Collider Magnet Design Status for FCC-ee

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CERN

FCC Week 2024, 12th June 2024.

Special thanks to the colleagues of the CERN power converter group (B. Wicki, D. Aguglia, et al.)

Many thanks to all the members of the FCC collaboration.

Outline

Specifications from beam optics

Collider arc magnets

- **Dipole**
- **Quadrupole**
- **Sextupole**

Global magnet circuit optimization

- **Methodology**
- **Magnet power consumption**

Next steps for magnet development

Conclusions

Magnet specifications from beam optics

Magnet specifications – strength and length

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

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

→ More than **13000 magnets**

	Mag. Length [m]	Pole tip field (max, tt_{bar}) [T]	Number of units (arcs)	Total magnetic length [km]	Ring filling factor (91 km) [%]
Dipole (S)	19.30	**0.061**	1128	21.77	
Dipole (M)	20.95		284	5.95	
Dipole (L)	22.65		1428	32.35	
Dipole total *(2 units per arc half-cell)*			**5680 ***	**60.1**	**66.3**
Quadrupole	**2.9**	**0.438**	**2836**	**8.2**	**9.1**
Sextupole	**1.5**	**0.442**	**4672 ****	**7.0**	**7.7**
		Gran total	**13188**		

* 2 dipole units per arc half-cell

** Maximum quantity (varies between Z/W and H/tt phases)

Arc magnet specifications for GHC optics – 2023 (K. Oide)

Alternative specifications

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

→ *Under study with beam dynamics*

[1] *see presentation K. Oide on Tuesday 08:30*

[2] *see presentation P. Raimondi on Tuesday 10:30*

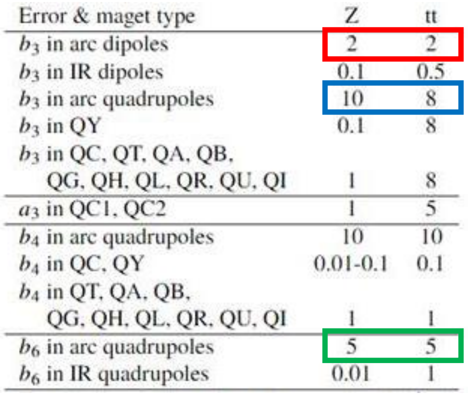
Magnet specifications – field quality (preliminary)

- FQ tolerances are **1 order of magnitude more stringent** from 2024 optics studies w.r.t. last year
  → *“ça va être **sport** !”*
- FQ below 1 unit of 10^{-4} is **hardly achievable** and **costly**, in particular for such large numbers of magnets

→ *Beam dynamics team are presently looking at options to relax the tolerances in the arcs*

2023

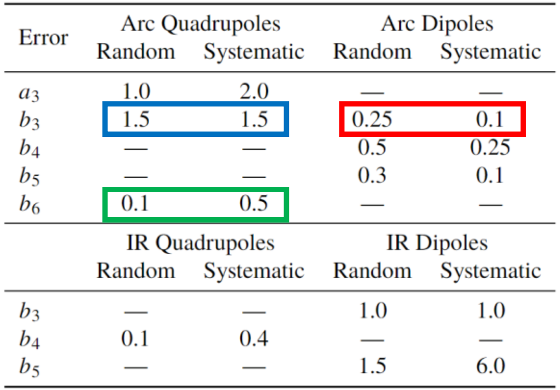
(@Z and tt, V22 optics)



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

2024*

(@Z, GHC optics)



Error	Arc Quadrupoles Random	Arc Quadrupoles Systematic	Arc Dipoles Random	Arc Dipoles Systematic
a_3	1.0	2.0	—	—
b_3	1.5	1.5	0.25	0.1
b_4	—	—	0.5	0.25
b_5	—	—	0.3	0.1
b_6	0.1	0.5	—	—
	IR Quadrupoles Random	**IR Quadrupoles Systematic**	**IR Dipoles Random**	**IR Dipoles Systematic**
b_3	—	—	1.0	1.0
b_4	0.1	0.4	—	—
b_5	—	—	1.5	6.0

Relative field quality tolerances in $[10^{-4}]$ units at 10 mm radius, R. Thomas et al.

***Left**: from on-momentum DA calculations, without radiation*
***Right**: without correction, from 6D tracking studies with radiation*

**see presentation R. Thomas on Wednesday 10:30*

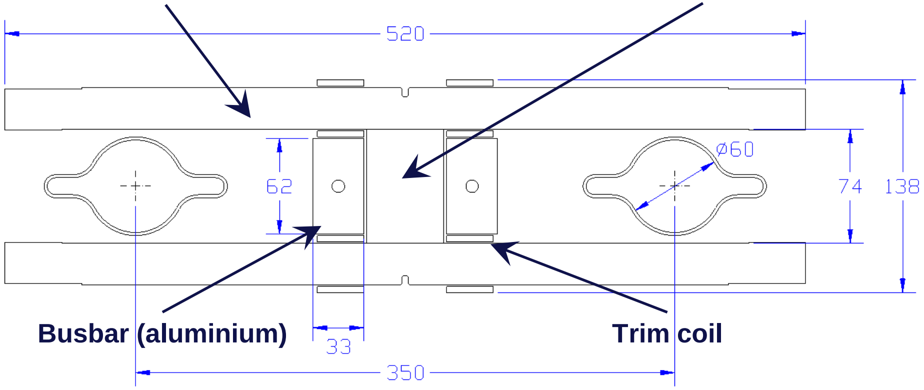
Collider dipole

Dipole mechanical design

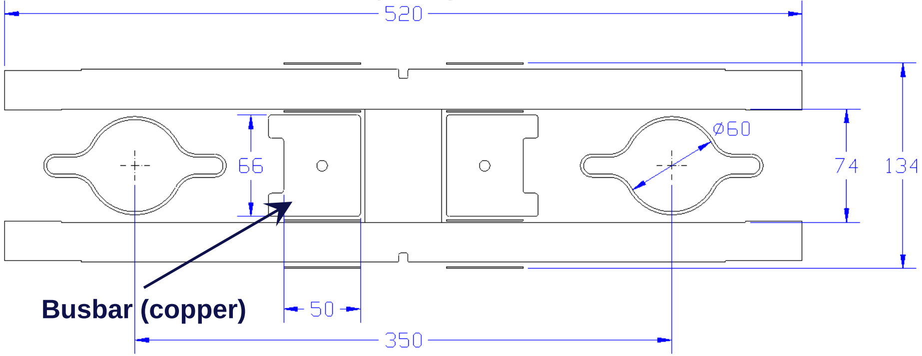
- **Twin aperture** magnet
- Yoke assembled from **solid iron** machined plates and central bar, bolted
- Water cooled **busbars**
  - **Material: lifetime cost optimization** shows better optimum for **aluminium**, now included in 2024 version
  - **Inorganic insulation** (e.g. air, inorganic coatings, ceramic spacers)
- **Trim coils** wound with solid copper conductor, current density and number of turns also optimized for lifetime cost

NB: trim converters on busbars or anodized aluminium stripes could be alternative options, to be studied

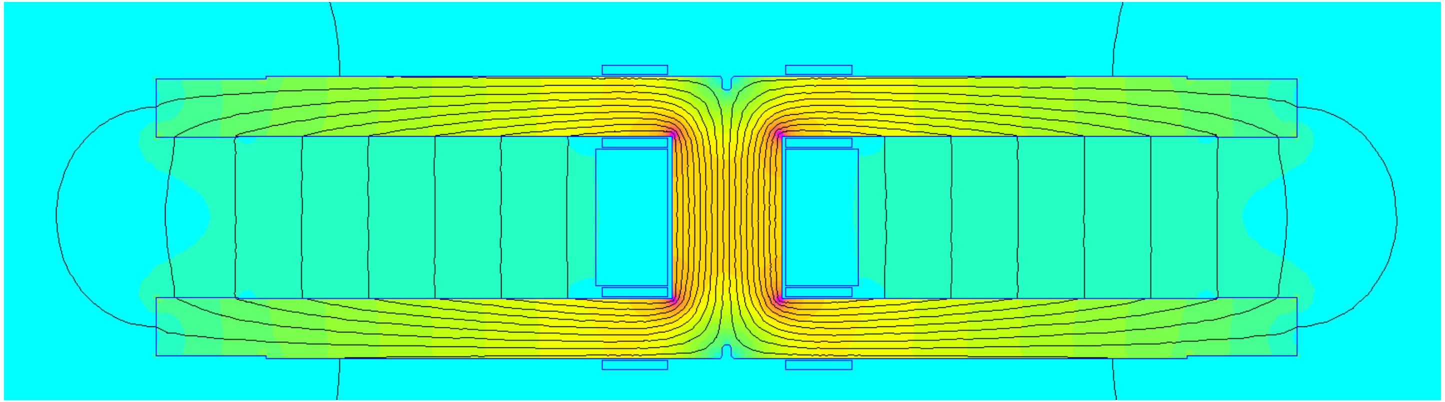
2024

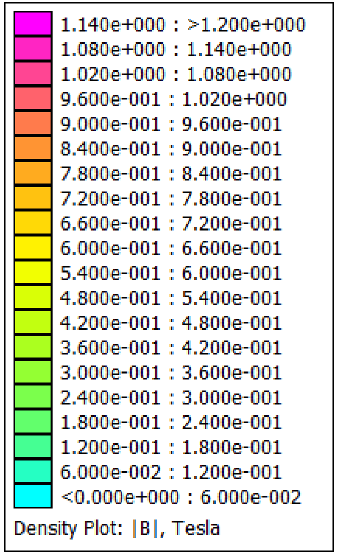

Yoke plates
Yoke central bar
Busbar (aluminium)
Trim coil

2023

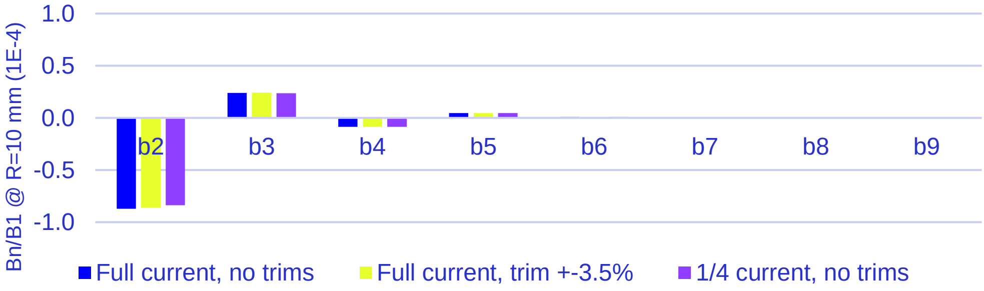

Busbar (copper)

Dipole magnetic design 2024





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



- **Trim coils** dimensioned for field tapering + tuning (J ≈ 1 A/mm^2)
- **Design field quality** (ideal, not incl. manufacturing tolerances) are within 2023 specifications (but not 2024 ones…)

Dipole parameters

- Main changes: **aluminium busbar** at **higher current density**
- Power dissipation is ~80% larger than 2023 Cu BB design, but the increased OPEX is far outweighted by the **reduced CAPEX,** with an **overall lower TOTEX*** over the lifetime!
- Busbar geometry adjusted to make more room for trim coils (adjusted current density) and match cooling requirements
- Total circuit voltage stays < 1kV

**see presentations B. Wicki on Tuesday 16:14 and Wednesday 14:06*

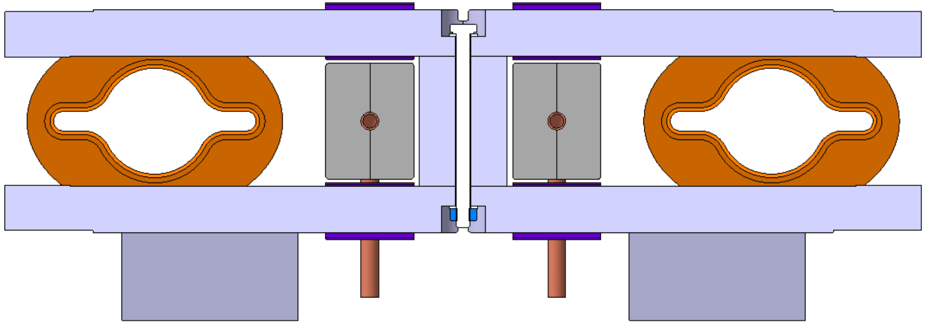
Parameter	Unit	Value 2023	Value 2024
Max strength	mT	61	61
Magnetic length (average)	m	21.15	21.15
Busbar material		Copper	**Aluminium**
Max current in busbars	A	3628	3665
Conductor dimensions	mm^2	66 x 55	**62 x 33**
Cooling diameter	mm	7	8.1
Current density	A/mm^2	1.01	**1.85**
Voltage drop per magnet	V	1.2	2.2
Resistance per magnet	mΩ	0.34	0.62
Power per magnet	kW	4,4	**8.2**
Number of water circuits	-	1	1
Water temperature rise	°C	11.2	14.2
Cooling water speed	m/s	2.4	2.7
Pressure drop	bar	5	5
Reynolds no.	-	23745	30380

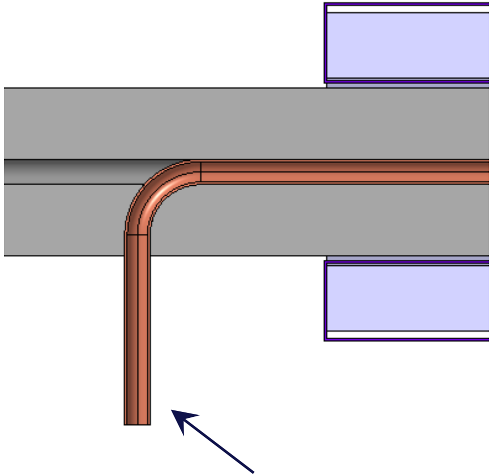
Busbar technology

- Impact of **aluminum** busbars:
  - Much cheaper bulk material
  - Lighter material (lower Z), so shields less the SR, but gets less activated
  - Surface can be anodized to get inorganic insulation layer (in addition to air/spacers)
  - Higher Joule losses than copper (at equivalent current density)
  - Not compatible with copper cooling circuit (galvanic corrosion), so requires:
    - Either a dedicated cooling circuit (expensive additional infrastructure)
    - Or a copper cooling tube embedded in the aluminum bulk (which also allows standard cooling fittings)

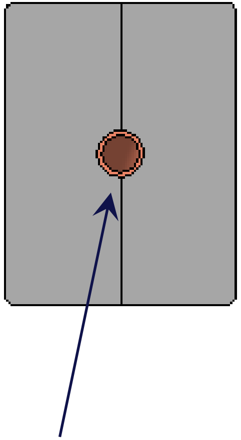
→ ***Both options to be evaluated***

(Copper tube option requires R&D)





Standard size tube allows standard fittings (brazed or crimped)



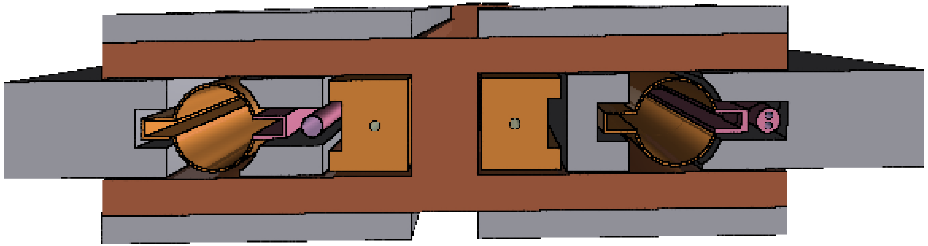
Aluminum busbar with embedded copper tube

SR absorbers and shielding

- Shielding design still preliminary, studies in progress*
- The **magnet yoke** should be designed to act as **supporting structure for all elements** (busbars, VC with SR absorbers, shielding)
- **Yoke deformations** induced by shielding weight can be addressed by:
  - **Reinforcing** the **yoke** (could also **improve shielding effect**)
  - **Adapt** the positioning scheme of the dipole **supports**

→ ***Mechanical design of assembly and supporting scheme under study***

Lead Shielding



+ 2300 kg / dipole

Courtesy: ***B. Humann***

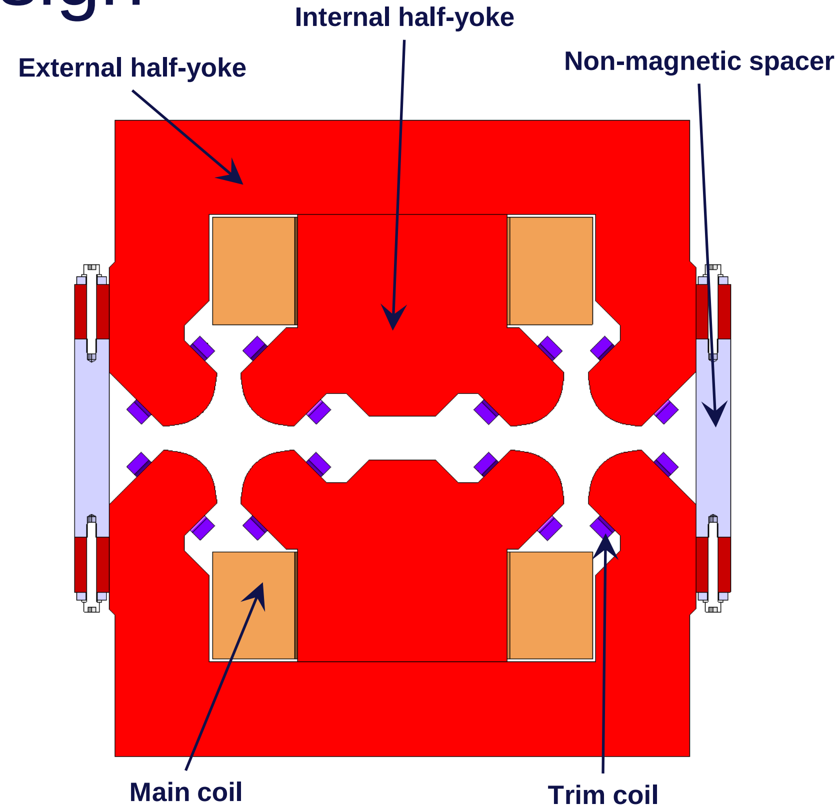
**see presentation B. Humann on Tuesday 16:36*

Collider quadrupole

Quadrupole mechanical design

- **Twin aperture** magnet
- **Laminated** yoke construction
- **Yoke lamination stacks** assembled with solid iron end plates and **welded** side plates
- Top and bottom **yokes** have to be **split in two halves** for coil integration
- **Assembly** of yoke parts with **bolts / pins / keys**
- Position of **non-magnetic spacers** for top-bottom assembly under study (mechanical tolerances, access to apertures from sides for measurements)
- **Hollow copper** conductor for **main** coils
- **Solid copper** conductor for **trim** coils

<u>NB</u>: similarly to the dipole, aluminium could be considered as conductor for main and trims

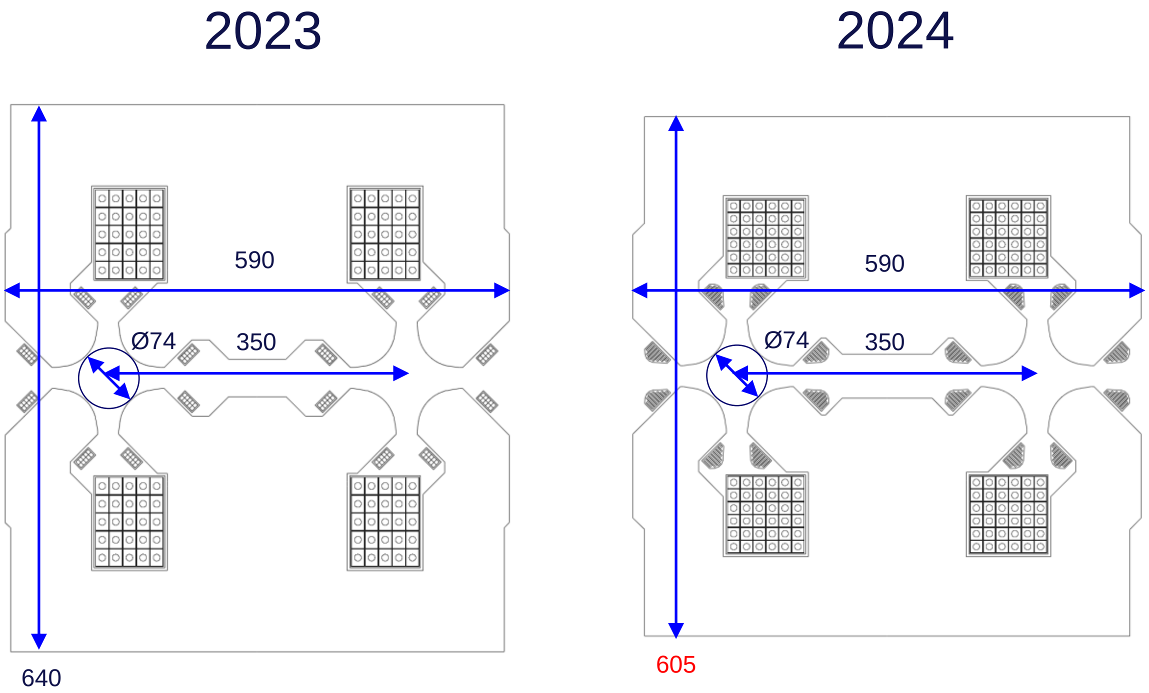


Courtesy: ***C. Tetrault***

Cross-section update

Compared to FCC week 2023:

- **Main coils:** current density and number of turns increased:
  - Current density: from 2.1 to 2.4 A/mm^2
  - Turns: from 25 to 36
- **Trim coils:** number of turns increased, from 10 to 43
- Slight reduction in iron cross-section size to accomodate new coil window



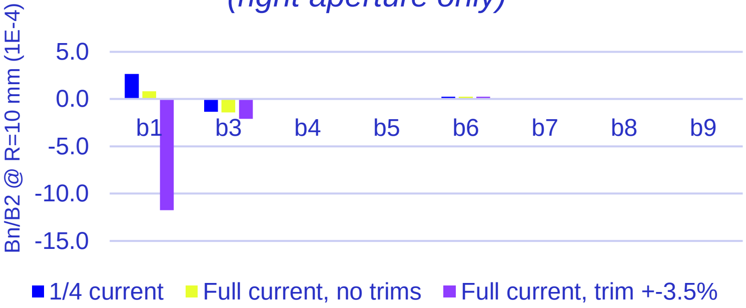
Quadrupole cross-sections (dimensions in [mm])

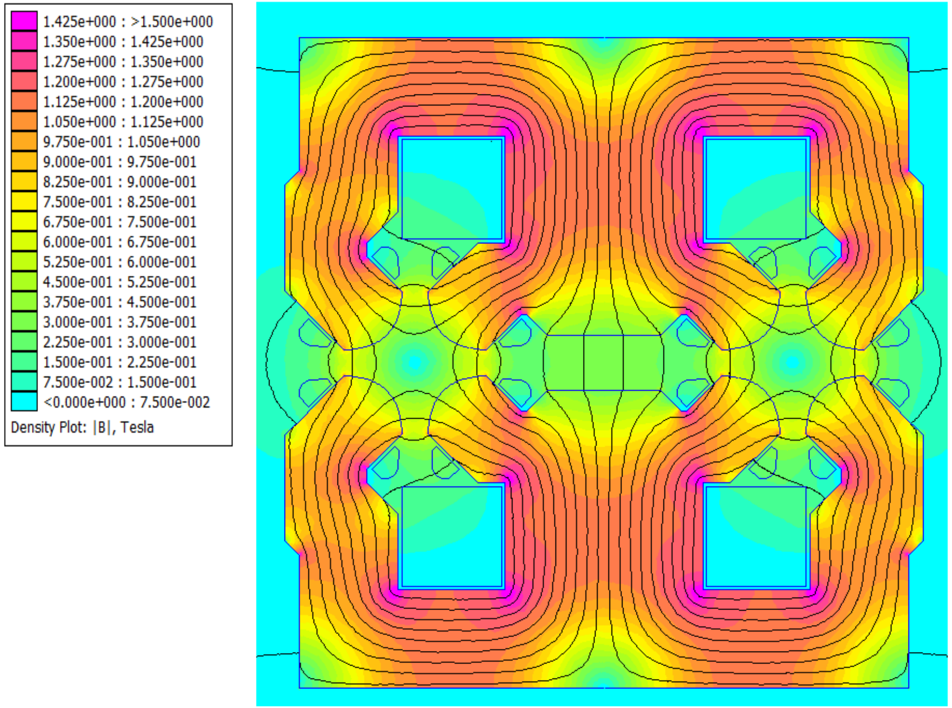
Quadrupole magnetic design 2024

- Trim coils for **field tapering** + **tuning** (J ≈ 1 A/mm^2)
- 10 units of b_1 ≈ 10 µm axis shift
- Integration of **V orbit correction in trims** previously studied

→ *not an option* as impacts on DA

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





Quadrupole parameters

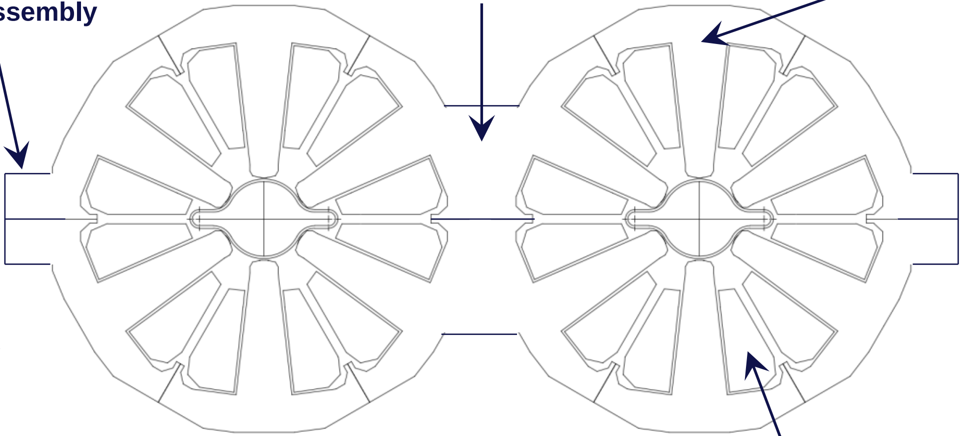
- **Number of turns** increased to reduce transport current (decrease of cabling cost) and match converters optimal parameters
- Slight increase in current density and **power dissipation** (17%), but again this allows to achieve a **lower overall TOTEX** over the machine lifetime

Parameter	Unit	Value 2023	Value 2024
Max gradient	T/m	12	12
Magnetic length	m	2.9	2.9
Conductor material		Copper	Copper
Number of turns per coil	-	25	**36**
Max current	A	528	**366**
Conductor dimensions	mm^2	20 × 15	**13.9 × 13.9**
Cooling diameter	mm	8	7.7
Current density	A/mm^2	2.1	**2.5**
Voltage drop per magnet	V	12.4	20.7
Resistance per magnet	mΩ	24.0	56.5
Power per magnet	kW	6.5	**7.6**
Number of water circuits	-	2	2
Water temperature rise	°C	12.9	19.7
Cooling water speed	m/s	1.2	1.0
Pressure drop	bar	5	5
Reynolds no.	-	13810	10630

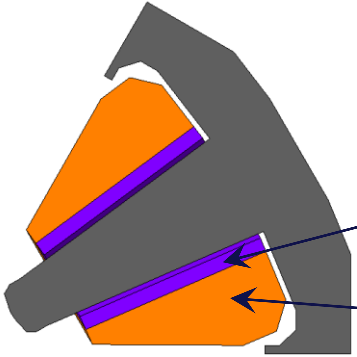
Collider sextupole

Sextupole design

- **Single aperture** magnet
- **Laminated** yoke construction
- Yoke sextants **lamination stacks** assembled with solid iron **end plates** and welded **side plates**
- Hollow copper conductor for **main coils**
- **Corrector coils** wound with solid copper conductor
- **Assembly of sextants** to be defined (bolts and pins to allow splitting at the mid-plane **may require twin configuration →** under study)



Sextupole cross-section

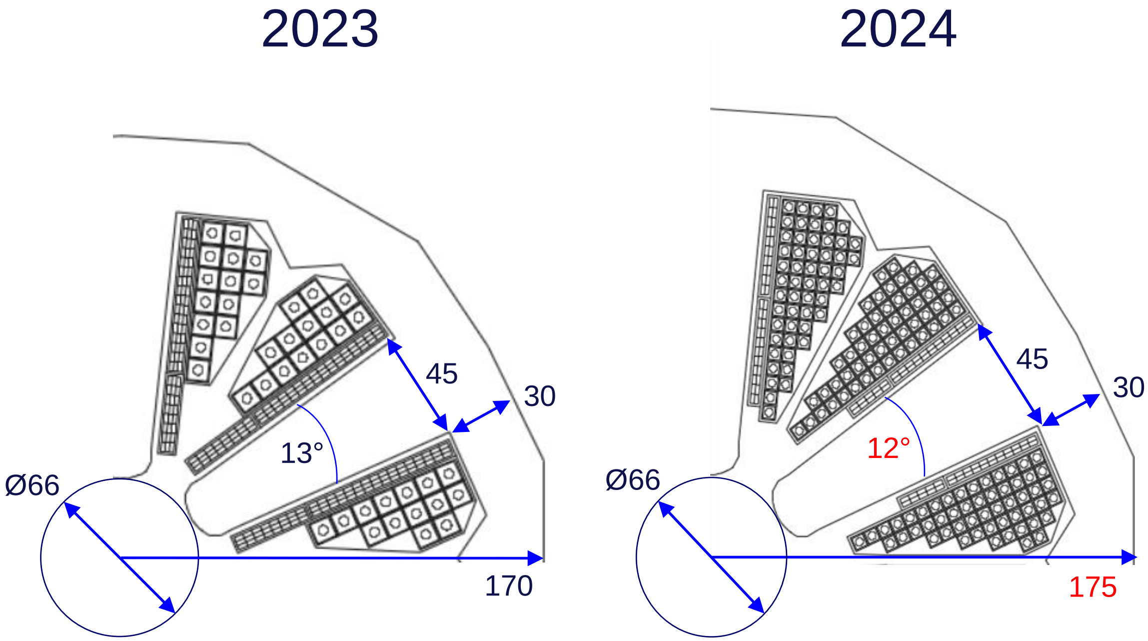


Sextant cross-section

Cross-section update

Compared to version 2023:

- **Main coils**: current density increased slightly, number of turns increased:
  - Current density: from 5.1 to 5.6 A/mm^2
  - Turns: from 14 to 53
- **Corrector coils**: number of turns roughly halved, current density roughly doubled for all correctors
- **Yoke** cross-section mostly unchanged



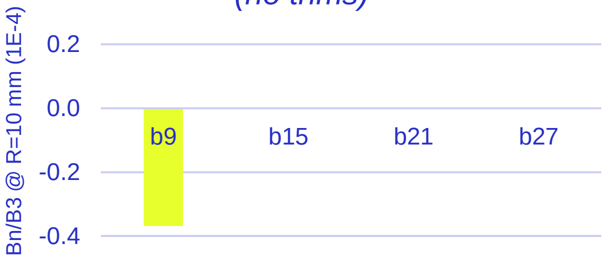
*Courtesy: **F. Saeidi***

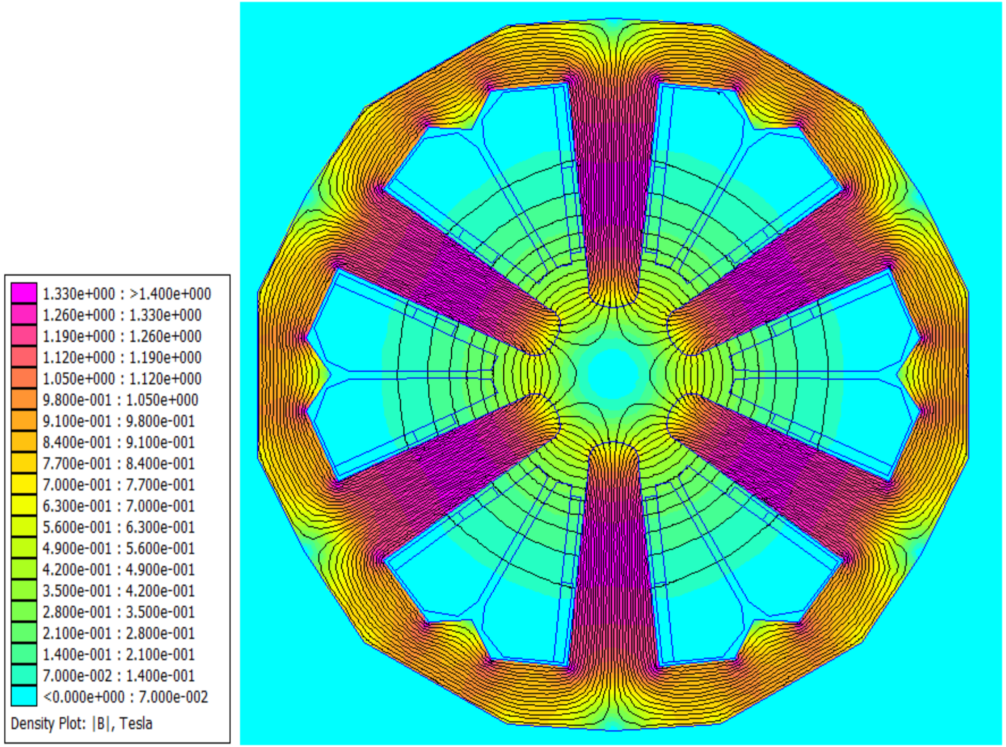
(Coil winding architecture not yet optimized!)

Quadrupole cross-sections (dimensions in [mm])

Sextupole magnetic design 2024

- Performance of the main circuit is unchanged with the updated design
- All allowed multipoles are less than 1 unit


Allowed relative harmonics – 2D (no trims)



Sextupole main circuit parameters

- **Number of turns** significantly **increased** to reduce current (decrease of cabling cost) and match converters optimal parameters
- Slight **increase in power dissipation** (11%), but again **outweighted on the lifetime TOTEX**
- Additional cost of two cooling circuits per coil not yet included in the optimization

→ *to be re-evaluated for global cost*

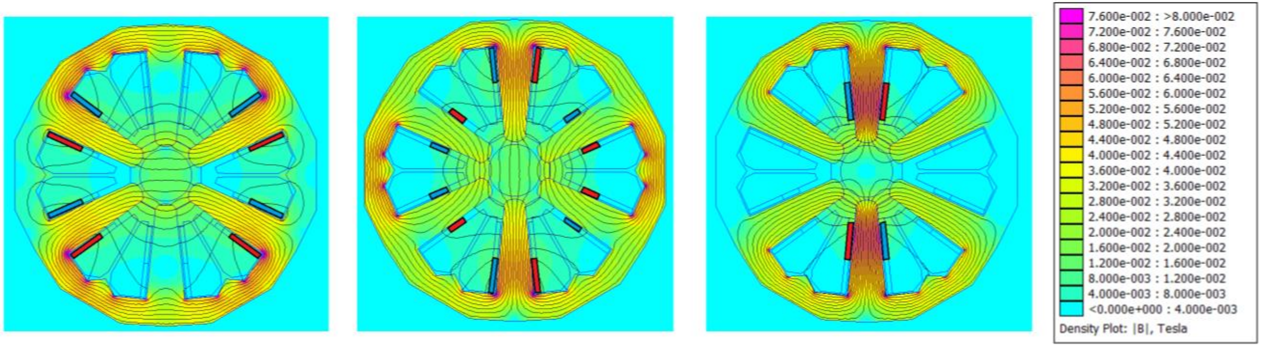
Parameter	Unit	Value 2023		Value 2024
Sextupole strength, B''	T/m^2	880		880
Conductor material		Copper		Copper
Max ampere-turns	A	4250		4280
Number of turns per coil	-	14		**53**
Max current	A	304		**81**
Conductor dimensions	mm^2	8.5 × 8.5		4.7 × 4.7
Cooling diameter	mm	4		3.1
Current density	A/mm^2	5.1		**5.6**
Voltage drop per magnet	V	23.4		99.3
Resistance per magnet	mΩ	78		1230
Power per magnet	kW	7.2		**8.0**
Number of water circuits	-	12	6	**12**
Water temperature rise	°C	4.4	13.2	19.7
Cooling water speed	m/s	2.6	1.8	1.0
Pressure drop	bar	6	6	6
Reynolds no.	-	5170	3530	4590

Correctors

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

** see presentation at* *FCCIS WS 2023*

Vertical Corrector **Horizontal Corrector** **Skew Quadrupole Corrector**



Parameter	V corrector	H corrector	Sk. Quad.
Integrated Strength(Tm) or (T)	0.02	0.02	0.6
Magnetic field (mT) or (T/m)	13	13	0.4
Ampere-Turns per pole (A)	336	588-194	378
Number of turns	22	20-10	22
Conductor size (mm^2)	3.5 × 1.5	3.5 × 1.5	3.5 × 1.5
Current (A)	15.3	19.4	16.8
Current Density (A/mm^2)	3.6	3.1	3.3
Resistance per magnet (Ω)	1.0	0.8	0.5
Total Voltage (V)	15.2	16.4	8.3
Total Power (W)	230	320	140

Global optimization of magnet circuits

Magnet scripts for global optimization

- New cross-sections guided by global optimization done together with the power converters group
- Previously existing designs were parametrized and represented by scripts, which the global optimizer calls

Method:

1. Optimizer controls magnet input parameters:
    - Number of turns
    - Current density
    - Conductor material (only for dipoles so far)
    - Aperture diameter (not used yet)
    - Inter-beam distance (not used yet)

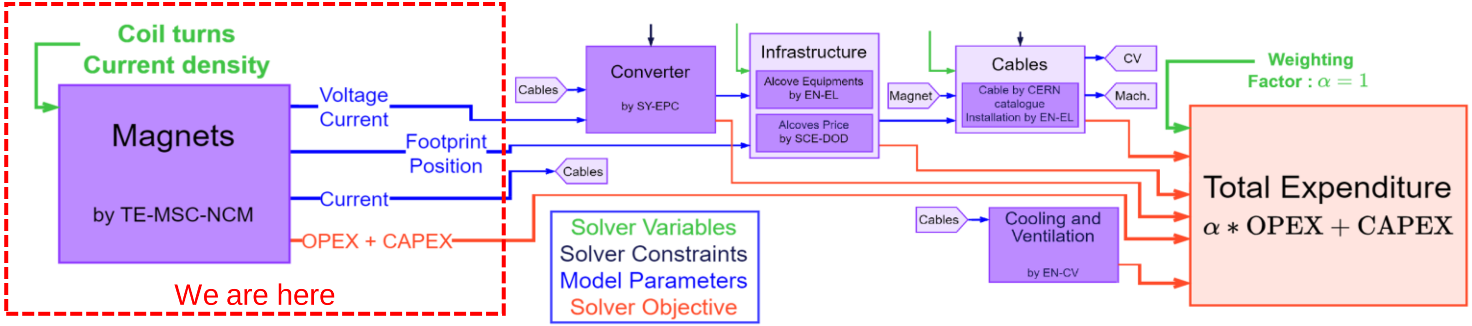
2. Parametrized magnet scripts resize the coil windows with respect to
    - Turns and current density
    - Coil cooling requirements (constant setting)

3. Coil dimensions determine powering requirements and yoke size, which are passed on to other sub-routines in the optimization

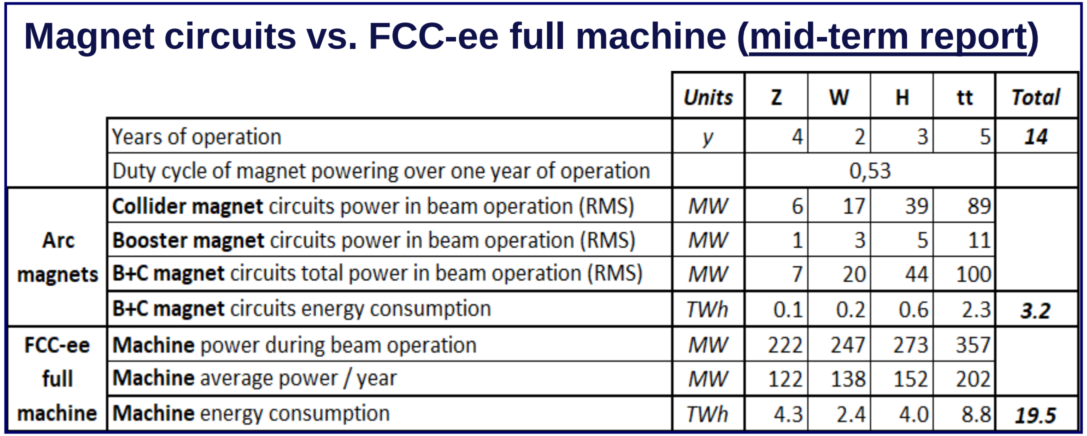
Solutions from the optimization are not yet definite, but provide good indication for design choices

- **Limits on magnet parameters to be adjusted**
- **Cost model to be refined**

Courtesy ***B. Wicki***



Magnet circuits power consumption



Magnet circuits vs. FCC-ee full machine (mid-term report)

		Units	**Z**	**W**	**H**	**tt**	***Total***
	Years of operation	*y*	4	2	3	5	***14***
	Duty cycle of magnet powering over one year of operation		0,53				
Arc magnets	**Collider magnet** circuits power in beam operation (RMS)	*MW*	6	17	39	89	
	Booster magnet circuits power in beam operation (RMS)	*MW*	1	3	5	11	
	B+C magnet circuits total power in beam operation (RMS)	*MW*	7	20	44	100	
	B+C magnet circuits energy consumption	*TWh*	0.1	0.2	0.6	2.3	***3.2***
FCC-ee full machine	**Machine** power during beam operation	*MW*	222	247	273	357	
	Machine average power / year	*MW*	122	138	152	202	
	Machine energy consumption	*TWh*	4.3	2.4	4.0	8.8	***19.5***

- **Power** of the FCC-ee magnets at tt_{bar} is **comparable to the CERN SPS main dipoles** (~90 MW peak)
- The **arc magnet circuit integrated power consumption** over the **project lifetime** is **3,2 TWh**
  - **This is only 17%** of the **full FCC-ee machine** (booster + collider)
  - **70%** of this consumption is for the **tt_{bar} phase only**

Courtesy ***J.P. Burnet***

With the **set of parameter presented today**:

- **RMS power** of **collider magnets** would scale up by **+33%** (119 MW @ ttbar)
  - **3.2 TWh → 4.3 TWh** of total magnet integrated power consumption
  - **17% → 22%** of FCC-ee full machine integrated power consumption
- Magnet circuit **TOTEX** would scale down by **-15%**

Next steps for magnet development

Prospects for collider magnets development

- For the feasibility study
  - ***Detailed mechanical design** of magnet assemblies (e.g. dipole with vacuum chambers, synchrotron radiation absorbers and shielding; sextupole pair joined in single mechanical assembly) and interconnections*
  - *Continue joint effort on **global cost optimization** to find optimal working point (e.g. add magnet Δp and ΔT as input parameters to optimize cooling and ventilation infrastructure efficiency and TOTEX)*
  - *Refine **cost evaluation** based on latest design and magnet procurement experience*
- Beyond the feasibility study
  - *Manufacturing processes for **large series** (automatized machining, assembly and measurements) and procurement strategies*
  - *Magnet designs for **alternative optics** (LCC, combined function magnets…)*
  - ***Model magnets** for performance validation and **arc half-cell mock-up***
  - ***R&D** on inorganic coatings for conductor insulation (dipole busbars, trim coils, sextupole coils)*
  - *And many more…*

Conclusions

Conclusions

The concepts of magnet designs proposed since the CDR have evolved to accommodate the features needed for the machine (e.g. field tapering, correction circuits).

The design process is now also part of a global optimisation of the magnet circuits lifetime cost. The results presented today are only the 1st iteration and the process will continue.

As from 2025, we will work on the engineering design of the baseline solution (e.g. integration of radiation shielding in dipoles), explore options for alternative optics (e.g. LCC) and check whether they can bring more cost savings or machine performance improvements.

In parallel, we will consider the industrialisation processes for the manufacturing and testing of the magnets.

The normal conducting magnets are the baseline for the FCC-ee machine: they are a simple, cost effective, proven and reliable solution.

Yes we can!

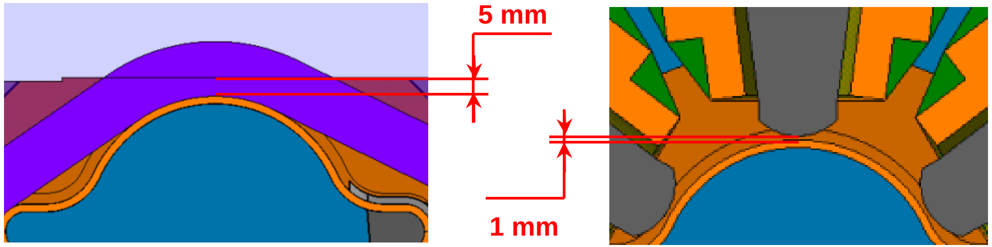
Thank you for your attention!

Questions?

SPARE SLIDES

Magnet apertures

- **Since 2023**, new baseline for vacuum chamber aperture **R = 30 mm**
- **VC – yoke clearances** kept identical as CDR to define magnet bore apertures
- **No bake-out jackets** foreseen in **sextupoles**



Dipole chamber integration

Sextupole chamber integration

N.B.: in 2023, the inter-beam distance has also been enlarged from 300 mm to 350 mm

	CDR			2023 baseline		
	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