FCC

FCC-ee Collider Magnets
-
Correction circuits with trim coils

J. Bauche, C. Eriksson, F. Saeidi

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Outline

Magnet field tapering and correction circuits

- Baseline specification and alternative options
- Trim circuits characteristics
  - Dipole
  - Quadrupole
  - Sextupole

Summary and next steps

Specifications

Field tapering and correction circuits

Baseline

- **Field tapering** trims on each aperture of **dipoles** and **quadrupoles**
  → granularity: every 4 FODO
- **Orbit** and **quadrupole corrections**: trim coils in **sextupoles**
  → granularity: at every sextupole, so only at ~60% of the arc half-cells

➔ ***We studied options to remove orbit correction from sextupoles***

- ➔ ***Improve granularity*** *of correction*
- ➔ ***Free space*** *in the sextupole to* ***decrease*** *its* ***power consumption*** *(current density)*

BASELINE	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Sextupole	1.5	0.013	0.02
Orbit correction V	Sextupole	1.5	0.013	0.02
Normal quadrupole	Sextupole	1.5	0.4	0.6
Skew quadrupole	Sextupole	1.5	0.4	0.6

Correction specifications from optics

Alternatives

- **1) H + V orbit corrections** use **quadrupole tapering trim coils**
  → granularity: at every arc half-cell
- **2) H orbit correction** uses **dipole tapering trim coils +**
  V orbit correction uses **quadrupole tapering trim coils**
  → granularity: at every arc half-cell

ALTERNATIVE 1	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Quadrupole	2.9	0.0067	0.02
Orbit correction V	Quadrupole	2.9	0.0067	0.02

ALTERNATIVE 2	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Dipole	21.15	0.0009	0.02
Orbit correction V	Quadrupole	2.9	0.0067	0.02

Dipole

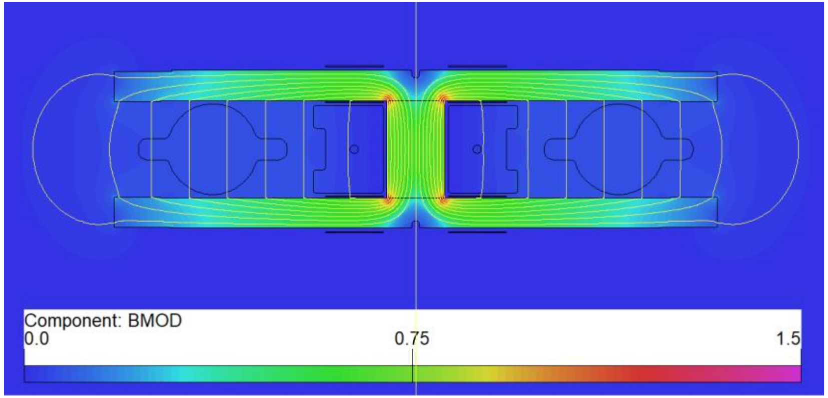
Dipole design

Trim coils

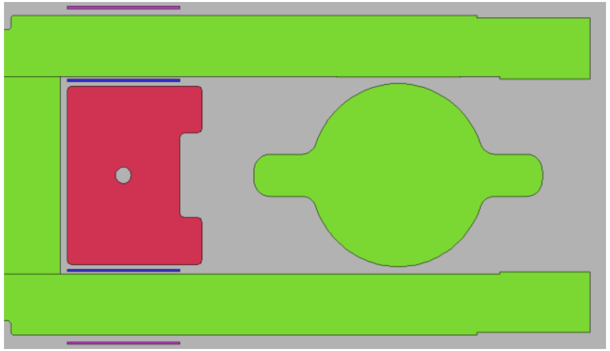
- Allow to modulate the field in the apertures **independently**
    - Used for **field tapering** up to **±2.5 %** (tt_{bar})
    - Can be used for **field tuning** up to **±1 %** (all phases) and **H orbit correction** up to **±1.5 %**

➔ **Worst case**: could be up to **5% of main field** variation

- Simulations performed assuming trim coils over the whole magnet length, but we could imagine a **shorter length with more ampere-turns** for a similar strength
- A part of the yoke could be **laminated** to operate with a **fast feedback system**



Magnetic model cross-section (tt_{bar} excitation, B = 61 mT)



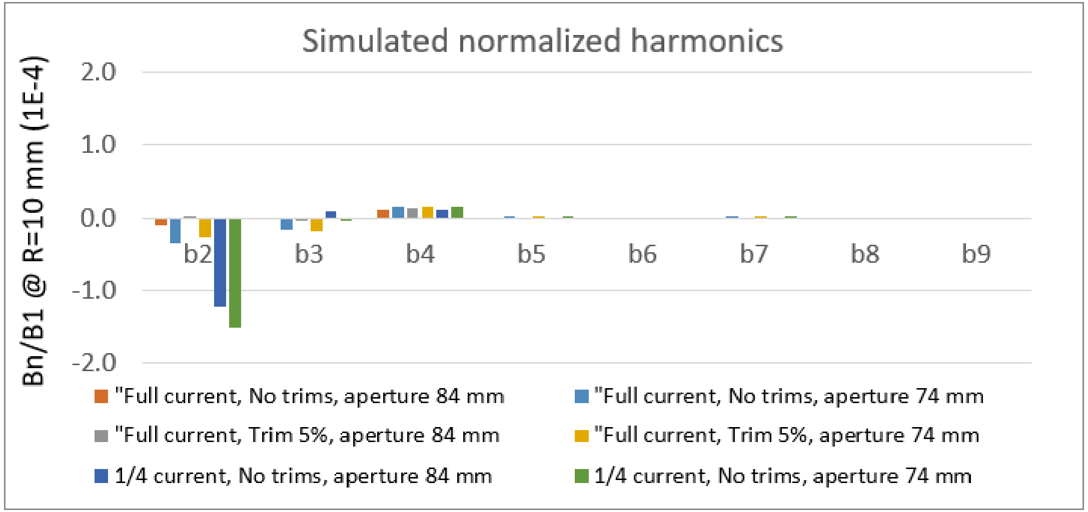
Trim coils wrapped around top and bottom poles

Dipole field quality

- The magnet **field quality is good** with all harmonics <1 unit, except a **quadrupolar component of 1.5 units** at low field (H operation)

  → *This could be **compensated** by the main quadrupole circuit*

- The **effect of the trim** coils for the field tapering, tuning and H orbit correction on the **field quality** is **negligible**

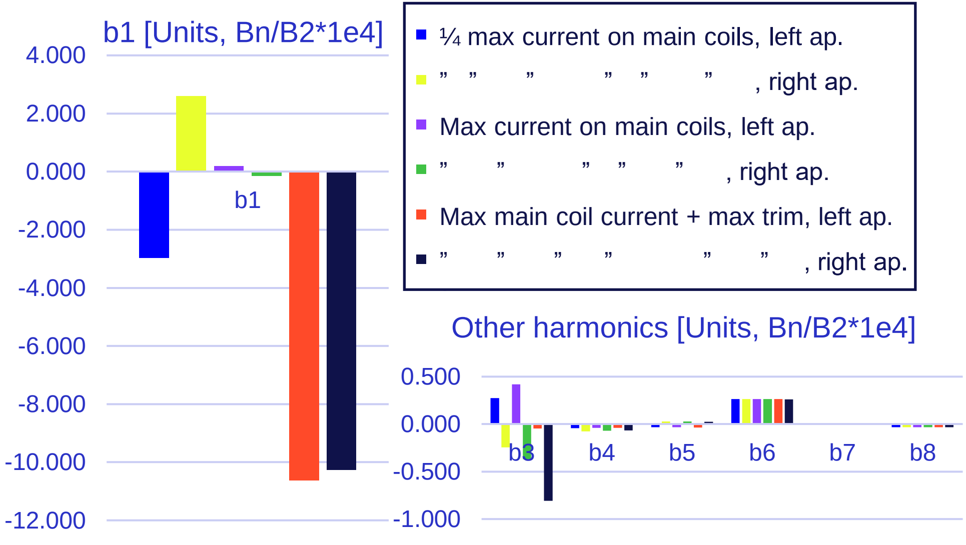


Computed field harmonics

Quadrupole

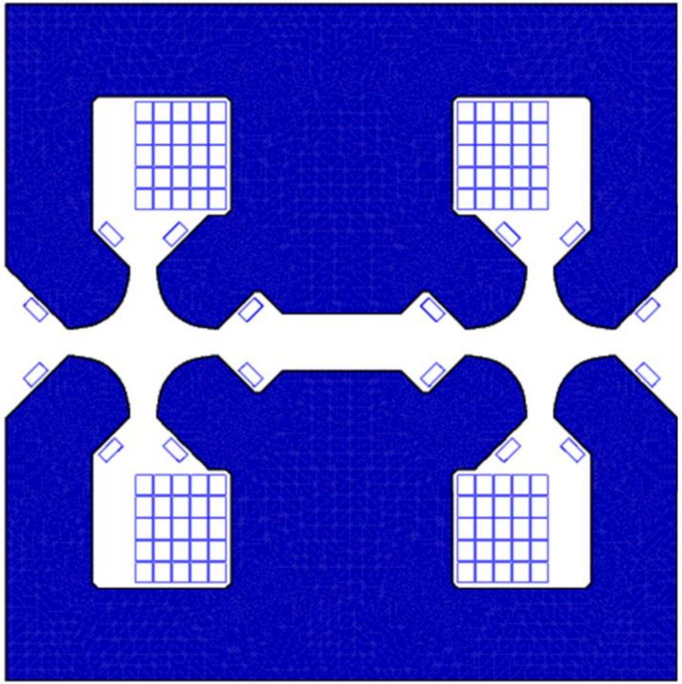
Quadrupole design

- **Trim coils at poles** (instead of at back leg in previous version)
- **Magnetic axis shift** well mitigated w.r.t. previous designs (~0.40 mm); worst case b1 is ~10 units, gives **~0.01 mm** shift.



Harmonics at reference radius 10 mm, for different powering cases.

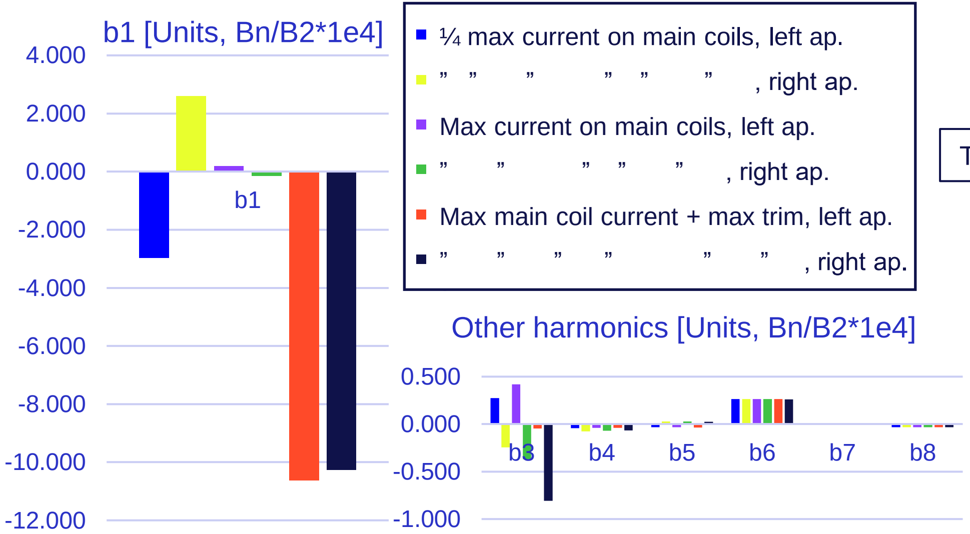
Presented at FCC week 2023: "Status of the FCC-ee booster and collider magnet developments", 7th June 2023.



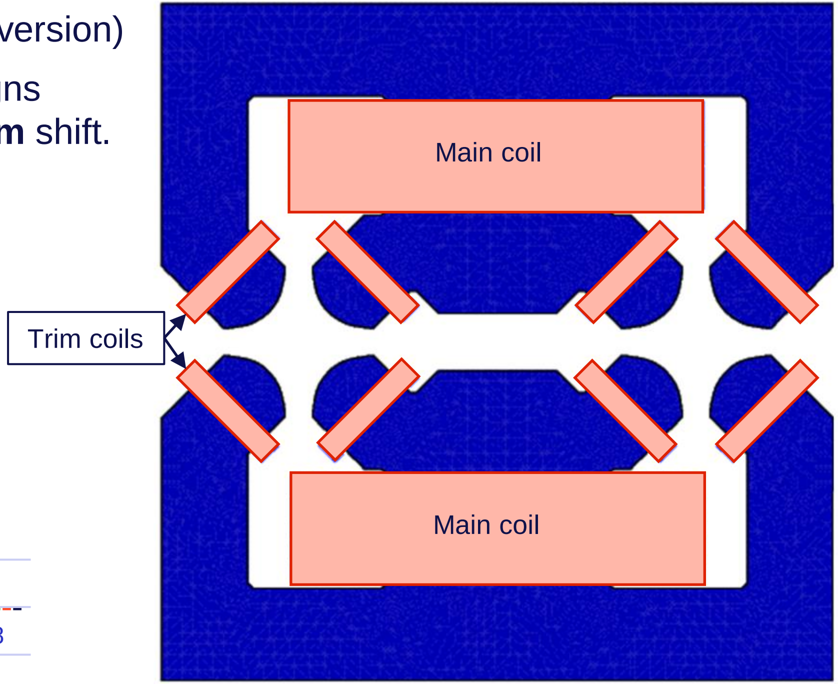
Collider quadrupole cross section, FCC week 2023

Quadrupole design

- **Trim coils at poles** (instead of at back leg in previous version)
- **Magnetic axis shift** well mitigated w.r.t. previous designs (~0.40 mm); worst case b1 is ~10 units, gives **~0.01 mm** shift.



Harmonics at reference radius 10 mm, for different powering cases.



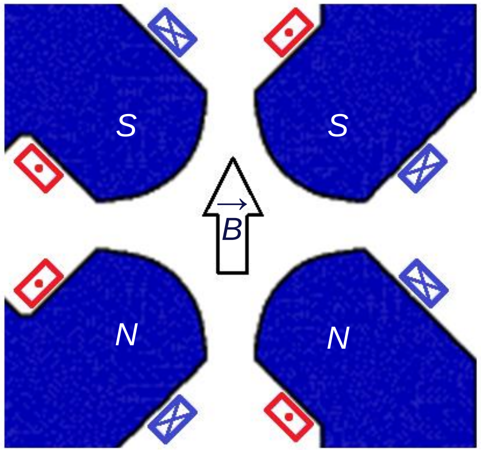
Collider quadrupole cross section, FCC week 2023

Presented at FCC week 2023: "Status of the FCC-ee booster and collider magnet developments", 7th June 2023.

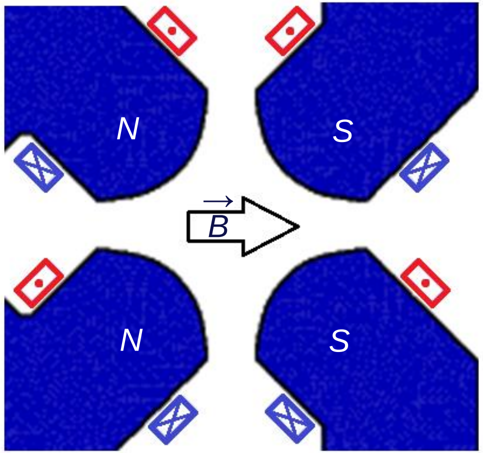
Horizontal & vertical correction

- **Trim coils** used for quadrupolar tapering and tuning can be used for generating a **dipolar component** if **polarities of 2 coils are reversed**
- Maximum field strength required for correction: $L_{sext} B_{corr,\, sext} = L_{quad} B_{corr,\, quad}$

$$\Rightarrow B_{corr,\, quad} = \frac{1.5\ \mathrm{m}}{2.9\ \mathrm{m}} 13\ \mathrm{mT} = 6.7\ \mathrm{mT}$$



Powering setup for horizontal correction (vertical B field)



Powering setup for vertical correction (horizontal B field)

Circuit requirements

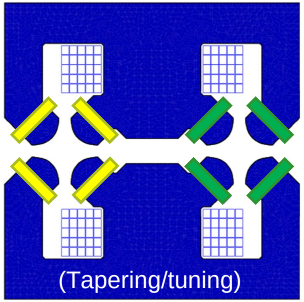
1. If only **quadrupolar tapering / tuning** is needed, all trim coils in each aperture can be powered in series
   → **1 trim coil power supply <u>per aperture</u>**

2. If either **vertical or horizontal correction** is required, each pair of adjacent trim coils can be powered in series
   → **2 trim coil power supplies <u>per aperture</u>**

3. If both **vertical and horizontal correction** is required, each trim coil needs to be powered independently
   → **4 trim coil power supplies <u>per aperture</u>**

Powered by:
- power supply # 1 (yellow)
- " " # 2 (green)
- " " # 3 (red)
- " " # 4 (blue)
Etc…

1.



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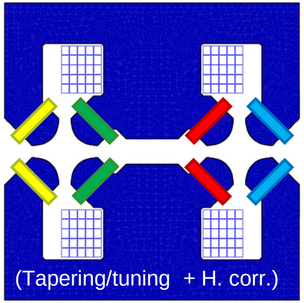
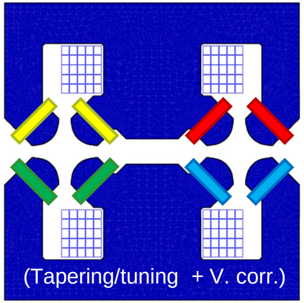


or



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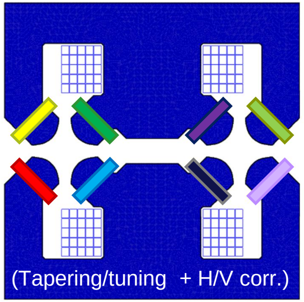
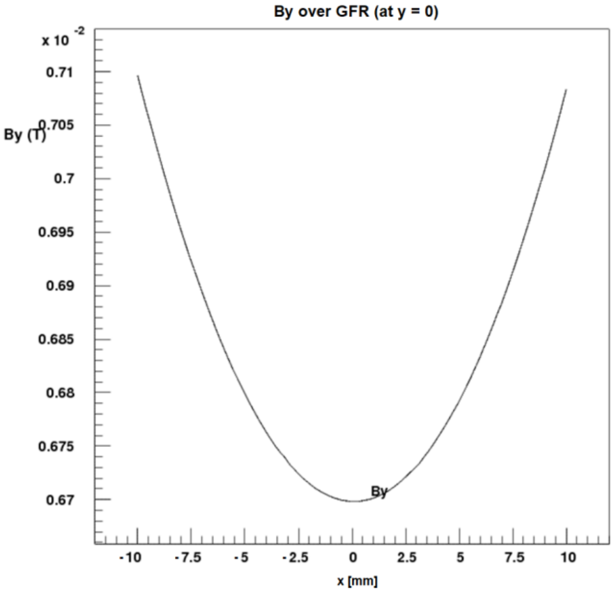


Horizontal correction: field quality

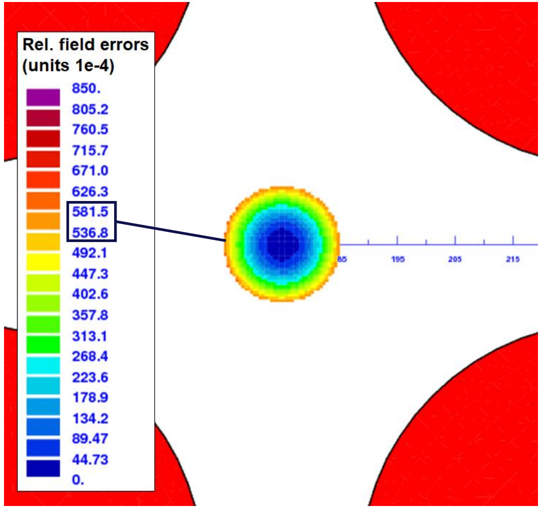
- Field quality **dB/B ≈ 6%**.
- Large **sextupole component**

Rref = 10 mm	Main harmonic: B1
b1	10000.000
b2	-9.499
b3	578.806
b4	-0.005
b5	5.581
b6	0.000
b7	-0.292
b8	-0.001
b9	-0.006
b10	0.000

Harmonics – horizontal correction dipole



Dipole field over GFR.



Field quality in GFR.

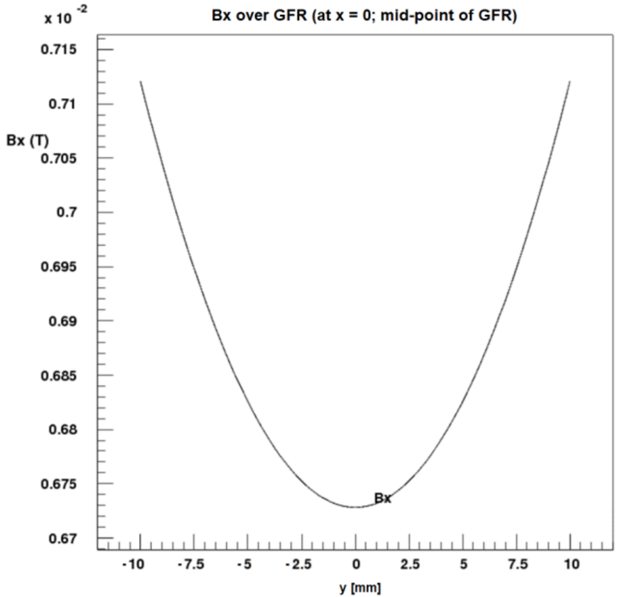
Main coils OFF → Field homogeneity and harmonics w.r.t. **dipole component**

Vertical correction: field quality

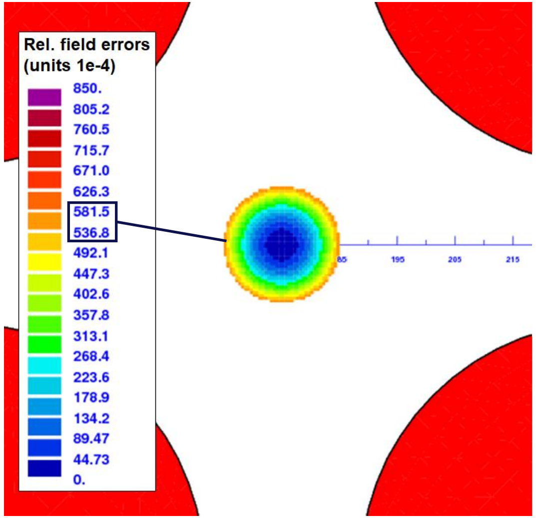
- Same as for horizontal corr., due to pole symmetry, but components are **skew**
- Field quality **dB/B ≈ 6%**.
- Large **skew sextupole component**

Rref = 10 mm	Main harmonic: A1
a1	10000.000
a2	0.265
a3	-577.456
a4	0.032
a5	5.659
a6	0.002
a7	0.295
a8	0.000
a9	-0.006
a10	0.000

Harmonics – vertical correction dipole



Dipole field over GFR.



Field quality in GFR.

Main coils OFF → Field homogeneity and harmonics w.r.t. **dipole component**

Quadrupole field quality with orbit correction

- **Sextupole component** introduced by horizontal or vertical correction is **significant** with respect to the main quad field

Rref = 10 mm	Main harm: B2	Rref = 10 mm	Main harm: B2
b1	554.930	a1	0.000
b2	10000.000	a2	0.000
b3	**31.367**	a3	0.000
b4	0.001	a4	0.000
b5	0.345	a5	0.000
b6	0.271	a6	0.000
b7	-0.018	a7	0.000
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max horizontal correction.

Rref = 10	Main harm: B2	Rref = 10	Main harm: B2
b1	-4.357	a1	554.098
b2	10000.000	a2	0.020
b3	-1.004	**a3**	**-31.996**
b4	0.000	a4	0.002
b5	0.033	a5	0.313
b6	0.271	a6	0.000
b7	-0.002	a7	0.016
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max vertical correction.

Powering requirements

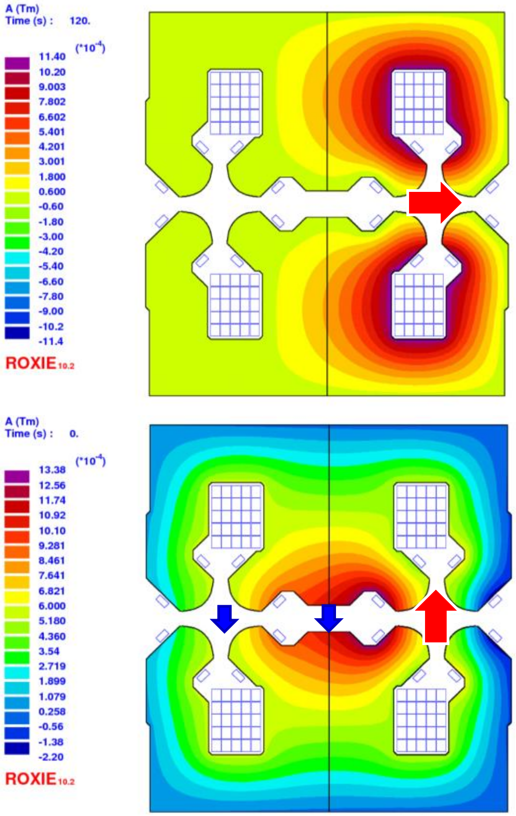
<u>Vertical correction:</u>

- Minimal cross-talk; **NI = 177 A** per trim coil to achieve max corr. field.

<u>Horizontal correction:</u>

- **Large cross-talk between apertures:** opposing aperture must apply an opposing correcting field to compensate
  - With peak correction field, each trim coil needs **NI = 477 A**

→ H orbit correction in the quad is <u>not a viable option</u>



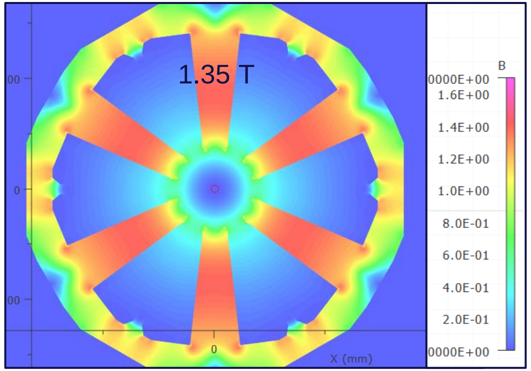
Flux potential for vertical (top) and horizontal (bottom) corrections (Latest design)

Sextupole

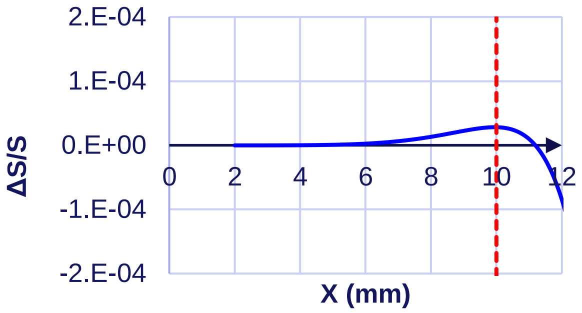
Main sextupole

Parameter	Unit	Value
Sextupole strength (B”=2*S)	T/m2	**880**
Bore aperture	mm	33
Ampere-turns	A	4250
Number of turns per coil	-	14
Peak current	A	304
Conductor dimensions	mm^2	8.5×8.5
Cooling diameter	mm	4
Peak current density	A/mm^2	**5.1**
Voltage drop per magnet	V	23.4
Resistance per magnet	mΩ	78
Peak power per magnet	kW	**7.2**
Number of water circuits	-	6
Water temperature rise	°C	13.2
Cooling water speed	m/s	1.8
Pressure drop	bar	6
Reynolds no.	-	3530

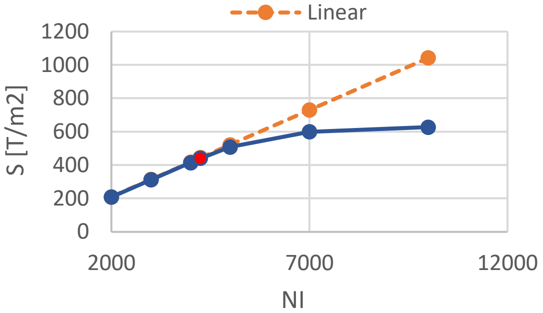
Main parameters



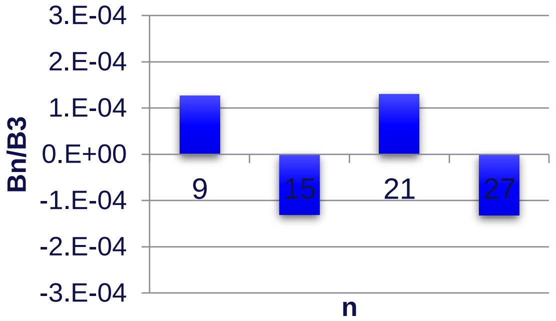
Flux density in iron



Sextupolar gradient homogeneity



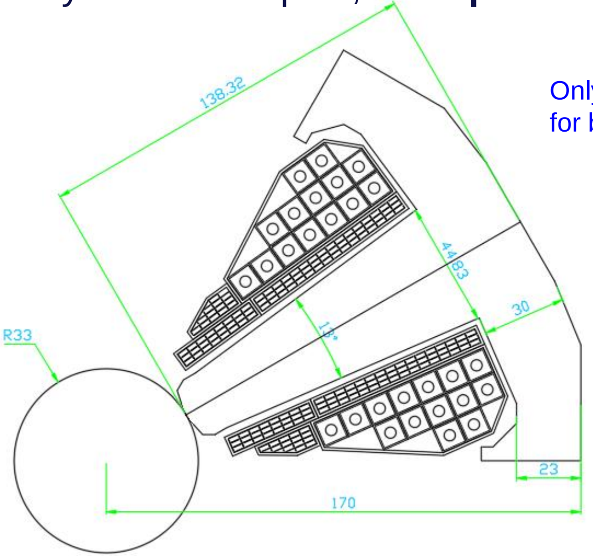
Transfer function



Natural normalized harmonics

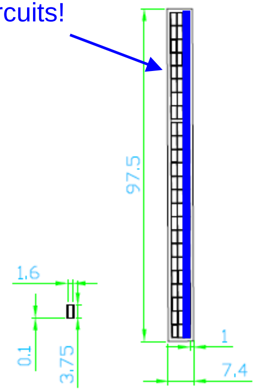
Trim coils layout

- **Space occupancy** in coil cross-section **dominated by orbit correction** circuits
- **Moving** orbit correction to **dipoles and quadrupoles** would allow to redistribute the space and **reduce** the current density in the sextupole, so its **power consumption**

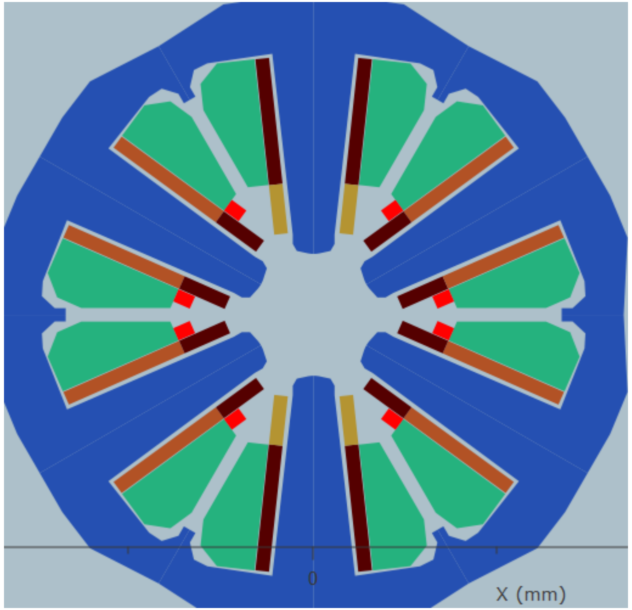


Sextant cross-section geometry

Only one layer is sufficient for both Quad circuits!



Trim coils detail



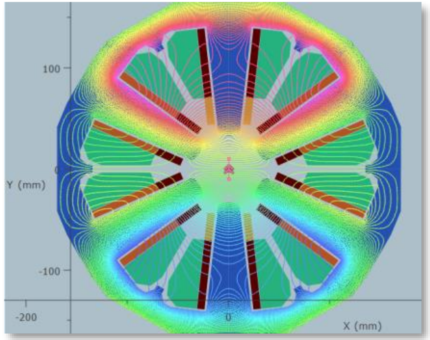
Green Coils: Main Sextupole
Brown Coils: Horizontal Corrector
Orange Coils: Vertical Corrector
Red Coils: Normal Quadrupole
Yellow Coils: Skew Quadrupole

Corrector circuits

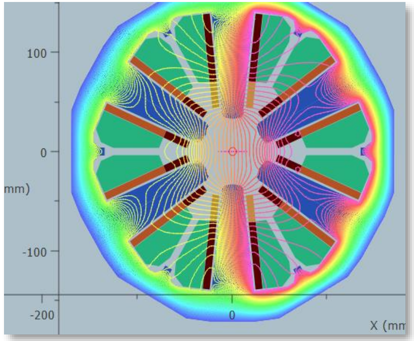
- **H corrector** is the most **power demanding**
- **J** is a bit **high** for the **quadrupole correction** circuits (would be cured if we move the orbit correction to the dipoles/quads)

Parameter	Ver. Corrector	Horiz. Corrector	Nor. Quad. Corrector	Sk. Quad. Corrector
Integrated Strength(Tm)/(T)	0.02	0.02	0.6	0.6
Magnetic field (mT)/(T/m)	13	13	0.4	0.4
Effective length (mm)	1500	1500	1500	1500
Ampere-Turns per pole (A.t)	345	400/200	210	378
Number of turns	48	48/24	14	24
Conductor size (mm^2)	3.75 × 1.6	3.75 × 1.6	3.75 × 1.6	3.75 × 1.6
Current (A)	7.2	8.3	15	15.8
Current Density (A/mm^2)	1.2	1.4	2.5	2.6
Resistance per magnet (Ω)	1.7	2.5	0.5	0.4
Total Voltage (V)	12.1	21	7.4	6.62
Total Power (W)	87	**175**	110	104
Total Cable Length (m)	590	885	172	147
Total Cable Weight (kg)	32	48	9	8

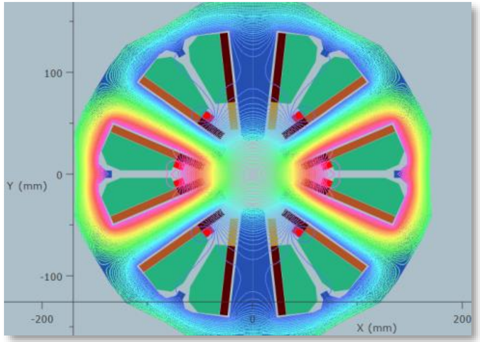
Vertical Corrector



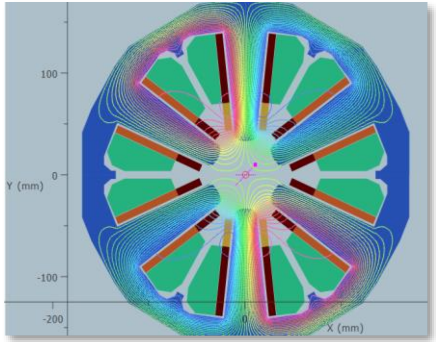
Horizontal Corrector



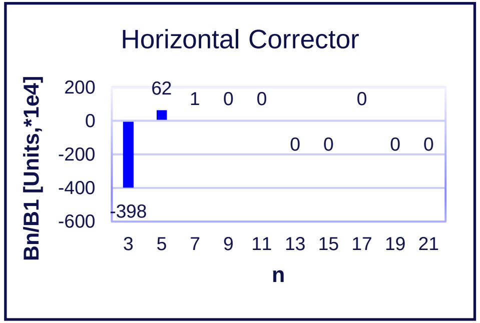
Normal Quad Corrector

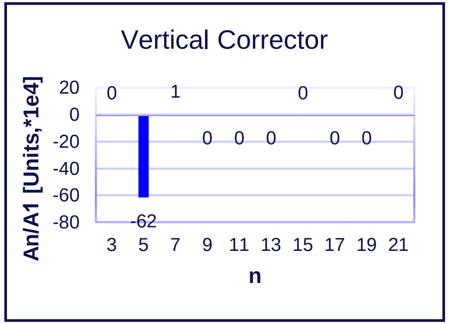


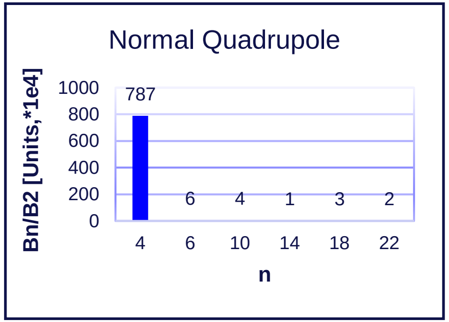
Skew Quad Corrector

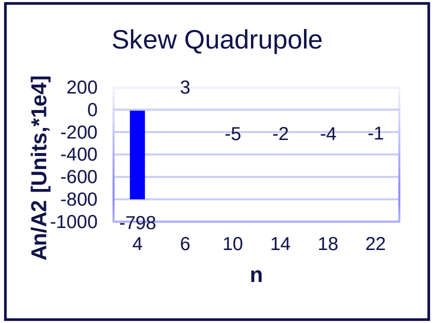


Correction circuits field quality

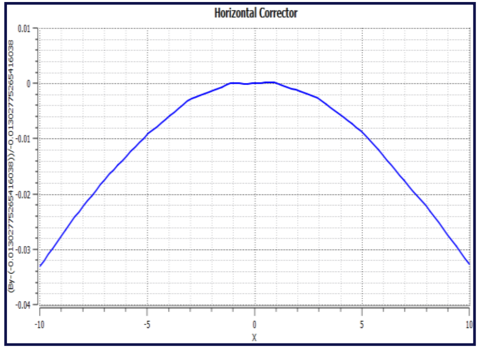




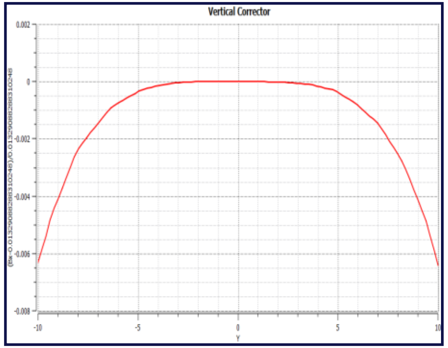




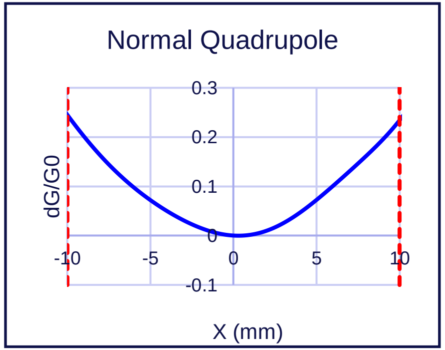
Main coils OFF → Field homogeneity and harmonics w.r.t. **correction field component**



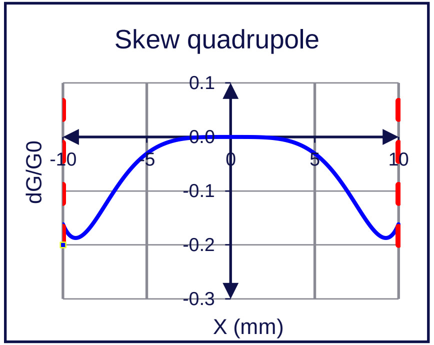
By field homogeneity
$B_y(0) = 0.013$ T



Bx field homogeneity
$B_x(0) = 0.013$ T

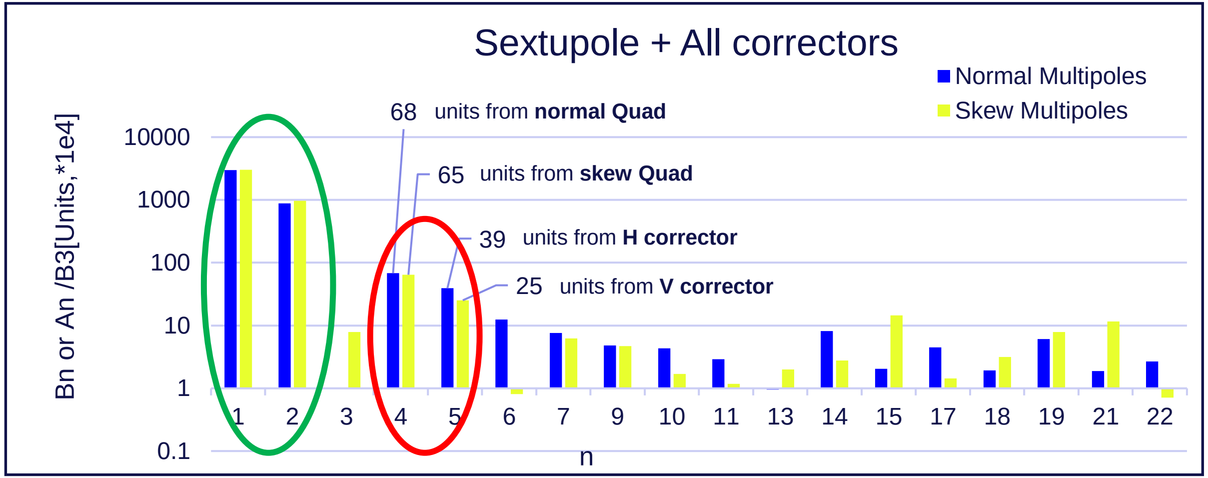


Normal gradient homogeneity
$G_n(0) = 0.4$ T/m



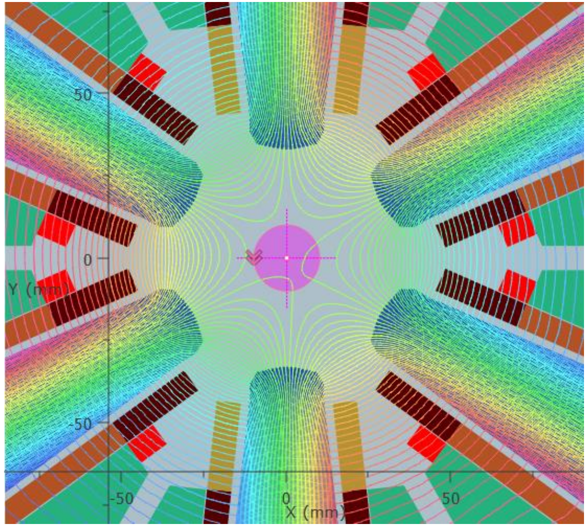
Skew gradient homogeneity
$G_s(0) = 0.4$ T/m

Correction circuits field quality



All coils ON (main **and** trim)

→ Field harmonics w.r.t. **sextupole component**



Flux potential with main and trim coils at peak current

- The Horizontal dipole corrector introduces a **strong normal sextupole** component that **can be cured by the main sextupole coil**
- The Horizontal/Vertical dipole correctors introduce **strong normal/skew decapole** components
- The Normal/Skew Quadrupole corrector introduce a **strong normal/skew octupole** term

Summary and next steps

Summary

- Impact of **orbit** and **quadrupole correction** circuits **hosted in the sextupole** on **field quality** is
  - Up to **~40 units of normal / skew decapoles** for H / V orbit corrections
  - Up to **~70 units of normal / skew octupoles** for normal / skew quadrupole corrections
- Hosting the **orbit correction circuits** in the **dipoles** and **quadrupoles**, using field tapering trim coils
  - Offers **orbit correction granularity** at **every arc half-cell**
  - **Reduces the number of circuits** by merging the orbit correction, tuning and tapering functions
  - Makes more room for the sextupole main coils and **reduce its power consumption**
- **H orbit correction** made by the **dipole trim coils** has no impact on the dipole field quality
- **H orbit correction** made by the **quadrupole trim coils** doesn't appear as a reasonable option as it requires a lot of ampere-turns and generates coupling between apertures
- **V orbit correction** made by the **quadrupole trim coils**, generates up to **~30 units of skew sextupole**

Can beam dynamics team **assess the suitability** of each option in terms of optics performance?

→ We could then **evaluate the lifetime cost** (CAPEX + OPEX) of each suitable option

Acknowledgements

We would like to thank all the members of the FCC collaboration for their contribution to the FCC-ee magnet development work, and in particular T. Raubenheimer, R. Tomas, K. Oide and F. Zimmermann for the fruitful exchange of ideas on the magnet correction circuits.

Thank you for your attention!

Questions?

SPARE SLIDES

Collider magnet specifications

- Includes **aperture reduction**
- **Aperture in sextupole** assumes **no bake-out system** (as in CDR baseline)
- **Sextupoles** are present in only about **½ of the arc half-cells**

	Mag. Length [m]	Bore aperture (reduced) [mm]	Vacuum aperture (reduced) [mm]	Pole tip field [T]	Number of units (arcs)	Total magnetic length [km]	Ring filling factor (91 km) [%]
Dipole (S)	19.30	**37**	**30**	**0.061**	1128	21.77	
Dipole (M)	20.95				284	5.95	
Dipole (L)	22.65				1428	32.35	
Total					**2840**	**60.1**	**65.9**
Quadrupole	**2.9**	**37**	**30**	**0.438**	**2836**	**8.2**	**9.0**
Sextupole	**1.5**	**33**	**30**	**0.442**	**4672**	**7.0**	**7.7**

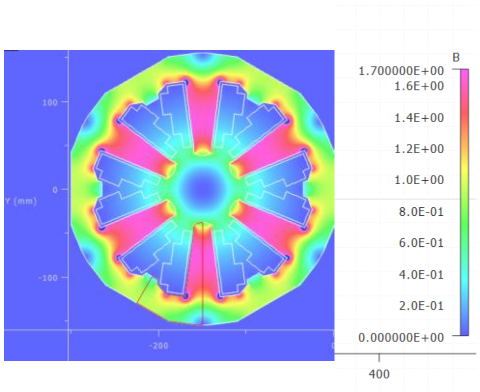
Arc magnet specifications from optics (with vacuum aperture Φ60 mm)

- **Field quality specifications** from latest beam dynamic studies

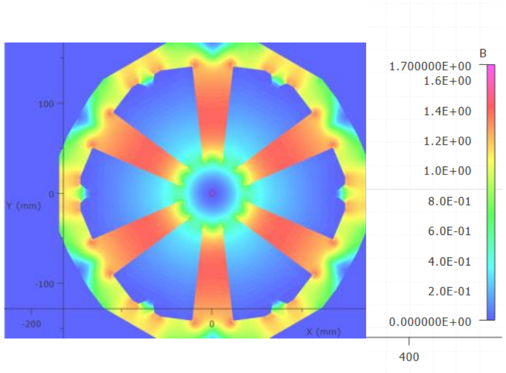
Error & maget type	Z	tt
b_3 in arc dipoles	2	2
b_3 in IR dipoles	0.1	0.5
b_3 in arc quadrupoles	10	8
b_3 in QY	0.1	8
b_3 in QC, QT, QA, QB, QG, QH, QL, QR, QU, QI	1	8
a_3 in QC1, QC2	1	5
b_4 in arc quadrupoles	10	10
b_4 in QC, QY	0.01-0.1	0.1
b_4 in QT, QA, QB, QG, QH, QL, QR, QU, QI	1	1
b_6 in arc quadrupoles	5	5
b_6 in IR quadrupoles	0.01	1

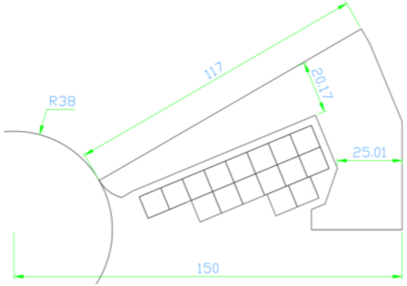
Magnet field quality specifications from optics – March 2023 (E. Ahmadi, R. Tomas)

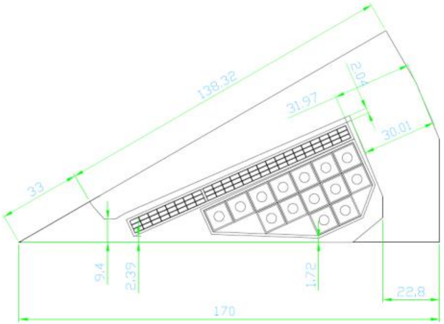
Comparing the Collider Sextupole Electrical and Cooling Parameters



Parameter	Unit	CDR (2019)	New (June 2023)
Inter-beam distance	mm	300	350
Sextupole strength	T/m2	807	880
Aperture radius	mm	38	33
Magnetic length	m	1.4	1.5
Pole tip field	T	0.59	0.48
Total current	At	6300	4250
Number of turns per coil	-	14	14
Operation current	A	448	304
Conductor dimensions	mm^2	8×8	8.5×8.5
Cooling diameter	mm	3	4
Current density	A/mm^2	7.87	5.1
Voltage drop per magnet	V	34.3	23.4
Resistance per magnet	mΩ	76	79
Power per magnet	kW	15.4	7.3
Number of water circuits	-	18	6
Water temperature rise	°C	10.4	13.4
Cooling water speed	m/s	2.77	1.75
Pressure drop	bar	6	6
Reynolds no.	-	4160	3450
Conductor length/magnet	m	255	277
Conductor mass/magnet	kg	128	147
Trim coil dimensions	mm	-	3.75 × 1.6
Number of trim coils	-	-	48+24
Trim coil length/magnet	m	-	1327
Trim coil wight/magnet	kg	-	72







Fcc-ee Sextupole Specifications Update

Main Parameter	Unit	CDR (2019)	New	Comment
Sextupole strength (B'')	T/m2	807	876.6	Including tapering (3%) & tuning (5%) margins
Bore aperture radius (CDR)	mm	38	38/33	Considering 2 mm thickness of the vacuum chamber and 1 mm clearance.
Reference radius for good field region (GFR)	mm	±10	±10	
Field quality in GFR	1.0E-04	≈1	1	
Magnetic length	mm	1400	1500	
Drift space between two consecutive sextupole magnetic lengths	mm	100	150	Considering in 3D designing
Magnet maximum physical half-width in inter-beam distance	mm	145	170	Considering that beam inter distance of 350 mm.
Horizontal orbit correction integrated field strength	Tm	-	0.02	B=0.013 T
Vertical orbit correction integrated field strength	Tm	-	0.02	B=0.013 T
Skew quadrupole correction integrated gradient	T	-	0.6	G=0.4 T/m

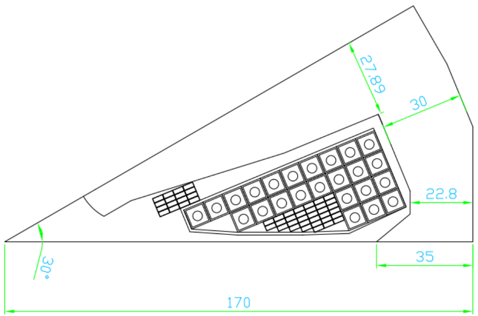
Info K.Oide and R. Tomas:
19th April 2023

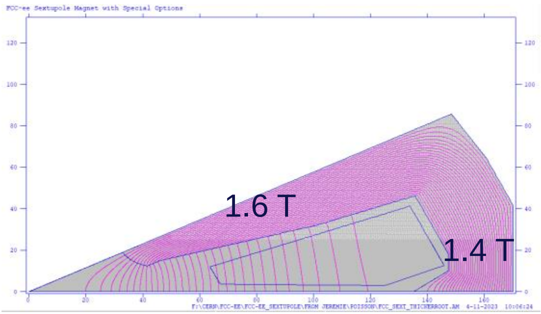
- It gets worse in the updates in point of magnet design with (R=38)
  - ✓ S=880 T/m2
  - ✓ L=1.5 m
- Inter-beam distance D=350 mm! The created space could be utilized for **more iron** or **more coil turns**!

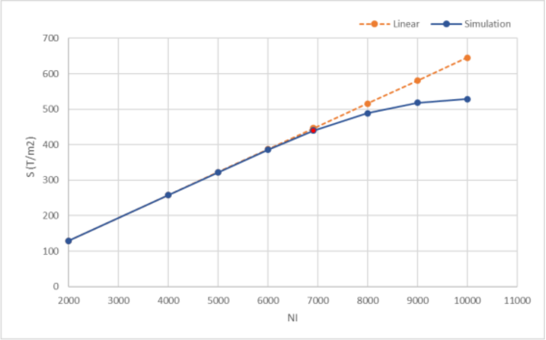
Sextupole (R = 38 mm)

- **Wider Pole width**
  - **Reserving space for Iron**
  - **N=22 turn**
  - **Auxiliary coils = 32+16 turns (too high current density)**

Parameter	Unit	Value
Sextupole Strength	T/m2	**880**
Total current	At	6920
Number of turns per coil	-	22
Conductor dimensions	mm^2	6.5×6.5
Cooling diameter	mm	3.5
Current density	A/mm^2	**9.6**
Voltage drop per magnet	V	70
Resistance per magnet	mΩ	223
Power per magnet	kW	**22.1**
Number of water circuits	-	18
Water temperature rise	°C	13.2
Cooling water speed	m/s	2.3
Pressure drop	bar	6
Reynolds No.	-	4030







- The current density is increased to 9.6 A/mm^2.
- The saturation is about **1.5%** but the power is increased to **22 kW**.
  - Problems in cooling (18 cooling circuits)
- Small space for Axillary coils.
- The larger inter-beam distance and increased magnetic length (D=350 mm) do not compensate the increase of field strength in the new specifications