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DYNAMIC APERTURE AT INJECTION ENERGY FOR THE HE-LHC*

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Abstract

As part of the Future Circular Collider study, the High Energy LHC (HE-LHC) is a proposed hadron collider situated in the already existing LHC tunnel. It aims at achieving a center of mass energy of 27 TeV, almost doubling the design c.o.m. energy of the LHC. This increase in energy relies on the use of 16 T Nb_3Sn dipoles to be developed for the FCC-hh. The field quality of these dipoles is expected to have a big impact on the Dynamic Aperture (DA) at injection energy and subsequently tracking studies are conducted to evaluate the impact of magnetic field errors on the beam dynamics. In the following the results of these studies for the different injection energies considered for the HE-LHC are presented and a possible strategy for increasing the DA is discussed.

INTRODUCTION

The HE-LHC, studied in the framework of the Future Circular Collider study [1], is a proposed successor to the High Luminosity LHC (HL-LHC). Located in the same tunnel as the LHC and using the 16 T Nb_3Sn dipoles, developed for the FCC-hh, the target center-of-mass energy of this collider is set to 27 TeV. As no major civil engineering is envisaged for the installation of the HE-LHC, the accelerator has to fit in the existing LHC tunnel while still reaching the target energy goal. This together with physical aperture considerations at injection and partial redesigns of some insertions puts severe constraints on the lattice design. The latest status and developments of the HE-LHC lattice design can be found in [2]. The parameters of the injected beam coming from the Super Proton Synchrotron (SPS) are assumed to be same as for the HL-LHC. A comparison of the key parameter of the (HL-)LHC and the HE-LHC is presented in Table 1. Using the current SPS as an injector for the HE-LHC the injection energy would remain at 450 GeV, resulting in an energy swing of a factor 30 for the HE-LHC magnets. The HE-LHC design studies also considered the option of a new, superconducting SPS, which would increase the injection energy up to 1.3 TeV [3]. At injection energy the field quality of the HE-LHC main dipoles is one of the major factors determining the size of the region of stable motion in phase space, also called dynamic aperture (DA). The current status for the DA at injection energy, using magnetic field error tables for the latest 16 T dipole design, is presented in the following.

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Table 1: Comparison between (HL-)LHC and HE-LHC Parameters [4–6]

Parameter	**(HL-) LHC**	**HE-LHC**
Center of mass energy [TeV]	14	27
Dipole Field [T]	8.33	16
$\beta^*_{x,y}$ [m]	(0.15) 0.55	0.45
No. of bunches per beam	2760	2808
Norm. Emittance [µm]	(2.5) 3.75	2.5
Bunch Population [10^{11}]	(2.2) 1.15	2.2
Beam Current [A]	(1.1) 0.58	1.12
Bunch Spacing [ns]	25	25

DYNAMIC APERTURE

The DA is computed for two HE-LHC lattice options and at three different injection energies (450 GeV, 900 GeV, 1.3 TeV). The tracking code SixTrack [7] is used to track particle pairs for 10^5 turns and using 5 different angles in x-y space. The tunes of the HE-LHC lattice are set to the fractional parts of the design injection tunes of the LHC (0.28/0.31) and the linear chromaticity is corrected to +2 units. The RF-voltage and momentum offset $\Delta p/p$ are set according to Table 2. Magnetic field errors are assigned to the main dipoles following [9]

Table 2: RF Parameters for Both HE-LHC Lattices [8]. The $\Delta p/p$ corresponds to 75% of the bucket height.

	18 arc cell lattice		**23 arc cell lattice**	
Energy [GeV]	Voltage [MV]	$\Delta p/p$ [10^{-4}]	Voltage [MV]	$\Delta p/p$ [10^{-4}]
450	10.7	6.53	10.4	8.27
900	10.8	4.61	10.5	5.84
1300	10.8	3.84	10.6	4.86

$$b_n = b_{nS} + \frac{\xi_U}{1.5} b_{nU} + \xi_R b_{nR} \,, \quad (1)$$

where b_{nS}, b_{nU}, and b_{nR} denote the systematic, uncertainty and random error component, respectively, and ξ_U and ξ_R are random numbers with a Gaussian distribution cut at 1.5 σ and 3 σ, respectively. The same random number ξ_U is used for dipoles belonging to the same arc whereas ξ_R changes for each dipole. 60 different initialisations of the random number generator (also called seeds) are used. Since the last report [10] the design of the dipoles has changed

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and correspondingly so the field quality tables. The new dipole design features an increased interbeam distance of 250 mm compared to the previous 204 mm and an asymmetric coil design in order to reduce the quadrupole component of the dipoles [11]. The filament size of the superconducting wire has been set to 20 µm and the addition of artificial pinning centers to reduce the magnetisation at low fields is assumed. The field quality tables for the main dipoles for three different injection energies and assuming half artificial pinning efficiency is presented in Table 3. The full errortable including skew components and for the case of full artificial pinning efficiency is presented in [11]. The

Table 3: Field Quality of the 16 T dipoles assuming half artificial pinning efficiency for various injection energies in units of 10^{-4} at a reference radius of 16.7 mm. Note that the random and uncertainty component share the same values. The full error table including skew components and the error table assuming full pinning efficiency can be found in [11].

Energy	Systematic			Uncertainty		
[GeV]	450	900	1300	450	900	1300
b_3	-50.8	-24.9	-16.2	0.7	0.7	0.7
b_4	0.6	0.8	0.9	0.5	0.5	0.5
b_5	12.3	5.1	3.2	0.3	0.3	0.3
b_6	1.1	0.7	0.5	0.2	0.2	0.2
b_7	-3.5	-1.3	-0.7	0.1	0.1	0.1
b_8	0.6	0.5	0.4	0.1	0.1	0.1
b_9	4.1	2.0	1.4	0.0	0.0	0.0

biggest difference between the full pinning efficiency and the half pinning efficiency case is in the systematic harmonics b_{3S}, b_{5S}, b_{7S}, and b_{9S} which are a factor 2 larger in the half pinning efficiency case. Due to the asymmetric design of coils there are, unlike to the previous case, nonzero systematic b_4, b_6, and b_8 components. The correction scheme of the nonlinear errors in the dipoles follows the one from the LHC. Attached to every dipole is a sextupole spool piece corrector to correct the b_3 error. All correctors in one arc belong to the same family and are set to correct the average b_3 in one arc. To correct the b_4 and b_5 errors, three nested octupole and decapole spool piece correctors are installed per cell. As with the b_3 correctors, all correctors in one arc belong to the same family and are powered to correct the average b_4 and b_5 error, respectively. For the evaluation of the DA, the same HE-LHC lattice version [12] as in the previously presented studies is used. This allows to compare the obtained results and see the impact on the DA of the field quality of the new dipole design. For the presented studies, the linear normal and skew errors of the dipoles were excluded and no misalignments of any element were taken into account to exclude the impact of feed-down. The minimum DA out of the 60 different seeds and 5 phase space angles is presented in Table 4 for both HE-LHC lattices and three injection energies.

Table 4: Minimum DA in σ for Both HE-LHC Lattices at Injection Energy

	# of	Energy [GeV]		
	arc cells	450	900	1300
half pinning	18	2.7	7.4	11.2
efficiency	23	5.4	12.3	15.9
full pinning	18	5.2	8.8	12.0
efficiency	23	7.9	12.9	16.9

Compared to previous dynamic aperture studies [10] a significant increase in DA is observed. As before, the LHC-like lattice option exhibits a higher DA compared to the 18-arc-cell option, partially attributed to the smaller beam size in the 23-arc-cell option. The difference between the error table with full pinning and the errors with half pinning efficiency only becomes evident at the lowest considered injection energy of 450 GeV. For the field quality tables with artificial pinning the target dynamic aperture of 12σ, assumed to be the same as for the LHC [4], is met by both lattices at 1.3 TeV injection energy and by the LHC-like lattice at 900 GeV.

β-beating from Corrector Misalignment

Following [9], the RMS beta-beating only due to the random b_2 is calculated for both lattices. It amounts to 3.9% in the 23-arc-cell option and 4.9% in the 18-arc-cell option. The higher beta-beating in the 18-arc-cell lattice is attributed to the larger beta functions in the dipoles. Due to a horizontal misalignment of the sextupole spool piece correctors attached to each dipole an additional linear optics perturbation from the feed-down from b_3 to b_2 can be generated. Using the criteria that the b_2 from feed-down should not exceed the random b_2 of the dipoles and other parameters such as a systematic spool piece setting error as specified in [9] the alignment tolerance of these spool pieces can be specified. For the case of an injection energy of 450 GeV the misalignment is required to be below 0.1 mm. As the systematic b_3 is smaller for the injection energies of 900 GeV and 1.3 TeV the tolerances are higher for these cases. At 900 GeV injection the misalignment should be below 0.28 mm whereas at 1.3 TeV the limit is set to 0.43 mm.

TOLERANCES ON SINGLE HARMONICS

For the cases where the DA is below its target value, additional studies were conducted to identify which harmonic has the biggest impact and to evaluate the need of additional correctors for higher order harmonics. For these studies only, the field quality assuming half artificial pinning efficiency was used as this one presented in all cases a lower DA. The results of these studies are presented in Table 5. Here, the entries 50% b_{3s} and 50% b_{5s} correspond to the cases where either the systematic b_3 or systematic b_5 component of the

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Table 5: Minimum DA in σ for studies evaluating the impact of single harmonics.

	18 arc cells		23 arc cells
Energy [GeV]	**450**	**900**	**450**
nominal minimum DA	2.7	7.4	5.4
50% b_{3s}	4.4	8.1	7.0
50% b_{5s}	2.8	7.7	5.4
no b_3 correction	0	1.7	0.8
no b_4 correction	2.6	7.7	6.4
no b_5 correction	1.1	4.1	2.0
$b_{6s} = 0$	2.7	7.4	5.5
$b_{7s} = 0$	2.9	8.2	5.5
$b_{9s} = 0$	2.7	7.7	5.3

dipoles was reduced by a factor 2. The remaining components including the random b_3 and b_5 were kept as before. In the cases indicated with *no b_n correction*, the corrector for the n th component was turned off to evaluate the need for this corrector circuit. In the last three cases $b_{6s} = 0$, $b_{7s} = 0$, and $b_{9s} = 0$ the systematic error component was set to 0 to simulate the effect of an ideal correction. From the results of these studies it is apparent that local correction of b_3 and b_5 is required. The removal of the b_4 corrections creates a significant change of the amplitude detuning which shows a beneficial impact on the DA for the 23 arc cell option at 450 GeV and at 900 GeV for the 18 arc cell option. Still, for the case of 450 GeV injection energy the high systematic b_3 of 50 units appears to be the limiting factor for the DA in these cases. Additionally, these studies currently do not support the installation of any other higher order correctors.

MAGNET SORTING

As a mitigation strategy, the effect of magnet sorting on the DA has been studied. Since the b_3 component has been identified as having the single biggest impact on DA these initial studies focused on sorting only for this component. In the LHC, sorting on b_3 was only necessary on one aperture given that the sextupole component in the LHC dipoles is well correlated between the apertures [13, 14]. For the 16 T dipoles of the HE-LHC, at present no such correlation between apertures can be assumed and the algorithm has to optimise both beams at the same time. The algorithm used in this case is a K-means clustering algorithm [15], adapted to provide clusters with an equal number of elements per cluster. By grouping together dipoles with a similar sextupole component in the same arc, the variance per arc is reduced and subsequently the correction using one family of sextupole correctors should improve. An example of the sorting is illustrated in Fig. 1. The dynamic aperture results with and without using this sorting algorithm are presented in Table 6, where an increase of at least 0.8 σ is observed in all cases. Here only the results for Beam 1 are presented due to the unavailability of a Beam 2 optics. Still, at 450 GeV injection energy the minimum DA seems insufficient and improvements in the correction strategies or in the field quality of the main dipoles are required.

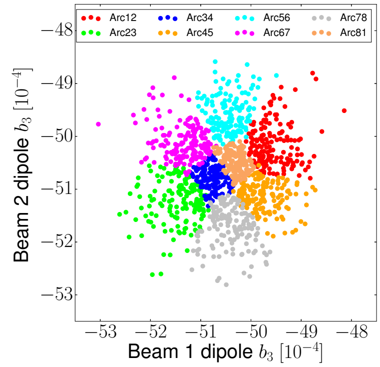

Figure 1: Illustration of the clustering to sort according to the b_3 component in both beams.

Table 6: Minimum DA in σ with sorting for both HE-LHC lattices at injection energy. Here only the results for the error table assuming half artificial pinning efficiency are shown.

	# of	Energy [GeV]		
	arc cells	**450**	**900**	**1300**
without sorting	18	2.7	7.4	11.2
	23	5.4	12.3	15.9
with sorting	18	3.8	9.0	14.4
	23	6.2	13.9	18.1

CONCLUSIONS AND OUTLOOK

The present status of the dynamic aperture at injection energy in the HE-LHC was described. With the current field quality tables for the main dipoles the DA at the lowest injection energy of 450 GeV is considered too low whereas the other two cases show more promising results. In addition, tolerances on the misalignment of the sextupole spool piece correctors attached to every dipole have been presented. Further studies show that a local correction of the b_3 and b_5 component of the dipoles is mandatory. At the current stage, the inclusion of other harmonics corrector circuits only shows a minor increase of the DA. Due to the high systematic b_3 at 450 GeV and the large impact seen while reducing it motivates further studies looking into the possible correction of higher order effects of the sextupoles, such as amplitude detuning and second order chromaticity due to their potential to increase the dynamic aperture. Using an adapted clustering algorithm to sort on the b_3 for both beams simultaneously, the minimum dynamic aperture increased by 0.8 σ. As this scenario assumes that all dipoles are available and measured before installation, future studies could look into more realistic cases assuming a limited pool of dipoles available for installation in a given slot. Similarly, as this sorting algorithm allows sorting also on more components, this option could also be studied in the future. In both cases, a decrease in DA is expected due to the additional constraints with the reduction still to be quantified.

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