LHC UPGRADE OPTIONS AND CARE-HHH ACTIVITIES

F. Zimmermann, CERN, Geneva, Switzerland

Abstract

The European Accelerator Network on High Energy High Intensity Hadron Beams (CARE HHH) is developing scenarios for luminosity and energy upgrades of the Large Hadron Collider (LHC). The LHC upgrade options under consideration differ in terms of beam parameters, electron-cloud effects, beam-beam compensation, use of crab cavities, and interaction-region layout. Complementary investigations concern injector upgrades, novel magnet technologies, advanced collimation schemes, and ultimate intensity limitations. Flanking these upgrade studies, an accelerator-physics code web repository has been set up, and an extensive simulation-code benchmarking campaign is being prepared.

INTRODUCTION

The Large Hadron Collider (LHC) now under construction at CERN is the world's next energy-frontier machine. It will collide two proton beams with a centre-of-mass energy of 14 TeV (7 times the energy of the Tevatron's proton-antiproton collisions) at design and ultimate luminosities of 10^{34} cm^{-2}s^{-1} and 2.3×10^{34} cm^{-2}s^{-1} (about 100 times that of the Tevatron). The start of the LHC ring commissioning is scheduled for the fall of 2007, and the first physics run expected in 2008. At the LHC two proton beams will circulate in separate pipes and cross at four detectors, two of which are designed for high luminosity.

Since several years, possible upgrade paths for this unique facility are being discussed; see, e.g., Ref. [1]. In 2004, these efforts were streamlined when the European Accelerator Network on **H**igh Energy **H**igh Intensity **H**adron Beams (HHH) [2] was launched. This network is part of CARE ("Coordinated Accelerator Research in Europe") [3], and supported within the 6th Framework Programme of the European Union. The primary goals of HHH are (1) to develop a road map for the upgrade of the European accelerator infrastructure, i.e., the LHC & GSI complexes, (2) to prepare the technical realization and scientific exploitation of the upgraded facilities, and (3) to guide pertinent accelerator R&D and experimental studies. The parallel development of higher field magnets, e.g., for an eventual LHC energy upgrade, is the objective of a separate European Joint Research Activity inside CARE, called NED ("Next European Dipole") [4].

A staged upgrade of the LHC is envisioned [1]. In the first stage, the LHC performance is pushed without new hardware, which should achieve the ultimate luminosity of 2.3×10^{34} cm^{-2}s^{-1} in collisions at two interaction points. After about 7 years of LHC operation, the low-β quadrupoles will need to be replaced for two reasons [5, 6]: first, it is expected that by then the first generation quadrupoles will be destroyed due to radiation damage from the collision debris, and, second, the efficient further reduction of statistical errors will require higher luminosity. By means of a two times lower β^*, using the new quadrupoles, the luminosity will be doubled to 4.6×10^{34} cm^{-2}s^{-1}. The next phase is the upgrade of the LHC injectors, which will allow, e.g., increasing the number of bunches, also by about a factor of two. This again doubles the luminosity, which may now exceed 9.2×10^{34} cm^{-2}s^{-1}. In a final step, the energy of the LHC could be increased two or three times, by installing stronger dipole magnets with a field of 15–24 T, depending on the technological progress. A few years ago, a proof-of-principle magnet based on Nb_3Sn s.c. material at LBNL has reached 16 T with a 10-mm aperture [7]. The European NED activity aims at developing a large-aperture (up to 88 mm), 15-T dipole-magnet model. For the LHC "energy tripler" Texas A&M University proposes a 24-T block-coil dipole with high-Tc superconductor (Bi-2212) in the inner high-field windings and Nb_3Sn for the outer low-field windings, whose coil area is about 4 times smaller than expected from scaling past magnet data [8].

This report is organized as follows. We first describe possible LHC upgrade paths, and, next, discuss pertinent beam-dynamics issues. After addressing the upgrade of the interaction region (IR), we turn to intensity limitations and sketch the LHC injector upgrade. Then we introduce the HHH accelerator-simulation code repository and briefly discuss plans for code benchmarking and development, before we close with an outlook at the time schedule.

UPGRADE PATHS

At the nominal bunch length and with a crossing angle 10% higher than nominal, the so-called ultimate beam-beam limited LHC performance is reached for a bunch population of about 1.7×10^{11} protons per bunch. The standard upgrade plan then simply calls for an increase in the number of bunches and a reduction of β^*. This likely requires a higher-harmonic rf for shortening the bunch length, as the crossing angle will need to be increased in order to limit the effect of long-range collisions, while at the same time it is desired to maintain a constant value for the product of crossing angle and bunch length, $(\theta_c \sigma_z)$, which determines the geometric luminosity loss, already significant in the nominal LHC. Alternative mitigation schemes, like wire compensation, crab cavities or detector-integrated dipoles, are being considered as well. Other upgrade scenarios raise the luminosity at the beam-beam limit by using fewer, more intense bunches or an increased crossing angle [9].

Table 1 compares selected parameters of the nominal and ultimate LHC with those for two different upgrade paths, in one case embracing a larger number of shorter bunches, in the other a smaller number of longer bunches. The peak luminosity is about the same for either upgrade path.

Table 1: Parameters for the nominal and ultimate LHC compared with those for two upgrade scenarios with (1) shorter bunches at 12.5-ns spacing [baseline], (2) longer more intense uniform bunches at 75-ns spacing [large Piwinski parameter], including heat loads per beam aperture [2]. The normalized transverse emittance is 3.75 μm in all cases.

parameter	symbol	nominal	ultimate	shorter bunches	longer bunches
protons/bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
no. bunches	n_b	2808	2808	5616	936
bunch spacing	$\Delta t_{\rm sep}$ [ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longit. profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
beta function at IP1&5	β^* [m]	0.55	0.5	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	ϕ	0.64	0.75	0.75	2.8
peak luminosity [10^{34} cm^{-2}s^{-1}]	L	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
luminosity lifetime ($\tau_{\rm gas} = 85$ h)	τ_L [h]	15.5	11.2	6.5	4.5
optimum run duration ($T_{ta} = 10$ h)	$T_{\rm run,opt}$ [h]	14.6	12.3	8.9	7.0
e-cloud heat load at 4.6–20 K	$P_{\rm ec}$ [W/m]	1.07	1.04	13.34	0.26
for $\delta_{\rm max} = 1.4$ (1.3)		(0.44)	(0.59)	(7.85)	(0.26)
synchrotron radiation heat at 4.6–20 K	P_γ [W/m]	0.17	0.25	0.50	0.29
image current power at 4.6–20 K	$P_{\rm ic}$ [W/m]	0.15	0.33	1.87	0.96
beam-gas scattering heat at 1.9 K	$P_{\rm gas}$ [W/m]	0.038	0.056	0.113	0.066

The long bunches have the advantage of avoiding electron-cloud problems and implying only a small increase in the total beam current. Their drawback is the much higher number of pile-up events in the physics detectors.

BEAM DYNAMICS

One decisive factor determining the choice of upgrade path may be the electron cloud, which is expected to build up in the LHC vacuum chamber due to photoemission from proton synchrotron radiation and secondary emission. Observations at many accelerators suggest that the threshold bunch intensity scales about linearly with the bunch spacing [10]. Therefore, doubling the number of bunches and reducing the bunch spacing from 25 ns to 12.5 ns may well turn out to be impossible. Electron-cloud instabilities have been observed at almost all past and present proton or positron accelerators, from INP PSR, ANL ZGS and BNL AGS around 1965, over the Bevatron, CERN ISR, LANL PSR, BNL AGS Booster, to KEKB, PEP-II, DAFNE, CERN SPS, RHIC, and Tevatron [11].

Data collected during the CARE-HHH-APD HHH-2004 workshop provided evidence that the electron-cloud is a "critical mass phenomena", which primarily depends on the central beam-charge density $\rho_{\rm center} \equiv ZN_b/(\sigma_x\sigma_y\sigma_z)$ in the laboratory frame [12], with N_b the bunch population, Z the charge per particle in units of the elementary charge, and the σ's the three rms beam sizes. The data in Table 2 suggest that the critical charge density value for hadron beams is of order 0.1–0.3$\times 10^8$ mm^{-3}. Preliminary experience at SNS indicates, however, that a careful design can push this limit higher, though the LHC parameters lie deep in the "dangerous" territory. On the other hand, so far no theoretical model has been proposed to support the singular role of the central charge density.

Table 2: Central charge density and observation, or likelihood, of electron cloud in various past, operating or future hadron machines [12].

accelerator	$\rho_{\rm center}$ [10^8/mm^3]	e-cloud?
ISR	0.14	yes
CPS	0.28	yes
SPS (LHC beam)	0.21	yes
SPS (FT beam)	0.13	(yes)
PSR	0.15	yes
RHIC	0.10	yes
ISIS	0.006	no
SNS	0.30	?
J-PARC (3 GeV)	0.04	safe?
FNAL 8-GeV p Driver	0.03	safe?
J-PARC (50 GeV)	0.17	?
FAIR SIS-18/100	0.23/0.31	?
LHC	159	?!

The electron cloud is "pinched" during the passage of a beam, which leads to an increase in the electron-induced tune shift from the bunch head towards the tail. This additional focusing which depends on the longitudinal coordinate with respect to the bunch center, z, may give rise to enhanced Landau damping or it could be destabilizing. We consider a simplified model, consisting of a quasi-parabolic longitudinal bunch profile $\rho_b(z) = 15/(16\sqrt{7}\sigma_z)\left(1 - z^2/(7\sigma_z^2)\right)^2$, for $|z| < \sqrt{7}\sigma_z$, and a linear tune shift along the bunch, $\Delta Q_{ec}(z) = (z - \sqrt{7}\sigma_z)/(2\sqrt{7}\sigma_z)\Delta Q_{ec,\rm max}$, with maximum value $\Delta Q_{ec,\rm max}$. Combining these two equations and following

established recipes [13] we derive the dispersion relation

$$-\Delta Q_{\rm coh} = \frac{\mathrm{PV.}\int_0^{\Delta Q_{ec,\max}} dQ_{ec}\,\frac{\rho(\Delta Q_{ec})\Delta Q_{ec}}{\Delta Q_{ec}-\Delta Q} + i\pi\rho(\Delta Q)\Delta Q - 1}{\mathrm{PV.}\int_0^{\Delta Q_{ec,\max}} dQ_{ec}\,\frac{\rho(\Delta Q_{ec})}{\Delta Q_{ec}-\Delta Q} + i\pi\rho(\Delta Q)} \quad , \tag{1}$$

where "$PV.$" denotes the principal value, ΔQ the real coherent tune shift, and $\Delta Q_{\rm coh}$ the one expected without Landau damping. The stability diagram is obtained by calculating $\Delta Q_{\rm coh}$ for ΔQ running along the real axis. It is displayed in Fig. 1, which shows that, with our model assumptions, the electron potential creates a non-trivial stability border. The underlying assumption is that z can be treated as a parameter, which is valid for instabilities with rise times much shorter than a synchrotron period.

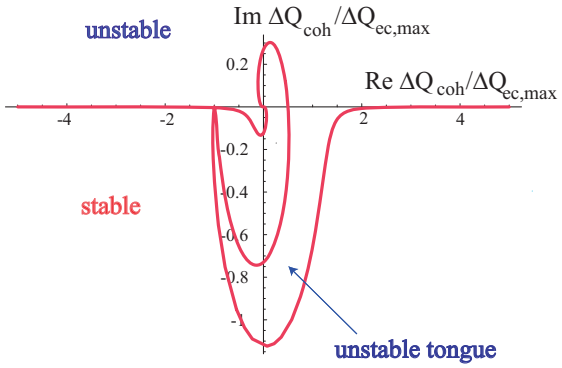

Figure 1: Stability diagram with pinched electron cloud.

Applying the theory of fast blow up [14] to a resonator impedance modeling the electron cloud [15] and including an approximation to the electron pinch in the vertical direction [16], we may also obtain an estimate for the electron density threshold of the fast TMCI-like instability driven by the electron cloud [17], namely

$$\rho_{e,\rm thr} \approx \frac{4\pi\eta\epsilon_{||,\rm rms}(E/e)}{ecZ_0\beta_y\sqrt{2\pi}\sigma_z^2} \quad . \tag{2}$$

Interestingly, using instead the two-particle model of [17] we find exactly the same dependence on all parameters, and only the numerical factor in front is several times smaller. Applying formula (2) to scale the density threshold from the SPS ($\sigma_z \approx 0.3$ m, $\beta_y \approx 40$ m, $E \approx 26$ GeV, $\alpha_c \approx 1.8\times10^{-3}$ $\epsilon_{||,\rm rms} \approx 0.32$ mm) to that in the LHC ($\sigma_z \approx 0.011$ m, $\beta_y \approx 100$ m, $E \approx 450$ GeV, $\alpha_c \approx 3.2\times10^{-4}$ $\epsilon_{||,\rm rms} \approx 0.053$ mm), the electron-density threshold for the electron-induced TMCI in the LHC is predicted to be about 5 times higher than that in the SPS. Direct simulations with the HEADTAIL PIC code indicate about the same threshold density of 5×10^{11} m^{-3} for both machines [18].

After surface conditioning and in the absence of coherent instabilities, the lifetime of the LHC beam in the SPS is still poor, about 15–20 minutes. The observed variation in bunch lifetime along two successive SPS trains [19] closely resembles the measured electron flux at the wall [20], suggesting that the residual electron cloud may be responsible for the poor lifetime of the LHC beam in the SPS [21].

Also in simulations, the emittance growth below the threshold of the coherent TMCI-like instability, though 10–100 times smaller than above, is not zero, and its value would be significant over a few hours of store. Closer inspection of experimental data has revealed that the particle losses in the SPS coincide with a shrinkage of the bunch length [22]. Two mechanisms of incoherent emittance growth due to an electron cloud have recently been identified [23], namely the periodic crossing of resonances or of regions with linear instability, respectively, which lead to halo formation and to core growth. These dynamical processes provide a plausible explanation for the poor beam lifetime in the SPS, for the associated bunch-length shrinkage, and for the incoherent emittance growth below coherent threshold seen in the simulations.

IR UPGRADE

The choice of IR upgrade is tied to the beam parameters. The IR "baseline" scheme features quadrupoles as first optical elements closest to the collision point, which minimizes the chromaticity, as in the nominal LHC IR. Two options then exist: either short bunches collide at a small crossing angle, facilitated by long-range beam-beam compensation, or longer bunches with a larger crossing angle are fed into two separate quadrupole channels, aided by crab cavities or operating at the beam-beam limit in the regime of large Piwinski parameter. The minimum full crossing angle required for separation into two different quadrupole channels is less than 2 mrad [24]. Alternative IR schemes consider "dipoles first," where the two beams are first separated before being focused. In this case, to cope with the collision debris a special type of magnet, namely an "open midplane" s.c. dipole, has been proposed in the US LARP [25]. Also the dipoles-first scenario allows for the options of small or large crossing angle, additional crab crossing, etc. Other innovative proposals include the collision of flat beams [26], and detector-integrated dipoles [27, 28] or quadrupoles [29]. The magnet technology for the new IR magnets has not been decided. Possibilities are standard NbTi, "pushed" NbTi, or Nb_3Sn. IR options for the LHC upgrade are compiled on a dedicated web site [30], and will be rated using a variety of criteria, such as risk, development time, expected performance, aperture, energy deposition, chromatic correction, beam-beam compensation, and operational difficulties.

Without crab cavities, the maximum aceptable crossing angle follows from the bunch length via the geometric luminosity reduction factor $R \approx 1/\sqrt{1+\phi^2}$, where $\phi \equiv \theta_c\sigma_z/(2\sigma_x^*)$ denotes the Piwinski angle [31]. Without wire compensation, a minimum crossing angle is imposed by the effect of the long-range beam-beam collisions occurring on either side of the primary collision point [31, 32, 33, 34]. Here we only note that a wire compensator can increase the dynamic aperture of the nominal LHC by 1–2 σ and it might allow keeping a constant crossing angle as the beam currents are increased. Successful experiments with prototype wire compensators, at excitations of

up to 320 Am, were performed in the CERN SPS [35]. Studies with real colliding beams are planned at RHIC in 2006/2007 [36]. For the efficient long-range compensation of all LHC bunches, the wire needs to be pulsed [37], at an average rate of 439 kHz, and with a turn-by-turn jitter of less than 10^{-4} in relative amplitude or, equivalently, less than 0.04 ns timing jitter [31, 37]. An attractive alternative is the recently proposed detector-integrated dipole "D0" [27, 28], which promises a similar improvement in the dynamic aperture. During 2006, crab cavities will be employed for the first time in an operating collider, at KEKB. Crab cavities at the LHC would combine all advantages of head-on and long-range collisions. In particular, for restoring the same Piwinski factor the crab-cavity rf voltage required is typically 100-1000 times less than the voltage of the equivalent bunch-shortening higher-harmonic rf system [31]. Applications in a hadron collider will require further tests. Also here jitter is a concern. Theory [38] and simulations [39] suggest that the relative left-right crab-rf timing jitter must stay below 0.002 ps for an emittance growth of less than 1% per hour, corresponding to a random IP offset of about 0.6 nm [31].

Considerations determining the optimum choice of IR upgrade give rise to the roadmap of Fig. 2.

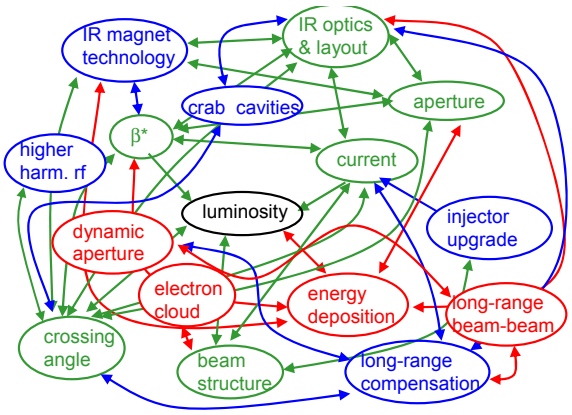

Figure 2: Upgrade roadmap for the LHC IR showing complex interdependence.

INTENSITY LIMITATIONS

Important beam intensity limits arise from collimator impedance, beam dump, machine protection, electron cloud, long-range and head-on beam-beam effects, and the injectors.

The most severe restriction comes from the collimator impedance, which limits the LHC beam intensity to about 40% of its design value [40]. The impedance can be reduced by employing local nonlinear elements which amplify the amplitude of halo particles at the location of the primary collimators. An optics with two skew sextupoles separated by a $-I$ transform has been developed for the LHC IR 7 [41]. For this optics, both dynamic aperture and cleaning efficiency are comparable to those in the baseline linear optics, while the total number of collimators is reduced and the gaps of most remaining collimators are increased, as is illustrated in Fig. 3. This scheme also represents a promising approach for the upgrade, where even higher beam current must be handled.

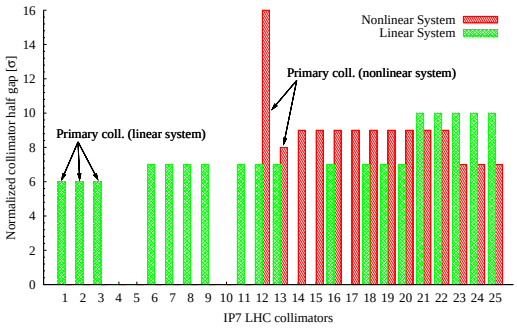

Figure 3: Normalized collimator half gaps and collimators employed with nominal linear and alternative nonlinear collimation in LHC IR 7 (J. Resta) [41].

The higher beam intensity must be provided by new injectors [42]. The 160-MV Linac-4 will supply beams with higher brightness. A Super-PS or PS2 will double the extraction energy from the PS to about 50 GeV. A Super-SPS will raise the LHC injection energy from 450 GeV to 1 TeV. And the Super-LHC itself will profit from the higher injection energy. At 1 TeV injection energy also the transfer lines connecting the Super-SPS and the LHC will need to be upgraded with s.c. dipole magnets. These could possibly be recuperated from HERA or from the Tevatron.

The motivation for the injector upgrades is to raise the beam intensity for a given geometrical aperture set by the accelerator beam pipe and for a constant limit on the maximum brightness set by space charge and beam-beam effects. At the same time the reduction of dynamic effects (persistent-current decay and snapback) is expected to reduce the LHC "turn-around time" by about a factor of 2, which will further increase the effective luminosity. Also, the higher LHC injection energy may be the first, and a necessary, step towards a future LHC energy upgrade. In addition, other CERN programmes, such as neutrino physics and beta beams, will benefit from the LHC injector upgrades. The injector R&D focuses on s.c. magnets with about 10-s cycle rate, strongly focusing optics, injection, and extraction.

CODE BENCHMARKING

CARE-HHH is also committed to improve the infrastructure of accelerator-physics codes, pursuing three goals: (1) a common repository for linear and nonlinear optics, programs, impedance estimates, and simulation codes for collective effects, such as conventional instabilities, beam-beam, space charge and electron-cloud effects; (2) the code validation by mutual comparisons and benchmarking against machine experiments and a centralised documentation, fostering code reliabilty; (3) the extension of simulation codes to cover relevant beam physics and implementation of effective procedures for beam measurements, machine protection, background control, and performance optimization. Two web sites for the code repository have been

established [43]. About 35 codes are presently included. Benchmarking of electron-cloud and space-charge codes is in progress, e.g., the weak-strong version of `HEADTAIL` has been validated against `MICROMAP` [44]. Details on the repository and the benchmarking effort are discussed in a companion paper [45]. Code extensions aim at more complete, more detailed, and more quantitative predictions [46], as sketched in Fig. 4.

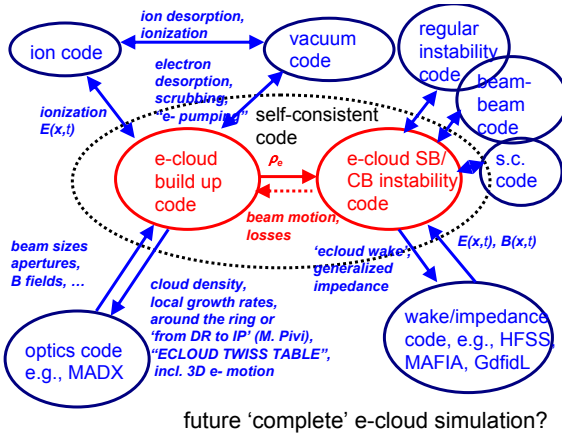

Figure 4: Schematic of ultimate simulation code developed around a self-consistent electron-cloud core [47].

OUTLOOK

Tentative milestones for the LHC upgrade comprise [48]: (2006) installation of crab cavities in KEKB, validation of KEKB beam-beam perfomance with crabbing, installation of long-range wire compensators in RHIC; (2007) experiments with three dc beam-beam compensators at SPS, dc compensation experiments with colliding beams in RHIC, SPS crystal-collimation tests, low-noise crab tests at RHIC; (2008) LHC collimation tests, LHC upgrade conceptual design report, RHIC pulsed wire compensators; (2009) further LHC collimation tests; (2010) LHC upgrade technical design report, (2011) LHC tests on collimation and beam-beam, nominal LHC luminosity; (2014) new SPS kickers, ultimate LHC luminosity; (2015) new IR magnets, new rf system, and beam-beam compensation.

In many supersymmetry scenarios consistent with cosmological and astrophysical constraints, the two lightest sparticles can only be found by an LHC energy tripler [8, 49]. Therefore, we should not lose sight of the ultimate goal, that is higher energy.

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