Chapter 22

Implications for Operations

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The HL-LHC will introduce a number of novel operational features and challenges including luminosity leveling. After a brief recap of the possible leveling techniques, the potential impact of the operational regime on overall efficiency is discussed. A breakdown of the operational cycle and the standard operational year, together with a discussion of fault time is presented. The potential performance is then explored and estimates of the required machine availability and efficiency for 250 fb^{-1} per year are given. Finally the e-cloud challenges, scrubbing runs requirements, and machine development potential are outlined.

1. Introduction

Come the commissioning and subsequent operation of the HL-LHC, the LHC itself will have been operational for over 10 years and a wealth of knowledge and experience will have been built up. The key operational procedures and tools will have been well established. The understanding of beam dynamics will be profound and refined by relevant measurement and correction techniques. Key beam related systems will have been thoroughly optimized and functionality sufficiently enhanced to deal with most challenges up to that point. Availability will have been optimized significantly across all systems. This collected experience will form the initial operational basis following the upgrade.

However the HL-LHC will pose significant additional challenges with the target integrated luminosity posing considerable demands on machine availability and operational efficiency. The planned beam characteristics will push beam dynamics to new limits. In the following the operational cycle is revisited in light of the key HL-LHC challenges. The expectations and issues relating to availability in the HL-LHC are outlined.

2. Leveling

As described in detail in preceding chapters, the planned bunch intensity, β^* , and compensation of the geometrical reduction factor lead to a potential bunch lumi-

osity well above the acceptable maximum in terms of pile-up for the experiments. Thus an obligatory operational principle of the HL-LHC is luminosity leveling. The aim is to reduce a potential peak or virtual luminosity to a more manageable leveled value by some luminosity reduction technique. As the number of particles in the beam falls with time, appropriate adjustments keep the luminosity at the leveled value. The options are outlined below and a combination of some of them (e.g. dynamic change of β^* and crab cavities) will be used in the HL-LHC. It has been realized recently that the longitudinal pile-up density is also another critical parameter for the experiments which must be taken into account during luminosity delivery.

2.1. Leveling options

2.1.1. Transverse offset

Transverse offsets of the beams at one interaction point have been used operationally for leveling in LHCb, and tested in 2011 with single bunches with HL-LHC like parameters. Offset leveling in one interaction point with two interaction points colliding head-on is certainly possible but concerns about coherent beam-beam instabilities and possible emittance growth rule this out as a universal solution.

2.1.2. Crab cavities

Crab cavities can be used to manipulate the beam overlap of the two beams in the luminous region, thereby reducing the effect of geometrical reduction factor. Details are given in Chapter 7.

The technique has the advantages of flexibility and IP independence. A possible operational scenario would be to start a fill with crab cavities effectively off and accept the full geometrical reduction factor. As the luminosity falls, the crab cavities could be used to an appropriate level to compensate the crossing angle, thus leveling the luminosity. The disadvantage is that the longitudinal vertex density of the fully uncompensated crossing angle exceeds the current performance expectations of the upgraded detectors. This implies that naive use of crab cavities would have to be supplemented with an additional technique. Alternatively the use of crab cavities in the separation plane can be used to tailor the longitudinal pile-up density and reduce its peak value while keeping the integral (i.e. events per crossing) constant [1].

Concerns about the use of crab cavities include phase or amplitude noise, synchronization errors that could lead to emittance blow-up and the fact that there

is little experimental evidence that crab cavities can work effectively in proton machines.

2.1.3. External crossing angle of the two beams

If partial compensation of the long-range beam–beam interactions in the common vacuum system with the help of wires can be established as a viable technique, the crossing angle can be reduced and adjustment of the geometrical reduction factor can be used as leveling parameter. This method has similar limitations with respect to the longitudinal pile-up density as the leveling technique based on crab cavities.

2.1.4. Dynamic change of β^*

Initial exploration of changing β^* during a fill have taken place with some success. This is a potentially interesting technique providing constant longitudinal vertex density and sufficient beam stability. The IPs can be treated independently, however any implementation must be operationally robust and must ensure that beams remain in collisions during the change in β^* .

2.2. Leveling — formulation

Relevant figures from the HL-LHC 25 ns baseline are shown in Table 1. Here k is defined as the ratio of the peak virtual luminosity to the leveled luminosity. The peak virtual luminosity is the peak luminosity that could be achieved if the geometric factor due to the crossing angle is fully compensated by crab cavities.

Table 1. Selected baseline HL-LHC parameters for 25 ns beam.

Protons per bunch	Number bunches	Total number protons	Peak luminosity without crab cavities $\text{cm}^{-2}\text{s}^{-1}$	Peak virtual luminosity $\text{cm}^{-2}\text{s}^{-1}$	Leveled luminosity $\text{cm}^{-2}\text{s}^{-1}$	k
2.2×10^{11}	2808	6.2×10^{14}	7.4×10^{34}	21.9×10^{34}	5×10^{34}	4.38

Considering luminosity burn-off and neglecting losses due to other mechanisms such as beam-gas and diffusion, the number of particles per beam as a function of time is given by Eq. (1):

$$N(t) = N_0 - n_{\text{ip}} L_{\text{lev}} \sigma_{\text{vis}} t \quad (1)$$

where N_0 is the initial number of particles, n_{ip} is the number of interaction points, L_{lev} is the leveled luminosity, and σ_{vis} the visible cross-section. Equation (1) can

be re-expressed in terms of an effective lifetime τ_{eff} .

$$N(t) = N_0 \left(1 - \frac{t}{\tau_{\text{eff}}} \right) \quad (2)$$

where

$$\tau_{\text{eff}} = \frac{N_0}{n_{\text{ip}} \sigma_{\text{vis}} L_{\text{lev}}}. \quad (3)$$

Assuming no additional losses due to diffusion/collimation during the fill and no transverse or longitudinal emittance blow-up, the number of particles at the end of the leveling period is:

$$N_e = \frac{1}{\sqrt{k}} N_0. \quad (4)$$

The leveled luminosity L_{lev} may be delivered for the leveling time T_{lev} before the luminosity starts to drop naturally below L_{lev} . T_{lev} is given by:

$$T_{\text{lev}} = \left(1 - \frac{1}{\sqrt{k}} \right) \tau_{\text{eff}}. \quad (5)$$

In an ideal world, T_{lev} is trivially calculated and one might naively imagine to let a fill run for T_{lev} . For the numbers shown in Table 1 T_{lev} is 10.6 hours. However, additional losses, primarily to the collimation system, will undoubtedly be present as a consequence of a number of emittance blow-up mechanisms (for example: beam-beam, noise, IBS, elastic scattering at the IP). These mechanisms will also contribute to an additional luminosity reduction because of the resulting emittance increase. An estimate of the virtual luminosity lifetime is possible and realistic numbers give a virtual luminosity lifetime of around 5 hours and a leveled time of 6 to 7 hours.

Once the luminosity falls below L_{lev} one could imagine keeping the fill for a certain amount of time (t_{decay}) before dumping. The contribution to the integrated luminosity from this part of the fill, assuming a constant luminosity lifetime (τ_L), is shown in Eq. (6):

$$L_{\text{decay}} = L_{\text{lev}} \tau_L \left(1 - e^{-\frac{t_{\text{decay}}}{\tau_L}} \right). \quad (6)$$

Optimization of fill length given the turnaround time and average fill length will be possible. Further consideration of the possibilities is given below when estimating potential integrated luminosity performance.

3. General Operations Considerations

3.1. Nominal cycle

The nominal operation cycle provides the framework underpinning luminosity production. As of 2012 the nominal operational cycle is well-established for 50 ns and bunch population exceeding nominal. A brief outline of the phases of the nominal cycle follows.

- (1) The working point of the various magnetic elements is reset by an appropriate magnetic cycle (“Precycle”).
- (2) The machine settings are verified with the injection of a limited number of bunches having a reduced population (pilot) or nominal population (intermediate). This is the so-called “Set-up” phase.
- (3) The two LHC rings are progressively filled with trains of bunches transferred from the SPS to the LHC at a momentum of 0.450 TeV/c (“Injection”).
- (4) Once the machine is filled with the maximum number of bunches possible the beams are accelerated to top momentum (up to 7 TeV/c) (“Ramp”).
- (5) The beam size at the interaction point is minimized with the aim of maximizing the luminosity once the beams are brought in collision. This is obtained by varying the current in the quadrupole magnet circuits in the two rings according to pre-calculated functions (“Squeeze”).
- (6) During the whole process of injection, ramp and squeeze the two counter-rotating beams are separated to avoid collisions and the detectors are in a safe state to avoid damage resulting from losses. At the end of the squeeze the beams are brought in collision at the interaction points (“Adjust”).
- (7) Once all the above procedures are completed and no abnormal conditions are detected (excessive losses or orbit excursions...) the conditions are met for safely switching on the detectors and the start of data taking (“Stable Beams”).

The differences between the key operational parameters before and after the start of the HL-LHC era are shown in Table 2.

Table 2. Comparison of key Run I and HL-LHC performance parameters.

Parameter	Value end Run 1	HL-LHC
Bunch population 25 ns	1.2×10^{11}	2.2×10^{11}
Normalized emittance [mm mrad]	2.5	2.5
β^* [cm]	60	15

The principal challenges during the cycle involve the injection, and transmission through the cycle of high bunch and high beam current while preserving small emittances. Given the experience of LHC operations thus far, the following potential issues may be identified.

- High total beam intensity brings with it possible issues with electron cloud, UFOs [2], beam induced heating, cryogenic heat load.
- High bunch population implies very good parameter control and the need to properly control beam loss through the cycle. Beam instabilities will have to be fully under control using a variety of measures.
- Low β^* implies strong non-linearities from the inner triplets and associated parameter control.

The following outline gives the results of folding these issues into the nominal operational cycle.

- **Precycle:** Following extensive experience during Run 1, it is known that the magnetic state of machine can be re-established before every fill by rigorous application of either: a combined ramp-down/precycle of the main circuits and a “de-Gauss” of the corrector circuits; or, following an access, by a full cycle of all circuits.

The ramp-down/precycle stage represents the adopted operational strategy for coming down from high energy: the main bends, quadrupoles, independently powered quadrupoles, inner triplets, etc. are ramped down to their pre-injection levels, while the other circuits are put through their normal “de-Gauss” cycle which puts them on the right hysteresis branch at injection.

- **Set-up of machine at 450 GeV:** Here the correction of the basic parameters (tune, chromaticity, orbit, RF phase and synchro errors) and the sequence of pre-injection checks can be assumed to have been mastered.
- **Injection:** The injection process should be very well optimized by the time of the upgrade. However high bunch intensities will have to be anticipated and all necessary mechanisms to minimize loss and maximize reproducibility should have been deployed. This process will certainly have to work like clockwork to ensure machine safety and high operational efficiency.

The persistent current decay at 450 GeV has a powering history dependence which is well described by the magnet model [3]. The correction of the effects of the decay are well established and correction mechanisms are in place. Any new magnets will, of course, have to be appropriately measured and characterized and integrated into the magnetic model.

- **Ramp:** The ramp should hold no surprises. The characteristics of snap-back and correction of associated parameter swings can be taken as given. The 10 A/s

ramp rate of main dipole power converters will still hold. Transverse feedback and tune feedback and their healthy cohabitation should be anticipated. Orbit feedback will be mandatory. Controlled longitudinal blow-up will certainly be required.

- **Squeeze:** The squeeze mechanics including feedbacks should and will have to have been fully mastered. Issues of beam instabilities should have been resolved, these might include squeezing with colliding beams — again this should have been made operational before the HL-LHC era. The possibility of combining the part of the squeeze process in the ramp is being considered to reduce the time required for the squeeze process.
- **Collisions:** There is some flexibility in sequencing the order in which the beams are collided in the different interaction points. The main issue here will be to avoid the loss of Landau damping during the process. Experience and understanding gained in future runs will be essential for validating the models presently being developed for explaining the observed instabilities.
- **Stable Beams:** With a leveled luminosity, the luminosity lifetime is, of course, infinite. There will, however, be a virtual luminosity lifetime which will fold in emittance growth, losses to diffusion, and luminosity burn and will give an operational leveling time somewhat below the ideal. In general, this phase is expected to be stable with overly sufficient Landau damping from beam-beam and small movements in beam overlap thanks to good orbit stability. Transverse and longitudinal emittance growth from intra beam scattering and noise sources should be estimated.

Given the higher than ever stored beam energy of the HL-LHC era, the nominal cycle must be fully mastered for effective, safe operation. In the performance estimates that follow this is assumed.

3.2. Turnaround

The turnaround time is defined as time taken to go from Stable Beam mode back to Stable Beam mode in the absence of significant interruptions due to fault diagnosis and resolution. A breakdown of the foreseen ideal HL-LHC turnaround time is shown in Table 3.

From Table 3, one can see that realistically a three hour minimum turnaround time may be assumed. The main components are the ramp-down from top energy, the injection of beam from the SPS, the ramp to high energy and the squeeze. The ramp-down, the ramp and the squeeze duration are given by the current rate limitations of the power converters. Of note is the 10 A/s limit up and down for the main bends; and the need to respect the natural decay constants of the main quadrupoles,

Table 3. Breakdown of turnaround with estimated minimum times shown.

Phase	Time [minutes]
Ramp down/precycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze	30
Adjust/collisions	10
Total	180

the individually powered quadrupoles and the triplets during the ramp-down and the squeeze. These quadrupoles are powered by single quadrant power converters and take a considerable time to come down. A faster precycle via upgrades to the power converters may be anticipated. Two quadrant power converters for the inner triplets, for example, would remove them as a ramp-down bottle neck.

In practice, the turnaround has to contend with a number of issues which could involve lengthier beam based set-up and optimization, or fault resolution. Typical beam based optimization might include: the need to re-steer the transfer lines, occasional energy matching between the SPS and LHC and the need for the SPS to adjust scraping during the injection process. Injector and LHC tuning and optimization are accounted for in the average turnaround time at present.

3.3. Availability and faults

Availability is defined as the overall percentage of the scheduled machine time left to execute the planned physics program after removing the total time dedicated to fault resolution.

Faults cover an enormous range from a simple front-end reboot to the loss of a cold compressor with corresponding loss of time to operations from 10 minutes to potentially days. Typical concerns are:

- Injector downtime.
- Hardware faults (broken PFNs, broken switches, faulty power supplies, broken computer components ...). Access is often required. Preparation and recovery from access comes out of availability.
- Software and control system problems.

- Cryogenics availability, quenches and quench recovery.

As will be seen below high availability will be key to getting anywhere near the stated HL-LHC target integrated luminosity [4] This will require far-sighted, targeted, consolidation in the years leading up to HL-LHC operation.

Operations can also be affected by a number of other factors.

- The challenges of high intensity and high energy, such as instabilities which can provoke losses and in the limit a beam dump.
- Premature dumps not related to faults which reduced the average fill length — for example: UFOs; vacuum spikes.

These factors reduce overall operation efficiency and during Run 1 were taken in account in either the turnaround time (fills lost in ramp and squeeze) or the average fill length (premature dumps in Stable Beams).

3.4. Operational year

The longer term operational model appears to be settling into a series of long years of operation interspersed with long shut-downs of order of a year or more. The long shut-downs are foreseen for essential plant maintenance, experiment upgrades and so forth. It is estimated that required length of a standard shut-down in the HL-LHC era will alternate between 16 and 20 months. The approximate breakdown of a generic long year is:

- 13-week Christmas technical stop including 2-week hardware commissioning (HWC) (this would count 3 weeks at the end of a year and 10 weeks at the start of the following year);
- around 160-day proton–proton operation;
- three technical stops of 5-day duration during the year;
- a 4-week ion run;
- and time for special physics and machine development.

A more detailed breakdown is shown in Table 4.

The longer period for scrubbing will be required after long shut-downs during which a significant fraction of the machine will be warmed-up and vented to air.

3.5. Integrated luminosity

A standard heuristic estimate for integrated luminosity takes the product of the scheduled physics time (minus MD, scheduled stops, etc.) and the peak luminosity and multiplies the result by the so-called Hübner factor to give an estimated integrated luminosity for said period. The Hübner factor is an approximation that

Table 4. Potential breakdown of a standard HL-LHC year.

Activity	Time assigned [days]
Christmas technical stop including HWC	91
Commissioning with beam	21
Machine development	22
Scrubbing	7 (to 14)
Technical stops	15
Technical stop recovery	6
Proton physics running including intensity ramp-up	160
Special physics runs	8
Ion run setup	4
Ion physics run	24
Contingency	7

implicitly takes into account luminosity lifetime, turnaround time, unplanned interventions, etc. During the LEP era it was typically around 0.2. During the first years of LHC operation the value of Hübner factor climbed with experience and targeted improvements in system availability and reached 0.18 in 2012. However luminosity leveling implies that this approach is no longer directly applicable.

Before considering any integrated luminosity estimates, the relevant terms are recalled.

- The scheduled proton physics time (SPT) is the total time assigned to high luminosity production. This is typically expressed in days per year. It does not include initial beam commissioning, special physics runs, ions, MD, technical stops etc. It does include the intensity ramp-up following initial commissioning.
- Machine availability (A) is the fraction of time realised for physics production after time lost to faults and fault recovery has been subtracted. The actual time available for physics production is thus: machine availability $\times$ scheduled physics time.
- Physics efficiency (PE) is the fraction of the scheduled physics time spent in Stable Beams.
- The turnaround time (T_{around}) is defined as time taken to go from Stable Beam mode back to Stable Beam mode in the absence of significant interruptions due to fault diagnosis and resolution. An average turnaround time maybe assumed based on explicit consideration of the operational phases, and experience. Recall that unsuccessful fill attempts that do not make it into Stable Beams are absorbed into the turnaround time.
- An average fill length (T_{fill}) may be assumed based on experience. It should be noted that an average fill length is based on a distribution of a certain number

of fills with given lengths that can span 0 to, say, 20 hours, and the ensemble can have a large number of low length fills, and longer fills that span lower luminosity delivery rates. At the HL-LHC, longer fills ($t_{\text{fill}} > T_{\text{lev}}$) will span the exponential decay region detailed above and this must be taken into account. The distribution of fill lengths motivates the use of a Monte Carlo [5] or an analytic approach [6].

Both the average fill length and fill length distribution will play an important role in the overall exploitation of the LHC. They will also be key factors in any estimates of future performance.

As the first step in an integrated luminosity estimate, the total time spent in Stable Beams for a given period is calculated.

- Reduced the scheduled physics time SPT by the availability factor.
- Assume an average turn around and an average fill length in the time that is left. Reduce the available time by the number of fills times the turnaround time to get the total time spent in Stable Beams (defined above as the Physics Efficiency (PE)).

The PE may thus be expressed as:

$$PE = \frac{(A \times SPT - N_f \times T_{\text{around}})}{SPT} \quad (7)$$

where N_f the number of fills given by:

$$N_f = \frac{A \times SPT}{T_{\text{fill}} + T_{\text{around}}}. \quad (8)$$

Thus:

$$PE = A \times \left(1 - \frac{T_{\text{around}}}{T_{\text{fill}} + T_{\text{around}}}\right). \quad (9)$$

Given the PE, the next question is how much luminosity might one hope to produce in said time. At this juncture consideration of the fill length distribution becomes of interest. It has already been established that for a fill of length t_{fill} :

- If $t_{\text{fill}} \leq T_{\text{lev}}$ the delivered luminosity is simply $t_{\text{fill}} \times L_{\text{level}}$.
- If $t_{\text{fill}} > T_{\text{lev}}$ the delivered luminosity is given by:

$$L_{\text{int}} = T_{\text{lev}} \times L_{\text{level}} + L_{\text{lev}} \tau_L (1 - e^{-\frac{t_{\text{decay}}}{\tau_L}}). \quad (10)$$

The fill length distribution is a non-trivial consideration. For example, the 2012 fill distribution showed a lot of short, prematurely dumped fills compensated by a number of long fills to give an average of around 6.0 hours. The cost of the short

fills is a corresponding number of extra turnarounds which fold directly into lost time for physics. The longer fills naturally include less productive latter stages.

A non-leveled adjustment factor (NLAf) may be introduced. This factor takes into account luminosity production in the exponential decay regime after leveling has been exhausted. The NLAf will depend on a number of factors including the leveling time, the fill length distribution, and the luminosity lifetime during the exponential phase.

The NLAf for a single fill may expressed in terms of these factors (see Eq. (11)):

$$\text{NLAf} = \frac{T_{\text{lev}} + \tau_L (1 - e^{-\frac{(t_{\text{fill}} - T_{\text{lev}})}{\tau_L}})}{t_{\text{fill}}}. \quad (11)$$

The aggregate NLAf will depend on the actual fill distribution (as well as the actual distribution of luminosity lifetime and leveling time). An estimate can be extracted from past experience.

A leveled Hübner factor (LHF) may be defined:

$$\text{LHF} = A \times \left(1 - \frac{T_{\text{around}}}{T_{\text{fill}} + T_{\text{around}}} \right) \times \text{NLAf}. \quad (12)$$

The LHF multiplied by product of the scheduled physics time and the leveled luminosity will give an estimate of integrated luminosity for an extended period.

The LHF defined here illustrates the factors that will contribute to the overall HL-LHC operational performance, namely: availability, turnaround time, mean fill length and, via the NLAf, the fill length distribution.

3.6. Integrated luminosity estimates

An estimate of the potential integrated luminosity per year may be made using: the above formulation, the 2012 data outlined in Table 5 and estimates of a realistic leveling time and luminosity lifetime.

- 2012 saw an average fill length of 6.0 hours and an average turnaround time of 5.5 hours.
- The HL-LHC virtual luminosity lifetime during leveling is estimated from the luminosity burn-off, an estimate of single beam losses to other processes, and an estimate of emittance blow-up. It is difficult at this stage to claim accurate predictions for lifetime estimates in the very high luminosity regime. Luminosity burn-off is given, reasonable assumptions on losses due to other processes and emittance growth give a leveled time of around 6 hours, to be compared with luminosity only leveled time of 10.6 hours calculated above.

Table 5. Overall operational performance 2012.

Scheduled physics time	201 days
Availability	71%
Physics efficiency	$\approx 37\%$
Average fill length	6.0 hours
Average turnaround	5.5 hours
Mean luminosity delivery rate	$12.97 \text{ pb}^{-1}/\text{hour}$
Peak luminosity delivery rate	$\approx 25 \text{ pb}^{-1}/\text{hour}$

- Taking leveled time of 6 hours, a luminosity lifetime of 5 hours in the exponential decay phase, mapped on to 2012 fill length distribution one gets a NLAf of 0.88.

Given this, and bearing in mind the provisos outlined above, a leveled Hübner factor of around 0.33 is obtained. With a leveled luminosity $= 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a scheduled physics time per year of 160 days this gives approximately 225 fb^{-1} . A leveled Hübner factor of 0.36 is required to integrate 250 fb^{-1} per year.

If one directly maps the 2012 fill time distribution on to a fill scenario with the same numbers for T_{lev} and luminosity lifetime, assumes a 13-hour fill length cut-off, and naively scales to 160 days (this implies the same availability and average turnaround time), one obtains a total integrated luminosity of around 221 fb^{-1} for a standard HL-LHC year [4].

A Monte Carlo approach [5] which also extends the 2012 figures to the full HL-LHC (and assumes the average turnaround time is increased from 5.5 to 6.2 hours) gets a figure of 213 fb^{-1} . The team also simulates the impact on the integrated luminosity of SEUs, UFOs, quenches and gives a range of 180 to 220 fb^{-1} in simulations that attempt to take these factors into account.

The details of the calculations are unimportant but what is clear is that given 2012's availability and turnaround, and reliable operation with leveling, approximately 85% of the HL-LHC annual target could be achieved. This is encouraging but clearly the already good availability must be maintained and improved if the ambitious goals of the HL-LHC are to be reached. Operational experience at or near design energy will provide valuable further input.

4. Scrubbing

Electron cloud build-up resulting from beam induced multipacting (see Chapter 4, Section 1.2.4) is one of the major limitations for the operation of the LHC with beams with close bunch spacing and in particular with 25 ns spacing. Electron

clouds induce unwanted pressure rise, heat loads on the beam screens of the superconducting magnets and beam instabilities leading to emittance blow-up and to a reduction of the luminosity. Multipacting is occurring when the values of the so-called Secondary Electron Yield (SEY) of the beam screen surface are larger than a given threshold value SEY_{th} depending on bunch spacing and to a lesser extent on bunch population (above the nominal one). Typical values of the SEY for uncoated surfaces exposed to air as those of the beam screens after venting to air can exceed 2.3–2.5. Operation with 25 ns beams below the multipacting threshold at 7 TeV implies reducing the SEY below 1.4 in the dipoles and below 1.2 in the main quadrupoles. These estimations are based on the present knowledge of the SEY dependence on electron energy and in particular of the probability of elastic reflection at low energy obtained from the benchmarking with experimental data in the SPS and LHC. Operation with 50 ns beams is more tolerant with threshold SEY of 2.1 in the dipoles and 1.6 in the main quadrupoles.

Laboratory measurements have shown that a progressive reduction of the SEY can be achieved by electron bombardment with an approximate dependence of the secondary electron yield on the logarithm of the integrated dose of electrons [7,8]. In practice this can be achieved in an accelerator environment by operating the machine in multipacting regime (scrubbing). In the LHC this has been done successfully for allowing operation with 50 ns beams up to 4 TeV in 2011–2012. Operation at 450 GeV with 50 and 25 ns beams in multipacting regime has been demonstrated and in 2012 the machine could be operated with 25 ns beams, gradually increasing the number of bunches up to 2748 within the limits imposed by the maximum heat load on the beam screens acceptable by the cryogenic system and by the vacuum levels reached in some critical high voltage components like the injection kickers. The studies conducted at the end of 2012 [9] in the LHC have shown a significant decrease of the rate of reduction of the SEY as a function of the dose for SEY below 1.45 in the main dipoles and quadrupoles, however so far the operation in an electron cloud free environment with 25 ns beams has not been demonstrated for a large number of bunches.

It is expected that a scrubbing run is needed after every long shut-down when significant fractions of the machine will be warmed up and possibly vented, while reduced scrubbing runs will be required for the operation with 25 ns beams after short stops where the machine sectors will not be vented and kept at low temperature. Even in this case, signs of de-conditioning have been observed. As an example, during the Christmas stop 2011–2012 the SEY has increased from 1.55 to 1.65 in the main dipoles and a similar increase was again found at the beginning of the scrubbing run in December 2012 [9]. From the present experience, the benchmarking with the simulations and the existing models/measurements for the evolution of the SEY as a function of the electron dose [10] the following sce-

narios can be envisaged. After a long shut-down and after the machine set-up at low intensity, a dedicated scrubbing run with increasingly longer trains of bunches spaced by 50 ns and (later) by 25 ns will be required for vacuum conditioning and for lowering the SEY in the arcs to a value below the threshold for electron cloud build up for 50 ns beams. It is expected that this mode of operation would require approximately 7–9 days of scheduled time, in which the second half of the period would see the injection and accumulation of trains of bunches spaced by 25 ns at 450 GeV. This period includes the setting-up of the injection of bunch trains and the progressive intensity ramp-up which will be driven by vacuum (in particular in critical areas like at the injection kickers) and maximum heat load and heat load transient on the beam screens. After this period, physics at 7 TeV with trains of bunches spaced by 50 ns will be possible allowing for a gradual increase of the number of bunches brought in physics according to machine protection considerations. Once this phase is completed, operation with 25 ns beams can be envisaged only after an additional scrubbing period at 450 GeV with trains of bunches spaced by 25 ns up to the maximum number of 2780 bunches. This period is expected to take approximately 5 days. After that it will be possible to accelerate trains of a few hundred bunches to 7 TeV with reduced electron cloud effects. According to the 2012 experience, the scrubbing process described above will however not be sufficient to suppress multipacting with 25 ns beams and a period with degraded beam characteristics has to be expected during the intensity ramp-up in physics. The length of this period is presently being estimated through a careful analysis of the data collected in 2011–2012 [11]. Scrubbing runs will be required also to reduce the occurrence of beam dumps due to UFOs.

5. Machine Development

A robust programme of machine studies will be required in preparation and in the initial phase of the operation of the HL-LHC. A non-exhaustive list of studies is presented below:

- Validation of the scrubbing run scenarios for 25 ns operation by extending the measurement of the evolution of the SEY in the warm and cold section of the LHC as a function of the electron dose.
- Investigation of scenarios to enhance the electron dose rate for more efficient machine conditioning.
- Validation of the dynamic aperture models and triplet error compensation for the present LHC machine and later for the HL-LHC layout.
- Validation of the leveling schemes to control the pile-up density at the experiments: β^* leveling, bunch flattening, etc.

- Operation of the machine (including leveling and luminosity scans) in the presence of large crossing angles, beam–beam tune spreads larger than 0.03^a and noise sources (power converters, transverse damper, crab cavities, etc.) and benchmarking with the weak-strong beam–beam simulation codes (including noise effects).
- Study of the long range effects in HL-LHC regime (e.g. pacman orbits).
- Halo measurement and control in collision in view of the operation with crab cavities.
- Operation of the crab cavities and their impact on transverse emittance blow-up with separated beams and in collision.

Approximately 20–22 days per year are expected to be devoted to the machine studies at least during the operation preceding the HL-LHC upgrade and during the first years of operation after the upgrade.

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^aAs those expected for the HL-LHC when operating with collisions at three Interaction Points and with crab cavities compensating completely the crossing angle at the high luminosity experiments.

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