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LHC UPGRADE PLANS: OPTIONS AND STRATEGY

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In the paper we will discuss the baseline plan for the lumi upgrade and the intial study for upgrading the collision energy, in the 27-33 TeV range.

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INTRODUCTION

Upgrading the LHC is an option that has been considered almost immediately after its design, by a study group led by F. Ruggiero in summer 2001 [1]. Two are the main drivers of the upgrade: 1) physics effectiveness will request a leap forward in performance; 2) the cost of the LHC infrastructure is such that any improvement in performance and physics reach is worth to consider, especially in view of the fact that part of the IRs (Interaction Regions) needs to be changed/modified anyway.

LUMINOSITY UPGRADE

The initial luminosity upgrade [1] was aiming to gain a factor ten, from L= 10^{34} to ~10^{35} cm^{-2}s^{-1}, by means of:

- Increase of the bunch population from 1.1 to 1.7 10^{11} protons ("ultimate" beam current: 0.56→0.86 A).
- Decrease of β^* from 0.50 down to 0.25 m by means of stronger (Nb$_3$Sn) IR quads.
- Halvening of the bunch length by means of a new 1200 or 800 MHz RF system, to compensate the increased crossing angle;
- Doubling bunch number with 12.5 ns bunch spacing.

The first three measures, would yield a luminosity of 4.6 L$_{nom}$, see Table 1 "Upgr. Base" column. Then doubling the bunch number would allow L$_{up}$ ~ 10 L$_{nom}$. Alternative scenarii, especially to the doubtful 12.5 ns option, were very large Piwinski angles (1.3 A) or long superbunches with a new RF barrier bucket. Beam-beam effects were the main concerns for luminosity: a total beam-beam, tune shift ΔQ of 0.01 was taken for the nominal operation and 0.15 was assumed for operation at ultimate parameters. Crab cavities were just mentioned in [1] considered as a vague possibility, levelling was not considered. The main goal was just the peak luminosity reach, integrated luminosity was considered to increase by 60-80% of the factor increase of the peak luminosity.

In Table 1 the LHC parameters as designed (usually called "nominal" machine) are listed together with the values that are usually called "ultimate LHC", as well as with the upgrade(s) parameters considered in [1].

Table 1: LHC parameters (7 TeV beam) in 2001 [1]

Parameter	Nom. 25 ns	Ultim. 25 ns	Upgr. base	Upgr. Piw.	Upgr. s-bun
N$_b$ [10^{11}]	1.1*	1.7	1.7	2.6	5600
n$_b$	2808	2808	2808	2808	1
I [A]	0.56	0.86	0.86	1.32	1
θc [μrad]	300	315	445	485	1000
β^* [m]	0.5*	0.5	0.25	0.25	0.25
ε$_n$ [μm]	3.75	3.75	3.75	3.75	3.75
ε$_s$ [eV s]	2.5	2.5	1.78	2.5	15000
f$_{RF}$ (MHz)	400.8	400.8	1202.4	400.8	10
V$_{p\,RF}$(MV)	16	16	43	16	3.4
σ$_s$ [cm]	7.55	7.55	3.78	7.55	7500
IBS h [h]	111	72	42	46	63
IBS l[h]	65	42	50	28	856
Piwinski	0.71	0.75	0.75	1.63	=
F red.fact.	0.81	0.80	0.80	0.53	=
L 10^{34}cm^{-2}s^{-1}	1	2.3	4.6	7.2	9.0
Pile up	19	44	87	137	=

The Path to the Present Upgrade Concept and Phase I Upgrade

The work of the task force [1] overlapped with the LHC crisis of 2001-02 and the technical and managerial (resources) difficulties of the LHC construction reduced the effort for the LHC upgrades. However, mainly thanks to the FP6-CARE-HHH networking activity [2] and thanks to US-LARP program [3] the studies and the R&D on luminosity upgrade of the LHC were never interrupted and big conceptual progress was made since then. The main results of that period 2002-2007 have been:

- The exclusion of the 12.5 ns scenario, based on cryogenic limitation difficult to overcome [4].
- Lay-outs based on very large aperture inner triplet quadrupoles: while in early studies about 90-100 mm were considered sufficient [5,6,7], the systematic studies and scaling law showed that solution with 120 mm and more were also possible and preferable, especially – but not only – in conjunction with small

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* Later on N$_b$ has been adjusted to 1.15, to compensate the increase of β^* from 0.5 to 0.55 m due to addition of beam screen in the low-β quads.

β^*(<25cm) [8,9,10]. Many schemes and variants were examined, like very large Piwinski angles, early separation scheme [11,12].

- Launch of hardware studies: i) larger aperture/higher gradient quads in Nb_3Sn (mainly LARP), see [3] and the copious literature; ii) wires [14] or electron lenses [15] for long range beam-beam compensation; iii) Crab cavities for the LHC [15]
- Luminosity levelling to limit the peak luminosity, while gaining in integrated luminosity [16,17].

In 2007 a project called Phase 1 upgrade [8] was proposed. The idea was to carry out a "quick" upgrade by installing after 2012 new larger aperture inner triplet quadrupoles and a new SC (superconducting) D1 [18].

The CERN plan changed dramatically after the incident of 19th September 2008 during LHC commissioning [19]. Furthermore, a more realistic evaluation of the possible luminosity increase profile (and associated radiation damage) and the relatively low gain in integrated luminosity suggested stopping Phase 1 project in 2010.

Its scope has been incorporated in the global High Luminosity LHC (HL-LHC) project defined by the CERN management in September 2010. Studies for Phase 1 evidenced difficulty in matching for β^* smaller than 30 cm, and the rigidity of the machine for β^* smaller than 40 cm (0.55 cm being the nominal) [20]. Subsequent studies to circumvent these limitations have brought to a novel scheme, the Achromatic Telescopic Squeeze (ATS) [21,22] a recent advance in the hadron collider design.

LHC Present Performance and Ten-Year Plan

For an updated and thorough presentation of the performance of the LHC we refer to [23]. The machine is operating at 3.5 TeV/beam (half the design value) and at *50 ns buch spacing*. The main outcomes, relevant for the luminosity considerations, are:

The head-on beam-beam limit is at least a factor 2 higher than anticipated. Actually runs at $\Delta Q = 0.023$ have been performed with acceptable beam losses. The long-range beam-beam encounters, which are today limited by the 50 ns beam structure, well fits the prevision, giving hope that they can be controlled and limited. Head-on wider limit is the biggest surprise of the LHC operation

The emittance preservation in the injector chain and through LHC is much better than anticipated. Furthermore, the single bunch population limit in the injector chain and namely in the SPS is higher than expected so at 50 ns we have a brightness twice lower than anticipated: we did run at ε_n of 2 μm (3.75 nominal) with bunch population of $1.3\ 10^{11}$ (1.1 nominal).

The present collimation system is capable to protect the beam up to nominal current and more: actually if the extrapolation of a recent experiment will be confirmed, the ultimate current (0.86A) can fed into the ring without quenching the superconducting magnets.

The previously mentioned ATS scheme works and can be used to generate β^* as small as 15 cm (and even smaller in a flat beam scenario).

The LHC master plan foresees a *first Long Shutdown in 2013-14, LS1,* mainly intended to consolidate the defective splices in between magnets. A few equipments, relevant for the HL-LHC project will be put in place in LS1, like installation of the L-R b-b compensation wire and some civil works in IP1 and IP5 and P7 related to SC links. *LS2, which is today foreseen in 2018*, will feature a number of equipment installations in the tunnel in view of the high luminosity, specifically addressing intensity limitation: 1) collimation in the cold arc coupled with novel technology 11 T twin dipoles; 2) installation of a new cryo-plant to decouple the SC magnet arc and IR from SCRF for sector 3-4, removing present low-β limitations in the left side of the CMS; 3) installation of LR b-b wires (and/or electron lenses) in all points; 4) SC links installation for removing some power converters from radiation sensible zones; 5) civil engineer work and infrastructure for the hardware to be installed in 2022; 6) installation of crab cavity prototype to study its behaviour in LHC. These activities will be complemented by the intervention for upgrading the injectors: a) connection of Linac4 to the LHC chain; b) upgrade from 1.4 to 2 GeV of the PS Booster; c) removal of e-cloud limitations in the SPS, etc. Finally, *LS3 in 2022-23* will be dedicated to the main hardware installation for the HL-LHC run.

High Luminosity Upgrade Baseline Scenario

Based on the previous assumptions the luminosity until LS3 is plotted in Fig. 1, where integrated luminosity is also plotted vs. time. The damage threshold (300-400 fb-1 in some components of the triplet assembly) is reached around 2021. In addition the time to half the statistical error is also reported (halving time). Both main indicators for the timing of the upgrade, radiation damage induced by $L_{int} \sim 500$ fb[-1] and halving-time well above 10 years, *call for the upgrade right after 2020*, very consistent with the time of LS3.
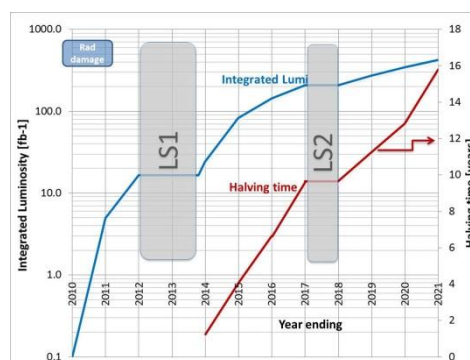

Figure 1: Integrated luminosity evolution and time to half the statistical error, in the next decade ("ultimate" peak luminosity reached in 2020).

The main goal of the HL-LHC has been set to reach *3000 fb[-1] of accumulated luminosity in 10-12 years after the upgrade, "limiting" the maximum peak luminosity to $5\ 10^{34}\ cm^{-2}s^{-1}$.* This implies automatically that the peak luminosity must be very near to the average luminosity in the run, i.e. *the luminosity levelling is strictly necessary.*

Levelling means having a virtual luminosity at the beginning of the run (L_{peak}) much higher than the levelled luminosity (L_{lev}): however the instantaneous lumi is kept at the – lower – levelling value by "detuning" from optimal value one (or more) of the parameters controlling the lumi itself. This parameter(s) is then slowly "retuned" toward its optimal value to compensate the proton lost in nuclear collisions (proton burning). Levelling has been already tested in 2011 in LHCb experiment (IP8) at L_{lev} $\cong 3.2 \ 10^{32}$ by varying the beam vertical separation.

The main features making levelling so attractive are:

- Limiting the pile up in the experiment, reducing the technical difficulty and cost of the detector upgrade.
- Limiting the power deposited in the magnetic elements of the IR, and in the DS (dispersion suppression) zone.

The classical formula for luminosity for the LHC conditions (short bunches, equal round beams) writes:

$$L = \gamma \frac{f_{rev} \, n_b \, N_b^2}{4\pi \varepsilon_n \beta^*} R \qquad R = \frac{1}{\sqrt{1 + (\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma)^2}}$$

γ being the relativistic factor, n_b the number of bunches, N_b the bunch population, ε_n the normalized transverse emittance, β^* the beta function at beam crossing, , θ_c the full crossing angle and R the geometric reduction factor.

Various scenarii for HL-LHC, have been examined at the LHC Performance workshop Chamonix2011 [21,24,25] both for 25 ns and 50 ns bunch spacing: the large b-b tune shift has opened the door for 50 ns, still the lower pile up with 25 ns is important. In Table 2 a few parameter sets for HL-LHC are listed with b-b separation of 10σ (L is in unit of $L_0 = 10^{34}$ cm^{-2}s^{-1}). The parameters set of column 2 should produce the luminosity ideal cycle and the integrated luminosity evolution plotted in Fig. 2, with an efficiency of 60% (in LHC at present it is 40%).
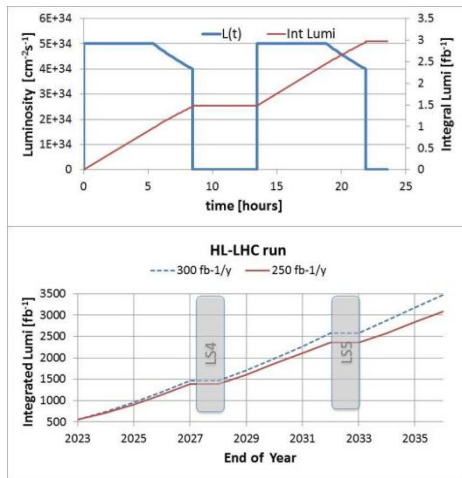

Figure 2: Top: ideal HL-LHC cycle (Table 2, column 2). Bottom: luminosity vs. time assuming 250 fb^{-1}/y (solid curve) or pushed to 300 fb^{-1}/y after 2032 (dashed curve).

The two last columns marked LIU in Table 2 gives performances attainable with present goals of the LHC Injector Upgrade project.

A discussion of each single parameters and their influence will be well beyond the scope of this papers. In bolt are the "pushed" parameters and in red the ones that are considered very difficult or dubious. As mentioned before we use all new parameter space opened by $\Delta Q_{b-b} = 0.02 \div 0.03$ (with full compensation of the long-range b-b tune shift) and by brightness twice the initial design. Also we assume a beam current around 1.1 A (impacting on cryogenics, RF, collimation, beam losses…) and β^* as low as 15 cm thanks to the ATS scheme that provides matching β_{peak} of 20 km in the triplet and enhances the chromatic correction capability of the machine. We assume attaining the required gradient and aperture in the low-β^* quads (with Nb$_3$Sn technology) and to use crab cavities to fully cancel the geometric reduction factor that goes with lower β^*, and as luminosity levelling tool.

Table 2: HL-LHC parameters at 25 - 50 ns bunch spacing

Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns	LIU 25 ns	LIU 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	1.02	0.84	0.86	0.64
θ_c [µrad]	300	475	445	480	430
β^* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [µm]	3.75	**2.5**	**2.0**	**2.5**	**2.0**
ε_s [eV s]	2.5	2.5	2.5	2.5	2.5
IBS h [h]	111	25	**17**	25	**10**
IBS l [h]	65	21	**16**	21	**13**
Piwinski	0.68	2.5	2.5	2.56	2.56
F red.fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP [10^{-3}]	3.1	3.9	**5**	3	**5.6**
L_{peak}	1	7.4	8.4	5.3	**7.2**
Crabbing	no	**yes**	**yes**	**yes**	**yes**
$L_{peak \ virtual}$	1	20	22.7	14.3	19.5
Pileup $L_{lev}=5L_0$	19	95	190	95	190
Eff.[†] 150 days	=	0.62	0.61	0.66	0.67

[†] Efficiency is defined as the ratio between the annual luminosity target of 250 fb^{-1} over the potential luminosity that can be reached with an ideal cycle run time with no stop for 150 days: $t_{run} = t_{lev} + t_{dec} + t_{turn}$. The turnaround time after a beam dump is taken as 5 hours, t_{decay} is 3 h while t_{lev} depends on the total beam current; for example in second column "Target 25 ns" $t_{lev} = 5.4$ h. If we would run with the cycle for 150 days we would get about 400 fb^{-1}: an efficiency of 62% would yield 250 fb^{-1}/y.

Alternatives

Various alternatives are possible, almost each parameter can be changed with different optimization, [21,24,25]. Here it suffices to say we need absolutely reaching current of 1 A or more at 25 ns and 0.85 A for the 50 ns, with high brightness, almost twice as better

than anticipated in Table 1. This has to do with injector performance, with LHC beam dynamics and also with the ability of all technical systems to withstand such a beam and collision debris. With lower beam current the levelling time is too short and we would need an improbably high machine efficiency to compensate the increased number of cycles, see Table 2: *efficiency is important as peak performance for integrated lumi.*

Would we not able to reach the desired β^*, either for shortfall in magnet technology or for unexpected limitation to the ATS scheme, we may compensate this with a decrease of the emittance, especially at 25 ns, and possibly also a reduction in the crossing angle.

If crab cavities would not work as expected, the peak lumi can be reached by reducing the bunch length (with a 800 MHz additional RF system) and by reducing the crossing angle. Again higher brightness will help, together with a further decrease in β^*, which might be possible with the ATS scheme. However, in this case long-range b-b effect compensation must work perfectly. Varying the crossing angle can be also used for levelling. Beam separation, as we do in LHCb, and varying β* are possible levelling tools, too.

Schemes with very large Piwinski angle, requiring high beam current, are considered with use of flat beam (β^*_x/β^*_y=0.075/0.3), a solution made possible by ATS.

Technical Reasons for the Upgrade and R&D

Beside the objective of increased beam peak performance (i.e. the virtual peak luminosity), the upgrade is aimed at removing technical bottlenecks that may impede reaching the desired parameters or may reduce the reliability and efficiency of the machine.

Reducing the frequency of SEU (Single Event Upset) in the electronic equipment installed in, or near to, the tunnel is important: additional shielding, relocation in more protected zone and replacement of sensible boards with rad-tol ones will be implemented, together with removal of power converters on surface, carrying the current through SC links down into the tunnel to various magnet circuits. SC links will employ HTS (MgB_2 or YBCO).

Cryogenics also will be much improved in two main steps: i) installation of a new plant to decouple the SCRF cavities from the cooling of the magnets of the arc and the IR regions; ii) installation of two new refrigerators in the high luminosity insertions (ATLAS and CMS), to face the increased cryo-losses in the new IR magnets from collision debris and to cool also the SC crab cavities. There will be a complete cryogenic separation between arcs and IRs, gaining in flexibility for maintenance.

The main R&D, beside the above cited SC links are:
- *Development of high field magnets (12-13 T peak field)* for the new inner triplets, to gain some 40% in gradient, stronger SC separation dipoles, stronger corrector magnets and larger matching section quads.
- *Developments of SCRF crab cavities for LHC.* The novelty is the fact that they must be very compact: a 400 MHz cavity is requested to have a radius less than 194 mm, the standard beam separation.

- *A new collimation system to protect the IR magnets* from a beam with an increased power and power density and *new collimators in the DS* (Dispersion Suppression) cold zone to protect the SC magnets.
- Development of *11 T LHC twin dipoles* to make room for such collimators in the cold arc.

The FP7-HiLumi LHC Design Study

The collaboration around the HL-LHC project is forming through the European FP7 Design Study called *HiLumi LHC*. *HiLumi* includes 20 laboratories, in EU, USA and Japan and will run for four years, starting 1st of November 2011. Its main deliverable will be a complete Technical Design Report that will enable to build the main hardware for the HL-LHC project from 2014 to be ready for installation from 2020. The total cost of the HL-LHC is, with a crude approximation, 500 M€.

ENERGY UPGRADE

The luminosity upgrade is a major step but it might not be the last one for the LHC tunnel. Indeed a study on a possible energy upgrade of the LHC, called High Energy LHC (HE-LHC) has been launched. Feasibility of such machine critically depends upon magnetic fields twice as higher than the LHC. First studies have indicated that there is no show stopper for a HE-LHC. In particular the synchrotron power, passing from 0.17 W/m-beam in LHC to 2.8 W/m-beam in the HE-LHC, may be dealt with a beam screen operating around 60 K, a value still reasonable for vacuum. The energy goal of the HE-LHC has been set *to 33 TeV collision energy*. The 16.5 TeV/beam can be reached by dipole field around 20 T, with a 2/3 filling factor as in the present LHC ring. HE-LHC magnets are the natural evolution of the one needed for HL-LHC, see Fig. 3. Their cost is about three times the present LHC magnets. Indeed the magnetic system is 80% of the cost of the entire machine, about 6,000 MCHF (very crude approximation). The cost can be reduced considerably with a field of ~15 T, rather than 20 T: in such a case Nb_3Sn technology, will be sufficient without using expensive and complex HTS cables.
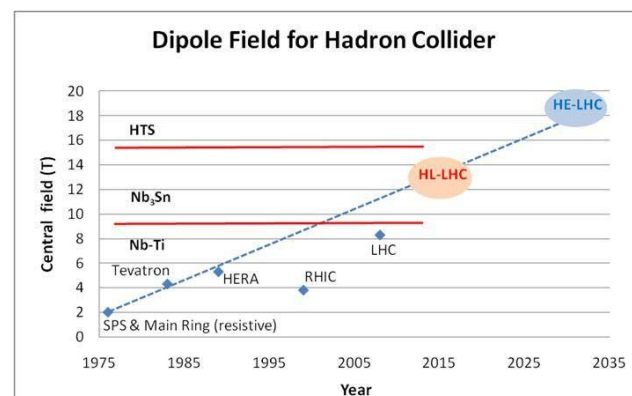

Figure 3: Progress in magnetic field vs. time for large colliders: intermediate field Nb-Ti, high field Nb_3Sn, very high field HTS (Bi-2212 or YBCO) region are indicated.

Other beam dynamics issues appear not more difficult than LHC itself, thanks also to the excellent beam dumping time of 2 hours (26 hours in the LHC). Also collimation seems not more difficult than the HL-LHC case since the beam power and power density will not increase. HE-LHC relies on injection energy > 1 TeV (0.45 TeV in LHC) to permit a small magnet aperture: 40 mm (56 mm in LHC), a critical issue to attaining 20 T. Many issue need to be addressed more deeply: one is quadrupole strength and the best lattice optimization, quad gradient cannot be doubled as "easy" as dipole field.

In addition to the main magnets the most critical points are the beam injection and extraction. In particular the beam dump with beam rigidity more than double and the more or less the same space allocated for the kickers looks problematic.

HE-LHC is certainly a very difficult machine but it is also a "saving" machine, making re-use of all existing infrastructure of CERN, and is one of the main options for the future of CERN and High Energy Physics. In any case the main technology for the HE relies on the advance already on going for the HL-LHC, plus a specific development on HTS that is just starting. In about four years we believe that the energy reach of HE-LHC can be finally assessed, allowing determining its physics reach, the design and construction issues as well as its cost with a reasonable approximation.

REFERENCES

[1] F. Ruggiero editor: O. Bruning, et al., "LHC Luminosity and Energy Upgrade: A Feasibility Study", LHC Project Report 626, CERN, Geneva, December 2002.

[2] High energy High intensity Hadron collider networking activity, HHH, supported by the EU through the FP6-CARE program, see website: http://care-hhh.web.cern.ch/care-hhh/)

[3] LARP, Lhc Accelerator Research Program, http://www.uslarp.org/

[4] L. Tavian, "Cryogenics Limits", talk at the CARE-HHH workshop LUMI'06 in Valencia, Spain, http://care-hhh.web.cern.ch/care-hhh/LUMI-06/

[5] J. Strait, et al., "Towards A New LHC Interaction Region Design for a Luminosity Upgrade", Proceedings of PAC03

[6] F. Ruggiero, et al., "Performance Limits and IR Design of a Possible LHC Luminosity Upgrade Based on NbTi Sc Magnet Technology", Proceedings of EPAC04

[7] R.Ostojic, et al., "Low-β Quadrupole Designs for the LHC Luminosity Upgrade", Proceedings of PAC05,

[8] J.P. Koutchouk, L. Rossi, E. Todesco, "A Solution for Phase-one Upgrade of the LHC Low-beta Quadrupoles Based on Nb-Ti", LHC Project Report 1000, CERN, Geneva, 2007.

[9] O. Bruning, R. De Maria, R. Ostoijc, "Low gradient, large aperture IR upgrade for the LHC compatible with the Nb-Ti magnet technology", LHC Project Report 1008, CERN, Geneva, 2007.

[10] E. Todesco, J. P. Koutchouk, "Scaling laws for β* in the interaction regions" Proceedings of CARE-HHH workshop LUMI'06 in Valencia, Spain, http://care-hhh.web.cern.ch/care-hhh/LUMI-06/.

[11] J. P. Kouthcouk, G. Sterbini, "An early beam separation scheme for the LHC luminosity upgrade", Procedings of EPAC06

[12] F. Ruggiero, F. Zimmermann, "Possible scenarios for an LHC upgrade", HHH workshop LUMI-2004, CERN Geneva 2004, http://care-hhh.web.cern.ch/care-hhh/HHH-2004/

[13] J. Shi, L. Jin, W. Herr, "Study of the wire compensation of long-range beam-beam interactions in LHC with a strong-strong beam-beam simulation", Proc. EPAC'02, 2002.

[14] W. Shiltsev, Electron lenses for compensation of beam-beam effects, HHH-CARE-APD BEAM07, CERN, 2007.

[15] W. Scandale, F. Zimmermann, "Scenarios for sLHC and vLHC," 18th Hadron Collider Physics Symposium 2007 (HCP 2007) 20-26 May 2007, La Biodola, Isola d'Elba, Italy. Published in Nucl. Phys. Proc. Suppl. 177-178: 207-211 (2008).

[16] V. Lebedev, "Levelling with beta*", CARE-HHH BEAM07, CERN 2007

[17] G. Sterbini, J.-P. Koutchouk, "A Luminosity Leveling Method for LHC Luminosity Upgrade using an Early Separation Scheme," LHC Project Note 403, CERN, Geneva, 2007

[18] V. Baglin et al., "Conceptual Design of the LHC Interaction Region Upgrade – Phase-I", R. Ostojic and L. Williams editors, LHC Project Report 1163.

[19] V. Parma and L. Rossi, "Performance of the LHC Magnet System", Proceedings of PAC09.

[20] S. Fartoukh, "Optics Challenges and Solutions for the LHC Insertion Upgrade Phase I", Proceedings of LHC Performance Workshop, Chamonix 2010.

[21] S. Fartoukh, "Breaching the Phase I Optics Limitations for the HL-LHC", Proceedings of LHC Performance Workshop, Chamonix 2011.

[22] S. Fartoukh, "An Achromatic Telescopic Squeezing (ATS) Scheme for the LHC Upgrade", Proceedings of IPAC11.

[23] M. Lamont, "LHC from Commissioning to Operation", Proceedings of IPAC11.

[24] O. Bruning, "Do we really need the LHC luminosity upgrade?", Proceedings of the LHC Performance Workshop, Chamonix 2011

[25] F. Zimmermann, "HL-LHC: Parameter Space, Constraints & Possible Options", Proceedings of the LHC Performance Workshop, Chamonix 2011

[26] Proceedings of the workshop on "The High-Energy Large Hadron Collider", E. Todesco and F. Zimmermann editors, Malta October 2010, CERN-2011-03, 8 April 2011.