19-23 May 2025 / FCC week

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FCC-EE TRANSFER LINES MAGNETS DESIGN STATUS

Outline

FCC-ee transfer lines magnet specifications

Magnets based on permanent magnet technology

- Magnets design description
- 2D modelling results
- Cost estimate

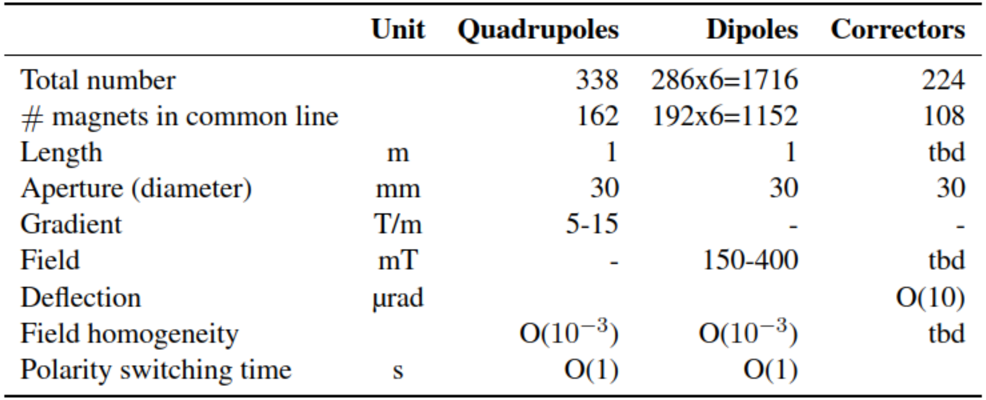
Conventional electromagnets

- Magnets design description
- 2D modelling results
- Cost estimate

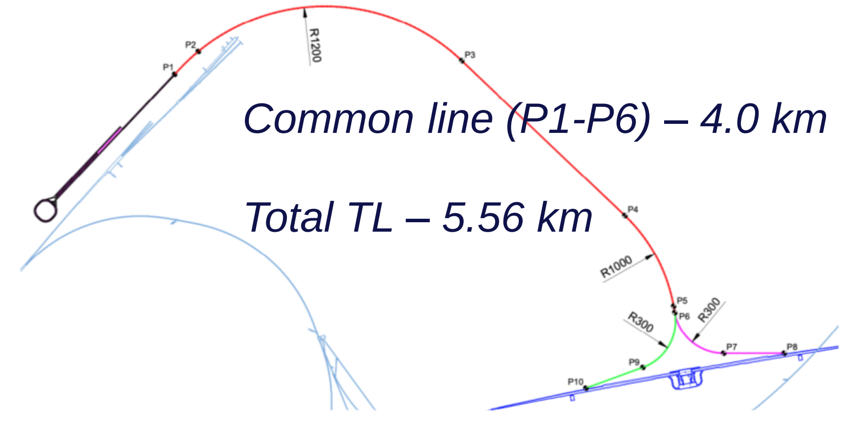
Comparison and Conclusion

Requirements

Reference: *Future Circular Collider Feasibility Study Report, March 2025*



	Unit	Quadrupoles	Dipoles	Correctors
Total number		338	286x6=1716	224
# magnets in common line		162	192x6=1152	108
Length	m	1	1	tbd
Aperture (diameter)	mm	30	30	30
Gradient	T/m	5-15	-	-
Field	mT	-	150-400	tbd
Deflection	μrad			O(10)
Field homogeneity		O(10^{-3})	O(10^{-3})	tbd
Polarity switching time	s	O(1)	O(1)	



Common line (P1-P6) – 4.0 km

Total TL – 5.56 km

Figure 1: Lepton transfer lines from pre-injector complex at surface to the collider tunnel.

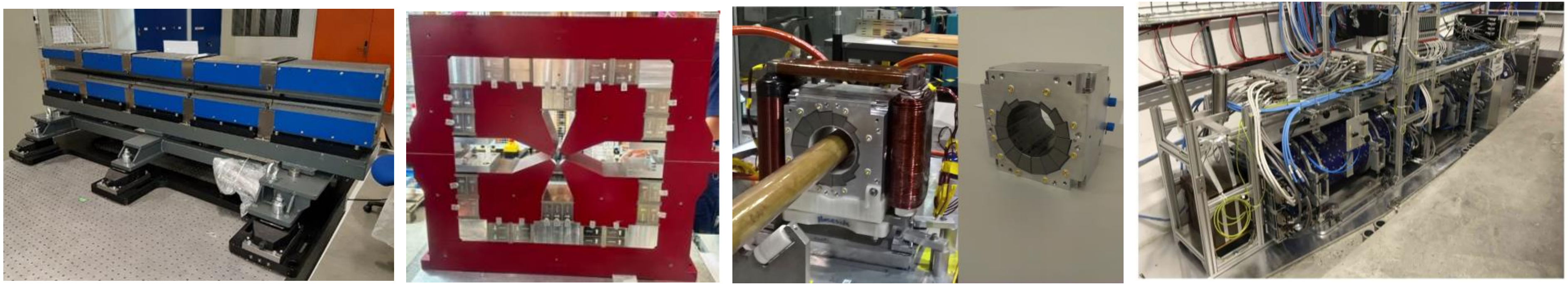
Magnet type	Position & Quantity	Strength	Unit
Dipole Type A	P1-P6 ,192 units × 6 m	0.15	T
Dipole Type B	P6-P8/P10, 47 units × 2 lines × 6 m	0.4	T
Quadrupole Type A	P1-P6 ,162 units × 1 m	5	T/m
Quadrupole Type B	P6-P8/P10, 88 units × 2 lines × 1 m	15	T/m

MAGNETS BASED ON PERMANENT MAGNET TECHNOLOGY

Use of permanent magnets in accelerators

Permanent magnets are largely used in accelerators, especially in storage rings, transfer lines, linacs, experimental areas or undulators, as for example:

- Dipoles for the EBS (ESRF)
- Dipoles and quadrupoles for the Swiss light source (PSI)
- Combined function magnets for CBETA (Cornell-BNL)
- Dipoles and quadrupoles for the Recycler ring (Fermilab)
- Quadrupoles for the Linac 4 (CERN)
- Dipoles for FASER (CERN)



Motivations for permanent magnets

Advantages of permanent magnet over electromagnet designs

- ❑ Cost efficient solution
  - ➢ No additional infrastructure required such as power convertors, cabling, water networks
  - ➢ No running cost
  - ➢ For low field magnets the required quantity of permanent magnet material stays low
- ❑ Fast process to assemble the magnets
- ❑ No additional heat load to evacuate from the transfer line tunnel
- ❑ Compact devices
- ❑ Reliability, interesting for large number of magnets (no hydraulic or electric failures)

Limitations

- ❑ Need 2 independent beam lines between points 1 and 6
- ❑ Fixed field (no flexibility for injection energy)

Design baseline

- Iron dominated designs (in opposition to Halbach designs)
    - Simplify the permanent magnet blocks shape
    - Lower the incidence of permanent magnet irregularities on field quality
    - Optimize magnet assembly and tunning process
- Maximum of 1-m long sections for both dipoles and quadrupoles
    - Stay within reasonable and largely available machining capabilities
    - Simplify permanent magnet blocks insertion
- Compensation for temperature dependence
- Cost effective design
- Series production
- Tuning possibility
    - Adjustment of field/gradient integral at magnetic measurement stage
    - Hybrid designs, with permanent magnets and some mechanism to provide remote tunability (coils or movable parts) are not considered, mainly due to cost and complexity increase

Design baseline

Choice of the permanent magnet material: Samarium Cobalt Sm_2Co_{17}

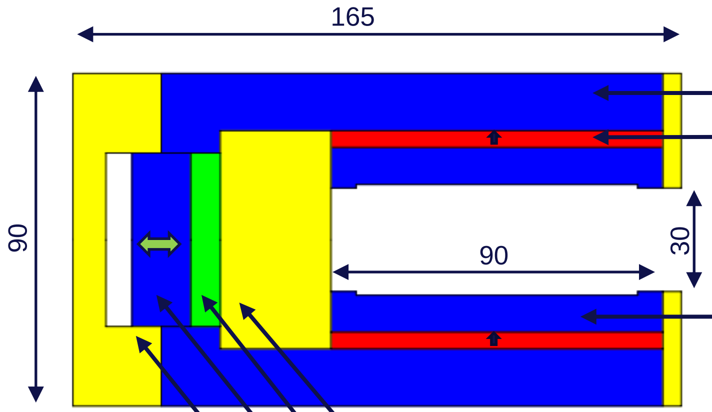
Neodymium (NdFeB) magnets have higher magnetic characteristics and are normally cheaper than Samarium Cobalt (SmCo) but for accelerator magnets SmCo presents some advantages:

- ❑ Grades with high remanent field (Br≥1.1 T) and coercivity Hcb ≥820 kA/m (however lower than NdFeB)
- ❑ Large range of energy product (from 5 to 34 MGOe)
  - => Interesting for FCC-ee TL as for some of the magnets the field/gradient is relatively low
- ❑ Good radiation resistance
- ❑ Can work at high temperature
- ❑ Acceptable corrosion stability even without protective coating
- ❑ High intrinsic coercivity Hcj ≥1990 kA/m to prevent from any risk of demagnetization
  - => Interesting for FCC-ee TL as magnet blocks are thin
- ❑ Small temperature coefficient: -0.035%/°C
  - => Interesting for FCC-ee TL for field stability

Dipole type A

B_0=0.15 T (P1-P6)

The field is adjusted in the aperture by moving away a shim to locally reduce the section of the yoke and bring it close to saturation.



Yoke (low carbon steel)

Permanent magnet (grade TC16 MGOe, temperature compensated Sm_2Co_{17})

Pole (low carbon steel)

Spacer (aluminum)

Adjustable spacer (aluminum)

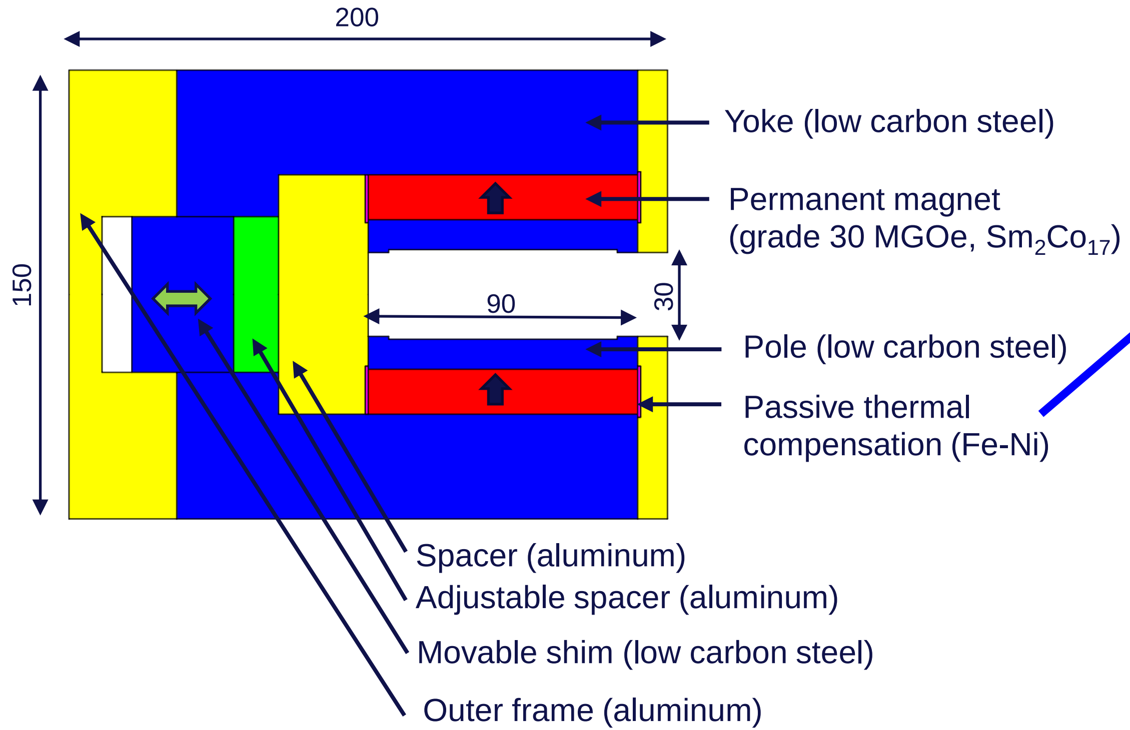
Movable shim (low carbon steel)

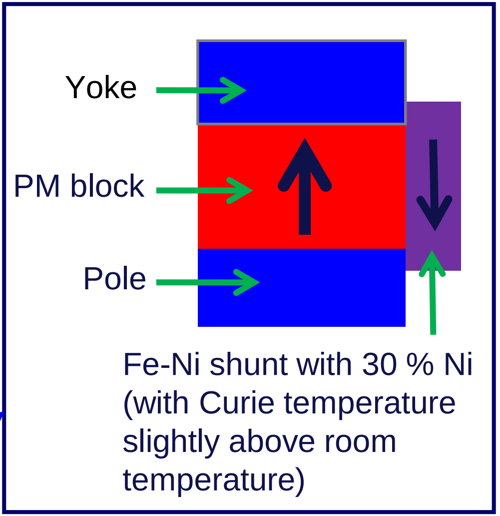
Outer frame (aluminum)

Parameter	Value	Unit
Number of dipoles	2304	-
Aperture height	30	mm
Mechanical length	1	m
Central field	0.15	T
Good Field Region H x V	±20 × ±10	mm^2
Permanent magnet mass	7	kg
Dipole mass	72	kg

Dipole type B

B_0=0.4 T (P6-P8/P10)





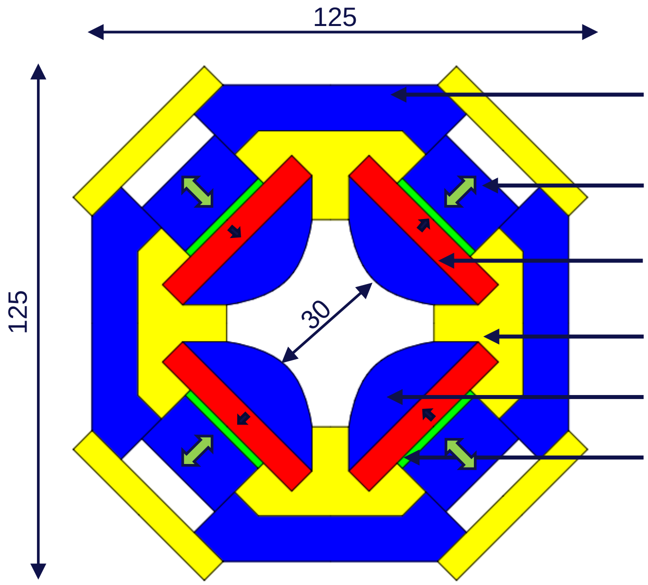
Fe-Ni shunt with 30 % Ni (with Curie temperature slightly above room temperature)

Parameter	Value	Unit
Number of dipoles	564	-
Aperture height	30	mm
Mechanical length	1	m
Central field	0.4	T
Good Field Region H x V	±20 × ±10	mm^2
Permanent magnet mass	22	kg
Dipole mass	165	kg

Quadrupole types A and B

Same cross section, different length, G_0=15 T/m

The gradient is adjusted by moving away some shims to change the reluctance of the magnetic circuit.



Return yoke (low carbon steel)

Movable shim (low carbon steel)

Permanent magnet (grade TC16 MGOe, temperature compensated Sm_2Co_{17})

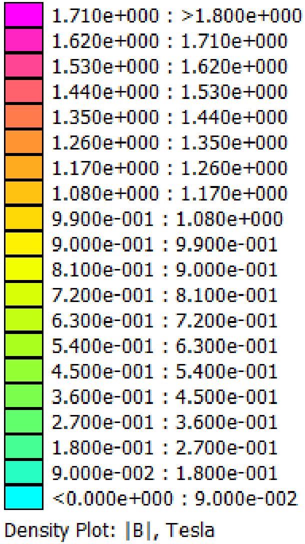
Frame (aluminum)

Pole (low carbon steel)

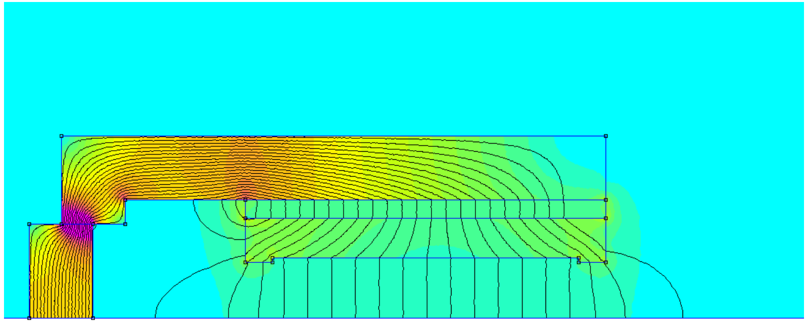
Adjustable spacer (aluminum)

Parameter	Type A (P1-P6)	Type B (P6-P8/P10)	Unit
Number of quadrupoles	324	176	-
Aperture diameter	30	30	mm
Mechanical length	0.333	1	m
Gradient	15	15	T/m
Good Field Region Ø	20	20	mm
Permanent magnet mass	3.5	10.5	kg
Quadrupole mass	23	69	kg

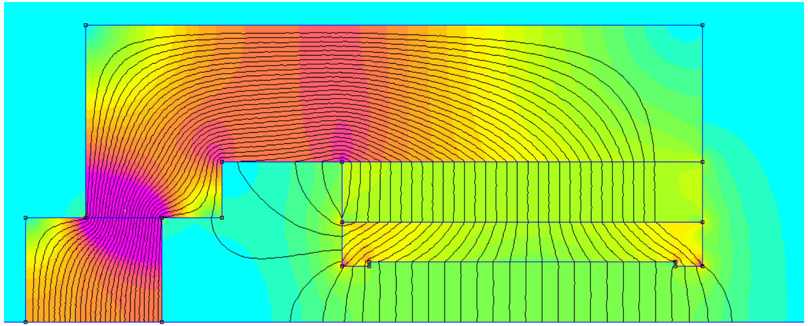
2 D modelling: dipoles



Dipole type A



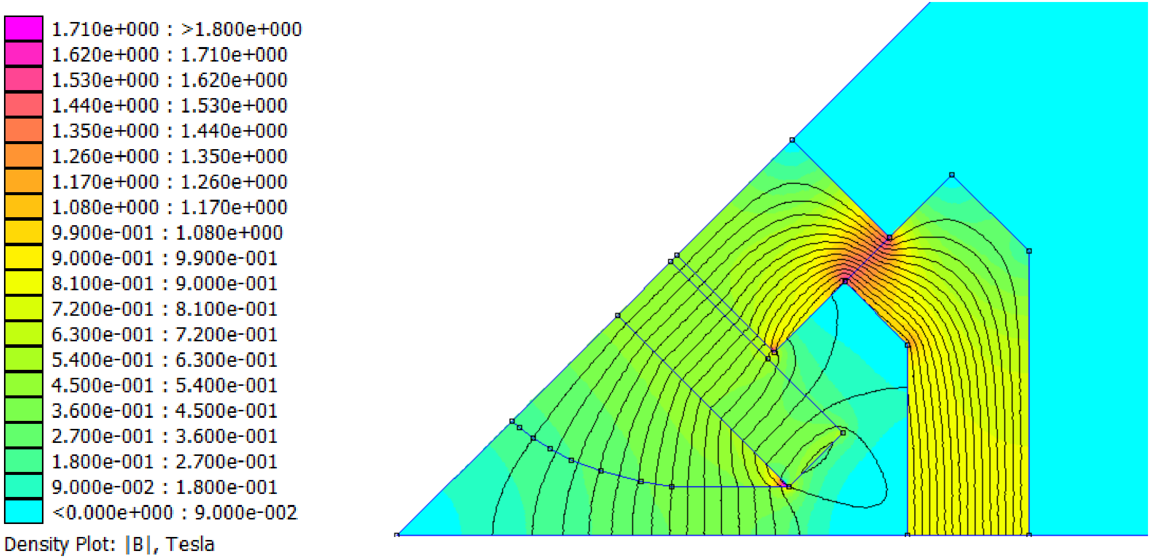
Dipole type B



Parameter	Type A	Type B	Unit
Field	0.15	0.4	T
Field homogeneity in GFR	± 5	± 5	10^{-4}
Tuning range	+6 / -30	± 6 / -15	%
Expected field stability / temperature	~0.004	~0.004	% /°C

2 D modelling: quadrupole

Quadrupole types A and B



Parameter	Value	Unit
Gradient	15	T/m
Gradient homogeneity in GFR	± 5	10^{-4}
Tuning range	+6 / -30	%
Expected gradient stability / temperature	~0.004	% /°C

Permanent magnet cost breakdown

	Category	Dipole type A	Dipole type B	Quadrupole type A	Quadrupole type B	Unit
Material	Low carbon steel	10	13	3	7	%
	Aluminium	4	5	2	3	%
	Permanent magnet blocks	18	33	8	15	%
	Ancillaries	2	2	2	2	%
Labour	Machining	37	27	54	48	%
	Surface treatment	1	1	1	1	%
	Assembly	14	10	16	14	%
	Magnetic measurements and tuning	14	9	14	10	%
TOTAL		100	100	100	100	%

- ❑ The budget is largely driven by labour due to the relatively small size of the dipoles and quadrupoles.
- ❑ The permanent magnet material cost would represent ~20% of the overall budget.
- ❑ The required quantity of Sm_2Co_{17} permanent magnet material would be ~ 30 tons for the whole transfer line, which stays within production capabilities of several known companies.

CONVENTIONAL ELECTROMAGNETS

Motivations for conventional electromagnets

- ❑ Electromagnets provide adjustable field strength and polarity
  - ➢ ±100 % tuning range
  - ➢ common (electron–positron) beam line between P1 and P6
- ❑ Field strength is not sensitive to possible temperature variation in the tunnel
- ❑ Well known manufacturing technology, price & availability of raw materials (steel & copper) are less sensitive to the market “perturbations” as compared to the permanent magnets

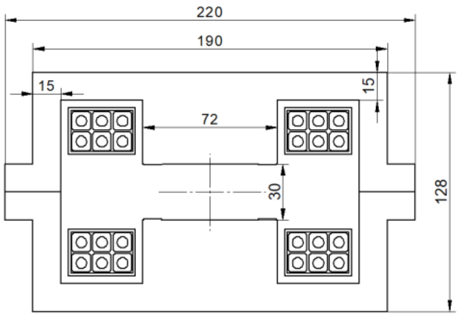
Design considerations

- ❑ Conventional EM with as simple as possible coil and magnet core cross-sections
- ❑ Current density in the “cost effective” range 3.5 – 5.0 A / mm^2 for Cu-conductor, (Al – e.g. 1 turn, high current busbar → large dissipated power(heat) of the cabling in the tunnel)
- ❑ Cooling water temperature rise < 10°C
- ❑ 2D FE modeling for all magnets, including pole shimming study to ensure that the required field quality is provided
- ❑ Optimized cross-section & engineering parameters as an input for the cost estimate

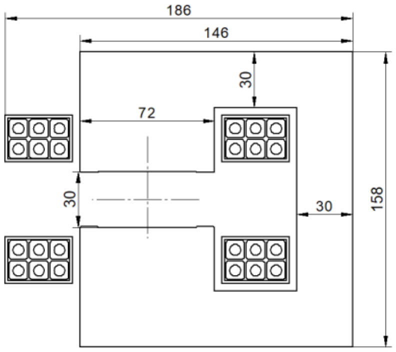
Dipole type A

Bo=0.15 T (P1-P6)

DIH-A



DIC-A

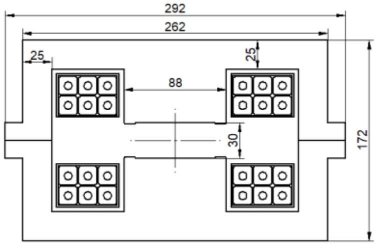


Parameter	H-type	C-type	Unit
Excitation current / Current density	307.7 / 4.3	307.7 / 4.3	A, A, A/mm2
Conductor dimensions, No turns per pole	10×10 Ø6, nw=6	10×10 Ø6, nw=6	mm
Magnet inductance / resistance@20°C	3.8 / 35.9	3.8 / 35.9	mH / mΩ
Voltage L·dI/dt, for t=1s (-Imax → Imax)	2.3	2.3	V
Voltage DC(warm) @Imax	11.4	11.4	V
Power consumption DC @ Imax	3.5	3.5	kW
Cooling circuits per mag / Trise @ImaxDC	2 / 3.0	2 / 3.0	/ °C
Good Field Region H x V	±20 with Sagitta × ±10		mm^2
Magnet length / mass	6 / 776	6 / 878	m / kg

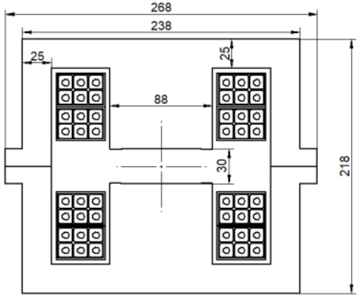
Dipole type B

Bo=0.40 T (P6-P8/P10)

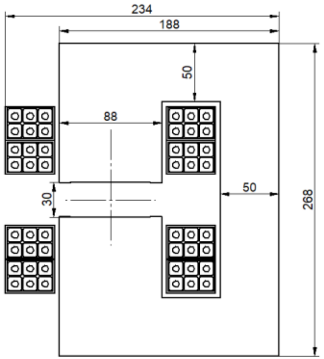
DIH-B (1 pancake /coil)



DIH-B (2 pancakes /coil)



DIC-B (2 pancakes /coil)

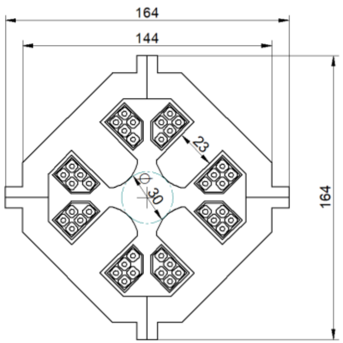


Parameter	H-type, 1 pancake / coil	H-type, 2 pancakes / coil	C-type, 2 pancakes / coil	Unit
Excitation current / Current density	820.3, 3.81	410.2, 3.57	410.2, 3.57	A, A/mm^2
Conductor dimensions, No turns per pole	16×16 Ø7 , nw=6	12×12 Ø6, nw=12	12×12 Ø6, nw=12	mm
Magnet inductance / resistance@20°C	4.4 / 11.8	18.4 / 44.3	18.2 / 4.3	mH / mΩ
Voltage L·dI/dt, for t=1s (-Imax → Imax)	7.3	15.1	15	V
Voltage DC(warm) @Imax	10.3	19	19	V
Power consumption DC @Imax	8.4	7.8	7.8	kW
Cooling circuits per mag / Trise @Imax	2 / 10	4 / 7.0	4 / 7	/ °C
Good Field Region H x V	±28(with Sagitta) × ±10			mm^2
Magnet length / mass	6 / 1617	6 / 1879	6 / 2162	kg

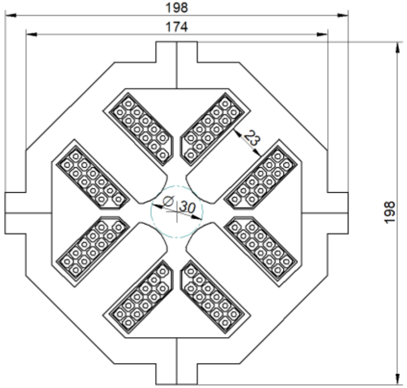
Quadrupole type A and B

Go=5 & 15 T/m

QA



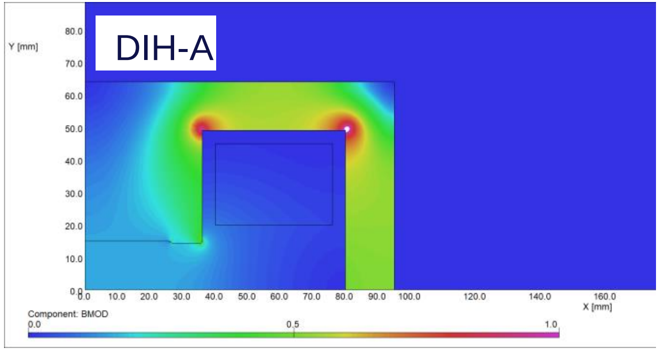
QB

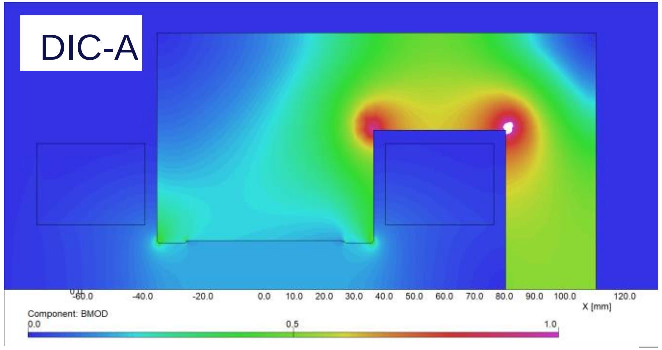


Parameter	Type A(P1-P6)	Type B(P6-P8/P10)	Unit
Excitation current / Current density	91.4 / 3.26	124.5 / 3.81	A, A/mm^2
Conductor dimensions, No turns per pole	6×6 Ø3, nw=5	6×6 Ø3, nw=11	mm
Magnet inductance / resistance@20°C	0.9 / 28.2	4.9 / 62.1	mH / mΩ
Voltage L·dI/dt, for t=1s (-Imax → Imax)	0.2	1.2	V
Voltage DC(warm) @Imax	2.7	8.0	V
Power consumption DC @Imax	0.2	1.0	kW
Cooling circuits per mag / Trise @Imax	2 / 2.0	4 / 5	/ °C
Good Field Region Ø	20	20	mm
Magnet length / mass	1 / 68	1 / 137	m / kg

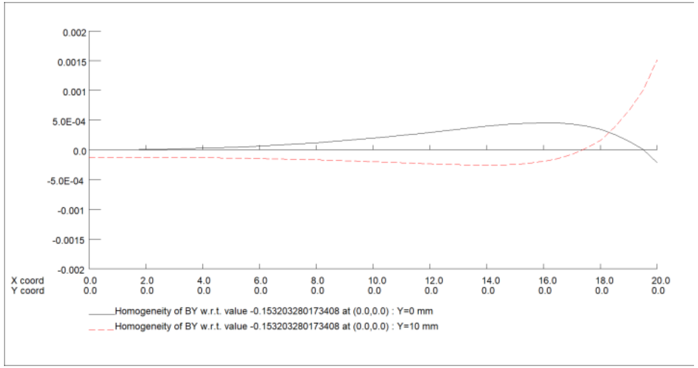
Dipole type A

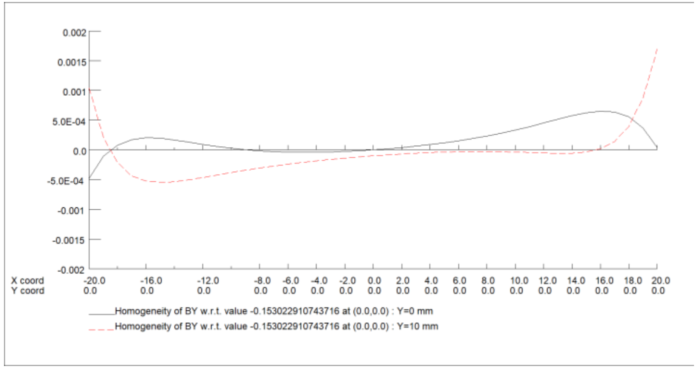
2D modelling





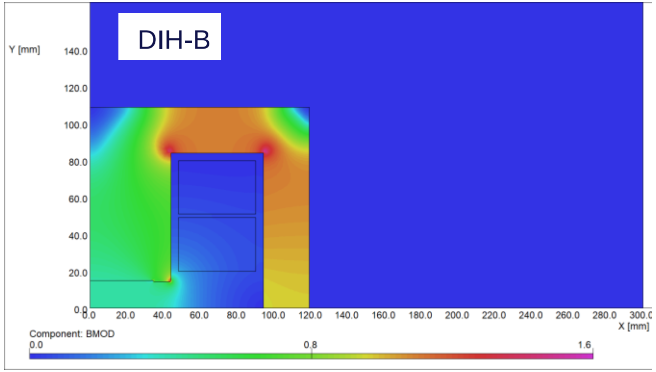
Field homogeneity @ GFR = ±20 (Hor.) × ±10 (Vert.)

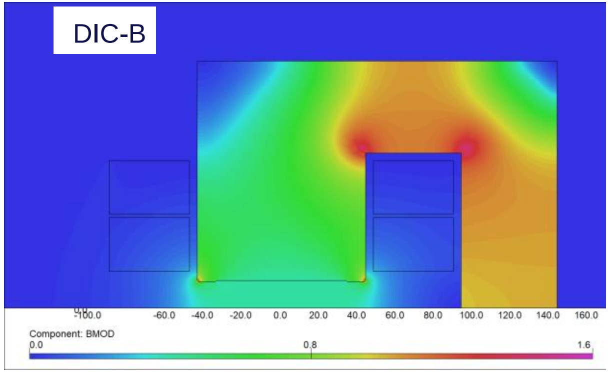




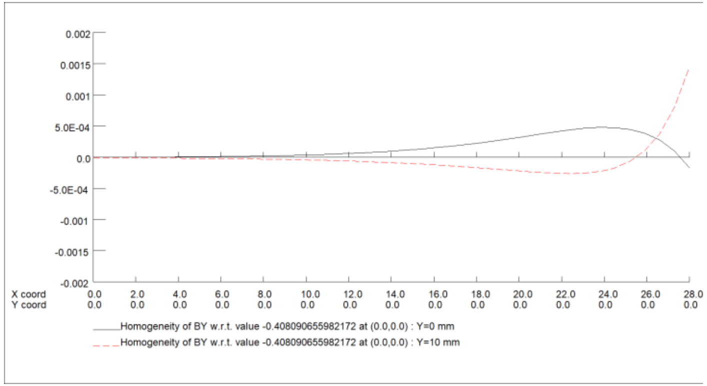
Dipole type B

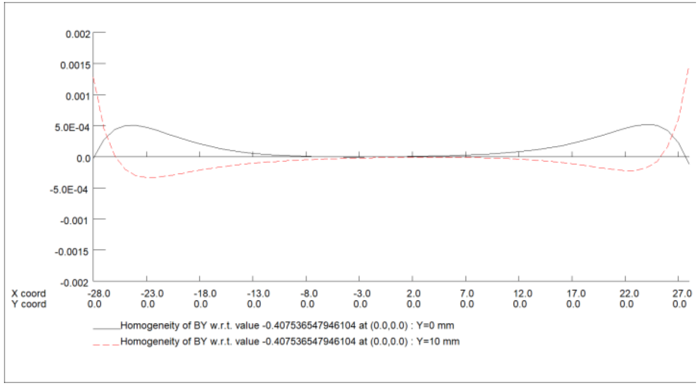
2D modelling





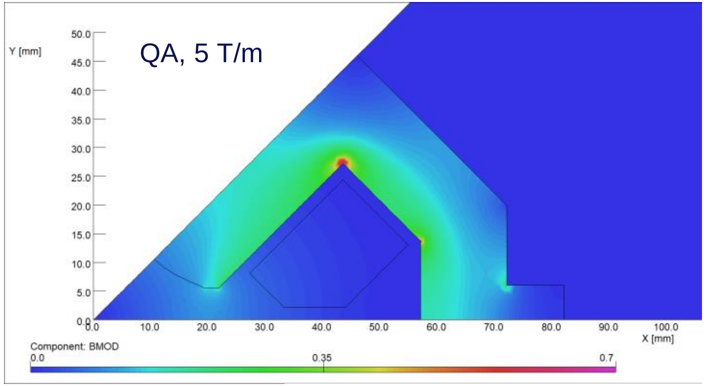
Field homogeneity @ GFR = ±28 (Hor.) × ±10 (Vert.)

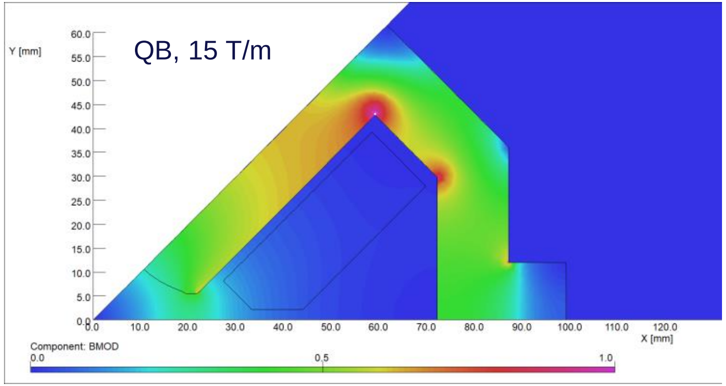




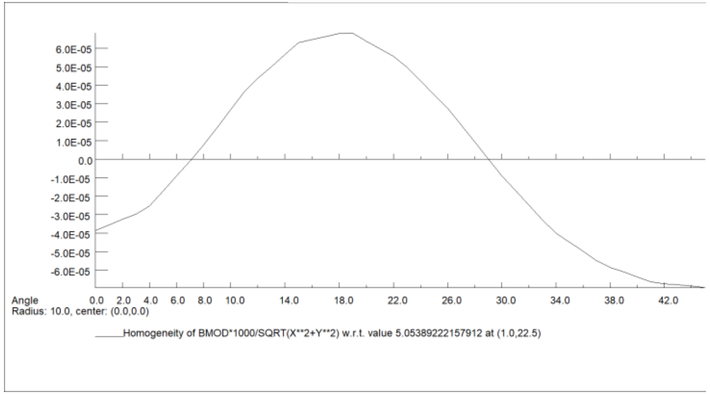
Quadrupole QA and QB

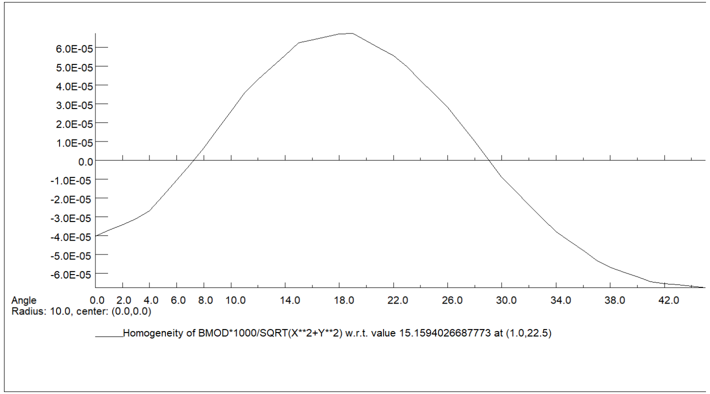
2D modelling





Field homogeneity @r=10 mm (good field region=2/3 aperture)





Cost estimate

only capital costs

	DIPOLE TYPE A		DIPOLE TYPE B			QUADRUPOLES		
	H-yoke	C-yoke	H-yoke (1 pancake)	H-yoke (2 pancakes)	C-yoke	type A	type B	unit
Steel	5.7	4.6	5.5	5.0	4.3	1.1	1.6	%
Copper OF	2.8	3.1	5.0	4.4	4.6	0.6	1.0	%
Yoke manufacturing	31.5	26.0	25.8	23.2	18.9	17.5	21.8	%
Coil manufacturing	46.2	50.4	52.7	57.6	61.1	72.4	66.8	%
Magnet assembly	11.3	13.1	9.6	8.5	9.6	4.7	5.7	%
TESTs + Measurements	2.7	2.9	1.6	1.3	1.4	3.7	3.3	%
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	%
Total cost dipole Normalised to C-yoke	1.1	1.0	0.9	1.1	1.0			%

Learning curve, rate=98%	Dipole Type A		Dipole Type B			Quadrupoles		unit
	H-yoke	C-yoke	H-yoke (1 pancake)	H-yoke (2 pancakes)	C-yoke	type A	type B	
Manufacturing cost 1st magnet	100.0	100.0	100.0	100.0	100.0	100.0	100.0	%
Manufacturing cost last magnet	85.8	85.8	87.6	87.6	87.6	86.2	87.8	%
Manufacturing cost AVERAGE	88.3	88.3	90.1	90.1	90.1	88.7	90.3	%
TOTAL /1 MAGNET	**0.92**	**0.92**	**0.93**	**0.92**	**0.92**	**0.93**	**0.94**	**%**

PM vs EM comparison

- ☐ Feasibility: Both technologies Permanent Magnets (PM) and Electromagnets (EM) are technically feasible
- ☐ Capital costs: in total the EM option is by factor ~1.5 more expensive than the PM
  - *Main contributions to the price increase are from: (magnets, power and signal cables, power converters and cooling)*
  - *PM more expensive for the Vacuum system: two transfer lines in parallel required for the initial 4 km*
- ☐ Running costs:
  - *The PM would require about a factor 10 less power (only for corrector magnets and ventilation)*
  - *However, the EM power consumption is also low 2.0 MW (100% duty cycle): <10% to overall injector complex (In fact even less duty cycle 5-75%)*
- ☐ Tunability:
  - *PM: from 20 to 35% by mechanical shunt, only possible with pre-characterized field values (shim position), would take several weeks to adjust shunts for all magnets*
  - *EM: ±100% by power converter*

Conclusion on baseline choice

Feasibility Study Report - 2025

Operational flexibility is the main aspect to consider when choosing between magnet technologies:

- If the are beam stability issues in the booster, a transfer energy increase can be beneficial.
- If the booster could accept a lower energy beam at injection, reducing the transfer energy reduces the power consumption of the whole injector complex which is driven by the HE-linac.
- Another argument for operational flexibility is the duty cycle of the injector complex, which varies between 5 and 75% depending on the operation mode. In particular, in the low-duty modes, the injector beam can be used for experiments beyond FCC physics and shot-to-shot variability of beam parameters, including the transfer energy, open the door to a very diverse physics program.

Conclusion & next steps:

- At this stage, electromagnets have been chosen as the baseline technology due to the higher operational flexibility for the FCC and any science programme beyond the FCC.
- EM design of the corrector magnets
- Design optimization considering the manufacturing cost

Thank you
for your attention.