U.S. MAGNET DEVELOPMENT PROGRAM

Nb3Sn Magnets: 16-17 T dipole design studies

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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Target parameters
- Parametric model
- 60-mm aperture 16 T dipole
- Large aperture dipoles
    - 120-mm 2-layer design
    - 120-mm 4-layer design
- Requirements to the Utility Structure

16 T dipole target parameters

1. Geometrical
   - Magnet total length — <2 m
   - Magnet straight section — >200 mm
   - Free coil aperture — 50 mm
   - Maximum magnet OD (reference number) — 620 mm (FNAL/1.9K), 660 mm (BNL/1.9K), ……………………………………………………..914 mm (LBNL/4.5K)
2. Conductor
   - Strand diameter — 0.7-1.2 mm
   - Cu:nonCu ratio — 1.0±0.1
   - Non Cu J_c(16T,4.2 K) — 1300 A/mm^2
   - RRR — >60
   - Reference J_c(B,T) fit — see below
   - I_c degradation due to cabling — 5%
   - Maximum number of strands in cable — 42 (FNAL), 60 (LBNL)
3. Operational
   - Reference temperature — 1.9 K
   - Nominal operation field — 16 T
   - Margin on the load-line @ 1.9K — 10 % with respect to cable I_c
   - Geometrical field harmonics at R_{ref}=17 mm — b_n<3 for n<10 (magnet straight section)
   - Target design field — 17 T
   - Maximum coil stress — 180 MPa (150 MPa during assembly)
   - Maximum coil-pole separation @ 17 T — <10 µm for cable width <50%
4. Quench protection
   - Maximum hot spot temperature — 350 K
   - Total time delay — 40 ms
   - Maximum voltage to ground @ quench — 1.0 kV
   - Ground insulation design voltage — >5 kV
5. Reference Jc(B,T) fit:

$$B_{c2}(T) = B_{c20}(1 - t^{1.52}),\ J_c = \frac{C(t)}{B_p} b^{0.5}(1-b)^2,\ C(t) = C_0(1-t^{1.52})^{0.96}(1-t^2)^{0.96}$$

where $t=T/T_{c0}$; $b=B_p/B_{c2}(t)$, B_p is the conductor peak field, T_{c0} = 16 K, B_{c20} =29.4 T, C_0 = 270 T·kA/mm^2.

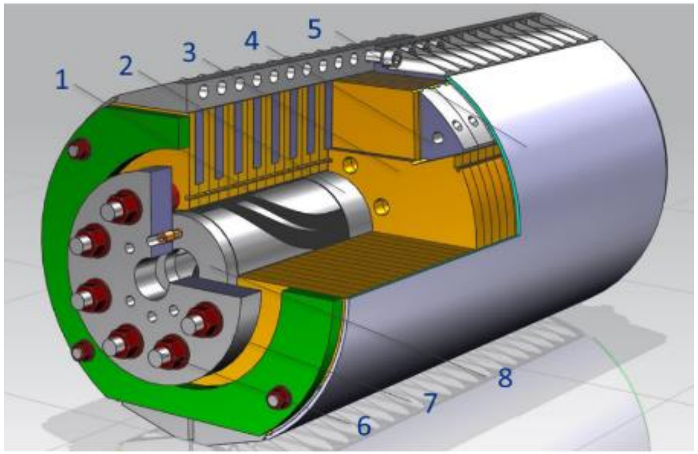
6. Each magnet concept should provide
   - Description of magnet design including
     - Strand, cable and insulation (before and after reaction)
     - Coil cross-section (number of layers, number of turns, conductor weight/m/aperture)
     - Coil end design concept
     - Magnet support structure including transverse and axial support
     - Quench protection system in the case of no energy extraction
   - Maximum magnet bore field B_{max} at conductor SSL for 1.9 K and 4.5 K
   - Dependence of B_{max} on conductor J_c(16T,4.2K)
   - Calculated geometrical field harmonics, coil magnetization and iron saturation effects in magnet straight section at R_{ref}=17 mm for B=1-16 T
   - Stress distribution in coil and structure at room and operation temperatures and at the nominal (16 T) and design (17 T) fields
   - Coil-pole interface (gap) at the nominal (16 T) and design (17 T) fields
   - Coil maximum temperature and coil-to-ground voltage during quench w/o energy extraction
   - Cost reduction opportunities

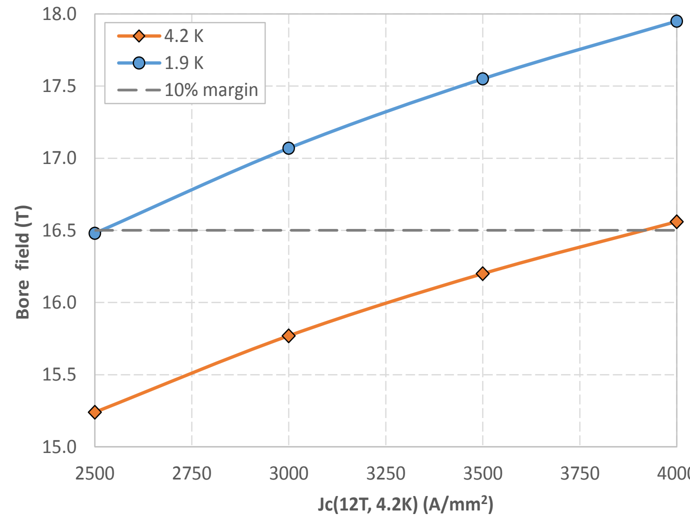
Target parameters has been formulated for the next MDP dipole model which will be fabricated and tested after the 15 T dipole demonstrator at FNAL and the CCT program at LBNL.

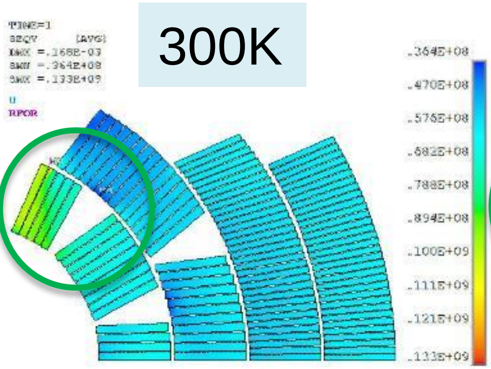
Timeline:

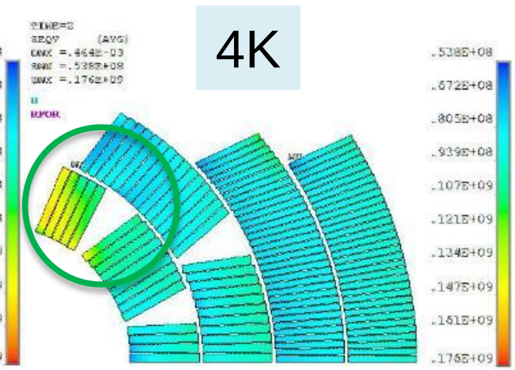
- Model fabrication in FY19+ per MDP plan.
- Engineering design and initial procurement FY18+
- Design studies and selection FY17+.

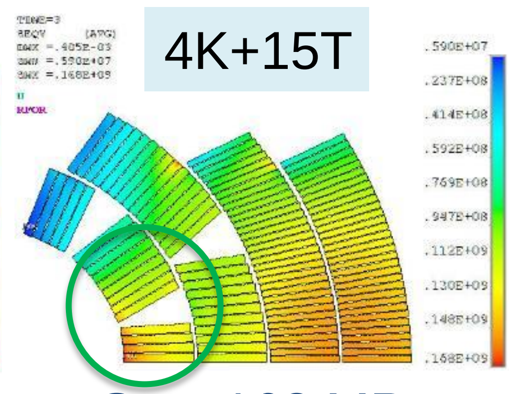
15 T dipole demonstrator: possibilities and limitations

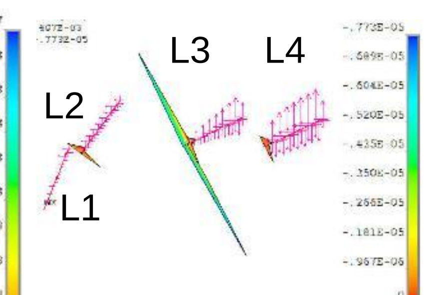










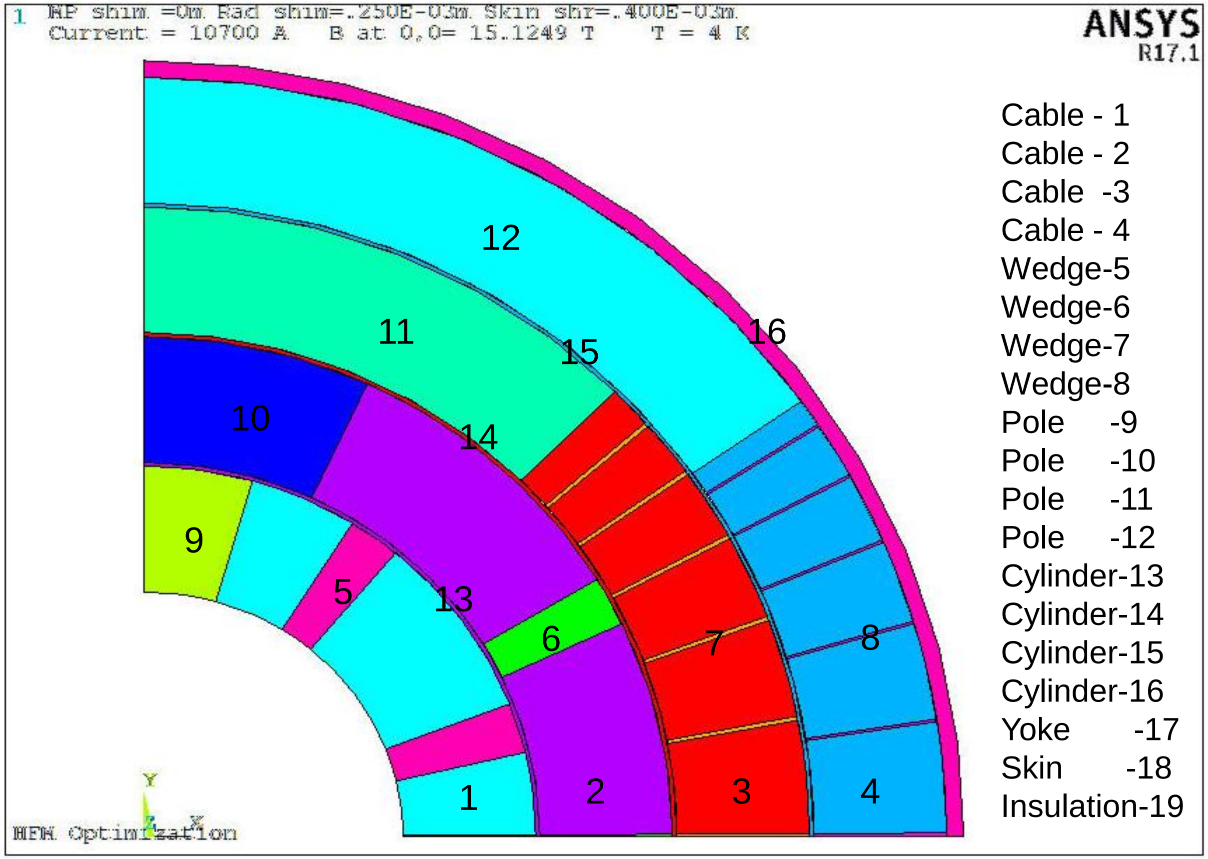


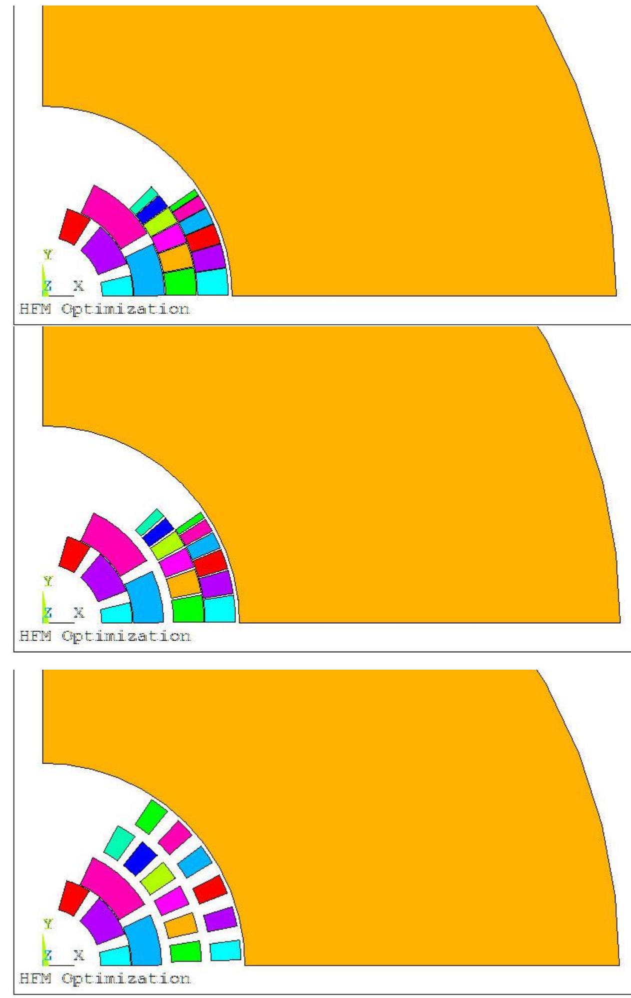
S_{eqv}=133 MPa

S_{eqv}=176 MPa

S_{eqv}=168 MPa

Parametric Model



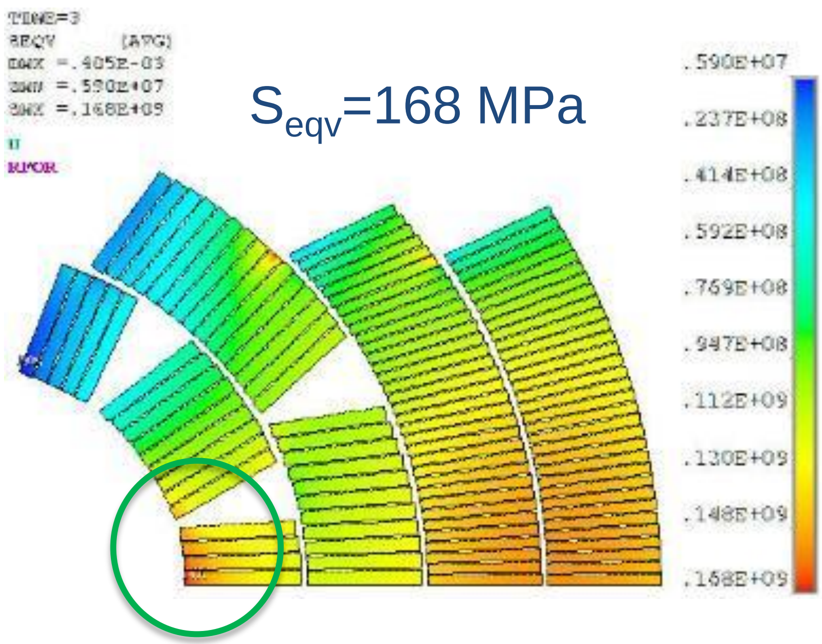


- Radial shim for coil prestress
- Iron yoke is vertically split and closed

Model verification

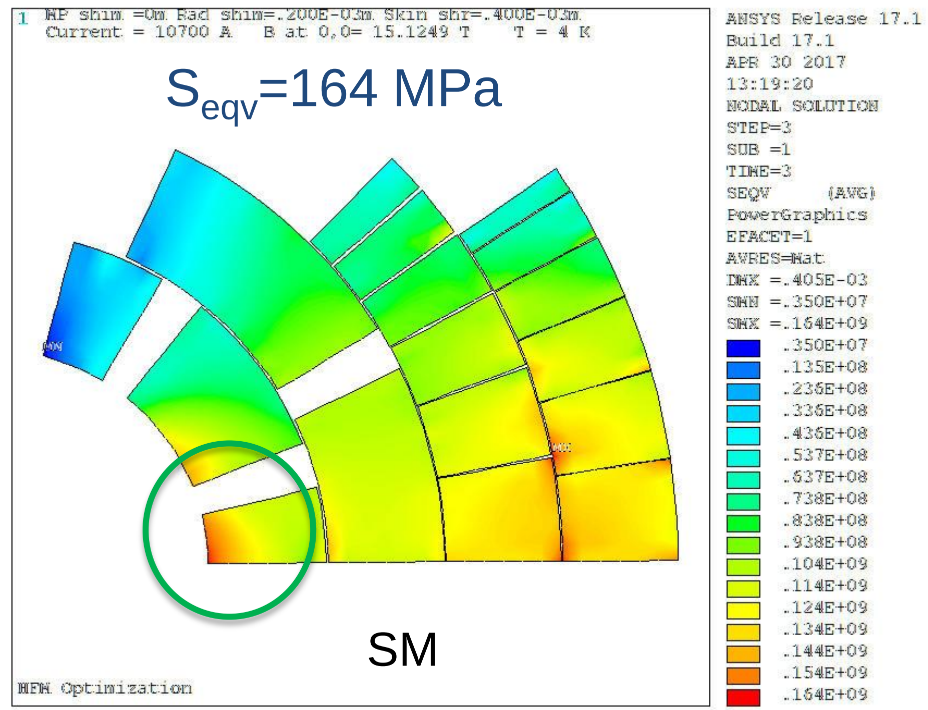
4K B=15T

S_{eqv}=168 MPa



BL

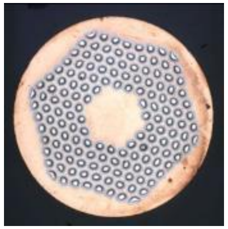
S_{eqv}=164 MPa



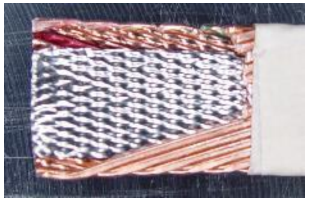
SM

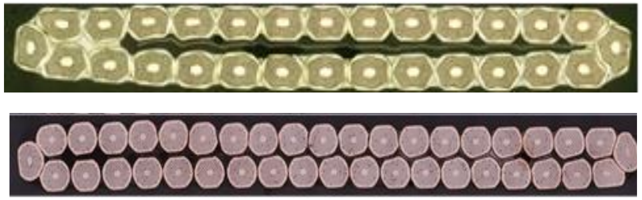
Cable parameters

RRP-108/127
0.7 mm



RRP-150/169
1 mm

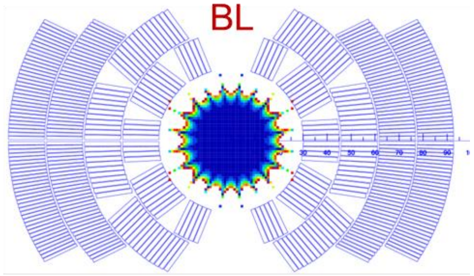


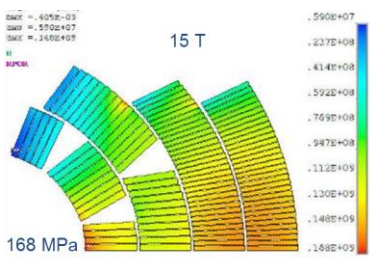


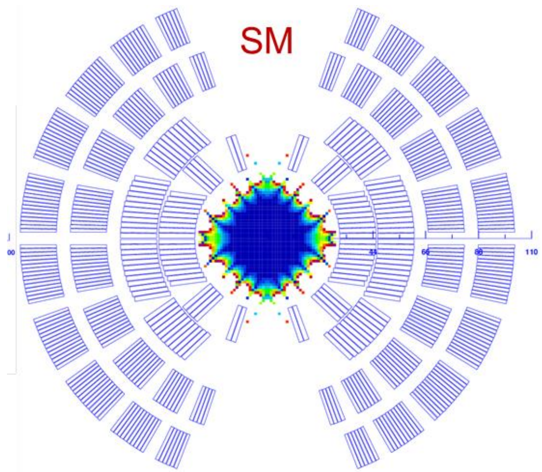
Parameter	Inner Coil	Outer Coil
Number of strands	28	40
Mid-thickness, mm	1.870	1.319
Width, mm	15.10	
Keystone angle, deg.	0.805	
Cu/nonCu ratio	1.13	
J_c(15T, 4.2K), A/mm^2	1500	

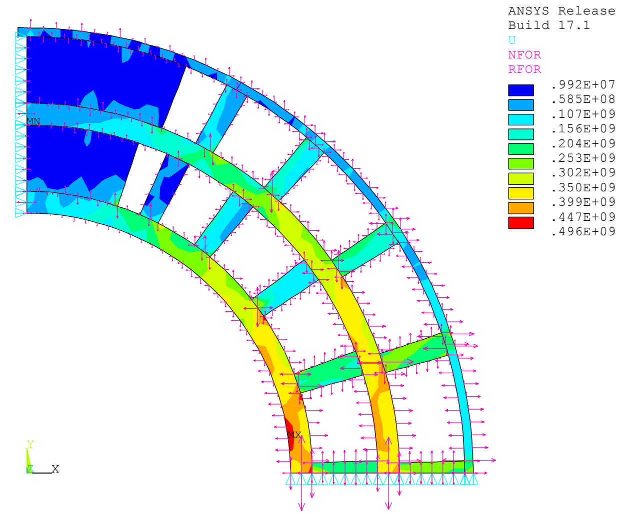
- **Both BL and SM coils use the same cables in the inner and outer coils.**

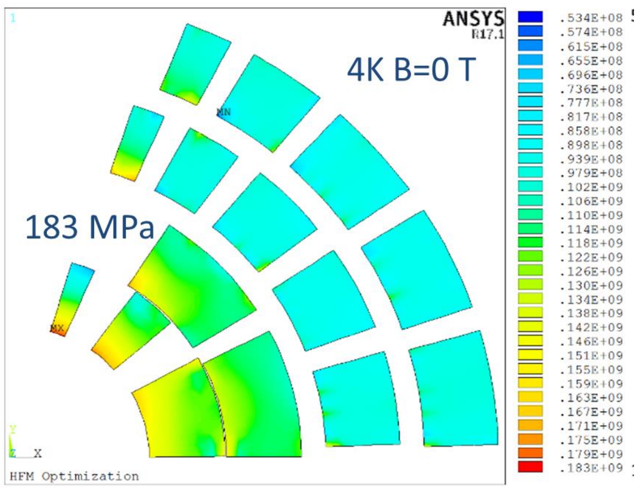
60-mm aperture 16 T dipole with SM

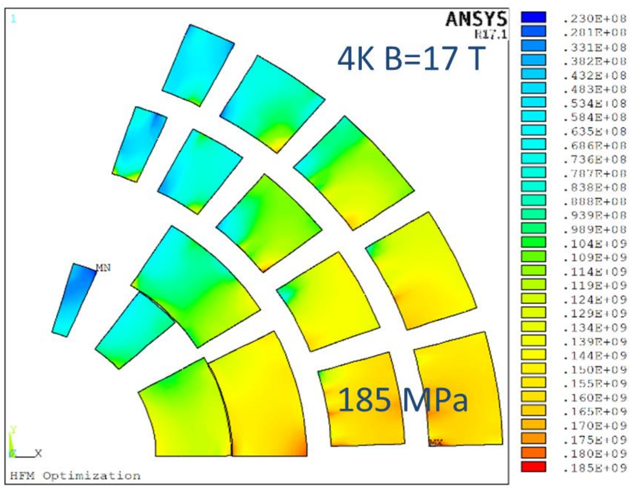


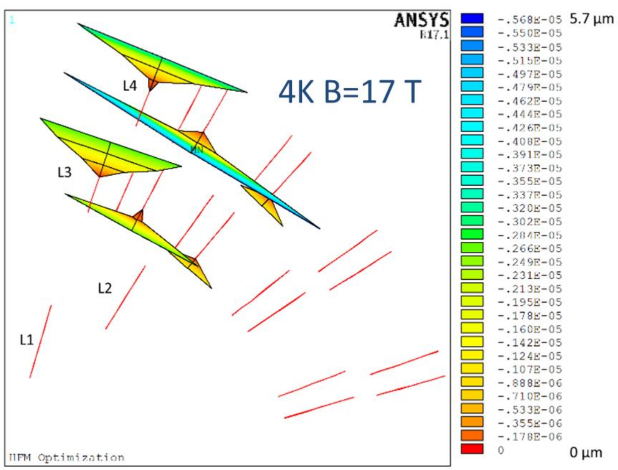




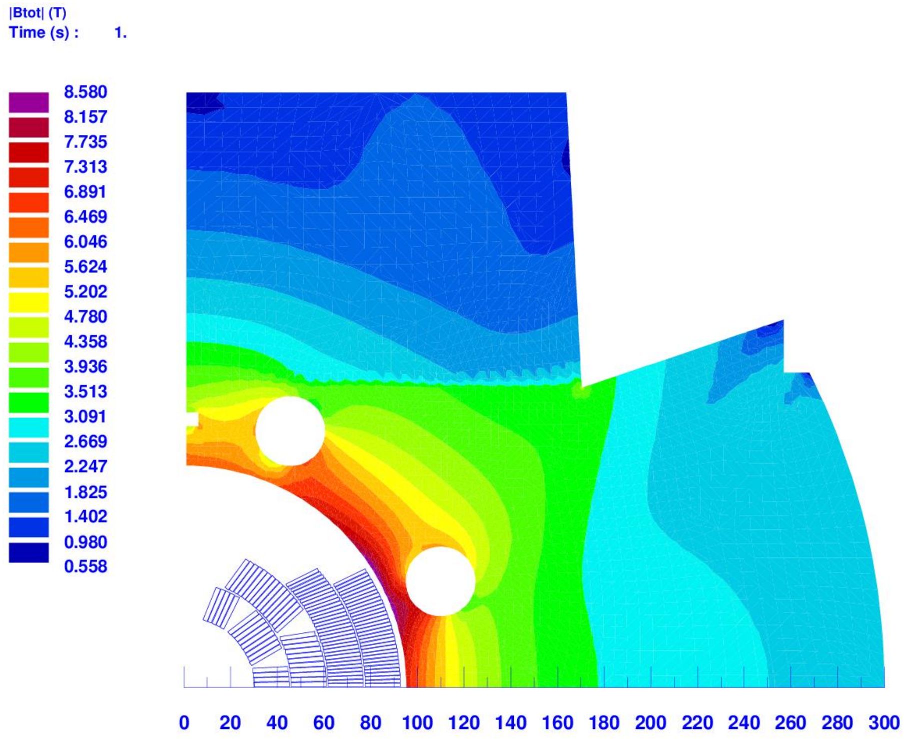


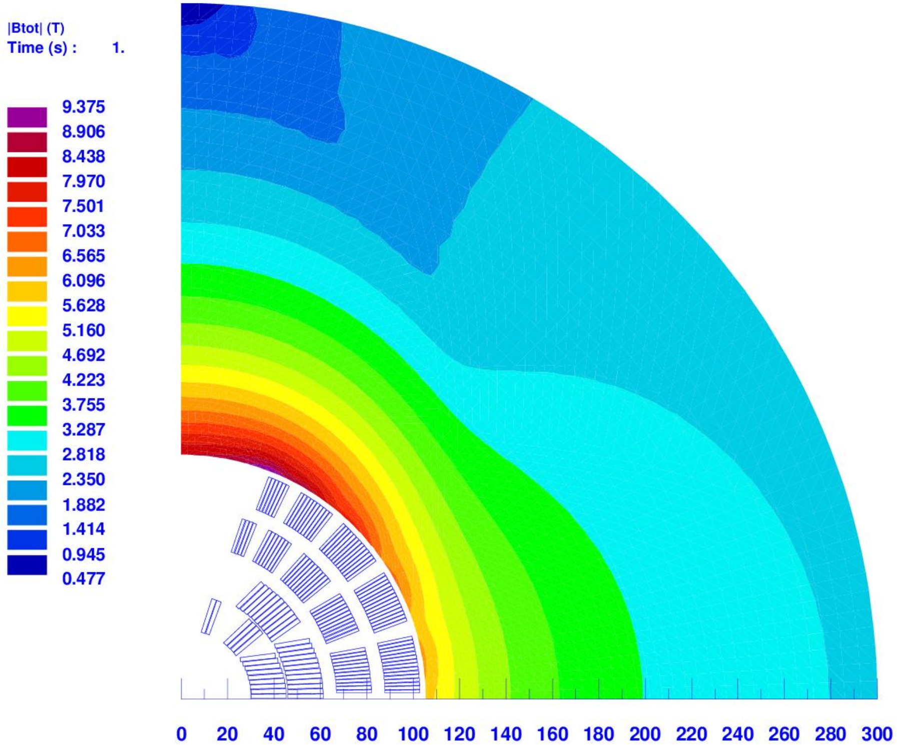






Iron yoke

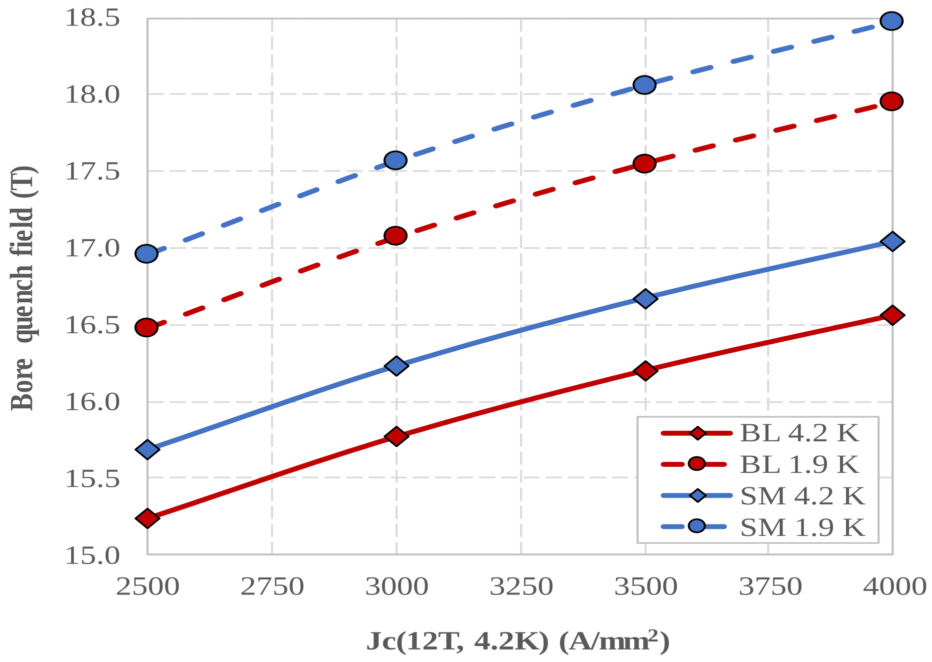




- The model included a cylindrical iron yoke with the outer diameter of 600 mm and non-linear magnetic properties for the purpose of field calculation.
- The yoke design is to be optimized based on the structural analysis.

Magnet parameters

Parameter	BL		SM	
	IC	OC	IC	OC
Bore field, T	15.61		16.07	
Peak field, T	16.25		16.44	
Current, A	11.34		10.80	
Inductance, mH/m	25.61		35.42	
Stored energy, MJ/m	1.65		2.06	
F_x, MN/m/quadrant	5.8	1.6	4.8	4.7
F_y, MN/m/quadrant	-1.2	-3.3	-0.5	-3.6
Number of turns	44	65	38	102



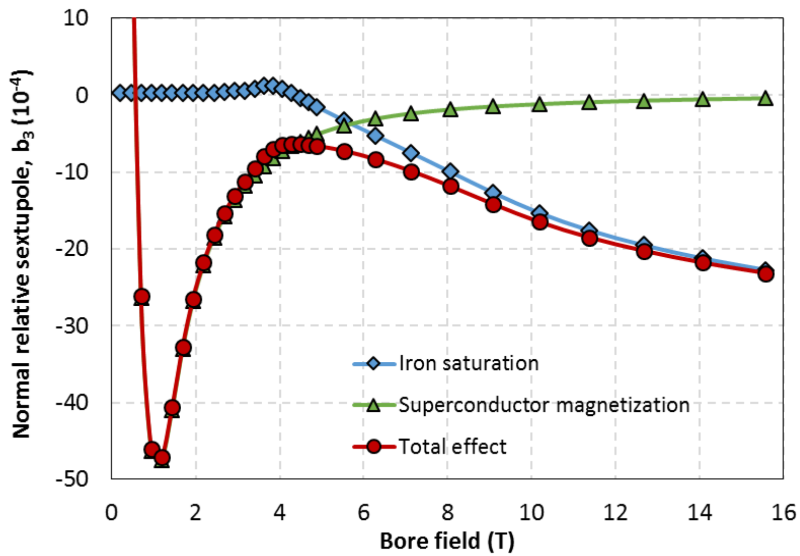
- SM design has 30% more turns, larger inductance and stored energy.
- The horizontal Lorentz force per the inner coil is a factor of 1.2 smaller and the vertical force is a factor of 2.4 smaller than in the BL design.
- The horizontal force on the outer SM coil is a factor of 3 higher than that for the outer BL coil, while the vertical force is practically the same.

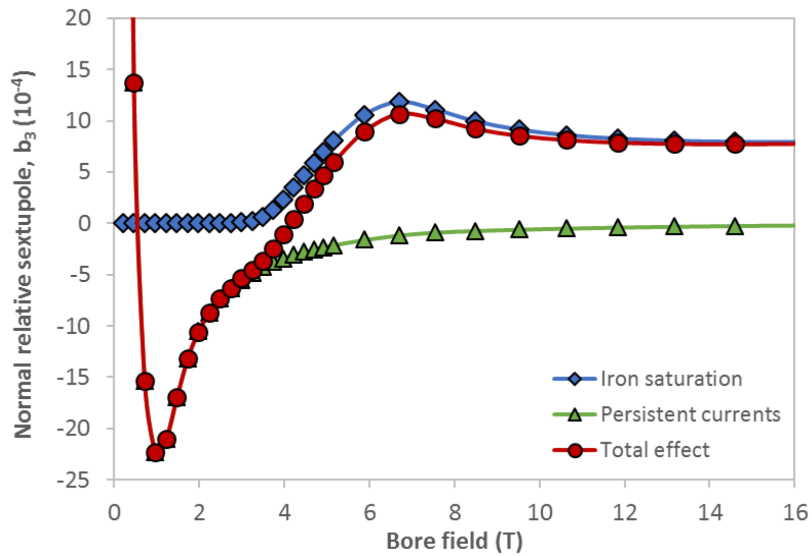
Field quality

Table 2: Geometrical harmonics at R_{ref}=17mm (10^{-4})

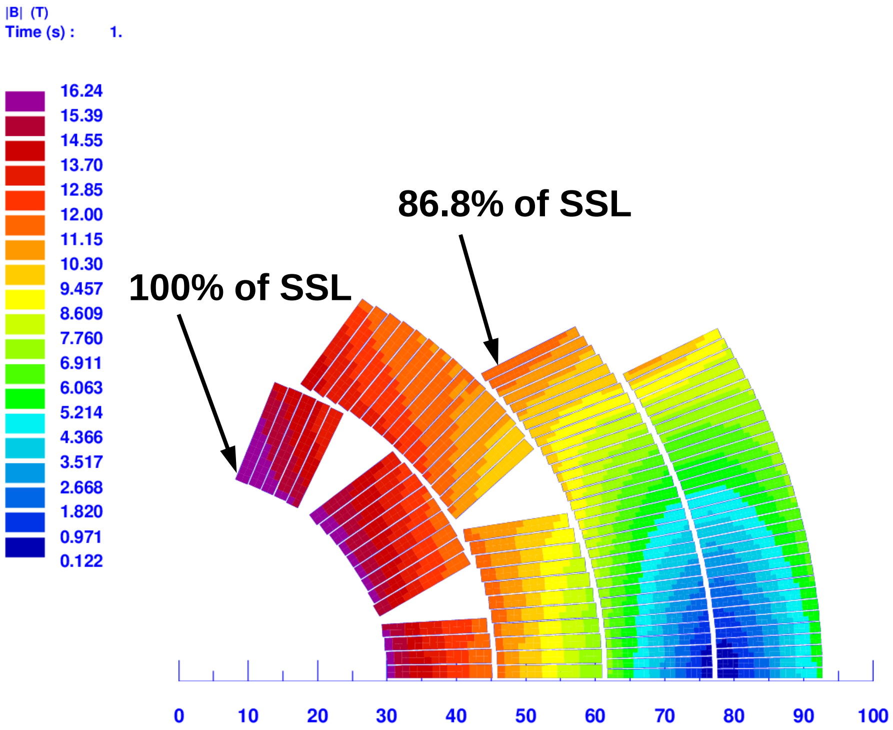
Harmonic	BL	SM
b_3	0.0018	0.0007
b_5	0.0154	-0.0087
b_7	0.0523	0.1170
b_9	0.0612	0.2626
b_{11}	0.3433	-0.0873

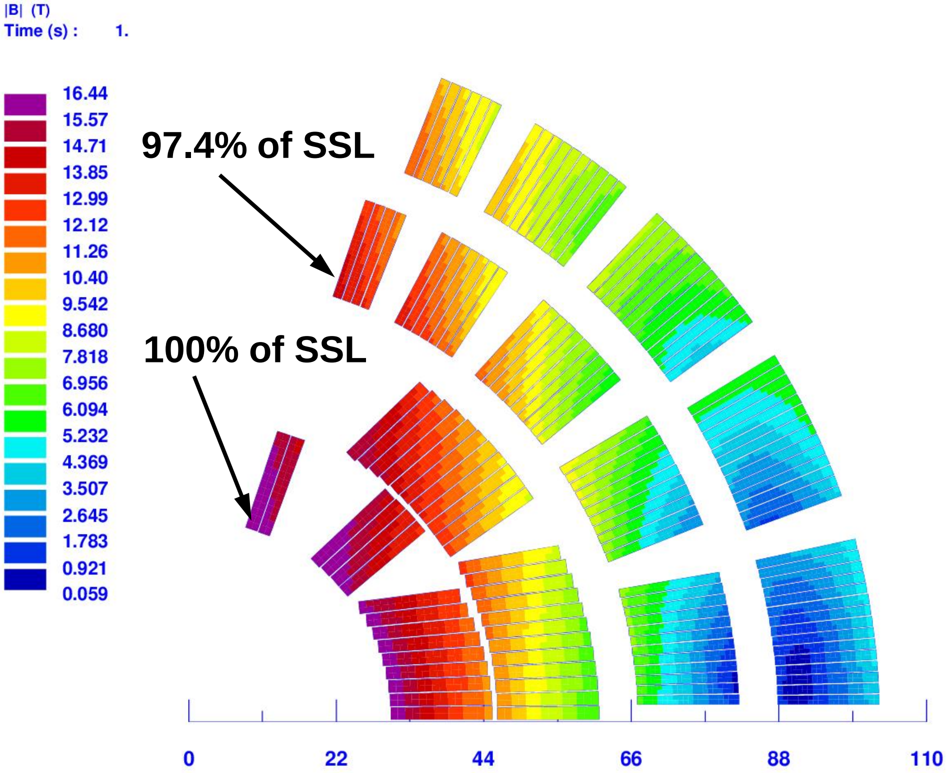
- Both designs provide the geometrical field quality better than 10^{-4} at R_{ref}=17 mm.
- There is a noticeable difference in the iron saturation and coil magnetization effects
  - b_3 variation is reduced by a factor of ~2.



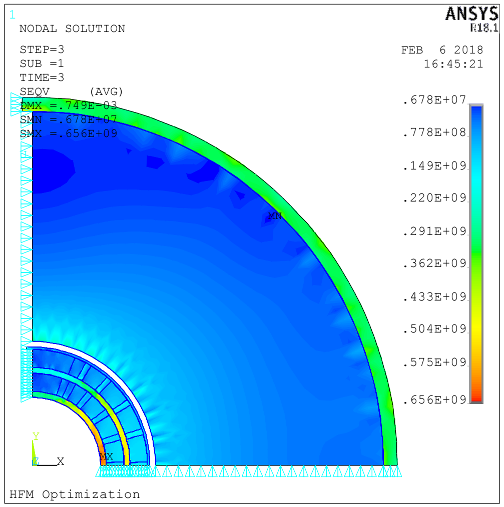


Coil fields and margins

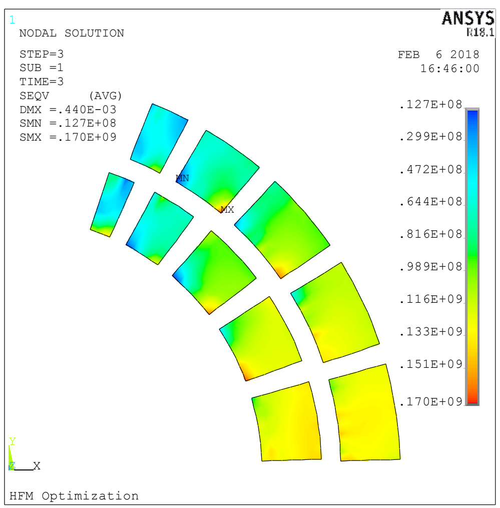


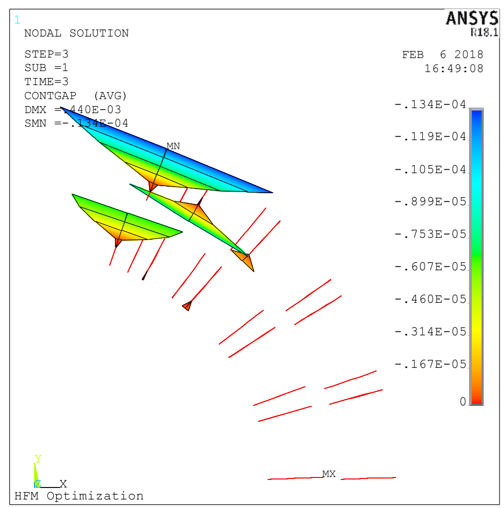


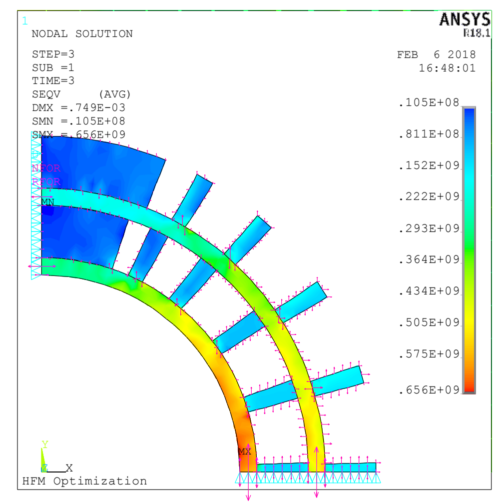
120 mm 2-layer dipole



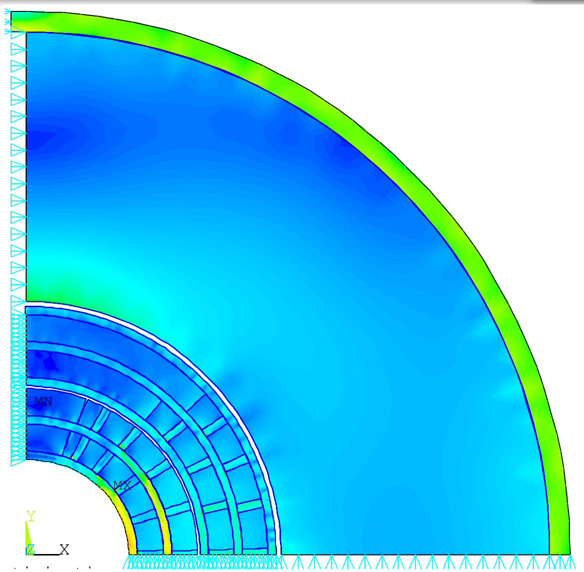
I kA	B T	Scoil MPa	Pole Gap µm	Ssup MPa
12	11.0	170	16	556
14	12.5	203	50	611
16	14.0	256	90	688



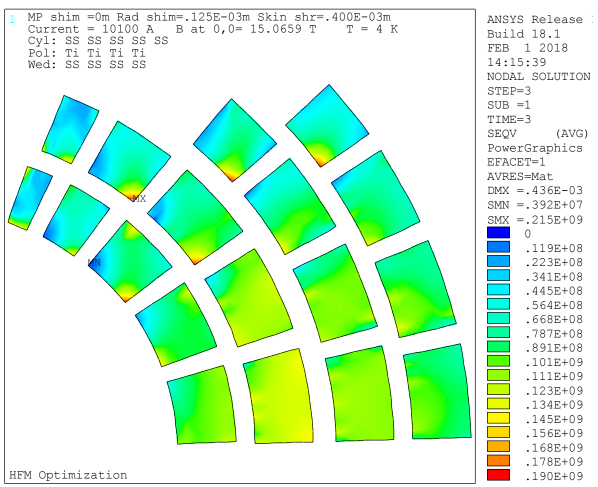


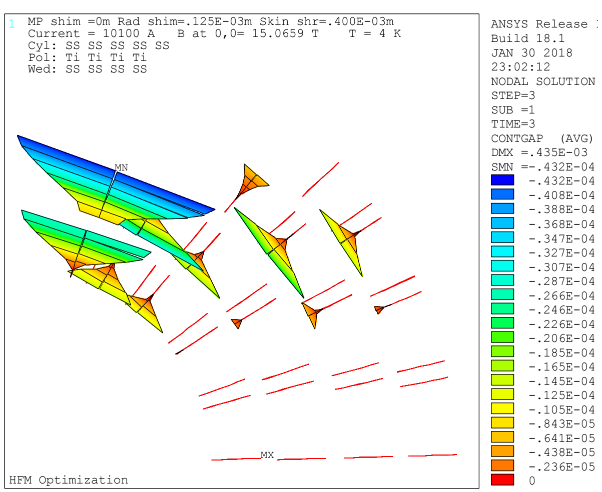


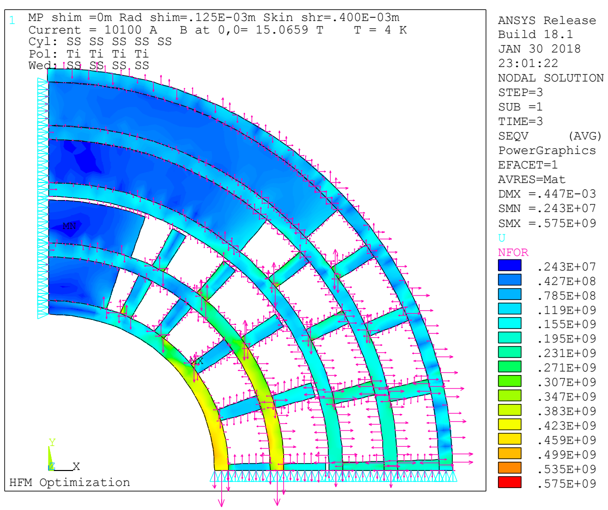
120-mm aperture 15 T dipole



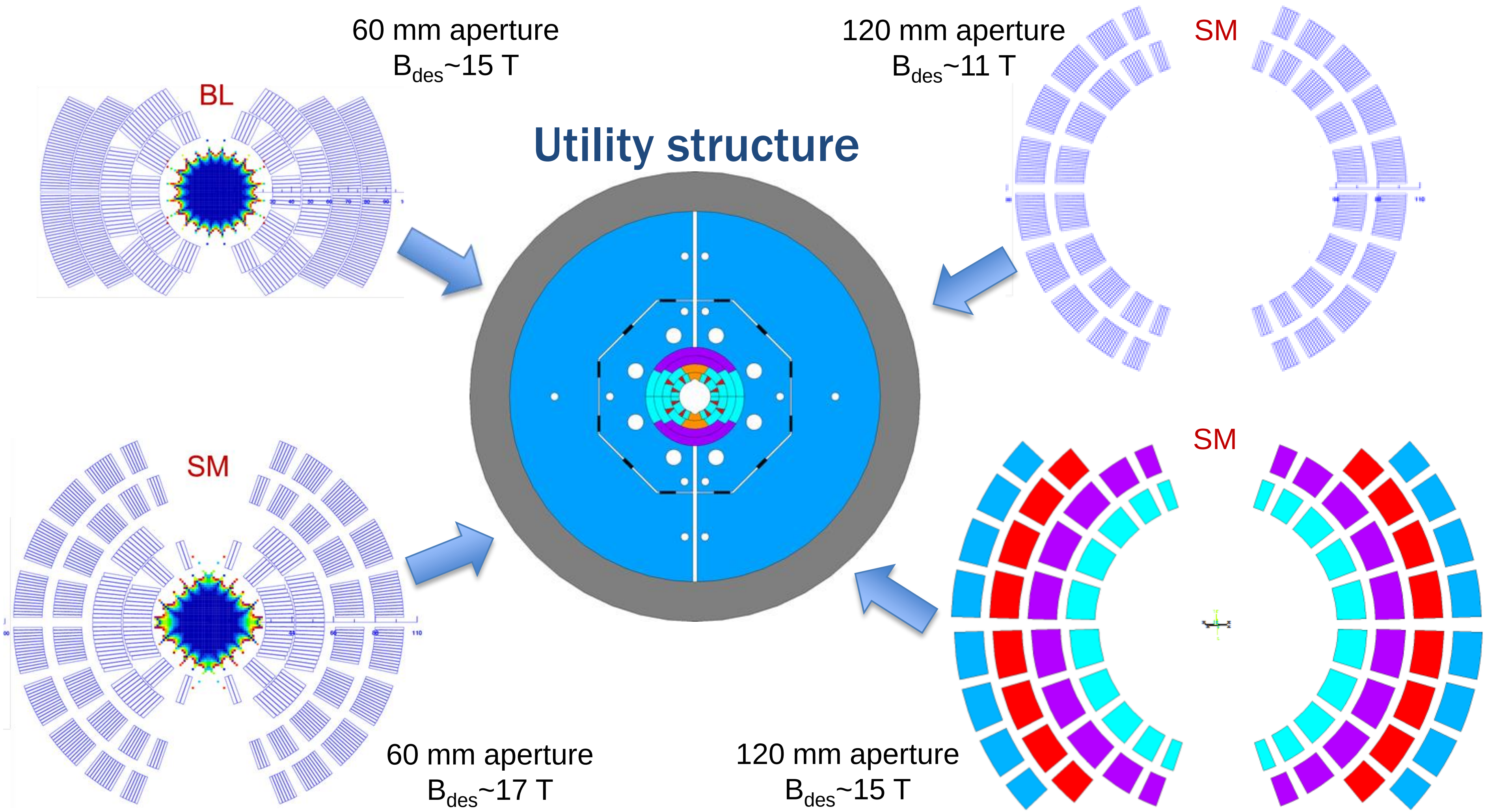
I kA	B T	Scoil MPa	Pole gap µm	Ssup MPa
10.1	15	190	24	575
10.8	16	200	50	637
11.6	17	210	90	699



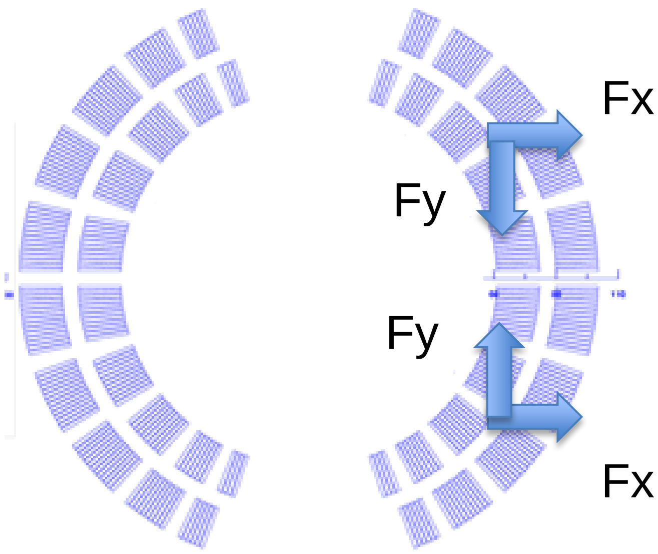


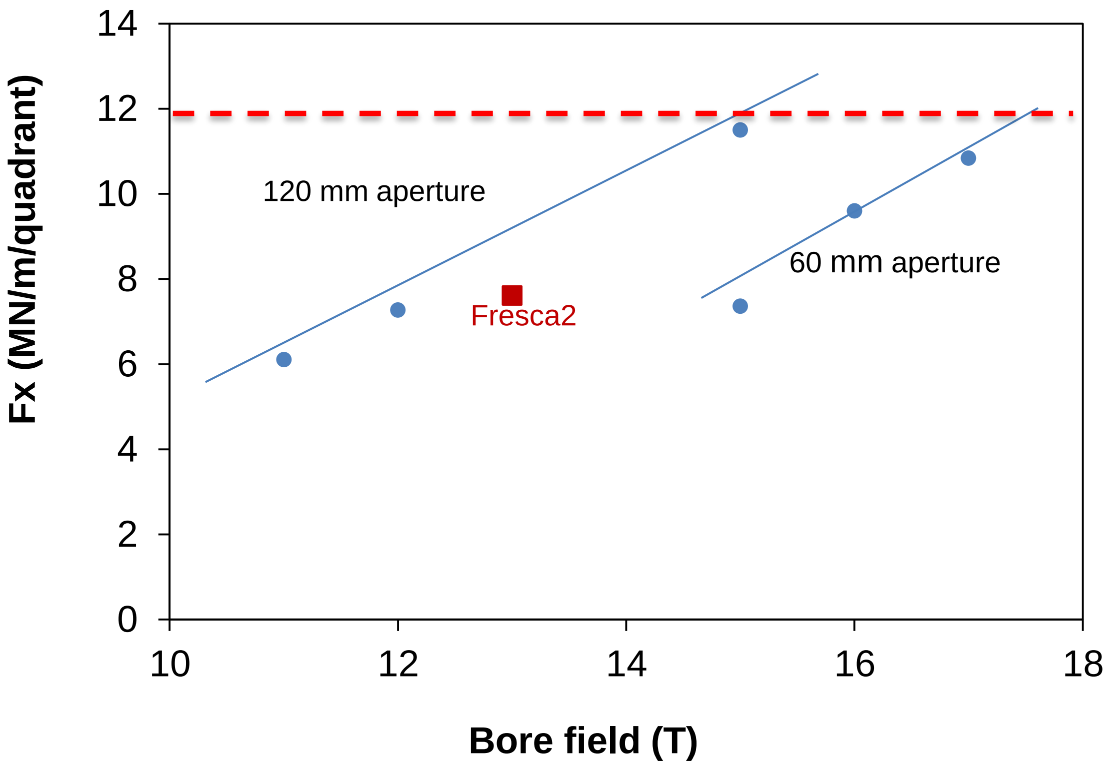


Cos-theta dipole sequence



Horizontal force





- Support structure has to keep iron yoke closed

Summary

- 60-mm 4-layer dipole design with stress management meets the design parameters of MDP Step 3
  - to be reviewed and approve before engineering design
- 120-mm 2-layer dipole based on two outer layers with stress management can provide design field up to 11-12 T
  - technological model to study stress management in cos-theta coils
  - outsert to test HTS coils
- 120-mm 4-layer dipole with stress management can provide design fields up to 15 T
  - can be used as outsert for hybrid dipole
  - study and optimization will continue