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FIRST CONSIDERATIONS ON BEAM OPTICS AND LATTICE DESIGN FOR THE FUTURE HADRON-HADRON COLLIDER FCC-HH

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Abstract

The main emphasis of the Future Circular Collider study is the design of a 100 TeV proton-proton collider in a new tunnel of about 100 km circumference. This paper presents the first optics design of the future hadron collider (FCC-hh). The basic layout follows a quasi-circular geometry "quasi racetrack" with 8 arcs and 8 straight sections, four of which designed as interaction points. Assuming 16 T dipole magnets, a first version of the ring geometry and magnet lattice is presented, including the optics of the foreseen high luminosity regions and of the other straight sections dedicated to the installation of injection/extraction lines, beam dump etc., and an arc structure with optimized dipole fill factor to reach the target center-of-mass energy of 100 TeV.

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 three possible storage rings options, housed in a tunnel of roughly 100 km circumference: an e^+e^- collider (FCC-ee), a hadron-hadron collider (FCC-hh), and an electron-hadron (FCC-eh) option. In order to reach the extreme high energy 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 geological and magnets constraints.

Layout of the FCC-hh Ring

Recently, the layout of the FCC-hh ring has converged to a "quasi racetrack" shape with 2 high luminosity interaction points (IPs) and 2 other with lower luminosity. The high luminosity operation IPs are located in Long Straight Sections LSS-PA-EXP and LSS-PG-EXP. Correspondingly, the lower luminosity IPs are located in LSS-PF[PH]-EXP (shown in Fig. 1). Two more LSS (LSS-PL[PB]-INJ) are dedicated to injection and two Extended Straight Section (ESS) are used for collimation and extraction [2]. The optics of the interaction regions are assumed to be anti-symmetric with respect to their centers. Moreover, the quadrupole is focusing at the beginning of all the long straight section and it is defocusing at the end. Four short arcs (SAR) and four long arcs (LAR) complete the layout, shown in grey and in black in Fig. 1, respectively. 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.

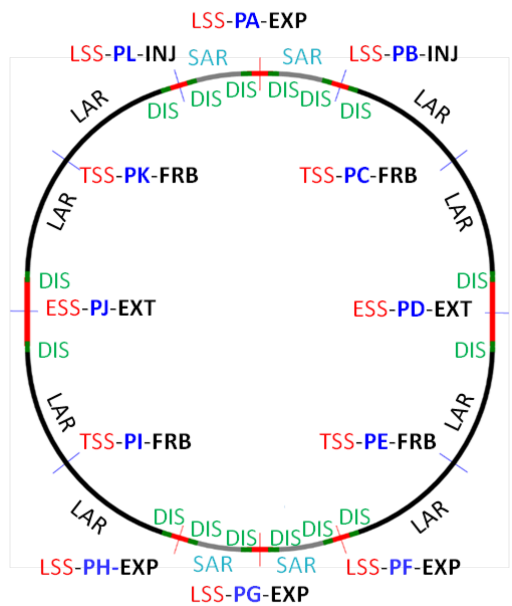

Figure 1: Layout of the FCC-hh ring.

FIRST ORDER OPTICS AND INTEGRATION WITH THE STRAIGHT SECTIONS

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 reported in Table 1.

Table 1: Input Parameters for the Optimization of the FCC-hh Arc Cells

Parameter	Value
center-of-mass energy	100 TeV
total ring length	100.12 km
LSS and ESS length	1.4 and 4.2 km
dipole magnetic length	14.3 m
dipole-dipole separation	1.36 m
magnet aperture radius	25 mm
sextupole magnetic length	0.5 m
quadrupole-sextupole separation	1.0 m
cell phase advance H/V	90 °

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The parameters we have assumed free are:

- FODO cell length;
- quadrupole-dipole separation (with a minimum value of 3.67 m);
- dipole field;
- gradient and magnetic length of the arc quadrupoles (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 to what is considered as target (420 T/m) [5].

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 (DIS) are considered:

- *Half-Bend (HB) configuration.* This configuration uses two FODO cells with twice weaker dipoles;
- *Full-Bend (FB) configuration.* This configuration uses two FODO cells with dipoles at the same field as in the arcs;
- *LHC-like configuration.* There are three half-cells downstream of which the length and the total length of dipoles are two thirds of the ones in the main cell. The dipoles can be shorter than in the arcs (for the same magnetic field as in the main cell).

Cell length between a minimum value of 200 m and a maximum value of 250 m are considered, the possible combinations of cell length and dipole parameters are computed as follows, and reported with more details in [7].

$$L_{\mathrm{FODO}} = \frac{C - 6 \times L_{\mathrm{LSS}} - 2 \times L_{\mathrm{ESS}}}{4M} \tag{1}$$

with $M = 8 + n_{\mathrm{SAR}} + 2 \times n_{\mathrm{LAR}}$. 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. 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 filling factor α_{DIS} of the DIS is equal to:

$$\alpha_{\mathrm{DIS}} = \begin{cases} 0.5 & \text{Half-Bend} \\ 1 & \text{Full-Bend} \\ 0.25 + \frac{n_{\text{bend-DIS}} L_{\text{bend-DIS}}}{n_{\text{bend}} L_{\text{bend}}} & \text{LHC-like} \end{cases} \tag{2}$$

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

$$B = \frac{\pi B \rho}{2 \times L_D \times (4 \times \alpha_{\mathrm{DIS}} + n_{\mathrm{SAR}} + 2 \times n_{\mathrm{LAR}}) \times n_{\mathrm{bend}}} \tag{3}$$

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
dipole maximum field	15.9 T
quadrupole magnetic length	6.29 m
quadrupole maximum gradient	356 T/m

The cell length which provides the maximum aperture at injection within the target dipole magnetic field has been chosen. The arc cell optical functions after optimization of 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. More details and different options of the interaction region can be found in [8]. 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 [9].

The arc cell and its magnet parameters resulting from the optimization are also reported in Table 2.

SENSITIVITY TO THE PARAMETERS AND LAYOUT CHOICES

In addition to the baseline circumference of 100.12 km we have investigated the possibility to use 3.5×LHC as length (93.45 km) and 4×LHC as length (106.80 km) for the ring. The optical functions are quite similar to the baseline in both cases. The required magnetic fields for a ring of 93.45 km, 100.12 km and 106.80 km at 50 TeV are respectively of at least 16.9 T, 15.9 T and 14.6 T, as shown in Fig. 4 of [7]. 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 [7]. The optimum cell length is between 210 and 220 m, depending on the chosen dipole length. Comparing the dipole field obtained using the three types of dispersion suppressor for a circumference of 100.12 km we found no solution in the case of the HB DIS with a main dipole field of 16 T (see [7] for more details). As expected, a longer ring implies weaker dipoles, and HB DIS is a less compact solution. 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, we note that with the present matching procedure the LHC-like DIS is the easiest to be matched. By comparing the dipole magnetic fields, the number of dipoles and the number of beam sigma at injection (σ_{max} ~0.6 mm) as a function of the cell length for different dipoles lengths we have:

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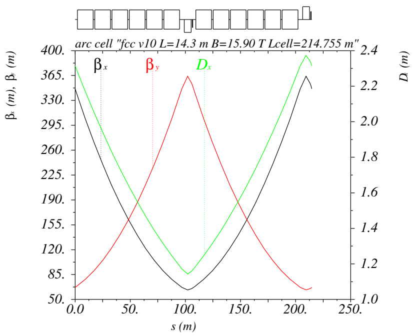
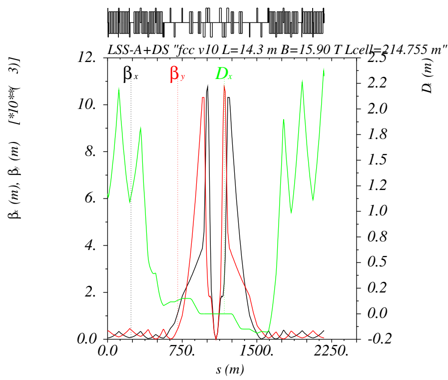
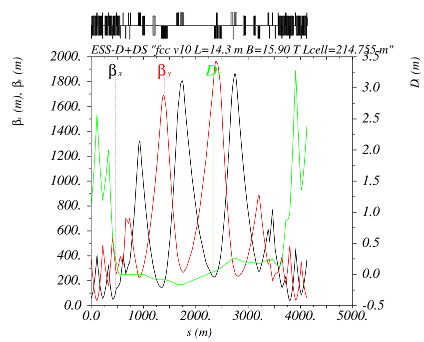


(a) Arc FODO cell



(b) LSS-PA-EXP (LHC-like DIS)



(c) ESS-PD-EXT (Collimation LHC-like DIS)

Figure 2: Optical functions for the baseline configuration of the FCC-hh arc cell, the insertion region and the betatron collimation region.

- for a dipole 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%;
- 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 quadrupole parameters, 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.

CONCLUSION

First considerations for the FCC-hh beam optics, taking into account the baseline machine parameters as well as the civil engineer and magnets constraints, have been studied and presented in this paper. The main conclusions that could be drawn are that for a 100 km ring with a dipole field of 16 T, a center-of-mass energy of 100 TeV is possible, however, relaxing a bit the length of the ring to 3.5 times the LHC, gives stronger dipole field 16.9 T, for the same center-of-mass energy. The Half-Bend dispersion suppression option does not meet the requirement of 16 T dipole field. On the contrary, the Full-Bend dispersion suppression allows to relax the dipole field requirement by 1% with respect to the LHC-like option, which has the advantage to leave some free space in the dispersion suppression region. Finally, there is a small margin of optimization of the baseline cell parameters, reported in Table 2, a slightly longer cell (219 m) and longer dipoles (14.8 m) allow to lower the dipole field of 1%, reducing only by 3% the beam stay clear at injection.

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