Abstract:
In this document we will describe the arc baseline design including a list of beam-line elements (type, description, quantity, physical element characteristics). The taken assumptions, requirements and constraints imposed onto the infrastructure and infrastructure services will be also described.
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1. NEEDS AND CONSTRAINTS IN THE ARCS

The baseline arcs are made of FODO lattices with a phase advance of 90 degrees in both planes. The length of the arc cells is optimised as a trade-off between the filling ratio, the available normalized aperture, the available gradients and civil engineering constraints [1] [2]. Civil engineering studies have shown that short arcs (SAR) should be 3.4 kilometres long. Since the SAR length is an integer multiple of the arc cell length, the solution space is thus strongly constrained. The FODO cell length is fixed to 213.03 meters. The long arcs (LAR) contain then 78 FODO cells and the short arcs (SAR) contain 20 FODO cells. Each arc begins and ends with a dispersion suppressor (DIS). The DIS is LHC-like with 3 first cells with a length equal to two thirds of the arc cell (with 8 dipoles thus instead of 12 dipoles). The following half-cell contains 4 dipoles but has the same length as the arc FODO cell. The matching between the insertions and the arcs is done with the quadrupoles 7, 8, 9, and 10 and the trim quadrupoles 11, 12, and 13.

Dipoles and quadrupoles will use Nb$_3$Sn whereas other multipoles will use NbTi. The maximum dipole field we can expect is 16 T. The gradient in the main quadrupoles and in the trim/skew quadrupoles should be respectively lower than 360 T/m and 220 T/m [3] [4]. The maximum gradient for the sextupoles is 7000 T/m$^2$. The next paragraphs will justify the chosen element lengths in the arcs as a trade-off between the integrated field needs and the reachable magnet strengths.

With 12 dipoles per arc cell, the dipole angle is 1.347 mrad. An upper limit on the dipole field of 16 T implies a minimum dipole length of 14.04 m. To enable the interconnection between dipoles, the distance between two dipoles must be greater than 1.5 m. The distance between the dipole and the short straight section (SSS) housing the quadrupoles and the correctors must be longer than 1.3 m. A limit of 16 T on the dipole field implies thus a maximum length of 11.95 m on the SSS. The distance between two magnetic elements in the SSS must be greater than 0.35 m. Dynamic aperture studies have shown that sextupole correctors MCS are mandatory near each dipole to correct the $b_3$ component defined by [5] [6] [7]:

$$b_3 = \frac{1}{2} \frac{R_{ref}^2}{B_0} \frac{\partial^2 B_y}{\partial x^2}$$

Where $R_{ref}=17$ mm is the reference radius and $B_0$ is the dipole field. Please take into account that the sextupole gradient $S$ is defined by $S = \frac{1}{2} \frac{\partial^2 B_y}{\partial x^2}$ and $|B|(r) = Sr^2$. The MCS corrects the $b_3$ dipole component if its integrated gradient is equal to the one of the sextupole component in the dipoles. We have then the relation:

$$S_{MCS} = \frac{L_{dip}}{L_{MCS}} \frac{B_0}{R_{ref}^2} b_3$$

Up to $b_3 = 4/60$ units (1 unit is 1/10,000 parts of the main field) can be corrected at collision/injection energy (3.3 TeV), corresponding to an integrated field in the MCS of 308 T/m, and to a gradient of 2800 T/m$^2$ if a length of 0.11 m is considered. For comparison, the currently used spool pieces in LHC have a maximum gradient of 1630 T/m$^2$ and an aperture of 58 mm.

The needs in quadrupole gradients are strongly related to the field errors and misalignments in the arcs. Studies have shown that a systematic value of a few tens of units of $b_2$ in the dipoles has a great impact on the first order optics and increases the requirements on the quadrupole fields. Indeed, the integrated gradient of the quadrupoles is 2280 T if the systematic value of $b_2$ is zero. It becomes 2580 T if $b_2=50$ unit. For a maximum gradient of 360 T/m, the quadrupole should be longer than 6.3 m if $b_2=0$ and longer than 7.2 m if $b_2=50$ unit. In the case of 7-meter-long quadrupoles, the systematic value of $b_2$ in the dipoles should not exceed 40 unit.
The arcs house several correction schemes: dipole correctors (in both planes) and BPMs to correct the closed orbit; thin quadrupoles to correct the horizontal spurious dispersion (at the entrance of the arcs neighbouring interaction sections), the beta-beating, the tune; skew quadrupoles to correct the vertical spurious dispersion (at the entrance of the arcs neighbouring interaction sections) and the coupling; other multipole lenses like octupoles to use Landau damping or to correct beam-beam effects.

The orbit is corrected by dipole correctors and BPMs located near each main quadrupole. The assumed misalignment and field errors are summarised in Table 1 [7]. The misalignment errors are given relatively to the machine axis, except for the BMPs with an error relatively to the nearest quadrupole. Studies have shown that the orbit correction requires integrated fields of 4 Tm in the dipole correctors at the 90-percentile. The requirements go up to 4.8 Tm if the error misalignment of 0.36 mm in the quadrupole cannot be reached and is increased to 0.5 mm [8] [9]. An upper limit of 4 T in the dipole correctors MCB fixes the minimum length at 1.2 m.

**Table 1: misalignment and field errors in the arcs**

<table>
<thead>
<tr>
<th>Element</th>
<th>Error</th>
<th>Error desc.</th>
<th>Units</th>
<th>FCC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>$\sigma_x, \sigma_y$</td>
<td>position</td>
<td>mm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_\psi$</td>
<td>roll angle</td>
<td>mrad</td>
<td>0.5</td>
<td>n/a</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_{b_1}$</td>
<td>random</td>
<td>%</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_{b_2}$</td>
<td>random</td>
<td>$10^{-4}$</td>
<td>0.92</td>
<td>0.8</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_{a_1}$</td>
<td>random</td>
<td>$10^{-4}$</td>
<td>1.04</td>
<td>1.6</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_{a_2}$</td>
<td>random</td>
<td>$10^{-4}$</td>
<td>1.04</td>
<td>0.5</td>
</tr>
<tr>
<td>Dipole</td>
<td>$\sigma_{\alpha_2}$</td>
<td>uncert.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrupole</td>
<td>$\sigma_x, \sigma_y$</td>
<td>position</td>
<td>mm</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>$\sigma_\psi$</td>
<td>roll angle</td>
<td>mrad</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>$\sigma_{b_2}$</td>
<td>random</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>BPM</td>
<td>$\sigma_x, \sigma_y$</td>
<td>position</td>
<td>mm</td>
<td>0.3</td>
<td>0.24</td>
</tr>
<tr>
<td>BPM</td>
<td>$\sigma_r$</td>
<td>read error</td>
<td>mm</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The horizontal spurious dispersion is corrected by the trim quadrupoles MQT.14LA.H1, MQT.16LA.H1, MQT.18LA.H1, MQT.20LA.H1, MQT.15RA.H1, MQT.17RA.H1, MQT.19RA.H1, MQT.21RA.H1, MQT.15LB.H1, MQT.17LB.H1, MQT.19LB.H1, MQT.21LB.H1, MQT.14RB.H1, MQT.16RB.H1, MQT.18RB.H1, MQT.20RB.H1, MQT.14LG.H1, MQT.16LG.H1, MQT.18LG.H1, MQT.20LG.H1, MQT.15RG.H1, MQT.17RG.H1, MQT.19RG.H1, MQT.21RG.H1, MQT.15LL.H1, MQT.17LL.H1, MQT.19LL.H1, MQT.21LL.H1, MQT.14RL.H1, MQT.16RL.H1, MQT.18RL.H1, and MQT.20RL.H1. At collision and for $\beta^*=0.3$ m, the maximum integrated field in one trim quadrupole is 93 T, corresponding to a gradient of 186 T/m for a length of 0.5 m.

The vertical spurious dispersion is corrected by the following skew quadrupoles MQS.15LA.H1, MQS.17LA.H1, MQS.19LA.H1, MQS.21LA.H1, MQS.23LA.H1, MQS.27LA.H1, MQS.14RA.H1, MQS.16RA.H1, MQS.18RA.H1, MQS.20RA.H1, MQS.22RA.H1, MQS.26RA.H1, MQS.14LB.H1, MQS.16LB.H1, MQS.18LB.H1, MQS.20LB.H1, MQS.15RB.H1, MQS.17RB.H1, MQS.19RB.H1, MQS.21RB.H1, MQS.15LG.H1, MQS.17LG.H1, MQS.19LG.H1, MQS.21LG.H1, MQS.23LG.H1, MQS.27LG.H1, MQS.14RG.H1, MQS.16RG.H1, MQS.18RG.H1, MQS.20RG.H1, MQS.22RG.H1, MQS.26RG.H1, MQS.14LL.H1, MQS.16LL.H1, MQS.18LL.H1, MQS.20LL.H1, MQS.15RL.H1, MQS.17RL.H1, MQS.19RL.H1, and MQS.21RL.H1. At collision and for $\beta^*=0.3$ m, the maximum integrated field in one skew quadrupole is 94 T, corresponding to a gradient of 182 T/m for a length of 0.5 m.
In previous versions of the arcs, the dispersion beating generated by the missing dipole at the middle of the long arcs for the technical straight section (TSS) is corrected by removing another dipole at a phase advance of 180 degrees from the middle (two FODO cells) [1]. However, in the case of systematic $b_2$ in the dipoles, the beta-beating generated by the missing dipole cannot be compensated by this solution. The beta-beating is evaluated at 29% for $b_2=50$ unit, which is not acceptable. Another solution is to use trim quadrupoles at the middle of the arc to cancel the betatron and dispersion waves created by the missing dipole. The used trim quadrupoles are MQT.79RB.H1, MQT.81RB.H1, MQT.83RB.H1, MQT.85RB.H1, MQT.86RB.H1, MQT.84LD.H1, MQT.82LD.H1, MQT.80LD.H1, MQT.80RD.H1, MQT.82RD.H1, MQT.84RD.H1, MQT.85LF.H1, MQT.83LF.H1, MQT.81LF.H1, MQT.79LF.H1, MQT.79RH.H1, MQT.81RH.H1, MQT.83RH.H1, MQT.85RH.H1, MQT.86RH.H1, MQT.84LJ.H1, MQT.82LJ.H1, MQT.80LJ.H1 MQT.80RJ.H1, MQT.82RJ.H1, MQT.84RJ.H1, MQT.85RJ.H1, MQT.83RJ.H1, MQT.81RJ.H1, MQT.79RJ.H1. For a systematic value of $b_2=50$ unit, the needed integrated gradient in the trim quadrupoles is evaluated at 97 T, corresponding to a gradient of 194 T/m for a length of 0.5 m.

In the baseline, the tune is corrected by the main quadrupoles. If this solution cannot be taken anymore, an alternative is to use the RFS section and the extraction section to correct the global tune. Trim quadrupoles at the entrance of the long arcs could be used to correct some residual phase advances between the insertions (a total of 8 at each entrance is then needed). The gradient of the trim quadrupoles for this use should not exceed a few tens of T/m with a length of 0.5 m. Trim quadrupoles are to be used for beta-beating correction. The needs are not yet evaluated and should be done in the near future.

Skew quadrupoles used for the coupling correction are located at MQS.63RB, MQS.65RB, MQS.67RB, MQS.69RB, MQS.71RB, MQS.73RB, MQS.75RB, MQS.77RB, MQS.63LD, MQS.65LD, MQS.67LD, MQS.69LD, MQS.71LD, MQS.73LD, MQS.75LD, MQS.77LD, MQS.63RD, MQS.65RD, MQS.67RD, MQS.69RD, MQS.71RD, MQS.73RD, MQS.75RD, MQS.77RD, MQS.63LF, MQS.65LF, MQS.67LF, MQS.69LF, MQS.71LF, MQS.73LF, MQS.75LF, MQS.77LF, MQS.63RH, MQS.65RH, MQS.67RH, MQS.69RH, MQS.71RH, MQS.73RH, MQS.75RH, MQS.77RH, MQS.63LJ, MQS.65LJ, MQS.67LJ, MQS.69LJ, MQS.71LJ, MQS.73LJ, MQS.75LJ, MQS.77LJ, MQS.63RJ, MQS.65RJ, MQS.67RJ, MQS.69RJ, MQS.71RJ, MQS.73RJ, MQS.75RJ, MQS.77RJ, MQS.63LL, MQS.65LL, MQS.67LL, MQS.69LL, MQS.71LL, MQS.73LL, MQS.75LL, MQS.77LL. Studies have shown that an integrated field of 76.8 T is need to correct the coupling for a systematic value of $a_2=1$ unit in the dipoles. The maximum gradient for these skew quadrupoles is thus $154$ T/m for a length of 0.5 m.

In conclusion, the maximum integrated gradient in the trim quadrupoles is 97 T in the case of a systematic value of $b_2=50$ unit. If the maximum reachable gradient in the trim quadrupole is 220 T/m, the trim quadrupoles should be longer than 0.44 m.

The global chromaticity is corrected by arc sextupoles. At collision and at $\beta^* = 0.3$ m, the integrated sextupole field is 8200 T/m. A maximum gradient of 7000 T/m² implies thus a minimum sextupole length of 1.17 m.
2. ARC DESIGN

The different requirements enumerated above have strongly constrained the design of the arcs. The arc elements are listed in Table 2. The layouts of the arc half-cell, of the cryo-dipole and of the SSS are respectively given in Figure 1, Figure 2, and Figure 3. The distance between two dipoles is 1.5 m, the distance between the dipoles and the SSS is 1.3 m. The distance between two magnets inside the SSS is 0.35 m. The total length of the SSS is 12.0 m.

The layout of the DIS is given in Figure 4. One-meter-long collimators have been inserted to protect the arc entrances from the debris coming from the insertions (mainly cleaning and experimental insertions).

Table 2: Types of element in the arcs.

<table>
<thead>
<tr>
<th>Element Description</th>
<th>Number</th>
<th>Max. Strength</th>
<th>Length</th>
<th>Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dipole (MB)</td>
<td>4668</td>
<td>16 T</td>
<td>14.069 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Dipole Corrector (MCB)</td>
<td>792</td>
<td>4 T</td>
<td>1.2 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Main Quadrupole (MQ)</td>
<td>744</td>
<td>360 T/m</td>
<td>7.2 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>DIS Quadrupole (MQDA)</td>
<td>48</td>
<td>360 T/m</td>
<td>9.7 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Trim Quadrupole (MQT)</td>
<td>120</td>
<td>220 T/m</td>
<td>0.5 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>DIS Trim Quadrupole (MQTL)</td>
<td>48</td>
<td>220 T/m</td>
<td>2.0 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Skew Quadrupole (MQS)</td>
<td>96</td>
<td>220 T/m</td>
<td>0.5 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Main Sextupole (MS)</td>
<td>696</td>
<td>7000 T/m²</td>
<td>1.2 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Sextupole Corrector (MCS)</td>
<td>4668</td>
<td>3000 T/m²</td>
<td>0.11 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>Main Octupole (MO)</td>
<td>480</td>
<td>200,000 T/m³</td>
<td>0.5 m</td>
<td>50 mm</td>
</tr>
<tr>
<td>BPM</td>
<td>792</td>
<td>-</td>
<td>0.5 m</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

Figure 1: Layout of an arc FODO half-cell.

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1 Eight skew quadrupoles are common with trim quadrupoles. If the trim quadrupole cannot have a normal and skew component, 8 more skew quadrupoles are needed in the lattice. An alternative is to use an orbit bump to correct the vertical spurious dispersion coming from the low-luminosity insertion.
Figure 2: Layout of the arc dipole.

Figure 3: Layout of the short straight section (SSS).

Figure 4: Layout of the DIS.
3. CONCLUSIONS

In this document we have described the requirements from optics and magnet limitations to the arc cells. The magnet characteristics is then a trade-off between the filling factor and the reachable strengths. This document lists finally the needs in magnets for the arcs (dipoles, quadrupoles, sextupoles, octupoles, and correctors).

It was possible to insert all elements in the arcs with strengths in the acceptable range given by magnet experts. However, there is very small room to insert other elements in the arcs. The current baseline accepts up to a systematic value of $b_2=40$ unit in the dipole. Larger $b_2$ will imply to enlarge the quadrupoles at the expense of shorter and stronger dipoles or shorter and stronger correctors.

4. REFERENCES


5. ANNEX GLOSSARY

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

BPM  Beam Position Monitor
C.m.  Centre of Mass
DA    Dynamic Aperture
DIS   Dispersion suppressor
EIR   Experimental Insertion Region
ESS   Extended Straight Section
FCC   Future Circular Collider
FCC-hh Hadron Collider within the Future Circular Collider study
FODO  Focusing and defocusing quadrupole lenses in alternating order
H1    Beam running in the clockwise direction in the collider ring
H2    Beam running in the anti-clockwise direction in the collider ring
HL-LHC High Luminosity – Large Hadron Collider
IP    Interaction Point
LHC   Large Hadron Collider
LAR   Long arc
LSS   Long Straight Section
Nb₂Sn Niobium-tin, a metallic chemical compound, superconductor
Nb-Ti Niobium-titanium, a superconducting alloy
RFS   Radio Frequency Section
RMS   Root Mean Square
σ     RMS size
SAR   Short arc
SSS   Short Straight Section
TSS   Technical Straight Section