

# DYNAMIC PRESSURE IN THE LHC: INFLUENCE OF IONS INDUCED BY IONIZATION OF RESIDUAL GAS BY BOTH THE PROTON BEAM AND THE ELECTRON CLOUD

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## Abstract

For the future HL-LHC or 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. The proton beam circulating in the LHC vacuum chamber ionizes the residual gas producing electrons as well as positive ions. In-situ measurements were carried out, on the LHC Vacuum Pilot Sector 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. Experimental measurements of electrical signals recorded by copper electrodes were compared to calculations taking into account both the Secondary Electron Yield of copper and electron energy distribution. Finally, it seems that copper electrodes were not fully conditioned and an ion current could be estimated.

## INTRODUCTION

Ultra-High Vacuum is an essential requirement to reach design performances in high-energy particle colliders. The presence of electrons, leading to the electron cloud phenomenon via multipacting process, is now well documented and have been intensively studied over the last few years. However, the behaviour of ions, created by ionisation of the residual gas by both the proton beam and the electron cloud, isn't widely known. These ions (e.g.  $H_2^+$  or  $CO^+$  [1]) are accelerated away from the beam and reach the vacuum chamber wall. The aim of this paper is to report the first investigation on the ion behaviour in the Vacuum Pilot Sector (VPS) installed in the LHC [2].

## EXPERIMENTAL DESCRIPTION

We investigated the ions produced by ionisation of the residual gas in the station 4 of VPS ("blue" beam and copper vessel) located in vacuum sector A5L8 between the quadrupoles Q4 and Q5 [2]. We used a negatively biased copper electrode to collect positive charges. This electrode could be polarized up to a voltage  $V_{bias} = -127$  V first, and after modifications during a technical stop, up to  $-1000$  V. In the same station, pressure (with Bayard Alpert gauge) and electron current were also monitored by two positively biased electrodes polarized at  $+9$  V (K11 and EKD respectively). Figure 1 shows measurements performed during the fill 7319 (beam structure: 25ns\_2556b\_144bpi\_20inj). For this fill, the negatively biased copper electrode was polarized at  $-600$  V. It is worth

noting that the same evolutions are observed for all proton beams for physics.

The pressure, the electron current and the positive current follow exactly the same behaviour along the time. Two major bumps are observed: the first one during the beam injection and the second during the energy ramp up. Four parts are observed: (i) "injection" of protons in the ring: more protons circulate and more ionization of residual gas is produced, leading to an increase of both pressure and electrical currents. After the injection a slight decrease of beam intensity is observed due to proton losses along their path. (ii) Energy ramp-up: evolution of measurements during this step depends on two main effects; first, pressure and electrical signal variations are related to modifications of energy spread (depending on both the bunch length and the RF) due to RF noise injected to mitigate longitudinal beam instability; then from 2.8 TeV, the main contribution comes from photoelectrons interacting also with the residual gas and the chamber walls. (iii) During Stable Beam, proton intensity decreases still due to proton losses; (iv) Beginning of proton-proton collisions. Indeed, from this time, electrical signals decrease with the pressure.

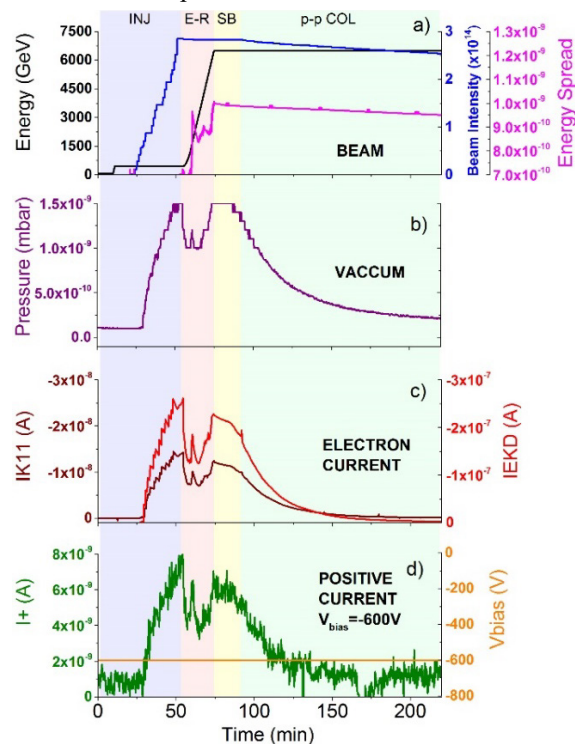


Figure 1: Measurements performed in station 4 of VPS during the Fill 7319: "blue" beam parameters (a), pressure (b), electron current (c) and positive current (d).

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The current ( $I_+$ ) collected by the negatively biased copper electrode depends on different contributions and can be given by:

$$I_+(E, V_{bias}) = I_{e^-} + I_{SE} + I_{ion} \quad (1)$$

- $I_{e^-}$  corresponds to electron current impinging the wall ( $I_{e^-} < 0$ ); only electrons with sufficient energy to overcome  $V_{bias}$  are collected (since  $V_{bias} < 0$ );
- $I_{SE}$  represents the current due to secondary electrons (SE) emitted when electrons impinging the wall; Usually  $I_{SE} = -SEY \cdot I_{e^-}$  where SEY is the secondary electron yield of copper;  $I_{SE} > 0$ ;
- $I_{ion}$  is the positive ion current collected by the electrode

It is worth noting that if the SEY is higher than 1,  $I_{e^-} + I_{SE}$  will be always positive for a negative electrode polarization. So it can be difficult to separate ion and SE contributions to the total current  $I_+$ . Moreover, the ion current should be very low compared to the electron signal, since equilibrium ion densities were estimated to be many orders of magnitude smaller than the electron densities [3]. Nevertheless, only the electron currents depend on energy spectrum of the electrons and on  $V_{bias}$ . So, in order to determine if it is possible to measure an ion flux impinging the beam pipe walls, we calculated the contribution of primary and secondary electrons to  $I_+$  (i.e. when  $V_{bias} < 0$ ).

## ELECTRON ENERGY SPECTRUM AND SECONDARY ELECTRON YIELD

The electron current is:

$$I_{e^-}(E > |V_{bias}|) \propto \int_0^\infty n(E - V_{bias}) dE \quad (2)$$

where  $n(E - V_{bias})$  is the energy spectrum of the electrons impinging the wall. The secondary electron current is given by:  $I_{SE}(E, V_{bias}) \propto \int_0^\infty \delta(E) \times n(E - V_{bias}) dE$  (3)

where  $\delta(E)$  is the secondary electron yield (SEY) of the copper surface. The total electron current is then:

$$I_{e^-} + I_{SE} \propto \int_0^\infty n(E - V_{bias})(1 - \delta(E)) dE \quad (4)$$

For our calculations, we used two different energy distribution  $n(E)$ : (i) an experimental measurement performed in the VPS during a fill recorded at 6500 GeV [4] (spectrum a); (ii) a calculated distribution inspired by the one given by G. Iadarola in [5] (spectrum b). In both cases, the energy spectra can be described as the sum of two “lognormal” distributions:

$$n(E) = n_1(E) + n_2(E)$$

$$n_i(E) = \frac{K_i}{(\sqrt{2\pi}) * w_i * E} * e^{-\left(\frac{\left(\text{Log}\left|\frac{E}{E_{c_i}}\right|\right)^2}{2 * w_i^2}\right)} \quad (5)$$

The first part at low energy (around 5 eV) corresponds to the contribution of SE produced initially by electrons impinging the wall (and with eventually a contribution of photo-electrons). The second component occurring at a higher energy is associated to electrons accelerated by the

proton beam or an electromagnetic field. Figure 2 shows both energy spectra fitted with equation (5) and used to calculate the electron current. The major difference between both spectra is the energy corresponding to the second peak maximum:  $E_{c_2}(a)=119$  eV and  $E_{c_2}(b)=450$  eV for the spectra (a) and (b) respectively.

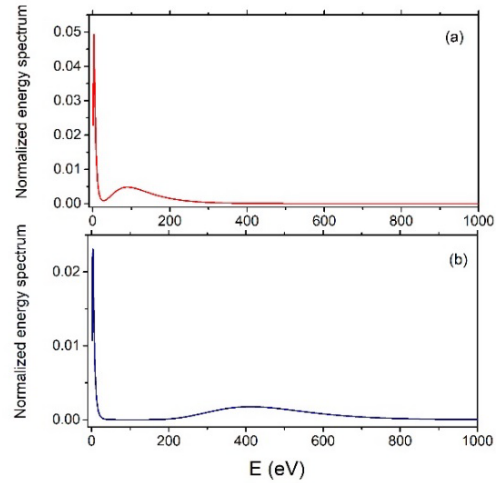


Figure 2: Normalized energy spectrum of the electrons impacting the wall;  $E_{c_2}(a)=119$  eV (a) and  $E_{c_2}(b)=450$  eV (b)

Concerning the SEY, a usual expression given by Scholtz [6] can be used to numerically express the variation of the secondary electron yield with the primary electron energy:

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

For the LHC beam chambers, the value  $s = 1.35$  can be used [5, 7]. SEY curves for different values of the  $E_{max}$  and  $\delta_{max}$  parameters are presented in Fig. 3. The progressive decreasing of SEY is related to the surface “conditioning” or “scrubbing”. This effect is observed when the surface is exposed to prolonged electron irradiation and occurred for the copper wall in the LHC.

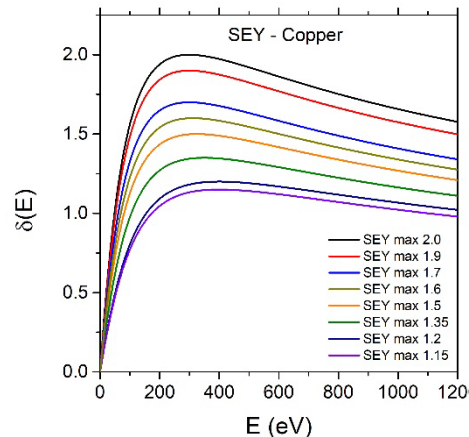


Figure 3: Calculated SEY curves for copper and for different values of the  $\delta_{max}$  and  $E_{max}$  parameters.

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The electron energy spectrum and the SEY are not well known in the case of our measurements in the VPS.

So a comparison of current measurements recorded with a  $V_{\text{bias}}$  scanning during a fill, to calculations performed for two different energy spectra and several SEY values, can allow us to determine: (i) if ions are really detected; (ii) the profile of the electron energy spectra; (iii) an approximate value of  $\delta_{\text{max}}$  for the copper electrode.

## CALCULATIONS AND EXPERIMENTAL MEASUREMENTS

First,  $I_+$  current was recorded for several scanning of  $V_{\text{bias}}$  from 0 to -127 V before (450 GeV) and after the energy ramp up (6500 GeV) of fill 6640. Comparisons between experimental results and calculations with several SEYs are presented on Fig. 4 (calculation performed with the electron spectrum a) and on Fig. 5 (electron spectrum b). For this,  $I_+$  was normalized to the total electron current.

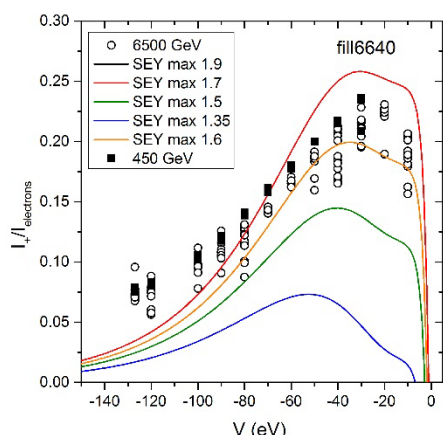


Figure 4: Variation of  $I_+/I_{\text{electrons}}$  vs  $V_{\text{bias}}$ : experimental data (white circles and black squares) and calculated values for several SEY using spectrum (a) (color lines).

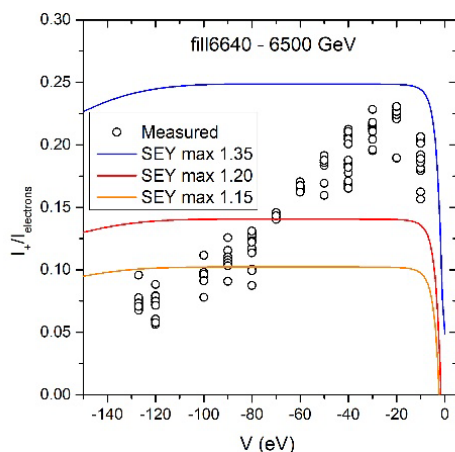


Figure 5: Variation of  $I_+/I_{\text{electrons}}$  vs  $V_{\text{bias}}$ : experimental data (white circles) and calculated values for several SEY using spectrum (b) (color lines).

The same behaviour is observed at 450 GeV and 6500 GeV, indicating that the photoelectron contribution

remains low. A better agreement is obtained with the spectrum a (Fig. 4), indicating that the high energy component of the electron energy distribution is located around 100 eV and not at a higher energy. A decrease of SEY leads to a lower SE current. A fast increase is first observed from 0 V up to a maximum value reached for  $V_{\text{bias}} \approx -20$  V, and then the signal decreases. A small discrepancy between calculated and experimental signals occurs from  $V_{\text{bias}} = -120$  V: whereas the calculated signal vanishes at the lowest  $V_{\text{bias}}$  values, experimental measurements reach a low but constant value, which could correspond to a positive ion current.

To confirm the presence of ions, several current measurements were performed during different fills, just after the energy ramp up, with  $-1000 \text{ V} \leq V_{\text{bias}} \leq 0 \text{ V}$  (see Fig. 6). It appears clearly that below -200 V, a constant value is reached ( $I_+/I_{\text{electrons}}=0.04$ ). As the signal from electrons and SE should be null at the lowest  $V_{\text{bias}}$ , the remaining signal can be related to positive ions. It is worth noting that if this ion current is taken into account, the maximum SEY of copper electrode should be around 1.6.

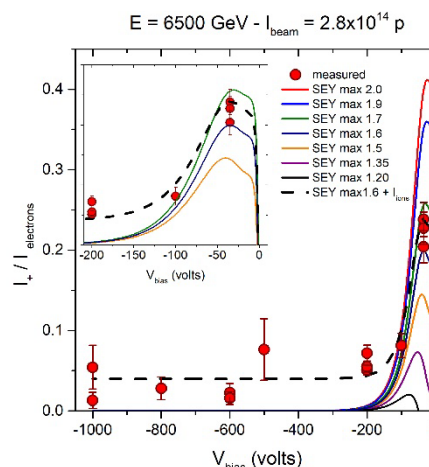


Figure 6: Variation of  $I_+/I_{\text{electrons}}$  vs  $V_{\text{bias}}$ : experimental data (red circle) recorded during different fills and calculated values for several SEY using spectrum (a) (color lines).

## CONCLUSION

Ions, created by ionisation of the residual gas by the proton beam and the e-cloud, were studding in a room temperature, non-magnetic straight section of LHC (VPS) between IP 7 and IP 8. Using copper electrodes polarized with positive and negative bias, an SEY was estimated to be around 1.6. In our measurement, the positive current could correspond to positive ions and represents 4% of the electron current. New measurement have be done during the next LHC RUN to confirm this huge value, which could be a crucial point that we need to mitigate for FCC-hh operation.

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