LHC Scrubbing Meeting, 23/05/2013

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Summary

The goal of the meeting was to address the following questions, which arose from the LHC observations in 2012:

1) Scrubbing speed: why has the scrubbing process seemingly stopped in the LHC?
2) Behavior of the heat load/stable phase shift with the beam energy

The 25 ns operation of LHC in 2012 was briefly reviewed to show how the scrubbing process seemed to stop (or dramatically slow down) after the first 60 – 70 hours of scrubbing. In particular, after about two days of scrubbing the heat load normalized to the beam current did not exhibit any further decrease and the beam lifetime was not observed to improve anymore in the same machine and filling conditions. Furthermore, the stable phase shift data can give detailed information on the bunch-by-bunch power loss. For these data, zero loss is assumed for the train of 12 bunches, which means that single bunch effects due to broadband impedances cannot be disentangled and only electron cloud (or multi-bunch impedance) losses are singled out. These data can not only provide the total power loss due to electron cloud and narrow band impedances by simply summing the individual bunch contributions, but also the structure of the build up of the power loss along the bunch train (and within batches), which can be a direct indication of the structure of the electron cloud build up. From these data a clear asymmetry between Beam 1 and Beam 2 is found especially in the fills during the scrubbing run, with Beam 1 losing more energy and having a more rapid energy loss decay than Beam 2. This is confirmed also by the beam lifetime measurements, which showed significantly better lifetimes for Beam 2 than Beam 1 almost consistently throughout the scrubbing run. The bunch-by-bunch energy loss data showed that while the electron cloud reached saturation within the injection of four trains for Beam 1, it took almost the whole Beam 2 to reach levels close to saturation. One reason for the asymmetry between the two beams could be different transverse emittances, as highlighted in the points of discussion below. It was also observed that stable phase shift measurements at 450 GeV usually provided values between 50 and 100% larger than those obtained from heat load measurements in the arcs.

During the 25 ns MDs, beams with 84, 15, 372 and 804 bunches were stored in the LHC for few hours (up to eight hours for the fill with 804 bunches and nominal bunch intensities). It was observed that the heat load was strongly enhanced during the ramp and then hardly decreased during the store at top energy. The stable phase shift measurements clearly revealed that the power loss increase happens smoothly along the ramp, with no threshold effect at any point (which would be expected at about 2 TeV, if the increase was caused by photoelectrons). Also, no obvious correlation with the average bunch length could be determined (it probably affects in a minor way the slope of the increase). In stable conditions at top energy, the stable phase shift measurements were systematically found to be only 20 – 30% larger than the heat load measurements in the arcs. Stable phase shift data also show the evolution of the bunch-by-bunch power loss along the ramp. The values eventually reached are very close to those measured at saturation at 450 GeV, i.e. 25 W/bunch. The distribution of the bunch-by-bunch power loss along the trains also shows a train-to-train build up, with an evident memory effect between trains. In spite of the still significant integrated amount of electron cloud present at top energy, the data from the BSRT seem however to suggest that, thanks to the high beam energy, the electron cloud has become harmless to the beam at this stage. In fact, the raw BSRT data only exhibit a 10% transverse emittance blow up during the eight hours fill (at least for Beam 1, which could be measured with the BSRT).

An interesting exercise was done. By fitting with simulations the measured heat load during the high energy fill with 800 bunches (fill 3429), which would require an SEY of about 1.6, we find the deposition of a scrubbing dose in the order of 10^{-3} C/mm^2 on the inner wall of the beam screen. This value, on whatever scrubbing curve measured in the lab for Cu, would correspond alone to almost the full scrubbing of the surface, yielding SEY values below 1.2 (inconsistent with the assumption SEY=1.6 in the simulation). There is obviously a gap to be bridged between what happens in the laboratory and what happens in the machine with circulating beam (either in the SEY curve modeling or in the scrubbing curve to be used in a cold environment in presence of magnetic field like the LHC arc).

Possible ideas to explain why scrubbing has stopped:

1) By this stage, the electron cloud might have been significantly mitigated in the dipoles, but it still survives strongly in the quadrupoles. The quadrupoles of the arcs have a much lower multipacting threshold, i.e. about 1.2, and consequently it is much harder to scrub them, as this value sits in the flat part of the Cu scrubbing curve. This explanation is consistent not only with the observed saturation of the scrubbing effect, but also with the strong memory effect observed and with the individual heat load data measured on the SAMs. In fact, the SAMs, grouped in Q5P1P5/Q6P1P5, Q5P2P8/Q6P2P8 and D3P4 (each including those left and right), show power loss in W/m much larger in quadrupoles (Q5, Q6) than in the dipole (D3). The difference can be as high as a factor 5 (but perhaps even larger, because the power losses per cryostat have been normalized to the cryostat length and not to the magnet lengths, which are up to almost a factor two shorter in the case of the quadrupoles). The difference becomes smaller (about a factor 2) at top energy, because the dipole D3 has an increase of heat load along the ramp, similarly to the arcs. All this seems to suggest that the heat load we still see in the arcs at 450 GeV can be strongly dominated by the quadrupoles, but then the dipoles "wake up" when ramping up the energy of the beam. It was noted that the D3 beam screen might not see any direct synchrotron radiation.

This must be verified both with respect to the possible radiation from D4 and from the arc. It must be noted that the undulator is installed in the same cryostat as D3. The synchrotron light trajectory should be checked with Federico Roncarolo (BE/BI). Furthermore, it should be checked whether the undulators were on for both beams, as well as the dipole magnets for the rest gas monitor, which is also in that area. **Action: BE/ABP**. It would be important to equip one of the standard arc cell with a measurement of the heat load, which can distinguish the quadrupoles from the dipoles to confirm this hypothesis. **Action: TE/CRG to verify the feasibility**

2) The modeling of the low energy part of the SEY curve has a strong impact on the definition of the absolute values of the SEY thresholds. For example, if one assumes that the curve flattens at 0.7 for energies of the incident electrons below 60 eV, the threshold for the arc dipoles moves from 1.4 to 1.1! If one assumes a cosine fit that moves the low energy dip to slightly higher energies, the threshold moves from 1.4 to 1.2. In either case, we enter a region in which scrubbing becomes more difficult than it could have been envisaged before. Also the presence of rediffused electrons can make a difference
3) Scrubbing in a cold environment and with a large magnetic field could behave differently than scrubbing at room temperature? Measurements in lab were done at low temperatures (10 K) and they seem to suggest scrubbing behaves similarly in these conditions. Apart from the SPS experience, the presence of a high magnetic field was never studied experimentally. The efficiency of scrubbing also depends on the C deposition on the surface, so it would be good to check whether the present LHC beam screen has a C layer. In particular, it would be worth looking at the surface of the beam screens of the magnets extracted from the ring to see a possible change in color as for the SPS magnets. **Action: TE/VSC**. It would be also advisable to install e-cloud diagnostics in cold regions to monitor directly both electron cloud build up and reduction through scrubbing.
4) StSt usually has a higher SEY saturation value than Cu (1.3 instead of 1.1, depending on the presence of C). The LHC beam screen is obtained by co-laminating a low permeability 1 mm thick austenitic StSt strip with a 75 μm copper sheet. Maybe the electrons see the underlying stainless steel. In the warm sections (Cu vacuum chambers — with or without coating) there seems to be conditioning, so this could also be used as complementary information.

Possible ideas to explain the energy dependence of the power loss

1) Dependence on the beam size. Since the bunch length is not changing significantly along the ramp, it is possible that the shrinking transverse beam size has an e-cloud enhancing effect. This effect was also seen in the past in simulations, when the SEY is close to its threshold value. More recent simulations (especially done for LHC) seem to have ruled out this effect, probably because the transverse beam size is much smaller than the chamber size. However, a detailed study via simulation will be

undertaken to check the possible influence of transverse beam sizes. **Action: BE/ABP**

2) Change of the surface properties with the magnetic field. There is no, or little, know-how on this specific topic. **Action: TE/VSC**

3) High energy photons generated the magnet edges capable of producing photoelectrons. This effect should be quantified and applied to both the arc dipoles and D3. **Action: BE/ABP**

Points of discussion

1) Elena commented about the discrepancy between heat load data and power loss data from stable phase shift. The latter should obviously be larger because they include also the contribution from the electron cloud in other places than the arcs (e.g., SAMs, triplets) and that of the narrow band impedances. Heat load data exhibit a delay, due to the fact that they are obtained averaging with a sliding window on a certain time window (the duration of this window needs to be checked, 45' or few minutes). **Action: TE/CRG to comment on this point**. Consequently, in non-stable conditions in which the acquired value is rapidly varying in time, this leads to a smoothed estimation that can significantly differ from the real value. In particular, in the case in which the value is fast decreasing, there can be an underestimation by up to a factor two for a 45' minutes averaging time. Therefore, for a correct comparison, the data should be considered at flat top in stable conditions (at injection energy conditions are never stabilized because of the continuous losses). In this case, the differences between phase shift data and heat load data are found in the order of 20-30%, as could be reasonably expected. **Action: BE/ABP and BE/RF (J. Esteban-Müller) to provide estimate of the contribution to energy loss due to impedance and to consider all sources of heat loads measured on the beam screens**
2) The observed difference between Beam 1 and Beam 2 was especially evident at the beginning of the scrubbing and confirmed by both lifetime and stable phase shift measurements. However, the previously accumulated electron dose for the two beams should have not been very different. Gianluigi suggested that this fact could be also due to different transverse emittances of the two beams, which is routinely measured with WS at injection. Beam 2 has usually larger emittances than Beam 1, that's why it maybe produces less and suffers less from electron cloud.
3) If quadrupoles are mainly responsible for the measured heat load, this is only the case after scrubbing and at injection energy. At top energy the electron cloud in the dipoles seems to return and produce again most of the heat load. Serge confirmed that at injection we were limited by the SAMs (quadrupoles), while at flat top the limitation came from the arcs (revived dipoles). Miguel recommended understanding how the thresholds in the quads would change when changing the modeling of the low energy electrons, because this would provide another consistency check with the experimental data. **Action: BE/ABP.** The expectation is that there will be an effect when changing the modeling according to the

same modifications applied for the dipoles, but it will be less pronounced than in dipoles because: 1) the threshold is already very low with the present modeling, and 2) the memory effect in quadrupoles is already very strong due to trapping in magnetic gradients, so the amount of survival of low energy electrons will not impact much on the memory effect.

4) Effect of transverse beam size: it may have an impact close to the threshold, this effect has to be studied in detail in simulations (was done for the SPS parameters only so far).
5) Diagnostics to install in LHC: it is important to envisage the installation of reliable diagnostics in cold sections, because that would be representative of the fraction of the machine that mostly produces electron cloud. This could be far more interesting than the instrumentation that will be installed in the pilot sector, as this resembles in many aspects the setup presently available in the SPS. Actually, also COLDEX in the SPS, which is being revived for the post-LS1 operation, could be used for cold measurements to interpret LHC data. **Action: TE/VSC**
6) Miguel wondered why the scrubbing time estimation given at Chamonix 2012 was of 2 weeks and now it seems that the 8 hours store at 4 TeV could already achieve a full scrubbing dose. The estimation provided in 2012 was based on the following assumptions, as was explained in detail in the Chamonix paper.
    a. It assumed the machine filled with degraded beams (full machine for Beam 1 and half machine for Beam 2) made of trains of 72 bunches, using the real bunch-by-bunch intensities from one of the last fills of 2011. The positive result of the Scrubbing run 2012 was that we could control beam stability with large number of bunches and trains of 288 bunches with adequate setting-up of transverse feedback and machine parameters (which was not demonstrated in 2011 and which was one of the aims of the 2012 scrubbing run – that is why this was requested already at the beginning of the run but not approved).
    b. It obviously took into account the reduction of the SEY iteratively, using a scrubbing curve from the lab
    c. The scrubbing curve that at that moment seemed to best fit the LHC data from 2011 was the one obtained with 20 eV electrons measured by R. Cimino et al.
    d. The error on the absolute value of the maximum SEY deriving from the modeling of the low energy electrons was neglected.

The calculation carried out with all the above assumptions yields 20 hours beam time to reduce the electron cloud density by one order of magnitude (meaning that the beam can still suffer incoherent effects from e-cloud at the end of the process). This beam time was then stretched to two weeks to include machine efficiency, safety margin and test ramps. On the contrary, the exercise done on the fill 3429, in which no reduction of the heat load along the top energy fill was seen, just corresponds to the calculation of an accumulated electron dose with a basically non-degraded beam at 4 TeV without any iterative SEY reduction. There is no obvious way of comparing these two different evaluations, which are conceptually different.

7) Other questions to be followed up in simulations (**action: BE/ABP**):
    a. Study the impact of the low energy part of the SEY curve on the quadrupole build-up (as was done for the dipoles);
    b. Study the intensity dependence of the electron cloud in the quadrupoles, in particular check that the observed leveling of the heat load value also in conditions of rapid beam losses can be reproduced by simulations;
    c. Study the effect of the different aperture and gradients of the standalone quads compared to the arcs.
8) It should be checked whether the synchrotron light from the upstream dipoles reaches into the standalone module of D3 in point 4. It would be also interesting in general to track the synchrotron radiation in the arcs to understand where the photoelectron seeding makes more sense.
9) As pointed out by Vincent, a staged approach should be chosen for any experiment aiming to study the dependence of the SEY on the magnetic field, i.e. first studies could be done on warm surfaces and then at a later stage repeated in a cryogenic environment. In any case, it will be very difficult to measure the low energy part of the SEY curve (both without and with magnetic field). A. Krasnov is working on an experimental set up to carry out this type of measurements.

GR, 27/05/2013