Overview of Magnet Design Options for LTS Dipoles in the 16 T Range

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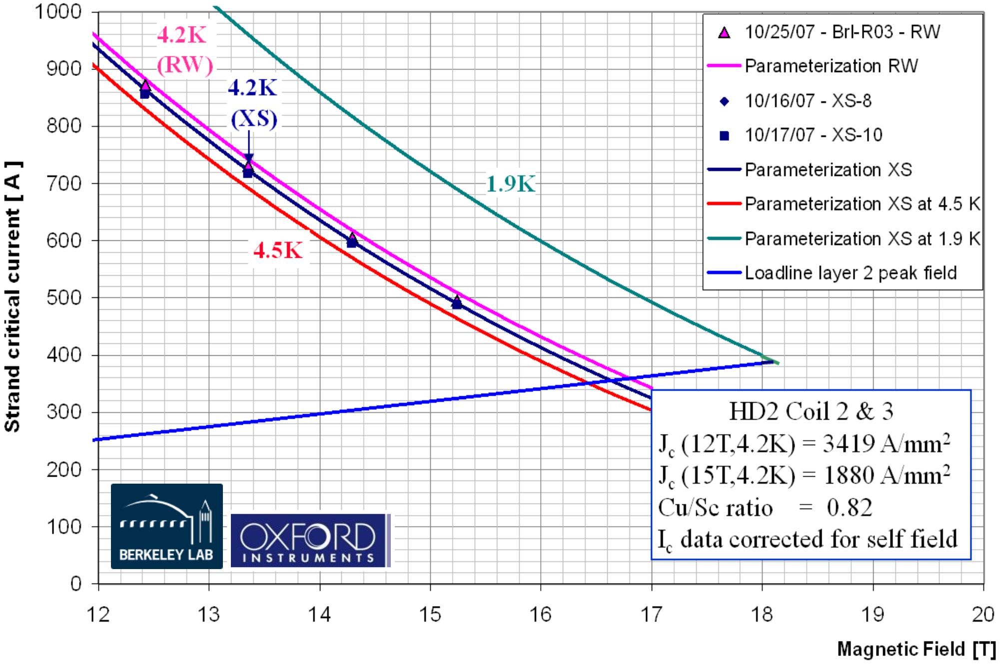
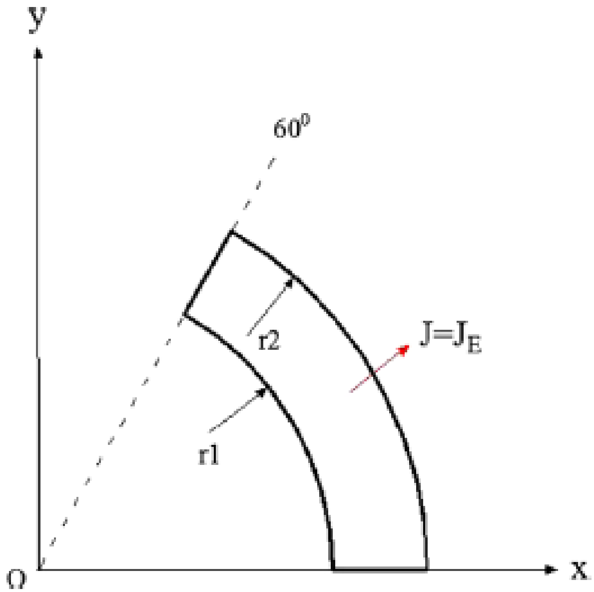
Current Density, Field and Coil Width

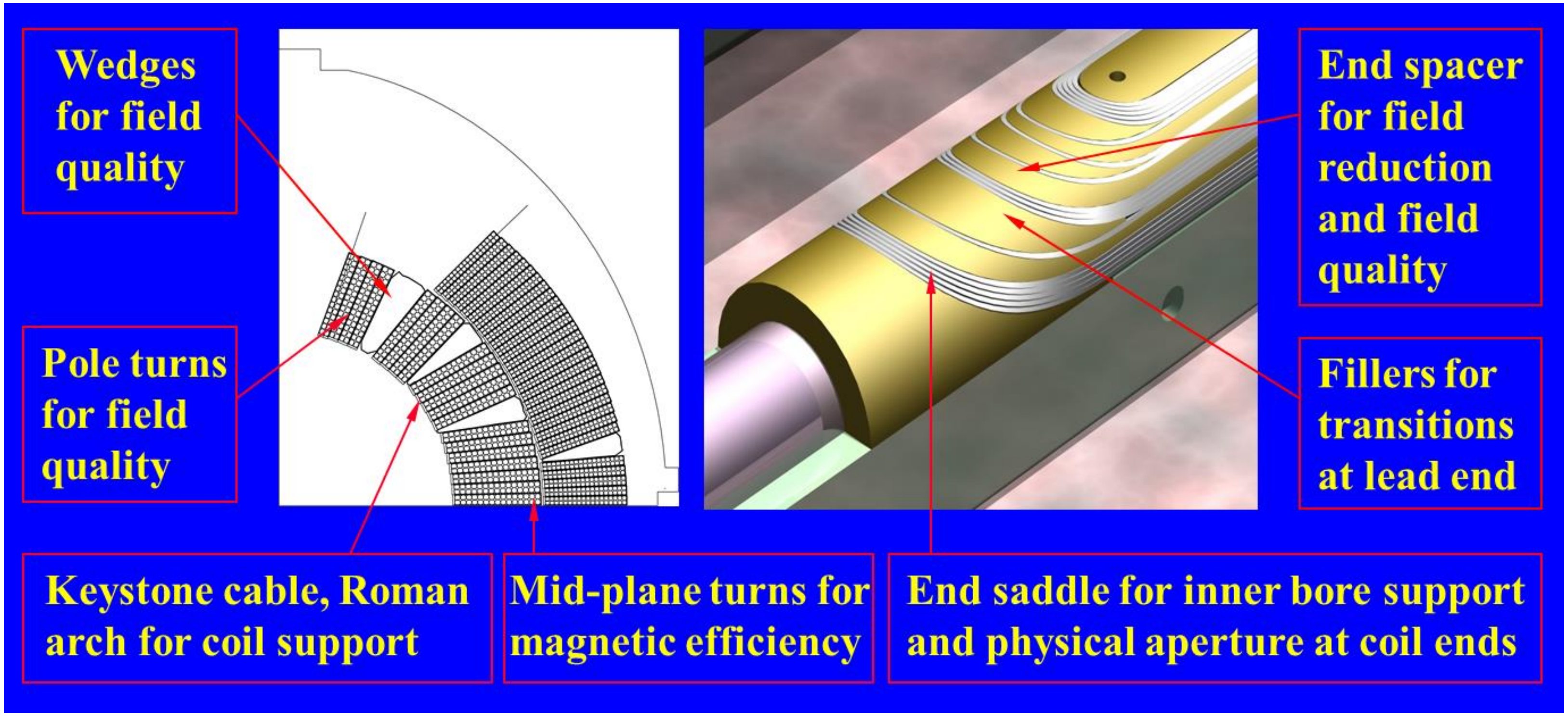
- Dipole coil width is determined by available current density and target field
- Coil width for 16 T and present J_c is in the range of 40 to 60 (to 80) mm
  - Large range results from different design assumptions/approaches, combined with the fast decay of J_c with field





Shell-type (Cosθ) Coils

- To date, all magnets for high energy hadron colliders used the cosθ coil layout



Wedges for field quality

Pole turns for field quality

Keystone cable, Roman arch for coil support

Mid-plane turns for magnetic efficiency

End saddle for inner bore support and physical aperture at coil ends

End spacer for field reduction and field quality

Fillers for transitions at lead end

- Wind & react technology allows to incorporate these features in Nb_3Sn magnets
- Shell type coil design selected for HL-LHC IR quadrupoles and 11 T dipoles

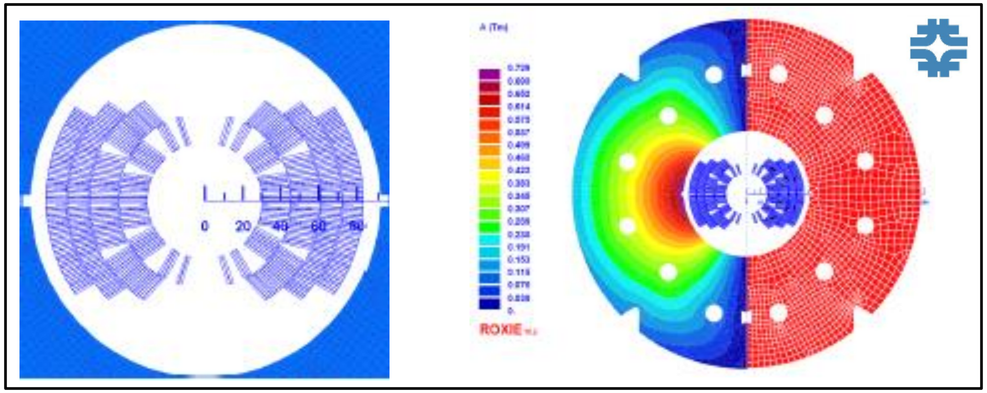
FCC Dipoles with shell-type coils

Experience and parameter range explored:

- LARP quadrupoles were built in a range of coil width of 20-30 (35) mm, and with apertures of 90-120 (150) mm reaching fields of 11-14 T
- 11 T dipoles with 56 mm and 30 mm coil width, reaching up to 12 T

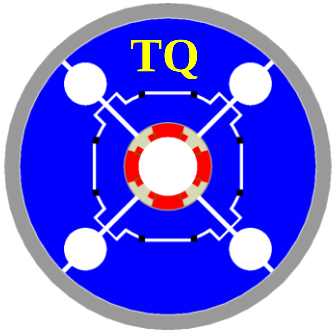
R&D issues for FCC:

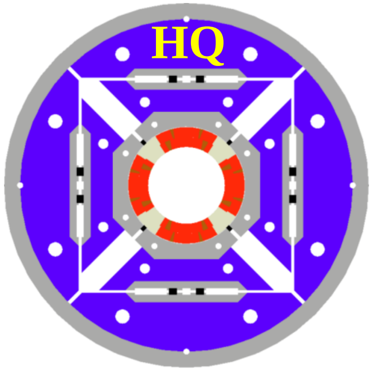
- Geometric parameters: 50 mm aperture and ~60 mm coil width
  - Limitations in the cable design options require 4 layer coil
  - Address issues related to nesting of two double-layers
- High stresses: conductor limits, design of mechanical support structure
  - Studies performed on LARP quads provide relevant experience



Stress limits in LARP shell-type coils

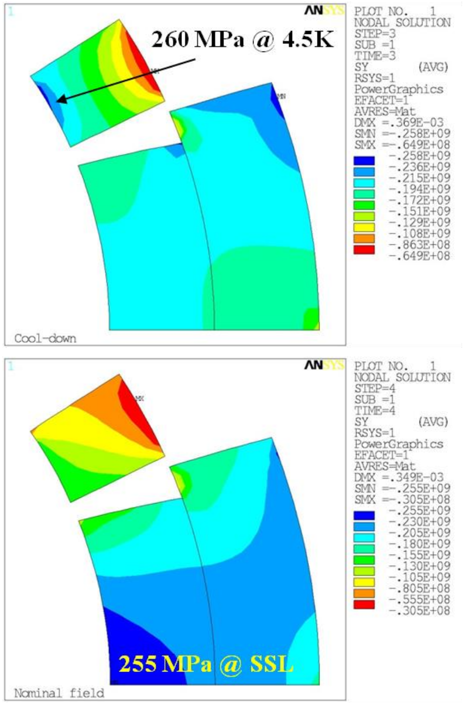
- Design optimization to decrease peak stresses while increasing field and aperture
  - *Bronze vs. Ti poles, coil geometry, minimize structural bending etc.*
- Dedicated tests with high pre-load to push peak stresses above 200-250 MPa
  - HQ nominal pre-loads correspond to peak stresses of /above 200 MPa

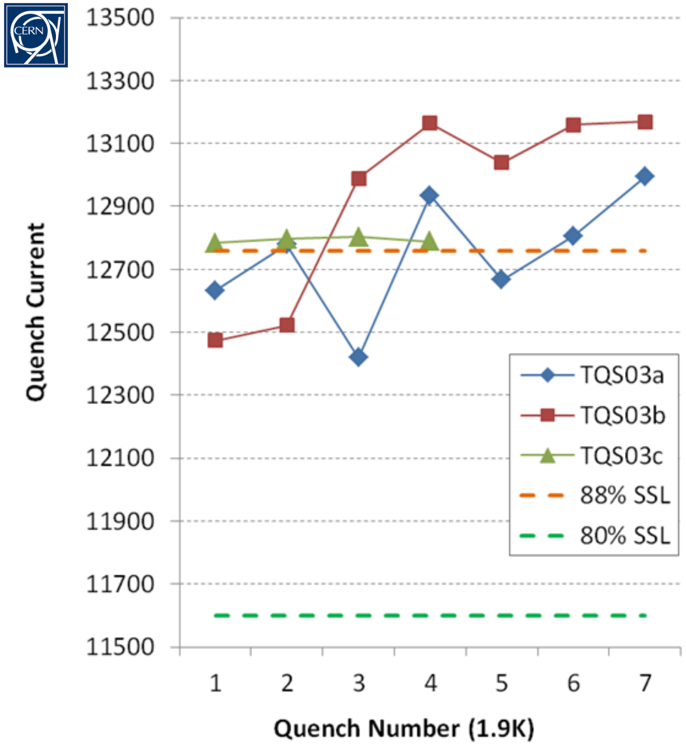




LARP

Calculated peak stresses in TQS03c





Block-Coils

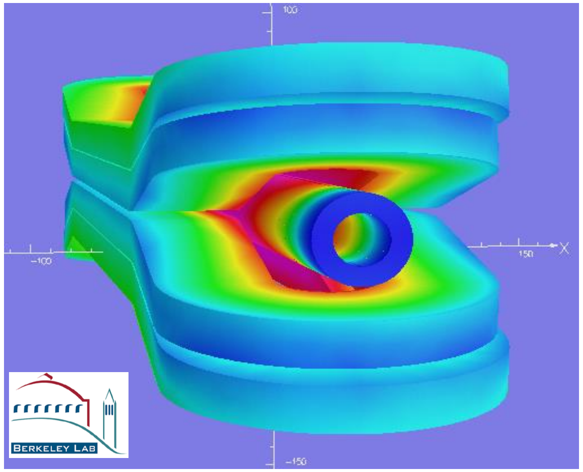
Defining characteristics:

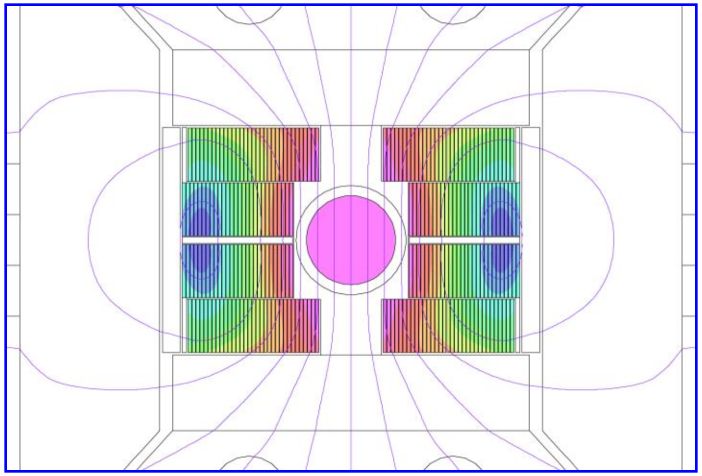
- Flat Rutherford Cable wound with its wide side parallel to dipole field orientation
- Coil width is controlled by the number of turns rather than the number of layers

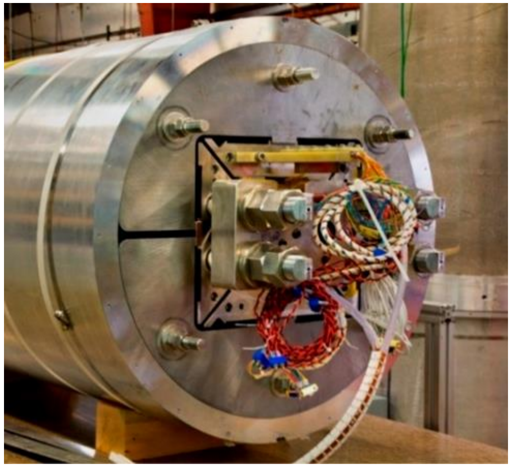
Design solutions were found that meet requirements using only two layers/pole:

- Satisfy constraints for cable, field quality, mechanical, protection etc.
- Opportunities: no internal coil spacers, stress concentrates in low-field region
- Challenges: internal bore support (vs. Roman arch), flared ends (vs. saddle)

Achieved highest fields to date in both technology tests & accelerator configuration



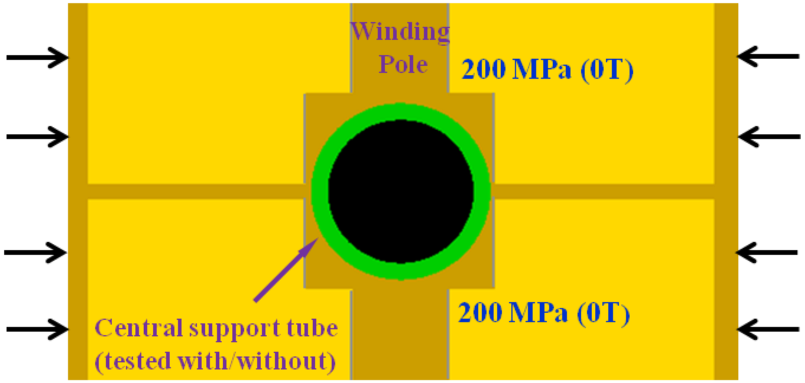


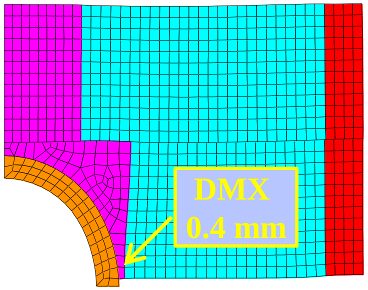


Bore Support and Stress in Block Coils

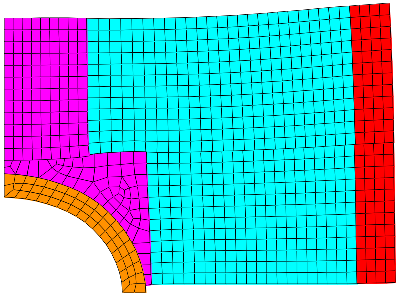
- Most critical area for block-coil mechanical design is internal (bore) support against pre-load forces
- Key issues: minimize peak stress, minimize space for structural material, rapid training to conductor limit [8]
- Further optimization of the bore support structure is one of the main design priorities, but the 16T level looks feasible without stress bypasses internal to the coil
- Explore opportunities from integration of magnet and vacuum system design

Bore structural support

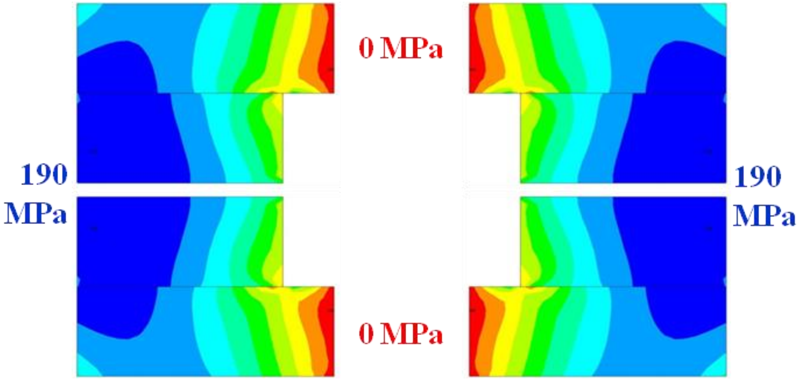




Displacements at cool-down



Displacements at full field

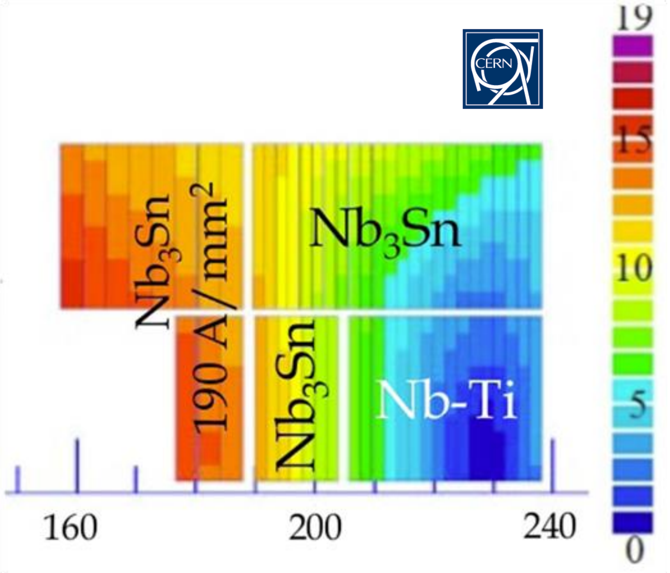


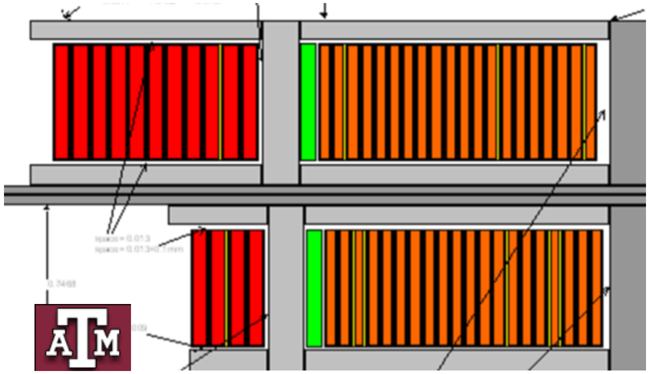
Coil Stress @ $B_0 = 16$ T

Coil Performance and Cost Optimization

Conductor grading:

- Standard for NbTi, but *Nb_3Sn coil fabrication is subject to much more severe constraints*
- Cosθ: since two double-layers are required, there is no added complication for grading
- Block: splitting the coil for grading has similar challenges to nesting two cosθ double-layers
- Graded block coils will likely require an internal structure, which will decrease Je but may help to lower the peak stresses
- Significant R&D required to develop graded block-coils, and to evaluate costs vs. benefits





Hybrid Nb3Sn/NbTi:

- Very different mechanical properties if NbTi is not impregnated; potential performance issues if impregnated

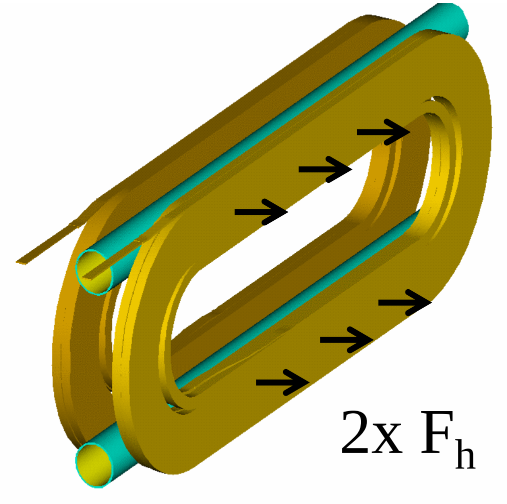
Common Coil

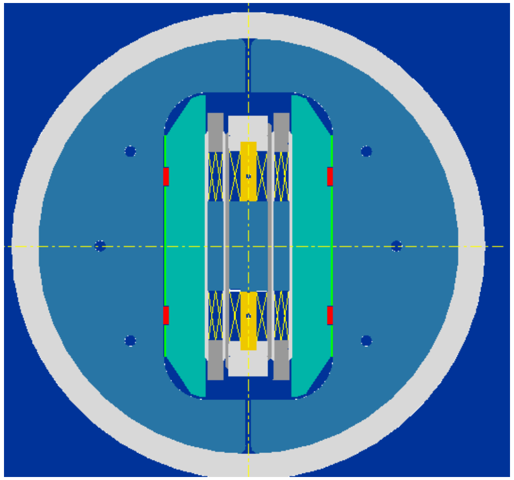
Concept: 2-in-1, vertical orientation, coil winding shared between apertures

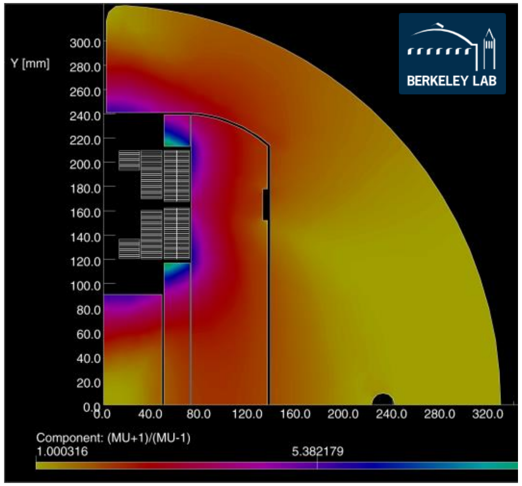
- Initial focus on large bending radius and possible use of pre-reacted cable
- For wind and react, potential advantages from modularity, flat cables, grading
- Achieved ~15 T in technology tests, and ~10 T with (limited) bore & field quality

R&D issues:

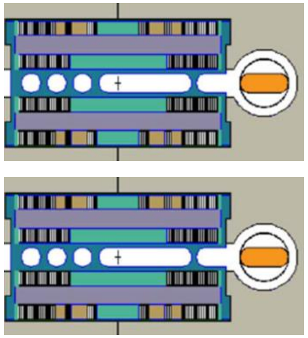
- Engineering design for aperture & field quality (auxiliary coils and/or flared ends)
- Optimization of bore support structure (similar to block-coil)
- Compactness, magnetic length vs. coil length, end field quality
- Outer structure challenges and opportunities (*compared with horizontal layout*)







2-in-1: Horizontal vs. Vertical Layout



Horizontal layout:

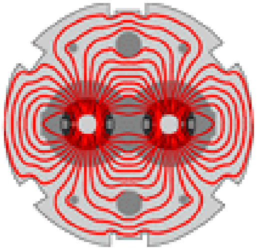
- Magnetic flux from one aperture is returned through the other
- Horizontal forces between apertures may be reacted against each other

Vertical layout:

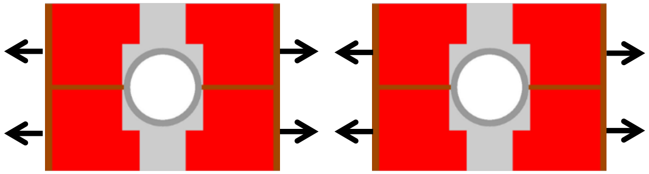
- Less efficient from the magnetic and mechanical standpoint
- More compatible with SR anti-chamber and photon stops

Horizontal 2-in-1 layout

Flux return:

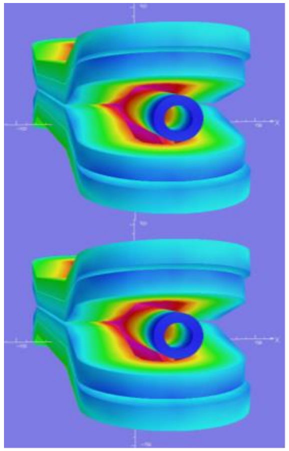


Horizontal forces

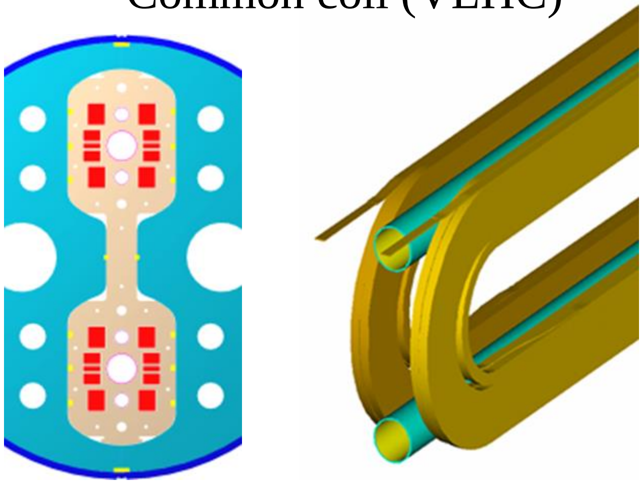


Vertical 2-in-1 layout

Block (or cosθ)

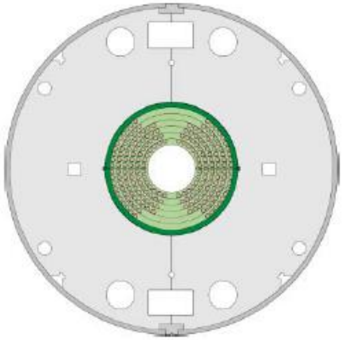


Common coil (VLHC)

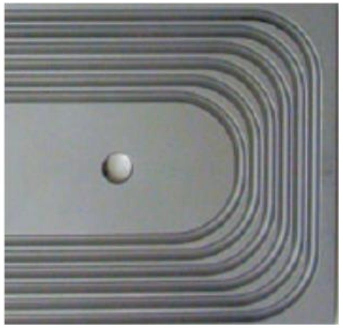


Cable-in-groove

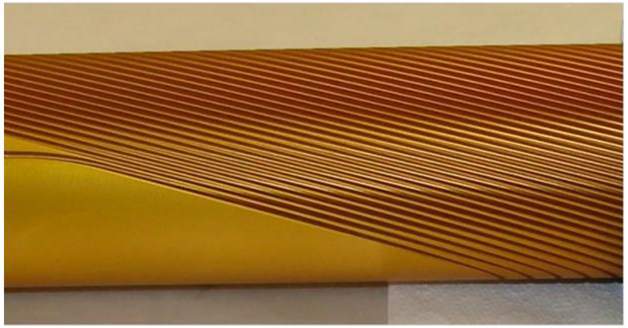
- Concept: place individual turns in grooved formers
- Goals:
  - More flexibility in the winding pattern, cable design, and coil grading
  - Internal structure to protect the conductor from force accumulation
- Issues to be addressed for application to high field Nb_3Sn magnets
  - Magnetic: engineering current density, quench propagation
  - Mechanical: pre-load transfer, or capability to operate without pre-load
  - Tooling/processes for reaction and impregnation; reliable insulation
  - Field quality: tolerances for cable insertion, module assembly/alignment



Cosθ



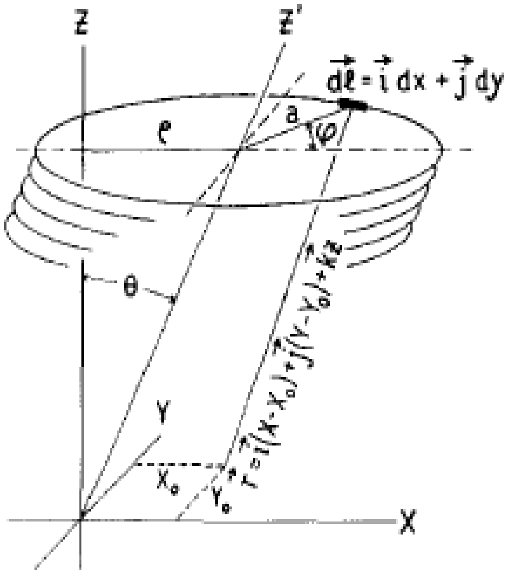
Racetrack



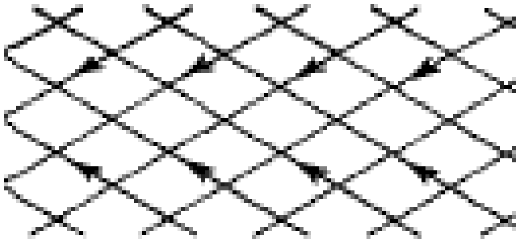
Helical Winding

Helical Windings

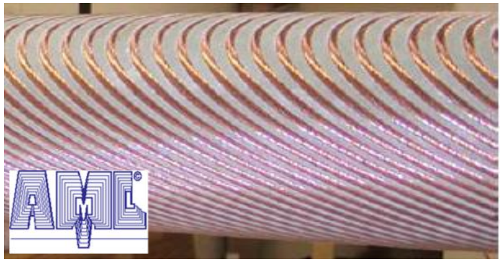
- Concept: generate a dipole field by superimposing two (2N) “skewed solenoids” with opposite skew direction
- Formers are required to guide the conductor along the desired path, and to fill the voids in the winding
    - “Cable-in-groove” advantages and challenges
- Other considerations for high field dipoles:
    - Magnetic length vs. coil length
    - Interplay between layer thickness and aperture range, grading efficiency, inductance



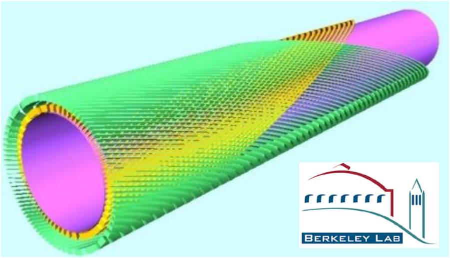
Meyer, NIM 80 (1970)



Skewed solenoid



Double Helix Dipole

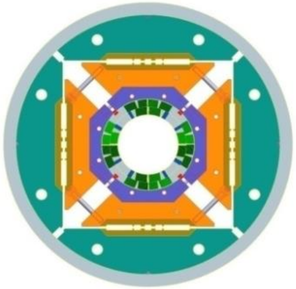


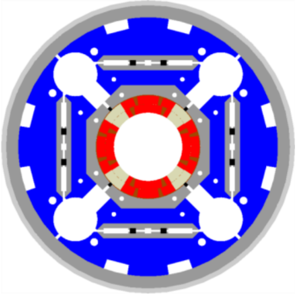
Canted Cosine Theta

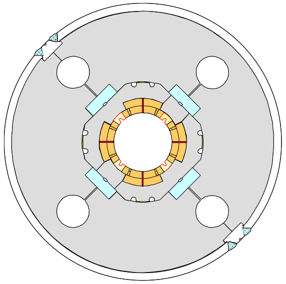
Support Structures

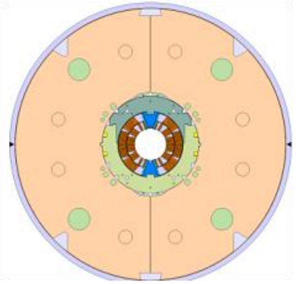
- Al shell:
  - Low assembly pre-load
  - Good assembly tolerances
  - Used in RD, HD up to 15 T
  - Fully developed by LARP
- Collar:
  - NbTi experience
  - Easy length scale-up
  - Used for TQC, 11 T
- Al clamp /hybrid
  - Similar to Al shell
  - Used in HFD, 11T
- No outer structure?
  - Coil formers provide support
  - No pre-load

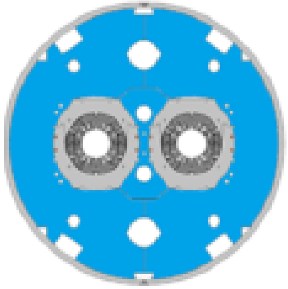

HD2

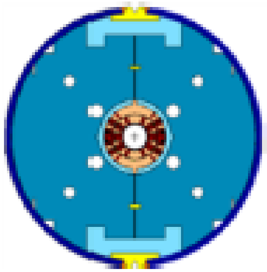

HQ

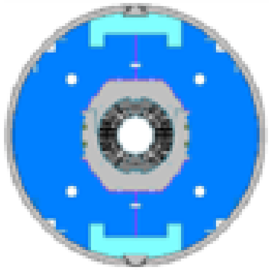

MQXF

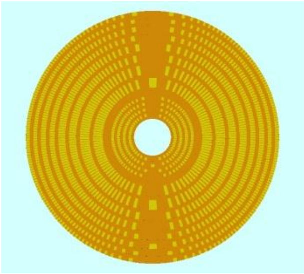

TQC


11T (CERN)


MBHDP

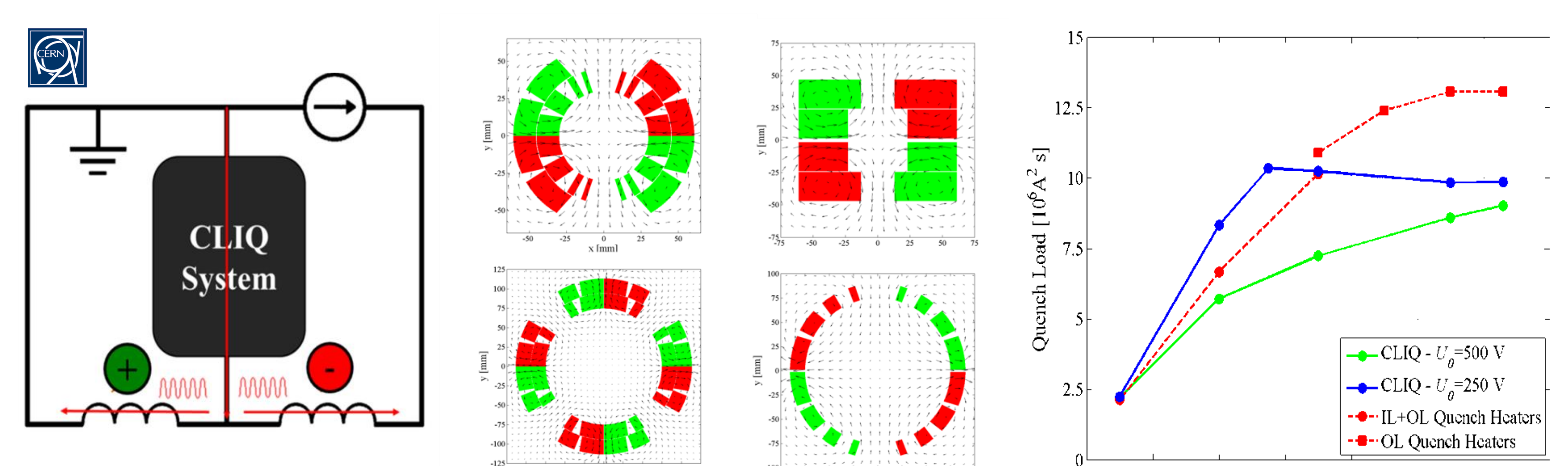

HFDA


MBHSP


CCT

Quench protection

- More effective protection can broaden the design space in critical areas:
    - Reducing the copper fraction from 60% to 40% equals a 50% increase of J_c
    - Limits on stored energy density may constrain the design to a less efficient operating point
    - Limits on the inductance may constrain the cable design to sub-optimal choices, or even eliminate design approaches requiring smaller cables
- The "Coupling Loss Induced Quench" (CLIQ) system developed by CERN has the potential for a transformative impact: take full advantage of this opportunity

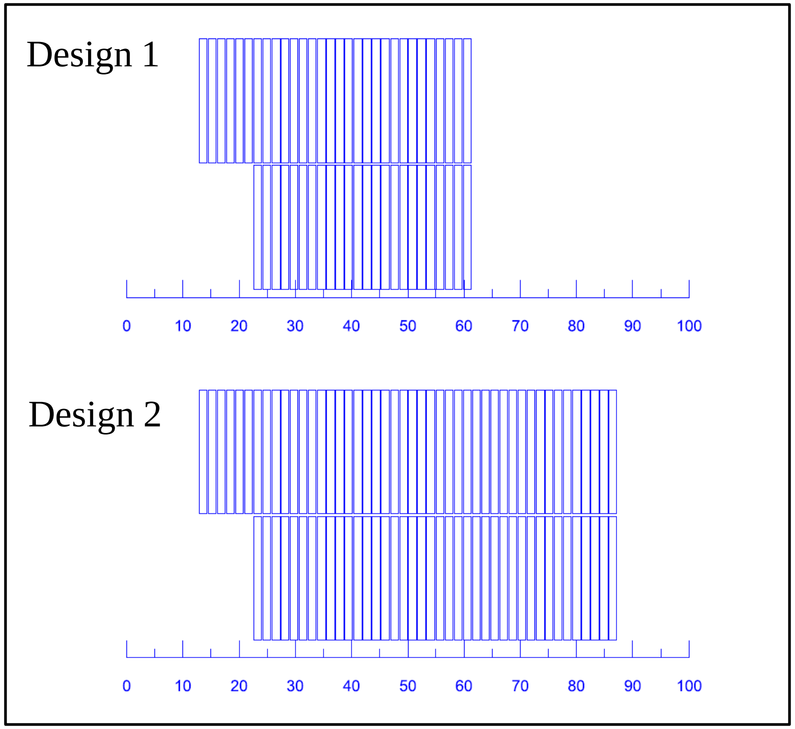


E. Ravaioli

Summary and Outlook: Design Strategy

Design parameters	Unit	Des. 1	Des. 2
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	Des. 1	Des. 1
Operating current	kA	18.6	13.5
J_e (insulated cable)	A/mm^2	517	375
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



Option 1: higher J_e requiring ~50% higher J_c for same margin, or lower margin and/or low copper fraction, more difficult mechanics, field quality; less conductor – or

Option 2: Lower J_e, requiring lower Jc, or providing 8% more margin and/or higher copper fraction, easier mechanical design, field quality; more conductor?