Field Quality of the FCC-ee Magnets

J. Bauche, FCC-ee tuning meeting, 17th March 2022.

Outline

Collider magnet designs (CDR)

Field tapering

Mitigation of field errors and orbit correction

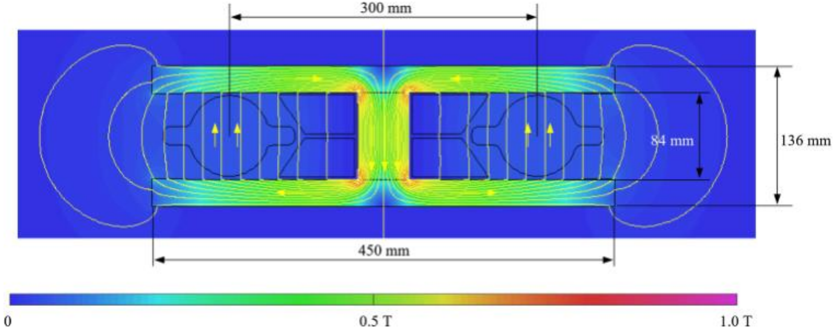
Booster magnet specifications

Conclusions

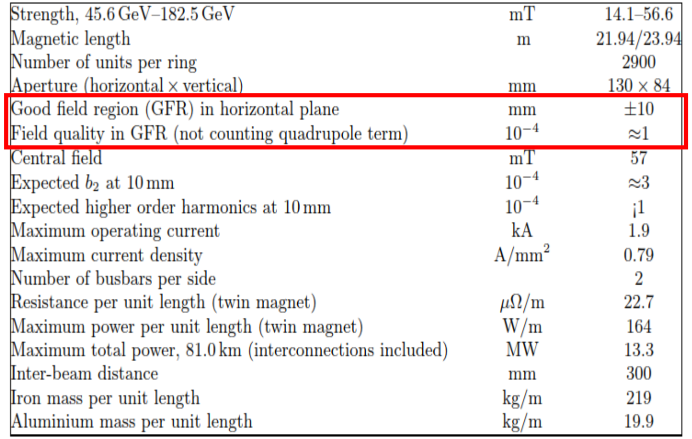
[References]

Dipole

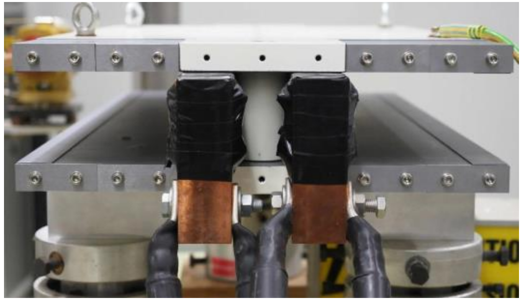
- Twin aperture design, magnetically coupled [1], [2], [3]
- Simple, pure, cost effective
- Low power consumption (50% w.r.t. separate magnets)
- 300 mm inter-beam distance shared between vacuum chamber size, SR absorbers, busbars and yoke return leg
- DC operation, compatible with solid iron yoke construction, but alternatives are possible
- Twin air-cooled aluminium busbar considered in CDR to be reviewed (SR in mid-plane)



Magnetic model cross-section (CDR), B_0 max = 57 mT



Strength, 45.6 GeV–182.5 GeV	mT	14.1–56.6
Magnetic length	m	21.94/23.94
Number of units per ring		2900
Aperture (horizontal × vertical)	mm	130 × 84
Good field region (GFR) in horizontal plane	mm	±10
Field quality in GFR (not counting quadrupole term)	10^{-4}	$\approx$1
Central field	mT	57
Expected b_2 at 10 mm	10^{-4}	$\approx$3
Expected higher order harmonics at 10 mm	10^{-4}	¡1
Maximum operating current	kA	1.9
Maximum current density	A/mm^2	0.79
Number of busbars per side		2
Resistance per unit length (twin magnet)	$\mu\Omega$/m	22.7
Maximum power per unit length (twin magnet)	W/m	164
Maximum total power, 81.0 km (interconnections included)	MW	13.3
Inter-beam distance	mm	300
Iron mass per unit length	kg/m	219
Aluminium mass per unit length	kg/m	19.9

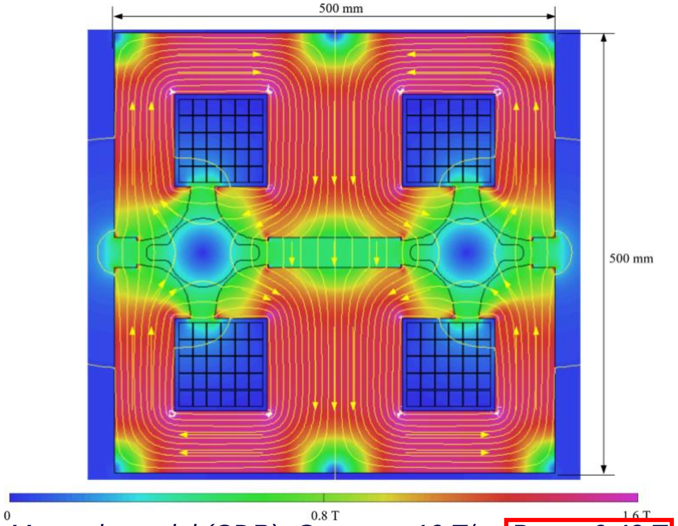


Prototype 1m-long, single busbar "coil", measurements reported in [4]

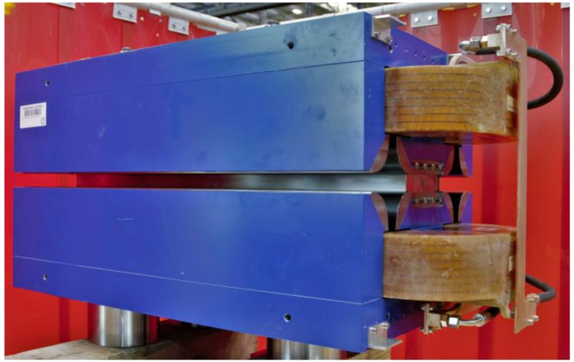
Parameters (CDR) [1]

Quadrupole

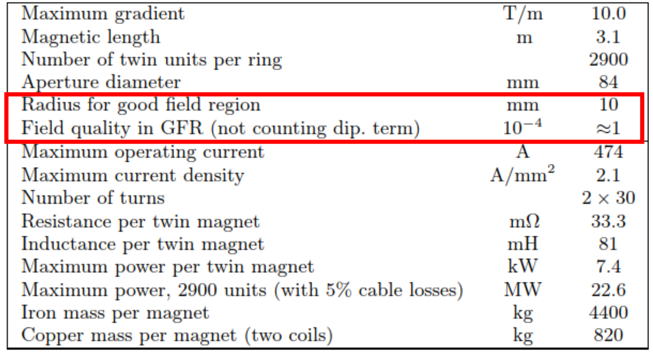
- Twin aperture design, magnetically coupled [1], [2], [3]
- Only 2 racetrack coils for 8 poles, out of mid-plane (SR)
- Top-bottom assembly via non-magnetic central spacer
- Equilibrium of parallel flux distribution between horizontal and vertical field lines controlled by central gap height (adjustable with end shims on prototype
- ~10x higher flux density than in dipoles; water-cooled coil (optimization of dipole filling factor)



Magnetic model (CDR), G_0 max = 10 T/m, $B_{pole\ tip}$ 0.42 T



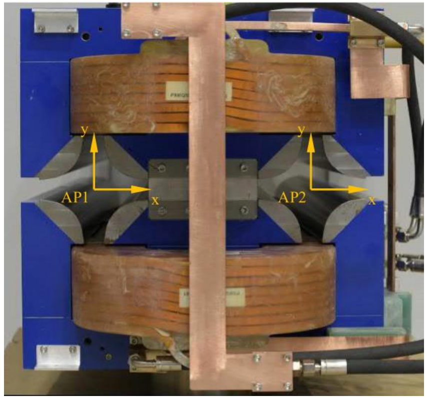
Prototype 1m-long



Maximum gradient	T/m	10.0
Magnetic length	m	3.1
Number of twin units per ring		2900
Aperture diameter	mm	84
Radius for good field region	mm	10
Field quality in GFR (not counting dip. term)	10^{-4}	≈1
Maximum operating current	A	474
Maximum current density	A/mm^2	2.1
Number of turns		2 × 30
Resistance per twin magnet	mΩ	33.3
Inductance per twin magnet	mH	81
Maximum power per twin magnet	kW	7.4
Maximum power, 2900 units (with 5% cable losses)	MW	22.6
Iron mass per magnet	kg	4400
Copper mass per magnet (two coils)	kg	820

Parameters (CDR)

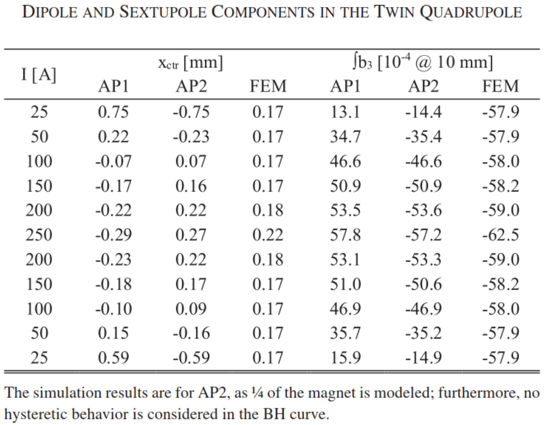
Quadrupole magnetic axis shift



Magnetic measurements performed on 1-m prototype [4]

- ~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

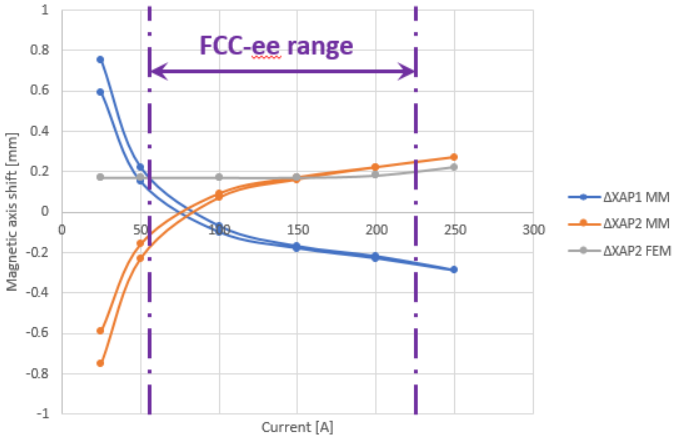


DIPOLE AND SEXTUPOLE COMPONENTS IN THE TWIN QUADRUPOLE

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

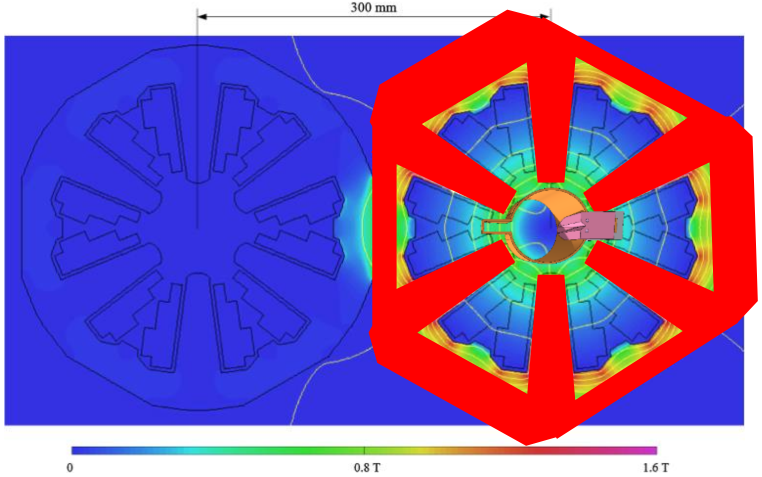


Magnetic axis shift

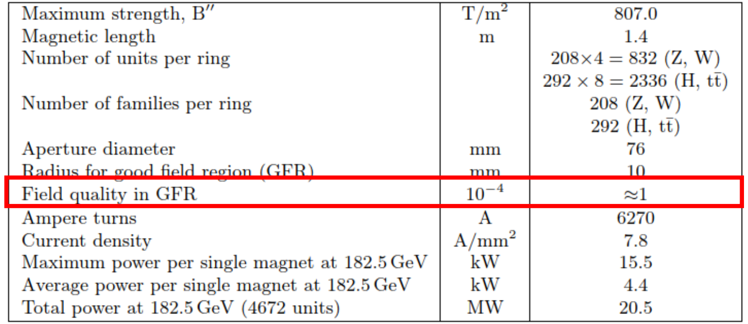
Sextupole

- Classical design as first approach for CDR
- Fits in 300 mm inter-beam distance, compatible with individual magnets for each beam
- Busy cross section, current and flux densities at upper values
- Vacuum chamber winglets and SR absorbers integration issue with coils on mid-plane
- Cross section could be optimized with 120° symmetry of return yoke

➔ Design to be reviewed with updated specifications



Magnetic model (CDR), S_0 max = 807 T/m², $B_{pole\ tip}$ 1.17 T

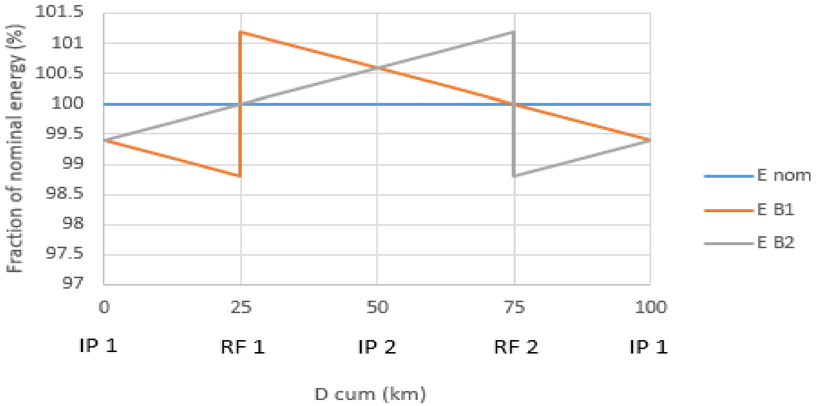


Maximum strength, B''	T/m²	807.0
Magnetic length	m	1.4
Number of units per ring		208×4 = 832 (Z, W) 292 × 8 = 2336 (H, $t\bar{t}$)
Number of families per ring		208 (Z, W) 292 (H, $t\bar{t}$)
Aperture diameter	mm	76
Radius for good field region (GFR)	mm	10
Field quality in GFR	10^{-4}	≈1
Ampere turns	A	6270
Current density	A/mm²	7.8
Maximum power per single magnet at 182.5 GeV	kW	15.5
Average power per single magnet at 182.5 GeV	kW	4.4
Total power at 182.5 GeV (4672 units)	MW	20.5

Parameters (CDR)

Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

Options:

Adjusted parameter	**System**	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

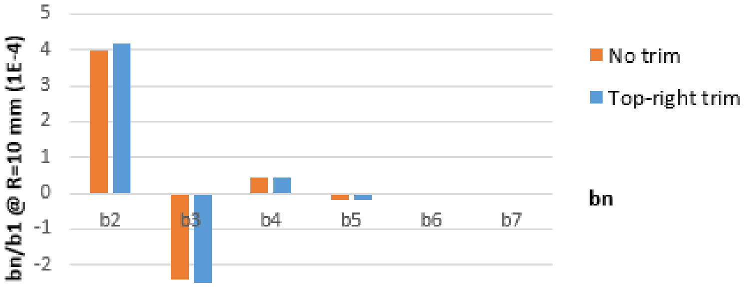
➔ Next slides will address effect of tuneable trims on magnet field quality

(More details on other options available in spare slides)

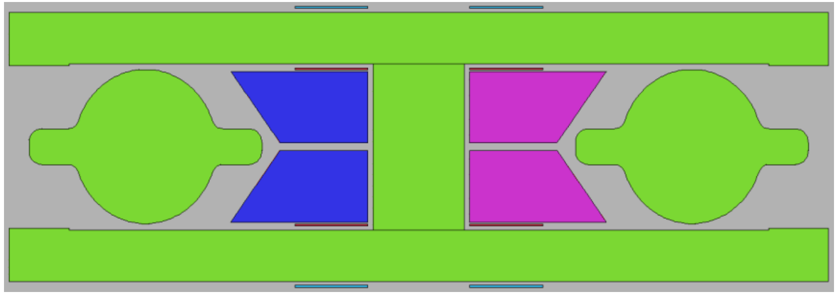
Dipole field tapering

Trim coils / trimmed busbar current

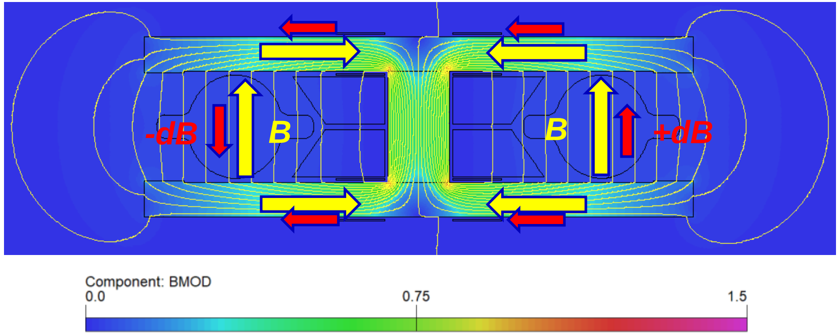
- Needed on each aperture for individual aperture trimming
- Can be made in single turn like the main busbars *(Discussed with TE-EPC)*
- One single branch per aperture is possible (top or bottom), with marginal impact on field quality
- No cross-talk between apertures (trim effect only on concerned aperture)
- Effect of trim coils or trimmed current on main busbar is identical



Normalized harmonics (FEM 2D)



Current polarities in main and trim conductors

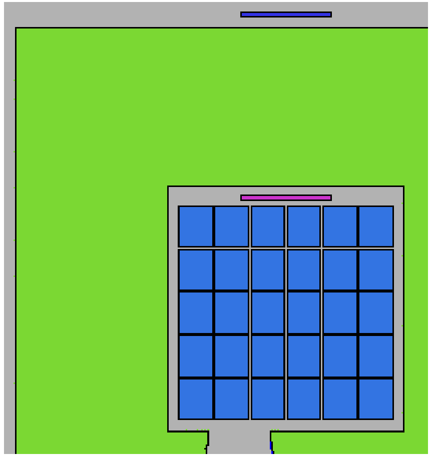


Flux density and field lines with trims activated

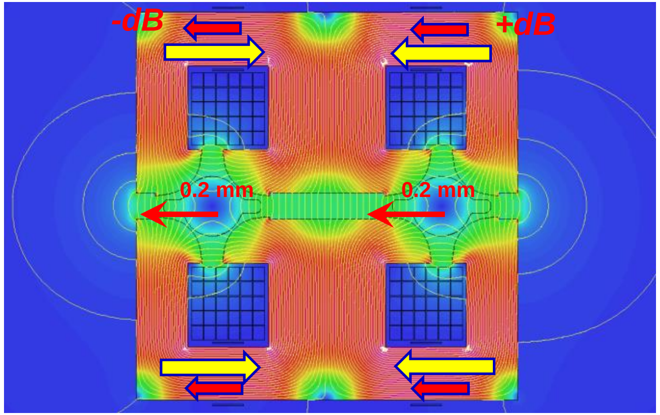
Quadrupole field tapering

Trim coils

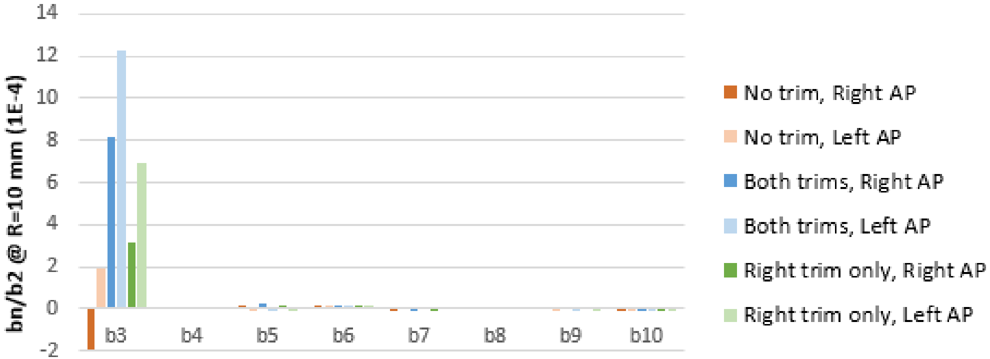
- Needed on each aperture for individual aperture trimming
- One single branch (top or bottom) per aperture not possible
- Gradient trim effect only on concerned aperture
- Significant cross-talk : both magnetic axes shift up to 0.2 mm @ 1.2% dB in same direction, even when single aperture trim is activated
- b_3 significantly affected in both apertures with same polarity



Current polarities in main and trim conductors



Flux density and field lines, trims activated

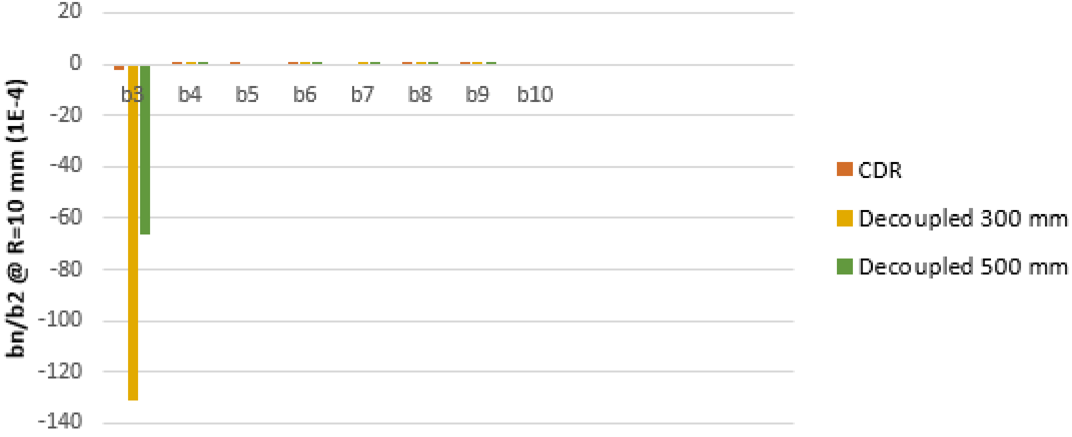


Normalized harmonics (FEM 2D)

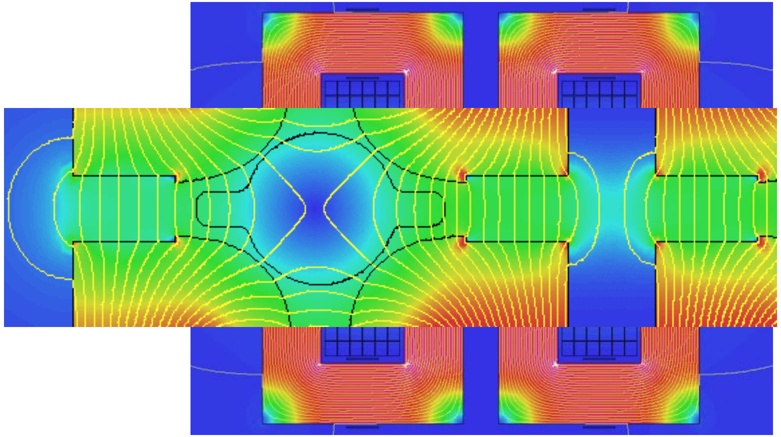
Investigation on coupling

Tentative to decouple yokes

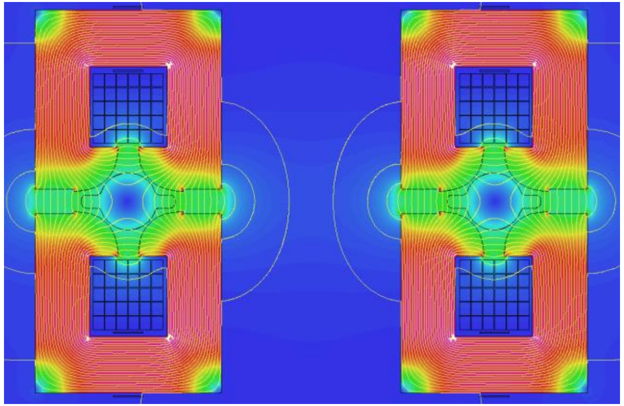
- Attempt to reduce flux crossing between apertures
- Coupling due to proximity of open apertures
- Effect reduces with aperture separation, but doesn’t disappear
- Magnetic axis shift 3 mm for 300 mm vs. 1.5 mm for 500 mm inter-beam



Normalized harmonics (FEM 2D)



Decoupled yokes, no trims activated, 300 mm inter-beam

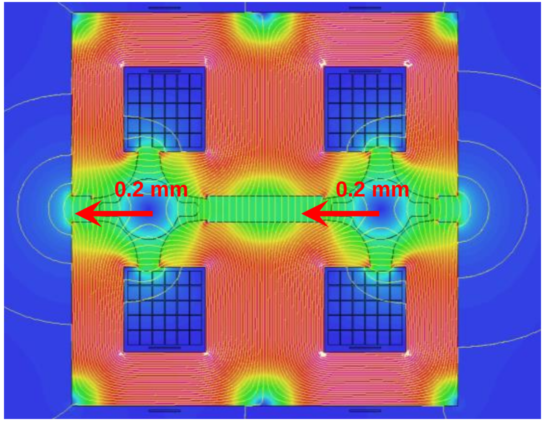


Decoupled yokes, no trims activated, 500 mm inter-beam

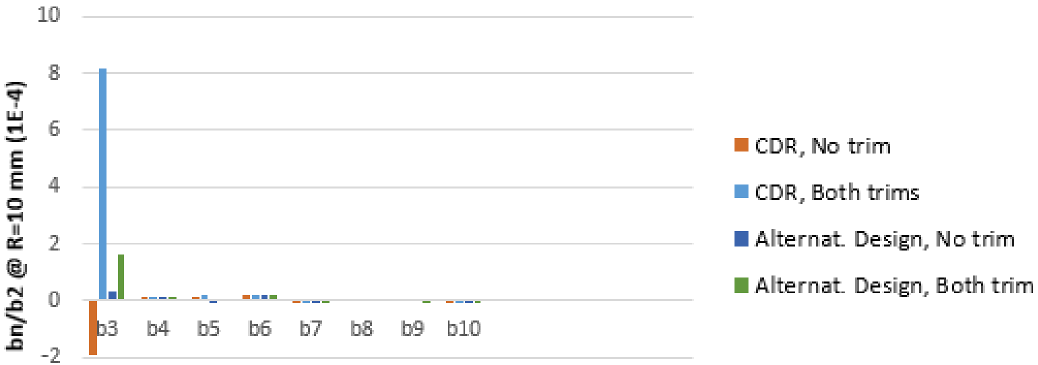
Alternative design

Compensation of inner/outer asymmetry

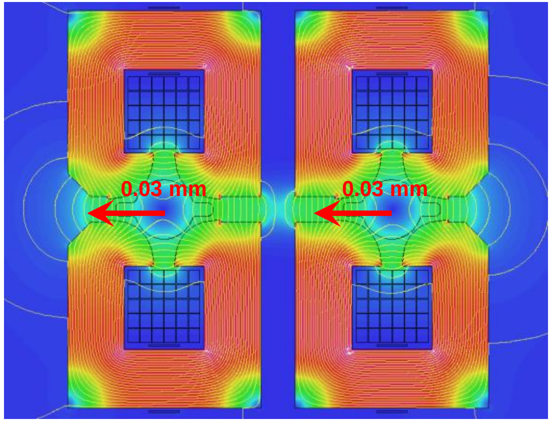
- Chamfer on outer sides to limit flux leakage
- Magnetic axis shift and b_3 mitigated but not suppressed
- To be checked with 3D simulations



CDR design, trims activated



Normalized harmonics (FEM 2D)



Alternative design, trims activated

Mitigation of field errors and orbit correction

- Systematic linear **b_2 in dipoles**

  → *could be compensated by arc quadrupoles*
- Magnetic **axis shift in quadrupoles**

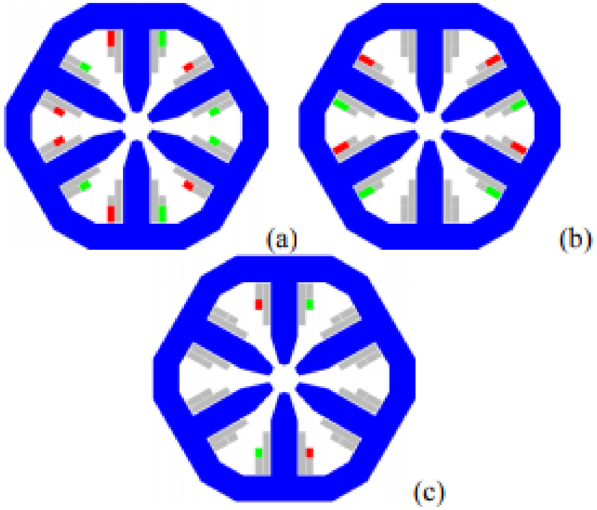
  → *could be compensated by dipole (active) trims*
- **b_3 in quadrupoles**

  → *could be compensated by the sextupoles?*
- **Dipole active trims**

  → *could be used for horizontal orbit correction, but limitations for connecting to a fast feedback system*
- **Horizontal** and **vertical** orbit as well as **skew quadrupole correctors**

  → *can be integrated in sextupoles with trim coils [5], [6]*

  … but the sextupole strength or length may need to be reviewed

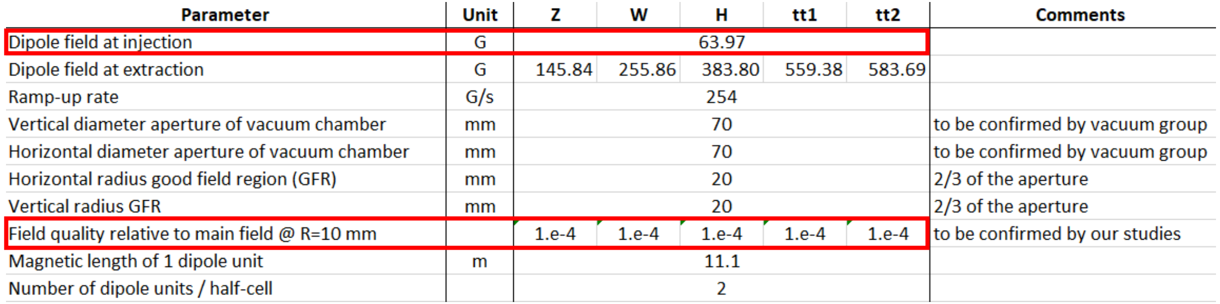


(a) Horiz. Steering; (b) Vert. steering; (c) Skew quad.

Trim coils in ALBA and SESAME sextupoles

Booster magnet specifications

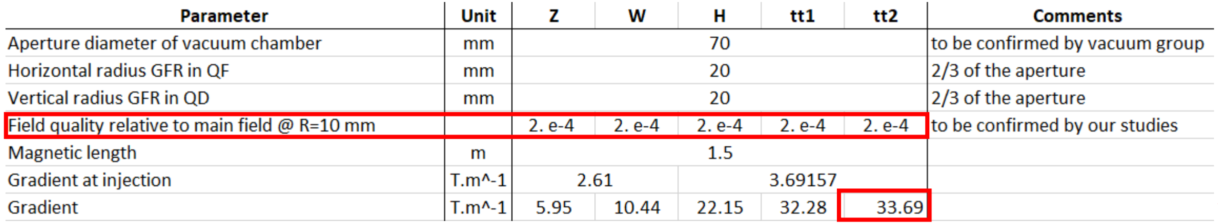
Dipole



Parameter	Unit	Z	W	H	tt1	tt2	Comments
Dipole field at injection	G	63.97					
Dipole field at extraction	G	145.84	255.86	383.80	559.38	583.69	
Ramp-up rate	G/s	254					
Vertical diameter aperture of vacuum chamber	mm	70					to be confirmed by vacuum group
Horizontal diameter aperture of vacuum chamber	mm	70					to be confirmed by vacuum group
Horizontal radius good field region (GFR)	mm	20					2/3 of the aperture
Vertical radius GFR	mm	20					2/3 of the aperture
Field quality relative to main field @ R=10 mm		1.e-4	1.e-4	1.e-4	1.e-4	1.e-4	to be confirmed by our studies
Magnetic length of 1 dipole unit	m	11.1					
Number of dipole units / half-cell		2					

Very low field at injection is challenging. Window-frame configuration under study, to be compared with coil dominated magnet design

Quadrupole



Parameter	Unit	Z	W	H	tt1	tt2	Comments
Aperture diameter of vacuum chamber	mm	70					to be confirmed by vacuum group
Horizontal radius GFR in QF	mm	20					2/3 of the aperture
Vertical radius GFR in QD	mm	20					2/3 of the aperture
Field quality relative to main field @ R=10 mm		2. e-4	2. e-4	2. e-4	2. e-4	2. e-4	to be confirmed by our studies
Magnetic length	m	1.5					
Gradient at injection	T.m^-1	2.61		3.69157			
Gradient	T.m^-1	5.95	10.44	22.15	32.28	33.69	

Corresponds to 1.93 T on pole tip, not realistic. Gradient will have to be reduced or magnetic length to be increased

Preliminary values given by beam optics team

Conclusions

Twin aperture magnet designs allow low consumption and cost efficient construction

Further optimization of the magnet designs is needed to address some open points on the field quality, in particular regarding the quadrupole magnetic axis shift due to magnetic coupling, accounting also for tuneable field tapering options

The orbit correction strategy needs to be defined to get the magnet specifications

References

1. *M. Benedikt et al.*, “Future circular collider conceptual design report, vol. 2: The lepton collider (FCC-ee),” Eur. Phys. J. ST., vol. 228, no. 2, 2019. (https://doi.org/10.1140/epjst/e2019-900045-4)
2. *A. Milanese*, “Efficient twin aperture magnets for the future circular e+/e- collider,” Phys. Rev. Accel. Beams, vol. 19, 2016, Art. no. 112401.
3. *A. Milanese and M. Bohdanowicz*, “Twin aperture bending magnets and quadrupoles for FCC-ee,” IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018, Art. no. 4000904.
4. *A. Milanese, C. Petrone, J. Bauche*, “Magnetic Measurements of the First Short Models of Twin Aperture Magnets for FCC-ee,” IEEE Trans. Appl. Supercond., vol. 30, 2020, Art. no. 4003905.
5. *M. Pont, E. Boter, M. Lopes*, “Magnets for the Storage ring ALBA”, Proceedings of EPAC 2006, Edinburgh, Scotland.
6. *A. Milanese*, “Design Report of the SESAME Storage Ring Sextupole and Corrector Magnets”, 2013, CERN EDMS 1257260.

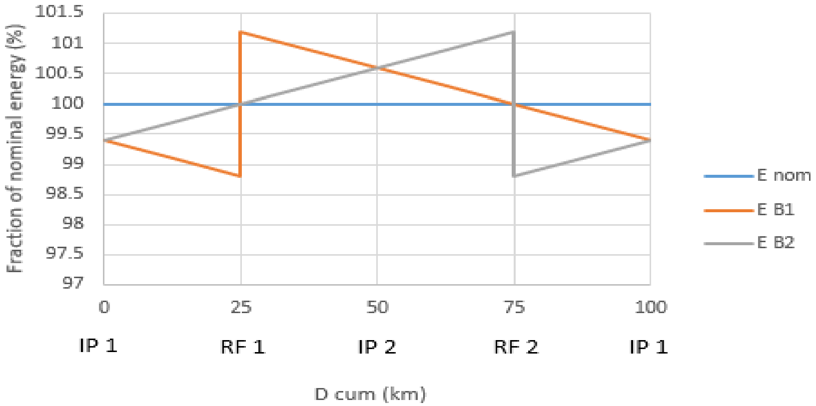
Thank you for your attention!

Questions?

Spare slides

Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

Options:

Adjusted parameter	System	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

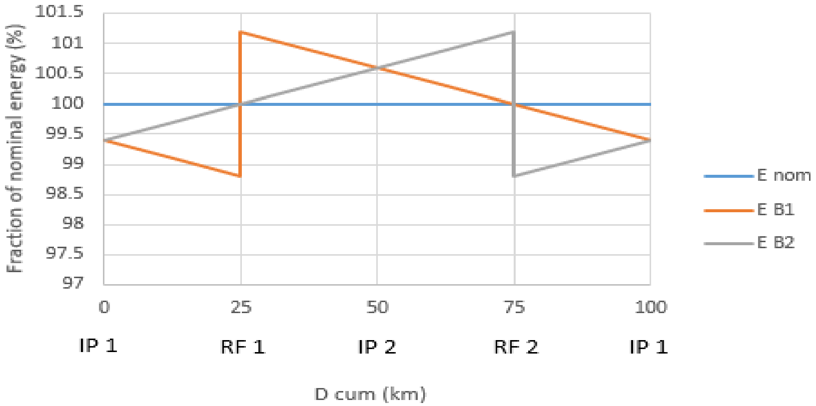
- Needs to be modified at each energy phase
- Needs calibration for each phase with magnetic measurements at production and strong QA system over machine lifetime
- 360 length variants for 4 FODO grouping

- For dipoles, lengths range of ~ 30 cm for 24 m

- For quads, lengths range of ~ 37 mm for 3.1 m

Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

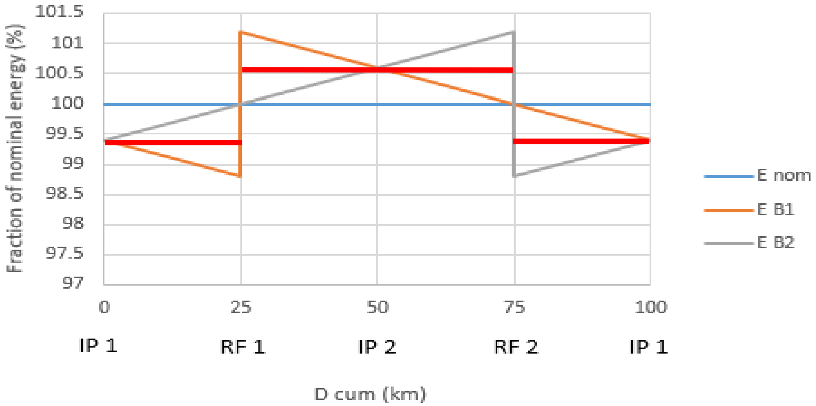
Options:

Adjusted parameter	**System**	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

- Tunability can be used for other corrections, e.g. horizontal orbit correction for dipoles on main bendings (limitations for feedback system)
- Impact on quadrupole axis shift and b3 (see next slides)
- Trim windings can be made simple and cheap to produce

Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

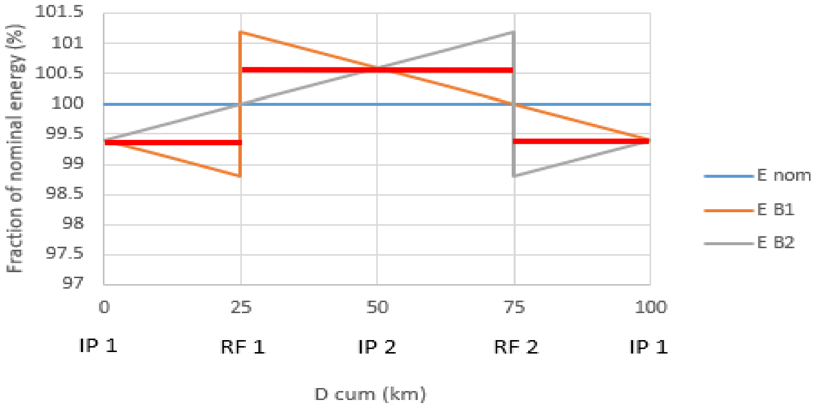
Options:

Adjusted parameter	System	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

- Mostly for dipole as access to conductors of each aperture is needed
- Can be made efficiently with symmetry thanks to powering by sectors

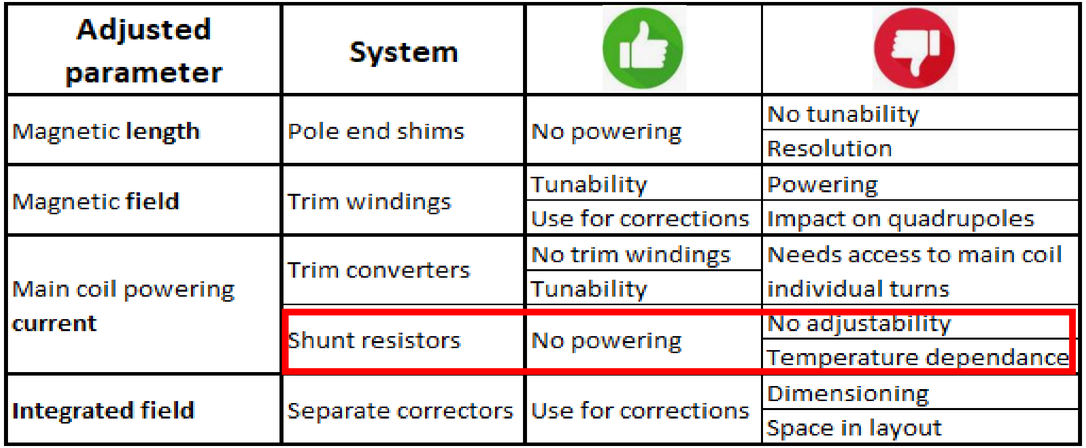
Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

Options:

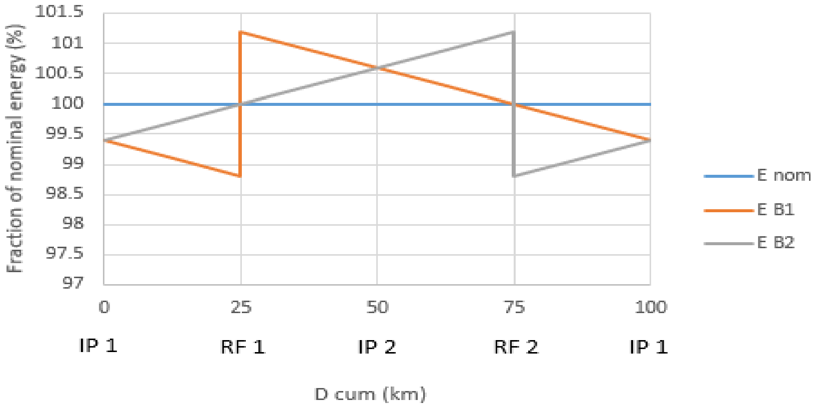


Adjusted parameter	**System**	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

- The cheapest! (for dipoles only)
- Precision and stability to be assessed
- Needs powering by sectors for symmetric correction

Field tapering

- Energy saw-tooth effect needs to be mitigated to limit losses
- Field tunability variable with energy, up to ±1.2% at 182.5 GeV [1]
- Grouped every 4 FODO in present layout



Beam energy along ring at 182.5 GeV

Options:

Adjusted parameter	System	👍	👎
Magnetic **length**	Pole end shims	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Impact on quadrupoles
Main coil powering **current**	Trim converters	No trim windings Tunability	Needs access to main coil individual turns
	Shunt resistors	No powering	No adjustability Temperature dependance
Integrated field	Separate correctors	Use for corrections	Dimensioning Space in layout

- For dipoles, probably ~10x higher strength needed than classical H orbit correctors