Magnet Technology Tutorial for John Adams Institute

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Attilio Milanese, CERN

Objective

The objective is to design conceptual cross sections of the main magnets – dipoles and quadrupoles – of the FCC-ee arcs, focusing only on the electromagnetic part. Mechanical analyses and considerations to optimize manufacturing – very important for such a large machine – are not covered. The report shall contain sketches of the 2D geometry (with the overall dimensions) and parameter tables with, in particular, currents, resistances (per m length and per magnet), resistive powers (per m length and total per ring), mass (per m length and total, separately for yoke and conductor), and expected field quality.

Tentative parameters of the FCC-ee main dipoles and quadrupoles are listed in the tables below. The values can be updated according to the details of your own lattice, as part of your Design Project.

In all cases, we assume that the magnets are operated in dc mode, with a beam energy of 175 GeV (per ring). Electromagnets are considered, as permanent ones cannot easily cover the beam energy range envisaged in the machine. Given the low strengths, the design can be of the normal conducting type. We will not cover possible issues related to having (relatively) low flux densities in the iron.

Preliminary thoughts about the main dipoles can be found in the slides "FCC-ee Warm Magnets", available at https://indico.cern.ch/event/455343. Here we consider for simplicity designs based on a single aperture, that is, we do not couple the magnets of the two rings together like it is, for example, in LHC.

OPERA-2D scripts are given for standard layouts and analyses; they can be used as a first basis for this work. Also an iron BH curve, relative to a common low Si electrical steel, is provided.

Literature search

It would be good to recall in your report the parameters and peculiarities of the main magnets of large machines with low field. Two such machines of the past are, for example, LEP at CERN and the electron ring of HERA at DESY.

Main dipoles

Tentative parameters for the main dipoles are reported in Table 1.

Table 1. Tentative parameters for FCC-ee main dipoles.

field	[T]	0.060	175 GeV
vertical gap	[mm]	70	
width of GFR	[mm]	20	
harmonics in GFR	[10^{-4}]	1	b_2 excluded
length	[m]	10	magnetic length
quantity	[/]	6528	per ring

The gradient component b_2 can be taken out of the field quality expansion: a (little) systematic quadrupolar component can most likely be dealt with by the lattice quadrupoles.

It is proposed to base the design on a slender C dipole, using busbars – instead of a proper coil, made of several turns – for the excitation coils. As a first guess, a current density $j \approx 1$ A/mm^2 can be considered.

No water cooling is usually needed at this j, though a cooling channel can be added in the busbars for convenience, to ease the load on the tunnel ventilation. No hydraulic computation is requested here.

The following steps can be followed for the design:
1. determination of the needed Ampere-turns and relative coil size
2. first sketches of the magnetic circuit – by hand – with some assumptions for the pole width, the return legs, and possibly some pole shims
3. adjustment of the magnetic circuit to make room for the coils, if needed
4. set up of a parametric (in particular, for the geometry) model of the cross section in OPERA-2D
5. analysis of simulated field in the gap, including field homogeneity
6. iteration on the Ampere-turns / pole width / pole shims / return legs according to the simulation results, as needed
7. computation of the main parameters, including resistance and power

The field quality in the good field region can be expressed by the (low order) allowed harmonics, taking as reference radius R = 10 mm – if the good field region is confirmed at ± 10 mm.

For the last computations, both Al and Cu can be considered as conductor material. Typical values for resistivity (at 30 °C) and density are $1.79 \cdot 10^{-8}$ / $2.76 \cdot 10^{-8}$ Ωm, 8.9 / 2.7 kg/m3

Table 2. Typical values for resistivity and density of Al and Cu.

resistivity (at 30 °C)	[Ωm]	$1.79 \cdot 10^{-8}$	$2.76 \cdot 10^{-8}$
density	[kg/m^3]	8.9	2.7

The report does not need to contain intermediate designs, just the final proposed one.

Main quadrupoles

Tentative parameters for the main quadrupoles are reported in Table 3.

Table 3. Tentative parameters for FCC-ee main quadrupoles.

gradient	[T/m]	22	175 GeV
aperture diameter	[mm]	70	
GFR radius	[mm]	10	
harmonics in GFR	[10^{-4}]	1	
length	[m]	1.5	magnetic length
quantity	[/]	2000	per ring

The first thing to check is the pole tip field. [Which is reasonable, but getting to the high side, compare with the 1.0 T of the SPS, as in the slides]

The design can be based on a standard quadrupole geometry. In this case, a proper coil with several turns – instead of a busbar, like for the dipoles – can be used, with a current density of 5 to 10 A/mm². Water cooling will be needed, though no hydraulic computations are required at this stage. To account for insulation and cooling, consider 75% of the coil surface as actually filled with conductor. Again, both Al and Cu can be analysed.

The pole tip can be parametrized with a circular arc and straight lines, or with a hyperbolic branch, followed by straight lines.

The analysis can proceed following the same steps detailed before for the dipoles.