BOOSTER MAGNET DESIGN STATUS

FCC week 2024
12th June 2024

H. Deveci, L. von Freeden (CERN)

with thanks to J. Bauche, C. Eriksson, A. Milanese, M. Pentella, C. Petrone, D. Schörling (CERN)

Overview

Latest (12th April) magnet requirements for v 24 FODO

Updated dipole parameters

Dipole hysteresis aspects modeling, indicative results, and prototype

Updated quadrupole and sextupole parameters

Design space maps

Conclusions and future directions

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Magnet requirements, FODO version 24

	Dipole	Quadrupole	Sextupole		Corrector
			Focus	Defocus	
Total number in lattice…	6176	3344	576	560	3344
…of which in arcs	5536	2768	576	560	
Aperture [mm]	65				
Length [m]	11	1.3	0.7	1.4	< 0.3
Max strength*, arcs ($t\bar{t}$ extraction)	58.9 mT	28.7 Tm^{-1}	1141 Tm^{-2}	1210 Tm^{-2}	20 mTm[†]
Min strength*, arc (injection, 20 GeV)	6.5 mT	3.2 Tm^{-1}	126 Tm^{-2}	134 Tm^{-2}	

[†] Issued before 12th April 2024 for indication only TBC for new optics

* Sextupole strength given as B'', B'' = 2S

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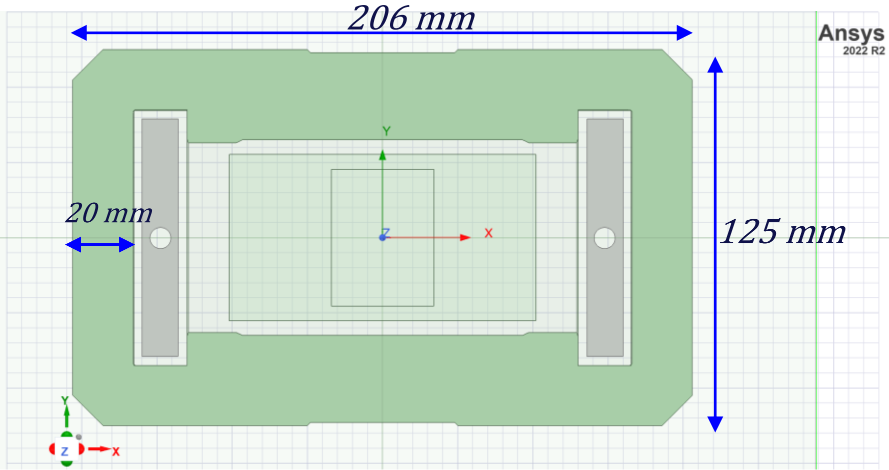
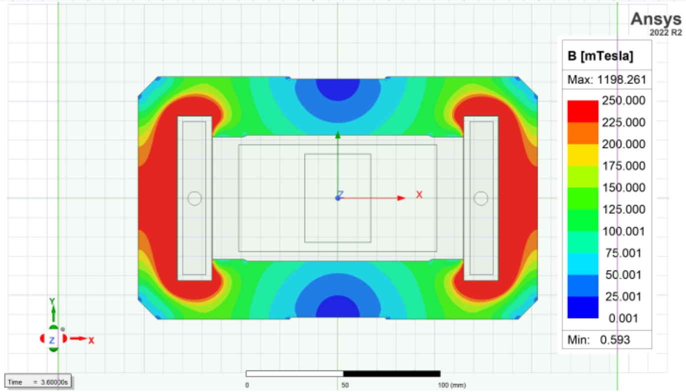
Proposed magnet

General Parameters

Parameter	Unit	Value
Number of units in the arcs		2768 x 2
Central field, 20 GeV–182.5 GeV	mT	6.5 - 65.0†
Aperture (horizontal × vertical)	mm	130 x 65
Good field region (GFR) radius	mm	17
Field quality in GFR	1.0E-04	< 1
Magnetic length	m	11
Magnet outer transverse dimensions	mm	206 x 125
Iron mass per unit length	kg/m	106.4
Aluminum mass per unit length	kg/m	4.89
Magnet unit mass (11 m length)	kg	1225
Total magnet mass, 65.4 km (only active parts)	tons	~6781
Maximum operating ampere-turns (tt_bar extraction)	A	3380
Maximum RMS current density (tt_bar)	A/mm2	2.12
Peak current (1 x coil with 1 turns)	*A*	*3380*
Resistance per unit length (1 x coil with 1 turns)	*μΩ/m*	*63.9*
Inductance per unit length (1 x coil with 1 turns)	*μH/m*	*4*
Peak voltage per octant (2 x coil with 1 turns)	*V*	*1695*
Maximum RMS power per unit length (tt_bar)	W/m	237
Maximum total peak power (tt_bar; cabling not incl.)	MW	44
Maximum total RMS power (tt_bar; cabling not incl.)	MW	14.3
Conductor Size	mm	12 x 79 (7 mm duct diameter)

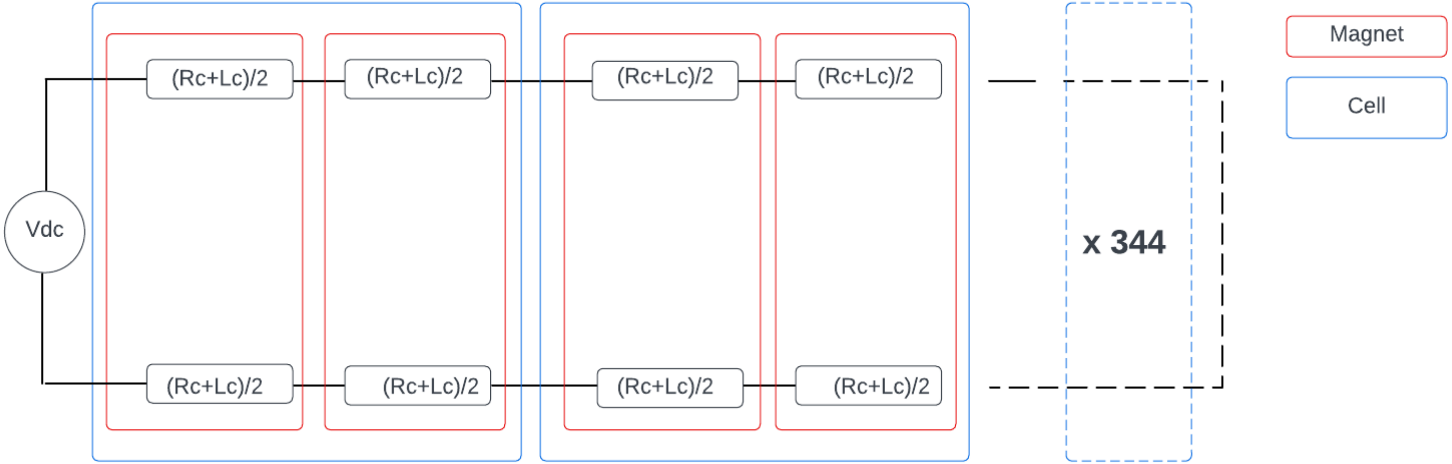
† These are the upper and lower bounds from the last 3 years





Proposed magnet

Circuit diagram

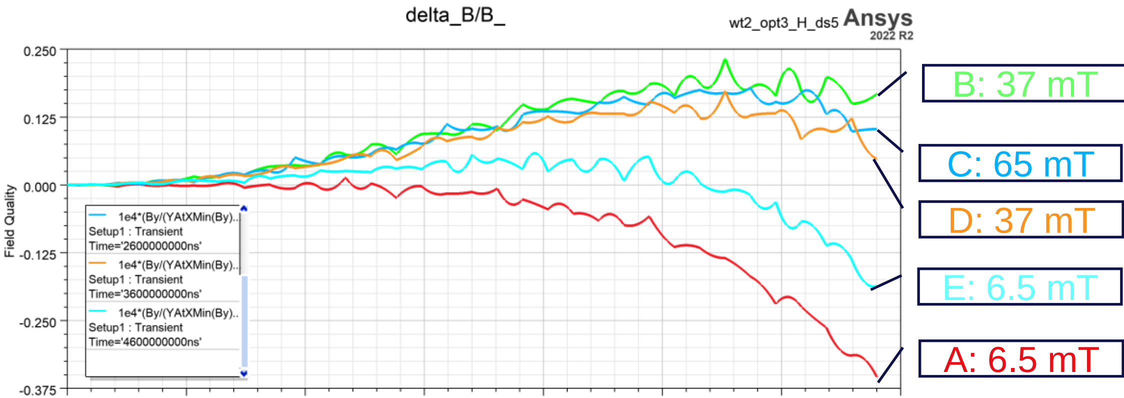


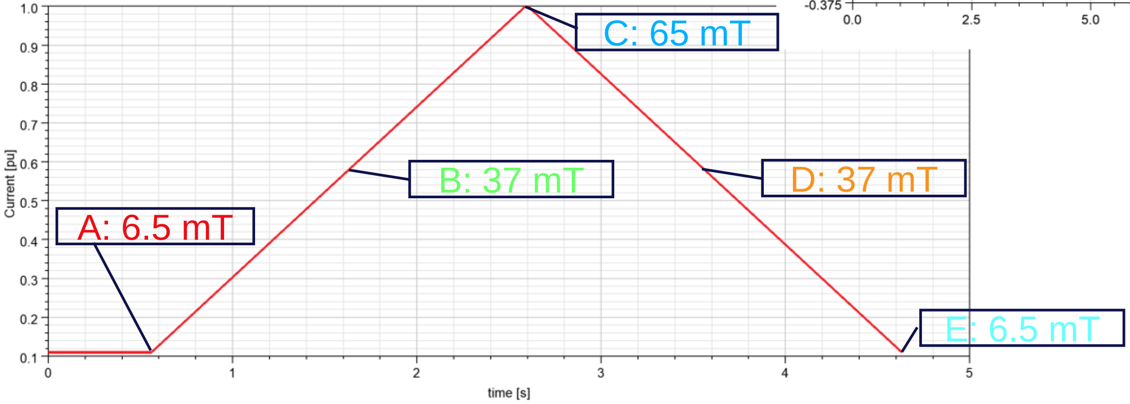
- Circuit diagram for one octant

Proposed magnet

Hysteretic effects

Yoke is optimised for the entire tt_ cycle to minimize the distortions in the field quality caused by the hysteretic effect



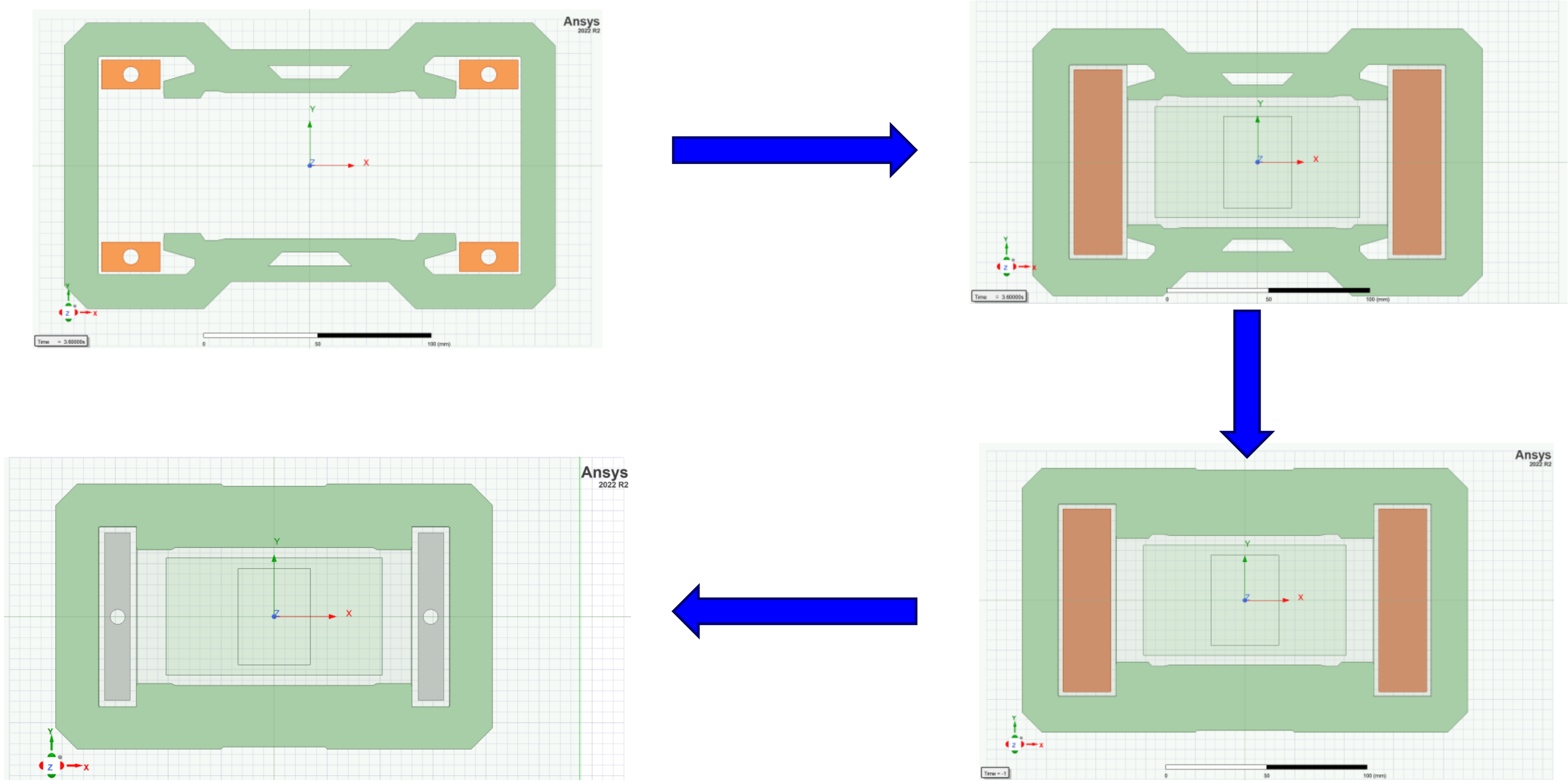


Current during tt_ cycle

Field quality @ GFR during the cycle (including hysteresis effects Hc=26 A/m)

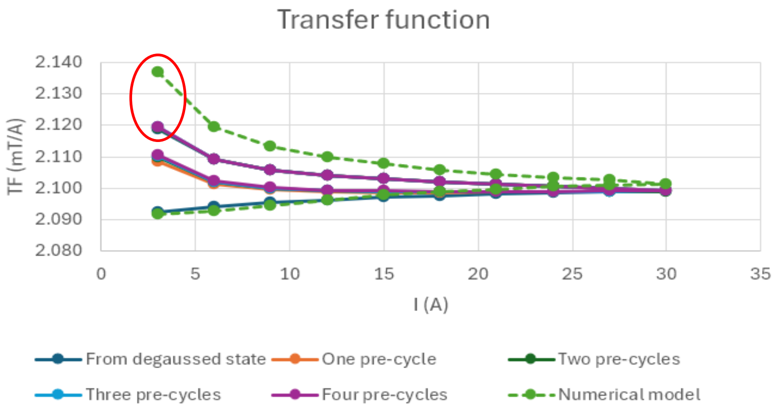
N.B. Numerical modelling of hysteresis is not straight forward

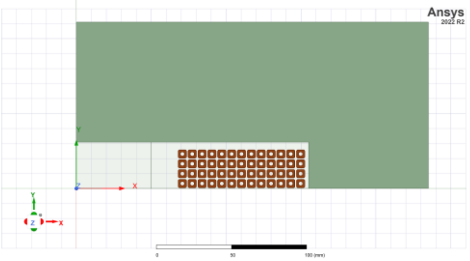
Design evolution



Preliminary test results from similar magnet

w/ thanks to M. Pentella and C. Petrone





- Numerical model good match to test: < 1% difference in transfer function, and harmonics match within ±0.15 units
- At 6.5 mT, $< 1 \times 10^{-4}$ harmonic field error ($R_{ref} = 10$ mm)
- Lower ratio of flux path to gap in booster dipole so even lower hysteretic effect expected

	Booster dipole	**Magnet measured**
Approx. mean flux length [mm]	270	460
Aperture [mm]	65 x 130	63 x 131
Gap to flux path length	1:4	1:7
Steel	M270-50A	M270-50A

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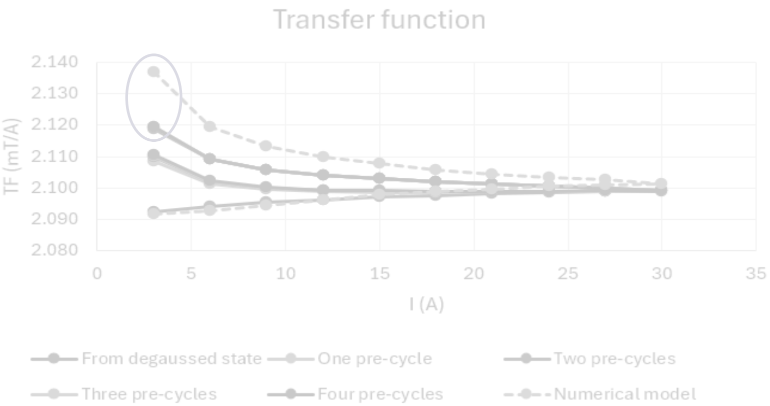

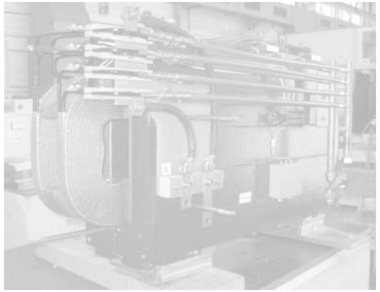

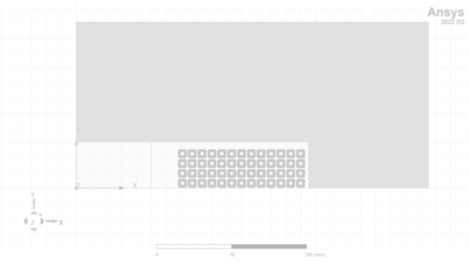

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Short prototype magnet production & test plan

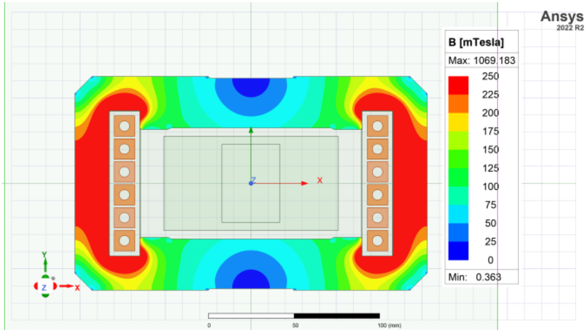
w/ thanks to the TE/MSC workshops

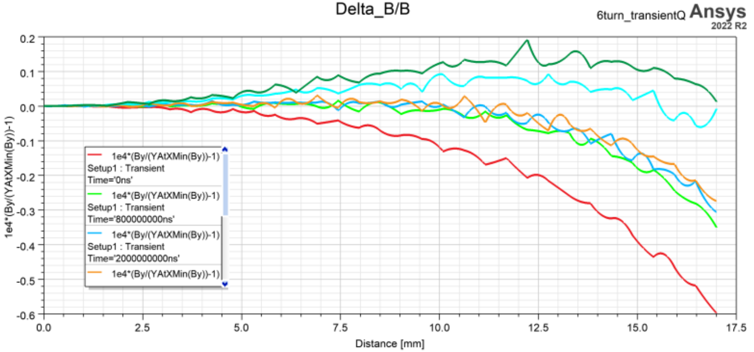
The number of turns is increased in the model magnet for convenience

The length of the model magnet is determined as 500 mm

Valid representation of the baseline dipole

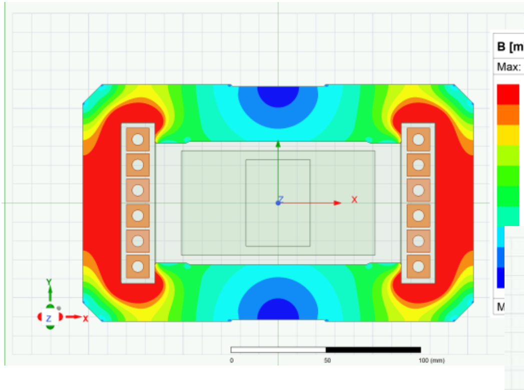
M270-50A steel coils are provided

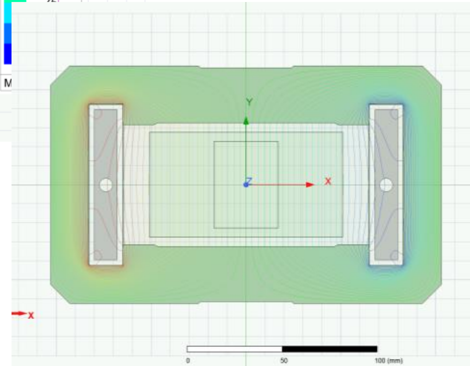


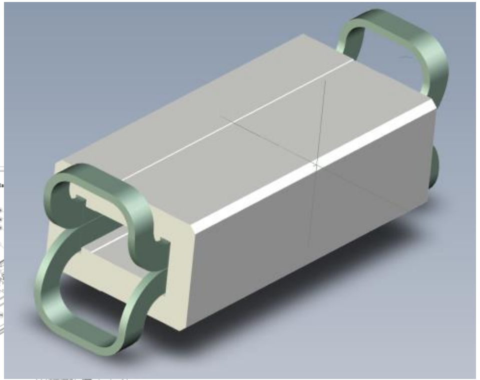


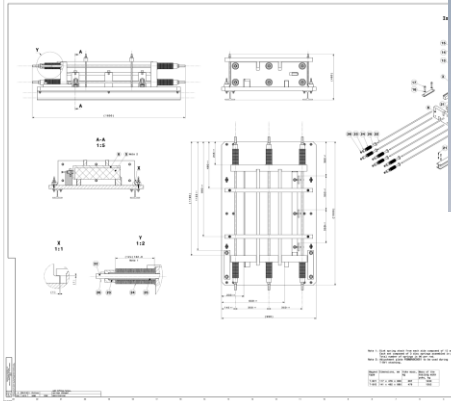
Conclusions

- Analytical design, numerical analysis, and optimization have been done for the booster ring dipole
- Numerical modeling and test results of a similar magnet suggest v 24 FODO requirements are within reach
- The model magnet production stage has been started to verify design and numerical modeling









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Requirements updates in v24 FODO

Increase aperture diameter 63 mm → 65 mm

- Ø 65 mm = R30 + R 1.5 mm vacuum tube + R 1 mm clearance

Lengths of lenses adjusted to maximise filling factor by maximising pole tip field

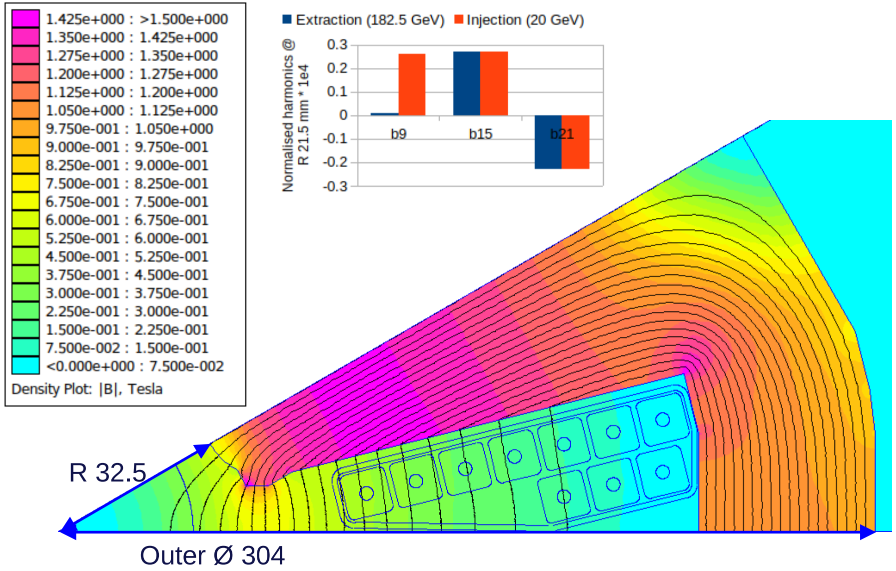
- maximising pole tip field also minimises power consumption/weight for a given ∫strength (ESRF-EBS quadrupole design [1])

	Quadrupole		Sextupole	
	FCC wk 23	V24 FODO	FCC wk 23	V24 FODO
Integrated strength	34.5 T	37.3 T	1408 $\mathrm{Tm^{-1}}$	1694 $\mathrm{Tm^{-1}}$
Length	1.5 m	1.3 m	0.5 m	1.4 m
Strength (B’ and B’’)	23 $\mathrm{Tm^{-1}}$	29 $\mathrm{Tm^{-1}}$	2816 $\mathrm{Tm^{-2}}$	1210 $\mathrm{Tm^{-2}}$
Pole tip field	0.72 T	0.94 T	1.4 T	0.63 T

[1] Le Bec, G. et.al. (2016). High gradient quadrupoles for low emittance storage rings. 19. 10.1103/PhysRevAccelBeams.19.052401.

Sextupole for v24 FODO

Parameter	Unit	Defocus	Focus
Strength, B’’	Tm^{-2}	1210	1140
Length	m	1.4	0.7
Peak current	A_{pk}	561	525
RMS current, ttbar	A_{RMS}	322	302
Magnet resistance	mΩ	52	27
Magnet inductance	mH	8.8	4.4
Peak voltage magnet	V	51	24
Peak voltage, half-octant	kV	1.7	0.80
Conductor (copper)	mm	8.4 x 8.4, Ø 2.5, R1	
Turns		10	
Current density, ttbar	$A_{RMS}\ mm^{-2}$	5.0	4.7
Magnetic efficiency		> 0.98	
Temperature rise (7 bar)	°C	26	8.2
Active mass	kg	614	312
Coil overhang	mm	50	

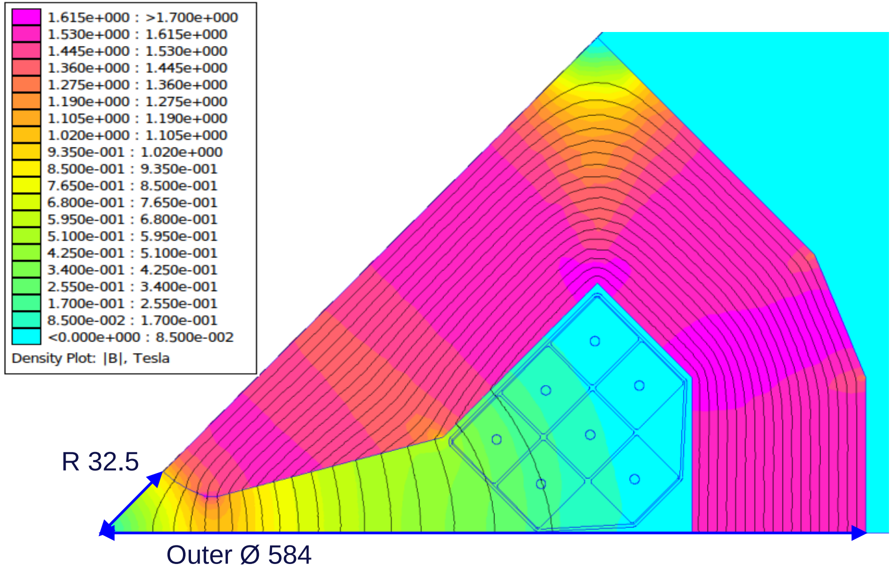


RMS resistive loss in arc sextupoles [kW]

	Z	W	ZH	ttbar
Defocus	0.42	0.49	1.2	5.4
Focus	0.19	0.22	0.56	2.4

Quadrupole for v24 FODO

Parameter	Unit	
Strength, B'	Tm^{-1}	30
Length	m	1.3
Peak current	A_{pk}	1937
RMS current, ttbar	A_{RMS}	1113
Magnet resistance	mΩ	2.9
Magnet inductance	mH	3.6
Peak voltage magnet	V	27
Peak voltage, half-octant	kV	0.92
Conductor (copper)	mm	22.5 x 25.0, Ø 3.5, R1
Turns		7
Current density, ttbar	$A_{RMS}\ mm^{-2}$	2.0
Magnetic efficiency		> 0.92
Temperature rise (7 bar)	°C	9.4
Active mass	kg	2150
Coil overhang	mm	140



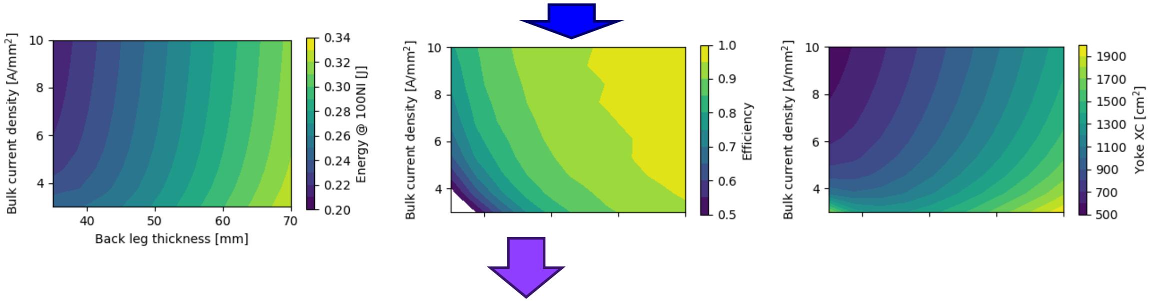
RMS resistive loss in arc quads [kW]

	Z	W	ZH	ttbar
Arc quad	0.28	0.33	0.82	3.6

Design space maps for global optimisation

Inputs:
- Turns
  - Current vs. Voltage
- Bulk current density
  - Mass vs. power loss
- Back-leg thickness
  - Mass vs. power loss

FEA scan: current and back leg thickness



Sizing equations:
- NI from efficiency and bulk J
- Cooling circuit Newton-Raphson
- R from cooling circuit and filling factor
- L from magnetic energy
- Mass from yoke XC and coil

Further details about utilisation in the talk of B. Wicki

Conclusions & future directions

Headline magnet requirements of v24 FODO optics are technically feasible including low dipole field and lens strengths.

Work ongoing to specify and optimise the harmonic errors to feed into dynamic aperture study

Large design space for magnets, opportunity for holistic design and cost optimised solution:

- Yoke and radiation shielding?
- Coils and quality heat source?
- Industrialisaiton
- Support structures

Corrector design

Thank you
for your attention.