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

B. Mercier, S. Bilgen, G. Sattonnay† LAL, Univ. Paris Sud, CNRS/IN2P3, Orsay, France
V. Baglin, CERN, The European Organization for Nuclear Research, Geneva, Switzerland

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). It is a modification of the VASCO code in order to take into account dynamic effects such as the electron cloud phenomenon leading to an increase of both the electron- and the ion-induced gas desorption. Re-sults obtained with the DYVACS code is compared to pressure measurements recorded during a typical physics fill in the Vacuum Pilot Sector of the LHC. First results show a good agreement between the calculated pressure and the experimental values.

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 (figure 1a). 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 (figure 1b). 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 and 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 take 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 Figure 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).

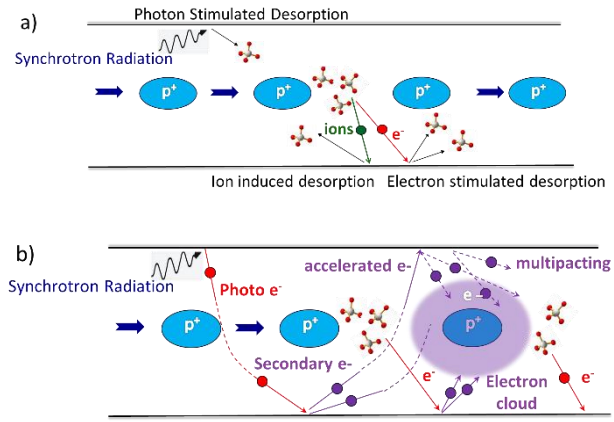

Figure 1: Ion, electron and photon-stimulated desorption phenomena in the beam pipe (a); electron cloud formation and electron multipacting (b).

For the moment, we applied this model only for beam pipes at room temperature. The cryo-pumping for instance is not yet taken into account.

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. More precisely this interaction occurs in the ion-induced desorption term: each of the gas species, once ionized, can desorb any species both from the wall beam pipes or the condensed gas layer in a cryogenic system. 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 $n_j = (n_{H2}, n_{CH4}, n_{CO}, n_{CO2})$ is:

† sattonnay@lal.in2p3.fr

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$$C_j \frac{\partial^2 n_j}{\partial x^2} + \eta_{i,j}\left(\sigma_{i-p,j} \cdot \frac{I_{beam}}{e} + \sigma_{i-e,j} \cdot \Gamma_e\right) \cdot n_j + \eta_{e,j}\Gamma_e + \eta_{ph,j}\Gamma_{ph} + a \cdot q_{th,j} - S \cdot n_j = 0 \quad (1)$$

Residual gas ionization; by p beam; by ECloud; Flux pumping

Molecular diffusion; Ionic desorption; e- desorption; Photon desorption; Thermal outgassing

- C_j=specific conductance for j gas species
- η = ion (i), electron (e) and photon (ph) induced gas desorption coefficients
- $\sigma_{i\text{-}p}$ = ionisation cross section of the gas-proton interaction;
- $\sigma_{i\text{-}e}$ = ionisation cross section of the gas-electron interaction;
- Γ = electron (e) and photon (ph) flux to the wall per unit length;
- q_{th}=thermal outgassing per unit length;
- a = surface area of the chamber wall per unit length;
- I_{beam} = beam current;
- e= electron charge.

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. With the multi-gas model, equation (1) is modified and the ionic desorption part becomes for the gas j:

$$\eta_i \sigma_{i-p,j} \cdot \frac{I_{beam}}{e} = \frac{I_{beam}}{e} \sum_{gas} \eta_{i,\,gas^+ \to j} \cdot \sigma_{i-p,gas} \cdot n_{gas} \quad (2)$$

with gas = H_2, CH_4, CO, CO_2.

Values of gas desorption coefficients η or ionisation cross section σ can be found in [6].
The photon flux can be estimated from:

$$\Gamma_{ph} = 7.017 \cdot 10^{13} \frac{E_{beam}}{\rho} I_{beam} \quad (3)$$

with E_{beam}=6500 GeV and the bending radius for LHC ρ=2803.95m. 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:

$$\rho_{m+1} = a\rho_m + b{\rho_m}^2 + c{\rho_m}^3 \quad (4)$$

with a = 1.3, b = -1, c = 0.5. 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:

$$\bar{\rho} = \frac{1}{T}\int \rho \, dt \quad (5)$$

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

$$\overline{\Gamma_e} = \frac{\bar{\rho} \times N_{batch}}{e \times t_L} \quad (5)$$

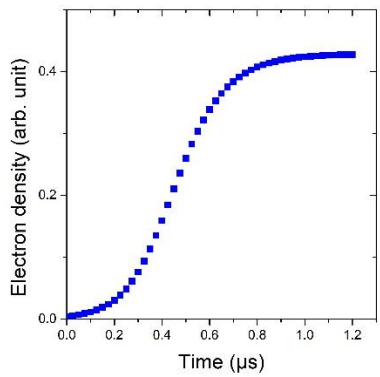

Figure 2: Time evolution of the electron density for one batch with 48 bunches of protons, given by equation (4).

The DYVACS code is implemented in MATHEMATICA and the solution to the set of equations (1) is given in [1]. A vacuum system can be composed by several elements (segments), each element being characterised by a different set of parameters. So, for each segment, equation (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 *VERSUS* 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 (figure 3). Then, results of calculation obtained in the copper vessel (segment 3 and 4) were compared to experimental measurements recorded during the fill 7319 (a typical physics fill with a filling scheme: 25ns_2556b_144bpi_20inj, figure 4) for the "blue" proton beam.

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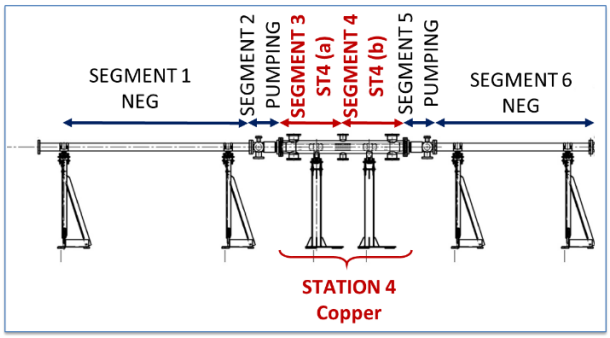

Figure 3: Drawing of the station 4 in the VPS (copper vessel) and definition of segments for the DYVACS simulation.

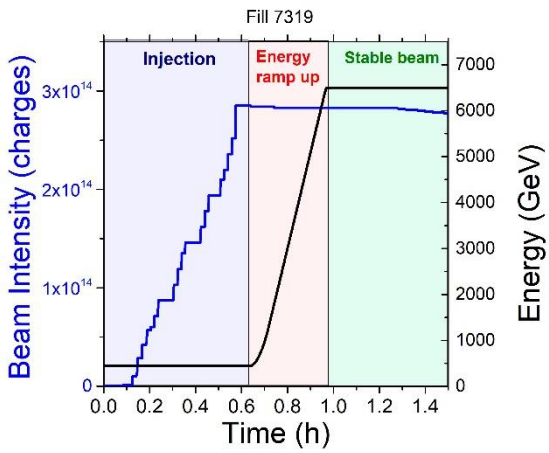

Figure 4: Energy and beam intensity ("blue" beam) during the fill 7319: proton injection (from 0 to a charge of 2.85x1014, blue line), energy ramp up (from 450 to 6500 GeV, black line) and then stable beam (p-p collisions).

Figure 5 presents a comparison of the calculated pressure in the station 4 and the recorded values during the fill 7319.

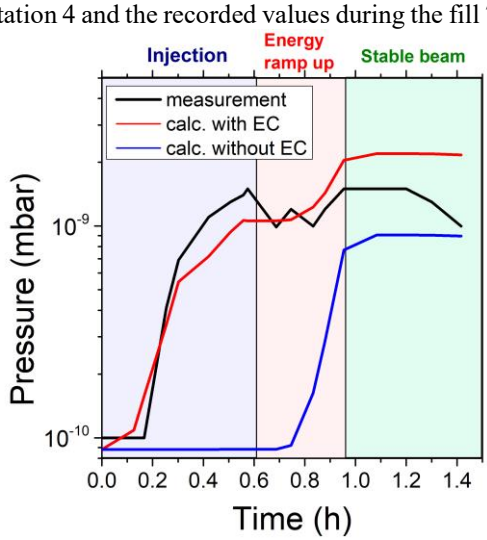

Figure 5: Time evolution of pressure during the fill 7319: measurements (black line), results of the DYVACS simulation with the electron cloud (red line) and without the electron cloud (blue line).

A very good agreement is obtained for the proton injection period: both show an increase in pressure (from 10^{-10} to 10^{-9} mbar) due to the residual gas ionization by the proton beam and the electron cloud. If the electron cloud is not taken into account in the calculations, this pressure increase is not observed by the simulation. This result shows that the electron cloud has an important influence on the pressure during the injection of protons. Then, the second increase in pressure due to photo-electrons occurring during the energy ramp-up is observed in the experimental results but it is a little overestimated by the calculation.

Figure 6 shows the time evolution of the partial pressures calculated with the DYVACS code for H_2, CO_2, CO and CH_4. During the injection, the pressure increase is higher for CO and CO_2 than for H_2 and CH_4, whereas during the energy ramp the amount of CH_4 increases faster than the other species.

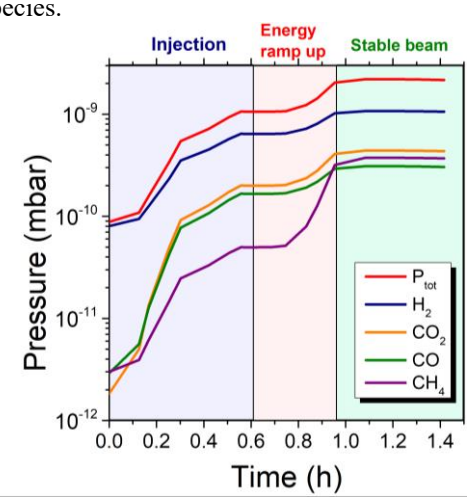

Figure 6: Evolution of partial pressures of H2, CO2, CO and CH4 and total pressure calculated with the DYVACS code for a typical LHC physics fill.

CONCLUSION

In this paper, the DYVACS code for residual gas pressure estimation in non-magnetic straight lines 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 phenomenon. Calculation successfully reproduces the pressure evolution measured in the station 4 of VPS in the LHC, even if the effect of photo-electron is a little overestimated. 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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