LHC SCRUBBING RUNS

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Abstract

To achieve its nominal performances, the LHC relies on the scrubbing runs to both improve the dynamic vacuum (beam lifetime) by a vacuum cleaning effect and decrease the electron cloud induced limitations (heat load and beam instabilities) by a beam conditioning effect.

An optimum scrubbing run scenario will be presented based on the vacuum cleaning and beam conditioning results in the SPS together with their applicability to the LHC and in particular for the role played by the physisorbed gasses and the magnetic fields.

The interdependence of the scrubbing run scenario with the beam parameters used during the first 3 years of operation will be presented and the limitations discussed, in particular the advantages and drawbacks of scrubbing runs at injection energy. The implications of the deconditioning effect observed when the machine is not operated with beams will be presented together with the consequences of a partial warming up of the cold parts during the shutdown.

To follow the evolution of the vacuum cleaning and beam conditioning during the scrubbing runs, diagnostics are foreseen in the RT and Cold vacuum pilot sectors in IR4. These diagnostics will be specifically design and operated to provide information on the beam conditioning levels of the RT and colds sections of the LHC.

INTRODUCTION

The LHC could be limited by the increase of the dynamic pressures and by the electron cloud-induced heat load when running with high intensity beams. This should occur above the electron cloud threshold measured in the SPS around 3.0×10^{10} p/bunch in the dipole field and around 5.5×10^{10} p/bunch in field free regions.

Below the electron cloud threshold and at injection energy (450 GeV), the dynamic pressure increase could only result from direct beam losses or losses resulting from the beam-gas scattering which will themselves be limited by the quench levels on the cold magnets. At top energy, a dynamic pressure increase is expected due to the photon flux (photon stimulated desorption – PSD) generated by the synchrotron radiation.

While running above the electron cloud threshold, the electron flux to the walls will induce a significant increase of the dynamic pressures by the electron stimulated desorption (ESD) phenomenon. The electron cloud induced heat load will also become a concern at injection energy and at top energy, but in the later case with a much-reduced margin in the cryogenics cooling capacity.

Finally, the presence of a high electron density in the vacuum chambers integrated over several kilometres of machine could also induce beam instabilities and emittance growth.

Table 1 summarises the four domains expected while running the LHC with the 25 ns bunch spacing beams.

Table 1: Four domains expected while running the LHC with the 25 ns bunch spacing beams

	@ Injection Energy 450 GeV	@ Top Energy 7 TeV
< 3 10^{10} p/bunch	Dynamic Pressure Rise Proton or Ions Beam Losses will only induced small pressure rises since dominated by the quench levels	Dynamic Pressure Rise + Photons Stimulated Desorption (synchrotron radiation)
> 3 10^{10} p/bunch in Dipole Field > 5 10^{10} p/bunch in Field Free	Dynamic Pressure Rise Beam losses, Beam gas scattering, Electron Stimulated Desorption (e- cloud) Electron Cloud-induced Heat Loads, Beam Instabilities and Emittance growths	Dynamic Pressure Rise As at 450 GeV + Photons stimulated Desorption Electron Cloud-induced Heat Loads, Beam Instabilities and Emittance growths (less cryogenic margin) Bunch length decrease?

EXPECTATIONS FROM THE SCRUBBING RUNS

To achieve its nominal performances, the LHC relies on the scrubbing runs to both improve the dynamic vacuum (beam lifetime) by a vacuum cleaning effect and decrease the electron cloud induced limitations (heat load and beam instabilities) by a beam conditioning effect.

The decrease of the dynamic pressure results from both the reduction of the photons and electrons desorption yields. The decrease of these two yields has been quantified in the laboratory and observed in several machines. An additional decrease of the ESD contribution is expected to come from the reduction of the electron cloud intensity by the beam conditioning process. The decrease of the dynamic vacuum pressure is known as vacuum cleaning effect.

The electron cloud build-up is a concern for most of the high bunch intensity proton and positron accelerators since it induces beam instabilities and emittance growth. In the LHC, the electron cloud-induced heat load is also a concern.

The electron cloud impact can be reduced by decreasing the secondary electron yield (SEY) of the electron-bombarded surface. This reduction is by analogy to the conditioning of the RF cavities, called beam conditioning. The conditioning efficiency of a bombarded surface comes both from the reduction of the yield at a given energy (see Fig.1) but also from the fact that only the relative yield above $\delta_0=1+d\delta$ counts in the avalanche process (Fig.1). $d\delta$ corresponds to the losses expected in the avalanche process. Fig.2 shows the relative decrease of the number of additional electrons above $\delta_0=1+d\delta$ as a function of the decrease of the δ_{max}. A decrease of 40% of the δ_{max} from 2.4 down to 1.6 results in a decrease by a factor of 5 of the number of additional electrons available in the avalanche process (Fig.2).

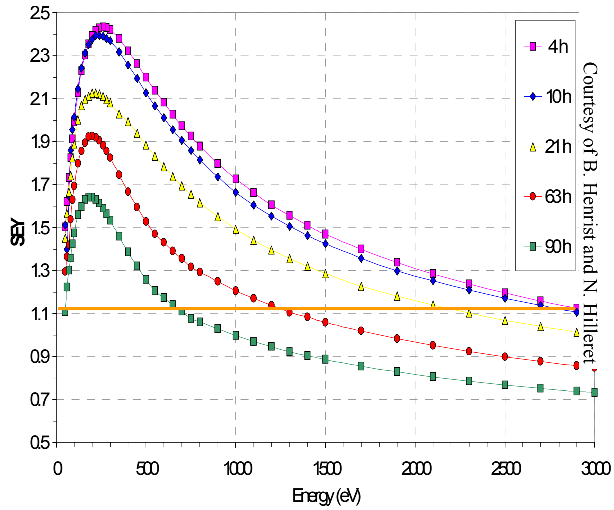


Fig.1: Decrease of the SEY of a bombarded surface with the electron dose.

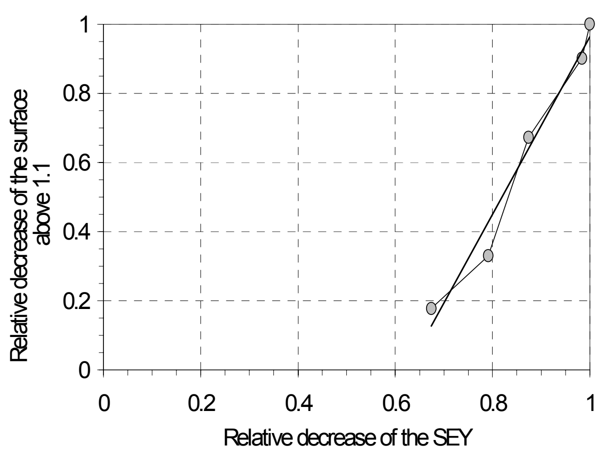


Fig.2: Relative decrease of the number of additional electrons above $\delta_0=1+d\delta$ (=1.1 in this example) as a function of the decrease of the δ_{max}.

MAIN RESULTS IN THE SPS

The electron cloud is being studied in the SPS since 2000. This paper summarise only the results relevant to the scrubbing of the LHC: the electron build-up, vacuum cleaning and beam conditioning, physisorbed gasses and ramp in energy.

Electron Cloud Build up

The electron cloud build up is a threshold phenomenon i.e. it takes place above a given bunch intensity for a given number of bunches in a batch. A batch consists in a train of 72 bunches spaced by 25 ns or 36 bunches spaced by 75 ns.

For the 25 ns bunch spacing, the SPS measurements showed thresholds of 3.0×10^{10} p/bunch and 5.5×10^{10} p/bunch for the dipole field and field free regions.

The electron cloud intensity showed a linear increase with the bunch intensity despite the observation of non-homogeneous spatial distributions in dipole and quadrupole fields.

Similarly, the electron cloud intensity varies linearly with the filling pattern i.e. the number of circulating batches. No extinction of the electron signal has been observed during the 225 ns batch spacing giving evidence of surviving electrons.

All ambient temperature (RT) parts will be equipped with NEG coatings, which decrease the electron cloud activity due to their intrinsic low SEY, i.e. 1.1 after activation and 1.3 if saturated by water.

Vacuum Cleaning and Beam Conditioning

A vacuum cleaning has been observed in the SPS during both the 25 ns and 75 ns running periods. Factors of 10 and 100 have been observed during the 75 ns and 25 ns period respectively in both field free (FF) and dipole field (DF) regions.

A beam conditioning of cold surfaces has been observed in the SPS. During the 75 ns running periods and in a dipole field, a factor of 100 was observed after 7 hours of continuous beam. A factor of 10 was observed while running with the 25 ns beams during 1½ day of continuous beam in a dipole field and a factor of 2.5 in a quadrupole field at RT after 2 days.

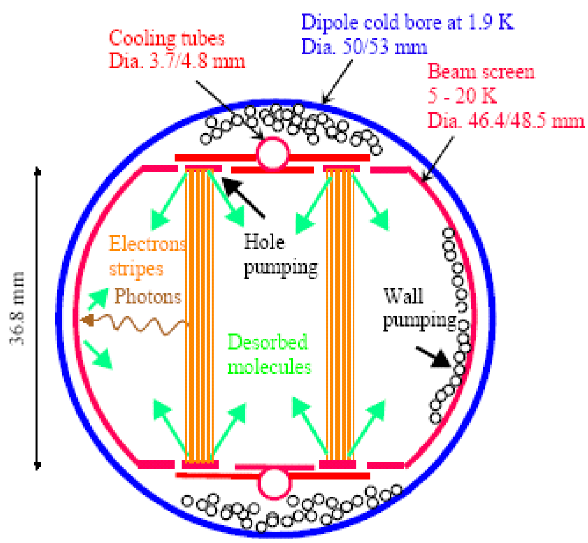
Role played by the Physisorbed Gasses

The scrubbing run'03 identified the physisorbed water as a potential problem for the beam conditioning of cold surfaces. If protected against water back streaming from the unbaked parts, a beam conditioning has been observed on the SPS cold detector. As expected from Laboratory measurements, SPS measurements confirmed that water condensation on a conditioned surface resets the conditioning i.e. the electron cloud intensity is back to the initial value before the conditioning. A temperature cycling up to 180 K did not helped to recover the initial value.

In the LHC, physisorbed water is not expected to be a limitation since a low coverage is expected resulting from the combination of a pumping down to 10^{-4} Pa of the cold parts prior to the cooling and a controlled cool down sequence where the cold bore is cooled while the beam screen is kept as warm as possible in order to push the water and other gasses to the cold bore surface (see Fig.3).

Nevertheless, the water condensation coming from an air leak in the transitions or the arcs of the LHC will have severe consequences on the operation.

The other gasses existing in the residual vacuum and physisorbed on the cold surfaces will also play a predominant role. Laboratory measurements have shown that CO_2 and water could have a detrimental effect on the SEY as hydrogen and CO will decrease the SEY (see Fig.4).



Courtesy of V. Baglin (CERN)

Fig.3: Cross-section of the Beam screen and cold bore showing the dynamic effects in presence of beams above the electron cloud threshold.

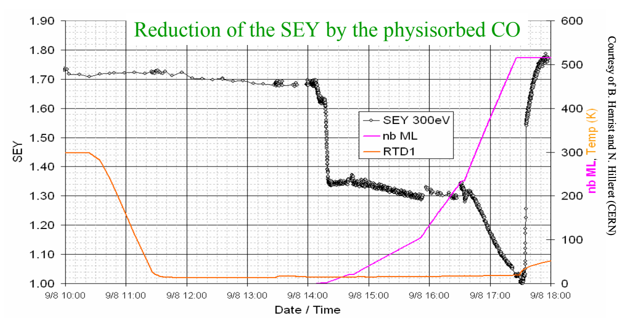


Fig.4: Variation of the SEY of a baked copper surface at cryogenic temperature as a function of the CO coverage.

Ramp in Energy

Running at injection energy (450 GeV) will increase the available cryogenic margin for the electron cloud-induced heat load. This scenario shall be considered provided that the machine is not limited by other effects like beam instabilities or emittance growths and if the beams is not subjected to a small orbit displacement during the ramp in energy.

In the SPS arcs (dipole field), the ramp in energy induces visible orbit displacement on the electron cloud strip detectors (Fig.5 and Fig.6) and on the pressures rises (Fig.7). The variations of the electron cloud intensity and pressure increase can be explained by the displacement of the electron cloud which follows the beam. The electrons bombard less cleaned and conditioned surfaces which appears on the recording as an increase of the collected electron current and pressure rise.

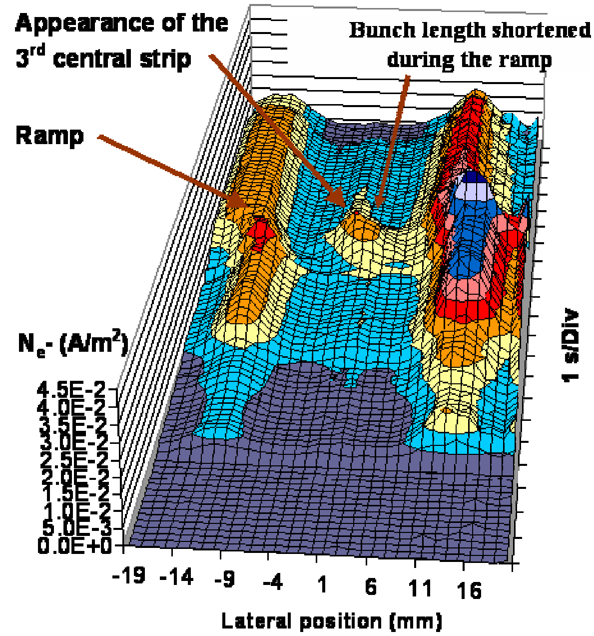


Fig.5: Displacement of the electron cloud spatial distribution resulting from a beam orbit displacement.

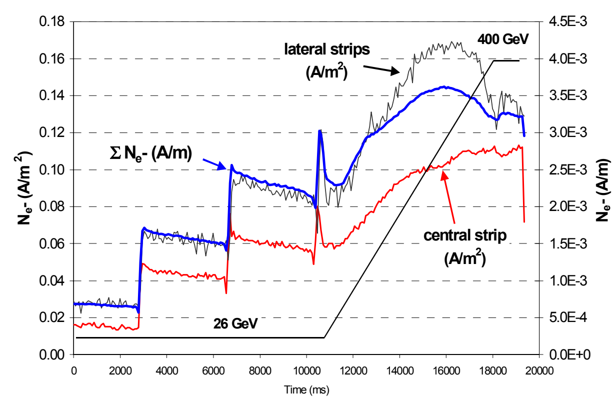


Fig.6: Variations of the electron flux to the wall with the beam energy during the ramp to 450 GeV.

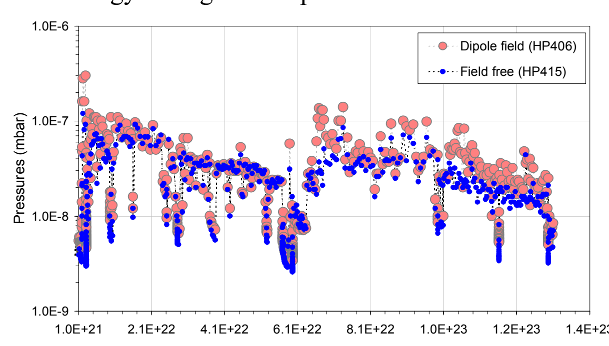


Fig.7: The negative slope characterise the cleaning effect as the visible offset between the two period and correlated with the introduction of the ramp results from the beam displacement. The cleaning is not completely lost.

DIAGNOSTICS FORESEEN IN THE LHC

LHC versus SPS Vacuum and Electron Cloud Diagnostics

The LHC diagnostics will aim to provide indications on the vacuum cleaning, beam conditioning of the non-NEG coated RT components and cryogenic sections and on the saturation level of the NEG coated sections. The later will define when reactivations are required.

These diagnostics will be dedicated to the operation follow-up and not to the electron cloud studies. In fact, if used during MDs, the subsequent additional conditioning of the detectors will result on an unknown "shift" between the detectors status as compared to the LHC machine.

As an alternative, the SPS electron cloud diagnostics will be kept operational while running the LHC for dedicated electron cloud studies in order to benchmark the simulation codes.

Vacuum Diagnostics

The vacuum diagnostics aimed to provide indications on the vacuum cleaning. At ambient and cryogenic temperatures, the information will be provided by the decrease of the dynamic pressure and by the partial pressure evolution. At cryogenic temperature, the measurement of the quantity of gas released by the photon and electron bombardments and physisorbed on the beam screen and cold bore surfaces within a given period of run will allow to recalculate the evolution of the desorption yields (η) of the different gasses.

Electron Cloud Diagnostics

The electron cloud diagnostics aimed to provide indications on the beam conditioning in the RT parts of the long straight sections (LSS) and in the arcs at cryogenic temperature.

An in-situ SEY measurement will provide a direct indication of the decrease of the SEY but could only be achieve in field free condition due to the overall dimensions of the gun and electron cage.

The decrease of the electron cloud will be followed at RT by the use of strip detectors and electron collectors which measure the electron flux to the walls and by a swapping detector which measures the electron cloud density. At cryogenic temperature and due to the aperture constraints in the cold bore/beam screens, only electron collectors are foreseen.

The dynamic pressures will provide indications on the electron cloud intensity at RT but not at cryogenic temperature due to the huge cryogenic pumping speed and the fact that the gauges are installed far from the beam channel.

The evolution of the electron cloud-induced heat load will be based on calorimetric measurements: dedicated calorimeters or upgraded thermometry and flow rate measurements on the magnets Q_5 and D_2Q_4 in IR4 or IR5. The installation of part of the diagnostics in IR5 will provide more flexibility since the underground areas are accessible with beam. An engineering change request (ECR) will be prepared by end of February 2005.

NEG Diagnostics

The NEG diagnostics aimed to provide indications on the saturation levels of the NEG coatings in the LHC LSS. A pilot sector equipped with Bayard-Alpert pressure gauges, hydrogen transmission measurement facility and partial pressure evolution with time will provide indications on the saturation levels. The predictions will be extrapolated to the other RT vacuum sectors using the other Bayard-Alpert pressure gauges of the LHC LSS.

SCRUBBING RUNS SCENARIOS

Maximizing the Efficiency…

The vacuum cleaning and beam conditioning efficiencies will result from the intensity of the electron bombardment. The highest will be the electron cloud intensity and the faster will be the cleaning and conditioning processes.

This scenario assumes that only the electron cloud-induced heat load limits the LHC and that the beam emittance, beam losses and beam instabilities remain under control. This consideration was not an issue for the SPS since a new beam is injected every 21 seconds but should be addressed for the LHC as it could be a major limitation.

Bunch Spacing, Filling Pattern, Beam Energy

No limitation is expected when running with the 75 ns bunch spacing up to the nominal bunch intensity. If running with the 25 ns bunch spacing, no limitation is expected below the electron cloud thresholds. Above the threshold, the induced heat load will fix the limit if beam instabilities and emittance growths are kept under control. Based on the SPS extrapolations, a bunch intensity of 8.0×10^{10} p/bunch could be achieved with the available cooling capacity at injection energy. No figures are available at top energy since the effect of the decrease of the bunch length can not be measured.

Changing the filling pattern by increasing the gaps between the batches shall be preferred to the reduction of the bunch intensity. RHIC machine successfully tested that scenario. The alternative, i.e. decreasing the bunch intensity, will result in a displacement of the lateral strips in a dipole field and a decrease the average energy of the electrons from the cloud. Both will decrease the conditioning efficiency.

Scrubbing Runs at Injection Energy

Doing the scrubbing runs at injection energy will release more cooling capacity for the electron cloud-induced heat load, but this scenario will only work if the machine is not limited by other effects like beam instabilities or emittance growths.

Since small orbit displacements are expected in the LHC during the ramp, an additional short scrubbing run period at top energy will be required.

De-Conditioning Effect

The de-conditioning effect is characterised by an increase of the SEY of a surface when this surface is no longer bombarded. This behaviour has been observed both in the Laboratories and in accelerators (EPA and SPS). However, the subsequent conditioning is 10 times faster.

The de-conditioning is expected as a consequence of a partial warming up of the cold parts during the shutdown since the physisorbed gasses will go back to the gas phase and be recondensed during the following cooling down. Therefore, a scrubbing run shall be scheduled right at the start-up.

Impact on the LHC Vacuum System

The continuous bombardment of the surfaces by the electrons will release a non-negligible amount of gas. In RT parts, the gas will be pumped by the NEG coatings and contribute to their saturation. The recovery of the vacuum performances will require a re-activation of the NEG coatings, which takes several weeks.

In the cryogenic parts at 4.5 K and in presence of an electron cloud, the hydrogen will be transferred to the cold bore through the beam screen pumping slots due to the high desorption yields of the electrons and be trapped by the cryosorbers. If saturated, the resulting equilibrium pressure will start to increase and therefore a thermal cycling shall be foreseen to recycle the cryosorbers.

This operation requires a long stop and therefore shall take place during the shutdown.

Recommended Scenario

The major scrubbing runs shall be scheduled right before the shutdown in order to allow the reactivation of the NEG coatings and the temperature cycling of the cold magnets. The later will occur naturally during the shutdown since the cryogenic sections will be warmed up. The main disadvantage could be the radioactive activation of the machine elements right before the shutdown which will impact on the doses received by the personnel.

A soft scrubbing run shall also be scheduled right at the start-up to recover the de-conditioning.

A possible scenario could be:

- Start with the 75 ns up to the nominal and at top energy. A vacuum cleaning is expected by the photons, electrons contribution should be negligible.
- Runs with the 25 ns below the electron cloud threshold. Similar vacuum cleaning as for 75 ns case.
- Runs with the 25 ns above the electron cloud threshold $<5.0\times10^{10}$ p/bunch (diluter limit).
- Scrubbing run schedule before the shutdown
- Short scrubbing run at the start-up after the shutdown to recover the de-conditioning.
- Runs with the 25 ns above the electron cloud threshold $>5.0\text{x}10^{10}$ p/bunch. Bunch intensity shall be increased by steps and playing with the filling pattern to stay within the cooling capacity.
- Scrubbing run schedule before the shutdown
- …

ON GOING ACTIVITIES

No result shall be expected from the SPS since it is stopped in 2005. Some studies will continue in the Laboratory to measure the effect of the physisorbed gasses on the SEY and ESD using gas mixtures.

In the frame of a CERN/BNL Collaboration, a set of detectors: strip detector, pick-ups, retarding field detectors will be installed in RHIC machine to study the effect of the filling pattern and the role played by the surviving electrons.

CONCLUSIONS

No limitation is expected with the 75 ns beams up to the nominal bunch intensity. If running with the 25 ns beams, an electron cloud build up is expected above the threshold (3.0×10^{10} p/bunch in dipole fields) but this build up always saturates and should not lead to over runs like for the ion instability avalanche, i.e. the beam should stay under control.

If the LHC is not dominated by the beam instabilities and emittance growths, the available cooling capacity should allow running with intensities up to 8.0×10^{10} p/bunch in presence of an electron cloud at injection energy. No figures are available at top energy since the effect of the decrease of the bunch length can not be measured.

Short scrubbing runs shall be scheduled while running above the electron cloud thresholds, after shutdowns or after venting of an arc sector and in case of long stops to recover the de-conditioning or in case of several quenches or severe leaks. In the later case, the scrubbing run will aim to homogenise the gas distribution along the cryogenic magnets to avoid quenching the magnets due to an excessive beam-gas scattering resulting from local pressure bumps.

The main scrubbing runs shall be scheduled balancing the impact on the vacuum systems and the consequences on the radioactive activation.

Finally, it is important to keep in mind that the vacuum cleaning and beam conditioning efficiencies will result from the intensity of the electron bombardment.

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