16 T compact common-coil design for a future collider

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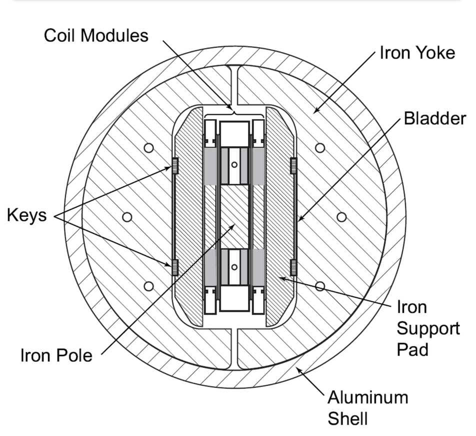
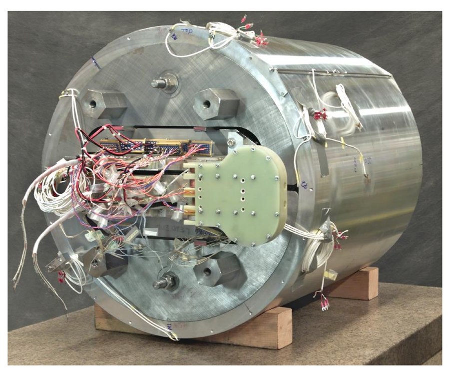
RD3b model (14.7 T)





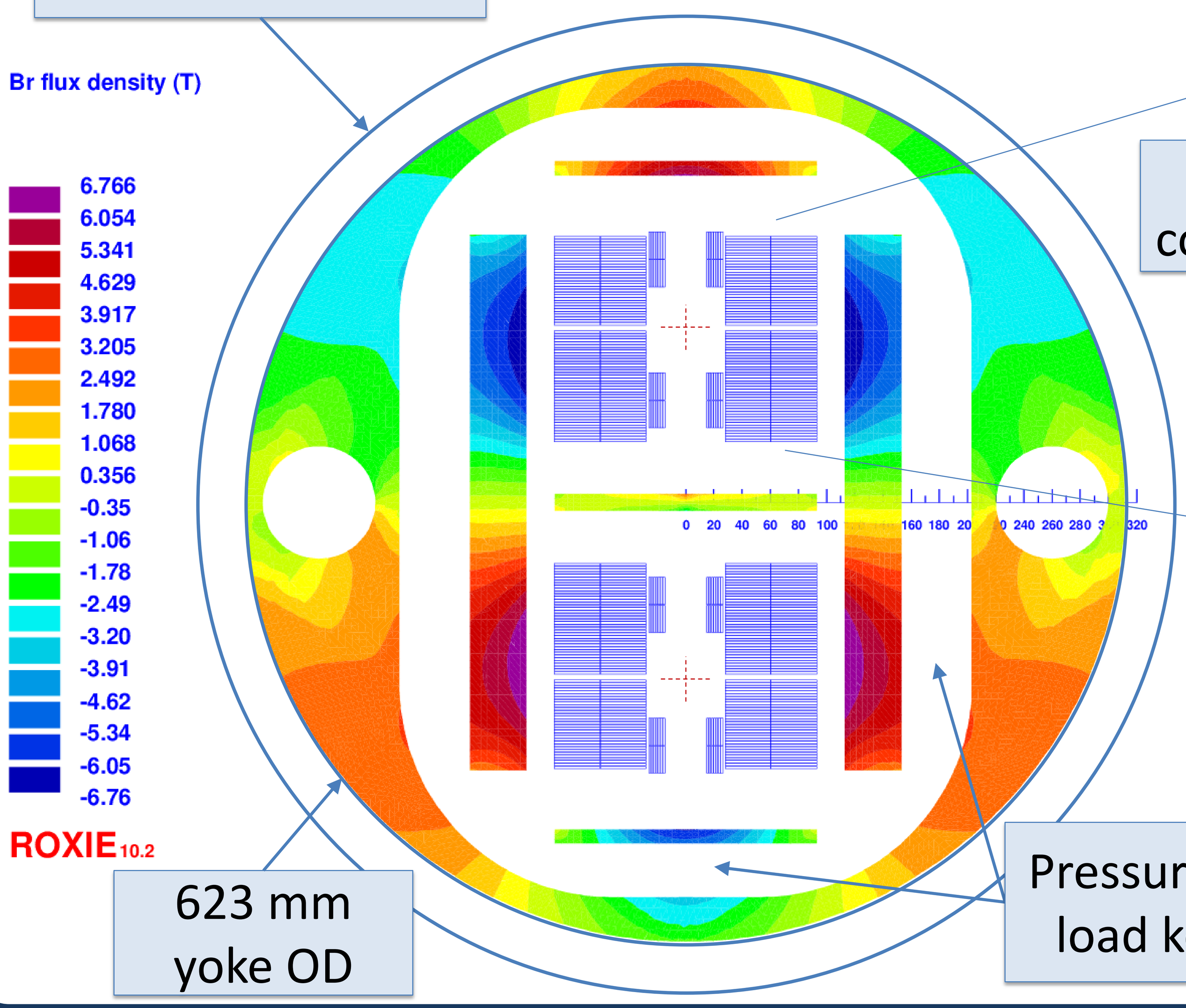
Goals of the present design

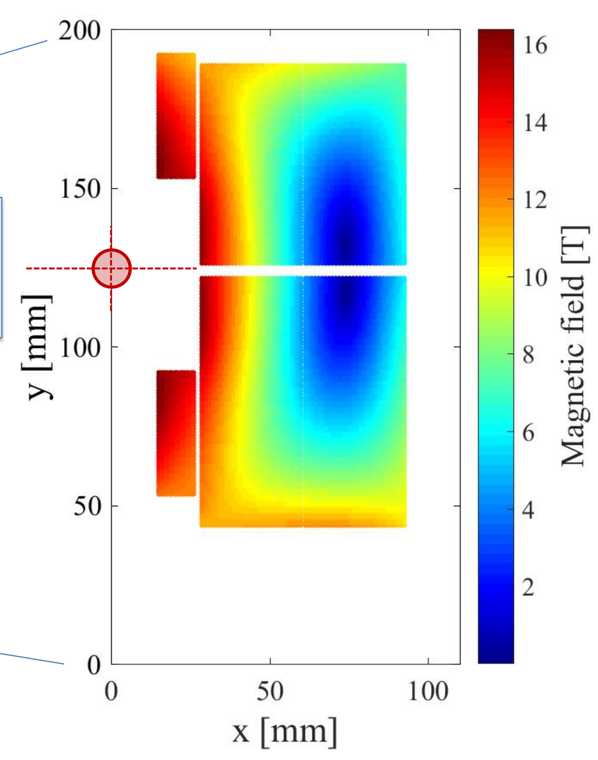
→ Achieving the **FCC target performance** (bore field, aperture, margin, field quality, quench protection) using a **compact design**
→ Lower **inductance**, easier **quench protection** and circuit **powering**

Main features

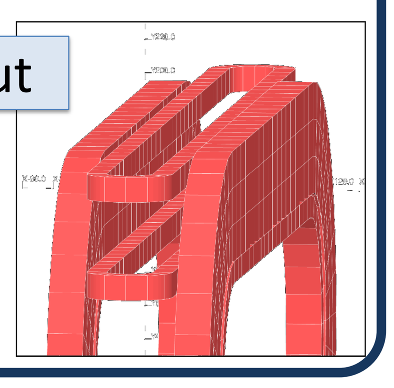
→ **Common coil**: 2-in-1, racetrack coils shared between apertures [1]
→ Based on the experience from **RD series** at **LBNL** (14.7 T achieved) [2-5]
→ Large **bending radius** for the main coil (allowing use of **large cable**)
→ Reduced beam separation with **top-bottom asymmetric coil** design
→ **Fabrication** and **cost**: Straight coils (no flared ends); Fewer layers and turns; **Compact** design: 623 mm iron yoke OD, ~700 mm shell OD
→ Compatible with **key & bladder** mechanical structure
→ Main and auxiliary coils powered in **independent electrical circuits**

Magnet cross-section





3D end layout



Design parameters

Nominal performance	Main coil	Auxiliary coil
Bore dipole magnetic field	16 T	
Operating temperature	1.9 K	
Operating current	23.0 kA	9.1 kA
Current density in the SC	784 A/mm²	645 A/mm²
Peak field in the conductor	16.0 T	16.4 T
Short sample magnetic field	19.8 T	20.4 T
Margin on the load line	19.0%	19.7%
Temperature margin	4.5 K	4.6 K
Turns per "quadrant"	72	14
Strand area per "quadrant"	33.9 cm²	3.2 cm²
Coil aperture	56 (h) x 61 (v) mm	
Clear aperture [6]	50 mm	
Minimum bending radius	43.1 mm	14.6 mm
Intra-beam separation	250 mm	
Iron yoke external diameter	623 mm	
Horizontal forces per quadrant	12.7 MN/m	1.7 MN/m
Vertical forces per quadrant	3.1 MN/m	0.3 MN/m
Self-inductance at 16 T	226 mH	
Self-inductance at 1 T	308 mH	
Magnet length	14.3 m	
Total stored energy	60 MJ	
Current density in the Cu	1288 A/mm²	1059 A/mm²
Hot-spot temperature* (40 ms quench detection and protection) *Preliminary!	251 K	-

The main and auxiliary coil are powered in **independent electrical circuits** but are magnetically coupled.

Conductor

Conductor	Main coil	Auxiliary coil
Superconductor	Nb_3Sn	Nb_3Sn
Number of strands	60	45
Strand diameter	1.0 mm	0.8 mm
Cu/noCu ratio	0.61	0.61
Cable width	32.3 mm	19.3 mm
Cable thickness	1.75 mm	1.40 mm
Insulation thickness	0.11 mm	0.11 mm
Jc(16 T, 1.9 K)	2250 A/mm²	2250 A/mm²

Common coil design is compatible with large cable size due to **large bending radius**.

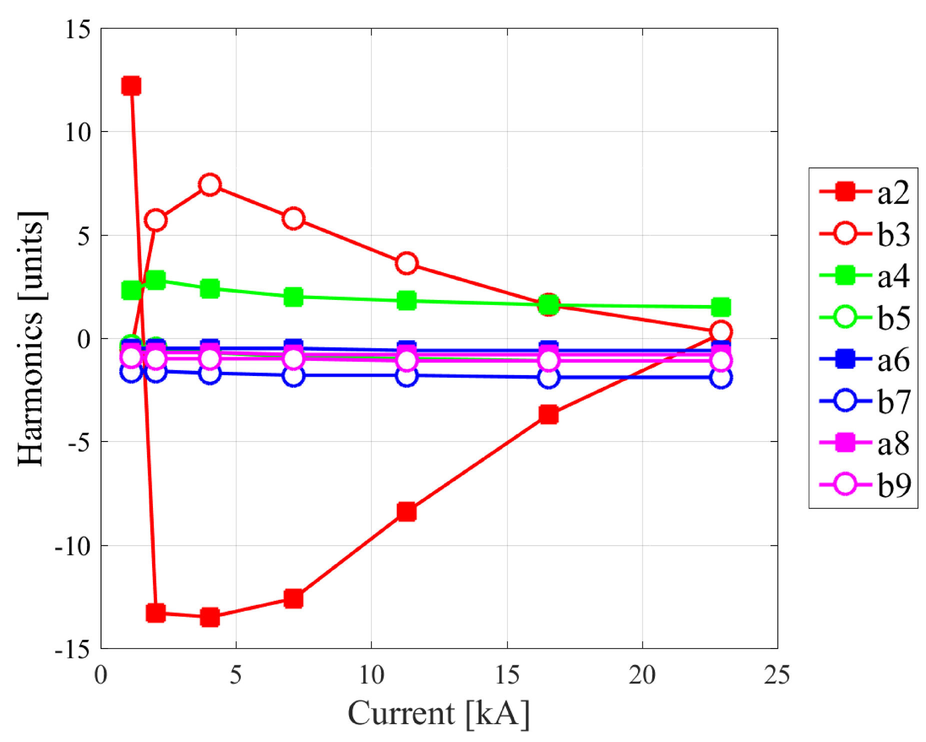
A **large cable** allows achieving the target field with **fewer layers** and **turns**

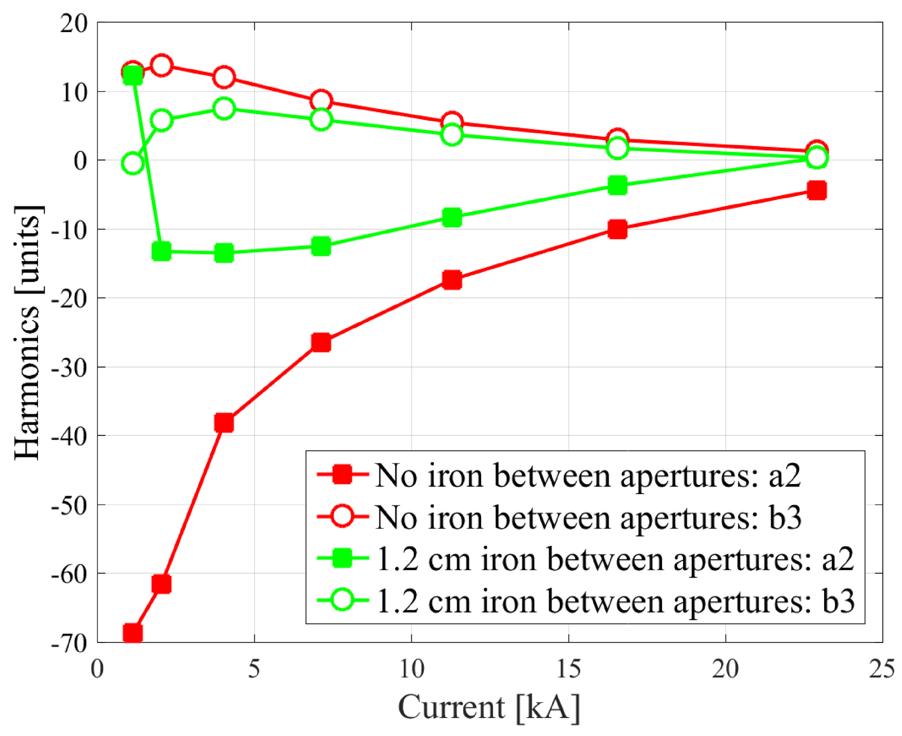
- Lower inductance
- Easier protection

Magnetic field quality

Harmonics at nominal current at 2/3 of the aperture [units]

Normal		Skew	
b3	0.3	a2	0.2
b5	-1.1	a4	1.5
b7	-1.9	a6	-0.6
b9	-1.1	a8	-0.8





Example: Effect of the layer of iron added between apertures

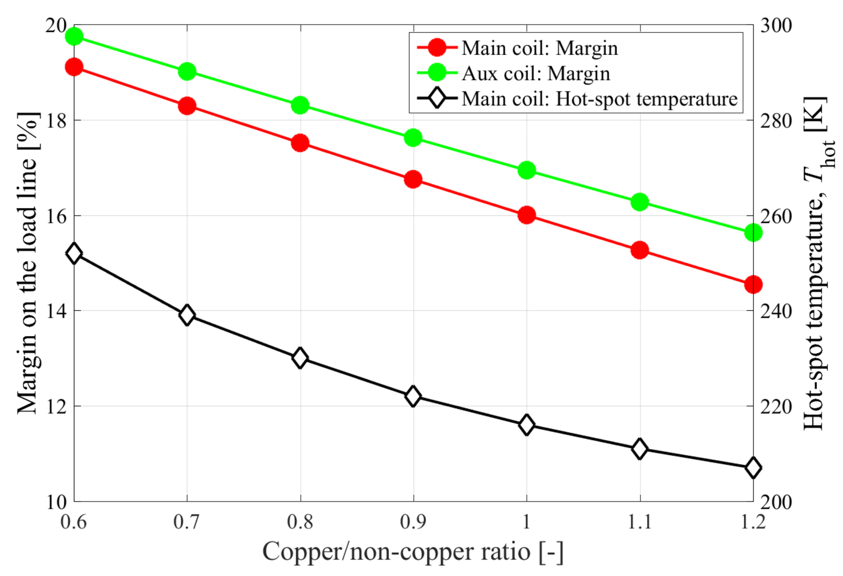
- Magnetic analysis and **optimization** performed with ROXIE
- Good **field quality** and **compactness** achieved with top-bottom **coil asymmetry** design (aperture center, turn numbers, auxiliary coil position)
- Several features included in the **iron cross-section** to improve control the **harmonics** in the full range 5-100% of nominal current

Quench protection

Protection of the main coil analyzed in **stand alone** configuration.

Preliminary results show the **hot-spot temperature** can be maintained in the range **200-250 K** even with low copper fraction.

Margin and hot-spot temperature as a function of the **Cu/noCu ratio**



Main design and performance parameters

- **16 T** bore magnetic field with **19% margin** at 1.9 K
- **43 mm** minimum bending radius (for the main coil)
- **297 cm²** of strand cross-section in the entire magnet
- **250 mm** beam separation
- **623 mm** outer diameter iron yoke
- **230 mH** self-inductance for the 14.3 m long magnet
- **250 K** hot-spot temperature at nominal current

Discussion

- This design meets the **FCC magnetic requirements** achieving very good **margin** and easier **operation/quench protection**
- The characteristics of common coil layout, such as featuring **flat cables** and **larger bending radius** at the coil ends, are well suited for using a **large cable**
- Using larger cable allows designing a magnet with **fewer turns**, hence with **lower inductance** and more **compact**
- Modifications to coil windings and iron cross-section allow efficiently compensating **field errors** arising due to the small beam separation distance
- Detailed **mechanical analysis** is required and will be performed soon

[1] R. Gupta, "A Common Coil design for High-Field 2-in-1 Accelerator Magnets," *1997 Particle Accelerator Conference*, 1997.
[2] GL. Sabbi et al., "Conceptual Design of a Common Coil Dipole for VLHC," *IEEE Transactions on Superconductivity*, 2000.
[3] GL. Sabbi et al., "Design of Racetrack Coils for High-Field Dipole Magnets," *IEEE Transactions on Superconductivity*, 2001.
[4] R. Benjegerdes et al., "Fabrication and test results of a high field, Nb_3Sn superconducting racetrack dipole magnet," *2001 Particle Accelerator Conference*, 2001.
[5] A.F. Lietzke et al., "Test Results of RD3c, a Nb_3Sn Common-Coil Racetrack Dipole Magnet," *IEEE Transactions on Applied Superconductivity*, 2013.
[6] GL. Sabbi et al., "Performance characteristics of Nb_3Sn block-coil dipoles for a 100 TeV hadron collider," *IEEE Transactions on Applied Superconductivity*, 2015.