FCC

Status of FCC-ee Booster and Collider Magnet Developments

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Many thanks to all the members of the FCC collaboration.

Outline

Collider magnets

- Inter-beam distance
- Aperture reduction
- Specifications
- Twin aperture dipole
- Twin aperture quadrupole
- Single aperture sextupole

Booster magnets

- Specifications
- Dipole
- Quadrupole

Next steps for magnet development

Conclusions

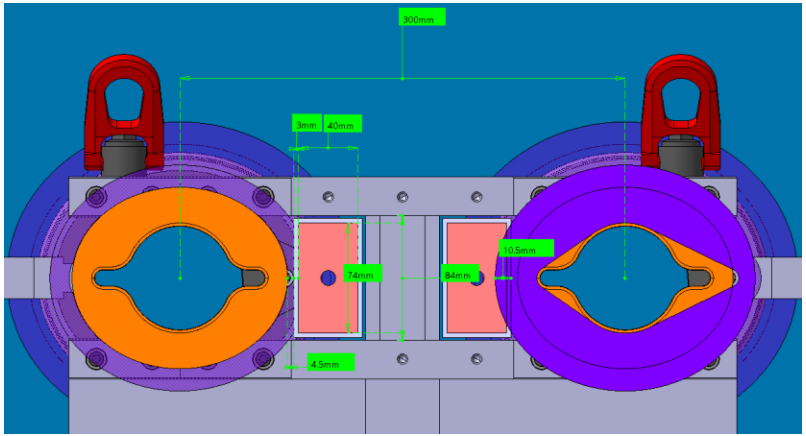
Collider magnets

Inter-beam distance

Mechanical design studies in Arc Half-cell Mock-up WG identified need for **larger space** for **SR absorbers**:

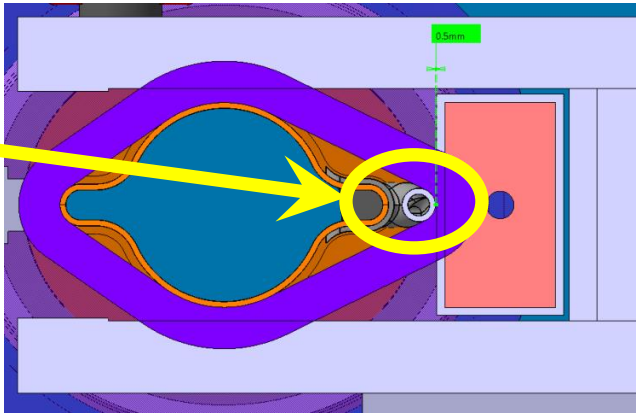
- water cooling piping and fittings of SR absorber
- electrical insulation distance to busbar)

➔ **Inter-beam distance increased to <u>350 mm</u>**

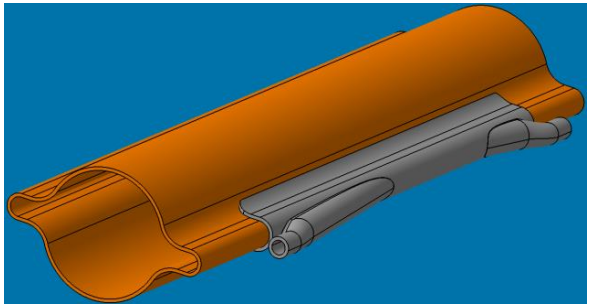


Dipole cross-section with SMA flanges

<u>Conflict</u>:
SR absorber - busbar



SR absorber integration in dipole



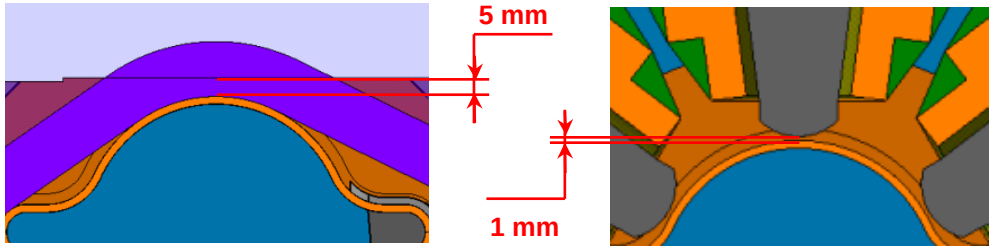
SR absorber

<u>Courtesy</u>: C. Tetrault

Aperture reduction

- **CDR baseline** for beam aperture (vacuum chamber inner radius) was **R = 35 mm**
- **2023**: exploration of new baseline with **R = 30 mm** to **reduce power consumption** (mostly in SSS magnets) and saturation in sextupole
- **Clearances kept identical as CDR** to determine magnet bore apertures

→ **Designs with R = 35 mm vs. R = 30 mm compared in next slides**



Dipole chamber integration *Sextupole chamber integration*

	CDR baseline			Reduced		
	Dipole	Quad.	Sext.	Dipole	Quad.	Sext.
Vacuum chamber inner radius	35			30		
Vacuum chamber wall thickness	2			2		
Clearance for tolerances and alignment (radial)	1			1		
Clearance for vacuum bake-out jackets (radial)	4	4	0	4	4	0
Magnet bore radius	**42**	**42**	**38**	**37**	**37**	**33**

Aperture dimensions in [mm] for arc collider magnets

Magnet specifications – latest update

- Includes **aperture reduction in SSS magnets**
- **Aperture in dipoles** depends on impedance studies (tapering of chambers upstream/downstream SSS
- **Aperture in sextupole** assumes **no bake-out system** (as in CDR baseline)
- Field quality specifications from latest beam dynamic studies

	Mag. Length [m]	Bore aperture (reduced) [mm]	Pole tip field [T]	Number of units (arcs)	Total mag. length [km]	Ring filling factor (91.1 km) [%]
Dipole (S)	19.30			1128	21.77	
Dipole (M)	20.95	**42 / 37 ?**	**0.061**	284	5.95	
Dipole (L)	22.65			1428	32.35	
Total				**2840**	**60.08**	**65.9**
Quadrupole	**2.9**	**37**	**0.438**	**2836**	**8.22**	**9.0**
Sextupole	**1.5**	**33**	**0.442**	**4672**	**7.01**	**7.7**

Arc magnet specifications from optics – May 2023 (K. Oide)

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 (R. Tomas)

Collider dipole

Dipole design

Yoke

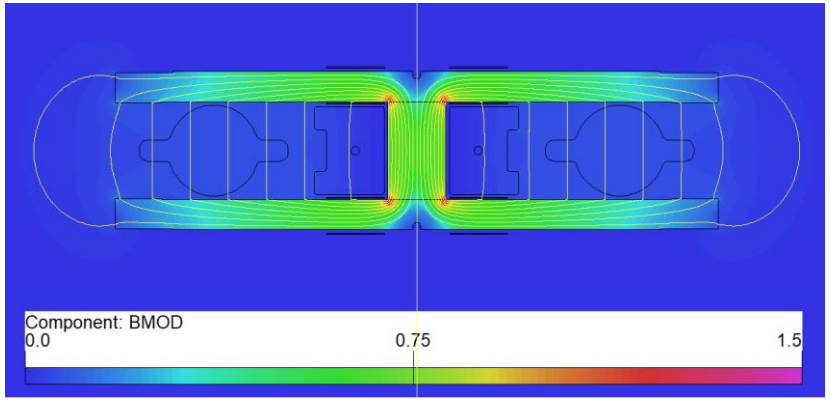
- Assembled from solid iron machined plates and beam
- Pole shape optimized with flat surfaces only to minimize machining operations for large scale production
- Slots for fiducialisation included

Busbars

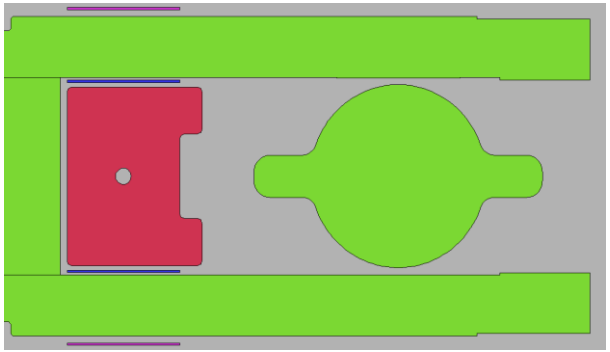
- Main busbars in extruded copper (freedom for shape), water-cooled (requirement from cooling and ventilation)
- Choice of copper vs. aluminium to be finalized during cost optimization exercise (capital cost vs. operational cost, including water cooling distribution system)
- Insulation with inorganic coating to be explored (SR)

Trim coils

- Air cooled enameled conductors



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

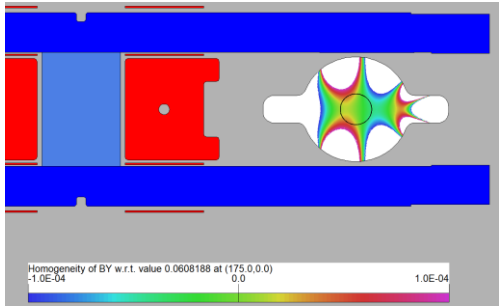


Details of yoke, busbar and coil geometry

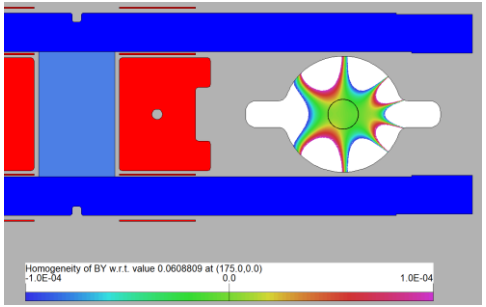
Magnetic design - Case 1: peak current, trim coils off (182.5 GeV)

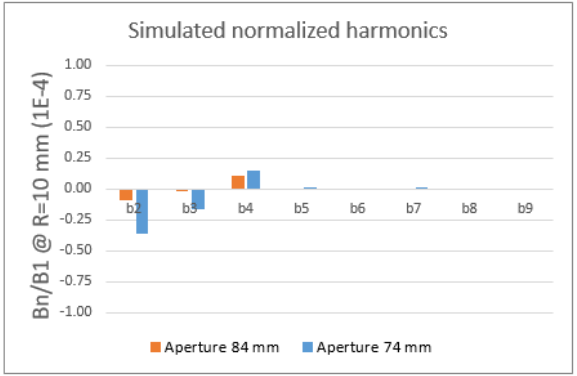
- ±1 unit range extends beyond R_{ref}, margin for manufacturing tolerances
- b2 decreased to 0.5 unit (w.r.t. 3 units in CDR design)

Aperture 74 mm

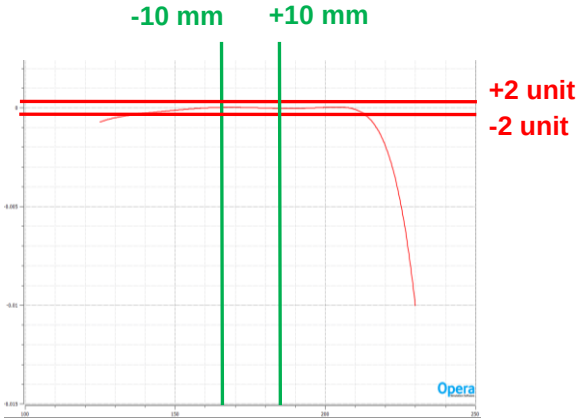


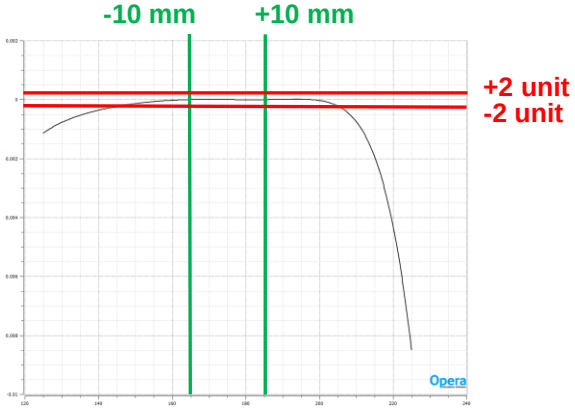
Aperture 84 mm





Computed field harmonics



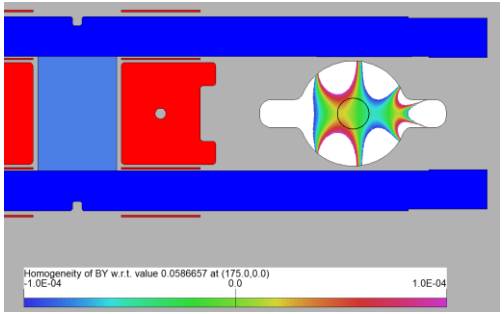


Field homogeneity in aperture (top) and along X axis (bottom)

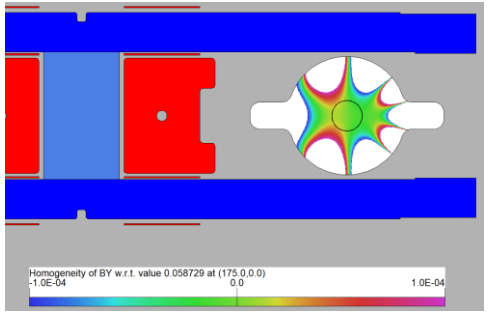
Magnetic design - Case 2: peak current, trim coils on (182.5 GeV)

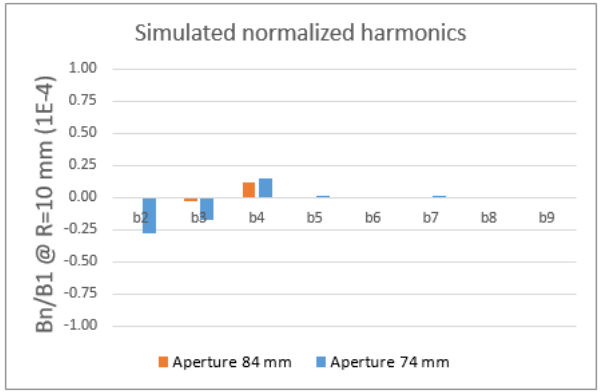
- Trim coils activated to tune B_{peak} by +3.5% in one aperture and -3.5% in the other
- Marginal effect from trims on field quality

Aperture 74 mm

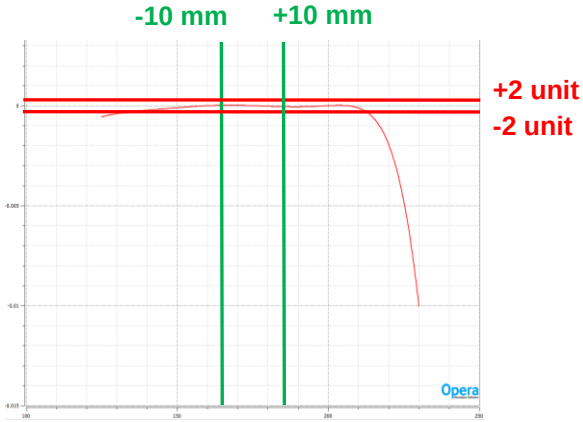


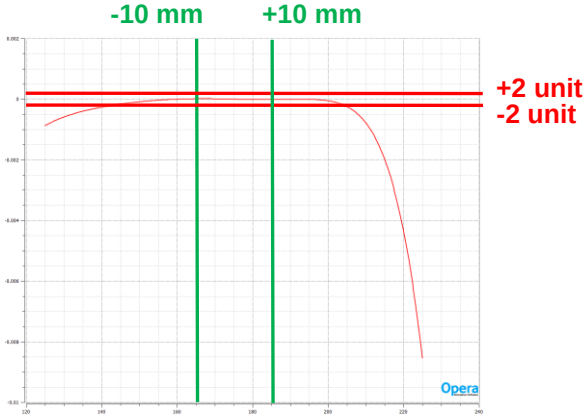
Aperture 84 mm





Computed field harmonics



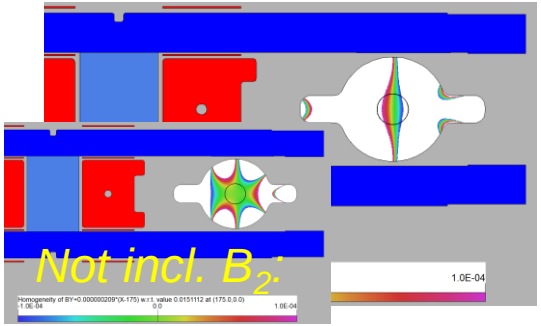


Field homogeneity in aperture (top) and along X axis (bottom)

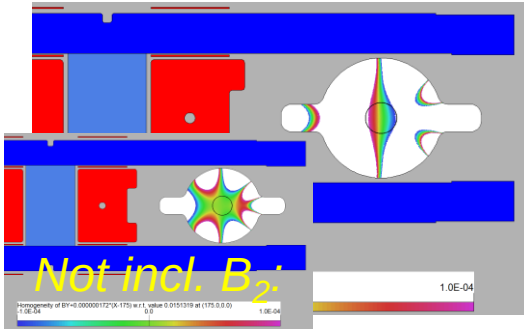
Magnetic design - Case 3: 1/4 current, trim coils off (45.6 GeV)

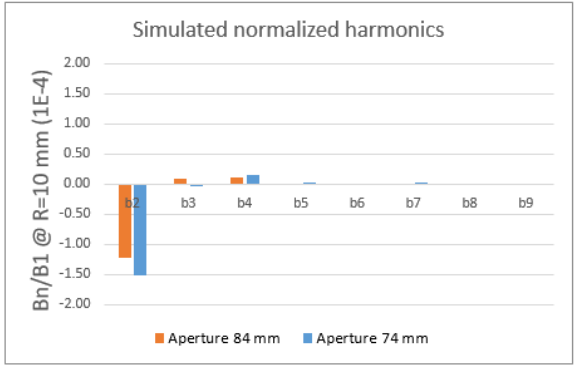
- Slight increase of b_2 at lower field
- Can be compensated with arc quadrupoles
- Will be further evaluated with prototype magnet

Aperture 74 mm

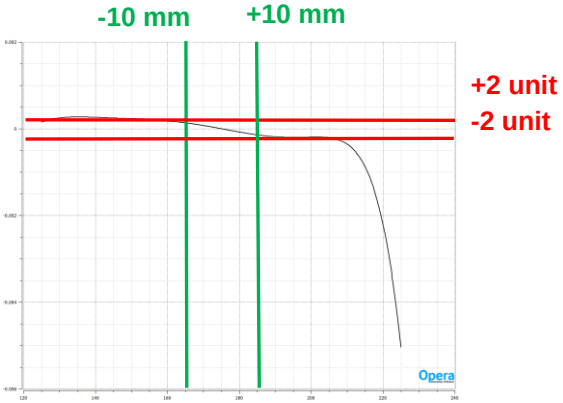


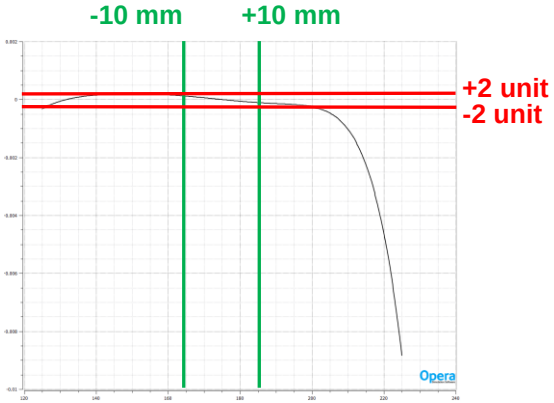
Aperture 84 mm





Computed field harmonics





Field homogeneity in aperture (top) and along X axis (bottom)

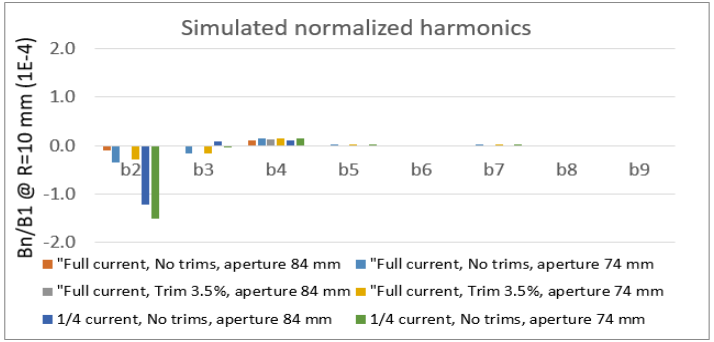
Dipole summary

Magnetic design

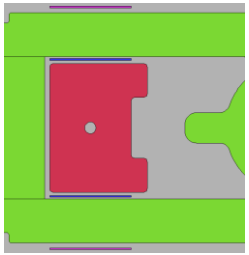
- The magnet geometry has been optimized to further limit b_2 to <1.5 units and other harmonics <0.5 units

Main parameters

- The magnet dimensions stay compact despite slightly larger inter-beam distance
- The **current density has increased** w.r.t. CDR due to conflict with SR absorber, so the new design has higher dissipated power at equivalent technology (Al busbars)
- **Copper busbars** allow **~35% of power consumption reduction** (to be optimized with total costs)
- The **aperture reduction** would reduce the **power consumption by ~10%**



Computed field harmonics



BB cross-section

		CDR	2023, ap. 84 mm		2023, ap. 74 mm	
		Al BB	Cu BB	Al BB	Cu BB	Al BB
Parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of units		2900	2840		2840	
Total magnetic length	km	65	60.1		60.1	
Central field, 45.6 GeV – 182.5 GeV	mT	14.1 - 56.6	15.3 - 61.3		15.3 - 61.3	
Inter-beam distance	mm	300	350		350	
Bore aperture	mm	84	84		74	
Magnetic lengths	m	10.6 - 12.2	19.30 - 22.65		19.30 - 22.65	
Magnet overall transverse dimensions	mm	450 x 136	520 x 144		520 x 134	
Iron mass per unit length	kg/m	219	243		239	
Busbar mass per unit length	kg/m	19.9	75	23	64	19
Magnet unit mass (10.6 m average length)	kg	2678	3562	2976	3395	2893
Total magnet mass, 60.1 km	tons	15529	19098	15954	18202	15509
Maximum operating current (tt_bar)	A	1900	4116		3628	
Maximum current density (tt_bar)	A/mm2	0.79	0.98		1.01	
Resistance per unit length	μΩ/m	22.7	8.22	12.66	9.59	14.78
Maximum voltage to ground per 1/2 octant (balanced at mid-point)	V	88	64	98	65	101
Maximum dissipated power per unit length (tt_bar)	W/m	164	139	215	126	195
Total dissipated power, 60.1 km (tt_bar; busbars interconn. not incl.)	MW	10.7	8.4	12.9	7.6	11.7
Total dissipated power, 83.0 km (tt_bar; busbars interconn. incl.)	MW	13.3	11.6	17.8	10.5	16.1

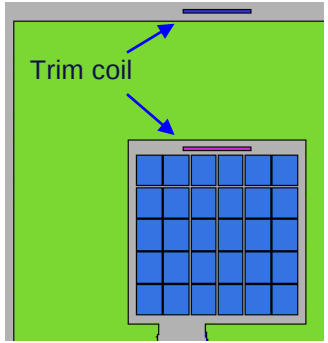
*

Main magnet parameter comparison (computed at tt_{bar})*

Collider quadrupole

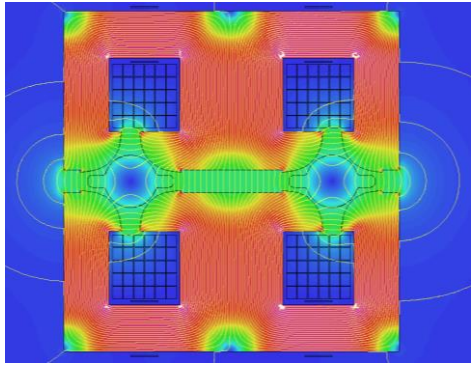
Collider quad: from FCC-week ’22

- Recall the twin aperture design with two racetrack coils from the CDR.
- By FCC-week ’22, an alternate design to the CDR was introduced.
- Magnetic gap between the apertures and chamfers on outer sides.
- Magnetic axis shift remained an issue, **up to ~0.2 mm shift**, when trim coils were activated.

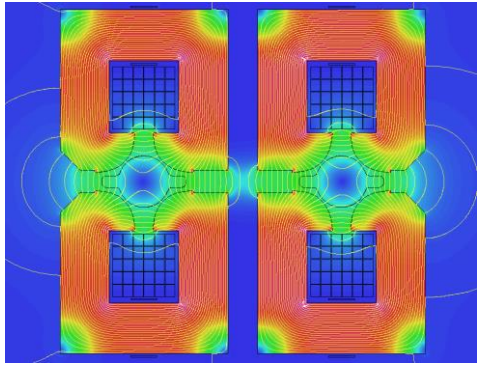


Close-up of one quadrant of the quad

- Recall the trim coils set-up:
  - Two trim coils on each aperture, mounted on the back-legs.
  - Trim coils for each aperture powered individually; needed for individual aperture trimming.



CDR design



Split cross-section design, as of FCC week 2022

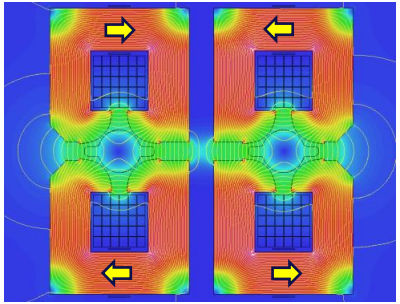
Cross-section optimization

Parameters of the cross-section design were varied to try and minimize the highest b1 case, and thus reduce magnetic axis shift:

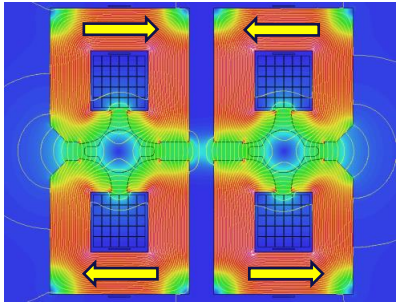
- Main coil position
- Back-leg thicknesses
- Pole profile; chamfers and inserts / notches.

Three powering cases assumed for the optimization:

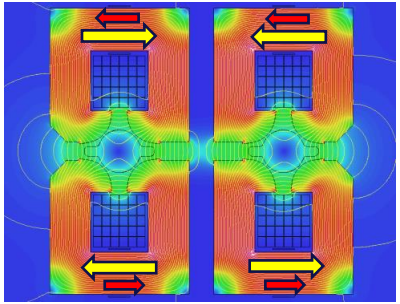
Case 1: Quarter current on main coils, trim coils off.
Case 2: Full current on main coils, trim coils off.
Case 3: Full current on main coils, max trim coils current
→ ($B_{max} + B_{trim}$ on one aperture, $B_{max} - B_{trim}$ on the other).



Case 1



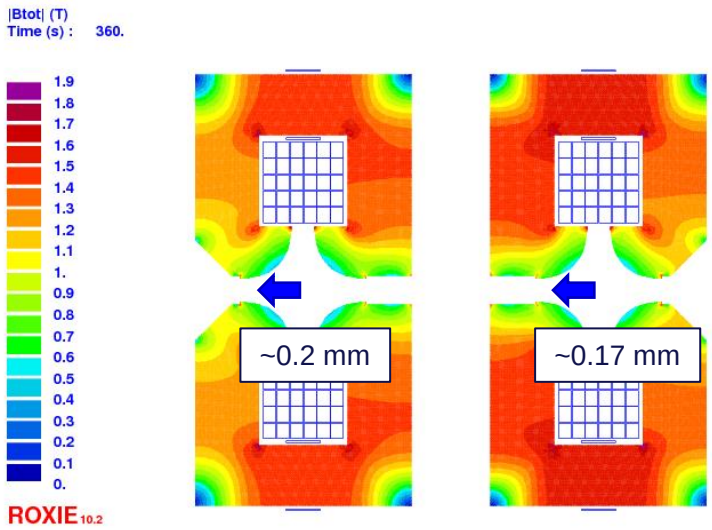
Case 2



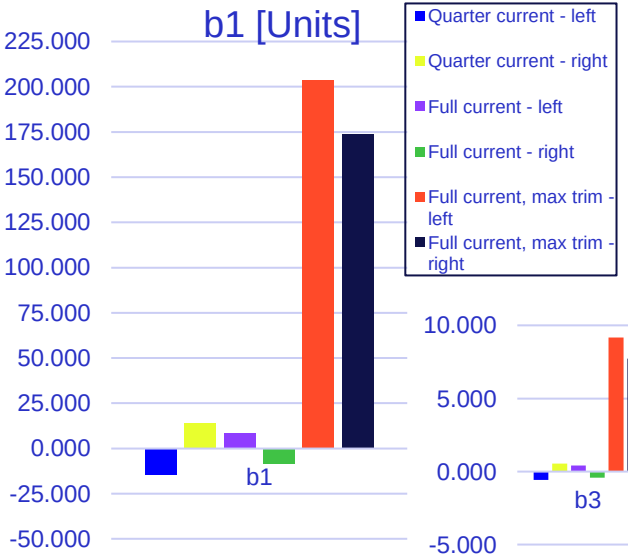
Case 3

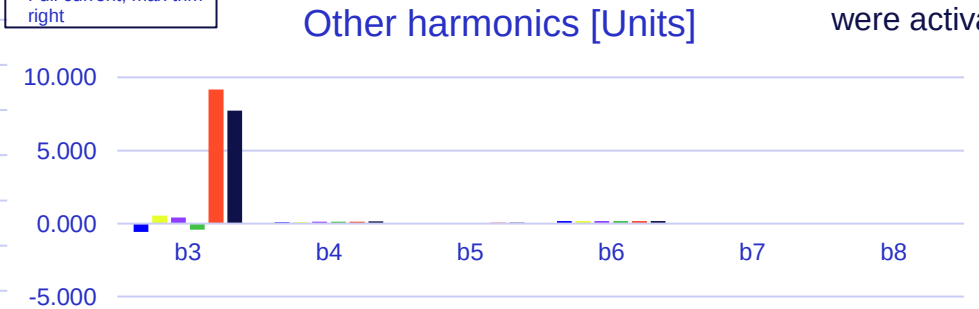
Version 1: split design, with 350 mm inter-beam distance

- Adaptation of the split design, apertures were separated by 50 mm and chamfers were modified.
- Only marginal improvements compared to the corresponding design with 300 mm inter-beam distance.



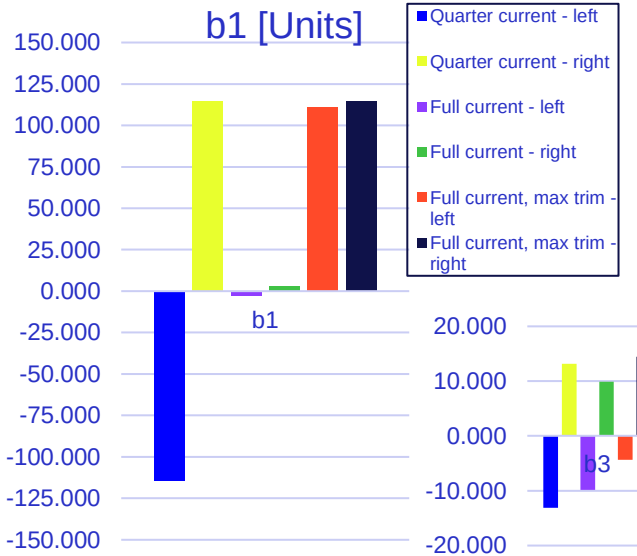
- Magnetic axis shift remained an issue, **up to ~0.2 mm shift**, when trim coils were activated.

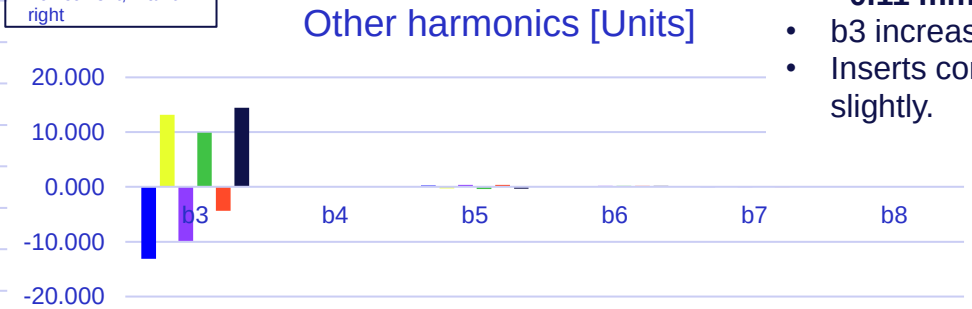


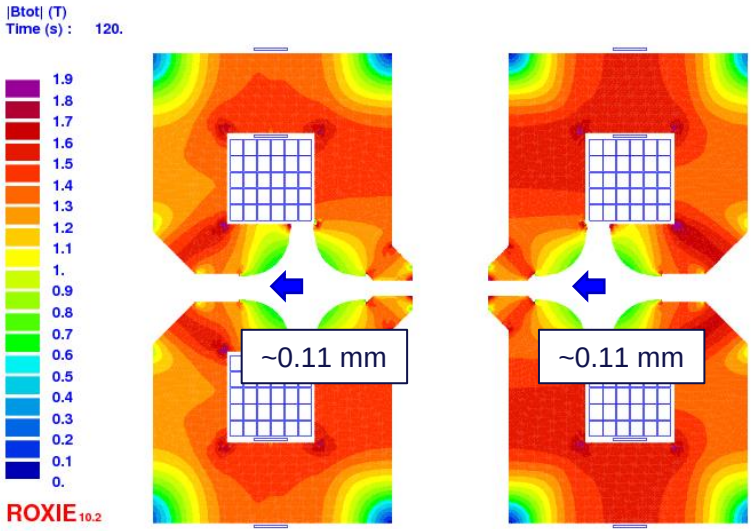


Version 2: alternate design, minimizing difference in b1

- Optimized to minimize the highest b1 + the difference in b1 over the three cases.
- Main coils distance increased, with inserts towards middle to steer flux.



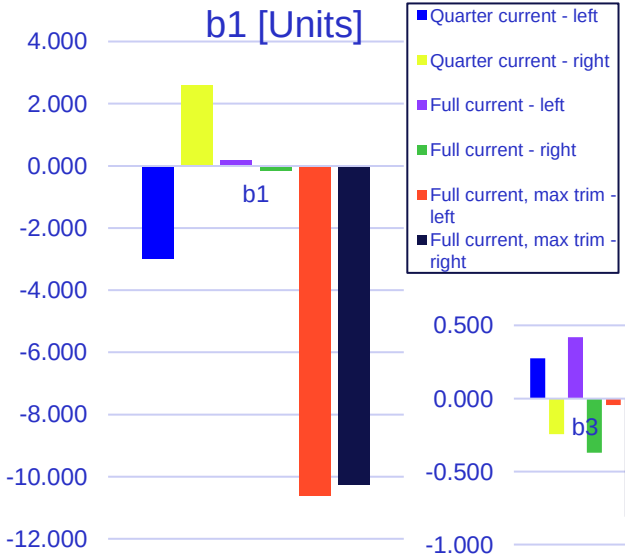


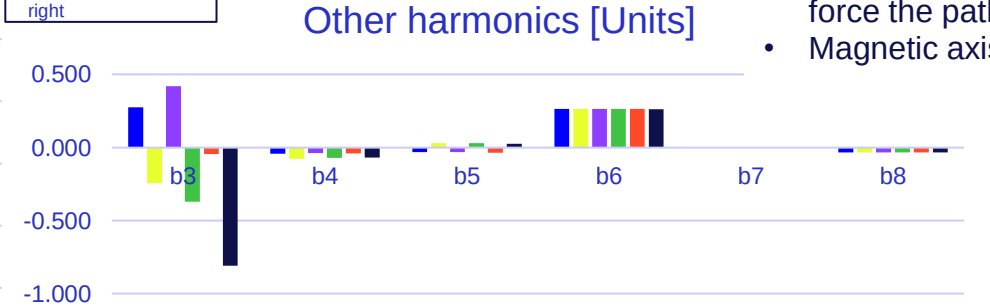


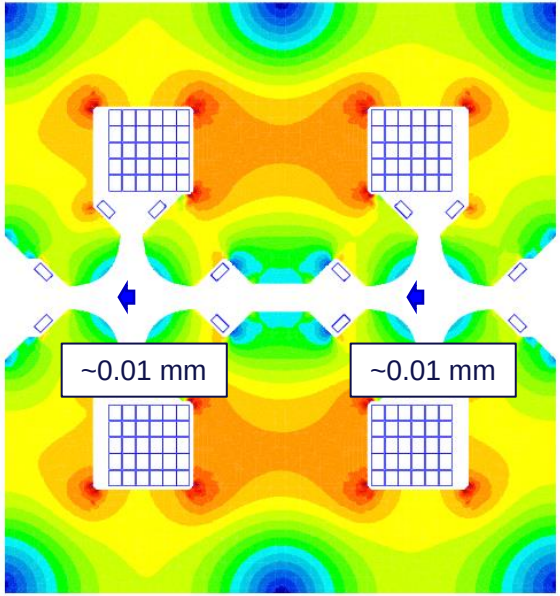
- b1 in cases 1 and 3 are evened out.
- Magnetic axis shift roughly halved, **~0.11 mm shift**, but still remains high.
- b3 increases in all cases.
- Inserts complicate the geometry slightly.

Version 3: new design with trim coils on poles

- Trim coils moved to the poles, one trim coil per pole; four per aperture.
- Magnetic gap was closed to simplify construction.
- Back-legs not optimized yet; kept thick to avoid saturation.





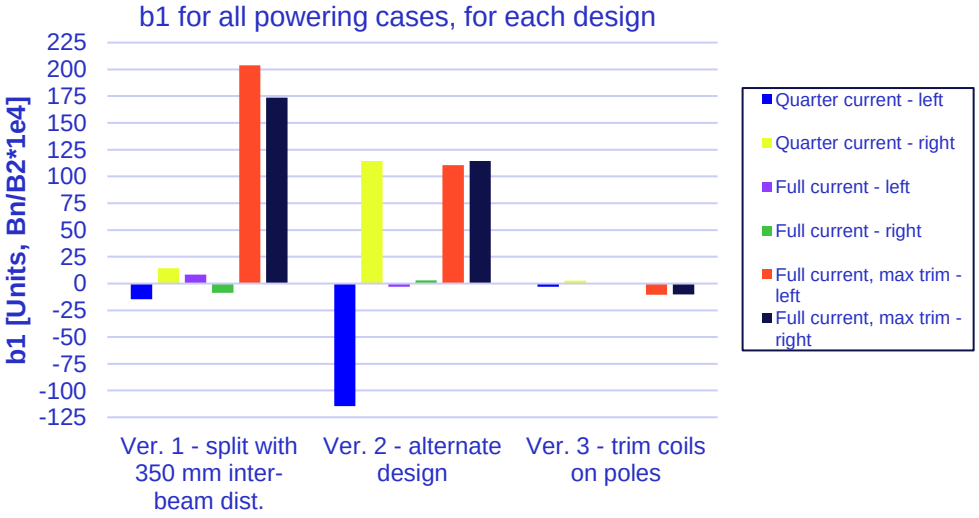


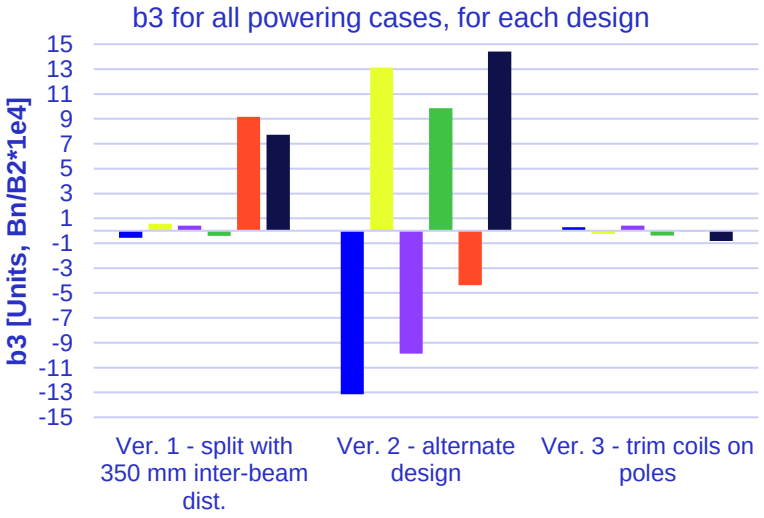
- b1 significantly reduced; trim coils help to force the path of the flux through the poles.
- Magnetic axis shift **~0.01 mm**.

Comparison of all three design versions

- Solution with trim coils on poles looks best:
  - All harmonics and magnetic axis shift greatly reduced.
  - Trim coils on the poles gives better control compared to previous solution with trim coils on back-legs.
  - Depending on power-supply set-up, trim coils could potentially be used for correction.

Design	Worst case mag. axis shift
Version 1	± 0.2 mm
Version 2	± 0.11 mm
Version 3	± 0.01 mm



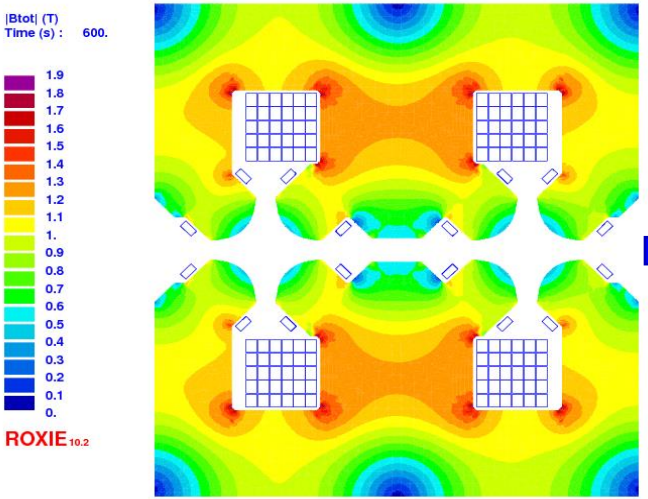


Reduction of aperture radius

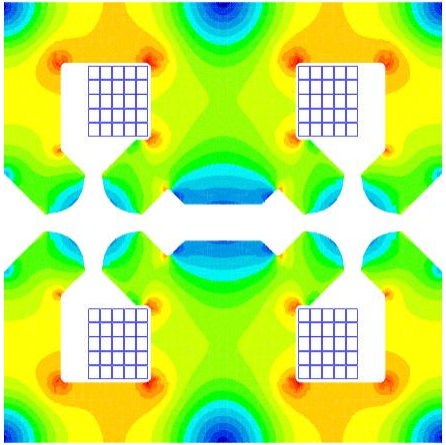
- Reduction of beam aperture radius from 35 mm to 30 mm was investigated.
- 5 mm reduction of magnet aperture radius was assumed: 42 mm → 37 mm.
- Downsized version already looks feasible in terms of field quality; iron geometry could still be optimized further (thinner back-legs, reducing gaps around the main coils, etc.).
- Allows for significant reduction in power consumption and materials (see table).

	% change after downsizing
Ampere-turns	-23 %
Dissipated power	-25 %
Copper mass	-24 %
Iron mass (preliminary)	-27%

Power and materials savings after downsizing



Ver. 3 design, with previous 42 mm aperture radius

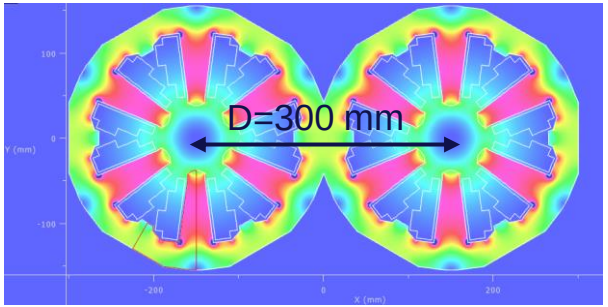


Downsized ver. 3 design, with 37 mm aperture radius

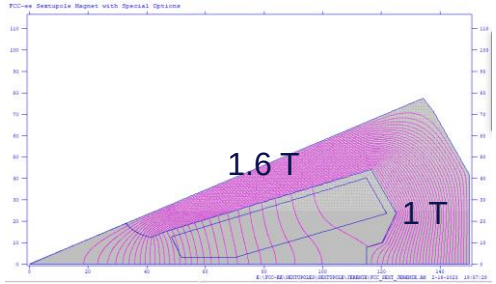
Collider sextupole

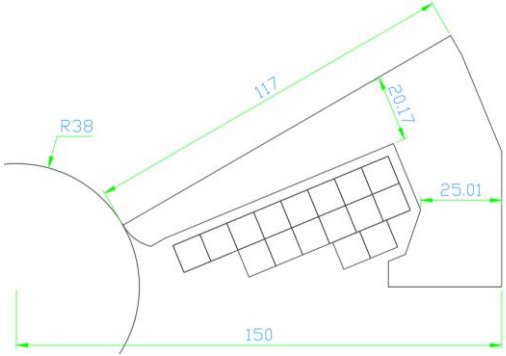
Sextupole in CDR (2019)

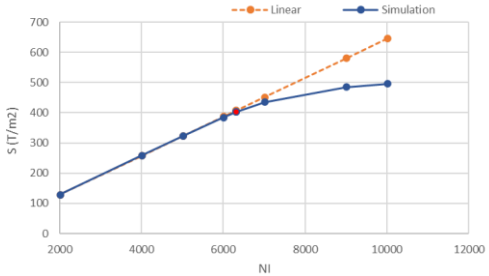
S_0 max = 807 T/m², $B_{pole\ tip}$ 0.59 *T*



- 300 mm inter-beam distance, compatible with **individual magnets** for each beam
- "Busy" cross section, **current** and **flux densities** at **upper values, dissipated power**
- Small space for Integration of **trim circuits** (H/V orbit correctors, skew quadrupoles) to be performed







✓ 1.5% Saturation

Parameter	Unit	Value
Sextupole Strength	T/m2	**807**
Total current	At	**6300**
Number of turns per coil	-	15
Conductor dimensions	mm²	8×8
Cooling diameter	mm	3
Current density	A/mm²	**7.87**
Voltage drop per magnet	V	34.5
Resistance per magnet	mΩ	77
Power per magnet	kW	**15.5**
Number of water circuits	-	**18**
Water temperature rise	°C	10.5
Cooling water speed	m/s	2.77
Pressure drop	bar	6
Reynolds No.	-	4150

Fcc-ee Sextupole Specifications Updates

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

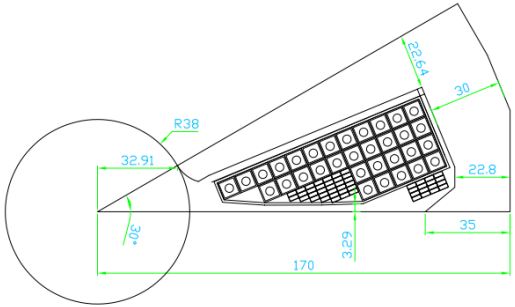
Info K.Oide and R. Tomas:
19th April 2023

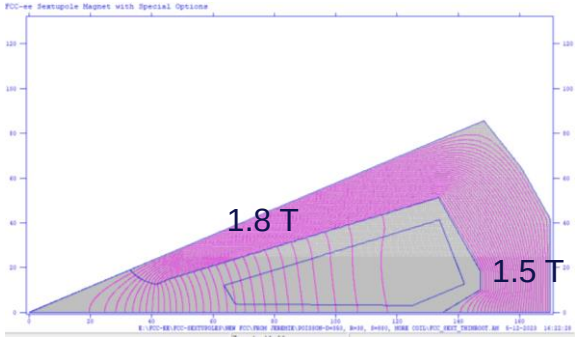
- It gets worse in the updates in point of magnet design with (R=38)
  - ✓ S=880 T/m2
  - ✓ L=1.5 m
- Inter-beam distance D=350 mm! The created space could be utilized for **more iron** or **more coil turns**!

Sextupole (D=350 mm)-I

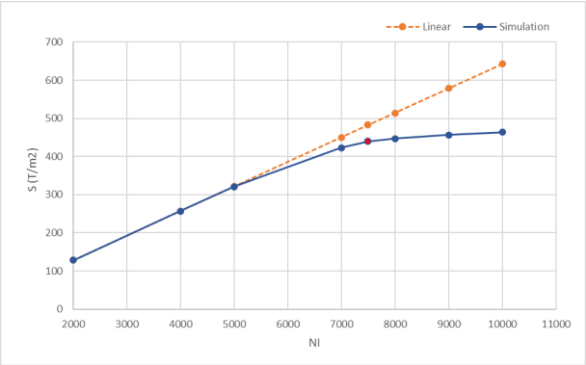
➢ More coil windings

- ❑ Pole width is saved as before
- ❑ N=32 turn
- ❑ Auxiliary solid coils = 32+16 turns (too high current density)





Parameter	Unit	Value
Sextupole Strength	T/m2	**880**
Total current	At	7500
Number of turns per coil	-	**32**
Conductor dimensions	mm^2	6.5×6.5
Cooling diameter	mm	3.5
Current density	A/mm^2	**7.24**
Voltage drop per magnet	V	77
Resistance per magnet	mΩ	326
Power per magnet	kW	**18.1**
Number of water circuits	-	18
Water temperature rise	°C	13.5
Cooling water speed	m/s	1.85
Pressure drop	bar	6
Reynolds No.	-	3250

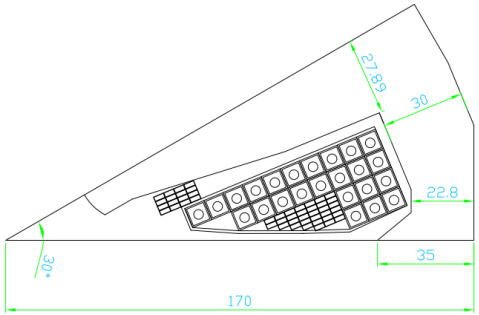


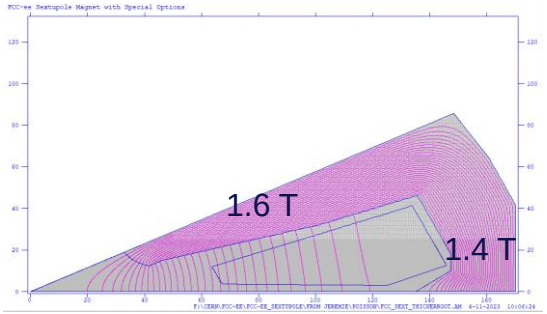
- ➢ The saturation is increased to 9 %.
- ➢ The power is more than 18 kW.
- ➢ Problems in cooling (18 cooling circuits, not fully in turbulent regime)
- ➢ Small space for Corrector coils

Sextupole (D=350 mm)-II

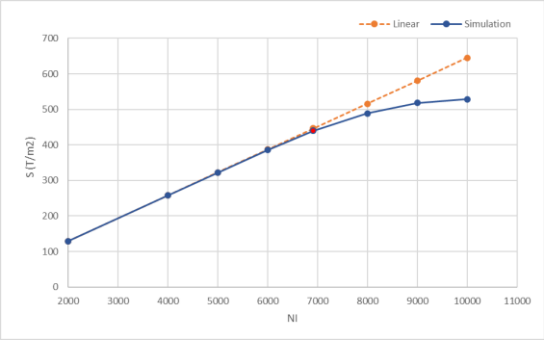
➢ Wider Pole width

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





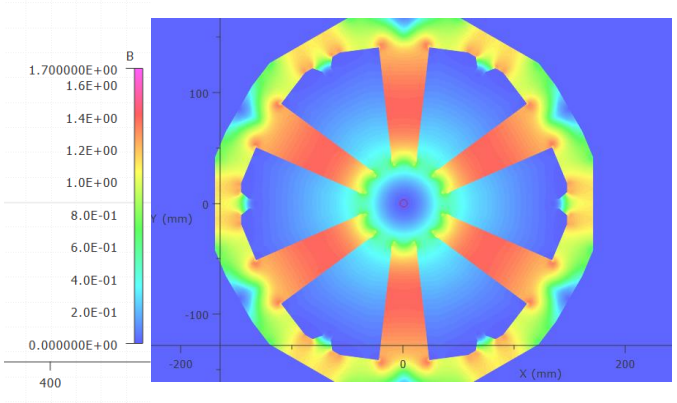
Parameter	Unit	Value
Sextupole Strength	T/m2	**880**
Total current	At	6920
Number of turns per coil	-	22
Conductor dimensions	mm^2	6.5×6.5
Cooling diameter	mm	3.5
Current density	A/mm^2	**9.6**
Voltage drop per magnet	V	70
Resistance per magnet	mΩ	223
Power per magnet	kW	**22.1**
Number of water circuits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

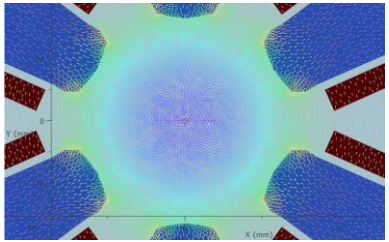


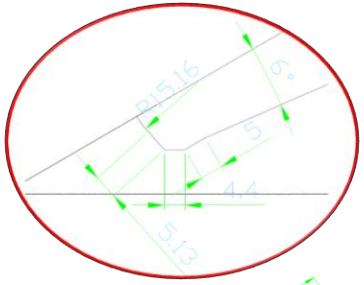
- ➢ The current density is increased to 9.6 A/mm^2.
- ➢ The saturation is about **1.5%** but the power is increased to **22 kW**.
  - ○ Problems in cooling (18 cooling circuits)
- ➢ Small space for Axillary coils.

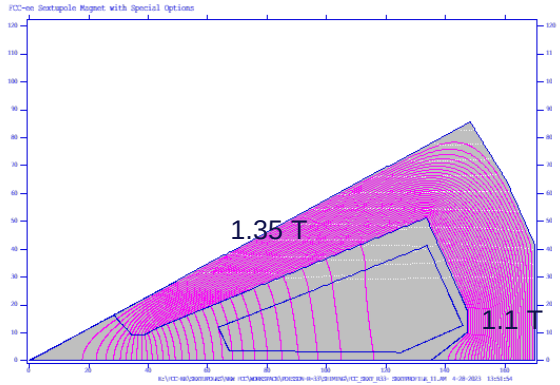
➢ It seems that this created space (D=350 mm) could not compensate effects of increasing the field strength and magnetic length in the specifications update.

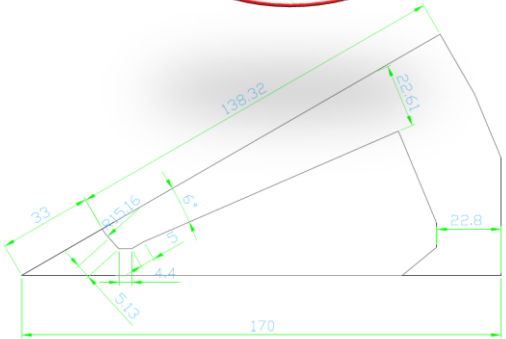
Sextupole (R=33 mm)

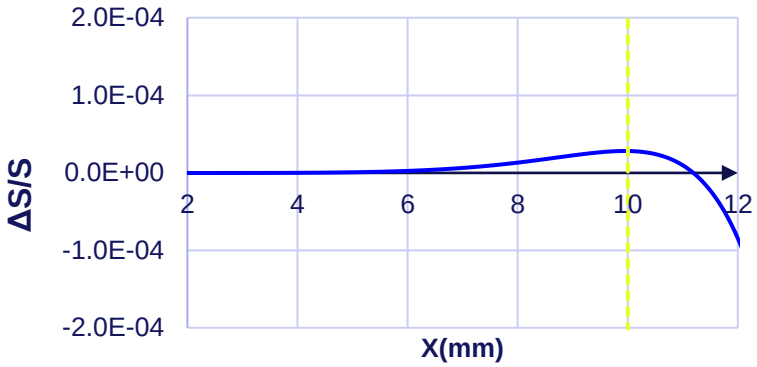




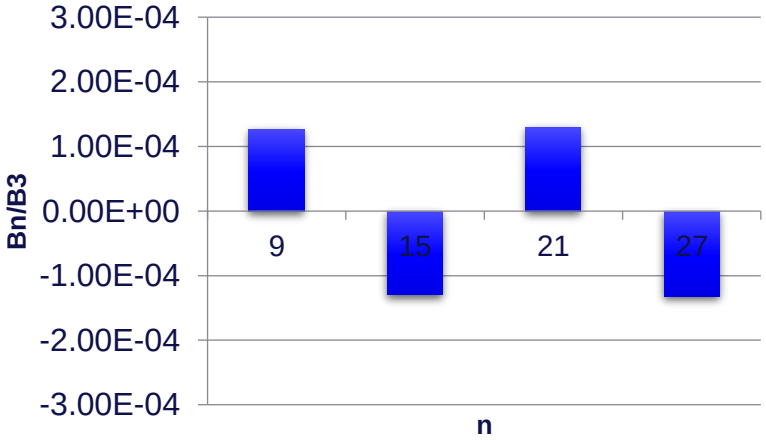




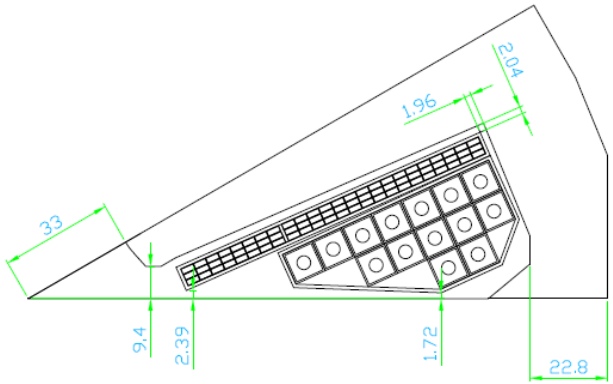


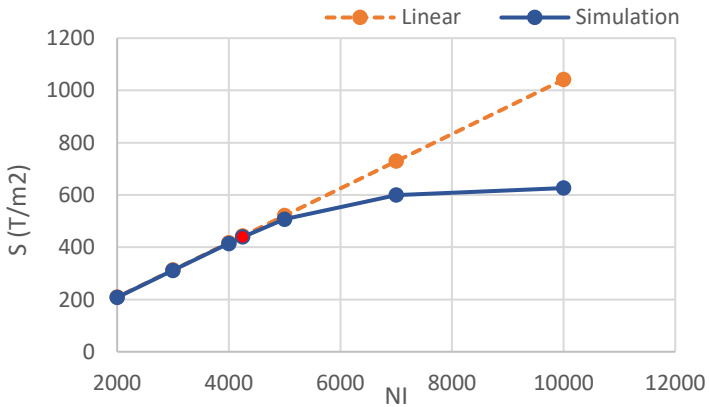


- Field quality better than 5.0E-05



Sextupole (R=33 mm)





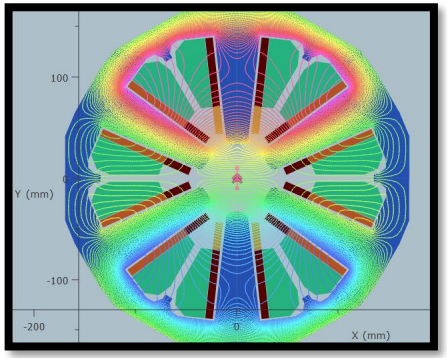
Electrical and Cooling Parameters

Parameter	Unit	Value			
Sextupole strength	T/m2	**880**			
Current	A	**4250**			
Number of turns per coil	-	24	14		8
Operation current	A	177	304		531
Conductor dimensions	mm^2	**6.5×6.5**	**8.5×8.5**		**11×11**
Cooling diameter	mm	3.5	4		6
Current density	A/mm^2	5.4	**5.1**		5.7
Voltage drop per magnet	V	43.2	23.4		15.6
Resistance per magnet	mΩ	243	78		29
Power per magnet	kW	**7.7**	**7.2**		8.2
Number of water circuits	-	18	12	**6**	6
Water temperature rise	°C	4.8	4.4	13.2	3.7
Cooling water speed	m/s	2.2	2.6	1.8	3.1
Pressure drop	bar	6	6	6	6
Reynolds no.	-	3850	5170	3530	9390

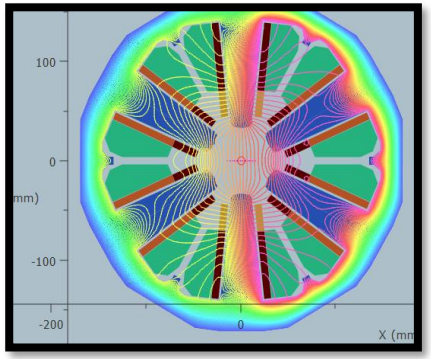
- The power is decreased to 7.2 kW.
  - ✓ 1/3 of R=38 (880 T/m2), ½ of CDR (807 T/m2)
- The saturation is less than % 1.

Correctors

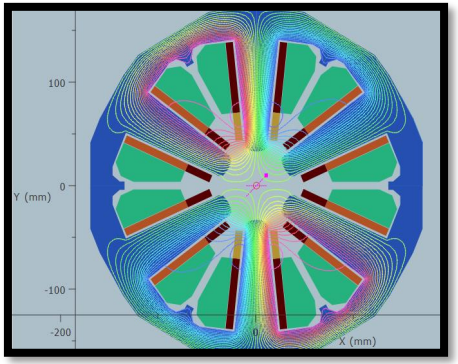
Vertical Corrector

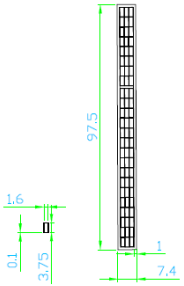


Horizontal Corrector



Skew Quadrupole Corrector





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

Parameter	Horiz. Corrector	Ver. Corrector	Sk. Quad. Corrector
Integrated Strength(Tm)(T)	0.02	0.02	0.6
Magnetic field (mT)/(T/m)	13	13	0.4
Effective length (mm)	1500	1500	1500
Ampere-Turns per pole (A.t)	400/200	345	378
Number of turns	48-24	48	24
Conductor size (mm^2)	3.75 × 1.6	3.75 × 1.6	3.75 × 1.6
Current (A)	8.3	7.2	15.8
Current Density (A/mm^2)	1.4	1.2	2.6
Resistance per magnet (Ω)	1.7/0.8	1.7	1.3
Total Voltage (V)	14/7	12.1	20
Total Power (W)	118/59	87	315

Sextupole Conclusion

- The sextupole with the updated parameters (R=38 mm, D=350 mm) was investigated:
  - The power is too high (20 kW).
  - There is little space for auxiliary coils.
  - The created space of inter beam distance (D=350 mm) could not compensate the effects of increasing the field strength and the magnetic length.
- Reducing the aperture radius to 33 mm was simulated.
  - The field quality, higher order multiples, electrical and cooling parameters were investigated and presented.
  - The required power (7.2 kW) is decreased significantly that is not comparable with the power in R=38 mm case (1/3) and the value in CDR(1/2).
- The horizontal and vertical correctors and skew quadruples are simulated and electrical parameters were investigated.
  - The field quality of sextupole plus correctors should be investigated and approved by beam dynamics.

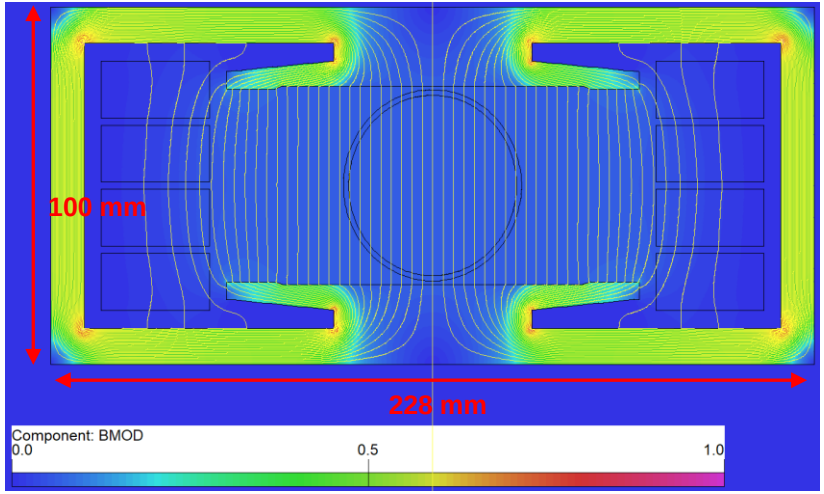
Booster magnets

Summary of requirements

	Minimum Field	Maximum field	Magnetic length	Good field radius	Field homogeneity
Dipole	7.1 mT	65 mT	11.1 m	17 mm	10 units
Quadrupole	1.7 Tm^{-1}	22.5 Tm^{-1}	1.5 m	10 mm	2 units
Sextupole	148.6 Tm^{-2}	1574.5 Tm^{-2}	0.5 m	17 mm	

Booster dipole candidate

Parameter	Unit	Value
Number of units		2944 x 2
Central field, 20 GeV–182.5 GeV	mT	7.1 - 65.0
Aperture (horizontal × vertical)	mm	123 x 55
Good field region (GFR) radius	mm	17
Field quality in GFR	1.0E-04	< 1
Magnetic length	m	11.1
Magnet overall transverse dimensions	mm	228 x 100
Iron mass per unit length	kg/m	55.5
Aluminium mass per unit length	kg/m	7.68
Magnet unit mass (11.1 m length)	kg	701
Total magnet mass, 65.4 km	tons	~ 4500
Maximum operating ampere-turns (tt_bar extraction)	A	2844
Maximum RMS current density (tt_bar)	A/mm2	0.92
Peak current (coil 4 turns)	*A*	*711*
Resistance per unit length (coil 4 turns)	*μΩ/m*	*596*
Inductance per unit length (coil 4 turns)	*μH/m*	*55*
Peak voltage per 1/2 octant (coil 4 turns)	*kV*	*1810*
Maximum RMS power per unit length (tt_bar)	W/m	64
Maximum total peak power, 65.4 km (tt_bar; cabling not incl.)	MW	20
Maximum total RMS power, 65.4 km (tt_bar; cabling not incl.)	MW	4.2

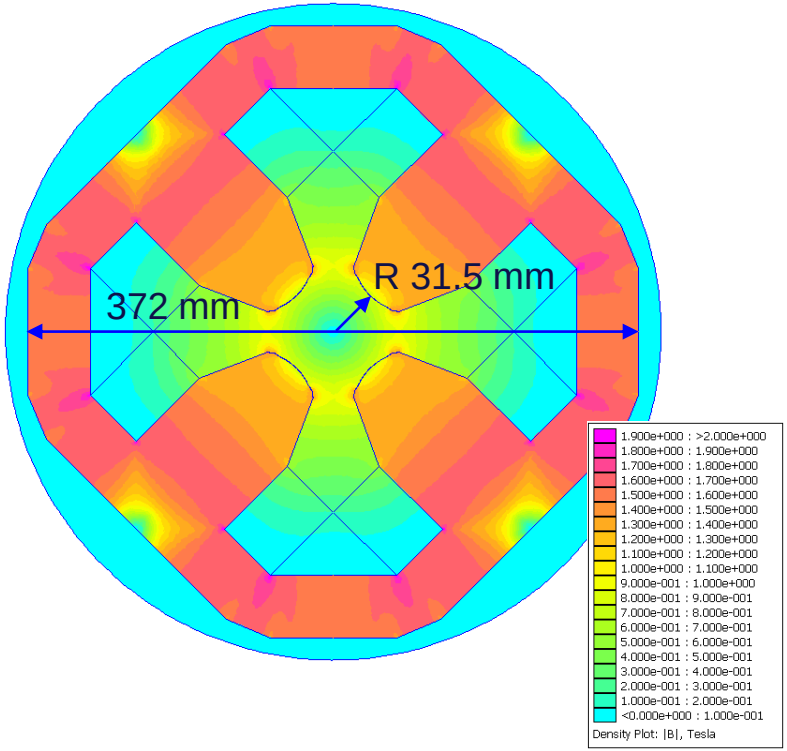


Booster quadrupole candidate

- Current density in copper: 5.1 A_{RMS} mm^{-2} @ tt2

	Z	W	H	tt 1	tt 2
Power Loss [MW]	0.9	1.5	5.0	18.9	20.8

- B_{peak} < 1.6 T @ tt2, η > 98 %
- Active mass: 750 kg (2210 tons total)
- Assumes 1.5 mm for vacuum tube and 5 mm bake-out jacket
- 6 turns per coil, [1.8 kA; 1.8 kV] per 92 magnet circuit
- ΔP cooling water 5.4 bar, ΔT < 22 K
- 70 mm coil overhang vs. 165 mm quad. to sext. distance
- **Matches key requirements, to be optimised…**



Next steps for magnet development

Prospects for magnets development

- Electromagnetic design
  - *Global cost optimization (capital and operational for magnet and cooling infrastructure) to find optimal working point (J in coils, ΔT, electrical parameters for converter efficiency)*
  - *Cross-section of collider quadrupole to minimize gaps in cross-section, optimize B_{mod} in iron*
  - *Alternative design of collider sextupoles with coils out of mid-plane (SR damage to evaluate)*
  - *Optimisation of booster dipole for remnant effects (Hc)*
- Mechanical design
  - *Manufacturing processes for large series (automatized machining, assembly, measurements)*
  - *Design of inter-connections to quantify exact drift space needed (dipoles with B-covered interconnects)*
- R&D, prototyping, and arc half-cell mock-up
  - *Model magnets for performance validation as well as integration checks*
  - *Inorganic coatings for insulation (dipole busbars, sextupole coils)*

Conclusions

Conclusions

The latest specifications – inter-beam distance, magnetic parameters, trim coils in collider sextupoles, etc. - have been reflected in the magnet design updates

The aperture coupling in the collider quadrupole has been significantly mitigated

The collider magnet designs evaluated with reduced aperture, can bring significant savings in materials, as well as power consumption (~10% for dipoles, ~25% for quadrupoles, ~50% for sextupoles), and is necessary for sextupole design with correction windings

A preliminary cross-section of the booster quadrupole is proposed, which matches the optics requirements

The next steps of the magnet development work will address the lifetime cost optimization, performance in the low fields, and large series manufacturing aspects through the production, test and measurement of model/prototype magnets

FCC

Thank you for your attention!

Questions?

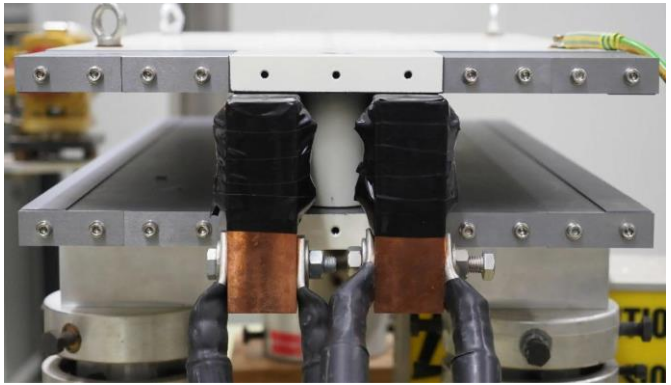
SPARE SLIDES

Dipole 1-m long models

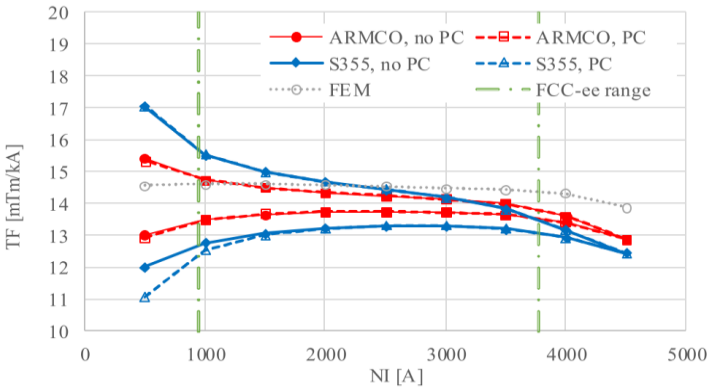
- 2 versions, S235 vs. ARMCO yoke
- Systematic b2 not included in field homogeneity budget (agreed with optics)

NI	ARMCO		S355		FEM
[A]	AP1	AP2	AP1	AP2	AP2
500	52.1	-53.4	60.5	-62.0	-22.2
1000	34.4	-35.3	47.3	-48.5	-22.2
1500	28.1	-28.8	40.3	-41.4	-22.1
2000	24.8	-25.5	36.0	-37.0	-21.9
2500	22.9	-23.5	33.1	-34.1	-21.7
3000	21.7	-22.2	31.3	-32.2	-21.6
3500	20.9	-21.3	30.0	-30.8	-21.5
4000	20.4	-20.9	29.4	-30.0	-21.4
4500	20.3	-20.9	29.2	-29.6	-21.5
4000	14.7	-15.4	26.2	-26.7	-21.4
3500	11.7	-12.4	23.2	-23.7	-21.5
3000	9.6	-10.4	19.3	-20.1	-21.6
2500	7.6	-8.4	15.1	-16.0	-21.7
2000	5.2	-6.0	10.4	-11.4	-21.9
1500	1.6	-2.5	4.2	-5.4	-22.1
1000	-4.9	4.1	-5.9	4.4	-22.2
500	-22.8	22.1	-30.3	28.3	-22.2

Quadrupole component

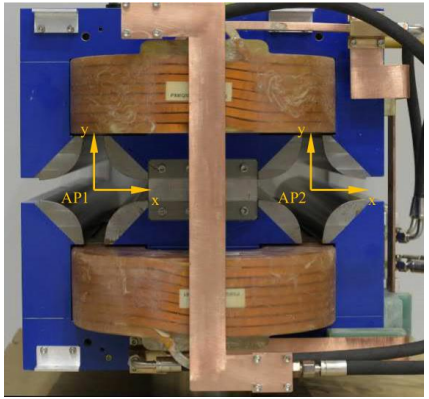


Prototype 1m-long, 2017



Transfer function

Quadrupole magnetic axis shift



Magnetic measurements performed on 1-m prototype [3]

- ~0.4 mm shift for each aperture between low and high fields
- Mismatch MM vs. FEM (3D) at low fields not completely explained

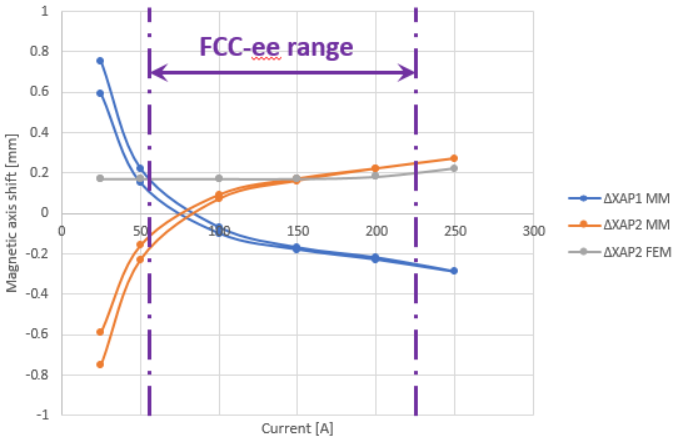
➔ To be further investigated

DIPOLE AND SEXTUPOLE COMPONENTS IN THE TWIN QUADRUPOLE

I [A]	x_{ctr} [mm]			$\int b_3$ [10^{-4} @ 10 mm]		
	AP1	AP2	FEM	AP1	AP2	FEM
25	0.75	-0.75	0.17	13.1	-14.4	-57.9
50	0.22	-0.23	0.17	34.7	-35.4	-57.9
100	-0.07	0.07	0.17	46.6	-46.6	-58.0
150	-0.17	0.16	0.17	50.9	-50.9	-58.2
200	-0.22	0.22	0.18	53.5	-53.6	-59.0
250	-0.29	0.27	0.22	57.8	-57.2	-62.5
200	-0.23	0.22	0.18	53.1	-53.3	-59.0
150	-0.18	0.17	0.17	51.0	-50.6	-58.2
100	-0.10	0.09	0.17	46.9	-46.9	-58.0
50	0.15	-0.16	0.17	35.7	-35.2	-57.9
25	0.59	-0.59	0.17	15.9	-14.9	-57.9

The simulation results are for AP2, as ¼ of the magnet is modeled; furthermore, no hysteretic behavior is considered in the BH curve.

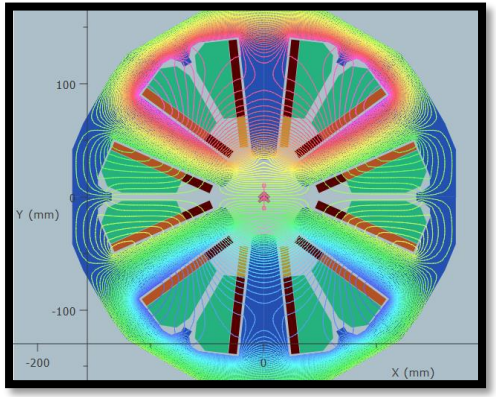
Measured magnetic axis shift and ∫b3



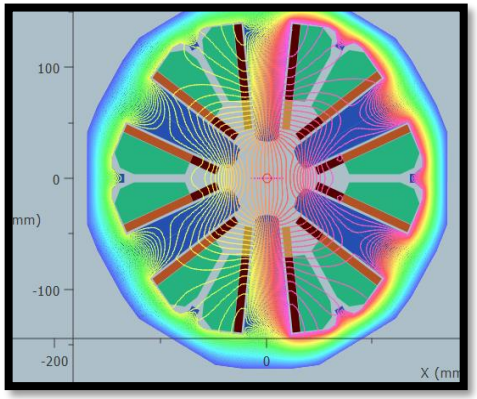
Magnetic axis shift

Correctors

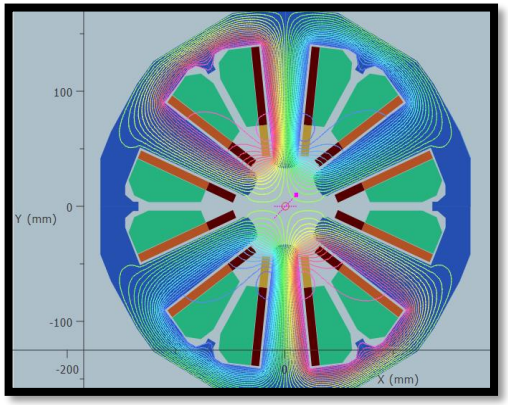
Vertical Corrector

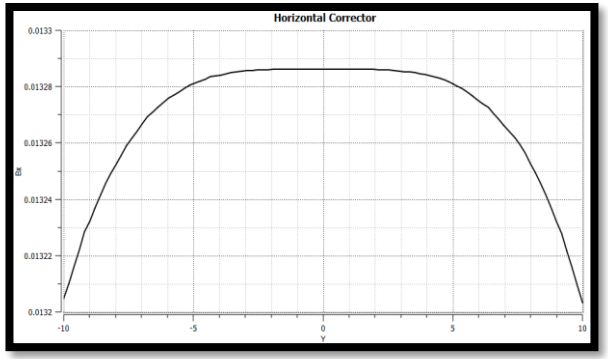


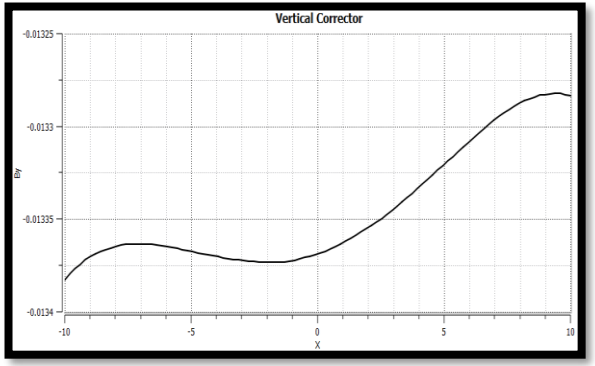
Horizontal Corrector

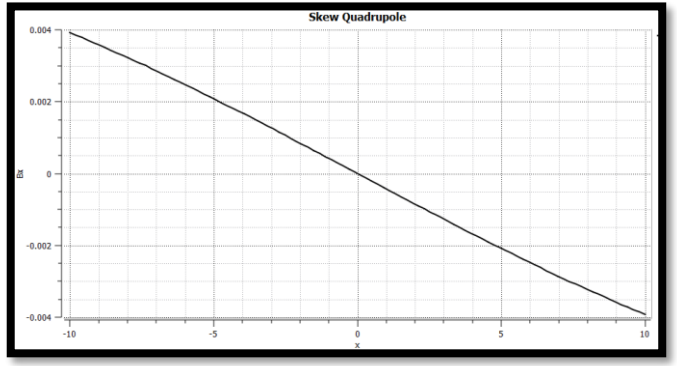


Skew Quadrupole Corrector









Horizontal Dipole
Bx=0.013 T

Vertical Dipole
By=0.013 T

G=0.4 T/m