VACUUM AND CRYOGENICS OBSERVATIONS FOR DIFFERENT BUNCH SPACING

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Abstract

Following the observations of high pressure rises induced by an electron cloud building up in the LHC beam pipes, studies were launched with beams with 50 and 75 ns bunch spacing at injection energy and with a ramp to 3.5 TeV (only 50 ns bunch spacing).

This talk will summarize the observations made on the beam vacuum and cryogenic systems for both 50 and 75 ns bunch spacing and with a ramp in energy (only 50 ns bunch spacing). Some extrapolations will be presented based on the measurements. Finally, the decided mitigation solutions and beam parameters to be used for the 2011 run will be reviewed.

INTRODUCTION

The electron cloud build-up is a threshold phenomenon which depends on the bunch population and number of bunches in the train. Above the threshold and in presence of a fast build-up, the build-up is roughly linear with the number of bunches [1]. As the electron cloud results from an electron multiplication, the avalanche depends highly on the secondary electron yield (SEY, δ), on the number of photo-electrons and on the surviving electrons. The surviving electrons are the electrons, mainly low energy, which can survive the gaps between bunch trains because of the high reflectivity of the surface for the low energies. These electrons are participating right from the beginning to the multiplication. At the contrary, the build-up is attenuated by the spacing between bunches and bunch trains. The electron cloud is affected by many other parameters like the size of the beam vacuum pipe, the magnetic field and the temperature of the beam pipe walls.

ELECTRON CLOUD INDUCED LIMITATIONS

The electron cloud is responsible for accelerator performance limitations such as vacuum pressure rises, heat loads on cryogenic components, beam instabilities, beam-gas scattering induced radiation to cables and electronics and background to the experiments.

The vacuum pressure rise result from the bombardment of the inner beampipe walls by the electrons from the cloud, kicked off by the beam potential. The effect of this local electron stimulated desorption (ESD) will depend on the ratio of the multipacting beampipe length versus the available pumping speed for all desorbed gas species.

In the cryogenic sections, the electrons heating the beampipe wall will deposit their energy inducing temperature rises unless compensated by cooling. By design, the LHC has two intrinsic limitations: the maximum cooling capacity through the beam screen cooling capillaries and the total available cooling capacity of the cryoplants.

The electron cloud induced beam instability is of great concern since it can also become a limiting factor for the scrubbing run as it can result in emittance blow-up and beam losses. This effect depends on the electron density in the beampipe and on the multipacting length.

The pressure bumps increase the induced radiation to cables and electronics and the background to the detectors. The amplitude of this effect will vary with the gas density and length of the pressure bump.

The bending sections of the LHC (arcs) and the standalone magnets (SAM) installed in the long straight sections have, by design, a non bakeable vacuum system. The beams see a copper envelope and the beam screen's pumping hole provide the required pumping speed. It has to be noted that the recycling desorption yields are much larger than primary desorption yields ($\eta'_{monolayer} >> \eta$) thus implying that the beam screen's surface coverage should stay below a monolayer. This can be achieved by keeping the temperature of the cold bore always below that of the beam screen. Regarding the efficiency of the scrubbing, i.e. decrease of the secondary electron yields, δ, measurements carried out in the laboratory confirmed that the scrubbing of surfaces at cryogenic and ambient temperature behave similarly.

The long straight sections (LSS) are mainly operated at ambient temperature (except SAM magnets) and rely on the use of NEG coatings, a coating which provides distributed pumping speed, low stimulated desorption yields and a secondary electron yield of 1.1 (after activation) which prevent an electron cloud to build up. The regions of concern for electron cloud build-up are the non NEG coated parts, e.g. the cold/warm transitions, the warm/warm transitions and the beam components (collimators, beam position monitors, pick-ups, etc.). In these regions, the electron cloud induced pressure rise results from the ratio of the multipacting length (non-coated part) to the locally available pumping speed for the desorbed gas species, in particular methane (CH_4) since not pumped by NEG coatings.

RESULTS FROM 2011 RUN

150 ns bunch spacing

In the long straight sections, the pressure rise observed in the sections with only one beam circulating (3.5 TeV) can be explained by the synchrotron radiation (SR) since energy and intensity dependent.

In the recombination areas where the two beams circulate in the same beampipe, the pressure rises (Fig.1) are the result of different effects: SR induced by the D1 or D2 bending magnets and the electron stimulated desorption induced by the electron cloud. The measurements showed the larger effect in the Cold/Warm transition of the Inner triplets on Q3/DFBX side for ATLAS, ALICE and LHCb. This location coincides with the position where the bunches from the two beams are again superposed (takes place exactly at 45 m from the interaction point) (Fig.2). Thus leading to enhanced multipacting conditions: higher beam potential and bunch spacing configuration. No pressure increase is observed in IR5 due to the stray magnetic field of the CMS solenoid variable from 1 up to 15 mT. Indeed, solenoid fields (2-5 mT) are known to suppress the electron cloud. In presence of a solenoid field, the secondary electrons cannot escape out from the surface since bent back by the field.

In the arcs, nothing was observed using the cryogenics instrumentation (resolution of 5 mW/m/aperture). Vacuum instrumentation, installed at ambient temperature outside the cryostat, cannot see pressure rise since the pumping speed by cold surfaces is very high.

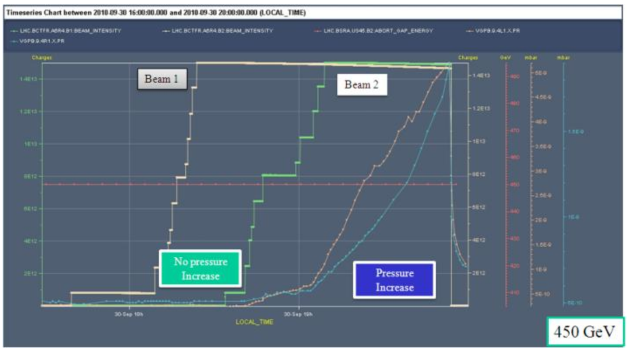

Fig.1: Pressure rise observed in the recombination areas with 150 ns beams

75 ns bunch spacing

With the injection of beams with 75 ns bunch spacing, pressures started to rise in most of the non NEG coated parts of the LSS (Fig.3). The variety in pressure rise results from the number of circulating beams in the beampipes (2 circulating beams enhance the build-up), the contribution of the photon stimulated desorption induced by the SR close to arcs or D1, D2, D3, D4 SAM magnets and the multipacting length versus pumping speed configurations. The pressure rises in the recombination areas are larger at 75 ns, in particular because of the superposition at 22.5 m and 45 m from the IP (Fig.4). The effects induced by the superposition taking place inside the cold sections are not detectable (no gauge and huge pumping speed by condensation).

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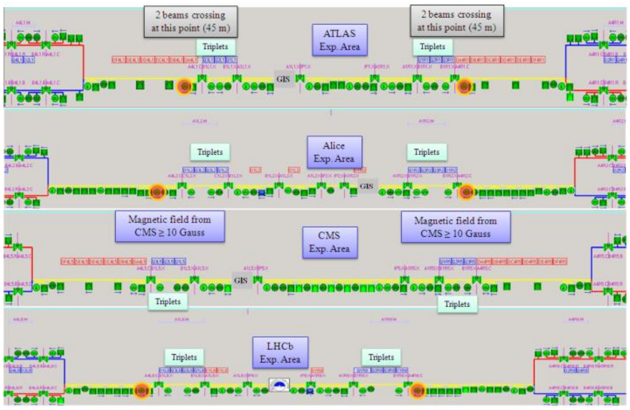


Fig.2: Localisation of the pressure rise in the LHC LSS with 150 ns beams

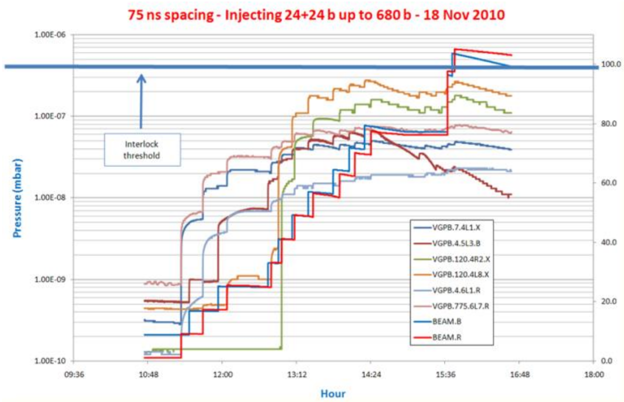


Fig.3: Pressure rise observed in all LSS with 75 ns beams

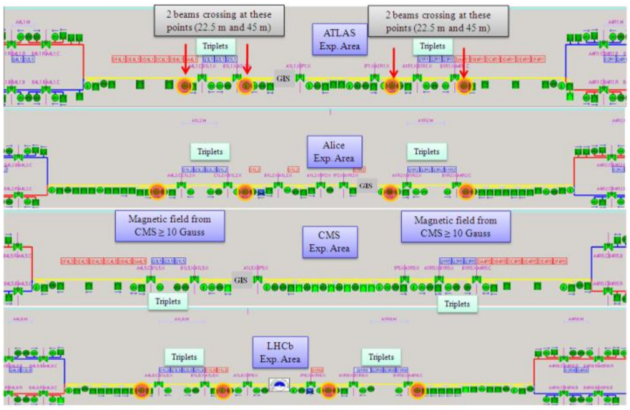


Fig.4: Localisation of the pressure rise in the LHC LSS with 750 ns beams

50 ns bunch spacing

The electron cloud build-up with 50 ns bunch spacing required nominal bunch populations to trigger the electron build-up (Fig.5). Similarly, the spacing between trains of bunches had to be reduced below 2 μs to enhanced the build-up (Fig.6) and long trains, at least 24 bunches in the train, had to be injected (Fig.7).

The observation of pressure rise confirmed that the pressure increase linearly with the number of trains (Fig.8) allowing pressure forecasts for given filling patterns. Globally, pressure rise with 50 ns are twice the one observed with 75 ns beams.

Operation with 50 ns beams showed for the first time a significant electron build-up in the arcs, a heat load of 40 mW/m was measured by the cryogenic instrumentation with 444 bunches at injection energy (Fig.9).

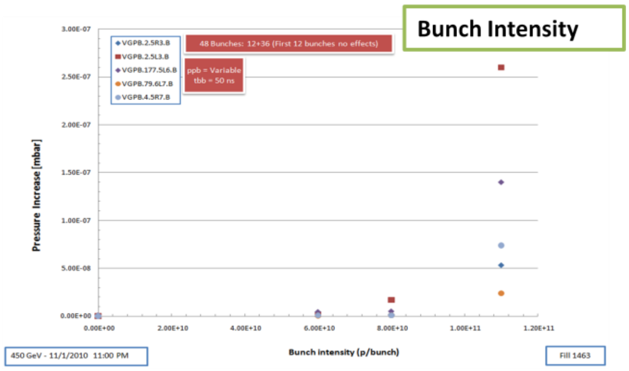


Fig.5: Pressure rise as a function of bunch population showing a shift of the electron cloud threshold to higher bunch populations

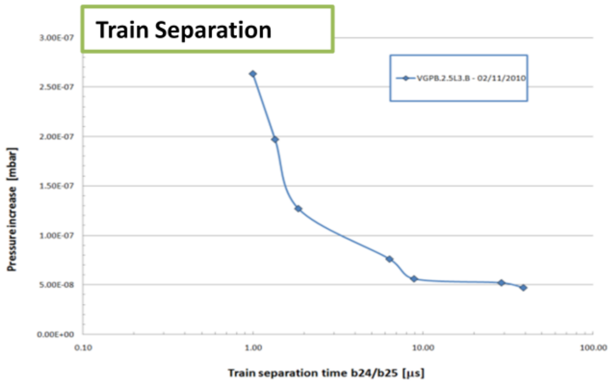


Fig.6: Effect of reduction of the spacing between trains on the electron cloud build-up

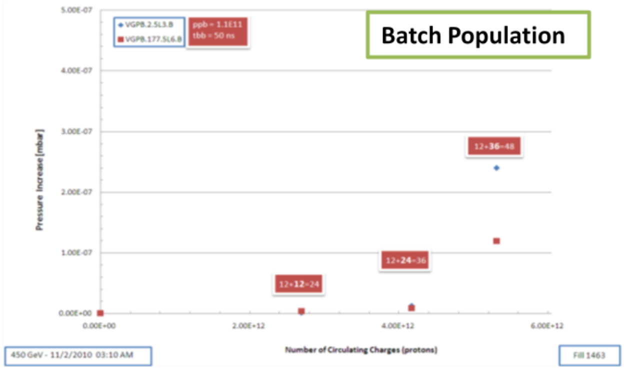


Fig.7: Effect of the number of bunches in the trains on the electron cloud build-up

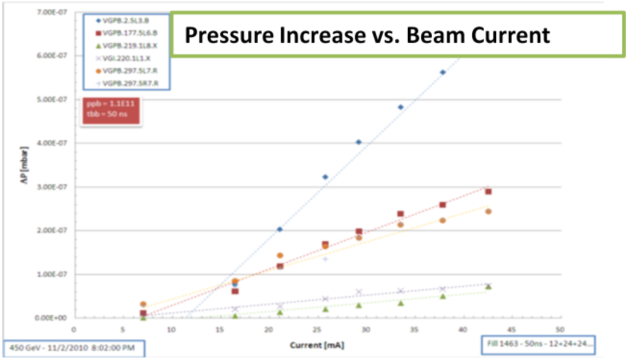


Fig.8: Pressure rise as a function of the number of circulating bunches

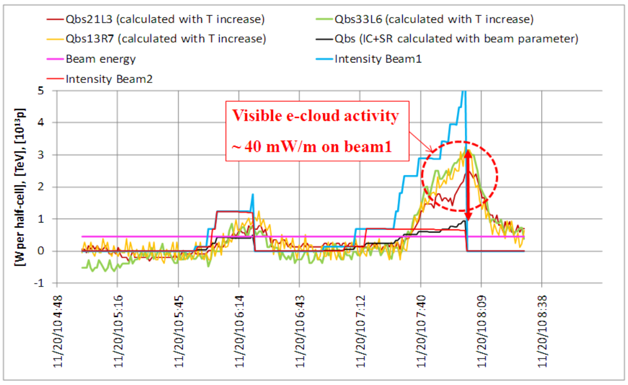


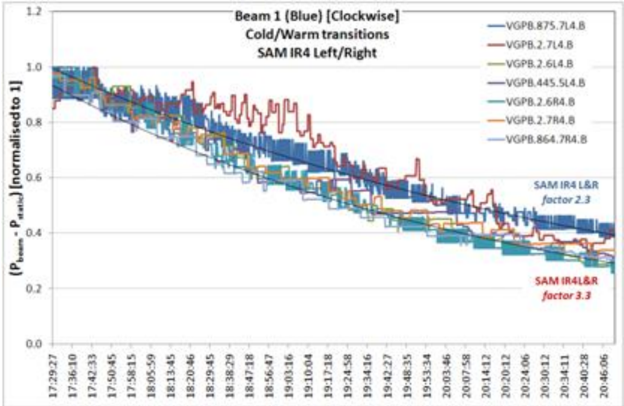
Fig.9: Heat load induced by 50 ns beams on the beam screens of the arcs

Vacuum conditioning and beam scrubbing

Vacuum conditioning is a dose effect induced by the electron bombardment which characterizes the reduction of the desorption yield, η, (i.e. the number of gas molecules desorbed from the surface/bulk by the primary electron). Beam scrubbing is also a dose effect which, characterizes the reduction of the secondary electron yield, δ, (i.e. the number of secondary electrons generated by impinging primary electrons). The pressure rise resulting from the electron stimulated desorption, decrease with the electron dose as a result of the combined effect of vacuum conditioning and beam scrubbing.

During the operation with 50 ns beams in Physics, clear evidence of vacuum conditioning effect were observed all LHC LSS and with similar behaviors, irrelevant of the operating temperature. Pressure rise decreased by a factor between 2.3 and 4.4 in about 3h15 (Fig.10), much faster than expected from the SPS measurements with LHC-type beams [1].

The vacuum conditioning effect shows an exponential behavior with electron dose, as expected (Fig.11). The trend indicates that a decrease of pressure rise by a factor of 100 at constant electron dose rates is expected after 16h of integrated beam time.



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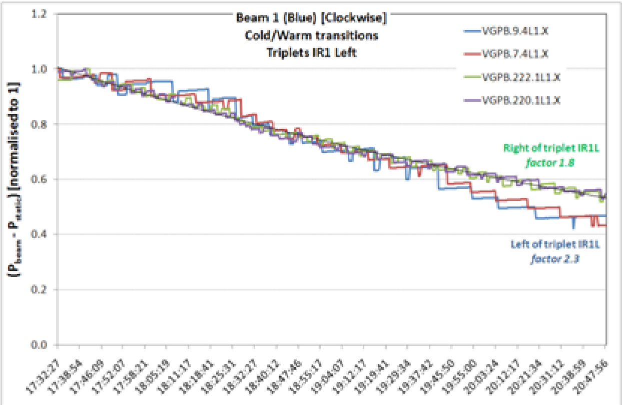

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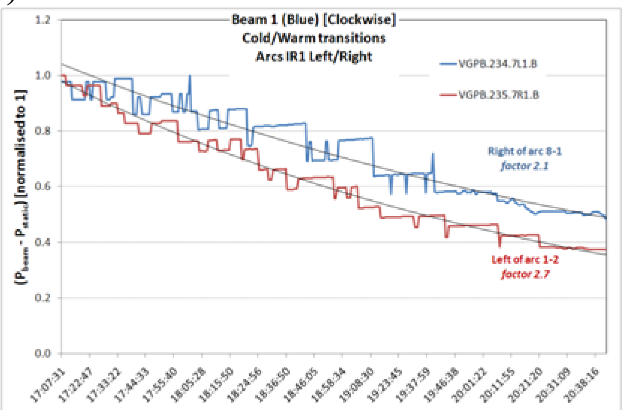

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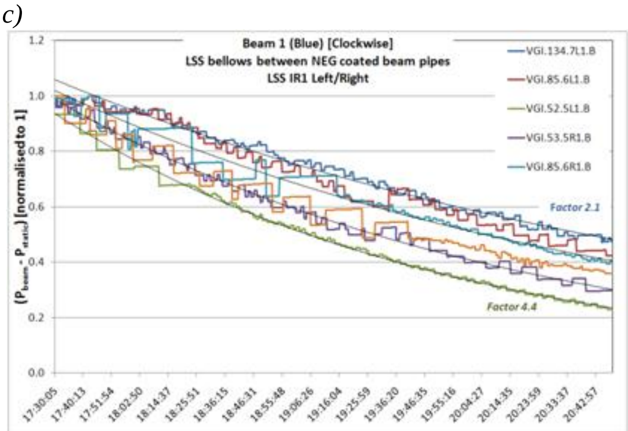

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Fig.10: Pressure rise evolution with beam time showing a vacuum conditioning effect in the cold/warm transitions of the SAM magnets, a), inner triplets, b), end of continuous cryostat arc, c), and warm transitions in the LSS, d).

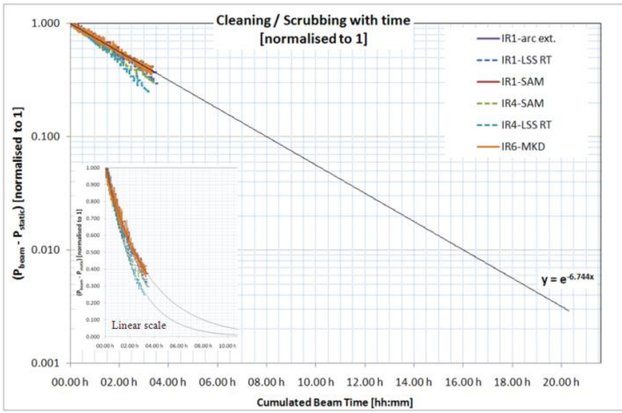
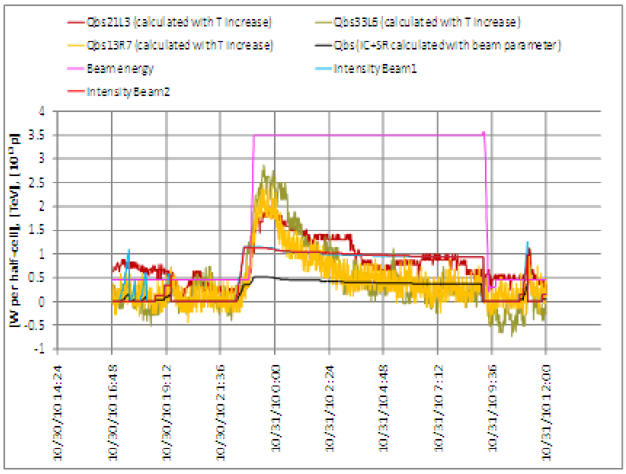


Fig.11: Prediction of vacuum conditioning as a function of beam time



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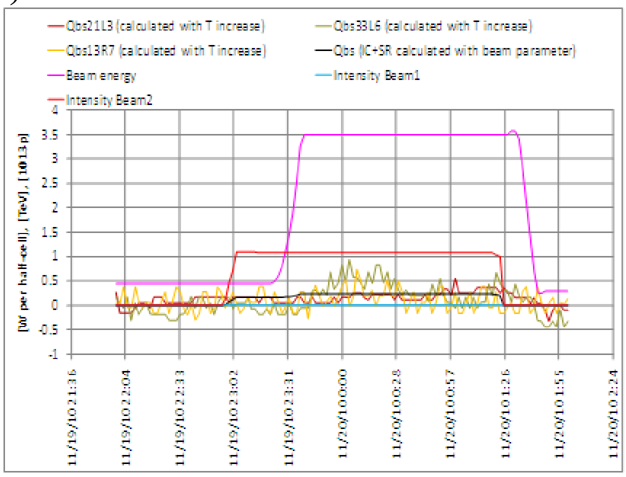


b)

Fig.12: Heat load induced by 50 ns beams at 3.5 TeV before October's scrubbing run, a) and after the scrubbing run, b).

As mentioned earlier, the operation with 50 ns beams showed an electron build-up in the arcs, this build-up was seen by the heat load onto the cryogenic system. Indeed, this is at the moment, the only mean to evaluate the electron cloud activity in the parts of LHC operated at cryogenic temperatures. The scrubbing run showed that the electron cloud induced heat load decreased by a factor of at least a factor 4 from 20 mW/m to 10 mW/m (Fig.12). The observed decrease of the heat load due to electron cloud after scrubbing is an encouraging indication that scrubbing at 450 GeV can be effective also for operation at 3.5 TeV.

OPERATION IN 2011

Expected decrease η and δ

Predictions of electron dose effects on secondary electron yields, δ, and on desorption yields, η, are based on the assumptions made for the electron dose rates. For a given electron density, the flux to the wall will depend on the magnetic field configuration. The field free regions have a homogeneous bombardment of the inner surface of the beampipes while in dipole fields, electrons are confined in one, two or three (the number depending on the bunch intensity) stripes parallel to the field direction [1]. The ratio of the transverse length of the strips to the perimeter explains why 15 times more dose is expected in LHC arcs in presence of a dipole field as compared to LSS transitions in field free conditions. Therefore, an electron could density of 1 mA/m shall induce a flux to the walls of 5×10^{12} $e^{-}/s.cm^{2}$ in the field free regions and 8×10^{13} $e^{-}/s.cm^{2}$ in the dipole field regions (Fig.13).

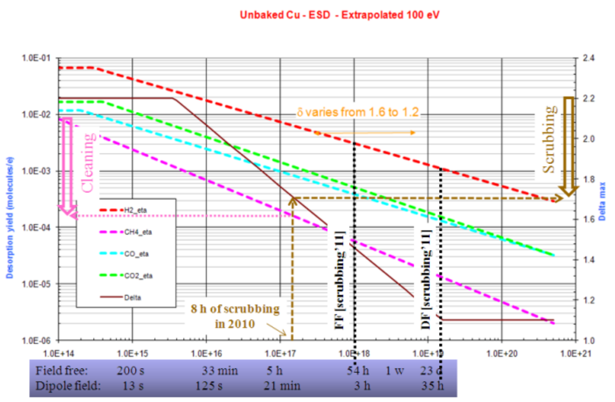
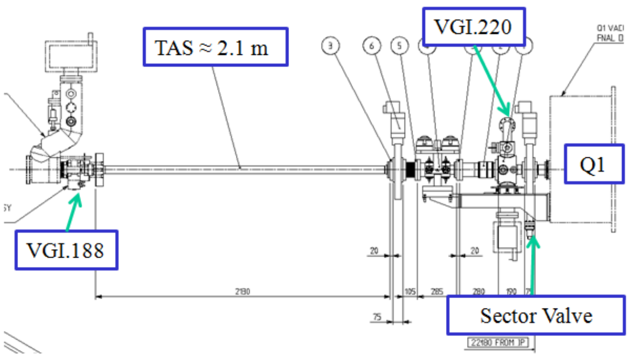


Fig.13: Expected decrease of the desorption yields, η, and secondary electron yield, δ, as a function of electron bombardment integrated dose.

Impact on NEG coatings

The gas released by the electron stimulated desorption is pumped out by the ion pumps and NEG coatings or condensed on the upstream and downstream beampipe surfaces at cryogenic temperatures (beam screens and cold bores). As the reactivation of NEG coatings requires a bake-out cycle which is expensive and time consuming, an evaluation of the impact of the vacuum conditioning on NEG coatings has been carried out, in particular in the experimental areas. The study case introduced here, concern the ATLAS experimental area, upstream and downstream of the TAS absorber (Fig.14a). The gas load being generated in the cold/warm transition of the Q1 quadrupole of the inner triplet, the pressure bump seen by the ion gauge on the other side of the TAS NEG coated chamber is proportional to the hydrogen transmission probability. Measurements show an attenuation of pressure bumps by 3 orders of magnitude (Fig.14b) and according to the Monte Carlo simulations, this correspond to a sticking factor of 5×10^{-3}, a sticking factor corresponding to a fully activated NEG coating (5×10^{-3} < Sticking factor < 5×10^{-2}) (Fig.14c). This result confirms that the vacuum conditioning during the 2010 run did not lead to the deterioration of NEG coating pumping performances.



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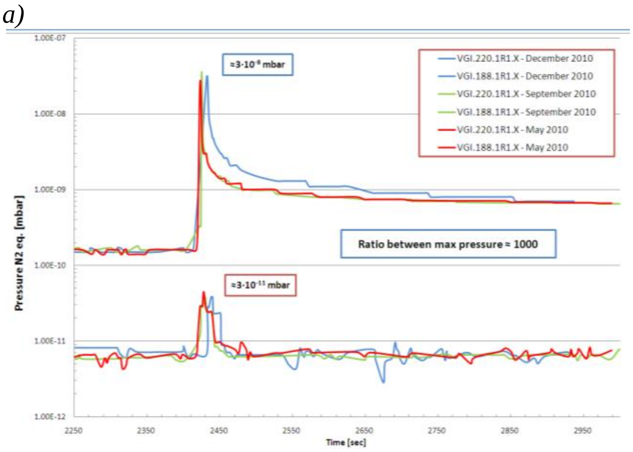

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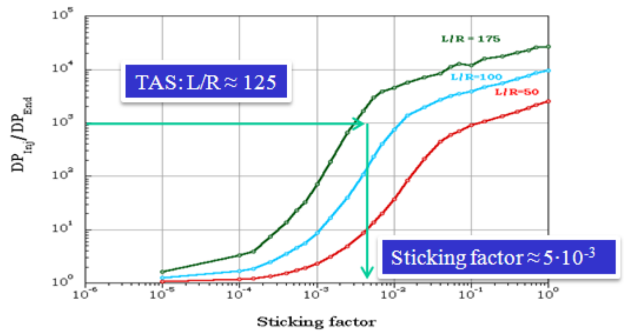


c)

Fig.14: Measurement of the NEG activation level using the vacuum instrumentation upstream and downstream the ATLAS TAS absorber, a), the attenuation of local pressure rise induced by the sector valve closure, b), and

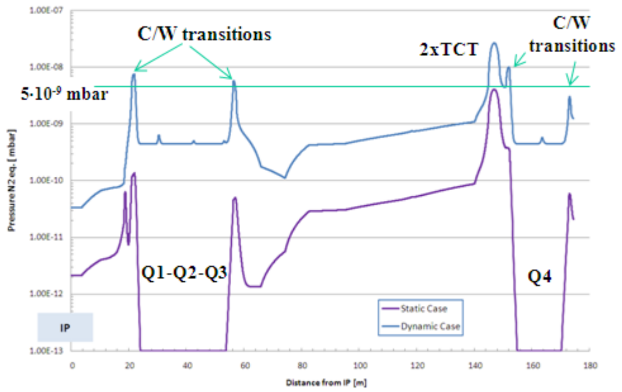
the Monte Carlo simulations of the expected attenuation of hydrogen through the beampipe, c).

Expected dynamic vacuum induced background

The operation with 75 ns beams resulted in an electron cloud build-up in the cold/warm transitions of all SAM magnets. Before the winter technical stop, about 9% in length of the LSS showed pressures higher than 5×10^{-9} mbar (Fig.15a). This corresponds to electron flux of 10^{16} e^{-}/m.s in the field free (outside magnets) sections at ambient temperature and 10^{14} e^{-}/m.s in cold sections (dipole field).

During the scrubbing run in 2011 with 50 ns beams, the pressure bumps above 5.10^{-9} mbar shall represent about 25% in length of the LSS (Fig.15b), 3 times more than with 75 ns beams.

As the NEG coatings provide a huge pumping speed for hydrogen, the pressure bumps will be quickly attenuated (Fg.16a) thus leading to residual vacuum dominated by methane since not pumped by NEG coatings (Fig.16b). The presence of ion pumps allows the pumping of this gas species and keeps the gas density at an acceptable level for the experimental areas.



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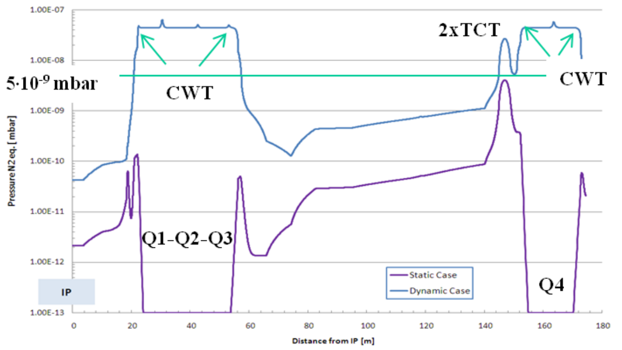


b)

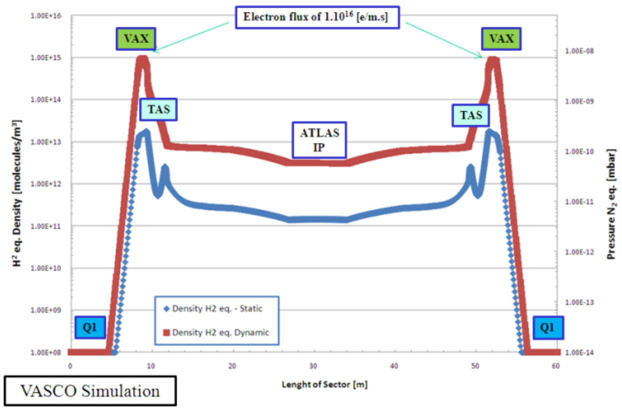
Fig.15: Pressure profile simulated for ATLAS upstream and downstream regions before the 2010 winter technical stop, a), and during the 2011 scrubbing run, b).

CLOSING REMARKS

The baseline for the operation of the LHC is to rely on vacuum conditioning and beam scrubbing and shortly after resuming the operation of the LHC with beams, a scrubbing run will be scheduled.

In case the scrubbing time does not provide the required reduction of electron cloud activities, solenoids are being installed in all cold/warm transitions and warm/warm transitions of the LHC LSS housing large detectors. LSS1 and LSS5 will be entirely equipped during the 2010-11 winter technical stop and only the recombination zones will be equipped in IR2 and IR8. For other non-NEG coated locations where huge pressure rise were observed e.g. IR3 and IR7, it was decided to rely on the vacuum conditioning. This work will be completed during the coming technical stops. In total, about 20 km of cables will be winded around the transitions!

In presence of an electron cloud build-up in the SAM magnets, the re-cooling sequence of SAM in case of failure of the cryogenics becomes critical. During the process of cool down, the beam screen shall be kept at a higher temperature than cold bore and in particular after a stoppage of a cryoplant. This procedure will imply longer recovery times but is absolutely required to avoid gas condensation on beam screens.



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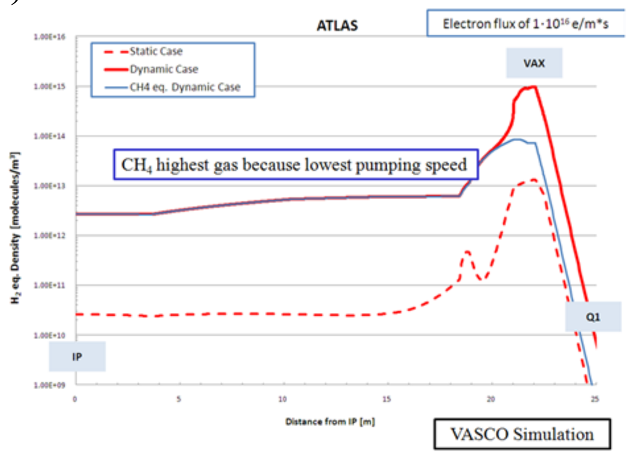

b)

Fig.16: Pressure profile simulated in ATLAS assuming an electron stimulated desorption localised at the Q1 cold/warm transition (VAX), a). Methane (CH_4) which is

not pumped by NEG coatings become the dominant gas in the experimental beampipe, b).

CONCLUSIONS

The operation with 50 and 75 ns beams in the LHC has evidenced the efficiency of the vacuum conditioning and of the beam scrubbing on beampipes at cryogenic and ambient temperatures, as expected from laboratory measurements. The beam scrubbing resulted in a reduction of the induced heat load by a factor of 2 after about 8 hours of integrated beam time. The pressure rise decreased by a factor between 2 and 4 resulting from the combination of the vacuum conditioning and beam scrubbing effects. The range of pressure rise in LSS results from local configurations of the multipacting length versus pumping speed. In addition, the electron cloud is enhanced in the recombination areas where the two beams circulate in the same beampipe thus increasing locally the beam potential.

Since the measurements showed that pressure rise are expected to be twice higher at 50 ns as compared to 75 ns beams, no major limitation is expected for the scrubbing run from the pressure rise point of view. If the electron cloud activity is kept at a level which generate an electron flux to the wall of about 10^{16} electrons/s.m, 3 orders of magnitude of vacuum conditioning can be expected in beampipes at ambient temperature after a week of scrubbing (30% beam efficiency is assumed). The secondary electron yield is also expected to decrease below 1.4, a value which shall allow operating with 50 ns beams. The beam-gas scattering in these regions will also be significantly reduced.

The major concern being the feasibility of such challenging approach since these levels of electron cloud will probably generate beam instabilities and emittance blow-up.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Jimenez et al., "*Electron cloud with LHC-type beams in the SPS: A review of three years of measurements*", LHC-Project-Report-632, CERN (2003).