LHC PHASE-2 UPGRADE SCENARIOS

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Abstract

The projected lifetime of the LHC low-beta quadrupoles, the evolution of the statistical error halving time, and the increased physics potential all call for an LHC luminosity upgrade by the middle of the coming decade.

Within the CARE-HHH network a phased upgrade plan has been proposed, consisting of a phase 1 that involves only the LHC interaction region, and a later phase 2 which is accompanied by major changes to the LHC injector complex.

Several schemes have been identified for increasing, in phase 2, the LHC peak luminosity by more than a factor of 10, to values above 10^{35} cm^{-2}s^{-1}, and four example scenarios were developed. All scenarios imply a rebuilding of the high-luminosity interaction regions (IRs) [at least compared with the nominal LHC] in combination with a consistent change of beam parameters. However, their respective features, bunch structures, IR layouts, merits and challenges, and luminosity variation with β^* differ substantially. In all scenarios luminosity leveling during a store would be advantageous for the physics experiments.

An injector upgrade must complement the upgrade measures in the LHC proper in order to provide the beam intensity and brightness needed as well as to reduce the LHC turnaround time for higher integrated luminosity.

A number of complementary advanced techniques, such as long-range beam-beam compensation, electron-cloud mitigation or crystal collimation, have been advanced and promise to further boost the performance of the upgraded LHC.

MOTIVATION

The Large Hadron Collider (LHC) will collide two proton beams with a centre-of-mass energy of 14 TeV at design and "ultimate" luminosities of 10^{34} cm^{-2}s^{-1} and 2.3×10^{34} cm^{-2}s^{-1}. The LHC proton beams will cross each other at the four detectors of the two high-luminosity experiments ATLAS and CMS, the B physics experiment LHCb, and the ion experiment ALICE. The LHC is set to explore an extremely rich physics landscape, spanning from the Higgs particle, over supersymmetry, extra dimensions, black holes, precision measurements of the top quark, the unitarity triangle, to the quark-gluon plasma [1].

Simple models for the LHC luminosity evolution over the first few years of operation [2] indicate that the IR quadrupoles may not survive for more than 8 years due to high radiation doses, and that already after 4–5 years of operation the halving time of the statistical error may exceed 5 years. Either consideration points out the need for an LHC luminosity upgrade around 2016. A third reason for an LHC upgrade is extending the physics potential of the LHC: A ten-fold increase in the luminosity will increase the discovery range for new particles by about 25% in mass [1]. Detailed physics examples can be found in Ref. [3]. The particle-physicists' goal for the upgrade is to collect 3000 fb^{-1} per experiment in 3–4 years of data taking. Similar upgrades were performed at previous hadron colliders, where, for example, the Tevatron upgrade has resulted in an integrated Run-II luminosity about 50 times larger than that of Run I.

PARAMETER DRIVERS

Key drivers determining the upgrade parameters are the head-on beam-beam limit, the detector pile up, the long-range beam-beam effects, the crossing angle, collimation & machine protection, the beam parameters available from the injectors, and the heat load on the beam screen in the cold arcs due to synchrotron radiation, impedance, and electron cloud.

The head-on beam-beam limit imposes constraints on the beam brightness (and the crossing angle), or for a given emittance on the bunch charge.

For a fixed luminosity the maximum acceptable detector pile up limits the possible values of bunch spacings. Long-range beam-beam effects determine the minimum crossing angle and, together with the available aperture, they introduce a lower bound on the IP beta function.

Increasing the crossing angle in turn leads to a rapid loss in geometric overlap of the colliding bunches; this loss can be compensated, for example, by shorter bunches, or by crab cavities, or by a smaller emittance.

Other limits arise from the collimation system, whose main task is quench protection. A beam loss of 1% beam loss in 10 s at 7 TeV corresponds to 500 kW energy, which is to be compared with a quench limit of 8.5 W/m [4]. The simulated cleaning efficiency with errors allows only for $\sim 5\%$ of the nominal intensity for the assumed loss rate. The phase-1 IR upgrade will not improve the intensity limit. An improvement will only come from a "phase-II collimation" with (sacrificial or consumable?) copper and cryogenic collimators which are presently under study. A factor 30 improvement in cleaning efficiency is predicted, from 99.997 %/m to 99.99992 %/m. In 2012 this system should be ready for nominal and higher intensity up to the ultimate bunch charge corresponding to 1.7×10^{11} protons.

The so-called electron-cloud phenomenon leads to heat load (which may result in magnet quenches), instabilities, emittance growth, and poor beam lifetime. Also synchrotron radiation and beam image currents add to the heat load on the beam screen. These heating processes add constraints on bunch spacing, bunch charge and bunch length.

The last important ingredient is the LHC injectors, in which the nominal LHC beam roughly corresponds to the present performance limit [5]. The target beam parameters for the injector complex that should correspond to the "ultimate" in the LHC ($N_b = 1.7 \times 10^{11}$ with 25 ns spacing and nominal emittance) are out of reach at present. Component aging & reliability problems compound the injector issues. Important limiting mechanisms like space charge and aperture are common to all injectors and will profit from an injection-energy increase; in particular the PS Booster will profit from the new LINAC4. TMCI is a major limitation for PS and SPS and an increase in the slippage factor is necessary (avoid transition crossing and choose $\gamma_{\rm inj} \gg \gamma_{\rm tr}$).

PARAMETER EVOLUTION 2001–2008

Possible LHC upgrade paths were first examined around 2001/02 as part of a feasibility study [6], which introduced the notion of phased upgrade with phase 0 pushing the performance without hardware changes, phase 1 modifying only the LHC interaction regions, and phase 2 involving major hardware changes, such as a rejuvenation of the injector complex. The phase 0 foresaw a reduction of the number of collision points from 4 to 2 (IP 1 and 5), allowing for a bunch-intensity increase from the nominal value $N_b = 1.15 \times 10^{11}$ to the ultimate $N_b = 1.7 \times 10^{11}$, maintaining the same, nominal beam-beam footprint, and yielding a luminosity of 2.3×10^{34} cm^{2}s^{-1}. This luminosity could be boosted further, still with $\beta^* \approx 0.5$ m, by increasing the crossing angle from about 300 μrad to 340 μrad, together with an increase of the bunch intensity to $N_b = 2.6 \times 10^{11}$, promising a luminosity of 3.6×10^{34} cm^{2}s^{-1}, without any hardware change. Two more advanced beam-parameter scenarios for highest peak luminosities around 10^{35} cm^{2}s^{-1} were identified: bunches with 12.5 ns spacing and $\beta^* = 0.25$ m, or a few superbunches. The beam-parameters have been further developed by the CARE [7] HHH network [8], in collaboration with the US LARP [9]. The HHH-2004 workshop eliminated the superbunch scheme. At the LUMI'05 workshop, the idea of an IR upgrade based on large-aperture quadrupoles made from conventional NbTi superconductor was introduced, as well as an "early-separation" scheme with slim dipoles embedded deep inside the detector, and the alternative "large-Piwinski angle" scenario. LUMI'06 finally abandoned the original 12.5-ns upgrade scheme in view of excessive heat load from image currents, synchrotron radiation, and electron cloud. This workshop also decided to pursue the so-called "quadrupole-first" layouts rather than "dipole-first" schemes à la RHIC. BEAM'07 proposed a third upgrade scheme, using full crab crossing, and it also looked at the production and maintenance of the LHC beam required for the large-Piwinski-angle scheme, as well as at possibilities for luminosity leveling. At HHH-2008, a fourth scheme was added, relying on higher-brightness lower-emittance beams from the new injectors.

UPGRADE STAGES

The present LHC upgrade plan consists of a series of improvements — primarily two discrete phases just as anticipated in Ref. [6] —, namely the first one consolidating the nominal performance and providing a luminosity of up to 3×10^{34} cm^{-2}s^{-1} and the second one increasing the luminosity by more than an order of magnitude from nominal, to values above 10^{35} cm^{-2}s^{-1}.

The first phase is planned to be implemented by 2014. It consists of new NbTi triplets with larger aperture, new D1 separation dipoles, and a new TAS, which may allow reaching a β^* of 0.25 m (half the ultimate) in the interaction points 1 and 5. The beam would be accelerated through the new Linac4, easily providing the ultimate intensity of 1.7×10^{11} protons per bunch.

The second phase would become operational around 2018. It coincides with the commissioning of two new injector-accelerators, the Superconducting Proton Linac (SPL) and the Proton Synchrotron 2 (PS2), which will replace the PS booster and the PS, respectively, and permit to reach twice the ultimate beam brightness with 25 ns spacing in the LHC. The LHC interaction region might again be rebuilt for phase 2. One option is to install a new triplet made from Nb_3Sn that might allow squeezing β^* down to about 15 cm.

It should be mentioned that the experiments also require time without beam to upgrade their detectors. ATLAS, for example, requests an 18-months shutdown, which should be scheduled to overlap with one of the two machine upgrade phases.

A number of complementary measures could be added in the time window 2010–2018, whenever sufficiently mature and needed: long-range beam-beam compensation, crab cavities, advanced collimators, coherent electron cooling, electron lenses, etc. In fact, depending on the upgrade path chosen the phase-2 upgrade may turn out to be just equal to the phase-1 upgrade plus some complementary measures.

In the longer term, for the year 2020 and beyond, an LHC energy upgrade and the possibility of a Large Hadron-electron Collider appear on the horizon.

UPGRADE SCENARIOS

Upgrades attempt to reduce the IP beta function, β^*, in order to maximize the luminosity. Smaller IP beta functions imply larger crossing angles and as a result a degraded geometric overlap of the colliding bunches, cancelling most of the gain from the reduced β^*. In response to this obstacle four different example scenarios have been constructed. The **early-separation scheme (ES)** uses dipole magnets embedded inside the detector to minimize the required residual crossing angle. The effect of the crossing angle is still noticeable though, and the scheme would profit from additional small-angle crab cavities. An alternative scheme, the **full crab crossing (FCC)**, avoids the detector-integrated dipoles and relies only on (stronger) crab cavities. A third scheme, recently proposed by R. Garoby [10], makes use of the higher brightness from the rejuvenated injector complex to regain luminosity that would otherwise be lost by the crossing angle. The **low emittance (LE)** is possible, since the head-on beam-beam tune shift is also reduced by the crossing angle, in a similar way as the luminosity. Lastly, the fourth scheme is based on the same reduction of the beam-beam tune shift by operating with fewer long flat bunches, and like the LE scheme with a **large Piwinski angle (LPA)**. The IR layouts and colliding bunches for the four upgrade scenarios are sketched in Fig. 1, while Table 1 compares example parameters for the four upgrade schemes with those of the nominal and ultimate LHC. Recent R&D progress on all four scenaries is sketched in Appendix A.

Figure 2 illustrates the ideal luminosity evolution for the various upgrade scenarios. It can be seen that the luminosity for the ES, FCC and LE scenarios starts higher, but decays faster than for the LPA case, leading to shorter runs. The parameters are constructed such that the average luminosity values are nearly identical for all four schemes. The high initial peak luminosity for the first three schemes may not be useful for physics in view of possibly required set-up and tuning periods. On the other hand, as shown in Fig. 3, the average event pile up for these options is about 30–40% lower than that for the LPA case.

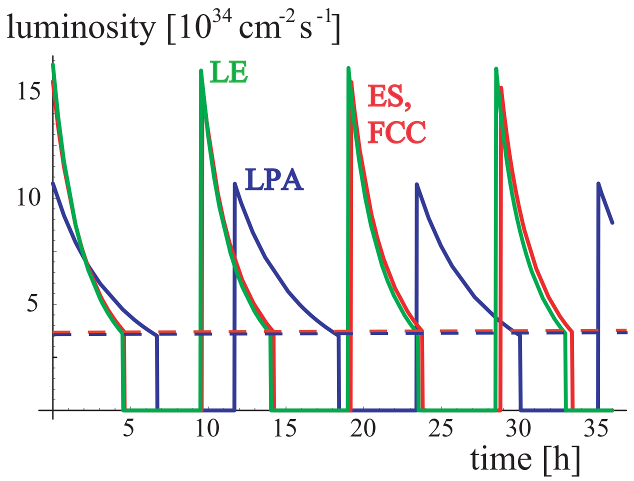

Figure 2: Ideal luminosity evolution for the ES & FCC (red), LE (green) and LPA scenarios (blue), considering the optimum run duration for a turn-around time of 5 h. The dashed lines indicate the corresponding time-averaged luminosities.

The LHC crossing angle θ_c introduces a geometric luminosity reduction factor which for bunches much shorter than β^* can be approximated as [11]

$$R(\phi) \approx \frac{1}{\sqrt{1+\phi^2}} , \tag{1}$$

where $\phi \equiv \sigma_z \theta_c / (2\sigma^*_{x,y})$ is the so-called Piwinski angle, with σ_z the rms bunch length and $\sigma^*_{x,y}$ the transverse

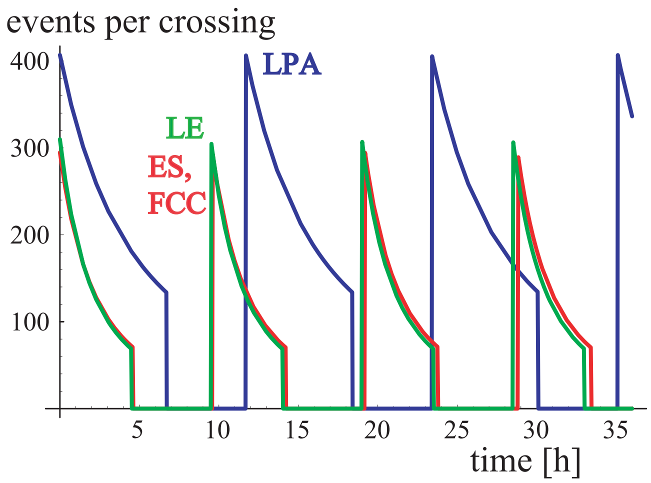

Figure 3: Time evolution of the event-per-crossing rate for the ES & FCC (red), LE (green) and LPA scenarios (blue), considering the optimum run duration for a turn-around time of 5 h.

rms (round) beam size at the collision point. The nominal LHC operates at $R(\phi) \approx 0.84$. The reduction factor $R(\phi)$ decreases steeply as ϕ is raised beyond nominal, e.g. for smaller β^* and larger crossing angle.

The crossing angle reduces not only the luminosity, but also the beam-beam tune shift. For alternating planes of crossing at two interaction points (IPs), the luminosity can be expressed as [11]

$$\begin{aligned} L &= \frac{f_{\rm rev}\gamma}{4\pi} n_b \frac{1}{\beta^*(\gamma\epsilon)} N_b^2 \frac{1}{\sqrt{1+\phi^2}} F_{\rm hg} & (2)\\ &= \frac{f_{\rm rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b \,\Delta Q_{\rm bb}\, F_{\rm profile} F_{\rm hg} & (3)\\ &= \frac{f_{\rm rev}\pi}{r_p^2} n_b \frac{\gamma^2\epsilon}{\beta^*}\, \Delta Q_{\rm bb}^2\, F_{\rm profile}^2 F_{\rm hg} \sqrt{1+\phi^2} , & (4) \end{aligned}$$

where $\Delta Q_{\rm bb}$ denotes the absolute value of the total beam-beam tune shift,

$$\Delta Q_{\rm bb} \approx \frac{N_b}{\gamma\epsilon} \frac{r_p}{2\pi F_{\rm profile}\sqrt{1+\phi^2}} , \tag{5}$$

which is limited to about 0.01 according to experience at previous hadron colliders (notably the $Sp\bar{p}S$), $f_{\rm rev}$ the revolution frequency, N_b the number of protons per bunch, $F_{\rm profile}$ a form factor that depends on the longitudinal profile (about 1 for a Gaussian and $\sqrt{2}$ for a uniform profile) and $F_{\rm hg}$ the additional reduction factor due to the hourglass effect, which is relevant only for bunch lengths comparable to, or smaller than, the IP beta function. In (2) the collision of two round beams has been assumed. Other variables are defined in Table 1. It is interesting that at low intensity smaller emittance and low Piwinski angle maximize the luminosity according to (2), but that the inverse is true at the beam-beam limit when the maximum beam-beam tune

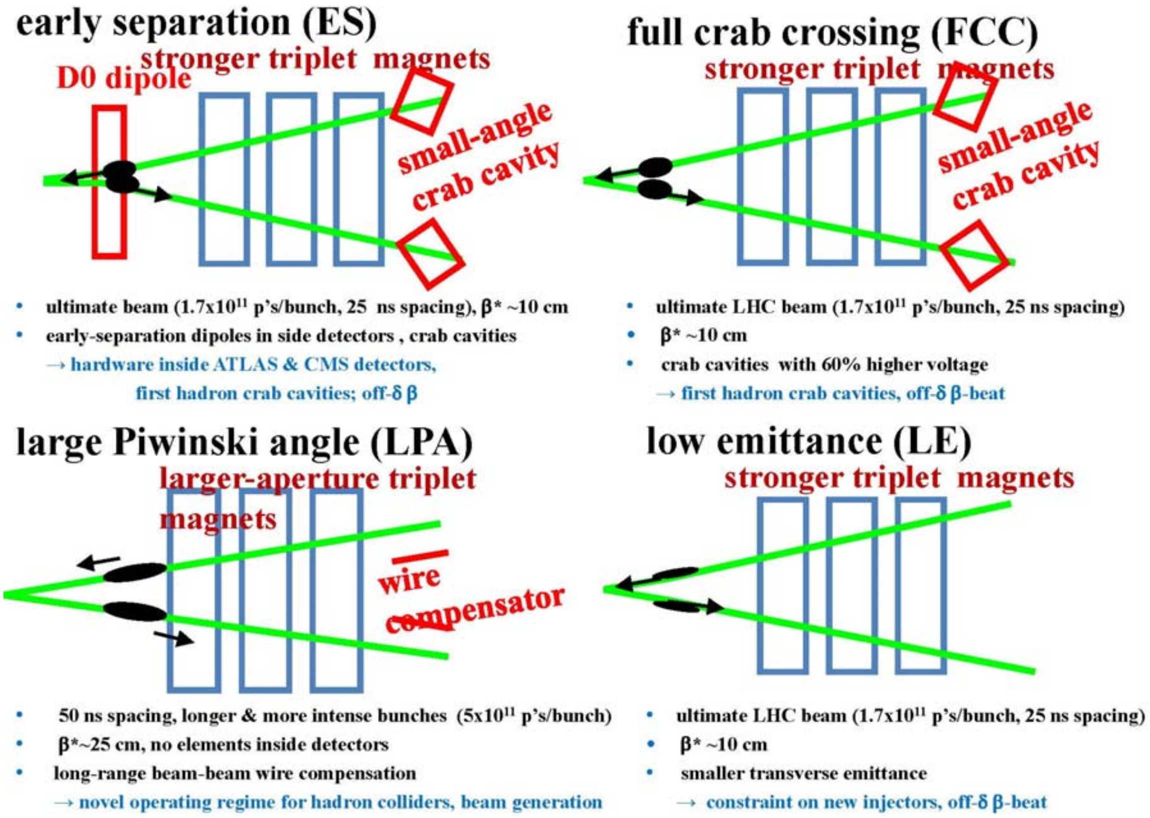

Figure 1: Example interaction-region layouts for the four different LHC high-luminosity upgrade scenarios of Table 1.

Table 1: Parameters for the (1) nominal and (2) ultimate LHC compared with those for the four upgrade scenarios with (3) more strongly focused ultimate bunches at 25-ns spacing with either early separation and crab cavities [ES], full crab crossing [FCC], or low emittance [LE], and (4) longer intense flat bunches at 50-ns spacing in a regime of large Piwinski angle [LPA]. The numbers refer to the performance without luminosity leveling.

parameter	symbol	nominal	ultimate	ES or FCC	LE	LPA
number of bunches	n_b	2808	2808	2808	2808	1404
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	1.7	4.9
bunch spacing	$\Delta t_{\rm sep}$ [ns]	25	25	25	25	50
average current	I [A]	0.58	0.86	0.86	0.86	1.22
normalized transverse emittance	$\gamma\epsilon$ [μm]	3.75	3.75	3.75	1.0	3.75
longitudinal profile		Gaussian	Gaussian	Gaussian	Gaussian	uniform
rms bunch length	σ_z [cm]	7.55	7.55	7.55	7.55	11.8
beta function at IP1&5	β^* [m]	0.55	0.5	0.08	0.10	0.25
(effective) crossing angle	θ_c [μrad]	285	315	0	311	381
Piwinski angle	ϕ	0.4	0.75	0	3.2	2.01
hourglass factor	$F_{\rm hg}$	1.00	1.00	0.86	0.92	0.99
peak luminosity	$\hat{L}$ [10^{34} cm^{-2}s^{-1}]	1.0	2.3	15.5	16.3	10.6
events per crossing		19	44	294	309	403
rms length of luminous region	$\sigma_{\rm lum}$ [mm]	45	43	37	15	53
initial luminosity lifetime	$\tau_{\rm L}$ [h]	22.2	14.3	2.2	2.0	4.5
average luminosity ($T_{\rm ta}=10$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.5	0.9	2.4	2.5	2.5
optimum run time ($T_{\rm ta}=10$ h)	$T_{\rm run}$ [h]	21.2	17.0	6.6	6.4	9.5
average luminosity ($T_{\rm ta}=5$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.6	1.2	3.6	3.7	3.5
optimum run time ($T_{\rm ta}=5$ h)	$T_{\rm run}$ [h]	15.0	12.0	4.6	4.5	6.7
e-cloud heat load for $\delta_{\rm max}=1.4$	$P_{\rm ec}$ [W/m]	1.07	1.04	1.0	1.0	0.4
e-cloud heat load for $\delta_{\rm max}=1.3$	$P_{\rm ec}$ [W/m]	0.44	0.6	0.6	0.6	0.1
SR heat load	$P_{\rm SR}$ [W/m]	0.17	0.25	0.25	0.25	0.36
image-current heat load	$P_{\rm ic}$ [W/m]	0.15	0.33	0.33	0.33	0.70
1.9-K gas scattering heat load for 100 h lifetime	$P_{\rm gas}$ [W/m]	0.04	0.06	0.06	0.06	0.08

shift has been reached, and Eq. (4) with constant value of ΔQ_{bb} best describes the behavior. The beam-beam limit defines a universal set of curves, distinguished through the longitudinal beam profile, of maximum acceptable beam brightness as a function of the Piwinski angle. Figure 4 illustrates how the various scenarios of Table 1 lie on one of these curves.

The upgrade parameters in (3) which differ from the "ultimate" LHC configuration are $1/\beta^*$, N_b, $\Delta Q_{\rm bb}$, $F_{\rm profile}$, and n_b for the LPA upgrade, where the peak luminosity increases by a factor 10.6 above nominal. For the ES and FCC or LE upgrade schemes, the parameters $1/\beta^*$, $\Delta Q_{\rm bb}$,and (partly) $F_{\rm hg}$ are different from the ultimate LHC, and translate into a gain in peak luminosity by a factor 15.5 or 16.3, respectively. A detailed breakdown of luminosity gain factors for all four upgrade scenarios is presented in Table 2.

Another important consideration for the upgrade is the luminosity lifetime, which can be written as

$$\tau_{\rm lum} = \frac{1}{2}\frac{N_b}{\dot{N}_b} = \frac{n_b N_b}{L\sigma} = \frac{4\pi\epsilon\beta^*}{f_{\rm rev}N_b\sigma} \ . \qquad (6)$$

Table 2: Peak-luminosity gain factors compared with the ultimate LHC for the different upgrade scenarios of Table 1. We note that the total beam-beam tune shift for the ultimate LHC with two collisions points is $\Delta Q_{\rm tot} = 0.008$ (i.e. less than 0.01) if the reduction due to the crossing angle is taken into account.

parameter	LPA	ES & FCC	LE
$1/\beta^*$	$\times 2$	$\times 6.3$	$\times 5.5$
N_b	$\times 2.9$	$\times 1$	$\times 1$
ΔQ_{bb}	$\times 1.13$	$\times 1.25$	$\times 1.3$
$F_{\rm profile}$	$\times\sqrt{2}$	$\times 1$	$\times 1$
n_b	$\times 0.5$	$\times 1$	$\times 1$
$F_{\rm hg}$	$\times 1.0$	$\times 0.86$	$\times 1.0$
total gain w.r.t. ultimate	$\times 4.5$	$\times 6.8$	$\times 7.1$
total gain w.r.t. nominal	$\times 10.6$	$\times 15.5$	$\times 16.3$

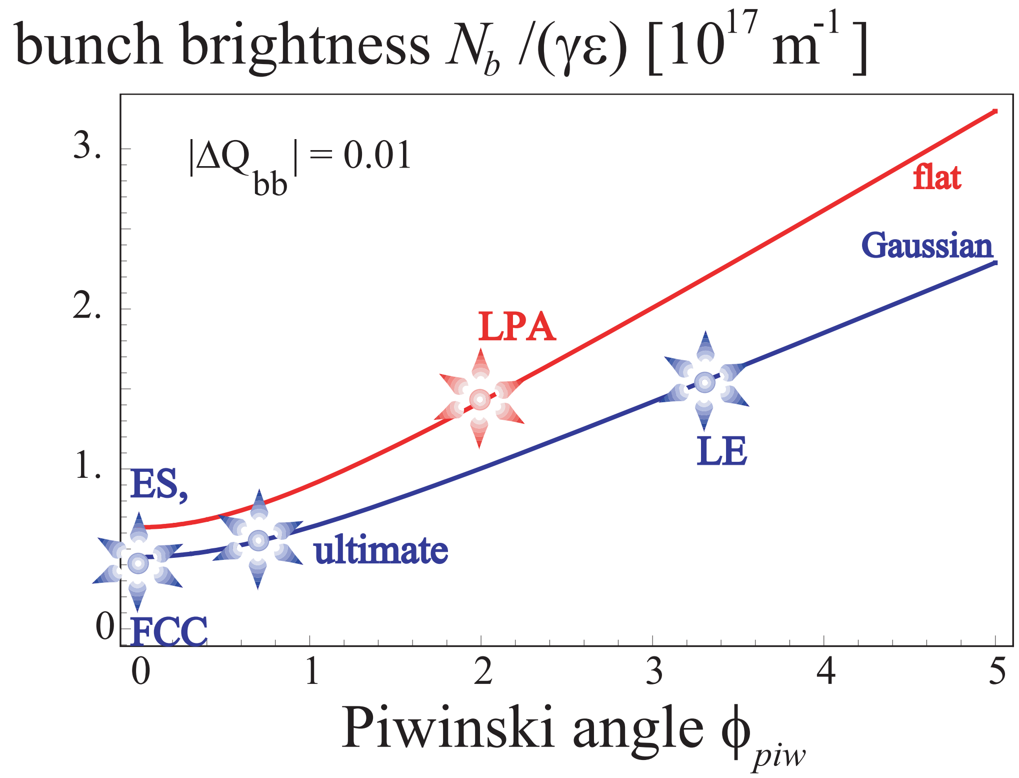

Figure 4: Brightness as a function of Piwinski angle for constant beam-beam tune shift, indicating the working points for the various scenarios of Table 1.

The luminosity lifetime is inversely proportional to the luminosity, or proportional to β^*. The lifetime can be increased only via a higher total beam current, proportional to $n_b N_b$. This implies either more bunches n_b (e.g. a previously considered scheme with 12.5-ns bunch spacing, which was ruled out at the CARE-HHH LUMI'06 workshop in view of excessive heat loads [12]) or a higher charge per bunch N_b, e.g. the LPA scheme. The effective luminosity lifetime can also be increased via "luminosity leveling," namely by suitably varying the beta function, the bunch length, or the effective crossing angle during a store (see later).

Without such leveling the instantaneous luminosity decays as

$$L(t) = \frac{\hat{L}}{(1 + t/\tau_{\rm eff})^2} \; , \tag{7}$$

with

$$\tau_{\rm eff} \equiv \frac{n_b N_b(0)}{\hat{L} \sigma_{\rm tot} n_{IP}} \tag{8}$$

denoting the effective beam lifetime due to burn-off at the collision points, $\sigma_{\rm tot} \approx 100$ mb the relevant total cross section, n_{IP} the number of IPs, and $\hat{L}$ the initial peak luminosity. The optimum average luminosity is

$$L_{\rm av} = \frac{\hat{L} \tau_{\rm eff}}{(\tau_{\rm eff}^{1/2} + T_{\rm ta}^{1/2})^2} \; , \tag{9}$$

where T_{ta} denotes the turn-around time. The corresponding optimum run time $T_{\rm run}$ is the geometric mean of effective lifetime and turn-around time:

$$T_{\rm run} = \sqrt{\tau_{\rm eff} T_{\rm ta}} \; . \tag{10}$$

Figure 5 shows the color-coded average luminosity as a function of total number of protons and IP beta function for a Gaussian and flat beam profile. The plotting symbols indicate the parameter sets corresponding to the ultimate LHC and the various upgrade scenarios. The color code represents a linar scale ranging from 10^{33} to 2×10^{35} cm^{-2}s^{-1}. For improved clarity, a few representative cuts through the 3-D plots are shown in Fig.6, which illustrates that in terms of average luminosity a factor 2.5 reduction in β^* is equivalent to a 50% intensity increase.

Figure 7 shows the IBS growth rates for the LHC upgrade scenarios as a function of longitudinal emittance. The IBS rise times remain long compared with the much shorter luminosity lifetime of the upgraded LHC.

EXPERIMENTERS' CHOICE

The experimenters' preferences were expressed at an LHCC meeting in July 2008 and are summarized as follows:

- no accelerator components inside the detector;

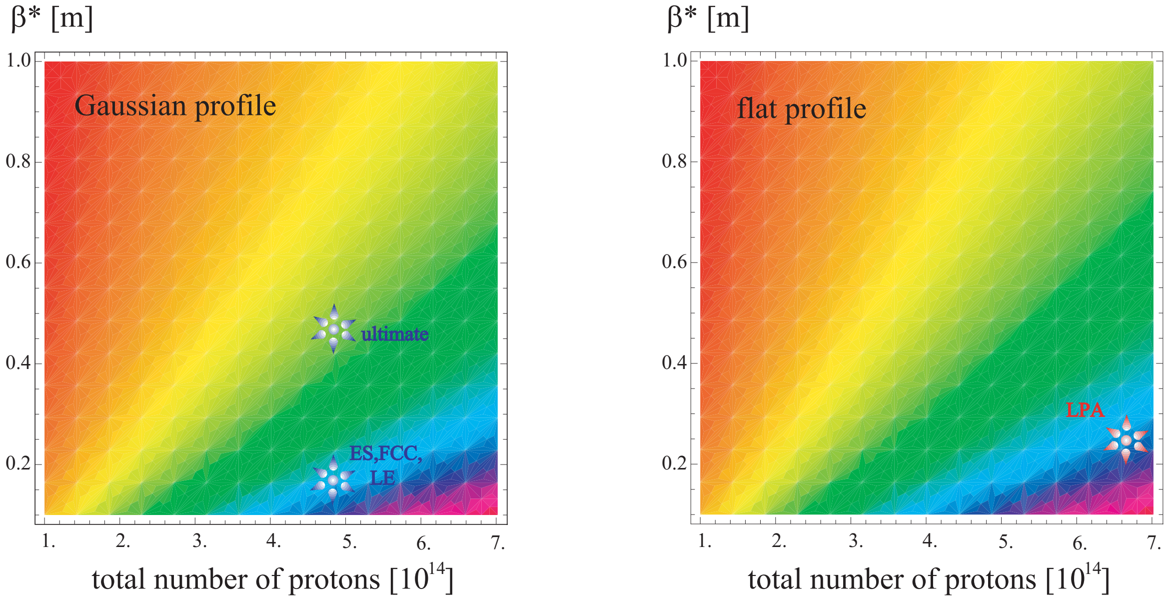

Figure 5: Average luminosity with 5-h turnaround time as a function of intensity beta function and intensity for a Gaussian (left) and a flat bunch profile (right); the symbols represent the various scenarios of Table 1.

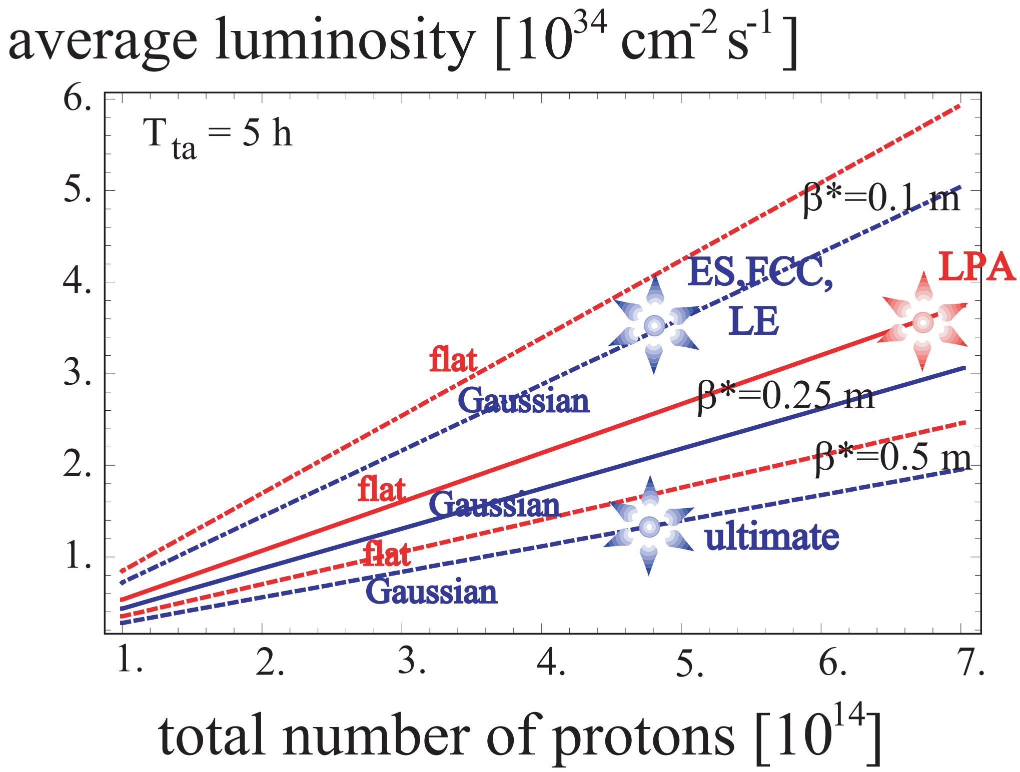

Figure 6: Average luminosity with 5-h turnaround time as a function of the total number of protons per beam for Gaussian and flat bunch profiles (blue and red colors) and various IP beta functions (dashed, solid, and point-dashed limes); the symbols represent the various scenarios of Table 1.

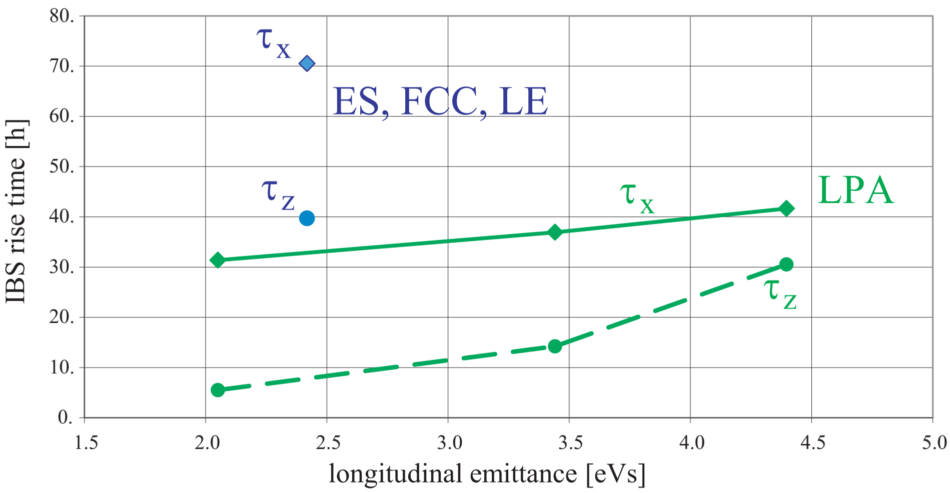

Figure 7: Intrabeam-scattering emittance-growth rates as a function of longitudinal emittance (defined as 4π times rms emittance) for the various scenarios of Table 1.

- lowest possible event pile up;
- possibility of easy luminosity leveling.

These combined conditions would be most easily fulfilled by the full crab crossing upgrade and/or the low-emittance upgrade. It should be noticed, however, that in order to reach luminosities at the 10^{35} cm^{-2}s^{-1} target level, the IP beta function must be decreased to about 10 or 15 cm. If it turned out that the minimum β^* is about 25–30 cm, the only scenario that, given all known constraints, can reach the targeted luminosity is the Large Piwinski Angle scheme (albeit this implies a 25–50% higher pile up).

LUMINOSITY LEVELING

The LHC experiments prefer constant luminosity, that is less pile up at start of run, and higher luminosity at the end of a physics store. For the ES or FCC scheme this could be achieved with a dynamic β squeeze, or via a dynamic change of the effective crossign angle θ_c (realized either with IP angle bumps or, more elegantly, through a varying crab voltage). For the LE scheme β changes or θ_c variations with orbit bumps are leveling options; and for LPA again a dynamic β squeeze, a reduction of the crossing angle during the store, or, possibely, a dynamic change of the bunch length.

Leveling provides a constant luminosity, equal to L_0, and the beam intensity then decreases linearly with time t as

$$N_b = N_{b0} - L_0 \sigma_{\rm tot} n_{IP}/n_b t \ . \qquad (11)$$

The accessible intensity range $\Delta N_{b,\max}$ is limited, e.g., by the range of the leveling variable, for example by the minimum value of β^*, so that the length of a run amounts to

$$T_{\rm run} = \frac{\Delta N_{b,\max}\tau_{\rm lev}}{N_0} \qquad (12)$$

with the leveling beam lifetime

$$\tau_{\rm lev} = \frac{N_0 n_b}{L_0 \sigma_{\rm tot} n_{IP}} \ , \qquad (13)$$

and the average luminosity with leveling becomes

$$L_{\rm av,lev} = \frac{L_0}{1 + \frac{\Delta N_{b,\max} n_b T_{ta}}{L_0 \sigma_{\rm tot} n_{IP}}} \ . \qquad (14)$$

Table 3 compares event rates, run times, and average luminosity values achievable in the various upgrade schemes. For example, attractive options may be to run with constantly 75 events per crossing for the ES, FCC and LE schemes, and at 150 events per crossing in the case LPA. Using these numbers, Figs. 8 and 9 illustrate the corresponding luminosity evolution and events-per-crossing rate as a function of time, which are to be compared with the corresponding unleveled cases of Figs. 2 and 3, respectively.

In case of β^* variation, the tune shift decreases during the store, while when leveling via the bunch length or crossing angle the tune shift increases. For leveling with dynamic β^* squeeze, the sensitivity of the average luminosity to the minimum β^* permitted by the IR optics greatly depends on the chosen number of events per crossing; see Ref. [13].

Equations (8) and (13) demonstrate that the luminosity lifetime scales with the total number of protons, and is inversely proportional to the luminosity itself.

LHCB COMPATIBILITY

An upgrade of LHCb to Super-LHCb is planned, in order to exploit luminosities up to 2×10^{33} cm^{-2}s^{-1}, or 2% of the (upgrade) luminosity delivered to ATLAS and CMS. The LHCb detector is special due to its asymmetric location in the ring, which opens up a new possibility of supplying LHCb with its target possibility.

Table 3: Event rate, run time, and average luminosity for the various upgrade scenarios with leveling, assuming 5 hr turnaround time.

	ES, FCC or LE	LPA
events/crossing	300	300
optimum run time	N/A	2.5 h
av. luminosity [10^{34} cm^{-2}s^{-1}]	N/A	2.6
events/crossing	150	150
optimum run time	2.5 h	14.8 h
av. luminosity [10^{34} cm^{-2}s^{-1}]	2.6	2.9
events/crossing	75	75
optimum run time	9.9 h	26.4 h
av. luminosity [10^{34} cm^{-2}s^{-1}]	2.6	1.7

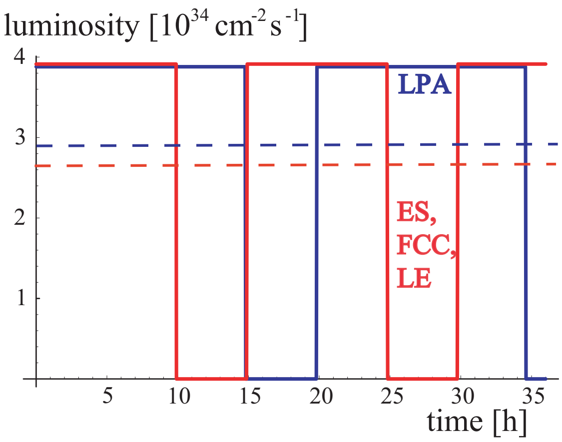

Figure 8: Ideal luminosity evolution for the ES & FCC (red), LE (green) and LPA scenarios (blue), considering the optimum run duration for a turn-around time of 5 h. The dashed lines indicate the corresponding time-averaged luminosities.

In the LPA case with 50-ns spacing between successive bunches in a train, we can arrange to have either collisions between the 50-ns bunches or no collisions at all in LHCb [14], depending on the distance in multiples of 25 ns which we choose between the various groups of bunch trains distributed around the ring. At 50-ns spacing, satellite bunches can be added in between the main bunches, as is illustrated in the bottom part of Fig. 10, displaying possible bunch patterns for various LHC configurations. Such satellites may be produced by asymmetric bunch splitting in the PS (possibly large fluctuation). In LHCb these satellites can be made to collide with main bunches at 25-ns time intervals. The intensity of the satellites should be lower than about 3×10^{10} protons per bunch in order to add less than 5% to the total tune shift and also to avoid electron-cloud problems. A beta function of about 3 m would result in the desired luminosity equivalent to 2×10^{33}

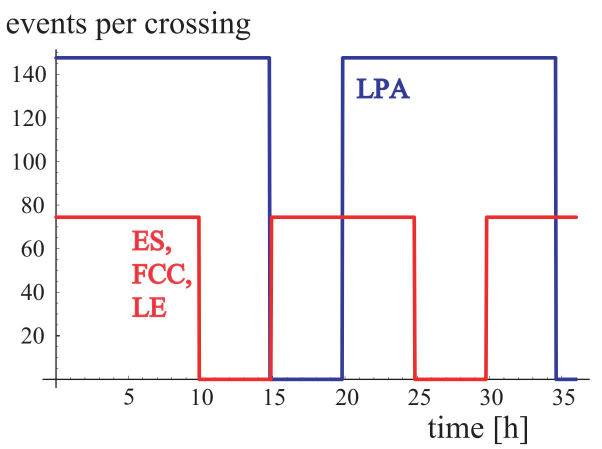

Figure 9: Time evolution of the event-per-crossing rate for the ES & FCC (red), LE (green) and LPA scenarios (blue), considering the optimum run duration for a turn-around time of 5 h.

cm^{2}s^{-1}. This value of β^* is easily possible with the present LHCb IR magnets and layout, which allows β^* squeezes down to 2 m [15].

For the ES or FCC scenarios with 25-ns bunch spacing, as well as for a different LPA filling with main-bunch collisions at LHCb, the resulting head-on collisions at Super-LHCb would contribute to the beam-beam tune shift of the bunches colliding in ATLAS and CMS, which would lower the peak luminosity for the latter. Two ways out are (1) colliding only during the second half of each store when the beam-beam tune shifts from IP1 and 5 have sufficiently decreased below the beam-beam limit, or (2) introducing a transverse collision offset, albeit the latter raises concerns about offset stability, interference with collimation, poor beam lifetime, background etc. poor beam lifetime, background etc. For transversely Gaussian bunches the luminosity scales with offset d as $L = L_0 \exp(-d^2/(4\sigma^2))$, and the tune shift as $\Delta Q(d) \approx 2\Delta(0)/(d/\sigma)^2$ (for $d \gg \sigma$). Requiring an LHCb contribution to the total tune shift of less than 10% implies transverse beam-beam offsets larger than 4.5σ, and $\beta^* \approx 0.08$ m, which is incompatible with the present LHCb IR configuration. For either option, the average luminosity delivered to Super-LHCb is considerably lower than for the LPA case with satellites.

INJECTOR UPGRADE

The present LHC injector chain is old. The PS was built in 1959, and the rest of the PS complex as well as the proton linac in the 1970s. The injectors operate far from their design parameters and close to the hardware limits. The infrastructure has suffered from the concentration of CERN resources on the LHC during the last 10 years [16]. To provide the necessary reliability a renewal of the injector complex is in order. At the same time the construction of new injectors allows for superior beam parameters that

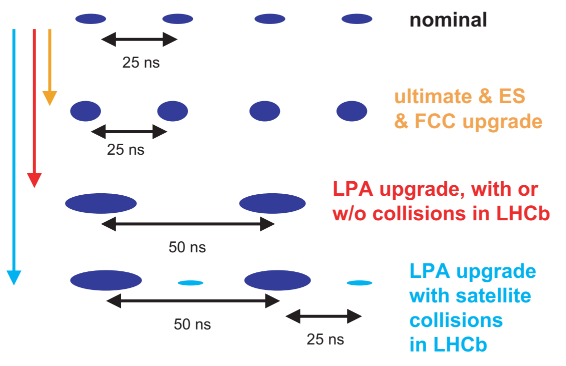

Figure 10: Bunch structures for nominal LHC; ultimate; ES, FCC or LE upgrade; LPA upgrade; and LPA with satellite-bunch collisions at LHCb.

the LHC can take advantage of [16]. In particular the upgraded injector complex should be able to deliver at least 2.5×10^{11} protons per bunch at 25 ns spacing, and flat bunches of 5×10^{11} at 50 ns spacing to the LHC. The new-injector design specificies even up to 4×10^{11} protons at 25 ns spacing, leaving some margin for other future upgrade schemes.

The new injector chain will raise the injection energy into the new or old machines (except for the LHC itself) by typically a factor of two, thereby relaxing space charge effects and beam instability thresholds. The sites of the new machines, Linac4, the Superconducting Proton Linac, and the PS successor PS2 have been decided.

The injector upgrade schedule is synchronized with the upgrade of the LHC interaction regions. Linac4 will come into operation at the time of the LHC IR phase-1 upgrade, around 2014. The SPL and PS2 will deliver their higher-intensity higher-brightness beam from about 2018 onward when the LHC phase-2 upgrade will be commissioned. The integrated luminosity projected by the LHC experiments is about 100 fb^{-1} per year for the nominal LHC and 1000 fb^{-1} per year after the phase 2 upgrade [17].

COMPLEMENTARY MEASURES

Many enabling technologies and concepts were advanced, such as LHC crab cavities, beam-beam compensation, crab-waist collisions, electron-cloud mitigation, crystal collimation and advanced cooling concepts.

Crab Cavities

Crab cavities can avoid the dramatic reduction in geometric overlap of two colliding bunches that comes along with a reduced β^*. Depending on the values of the latter, the crab cavities can increase the luminosity by 30–200%. Crab cavities were invented for linear colliders in 1988 by R. Palmer. They are used for the first time in an operating collider at KEKB since 2007. The KEKB experience is invaluable for defining an LHC crab-cavity path.

A global R&D plan for LHC crab cavities has been established [18, 19]. The staged approach towards LHC crab cavities foresees the construction of a prototype, a "global" crab cavity in LHC interaction region 4, and later on local crab cavities around IP 1 and 5. The goals for phase 1 are to show the feasibility of crab crossing in a hadron machine, to explore the limits of superconducting RF systems in deflecting mode, and to investigate the impact on the collimation system, as well as the possible effect of the crab-cavity impedance. Important operational aspects like cryogenics, crab-voltage ramp at top energy, luminosity gain and leveling, detuning, trip rates, and emittance growth due to crab-RF noise can all be explored during phase 1.

The experience at KEKB so far is reassuring. No serious instability has been observed at high beam currents of up to 1.62 and 0.9 A with crab cavities. Detuning, ramping and dephasing of KEKB the crab cavities were demonstrated with high beam intensity. The same luminosity as without crab cavities was reached at about 30% lower beam current. The beam-beam tune shift limit with crab cavities was 10–20% higher than without crab cavities, at all beam currents, with a corresponding further increase in luminosity. An even larger gain is predicted and will be pursued. The crab-cavity trip rate in the KEKB LER established in the late 2008 KEKB run would be sufficient for LHC. The crab-cavity trip rate in the HER is too high and must be improved for more reliable operation. In December 08 and throughout 2009 KEKB will probe many LHC related concerns, in the frame of the CERN-KEK crab collaboration. A top level CERN-KEK agreement might allow a funding request by KEK to the Japanese government for a major contribution to LHC crab cavities.

Challenges for LHC include the separation between the two beams (190 mm in most of the LHC) and associated space constraints, the proton bunch length of 7.55 cm (imposing a maximum frequency of 800 MHz), and constraints from collimation and machine protection.

Various cavity and coupler designs exist and a down-selection is planned for the second half of 2009. A global crab-cavity simulation and theory effort is underway. Concerning beam-beam effects in the presence of crab cavities, weak-strong and strong-strong simulation studies were performed including white noise with the BBSS code, confirming a scaling law with respect to the noise correlation time, studying the effect of RF curvature, and producing luminosity estimates [20]. In parallel the single particle dynamics with crab cavities was explored through the Sixtrack, MADX and BBTRACK simulation codes, e.g. [21, 22, 23]. In weak-strong simulations beam-beam tune footprints and expected luminosity were investigated, as well as the effect of a realistic RF noise spectrum as measured on the KEKB crab cavities. Strong-strong simulations with the BeamBeam3D code were also conducted as a cross-check [24].

As for collimation and impedance, Sixtrack/Colltrack tracking studies were performed to derive the impact of global LHC crab cavities on the collimation cleaning efficiency [25, 26]. Impedance estimates were developed and the related HOM damping requirements derived [27]. Tracking studies also illuminated the IP bunch shape for crab cavities of different frequency, and their limited impact on the dynamic aperture.

For the development of operational scenarios, crab-ramping and detuning studies were simulated with and without additional tune spread. No emittance growth is predicted if the crab cavities are ramped up over more than 10 turns [28]. KEKB has already demonstrated many operational aspects relevant for the LHC. Joined KEKB machine experiments & studies have started [29].

An aggressive implementation schedule presented at the 21-August-2008 CARE-HHH LHC crab-cavity validation mini-workshop projects the installation of a prototype cavity in the LHC as early as 2012 [30].

Beam-Beam Compensation

The nominal LHC bunches will suffer up to 120 long-range collisions. Prototype wire compensators for the long-range beam-beam effects are installed in the SPS since several years. The compensation efficiency over a significant tune space was proven with two such wires, one cancelling the effect of another. The reason why the compensation is not perfect at other tunes is not fully understood, but this effect appears to be reproducible in the beam experiments. In SPS studies, the beam lifetime was measured as a function of wire separation. The result, fitted by a power law, strongly depends on the working point.

For the LHC a wire made from high-temperature superconductor was proposed by A. Ballarino, together with a possible practical implementation [31]. A. Valishev proposed the use of an electron lens to improve the lifetime of colliding beams in the LHC by a factor of two [31].

Crab-Waist Collisions

The crab-waist uses sextupoles instead of crab cavities to “crab” the beam at the collision point for maximum geometric overlap and for removing synchro-betaron resonances. At DAFNE the scheme was successfully verified in practice. K. Ohmi studied its possible application for the LHC. With a Piwinski angle of 3.5 rad and a tiny β^* of 2.1 cm he obtained a luminosity increase by almost a factor of 3, accompanied with a reduced beam-beam tune shift [31]. K. Ohmi suggested other possible uses of crab-waist sextupoles at the LHC, for mitigating the effect of long-range collisions by pushing the halo away from the opposing beam or for improving collimation cleaning efficiency [31].

Electron-Cloud Mitigation

In 2008, electron-cloud simulations for all upgrade scenarios were performed in collaboration with CINVESTAV, Mexico [32]. Figure 11 demonsrates that maximum secondary emission yields of up to 1.4 should be acceptable for all upgrades with 25 ns, assuming dedicated new cryoplants for the interaction region which must handle largely enhanced heat loads from the collision debris. For the LPA scheme, even a maximum emission yield of 1.5 would be tolerable.

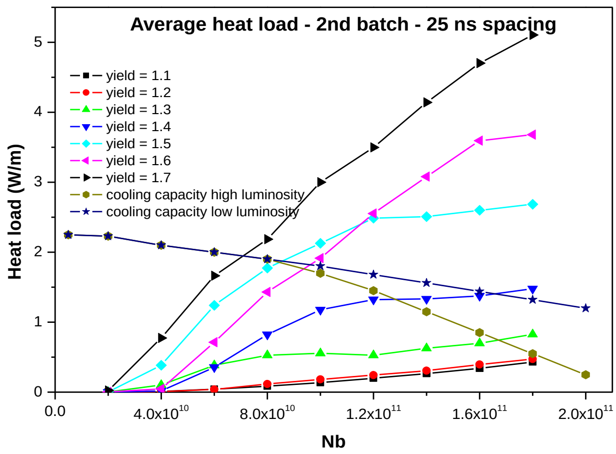

Figure 11: Simulated average heat load per unit length and per aperture on the beam screen in an arc cell as a function of bunch population for the ES and FCC (or LE) schemes, together with the presently available cooling capacity [32]. The various heat load curves correspond to different values of the maximum secondary emission yield $\delta_{\max}$ as indicated. The low-luminosity cooling capacity would correspond to the case of an additional dedicated cryoplant for the interaction region.

In parallel, novel rough surface coatings are being developed for the LHC injector upgrades. They can be produced by evaporation of metals in a rare gas of relatively high pressure. These coatings are characterized by exceptionally small secondary emission yields, with a maximum below 1.0. Some of them show little degradation even after extended periods of air exposure, making them highly attractive for accelerator applications.

A collaboration with the European Space Agency and its partners was initiated on related electron-cloud mitigation techniques[41].

Crystal Collimation

Experiments on advanced crystal collimators have been underway in the SPS North Area since 2005. In 2008 the crystal deflection of negative ions and muons was observed. A parallel simulation effort is ongoing. A highlight of 2008 was the approval of an experiment in the SPS ring proper, where the potential of crystal collimators for the LHC will be scrutinized. Crystal collimators may help overcome one of the most serious intensity limitations of the LHC.

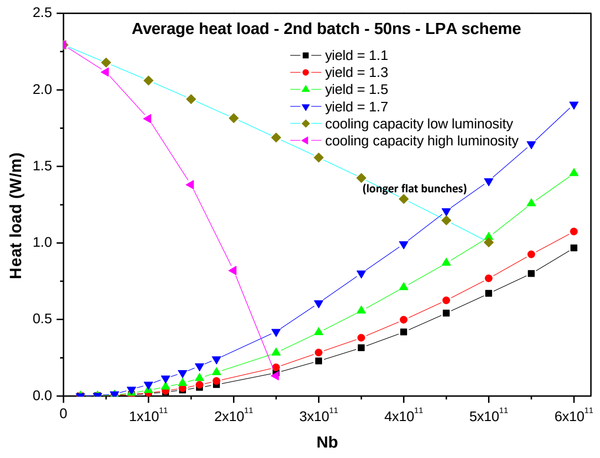

Figure 12: Simulated average heat load per unit length and per aperture on the beam screen in an arc cell as a function of bunch population for the LPA scheme, together with the presently available cooling capacity [32]. The various heat load curves correspond to different values of the maximum secondary emission yield $\delta_{\rm max}$ as indicated. The low-luminosity cooling capacity would correspond to the case of an additional dedicated cryoplant for the interaction region.

Cooling

A lower beam emittance can compensate for the geometric luminosity loss due to the finite crossing angle. A smaller emittance beam can be provided by the new injectors and/or by the new technique of coherent electron cooling, which promises an LHC damping time of 1 hour at 7 TeV, and will be demonstrated in proof-of-principle experiment at RHIC in 2012 [42].

CONCLUSIONS

The nominal LHC is challenging. An upgrade of the collimation system is mandatory. The beam parameter sets for the upgrade have evolved over the past 8 years. Several scenarios exist on paper which can reach 10 times the nominal luminosity with acceptable heat load and pile up; the various schemes have different merits and drawbacks (the design is not in a corner). If possible, raising the beam intensity is preferred over reducing β^* (better beam lifetime); but the intensity might be limited by collimation!

Work should continue on s.c. IR magnets for phase 2 and on complementary measures (LR beam-beam compensation, crab cavities, etc.). A close coordination of the LHC machine upgrade with the detector upgrades is essential.

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PROGRESS IN 2008

In 2008 significant progress was made with all four scenarios:

- For the Early-Separation scheme, SPS beam studies explored the effect of a few long-range encounters at reduced separation [37]. A CARE-HHH beam-beam working meeting was held in August [31]. A detailed design was being worked out and discussions with the experiments continued. An early-separation dipole installed at about 14 m from the collision point is retained as option both for ATLAS and CMS. The required integrated dipole field is about 13 T-m, and the luminosity gain 30–60% for $\beta^* = 15$ cm, depending on the acceptable minimum separation for the closest encounters (7–5 σ). The heat load in the interaction region may be a problem. Other issues are the effect of the CMS solenoid on the embedded separation dipole, and the impact on the detector background.

- A global collaboration, involving US-LARP, KEK, UK’s Daresbury Laboratory and the Cockcroft Institute, non-LARP laboratories in the US and institutes in China, has been advancing the LHC crab cavity design. So far, a phased approach to an LHC crab-cavity implementation has been developed, iniitally foreseeing one or two prototype global crab cavities and later on a final scheme with local crab cavities in the LHC interaction points 1 and 5 [38]. Two CARE-HHH mini-workshops on LHC crab cavities were held, in January 2008 at BNL [19] and in August 2008 at CERN [18]. Joint KEK-CERN studies have been launched, with regular video meetings and participation of CERN accelerator physicists in KEKB crab-cavity studies.

- A greater insight was also gained in the beam production for the Large Piwinski Angle scheme via simulations and beam-studies in the LHC injector complex [39]. However, many open question persist regarding the production scheme and stability of this beam. Options include the generation of this beam in the PS2 at capture or slip stacking in the SPS at high energy [40].

- For the Low-Emittance scenario [10] a parameter study was conducted. This scheme inevitably implies a trade-off between intensity and emittance, controlled by the Piwinski angle (see Fig. 4). Smaller brightness is easier for the injectors, but it comes together with higher bunch charge, higher heat loads etc.