BEAM PARAMETERS AND LUMINOSITY TIME EVOLUTION FOR AN 80-KM VHE-LHC *

O. Domínguez† ‡ and F. Zimmermann, CERN, Geneva, Switzerland

Abstract

The Very High Energy LHC (VHE-LHC) is a recently proposed proton-proton collider in a new 80-km tunnel. With a dipole field of 15-20 T it would provide a collision energy of 76-100 TeV c.m. We discuss the VHE-LHC beam parameters and compute the time evolution of luminosity, beam current, emittances, bunch length, and beam-beam tune shift during a physics store. The results for VHE-LHC are compared with those for HE-LHC, a 33-TeV (20-T field) collider located in the existing 27-km LHC tunnel.

INTRODUCTION

The beam energy is a key parameter for the particle-physics discovery potential of a hadron collider like the LHC. This, together with the expected long development time, motivates scenarios for a higher energy machine, which could shed light on New Physics beyond the standard model.

The High Energy Large Hadron Collider ("HE-LHC") is a proposed LHC energy upgrade currently under study at CERN [1, 2], which would install 20-T dipole magnets in the existing 27-km tunnel, in order to achieve a centre-of-mass energy of 33 TeV in pp collisions. A large R&D effort on superconducting magnets is still required to achieve — in industrial production — the targeted 20-T operating magnetic field envisaged for this project, but the current state of the art and recent progress with Nb_3Sn, Nb_3Al and HTS materials (e.g. [3, 4]) bode well.

More recently, in August 2012, first studies on the feasibility of an 80-km tunnel in the CERN/Geneva area have been carried out [5]. The associated accelerator complex has taken further shape during the *European HEP strategy update* [6] . Namely, the 80-km tunnel could host a high-luminosity lepton collider serving as Higgs, Tera-Z, Mega-W and top factory (Triple LEP or "TLEP"), a hadron collider (Very High Energy LHC, or "VHE-LHC"), as well as a higher-energy lepton-hadron collider (tentatively called "VHE-TLHeC"). In the next section we discuss beam dynamics related issues for the VHE-LHC and compare the resulting parameters with those for HE-LHC.

BASIC PARAMETER CHOICES

Considering the same geometry and the same filling factor (around 66%) for the bending magnets as for the nominal LHC, a 20-T field in the 80-km tunnel would yield a beam energy of 50.4 TeV, which is to be compared with the 7-TeV design energy of the LHC and the 16.5 TeV of the HE-LHC. An initial target luminosity value of $L = 5 \times 10^{34}$ cm^{-2}s^{-1} has been defined, equal to the design target value of the (leveled) peak luminosity for the High Luminosity LHC ("HL-LHC" [8]) and to the recently revised HE-LHC figure.

The nominal VHE-LHC bunch spacing is 25 ns, with a total number of $n_b = 8420$ bunches per beam. Electron cloud simulation studies, with results presented in Fig. 1, reveal that at a bunch spacing of 25 ns the heat load due to electron cloud remains acceptable under conservative assumptions for the maximum secondary emission yield, e.g. $\delta_{\max} < 1.7$. Indeed after a few days of surface conditioning with 25-ns beams, the present value of $\delta_{\max}$ in the LHC arcs already meets this requirement [9]. Even a 5-ns spacing appears possible for the VHE-LHC and could be interesting since it would further lower the event pile up, if compatible with detector electronics.

At both HE-LHC and VHE-LHC specific countermeasures must be taken against the high photon flux (and heat) from synchrotron radiation. For example, regularly spaced photon absorbers at warm temperature are being considered, which could also be biased with a positive voltage to prevent the escape of photoelectrons or to serve, in addition, as clearing electrode.

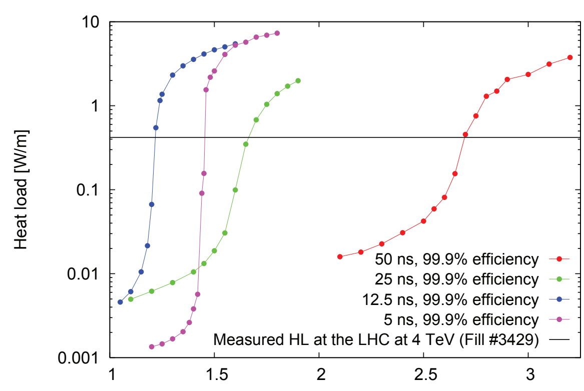

Figure 1: Simulated electron-cloud heat load in the VHE-LHC arc dipoles as a function of the maximum secondary emission yield for different bunch spacings, considering a chamber half aperture of 13 mm, and assuming that 99.9% of the synchrotron radiation photons are absorbed in dedicated photon stops and do not contribute to the primary photoelectrons initiating the EC build up.

The LHC total design beam-beam tune shift is 0.01. To be conservative the same limit of 0.01 has been adopted for the VHE-LHC baseline. Dedicated LHC machine studies

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† Also at EPFL, LPAP, CH-1015 Lausanne, Switzerland
‡ octavio.dominguez@cern.ch

indicate that the chosen value for the total beam-beam tune shift is indeed conservative [10]. On the other hand, Table 1 illustrates that the synchrotron-radiation power and the stored beam energy, both scaling in proportion to the beam current, are already challenging for this value of tune shift. Thus, a higher maximum achievable tune shift may allow an optimization of some machine parameters (e.g. increasing β^* for non-zero crossing angle or decreasing the emittance), but it should not be considered as a license for increasing the beam current.

The crossing angle is chosen so as to provide a separation of 12σ at the parasitic long-range encounters, which is higher than the 9.5σ separation of the nominal LHC, and ensures that long-range beam-beam effects are negligible.

Synchrotron radiation (SR) is significant at these higher proton energies, posing numerous challenges for vacuum and cryogenics. It also becomes one of the key ingredients of beam dynamics due to the consequent strong damping. Another item considerably affected by the strong radiation is the RF system. The LHC RF voltage (16 MV) was chosen to meet the imposed emittance and bunch length conditions at collision energy (2.5 eVs and 7.6 cm ($\approx 1\,\mathrm{ns}$) respectively) [11]. This voltage appears to have an important margin to fulfil the desired conditions [12]. This fact together with the increased bucket area ($A \propto \sqrt{E}$) suggest that the HE-LHC would not need to change the RF voltage with respect to the LHC. Nevertheless, in the case of the VHE-LHC, the synchrotorn-radiation energy loss per turn reaches the value of 5.9 MeV, unprecedented in a hadron accelerator. As a result, the synchronous phase shift and the resulting change of shape of the bucket area are non-negligible. In particular one can no longer consider a static RF bucket with $\phi_s = \pi$. Part of the total RF voltage is used to recover the energy lost per turn. For this reason we have increased the total voltage of the VHE-LHC with respect to LHC (and HE-LHC) by about 5.9 MV, i.e. we consider a total RF voltage of about 22 MV. The longitudinal emittance has been chosen to achieve the same bunch length as in the LHC (about 7.6 cm), which together with the RF voltage, energy loss, and RF frequency translates to a longitudinal emittance ($4\pi\Delta E_{\mathrm{rms}}\sigma_z/c$) of 13.5 eVs.

Bunch population and transverse emittance have been chosen by imposing the aforementioned conditions on luminosity and beam-beam tune shift for a certain value of β^*. For each value of β^* we obtain a different set of parameters and the baseline set of parameters has been chosen so as to obtain a similar beam current to the HE-LHC. In addition, two flat beam scenarios (with horizontal/vertical emittance ratios equal to 2 and 10) and a round beam option have been studied. In terms of luminosity performancem the options turned out to be completely equivalent, so that here we present only the round-beam results.

Proton beam lifetime is assumed to be entirely due to consumption in collision, which depends on the luminosity, the number of collision points, and the total cross section. To estimate the energy dependence of the scattering cross sections we have applied an extrapolation based on Ref. [13] (values in Table 1). Latest measurements in the TOTEM experiment at the LHC at 7 and 8 TeV c.o.m energy show a perfect agreement with this scaling law [14].

The VHE-LHC injection energy is assumed to be equal to, or higher than 3 TeV (to be compared to 450 GeV for the LHC and to about 1 TeV for the HE-LHC), in order to confine the VHE-LHC energy ramp to a factor of about 16, similar to the present LHC.

TIME EVOLUTION AND LUMINOSITY

The same procedure as used for HE-LHC studies [1, 7] has been followed for the VHE-LHC, i.e. we have applied the same simulation tool to calculate relevant beam parameters and their evolution in time during a physics store, including the optimum run time and integrated luminosity per day. Table 1 lists some of the main VHE-LHC parameters obtained as output of our program.

The 20 times higher stored beam energy and the about 800 times higher SR power per ring for VHE-LHC compared with the nominal LHC will place additional demands on the machine protection and cryogenic systems. The energy stored in the magnets is also greatly increased for the 20-T field, possibly requiring a different approach to magnet protection.

In the VHE-LHC, the emittance evolution with time is determined by intra-beam scattering (IBS) and SR damping. Another key ingredient for the luminosity time evolution is proton burn off. However, SR damping times are much shorter than IBS growth times (see Table 1). Therefore, if the emittance is left to shrink naturally under the influence of the strong SR damping, the beam-beam tune shifts and luminosity (and consequently radiation due to collision debris, inner tracker heating, as well as detector pile up) would quickly rise to unacceptable values during the store. Also, the rapid decrease of the bunch length is likely to lead to the loss of longitudinal Landau damping. As mitigation for both these problems, we consider a continuous controlled emittance blow-up through noise injection in all three planes [15, 16]. The transverse blow up is taylored so as to limit the tune shift at its maximum target value, which yields the optimum integrated luminosity per run. The controlled longitudinal blow up can be applied to maintain a constant longitudinal emittance, and hence bunch length. Also a reduction of the crossing angle during the store is possible, along with the shrinking transverse emittance. Simulations show that both longitudinal emittance and crossing angle can be kept constant during a physics store (baseline scenario for the VHE-LHC).

SUMMARY

A proposed set of key parameters for the Very High Energy LHC has been presented and justified. A few beam-dynamics and optics issues have also been highlighted, such as the fast radiation damping, the resulting potentially high beam-beam tune shifts, and the implied need for transverse and longitudinal emittance control through noise injection. Overall, however, the beam dynamics challenges appear benign. By virtue of its radiation damping

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Table 1: Preliminary VHE-LHC parameters for round beams. LHC, HL-LHC and HE-LHC parameters have been included for comparison. For all cases a bunch spacing of 25 ns and an rms bunch length of 7.6 cm is considered. For the HL-LHC, in the integrated luminosity per day and optimum run time calculations, the effects of crab cavities and luminosity leveling are included. HE-LHC values have been updated with respect to reference [1, 2].

	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14		33	100
circumference [km]	26.7			80
dipole field [T]	8.33		20	
dipole coil aperture [mm]	56		≤ 40	
beam half aperture [mm]	18 (x), 22 (y)		≤ 13 (x & y)	
no. bunches	2808			8420
av. bunch population [$\cdot 10^{11}$ ppb]	1.15	2.2	0.94	0.97
initial transverse norm. emittance [μm rad]	3.75	2.5	1.38	2.15
β_x^* [m]	0.55	0.15 (min.)	0.35	1.1
RF voltage [MV]	16			22
longitudinal emittance [eVs]	2.5		3.8	13.5
rms momentum spread [$\cdot 10^{-4}$]	1.13		0.74	0.85
no. IPs contributing to tune shift	3	2		
max. total beam-beam tune shift	0.01	0.015	0.01	
beam circulating current [A]	0.584	1.12	0.478	0.492
stored beam energy [GJ]	0.362	0.694	0.701	6.61
SR power per ring [kW]	3.6	7.3	96.2	$2.9\cdot 10^3$
arc heat load [W m^{-1}/aperture]	0.17	0.33	4.35	43.4
energy loss per turn [keV]	6.5		201.3	$5.9\cdot 10^3$
critical photon energy [eV]	44		575	$5.5\cdot 10^3$
transverse SR damping time [h]	12.9		1.01	0.32
longitudinal SR damping time [h]	25.8		2.02	0.64
initial horizontal IBS rise time [h]	103	20.4	20.1	157
initial longitudinal IBS rise time [h]	57	23.3	40.0	396
peak luminosity [$\cdot 10^{34}$cm^{-2}s^{-1}]	1.0	5.0 (leveled)	5.0	
crossing angle [μ rad]	285	590	185	72
max. number of events per crossing	27	135	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
beam lifetime due to proton burn-off [h]	40.2	15.4	5.7	14.8
optimum run time [h]	16.9	10.2	5.8	10.7
integrated luminosity per day [fb^{-1}]	0.53	2.8	1.43	2.08

the VHE-LHC will be an even more forgiving machine than the LHC. VHE-LHC R&D activities should focus on high-field dipole magnets, the 80-km tunnel, machine protection issues, and the (upgraded or new) injector chain.

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