POST LS1 OPERATION

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Abstract

The expected mode of operation and performance after Long Shut-Down 1 (LS1) are outlined based on the outcome of the LHC Beam Operation workshop - Evian 2012 [1]. The paper will focus on proton operation with particular emphasis on performance for the high luminosity interaction points.

ASSUMPTIONS

The characteristics of the beams delivered by the injectors and the beam parameters expected in collision, including the blow-up in the LHC, are based on the 2012 experience and are listed in Table 1. For the 25 ns beams no additional blow-up due to electron cloud is considered. This condition will be achieved after a scrubbing run at 450 GeV and a significant period of operation with 25 ns beams at 6.5 TeV. Both the nominal and BCMS (Batch Compression Merging and Splitting) schemes for producing the LHC beams in the PS are considered. For the BCMS scheme the considered number of bunches circulating in the LHC is smaller to account for the shorter trains delivered by the PS (in case of the 25 ns beam: 48 bunches per train for the BCMS scheme instead of 72 bunches per train for the nominal scheme, in case of the 50 ns beam: 24 instead of 36).

Table 1: Assumed beam parameters at SPS extraction and in collision at the LHC

	# bunches	$N_{bunch-coll}$ [10^{11}]	$\varepsilon^*_{SPS-ext}$ [μm]	$\varepsilon^*_{LHC-coll}$ [μm]
25 ns	2760	1.15	2.8	3.75
25 ns BCMS (48 bunches/ PS batch)	2520	1.15	1.4	1.9
50 ns	1380	1.6	1.7	2.3
50 ns BCMS (24 bunches/ PS batch)	1260	1.6	1.2	1.6

A beam energy of 6.5 TeV and a beam-beam separation at the first parasitic encounter of 10 σ (where σ is the r.m.s. beam size) for the 50 ns beam and of 12 σ for the 25 ns beam are considered. While the value assumed for 50 ns operation is approximately the same as in 2012 the value for 25 ns operation might be rather conservative if no-blow-up due to electron cloud occurs. However, for the initial phase where the scrubbing is not complete this is a reasonable assumption.

The same excellent aperture, orbit control along all the phases of the operational cycle, and beta-beating as in 2012 are assumed.

COLLIMATION

During LS1 new collimators with integrated Beam Position Monitors (BPM) (16 tertiary Tungsten collimators – TCT and 2 secondary collimators – TCSG - in point 6) will replace the corresponding collimators [2][3]. This will help in reducing the tolerances considered for the collimator set-up. This will allow a further reduction of the β* at the interaction point and an increase of the crossing angle to maintain the above mentioned beam-beam separation at the parasitic encounters. It must be noted that this will be possible only after some experience has been gained with the BPM collimators, likely in the second year of operation after LS1.

The collimator apertures expressed in beam σ (for a normalized emittance of 3.5 μm) corresponding to different tolerances are listed in Table 2 together with the expected impedance relative to the estimated impedance for the 2012 collimator aperture settings [3][4].

Table 2: Collimator apertures (in beam σ) for different operational scenarios and corresponding impedance.

	Case 1:	Case 2:	Case 3:	Case 4:	Case 5:
buttons	no BPM buttons			BPM buttons	
tolerance	*relaxed*	*tight** (same as 2012 in mm)	*nominal* (keep retraction in σ)	*tight** (same as 2012 in mm)	*nominal* (keep retraction in σ)
TCP 7	6.7	5.5	5.5	5.5	5.5
TCSG 7	9.9	8.0	7.5	8.0	7.5
TCLA 7	12.5	10.6	9.5	10.6	9.5
TCSG 6	10.7	9.1	8.3	9.1	8.3
TCDQ 6	11.2	9.6	8.8	9.6	8.8
TCT	12.7	11.1	10.3	10.0	9.1
Aperture	14.3	12.6	11.7	11.2	10.3
Relative Impedance w.r.t. 2012	0.75	1.1	1.5	1.1	1.5

In the following, case 4 of Table 2 (tight collimator settings) will be considered as it allows maximizing the performance reach in terms of peak luminosity (smaller β*) for a negligible increase in machine impedance. The single beam stability limits in bunch population for the 25 and 50 ns beams considered in Table 1, corresponding to the relaxed, tight and nominal collimator settings and resulting from impedance are shown in Fig. 1 [4]. Operation with maximum Landau Octupole current (550 A, positive polarity – as in the second part of the 2012 proton run), high chromaticity (Q'~15-20) and maximum damper gain (corresponding to a damping time of 50 turns) have been assumed for these estimates. The chosen polarity of

* These settings are referred to as the 'tight settings' for historical reasons. In reality they are more relaxed than the nominal settings.

the octupoles represents a conservative case form the point of view of single beam stability.

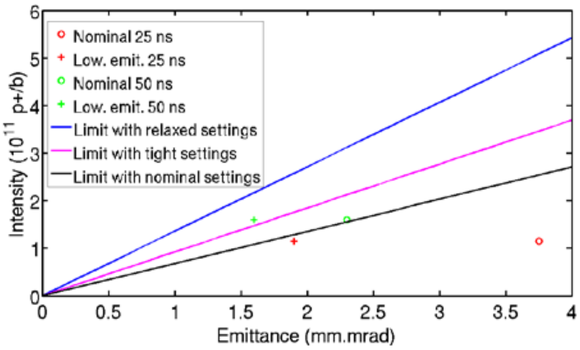

Figure 1: Single beam stability limits for the bunch population for different collimator settings. The dots correspond to the beam parameters listed in Table 1 for the LHC in collision [4]. Courtesy N. Mounet.

While operation with 25 ns beams does not pose any problem from the point of view of stability due to impedance, operation with 50 ns beams with small emittance (BCMS scheme) is marginal with the tight collimator settings and might imply operation with relaxed settings.

EXPECTED PEAK PERFORMANCE

The expected peak performance for 50 and 25 ns operation at 6.5 TeV with the above assumptions is presented in Table 3. Operation with 50 ns beams would entail an unacceptable pile-up for the experiments. Furthermore the peak luminosity for the 50 ns BCMS might be limited by the heat load induced by the luminosity debris at the triplets in IP1 and IP5 to ~1.75×10^{34} cm^{-2}s^{-1} [5]. Operation with 50 ns beams would therefore require the implementation of a levelling mechanism robust with respect to instabilities.

Levelling might be required also for 25 ns beam operation for the BCMS scheme.

Table 3: Expected peak performance at 6.5 TeV.

	50 ns beams		25 ns beams	
	nominal	BCMS	nominal	BCMS
β* [m] (separation/crossing planes)	0.4/0.4	0.4/0.35	0.4/0.55	0.4/0.45
ε*[mm] at start of fill	2.3	1.6	3.75	1.9
Max. Bunch Population [10^{11} p]	1.6	1.6	1.15	1.15
Max. Number of bunches/colliding pairs IP1/5	1380	1260	2760	2520
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.35/10.1	1.35/10.1	1.35/10.1	1.35/10.1
Max. Beam Current [A]/population[10^{14} p]	0.4 / 2.2	0.36 / 2.0	0.57 / 3.2	0.52 / 2.9
Max. Stored energy [MJ]	230	210	330	300
Peak luminosity [10^{34} cm^{-2}s^{-1}] in IP1/5	1.5	2.0	0.85	1.5
Half External Crossing angle IP1/5 [μrad]	140	120	195	155
Beam-beam tune shift (start fill)/IP [0.001]	5.3	7.3	2.5	4.3
Min. beam-beam separation (σ) d_{sep}	9.3	9.3	12	12
Maximum Average pile-up ($\sigma_{inel.}$=85 mb)	82	120	23	44

OPERATIONAL CYCLE

Ramp

Beam stability implies the use of the transverse damper at high gain (a few tens of turns damping time), nominal Landau Octupole current (550 – 600 A) and high chromaticity (Q' ~15-20 units) as soon as the collimator aperture is reduced to achieve tight settings at 6.5 TeV. Tighter collimator settings are required only when the β* is reduced below a few meters. Therefore the collimator aperture should be reduced to tight settings only when required and the ramp should be performed with relaxed collimator settings to avoid instabilities driven by the impedance, which at high energy is dominated by the impedance of the collimators.

It is possible to increase (double) the octupole equivalent strength if needed using the MCO and MCOX circuits but this implies a significant reduction of the dynamic aperture as shown in Fig. 2 [6].

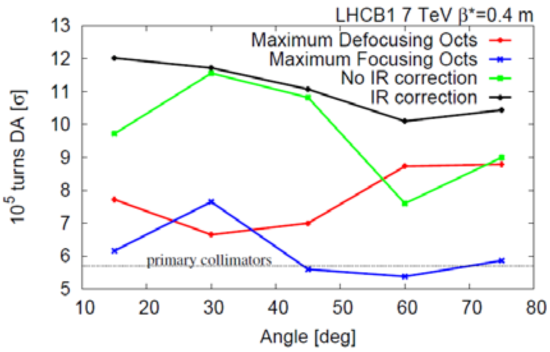

Figure 2: Dynamic aperture as a function of the phase space angle using all the available octupole circuits (Landau Octupoles, Octupole Spool pieces, Inner Triplet Octupole correctors). Courtesy R. Tomàs.

Squeeze

The collimators should be moved to tight settings only for small β* (< 3 to 5 m) when the triplets' aperture is no more in the shadow of the arcs' aperture.

The operation in 2012 has shown that the head-on beam-beam tune spread (which does not depend on β*) can be used to stabilize the beam, therefore it is suggested to go in collision at β*> 3 to 5 m and run the rest of the squeeze in collision [7][8]. The collimators would then be moved to tight settings only once the beams are in collision and before continuing the squeeze. The increased Landau damping provided by head-on beam-beam will damp the instabilities that might arise as a result of the increase in impedance when the collimators are moved to tight settings.

This restrains the presence of non-colliding bunches, which might suffer from instabilities due to the lack of the extra Landau damping. These instabilities might lead to significant population loss and might generate spurious position readings at the beam interlocked BPMs, resulting in beam aborts. An upgrade of the interlock logic based on the LSS6 BPM readings would solve this problem and could allow the operation with few non-colliding bunches. However, this would not avoid the above-mentioned losses.

Collision Process (Adjust)

Going in collision in IP1 and IP5 should be performed in sequence to avoid a minimum in tune spread in both planes at the same time [8].

Once in collision, chromaticity and Landau octupole currents should be lowered to few units and to less than 100 A, respectively, to guarantee a good lifetime taking into account that the squeeze below 3 m has to occur in collision. In this scenario the beams will be colliding for at least 10-15 minutes during the last part of the squeeze in adjust mode with the experiments in standby and therefore not using the luminosity delivered by the LHC.

It might be advantageous to combine the ramp and the first part of the squeeze down to 3-5 m and to move the collimators to their tight settings during the last part of this combined process. This in order to avoid beam loss peaks during the collimator movement at high energy that might lead to beam dumps. In that case the beams should be brought in collision during the same process.

Stable Beams and levelling

β* levelling is the preferred option to limit pile-up to acceptable values for the high luminosity experiments in case of operation with 50 ns beams and possibly for the 25 ns high brightness beams (BCMS beams).

Levelling by separation should be considered for "simplicity" of operation (at least initially) in IP2 and 8.

A schematic representation of the phases of the present and possible operational cycle after LS1 is shown in Fig. 3.

POTENTIAL ISSUES

Electron Cloud Effects [9]

During the scrubbing run in December 2012 the possibility of completely filling the machine with nominal trains of 288 bunches spaced by 25 ns and to control beam stability with an adequate setting-up of the transverse feedback and machine parameters has been demonstrated at 450 GeV. Unmistakable signs of conditioning (reduction of the normalized heat load in the arc beam screens and improvement of the beam lifetime) have been observed in the first part of the scrubbing run but this process slowed down and became almost undetectable during the last scrubbing fills at injection and during a series of fills at 4 TeV.

During LS1 most of the machine will be vented to air and it is expected that the Secondary Electron Yield (SEY), responsible for the onset of the electron cloud build-up, will recover the initial values observed at the beginning of the operation of the LHC. The same will happen for the beam induced desorption yield responsible for the pressure rises observed in the presence of LHC beams in the warm areas. Conditioning with 50 ns and 25 ns beams will be required at 450 GeV before operation with high intensity beams with 50 ns and 25 ns spacing. Based on the 2012 experience it is expected that a scrubbing run at 450 GeV will not be sufficient to provide an electron-cloud free environment. Physics at 6.5 TeV with 25 ns beams with degraded conditions in terms of emittance blow-up and significant heat loads in the arc beam screens are to be expected initially and will result in a slower intensity and performance ramp up.

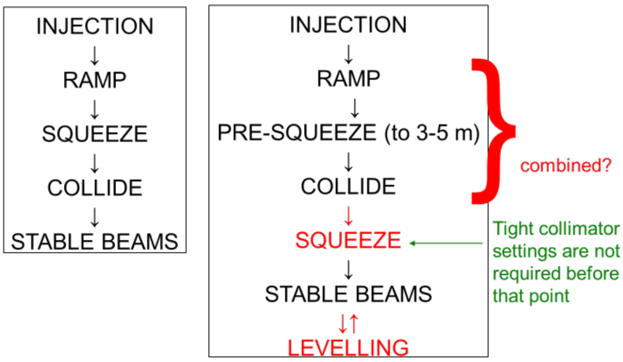

Figure 3: Comparison of the present (left) and possible future operational cycle.

UFOs [10]

Unidentified Falling Objects (dust particles falling into the beam and leading to beam losses) might hamper physics operation at higher energy due to the higher losses generated because of the higher energy as compared to 2012 and because of the lower beam loss thresholds. 91 arc UFOs in 2012 would have led to a dump at 7 TeV. It must be noted that conditioning has been observed in 2011-2012 with 50 ns beams.

A tenfold increase of the UFO rate has been observed with 25 ns beams at the beginning of the scrubbing run in December 2012 but signs of conditioning have been seen (see Fig. 4 [10]).

"Deconditioning" has to be expected after LS1 because (almost) all the vacuum sectors will be opened to air. The results of the quench tests might allow relaxing the BLM thresholds for the short timescales which are involved in the UFO events [11].

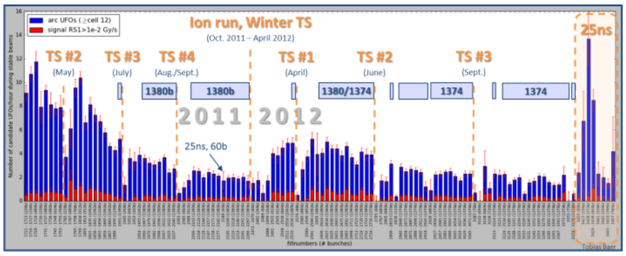

Figure 4. Evolution of the UFO rate during the 2011-2012 proton runs with 50 ns beams and during the 25 ns runs. Courtesy T. Bär.

Beam Induced RF Heating [12]

Beam induced heating related to impedance has been an issue for the operation at high intensity in 2012 leading to damage of components (e.g. BSRT), outgassing (TDI), deformation (TDI). This will remain an issue and it will be important to anticipate potential problems by adequate monitoring during the ramp-up phase. The main concern for the operation in 2015 is the TDI, which has been one of the limiting components during the 25 ns run in December 2012 [12]. Follow-up of the possible limitations resulting from beam induced heating is in place but should possibly be formalized in the form of a working group.

POSSIBLE STRATEGY IN 2015

During 2011-2012 it has been demonstrated that a short scrubbing run at 450 GeV is sufficient to operate for physics with 50 ns beams with no electron cloud effects [9]. However, operation with 50 ns is not attractive for luminosity production at nominal pile-up as it would require levelling at luminosities approximately twice smaller than with 25 ns beams as the pile-up depends uniquely on the bunch-by-bunch luminosity. Levelling might be required also for 25 ns operation in case high brightness beams produced with the BCMS scheme in the PS are required. The exact gain in integrated luminosity achievable with the 25 ns as compared to the 50 ns beam depends on the pile-up that can be handled by the experiments and on the expected average fill length.

Impedance related effects are expected to be milder for 25 ns but UFOs and electron cloud effects will imply slower ramp-up for this mode of operation.

The above considerations privilege the operation with 25 ns beams in terms of potential performance, provided that the electron cloud effects can be mitigated by a progressive reduction of the SEY in the cold regions. This remains to be demonstrated for SEY<1.45.

A running period at 50 ns after a short scrubbing run is desirable at the beginning of the run (it could be at a pile-up of up to 40 with a β^* of 50 cm and close to nominal bunch intensity but low emittance) to re-discover the machine at 6.5 TeV. After this initial period in which the number of bunches will be progressively increased, operation with 25 ns beams after an additional period of scrubbing (~10 days) could be envisaged and followed by a ramp-up in the number of bunches. The length of this process will depend on the speed at which the SEY reduces with the electron dose generated by the multipacting.

Operation with 50 ns beams with levelling should be considered as a back-up in case of serious issues related to electron cloud and UFOs.

ISSUES FOR MACHINE PROTECTION

As mentioned above the high brightness beams produced with the BCMS schemes are very attractive in terms of peak luminosity performance, in particular for the 25 ns spacing but their average energy density is higher than that of the ultimate 25 ns beam (with a bunch population of 1.7×10^{11} p and a normalized transverse emittance of 3.5 μm at injection and 3.75 μm in collision at 7 TeV) as it is summarized in Table 5.

Table 5: Relative energy density of the BCMS beams with respect to the ultimate LHC 25 ns beam at injection and in collision (see Table 1 for the beam parameters of the 25 and 50 ns BCMS beams).

	Injection	Collision (6.5 TeV)
25 ns BCMS	1.7	1.25
50 ns BCMS	1.35	1.02

The 2012 experience has shown that operation at high intensity and tight collimator settings is heavily dependent on:

- Strong Landau Damping provided by the Landau octupoles running at maximum strength until the beams are in collision;
- Maximum damper gain until the beams are in collision;
- Tight orbit control with the orbit feedback during the squeeze to avoid sudden increase in beam loss rates. This is even more crucial if the squeeze is performed in collision to avoid loss of Landau damping when the beam are separated due to relative orbit variations.

Unavailability or degraded operation of any of these systems could result in instabilities and beam losses leading to beam dumps. The expected rise-times of the instabilities are in the range of more than 1000 turns and are presently being re-evaluated in light of 2012 experience.

As previously mentioned operation at high intensity and in particular with 25 ns implies:

- the co-existence with electron cloud and its effects (vacuum, cryogenic load, beam blow-up, lower lifetime) during the whole operational cycle;
- the occurrence of fast beam losses in the millisecond scale or sub-millisecond scale due to UFOs.

Both the above phenomena are expected to require a careful intensity ramp-up and conditioning taking into account that most of the machine will be vented to air during the long shutdown.

Several measures have been taken to address the non-conformities and to review the design of components that have led to beam induced heating in 2012. In spite of this, a thorough follow-up of the evolution of temperatures and vacuum levels in critical areas, and the implementation of alarms on warning levels and interlocks is suggested to timely intercept conditions that could lead to potential damage.

The capability of squeezing in collision routinely has been identified as the more realistic mean of fighting transverse instabilities at high energy with tight collimator settings and of providing luminosity leveling at the high luminosity interaction points if it is required to limit the pile-up at the experiments. The setting-up of this process and in particular the possibility of leveling the luminosity by varying the β^* in stable beams will have implications for the collimation set-up and validation that need to be addressed.

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