Collider Magnet Designs for FCC-ee

J. Bauche, C. Järmyr Eriksson, on behalf of the CERN Magnet Team

FCC Week 2025, 21st May 2025.

With acknowledgement to many members of the FCC collaboration for their contributions.

Outline

Arc magnets for GHC optics - FSR baseline

- Dipole
- Quadrupole
- Sextupole

Arc magnets for LCC optics - conceptual design

- Comparison GHC / LCC magnet parameters
- Concepts of twin quadrupoles
- Single aperture quadrupoles

Magnet development during pre-TDR phase

Summary

Magnet functional specifications from optics

Baseline specifications – **GHC** optics[1]

- Long low field dipoles (split in 2 units) with 3 length variants depending on sextupole presence
- Short SSS (larger field) to maximize dipole filling (SR losses)

→ More than **13000 magnets**

Alternative specifications

- **LCC** optics[2]
- **Combined function (resistive)** magnets

→ *Under study by beam dynamics team*

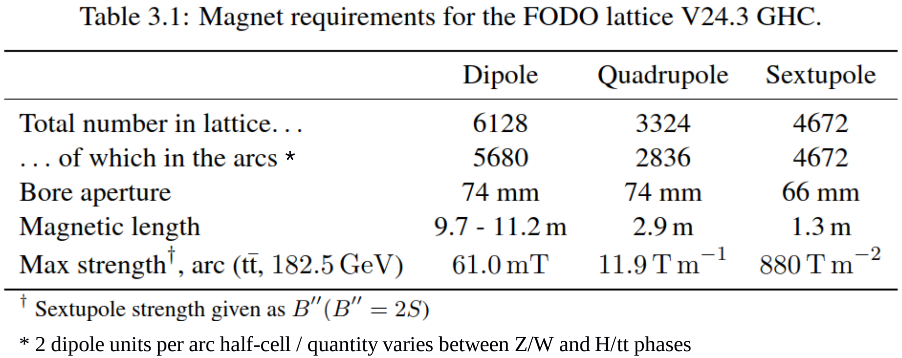


Table 3.1: Magnet requirements for the FODO lattice V24.3 GHC.

	Dipole	Quadrupole	Sextupole
Total number in lattice. . .	6128	3324	4672
. . . of which in the arcs *	5680	2836	4672
Bore aperture	74 mm	74 mm	66 mm
Magnetic length	9.7 - 11.2 m	2.9 m	1.3 m
Max strength†, arc ($t\bar{t}$, 182.5 GeV)	61.0 mT	$11.9\,\mathrm{T\,m^{-1}}$	$880\,\mathrm{T\,m^{-2}}$

† Sextupole strength given as B'' ($B'' = 2S$)

* 2 dipole units per arc half-cell / quantity varies between Z/W and H/tt phases

Arc magnet specifications - GHC V24.3 baseline, FCC FSR, pp.115.

1: see presentation K. Oide on Tuesday 08:30

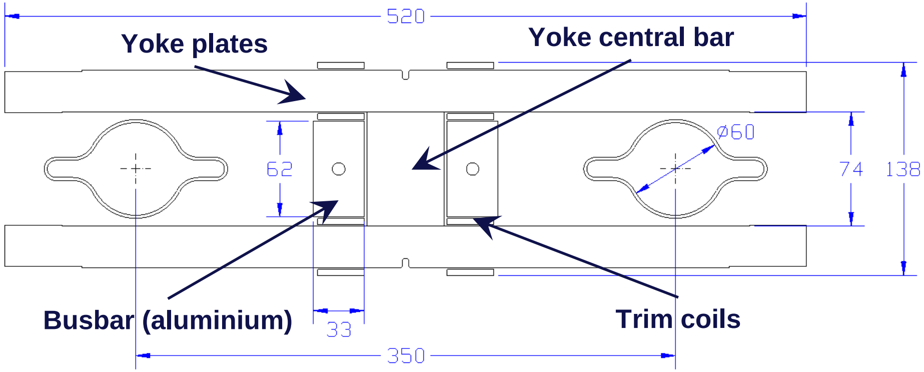
2: see presentations K. André and G. Roy on Tuesday 10:30

Collider dipole

(Baseline optics GHC 24.3)

Dipole mechanical design and parameters

- Yoke assembled from **solid iron** machined plates and central bar, bolted
- Water cooled **busbars, aluminium with embedded copper cooling tube**
- **Trim coils** wound with **solid copper conductor** or **anodized aluminum strips** (under study)
- **Inorganic insulation** (air + ceramic spacers)



Dipole magnetic model, FCC FSR, pp.117.

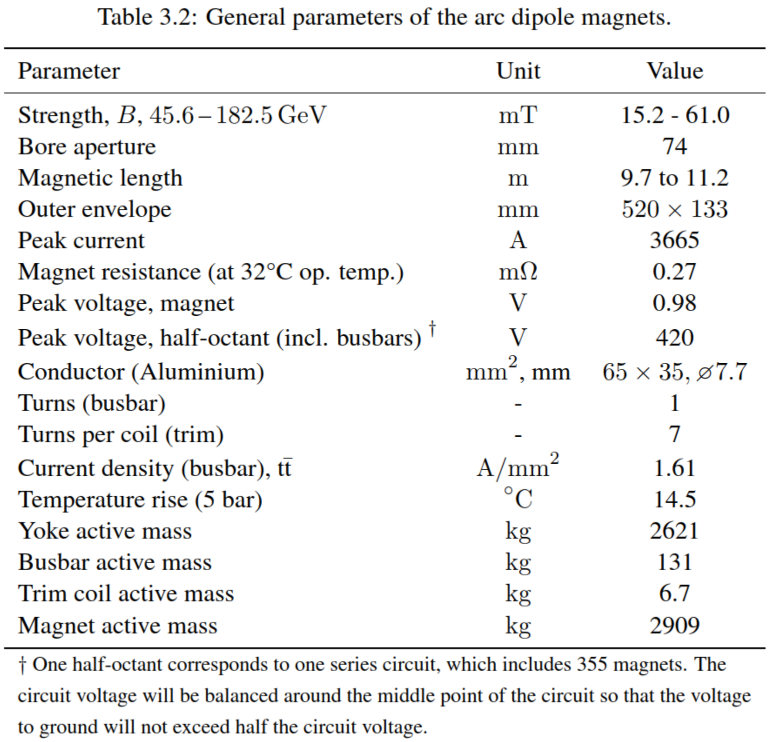


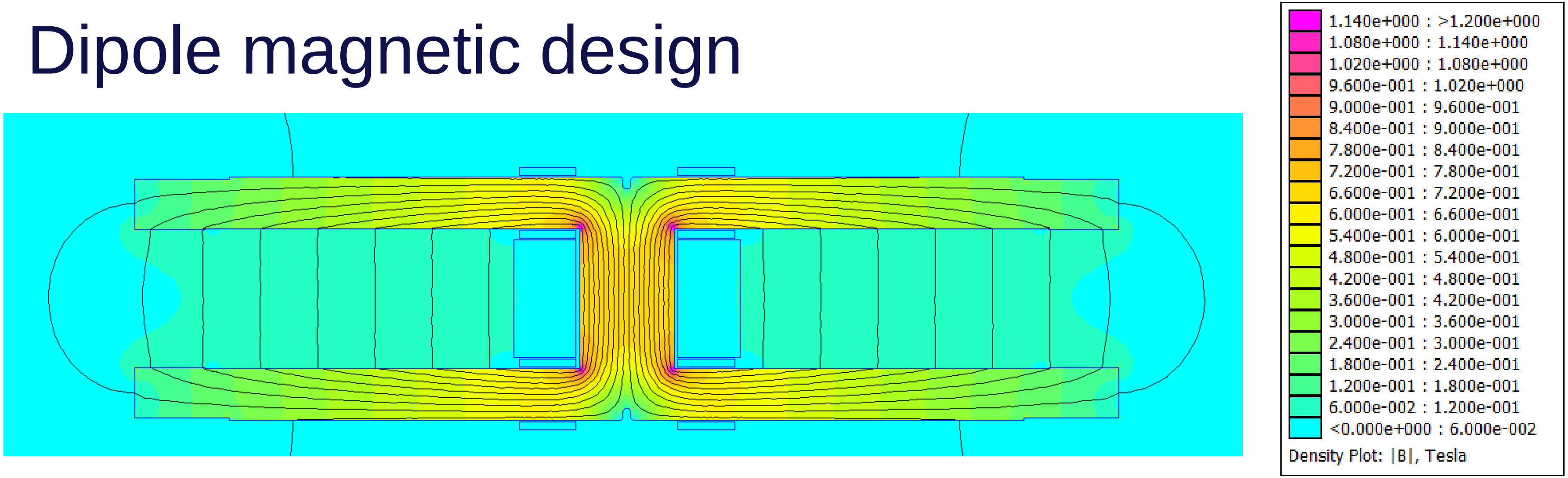
Table 3.2: General parameters of the arc dipole magnets.

Parameter	Unit	Value
Strength, B, 45.6 – 182.5 GeV	mT	15.2 - 61.0
Bore aperture	mm	74
Magnetic length	m	9.7 to 11.2
Outer envelope	mm	520 × 133
Peak current	A	3665
Magnet resistance (at 32°C op. temp.)	mΩ	0.27
Peak voltage, magnet	V	0.98
Peak voltage, half-octant (incl. busbars) †	V	420
Conductor (Aluminium)	mm^2, mm	65 × 35, ⌀7.7
Turns (busbar)	-	1
Turns per coil (trim)	-	7
Current density (busbar), $t\bar{t}$	A/mm^2	1.61
Temperature rise (5 bar)	°C	14.5
Yoke active mass	kg	2621
Busbar active mass	kg	131
Trim coil active mass	kg	6.7
Magnet active mass	kg	2909

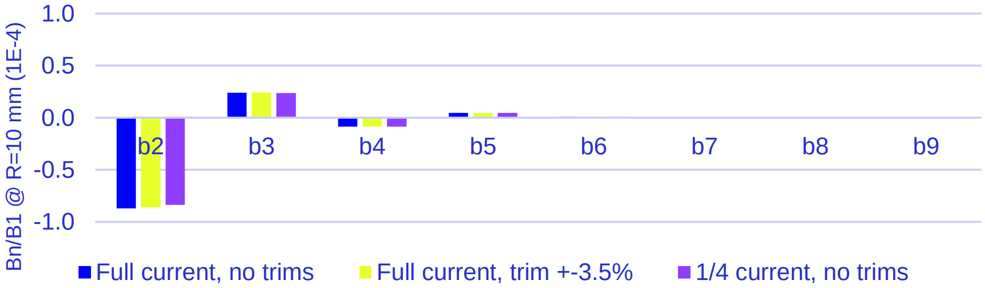
† One half-octant corresponds to one series circuit, which includes 355 magnets. The circuit voltage will be balanced around the middle point of the circuit so that the voltage to ground will not exceed half the circuit voltage.

Dipole parameters, FCC FSR, pp.116.

Dipole magnetic design



Relative harmonics per powering case – 2D
(right aperture only)



- **Trim coils** for field tapering + tuning (J ≈ 1 A/mm^2)
- **Design field quality** below 1 unit (mostly b2 due to C-shape aperture)

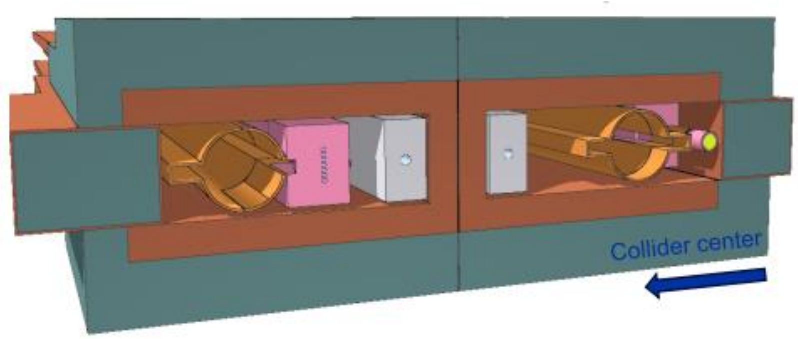
SR absorbers and shielding

- SR absorbers and shielding design studies in progress*

- Dipole yoke design will follow the design evolutions of the shielding to **minimize deformations** from its lumped masses:
  - **Reinforcing the yoke** (could also improve shielding effect)
  - Defining a **suitable positioning scheme** of the dipole **supports**

→ ***Design of the dipole assemblies** under study within **specific WG***

SR absorbers and shielding



*Courtesy: **B. Humann, A. Lechner***

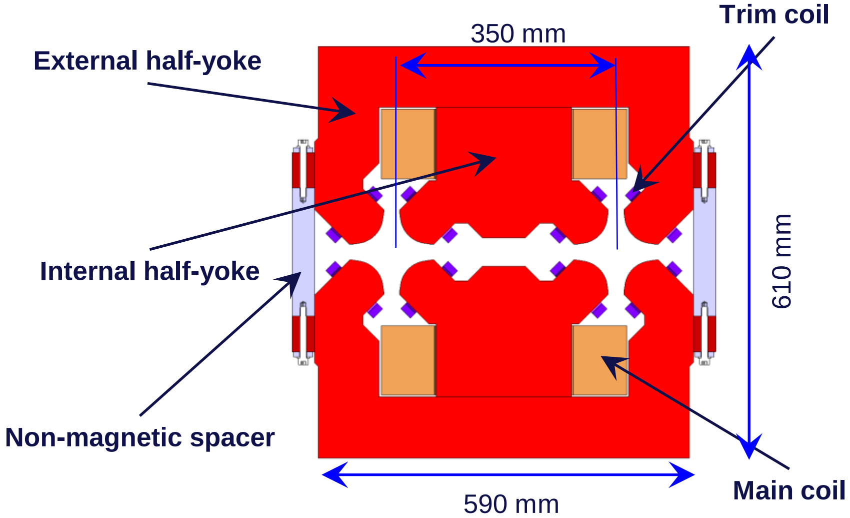
* *see presentations of B. Humann on Thursday 9:35 and M. Morrone on Wednesday 10:30*

Collider quadrupole

(Baseline optics GHC 24.3)

Quadrupole mechanical design and parameters

- **Laminated** yoke construction
- Assembly of yoke parts with bolts / pins / keys and **non-magnetic spacers**
- Hollow **copper conductor** for **main coils**
- Solid **copper conductor** or **aluminum anodized strips** for **trim coils**



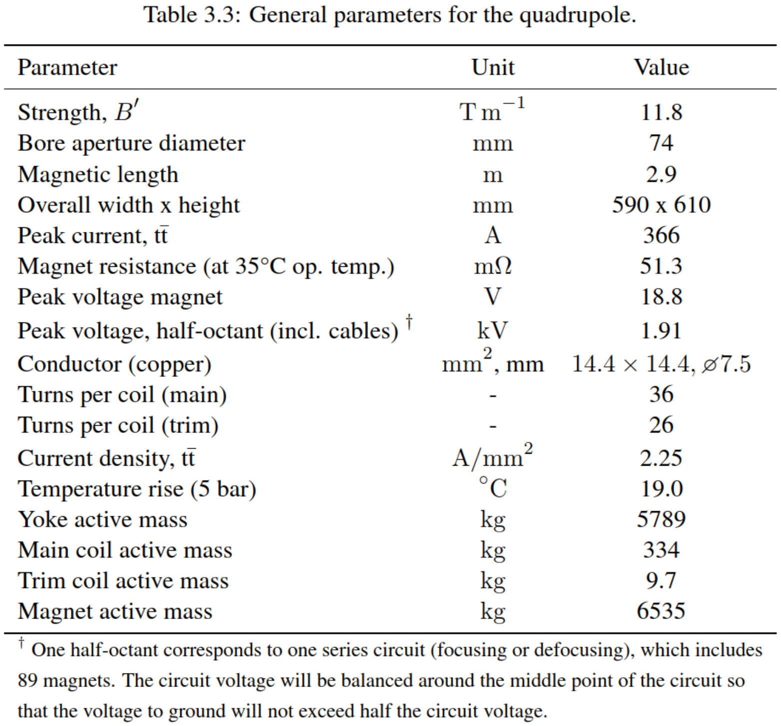


Table 3.3: General parameters for the quadrupole.

Parameter	Unit	Value
Strength, B'	$\mathrm{T\,m^{-1}}$	11.8
Bore aperture diameter	mm	74
Magnetic length	m	2.9
Overall width x height	mm	590 x 610
Peak current, tt̄	A	366
Magnet resistance (at 35°C op. temp.)	mΩ	51.3
Peak voltage magnet	V	18.8
Peak voltage, half-octant (incl. cables) †	kV	1.91
Conductor (copper)	$\mathrm{mm^2}$, mm	14.4 × 14.4, ⌀7.5
Turns per coil (main)	-	36
Turns per coil (trim)	-	26
Current density, tt̄	$\mathrm{A/mm^2}$	2.25
Temperature rise (5 bar)	°C	19.0
Yoke active mass	kg	5789
Main coil active mass	kg	334
Trim coil active mass	kg	9.7
Magnet active mass	kg	6535

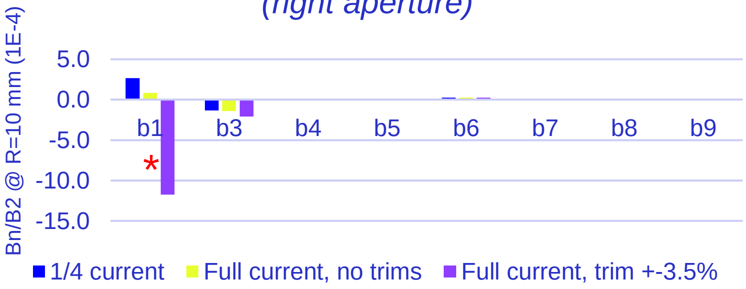
† One half-octant corresponds to one series circuit (focusing or defocusing), which includes 89 magnets. The circuit voltage will be balanced around the middle point of the circuit so that the voltage to ground will not exceed half the circuit voltage.

Quadrupole parameters, FCC FSR, pp.118.

Quadrupole magnetic design – 2D

- Trim coils for **field tapering** + **tuning** (J ≈ 1 A/mm^2)
- Magnetic axis shift due to aperture coupling
- Reminder: **V orbit correction with trims** is **not an option** (impact on DA)

Relative harmonics per powering case – 2D (right aperture)



* 10 units of b_1 = 10 µm axis shift

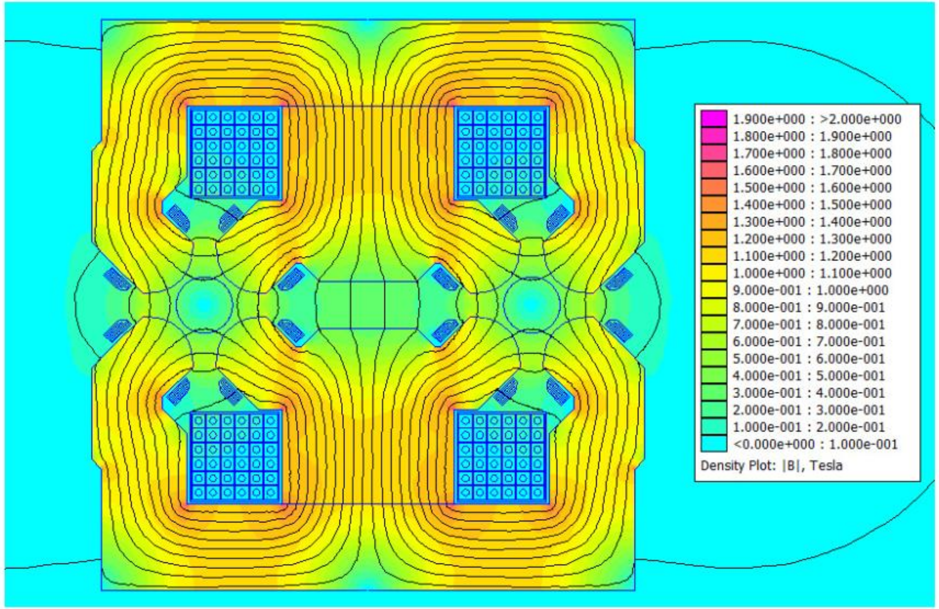


Fig. 3.2: Field map in the quadrupole cross-section at $t\bar{t}$ operation.

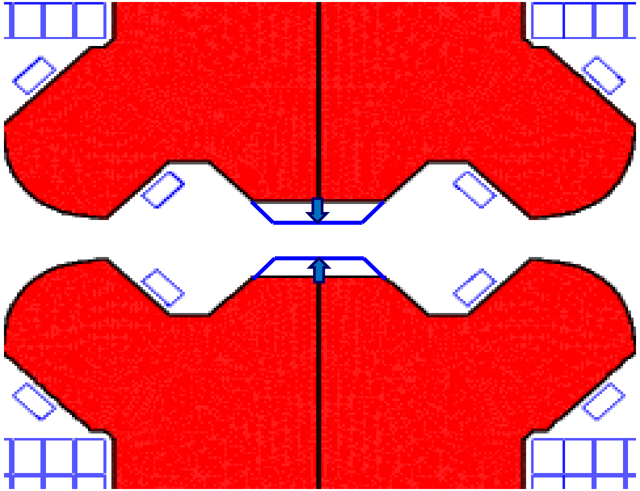
Quadrupole magnetic model, FCC FSR, pp.118.

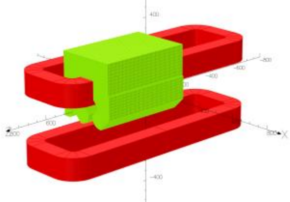
Quadrupole magnetic design – 3D

- **Mismatch** between **harmonics** in centre of **3D model** and harmonics in **2D model** (equivalent to infinitely long)
  - **Dependency of B1 to iron length** inside the magnet, but not in stray field region

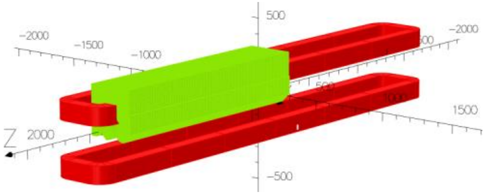
→ Can be **mitigated at one powering level,** but **not suppressed**

B1 along the iron can be modified by **changing the gap in the central magnetic by-pass**

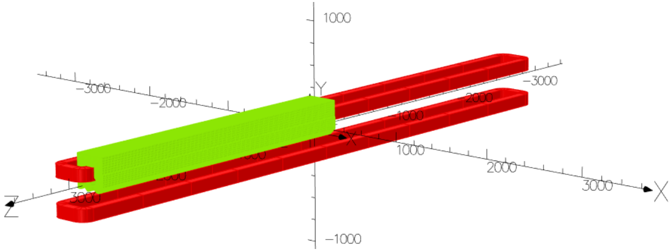




900 mm long yoke



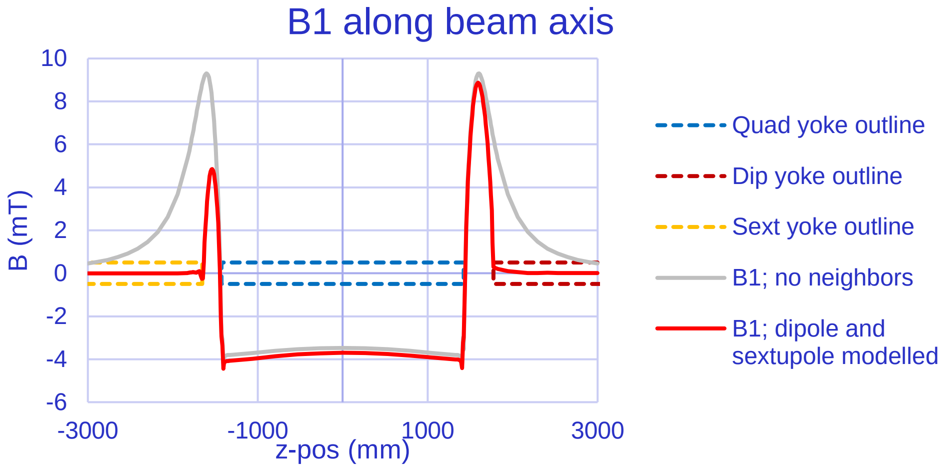
2.9 m long yoke

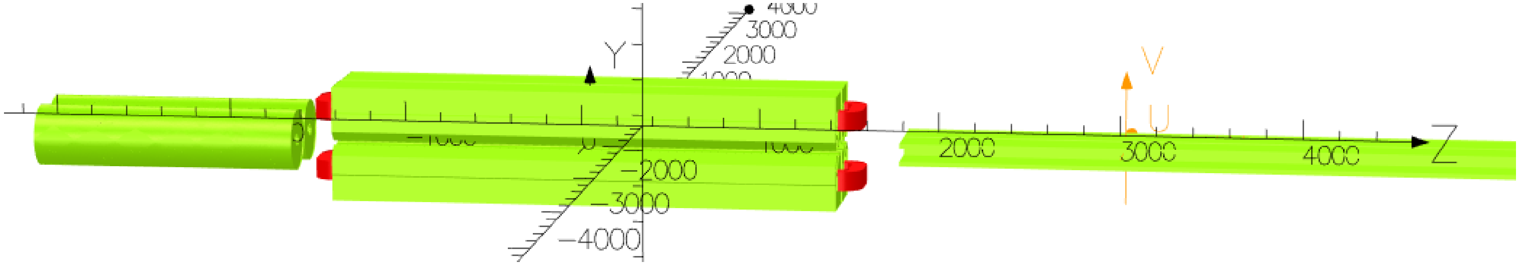


6 m long yoke

Quadrupole magnetic design – 3D

- **Sensitivity to adjacent magnets**
  - Extended **stray field** absorbed by neighbouring yokes
  - The **compensation** between B1 inside and outside the yoke is **variable with the environment**

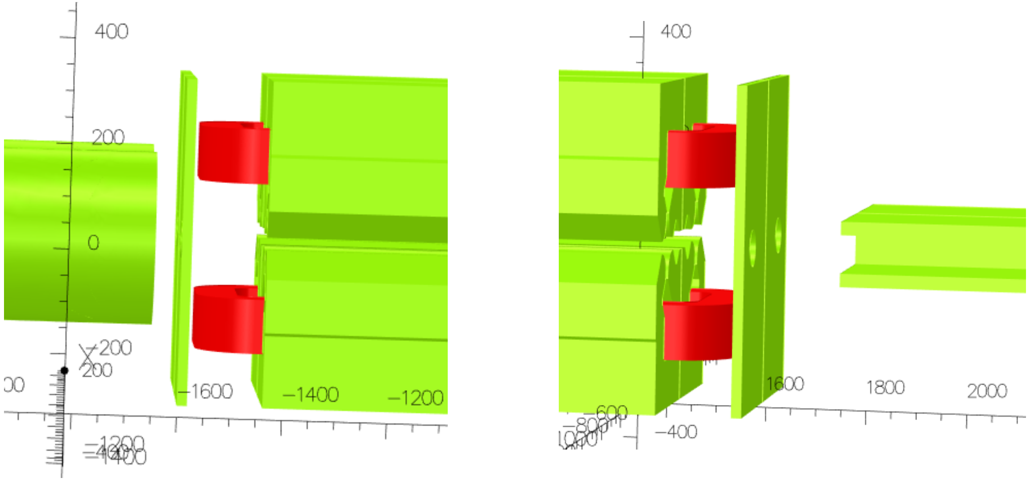


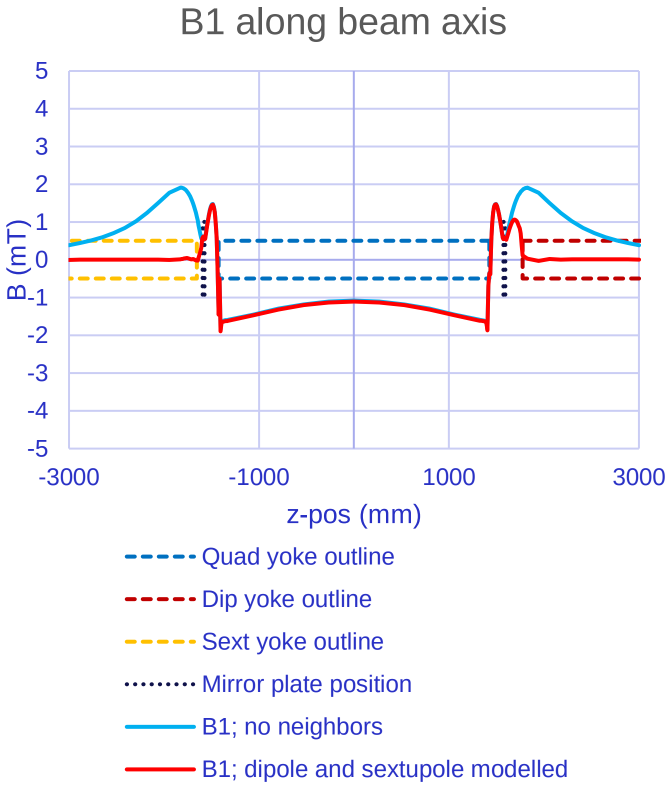


Quadrupole magnetic design – 3D

- Option to **mitigate sensitivity** to environment: installation of **mirror plates** at magnet extremities

→ **Scale 1:1 prototype magnet under preparation** to validate design and axis shift mitigation options




B1 along beam axis

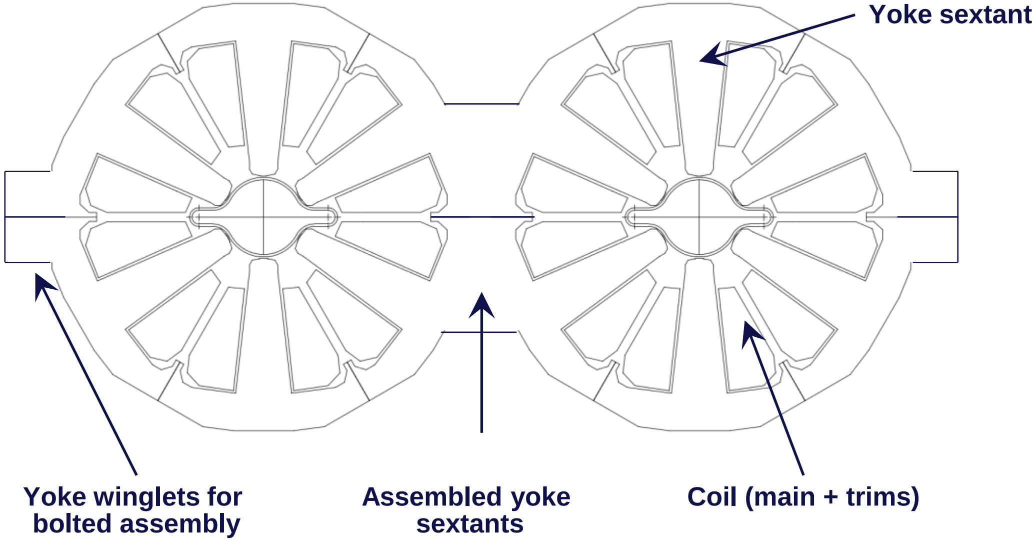
Collider sextupole

(Baseline optics GHC 24.3)

Sextupole mechanical design

* Collaboration with CMU, Thailand

- **Single aperture** magnet, **laminated** yoke construction
- **Hollow copper conductor** for **main coils; solid copper** conductor or **aluminium anodized strips** for **trim coils**
- **Yoke assembly** under study (two single on a craddle or **twin configuration) → prototype to be manufactured in 2026** *



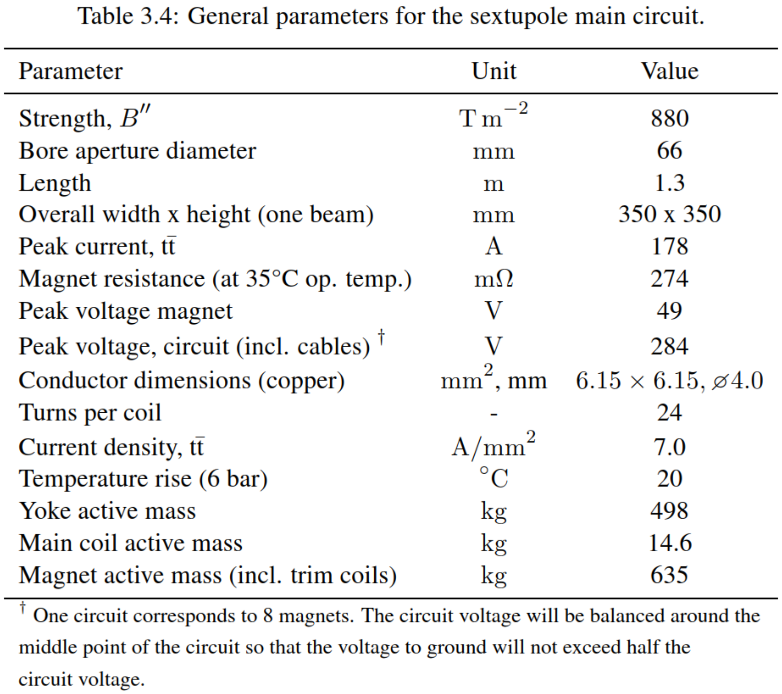


Table 3.4: General parameters for the sextupole main circuit.

Parameter	Unit	Value
Strength, B''	$\mathrm{T\,m^{-2}}$	880
Bore aperture diameter	mm	66
Length	m	1.3
Overall width x height (one beam)	mm	350 x 350
Peak current, $t\bar{t}$	A	178
Magnet resistance (at 35°C op. temp.)	mΩ	274
Peak voltage magnet	V	49
Peak voltage, circuit (incl. cables) [†]	V	284
Conductor dimensions (copper)	$\mathrm{mm^2}$, mm	6.15×6.15, ⌀4.0
Turns per coil	-	24
Current density, $t\bar{t}$	$\mathrm{A/mm^2}$	7.0
Temperature rise (6 bar)	°C	20
Yoke active mass	kg	498
Main coil active mass	kg	14.6
Magnet active mass (incl. trim coils)	kg	635

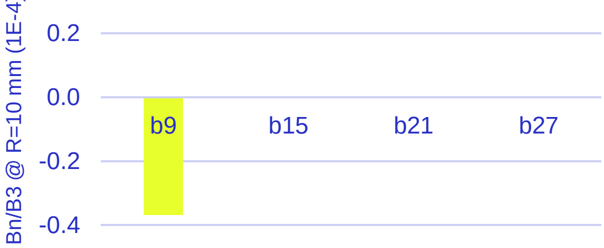
[†] One circuit corresponds to 8 magnets. The circuit voltage will be balanced around the middle point of the circuit so that the voltage to ground will not exceed half the circuit voltage.

Sextupole parameters, FCC FSR, pp.119.

Sextupole magnetic design

- Magnet designed to opertate **below iron saturation** (necessary to operate linearly with trims)
- All allowed multipoles below 1 unit in 2D

Allowed relative harmonics – 2D (no trims)



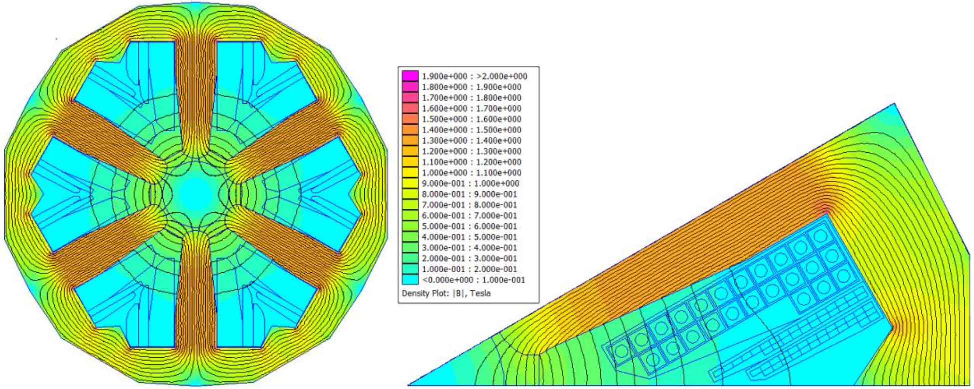


Fig. 3.3: Left: Field map in the sextupole cross-section at $t\bar{t}$ operation (peak field). Right: Detailed view of a half-sextant. The conceptual positioning of the conductor has been generated from parametric modelling for checking integration feasibility. It will be optimised for industrial production during the pre-TDR phase.

Sextupole magnetic model, FCC FSR, pp.120.

Correctors

- **Baseline design** with **correction circuit** as trim coils **embedded in the sextupole**
- They generate **quite large multipoles***:
  - ~40 units of b_5 for H orbit and of a_5 for V orbit corrections
  - ~70 units of a_4 for skew quadrupole correction
- Beam dynamics are **reevaluating the needs** (e.g. 1 plane corrector per arc half-cell may be suffucient) **and acceptable field errors**

** see presentation at FCCIS WS 2023*

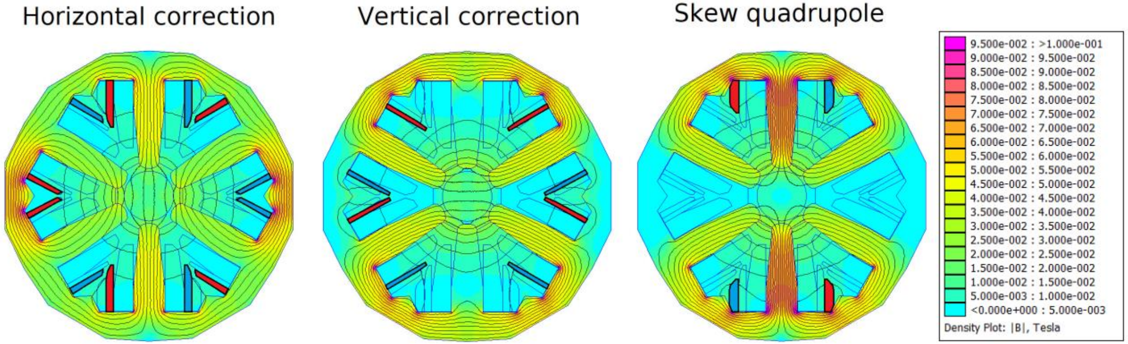
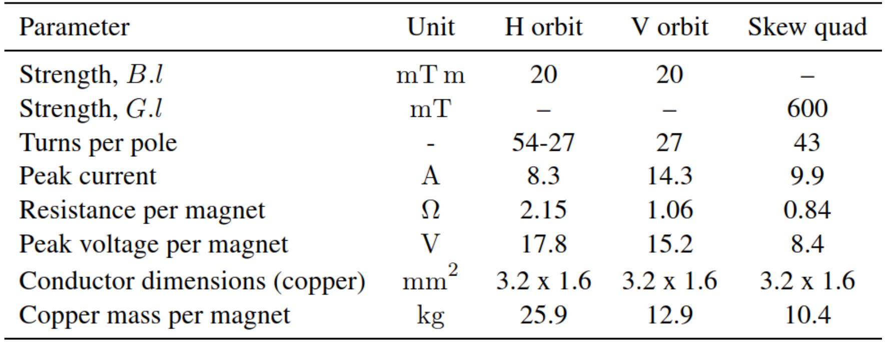


Fig. 3.4: Field maps of the correction circuits at peak correction fields. Left: horizontal orbit correction; middle: vertical orbit correction; right: skew quadrupole correction.

Table 3.5: General parameters for the sextupole correction circuits.



Parameter	Unit	H orbit	V orbit	Skew quad
Strength, $B.l$	mT m	20	20	–
Strength, $G.l$	mT	–	–	600
Turns per pole	-	54-27	27	43
Peak current	A	8.3	14.3	9.9
Resistance per magnet	Ω	2.15	1.06	0.84
Peak voltage per magnet	V	17.8	15.2	8.4
Conductor dimensions (copper)	mm^2	3.2 x 1.6	3.2 x 1.6	3.2 x 1.6
Copper mass per magnet	kg	25.9	12.9	10.4

Sextupole correctors, FCC FSR, pp.120.

Comparison GHC / LCC magnet parameters

LCC vs. GHC layout

- Longer arc cells in LCC optics
  - Up to **~30 m dipole / half-cell** (vs. ~24 m for GHC) → **3 dipole units of ~10 m** / half-cell required (instead of 2x 12m in GHC) since ~12 m considered maximum length feasible for vacuum chamber production, and overall logistics (containers, tunnel shafts, etc.)
- Shorter SSS in LCC optics
  - **1.8 m** QD / **2.4 m** QF (vs. **2.9 m** QF & QD **for GHC**)
  - **0.52 m** SD / **0.3 m** SF (vs. **1.3 m** SF & SD **for GHC**)
  - **Same polarities (FF or DD)** for e+ / e- beams at same location **not compatible with twin quadrupole design of GHC**

OR… **e+ or e- lattices could be shifted by 1 half-cell** to recover GHC polarities, but QD – QF lengths not matching, so:

- 60 cm of dipole field (1%) would be ”lost” at each cell (… or could be used for separate correctors or other equipment?)
- A single aperture QF of 60 cm would be needed in addition to each 1.8 m twin aperture quadrupole

LCC magnet parameters (vs. GHC)

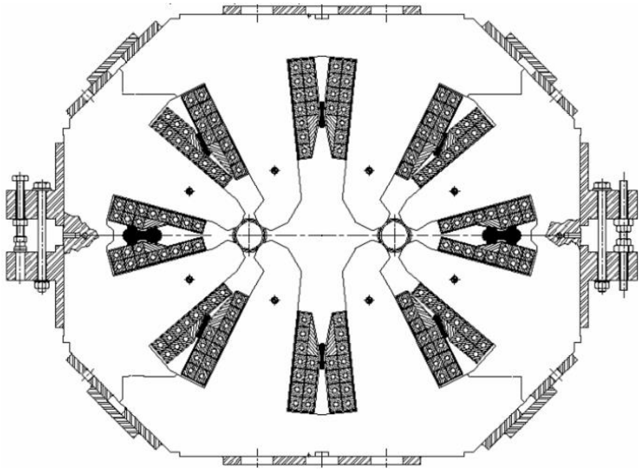
- Magnet quantities
  - **More dipole** units, but **less SSS magnets**
  - → Dipole are much cheaper to produce than the SSS magnets
- Cumulated integrated field
  - Most **relevant parameter for cost comparison** (CAPEX)
  - Significantly **smaller quadrupoles** (-39%), **sextupoles** (-60%) in LCC optics; saves space for drifts (+13%) and longer dipoles (B_{avg} -9%)
  - SSS magnets are however about 10% stronger
- Number of circuits
  - **Significantly less sextupole circuits** in LCC optics, thanks to long strings of magnets connected in series in the arcs
- **Potential** magnet CAPEX **cost saving** of LCC: **~30%** *(if **scaled to cumulated integrated field**)*

Parameter	Unit	GHC	LCC	Ratio LCC/GHC
Dipole				
Magnet quantity (all incl. LSS)		6128	7248	**+18%**
Magnet quantity in arcs (twin aperture)		5680	6624	+17%
Circuit quantity		40	33	-18%
Cumulated magnetic length	m	66567	71664	+8%
Cumulated integrated field	Tm	3911	3825	**-2%**
Average field	T	0.0588	0.0534	-9%
Cost fraction of arc magnets	%	31%	45%	
Quadrupole				
Magnet quantity (all incl. LSS)		3312	2704	**-18%**
Magnet quantity in arcs (twin aperture)		2836	2168	-24%
Circuit quantity		112	106	-5%
Max peak field (arcs)	T/m	11.8	13.7	+16%
Cumulated magnetic length	m	9472	5180	-45%
Cumulated integrated field	T	110669	67437	**-39%**
Average field gradient	T/m	11.7	13.0	+11%
Cost fraction of arc magnets	%	48%	43%	
Sextupole				
Magnet quantity (all, single aperture)		4736	4000	**-16%**
Circuit quantity		150	62	-59%
Max peak field	T/m^2	796	891	+12%
Cumulated magnetic length	m	3044	773	-75%
Cumulated integrated field	T/m	1385459	556217	**-60%**
Average sextupole field	T/m^2	455	719	+58%
Cost fraction of arc magnets	%	21%	12%	
Other elements				
Machine circumference	m	90658.7	90658.6	0%
Drifts or other elements	m	11575	13042	**+13%**
Total cost arc magnets scaled				
Cost fraction of GHC baseline magnet CAPEX	%	100%	68%	**-32%**

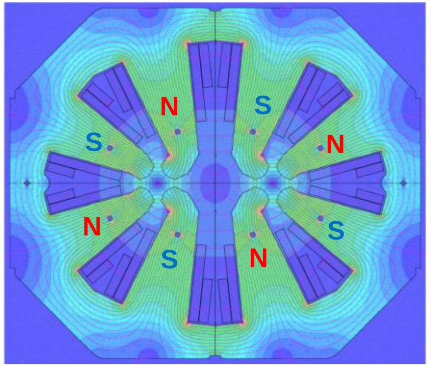
Concepts of twin quadrupoles

Twin aperture quadrupoles with configurable aperture powering

- Example: MQW magnets in LHC

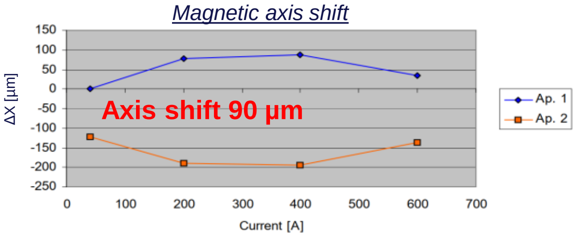


8 coils in series; 2 different coil types

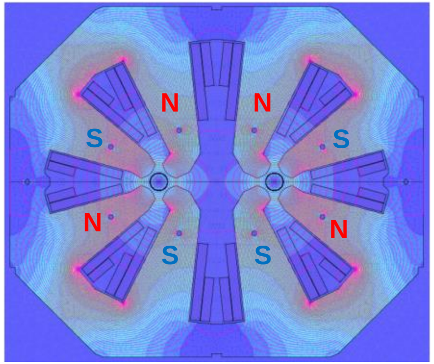


MQWA configuration F/D or D/F

- Field lines ⊥ to vertical mid-plane
- Would be F/F (or D/D) for e+/e- beams

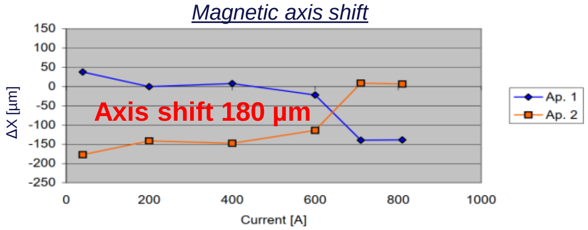


Axis shift 90 µm



MQWB configuration F/F or D/D

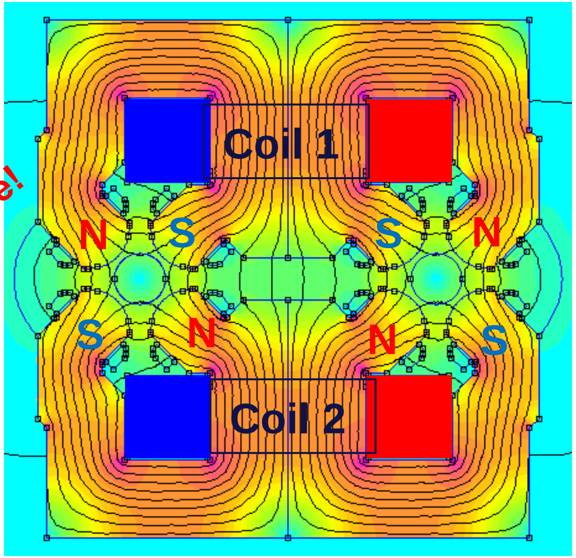
- Field lines // to vertical mid-plane
- Would be F/D (or D/F) for e+/e- beams



Axis shift 180 µm

Twin aperture quadrupoles with configurable aperture powering

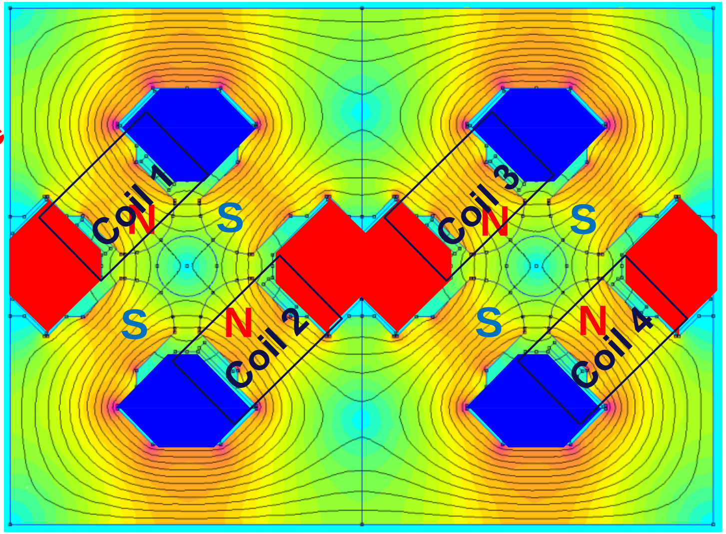
- Present design, F/D (or D/F) configuration
- Design with F/F (or D/D) configuration



Fixed polarity, NOT configurable!

2 main coils; **8 <u>separate</u> trim** coils

(10 impregnated objects of 2 types)



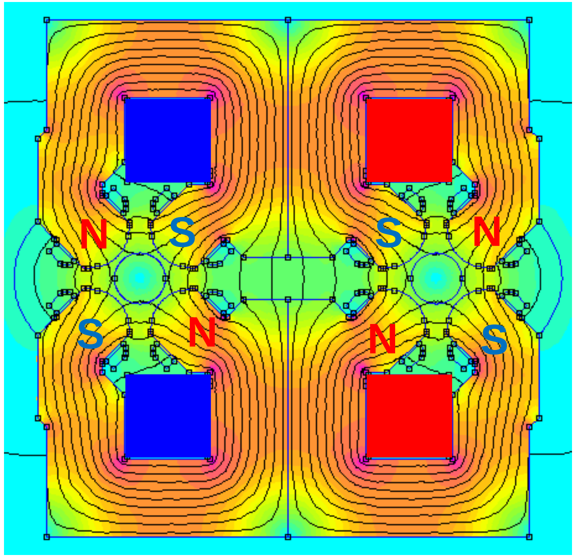
Configurable polarity!

4 main coils with **4 <u>embedded</u> trim** coils

(4 identical impregnated objects)

Twin aperture quadrupoles with configurable aperture powering

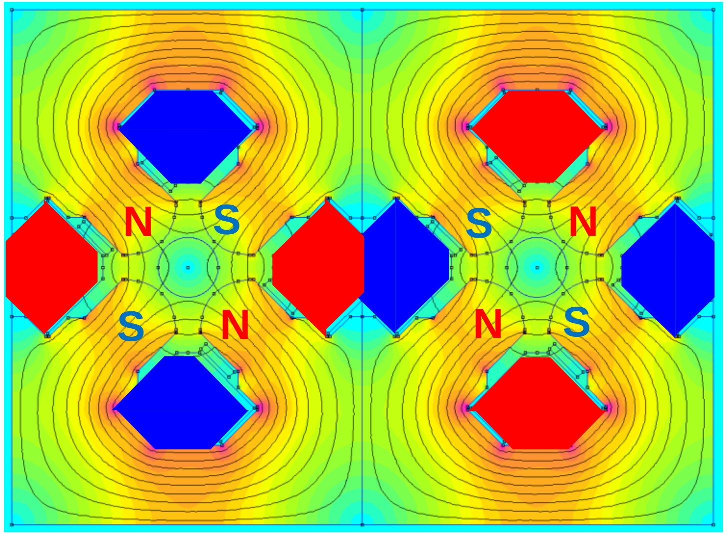
- Present design, F/D (or D/F) configuration



2 main coils; **8 separate trim** coils

(10 impregnated objects of 2 types)

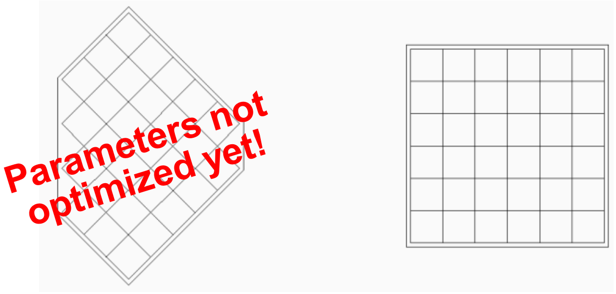
- Design with F/D (or D/F) configuration



4 main coils with **4 embedded trim** coils

(4 identical impregnated objects)

Electrical parameters and power consumption



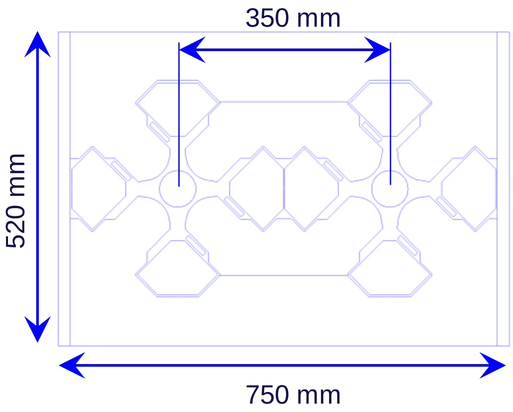
Parameters not optimized yet!

Same polarities	Opposite polarities
29 turns	**36 turns**
Conductor size [mm] 14 x 14 x d.6/7 mm	Conductor size [mm] 14.4 x 14.4 x d.7.5 mm
J = 3.6 A/mm^2	J = 2.25 A/mm^2

→ The **larger consumption** of the twin quadrupoles with same polarities is **recovered by the shorter and less numerous SSS magnets**

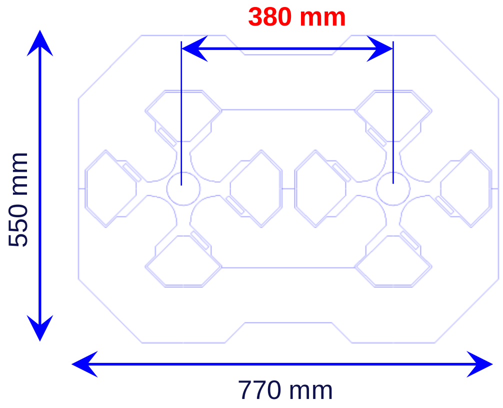
			Z	WW	ZH	tt	Total	
			MWh	*MWh*	*MWh*	*MWh*	*MWh*	*%*
GHC	**Collider**	Dipole	30290	46614	157324	606465	840693	25%
		Quadrupole	*27502*	*42324*	*142842*	*550640*	*763308*	*22%*
		Sextupole	*20016*	*30803*	*103960*	*400759*	*555538*	*16%*
		LSS	12522	19270	65038	250714	347544	10%
		Trims	5672	8728	29458	113559	157417	5%
		Sub-total	**96002**	**147739**	**498622**	**1922137**	**2664500**	**78%**
	Booster	Dipole	15313	12943	30822	163435	222513	7%
		Quadrupole	18668	15779	37575	199243	271265	8%
		Sextupole F	2843	2403	5722	30341	41309	1%
		Sextupole D	4977	4207	10018	53120	72322	2%
		LSS	6778	5729	13642	72339	98488	3%
		Trims	3384	2861	6812	36122	49179	1%
		Sub-total	**51963**	**43922**	**104591**	**554600**	**755076**	**22%**
		Gran total	**147965**	**191661**	**603213**	**2476737**	**3419576**	**100%**
LCC	**Collider**	Dipole	30290	46614	157324	606465	840693	0%
		Quadrupole (computed with coil parameters)	*38479*	*59217*	*199856*	*770423*	*1067976*	*+40%*
		Sextupole (scaled with integrated field)	*8036*	*12366*	*41737*	*160892*	*223030*	*-60%*
		LSS	12522	19270	65038	250714	347544	0%
		Trims	5672	8728	29458	113559	157417	0%
		Sub-total	**94999**	**146196**	**493413**	**1902053**	**2636660**	**-1%**

Twin aperture quadrupoles with configurable aperture powering



Open mid-plane

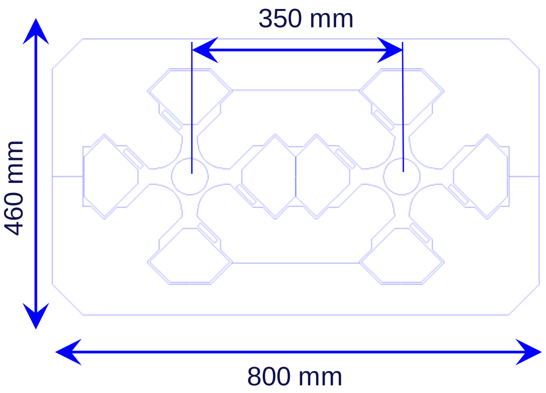
- Non-magnetic spacers on the sides
- Possible magnetic interference with surrounding equipment



Assembled

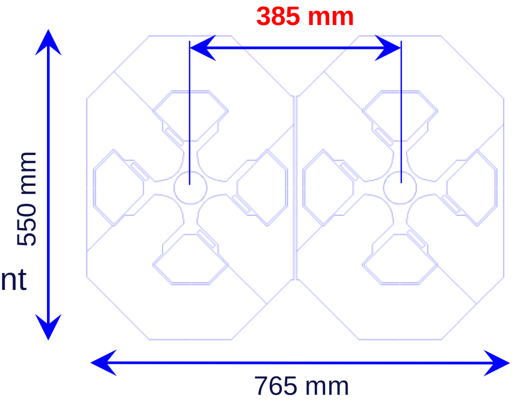
Fully-closed mid-plane

- External sides closed
- No magnetic interference with surrounding equipment
- Magnetic material along vertical mid-plane
- 350 mm inter-beam distance gets too short (to be optimized)



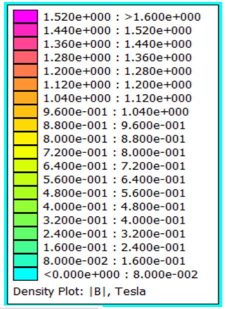
Semi-closed mid-plane

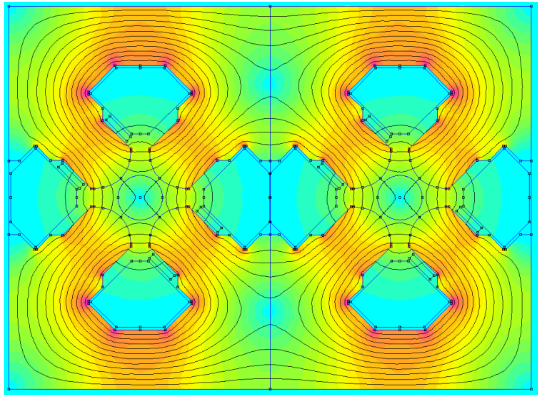
- External sides closed
- No magnetic interference with surrounding equipment



Separated with 5 mm air gap

Open mid-plane twin aperture quadrupole

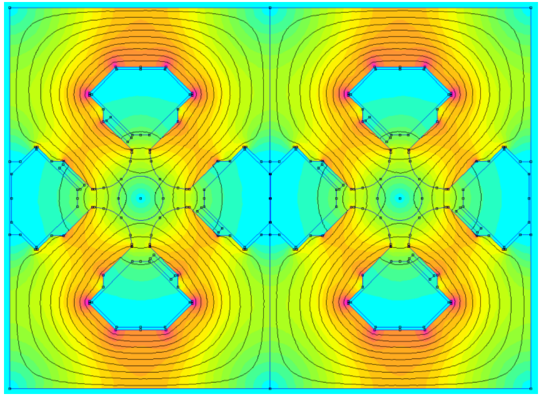




FF/DD configuration

- Axis shift between Z and tt operation:

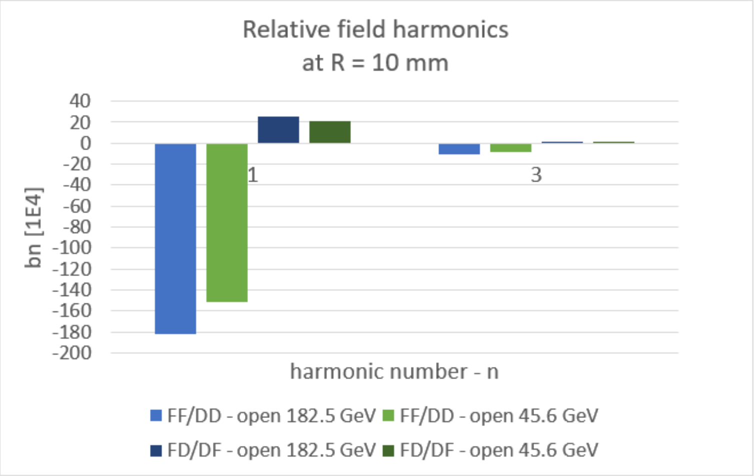
30 µm

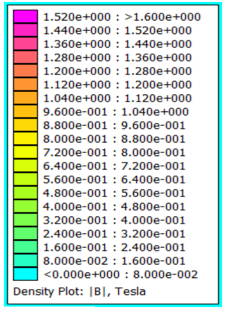


FD/DF configuration

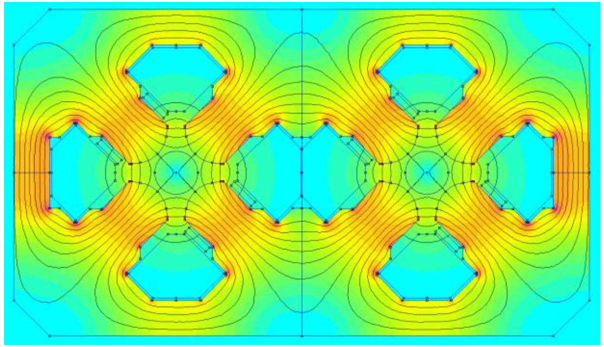
- Axis shift between Z and tt operation:

4 µm





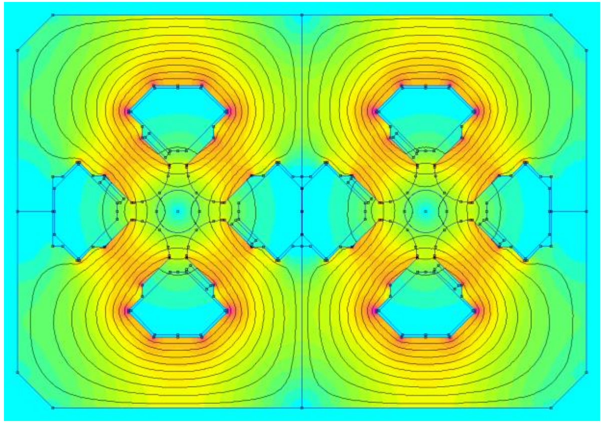
Semi-closed mid-plane twin aperture quadrupole



FF/DD configuration

- Axis shift between Z and tt operation:

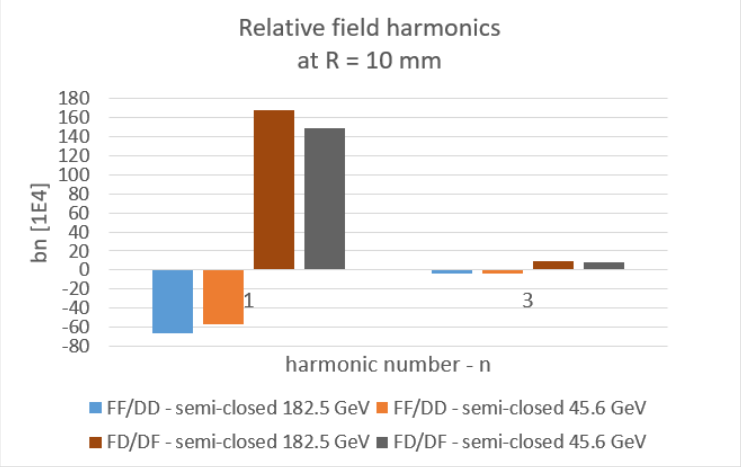
9 µm



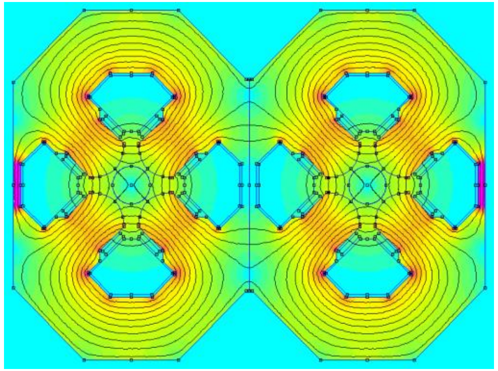
FD/DF configuration

- Axis shift between Z and tt operation:

20 µm



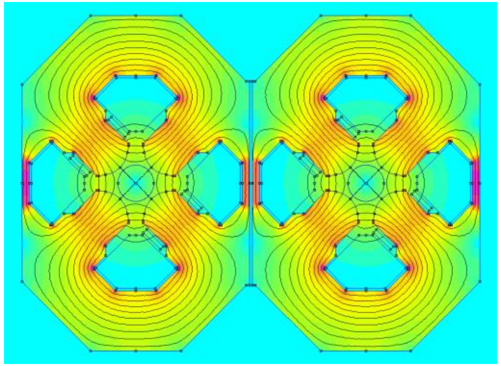
Fully closed mid-plane twin aperture quadrupole



FF/DD configuration

- Assembled magnetic circuits
- Axis shift between Z and tt operation:

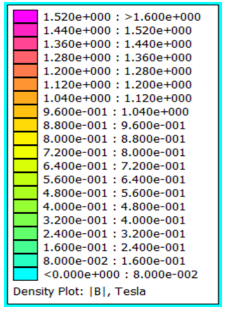
40 µm

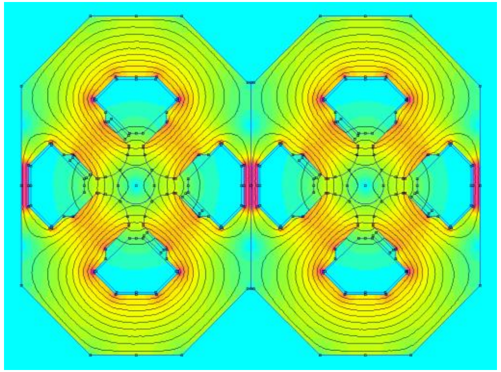


FF/DD configuration

- 5 mm air gap between magnetic circuits
- Axis shift between Z and tt operation:

19 µm

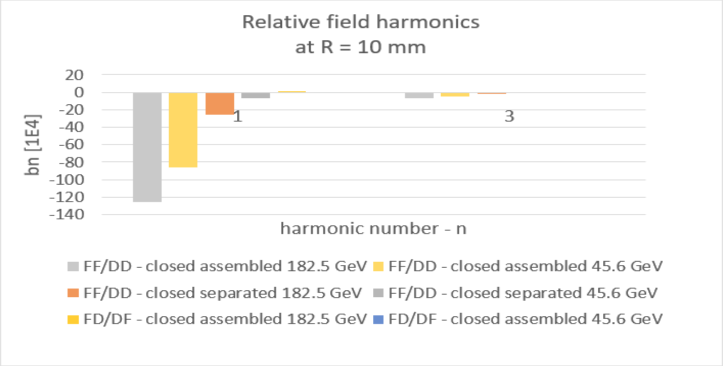




FD/DF configuration

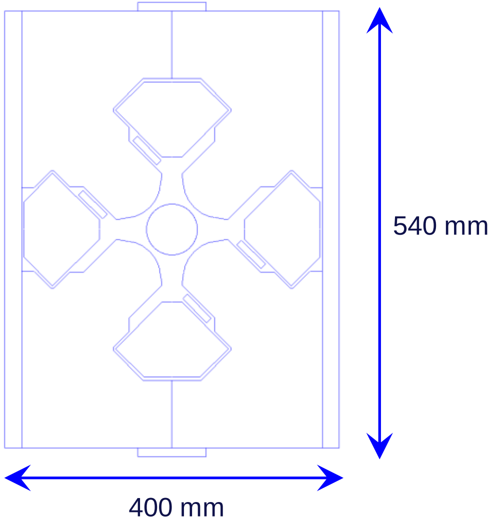
- Assembled magnetic circuits
- Axis shift between Z and tt operation:

1 µm



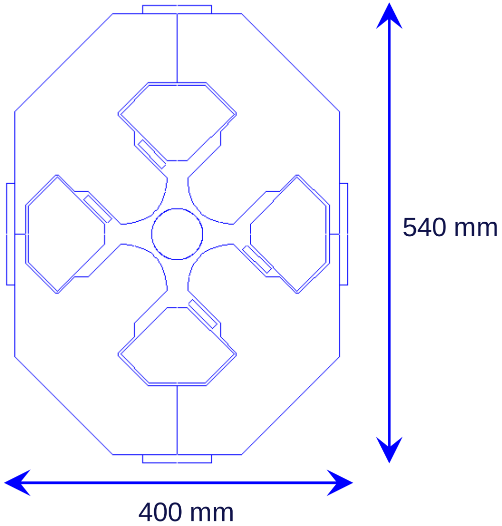
Concepts of single aperture quadrupoles

Single aperture quadrupoles topologies (for LCC or RF LSS)



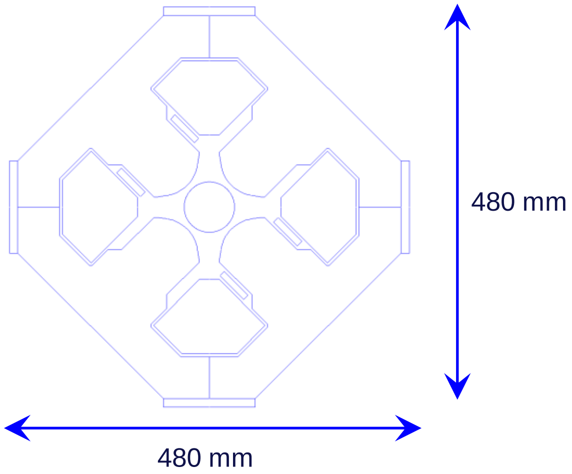
Open mid-plane

- Non-magnetic spacers on the sides
- Possible magnetic interference with surrounding equipment



Closed figure-of-eight

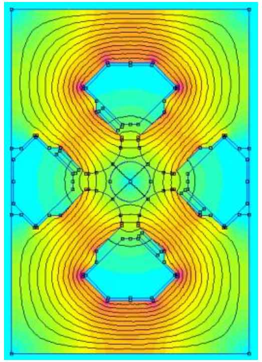
- External sides closed
- No magnetic interference with surrounding equipment



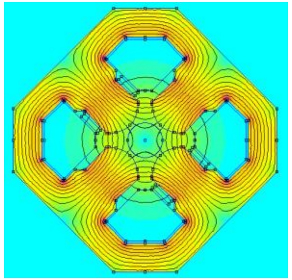
Closed symmetric

- External sides closed
- No magnetic interference with surrounding equipment

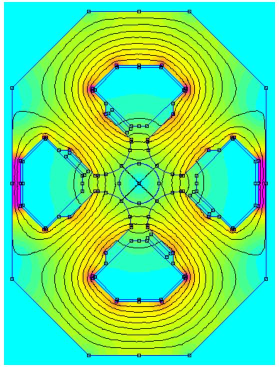
Magnetic performance of single aperture quadrupoles



Open mid-plane



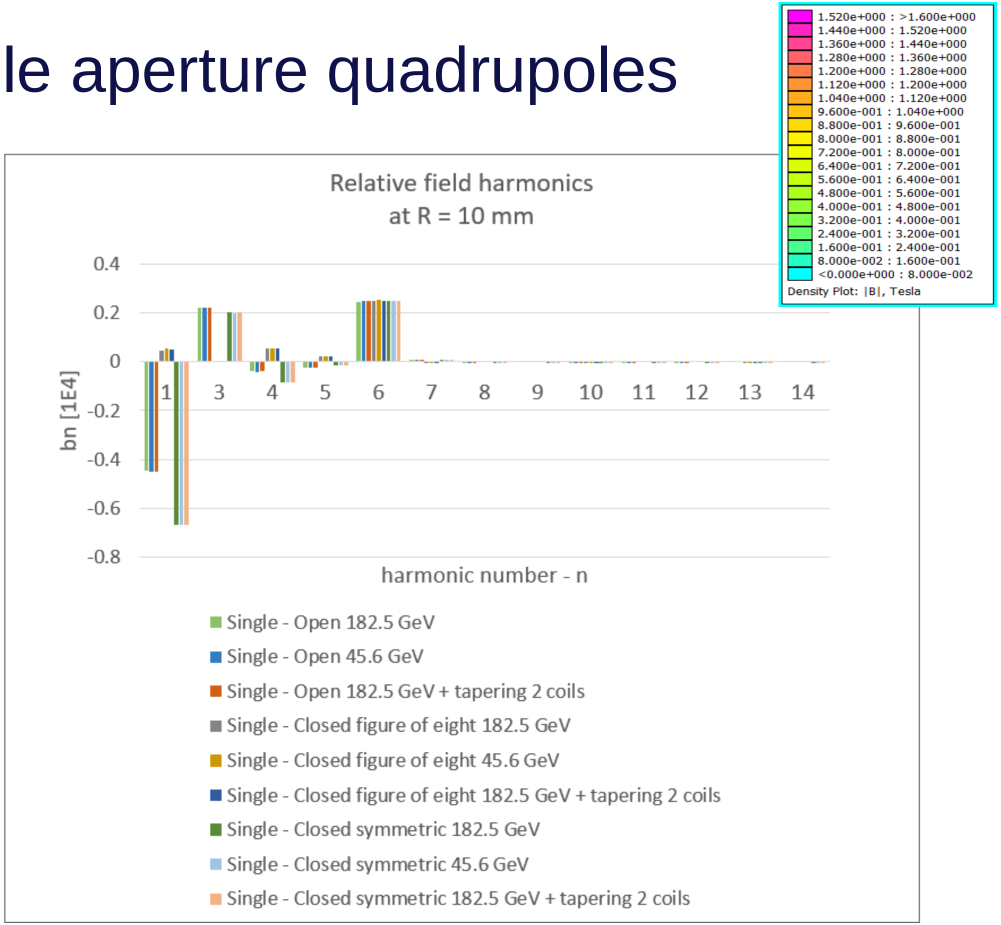
Closed symmetric



Closed figure-of-eight

Simulation results

- All harmonics are below 1 unit
- Harmonics b1 to b5 may come partially from numerical noise (should be 0 on the closed symmetric design)
- No dependency on powering level observed



Next steps for magnet development

Collider magnets development during pre-TDR

- Design
    - *Detailed* ***mechanical design*** *of magnet assemblies*
        - *Dipole assembly with vacuum chambers, synchrotron radiation absorbers and shielding*
        - *Assemblies of quadrupoles / sextupoles pairs*
        - *Interconnections*
    - *Evaluation of* ***magnet design*** *(and cost)* ***alternatives*** *to support* ***optics baseline selection*** *(incl. parameters optimisation), also including a study for separate correctors*
    - *Refine* ***cost evaluation*** *model*
- Manufacture
    - ***Magnet prototypes*** *for performance validation and arc half-cell mock-up (e.g. twin aperture quad)*
    - *Manufacturing processes for* ***large series*** *(automatized machining, assembly and measurements) and procurement strategies.* ***Collaboration with TU Wien*** *from September 2025.*
    - ***R&D*** *on* ***inorganic*** *coatings for conductor* ***insulation*** *(dipole busbars, trim coils, sextupole coils)*

Summary

The collider magnet designs reported in the Feasibility Study Report have been based on the GHC baseline optics. They will continue to evolve during the pre-TDR phase to address the requirements of the machine which are still under evaluation (e.g. optics choice, integration of the radiation shielding in the dipoles, supporting scheme, separated orbit correctors, etc.)

The **LCC optics** with its shorter SSS show **potential for savings** on the magnet CAPEX:

- The **dipoles and sextupole** cross-section designs are rather similar as for the GHC optics, but
  - The dipole arc half-cell longer length imposes splitting it in three units
  - The **sextupoles are much shorter**
- Two options are possible for the **quadrupoles**:
  - Twin aperture with **opposite polarities** (like GHC baseline design), followed by a short single aperture QF
  - Twin aperture with **same polarities**, which require twice the ampere-turns of the opposite polarity version

→ The **power consumption difference** is however **compensated by the shorter magnets** of the LCC optics

The most significant benefits of the LCC optics are:

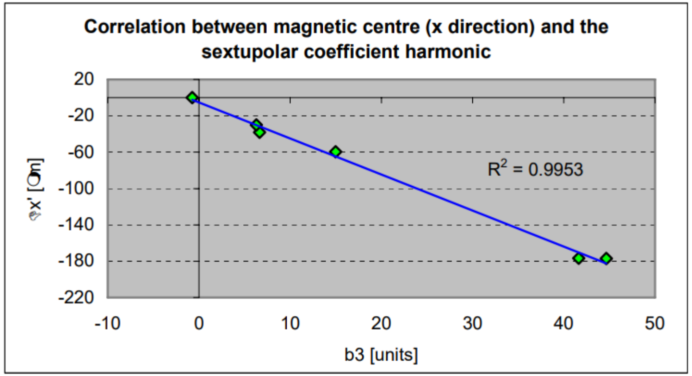
- The **magnet CAPEX** could be much **reduced** (as well as the power converters and cabling)
- A **single configuration** which covers all phases of the operation from H to tt_{bar}

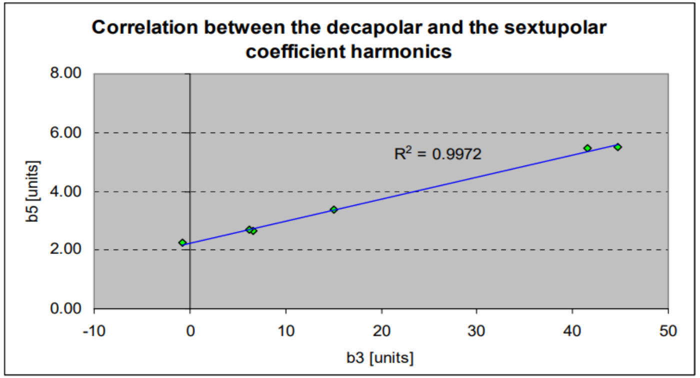
Thank you for your attention!

Questions?

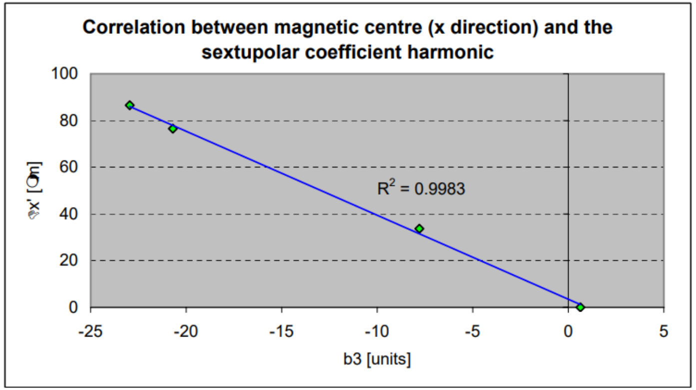
Spare slides

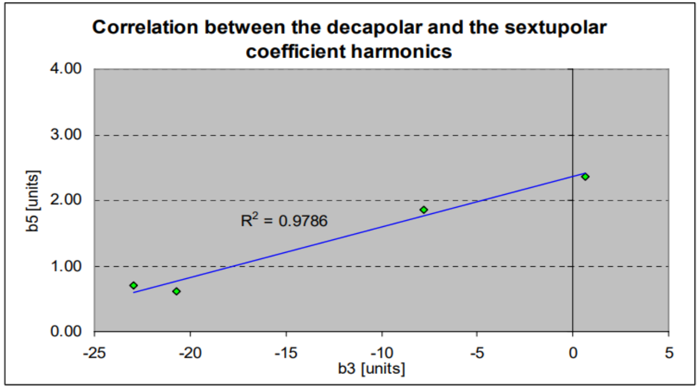
Aperture coupling of LHC MQW twin quadrupoles





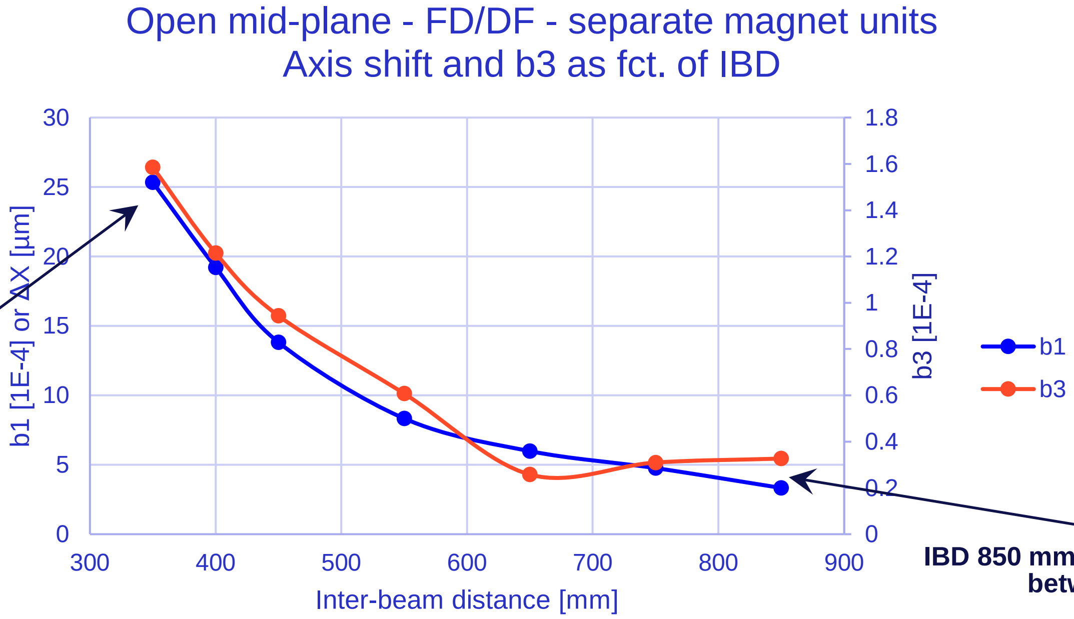
MQWA configuration





MQWB configuration

Aperture coupling of FCC-ee twin quadrupole (open mid-plane design, for FD/DF polarity)



IBD 350 mm = no separation between magnets

IBD 850 mm = 500 mm separation between magnets