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First results for a FCC-hh ring optics design

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First results for a FCC-hh ring

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Abstract

The first order considerations of the optics for the FCC-hh ring are presented. The arc cell is generated taking into account some general considerations like the whole circumference, maximum gradients and lengths of the elements in the cell. The integration of the insertion regions started. Three types of Dispersion Suppressors (DIS) are studied. The sensitivity of the arc parameters to these layout considerations is studied in more detail. An alternative layout is shown as well.

1 Introduction

Following the recommendations of the European Strategy Group, an integrated design study for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines has been undertaken. The Future Circular Collider study FCC is investigating two possible storage rings options, housed in a tunnel of roughly 100 km circumference: an e^+e^- collider (FCC-ee) and an hadron-hadron collider (FCC-hh). In order to reach the 100 TeV collision energy goal of the FCC-hh collider, an R&D program on dipole magnets started with the aim of producing a field as high as 16 T. In the following we present the first considerations for the FCC-hh beam optics, taking into account the main machine parameters given in [1] as well as the site and magnets constraints.

1.1 Layout of the FCC-hh ring

Recently, the layout of the FCC-hh ring has converged to a “quasi racetrack” ring with 2+2 interaction points (IPs) where 2 IPs are with high luminosity and 2 other with lower luminosity. Other two Long Straight Sections (LSS) are dedicated to injection and two Extended Straight Section (ESS) are used for collimation and extraction. In the following we describe the first order optics taking into account these parameters and considerations on the proposed layout. An alternative layout is briefly discussed as well. We use the naming convention illustrated in Table 1, and reported with more details in [2]. The optics of the interaction regions are assumed to be anti-symmetric with respect to their centers. In other terms, if the quadrupole is focusing at the beginning of the long straight sections, it is defocusing at the end. The IPs foreseen for high luminosity operation are located in LSS-PA-EXP and LSS-PG-EXP. The IPs at low luminosity are located in LSS-PF-EXP and LSS-PH-EXP (see Fig. 1). A first version of the optics can be found in [4]. The problem we want to handle is to compute the different parameters of the main quadrupoles and dipoles to fit with the layout and to match the arcs cells to the insertions regions. At the same time we want to explore the sensitivity of the overall lattice to these parameters.

1.2 Constraints on the baseline lattice

Some parameters of the optics are considered as fixed and other as advised. The parameters we have considered as fixed for the optimization of the baseline lattice are:

Table 1: Allocated functions to the FCC-hh ring.

Abbreviation	Generic name	Number	Length [km]
LSS	Long Straight Section	6	1.4
ESS	Extended Straight Section	2	4.2
TSS	Technical Straight Section	4	ϵ
DIS	Dispersion Suppressor	16	0.4
SAR	Short Arc	4	3.2
LAR	Long Arc	8	depends on circumference

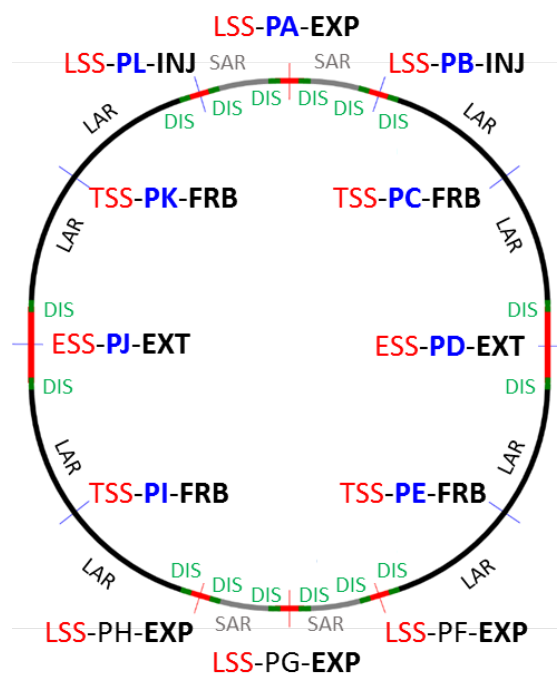


Figure 1: Layout of the FCC-hh ring.

- target centre-of-mass energy: 100 TeV;
- perimeter of the storage ring: $3.75 * \text{LHC} = 100.12 \text{ km}$;
- the length of the LSS and ESS (1.4 km and 2.8 km respectively);
- the length of the short arcs (SAR) (3.2 km);
- the dipoles magnetic length (14.3 m);
- the spacing between the dipoles (1.36 m);
- a magnets aperture radius of 25 mm;
- a sextupoles magnetic length of 0.5 m;
- the distance between the quadrupole and sextupole is fixed to 1.0 m;
- the phase advance in the FODO cells H/V (90 degree).

The parameters we have assumed free are:

- the length of the FODO cell;
- the spacing between the quadrupoles and the dipoles (with a minimum value of 3.67 m);
- the dipoles fields;
- the gradient and the magnetic length of the quadrupoles of the arcs (with a maximum value of 370 T/m).

The main motivation behind these parameters choices arise from the LHC design, construction and maintenance experience. For the quadrupole maximum gradient a safety margin has been considered (370 T/m) with respect to what is considered realistic nowadays (380 T/m) and what is considered as target (420 T/m) [5]. Of course the possibility to have a maximum gradient for the quadrupole higher than 400 T/m is advisable, since it would reduce the dipole field of few %.

2 First order optics and integration with the straight sections

A python class has been created to generate the optics of the FCC-hh ring. It is interfaced with MAD-X [6]. The python script creates input files for MAD-X taking into account the different constraints given above. It computes a first guess for the quadrupole strengths to reduce the matching time for MAD-X. In the case of too strong quadrupoles in the FODO cell, the quadrupole length is increased to keep the gradient below the allowed maximum.

Three types of dispersion suppressor are considered:

- Half-Bend (HB) configuration. This configuration uses two FODO cells with dipoles that operate at half the arc dipoles' flux density. The advantage of this configuration is to cancel the dispersion with quadrupoles with same strengths in the LAR and no dispersion bump. The drawback is to reduce the mean filling factor because the ratio between the integrated angle in this DIS and 2 FODO cells is only 50%;
- Full-Bend (FB) configuration. This configuration uses two FODO cells with dipoles at the same field as in the the arcs. The advantage of this configuration is to have the best achievable filling factor (equal to 1). The drawback is to increase the dispersion in the first part of this section to enable the dispersion canceling in the second part;
- LHC-like configuration; There are 3 half-cells downstream of which the length and the total length of dipoles are two thirds of the ones in LAR. The dipoles can be shorter than in the arcs (for the same magnetic field). The advantage of this configuration is to have a good filling factor because the ratio between the integrated angle in this DIS and 2 FODO cells is 11/12 (in the case where the number of dipoles per cell is a multiple of 6), which is near to 1. The drawbacks with respect to the other to configurations are an increase of the dipole family number and a larger dispersion bump in the DIS than in the Half-Bend configuration.

For each cell length between a minimum value of 200 m and a maximum value of 250 m the cell length and the dipoles parameters are computed as follow. We shall note \mathcal{C} , L_{FODO} , L_{LSS} , L_{ESS} the respective length of the whole ring, of a FODO cell in LAR, of a LSS and of an ESS. Let us note n_{SAR} and n_{LAR} the respective number of FODO cells in SAR and LAR. We have the equation:

$$\mathcal{C} = 6 \times L_{\text{LSS}} + 2 \times L_{\text{ESS}} + 4 \times (4 \times 2 + n_{\text{SAR}} + 2 \times n_{\text{LAR}}) \times L_{\text{FODO}} \quad (1)$$

$$L_{\text{FODO}} = \frac{\mathcal{C} - 6 \times L_{\text{LSS}} - 2 \times L_{\text{ESS}}}{4M} \quad (2)$$

with

$$M = 8 + n_{\text{SAR}} + 2 \times n_{\text{LAR}} \quad (3)$$

We have made M vary from $M_{\min} = \left\lfloor \frac{C-6 \times L_{\text{LSS}} - 2 \times L_{\text{ESS}}}{4L_{\max}} \right\rfloor + 1$ to $M_{\max} = \left\lceil \frac{C-6 \times L_{\text{LSS}} - 2 \times L_{\text{ESS}}}{4L_{\min}} \right\rceil$ where $\lfloor x \rfloor$ is the largest integer not greater than x , $\lceil x \rceil$ is the smallest integer not less than x , L_{\min} and L_{\max} are the variation boundaries for L_{FODO} . We have then deduced the values of n_{SAR} and n_{LAR} from the value of M .

The number of dipoles per cell n_{bend} is optimized to fit the FODO cell length. Let us be L_{QP} , L_{D} , L_{DD} and L_{QD} the quadrupole length, the dipole length, the spacing between dipoles and the spacing between quadrupole and dipole. L_{DD} is fixed and L_{QD} is adjusted above a minimum value $L_{\text{QD},\min}$ to fit with cell length. n_{bend} is necessarily a multiple of 2. This constraint has been taken into account in the optimization. We have then:

$$n_{\text{bend}} = 2 \left\lfloor \frac{L_{\text{FODO}} - 2L_{\text{QP}} - 4L_{\text{QD},\min} + 2L_{\text{DD}}}{2(L_{\text{D}} + L_{\text{DD}})} \right\rfloor \quad (4)$$

$$L_{\text{QD}} = \frac{L_{\text{FODO}} - 2L_{\text{QP}} + 2L_{\text{DD}} - n_{\text{bend}}(L_{\text{D}} + L_{\text{DD}})}{4} \quad (5)$$

In the case of the LHC-like configuration, we had to adjust the length of the dipoles in the DIS to fit with the reduced cell length (2/3 of the FODO cell in the arcs). The number of DIS-bends per cell in the DIS is then:

$$n_{\text{bend-DIS}} = 2 \left\lfloor \frac{1}{3} n_{\text{bend}} \right\rfloor \quad (6)$$

The length of the dipoles in this section (to have a cell length of two thirds of the arc cell) and the spacing between the quadrupole and the dipole are then:

$$L_{\text{bend-DIS}} = \frac{\frac{2}{3}L_{\text{FODO}} - 2L_{\text{QP}} - 4L_{\text{QD},\min} - (n_{\text{bend-DIS}} - 2)L_{\text{DD}}}{n_{\text{bend-DIS}}} \quad (7)$$

$$L_{\text{QD-DIS}} = \frac{\frac{2}{3}L_{\text{FODO}} - 2L_{\text{QP}} + 2L_{\text{DD}} - n_{\text{bend-DIS}}(L_{\text{bend-DIS}} + L_{\text{DD}})}{4} \quad (8)$$

The filling factor α_{DIS} of the DIS is the ratio between the integrated field over 2 arc cells in the DIS over the integrated field in the arc. It is equal to:

$$\alpha_{\text{DIS}} = \begin{cases} 0.5 & \text{Half-Bend} \\ 1 & \text{Full-Bend} \\ 0.25 + \frac{n_{\text{bend-DIS}}L_{\text{bend-DIS}}}{n_{\text{bend}}L_{\text{bend}}} & \text{LHC-like} \end{cases} \quad (9)$$

The total integrated field $2\pi B\rho$ in the ring is thus equal to (where B is the magnetic field in the arc dipoles):

$$2\pi B\rho = 4 \times B \times L_{\text{D}} \times (4 \times \alpha_{\text{DIS}} + n_{\text{SAR}} + 2 \times n_{\text{LAR}}) \times n_{\text{bend}} \quad (10)$$

The magnetic field in the arc dipoles is thus equal to:

$$B = \frac{\pi B\rho}{2 \times L_{\text{D}} \times (4 \times \alpha_{\text{DIS}} + n_{\text{SAR}} + 2 \times n_{\text{LAR}}) \times n_{\text{bend}}} \quad (11)$$

The optical functions for the arcs cell resulting from the optimization for a 100.12 km long ring are shown in Fig. 2. The lattice functions and the integration of the optics of the two high luminosity IRs and the collimation are also shown, using the LHC-like type of DIS. For the other two lower luminosity Interaction Regions a simple FODO cell is considered for the moment. The same holds for the two injection insertions where the space between quadrupoles has been increased to 150 m, for the installation of the injection elements. This allows to compute the arc cell parameters with insertions optics even if they are not in their final optimum stage. The arc cell and its magnet parameters resulting from the optimization are also reported in Table 2. Some

Table 2: Arc cell parameters resulting from the optimization of the FCC-hh ring.

Parameter	Value
cell length	214.755 m
number of dipoles per cell	12
total number of main dipoles	4368
dipoles maximum field	15.9 T
quadrupoles magnetic length	6.29 m
quadrupoles maximum gradient	356 T/m
total number of main quadrupole and sextupole	700

overall lattice parameters are reported in Table 3. The equilibrium emittance and the dumping times have been computed using the formula:

$$\epsilon_{eq} = \frac{C_q \gamma^2 I_5}{(I_2(1 - \frac{I_4}{I_2}))} \quad (12)$$

$$\tau_t = \frac{2E_0 T_0}{U_0} \quad (13)$$

$$\tau_l = \frac{2E_0 T_0}{U_0(2 + \frac{I_4}{I_2})} \quad (14)$$

and using the synchrotron integrals calculated by MadX.

Table 3: Lattice parameters resulting from the optimization of the FCC-hh ring.

Parameter	Value
$B\rho$	166667 T m
γ	53289
$\gamma_{transition}$	97
α	0.0001
β^*	1.1 m
Natural chromaticity (H/V)	-196./-197.
Equilibrium emittance	$1e^{-12}$ m rad
$\epsilon_{norm}/\beta\gamma$	$4.1e^{-11}$ m rad
Transverse/Longitudinal Damping time	2/1 h

In the following we investigate:

- the impact on the cell parameters of choosing another circumference for the ring;
- the comparison with the two other DIS types;
- the sensitivity of the magnets parameters to different arc cell and dipole lengths.

3 Sensitivity to the parameters and layout choices

In addition to the baseline circumference of 100.12 km we investigate the possibility to use $3.5 \times \text{LHC}$ as length (93.45 km) and $4 \times \text{LHC}$ as length (106.80 km) for the ring, which respects the synchronism required to inject from the LHC. The optical functions are quite similar in the case of a ring of 93.45 km or of 106.80 km. We have plotted in Fig. 3 the variation of the magnetic field in the dipoles as a function of the FODO cell length for different dipole length. The optimum cell length is between 210 and 220 m, depending on the chosen dipole length. The step is when the number of dipoles per cell increases. When it occurs, we have a step on the arc's filling factor and thus on the magnetic field. The needed magnetic fields for a ring of 93.45 km, 100.12 km and

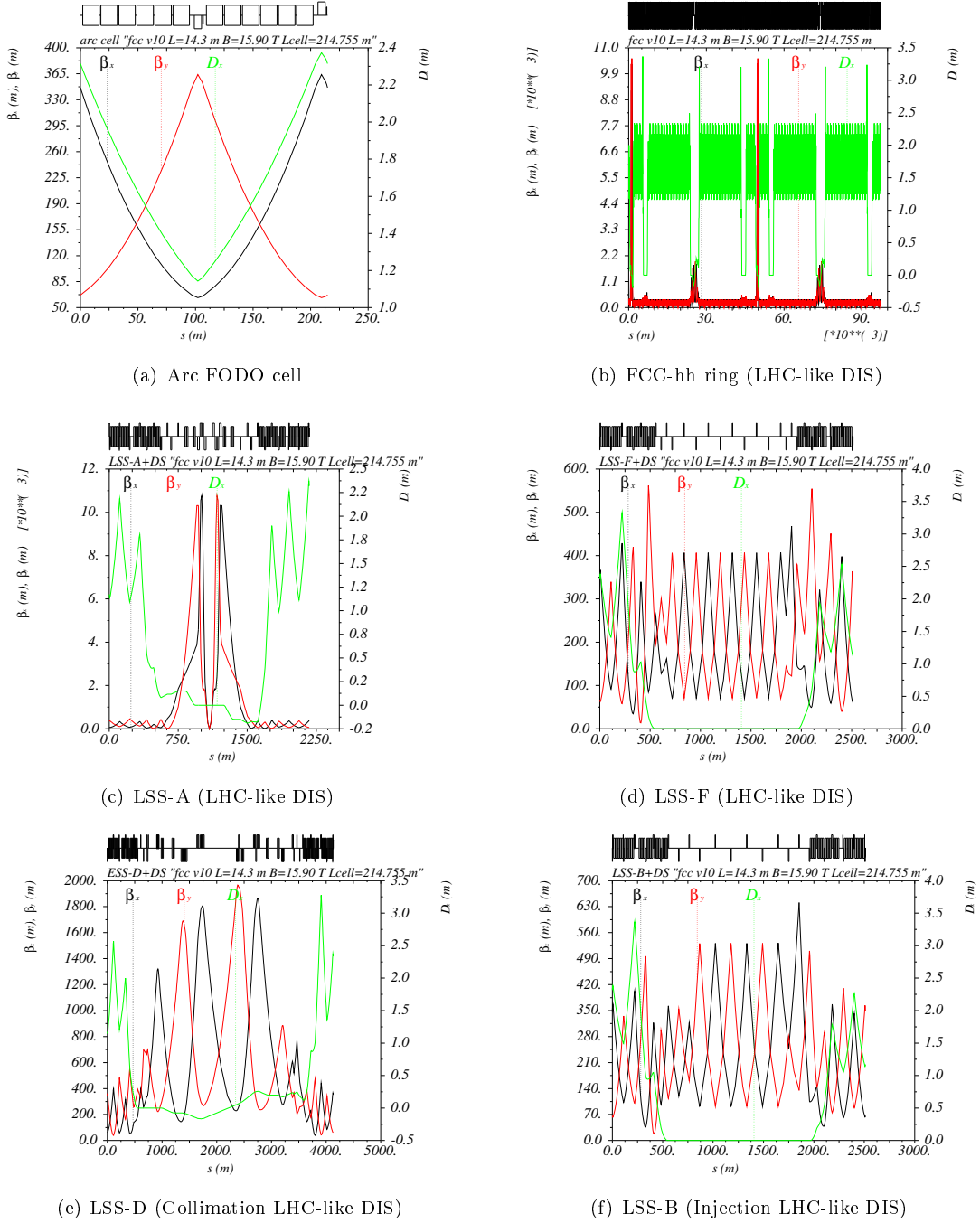


Figure 2: Optical functions for the baseline configuration of the FCC-hh ring: dipole length 14.3 m, circumference=100.12 km.

106.80 km at 50 TeV are respectively around 17 T, near to 16 T and a bit more than 14 T. In the case where the dipole field is fixed to 16 T, the corresponding kinetic energy of the beam is given in Fig. 4. The energy of the beam can be greater than 50 TeV for circumferences of 100.12 km and 106.80 km. If the solution of a ring of 93.45 km is chosen, the center-of-mass energy is likely to decrease.

In Fig. 5 we compare the dipole field obtained using the three types of dispersion suppressor for

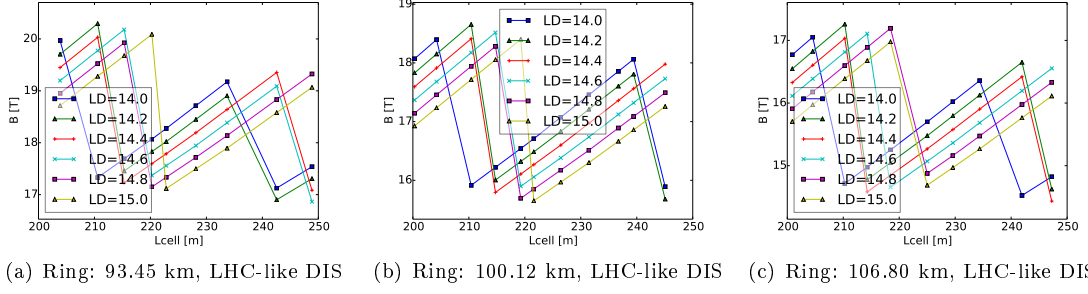


Figure 3: Magnetic field of the dipoles as a function of the cell length for the three different values of circumference.

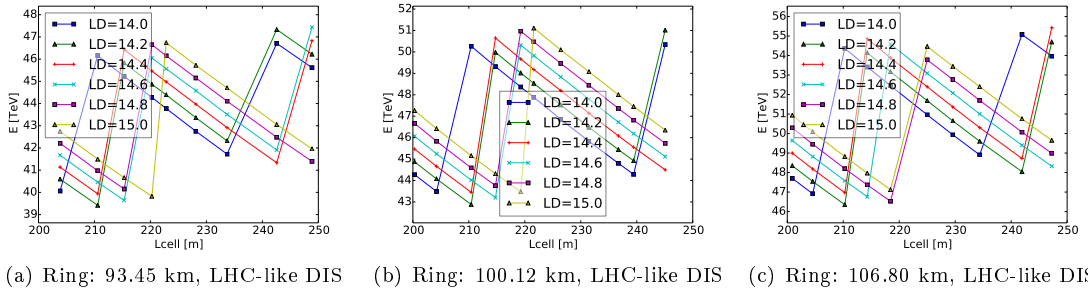


Figure 4: Kinetic energy to have a dipole field of 16 T in dipoles as a function of the cell length.

a circumference of 100.12 km. In the case of the HB DIS no solution is found with a main dipole field of 16 T. As expected, a longer ring implies weaker dipoles, and HB DIS is a less compact solution. The LHC-like DIS has about 0.5 T lower dipoles magnetic field with respect to HB DIS. In the case of FB DIS the maximum field of the dipole is 1% lower than in the case of LHC-like type, having 32 dipoles more than the LHC-like DIS, but with the same length of the main dipoles. The optical functions are very similar for the three types of DIS, except that with the present

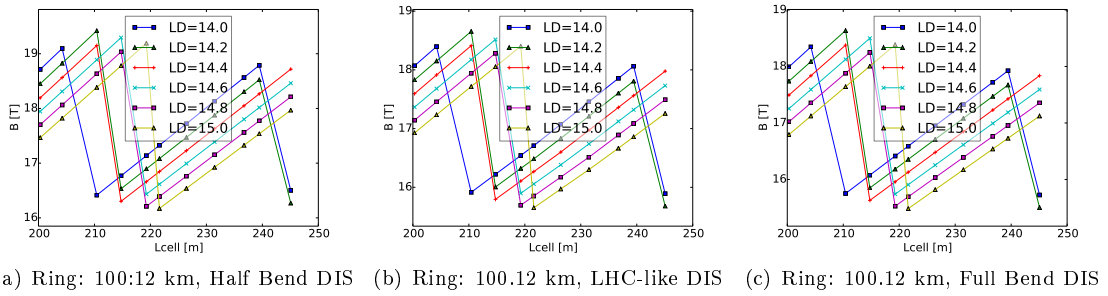


Figure 5: Comparison of the reachable dipole field using three different dispersion suppressors.

matching procedure the LHC-like DIS is the easiest to be matched, as shown in Fig. 6.

By comparing the dipole magnetic field, the number of dipoles and the number of beam sigma at injection ($\sigma_{max} \sim 0.6$ mm) as a function of the cell length for different dipoles lengths we have:

- for a dipole length between 14 and 14.3 m and a cell length of 245 m the required dipole field is 2% lower with respect to the baseline, but the beam stay clear at injection is also reduced by 15%;

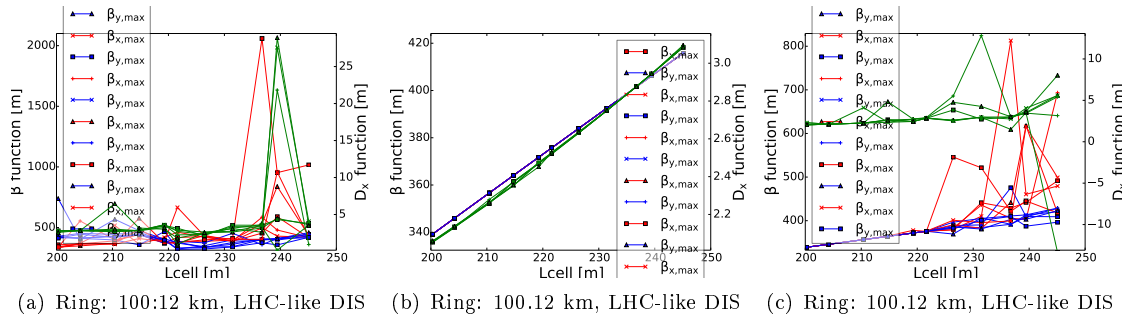


Figure 6: Comparison of optics functions using three different dispersion suppressors.

- for a dipole length of 14.8 m and a cell length of about 219 m, 1% of dipole field can be saved requiring about 3% less dipoles and losing about 3% of beam stay clear at injection.

Concerning the quadrupoles parameters, the results of this first optimization is that choosing a cell length of 245 m 14% of quadrupole gradients and 20% of quadrupoles can be saved, but losing about 15% of beam stay clear at injection. Summing up, in the case of a 93 km ring options the reachable center of mass energy is lower than 100 TeV, for a maximum dipole field of 16 T. While an higher center of mass energy is possible in the case of 106 km ring. The ~ 100 km ring allow to reach the target center of mass energy of 100 TeV with the 16 T dipoles and using the LHC-like or the Full Bend types of dispersion suppressor. For the ~ 100 km option and the LHC-like dispersion suppressor choosing a slightly longer dipole magnetic length (14.8 m) and cell length (219 m) the dipole field can be reduced of 1 %, and the number of dipoles can be reduced by $\sim 3\%$ losing only 3% of beam stay clear. Finally few % of the dipole field can be reduced allowing a stronger quadrupole gradient and shortening the quadrupoles length.

4 Alternative layout: a 8-fold symmetric ring

In this section we investigate an alternative layout where we have 4 long straight sections (LSS) of 1.4 km and 4 extended straight sections (ESS) of 2.8 km. Two of them contain the collimation sections. We have combined the injection and the extraction sections in the same straight sections. The LSS contains the experiments and they are located at each quarter of turn of the ring. Thus, we do not have the synchronism issue anymore. The proposed baseline layout is conform to geological and injection requirements, within a margin of about 1 km. On the contrary, we lose the advantage of having the extraction region before the collimation section [7].

The place taken by this geometry is very similar to the baseline geometry as shown in Fig. 7. So, the total length of the section is 2.8 km too. It keeps the same number of dispersion suppressors and the same total length of straight sections as the baseline geometry. The drawback is the location of the technical straight sections (TSS) in the arcs, which are required for the baseline due to the length of the long arcs. If the TSS is necessary for less than 10 km arcs as well, and they must be located in the middle of the arcs then more TSS are needed. In this case, there is still the problem to have enough place in the middle of the arcs to insert the TSS. Another drawback of this layout is that the injection transfer lines from the LHC injector are longer with respect to the baseline [8].

5 Conclusion

A tool to generate MAD-X input files for different FCC-hh configurations has been developed. It allows to compute the arc cell parameters to fit the layout and to integrate the insertion regions in the overall layout. The results show that the dipole field is stronger than 16 T to run at 100 TeV c.m in the case of 3.5 times the LHC circumference. For the 100.12 km circumference and a

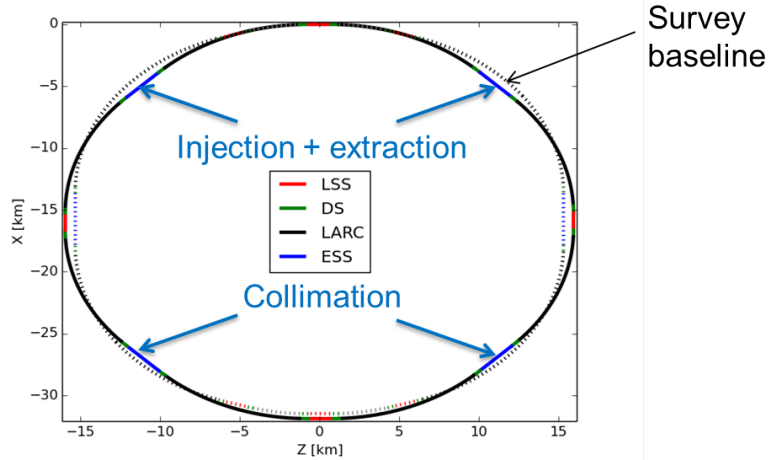


Figure 7: Survey of the baseline and of the alternative 8-fold symmetric geometry for a 100.12-kilometer-long ring.

dipoles field of 16 T the 100 TeV is affordable. The Half Bend DIS is not an option for a dipole field of 16 T, while the Full Bend DIS save 1% of dipole's field with respect to the LHC-like DIS, which also leaves some free space in the DIS keeping a good filling factor. We have still some small margin in the choice of the arc cell parameters, such as the dipole and cell length as well as in the quadrupoles parameters. An alternative layout with a 8-fold symmetric geometry is also presented. The arc cell optics is similar to the baseline. Indeed, longer transfer lines from the LHC used as an injectors are required. More investigation is necessary though to evaluate the gain with this solution.

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