# Dynamic pressure in the LHC

## Detection of ions induced by ionization of residual gas by both the proton beam and the electrons in the LHC : implications for the FCC project*

S. BILGEN†[1], C. BRUNI[1], B. MERCIER[1], G. SATTONNAY[1], V. BAGLIN[2].

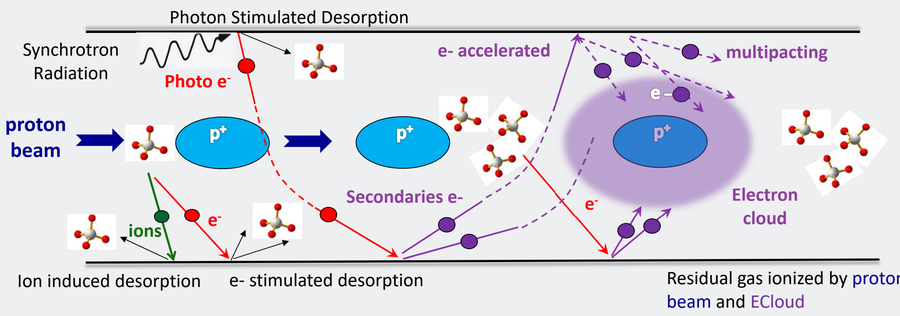
[1]LAL, Paris-Sud University, CNRS/IN2P3, Orsay, France.

[2]CERN , The European Organization for Nuclear Research, Geneva, Switzerland.

† bilgen@lal.in2p3.fr * Work supported by FCC project

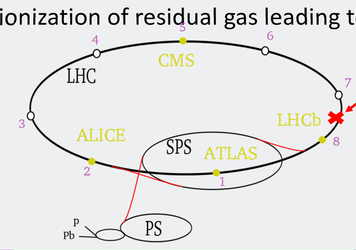
## Introduction

For the FCC study, the understanding of the beam interactions with the vacuum chamber is fundamental to provide solutions to mitigate the pressure rises induced by electronic, photonic and ionic molecular desorption [1].




In-situ measurements were carried out, on the LHC Vacuum Pilot Sector [2] during the LHC RUN II, to monitor the dynamic pressure, and to collect the electrical signals due to the electron cloud and to the ions interacting with the vacuum chamber walls.

Development of DYVACS code was performed at the Linear Accelerator Laboratory (LAL) in France, in order to estimate gas density profiles taking into account electron cloud build-up (maps [3]) and ionization of residual gas leading to electron- and the ion-induced desorption.




VPS Conditions: Room temperature in a straight section

**VPS station 4, "blue" beam, copper vessel, RUN II**

- Positive current $I_+$ : copper electrode (-1000<Vbias<0).
- Electrons current $I_{e-}$ : ($K_{11}$ and EKD, Vbias=+9 V ).
- Total Pressure : Bayard Alpert gauge.

## In-situ measurements

**LHC-VPS station 4, "blue" beam, copper vessel, RUN 7319**

The pressure, the electron current and the positive current follow exactly the same behaviour along the time. Three major bumps are observed: Fig. 1 b)

**"Proton injection"** bump 1:
- ↗ ionization of residual gas
- ↗ pressure
- ↗ electrical currents

**Energy ramp-up:**
-bump 2: modifications of energy spread (depending on both the bunch length and the RF)
-bump 3: photoelectron contribution from 2.8TeV

**Stable Beam**
Recorded signals decrease slowly due to proton losses.

**Proton-proton collisions**
Signals decrease faster due to higher losses in p-p collisions.

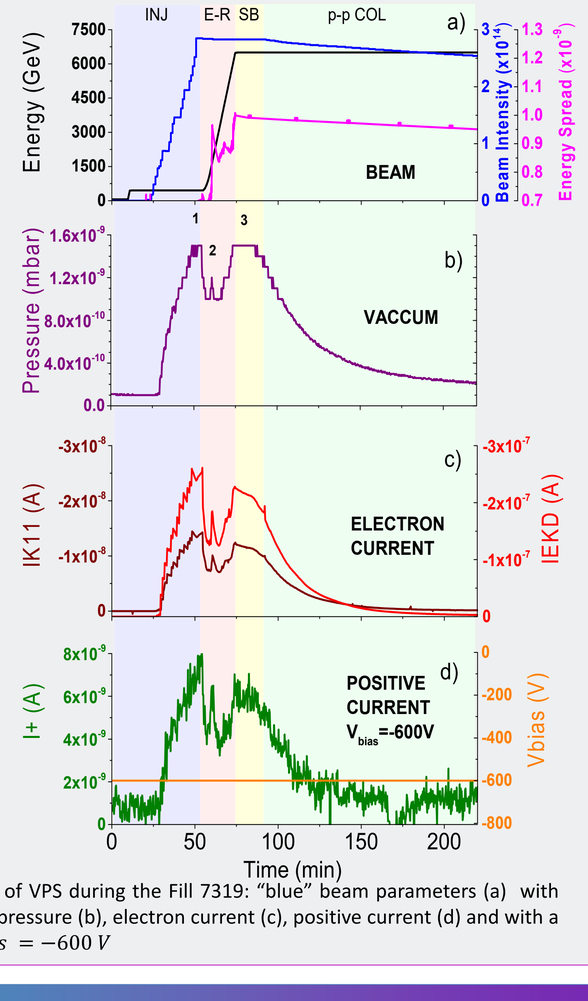



Figure 1: Measurements performed in station 4 of VPS during the Fill 7319: "blue" beam parameters (a) with the beam structure: 25ns_2556b_144bpi_20inj, pressure (b), electron current (c), positive current (d) and with a negatively biased copper electrode current $Vbias = -600\ V$

## DYVACS

**Analytical model of the dynamic pressure based on VASCO code**

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 | Electronic Desorption (e- Cloud) | Photon Desorption | Pumping Flux

Multi-gas model [1]

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

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

**Initial electronic density**:

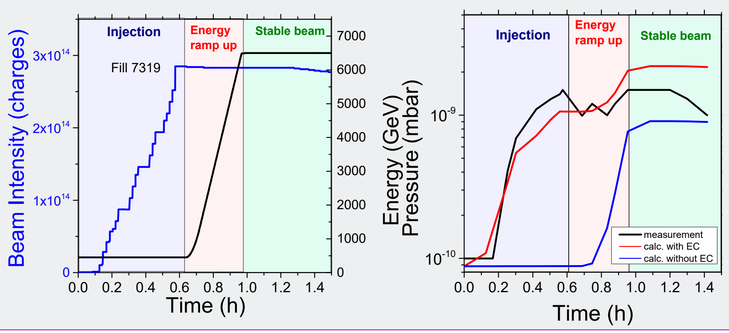
$$\rho_0 = \sum_{gas}\sigma_{gas-p}\cdot\frac{P_{gas}}{kT}\cdot I_{beam}\cdot t_T$$

($t_T$ = time for one lap= 89 µs)

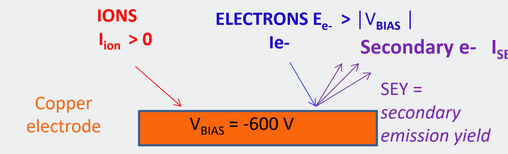
**Electron density build-up (map method [3]):**

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

(with a=1.3 b=-1 c=0.7)




## Ions or not ions?




$I_{ion} > I_{SE}$ or $I_{SE} > I_{ion}$ ?

$I_+(E, Vbias) = I_{e-} + I_{SE} + I_{ion} > 0$

*$I_{e-}$: e- current collected with e- energy E > $|V_{BIAS}|$;*
*$I_{SE}$ : positive current due to secondary electrons (SE);*
*$I_{ion}$ is the positive ion current collected by the electrode.*

**Contribution of all electrons to $I_+$**

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

$$SEY = \delta(E) = \delta_{max}\frac{s*\left(\frac{E}{E_{max}}\right)}{s-1+\left(\frac{E}{E_{max}}\right)^s}$$ [6]

Depends on e- energy spectrum

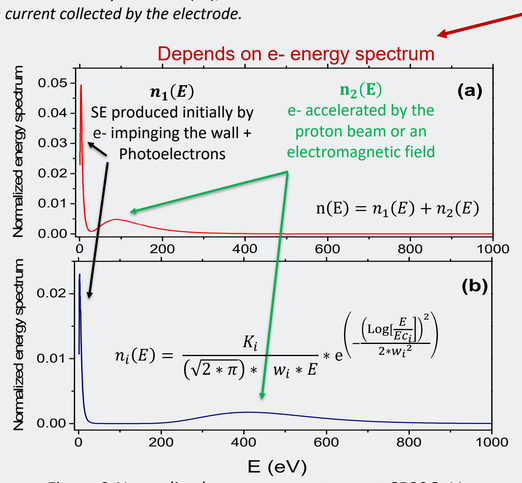



Figure 2:Normalized e- energy spectrum at 6500GeV
*a) experimental measurement performed in the VPS[4]*
*b) calculated distribution inspired by G. Iadarola in [5]*

Depends on SEY=f(Ee-)

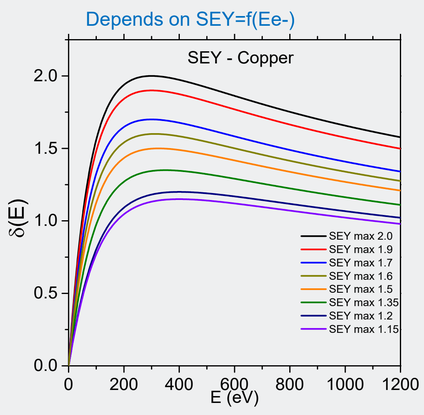



Figure 3: Calculated SEY curves for copper and for different values of the dmax and Emax parameters.

**→ Calculation of $I_+$ as a function of $V_{bias}$**

## Calculations *vs* experimental measurements

$I_+$ and $I_{e-}$ with a $V_{bias}$ scanning (Fill 6640 Fig. 3) *(bleu squares and violet circles)* vs calculated values (color lines, Fig. 5)

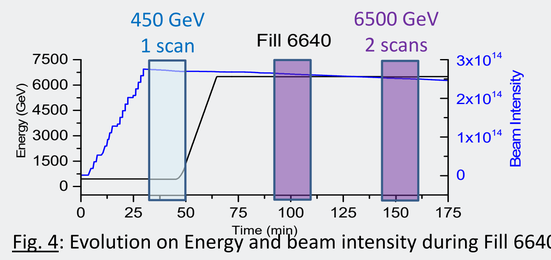



Fig. 4: Evolution on Energy and beam intensity during Fill 6640

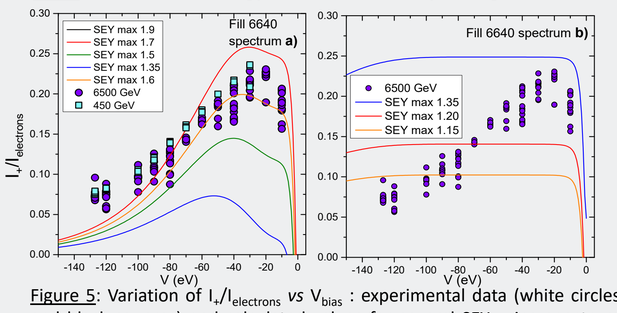



Figure 5: Variation of $I_+/I_{electrons}$ *vs* $V_{bias}$ : experimental data (white circles and black squares) and calculated values for several SEY using spectrum (a) and (b) (color lines).

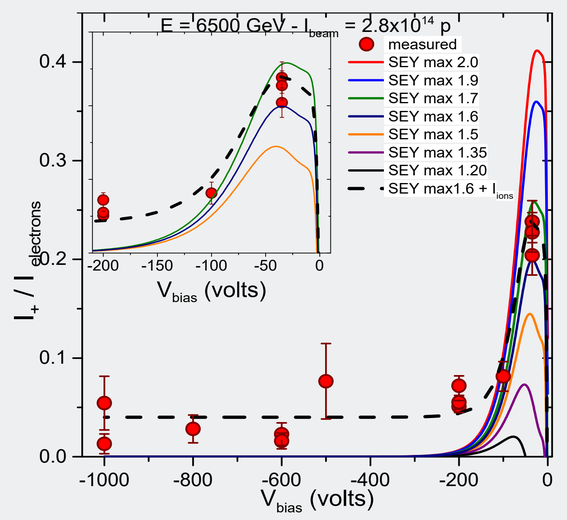



Figure 6: Variation of $I_+/I_{electrons}$ *vs* $V_{bias}$ : experimental data (red circle) recorded during different fills and calculated values for several SEY using spectrum (a) (color lines).

- **Same behaviour at 450 and 6500 GeV,**
  **→ low contribution of photoelectrons**
- **Which n(E) should we consider?**
  **→ a better agreement with the spectrum a)**

- **Below -200 V, a constant value is reached :**
  **$I+/I_{electrons}$ = 0.04 → IONS! SEY(copper electrode)=1.6**

**NUAGE code [7] gives the kick that an ion will feel when the proton beam is going through the beam pipe.**

**$E_{max}(CO^+)$=0.6 keV $E_{max}(H^+)$=1.6 keV**

## Conclusion

- **Ions, created by ionization of the residual gas by the proton beam and the e-cloud, were measured during the RUN II in the VPS between IP 7 and IP 8 of LHC.**
  **$I_+$ = 4% $I_{electrons}$ & SEY(copper electrode)=1.6 & $E_{max}(CO^+)$=0.6 keV; $E_{max}(H^+)$=1.6 keV**
- **DYVACS seems to be in good agreement with measurements, Ecloud build-up must be considered and ionic desorption measurement should be performed and use as inputs.**
- **New measurement should be done during the next LHC RUN to confirm the ion current .**
- **WHERE DO IONS COME FROM??? This question is a crucial point that we need to answer to mitigate pressure rise during FCC-hh operation to reach beam performances that is expected.**

## Acknowledgments

*The authors would like to address their gratitude to Bernard Henrist (CERN) and Elena Buratin (CERN) for their contribution to this work*

## References

[1] O. B. Malyshev, "The Ion Impact Energy on the LHC Vacuum Chamber Walls", in Proc. 7th European Particle Accelerator Conf. (EPAC'00), Vienna, Austria, Jun. 2000, paper THP1B20.
[2] B. Henrist, V. Baglin, G. Bregliozzi, and P. Chiggiato, "The LHC Vacuum Pilot Sectors Project", in Proc. 5th Int. Particle Accelerator Conf. (IPAC'14), Dresden, Germany, Jun. 2014, pp. 2360-2362. doi:10.18429/JACoW-IPAC2014-WEPME042.
[3] U. Iriso and S. Peggs, Maps for electron clouds, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 024403 (2005)
[4] E. Buratin, personal communication.
[5] G. Iadarola, "electron cloud studies for cern particle accelerators and simulation code development", CERN Thesis 2014.
[6] J.J. Scholtz, D. Dijkkamp, R.W.A. Schmitz, "secondary electron emission properties" Philips J. Res. Vol 50, 375-389, 1996.
[7] A. Gamelin, C. Bruni, NUAGE model to describe the beam-ion interaction, LAL