ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB291

DYVACS (DYnamic VACuum Simulation) CODE: GAS DENSITY PROFILES IN PRESENCE OF ELECTRON CLOUD IN THE LHC

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Abstract

The computation of residual gas density evolution in the LHC in the presence of proton beams was performed with a new simulation code called DYVACS (DYnamic VACuum Simulation) code. It could be considered as an upgrade of the VASCO code [1] to take into account dynamic effects such as the electron cloud density evolution along the beam passage leading to an increase of both the electron- and the ion-induced gas desorption. Results obtained with the DYVACS code is compared to pressure measurements recorded during a typical fill for physics in the Vacuum Pilot Sector of the LHC. First results show a good agreement between the calculated pressure and the experimental values, and partial pressure at different period of the beam life were presented.

INTRODUCTION

The computation of residual gas density profiles in particle accelerators is an essential task to optimize beam pipes and vacuum system design. In a hadron collider such as the LHC, the beam induces dynamic effects due to ion, electron and photon-stimulated gas desorption (Fig. 1 (a)). The well-known VASCO code [1, 2] developed at CERN in 2004 (and then PyVASCO [3]) is already used to estimate vacuum stability and density profiles in steady state conditions. Nevertheless, some phenomena are not taken into account specifically. Photoemission and/or ionization of the residual gas in the beam pipe produces electrons, which move under the action of the beam field and their own space charge. These primary electrons may initiate the build-up of a quasi-stationary electron cloud, which can severely affect the machine operation (Fig. 1 (b)). Therefore, we propose an upgrade of the VASCO code by introducing electron cloud maps [4] to estimate the electron density and the ionization of gas by electrons leading to an increase of both the electron- and the ion-induced desorption. Results obtained with the DYVACS code will be compared to pressure measurements in the Vacuum Pilot Sector [5], a room temperature, non-magnetic straight section of LHC. We focused on measurements performed in station 4 ("blue" beam or beam 1, in a copper vessel) located in the vacuum sector A5L8 between the quadrupoles Q4 and Q5.

VACUUM MODEL

The aim of the DYVACS code is to calculate the gas density evolution in a beam pipe and to be able to compute partial pressure at each time taking into account dynamic effects. We proposed thus a modification of the vacuum model implemented in the VASCO code [1]. The rate of change of number of molecules per unit volume (schematically shown in Fig. 1) depends on:

- Molecular diffusion along the chamber;
- Ion, electron and photon-stimulated gas desorption;
- Gas lumped pumping and gas pumping distributed along the pipe;
- Residual gas ionization by proton beams (for the LHC) and by electrons (from the electron cloud).

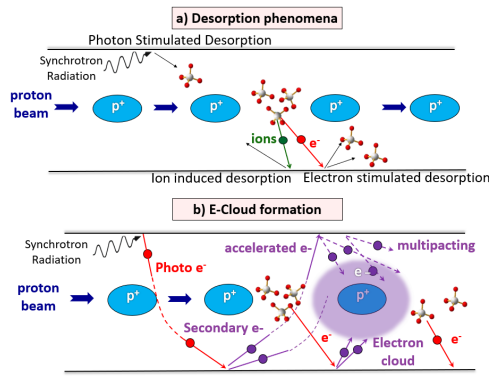

Figure 1: Ion, electron and photon-stimulated desorption phenomena in the beam pipe (a); electron cloud formation and electron multipacting (b).

For the moment, we applied this model only for beam pipes at room temperature to model the VPS. We assumed that the vacuum chamber is cylindrical, so the calculations are performed for a one-dimensional approximation, along the beam axis.

The dominant gas species, which are present in a vacuum system, are hydrogen (H_2), methane (CH_4), carbon monoxide (CO) and carbon dioxide (CO_2). Our calculations are performed in the framework of the multi-gas model, so interactions between the different gas species are also taken into account in the ion-induced desorption term: each of the gas species, once ionized, can desorb any species both from the wall beam pipes. The equation of each species depends on the gas densities of other species, and all the equations are inter-dependent.

It is worth noting that the time scale is divided in steps in which a quasi-steady state is considered to describe the gas density evolution. In the case of "one-gas" model, considering the gas flow in and out of the system, the mass-balance equation used to describe the evolution of each species with the gas density $n_j = (n_{H_2}, n_{CH_4}, n_{co}, n_{co_2})$ is:

$$C_j \frac{\partial^2 n_j}{\partial x^2} + \mathrm{D}_{ion-j} + \mathrm{D}_{e-j} + \mathrm{D}_{ph-j} + D_{th-j} - S \cdot n_j = 0. \quad (1)$$

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The first term $C_j \frac{\partial^2 n_j}{\partial x^2}$ refers to molecular diffusion. D_{ion-j}, D_{e-j} , D_{ph-j} and D_{th-j} (molec/m/s) describe the desorption phenomena: ion, electron and photon stimulated desorption, as well as thermal desorption, respectively. The last term $S \cdot n_j$ refers to the pumping flux.

- C_j = specific conductance for j gas species (m^4/s);
- n = gas density (molec/m^3);
- S = pumping speed per length unit (m^2/s).

The term describing the ionic desorption (Eq. (2)) can be split into two parts to derive the residual gas ionisation by the proton beam and by the electron cloud.

$$D_{ion-j} = \sum_{i=1}^{4} \eta_{ion-i\rightarrow j} \left(\sigma_{p\rightarrow i} \cdot \frac{I_{beam}}{e} + \sigma_{e\rightarrow i} \cdot \rho_e \cdot v_e\right) n_i, \quad (2)$$

for i = H_2, CH_4, CO, CO_2.

- ρ_e (e-/m) is the electron linear density;
- v_e (m/s) the mean velocity of electrons;
- $\eta_{ion-i\rightarrow j}$ is the ion stimulated desorption yield of gas j induced by the ion i (multi-gas model);
- $\sigma_{p\rightarrow i}$ is the ionization cross section of gas i by protons (m^2);
- $\sigma_{e\rightarrow i}$ is the ionisation cross section of gas i by electrons (m^2);
- I_{beam} is the proton beam current (A);
- e is the electron charge (C).

Equation (3) describes all other desorption phenomena: electronic desorption, photon stimulated desorption and thermal desorption.

$$D_{e,j} + D_{ph,j} + D_{th,j} = \eta_{e,j}\Gamma_e + \eta_{ph,j}\Gamma_{ph} + a \cdot q_{th,j}\,, \quad (3)$$

- Γ = electron (e) and photon (ph) flux to the wall per unit length (e- or ph/s/m);
- q_{th}=thermal outgassing per unit length ($s^{-1}m^{-2}$);
- a = surface area of the chamber wall per unit length (m).

Parameters are set according to the properties of gas species. For example, CH_4 is a non-getterable gas, thus NEG pumping has no influence on its density.

Values of gas desorption coefficients η or ionisation cross section σ can be found in [6].

The photon flux can be estimated from:

$$\Gamma_{ph} = 7.017 \cdot 10^{13} \frac{E_{beam}}{\rho} I_{beam}\,, \quad (4)$$

with E_{beam} = 6500 GeV and the bending radius for LHC ρ = 2803.95 m. A correction factor is used to take into account the distance between the last dipole and the VPS.

The evolution of the electron density at a point, averaged over the time interval between successive bunch passages, can be accurately described by a simple cubic map [4]. The electron density after the bunch m passes by (referred to as ρ_{m+1}) is a function only of the interaction between the bunch and the electron density before the bunch m passed by (referred to as ρ_m). So, the electron density was estimated from:

$$\rho_{m+1} = a\rho_m + b{\rho_m}^2 + c{\rho_m}^3, \quad (5)$$

with a = 1.4, b = -0.1, c = 0. Figure 2 shows an example of the time evolution of the electron density for one batch with 48 successive charged bunches and with a bunch spacing of 25ns. The average electron density is given by:

$$\bar{\rho} = \frac{1}{T}\int \rho\, dt\,, \quad (6)$$

with T = number of bunches × 25 ns. The electron flux is finally averaged on a time t_L = 89 µs (corresponding to one revolution period in the ring) and calculated from the number of batch (N_{batch}):

$$\overline{\Gamma_e} = \frac{\bar{\rho} \times N_{batch}}{e \times t_L}\,. \quad (7)$$

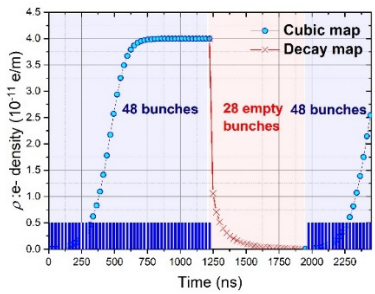

Figure 2: Evolution of the electron density for a nominal LHC fill using 48 bunches followed by 28 empty bunches for the decay, with N = 1.2x10^{11} ppb, T = 1 ns, tau = 25 ns, δ_max = 1.6 (so SEY for Ee- = 150 eV = 1.4) and an initial electron density 109 e/m. EC parameters: a = 1.4, b = -0.1, c = 0. Decay parameters a = 0.858, b = -0.1905 and c = 0.0105.

The DYVACS code is implemented in MATHEMATICA and the solution to the set of Eq. (1) is given in [1]. A vacuum system can be composed by several elements (segments coated S1 to S6 in Fig. 3), each element being characterised by a different set of parameters. So, for each segment, Eq. (1) is solved. Therefore, for each time step that are defined into the code:

- ion flux (from ionization and desorption);
- Γ_e electron flux (from ionization and electron cloud);
- Γ_{ph} photon flux (due to synchrotron radiation);
- are calculated. Then, n_j and the partial pressures of H_2, CH_4, CO and CO_2 were determined.

CALCULATION vs. EXPERIMENT

In order to validate the DYVACS model, the dynamic pressure in the station 4 (copper vessel) of VPS in LHC was simulated and compared to experimental measurements performed during the Run 2.

First, the station 4 is divided into 6 segments (Fig. 3). The Fig. 4 presents the time evolution of the beam energy in black, and beams intensities ("blue and red" beams) during a typical physics fill: from proton injection to proton-proton collisions step. Then, results of pressure calculation obtained in the copper vessel (segment S3 and S4) were compared to experimental measurements recorded during the fill 6636 (a typical physics fill with a filling scheme:

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25ns_2556b_144bpi_20inj, Fig. 5) for the "blue" proton beam (or beam 1).

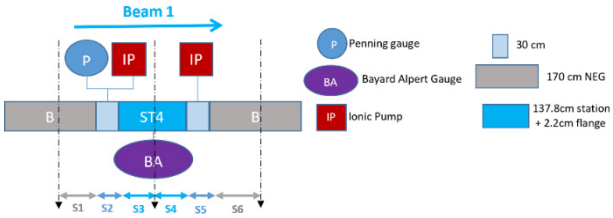

Figure 3: Drawing of the station 4 in the VPS (copper vessel) and definition of segments for the DYVACS simulation.

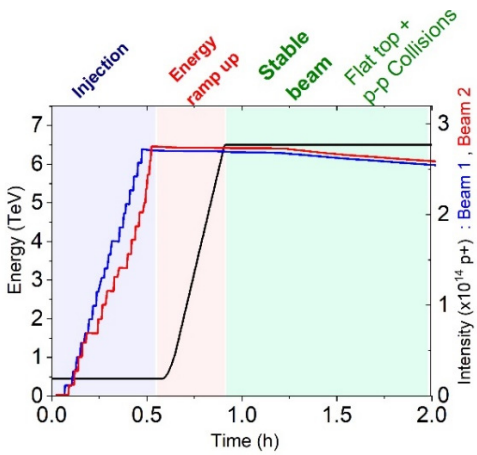

Figure 4: Energy and beam intensity ("blue" beam) during the fill 7319: proton injection (from 0 to a charge of 2.85x1014, blue line), energy ramp up (from 450 to 6500 GeV, black line) and then stable beam (p-p collisions).

Figure 5 presents a comparison of the calculated pressure in the station 4 and the recorded values during the fill 6636.

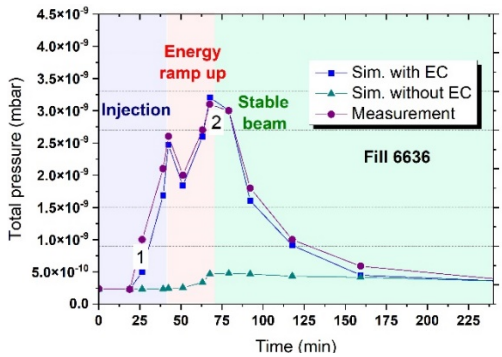

Figure 5: Experimental pressure (purple line) and computed pressure using DYVACS with EC (blue line) and without EC (green line) for fill 6636 (beam 1) on 2 May 02 2018. The time scale stars at the proton injection (from 0 to a charge of 2.85x10^{14}), covers the energy ramp up (from 450 to 6500 GeV) and the stable beam period (flat top plus proton-proton collisions).

A very good agreement is obtained for the proton injection period: both show an increase in pressure (from 10^{-10} to 2.7x10^{-9} mbar) due to the residual gas ionization by the proton beam and the electron cloud. If the electron cloud density evolution is not taken into account in the calculations (green line in Fig. 5), this pressure increase is not observed by the simulation. This result shows that the electron cloud has a large influence on the pressure evolution during the LHC operation. Then, the second increase in pressure measurement due to photo-electrons production occurring during the energy ramp-up is also observed in the calculation. The model used reproduced all the pressure evolution from the beam injection to the collision period.

Figure 6 shows the partial pressures calculated with the DYVACS code for H_2, CO_2, CO and CH_4 at two different period (period 1at the beginning of injection and period 2 during the stable beam step, see Fig. 5). At the injection beginning, only few protons ionize the residual gas, and so a small amount of gas is desorbed. The partial pressure of H_2 is around 2x10^{-10} mbar (left of the Fig. 6). At the end of the energy ramp up period, all protons circulate in the ring, and photoelectrons lead to an increase of electron stimulated desorption phenomena. At this time coated 2 in Fig. 5, the partial pressure of H_2 is around 2x10^{-9} mbar. So finally, from the injection period to the end of the energy ramp-up step, the partial pressure of H_2 increases of about one order of magnitude.

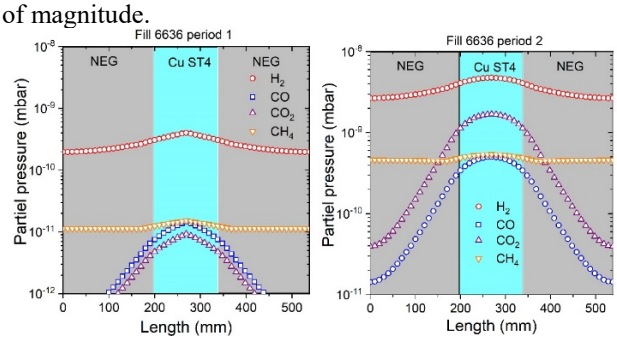

Figure 6: Evolution of partial pressures of H_2, CO_2, CO and CH_4 and total pressure calculated with the DYVACS code for a typical LHC physics fill, for two different periods.

As it was presented, in DYVACS code, CH_4 is a non-getterable gas, thus NEG pumping has no influence on its density, that is why no difference is observed between NEG and Copper vessel.

CONCLUSION

In this paper, the DYVACS code for residual gas pressure estimation in a non-magnetic straight line at room temperature in the LHC is presented. The initial model developed in VASCO was modified to take into account dynamic effects such as the electron cloud evolution along the LHC operation. Calculation successfully reproduces the pressure evolution measured in the station 4 of VPS in the LHC, from the proton injection period to the proton-proton collisions step. Improvements of the code are in progress in order to obtain a better agreement between experimental values and the calculated ones. It is worth noting that the DYVACS code can be easily adapted to other types of vacuum system pipes.

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