SUMMARY OF SESSION 4 - UPGRADE SCENARIO 2

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Abstract

The performance target for Upgrade Scenario 2 (US2) was defined for the purposes of the RLIUP meeting as accumulating 3000 fb^{-1} in the years to 2035. As shown earlier in the meeting, this sets the requirement for ~270 fb^{-1} per year of operation after LS3. The presentations in Session 4 were arranged to evaluate the performance of HL-LHC given the assumed baseline upgrade path, to present the optimum beam parameters in collision and from the injectors, to evaluate whether the injectors could reach the required parameters in view of the LIU upgrades, and to then investigate possible alternative (i.e. non-baseline) ideas or possibilities for improving the performance reach of HL-LHC and its injector chain. The session concluded with two talks, one on the challenges and outlook for improving the achieved physics availability of HL-LHC, and the second on the analysis of the possible issues with the baseline 25 ns bunch spacing and the estimate of the performance potential with the alternative option of 50 ns.

SESSION AGENDA

The presentations for Session 4 were aimed at evaluating the performance of, and work-effort for, HL-LHC with all baseline upgrades, and also whether any previously unconsidered or non-baseline ideas could really contribute to a performance improvement. In addition the challenges of reaching the demanding availability targets were highlighted, together with the performance evaluation for 50 ns bunch spacing. The session contained seven presentations, for which the presenters and titles were:

1. **R. de Maria** How to maximize the HL-LHC performance;
2. **H. Bartosik** Can we ever reach the HL-LHC requirements with the injectors;
3. **L. Rossi** How to implement all the HL-LHC upgrades;
4. **R. Tomas Garcia** HL-LHC: exploring alternative ideas;
5. **H. Damerau** LIU: exploring alternative ideas;
6. **M. Lamont** How to reach the required LHC availability;
7. **V. Kain** 50 ns back-up scenario.

In addition, the talk in Session 3 on Work Effort in the LHC Injector Complex, including Linac4 connection, for the Upgrade Scenarios by **B. Mikulec and J.-B. Lallement** included the full information on the work effort in the shutdowns for the injector complex for Upgrade Scenario 2, as these were essentially identical.

4.1: HOW TO MAXIMIZE THE HL-LHC PERFORMANCE

The talk presented the performance estimates for the full baseline upgrade, and highlighted the limitations on the total integrated luminosity. The required parameters for the injectors were defined. The performance reach against the key factors of machine availability (expressed as average fill length) and acceptable pile-up (expressed as levelling luminosity) were plotted, Fig. 1. The attainable peak virtual luminosity (for example through β^*, emittance or bunch intensity) play a role in defining the boundaries of the accessible region, and thus are secondary considerations compared to the machine availability for physics and the pile-up limit.

With the assumption of constant 6 h fill length and 140 pile-up limit, the HL-LHC could deliver about 230 fb^{-1} per year.

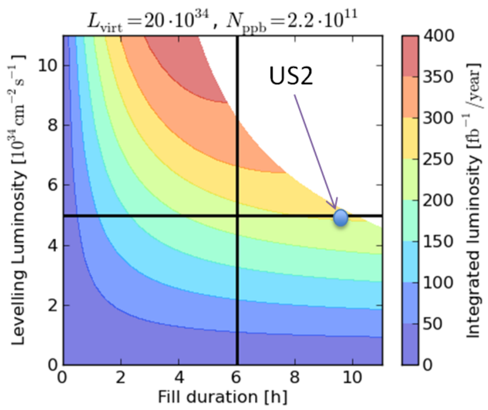

Figure 1: HL-LHC performance reach assuming that all fills optimistically last the same duration (delta function distribution). A fill duration of above 10 h would be needed to approach the HL-LHC target. The coloured region is accessible with 2.2 $\times$ 10^{11} p+ per bunch at 25 ns, with 2.0 $\times$ 10^{35} $cm^{-1}s^{-1}$ peak virtual luminosity.

Main conclusions from 4.1

- The LIU-US2 standard production scheme approaches the bunch intensity target, assuming that operation at 25 ns with a bunch population of 1.9 – 2.2 $\times$ 10^{11} p+ is possible;
- The LIU-BCMS schemes offer lower emittance that increases peak luminosity but the reduction of colliding bunches and IBS lifetime reduce overall performance - there is no real interest in emittances below about 2.0 μm in collision;

- The present pile-up limit of 140 events per crossing (with a maximum pile-up density of 1.3 mm^{-1}) and the assumed machine availability smear out the performance differences, in the strongly-levelled regime;
- Baseline hardware is well advanced and the layout is being validated before next iteration;
- Intensity limitations are being investigated and need to be overcome, in particular ecloud;
- Beam-beam effects and wire compensation are critical for flat beam schemes;
- The full leveling scheme via β^* is a challenge and remains to be detailed and studied – for this reason it is essential to deploy in IP8 for Run 2;
- The pile-up density can be mitigated with crab kissing, or longer/flattened bunches. Flat beams at the IP and the wire compensation are interesting to reducing the crabbing requirements;
- The HL-LHC baseline can meet the luminosity target if machine availability can be significantly improved. It could even exceed the target if, in addition, the pile-up limit can be significantly increased.

4.2: CAN WE EVER REACH THE HL-LHC REQUIREMENTS WITH THE INJECTORS?

The performance reach of the injector chain after all baseline LIU upgrades was evaluated, after a recall of the main limitations and upgrade items. Assuming that the LINAC4 connection and 160 MeV H- injection allows a doubling of the present brightness from the PSB, that 2 GeV injection into the PS removes the space charge limit there, and that electron cloud can be solved in SPS, the remaining limitations in the complex are the PSB brightness and the longitudinal beam stability in the SPS which is directly linked to the RF power available. The SPS will be able to deliver about 2.0 $\times$ 10^{11} p+ per bunch in a transverse emittance of 1.88 μm, at injection into the LHC, Fig. 2. This is enough to 'saturate' the LHC performance for the assumed pile-up limit and availability/fill length.

The decision-making process for whether to coat the SPS with aorphous carbon (aC) was also outlined; two sets of scrubbing tests are planned, in late 2014 and early 2015, to decide experimentally whether scrubbing after a long shutdown is a viable path back to operational performance.

Main conclusions from 4.2

- With the full program of baseline upgrades the injector complex can just about match the parameters needed by HL-LHC, for the presently assumed pile-up limit and machine physics efficiency;
- The main necessary upgrades are LINAC4 connection and 160 MeV PSB injection, 2 GeV PS injection and RF system upgrade, SPS 200/800 MHz power increase and ecloud mitigation. Many, many other systems across the complex also need major upgrades;
- With all baseline upgrades there is little or no margin to further increase the number of protons per bunch transferred from SPS, should improvements in LHC allow an increase in the optimal intensity.

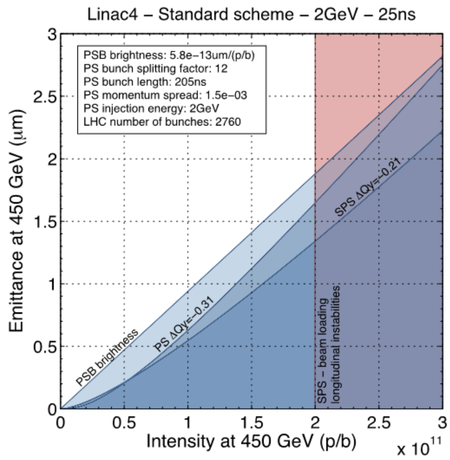

Figure 2: Accessible beam parameters with standard 25 ns production scheme at injection into LHC, from the injectors after all baseline upgrades.

4.3: HOW TO IMPLEMENT ALL THE HL-LHC UPGRADES

The vast amount of work required for HL-LHC was recalled in detail, encompassing a significant fraction of the ring. New triplets and deep changes in IP1 and 5 are the core of the work, but many other systems are affected. The total material budget is estimated at 810 MCHF.

Some work is already being prepared for LS2, including DS collimators in P2 and perhaps in P7, horizontal SC links in P7, an additional cryoplant in P4 and some reduced impedance collimators. The LS2 work is expected to fit inside 18 months with adequate margin. The main uncertainty is the availability of two sets of 11 T/DS collimator unit for P7.

The major part of the work is planned for LS3, and is expected to fit inside 26 months. Detailed shutdown planning is needed to handle the massive co-activity and possible contstraints from radiation dose to personnel, which becomes more of an issue as the integrated luminosity increases.

In addition to the agreed baseline, other potentially beneficial systems are actively under study. These include extra SC RF systems (800 or 200 MHz), hollow electron lens, long range beam beam wire compensator and crystal collimation. It is expected that these options will be evaluated as part of the design study which should be finished in 2015 with a Technical Design Report. Any extra systems should to push HL-LHC to reach and even exceed the luminosity target, since there is interest in establishing some margin in the performance reach, given the uncertainties which are still attached to some of the limitations in the LHC and the injectors.

The upgrades should also improve the robustness of the hardware in the face of increasing radiation dose - the SC link, QPS upgrades and new triplets will all contribute in this direction, and the objective is that the hardware will be more robust for the 3000 fb^{-1} than it is for the present 300 fb^{-1}.

Main conclusions from 4.3

- Some work will take place inside the 18 month LS2, with the bulk of the HL-LHC work happening inside a 26 month LS2;
- Detailed resource loaded LS2 and LS3 shutdown planning is needed, together with all other co-activity, to validate the schedule assumptions;
- Widespread performance upgrade should also make the machine robust to the expected radiation dose;
- Margin in the performance reach is highly desirable, hence alternative ideas are to be actively pursued.

4.4: HL-LHC: EXPLORING ALTERNATIVE IDEAS

Many ideas for improving the HL-LHC performance have been discussed and evaluated, of which the most promising were presented in some detail. In view of the possible problems with electron cloud, the performance reach with an alternative "8b+4e" structure from the injectors (instead of the regular 12b produced per PSB bunch) was evaluated. The same number of protons are redistributed into a sub-train of only 8b, separated by gaps of 125 ns, which should be compatible with the available peak RF power at 200 MHz in the SPS because the duration of 12x25 ns is shorter than the filling time of the Travelling Wave cavities. This is expected to give much less electron cloud in the LHC, compared to the regular 25 ns beam, with a threshold δ_{max} of about 1.6 for the acceptable heat load in the arcs, while giving better luminosity at the pile-up limit than a full 50 ns beam. This scheme should therefore be maintained as an intermediate possibility between 50 and 25 ns, for instance during a slow scrubbing/physics production operation.

Another very promising option is to add a new 200 MHz SC main RF system in LHC. This would allow transfer of longer bunches from SPS, which opens the way to 25 ns bunch intensities of around 2.5×10^{11} p+ per bunch. The longer bunches also give less electron cloud, reduce the pile-up density and give less higher-order-mode heating. This option is interesting even without the addition of the crab cavities; together these two systems give a slight performance improvement compared to crab cavities alone, or 200 Hz system alone. First studies of the system indicate that the required ~3 MV could be feasible within the present technical constraints.

Also explored was pile-up density levelling, which would still allow an integrated yearly luminosity of around 250 fb^{-1} per year. The four options explored were β^* levelling with 10 cm long bunches, 800 MHz system plus β^* levelling, crab kissing and 800 MHz plus crab kissing.The peak pile-up density can be levelled by β^* alone to 1.0 mm^{-1} without any new hardware and with little (~%) loss in performance. A new 8 MV 800 MHz system would allow a reduction to about 0.9 mm^{-1}. With a new 200 MHz system the pile-up density could also be levelled to 1.0 mm^{-1} for a similar integrated luminosity, while using the crab cavities for "kissing", plus the 800 MHz the pile-up density can be levelled to 0.7 mm^{-1}.

Other more exotic proposals for beam cooling were also presented, including coherent electron cooling and optical stochastic cooling. These were not considered to presently offer significant performance potential.

Main conclusions from 4.4

- The 8b+4e scheme should be followed up as a promising alternative, intermediate between 50 and 25 ns, in case of prolonged difficulties with 25 ns beams;
- A new 200 MHzSC main RF system for LHC looks very promising in several regards (2.5×10^{11} p+ per bunch from SPS, better for electron cloud and beam heating, similar for pile-up density levelling). This option has started to be studied in detail and should be a high priority;
- Pile-up density levelling to ~1.0 mm^{-1} or even below will be possible using whichever combination of hardware is installed, and will cost maximum ~7% in integrated luminosity;
- No other highly promising ideas were indentified (which means that the baseline is well adapted).

4.5: LIU: EXPLORING ALTERNATIVE IDEAS

For the injector chain, a wide range of ideas for alternative performance improvements was considered. A review of possible additional batch compression, merging and splitting (BCMS) schemes showed that the 48b version tested in 2012 would matched perfectly the parameters to the PS space charge tune shift limit (at 2 GeV after the PSB extraction energy upgrade), and also that the resulting brightness reach would in fact be beyond that requested by HL-LHC, due to the very small attainable emittance. The case of no low-energy bunch splitting at all in the PS was considered as the logical extreme of the possible potential BCMS scheme. The bunches would only then be split at high energy by a factor 4, to give batches of 32b, which would result in about 13% fewer colliding bunches in LHC. This would push the SPS to its assumed space charge limit, but again is of limited use to HL-LHC limited by pile-up and operating in the strong levelling regime. Also concerning bunch patterns, the 8b+4e scheme potential was also explored more in detail, with important tests to make in the injectors and possibly LHC during Run 2, as a function of the results of 25 ns operation.

Ideas to mitigate space charge were considered. The production of flat bunches in the PSB using a double harmonic RF system or hollow bunch distribution were shown to give a potential reduction in space charge tune shift of ~25%, and longer bunches were also evaluated. Overall a possible increase in the PS brightness of about 15% might be achievable, but this would be technically challenging and in any case obviated by the eventual upgrade of the PSB extraction to 2 GeV. Ideas for space charge mitigation by resonance compensation and optics modifications were also considered - these need more study and will be pursued.

For the SPS transfer to LHC, it was shown that more additional 200 MHz RF power beyond the presently foreseen doubling suffers from the law of diminishing returns, with not much additional benefit. The benefits of a 200 MHz capture system in the LHC were again clearly shown - with the important qualification that this will only help overall in tandem with the 200 MHz power upgrade in the SPS.

The benefit of a possible increase of the SPS injection energy to 28 GeV would be to reduce space charge tune shift by ~15%. Operating the SPS with a split-tune optics of Q_h=20 and Q_v=26 would give ~5% gain in space charge tune shift, and would also help facilitate injection at 28 GeV. There is less opportunity than in the PS to deploy an irregular optics with significant vertical dispersion, and this would require important cabling changes and the installation of dedicated skew quadrupoles. Overall the SPS appears less flexible than the PS with less margin for this type of improvement.

Main conclusions from 4.5

- There is no magic alternative to the baseline LIU upgrade core, of LINAC4 plus 2 GeV PSB extraction plus SPS 200 MHz power upgrade;
- A large number of schemes exist to increase the bunch intensity and brightness from the injectors, where the SPS may be pushed to its space charge limit;
- An LHC 200 MHz RF system produces a significant gain in the bunch population which can be transferred from SPS, but there is not much motivation to look at increasing the SPS 200 MHz system RF power beyond the proposed upgrade;
- Interesting alternatives can be studied during Run 2, like long/flat/hollow bunches in PSB and PS, different BCMS schemes n PS and split tune in SPS;
- Important to keep the flexibility in the injectors to be able to produce the different beam types, to follow LHC performance evolution.

4.6: HOW TO REACH THE REQUIRED LHC AVAILABILITY

The challenges and specific issues of obtaining and maintaining a high physics efficiency were explored. A lot of effort and progress is already evident for large distributed systems with major down-time potential, like cryogenics and the electrical network, spread across operations, R2E, the equipment groups and HL-LHC project. A reduction in the rate of faults requires more rigorous preventive maintenance, which also depends on sustained and well-planned consolidation of installations. Redundancy can help for key systems, and design with reliability in mind is clearly important. The newly-formed Availability Working Group is covering part of this analysis, but the issues are spread across many projects in the whole complex, and deserve a more comprehensive approach in terms of identification of areas to improve, prioritisation of resources and approbation of actions between projects.

The overhead for recovery after faults is being addressed by better fault tracking and measures to reduce the number of tunnel interventions, with remote resets and surface controls, and the speed of fault interventions is being improved with measures like remote radiation surveys.

For improving still further the operation efficiency, all procedures for the HL-LHC should be robustly established and maintained, with optimisation of important items like BLM thresholds made regularly. Cycle efficiency can be improved with actions like combined ramp and squeeze, and more efficient and optimised set up, including beam preparation in the injectors, is also important. There are also specific system upgrades which should be examined in this context, for example deploying 2-quadrant power supplies on critical circuits to reduce ramp-down time.

The key topic of R2E was also described in some detail, drawing attention to the fact that the requirement for HL-LHC in terms of "false" beam dumps per accumulated fb^{-1} of data is more than a factor 100 below that achieved in 2011.

Main conclusions from 4.6

- Fault fixing is only part of the problem: there are also large overheads when a fill is slot (in ramp, squeeze or physics);
- The number one cause of lost fills was not fault related, but due to beam losses with the tight collimator settings. The gain in efficiency from choosing somewhat relaxed operational parameters might outweigh the slight loss in peak performance;
- The faults on the systems, especially the huge distributed ones like QPS and cryogenics, must continue to be addressed, with the R2E mitiagations critical;
- Further big improvements are not realistic - instead the performance needs to be edged up by working "on the % level" on many fronts;
- A large effort in the HL-LHC era will be needed just to reach the 2012 efficiency levels. We cannot count at this stage on doing much better;
- Coordination of the overall efforts to improve HL-LHC efficiency is needed; presently this effort is distributed widely.

4.7:50 NS BACKUP SOLUTION

The target and achievable parameters for 25 and 50 ns operation were compared. For 50 ns, the injector chain falls short of the required bunch population of ~3.7×10^{11} p+ due to the intensity limits in the PS from longitudinal instabilities. A realistic bunch population limit of 3.0×10^{11} p+ was used in the performance comparison.

The possible show-stoppers for 25 ns operation were presented and evaluated. These include machine protection absorbers, beam induced heating, UFOs, beam-beam and e-cloud. The expected limits for each of these effects were presented. The protection absorbers will require new materials and possibly new optics and layouts, but should be solvable. Beam-induced heating depends on whether a broad- or narrow-band impedance is being considered - for both 25 and 50 ns beams, the factor of increase in power deposited is about the same, with 50 ns slightly worse for broad-band impedances. For UFOs the 25 ns beam provoked an order of magnitude increase in the rate, but this appeared to condition down quickly. For beam-beam the head-on tune shift will be worse with 50 ns beam, and the crossing angle of 590 μrad should be enough for the long-range for both 50 and 25 ns.

Given the present state of knowledge, the main threat for 25 ns seems to be from e-cloud. The 2012 scrubbing tests showed that the scrubbing at 450 GeV does not behave as expected. The e-cloud is still present in the triplets, despite 2 years of high-intensity 50 ns operation, and the cryogenic heat load at 4 TeV increased by a factor of 4, coming only from e-cloud in the dipoles. No scrubbing was seen at 4 TeV.

This could limit the total number of bunches in the LHC to around half of the nominal 2808. Possible mitigations include the use of the special doublet scrubbing beam developed initially for LIU-SPS and tested in 2012, increasing the cryogenic power of the arcs for the dipoles, and coating or electrodes in the new HL-LHC triplets.

The possible performance reach with 50 ns spacing was evaluated to estimate what this beam could bring as a backup. The fill length was modelled using the observed exponential fit, which gives results close to those observed in 2012 (and about 15% lower than modelling using a fixed average fill length of 6 hours). taking 160 days of physics operation and luminosity levelled to a pile-up limit of 140, the expected performance with 2012 efficiency is bout 120 fb^{-1} per year with or without crab cavities. For comparison the same model with 25 ns gives 220 and 170 fb^{-1} per year with and without crabs, respectively.

It was noted that a physics efficiency of beyond 50% is unrealistic - already to reach the 36% achieved in 2012 will be a major accomplishment.

Extending the run length obviously benefits the total prorata, for both 25 and 50 ns spacing. Because of the strong levelling and relatively short (compared to the levelling time) fill lengths expected, there are no injector upgrades identified which could make a significant improvement to the 50 ns LHC performance. It was also pointed out that the very high single bunch intensity of 3×10^{11} p+ might also pose stability problems in LHC, as the maximum accelerated and collided in 2012 was 1.8×10^{11} p+.

Main conclusions from 4.7

- 25 ns spacing is the clear preference but some uncertainties remain, the main one of which is e-cloud. 2015 operation will be key in determining whether LHC can run efficiently with this bunch spacing;
- The alternative of 50 ns bunch spacing is attractive from an e-cloud point of view, but cannot compete in terms of delivered performance, with the pile-up limit of 140 restricting the luminosity. The expected performance is about half that of 25 ns, under the current assumptions;
- No additional improvements have been identified which would allow 50 ns to compete with 25 ns. Efficiency and the crab cavities (for 25 ns) are more important than stretching the beam parameters from the injectors;
- Intermediate schemes (e.g. 8b-4e) should be tested during Run 2, as they provide a bridge between 25 and 50 ns in terms of performance and also in terms of limitations.

OVERALL CONCLUSIONS AND DISCUSSION

The analysis of the performance reach with the full baseline upgrade scenario showed that, under the agreed assumptions of maximum pile-up of 140 events per crossing and a physics efficiency of 36%, the HL-LHC integrated luminosity per year would be about 230 fb^{-1} for a uniform fill length of 6 hours. This number will be reduced for a realistic distribution of fill lengths, such that the yearly total is expected to be around 220 fb^{-1}.

This yearly total is rather insensitive to the injected bunch population, provided that this is above about 1.9×10^{11} p+. Increasing the number of protons available from the injector chain only contributes to improving the integrated luminosity if either the efficiency or the pile-up limit can be improved.

The foreseen injector upgrades therefore match well to the expected performance limits in the HL-LHC. However, there appears to be little margin, either to improve performance should HL-LHC be able to accept higher intensities, or for alternative schemes should unforeseen limitations arise. It is therefore very important to keep pushing in directions which could bring more margin for operation and improvement - in this regard, the proposal to investigate a 200 MHz RF system in the LHC appears to be very promising, to gain 25% in the intensity which can be injected into the LHC, and to help overcome several of the identified limitations in the LHC proper.

More detailed planning of the LS2 and LS3 shutdowns is needed for HL-LHC, to account for co-activities and to identify potential bottlenecks like cabling, where extra resources might be required well in advance to prepare or advance key activities. The work already done for the injectors needs to be integrated, and all other major projects need to be included in this exercise to avoid last-minute difficulties.

Improving the LHC physics efficiency and the pile-up limit are the keys to opening the door to higher overall performance, and both should be investigated with all possible means. Strengthening the coordination of the efficiency improvements for the HL-LHC era seems mandatory, and all methods to allow an increase in the acceptable pile-up for the experiments should be followed up, both on the experiments' and machine side (including schemes for reducing pile-up density which may allow some trade-off with pile-up).

The flexibility in the beam production schemes in the injectors is important to maintain and even enhance, to allow efficient luminosity ramp-up and the ability to react rapidly to unexpected situations, as well as giving access to the widest parameter space to match to HL-LHC's needs. THe investigations of alternative schemes and ideas should continue across the complex.

In case of severe problems with 25 ns it seems inevitable that the overall luminosity production will suffer, since there is no way to reach an equivalent performance with 50 ns. For similar machine efficiency and pile up limit the luminosity production with 50 ns is about 50% of that expected with 25 ns. No upgrades specific to 50 ns were identified. Intermediate filling schemes should be tested ready to be deployed if needed, to minimised the impact of a difficult commissioning with 25 ns. Experience with LHC Run 2 will be critical in this respect.

ACKNOWLEDGMENT

The speakers are congratulated for the excellent quality of their presentations, together with the impressive preparatory work. In addition the many people who have contributed to the results and analyses presented are gratefully thanked for their invaluable contributions.