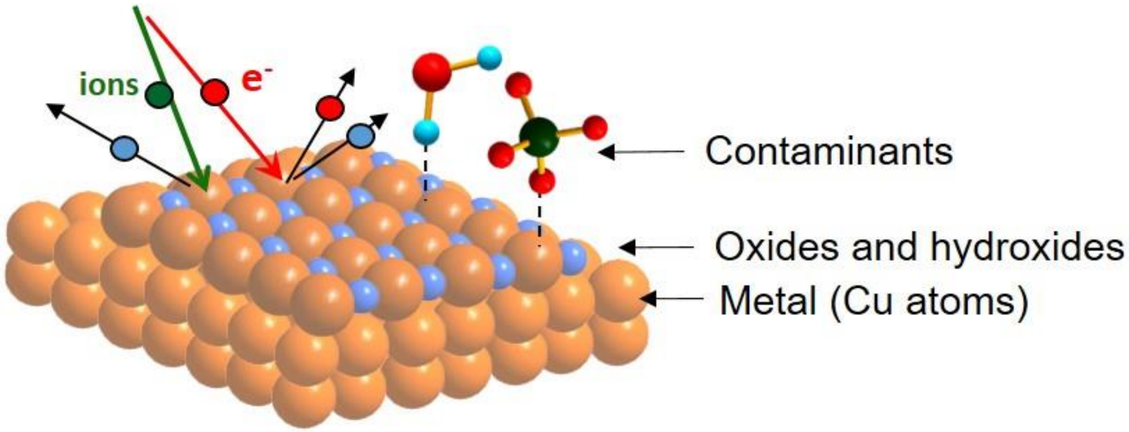
EC $_{photon}$**≈35 eV**

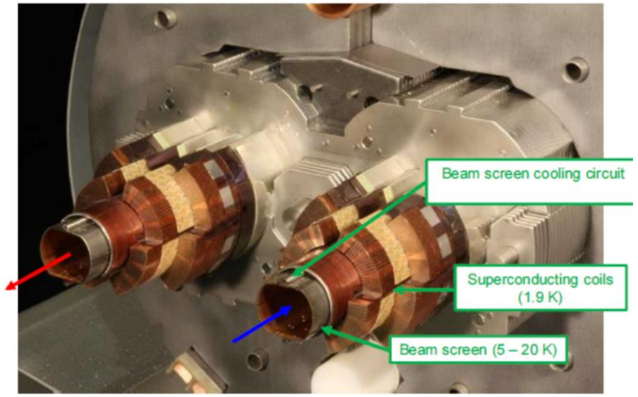
E$_{ion}$**≈200-400 eV**



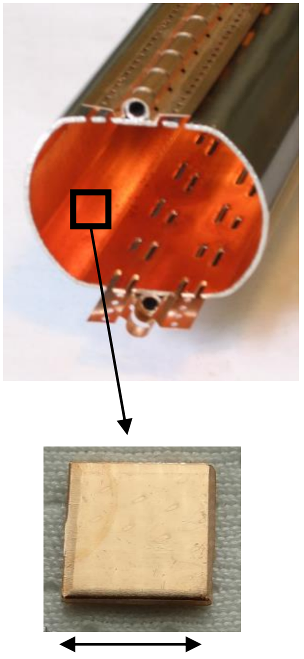
E$_{e-}$**≈5-150 eV**

Which surface to consider?





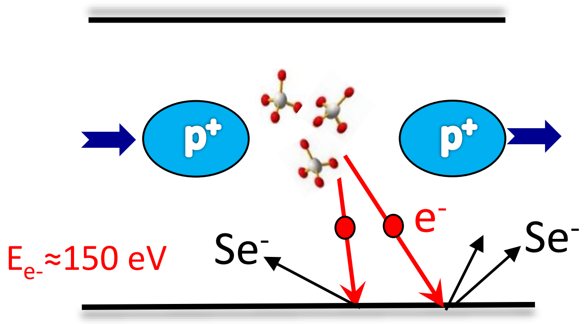
→ All surface yield parameters: SEY, ISD, ESD, PSD, PY etc. **depend on the surface properties**.
→ A surface is composed of pollutants (whatever cleaning is done!) then a layer of native oxide before considering the metal contribution.
→ We must keep in mind that we investigate surfaces in accelerators which are **technical surfaces**.

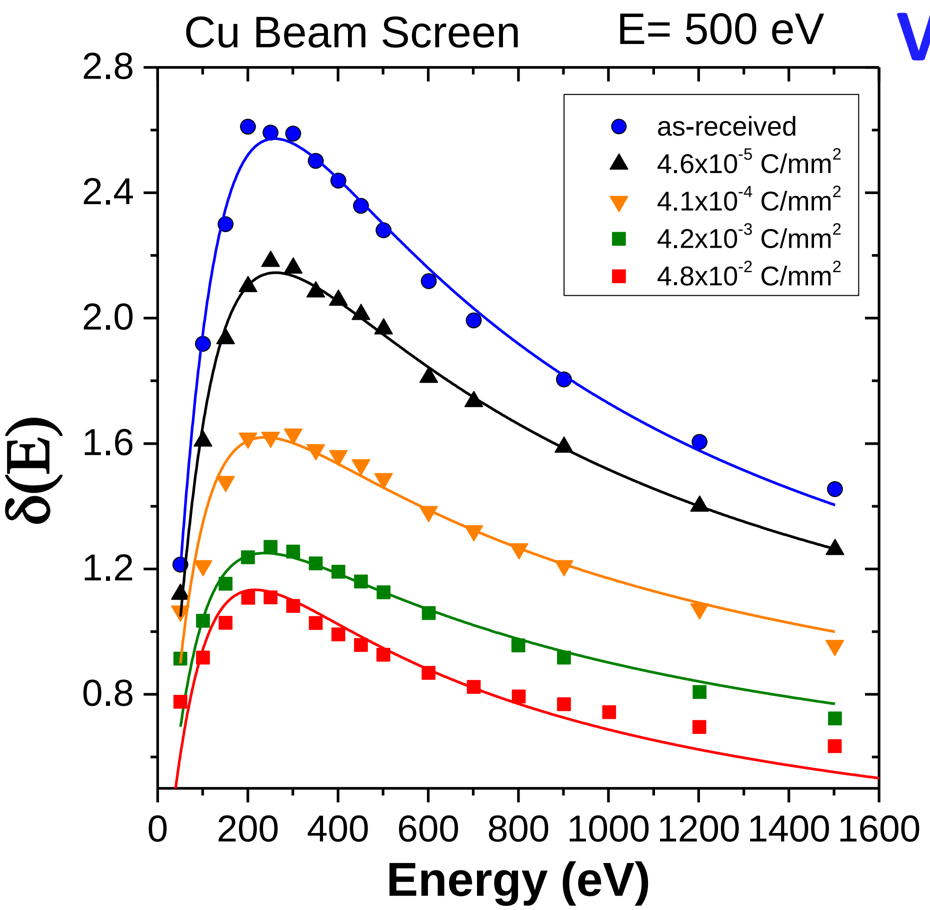


All laboratory measurements have to be performed directly on these surfaces

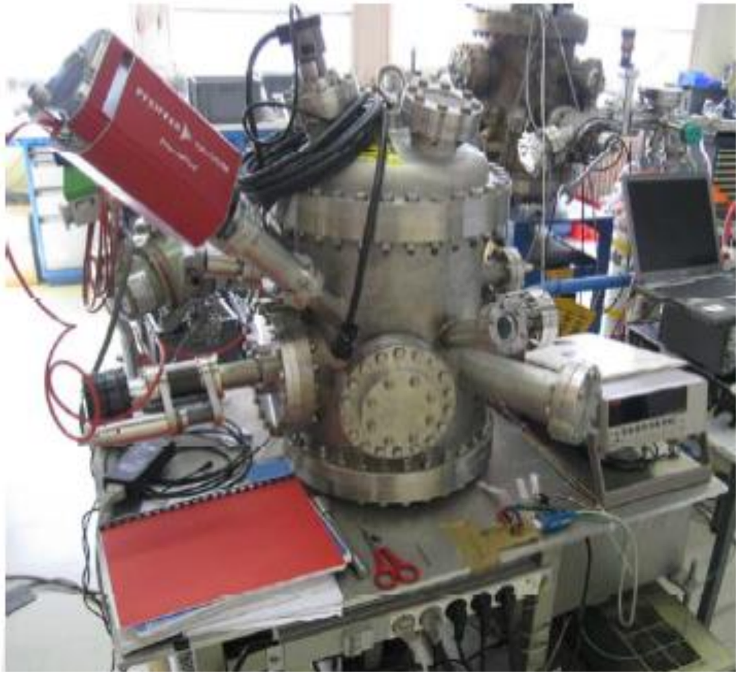
SEY measurements at IJC-Lab

$$SEY = \frac{number\ of\ SE}{incident\ e-}$$



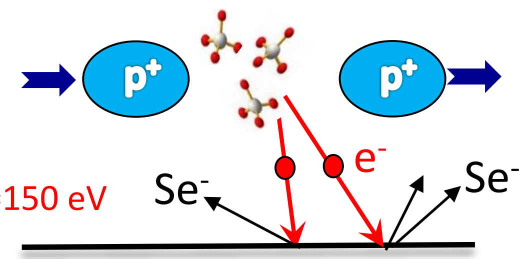


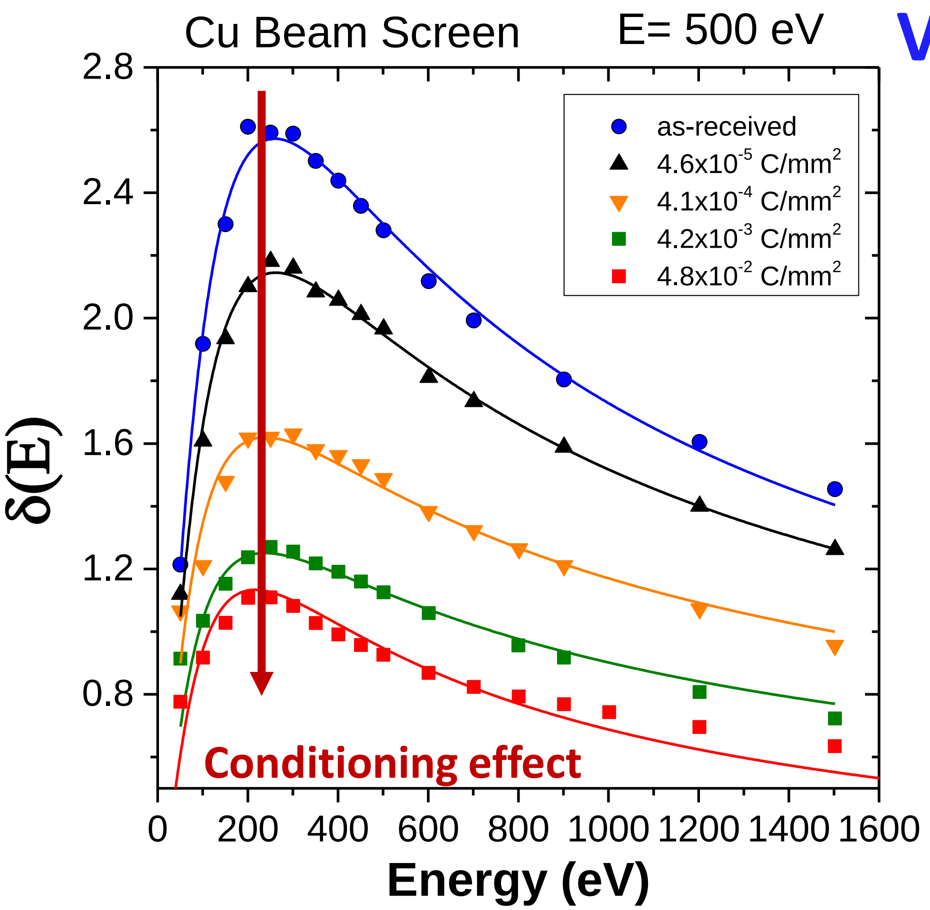
Vacuum & Surface Platform



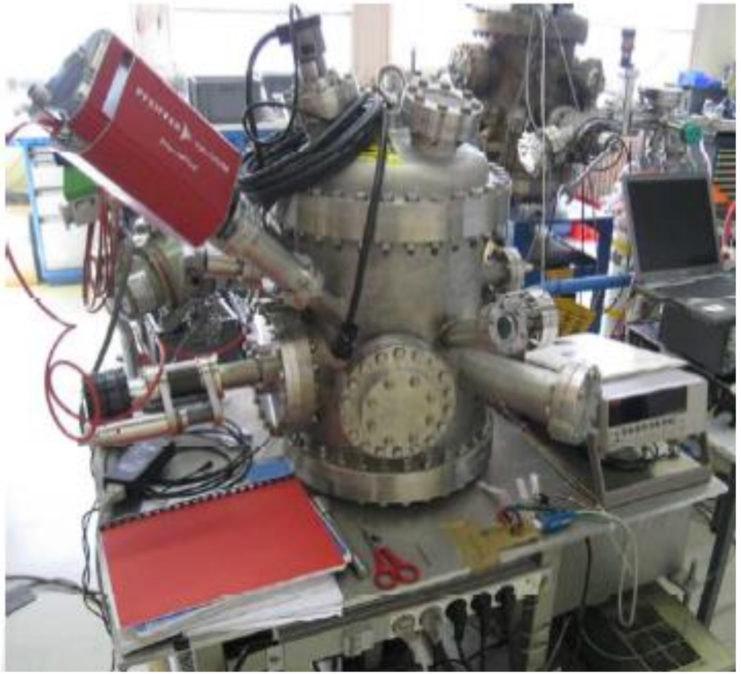
SEY measurements at IJC-Lab

$$SEY = \frac{number\ of\ SE}{incident\ e-}$$



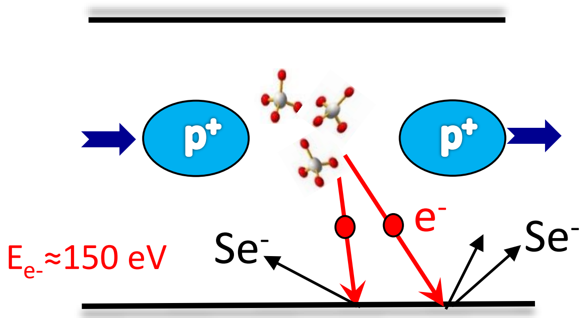


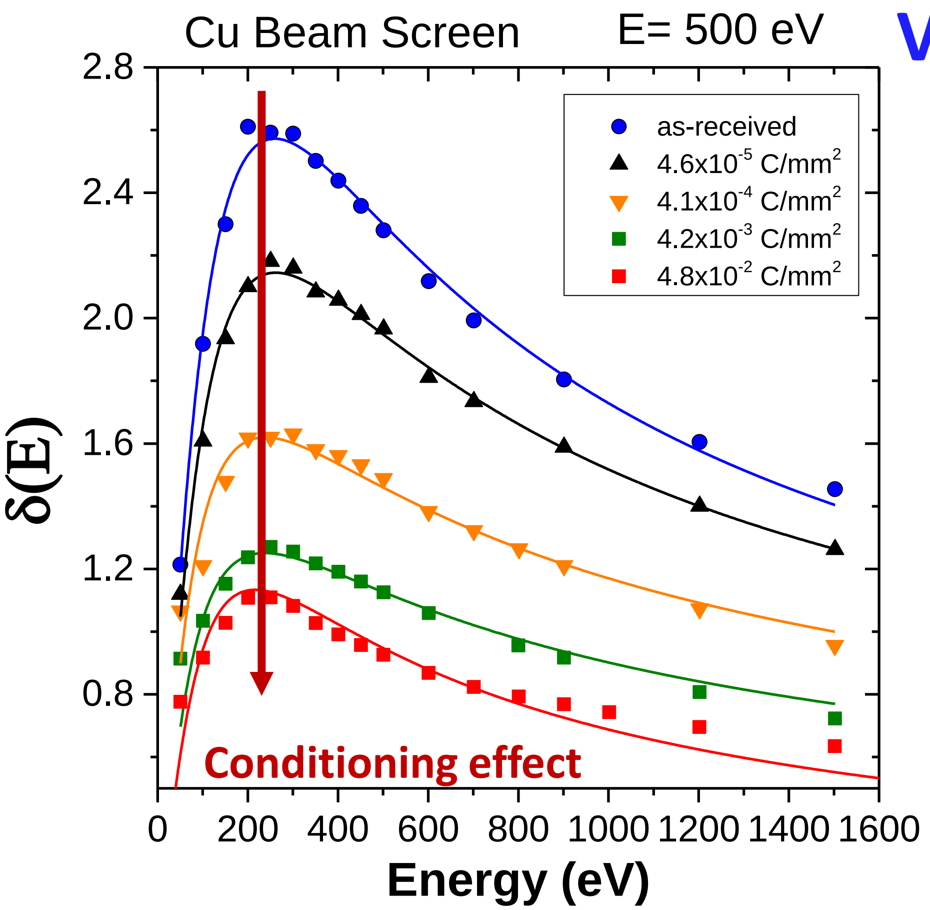
Vacuum & Surface Platform



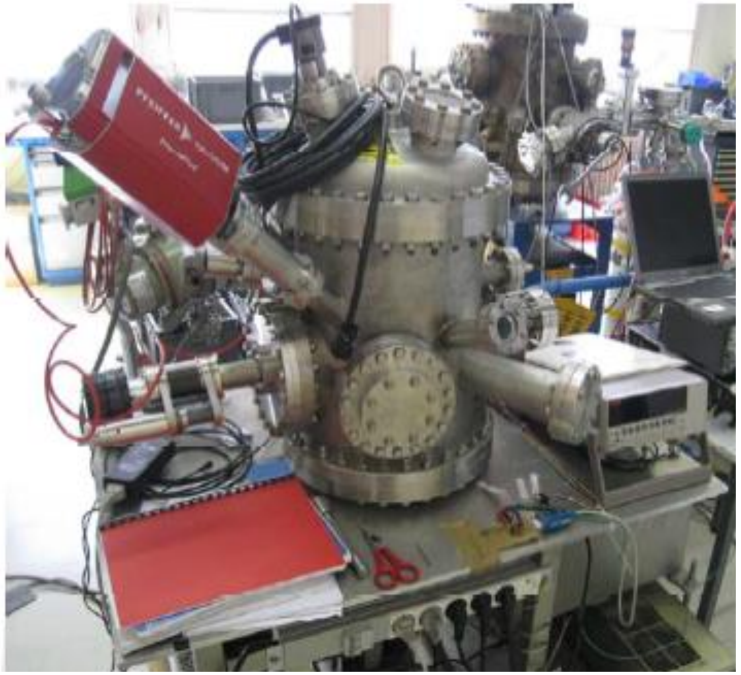
SEY measurements at IJC-Lab

$$SEY = \frac{number\ of\ SE}{incident\ e-}$$





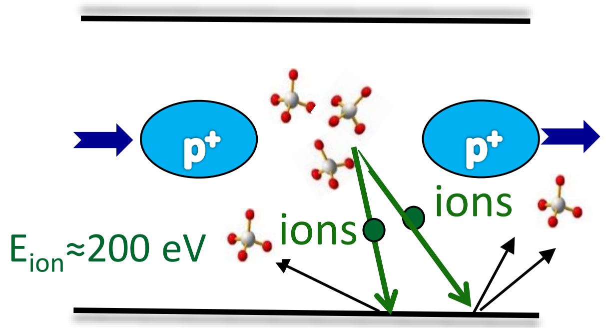
Vacuum & Surface Platform



The SEY ↘ when the e- dose ↗ due to a modification of the surface chemistry induced by electron bombardment.

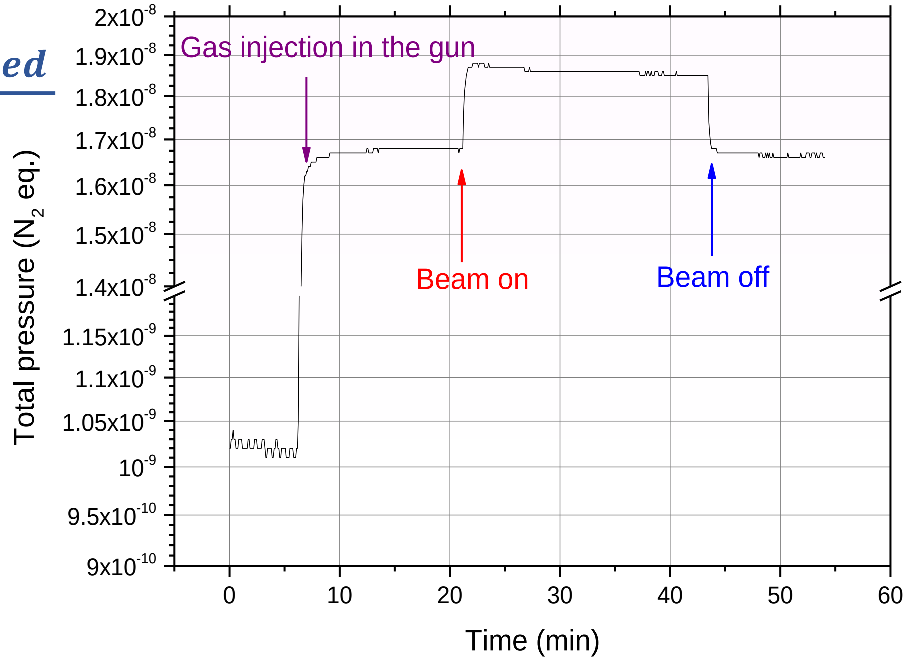
ISD measurements at CERN

$$\text{ISD} = \frac{\textit{number of gas molecule desorbed}}{\textit{incident } i+}$$

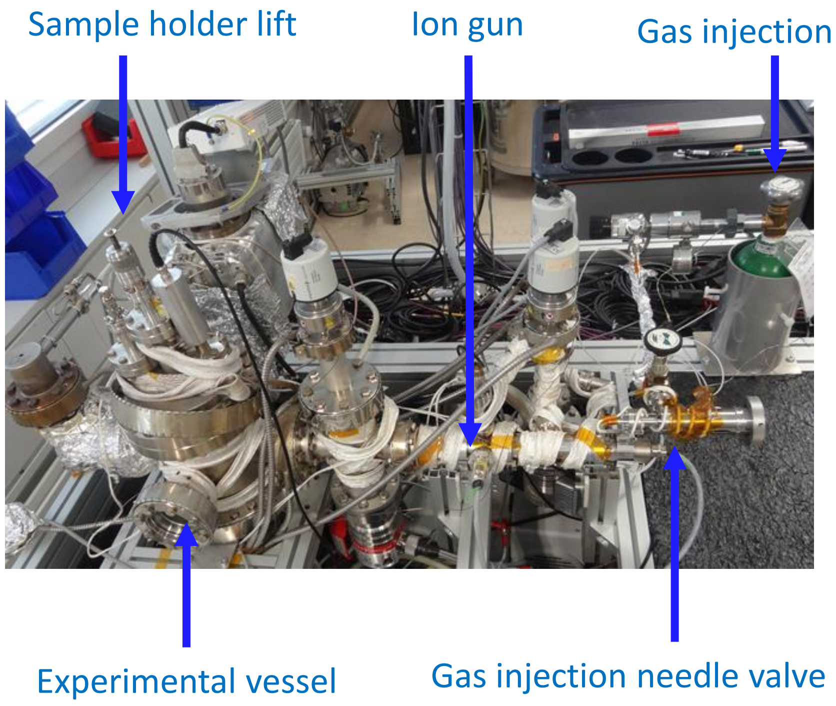


$$\eta_i > \eta_{e-} > \eta_{ph}$$

Pressure increase due to the gas desorption induced by the ion bombardment



CERN-TE-VSC-Lab



→ Only few data are available on ISD yield in the literature.

Summary:

→ All surface yield parameters: SEY, ISD, ESD, PSD, PY etc. depend on contaminants and oxides.

→ Experiments in laboratory are necessary :

- to investigate separately the complex phenomena occurring in accelerators;
- to accumulate data on the different phenomena (electron emission, desorption yield, conditioning,…);
- to understand the relationship between surface chemistry and these phenomena.

Summary:

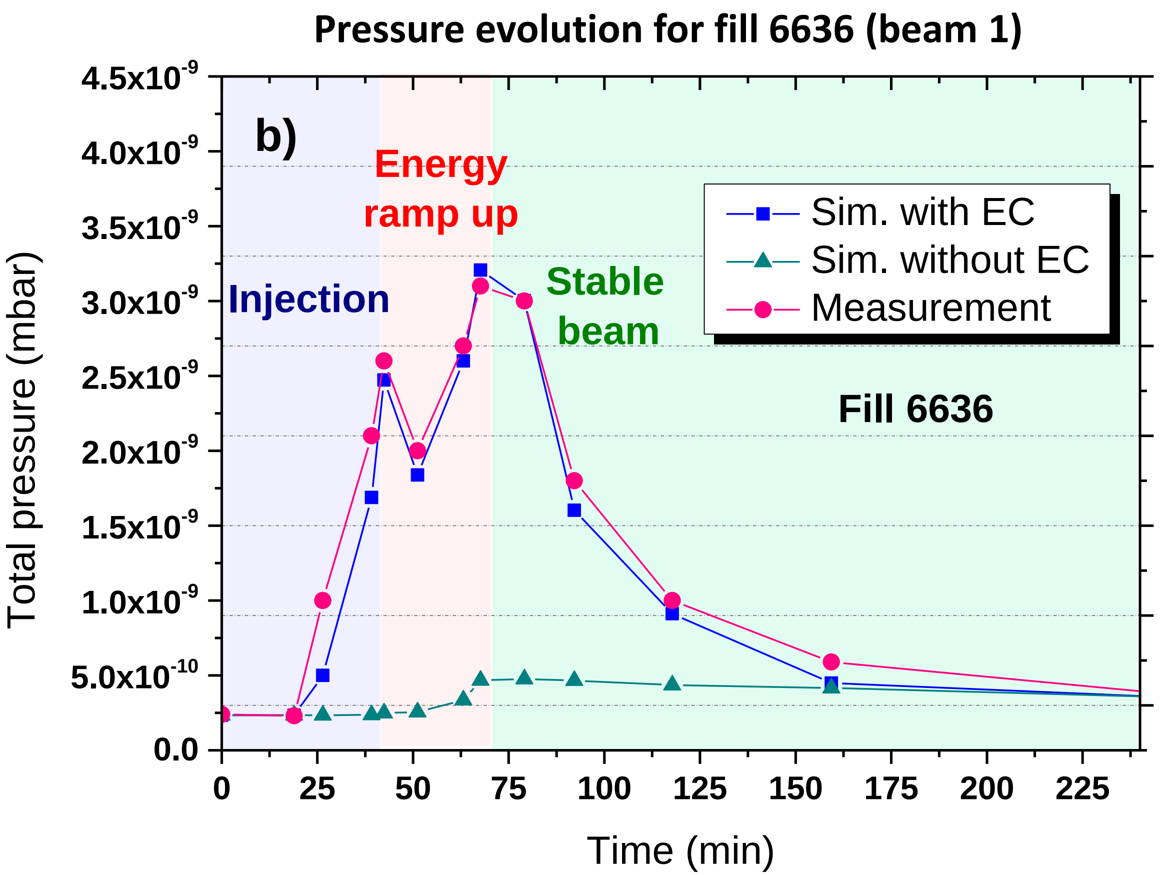
→ All surface yield parameters: SEY, ISD, ESD, PSD, PY etc. depend on contaminants and oxides.

→ Experiments in laboratory are necessary :

- to investigate separately the complex phenomena occurring in accelerators;
- to accumulate data on the different phenomena (electron emission, desorption yield, conditioning,…);
- to understand the relationship between surface chemistry and these phenomena.

Using laboratory experiments and *in situ* measurements in the LHC to get input parameters, dynamic pressure simulation can be performed.

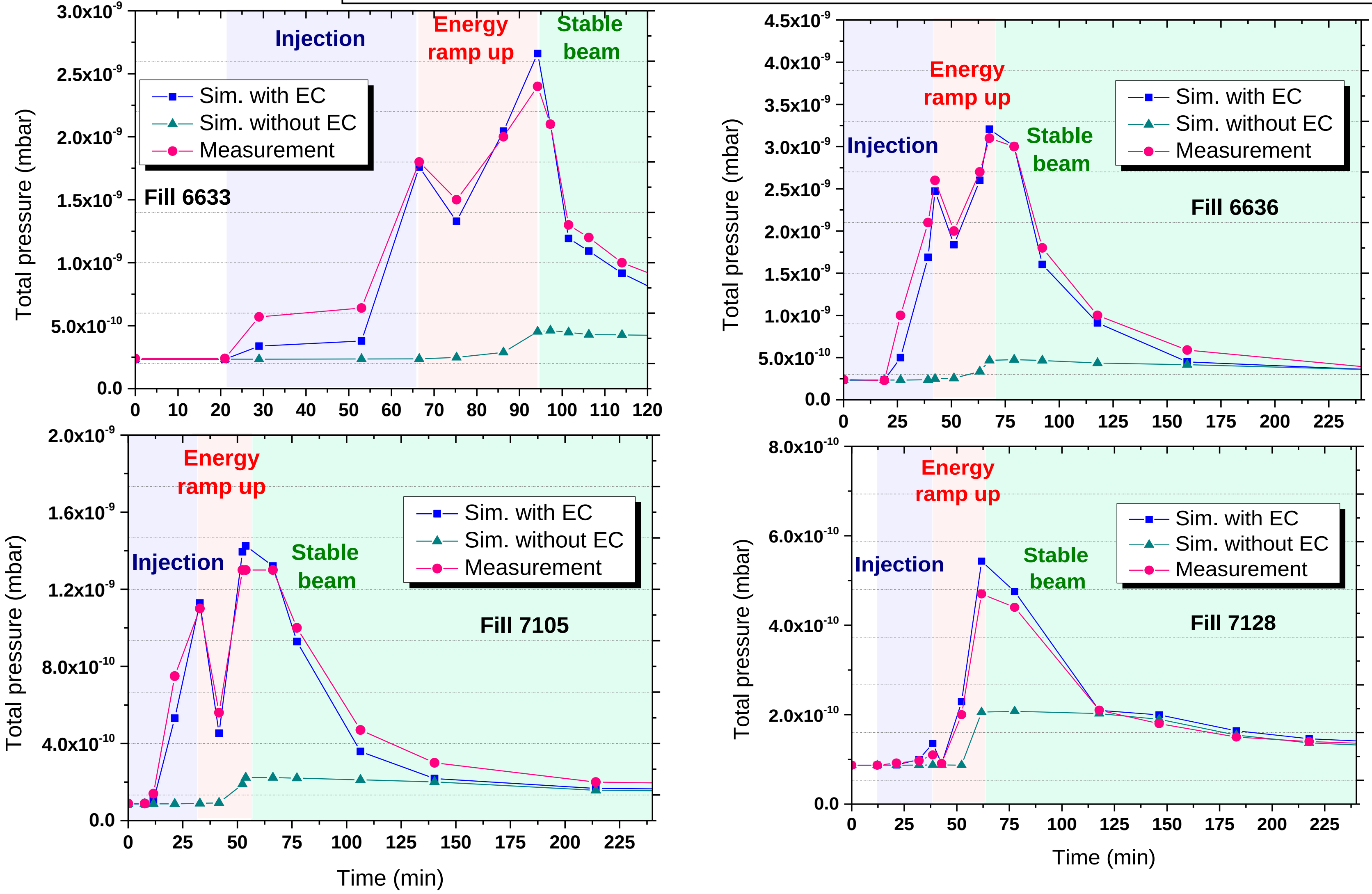
Comparison between *in situ* measurements in the LHC and the DYVACS simulation



- Experimental pressure (pink line)
- computed pressure using DYVACS with EC (blue line)
- and without EC (green line)

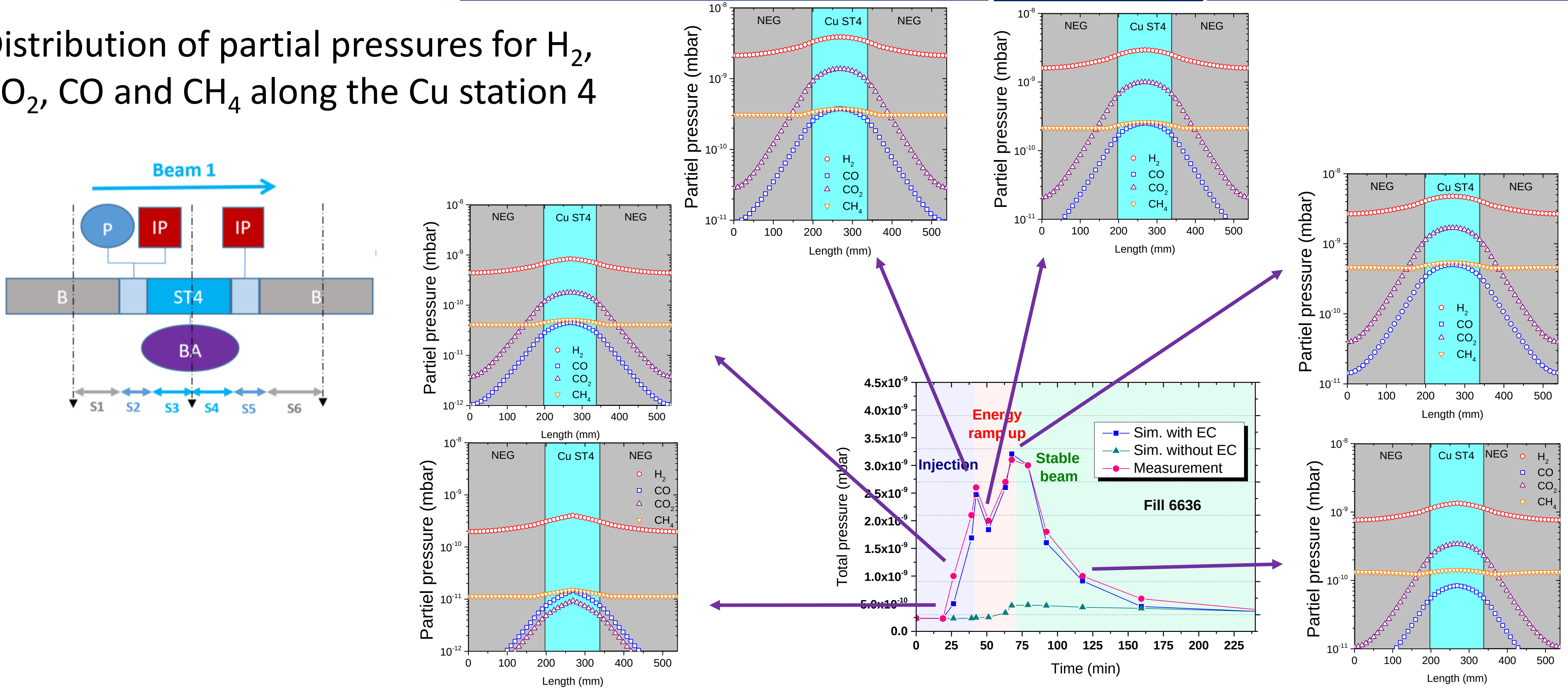
A **good agreement** was observed in a short computation time, between the *in situ* pressure measurements and DYVACS simulation

Pressure time evolution measurements vs DYVACS simulations



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 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

Conclusion

Goal: Develop DYVACS to simulate the dynamic pressure in Future particle accelerators, as FCC, using experimental inputs.

- Experimental measurements :

→ First results of **ISD yields and SEY were obtained to fill the data gap in this field**.

- *In situ* measurements in the LHC :

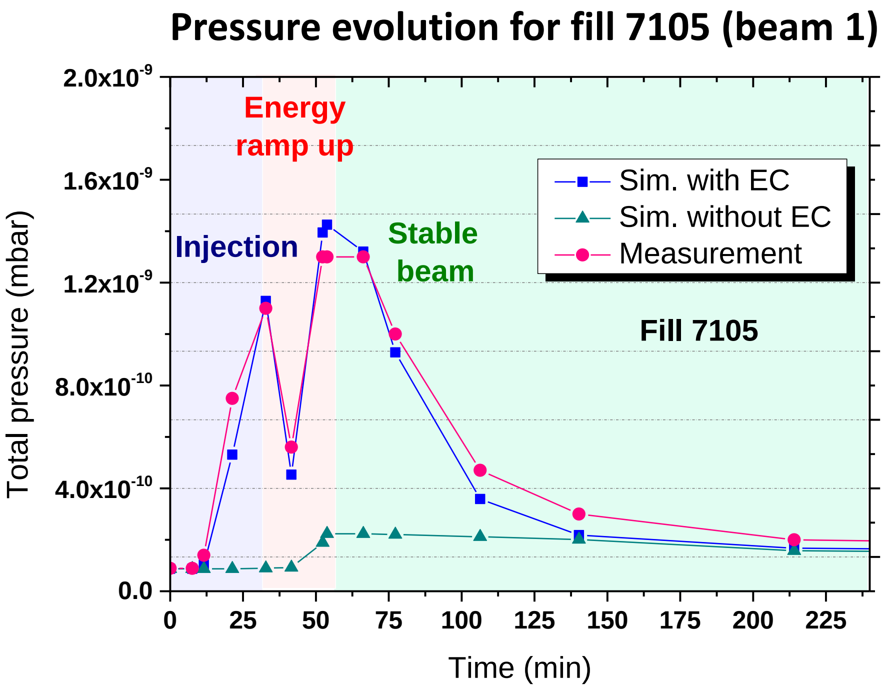
→ ***In situ* measurements in the LHC are essential to improve our understanding of complex phenomena** occurring in particle accelerator beam pipes.

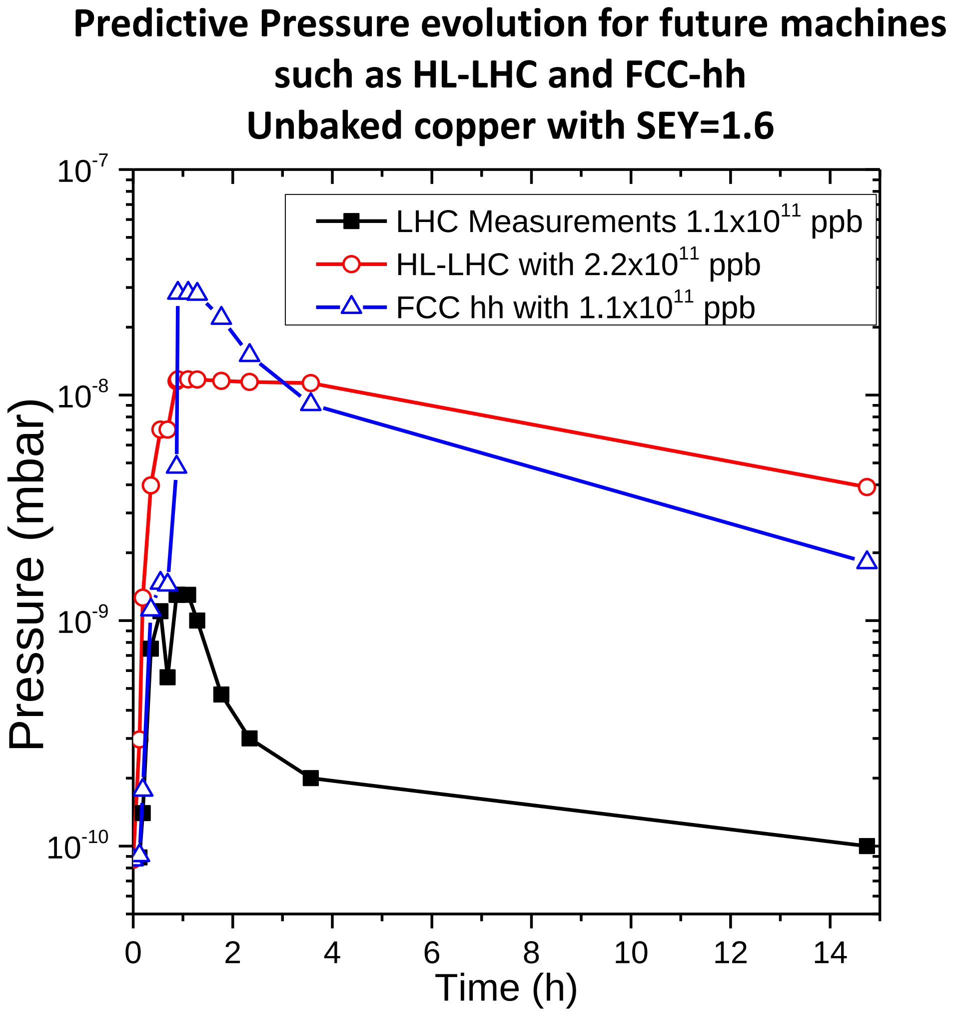
- Dynamic pressure simulation in the LHC:

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

Using experimental inputs, beam and accelerator parameters, **predictive simulation of dynamic pressure can be performed for Future particle accelerators using DYVACS.**

Preliminary results for HL-LHC and FCC hh





→ **DYVACS = f (nppb, ESD, PSD, etc.)**

→ **DYVACS (HL-LHC) ≈ f (E_{beam}, nppb → EC)**

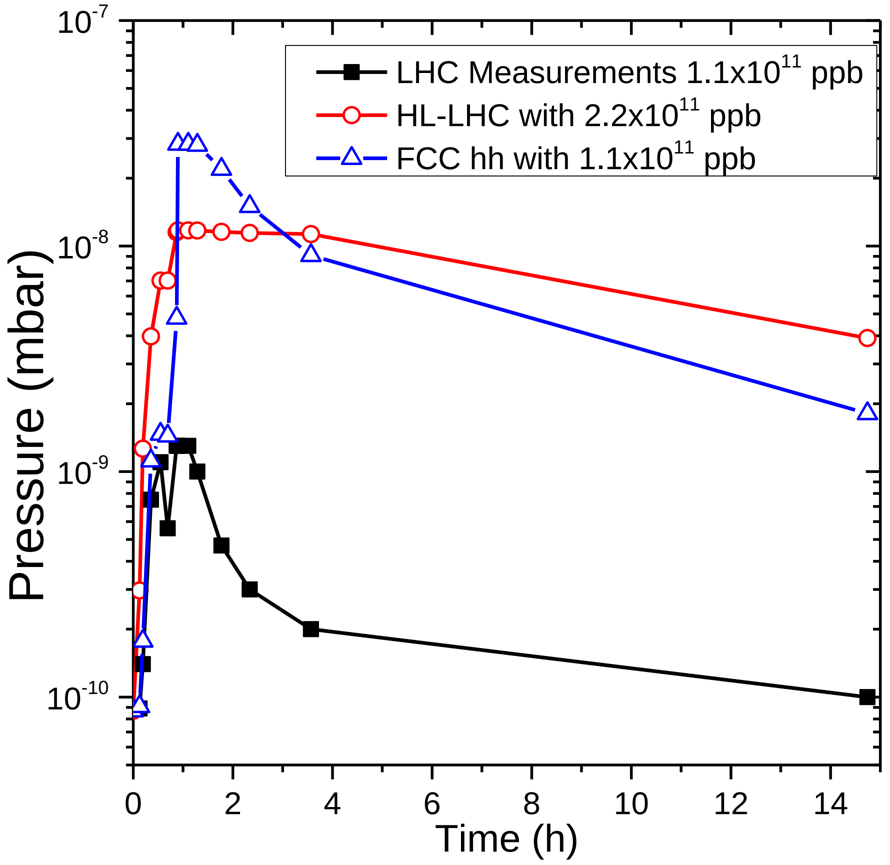
→ **DYVACS (FCC-hh) ≈ f (E_{beam}, SR →PSD, PY → EC)**

Dynamic pressure for FCC-ee

DYVACS = f (x_i)

- x_1 = accelerator design, pumping systems
- x_2 = material used
- x_3 = SR flux/m (photon critical energy)
- x_4 = PY, PSD yields
- x_5 = EC energy
- x_6 = EC density evolution (Map)
- x_7 = ions from the residual gas ionization energy
- x_8 = ionization cross section
- x_9 = ESD, ISD yields
- x_{10} = PY, PSD, ESD, ISD, SEY, EC Map evolution as a function of the dose

Predictive Pressure evolution for future machines such as HL-LHC and FCC-hh
Unbaked copper with SEY=1.6



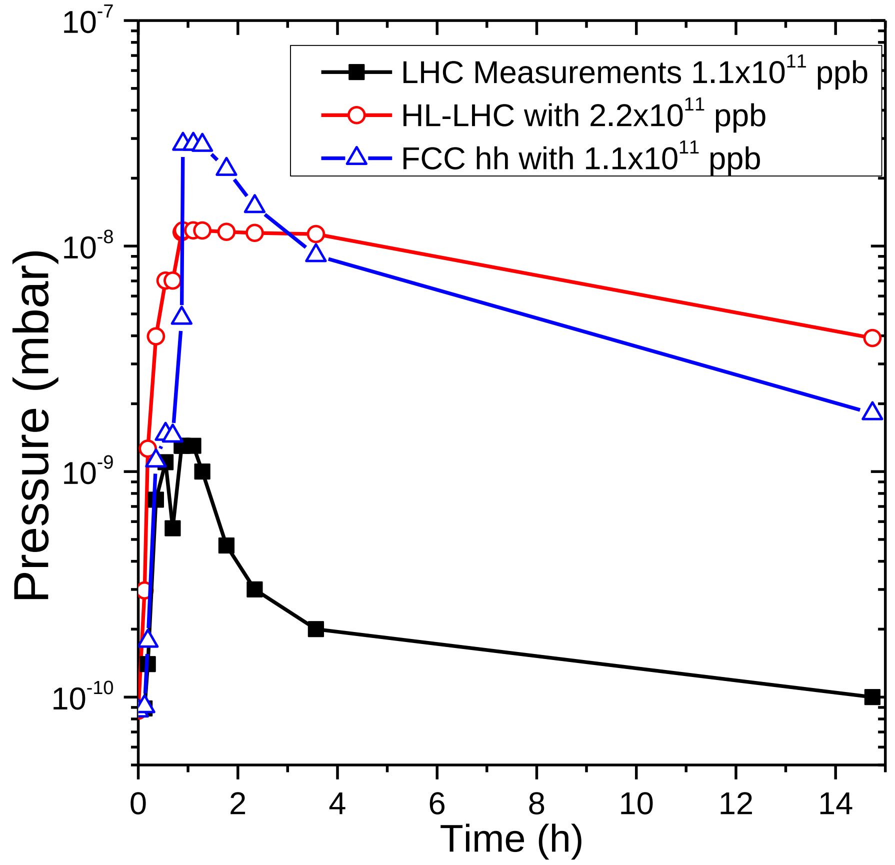
DYVACS to simulate dynamic pressure for FCC-ee

Dynamic pressure for FCC-ee

DYVACS = f (x_i)

- x_1 = accelerator design, pumping systems
- x_2 = material used
- **x_3 = SR flux/m (photon critical energy)**
- **x_4 = PY, PSD yields**
- x_5 = EC energy
- x_6 = EC density evolution (Map)
- x_7 = ions from the residual gas ionization energy
- x_8 = ionization cross section
- x_9 = ESD, ISD yields
- x_{10} = PY, PSD, ESD, ISD, SEY, EC Map evolution as a function of the dose

Predictive Pressure evolution for future machines such as HL-LHC and FCC-hh
Unbaked copper with SEY=1.6



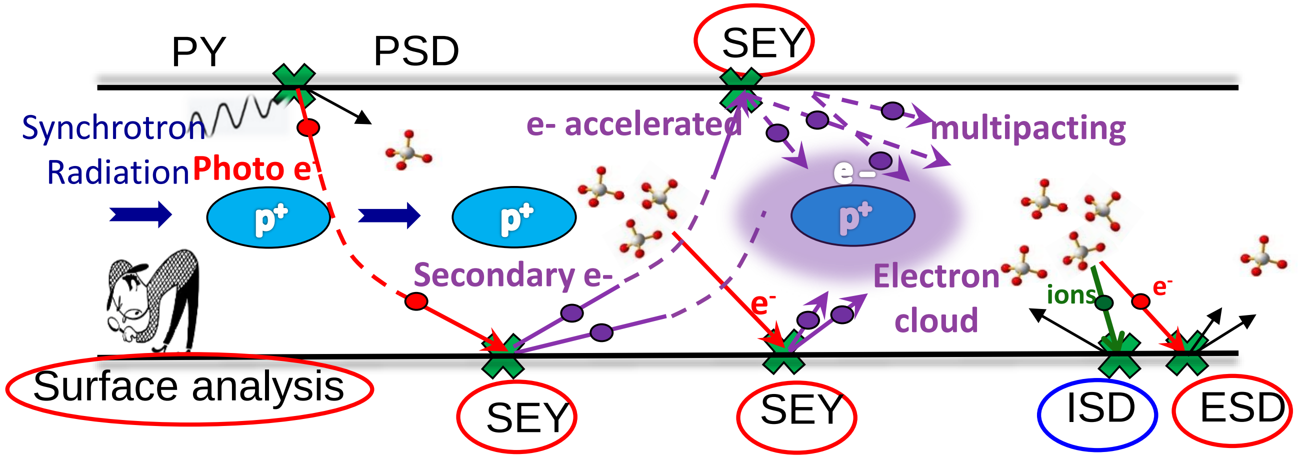
Perspectives

- **Laboratory measurements :**
  - Consolidate **ISD, ESD yield and SEY measurements (in particular the NEG coating due to the high SR in FCC-ee)** **IJCLab, CERN**
  - Study the **relationship between conditioning effects and surface chemistry** of materials **IJCLab**

- **In situ measurements in the LHC** in the **next LHC RUN** **CERN**

- **Simulation of the dynamic pressure** **IJCLab**
  - **Improve and optimize** the DYVACS code
  - Use the DYVACS code as a predictive tool for **FCC-ee**

Experimental resources for FCC-ee



IJCLab:

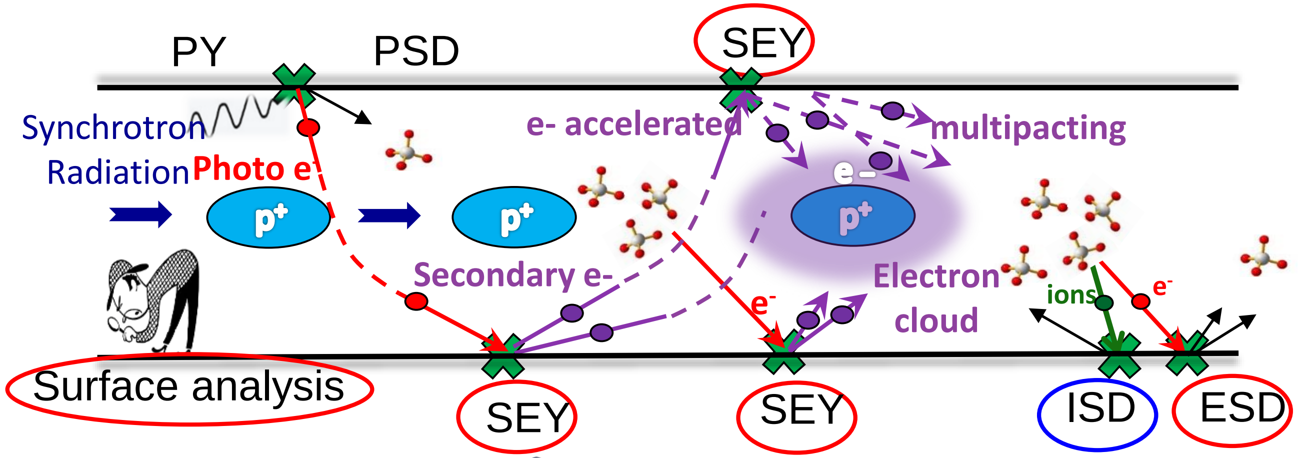
- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure

CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC

Dynamic pressure is a complex field which needs more investigation.

Experimental resources for FCC-ee



IJCLab:

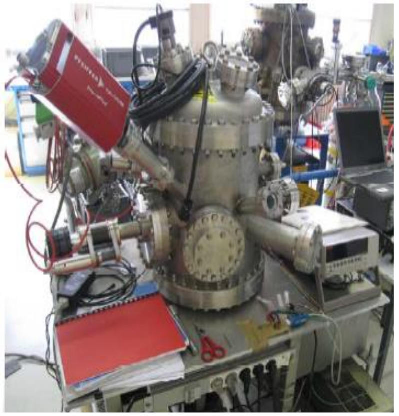
- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure

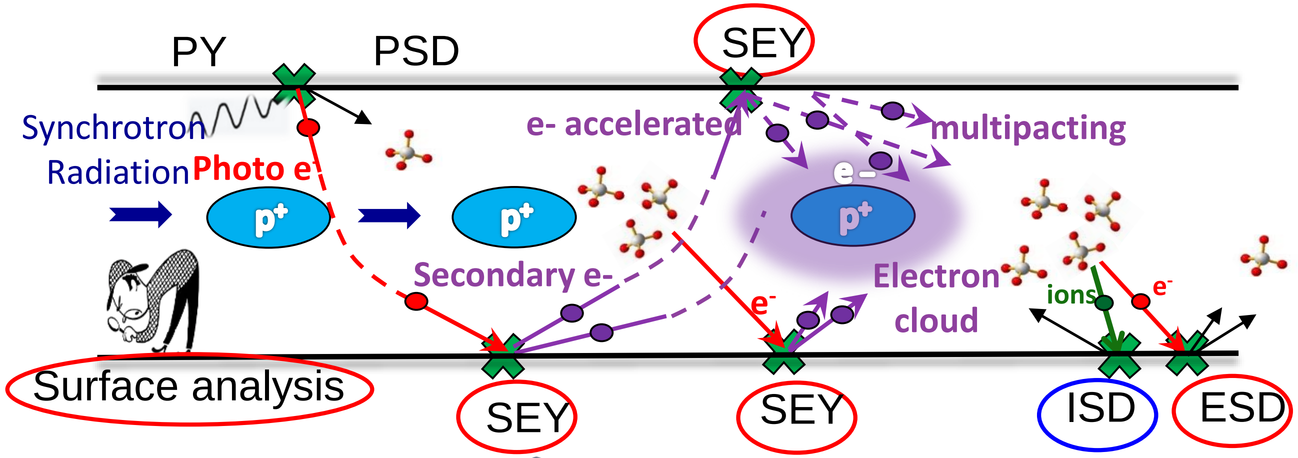
CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC

Dynamic pressure is a complex field which needs more investigation.

Experimental resources for FCC-ee





IJCLab:

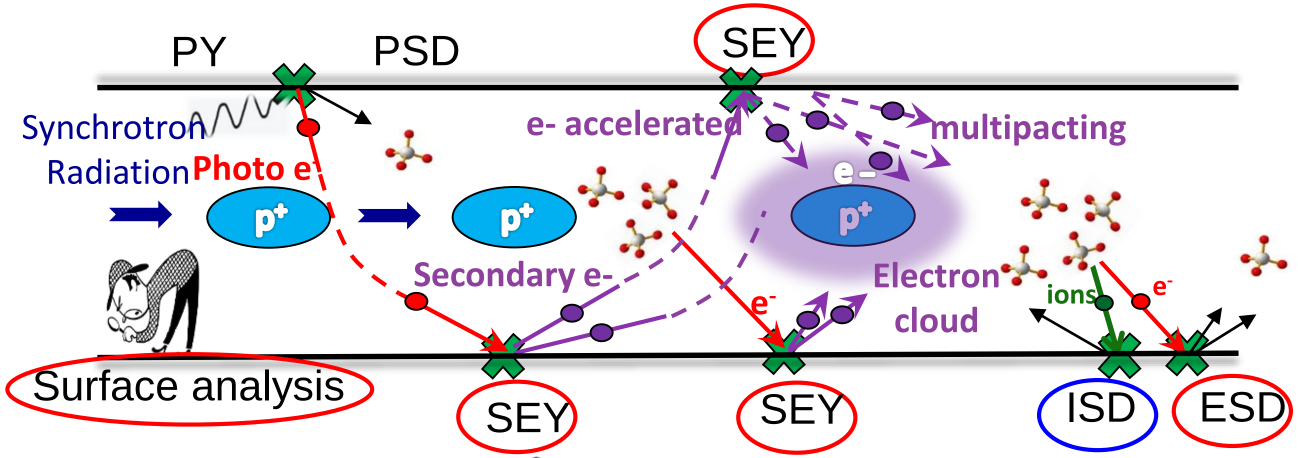
- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure

CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC

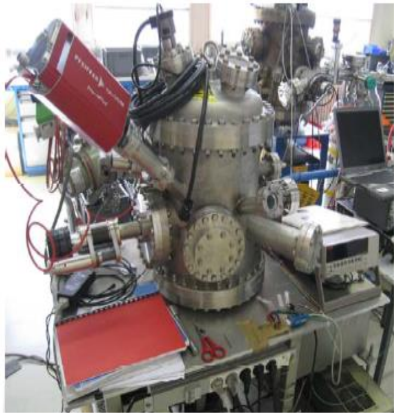
Dynamic pressure is a complex field which needs more investigation.

Experimental resources for FCC-ee



IJCLab:

- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure



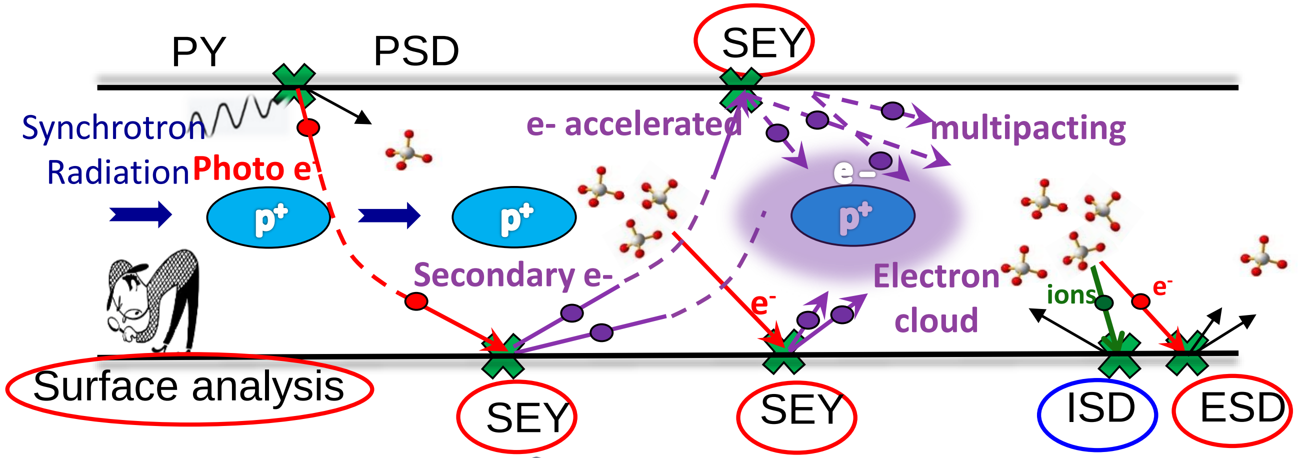
ANDROMEDE

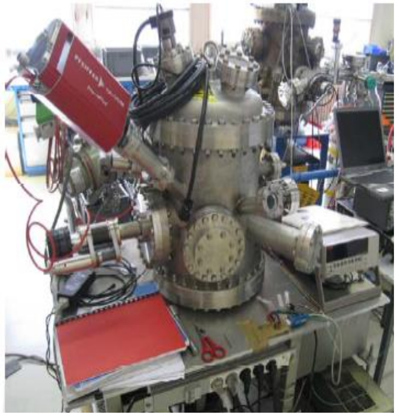
CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC

Dynamic pressure is a complex field which needs more investigation.

Experimental resources for FCC-ee



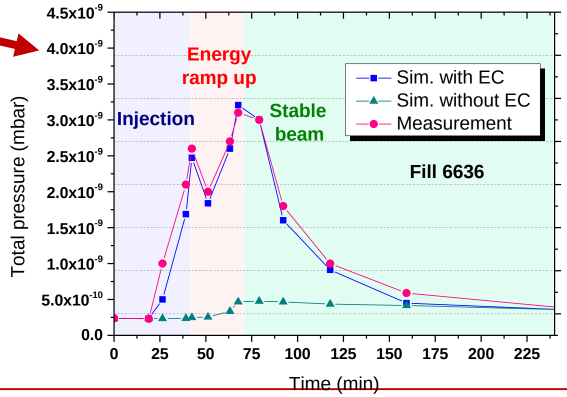


IJCLab:

- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure

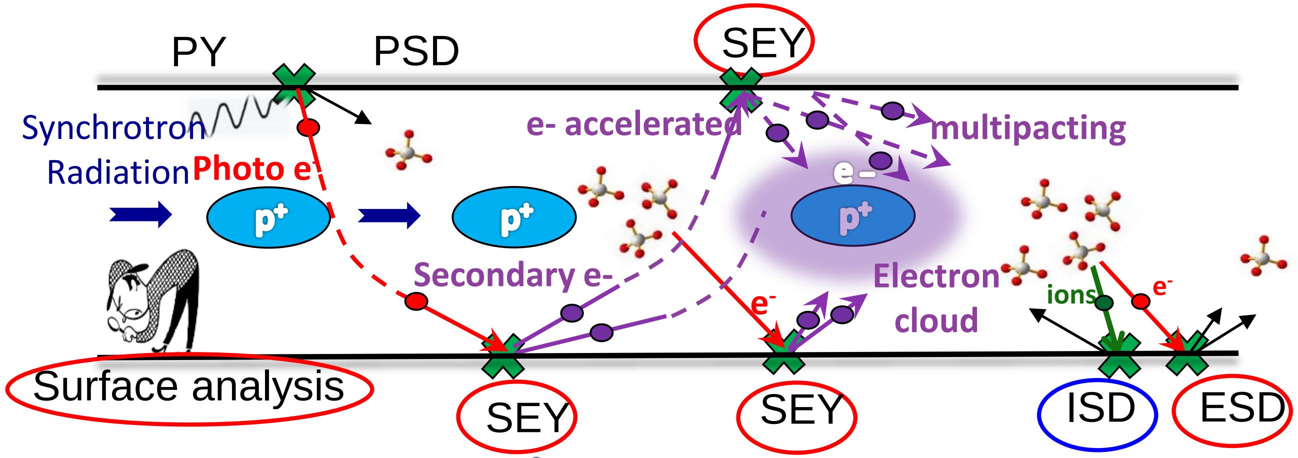
CERN:

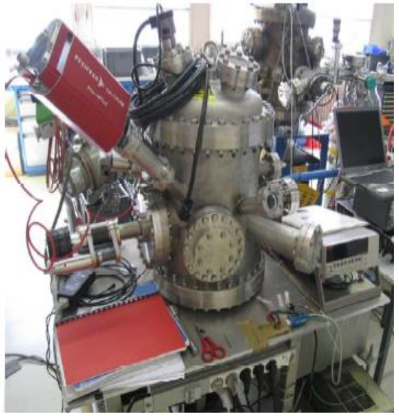
- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC



Dynamic pressure is a complex field which needs more investigation.

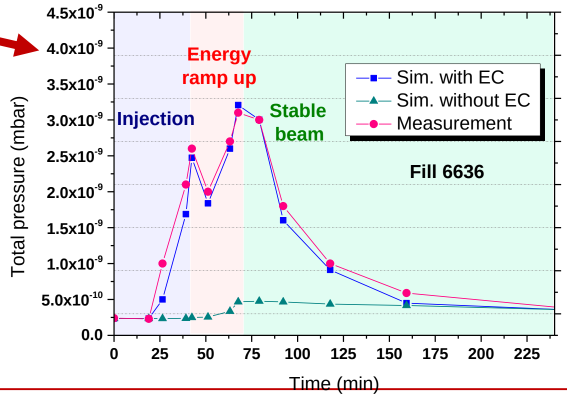
Experimental resources for FCC-ee

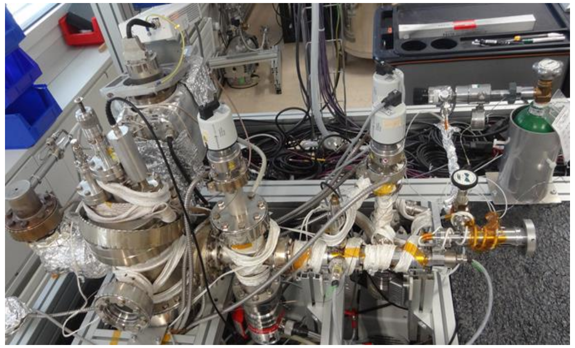




IJCLab:

- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure



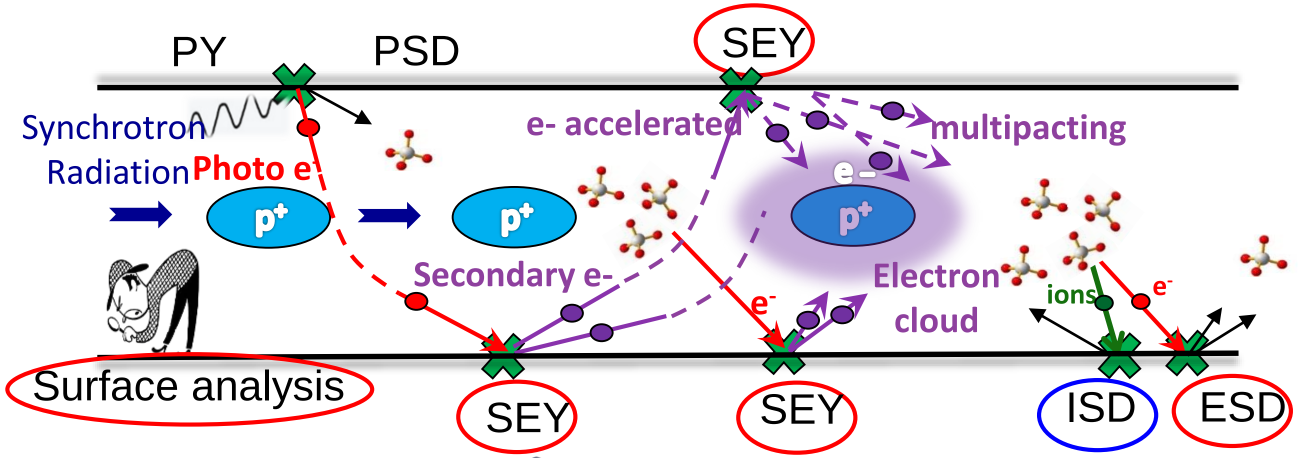


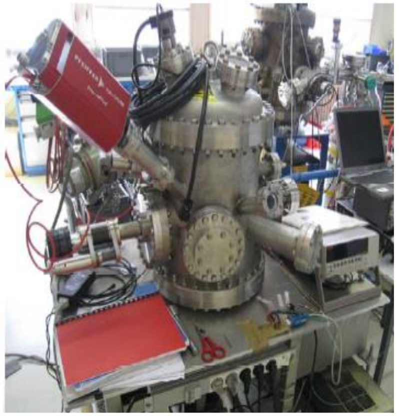
CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC

Dynamic pressure is a complex field which needs more investigation.

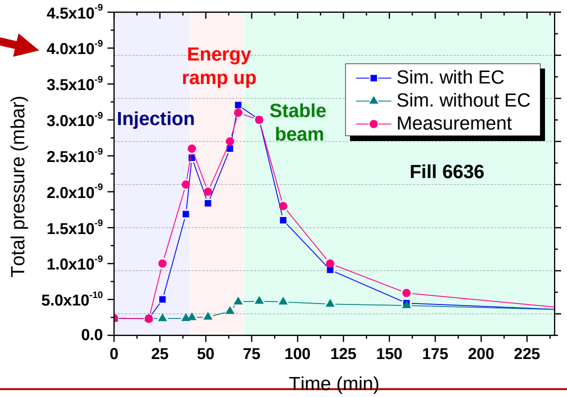
Experimental resources for FCC-ee

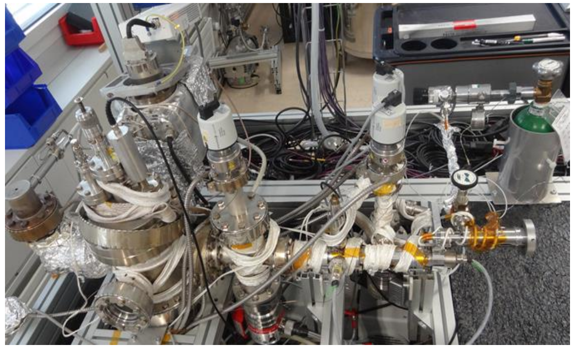




IJCLab:

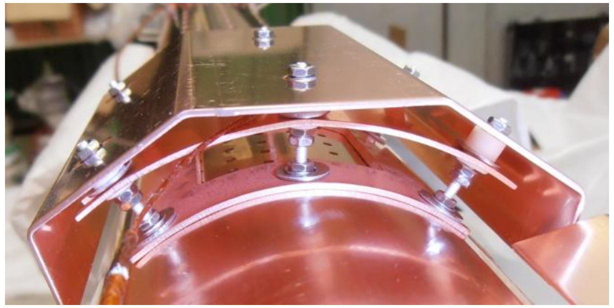
- Surface Analysis: XPS, XRD, SEM → Vacuum & Surfaces Platform
- SEY, ESD → Vacuum & Surfaces Platform
- Surface Analysis: Tof SIMS → Andromede facility
- DYVACS Simulation of the dynamic pressure





CERN:

- ISD → CERN-TE-VSC-Lab
- *In situ* measurements in the LHC



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

Dynamic pressure is a complex field which needs more investigation.

Dynamic pressure in particle accelerators
Simulation for the FCC studies

Thank you for your attention!

Suheyla BILGEN, Bruno MERCIER, Gaël SATTONNAY, Vincent BAGLIN*, Bernard HENRIST*

IJCLab - MAVERICS team of the Accelerator division
(Materials for Accelerator, dynamic Vacuum studiEs and innovative Research on superconductIng CavitieS)

*CERN-TE-VSC team *(Vacuum, Surface and Coating)*

2nd FCC-France Workshop

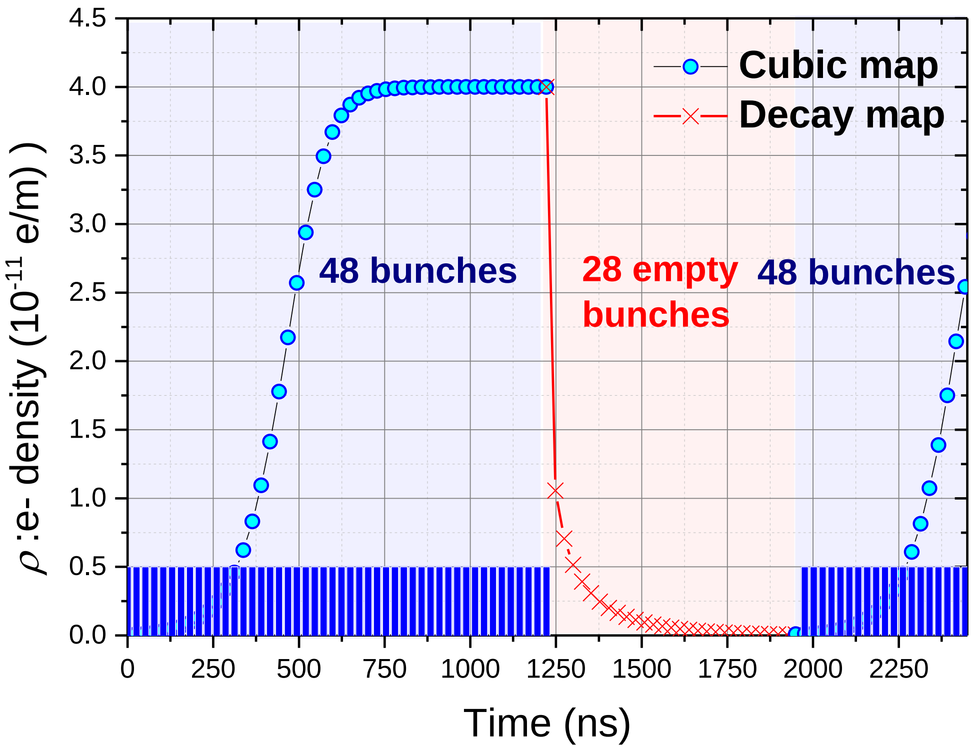
BACK SLIDES

Electronic density build up of the EC computed using the map model

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

T. Demma *et al.* Model

→ ρ_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.

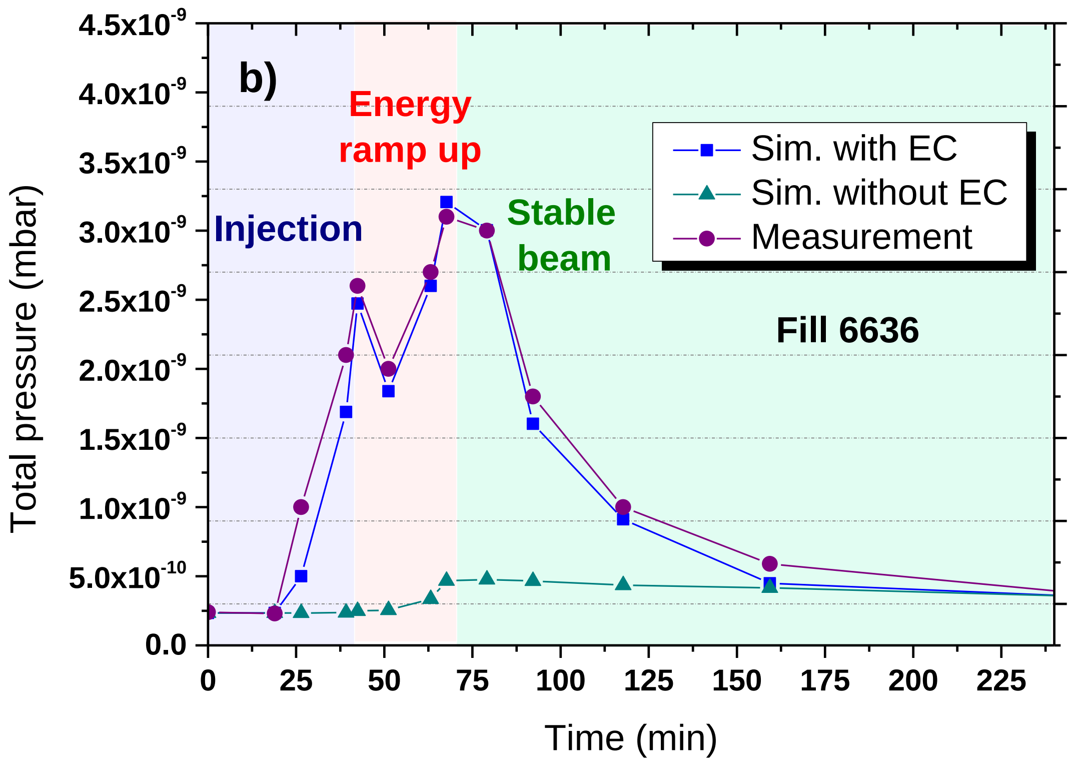
b: quadratic term

- 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.

Pressure evolution for fill 6636 (beam 1)



- Experimental pressure (purple line)
- computed pressure using DYVACS with EC (blue line)
- and without EC (green line)

Map parameters:

→ a=cste because SEY=1.6
→ **b** evolution is computed using nppb measurements.
b= [-0,1; -5]
→ c=0

Fitted inputs:

ESD
PSD (evolution with critical E and ph. dose)

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