IMPLICATIONS OF HIGHER ENERGY – SUMMARY OF BENEFITS, ISSUES, COMMISSIONING COST, SEU, CRYO, QPS MARGINS, POTENTIAL AVAILABILITY ISSUES

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Abstract

The LHC is technically almost ready to run at 4 TeV per beam in 2012. Nevertheless, a review of the advantages and disadvantages of such an energy step should be carefully made before taking this decision. Therefore, this paper will summarize the benefits from the physics point of view; the potential issues like a possible increase of Single Event Errors, Unidentified Flying Objects, or a significant decrease of the quench margin from beam losses that, all in all, could lead to availability issues, compromising the integrated luminosity. And last but not least, the commissioning cost will be addressed.

INTRODUCTION

The unknown number of expected quenches in 2011 was one of the main reasons to run LHC at 3.5 TeV in 2011, since this number determines the probability of burn-through a defective 13 kA joint [1]. In 2010, up to 20 quenches (in some occasions they were massive quenches) took place. Extrapolating this number to 2011, the probability of burn-through a defective 13 kA joint was too high to assume the corresponding risk, i.e. a down time of 8 to 12 months given the present consolidation status.

At the end of 2011, however, only one single-magnet spurious quench with beam was experienced. The reasons for such an impressive improvement compared to 2010 are, amongst others: the installation of the snubber capacitors in all dipole circuits at the beginning of the 2011 that reduced considerably the electromagnetic noise in the Quench Protection System (QPS) and the corresponding amount of spurious quenches; through 2011 many QPS consolidation work took place; and, last but not least, the excellent protection of the BLM system.

Extrapolating the 2011 experience in terms of number of quenches into 2012, translates into a probability of burn-through a defective 13 kA joint at 4 TeV of the same order as at 3.5 TeV (keeping the same time constant of the Energy Extraction System, EES, at 50 s).

BENEFITS FROM THE PHYSICS POINT OF VIEW

Figure 1 [2] shows the ratio of LHC parton luminosities for different energies. The blue curve shows the increase in event rate when comparing two beam energies, 4 TeV w.r.t. to 3.5 TeV, for gluon-gluon fusion, quark-antiquark collision and quark-gluon inelastic scattering, as a function of the mass of a potentially produced massive object, Mx (GeV). The Figure highlights the most promising searches and the gain factor for each of them.

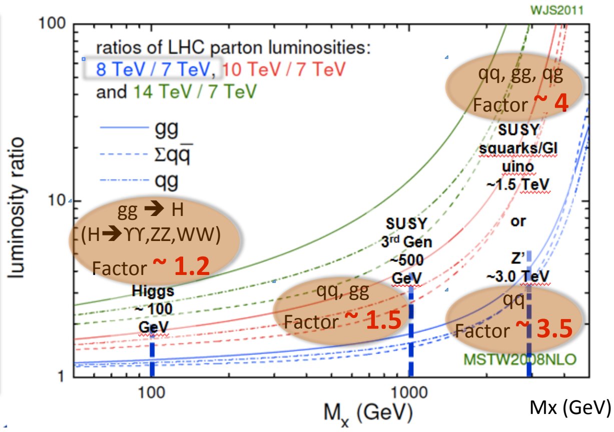

Figure 1: ratio of LHC parton luminosities for different energies. The blue curve corresponds to the event rate gain if LHC accelerates the beams to 4 TeV w.r.t. to 3.5 TeV, for gluon-gluon fusion, quark-antiquark collision and quark-gluon inelastic scattering, as a function of the mass of a potentially produced massive object, Mx.

Higgs production with a mass in the range of 100 GeV increases a factor ~1.2. The production of a third generation squark with a mass of the order of 500 GeV (two of them need to be produced) increases a factor ~ 1.5. The gain in the search for squarks and gluinos of masses around 1.5 TeV is a factor ~4. Finally, the search for heavy bosons, like the Z' with a mass of the order of 3 TeV, benefits from an increased factor of 3.5.

For SUSY and Exotica searches the increase in energy opens up new territory. There is a point, however, where further increase in luminosity affects the search reach very slowly (due to the steep drop in cross section as a function of the mass at fixed energy), while an increase in energy increases the mass reach by a considerable step. For these searches, any 1 TeV increase is a gain.

For Higgs discovery the gain of an energy increase is not too impressive and the Higgs search benefits more of an increase in luminosity over an increase in energy. But any increase in energy comes together with an increase in luminosity as will be discussed in the next section.

BENEFITS IN TERMS OF LUMINOSITY

Any energy increase implies an emittance shrink during the ramp such the luminosity ratio is proportional to the ratio of the relativistic gamma as indicated in the following equations:

$$L^{o}_{4TeV} = \frac{\gamma_{4TeV}}{\gamma_{3.5TeV}} L^{o}_{3.5TeV} \qquad (1)$$

where L^o is the luminosity given by:

$$L^0 = \frac{N_1 N_2 f_{rev} N_b}{4\pi\sigma^2} \qquad (2)$$

N_1 and N_2 is the number of protons per bunch in each beam (1: beam 1, 2: beam 2), f_{rev} is the revolution frequency, N_b is the number of bunches and σ is the beam size at the interaction point. The equation above assumes Gaussian beams with $\sigma_{1x}=\sigma_{1y}=\sigma_{2x}=\sigma_{2y}$.

If the emittance decreases the beam size decreases and more aperture margin is obtained at the inner triples and tertiary collimators. In order to keep the beam size constant at those critical positions, the beta function (β) could be increased by the right amount. By increasing the beta function at the inner triplets and tertiary collimators, the β*, i.e. the β function at the collision point, automatically diminishes by an amount given by:

$$\beta^*_{4TeV} \approx \frac{\gamma_{3.5TeV}}{\gamma_{4TeV}} \beta^*_{3.5TeV} \qquad (3)$$

which corresponds to a β*=0.875 m. If the β* improvement is included in the Equation 2, the total luminosity gain becomes:

$$L^o_{4TeV} = \left(\frac{\gamma_{4TeV}}{\gamma_{3.5TeV}}\right)^2 L^o_{3.5TeV} \qquad (4)$$

The total luminosity, including the crossing angle (F) factor given by Equation 5, is a little bit lower than L^o since F reduces with decreasing emittance and β*:

$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}} \qquad (5)$$

where σ_s is the longitudinal bunch length, ϕ is the crossing angle and σ_{1x} and σ_{1y} are the beam sizes at the interaction point.

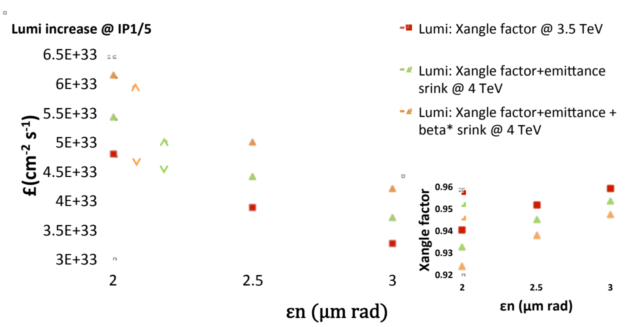

Figure 2: Luminosity evolution, including the crossing angle factor, as a function of the normalize emittance for N_1=N_2 = 1.5 10^{11} p+/bunch, N_b = 1380 (i.e. 50 ns bunch spacing) and $\phi/2$ = 120 μrad. Figure 2 - right shows the evolution of the crossing angle factor for the same set of parameters.

Figure 2 shows the evolution of the luminosity in IP1 and IP5, including the crossing angle factor, as a function of the normalize emittance for N_1 = N_2 = 1.5 10^{11} p+/bunch, N_b = 1380 (i.e. 50 ns bunch spacing) and $\phi/2$ = 120 μrad. Figure 2 - right shows the evolution of the crossing angle factor for the same set of parameters. From Figure 2 can be concluded that the luminosity at 4 TeV (green curve) with respect to 3.5 TeV (red curve) increases by ~ 14% if only emittance shrink is considered. If the decrease in β* (keeping the same crossing angle) is taken into consideration, then the luminosity at 4 TeV (orange curve) increases by the non-negligible amount of 30%.

The pile-up, or number of proton-proton collisions per beam crossing, evolution in IP1 and IP5 for the same set of parameters is given in Figure 3. As stated by the experiments during the Evian workshop, a pile-up of the order of ~30 events could be acceptable. Higher values would start to compromise the detector event reconstruction efficiency, but quantitative estimations are not yet available.

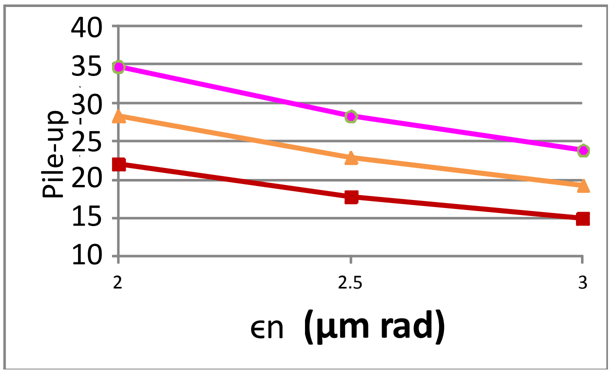

Figure 3: Pile-up evolution in IP1 and IP5 for the same parameters (same colour code for the functions) as Figure 2. The pile-up has been calculated assuming an inelastic total cross-section of 70 mbar.

OVERHEAD IN TERMS OF HARDWARE COMMISSIONING

Main circuits commissioning

The commissioning of the main circuits up to 4 TeV would imply two extra steps at ~7000 A: one normal cycle and one energy extraction from QPS. The time estimate is around 5 hours/circuit (circuit = RB, RQD, RQF). Eventually all the sectors could be commissioned in parallel.

The inductance coefficients would have to be recalculated since the circuits will be ramped to a different current. This implies at least 2 ramps, one per QPS board and per circuit.

A series of system reconfigurations are not needed in case the main circuits are not powered beyond 4 TeV. In particular the reconfiguration of EES, which would be certainly needed for 5 TeV. At 4 TeV the EES can keep the energy extraction time constant at the same value as for 3.5 TeV, i.e. 52 s. At 4 TeV some values are approaching the warning levels, like the voltage across a quenched magnet (13 V, being the limit 15.5 V) or the dI/dt (130 A/s, being the limit 150 A/s). But the operational values at 4 TeV and 52 s are still considered safe [3].

The change of the new QPS thresholds to adapt to a reduced quench margin would not be needed for 4 TeV. And finally, no quench issue is expected till ~5 TeV, although should be kept in mind that RB.A78 had a training quench below 5 TeV.

None of the main circuits shows non-conformities at 4 TeV or below. However, the statement is not longer true for energies above 4 TeV, for which RB.A78 (B30.R7), which qualification voltage is 1.6 kV instead of 1.9 kV (as for all the other main circuits) due to bad insulation on the magnet [4], limits its energy to 4 TeV. The energy veto would have to be lifted for higher energies.

Inner triples

All inner triples have been commissioned up to 5 TeV except IT.R1, which has a weak electrical insulation of QH YT1121 to coil, and/or ground [5] that currently limits the circuit to 3.5 TeV. However, a dedicated Quench Heater Power Supply is under construction and it will be installed and ready for start up with beam in 2012.

Independent Powered Quadrupoles and Dipoles

The current powering test commissions those circuits up to 3.5 TeV. What has to be done is, simply, to extend the last powering test to a nominal current (I_PNO) corresponding to 4 TeV.

Circuit correctors

The 600 A and 120 A correctors are commissioned every year up to 5 TeV. The 60 A correctors are commissioned up to 7 TeV.

Conclusion

The total estimated hardware commissioning time overhead is of the order of 3 days.

UNIDENTIFIED FLYING OBJECTS (UFO)

During 2011 17 beam dumps were due to UFOs; 11 of them at the injection kickers (MKI) location, 4 at the LHC experiments and 2 in the LHC arcs. Several mitigation measurements will be put in place during the 2011 Christmas Shutdown to reduce the number of UFOs at the MKIs. Concerning the experiments, it is known that the thresholds are quite conservative; therefore in case of unexpected increase of UFOs at the experiments, those thresholds could be reviewed. On the contrary, there are no solutions for the UFOs at the arcs. Analyzing the arc UFOs data from 2011 (from 14th of April to 31st of October), the losses of all arc UFOs have been scaled up as a function of energy [6] and compared to the Beam Loss Monitors (BLM) thresholds at the corresponding energy. The UFO predictions are presented in Figure 4 [7] together with the BLM signal over threshold factor w.r.t. 3.5 TeV. The value at 4 TeV indicates that, at this energy, three arcs UFO dumps would have to be expected. The signal/threshold for UFOs is about 55% higher at 4 TeV than at 3.5 TeV, indicating that 3 dumps would have been expected running at 4 TeV in 2011, compared to 2 dumps, which actually happened. Therefore, it can be concluded that the expected UFOs in 2012, if running at 4 TeV, will not limit the machine availability.

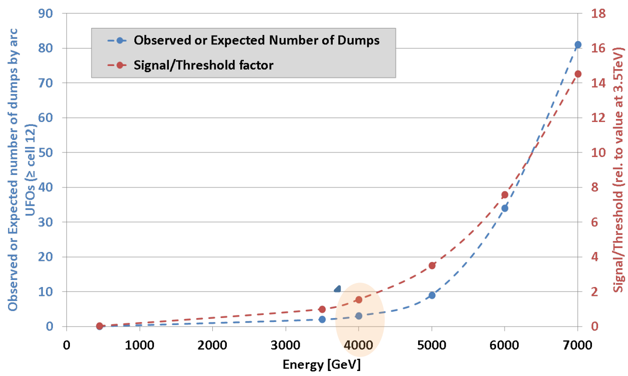

Figure 4: Arc UFO predictions [7] as a function of energy (blue curve) together with the BLM signal over threshold factor w.r.t. 3.5 TeV (red curve). The analysis does not include any margin between BLM thresholds and actual quench limit, nor the effect of 25ns bunch spacing, intensity increase, beam size reduction or scrubbing.

SINGLE EVENT ERRORS

2011 finished with a total of 237 Single Event Error (SEE) candidates out of which 26% were confirmed beam dump events [8,9]. Out of this 26%, 27% were QPS events and 40% cryogenic events. Many mitigation measurements were undertaken during 2011 to dismiss the number of dumps due to SEE, which were very effective. During the 2011 Christmas shutdown many other mitigation actions will be put in place in order to decrease even further the SEE in 2012. All those activities are listed over different talks in these Proceedings.

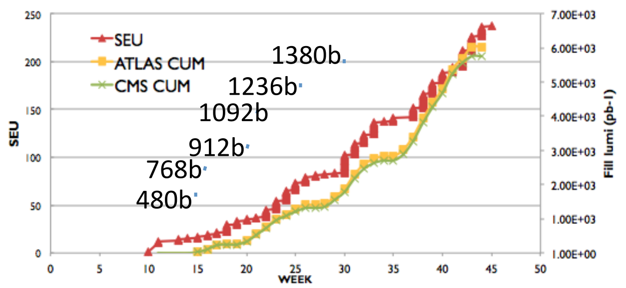

Figure 5: Correlation between SEE (red curve) and integrated luminosity in ATLAS and CMS (yellow and green curves respectively) in 2011. The weeks were an increased number of bunches were commissioned are shown for reference.

Figure 5 shows the correlation between SEE (red curve) and integrated luminosity in ATLAS and CMS (yellow and green curves respectively) in 2011. The weeks were an increased number of bunches were commissioned are shown for reference. Next year due to the increase of luminosity, partly due to a possible energy increase, an increasing number of SEE should be expected. However, thanks to the already mentioned mitigation measurements, 45 SEE are the forecast for 2012 (if no measurements are put in place 150 SEE should be expected), which is acceptable for operations.

In what concerns the experiments [10], this is a non-problem since the LHC detectors have been designed with SEE problem in mind. On the other hand, the experiments do not need 100% efficiency of the front-end electronics to collect good statistics, and data and trigger problems due to SEE (corrupted data) can be filtered by software and regular system re-configuration or resets are done on-line which are transparent to the data tacking.

BEAM LOSS MONITORS

If the energy is increased, the Beam Loss Monitors (BLM) dump thresholds will have to be decreased. Figure 6 [11] shows the maximum noise level per monitor as a function of the dump threshold for the 40 μs running sum as obtained from simulations. The noise level is calculated during a period without beam in the machine, in particular for Figure 6 corresponds to data from 34 hours starting on 2011-11-07 07:00:00 (last technical stop of 2011). The different colours correspond to different energies. The red line shows the noise level at 100% of the dump threshold, every monitor staying at that curve or above will dump the beam. The thresholds are set at 10% of the dump threshold (green line). Ideally all monitors should stay below 10%, however, few monitors go above 10% of the threshold and it will be studied whether or not more tolerant thresholds would have to be applied to those. For the rest, some margin is present and it can be concluded that in 2012, if running at 4 TeV, no dump on noise spikes will happen.

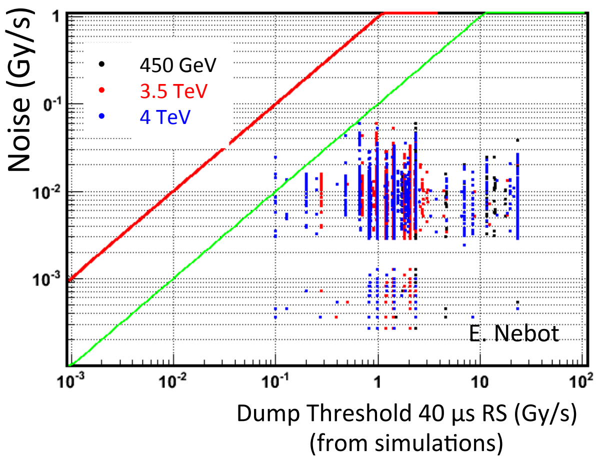

Figure 6: Maximum noise level per BLM monitor as a function of the dump threshold for the 40 μs running sum as obtained from simulations. The noise level is calculated during a period without beam in the machine. The red line shows the noise level at 100% of the dump threshold. Ideally all monitors should stay below 10% of the dump threshold (green line).

LHC BEAM DUMP SYSTEM

The LHC Beam Dump System (LBDS) has been investigated to find out if any modification or extra commissioning steps are needed to make the system operational at 4 TeV since at Chamonix 2011 some asynchronous dump problems due to issues with some isolators were reported. In the end, the decision was clamping the system at 5 TeV in the Beam Energy Interlock, therefore no changes are need to go to 4 TeV. Nevertheless, as a follow up of the issue, tests during the 2011 Christmas shutdown with 7 MKD generators up to 7 TeV (where new isolators have been installed) will be performed, as well as testing the cooling up to 7 TeV.

In what concerns eXternal Post Operational Checks (XPOC) for the BLM limits, they will be extrapolated to 4 TeV from 2011 measurements at energies up to 3.5 TeV, likely to be fine tuned during operation when data with high intensity dumps at 4 TeV will be available.

For the Abort Gap Cleaning, validation at 4 TeV will be needed, but probably this will be requested any way if LHC stays at 3.5 TeV after the winter technical shutdown.

TCDQ functions will have to be extended to 4 TeV, like all the other collimators.

MACHINE PROTECTION VALIDATION

Standard Machine Protection tests will be done irrespective of the energy. The exact details will depend on the changes that will be made during the 2011 Christmas shutdown (that may be unrelated to the energy itself).

Settings at 4 TeV will be different (BLMs, etc) therefore they will have to be checked more carefully (since the values change), but most of this will be transparent during the beam commissioning time.

RF LONGITUDINAL STABILITY

In the longitudinal plane the beams might suffer from two types of instabilities coming from: 1) a broad band impedance affecting single bunches from short-range wakefield originated by all vacuum chamber components; 2) a narrow band impedance inducing coupled-bunch instabilities originated from long-rang wakefield in the RF cavities and the resistive walls. An instability threshold, above which the beams become instable and they could be eventually lost, characterizes both impedances. The RF longitudinal stability aims at maintaining the instability thresholds above the operating parameters. The way to do this during the ramp is to keep the bunch length constant while the emittance shrinks and the energy increases. By applying the right emittance blow up during the ramp, the instability thresholds are not anymore a function of the emittance and energy, but scale linearly with the voltage [12]. If running at 4 TeV in 2012 the longitudinal blow up will have to be adapted to the new energy.

CHROMATICITY CONTROL

At 3.5 TeV the chromaticity decay amplitude is of the order of 25 to 30 units of chromaticity (depends on the powering history). Going to 4 TeV an increase of 15% is expected [13]. A linear scaling would imply a change of decay of 4 to 6 units, which is not negligible and there are some unknowns concerning the time constants and the degree of precisions of the linear scaling.

It could be worth to dedicate two shifts to measure the chromaticity decay and powering dependence.

In 2012, if tight collimators settings are put in operation, impedance effects on beam stability will become crucial and the main beam parameter that allows controlling instabilities is a well-measured and well-trimmed chromaticity.

CONCLUSIONS

From beam operation point of view, no overhead is expected if running next year at 4 TeV, therefore, the total commissioning overhead remains the three days due to hardware commissioning.

Considering this overhead negligible, given the fact that no show stoppers have been found in any of the equipment or from radiation issues point of view, assuming that there is the same probability of burn-through of a defective 13 kA joint for 3.5 TeV and 4 TeV (if the same number of quenches happen in 2012 as in 2011) and since the risk of running at 3.5 TeV and 4 TeV is rather similar, the most important argument to run at 4 TeV comes from physics: higher cross-sections and luminosities (~30% increase). Therefore it can be concluded that running at 4 TeV in 2012 is really worth doing.

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