VACUUM PERFORMANCE OF AMORPHOUS CARBON COATING AT CRYOGENIC TEMPERATURE WITH PRESENCE OF PROTON BEAMS

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Abstract

Amorphous carbon (a-C) coating is the baseline electron multipacting mitigation strategy proposed for the Inner Triplets (IT) in the High Luminosity upgrade of the Large Hadron Collider (HL-LHC). As of 2014, the COLD bore EXperiment (COLDEX) is qualifying the performance of a-C coating at cryogenic temperature in a LHC type cryogenic vacuum system. In this paper, the experimental results following a cryogenic vacuum characterization of a-C coating in the 5 to 150 K temperature range are reviewed. We discuss the dynamic pressure rise, gas composition, dissipated heat load and electron activity observed within an accumulated beam time of 9 Ah. The results of dedicated experiments including pre-adsorption of different gas species (H_2, CO) on the a-C coating are discussed. Based of phenomenological modeling, up-to-date secondary emission input parameters for a-C coatings are retrieved for electron cloud build-up simulations. Finally, first implications for the HL-LHC ITs design are drawn.

INTRODUCTION

After successful completion of the Long Shutdown 1, the Large Hadron Collider resumed operation in 2015 with circulation of 25 ns spaced beams, accelerated for the first time to 6.5 TeV. Strong electron cloud effects were observed in all the machine, with the main performance limitation sitting in the response to the beam induced heat load transients at injection and reach of the available cooling capacity of the cryogenic system (estimated: 135 W/half-cell in arc 2-3, 160 W/half-cell in the others) [1]. Mitigation was achieved by modulation of the intensity ramp-up, optimization of the filling schemes and beam conditioning in dedicated scrubbing runs and throughout the physics runtime. Observations in the Standalone and Inner Triplet areas confirmed the weight of electron cloud multipacting at IT 1/5 and IT 2/8, exhibiting a transient specific (global) heat load up to ~3.1 W/m/aperture (~110 W) and ~2.2 W/m/aperture (~100 W), over a current expected global operational limit of ~120 W [1].

In view of the intensity ramp-up toward 2748 bunches - in trains of 288 - of 2016, the expected rises in heat load will be counterbalanced by new feedforward logic in the beam screen control loop [1] and optimization of the global capacity of the cryogenic plants. Recent extrapolations [1] of the Run 1 observations to the High Luminosity upgrade (HL-LHC) beams of $2.2 \cdot 10^{11}$ ppb predict no significant increase in the heat due to electron cloud in the HL-LHC arcs and quadrupoles for fully scrubbed Cu (SEY≤1.3) but confirm an intolerable increase of heat load in IT 1/5 and IT-D1 2/8 of a factor 5÷7 for 1.2≤SEY≤1.3. Limitations in the maximum luminosity and total beam intensity in collision operational mode, potential beam stability issues and increased background to the LHC experiments are expected. Modifications in the cryogenic installation are hardware invasive; an increase in the maximum tolerable temperature excursion of the beam screen may turn in undesirable dynamic pressure rises. In order to avoid multipacting and be compatible with a postulated IT cooling capacity of 200 W, the current electron mitigation baseline stays amorphous carbon (a-C) coating for the new HL-LHC triplets in IR1/5, and to be carried *in-situ* at IR2/8.

The COLDEX experiment, re-commissioned in 2014 [2], is further validating the HL-LHC baseline at cryogenic temperature in the Super Proton Synchrotron (SPS) in presence of LHC type beams. Typical measurements during beam runtime are the dynamic pressure rise, gas composition, dissipated heat load and electron activity observed as a function of the beam parameters and the cold bore and beam screen surface conditions (temperature and gas coverage). After the first beam runs in 2014 [3], three additional runs were carried in 2015, pushing the total accumulated beam time to 9.88 Ah. Two of them included pre-adsorption of a gas specie, H_2 and CO respectively. During periods without beam, the setup was used to study the cryogenic vacuum characteristics of a-C coating in the 5 to 150 K temperature range.

PRELIMINAR CRYOGENIC VACUUM CHARACTERIZION

The COLDEX setup provides a quasi-closed system where the physical adsorption of gas species onto the a-C coated (400 nm) BS surface can be studied. The tubular geometry is characterized by a L/R = 66.6. BS temperatures ranging from 5 to 150 K are obtained in steady state. For these studies, the CB temperature is usually kept well above the corresponding temperature of physisorption and condensation for most of the gases (e.g. >150 K) on stainless steel (SS), so that adsorption is practically only possible for H_2O. Gases are either accumulated on a-C from desorption of room temperature (RT) parts, or injected at RT from a single, downstream, point via a Gas Injection System (GIS) [2]. The gas molecules stick preferentially at the BS extremities. The coverage is redistributed uniformly along the surface by complete thermal desorption via induced warm-up, followed by a slow (<1 K/min) cool-down. Successful redistribution is checked by pressure uniformity along the system. For $\theta_0 < 1 \cdot 10^{15}$ molecules/cm^{-2}, effective physical adsorption is observed on a-C for temperatures well above than of Cu or SS, *i.e.* below 35 K for H_2, and 80 K for N_2 and CO. Desorption, *i.e.* loss of physisorption, is monitored

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in slow (≤0.5 K/min) induced warm-up by Thermal Desorption Spectroscopy (TDS) at constant heating rate β. The effect of re-adsorption during the process is assumed negligible. Fig. 1 shows a compilation of TDS for H_2, N_2 and CO measured on a-C coating as a function of the initial coverage θ_0 and β. The maximum desorption rate, identified by $T_p=T(p_{max})$, is dependent on the coverage θ_0; in particular, T_p decreases with increasing coverage. Assuming a 1st order desorption model, differences in β spanning over one order of magnitude do not reflect the shift in the peaks. The a-C is thus capable of dissociative molecule adsorption and desorbs thermally following a 2nd order model [4], as the symmetry of the desorption peaks also suggests.

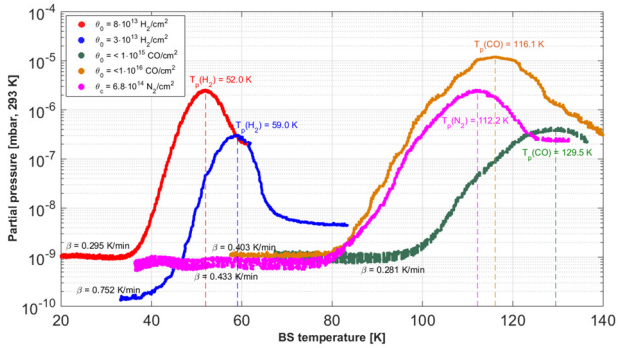

Figure 1: TDS for H_2, N2 and CO measured for a-C coating as a function of θ_0 and β.

The adsorption capacity for H_2 has been measured at 6.5 K and 11.1 K by subsequent gas injections and uniformizations. The built-up adsorption isotherms are shown in Fig. 2. Signs of surface saturation were recorded with a coverage of > $4\cdot10^{17}$ H_2/cm^2 and > $2\cdot10^{17}$ H_2/cm^2 respectively, *i.e.* two orders of magnitude higher than the monolayer capacity of metallic surfaces like Cu or SS. This result points to a porous surface morphology of a-C.

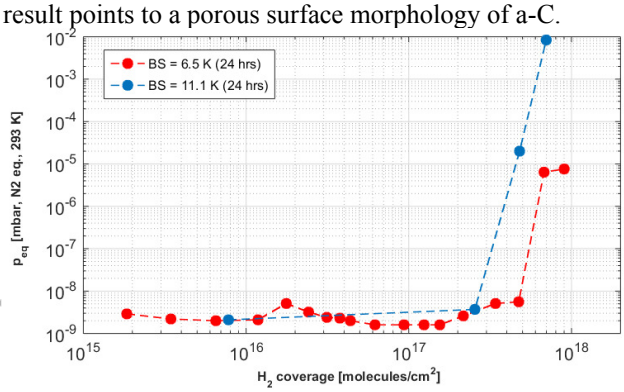

Figure 2: a-C H_2 adsorption isotherms at 6.5 K and 11.1 K.

RESULTS DURING BEAM RUNS

The first COLDEX experimental beam run of 2015 took place in a 3.5-days period, the accumulated beam dose exceeding 2.5 Ah. Two BS temperatures have been chosen: first ~10 K, then ~60 K, while the CB was kept at ~4.5 K and ~3K, respectively. One to four batches of 72 bunches, 25 ns spaced, up to $2.0\cdot10^{11}$ ppb, circulated into COLDEX, principally at 26 GeV/c. At 10 K, pressure rises up to ~$1\cdot10^{-6}$ mbar, correlated to the beam circulation, were observed upstream and downstream of COLDEX due to electron stimulated desorption in RT parts, while a steady pressure trend (~$3\cdot10^{9}$ mbar) was observed at the BS centre. A global re-conditioning of the RT surfaces was visible thanks to beam scrubbing, reducing the dynamic pressure rise by a factor 3 in 0.7 Ah. During beam off, the sector valves were closed and the BS temperature raised to 60 K, inducing desorption of the accumulated gas, which was principally H_2. The flushing of about $2.3\cdot10^{-3}$ mbar·l of H_2 covered the CB surface, held at 4.2 K, with a tenth of monolayer. Beam was resumed in these conditions (see Fig. 3), and transmission of the desorbed H_2 from the RT parts toward the BS was observed building-up in a dynamic slow pressure rise up to ~$6.5\cdot10^{-8}$ mbar (H_2 eq., RT), similarly to what observed in [3]. At 60 K, the BS was capable to physisorb only a very limited quantity of H_2, and the only source of pumping was the CB held at 4.2 K. At the end of the transient, the CB was covered with about 8 tenth of a monolayer and as such dominated by its vapour pressure (~$7.7\cdot10^{-9}$ mbar at 4.2 K). A rapid variation of the CB LHe bath pressure from 950 mbar to 700 mbar lowered the CB temperature to 3.8K, thereby significantly reduced its H_2 vapour pressure and reestablished a Δp of two orders of magnitude between RT parts and the BS centre. The background pressure inside COLDEX lowered to ~$6\cdot10^{-9}$ mbar (RT), and transmission peaks of ratio ~25 were again visible during beam induced desorption in the RT parts.

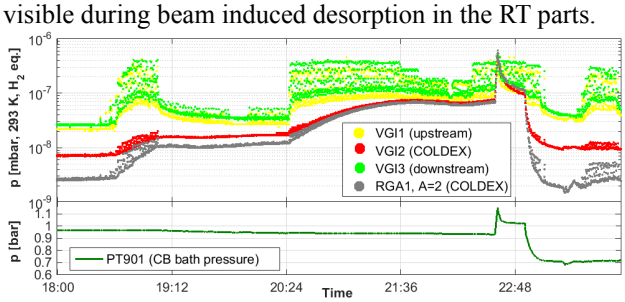

Figure 3: Pressure evolution (in H_2 equiv.) during Run 3.

The run continued with the CB at 3 K. Reduction in the gas transmission of a factor about 2 was observed by mitigating multipacting and so electron desorption in the RT transitions with the application of a solenoidal magnetic field (2 mT). Throughout the whole run, due to unstable cryogenic conditions caused by poor insulation vacuum, observations of dynamic heat load were limited to beam/no beam transients. No dynamic heat load was observed with 4x72 bunches of $1.7\cdot10^{11}$ ppb above the measurement detection sensitivity (~100 mW/m). The electron activity, monitored by the chimney electrode, never exceeded values above the noise level, which corresponded to a flux of $2.1\cdot10^{8}$ $e^-/(mm^2s)$.

A second experimental of 24 hours period took place with the BS surface prepared 10 days in advance with a coverage of ~$3.2\cdot10^{16}$ H_2/cm^2. The BS temperature was scanned from 14 K, to 21 K and finally 28 K, while the CB was held at 3 K, i.e. a saturated vapour pressure of ~10^{-10} mbar was ensured. No total or partial pressure rise due to stimulated desorption was observed, nor H_2 recycling

and/or flushing in any beam condition. Loss of H_2 physisorption was later thermally induced by heating the BS above 31 K. During the intensity ramp-up from N_B=1 to 4 batches of 72 bunches ($1.5\cdot10^{11}$ ppb), at 26 GeV/c, a linear dynamic heat load, associated to the beam circulation, was observed. The observed relation was $P[W/m] \approx 4.87\cdot10^{-2} N_B \pm 7.8\cdot10^{-2}$, that corresponds to ~0.2 W/m for four batches. At the same time, no electron activity was observed above a detection limit of $0.8\cdot10^{7}$ $e^-/(mm^2s)$. Considering a mean electron impinging energy $<E_{e^-}>$ = 100 eV, the two observations seem inconsistent with electron cloud. For comparison with past results [5] with a scrubbed Cu BS (SEY≈1.3), held at 12 K, the circulation of 4x72 bunches of $1.1\cdot10^{11}$ ppb induced an electron cloud flux of $4.5\cdot10^{11}$ $e^-/(mm^2s)$, corresponding to a power of 1.6 W/m, which was readily observed as cryogenic load.

A third 24 hours experimental run was performed with a BS surface prepared 14 days in advance with a coverage of ~$2.1\cdot10^{16}$ CO/cm^2. The run was influenced by longitudinally uncaptured beam, accounting to ~1% on the 200 MHz component measured by the SPS Mountain Range and caused during PS to SPS bucket transfer especially of the first batch. The BS temperature was initially held at 56 K, while the CB was permanently at 3.4 K. Transmission of H_2 was observed from the RT parts toward the BS centre with pressure rise ratio of 10, with 4x72 bunches of $1.4\cdot10^{11}$ ppb, while no partial pressure rise due to stimulated desorption of CO was observed, nor CO recycling and/or flushing in any beam condition. The BS temperature was then lowered, by steps, to 12 K with beam off. Beam was resumed, and slightly lower pressure rises were still detected at the BS centre, with a transmission ratio now increased to 16. Analysing the partial pressures for all gases, no specie was prevalently transmitted, instead, the RGA ion current was suffering of beam induced background distortion. Applying a 2mT solenoid field over the RT parts did not decrease the pressure rise hence increase the observed transmission ratio. Reduction of the bunch intensity to $0.8\cdot10^{11}$ ppb had no effect either. Based on these clues and considered the detected high beam losses, a preliminary conclusion is the instrumentation was influenced by beam induced electronic noise.

SIMULATIONS

An updated model of the a-C coating was developed as input to build-up codes. Based on the phenomenological modeling of the SEY energy dependence described in [6] and [7], a set of parameters was derived by the RT experimental curves of SEY available from samples obtained during the COLDEX BS a-C coating process. In the window R_0 = [0.7:1.0] and for E_0 = 150 eV, is found δ_{max} = 1.059±0.002, $E_{max}(\delta_{max})$ = 271.5±0.9 eV, s=1.773. The fit results are shown in Fig. 4. This model was entered in a pyECLOUD simulation set considering the nominal COLDEX parameters and LHC type beams, similarly to the study in [3]. For SEY = 1.05, the expected deposited heat load due to electron cloud is lower than 1mW/m for every bunch intensity. The electron reflectivity R_0 in [0.7:1.0] has an influence of an order of magnitude. Due to a lower SEY portion for which $\int\varphi(E)[\delta(E)-1]dE > 1$ (being $\varphi(E)$ the normalized impinging electron flux), caused by the higher s parameter than Cu, the multipacting threshold is severely dependent on the bunch intensity for SEY > 1.25.

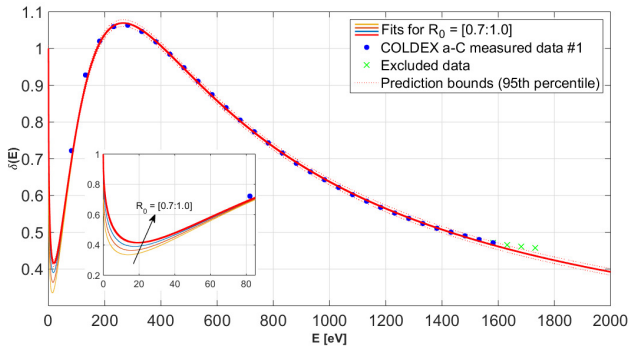

Figure 4: The a-C SEY curve fitted model.

CONCLUSIONS AND PERSPECTIVES

Preliminary cryogenic vacuum characterization of a-C coating shows that physical adsorption is obtained below 35 K for H_2 and 80 K for N_2 and CO ($\theta_0 < 1\cdot10^{15}$ molecules/cm^{-2}). The activation energy for desorption is dependent on the coverage. The cryosorption capacity for H_2 is $\geq2\cdot10^{17}$ H_2/cm^2 below 10 K and is intermediate between metallic surfaces and common cryosorbers (carbon fibers, activated charcoal). The baseline HL-LHC IT BS temperature window, now situated in the 40-60 K range, may be affected by undesirable vacuum transients, principally due to H_2 desorption. Although the presence of a cold bore below 3 K ensures the required pumping capacity, the influence of temperature excursions (especially those not reaching complete desorption) must be sized to the available pumping speed. Throughout the SPS beam runs with LHC type beams, no dynamic pressure activity imputable to electron stimulated desorption was observed in COLDEX. Transmitted gas load produced externally by electron cloud was partially mitigated by the installed solenoids; slow pressure excursions due to monolayer build-up on the CB are avoided if a low H_2 vapour pressure (3K) is ensured. The coverage of ~$3.2\cdot10^{16}$ H_2/cm^2 or ~$2.1\cdot10^{16}$ CO/cm^2 on a-C did not influence the electron cloud build-up in COLDEX. The survey of dissipated dynamic heat loads, which were in any case lower than 0.2 W/m, requires better cryogenic stability, entrusted for 2016, and additional beam time. No electron cloud flux was detected by the chimney electrode. An additional indication is expected by the BS electrode [2] in 2016.

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