Magnets for FCC-ee

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Outline

FCC-ee accelerator complex
- **Physics case, operation plan and layout**
- **General considerations for magnet design**

Collider magnets
- **Arc main magnets**
  - Dipole
  - Quadrupole
  - Sextupole
- **IR magnets**
  - Beamstrahlung photon extraction line
  - Polarization wigglers

Booster magnets
- **Specifications and challenges**
- **Dipole**
- **Quadrupole**

FCC-ee feasibility study
- **Scope and timeline of magnet development work**
- **Cost estimate and optimization**

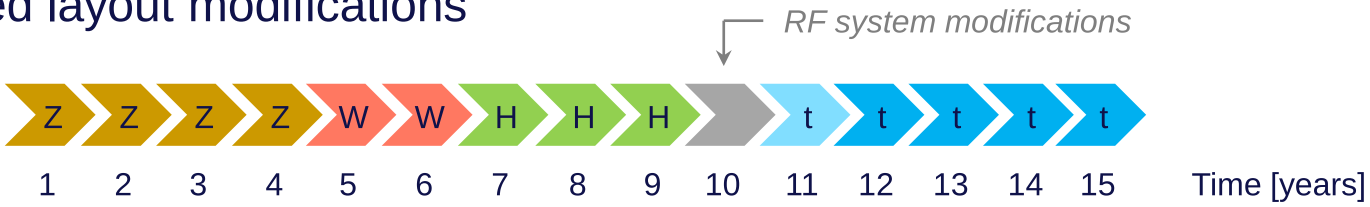
Concluding remarks

FCC-ee accelerator complex

Physics case and operation plan

- **FCC-ee** is a high luminosity Higgs and electroweak factory
- Study of **Z**, **W**, **Higgs** and **top** particles with high precision
- High luminosity provides 3 orders of magnitude higher **sensitivity** to small deviations from the Standard Model → potential to discover new physics
- 4 periods of exploitation, **4 energies**, staged layout modifications

FCC project time plan

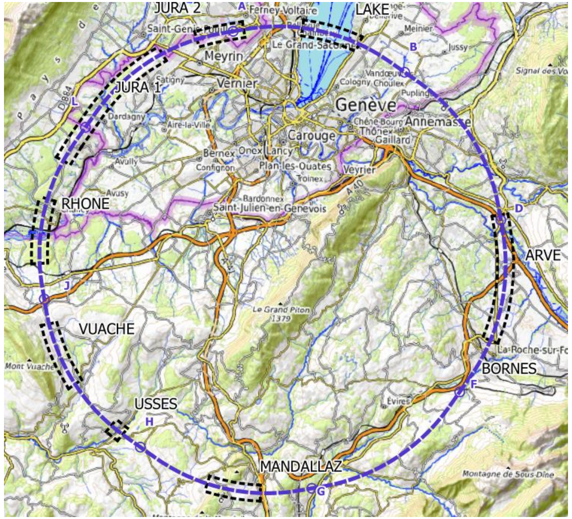


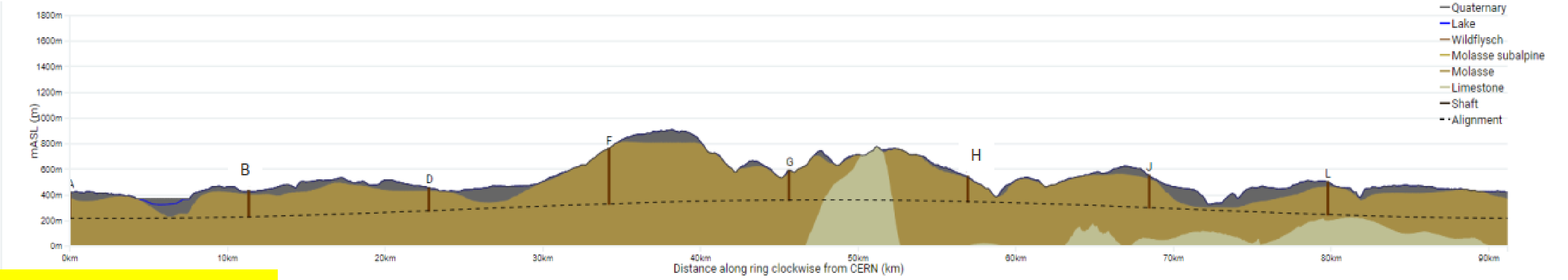
C. Paus (MIT)

FCC-ee exploitation timescale

Placement in Geneva region

- Layout chosen out of **50 initial variants**
- 95% in **molasse** geology to minimize construction risks
- Layout matched with **electrical power distribution**
- Site investigations planned for 2024-2025





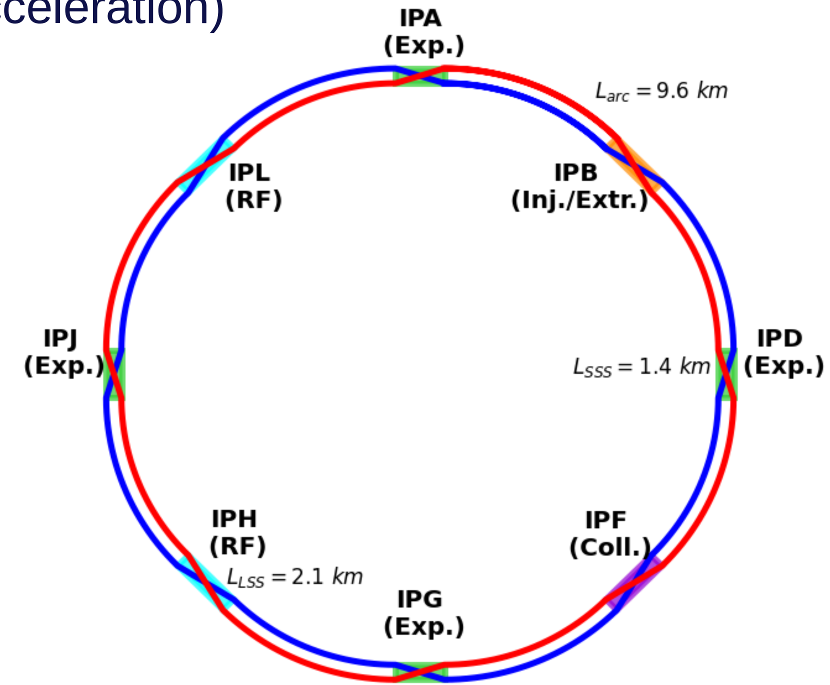
T. Raubenheimer (SLAC)

Altimetry and geological layers along machine circumference

Collider layout and main parameters

- Electron / positron **storage ring** (no acceleration)
- Machine circumference: 90.6 km
- 2840 arc half-cells, ~60 km of dipoles
- Top-up injection from booster

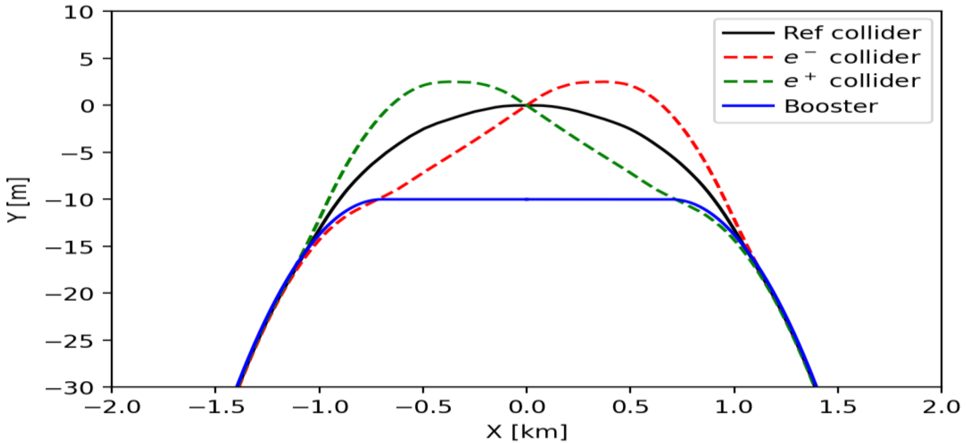
	Z	W	H	$t\bar{t}$
Beam energy [GeV]	45.6	80	120	182.5
Beam current [mA]	**1270**	137	26.7	4.9
Energy loss / turn [GeV]	0.04	0.37	1.89	**10.4**

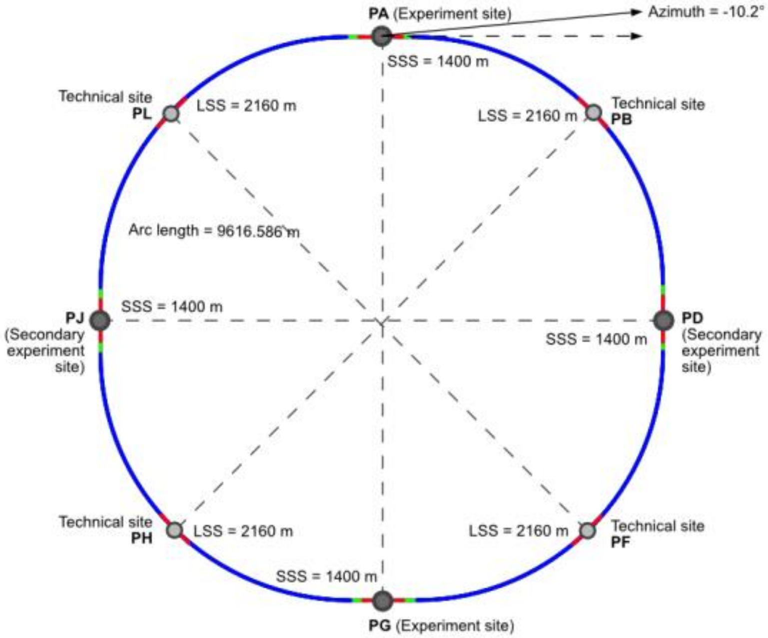


K. Oide

Booster layout and main parameters

- Installed in **same tunnel as collider**
- 2944 arc half-cells, ~65 km of dipoles
- Injection at 20 GeV
- Ramp-up time ~2 sec. at tt_bar



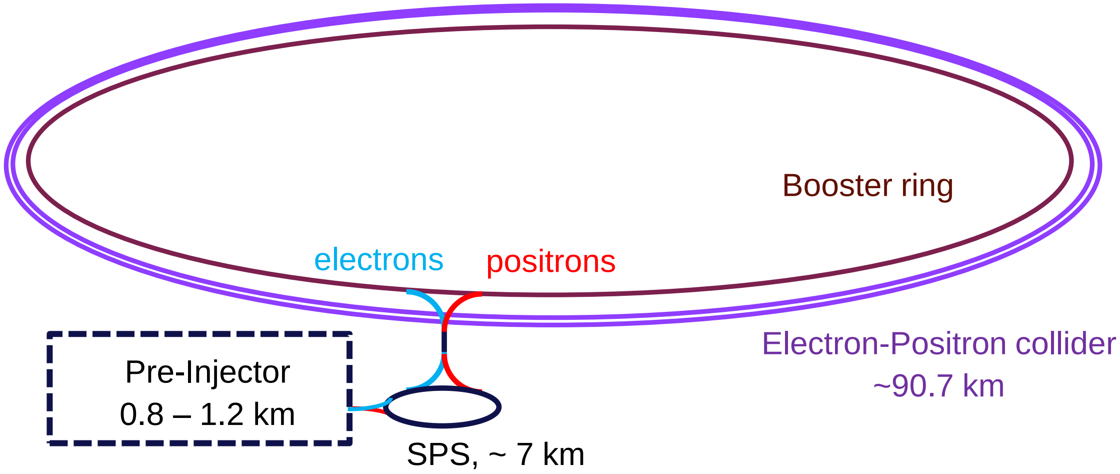


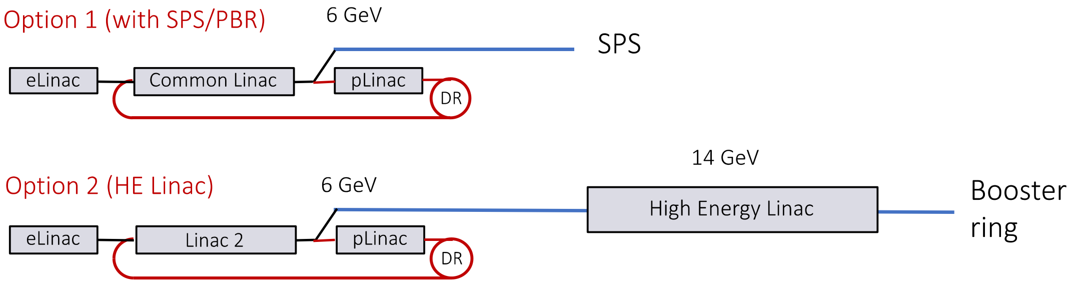
Parameter	Unit	Z	W	H	$t\bar{t}_1$	$t\bar{t}_2$
Flat bottom duration	s	51.1	11.8	5.0	1.6	1.6
Cycle duration	s	51.7	13.3	7.5	5.5	5.7
Ramp rate up	G/s			254		

A. Chancé, B. Dalena (CEA)

Pre-injector layout

- Two options for pre-injector:
  - **SPS** as pre-booster ring
  - **High Energy LINAC**
- Both would inject at **20 GeV** in the booster
- Choice will depend on budget and performance
- Magnet specifications under evaluation by beam optics





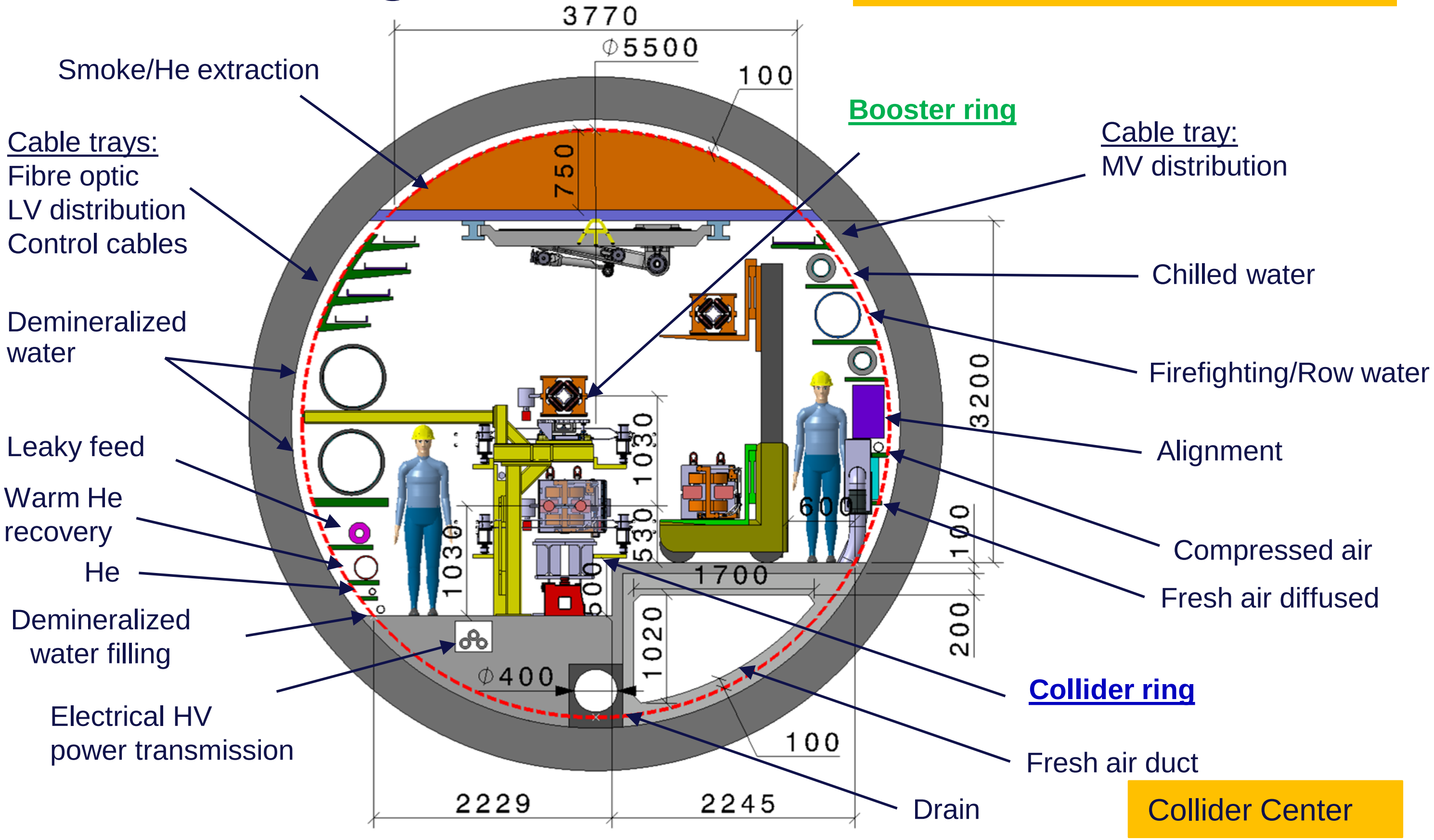
P. Craievich (PSI)

Integration - main ring arcs

Machine tunnel 5.5m in diameter

Diameter and layout of tunnel shall fulfil both **FCC-ee and FCC-hh** requirements

Compactness of components is a key design factor

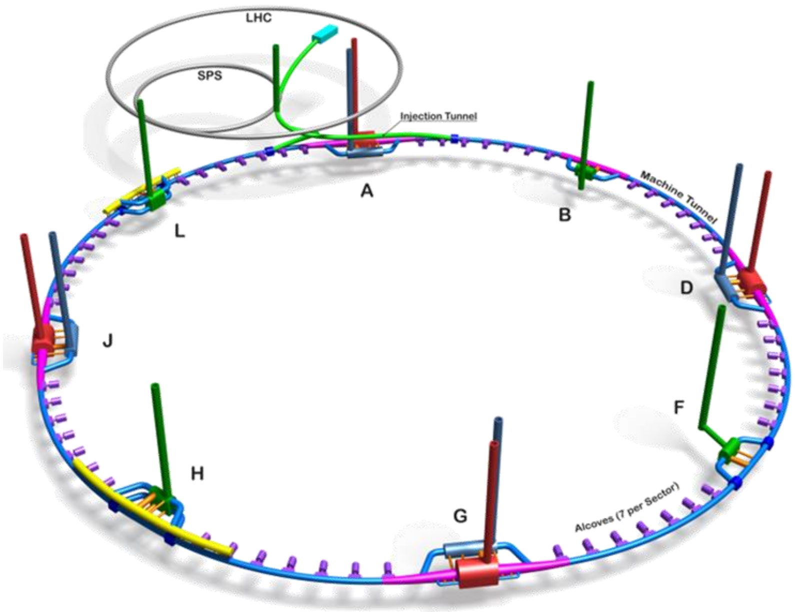


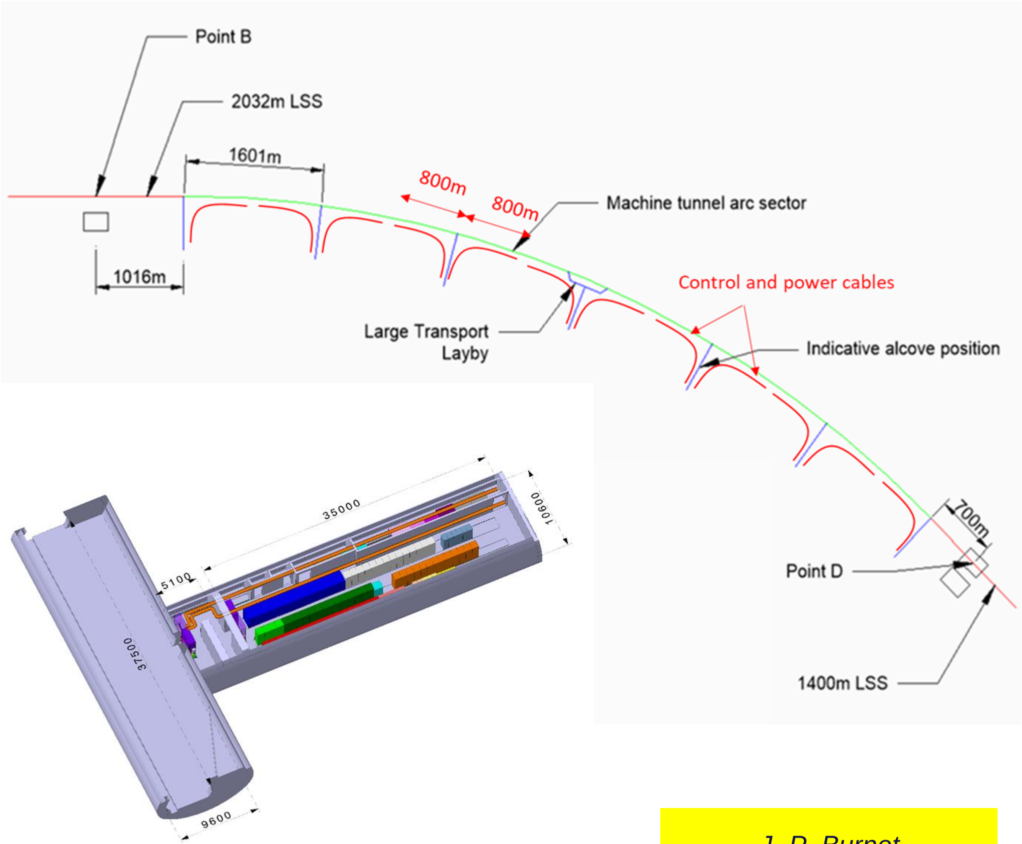
F. Valchkova-Georgieva

Collider Center

Alcoves

- Placed every **1.6 km** to host
  - **Electrical racks** for correction circuits powering, vacuum, instrumentation, etc.
  - **Transport layby** for crossing vehicles

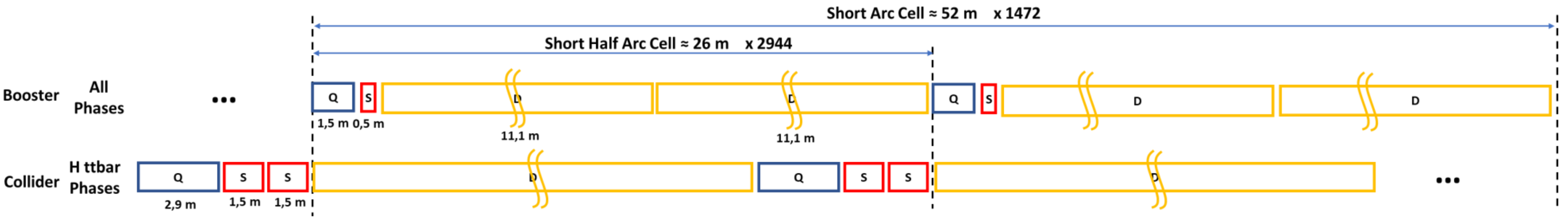




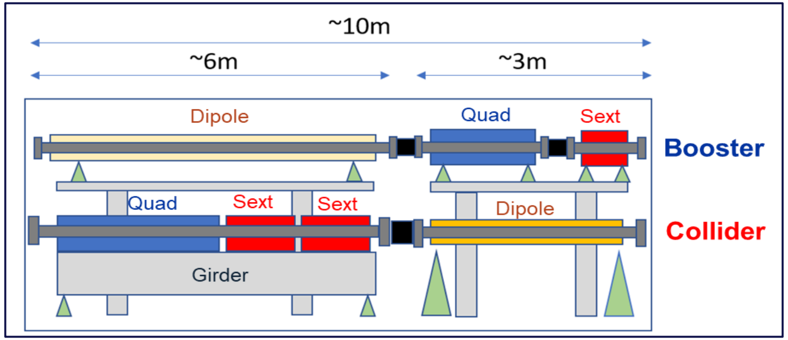
Standard FCC alcove layout

J.-P. Burnet

Regular arcs, half-cell layout



Regular arc half-cell layout



Arc half-cell mock-up proposal from WG

- **SSS are shifted azimuthally** to gain space verticaly, since dipoles are thinner
- An arc **half-cell mock-up** with reduced length elements is under design, to be built in the frame of the feasibility study

F. Carra &
Arc half-cell WG

General considerations for magnet design

General considerations for magnet design

Due to the large **size** of the machine and **number** of elements, the key **design objectives** are:

- **Optimised performance**
  - **Achieving specified** parameters and **integration**
  - **Robust design** to ensure machine **availability** (minimized maintenance)
- **Minimised costs**
  - **CAPEX - Production** costs (**design simplicity and compactness**, automated manufacturing and installation)
  - **OPEX - Operational** costs (**low energy consumption**, minimized maintenance)

Main magnets (arcs)	Quantity	Length [m]
Collider dipole	5680	10.6
Collider quadrupole	2840	2.9
Collider sextupole	4672	1.5
Booster dipole	5888	11.1
Booster quadrupole	2944	1.5
Booster sextupole	1120	0.5
Total	**23144**	

Energy consumption forecast

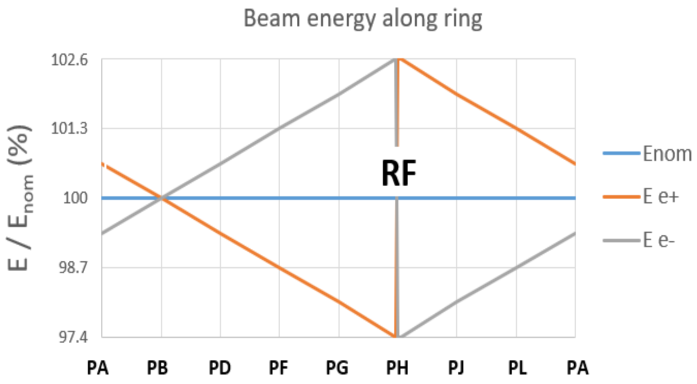
- Power demand dominated by **RF** (41% to 67 %) of total power
- RF power demand is constant at all energy stages, since **SR power losses are constant** (50 MW/beam)
- **Magnet power** demand ranges from **3%** (Z) to **28%** (tt) of total power

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**

J.-P. Burnet

Field tapering

- **Synchrotron radiation** will generate **up to 5.2% of energy loss per turn** at top energy! Scales with 3rd power of energy
- Energy saw-tooth effect needs to be **mitigated** to limit losses and preserve **beam orbit** in collider
- **Field** shall be **tuneable** along machine circumference, up to ±2.6% at 182.5 GeV (but only ±0.04% at 45 GeV)
- Tapering circuits grouped every 4 FODO in present optics layout



Beam energy along ring at 182.5 GeV

→ **Tapering options for large magnet series circuits:**

Adjusted parameter	System		
~~Magnetic length~~	~~Pole end shims~~	No powering	No tunability Resolution
Magnetic **field**	Trim windings	Tunability Use for corrections	Powering Field quality
~~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

Correction circuits

Baseline: synchrotron light source scheme

→ **Orbit** and **quadrupoles corrections**: trim coils in **sextupoles**

→ granularity < arc half-cell (40% of half-cells with no sextupoles)

BASELINE	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Sextupole	**1.5**	**0.013**	**0.02**
Orbit correction V	Sextupole	**1.5**	**0.013**	**0.02**
Normal quadrupole	Sextupole	**1.5**	**0.4**	**0.6**
Skew quadrupole	Sextupole	**1.5**	**0.4**	**0.6**

Correction specifications from optics

Alternatives

1) H + V orbit corrections use **quadrupole** tapering trim coils

→ granularity: at every arc half-cell

2) H orbit correction uses **dipole** tapering trim coils **+ V orbit correction** uses **quadrupole** tapering trim coils

→ granularity: at every arc half-cell

ALTERNATIVE 1	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Quadrupole	**2.9**	**0.0067**	**0.02**
Orbit correction V	Quadrupole	**2.9**	**0.0067**	**0.02**

ALTERNATIVE 2	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Dipole	**21.15**	**0.0009**	**0.02**
Orbit correction V	Quadrupole	**2.9**	**0.0067**	**0.02**

Collider magnets – Regular arcs

Arc magnet specifications

- **Luminosity** depends on **dipole filling factor**, needs to be maximized to minimize SR
  - → **Low field in dipoles** compared to quads and sextupoles
  - → **Dipole length** variable with sextupole presence in SSS
- **Apertures** have been reduced recently, still under evaluation…
- Smaller aperture in sextupole (no vacuum bake-out system)
- **Field quality** specifications from latest beam dynamics studies, **achievable for arc magnets**

	Mag. Length [m]	Bore aperture (reduced) [mm]	Vacuum aperture (reduced) [mm]	Pole tip field [T]	Number of units (arcs)	Total magnetic length [km]	Ring filling factor (91 km) [%]
Dipole (S)	19.30				1128	21.77	
Dipole (M)	20.95	**37**	**30**	**0.061**	284	5.95	
Dipole (L)	22.65				1428	32.35	
Total					**2840**	**60.1**	**65.9**
Quadrupole	**2.9**	**37**	**30**	**0.438**	**2836**	**8.2**	**9.0**
Sextupole	**1.5**	**33**	**30**	**0.442**	**4672**	**7.0**	**7.7**

Arc magnet specifications from optics – May 2023 (K. Oide)

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

Magnet field quality specifications from optics – March 2023 (R. Tomas)

Collider dipole

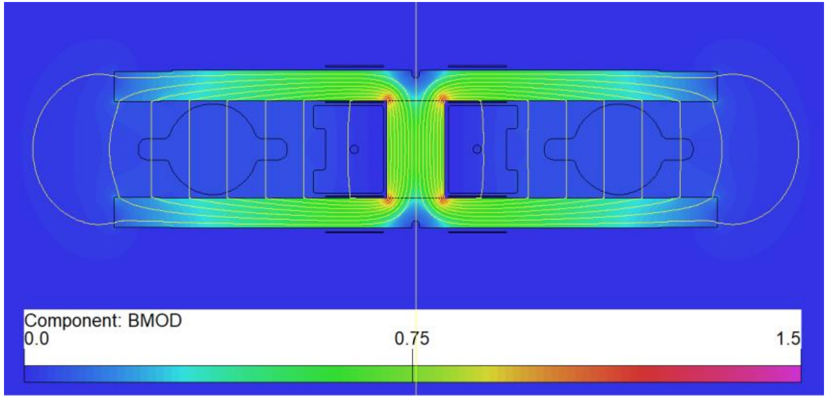
Dipole design

- **Twin aperture** design, **magnetically coupled**, low field

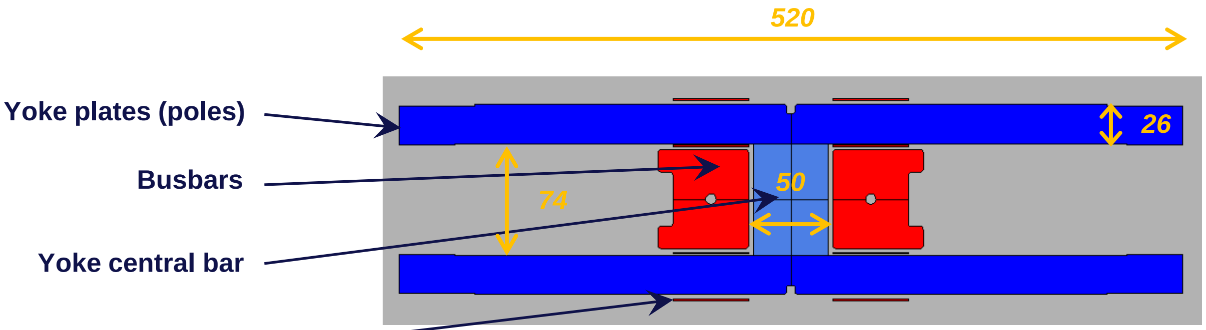
→ **Low power consumption** (50% w.r.t. separate magnets)

- I-shape yoke allows compactness and simplicity
- **Inter-beam distance** 350 mm shared between vacuum chamber, SR absorbers, busbars and yoke return leg
- DC operation, compatible with **solid iron** yoke technology
- Single water-cooled busbar; trim coils for corrections

➔ **Design compatible with low-cost production**



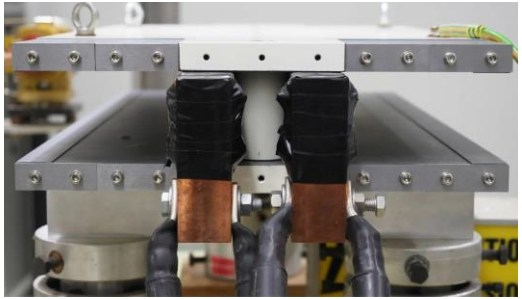
Magnetic model cross-section at peak excitation (B = 61 mT)



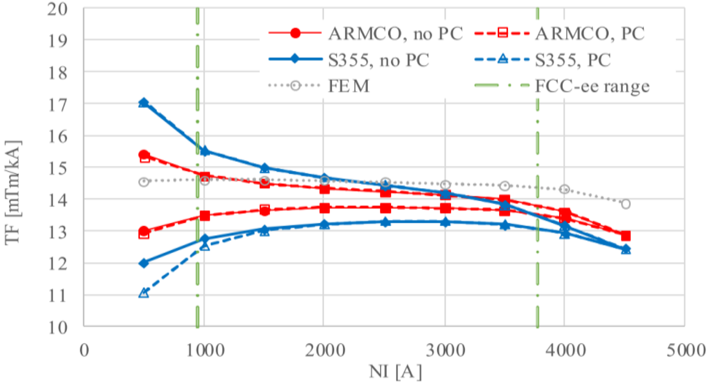
Cross-section geometry

Dipole – 1st model magnets

- Two **model magnets** built with different yoke materials
  - «Noble» **pure iron** (ARMCO)
  - Standard **constructional steel (**S355)
- **Hysteresis** loop more pronounced with constructional steel, as expected from coercivity
- Machine operated in DC, **degaussing** and **precycling** can be included during **machine set-up**
- Tapering trim coils not yet included in design at this stage



1st model magnet 1m-long, single busbar



Measured transfer function – comparison ARMCO vs. S355

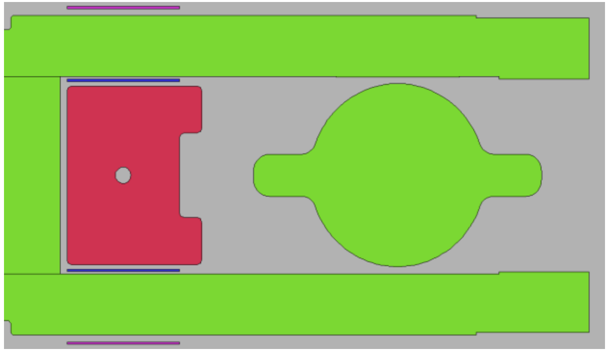
Dipole field tapering and tuning

Trim coils

- Allow to modulate the field in the apertures independently for:

→ **Field tapering** up to **±2.6 %** (tt_{bar})
→ **Field tuning** up to **±1 %** (all phases)
→ Possibly, **H orbit correction** (up to **±1.5 %**)

→ **Worst case**: could be up to ~**5% of main field** variation



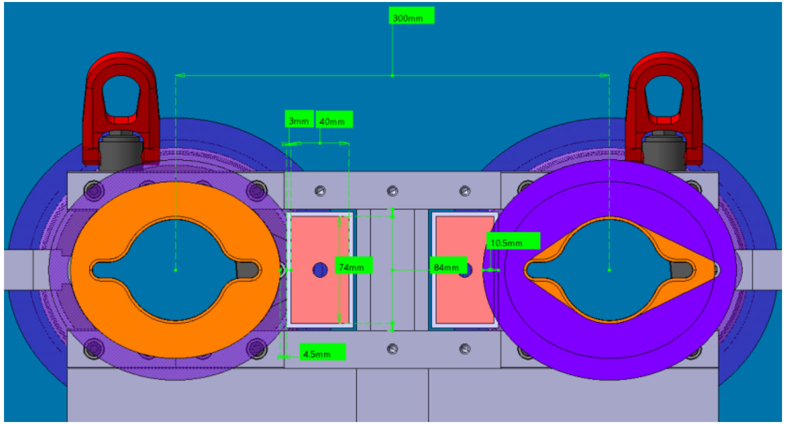
Trim coils wrapped around top and bottom poles

Vacuum integration

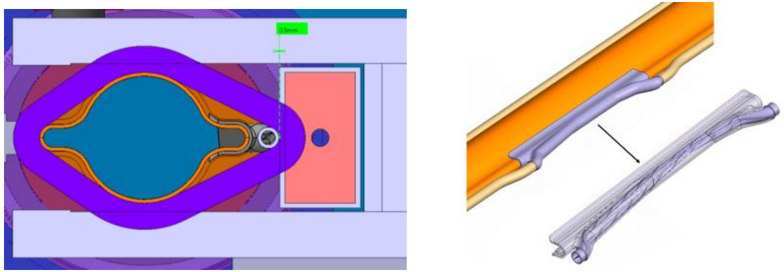
- **SR power** is collected by **absorbers** integrated on vacuum chamber winglets
- Large amount of **radiation** still expected in the surrounding equipment (under evaluation)

→ **Single busbar** design

- Provides significantly better **radiation hardness** w.r.t. multi-turn “coil” solution
- Much **cheaper to produce** (extrusion), no winding, no complex impregnation…
- However, **larger dissipated power** due to higher transport current (still… only about 25% of the dipole circuit power, which is only between 0.5 and 5.5% of the full machine power…)
- **Insulation technology** to be assessed based on outcome of radiation studies (e.g. inorganic coatings, mica-based wrapping with cyanate-esther impregnation, etc.)



Dipole cross-section with SMA flanges



SR absorber integration in dipole

C. Tetrault, S. Rorison, R. Kersevan, C. Garion

Dipole performance

Magnetic design

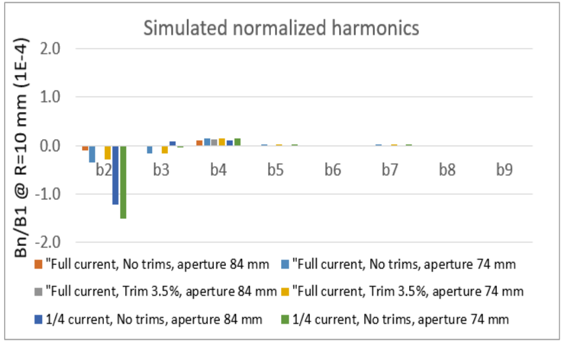
The magnet geometry optimized for:

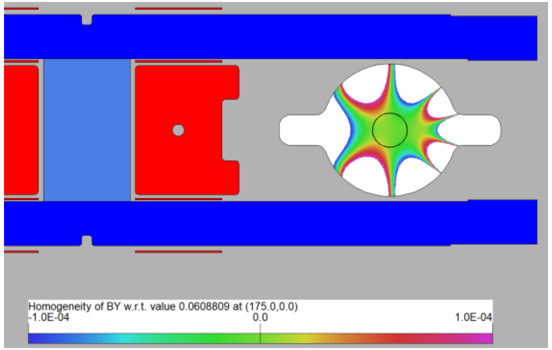
- b_n < 0.5 units
- b_2 < 1.5 units (not incl. in field error budget for optics)

Main parameters

- **Aperture reduction** would reduce the **power consumption** by **~10%**
- **Copper busbars** would reduce the **power consumption** by **~35%**

→ to be decided from **lifetime cost optimization**





Field harmonics (left) and homogeneity at peak field (right)

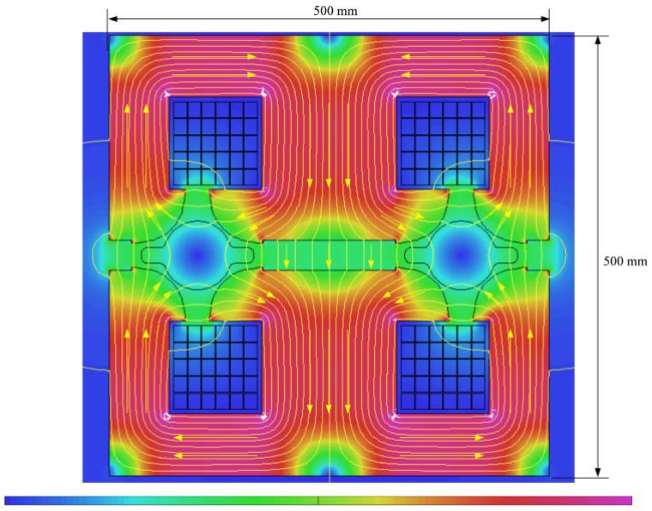
Parameter	Unit	CDR	2023, ap. 84 mm		2023, ap. 74 mm	
		Al BB	Cu BB	Al BB	Cu BB	Al BB
		Value	Value	Value	Value	Value
Number of units		2900	2840		2840	
Total magnetic length	km	65	60.1		60.1	
Central field, 45.6 GeV – 182.5 GeV	mT	14.1 - 56.6	15.3 - 61.3		15.3 - 61.3	
Inter-beam distance	mm	300	350		350	
Bore aperture	mm	84	84		74	
Magnetic lengths	m	10.6 - 12.2	19.30 - 22.65		19.30 - 22.65	
Magnet overall transverse dimensions	mm	450 x 136	520 x 144		520 x 134	
Iron mass per unit length	kg/m	219	243		239	
Busbar mass per unit length	kg/m	19.9	75	23	64	19
Magnet unit mass (10.6 m average length)	kg	2678	3562	2976	3395	2893
Total magnet mass, 60.1 km	tons	15529	19098	15954	18202	15509
Maximum operating current (tt_bar)	A	1900	4116		3628	
Maximum current density (tt_bar)	A/mm2	0.79	0.98		1.01	
Resistance per unit length	µΩ/m	22.7	8.22	12.66	9.59	14.78
Maximum voltage to ground per 1/2 octant (balanced at mid-point)	V	88	64	98	65	101
Maximum dissipated power per unit length (tt_bar)	W/m	164	139	215	126	195
Total dissipated power, 60.1 km (tt_bar; busbars interconn. not incl.)	MW	10.7	8.4	12.9	7.6	11.7
Total dissipated power, 83.0 km (tt_bar; busbars interconn. incl.)	MW	13.3	11.6	17.8	10.5	16.1

Main magnet parameter comparison (computed at tt_{bar})

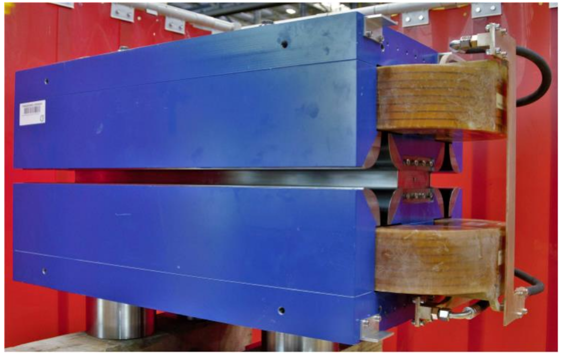
Collider quadrupole

Quadrupole design, CDR

- **Twin aperture** design, **magnetically coupled**
- Only **2 racetrack coils** for 8 poles, out of mid-plane (SR)
- **Low power consumption** (50% w.r.t. separate magnets)
- Top-bottom assembly via non-magnetic central spacer
- Balance of **parallel flux loops** controlled by central gap height (adjustable with end shims)
- **DC** operation (solid iron yoke), classical field range



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

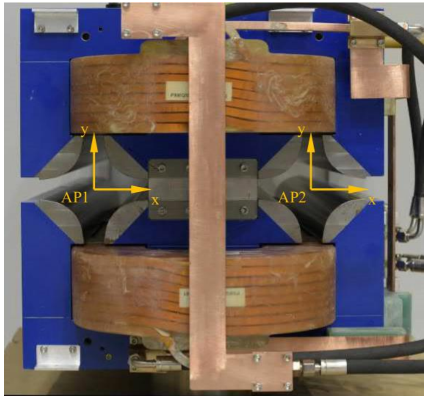


1st model magnet, 1m-long

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 model magnet, CDR



Magnetic measurements performed on 1-m model magnet

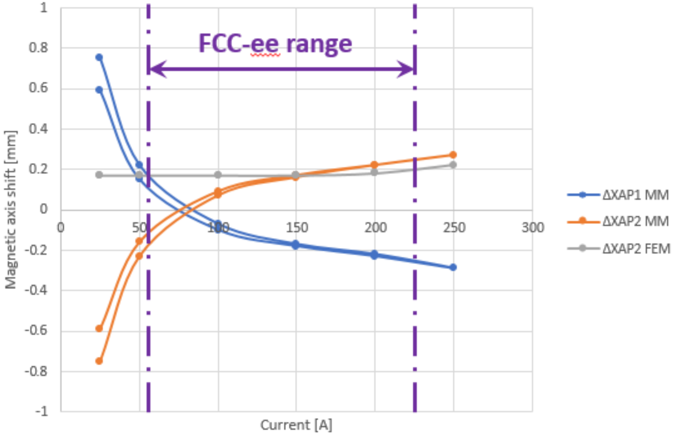
- **~0.4 mm magnetic axis shift** for each aperture between low and high fields
- Mismatch MM vs. FEM (3D) at low fields has been further investigated
- Trim circuits not yet implemented in the design at this stage

DIPOLE AND SEXTUPOLE COMPONENTS IN THE TWIN QUADRUPOLE

I [A]	x_{ctr} [mm]			∫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

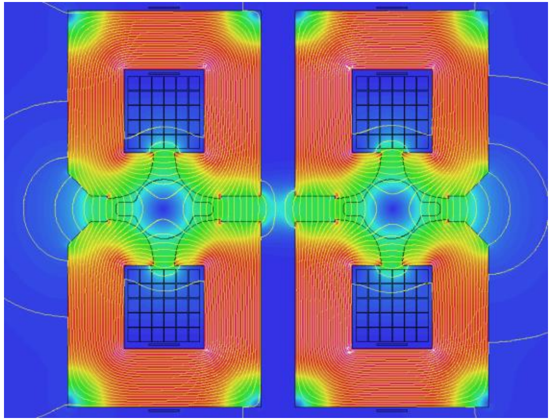
Quadrupole field tapering v.1

Trim coils

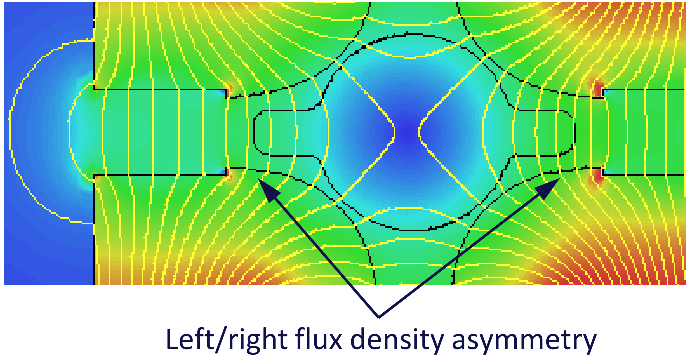
- Wrapped around the back legs to trim individually each aperture
- **Significant cross-talk** : both magnetic axes shift up to 0.2 mm in same direction, even when single aperture trim is activated
- b_3 scaling accordingly

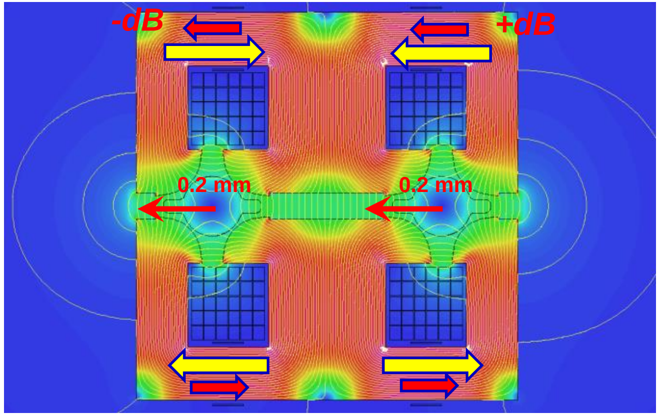
→ Issue coming from **unbalanced flux densities** on either sides of the apertures, scaling with powering and trim currents

→ Attempt to re-equilibrate the flux densities with yoke separation and side chamfer → partially successful, but not at all powering levels



Separated yokes with chamfer



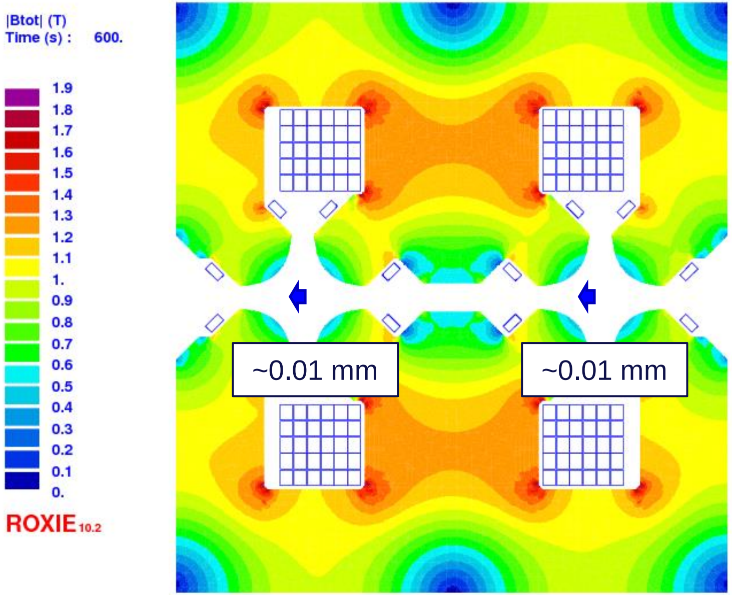


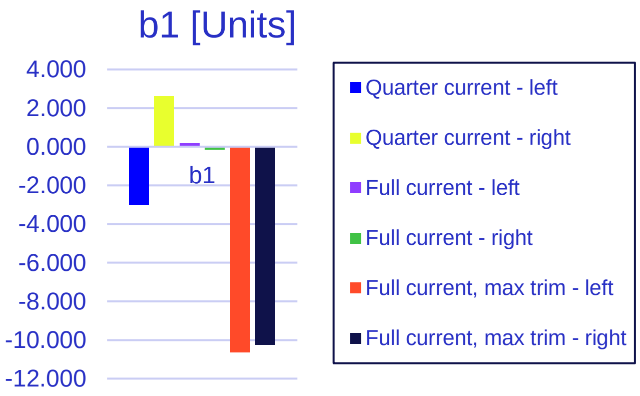
Flux density and field lines, trims activated

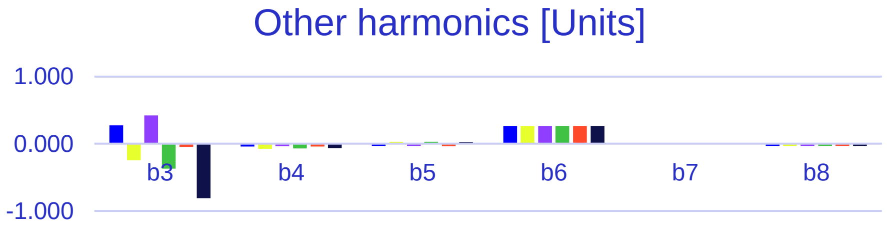
Quadrupole - new design

- 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):
  - → **b1** reduced to **~10 units**
  - → Magnetic **axis shift** reduced to **~0.01 mm**







Trim circuit options

1. If only **quadrupolar tapering / tuning** is needed, all trim coils in each aperture can be powered in series
   → **1 trim power supply** per aperture

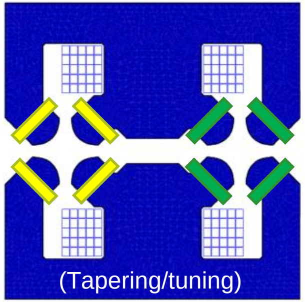
2. If either **horizontal <u>or</u> vertical dipole correction** is required, each pair of adjacent trim coils can be powered in series
   → **2 trim power supplies** per aperture

3. If both **horizontal <u>and</u> vertical dipole correction** is required, each trim coil needs to be powered independently
   → **4 trim power supplies** per aperture

Powered by:
- power supply # 1 (yellow)
- " " # 2 (green)
- " " # 3 (red)
- " " # 4 (blue)

Etc…

1.



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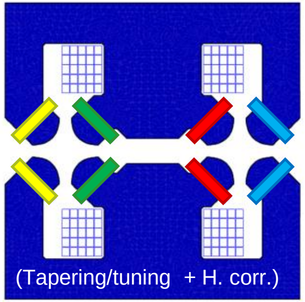
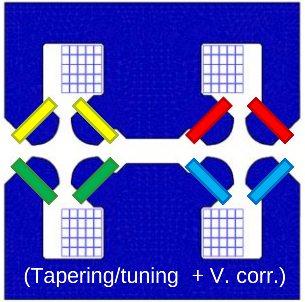


or



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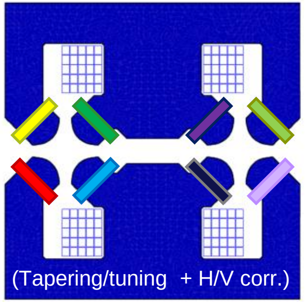
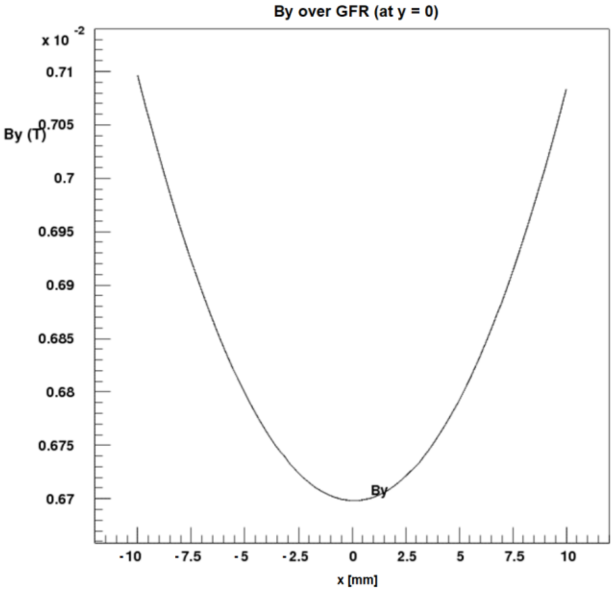


Horizontal correction: field quality

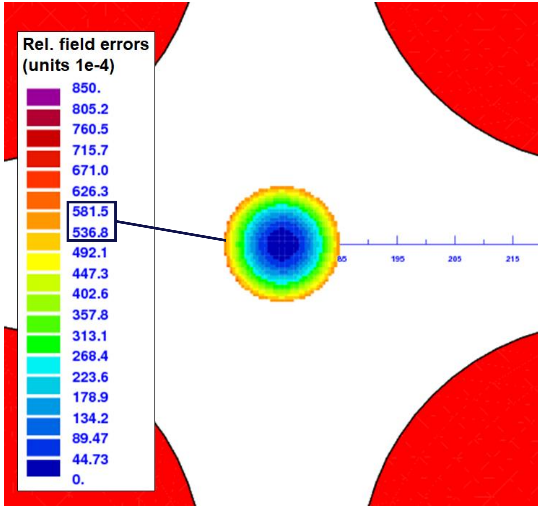
- Field quality **dB/B ≈ 6%**.
- Large **sextupole component**

Rref = 10 mm	Main harmonic: B1
b1	10000.000
b2	-9.499
b3	578.806
b4	-0.005
b5	5.581
b6	0.000
b7	-0.292
b8	-0.001
b9	-0.006
b10	0.000

Harmonics – horizontal correction dipole



Dipole field over GFR axis



Field quality in GFR

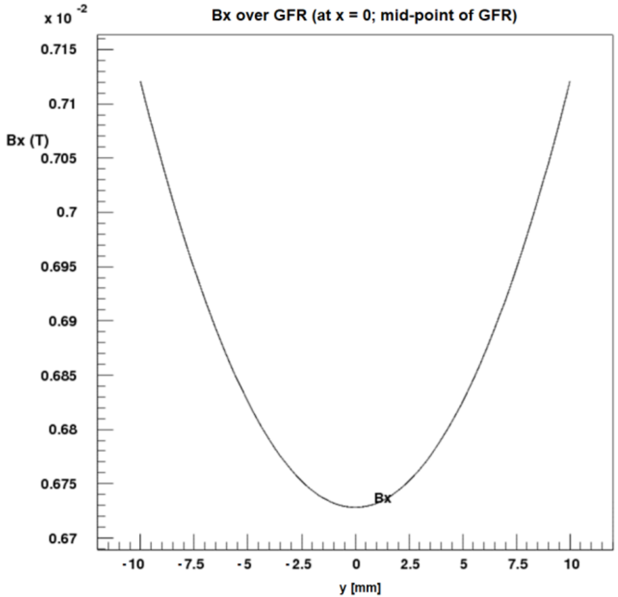
Main coils OFF → Field homogeneity and harmonics w.r.t. **dipole component**

Vertical correction: field quality

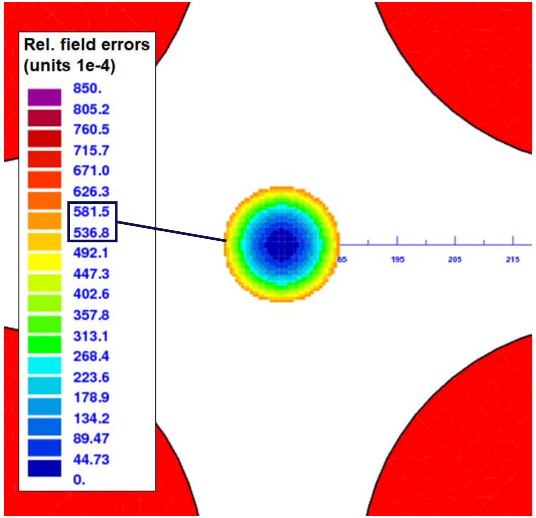
- Same as for horizontal corr., due to pole symmetry, but components are **skew**
- Field quality **dB/B ≈ 6%**.
- Large **skew sextupole component**

Rref = 10 mm	Main harmonic: A1
a1	10000.000
a2	0.265
a3	-577.456
a4	0.032
a5	5.659
a6	0.002
a7	0.295
a8	0.000
a9	-0.006
a10	0.000

Harmonics – vertical correction dipole



Dipole field over GFR axis



Field quality in GFR

Main coils OFF → Field homogeneity and harmonics w.r.t. **dipole component**

Quadrupole field quality with orbit correction

- **Sextupole component** introduced by horizontal or vertical correction is **significant** with respect to the main quad field

→ Values sumbmitted to beam optics physicists, expecting feedback

Rref = 10 mm	Main harm: B2	Rref = 10 mm	Main harm: B2
b1	554.930	a1	0.000
b2	10000.000	a2	0.000
b3	**31.367**	a3	0.000
b4	0.001	a4	0.000
b5	0.345	a5	0.000
b6	0.271	a6	0.000
b7	-0.018	a7	0.000
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max horizontal correction

Rref = 10	Main harm: B2	Rref = 10	Main harm: B2
b1	-4.357	a1	554.098
b2	10000.000	a2	0.020
b3	-1.004	**a3**	**-31.996**
b4	0.000	a4	0.002
b5	0.033	a5	0.313
b6	0.271	a6	0.000
b7	-0.002	a7	0.016
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max vertical correction

Main coils ON → Field homogeneity and harmonics w.r.t. **quadrupole component**

Powering requirements

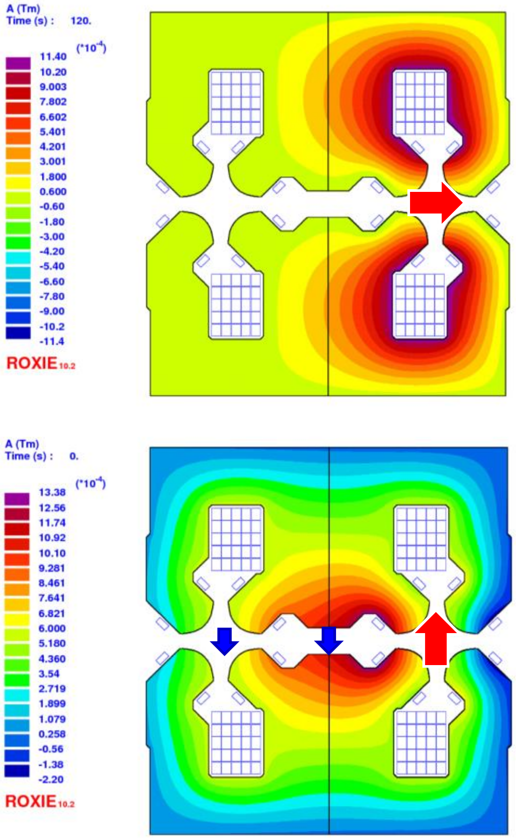
<u>Vertical correction:</u>

- Negligible cross-talk; **NI = 177 A** per trim coil to achieve max corr. field

<u>Horizontal correction:</u>

- **Large cross-talk between apertures:** opposing aperture must apply an opposing correcting field to compensate
  - With peak correction field, each trim coil needs **NI = 477 A**

→ **<u>Not really a viable option</u>**

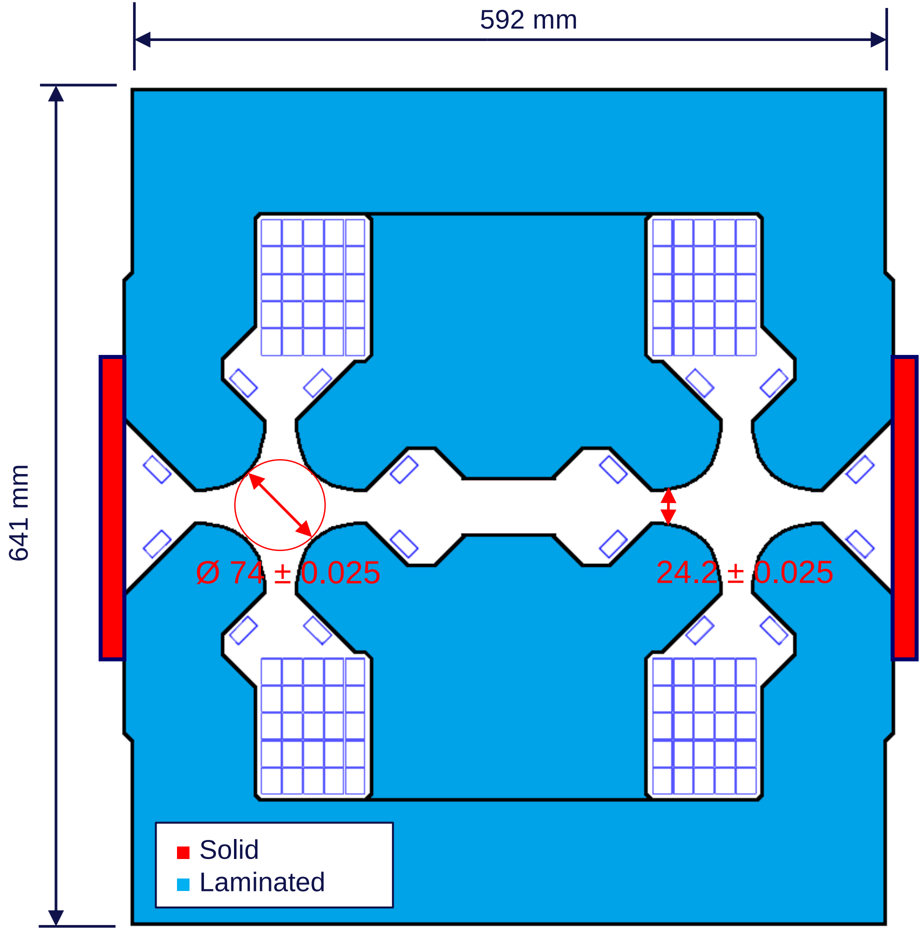


Flux potential for vertical (top) and horizontal (bottom) corrections

Collider quadrupole - mechanical design

- Top and bottom yokes have to be **split** in two halves for coil integration
- **Laminated** yoke construction required for **cost-effectiveness**
- **Mechanical tolerances** to be evaluated with sensitivity studies
- For U-shape external pieces, **stamping** in **2 steps** may be needed to release internal stress in the material
- Position of **non-magnetic spacers** for top-bottom assembly to be studied

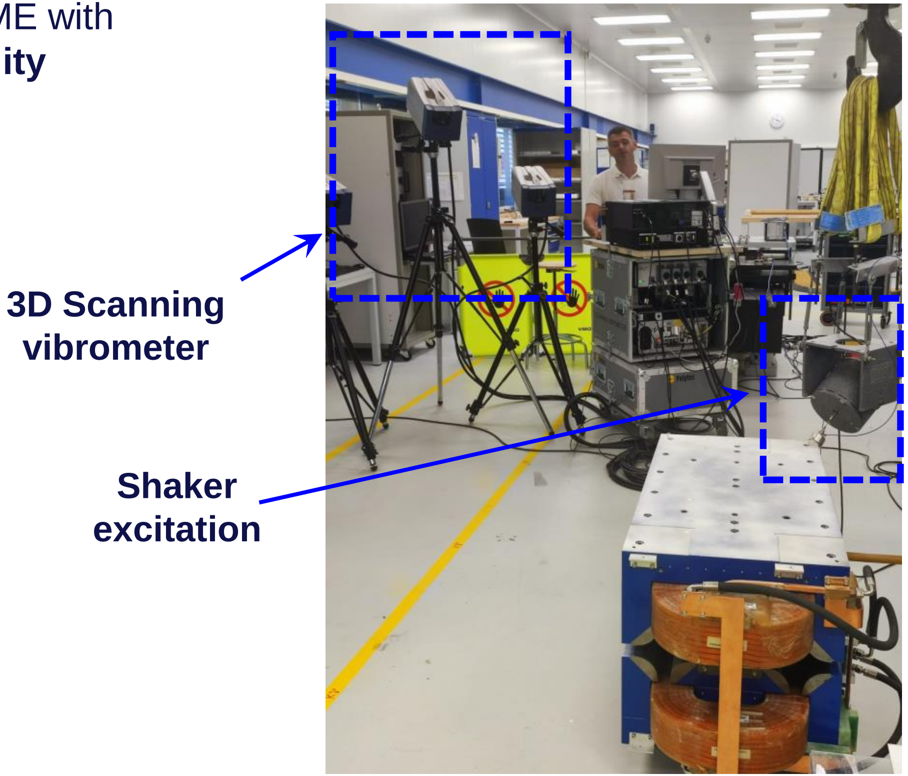
Yoke mass ≈ 6300 kg
Coils masses (main + trims) ≈ 900 kg



Latest cross section design

Experimental Modal Analysis of FCC quadrupole

- Model magnet **modes measured** by MME with vibrometer to assess **mechanical stability**

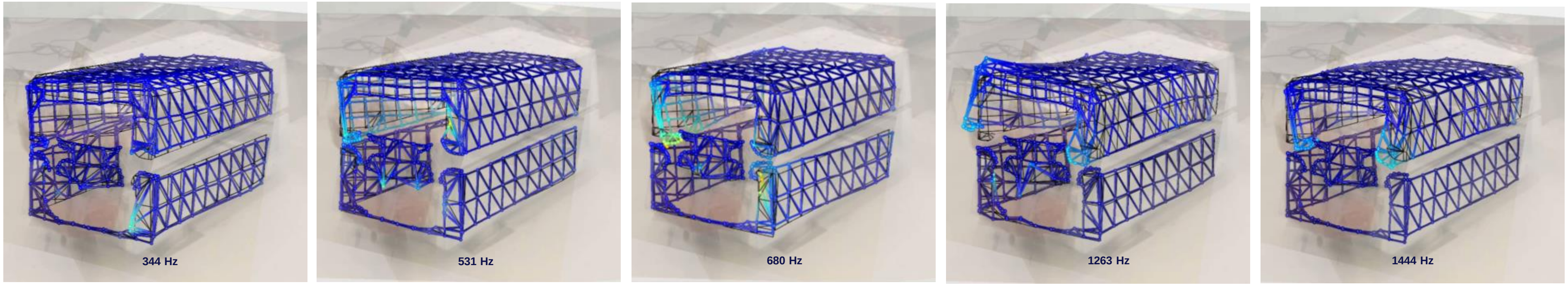


M. Guinchard, D. Thuliez

Comparison of shape modes results

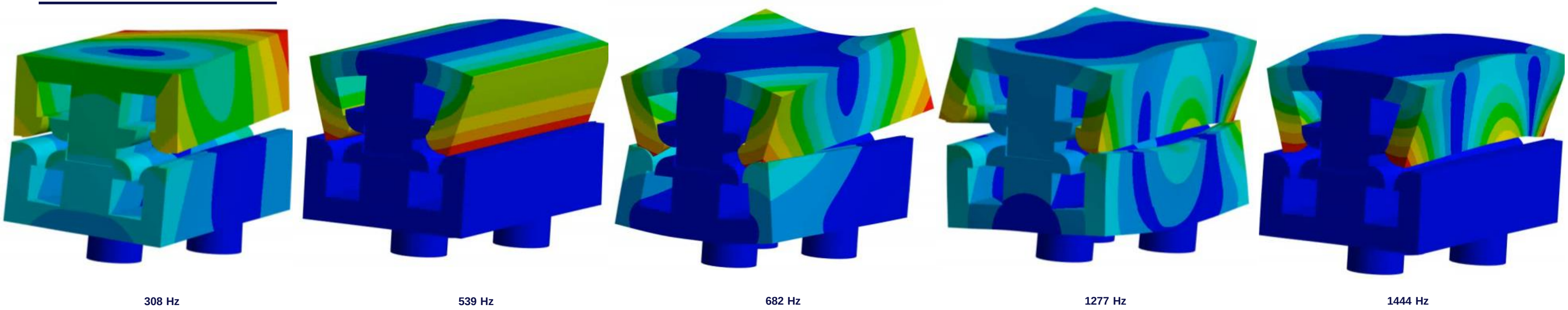
M. Guinchard, A. Piccini

Experimental results:



Simulation results well benchmarked with experimental results

Simulation results:

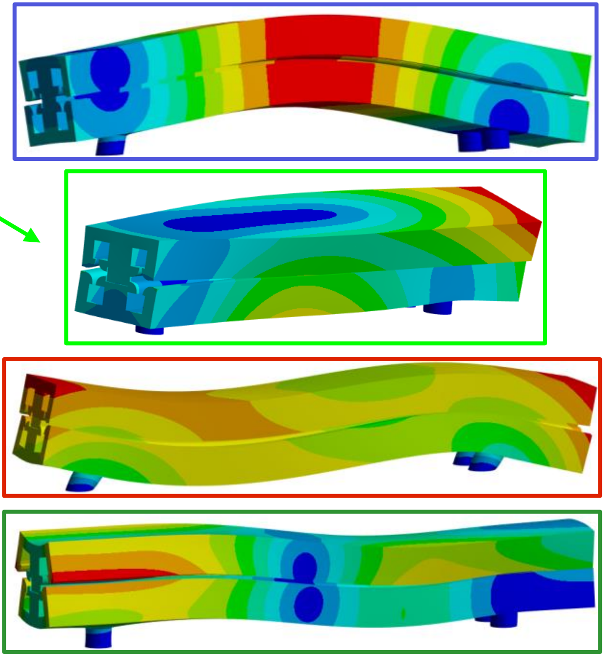


Results for the 2.9 m long quadrupole

A. Piccini

SIMULATION 1 m long	
Modes	Frequency (Hz)
S1	187
S2	308
S3	363
S4	460
S5	539
S6	597
S7	614
S8	652
S9	682
S10	780
S11	810
S12	867
S13	973
S14	1037
S15	1151
S16	1277
S17	1314
S18	1332
S19	1349
S20	1418
S21	1454

SIMULATION 2.9 m long	
Modes	Frequency (Hz)
S1	76
S2	161
S3	186
S4	201
S5	247
S6	297
S7	417
S8	423
S9	446
S10	447
S11	463
S12	518
S13	528
S14	553
S15	556
S16	572
S17	596
S18	605
S19	625
S20	630
S21	647

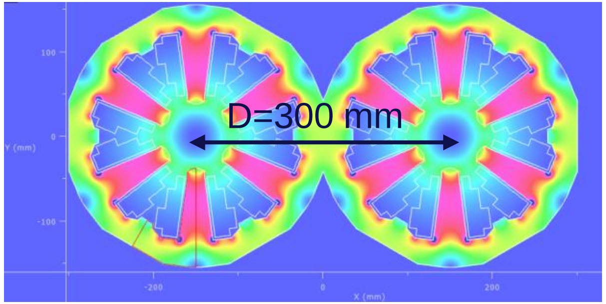


Shape modes of CDR cross section at nom. length expected > 100 Hz

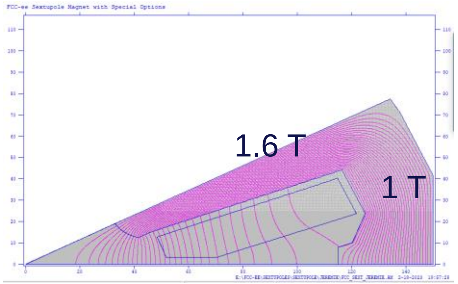
Collider sextupole

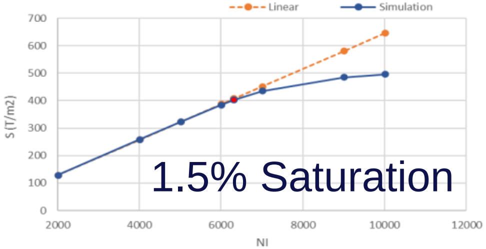
Sextupole in CDR (R_{bore} = 38 mm)

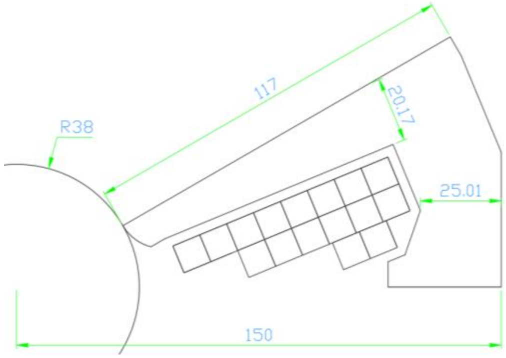
- **Single aperture** magnet, powered in **small series** (4 FODO)
- 300 mm **inter-beam distance**, was at the limit of compatibility for **individual magnets** on each beam
- **Current** and **flux densities** at **upper values, large dissipated power**
- Space for integration of **trim circuits** (H/V orbit correctors, skew quadrupoles) was not considered



Parameter	Unit	Value
Sextupole Strength	T/m2	**807**
Total current	At	**6300**
Number of turns per coil	-	15
Conductor dimensions	mm^2	8×8
Cooling diameter	mm	3
Current density	A/mm^2	**7.87**
Voltage drop per magnet	V	34.5
Resistance per magnet	mΩ	77
Power per magnet	kW	**15.5**
Number of water circuits	-	**18**
Water temperature rise	°C	10.5
Cooling water speed	m/s	2.77
Pressure drop	bar	6
Reynolds No.	-	4150







F. Saeidi

Sextupole specifications update

Main Parameter	Unit	CDR (2019)	Latest (2022)	Comment
Sextupole strength (B’’)	T/m2	807	876.6	Incl. tapering (3%) & tuning (5%) margins
Bore aperture radius (CDR)	mm	38	38/33	Incl. 2 mm VC thickness and 1 mm clearance
Reference radius for good field region (GFR)	mm	±10	±10	
Field quality in GFR	1.0E-04	≈1	1	
Magnetic length	mm	1400	1500	
Drift space between two consecutive sextupole magnetic lengths	mm	100	150	Considering in 3D designing
Magnet maximum physical half-width in inter-beam distance	mm	145	170	Considering inter-beam distance of 350 mm
Horizontal orbit correction integrated field strength	Tm	-	0.02	B=0.013 T
Vertical orbit correction integrated field strength	Tm	-	0.02	B=0.013 T
Skew quadrupole correction integrated gradient	T	-	0.6	G=0.4 T/m

→ Latest requirements more challenging than CDR

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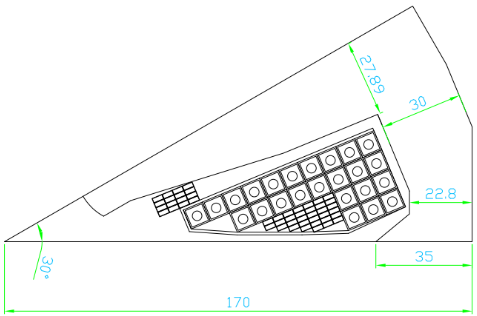
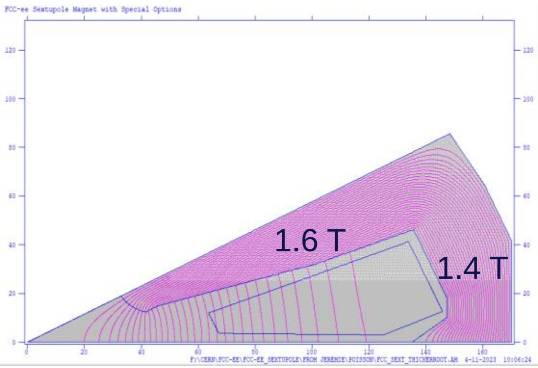
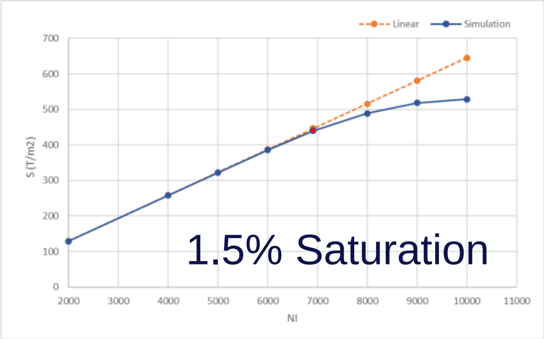
Sextupole v2 (R_{bore} = 38 mm)

- Addition of auxiliary coils
- Reworked yoke geometry to limit saturation to ~**1.5%**







Parameter	Unit	Value
Sextupole Strength	T/m2	**880**
Total current	At	6920
Number of turns per coil	-	22
Conductor dimensions	mm^2	6.5×6.5
Cooling diameter	mm	3.5
Current density	A/mm^2	**9.6**
Voltage drop per magnet	V	70
Resistance per magnet	mΩ	223
Power per magnet	kW	**22.1**
Number of water circuits	-	18
Water temperature rise	°C	13.2
Cooling water speed	m/s	2.3
Pressure drop	bar	6
Reynolds No.	-	4030

- The current density is increased to 9.6 A/mm^2.
- Power increased to **22 kW**
  - Requires 18 parallel cooling circuits
- Still very limited space for auxiliary coils

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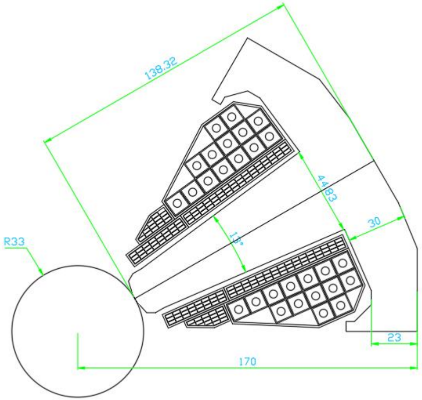
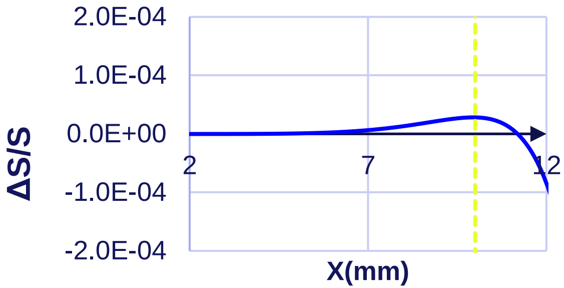
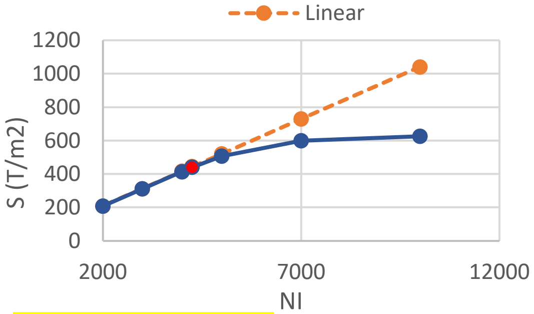
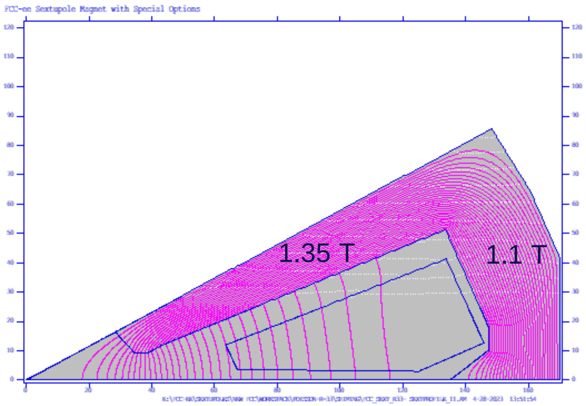
Sextupole v3 (R_{bore} = 33 mm)

- Reduced aperture









Parameter	Unit	Value
Sextupole strength	T/m2	**880**
Current	A	**4250**
Number of turns per coil	-	14
Operation current	A	304
Conductor dimensions	mm^2	**8.5×8.5**
Cooling diameter	mm	4
Current density	A/mm^2	**5.1**
Voltage drop per magnet	V	23.4
Resistance per magnet	mΩ	78
Power per magnet	kW	**7.2**
Number of water circuits	-	**6**
Water temperature rise	°C	13.2
Cooling water speed	m/s	1.8
Pressure drop	bar	6
Reynolds no.	-	3530

- Power decreased to 7.2 kW
  - ✓ 1/3 of R=38 (880 T/m2)
  - ✓ 1/2 of CDR (807 T/m2)
- Saturation <1%
- Gradient homogeneity < 0.5 units

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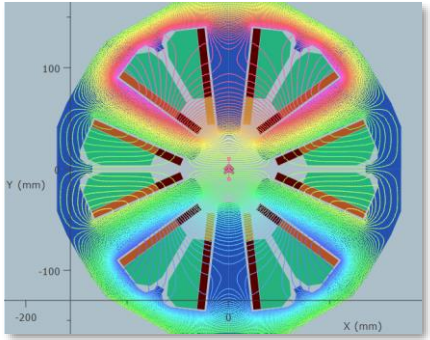
Corrector circuits

- **Baseline**: similar scheme as synchrotron light sources
- **Orbit correction** circuits could be **moved to dipoles and quads**

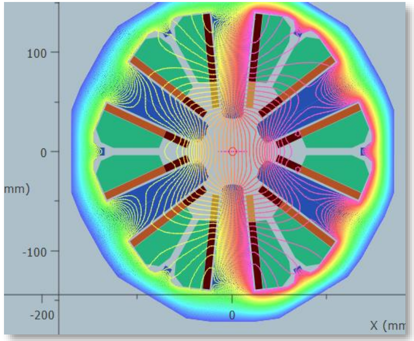
Green Coils: Main Sextupole
Orange Coils: Vertical Corrector
Brown Coils: Horizontal Corrector
Red Coils: Normal Quadrupole
Yellow Coils: Skew Quadrupole

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

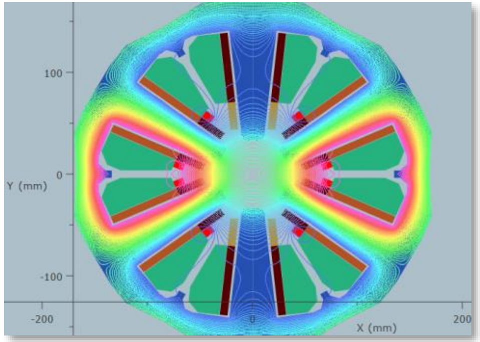
Vertical Corrector



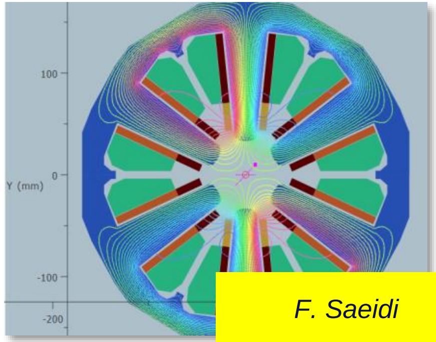
Horizontal Corrector



Normal Quad Corrector



Skew Quad Corrector



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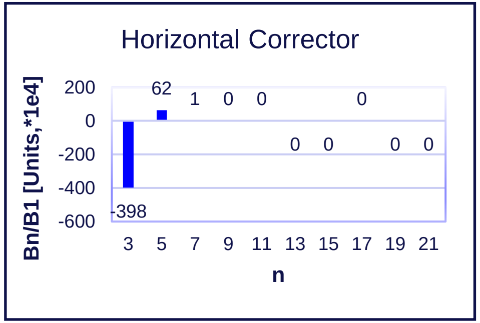
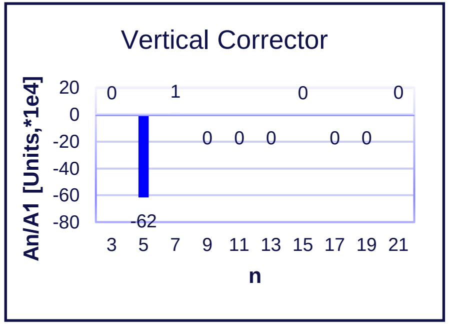
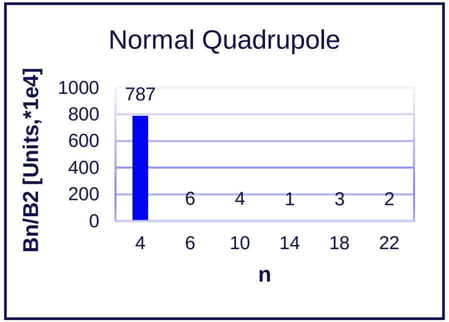
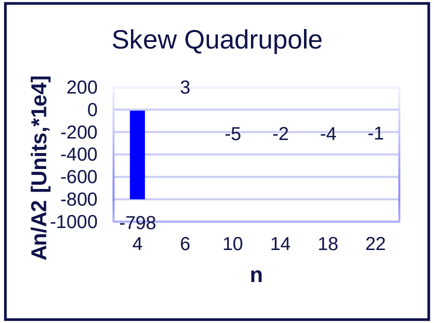
Correction circuits field quality

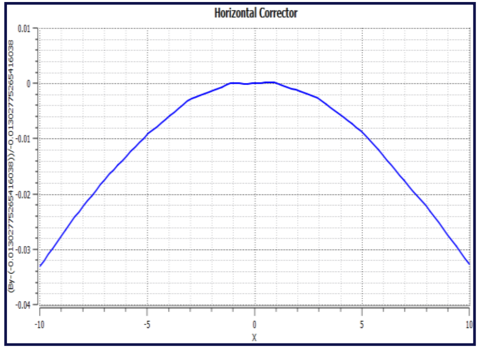




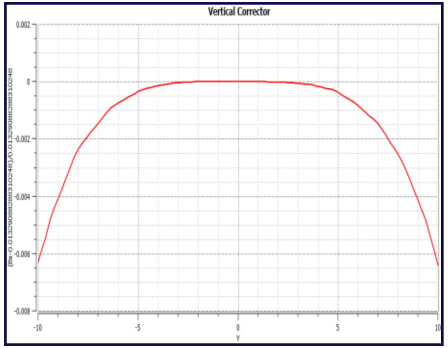




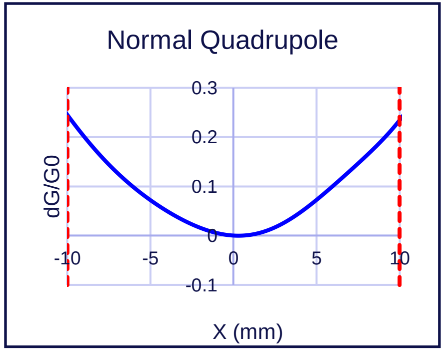
Main coils OFF → Field homogeneity and harmonics w.r.t. **correction field component**



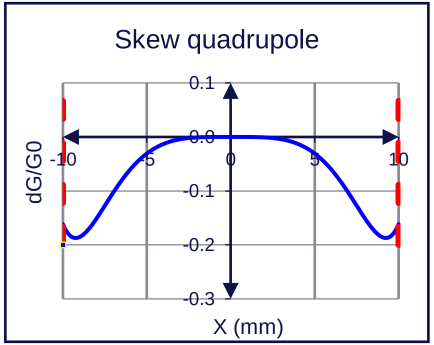
By field homogeneity
$B_y(0)$ = 0.013 T



Bx field homogeneity
$B_x(0)$ = 0.013 T

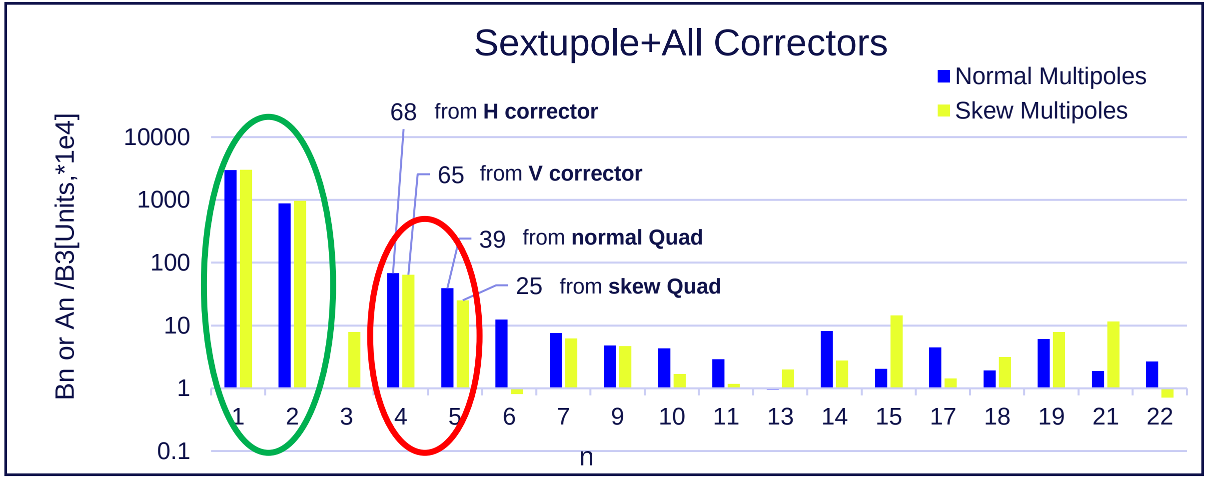


Normal gradient homogeneity
$G_n(0)$ = 0.4 T/m



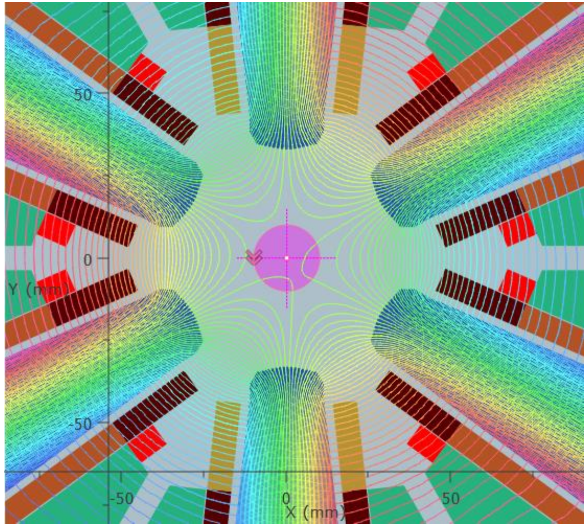
Skew gradient homogeneity
$G_s(0)$ = 0.4 T/m

Correction circuits field quality



<u>All coils ON</u> <u>(main **and** trim)</u>

→ Field harmonics w.r.t. **sextupole component**



Flux potential with main and trim coils at peak current

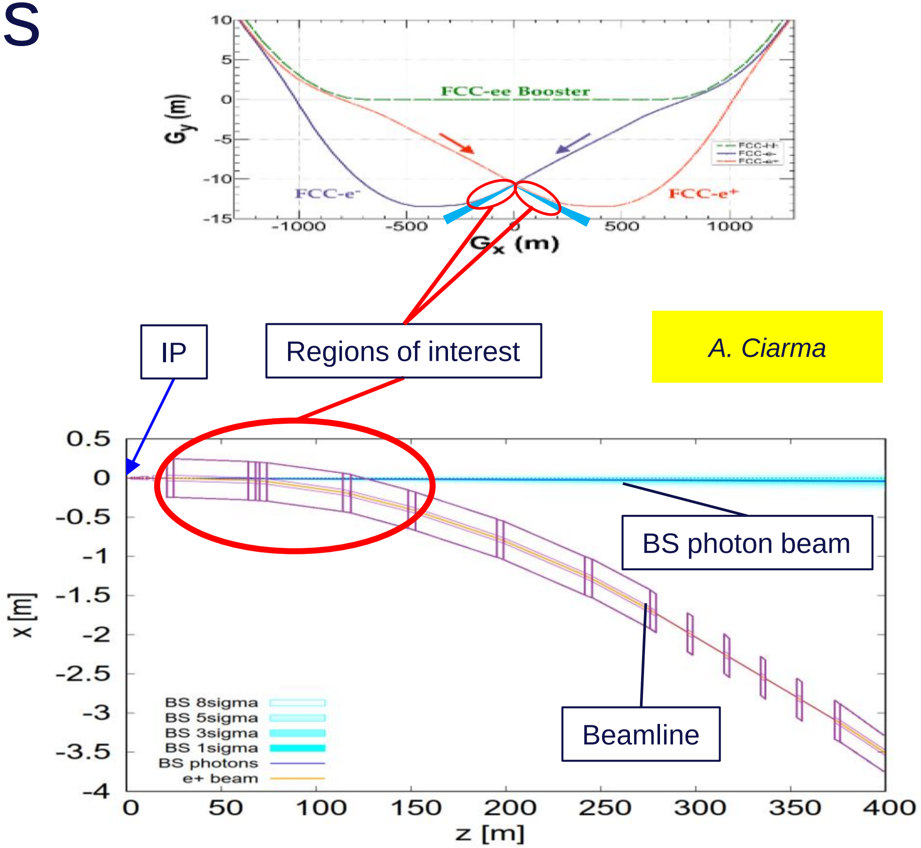
- The Horizontal dipole corrector introduces a **strong normal sextupole** component that **can be cured by the main sextupole coil**
- The Horizontal/Vertical dipole correctors introduces **strong normal/skew decapole** components
- The Normal Quadrupole corrector introduces a **strong normal octupole** term
- The Skew Quadrupole corrector introduces a **strong skew octupole** term

Collider magnets – Interaction regions

Beamstrahlung photon extraction line

Magnets downstream IPs

- **Collisions at IPs** will generate highly energetic **"Beamstrahlung" (BS) photons** → beam power **~400 kW**
- BS photons must be channelled to a dedicated beam dump via a straight extraction line **through the magnets**
- **Preliminary magnet designs** needed to identify potential conflicts
- First approach: define cross-sections based on **analytical formulae**, via a script and check interferences with BS envelope



BS photon extraction and e+ layout

Method for preliminary magnet designs

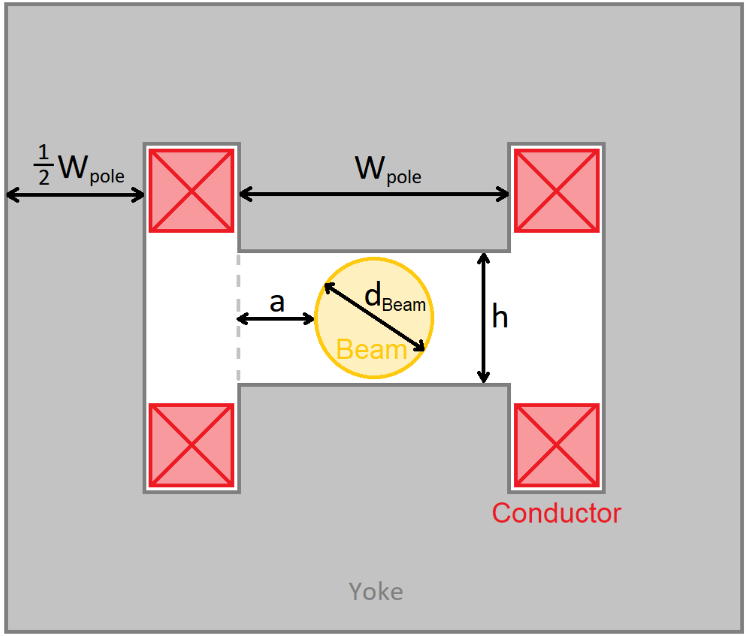
<u>Dipoles</u>

Assumptions made:

- H-shaped cross-section.
- Conductor shape and current density assumed.
- Spacing around beam aperture and conductors assumed.

Dimensions then given by magnet strength and beam aperture:

- Max field per magnet given by: $B_{max} = 3.3356 K_0 (B\rho)_{max}$
- Current per pole approximated by: $NI \approx \frac{B_{max} h}{2\mu_0}$
- Pole tip overhang given by: $2\frac{a}{h} = -0.14 \ln \frac{\Delta B}{B} - 0.25$
- Pole width given by: $W_{pole} = d_{Beam} + 2a$



Method for preliminary magnet designs

<u>Quadrupoles</u>

Assumptions made:

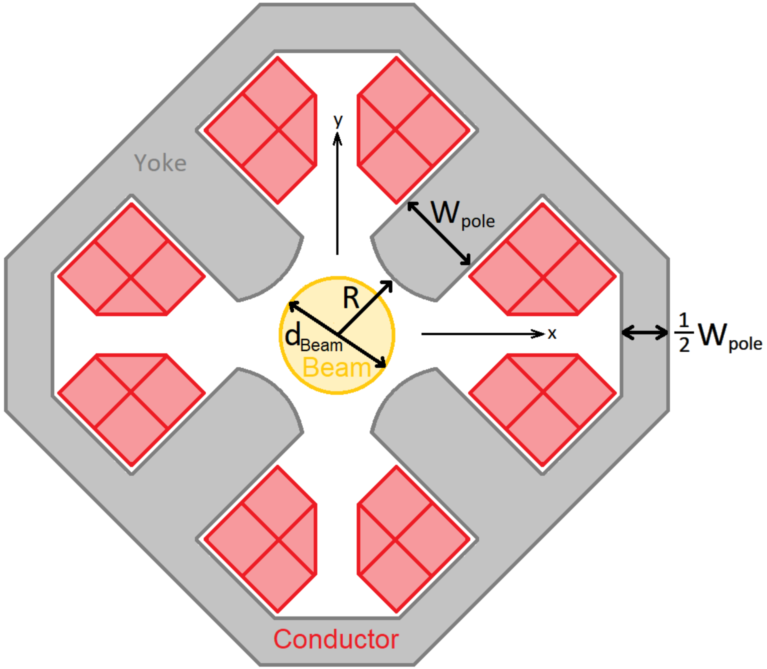
- Standard quadrupole cross-section.
- Straight poles assumed for simplicity.
- Conductor shape and current density assumed.
- Spacing around beam aperture and conductors assumed.

Dimensions then given by magnet strength and beam aperture:

- Max gradient per magnet given by:

$$G_{max} = 3.3356 K_1 (B\rho)_{max}$$

- Current per pole approximated by: $NI \approx \frac{G_{max} r^2}{2\mu_0}$
- Hyperbolic pole tips assumed: $2xy = R^2$
- Pole tip cut-off points given by conformal mapping of an optimal dipole tip; the cut-off points determine the pole width.



Magnet-BS conflicts along lattice

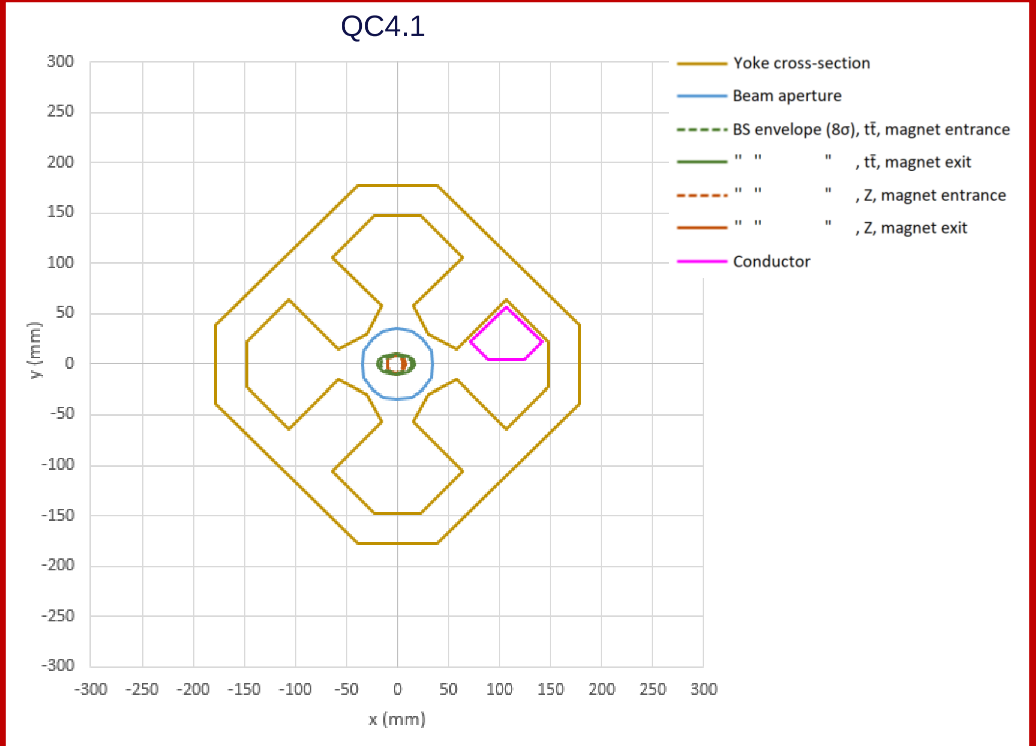
- BS envelope within beam aperture (blue)
- BS envelope intersects beam aperture edge (yellow)
- BS envelope intersects magnet poles (red)
- BS envelope intersects magnet back-leg (orange)
- BS envelope fully separated from magnet cross-section (green)

Name	L [m]	S [m]	BS status	Comment
QC4.1	3.50	24.55	(blue)	BS envelope within beam aperture for all magnets before and up to this point.
BC1.1	39.39	64.25	(yellow)	BS envelope intersects beam aperture edge, enlarged vacuum chamber (VC) needed.
QC5.1	3.50	68.05	(red)	Magnet aperture radius needs to be enlarged significantly.
BC2.1	1.70	70.05	(yellow)	BS envelope intersects beam aperture edge, enlarged VC needed.
QC6.1	3.50	73.85	(red)	Magnet aperture radius needs to be enlarged significantly.
BC3.1	39.66	113.81	(orange)	C-shape cross-section required.
QC7.1	3.50	117.61	(orange)	Figure-of-eight cross-section required.
SY1R.1	0.15	118.06	-	Superconducting; not investigated.
SY1R.2	0.15	118.21	-	Superconducting; not investigated.
BC4.1	29.92	148.43	(orange)	C-shape cross-section required.
QY2.1	3.50	152.23	(green)	BS envelope outside of magnet cross-section.
BC5.1	42.45	194.98	(green)	BS envelope outside of magnet cross-section, no conflicts foreseen beyond this point.

Magnet-BS conflicts along lattice

- BS envelope within beam aperture
- BS envelope intersects beam aperture edge
- BS envelope intersects magnet poles
- BS envelope intersects magnet back-leg
- BS envelope fully separated from magnet cross-section

Name	L [m]	S [m]	BS status	Comm
QC4.1	3.50	24.55		BS env
BC1.1	39.39	64.25		BS env
QC5.1	3.50	68.05		Magne
BC2.1	1.70	70.05		BS env
QC6.1	3.50	73.85		Magne
BC3.1	39.66	113.81		C-shap
QC7.1	3.50	117.61		Figure-
SY1R.1	0.15	118.06	-	Superc
SY1R.2	0.15	118.21	-	Superc
BC4.1	29.92	148.43		C-shap
QY2.1	3.50	152.23		BS env
BC5.1	42.45	194.98		BS env



Magnet-BS conflicts along lattice

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BC3.1	39.66	113.81		C-shap
QC7.1	3.50	117.61		Figure-
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SY1R.2	0.15	118.21	-	Superc
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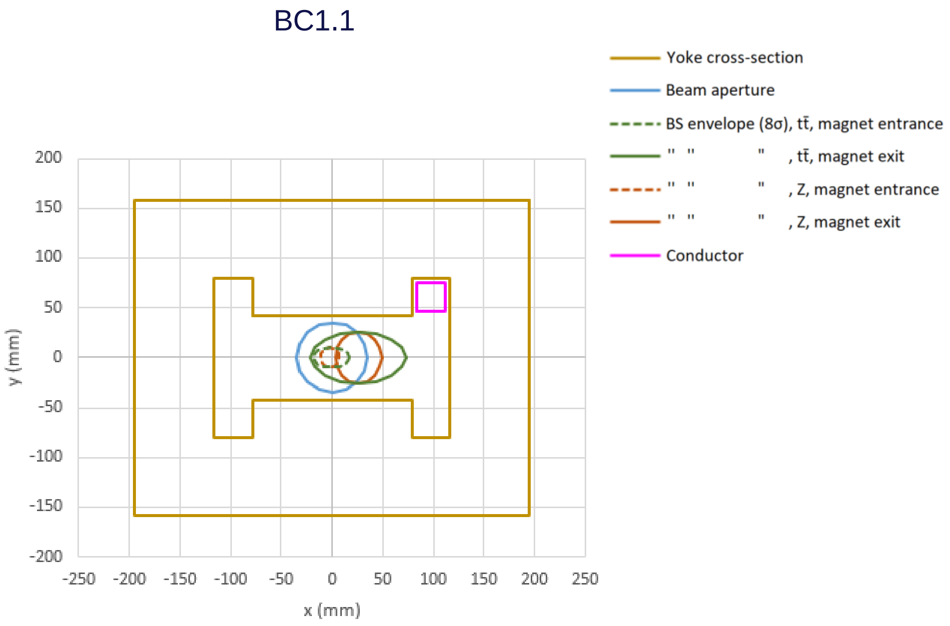
BC5.1	42.45	194.98		BS env



Magnet-BS conflicts along lattice

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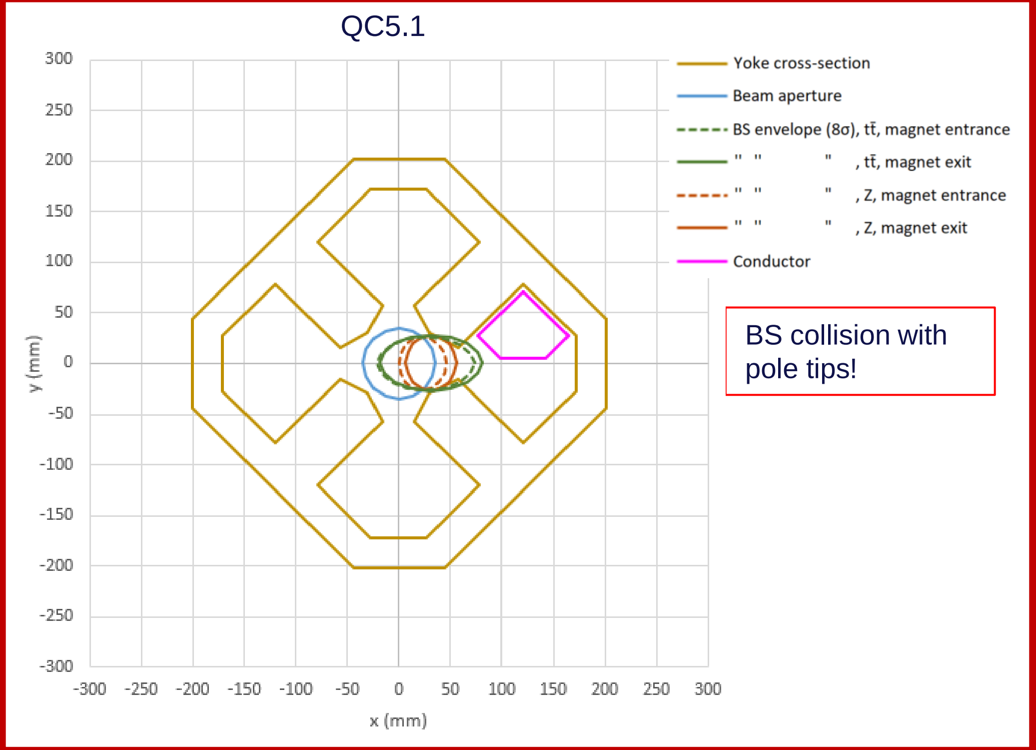
QC7.1	3.50	117.61		Figure-
SY1R.1	0.15	118.06	-	Superc
SY1R.2	0.15	118.21	-	Superc
BC4.1	29.92	148.43		C-shap
QY2.1	3.50	152.23		BS env
BC5.1	42.45	194.98		BS env



Magnet-BS conflicts along lattice

- BS envelope within beam aperture
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BC3.1	39.66	113.81		C-shap
QC7.1	3.50	117.61		Figure-
SY1R.1	0.15	118.06	-	Superc
SY1R.2	0.15	118.21	-	Superc
BC4.1	29.92	148.43		C-shap
QY2.1	3.50	152.23		BS env
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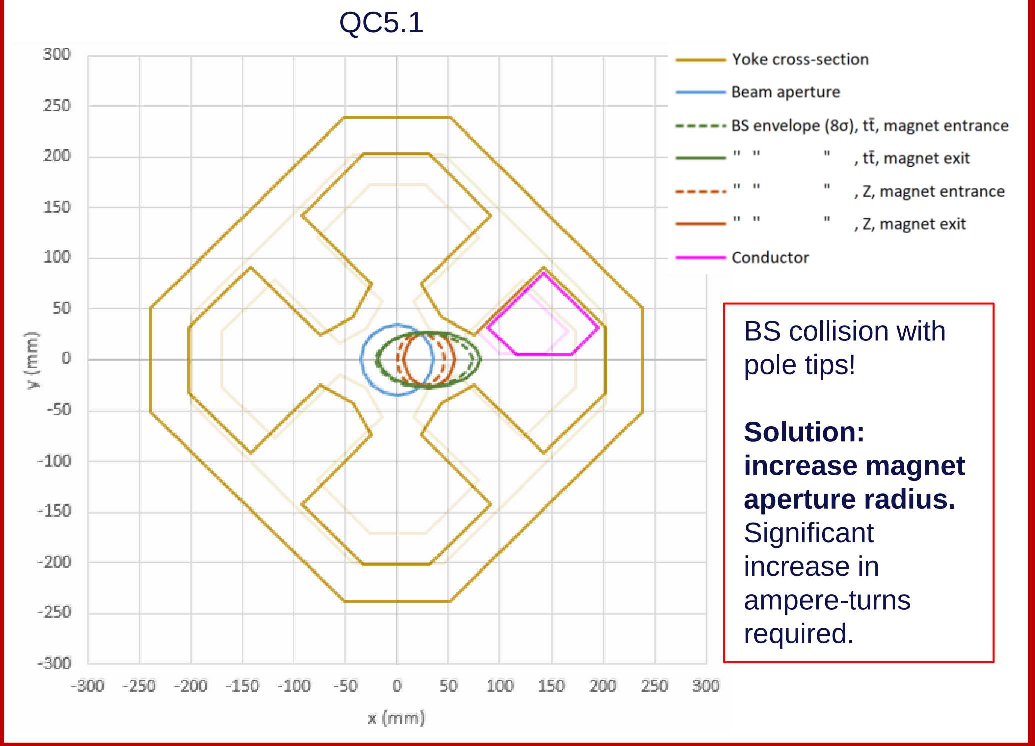

BS collision with pole tips!

Solution: increase magnet aperture radius. Significant increase in ampere-turns required.

Magnet-BS conflicts along lattice

- BS envelope within beam aperture
- BS envelope intersects beam aperture edge
- BS envelope intersects magnet poles
- BS envelope intersects magnet back-leg
- BS envelope fully separated from magnet cross-section

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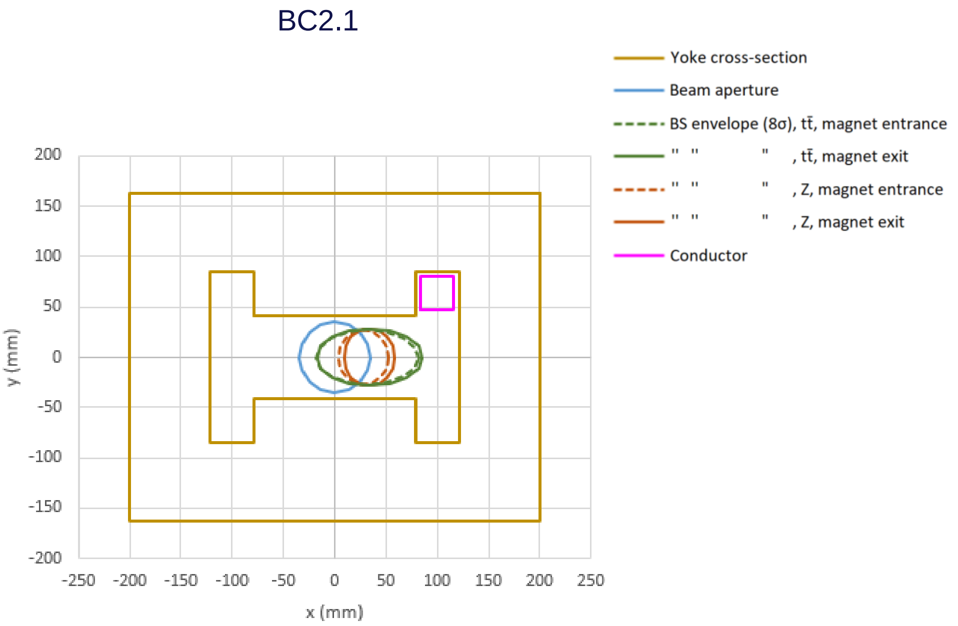

Magnet-BS conflicts along lattice

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QC6.1	3.50	73.85		Magne
BC3.1	39.66	113.81		C-shap
QC7.1	3.50	117.61		Figure-
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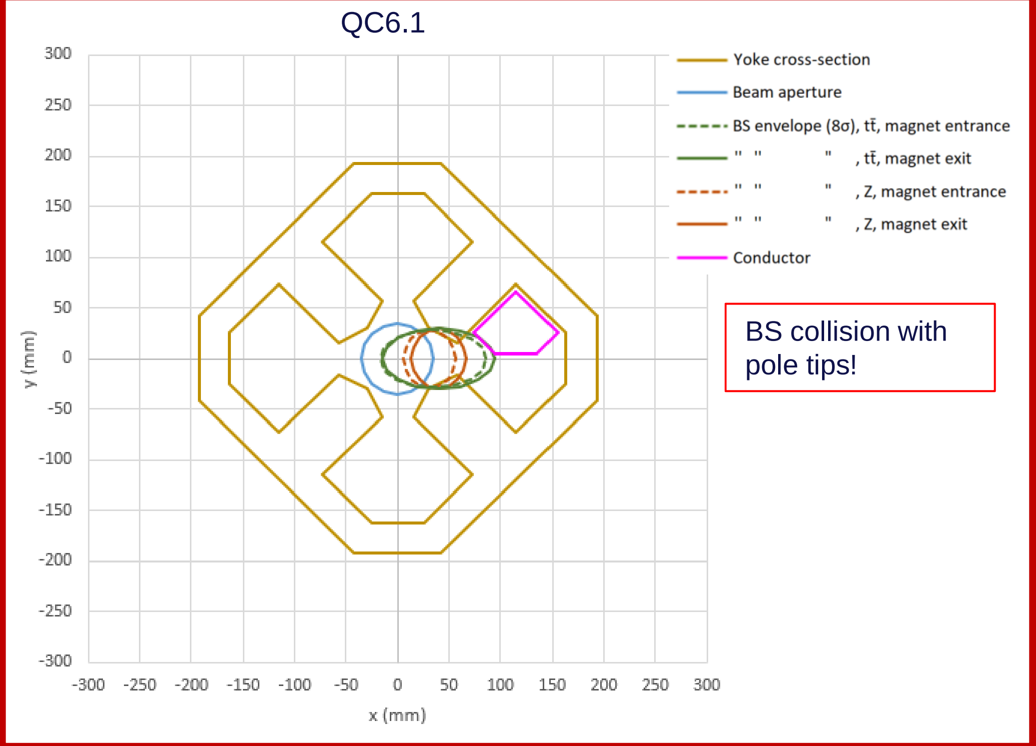
BC4.1	29.92	148.43		C-shap
QY2.1	3.50	152.23		BS env
BC5.1	42.45	194.98		BS env



Magnet-BS conflicts along lattice

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QC6.1	3.50	73.85		Magne
BC3.1	39.66	113.81		C-shap
QC7.1	3.50	117.61		Figure-
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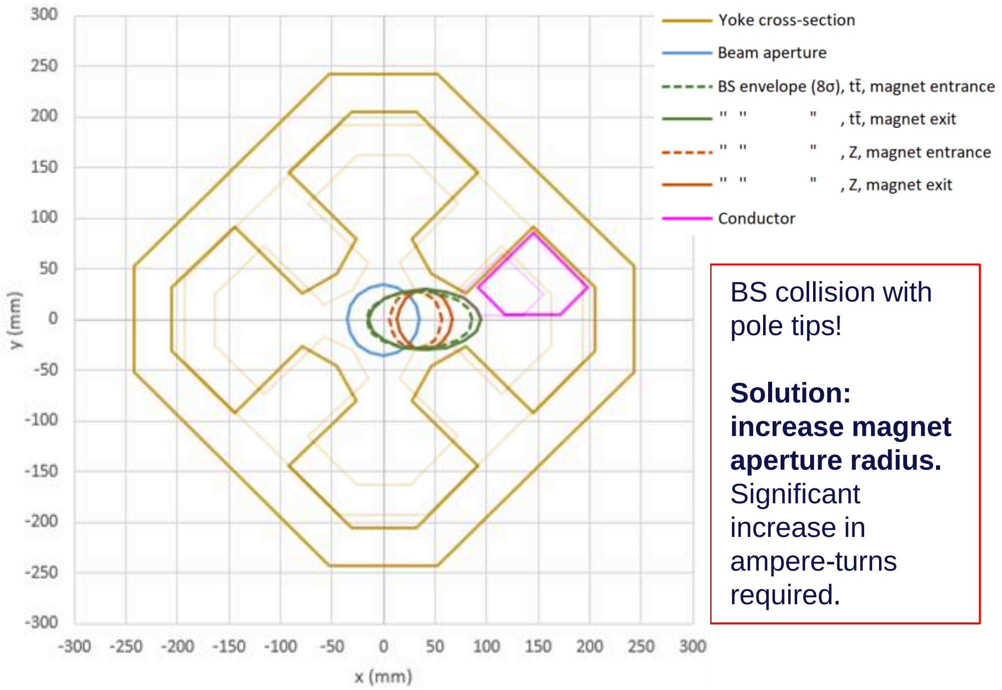
SY1R.2	0.15	118.21	-	Superc
BC4.1	29.92	148.43		C-shap
QY2.1	3.50	152.23		BS env
BC5.1	42.45	194.98		BS env

QC6.1



BS collision with pole tips!

Solution: increase magnet aperture radius. Significant increase in ampere-turns required.

Magnet-BS conflicts along lattice

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QC7.1	3.50	117.61		Figure-
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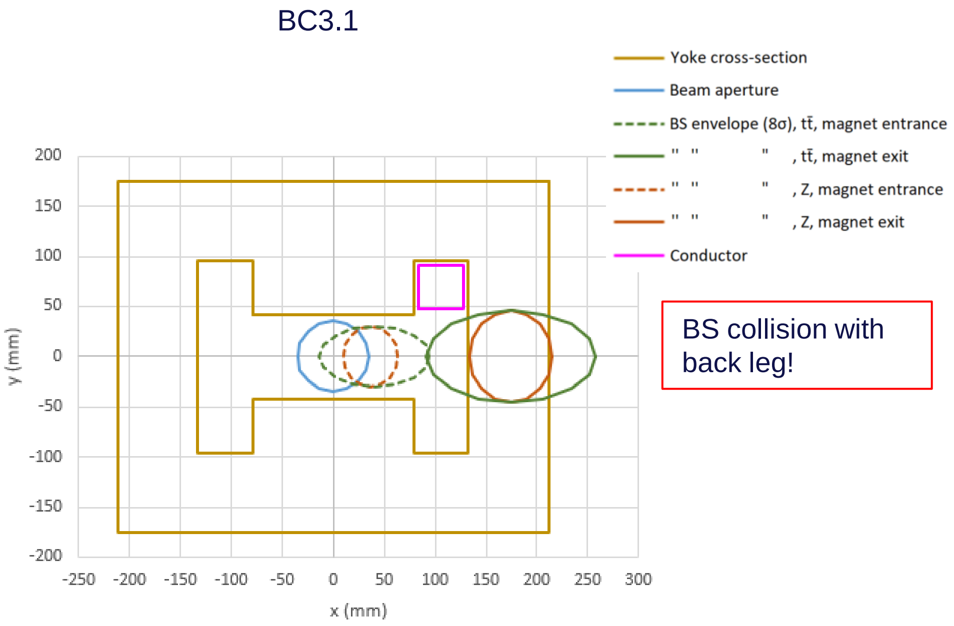

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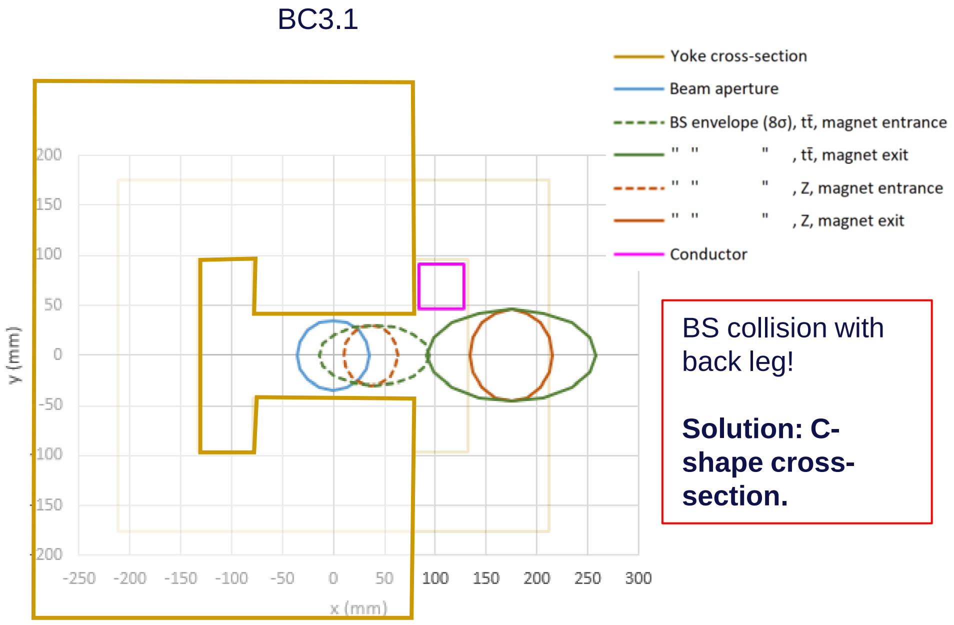

BS collision with back leg!

Solution: C-shape cross-section.

Magnet-BS conflicts along lattice

- BS envelope within beam aperture
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QC7.1	3.50	117.61		Figure-
SY1R.1	0.15	118.06	-	Superc
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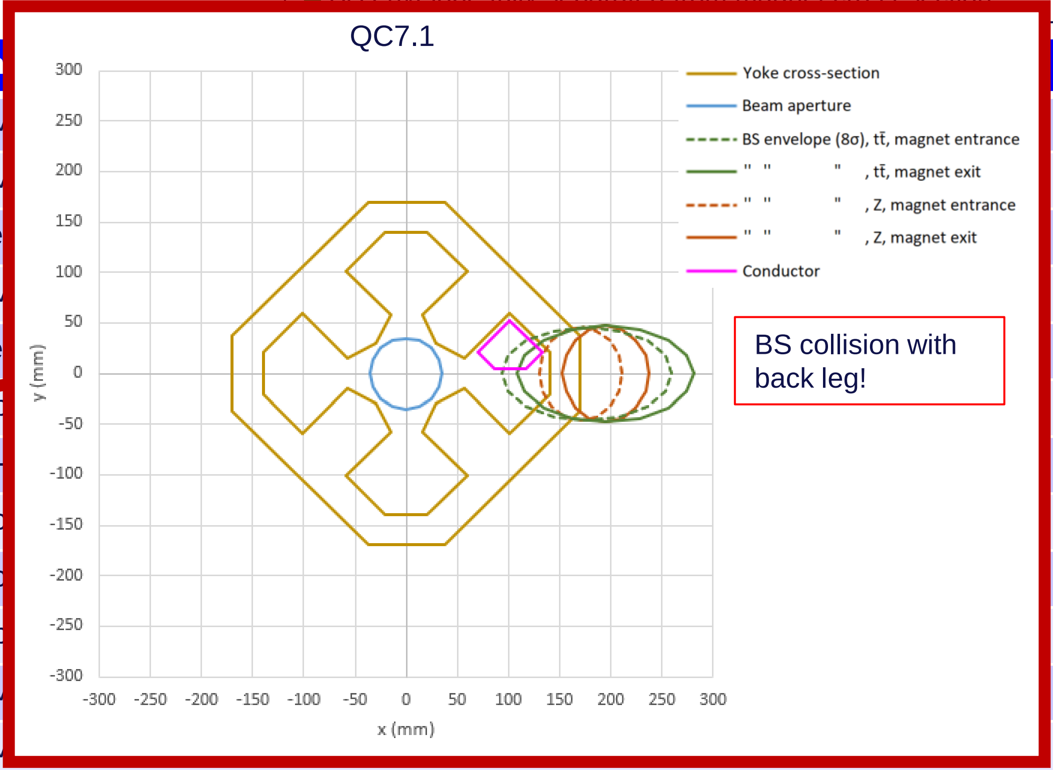

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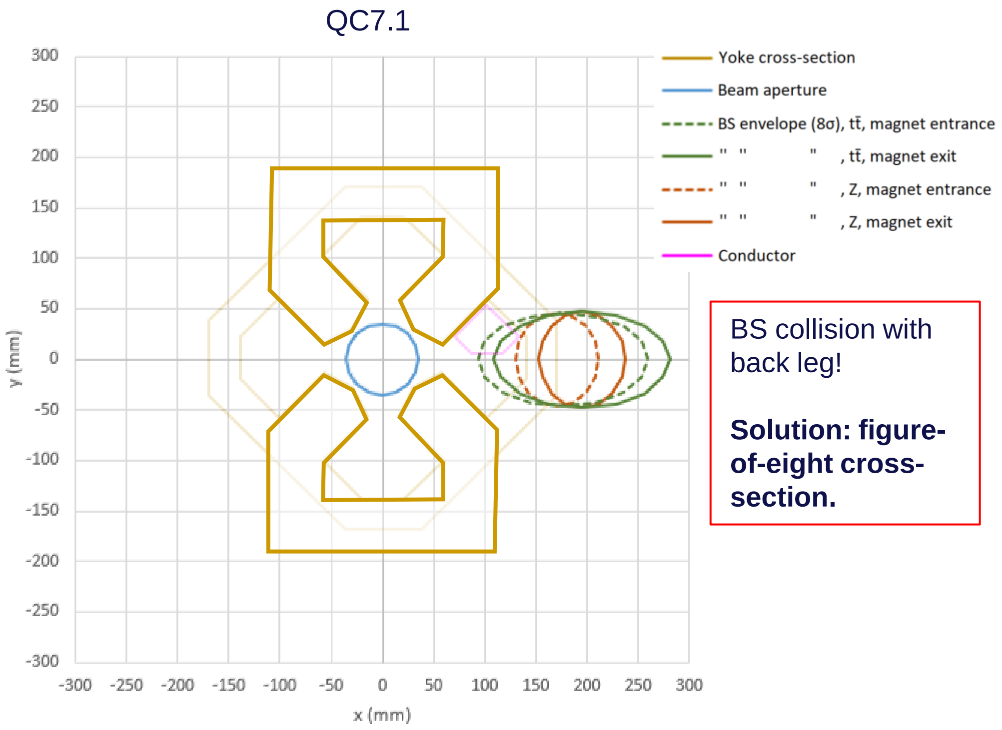

Magnet-BS conflicts along lattice

- BS envelope within beam aperture (blue)
- BS envelope intersects beam aperture edge (yellow)
- BS envelope intersects magnet poles (red)
- BS envelope intersects magnet back-leg (orange)
- BS envelope fully separated from magnet cross-section (green)

Name	L [m]	S [m]	BS status	Comm
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SY1R.1	0.15	118.06	-	Superc
SY1R.2	0.15	118.21	-	Superc
BC4.1	29.92	148.43	(orange)	C-shap
QY2.1	3.50	152.23	(green)	BS env
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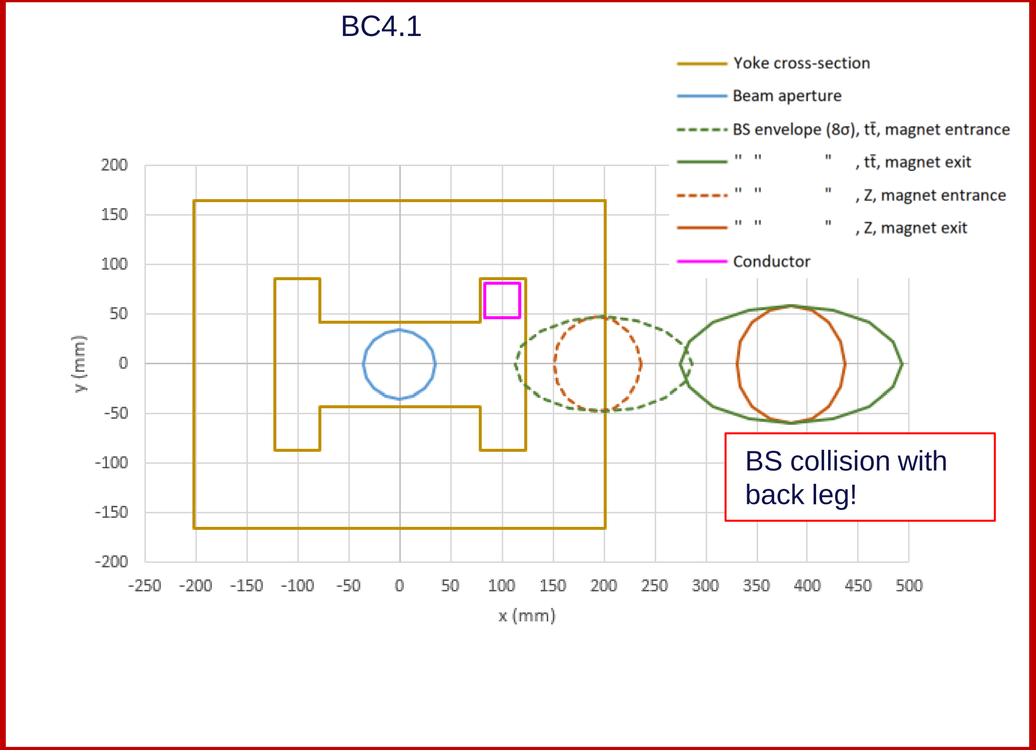

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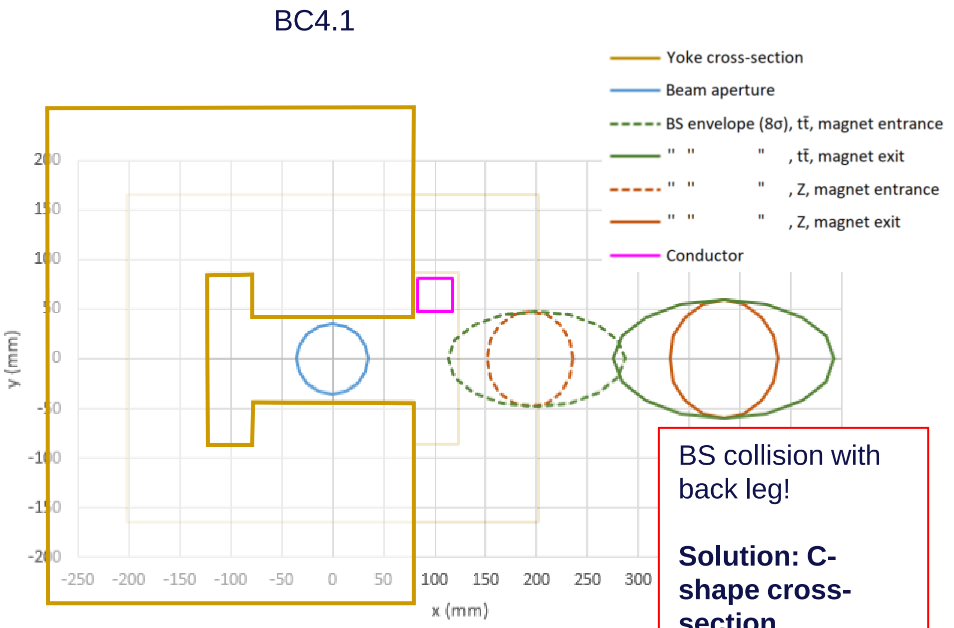

BS collision with back leg!

Solution: C-shape cross-section.

Magnet-BS conflicts along lattice

- BS envelope within beam aperture
- BS envelope intersects beam aperture edge
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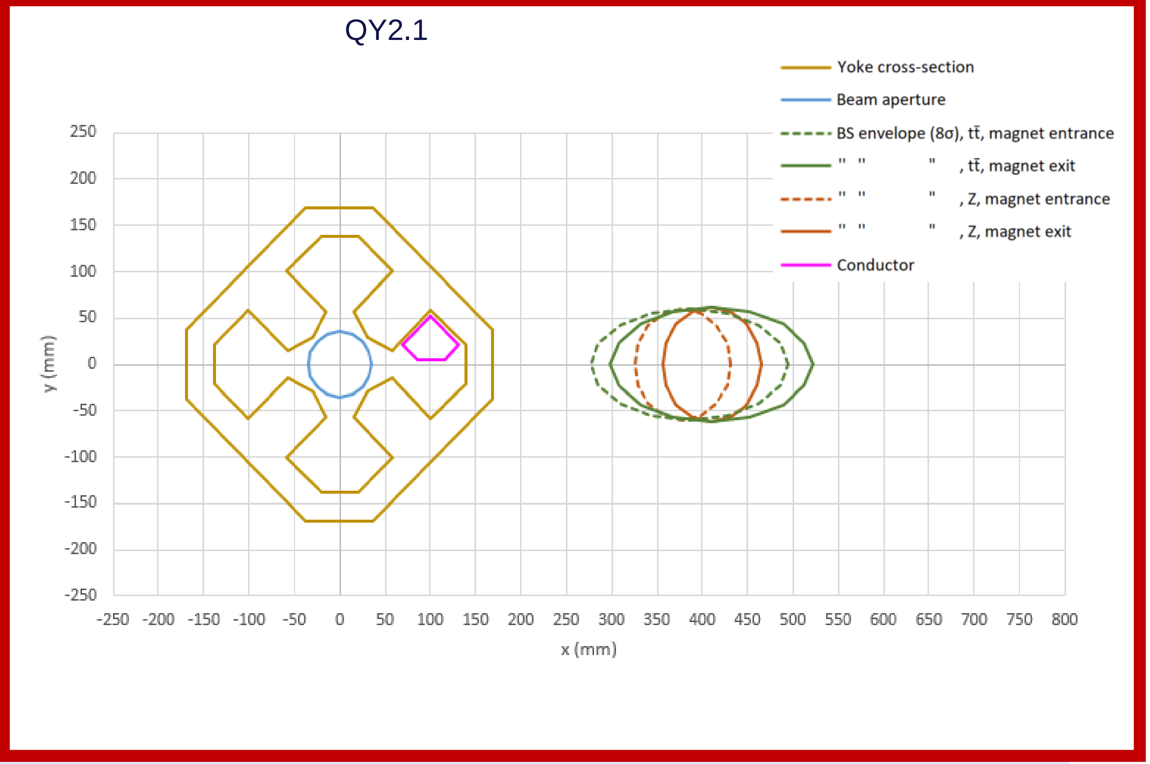

Magnet-BS conflicts along lattice

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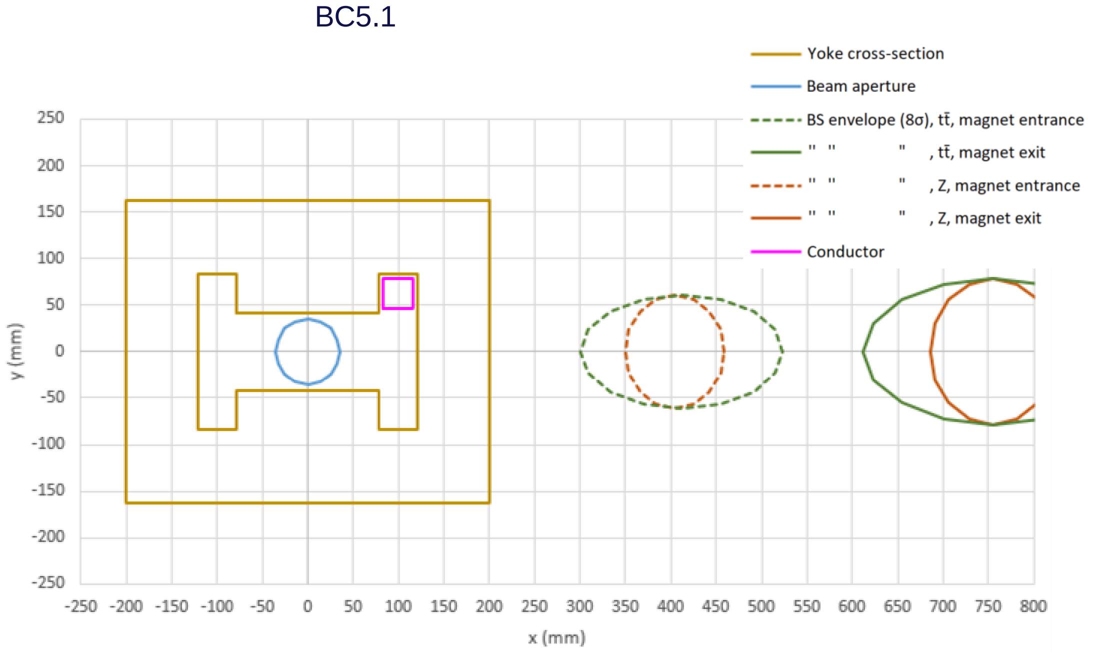
- BS envelope intersects beam aperture edge (yellow)
- BS envelope intersects magnet poles (red)
- BS envelope intersects magnet back-leg (orange)
- BS envelope fully separated from magnet cross-section (green)

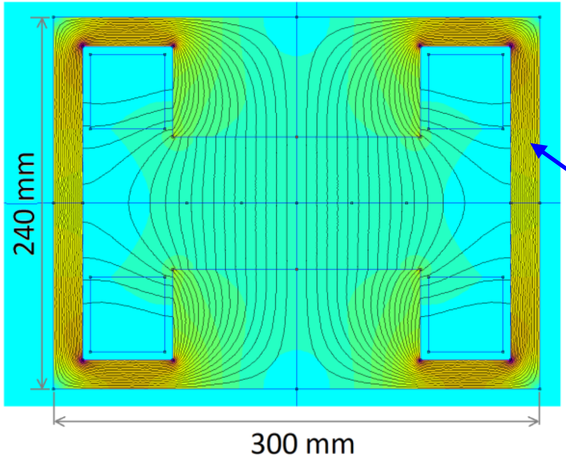
Name	L [m]	S [m]	BS status	Comm…
QC4.1	3.50	24.55	(blue)	BS env…
BC1.1	39.39	64.25	(yellow)	BS env…
QC5.1	3.50	68.05	(red)	Magne…
BC2.1	1.70	70.05	(yellow)	BS env…
QC6.1	3.50	73.85	(red)	Magne…
BC3.1	39.66	113.81	(orange)	C-shap…
QC7.1	3.50	117.61	(orange)	Figure-…
SY1R.1	0.15	118.06	-	Superc…
SY1R.2	0.15	118.21	-	Superc…
BC4.1	29.92	14[illegible].43	(orange)	C-shap…
QY2.1	3.5[illegible]	152.23	(green)	BS env…
BC5.1	42.45	194.98	(green)	BS env…



Dipoles – cross-sections

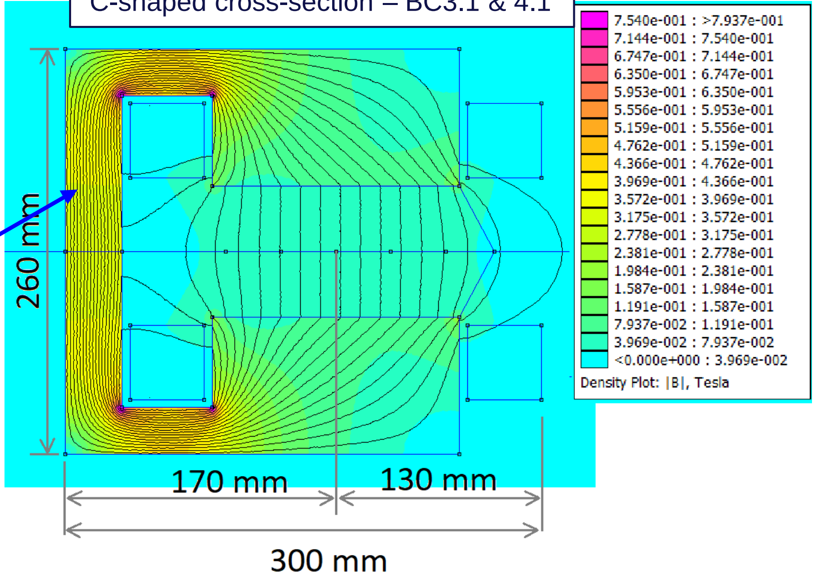
- 2 designs could cover the needs
  - One **H-type** for cases **without interference**
  - One **C-shape** for cases with **back-leg interference**
- The C-shape design could also be standardized

Common H-shaped cross-section



Narrowed back-legs thanks to low flux density

C-shaped cross-section – BC3.1 & 4.1

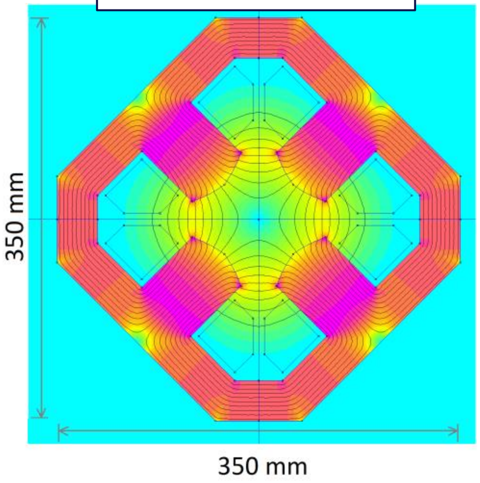


Magnetic simulation sofware used: FEMM

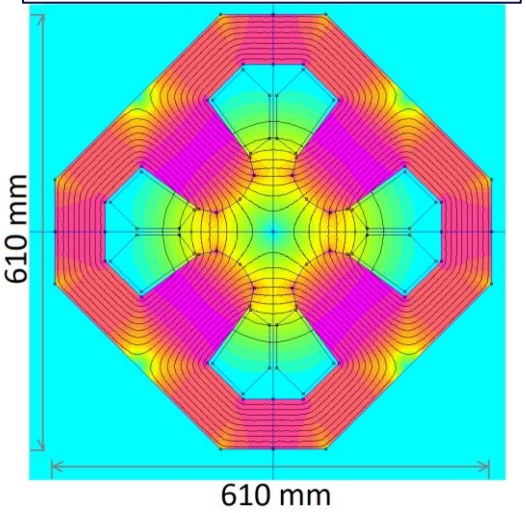
Quadrupoles – cross-sections

- 3 designs could cover the needs
  - One **4-fold** with **nominal aperture** for cases without interference
  - One **4-fold** with **enlarged aperture** for cases with pole interference
  - One **figure-of-eight** for cases with back-leg interference

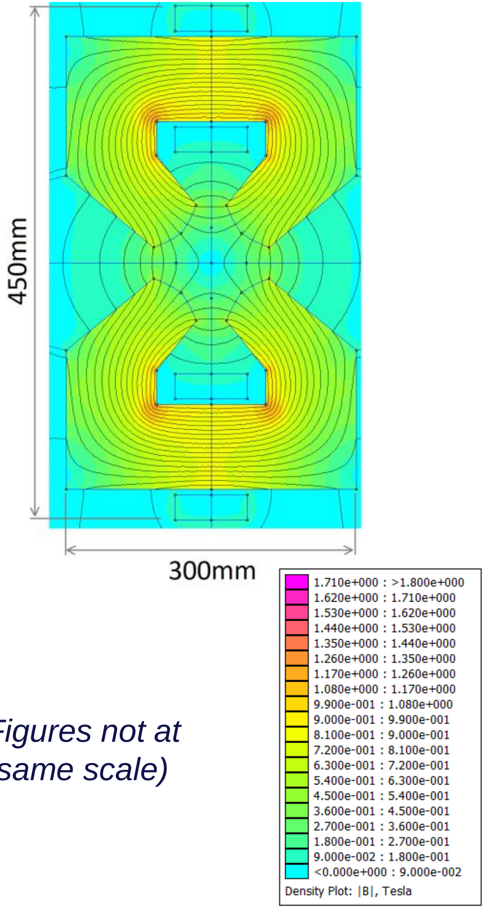
Common cross-section



QC5.1 & 6.1 – Enlarged aperture



QC7.1 – Figure-of-eight



(Figures not at same scale)

Magnetic simulation sofware used: FEMM

Space claim summary

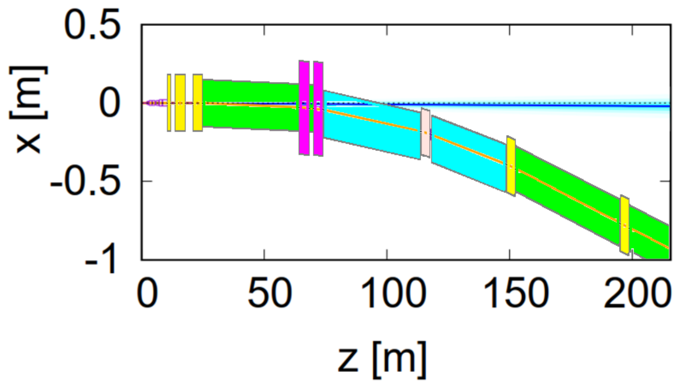
Name	S [m]	Length [m]	Height [mm]	Width [mm]	Cross-section
QC2R2.1	8.44	1.25	-	-	Superconducting; not investigated
QT1.1	11.73	1.00	350	350	Common quad cross-section
QC3.1	17.51	3.50	350	350	Common quad cross-section
QC4.1	24.55	3.50	350	350	Common quad cross-section
BC1.1	64.25	39.39	240	300	Common H-shape
QC5.1	68.05	3.50	610	610	Enlarged aperture
BC2.1	70.05	1.70	240	300	Common H-shape
QC6.1	73.85	3.50	610	610	Enlarged aperture
BC3.1	113.81	39.66	260	300	C-shape
QC7.1	117.61	3.50	450	300	Figure-of-eight cross-section
SY1R.1	118.06	0.15	-	-	Superconducting; not investigated
SY1R.2	118.21	0.15	-	-	Superconducting; not investigated
BC4.1	148.43	29.92	260	300	C-shape
QY2.1	152.23	3.50	350	350	Common quad cross-section
BC5.1	194.98	42.45	240	300	Common H-shape

Region of BS-magnet conflicts (QC5.1 to BC4.1)

All superconducting before this point → not investigated.

Same respective cross-sections for quads and dipoles beyond this point.

5 different cross-sections in total:
- Dipoles:
  - Common H-shape
  - C-shape
- Quads:
  - Common cross-section
  - Enlarged aperture
  - Figure-of-eight



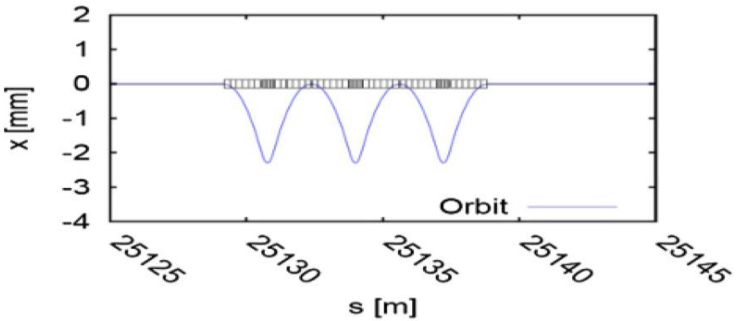
Polarization wigglers

Specifications

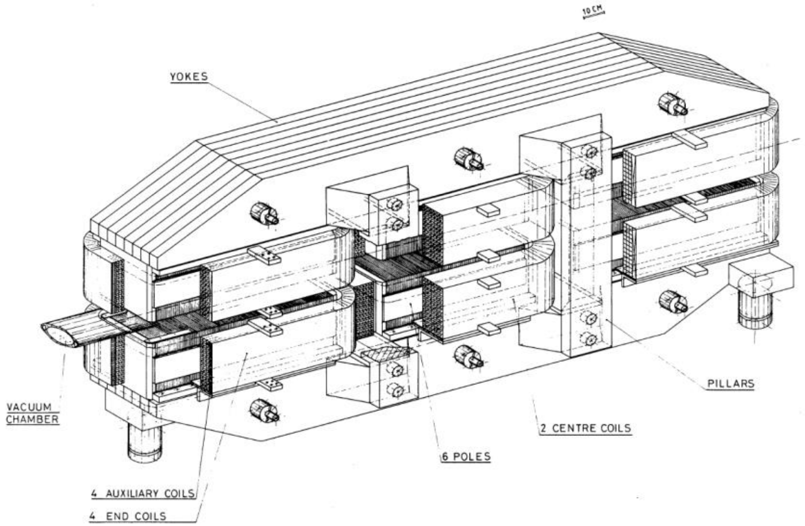
Polarization wigglers are needed to measure beam characteristics

	FCC-ee	LEP
Number of units per beam	8×3	8
Full gap height (mm)	90	100
Central field B^+ (T)	0.7	1.0
Central pole length (mm)	430	760
Asymmetry ratio B^+/B^-	6	2.5
Critical energy of SR photons (keV)	900	1350

FCC-ee CDR wiggler specifications



Orbit excursion in FCC-ee wigglers

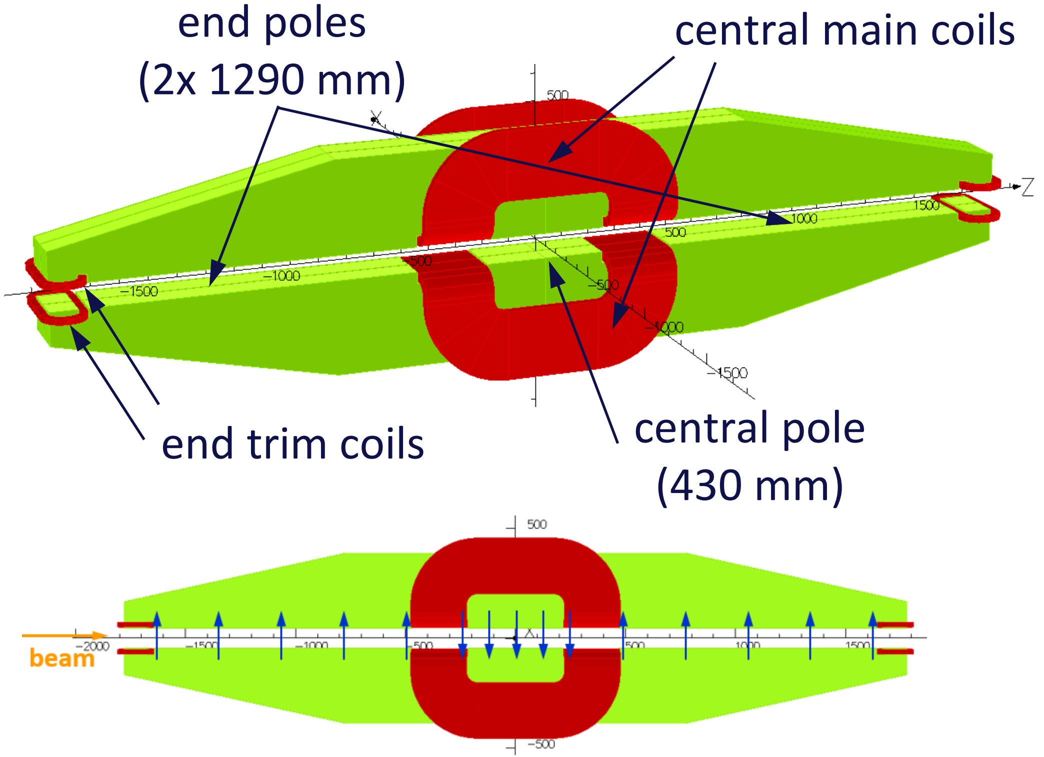


LEP damping / emittance wiggler, 1983

Magnetic concept with floating poles

Design features

- Magnetic **flux** in **central pole** loops back through **end poles**
- **Single main** coil with enough ampere-turns is sufficient
- The **coil width** conditions a **clean transition** from B+ to B-
- A central **saddle coil** allows **smaller** magnet **transverse size**
- A design with **trim coils** at the pole ends has been explored



Concept of FCC-ee polarization wiggler with floating poles

Field self-cancellation

W *= effective magnetic width*

L *= effective magnetic length*

Flux conservation

$$\Phi_{cen} = \Phi_{end}$$

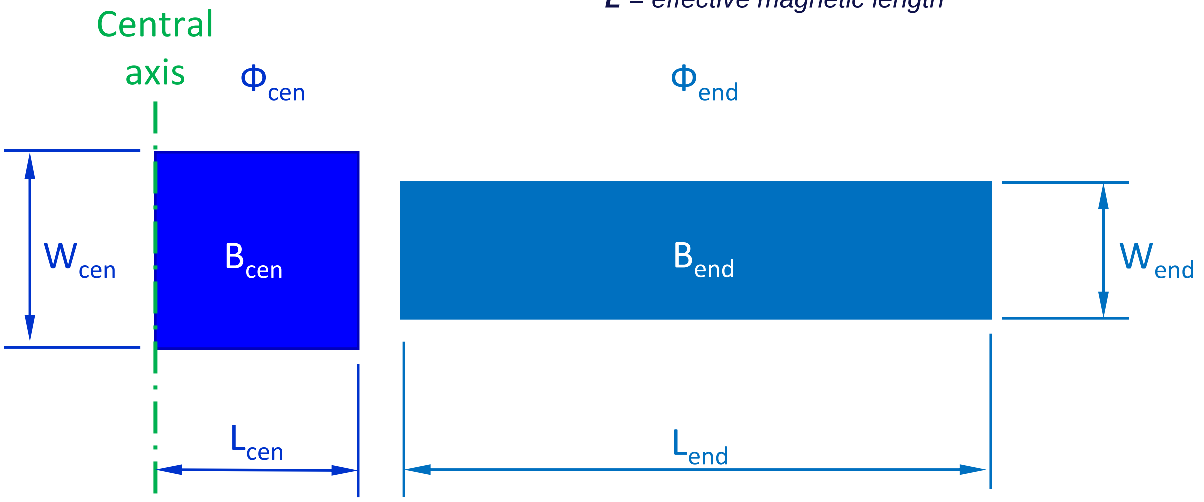
$$\Phi = B*S = B*W*L$$

Condition for self-cancellation of wiggler integral field strength:

$$B_{cen}*L_{cen} = B_{end}*L_{end}$$

Consequently:

$$W_{cen} = W_{end}$$



Schematic representation of pole effective surfaces (½ wiggler)

The translation of effective **magnetic** width/length to **physical** pole width/length is **valid outside saturation** and with **same aperture heights** on all poles

→ We could **shim** the end pole **width** to adjust the field integral to 0 during **magnetic measurements**

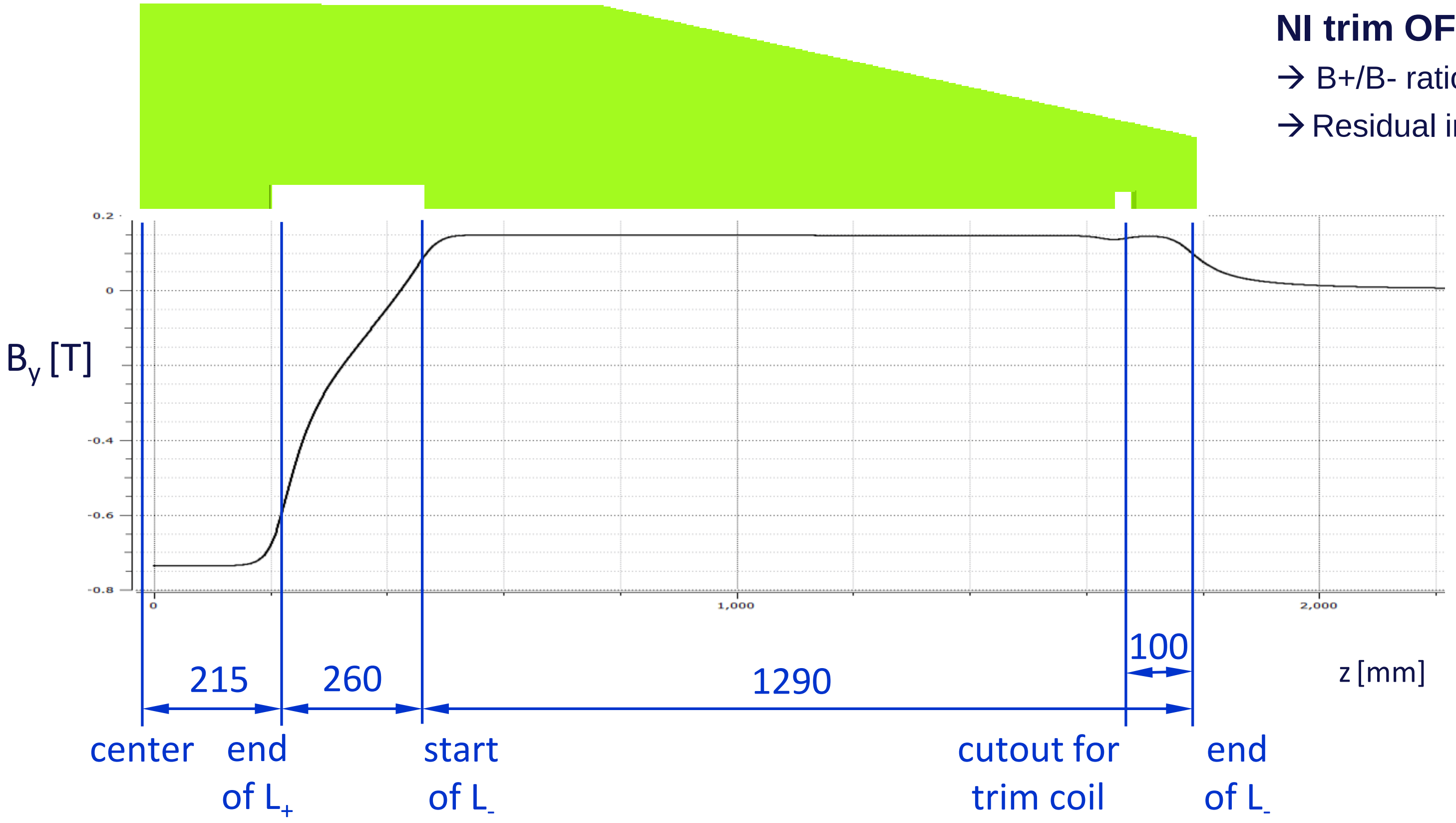
→ The (small) **dynamic range** of the wigglers needs to be **confirmed**

Longitudinal field distribution – trim coils

NI trim OFF

→ B+/B- ratio change: 0%

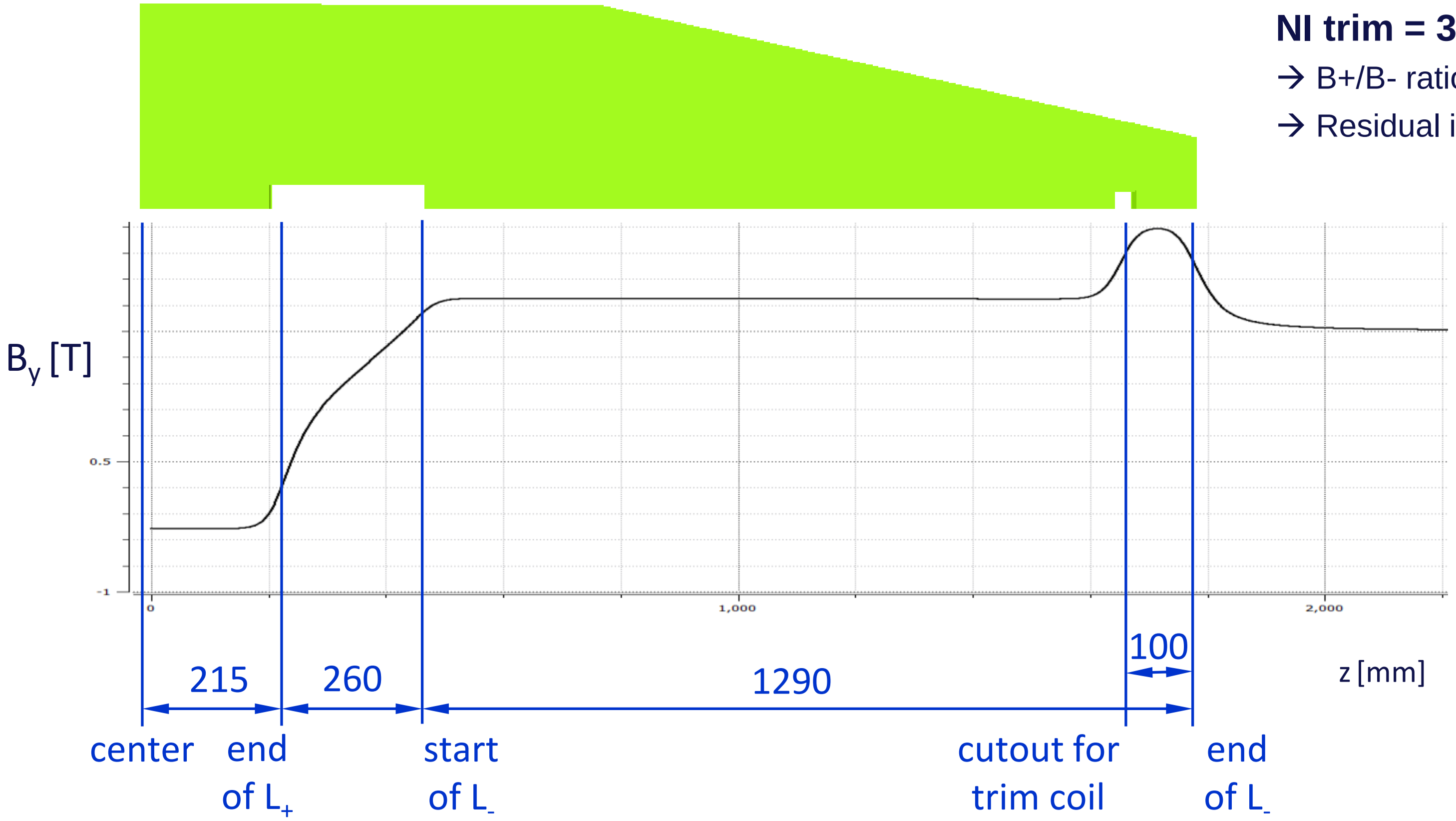
→ Residual int. field: 3.2 mTm



Beam excursion

~ 0.02 mrad at 45 GeV

Longitudinal field distribution – trim coils

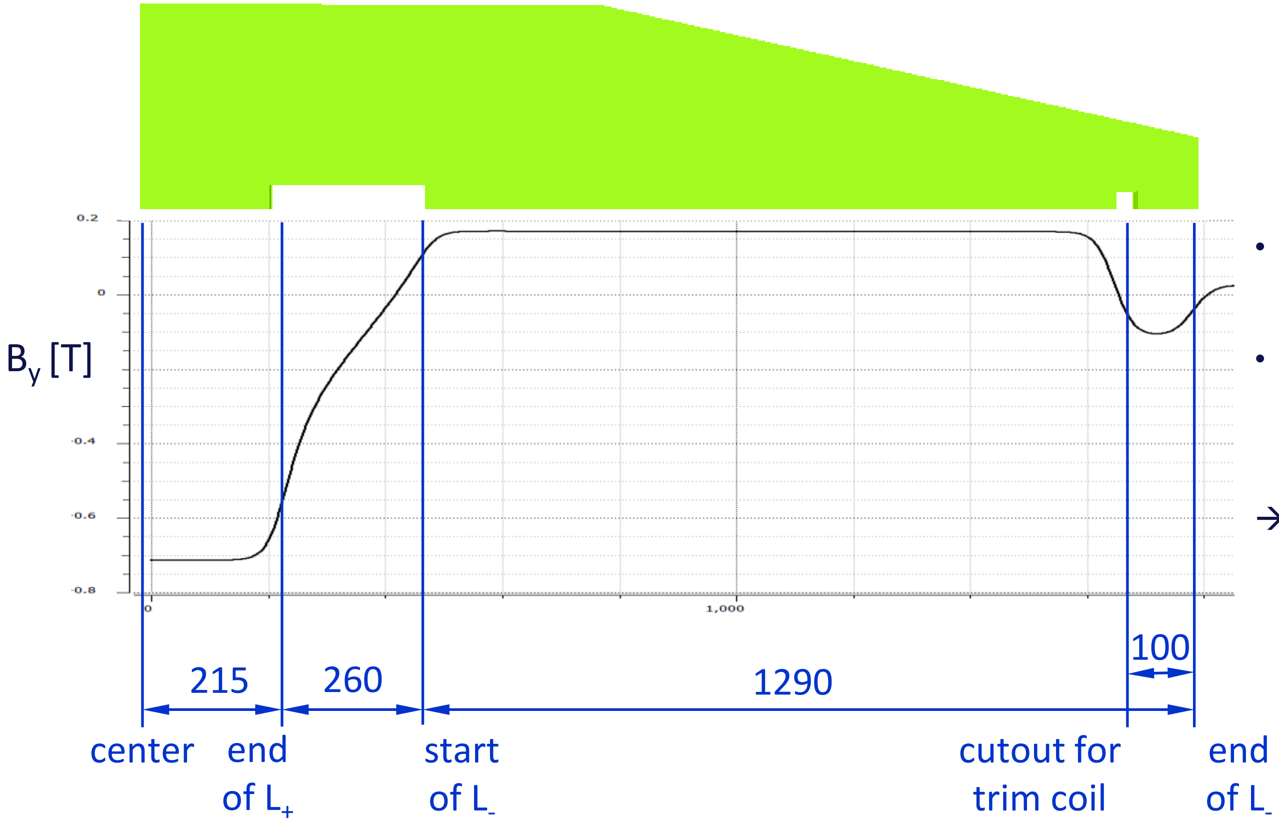


NI trim = 30% NI main

→ B+/B- ratio change: 22%

→ Residual int. field: 2.8 mTm

Longitudinal field distribution – trim coils



NI trim = -30% NI main

→ B+/B- ratio change: -16%

→ Residual int. field: 3.7 mTm

- **B+/B- ratio** can be adjusted… but longitudinal **field profile affected**
- The **residual field integral** is not much affected (already small due to field self-cancellation)

→ However, this could change if **saturation** occurs in some parts of the magnet within the dynamic range

Booster magnets – Regular arcs

Magnet specifications and challenges

dipoles = 2×2944
quadrupoles = 2944
sextupoles = 2632/4

- **Single aperture** machine, **cycled**
- No field “tapering” needed for E saw tooth
- **Beam aperture** Ø 50 mm (under discussion… 60 mm, and soon 84 mm to be studied)
  - GFR over 2/3 aperture
  - Field homogeneity between 2 and 10 units
- **Challenging dipole field at injection**
  → only ~130 x B_{earth}

Magnet	Parameter	Unit	Value
Dipole	Min./Max. field	G	64/593
	Length	m	11.1
Quadrupole	Min./Max. gradient	T/m	2.5/23
	Length	m	1.5
Sextupole	Min./Max. gradient	T/m²	304/2816
	Length	m	0.5

Booster magnet parameters

The injection energy for the booster is determined by the field quality and reproducibility of the magnetic field in the dipole magnets of the arc sections. The current design features an energy of 20 GeV, corresponding to a magnetic field of $B = 6\,\text{mT}$.

CDR, Booster chapter, p. 495

Parameter	Unit	Z	W	H	tt_1	tt_2
Flat bottom duration	s	51.1	11.8	5.0	1.6	1.6
Cycle duration	s	51.7	13.3	7.5	5.5	5.7
Ramp rate up	G/s			254		

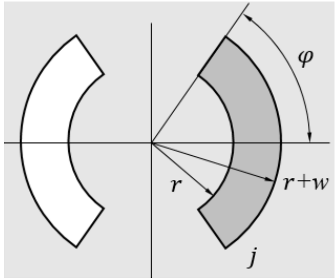
CDR, Booster cycle

A. Chancé, B. Dalena (CEA)

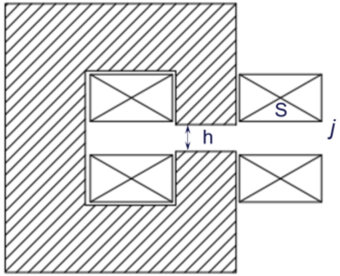
Booster dipole

Dipole design

- **Main considerations for design**
  - ***Performance***: *field quality, reproducibility, and limited sensitivity to perturbations (@ injection)*
  - ***Cost optimization***: *large scale manufacturing, power consumption and energy storage*
  - ***Size***: *integration in same tunnel as collider*



$$B = \frac{2\mu_0 \sin\varphi\, j\, w}{\pi}$$



$$B = \frac{2\mu_0\, j\, S}{h}$$

Ampere-turns much larger for ironless magnet for same aperture

- **Design options**

→ ***Coil dominated*** *magnet or* ***iron dominated*** *magnet?*

- ***Field range achievable*** *in normal conducting mode for both options*
- *Required* ***ampere-turns much larger*** *for* ***coil dominated****, even with iron shell (power consumption, capital cost, size)*
- ***Ironless*** *magnet does not shield the* ***earth magnetic field*** *(B_{earth} ≈ 70 units of B_{inj})* → <u>*not acceptable*</u>
- ***Strong sensitivity*** *of field quality to* ***coil positioning*** *for* ***coil dominated***
- *Required* ***conductor shape not commercially available*** *for* ***coil dominated***

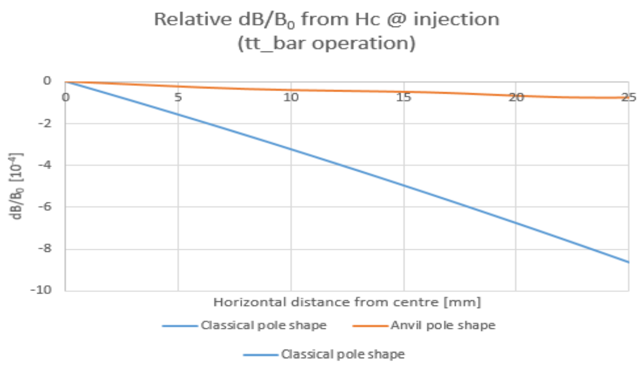
} → <u>*costly for large scale manufacturing*</u>

- *Effect of iron* ***coercivity*** *on low field performance larger for* ***iron dominated*** *magnet*

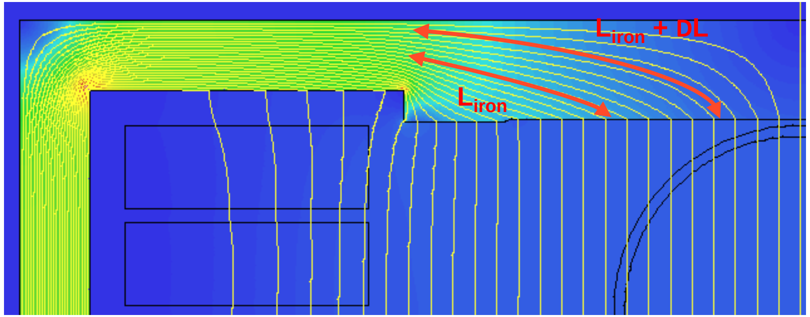
→ iron dominated magnet

Dipole – 1st version

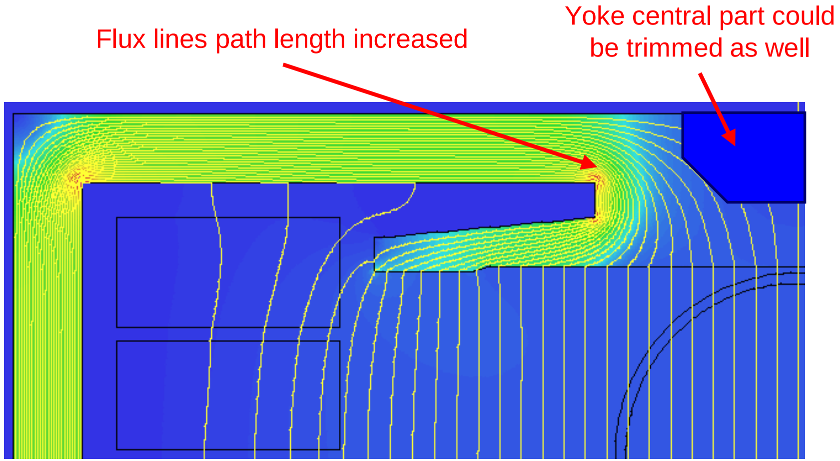
- **Effect of coercivity**
  - ***Flux lines*** *along the pole iron → different path lengths*
  - *At low fields,* $DB_{rem} \propto DH_c * Dl_{iron}/l_{air}$
  - H_c *scales with iron magnetization, ~10 times larger at* tt_{bar} *extraction than at injection*
  - *An* ***"anvil" pole shape*** *can mitigate the effect, in the spirit of the LHeC dipole**



dB/B_0 from H_c (B) for FCC-ee, fit from ELENA and SPS iron data



O-shape magnet



"Anvil" pole shape magnet

* D. Tommasini, M. Buzio, and R. Chritin, "Dipole magnets for the LHeC ring-ring option", IEEE Trans. Appl. Supercond. 22, 4000203 (2012)

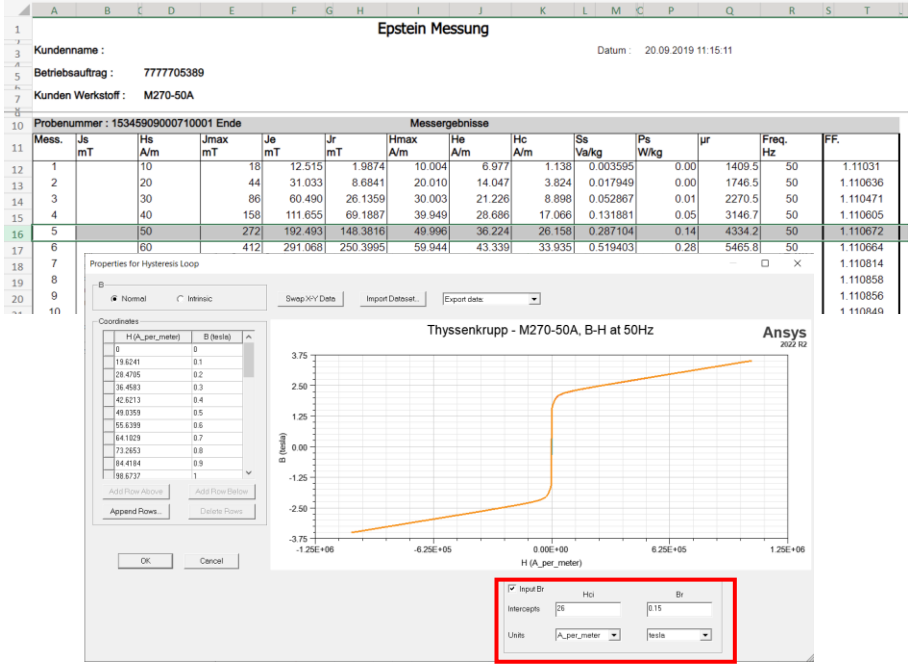
Dipole – 1st version

- **Parameters list**
  - *Only **~4500 tons** of iron and aluminum for the 5888 dipoles of the whole ring (~1/3 of the collider dipoles)*
  - *Power consumption minimized with **low current density***
  - *Max RMS power ~4.2 MW at tt_{bar} operation*
  - ***Average RMS power** over lifetime **~2 MW***
  - ***Number of turns** selected to match **power converters characteristics** and **limit operational voltage in the machine < 1 kV** (electrical safety regulations)*

Parameter	Unit	Value
Number of units		2944 x 2
Central field, 20 GeV–182.5 GeV	mT	7.1 - 65.0
Aperture (horizontal × vertical)	mm	123 x 55
Good field region (GFR) radius	mm	17
Field quality in GFR	1.0E-04	< 1
Magnetic length	m	11.1
Magnet overall transverse dimensions	mm	228 x 100
Iron mass per unit length	kg/m	55.5
Aluminium mass per unit length	kg/m	7.68
Magnet unit mass (11.1 m length)	kg	701
Total magnet mass, 65.4 km	tons	~ 4500
Maximum operating ampere-turns (tt_bar extraction)	A	2844
Maximum RMS current density (tt_bar)	A/mm2	0.92
Peak current (coil 4 turns)	*A*	*711*
Resistance per unit length (coil 4 turns)	*μΩ/m*	*596*
Inductance per unit length (coil 4 turns)	*μH/m*	*55*
Peak voltage per 1/2 octant (coil 4 turns)	*kV*	*1810*
Maximum RMS power per unit length (tt_bar)	W/m	64
Maximum total peak power, 65.4 km (tt_bar; cabling not incl.)	MW	20
Maximum total RMS power, 65.4 km (tt_bar; cabling not incl.)	MW	4.2

Dipole – latest version

Transient Analysis of the Core



Epstein Messung

Kundenname : Datum : 20.09.2019 11:15:11

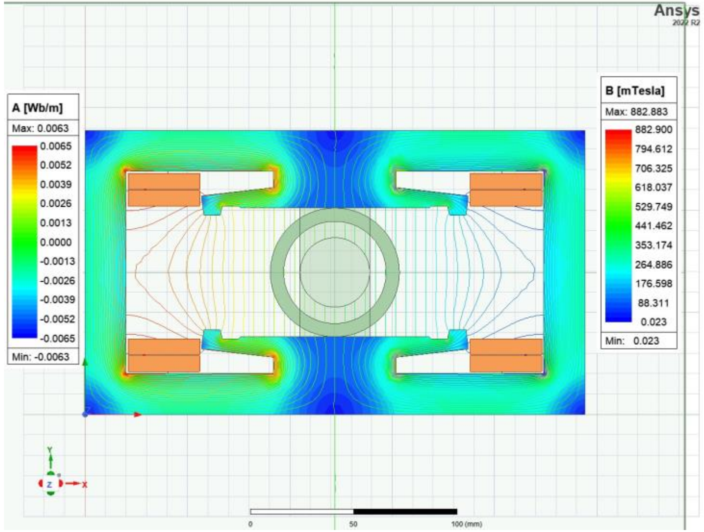
Betriebsauftrag : 7777705389

Kunden Werkstoff : M270-50A

Probenummer : 15345909000710001 Ende — Messergebnisse

Mess.	Js mT	Hs A/m	Jmax mT	Je mT	Jr mT	Hmax A/m	He A/m	Hc A/m	Ss Va/kg	Ps W/kg	μr	Freq. Hz	FF.
1		10	18	12.515	1.9874	10.004	6.977	1.138	0.003595	0.00	1409.5	50	1.11031
2		20	44	31.033	8.6841	20.010	14.047	3.824	0.017949	0.00	1746.5	50	1.110636
3		30	86	60.490	26.1359	30.003	21.226	8.898	0.052867	0.01	2270.5	50	1.110471
4		40	158	111.655	69.1887	39.949	28.686	17.066	0.131881	0.05	3146.7	50	1.110605
5		50	272	192.493	148.3816	49.996	36.224	26.158	0.287104	0.14	4334.2	50	1.110672
6		60	412	291.068	250.3995	59.944	43.339	33.935	0.519403	0.28	5465.8	50	1.110664
7													1.110814
8													1.110858
9													1.110856
10													1.110849

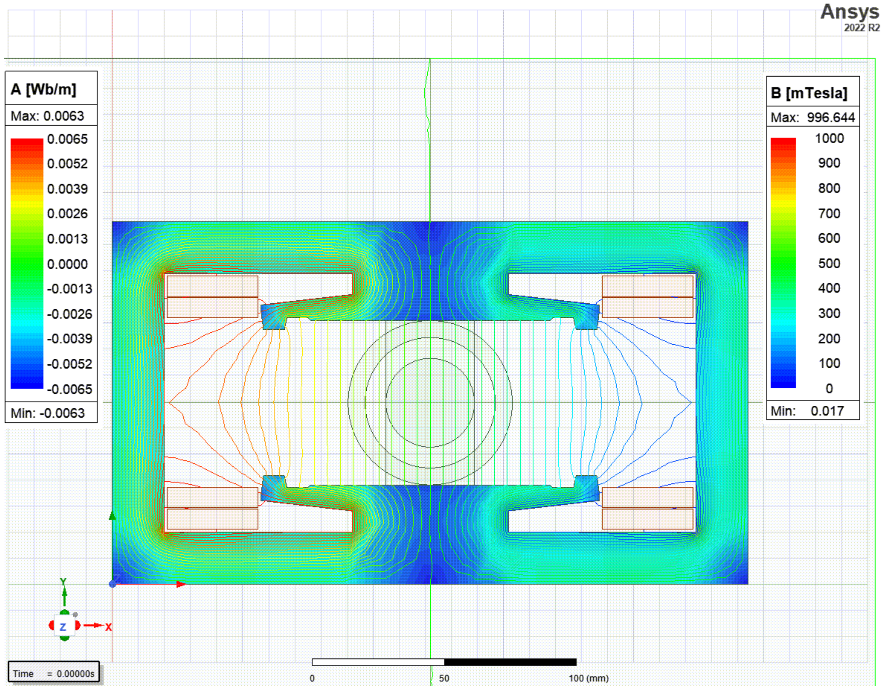
Magnetic properties and anhysteretic curve values of chosen material



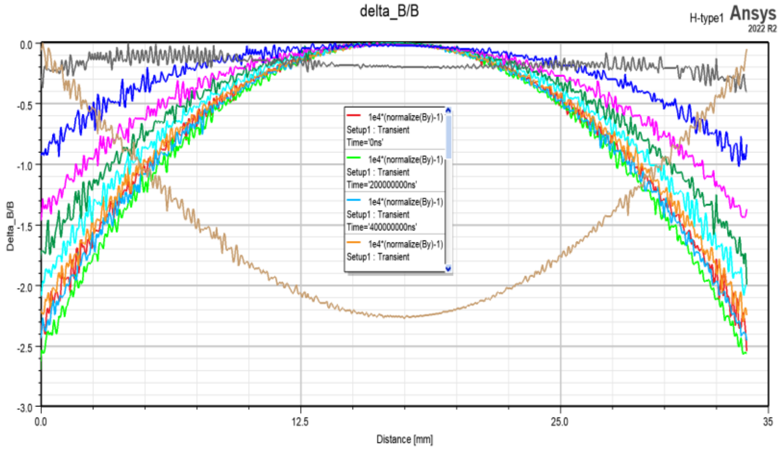
Magnetostatic analysis results at maximum field [65 mT @ airgap]

Dipole – latest version

Transient Analysis of the Core

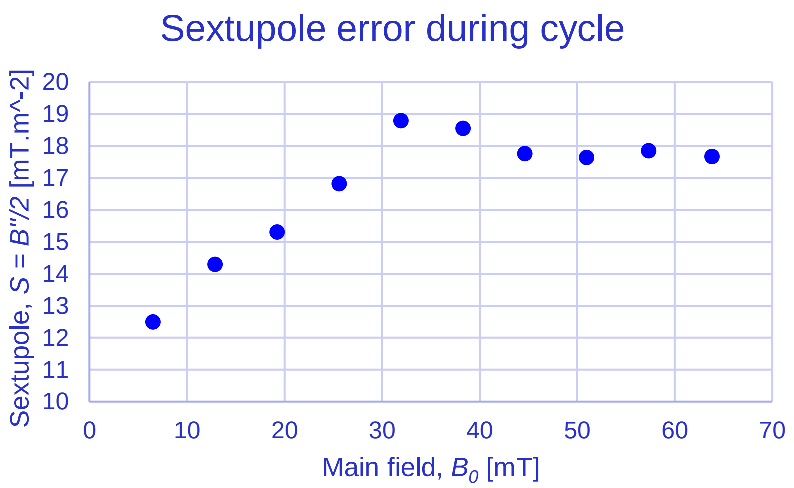


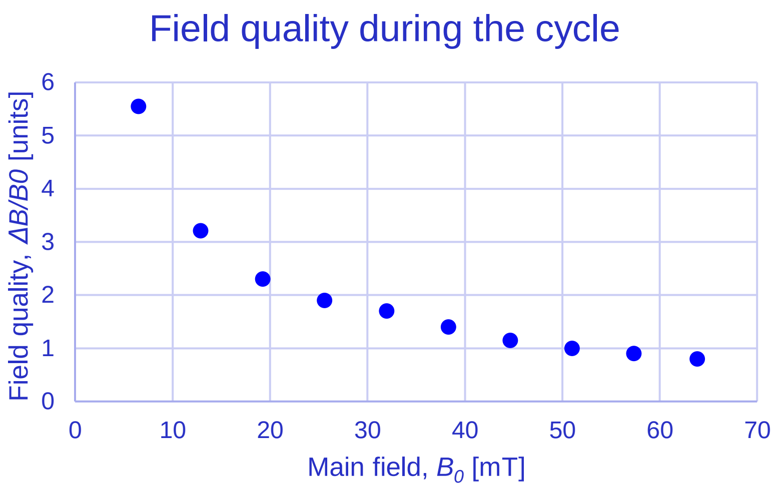
Transient analysis with hysteretic effects



- Dynamic simulation (without Eddy currents) from **65 mT → 6.5 mT, in 2 seconds**
- Design optimized for whole dynamic range, filed homogeneity **dB/B < ±2.5 units**

Hysteresis in H shape dipole





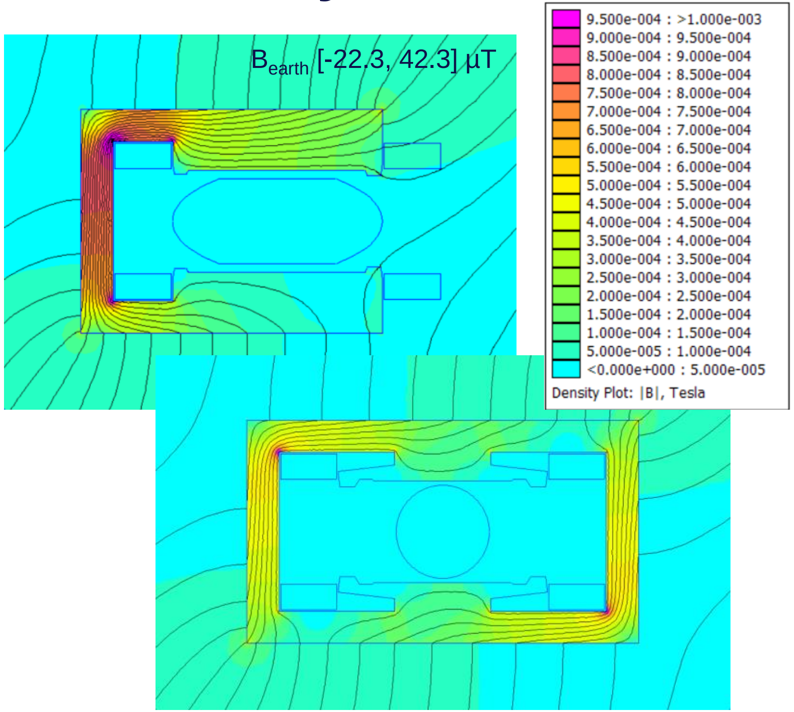
Good field region radius: ±17 mm

Earth magnetic field and other stray field

	H shape	C shape
Shielding factor x	> 400	> 10
Shielding factor y	> 65	> 30
Δ Normal FQ	<0.(1) units	<0.(1) units
Δ Skew FQ	<0.(1) units	3 units
ΔB0	0.(8) units	1.(3) units

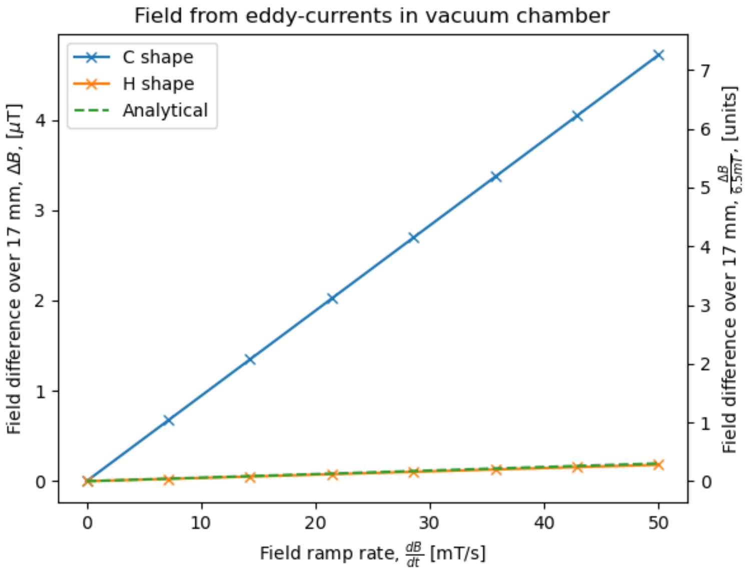
The C shape dipole is poor at shielding background field, in particular in the x-plane

The system is sufficiently linear to make predictions based upon shielding factor to 1 sig fig.

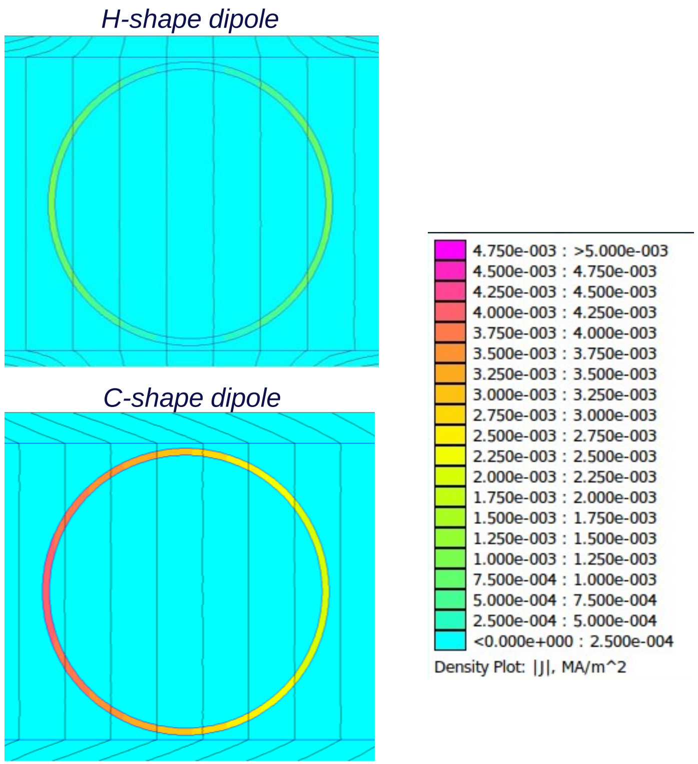


Earth's magnetic field shielding the for H and C shape (w/o excitation)

Vacuum tube eddy field



Eq.12 of Y. Chen et.al, 2019, *An expression for the eddy field in a circular vacuum chamber for HEPS booster dipole,* https://arxiv.org/pdf/1910.09781.pdf



Eddy currents in the vacuum chamber for 25.4 mT/s ramp

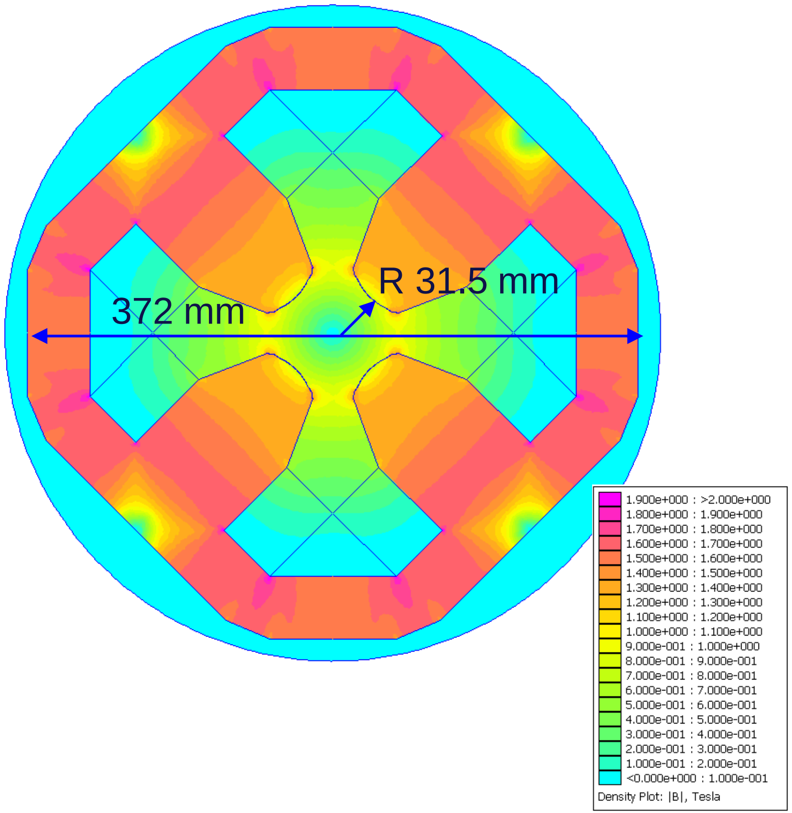
Booster quadrupole

1st quadrupole candidate

- Current density in copper: 5.1 A_{RMS} mm^{-2} @ tt2

	Z	W	H	tt 1	tt 2
Power Loss [MW]	0.9	1.5	5.0	18.9	20.8

- B_{peak} < 1.6 T @ tt2, η > 98 %
- Active mass: 750 kg (2210 tons total)
- Assumes 1.5 mm for vacuum tube and 5 mm bake-out jacket
- 6 turns per coil, [1.8 kA; 1.8 kV] per 92 magnet circuit
- ΔP cooling water 5.4 bar, ΔT < 22 K
- 70 mm coil overhang vs. 165 mm quad. to sext. distance
- **Matches key requirements, to be optimised…**

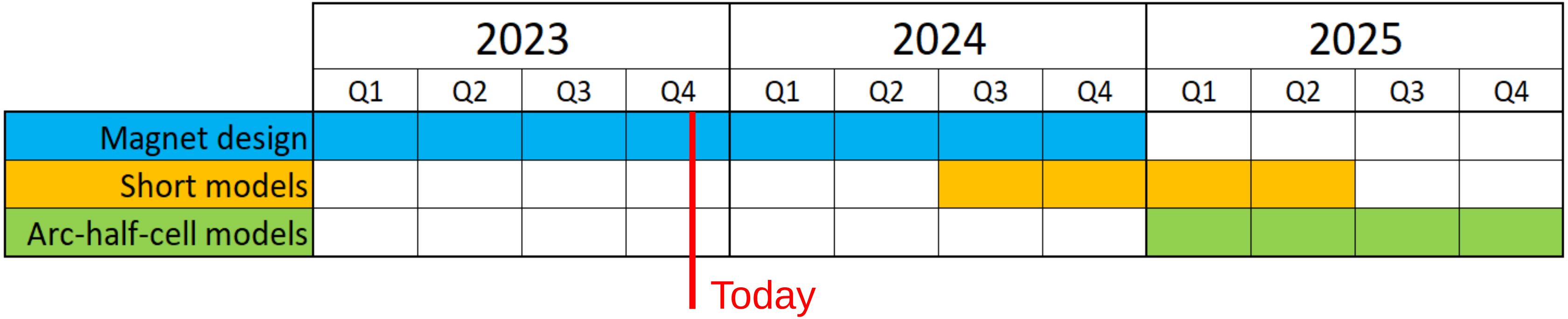


Magnet work for FCC feasibility study

WIP and next steps for magnet development

- Electromagnetic design
  - *Lifetime cost optimization (CAPEX vs. OPEX for magnet and cooling infrastructure) to define optimal working point (J in coils, ΔT, electrical parameters for converter efficiency, hydraulic impedance, etc.)*
  - *Design optimization (collider quadrupole, trim circuits, booster dipole for low field and cycling, etc.)*
- Mechanical design
  - *Design adapted to large scale production (automatised machining, assembly, measurements)*
  - *Design of inter-connections and interfaces*
- Prototyping
  - *Functional model magnets to validate performance*
  - *Model magnets for arc half-cell mock-up*

Timeline for feasibility study



Timeline of magnet development for FCC-ee feasibility study

Timeline

- Electromagnetic and mechanical design to be completed by end of 2024
- Construction of functional model magnets until mid-2025, followed by tests and measurements
- Construction of model magnet for arc half-cell mock-up over 2025 (scope and deliverables to be defined with the working group based on decisions from the project management)

Preliminary cost estimate

ARCS only

			Collider				Booster		
			Dipole 10.6 m (Cu busbars)	Dipole 10.6 m (Al busbars)	Quadrupole 2.9 m	Sextupole 1.5 m	Dipole 11.1 m	Quad 1.5 m	Sextupole 0.5 m
Yoke	Mass	kg	2576	2576	4400	880	611	612	
	Iron material cost	CHF/kg	2	2	2	2	2	2	
	Manufacturing cost	CHF/kg	6	6	12	18	12	12	
Coil or BB	Mass	kg	795	398	820	150	170	133	
	Conductor cost	CHF/kg	20	5.3	20	20	20	20	
	Manufacturing cost	CHF/kg	10	10	30	50	30	30	
Ancillaries	Material cost	CHF	5000	5000	5000	5000	5000	5000	
Assembly	Manpower cost per unit	CHF	1000	1000	5000	3000	3000	5000	
Total	***Per unit magnet***	***kCHF***	***50***	***33***	***113***	***36***	***25***	***25***	***12***
Quantity			5680	5680	2840	4672	5888	2944	1120
Gran total	***For ARCS***	***MCHF***	***287***	***186***	***320***	***169***	***148***	***74***	***13***

Full ring (ARCS + LSS)

	LSS to ring mag. length ratio		0	0	0.176	0.176	0	0.176	0.176
Gran total	***For full RING***	***MCHF***	***287***	***186***	***376***	***198***	***148***	***87***	***16***

		with dipole Cu busbars	with dipole Al busbars
Gran total (full ring)*	***MCHF***	***1112***	***1011***

* Does not include beamstrahlung line magnets downstrean IPs and wigglers

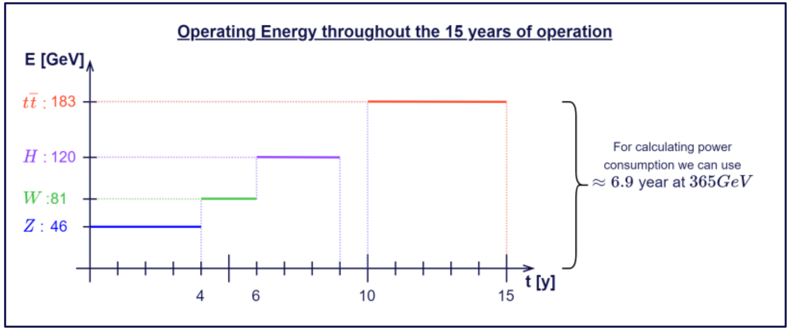
- Based on magnet **size**, **weight** and **complexity**
- **Booster** sextupole **scaled** from collider
- **Previous estimates** have been done with similar approach for the **CDR. Estimate (**approved by DG) was 860 MCHF for the arc magnets of the booster and collider (with Al busbars), which is close to the latest estimate
- **LSS and IR magnets to be included**

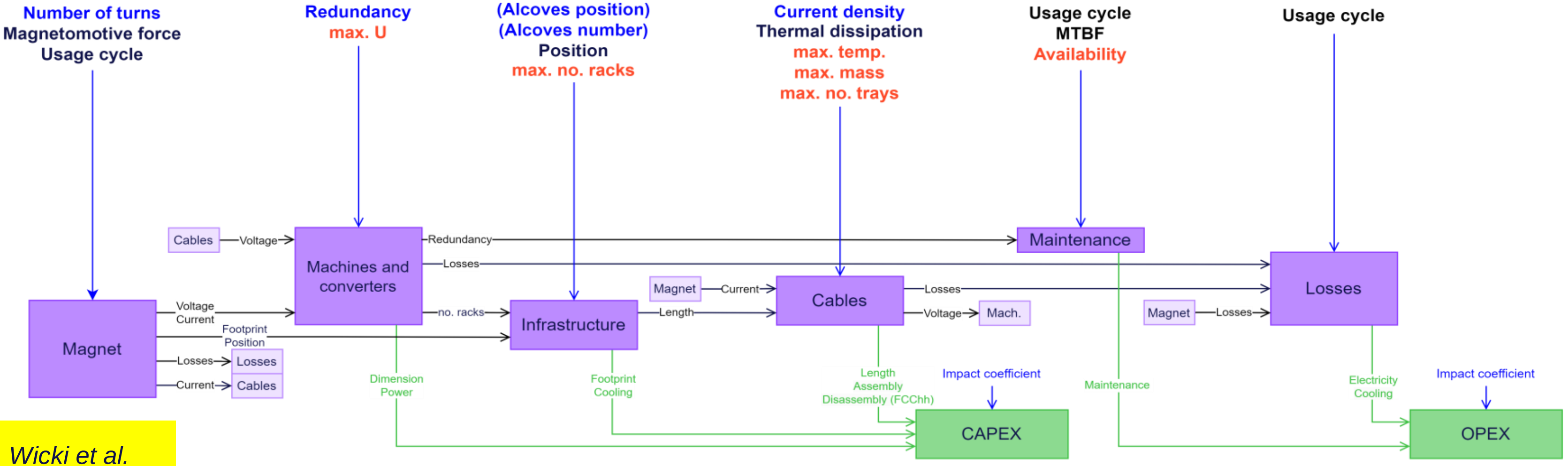
→ Next step: refined estimate based on global cost optimization

Global cost optimisation

Optimization of magnet system total cost over machine lifetime based on key parameters

Optimisation input
Parameters
Constrain
Cost





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***Ca**pital **Ex**penditure*

***Op**erational **Ex**penditure*

Concluding remarks

The FCC-ee study provides interesting opportunities and challenges in terms of magnet design. The unprecedented number of magnets imposes to include manufacturing aspects from the early design stage with a cost-optimized approach.

For the collider, this is done with simple compact low-consumption magnets. The design effort continues to further improve the magnet performance, integrating also the correction circuits needed for the controllability of the machine.

The design of the booster magnets is in progress addressing the challenges of cycled operation and low injection field.

For the feasibility study, the objective is to validate experimentally the key design features with model magnets and to optimize the lifetime cost of the magnet systems, so that feasibility is proven, and cost is properly estimated to help the decision makers at the next update of ESPP.

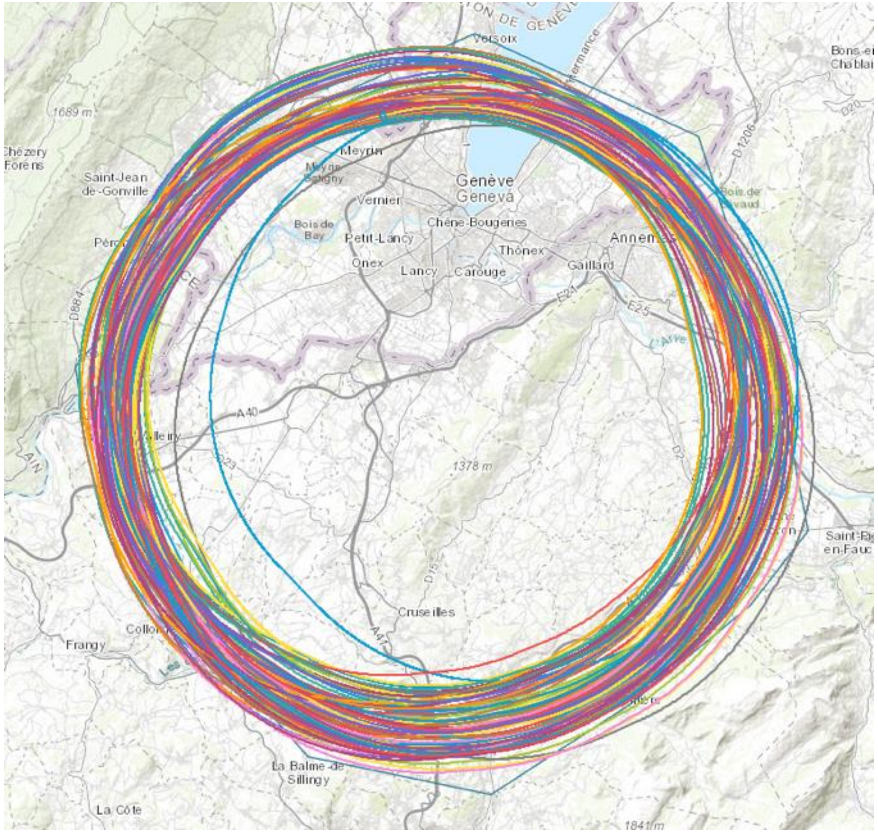
Thank you for your attention!

Questions?

FCC

SPARE SLIDES

More than 100 scenarios developed & analysed



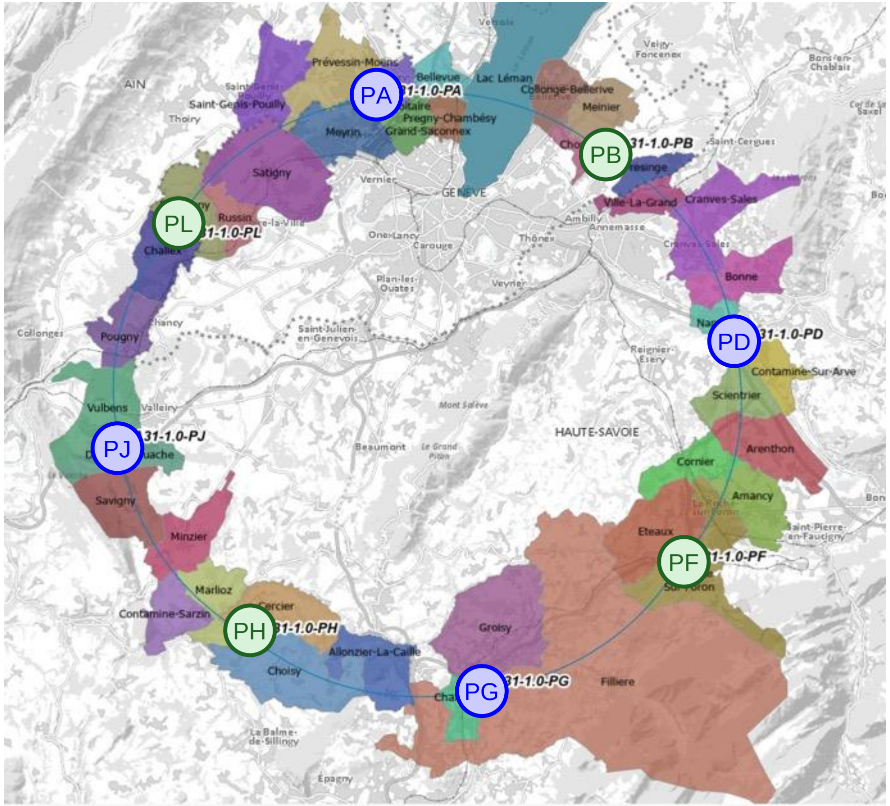
Multi-criteria approach covering 37 aspects

Legal and administrative aspects – 5 criteria
Connectivity – 2 criteria
Availability of services – 2 criteria
Accessibility of infrastructures – 6 criteria
Land plot related aspects – 9 criteria
Environnement – 8 criteria
Accelerator configuration – 3 criteria
Cost of construction
Risks linked to the construction

J. Gutleber

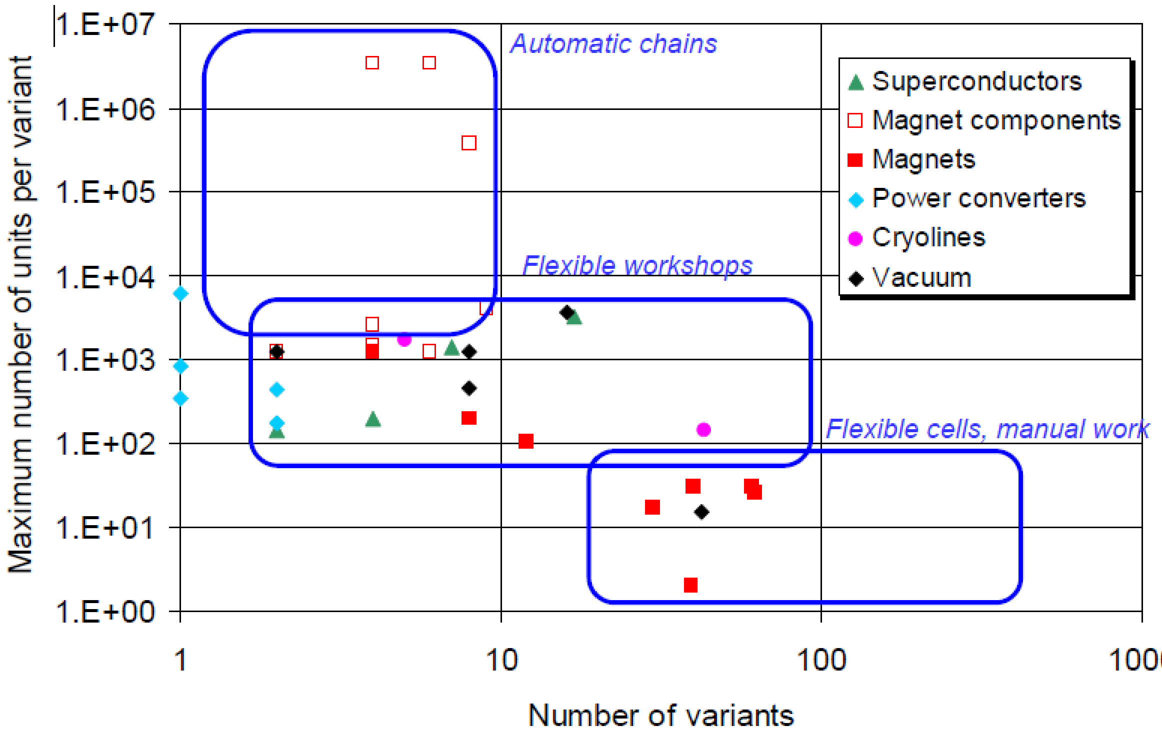
Surface site locations

1. **PA – Ferney Voltaire** (FR, 01) – experiment
2. **PB – Choulex** (CH) – technical
3. **PD – Nangy** (FR, 74) – experiment
4. **PF – Etaux/La Roche-sur-Foron** (FR, 74) - technical
5. **PG – Charvonnex/Groisy** (FR, 74) - experiment
6. **PH – Cercier/Marlioz** (FR, 74) – technical, RF
7. **PJ – Vulbens/Dingy en Vuache** (FR, 74) – experiment
8. **PL – Challex** (FR, 01) – technical, booster RF



J. Gutleber

Production volumes of LHC components



P. Lebrun

Experimental learning curves

LHC superconducting dipole magnets

- Unit cost c(n) of nth unit produced

$$c(n) = c(1)\, n^{\log_2 a}$$

with a = « learning percentage », i.e. remaining cost fraction when production is doubled

- Cumulative cost of first nth units

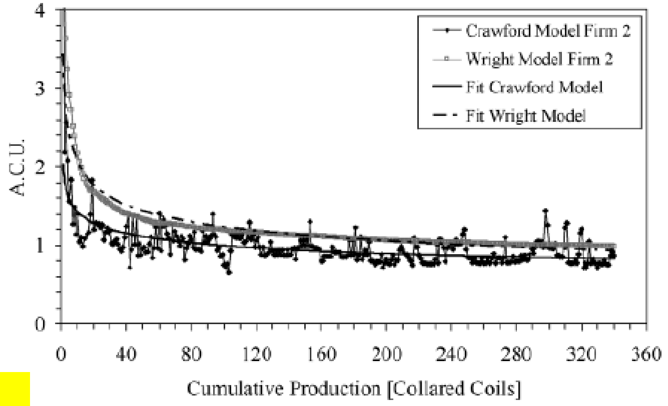
$$C(n) = c(1)\, n^{1+\log_2 a} / (1+\log_2 a)$$

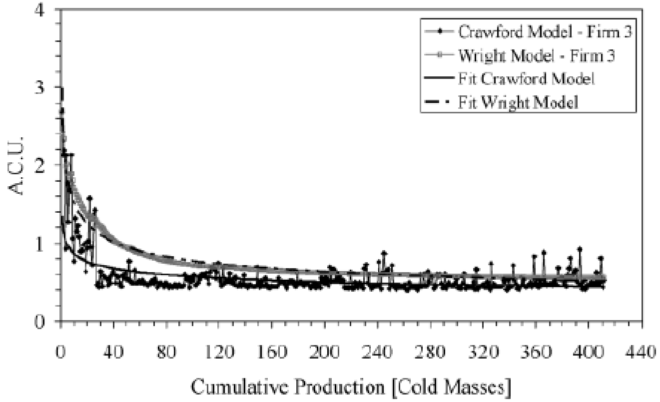
with C(n)/n = average unit cost of first nth units produced

TABLE IV
LEARNING PERCENTAGE OF SELECTED REFERENCE INDUSTRIES

Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
LHC magnets	80%-85%
Shipbuilding	80%-85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

Learning coefficients





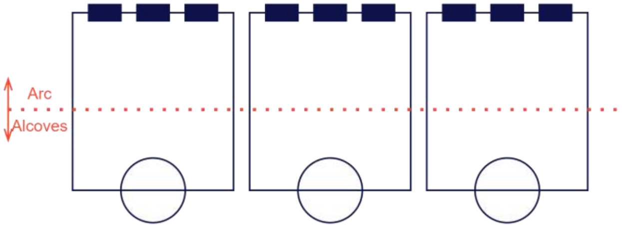
P. Lebrun

Example - Collider Sextupole

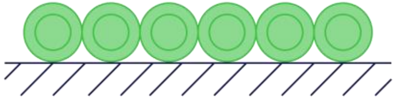
Other powering solution depending on controllability

Controllability : -100% to +100%

Polarity of group can be reversed during run



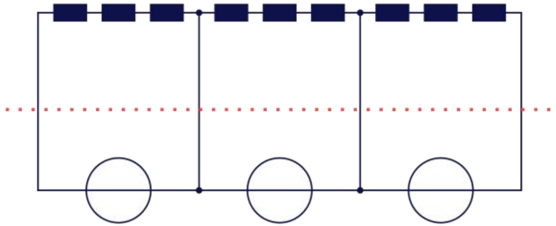
$$N_{cable} = 2N_{circ}$$



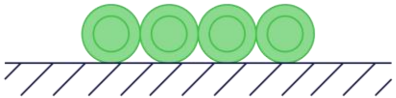
Power converters are too big to be put in the arcs.

Controllability : 0% to +100%

Polarity of group not reversed during run



$$N_{cable} = N_{circ} + 1$$



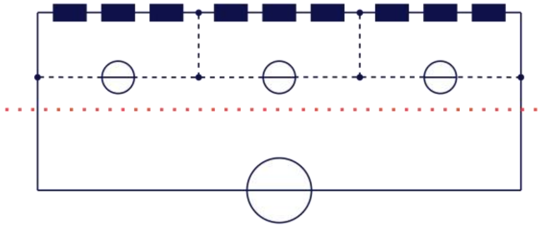
Close to half the space by using cable sharing.

CAPEX –

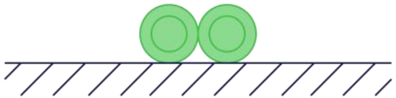
OPEX –

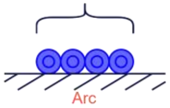
Controllability : 0% to +10%

Polarity of group not reversed during run
+ lower change percentage



$$N_{cable} = 2 \qquad +(N_{circ} + 1)$$





Only one converter in the alcoves.

The trimmers + cabling in the arc section, closest to magnets

CAPEX – – –

OPEX – – –

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