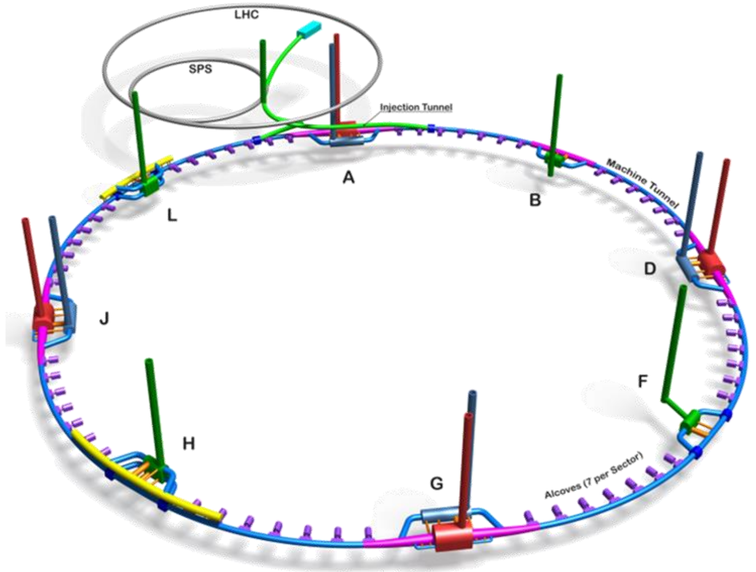
Collider Magnets for FCC-ee

TE-FCC meeting



Daniel Schoerling

J. Bauche, H. Deveci, C. Eriksson, L. von Freeden, A. Milanese

16 May 2024

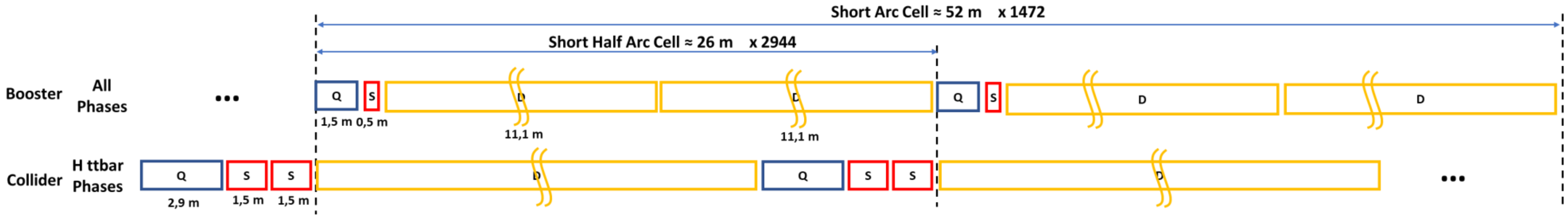
Magnet numbers

- **Robust design** to ensure machine **availability** (minimized maintenance)
- **CAPEX - Production** costs (**design simplicity and compactness**, automated manufacturing and installation)
- **OPEX - Operational** costs (**low energy consumption**, minimized maintenance)

Not included here:

- Wigglers
- Interaction regions
- Transfer Lines

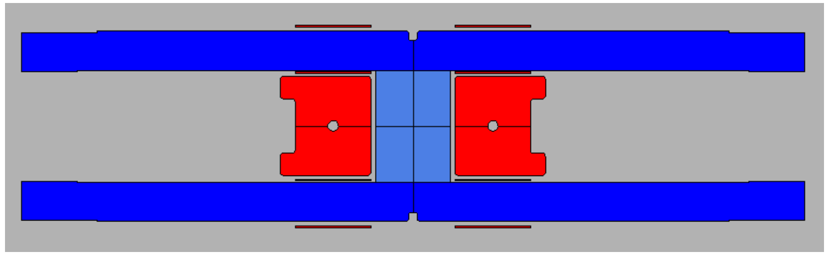
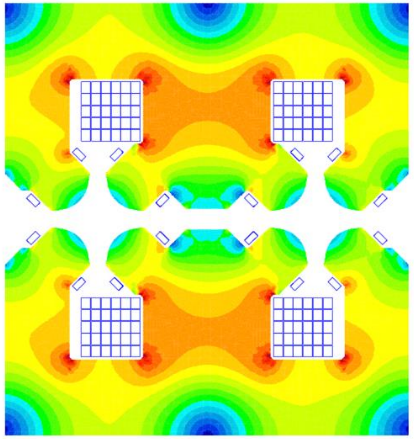
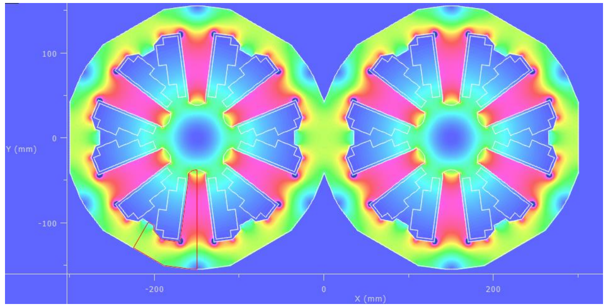
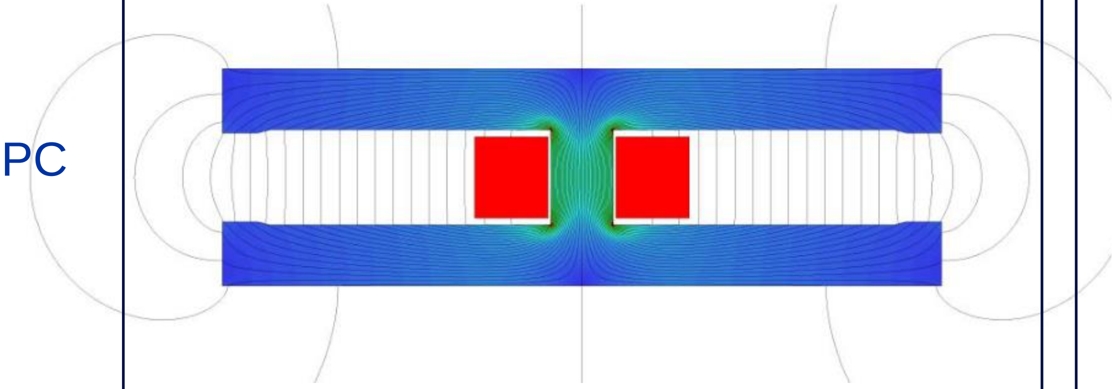
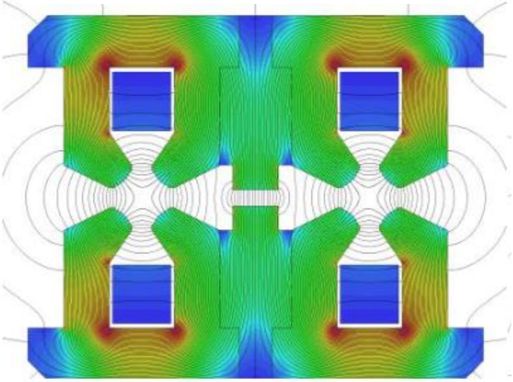
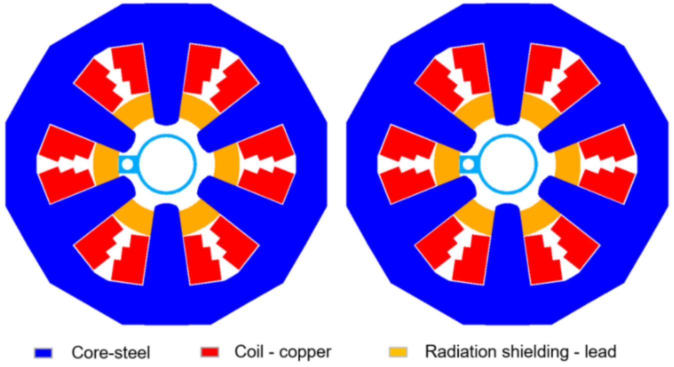
Main magnets (arcs)	Quantity	Length [m]	Total length [m]
Collider dipole	5’680	10.6	60’208
Collider quadrupole	2’840	2.9	8’236
Collider sextupole	4’672	1.5	7’008
Total collider	**13’192**		**75’452**
Booster dipole	5’888	11.1	65’357
Booster quadrupole	2’944	1.5	4’416
Booster sextupole	1’120	0.5	560
Total booster	**9’952**		**70’333**



Timeline – What was done?

Event/Milestone	Date	Title	Link
Initial Design Paper	November 2016	Efficient twin aperture magnets for the future circular e+/e- collider	Link
FCC week 2021	June 2021	Design of the FCC-ee collider magnets	Link
FCC week 2022	June 2022	Status of Collider and Booster Magnets for FCC-ee	Link
2nd FCC polarization workshop	September 2022	FCCee polarization wigglers	Link
CEPC workshop 2022	October 2022	Status of Collider and Booster Magnets for FCC-ee	Link
FCC week 2023	June 2023	Status of the FCC-ee booster and collider magnet developments & Magnet design for beamstrahlung photons extraction line	Link Link
Optics Tuning and Correction for Future Colliders workshop	June 2023	Field corrections for FCC-ee magnets	Link
TE-TM #205	July 2023	FCC-ee study magnet development	Link
FCCIS WP2 workshop 2023	November 2023	Magnet Trim Coils for Correction Circuits	Link
TE-MSC seminar	November 2023	Magnets for FCC-ee	Link
FCC Week 2024	June 2024		
Final deadline for Feasibility Report	December 2024		
Documentation to CERN Council of Feasibility Report	March 2024		

FCC-ee vs CEPC magnets

	Dipole	Quadrupole	Sextupole
FCC-ee			
CEPC			

Inter-beam distance 350 mm

CEPC: https://arxiv.org/pdf/2312.14363; FCC-ee: https://fcc-cdr.web.cern.ch/

FCC-ee vs CEPC magnets

	Dipole		Quadrupole		Sextupole#	
	FCC-ee	CEPC	FCC-ee	CEPC	FCC-ee×	CEPC
Number of units	5680	1024/1920	2840	3008	4672	3072
Magnet length, m	10.6	19.7/23.1	2.9	3	1.5	1.4
Total length, m	60.2	64.5	8.2	9.0	7.0	4.3
Total length, % of machine	66.1	64.5	9.0	9.0	7.7	4.3
Field, 45.6 GeV-182.5 GeV	14.1-56.6 mT	15-59.7 mT	3.6*-14.6 T/m	1.9-10.6 T/m	200-807 T/m^2	210-850 T/m^2
Bore aperture, mm	74	66	74	72	66	76

CEPC: 100 km

FCC-ee: 91 km

*to be defined with BE-ABP

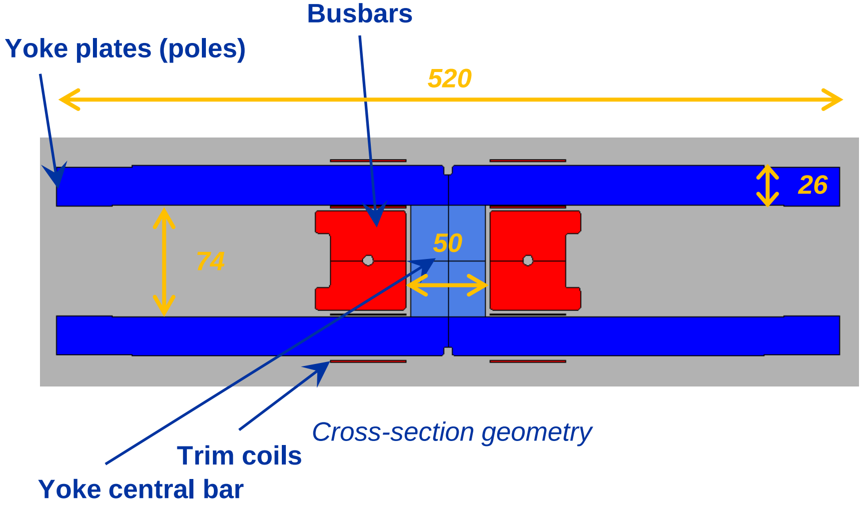
#FCC-ee has the correctors integrated in the sextupoles (HV, normal and skew quad), whereas CEPC has separate corrector HV corrector magnets (not reported here); vacuum aperture in FCC-ee remains the same with reduced magnet aperture; difference in filling factor compared to CEPC to be understood.

Field quality under discussion with BE-ABP

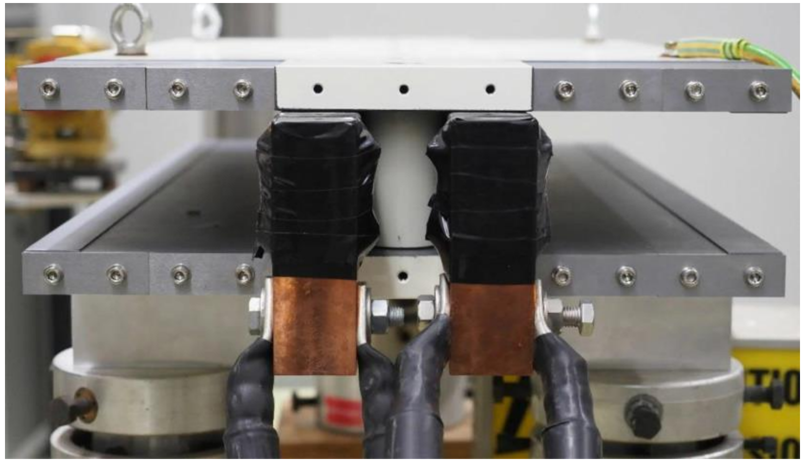
Collider Dipole (2D)

- Two vacuum chambers (separate for e- and e+)
- Tapering either with coils or by de- and increasing the current in the busbars -> cost optimal solution to be found
- Access needed for vacuum chamber -> C-shaped dipole
- 'Naked' conductor w/o insulation (radiation hard and cost efficient)
- Shielding (for other equipment in the tunnel only)
- Al/Cu resistivity ratio 1.55 -> For the same cross section the losses are 1.55 larger, or the beam distance has to be increased

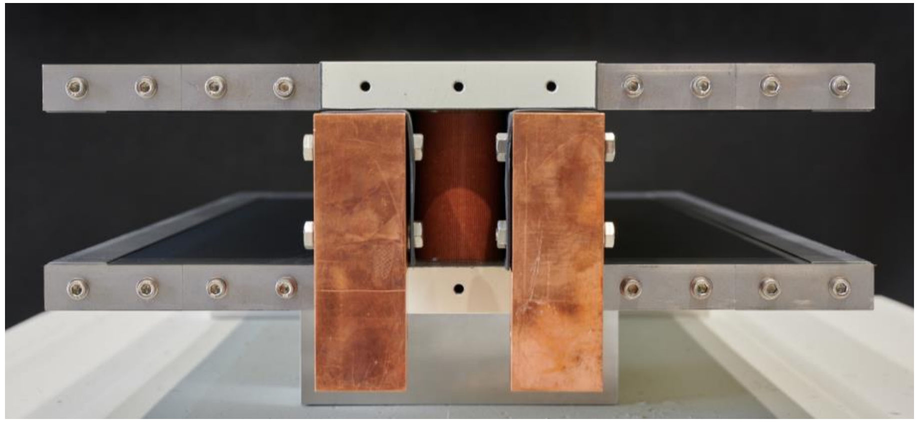
https://indico.cern.ch/event/763185/contributions/3415515/

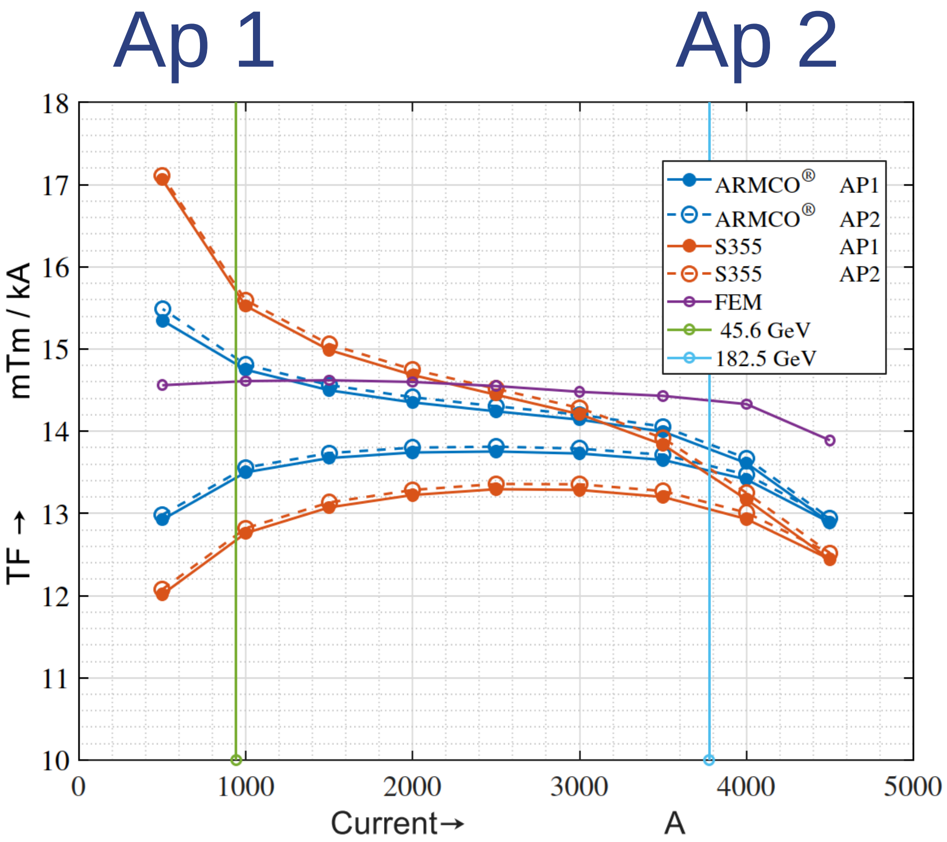


Cross-section geometry



Dipole, results of prototype





- The design of the twin-aperture dipole using only one coil (busbars) is validated
- The cost-effective design of the dipoles using construction steel for the yoke is possible
- For both materials, pre-cycling may be required and compatible with the machine operation

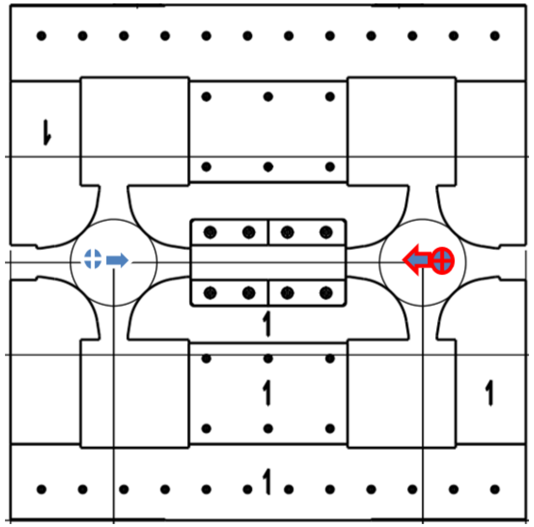
A. Milanese et al., IEEE Transactions on Applied Superconductivity PP(99):1-1, DOI:10.1109/TASC.2020.2976949

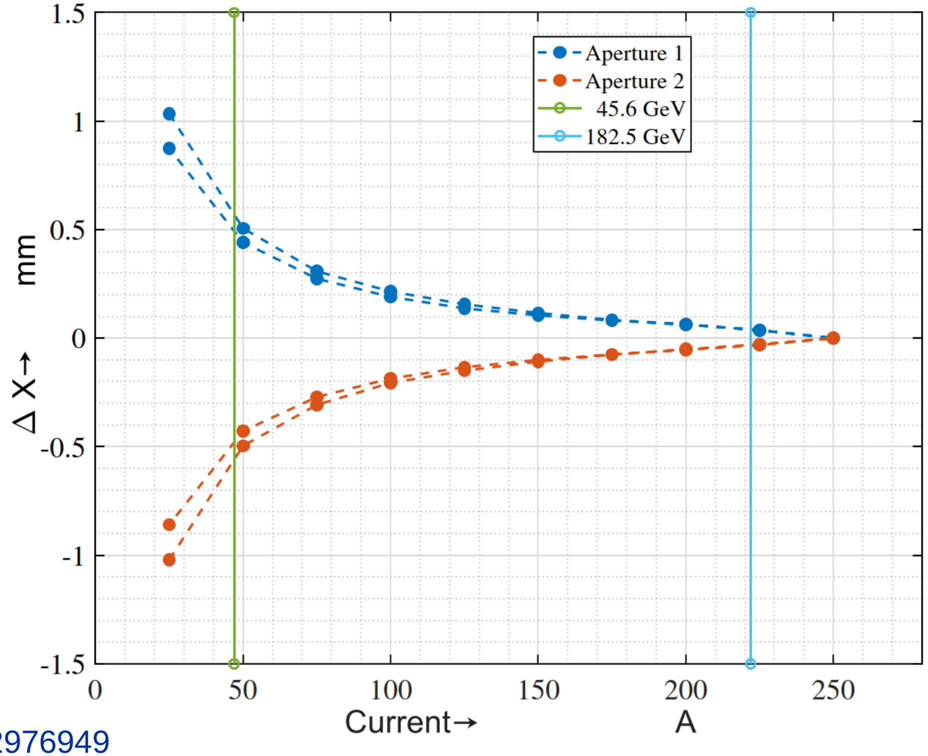
Quadrupole

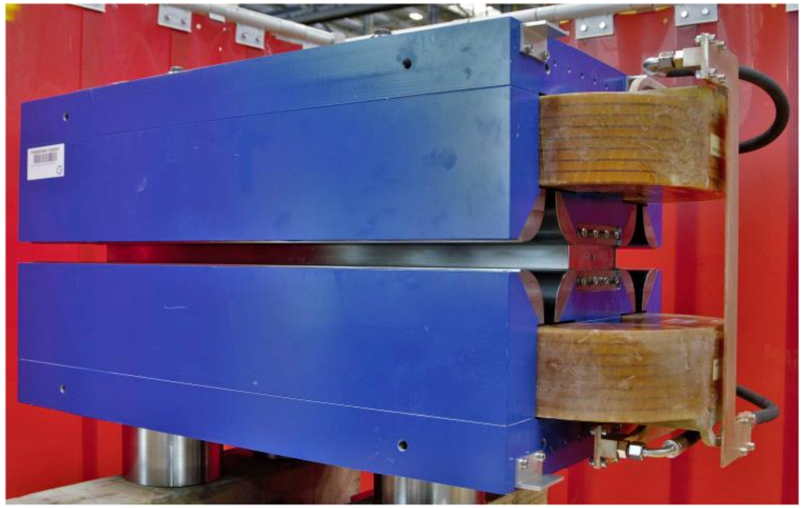
Efficient quadrupole design, simple to manufacture

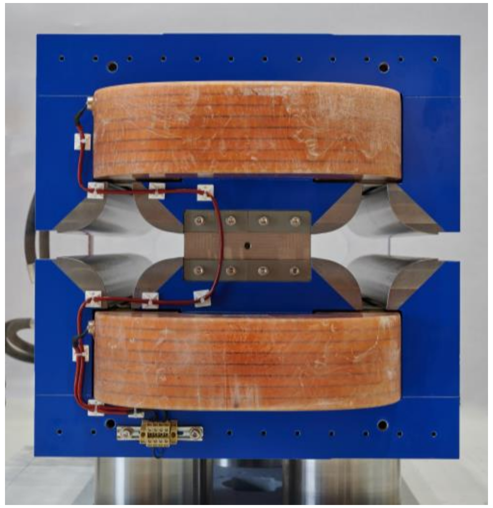
Currently, two optics are under study in FCC-ee:

- **Global Hybrid Correction GHC (aka Oide-san's optics)**
- **Local chromaticity correction LCC (aka Pantaleo's optics)**
- **LCC does not seem compatible with the current quadrupole magnets**
- **More optics are studied, for example with combined function magnets [1]**





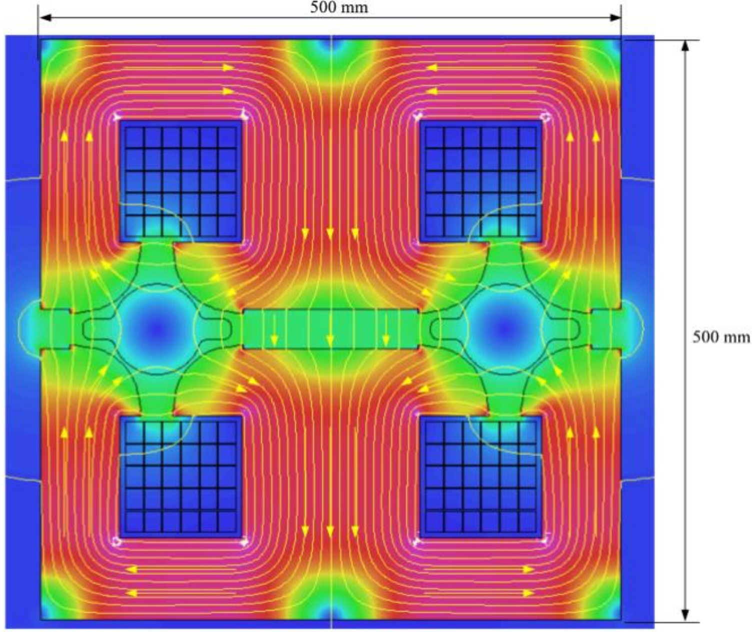




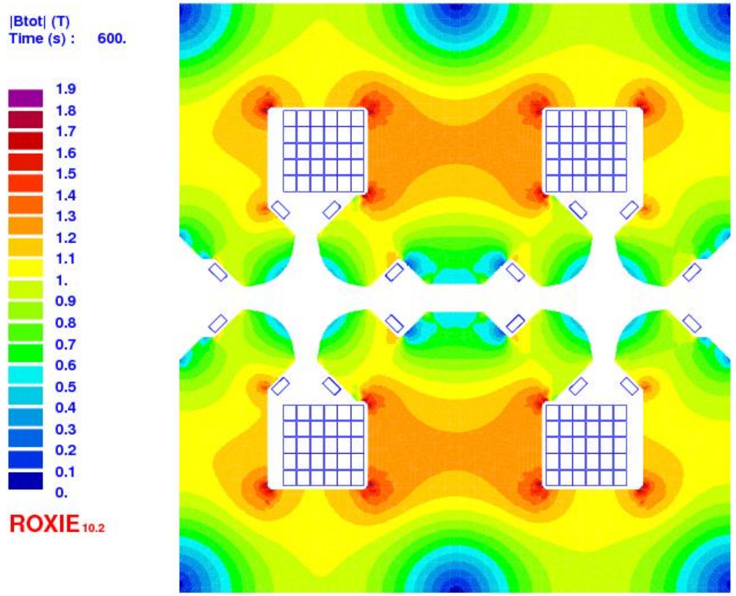
A. Milanese et al., IEEE Transactions on Applied Superconductivity PP(99):1-1, DOI:10.1109/TASC.2020.2976949

Updated quadrupole design

- **Pole shape modifed to streamline flux through the poles**
- **Trim coils for field tapering placed at pole level**
  - **→ Opens possibility to host orbit correction circuits**



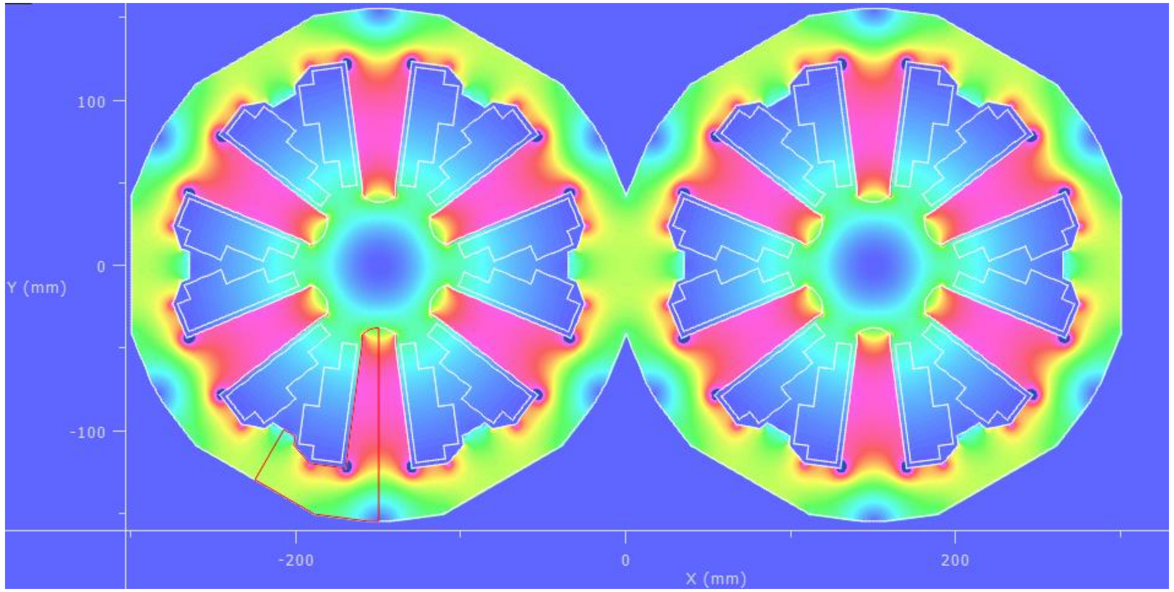
- **Coupling significantly mitigated (2D simulations):**
  - **→ b_1 reduced to ~10 units**
  - **→ Magnetic axis shift reduced to ~0.01 mm**

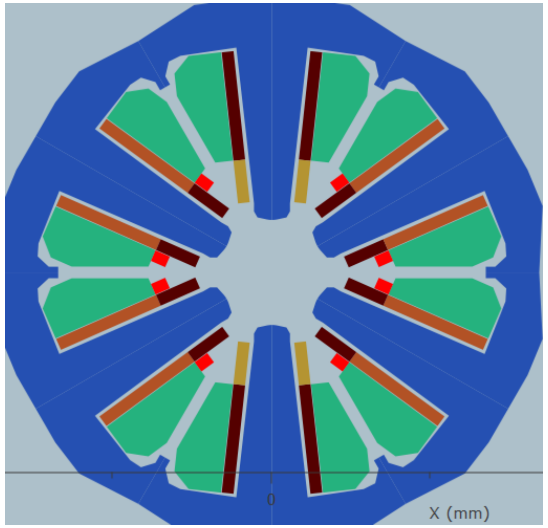


J. Bauche and C. Eriksson

Sextupole

- **Single aperture magnet, powered in small series (4 FODO)**
- **300 mm inter-beam distance, was at the limit of compatibility for individual magnets on each beam**
- **Corrector circuits are integrated**





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

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

Collider magnets (3D) and integrated luminosity

- **Integrated Luminosity shall be maximized**
- **Energy consumption in FCC-ee is mainly driven by RF to compensate for the ‘parasitic’ synchrotron radiation**
- **In light particle machines a high filling factor is important to reduce the ‘parasitic’ synchrotron radiation (*P* ∝ *B*)**
- **Integrating quadrupoles and sextupoles into the dipole, allows to increase the filling factor - at the cost of flexibility**

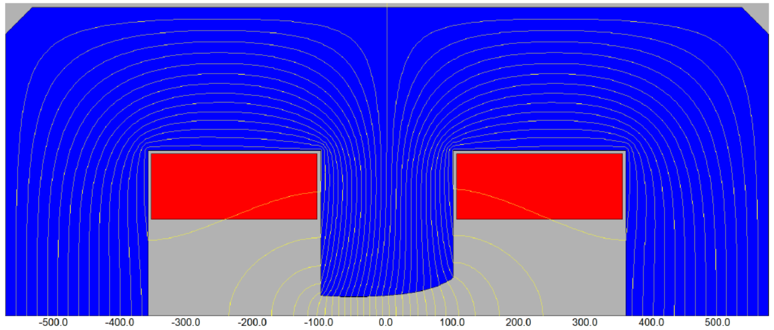
Energy consumers in beam operation		Z	W	H	tt
Beam energy [GeV]		45.6	80	120	182.5
Magnet current ratio (OP/peak)		**25%**	**44%**	**66%**	**100%**
Magnet power ratio (OP/peak)		**6%**	**19%**	**43%**	**100%**
Magnets [MW]	**Collider**	**6**	**17**	**39**	**89**
	Booster	**1**	**3**	**5**	**11**
RF [MW]	Collider	146	146	146	146
	Booster	2	2	2	2
Cryo [MW]	Collider	1.2	11.5	11.5	27.6
	Booster	0.35	0.80	1.50	7.40
C&V [MW]		25	26	28	33
Experiments [MW]		10	10	10	10
Data centers [MW]		4	4	4	4
General services [MW]		26	26	26	26
Total power [MW]		**222**	**247**	**273**	**357**

"I believe CERN should become a role model for an environmentally aware scientific laboratory.“

Fabiola Gianotti, CERN, https://home.web.cern.ch/about/what-we-do/environmentally-responsible-research

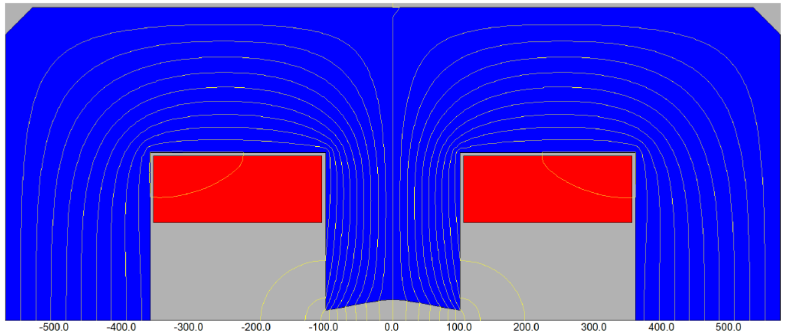
Combined function magnets

- **Normal-conducting dipole magnets can be designed with a certain % of fixed quadrupolar and sextupolar components**
- **Overall alignment strategy might need to be adapted**
- **Quadrupolar and sextupolar components are increasing linearly with dipolar field**
- **Advantages:**
  - Up to 20% more longitudinal space for dipoles
  - Less circuits
  - Lower fields in remaining quadrupole and sextupole 'correctors'



	B_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}
	[T]	$[1\cdot10^{-4}]$ at R_{ref} = 20 mm									
ideal	1	-500	-100	0	0	0	0	0	0	0	0
simulation	0.99998	-499.8	-100.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 3.6. Comparison with a FEM simulation, for a dipole with gradient and sextupole terms.



	B_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}
	[T]	$[1\cdot10^{-4}]$ at R_{ref} = 20 mm									
ideal	1	0	400	0	0	0	0	0	0	0	0
simulation	1.00002	0.0	399.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 3.7. Comparison with a FEM simulation, for a dipole with a positive sextupole.

[1] A. Milanese: Combined dipole + quadrupole + sextupole, Internal Note, April 2024, not yet published
[2] GE. Fischer, SLAC arc magnet transport system, https://accelconf.web.cern.ch/p85/PDF/PAC1985_3657.DF

Participation to working groups & interfaces

Working group	Indico category	Regularity	Comment
FCC-ee Accelerator Design Meeting	https://indico.cern.ch/category/6528/	Every 2 weeks	Formerly named FCC-ee Optics meeting
FCC-ee Accelerator Technical Design Coordination meeting	https://indico.cern.ch/category/18049/	Every 2 weeks	Since 28-03-2024
FCC integration meeting	https://indico.cern.ch/category/8260/	Every 2 weeks	
FCC-ee Radiation and Shielding meeting	https://indico.cern.ch/category/17958/	Every 2-3 weeks	Since 14-02-2024
FCC-ee Arc Half-cell Mock-up meeting	https://indico.cern.ch/category/16838/	On demand	
FCC-ee booster meetings	https://indico.cern.ch/category/17822/	Every 2-4 weeks	Since 18-01-2024

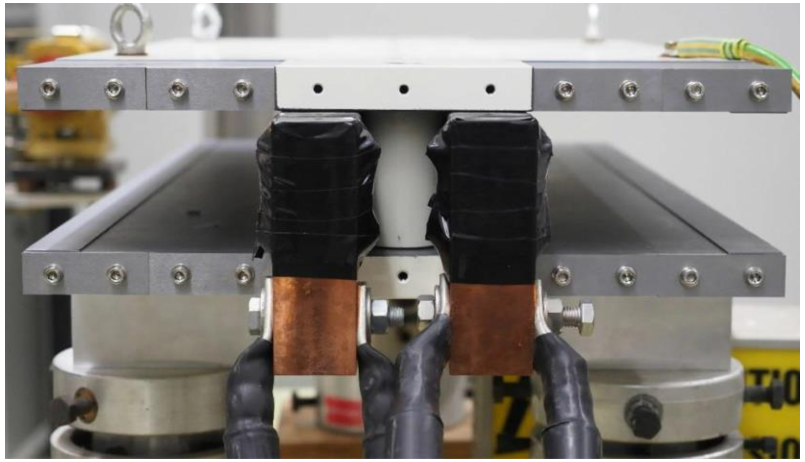
CERN Group with Interfaces to NCM	Impact on Design	Criticality	Comment
BE-ABP	All magnet parameters and machine parameters	Extremely high	Currently baseline optics studied: worth studying other optics with the potential to save on energy, circuits, magnets, etc
SY-EPC	Electrical parameters (current, voltage, powering scheme)	High	Work on-going with modelling in both groups
TE-VSC	Magnet design (access to vacuum chambers), final aperture depending on space requirements, shielding (with input from SY-STI)	High	
SY-STI	Simulations of radiation load (including activation)	High	Disposal strategy
EN-CV	Cooling	High	
BE-GM	Alignment	High	
EN-MME	Girder, 3D design, Integration model	High	

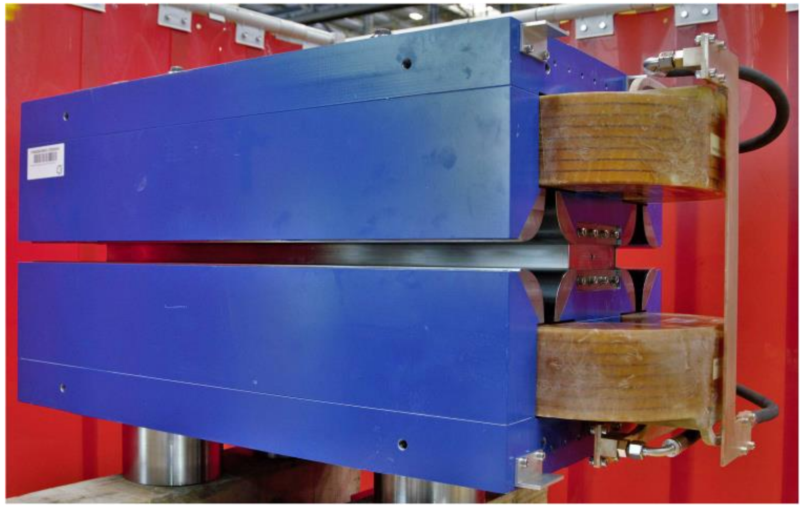
Feasibility Study

An investigation to establish whether a project will work and achieve the desired results.

A study to evaluate alternative remedial actions from a technical, environmental, and cost perspective, which *normally* recommends selection of a cost-effective alternative.

Oxford Reference





What is NCM proposing to do for the feasibility study?

Considering the timeline for the feasibility report, we focus on:

- ***A dipole prototype for the booster with the aim to understand the possible minimum injection field***
- **Circuit optimization for GHC optics: Optimize and select a conductor material: Al vs Cu**
- **Provide support for integration of shielding to TE-VSC and SY-STI, understand the limitations for quadrupoles and sextupoles (if any) in the framework of a working group (with MSC, VSC, STI and MME representatives)**
- **The cost estimate for this option has been performed and will be refined based on the optimized circuit model and the implications of the shielding on the magnet design**

What is NCM proposing to do for after the feasibility study?

Next years:

- ➢ **Beam optics: Continue and intensify discussion with beam optics for 3 optics: GHC, LCC, combined function magnet optics.**

Once a down-selection of a collider layout is confirmed:

- **Finalize an integration model for a half-cell and build short prototype magnets (confirming the choice of material, design, and pre-select a cost-efficient construction method)**
- **Define a strategy for the production, in particular with respect to the steel quality (reproducibility between magnets)**

Afterwards:

- ➢ **Build a half-cell functional mock-up (with a focus on functionality and integration)**

Conclusion

- **FCC-ee magnets are feasible, we are confident that the magnets will work and achieve the desired results**
- **We will participate actively to the integration and optimization of the circuits for finalizing the feasibility report**
- **A proposal for the work for the next few years has been presented (time span depends on available resources inside NCM and CERN wide (for example BE-ABP)**
- **We are ready to give input to further optics studies, to find an energy and cost-efficient collider design**
- **Other magnets (transfer lines, interaction regions, etc.) may be studied alongside**