Block-Coil Dipole Designs for 16 T

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Acknowledgement

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First Annual Meeting of the Future Circular Collider Study

Washington, DC, March 23-27, 2015

Presentation Goals

- Main focus is on providing key design features and performance parameters of block coils for comparisons with other approaches, and overall machine optimization
- An implicit question is how to best analyze and present the information:
  - Choice of appropriate criteria and targets to improve consistency and facilitate comparisons
  - Provide information covering a range of design parameters and features of potential interest to FCC
  - Incorporate experience from model magnet fabrication and test
- Not covered in this presentation:
  - Analysis details; engineering aspects; feedback from fabrication and test of model magnets; R&D priorities
  - A list of references on these topics is provided at the end

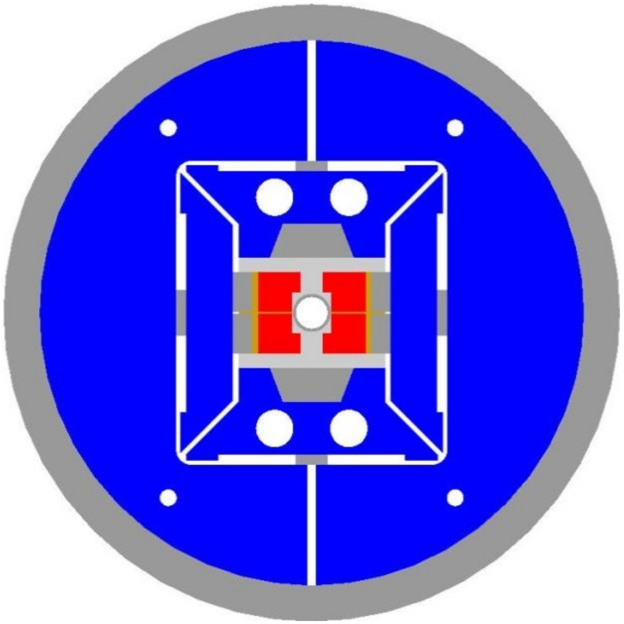
Outline

- Reference design (single aperture)
    - Objectives, features and parameters
    - Quench protection analysis (CLIQ)
- Reference conductor properties and short sample performance
- Opportunities for improved conductor, and related performance gains
- Design optimization for FCC
    - Increased aperture
    - Increased margin: graded coils, larger coils
- Double aperture designs
    - Reference case, compact option
- Field quality considerations
- Summary

Reference Design (Single Aperture)

Guiding criteria and strategy:

- Base reference on solid experience from model magnet fabrication, test & analysis
- This design (HD2) achieved 13.8T at 4.5K, highest field on record for a dipole with accelerator relevant bore and field quality
- From this starting point, we study variants in areas of interest to FCC

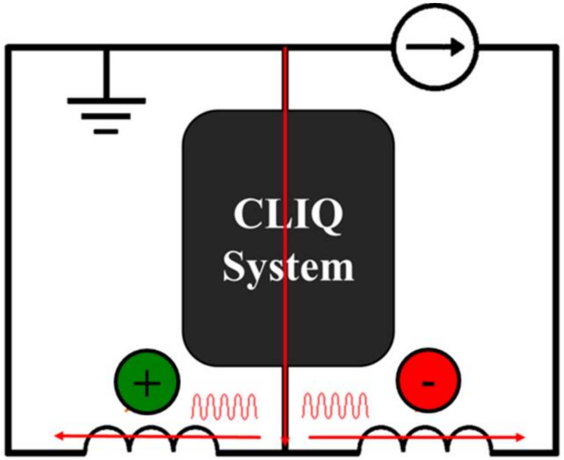


Design parameters	Unit	Ref (1ap)
Strand diameter	mm	0.8
Number of strands		51
Cable width	mm	22.0
Insulation thickness	mm	0.1
Coil aperture (x/y)	mm	45/47
No. turns (1 quadrant)		54
Minimum bending radius	mm	12.8
Coil area (1 quadrant)	cm^2	13.8
Clear bore diameter	mm	~40
Yoke diameter	mm	623

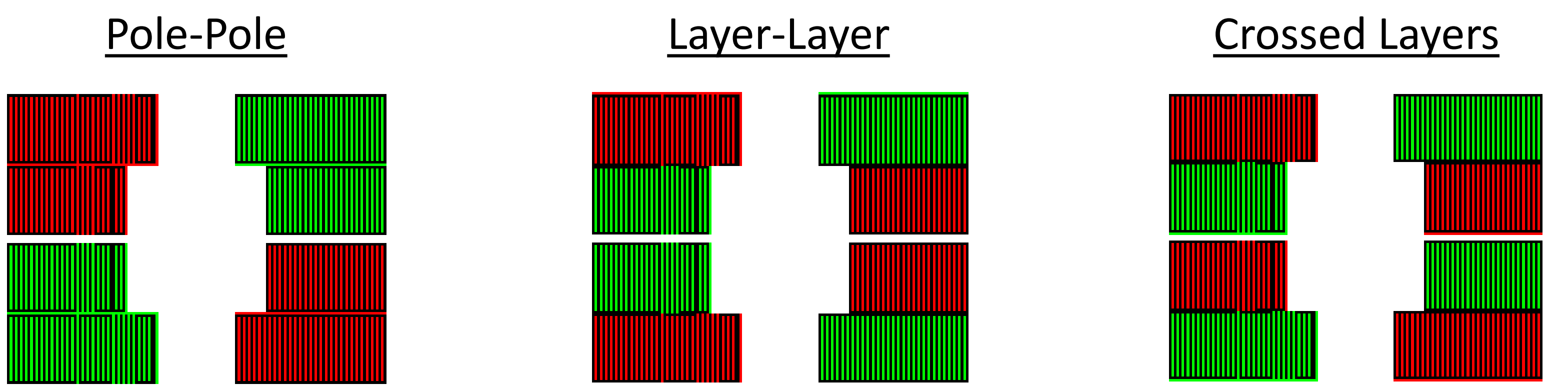
Performance at 16 T	Unit	Ref (1ap)
Operating current	kA	18.6
J_e (insulated cable)	A/mm^2	517
Peak field in the coil	T	16.9
Horizontal force (I+/I-)	MN/m	6.3/-6.3
Vertical force (I+/I-)	MN/m	-2.9
Inductance	mH/m	5.1
Stored energy	MJ/m	0.85

Quench Protection with CLIQ

- CLIQ = Coupling Loss Induced Quench system under development by CERN.
- Capacitive discharge to induce fast oscillations of the transport current *(ref: E. Ravaioli et al., IEEE Trans. Appl. Supercond. 24 (3) June 2014)*
- Recently tested on several magnets, including NbTi and Nb_3Sn models, with very good performance



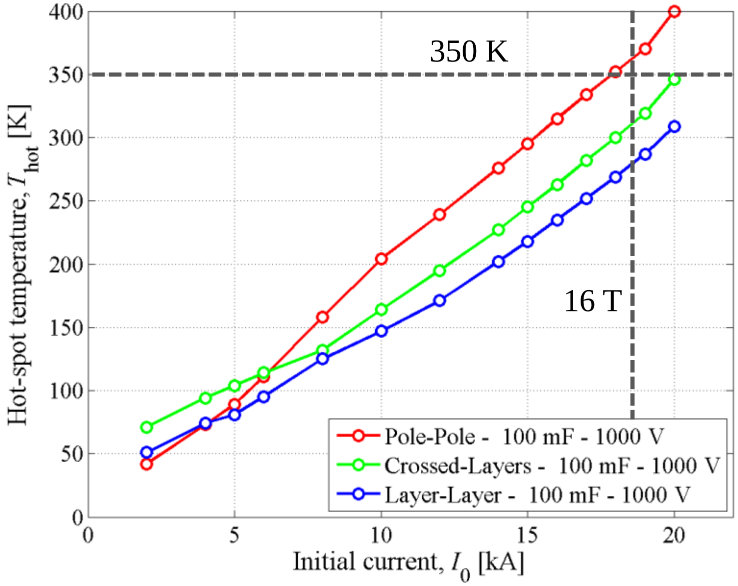
Three configurations considered for the case of a block-coil made of two double-layers:

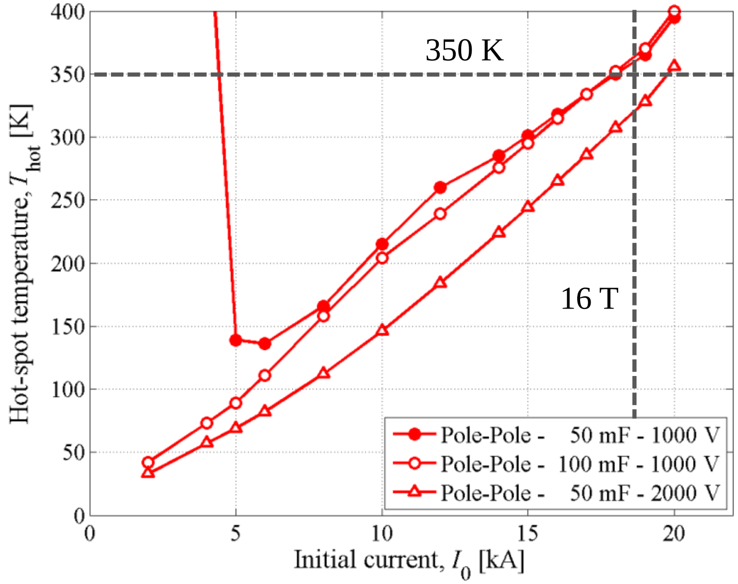


Note: Layer-Layer and Crossed Layers require an additional (lower current) lead

Quench Model Parameters and Results

- Based on single aperture reference cross section, 14 m long coil (expect similar results for double aperture, using two CLIQ units)
- CLIQ parameters: 1kV, 100 mF; simulations include 10 ms delay (quench validation time)
- Conductor parameters (HD2): 0.8 mm strand diameter, 14 mm twist pitch, 51 strands, 127 mm transposition length, J_c(16T, 4.2K)=1.49 kA/mm^2, RRR=287, f(non-Cu)=0.55





- Maximum temperature within acceptable level (350K) for layer-layer and crossed layers
- Pole-pole configuration can achieve temperature below 350 K by increasing voltage

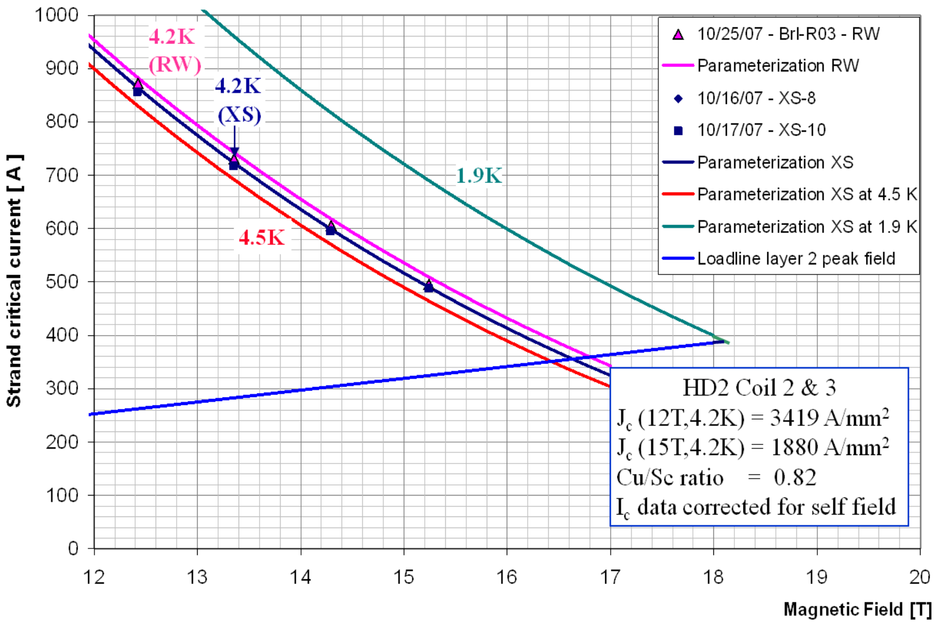
Short Sample Performance Reference

- Critical current **measured on wires used in the HD2 models** is used as initial reference
  - **J_c =1 .5 kA/mm² at 16 T, 4.2K**: same as FCC target. RRR=287, D_{fil}=74 µm
- A range of conductor designs and properties will be discussed in the following slides

Strand Parameter	Unit	HD2 Coil 2&3
Non-Cu Fraction	%	55
J_c (12T, 4.2K) (*)	A/mm²	3419
J_c (15T, 4.2K) (*)	A/mm²	1880
I_c (15T, 4.2K) (*)	A	520

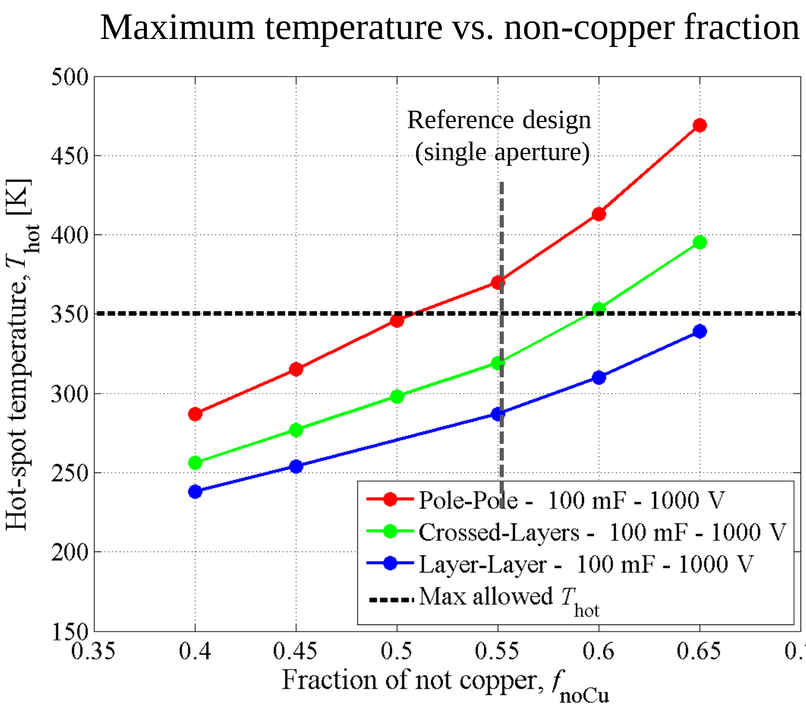
(*) From extracted strands; self-field corrected

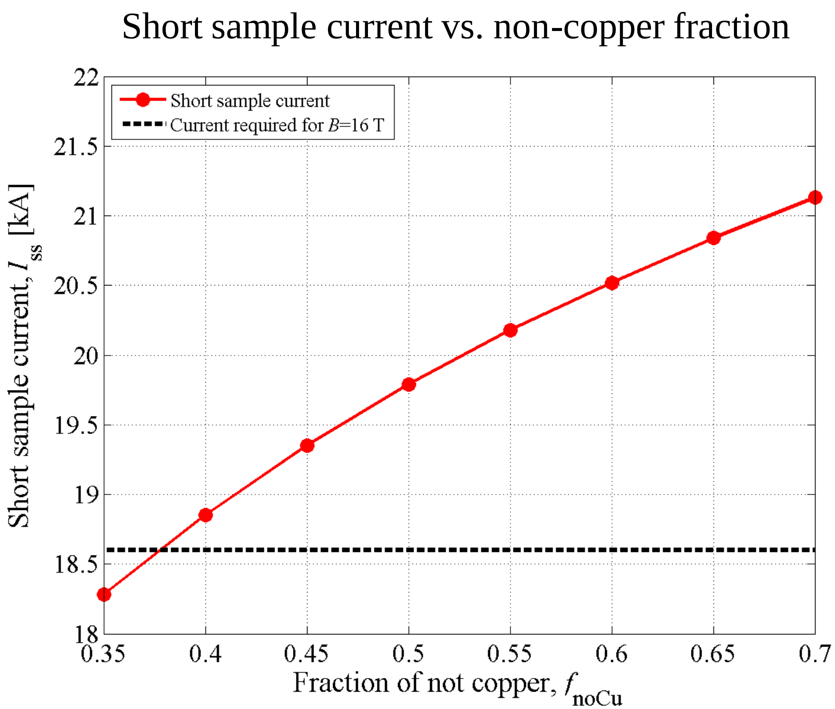
Reference	I_{ss}		B_1^{ss}	
Temperature	4.5K	1.9K	4.5K	1.9K
Single aperture	18.0	20.1	15.52	17.15
Double aperture	17.8	19.7	15.49	17.12



- Almost identical result for single aperture and double aperture designs, as expected
- Operation at 4.5K, 16 T is excluded with reference conductor properties
- Operating point for 1.9K, 16 T is at 92% on the load line: need to increase margin

Performance vs. Copper fraction

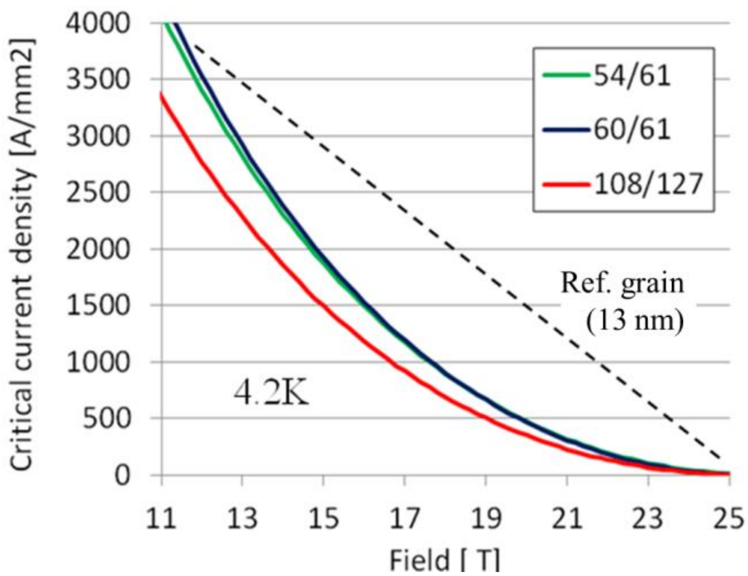


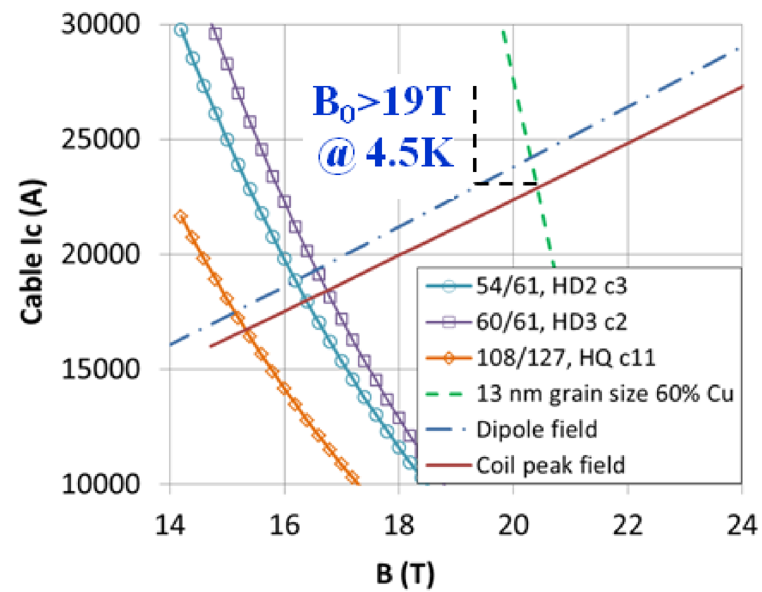


- Results indicate that optimized CLIQ configurations may allow to protect the magnet using significantly lower copper fraction with respect to traditional quench heaters [2]
- Going from f(non-Cu) = 0.4 to 0.6 corresponds to an effective 50% improvement in J_c
- CLIQ simulations have been experimentally validated in a broad range of parameters, but specific tests on block-coil dipoles should be performed to confirm results

Performance with improved Nb_3Sn J_c

- Principle: increase of Nb_3Sn pinning force at high field through grain refinement
- Exciting recent demonstration in wires *(X. Xu et al, Appl. Phys. Lett. 104 082602)*
  - Discussed in Wednesday's presentation by D. Larbalestier (x6 potential)
- Corresponding gain in J_c if extrapolated to 13 nm grain size: x4.5 @ 16T [ref. 1]
- Sufficient to bring the operating point of the reference design below 85% at 4.5 K

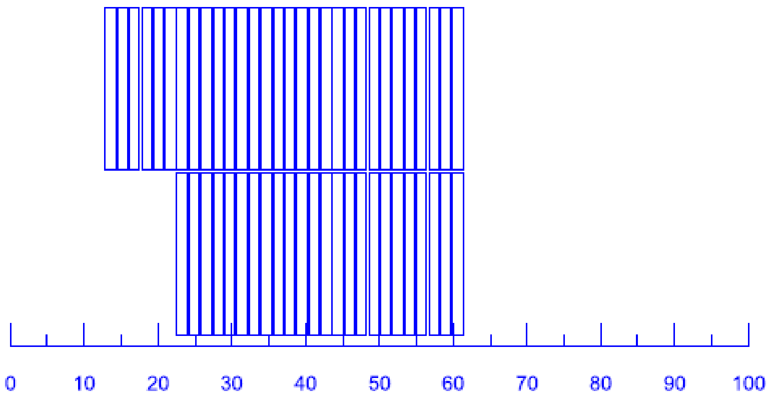


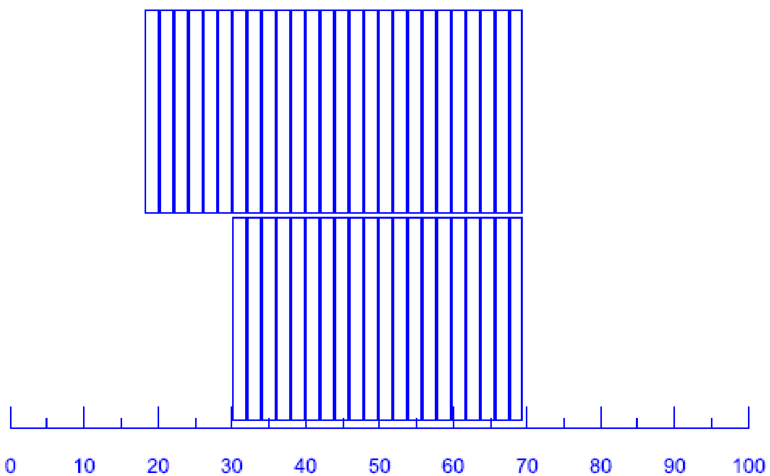


- A ~10% fraction of these gains would be sufficient to bring the operating point of the reference design below 85% at 1.9K

Block-Coils with Larger Aperture

- Increasing the aperture up to ~55 mm brings several attractive features, but coil area increase is significant





Design parameters	Unit	Ref	Lrg Ap
Strand diameter	mm	0.8	1
Number of strands		51	51
Number of turns	mm	54	46
Coil aperture (x/y)	mm	45/47	60/58
Minimum bending radius	mm	12.8	18.3
Strand area (1 quadrant)	cm^2	13.8	18.4
Clear bore diameter	mm	~40	~55

Performance at 16 T	Unit	Ref.	Lrg Ap
Operating current	kA	18.6	26.4
Peak field in the coil	T	16.9	17.2
Av. stress (F_x/coil height)	MPa	143	141
Inductance	mH/m	5.5	4.1
Stored energy	MJ/m	0.85	1.42

Short sample and margin	Unit	Ref.	Lrg Ap
Maximum current	kA	20.1	29.0
Maximum dipole field	T	17.1	17.4
Operating point for 16 T	%	92.5	90.8

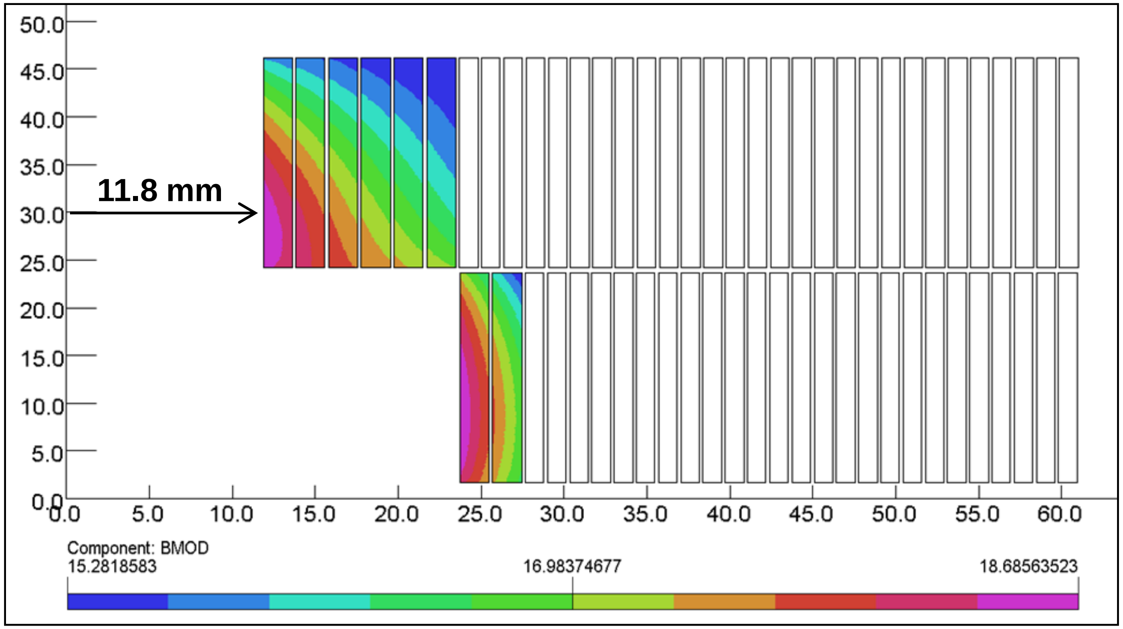
(*) At 1.9K, assuming reference conductor properties

Increased Margin with Graded Coil

Cable Parameters	HF	LF
Strand diameter [mm]	1.0	0.65
No. Strands	41	64
No. turns (L1+L2)	6+2	28+25
Strand area [cm^2]	2.57	11.25

B_1 (SSL) [T]	4.5K	1.9K
Reference (HD2)	15.52	17.15
Graded (*)	16.67	18.42
Dipole field increase	+1.15	+1.27

(*) I_c scaled with strand area from HD2



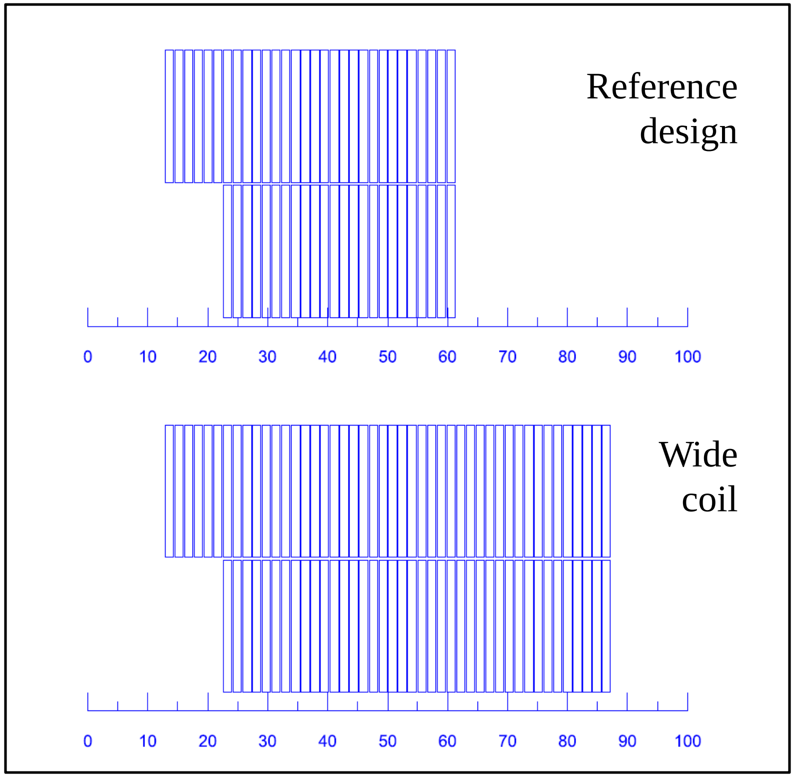
Benefits: higher field than HD2 with same strand area (13.8 cm^2/quadrant)

Challenges:

- High Field cable: thickness +0.35 mm, winding radius -1 mm
- Low Field cable: (further) increased aspect ratio (beyond limits?)
- Fabrication and splicing of the two sub-coils (a long list…)

Increased Margin with Wider Coil

- Goal: lower operating point to ~85%
- Ref. cable, more turns, still 2 layers/pole
  - +1.5T field, +8% margin
  - +60% strand, x2.8 inductance



Design parameters	Unit	Ref.	Wide
Coil aperture (x/y)	mm	45/47	45/47
No. turns (1 quadrant)		54	86
Minimum bending radius	mm	12.8	12.8
Strand area (1 quadrant)	cm^2	13.8	22.0

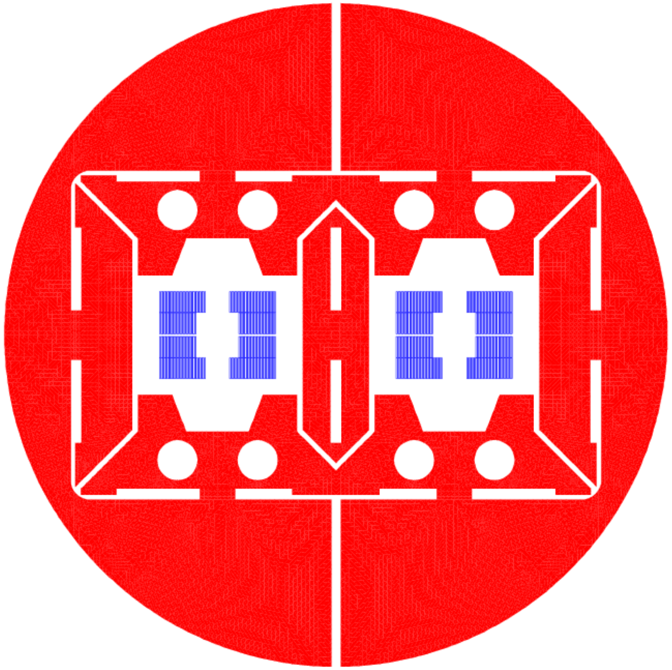
Performance at 16 T	Unit	Ref.	Wide
Operating current	kA	18.6	13.5
Peak field in the coil	T	16.9	16.4
Horizontal force (I+/I-)	MN/m	6.3	7.2
Vertical force (I+/I-)	MN/m	-2.9	-3.5
Inductance	mH/m	5.5	15.2
Stored energy	MJ/m	0.85	1.4

Short sample & margin (*)	Unit	Ref.	Wide
Maximum current	kA	20.1	16.0
Maximum dipole field	T	17.1	18.6
Operating point for 16 T	%	92.5	84.4

(*) At 1.9K, assuming reference conductor properties

Two-in-One Design Reference

- Guideline: direct extension of single aperture case
- 250 mm separation, 700 mm yoke
- Magnetic parameters and field quality are the same as for single aperture
- Outward forces are the same as for a single aperture

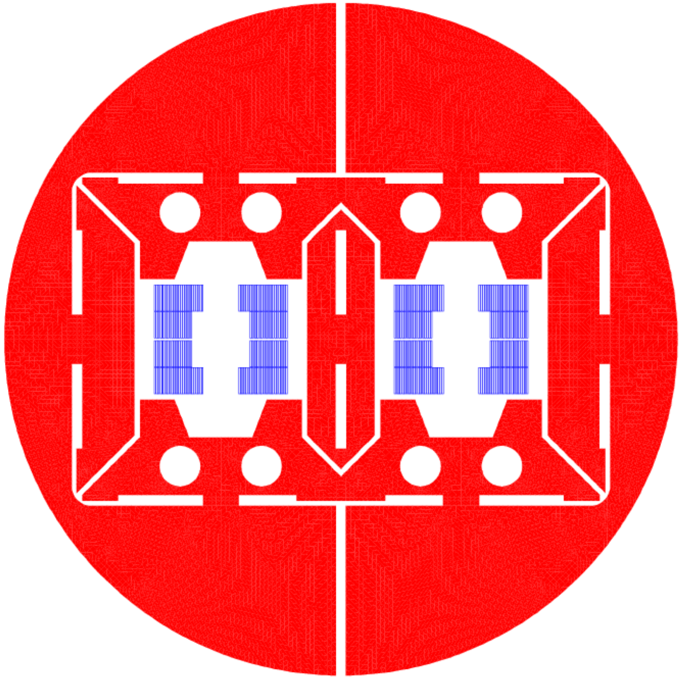


Design parameters	Unit	1 Ap	2 Ap
Strand diameter	mm	0.8	0.8
Number of strands		51	51
Cable width	mm	22.0	22.0
Insulation thickness	mm	0.1	0.1
Coil aperture (x/y)	mm	45/47	45/47
No. turns (1 quadrant)		54	54
Minimum bending radius	mm	12.8	12.8
Strand area (1 quadrant)	cm^2	13.8	13.8
Clear bore diameter	mm	~40	~40
Yoke diameter	mm	623	700

Performance at 16 T	Unit	1 Ap	2 Ap
Operating current	kA	18.6	18.5
J_e (insulated cable)	A/mm^2	517	514
Peak field in the coil	T	16.9	16.7
Horizontal force	MN/m	6.3	6.4
Vertical force	MN/m	-2.9	-2.9
Inductance	mH/m	5.1	11.2
Stored energy	MJ/m	0.85	1.9

Two-in-One with Larger Aperture

- Guideline: direct extension of single bore case with increased aperture
- 250 mm separation, 700 mm yoke
- Some coupling between apertures, may require further optimization or larger yoke



Design parameters	Unit	1 Ap (L)	2 Ap (L)
Strand diameter	mm	1	
Number of strands		51	
Number of turns	mm	46	
Coil aperture (x/y)	mm	60/58	
Minimum bending radius	mm	18.3	
Strand area (1 quadrant)	cm^2	18.4	
Clear bore diameter	mm	~55	
Yoke diameter	mm	623	700

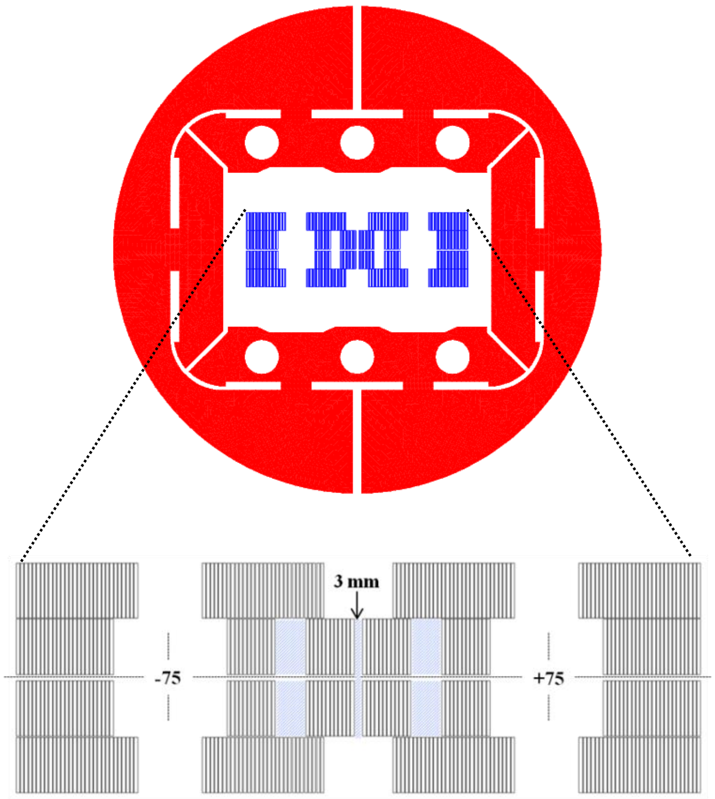
Performance at 16 T	Unit	1 Ap (L)	2 Ap (L)
Operating current	kA	26.4	25.8
Peak field in the coil	T	16.9	16.9
Inductance	mH/m	4.1	8.4
Stored energy	MJ/m	1.42	2.8

Short sample and margin	Unit	1 Ap (L)	2 Ap (L)
Maximum current	kA	29.0	28.5
Maximum dipole field	T	17.4	17.5
Operating point for 16 T	%	90.8	90.4

A Compact Twin Aperture Design

Guiding criteria and objectives:

- High efficiency, minimum overall size
- Asymmetric coil design (as proposed for HiLumi D2) to reach 150 mm beam separation and 60 mm yoke



Design parameters	Unit	1 Ap	2 Ap
Strand diameter	mm	0.8	0.8
Number of strands		51	51
Cable width	mm	22.0	22.0
Insulation thickness	mm	0.1	0.1
Coil aperture (x/y)	mm	45/47	45/47
No. turns (1 quadrant)		54	54
Minimum bending radius	mm	12.8	12.8
Strand area (1 quadrant)	cm^2	13.8	13.8
Clear bore diameter	mm	~40	~40
Yoke diameter	mm	623	600

Performance at 16 T	Unit	1 Ap	2 Ap
Operating current	kA	18.6	18.4
J_e (insulated cable)	A/mm^2	517	508
Peak field in the coil	T	16.9	16.8
Horizontal force (I+/I-)	MN/m	6.3/-6.3	6.3/-7.3
Vertical force (I+/I-)	MN/m	-2.9	-2.9/-3.5
Inductance	mH/m	5.1	11.5
Stored energy	MJ/m	0.85	1.9

Field Quality

Accelerator quality is essential for design evaluation and comparison

- Requires realistic designs

- Need to define preliminary FCC targets for design and fabrication errors (tolerances in coil fabrication will likely be the dominant source)
- Persistent current correction with magnetic shims should be foreseen (smaller filaments, use of NbTi in low field region will also help)

Geometric and Saturation Harmonics for twin-aperture and large single-aperture designs

Twin ap. (R=13 mm)	Injection (1T)		Collision (16T)	
	Ref.	Comp.	Ref.	Comp.
b_2	-0.3	9.5	-4.0	-20
b_3	2.3	-9.3	-2.0	-1.2
b_4	0.0	2.2	-0.1	2.2
b_5	-1.3	0.4	-0.6	0.4
b_6	0.0	0.1	0.0	0.1
b_7	-0.9	-0.5	-1.0	-0.6
b_8	0.0	0.0	0.0	0.0
b_9	-0.9	-0.8	-1.0	-0.9

Large ap. (R=15 mm)	Collision (16T)
b_2	0
b_3	0.5
b_4	0
b_5	-0.5
b_6	0
b_7	0.6
b_8	0
b_9	-0.3

Summary

- A reference block-coil dipole was defined, using parameters and features based on model magnet fabrication and test results
  - Performance parameters at 16 T meet basic requirements/constraints for field quality, mechanical support, coil stress and quench protection
  - Reference current density from model magnets, equivalent to FCC target, results in an operating point at 92.5% of the short sample limit (16 T, 1.9K)
  - Achieving an 85% operating point at 1.9K, 16 T requires a moderate increase in critical current density and/or a graded coil design
  - Operation at 4.5K, 16 T would require a substantial improvement in critical current density. This level of improvement is possible, and very promising results were obtained in recent months.
  - Protection with CLIQ meets requirements with copper fraction of 40%
- Block coil designs for aperture in the 50-55 mm range are possible while maintaining 2 layers/pole, and may be easier to implement in several respects, but increase in conductor, structural material materials are significant
- No issues for reference two-in-one design for 250 mm separation and 700 mm yoke. Increased aperture requires some further optimization. A compact design with 150 mm separation and 600 mm yoke is possible using an asymmetric coil layout.

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