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OPTIMIZED ARC OPTICS FOR THE HE-LHC*

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Abstract

The High Energy LHC (HE-LHC) proton-proton collider is a proposed replacement of the LHC in the existing 27-km tunnel, with the goal of reaching the centre-of-mass beam energy of 27 TeV. The required higher dipole field can be realized by using 16-T dipoles being developed for the FCC-hh design. A major concern is the dynamic aperture at injection energy due to degraded field quality of the new dipole based on Nb_3Sn superconductor, the potentially large energy swing between injection and collision, and the slightly reduced magnet aperture. Another issue is the field in quadrupoles and sextupoles at top energy, for which it may be cost-effective, wherever possible, to stay with Nb-Ti technology. In this study, we explore design options differed by arc lattice, for three choices of injection energy, with the goal of attaining acceptable magnet field and maximum injection dynamic aperture with dipole non-linear field errors.

INTRODUCTION

The High Energy LHC (HE-LHC) proton-proton collider is a proposed replacement of the LHC [1] in the existing 27-km tunnel, with the goal of increasing the centre-of-mass (CM) beam energy from 14 to 27 TeV. Some of the challenges of this machine are: a factor of almost two higher dipole field; high field quadrupoles and sextupoles; fitting the rings to the LHC layout within the existing tunnel; sufficient beam aperture at injection; sufficient dynamic aperture (DA) with expected large field errors in dipoles at injection.

The LHC arc magnets have the aperture of 56 mm, and nominal field of 8.33 T in dipoles (up to 9 T for the so-called ultimate performance), 223 T/m in quadrupoles, and 4430 T/m^2 in sextupoles [1]. The high-field magnets for the HE-LHC can be realized by taking advantage of the magnet technology being developed for the 100-km FCC-hh [2]. This proposed ring aims at reaching 16 T field in dipoles, 400 T/m gradient in quadrupoles, and 7800 T/m^2 in sextupoles, with the magnet aperture of 50 mm [3,4]. The present LHC lattice, scaled to 27 TeV CM energy, requires magnets exceeding the FCC field limit; therefore, a new lattice with a lower magnetic field is required for the HE-LHC.

The 16-T dipole is based on Nb_3Sn superconductor, which is expected to degrade the dipole field quality (FQ), compared to the present LHC dipole. Further degradation may be due to a potentially larger energy swing between injection and collision, and the slightly smaller magnet aperture. The degradation mostly occurs at injection energy since the FQ at top energy is better optimized. As a result, the injection DA may be reduced. We explore performance of several lattice options, differing by arc design, with the goal of attaining acceptable DA and magnet strengths. Since the FQ and beam size depend on energy, we also compare three choices of injection energy, namely 450, 900, and 1300 GeV.

LATTICE

The LHC consists of eight octants, where each one includes a FODO arc, a dispersion suppressor at each arc end, and a Long Straight Section (LSS) comprising an Interaction Region (IR). Initially, we design and study a simplified model of HE-LHC injection lattice with realistic arcs and dispersion suppressor optics, but simple IRs without separation dipoles. The simplified ring matches the LHC circumference of 26658.8832 m and approximates the average geometry of the two LHC rings. Later, we upgrade to more realistic designs with the appropriate IR optics and the layout closely following the LHC rings.

Two methods are considered for the reduction of the arc quadrupole and sextupole field: 1) a lower phase advance μ_c per arc cell; 2) a longer arc cell length L_c, where the number of cells is reduced as $1/L_c$. The second option provides more space for the dipoles, thus increasing the fill factor and reducing the dipole field. In both options, however, the arc's dispersion is increased; and a longer cell yields higher beta functions ($\sim L_c$). The drawback is a larger beam size enhancing aperture issues and the effects of field errors.

One strategy to reduce the impact of non-linear field errors is to choose the number of arc cells N_c and the cell phase advance such that $N_c\mu_c = 2\pi\times$integer. This results in cancellation of the second order effects from periodic sextupoles and the suppression of some of the high order resonances driven by systematic non-linear field errors in the periodic arcs [5-7]. Hence, the corresponding error tolerances may be looser. Example of cancellation of the third order resonance driving terms in each arc of a simplified 18×60 HE-LHC lattice model with 18 FODO cells per arc and 60° cell phase advance is shown in Fig. 1.

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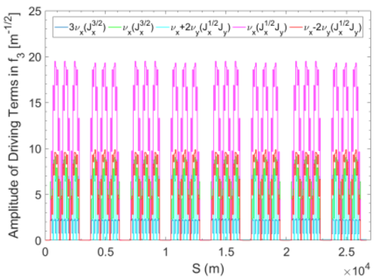

Figure 1: The third order resonance driving terms from arc sextupoles in 18×60 simplified lattice.

Parameters of four realistic designs of HE-LHC injection lattice are shown in Table 1, where the LHC lattice is also included for comparison. The designs have realistic IRs, and are differed by the number of arc cells and cell phase advance. The rings have the correct circumference, and follow the LHC layout with less than 10 cm radial deviations. Cell optics in the four HE-LHC designs is shown in Fig. 2. Detailed description of the most advanced 18×90 and 23×90 designs is presented in Ref. [8].

To determine the maximum required field in arc magnets, the field is shown at 13.5 TeV in Table 1. The nominal LHC lattice does not satisfy the FCC field limit. Quadrupole and sextupole strengths in the 24×60, 20×90 and 18×90 designs are naturally lower, while the magnets in the 23×90 lattice are made longer. As a result, the quadrupole field is acceptable in the HE-LHC designs. Sextupole strengths in the injection optics are acceptable with a good margin, but need to be further checked in collision optics, where chromaticity is higher. Dipole length in the HE-LHC designs is maximized for a lowest possible field. Still, only in the 20×90 and 18×90 options the target CM energy of 27 TeV can be reached with the 16-T dipole. The other two designs would limit the top energy, as shown in Table 1.

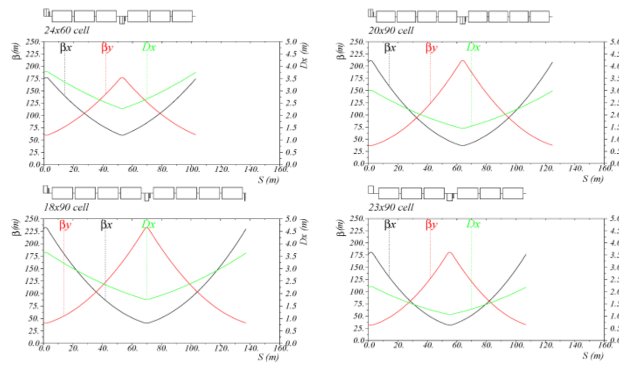

Figure 2: Arc cell optics in the 24×60, 20×90 (top), and 18×90, 23×90 (bottom) designs.

Table 1: Parameters of the HE-LHC Injection Lattice Options and the LHC Injection Lattice at 13.5 TeV Beam Energy

	LHC V6.503	**HE-LHC V3.1a**	**HE-LHC V3.1a**	**HE-LHC V0.3**	**HE-LHC V0.3**
Cells per arc × μ_c [deg]	23 × 90	24 × 60	20 × 90	18 × 90	23 × 90
Cell length [m]	106.90	102.90	124.80	137.23	106.90
Dipole length [m]	14.3	13.56	12.625	13.95	13.83
Dipoles per cell	6	6	8	8	6
Arc dipole fill factor	0.803	0.791	0.809	0.813	0.776
Arc dipole B [T]	16.06	16.30	15.92	15.85	16.61
Arc quad B′ [T/m]	404.8	288.2	334.8	336.1	348.1
Sextupole B″ [T/m^2]	4883	1891	3020	1639	2043
Max arc β function [m]	184	177	212	230	177
Max arc dispersion [m]	2.03	3.78	3.01	3.80	2.20
Tune, horiz. / vert.	64.28 / 59.31	46.28 / 45.31	54.28 / 53.31	49.28 / 47.31	62.28 / 59.31
Momentum compaction	$3.22 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$	$4.75 \cdot 10^{-4}$	$5.82 \cdot 10^{-4}$	$3.53 \cdot 10^{-4}$
CM energy at 16 T [GeV]	26.90	26.50	27.13	27.25	26.00

DYNAMIC APERTURE

LEGO [9] code is used to evaluate dynamic aperture of the lattice designs in Table 1. The calculations are done for three options of injection energy – 450, 900, and 1300 GeV, using short-term tracking with 1024 turns. This is deemed sufficient to perform the initial comparison and select the best designs; later, the DA of the selected lattice will need to be more accurately evaluated with a long-term tracking.

The DA is calculated at 21 angles in X-Y space, and expressed in units of rms beam size (σ) for the normalized emittance of 2.5 µm-rad. Linear chromaticity is corrected to +3 using the two-family arc sextupoles. Simulations are performed with and without momentum offset Δp/p, with synchrotron oscillations included. RF-voltage and the Δp/p settings for the three energy options are listed in Table 2. The RF frequency is 400 MHz.

Table 2: RF-Voltage and Δp/p in DA Simulations

E [GeV]	**450**	**900**	**1300**
Voltage [MV]	14	12.1	10.5
Δp/p [10^{-4}]	9	6.2	5.5

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Initially, we compare the DA without errors. The minimum DA with the Δp/p, for the three energy options, are shown in Fig. 3, where the nominal LHC is at the right end of the figure. The DA is large in all cases, with the maximum achieved in the 20×90 and 24×60 designs. The latter may be attributed to a better compensation of the sextupoles non-linear effects due to the choice of the arc phase advance of 2π×integer.

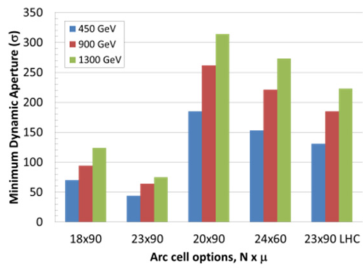

Figure 3: DA of the HE-LHC and LHC designs with Δp/p, without magnet errors.

Large non-linear field errors in the 16-T dipole are expected due to the Nb_3Sn superconductor, a potentially large energy swing between injection and collision, and smaller magnet aperture. Table 3 shows the largest normal field components of the HE-LHC dipole FQ for the three injection energy options, based on the latest estimate, assuming the wire filament size of 20 μm [10]. Here, the b_n are determined by [1]

$$b_n = b_{ns} + \frac{\xi_u}{1.5} b_{nu} + \xi_r b_{nr}, \qquad (1)$$

where b_{ns}, b_{nu}, and b_{nr} are the systematic, uncertainty and random terms in Table 3; and ξ_u, ξ_r are random Gaussian values with σ = 1, truncated at 1.5σ and 3σ, respectively. The same ξ_u applies to magnets of a given class, while ξ_r differs for each magnet; both change from seed to seed.

Table 3: Largest Field Components of the HE-LHC Dipole FQ in 10^{-4} Units at the Reference Radius of 16.7 mm

E [GeV]	450		900		1300	
	s	u/r	s	u/r	s	u/r
b_3	-35	10	-55	4	-40	3
b_5	8	1.5	8	1.5	4	0.8
b_7	0.2	0.211	0.6	0.211	1.1	0.211
b_9	3.8	0.5	4.2	0.5	2.9	0.2
b_{11}	0.75	0.028	0.86	0.028	1	0.028

The large b_3 and b_5 errors without correction result in a small DA. Similar to the LHC, the b_3 and b_5 correctors are included in the HE-LHC design. The nominal scheme includes one b_3 corrector per arc dipole, but we also check the option of two correctors per dipole (one per each side). The latter improves the local correction yielding a slightly better DA. The b_5 correction scheme includes three correctors per arc cell and four correctors per dispersion suppressor, however it is included only in the latest 18×90 and 23×90 designs. Hence, to compare the DA of all four designs, instead of the b_5 correctors we simulate the correction by reducing the b_{5s} to 30% of its value in Table 3. Later, we verify the DA of the 18×90 and 23×90 designs with the actual b_5 correctors; this produces a slightly larger DA. In this study, we use one-family b_3 and b_5 correctors; it may be possible to improve the DA with multi-family correctors.

Short-term tracking with the dipole normal and skew field errors of order 3 to 15 is performed in LEGO for 10 seeds of random errors. LEGO allows only the systematic and random errors to be included; in order to account for the uncertainty terms, the random errors are increased by ≈20% to obtain the same rms value as in Eq. (1). Minimum DA of the four HE-LHC designs and the LHC with dipole field errors and Δp/p are shown in Fig. 4, where two b_3 correctors per dipole are used. Only the 23×90 and 20×90 designs at 1.3 TeV produce sufficiently large aperture. The DA at 450 and 900 GeV for all the designs is insufficient; this is due to the generally larger persistent current field errors at the low dipole field and a larger beam size at lower energy.

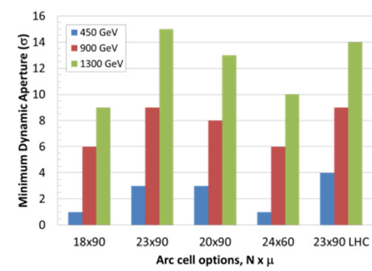

Figure 4: DA of the HE-LHC and LHC designs with Δp/p, 10 seeds of dipole field errors, and b_3, b_5 correction.

Figure 5 shows the short-term DA for the most developed 18×90 and 23×90 designs at 1.3 TeV, including the dipole field errors and the nominal b_3, b_5 correctors; the minimum DA is 10σ and 16σ, respectively.

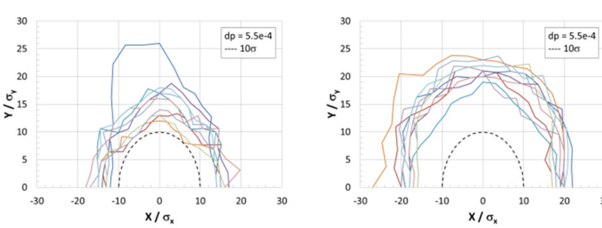

Figure 5: DA of the 18×90 (left) and 23×90 (right) designs at 1.3 TeV with errors and b_3, b_5 correction.

CONCLUSION

Comparison of realistic HE-LHC injection lattice options with various arc designs shows that the 23×90 option provides the maximum dynamic aperture at 1.3 TeV of injection energy. This design, however, limits the collision CM energy to 26 TeV with the 16-T dipole. The 18×90 option offers the lowest dipole field sufficient to reach the target 27 TeV CM energy, but the FQ needs to be strongly improved. The 20×90 design may be also considered as a compromise between the above two options, both in terms of the DA and the dipole field. Dynamic aperture at 450 and 900 GeV for all the designs is insufficient due to the large field errors and beam size.

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