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DYNAMIC PRESSURE IN THE LHC: DETECTION OF IONS INDUCED BY IONIZATION OF RESIDUAL GAS BY THE PROTON BEAM AND BY THE ELECTRON-CLOUD

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Abstract

For the accelerator community and the vacuum scientist, the understanding of the beam interactions with the vacuum chamber is fundamental to provide solutions to mitigate pressure rises induced by electronic, photonic and ionic molecular desorption, and also beam instabilities induced by ion and electron clouds. This study presents in situ measurements of pressure evolutions and electrical currents performed during the LHC RUN II (2018). The proton beam circulating in the LHC vacuum chamber ionizes the residual gas producing electrons as well as positive ions. These charge particles are accelerated away from the beam and reach the vacuum chamber wall inducing, among other phenomena, stimulated desorption and secondary electron emission. Moreover, protons emit synchrotron radiations which induced also photo – desorption and photoelectron production. Experimental measurements of electrical signals recorded by copper electrodes were compared to calculations considering both the Secondary Electron Yield of copper and electron energy distribution. All measurements performed in the Vacuum Pilot Sector in the LHC ring, show the importance to take into account several phenomena in order to understand the pressure evolution in the LHC. Finally, results show that copper electrodes were not fully conditioned. Moreover, an ion current much higher than expected were estimated.

INTRODUCTION

Accelerators with the highest energy (above several GeV) are used to explore the structure of matter, more particularly collider accelerators, the most powerful being the Large Hadron Collider (LHC) operated by the CERN, SuperKEKB in Japan, RHIC at Brookhaven National Laboratory in New York and the Tevatron at Fermilab in Illinois. Regarding the luminosity of the beam which provides a measure of how many collisions per time are happening in the accelerator, one of the potential main limitations of these machines is the dynamic pressure. The energetic charged particles interact with gas molecules and these interactions cause many unwanted effects, such as a loss of the accelerated particles, the change of a charge state, residual gas ionization and the creation of a charged particle cloud (electrons for positive accelerated particle beams or ions for accelerated electron beams). The LHC is designed to accelerate and collide two counter-rotating protons beams up to an energy of 7 TeV. Along its path, the beam ionizes the residual gas inside the LHC beam pipe ring causes production of electrons as well as of positive ions, which then move under the action of the beam field forces and their own space charge. The presence of electrons, from which a multipacting process may get started, eventually leads to the so-called build-up of a quasi-stationary electron cloud (EC). 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 inducing stimulated desorption. This paper investigates the pressure changes and the first investigation on the ion creation related to the LHC operation. We performed measurements in a sector of the LHC ring dedicated to the monitoring of these phenomena, the Vacuum Pilot Sector [2] during the LHC RUN II (May, July and October 2018) using a bunched proton beam.

EXPERIMENTAL DESCRIPTION

We monitored the ions produced by ionisation of the residual gas in the station 4 (copper vessel) of VPS on the beam 1 or blue beam (external line), located in vacuum sector A5L8 between the quadrupoles Q4 and Q5 [2]. We used a negatively biased copper electrode to collect all positive charges. This electrode could be polarized up to a voltage of -1000 V. On the same location the pressure (with Bayard Alpert gauge) and electron current were also monitored by a positively biased electrode called K11 polarized at +9 V. 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 noted 1 and 3: the first one during the beam injection and the bump 3 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 (bump coated 2); 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

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decreases still due to proton losses; (iv) Beginning of proton-proton collisions. Indeed, from this time, electrical signals decrease with the pressure.

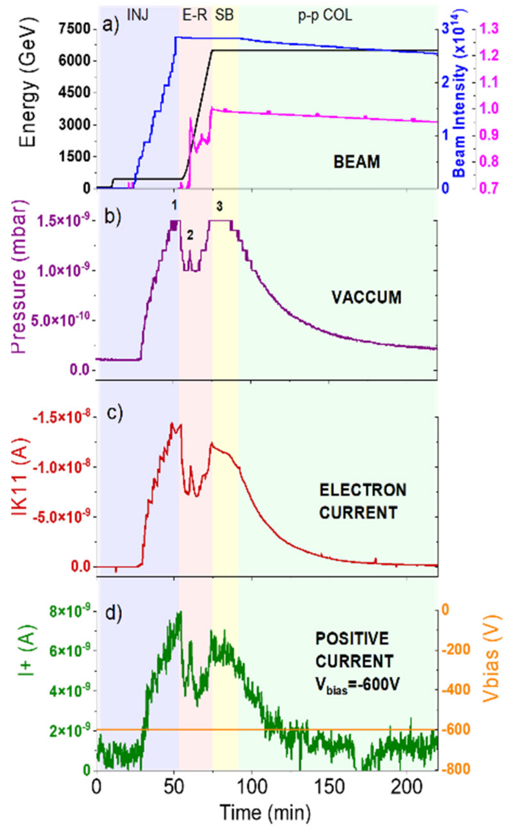

Figure 1: Measurements performed in station 4 of VPS during the Fill 7319: "blue" beam parameters (a), pressure (b), electron current (c) and positive current (d).

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

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

- 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 x 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 negatively polarized electrode. So, it looks difficult to separate ion and SE contributions to the total current I_+. Moreover, the ion current should be very low compared to the electron one, 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}. Finally, to compute the ion current, 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 intensity measured by the electrode if all incident (or primary) electrons are collected is given by:

$$I_{e-} = \mathrm{K} \int_0^\infty n(E) dE, \tag{2}$$

where n(E) is the normalized energy distribution of the electrons impinging the wall and K a constant to convert an electron density to a current.

For our calculations, we used an energy distribution n(E) recorded in the VPS during a fill recorded at 6500 GeV [4]; a calculated distribution inspired by the one given by G. Iadarola in [5] were also used. The energy spectrum can be described as the sum of two "lognormal" distributions:

$$\mathrm{n(E)} = n_1(E) + n_2(E)$$

$$n_i(E) = \frac{K_i}{(\sqrt{2*\pi})*w_i*E} * \mathrm{e}^{\left(-\frac{\left(\mathrm{Log}\left[\frac{E}{Ec_i}\right]\right)^2}{2*w_i^2}\right)}. \tag{3}$$

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. Equation (3) was used to fit the experimental energy spectrum; the values of parameters (Ec_i, w_i and K_i for both distributions) are reported in Table 1. Figure 2 shows both energy spectra fitted with Eq. (3) and used to calculate the electron current.

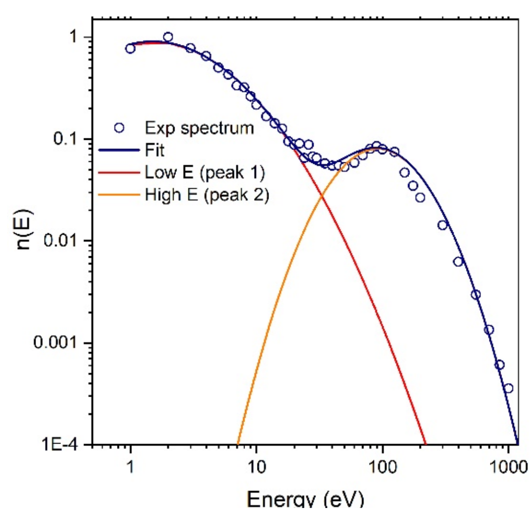

Figure 2: Normalized energy spectrum of electrons n(E) (blue open circle) recorded by an electrode in station 4 during a fill at 6500 GeV [4]. Lines are fits to experimental data with Eq. (3): total spectrum (blue line), low energy part (red line) and high energy part (yellow line).

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Table 1: Values of the Parameters Obtained from the Fit to the Experimental Electron Energy Spectrum

Parameters	**Peak 1**	**Peak 2**
Ec (eV)	6	150
K	7.9	16.5
W (eV)	1.17	0.7

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:

$$\delta(\mathrm{E}) = \delta_{max} \frac{s*\left(\frac{E}{E_{max}}\right)}{s-1+\left(\frac{E}{E_{max}}\right)^{s}} . \quad (4)$$

For the LHC beam chambers, the value s = 1.35 can be used [5, 7]. 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.

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_{bias} scanning during a fill, to calculations performed for 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 δ_{max} for the copper electrode.

CALCULATIONS AND EXPERIMENTAL MEASUREMENTS

First, I_+ current was recorded for several scanning of V_{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. 3. For this, I_+ was normalized to the total electron current.

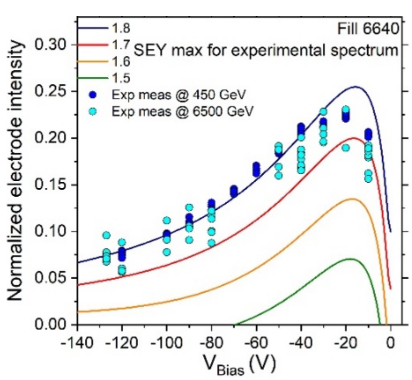

Figure 3: Variation of I+/Ielectrons vs Vbias : experimental data (white circles and black squares) and calculated values for several SEY using experimental spectrum (color lines).

The same behaviour is observed at 450 GeV and 6500 GeV, indicating that the photoelectron contribution remains low regarding the electron cloud contribution. 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 $V_{bias} \approx$ -20 V, and then the signal decreases. A small discrepancy between calculated and experimental signals occurs from V_{bias} = -120 V: whereas the calculated signal vanishes at the lowest V_{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 V $\leq V_{bias} \leq$ 0 V (see Fig. 4). It appears clearly that below -200 V, a constant value is reached ($I_+/I_{electrons}$ = 0.025). As the signal from electrons and SE should be null at the lowest V_{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.

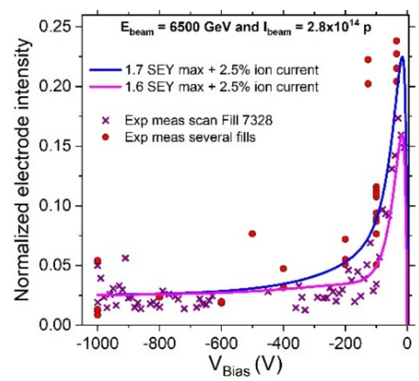

Figure 4: Variation of $I_+/I_{electrons}$ *vs* V_{bias}: experimental data (red circle recorded during different fills and purple cross for a voltage bias scanning during the fill 7328) and calculated values for several SEY (color lines) considering an ion current of 2.5% of the total electron one.

CONCLUSION

Ions, created by ionisation of the residual gas by the proton beam and the e-cloud, were studding at room temperature, in a 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. After a beam surface conditioning, this value appears to be higher than expected. We found that the ion current measured in station 4 of VPS represents in average 2.5% of the incident electron current, i.e. two orders of magnitude lower than the electron amount. It is usually considered that the ion amount is 5 orders of magnitude lower than the equilibrium electron density and thus their effects are negligible [3]. So, our experimental ion current is higher than it would be expected. Another source of ion should explain the unexpected high values of ion currents recorded in the VPS, which is not yet identified at present.

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