AMORPHOUS CARBON COATINGS AT CRYOGENIC TEMPERATURES WITH LHC TYPE BEAMS: FIRST RESULTS WITH THE COLDEX EXPERIMENT

R. Salemme, V. Baglin, G. Bregliozzi, P. Chiggiato, R. Kersevan, CERN, Geneva, Switzerland

Abstract

Extrapolations of the Large Hadron Collider (LHC) Run 1 observations to the High Luminosity upgrade (HL-LHC) beam parameters predict intolerable increase of heat load on the beam screens of the Inner Triplets due to electron cloud. Amorphous carbon (a-C) coating of the beam screen surface is proposed to reduce electron cloud build-up, thereby minimising its dissipated power. In order to validate this baseline, COLDEX (COLD bore EXperiment) has been re-commissioned. Such experiment mimics the performance of the LHC cold bore and beam screen cryogenic vacuum system in the Super Proton Synchrotron (SPS). The main objectives of the study is the performance qualification of a-C coatings with LHC type beams while operating the beam screen in the 10 K to 60 K temperature range and the cold bore below 4.5 K. This paper reviews the status of COLDEX and the results obtained during its first experimental runs.

INTRODUCTION

During the Large Hadron Collider Run 1, considerable heat load (~200W) due to electron cloud was observed on the Inner Triplets (IT) beam screens during operation with 25 ns bunch spaced beams of nominal intensity. Extrapolations of these observations to the High Luminosity upgrade (HL-LHC) beam parameters predict an intolerable increase of heat load due to electron cloud build-up [1]. The increase of heat load is expected to be accompanied by increase of background to the LHC experiments. In order to mitigate the electron cloud build-up and, in turn, limit the heat load to an amount compatible with the IT cryogenics cooling capacity, the current baseline is to lower the IT beam screen surface Secondary Electron Yield (SEY) by amorphous carbon (a-C) thin film coating. Previous studies have shown that such a coating provides reliably low, as-received, SEY (typically <1.1 at room temperature) suitable in un-bakeable vacuum systems [2].

Successful mitigation of the electron cloud build-up with a-C coatings has been demonstrated in some SPS room temperature (RT) vacuum chambers with LHC type beams [2]. In order to further validate the HL-LHC baseline at cryogenic temperature, the COLDEX experiment has been re-commissioned in 2014. COLDEX is an experimental cryostat installed on a field-free by-pass of the SPS Long Straight Section (LSS) 4 which mimics the LHC cold bore and beam screen cryogenic vacuum system. A detailed description of the re-commissioning phases performed in 2014 and the current experimental setup is available in [3]. The main goal is the performance qualification of a-C coatings with LHC type beams while operating the beam screen in two temperature windows: the 5 to 20 K range, currently adopted for LHC and suitable for HL-LHC Inner Triplets, and the 40 to 60 K range under study for HL-LHC matching sections.

The experimental setup is conceived to study the beam induced multipacting in a LHC type cryogenic vacuum system as a function of the BS temperature (and, depending on it, of the presence of adsorbed gas species on its surface) and the circulating beam parameters (bunch intensity and spacing, total circulating intensity, at injection and flat-top energy). During a run, total pressure is measured along the vacuum system, *i.e.* in the RT upstream and downstream sections and in the cryogenic BS atmosphere. The dynamic pressure rise due to electron cloud is monitored with respect to the different circulating beams, and the conditioning obtained by beam dose is observed. The gas composition is followed-up constantly in both cryogenic and warm parts by residual gas analysers. In case of gas desorption, the primary and recycling desorption yields of the system can be estimated. The heat load dissipated by electron cloud onto the BS surface is measured as well as the electrons activity. Through benchmarking with available electron cloud build-up codes, the SEY of the surface can be deduced. The effects of adsorbed gas on the BS surface at cryogenic temperature is reproduced in dedicate runs by gas injections.

RESULTS DURING RUN 1

COLDEX first experimental run with a-C coating took place during the first SPS Scrubbing Run in November 2014. In a 7-day period, the accumulated beam dose exceeds 4 A·h. Two BS temperatures have been chosen: first 50 K, then 5 to 10 K. The CB was constantly kept at 4.5 K. At this temperature, the CB is capable of condensing all gas species (except He, which is only adsorbed up to 10^{14} He/cm^2), with a pumping speed fixed by the 1% transparency to the BS. One to four batches of 72 bunches, 25 ns bunch spaced, up to $1.3 \cdot 10^{11}$ proton per bunch (ppb), passed into COLDEX, mainly at 26 GeV/c, but also with energy ramp to 450 GeV/c. Hybrid (5+20 ns) bunch spaced doublet beams circulated as well, up to 4 batches and with a maximum intensity of $1.4 \cdot 10^{11}$ proton per doublet (ppd), equally split. Figure 1 shows the pressure evolution during the run along the COLDEX sector as well as the temperature range kept on the BS.

Significant pressure rises (up to ~$5 \cdot 10^{7}$ mbar, green and yellow curves) correlated to the beam circulation were observed upstream and downstream the COLDEX BS due to electron stimulated desorption. These parts are made of bare 316LN stainless steel, DN100, room temperature pipes, vented to air during COLDEX re-commissioning. A global conditioning of those surfaces is visible throughout the scrubbing run. A dynamic slow pressure rise (up to ~$3.5 \cdot 10^{8}$ mbar, red curve) was observed in the COLDEX BS at 50 K. The pressure rise was dominated by H_2, as observed through residual gas analysis, and possibly linked to the large desorption rate from the RT beam pipes of the SPS LSS during electron bombardment. At 50 K, the BS was capable to adsorb only CO_2 and H_2O by cryocondensation, therefore the only, limited, source of pumping for the other relevant gases (H_2, N_2 and CO) was the CB.

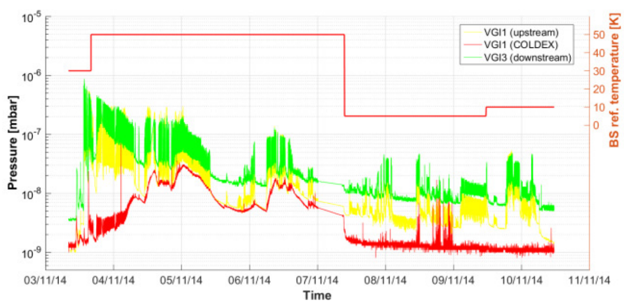

Figure 1: Pressure evolution during SPS Scrubbing Run 1.

During the BS cool-down from 50 K to 5 K, a net pressure decrease was observed in the BS (~$4 \cdot 10^{-9}$ mbar) and partially at the extremities (~$2 \cdot 10^{-9}$ mbar). At 5-10 K, the BS was capable of physisorbing the residual H_2 and cryocondensing N_2 and CO. Throughout the run, during beam circulation, no pressure rise was observed at 5-10 K in the COLDEX BS, nor vacuum degradation imputable to electron stimulated desorption. Pressure rises up to ~$2 \cdot 10^{-8}$ mbar were instead measured at the extremities. In this period, extensive use of doublet 5+20 ns beams was deployed in the machine for further scrubbing. With respect to comparable 25 ns bunch and circulating beam intensities, no increase in the electron stimulated desorption rate was observable in the RT COLDEX sections. This behaviour is consistent with what was observed in the other SPS field-free regions.

RESULTS DURING SCRUBBING RUN 2

The second COLDEX experimental run with a-C coating took place during the second SPS Scrubbing Run in December 2014. In a 4-day period, the accumulated beam intensity was up to 2 A·h. In this run the BS temperature was kept at 10 K, while the CB was initially at 4.5 K, and afterward, at 3K. One to five batches of 72 bunches, 25 ns bunch spaced, were passed into COLDEX, with a top bunch intensity of $1.9 \cdot 10^{11}$ ppb. Hybrid (5+20 ns) bunch spaced doublet beams were circulated, and, in addition, different intermediate injection schemes (8b+4e, BCMS) were adopted. Beam was mainly circulated at 26 GeV/c, but also energy ramped to 450 GeV/c. Figure 2 shows the pressure evolution during the run 2 along the COLDEX sector as well as the temperature range kept on the CB.

The observations of the second part of the first 2014 run were confirmed. Significant pressure rises were observed at COLDEX extremities with highly intense beams (~ $2 \cdot 10^{-7}$ mbar with beams up to 4 batches, $4.6 \cdot 10^{13}$ p, $1.6 \cdot 10^{11}$ ppb, dump at 17 s), while a steady pressure trend (~ $6 \cdot 10^{-10}$ mbar) was measured in the COLDEX BS held at 10 K. During and after the CB cool-down to 3K, no effect was observed on the BS pressure trend. With doublet beams, an equivalent behaviour to standard 25 ns beams, of comparable intensity, was confirmed.

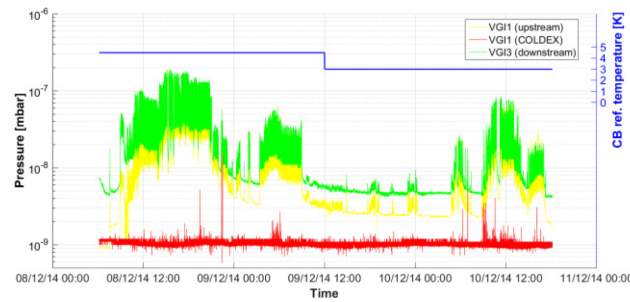

Figure 2: Pressure evolution during SPS Scrubbing Run 2.

HEAT LOAD AND ELECTRON ACTIVITY

The electron cloud heat load dissipated on the COLDEX BS was monitored during the 2014 experimental runs. A detailed explanation of the heat load measurement is available in [3]. Static heat load of typically ~ 1.9 W/m was measured after facility cool-down, without beam, due to conductive and radiative thermal losses, and kept into account in the heat load budget. Dynamic heat load observed along the a-C coated beam screen during the runs was less than 0.3 W/m. If compared to previous results [4] with copper BS after a comparable beam dose (estimated δ_{max}: 1.2÷1.3), a reduction of ~ 80% in the heat load was obtained. The influence on the heat load of physisorbed (H_2) and condensed (CO, CO_2) gases on the BS surface will be studied in dedicated runs. The influence of beam losses, inevitably present during the runs, should also be addressed, even though not trivial to estimate.

Electron activity in the BS was monitored during the experimental runs via the BS chimney electrode. Given the measurement system [3] topology, a lower detection limit of ~$5 \cdot 10^{-9}$ A was achievable due to noise electric current. Throughout the experimental runs, no signal correlated to electron cloud activity was detected. If compared to previous results [4], and in agreement with the 2014 pressure and heat load observations, this observation indicates a net reduction of electron activity in the a-C coated BS. Peaks of ~$2 \cdot 10^{-8}$ A signal were instead observed during periods of high beam losses (instable or longitudinally debunched beam). Those signals were correlated to the increase of electric noise on the vacuum ionization gauges (VGI) and partially correlated to the closer SPS Beam Loss Monitor signal available (30 m downstream).

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SIMULATIONS

The COLDEX experiment case has been simulated in the electron cloud build-up code pyECLOUD v4.09 [5]. pyECLOUD is a 2D MacroParticle (MP) code capable of simulating the electron cloud build-up of arbitrary shaped (convex) chambers, ultra-relativistic charged beams, externally applied (uniform) magnetic fields and dynamic MP size management. The underlying SEY angular and energy dependence model described in [6] and [7] was adopted. For the a-C coating case, an $E_{max}(\delta_{max}) = 300$ eV has been initially chosen. The secondary emission angular and energy spectrum proposed in [8] was adopted, with a reflectivity factor $R_0 = 0.7$. Given to the SPS beams energy, only the electron seeding due to residual gas ionization was took into account. In Figure 3, the simulation results of expected heat load for the nominal COLDEX parameters (BS temperature = 10 K, $p = 2.0 \cdot 10^{-9}$ mbar, $\sigma_i = 0.2$ Mbarn) and beam (26 GeV/c, 4x72 bunches, 25 ns bunch spacing, $1.2 \cdot 10^{11}$ to $1.9 \cdot 10^{11}$ ppb) are shown.

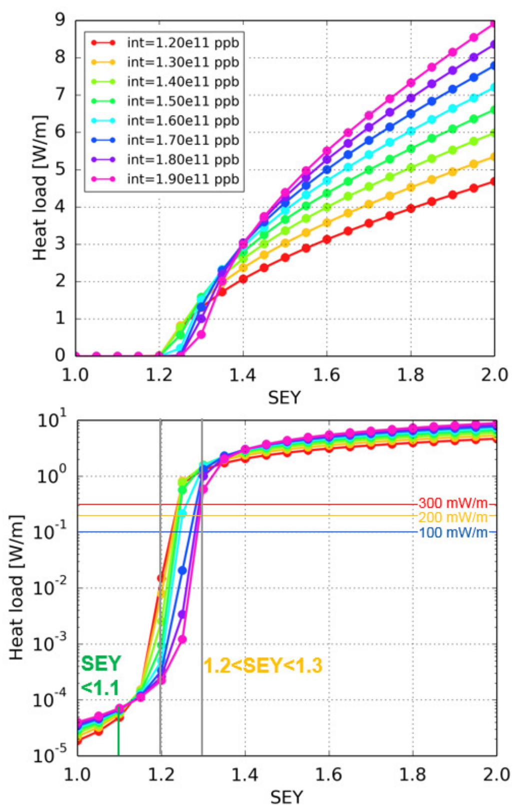

Figure 3: Heat load (linear, logarithmic scale) versus SEY for different simulated SPS bunch intensity.

Simulations show that in COLDEX the multipacting threshold should be situated in the 1.15 - 1.30 SEY window. For SEY < 1.1, the deposited heat load is negligible (< 1mW/m). Between SEY = 1.2 and SEY = 1.3, the heat load spans from tens of mW/m to 1 W/m depending on the bunch intensity. As a consequence, the simulations of the heat load show that the SEY should be lower than about 1.25. The impinging electron rate (A/m) has been calculated as well, with a bunch intensity of $1.5 \cdot 10^{11}$ ppb. For SEY < 1.15, the expected current on the chimney electrode is $< 5 \cdot 10^{-9}$ A. Additional experimental runs in conjunction with further simulation studies are required to better quantify the SEY value.

CONCLUSIONS AND PERSPECTIVES

COLDEX first runs took place during 2014 SPS Scrubbing Runs. First observations on a-C coating at 50 K and 5-10 K with LHC type beams and doublet beams did not reveal strong effects of vacuum degradation imputable to electron cloud. Throughout the runs, significant pressure rises (up to $5 \cdot 10^{-7}$ mbar) were observed outside the cold system, while in the COLDEX BS a pressure rise (up to $3 \cdot 10^{-8}$ mbar) has been observed mainly due to H_2 gas accumulation at 50 K. At 10 K, no pressure rise was observed during beam circulation. The observed dissipated dynamic heat loads along the a-C coated beam screen were smaller than 0.3 W/m, while no electron cloud signal was detectable.

In order to confirm these first results and perform specific studies on the a-C coating, further beam time is expected in the 2015-2016 period.

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