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DYVACS (DYnamic VACuum Simulation) CODE: GAS DENSITY PROFILES FOR DYNAMIC CONDITIONS IN PARTICLE ACCELERATORS - SIMULATIONS FOR THE LHC AND THE FCCe^+e^-

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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 takes 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 for copper, NEG (None Evaporable Getter) composed of Ti-Zr-V and carbon coating beam pipes. 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. The DYVACS code is also used as a predictive tool for future machines such as FCC-e^+e^-. For specific beam conditions, pressure evolution for stainless steel pumping pipes and NEG beam pipes are presented.

INTRODUCTION

The beam induces dynamic effects due to (i) pressure increases induced by the desorption of electrons, photons and ions; (ii) clouds of ions or electrons inducing a multipacting effect leading to beam instabilities and heat deposits on the vacuum chamber walls (Fig. 1). 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. Photoemission and/or ionization of the residual gas in the beam pipe produces electrons, which are accelerated by 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). Depending on the beam characteristics, an ion cloud can also be produced. 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, 1 and 2 ("blue" beam or beam 1, respectively in a copper, NEG and carbon coating vessel) located in the vacuum sector A5L8 between the quadrupoles Q4 and Q5.

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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) by an electron beam (for the FCC) and by electrons (from the electron cloud).

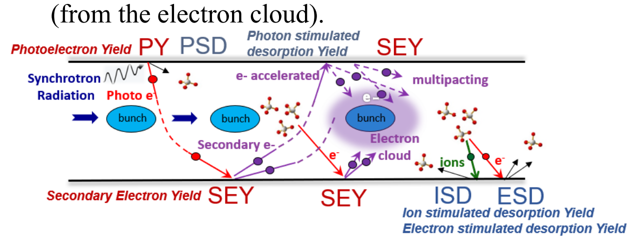

Figure 1: Ion, electron and photon-stimulated desorption phenomena in the beam pipe and the electron cloud formation with the multipacting effect.

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.

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:

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

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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 particle beam and by the electron cloud.

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

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;
- $\eta_{ion-i\to j}$ is the ion stimulated desorption yield of gas j induced by the ion i (multi-gas model);
- $\sigma_{p\to i}$ is the ionization cross section of gas i by particle beam (proton for the LHC or electron for the FCC) (m^2);
- $\sigma_{e\to i}$ is the ionisation cross section of gas i by electrons (m^2);
- I_{beam} is the particle beam current (A);
- e is the electron charge (C).

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

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

- 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] for proton beams, and the cross section for an inelastic collision between a molecule or an atom by a relativistic electron can be estimated using the relativistic Bethe asymptotic formula [7].

The photon flux for a proton and electron beam can be estimated from Eq. (4):

$$\Gamma_{ph}^{prot} = 7.017 \cdot 10^{13} \frac{E_{beam}}{\rho} I_{beam}\,,$$
$$\Gamma_{ph}^{elect} = 1.288 \cdot 10^{17} \frac{E_{beam}}{\rho} I_{beam}\,, \qquad (4)$$

with E_{beam} = 6500 GeV and 182.5 GeV and the bending radius ρ = 2803.95 m and 10760 m respectively for the LHC and the FCC. A correction factor is used to take into account the distance between the last dipole and the position of the pressure computation to evaluate de photon flux.

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 DYVACS code is implemented in MATHEMATICA and the solution to the set of Eq. (1) is given in [1]. Therefore, for each time step that are defined:

- 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

The dynamic pressure in the station 4, 1 and 2 (respectively copper, NEG and carbon coating vessel) of VPS in LHC was simulated and compared to experimental measurements performed during the Run 2. The Fig. 2 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, NEG and carbon coating vessel were compared to experimental measurements recorded during the fill 6636 (a typical physics fill with a filling scheme: 25ns_2556b_144bpi_20inj, Fig. 3) for the "blue" proton beam (or beam 1).

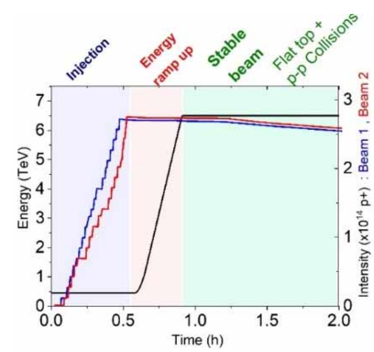

Figure 2: Energy and beam intensity ("blue" beam) during the fill 7319: proton injection (from 0 to a charge of 2.85· 10^{14}, blue line), energy ramp up (from 450 to 6500 GeV, black line) and then stable beam (p-p collisions).

Figure 3 presents a comparison of the calculated pressure in the station 4, 1 and 2 and the recorded values during the fill 6636. A very good agreement is obtained for the proton injection period: both show an increase in pressure (from 10^{-10} to $2.7 \cdot 10^{-9}$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. 3). 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.

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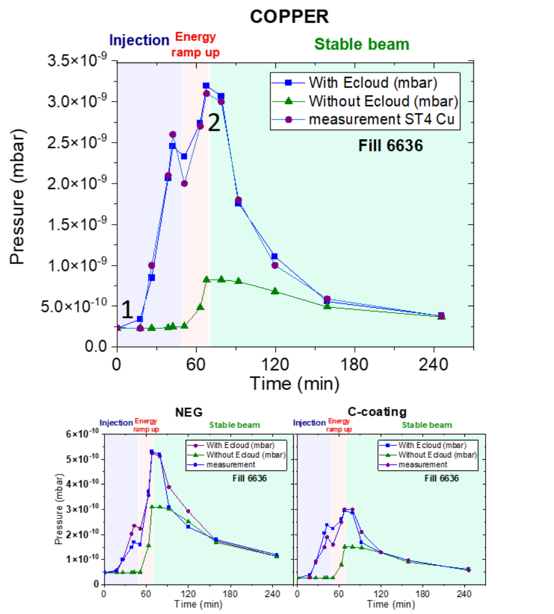

Figure 3: Experimental pressure (purple line) and computed pressure using DYVACS with EC (blue line) and without EC (green line) for fill 6636 (beam 1) on 2 May 02 2018 for copper, NEG and carbon coating vessel. The time scale stars at the proton injection (from 0 to a charge of $2.85\cdot 10^{14}$), covers the energy ramp up (from 450 to 6500 GeV) and the stable beam period (flat top plus proton-proton collisions).

The model used reproduced all the pressure evolution from the beam injection to the collision period. NEG vessel has a lower pressure increase than the copper vessel because of it distributed pumping properties. For Carbone coating vessel, the main difference is it lower SEY value.

The DYVACS code can be used as a predictive tool for future machines such as FCCe$^+$e$^-$. Preliminary results on pressure evolution were obtained and presented in the following part.

THE DYVACS CODE USE AS A PREDICTIVE TOOL FOR FCCe$^+$e$^-$

NEG thin film (None Evaporable Getter) composed of Ti-Zr-V has been chosen as a good candidate for FCCe$^+$e$^-$ vacuum chamber due to the low secondary electron emission yield (SEY), and to perform a distributed pumping around a twin-ring of 100 km circumference.

The dynamic pressure for a 4 m NEG vessel connecting to 30 cm of stainless steel pipe in the FCCe$^+$e$^-$ was simulated. The Table 1 summarizes input parameters used for DYVACS computations. Ionisation cross section σ for the beam were computed using Bethe formula [7], and ionisation cross section for Compton electrons at 100 keV were obtained on NIST data base [8]: $\sigma_{e-/H2}$=5·10^{-23} m^2; $\sigma_{e-/CO}$=1.8·10^{-22} m^2; $\sigma_{e-/CO2}$=2.7·10^{-22} m^2; $\sigma_{e-/CH4}$=1.8·10^{-22} m^2.

The Fig. 4 presents the time evolution of the beam energy in red, and beams intensities in blue: from electron and positron injection to a stable beam period after the beam energy ramp up from 45 GeV (the Z-configuration) to 182.5 GeV the ttbar configuration.

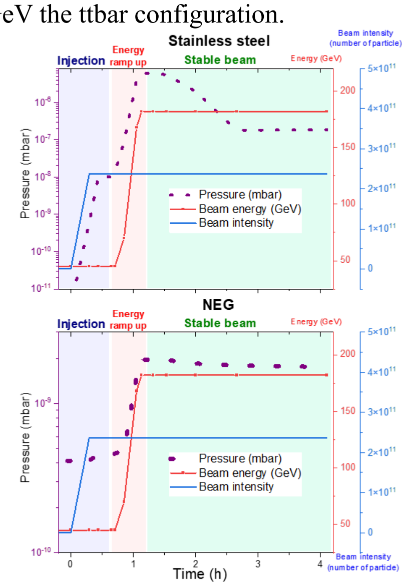

Figure 4: Computed pressure (purple dotes) using DYVACS with the beam energy (red line), and beams intensities (blue line).

For stainless steel following by the NEG section both show an increase in pressure due to the residual gas ionization by the electron beam. Then, the second increase in pressure measurement due to the variation of photo-electrons production occurring during the energy ramp-up.

Table 1: Input Parameters for DYVACS Simulations for Fcce+e- in Ttbar Configuration

Parameters	Units	values
Energy	GeV	182.5
Current	A	5·10^{-3}
Number of particles per bunch	e/bunch	2.37·10^{11}
Number of Bunches	bunches	40
Circumference	km	97.756
Bending radius	km	10.760
NEG SEY		1.2
NEG ESD	Molecules/e$^-$	10^{-5}
NEG PSD	Molecules/ph	10^{-4}
Photoelectron yield	e$^-$/photon	0.23
Time per turn	µs	315
Bunch spacing	ns	25

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. Calculation successfully reproduces the pressure evolution measured in the station 4, 1 and 2 of VPS in the LHC. Concerning pressure evolution computed for FCCee, the pressure increases up to 10^{-6} mbar in stainless steel but keep under 3·10^{-9}mbar for the NEG section. These preliminary results have to be cross check and an electron spectrum have to be implemented but the evolution follows the pressure evolution obtained on the LHC. Improvements of the code are in progress in order to obtain a better agreement.

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