Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

Updated Design of Q3pF Package for Simpler Quench Protection

Ramesh Gupta



Electron-Ion Collider

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Update Design Requirements of Q3pF Package

Integral field (gradient) specifications for the magnetic design:

- ❑ 8.4 T Q3pF normal quad (NO CHANGE, field quality must be good)
- ❑ 1 T skew quadrupole corrector (INTEGRAL REDUCED FROM 3 TO 1)
- ~~❑ 0.1 T-m normal dipole corrector~~ (NO LONGER NEEDED)
- ❑ 0.1 T-m skew dipole corrector (NO CHANGE)
- ❑ Yoke od increased to match B2pF Al shell od (yoke od 614 mm)

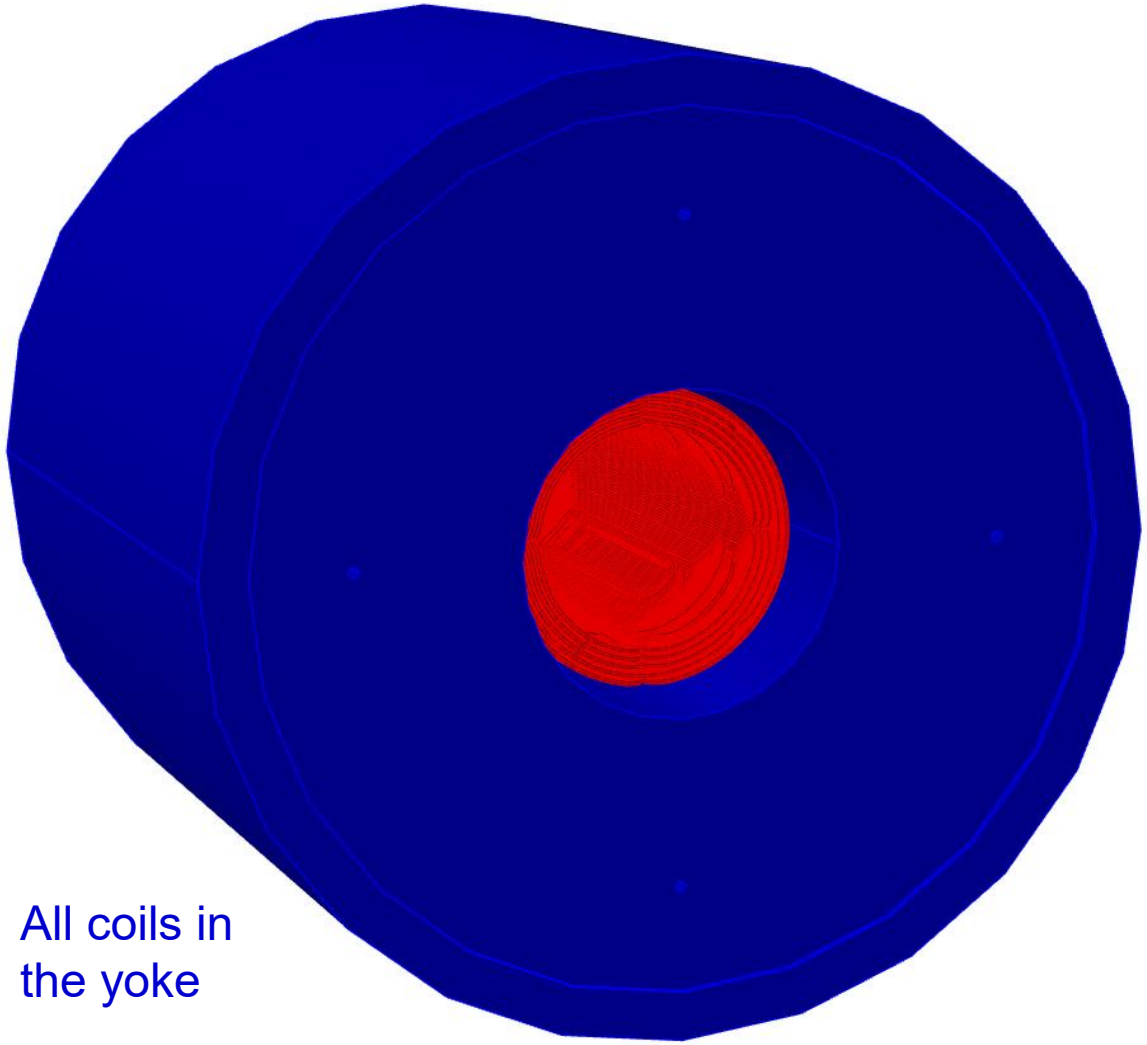
These changes do not change the fundamental coil design, particularly since the coil length has not increased from the current value of 400 mm

- **Inner diameter of the 1st winding: 137.4 mm (id of the tube 127 mm)**

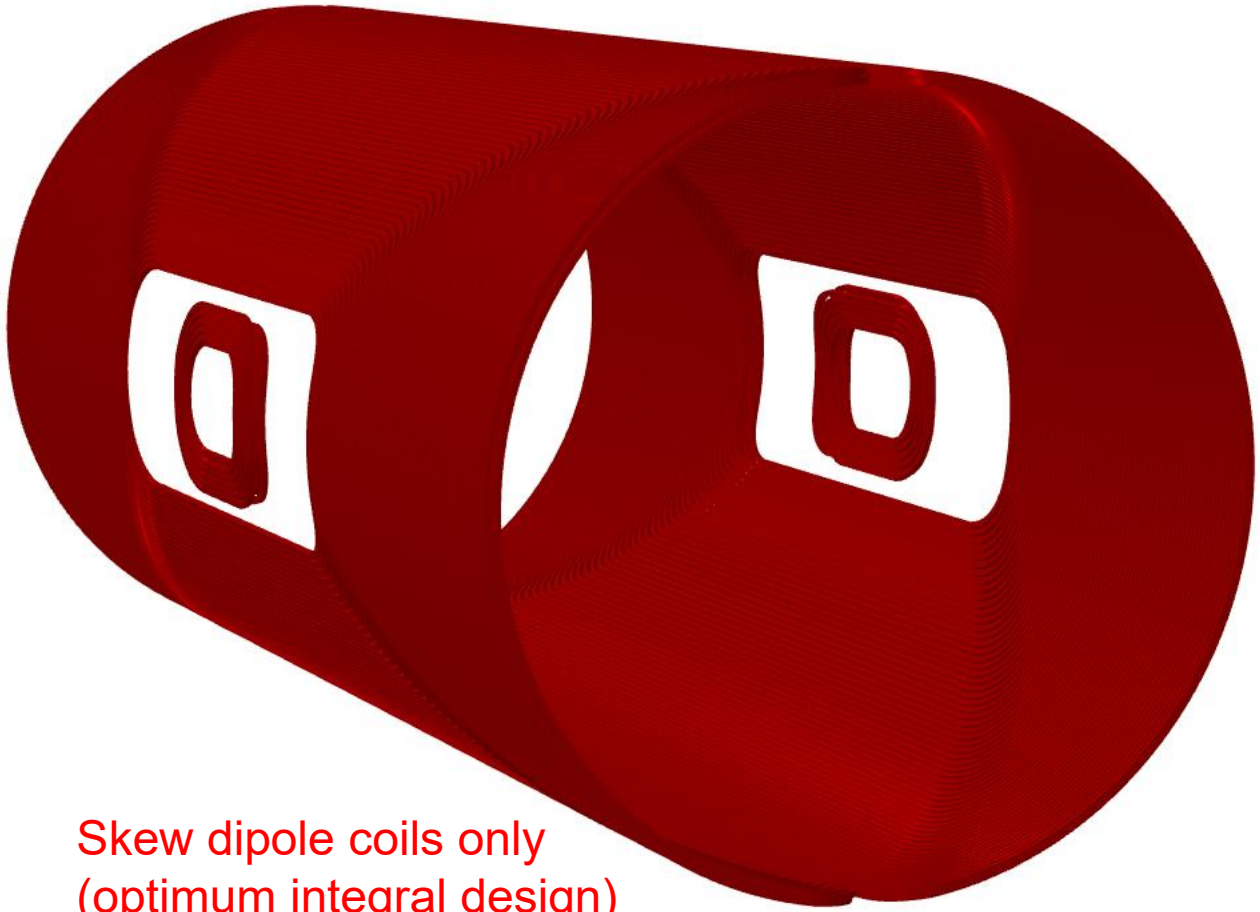
All coils in Q3 package have very small length/aperture ratios (<3)

✓ **Optimum Integral Design offers efficient designs for short magnets.**

The Basic 3-d Model



All coils in the yoke



Skew dipole coils only (optimum integral design)

Overall Optimization of the Detailed Design

Design iteration for a simpler, reliable and less expensive system:

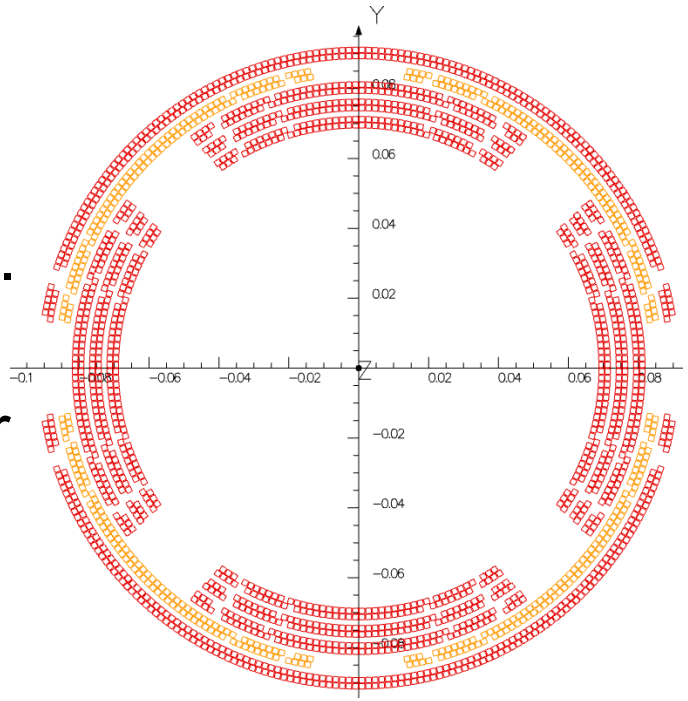
- **Elimination of a corrector (normal dipole) and reduction in the integral strength of the skew quad could reduce the number of layers: from eight to six (coil set from 5 to 4)**
- **The design that is being investigated now, however, will maintain the same number of layers (8) but increase the coil set (from 5 to 6)**
- **Goal is to reduce the maximum current in the coils to possibly eliminate the need for external energy extraction (need to confirm)**
- **Compare the cost differential: increase in cost from increasing the coil sets Vs. savings from removing many external energy circuits**
- **Initial feedback is that it is likely to reduce the cost and complexity of the overall system, while increasing the reliability and margins**

Basic Coil Parameters of the Q3pF Package

Coil i.d.: ~134.4 mm, coil length: 400 mm

Yoke od: 614 mm, yoke length 630 mm

- Q2pF Main Quad: 3 coil sets (original design had 3, reduced in the last design with increased yoke length to 2 now back to 3). Nominal current is 643 A (B0pF: ~900 A, B0ApF: ~1200 A).
- Skew Quad corrector: one coil set (no change). Nominal current reduced to 440 A with a single layer winding (220 A for 2layer winding).
- Skew dipole corrector: one coil set (no change). Nominal current 460 A for 1 layer (no change) (or 230 A for 2 layers)



✓ **Field quality requirements are comfortably met for all (next slides)**

Computed Optimized Harmonics @33 mm in Three Coil Sets of Quad

Coil set #1 (normal quad)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14178E+00	10000.0000
5	-0.34692E-07	-0.0024
9	0.22415E-08	0.0002
13	0.10721E-05	0.0756
17	-0.25229E-07	-0.0018
21	-0.36635E-09	-0.0000
25	-0.77951E-10	-0.0000
29	0.20190E-11	0.0000

Coil set #2 (normal quad)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14235E+00	10000.0000
5	0.56241E-08	0.0004
9	-0.54314E-08	-0.0004
13	0.33484E-06	0.0235
17	-0.84878E-08	-0.0006
21	-0.10765E-09	-0.0000
25	-0.15721E-10	-0.0000
29	0.67831E-12	0.0000

Coil set #3 (normal quad)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14312E+00	10000.0000
5	-0.19681E-08	-0.0001
9	-0.44183E-07	-0.0031
13	0.12682E-06	0.0089
17	-0.27341E-08	-0.0002
21	-0.28489E-10	-0.0000
25	-0.12566E-11	-0.0000
29	0.11166E-12	0.0000

Very low computed design harmonics in each coil set

- Old US definitions, b_2 is sextupole

Specifications are <2 units for Q3pF normal Quad at 30 mm radius

Above are computed harmonics in each coil set (2 layers each).

- **DW strategy to keep them low: correct measured harmonics after each coil set.**

Computed Optimized Harmonics @33 mm in Corrector Magnets

Specifications: <10 units @ 30 mm in both skew quad and skew dipole correctors

Skew Quad

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14486E+00	10000.0000
5	0.29504E-07	0.0020
9	-0.69802E-08	-0.0005
13	0.67982E-07	0.0047
17	-0.14435E-08	-0.0001
21	-0.97078E-12	-0.0000
25	0.24836E-12	0.0000
29	0.56014E-14	0.0000

Old US definitions, b2 is sextupole

Low design harmonics for correctors

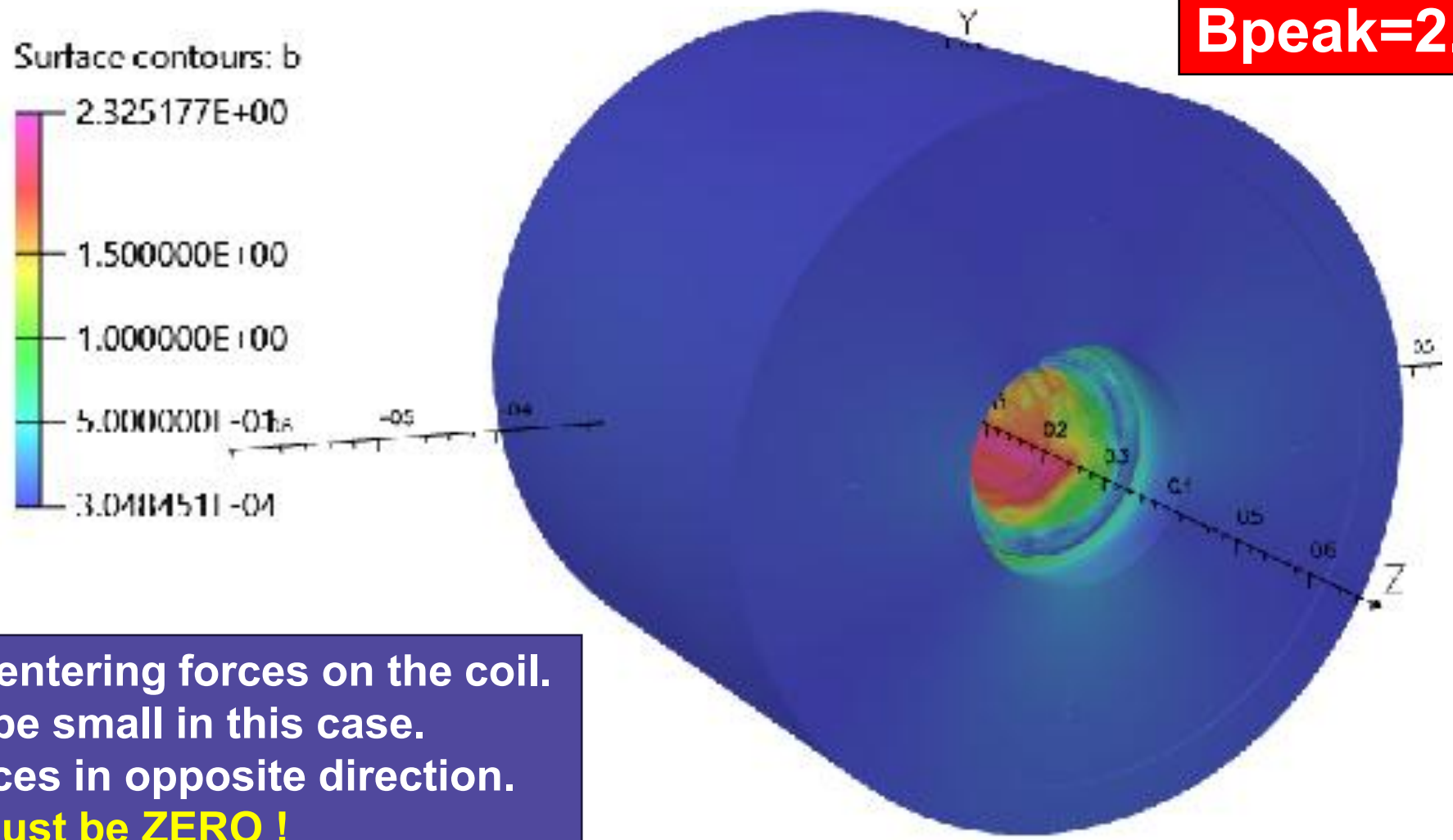
Skew Dipole

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.43714E+00	10000.0000
2	0.21699E-04	0.4964
4	0.55385E-04	1.2670
6	0.29103E-04	0.6658
8	-0.36047E-05	-0.0825
10	0.30127E-06	0.0069
12	-0.17425E-07	-0.0004
14	-0.22701E-08	-0.0001
16	0.47303E-09	0.0000
18	-0.80231E-10	-0.0000
20	0.64499E-11	0.0000
22	-0.20905E-12	-0.0000
24	-0.60086E-13	-0.0000
26	0.16787E-13	0.0000
28	-0.18169E-14	-0.0000
30	0.17126E-15	0.0000

Magnetic Model with All Coils in Iron Yoke

- Normal quad
- Skew quad
- Skew dipole



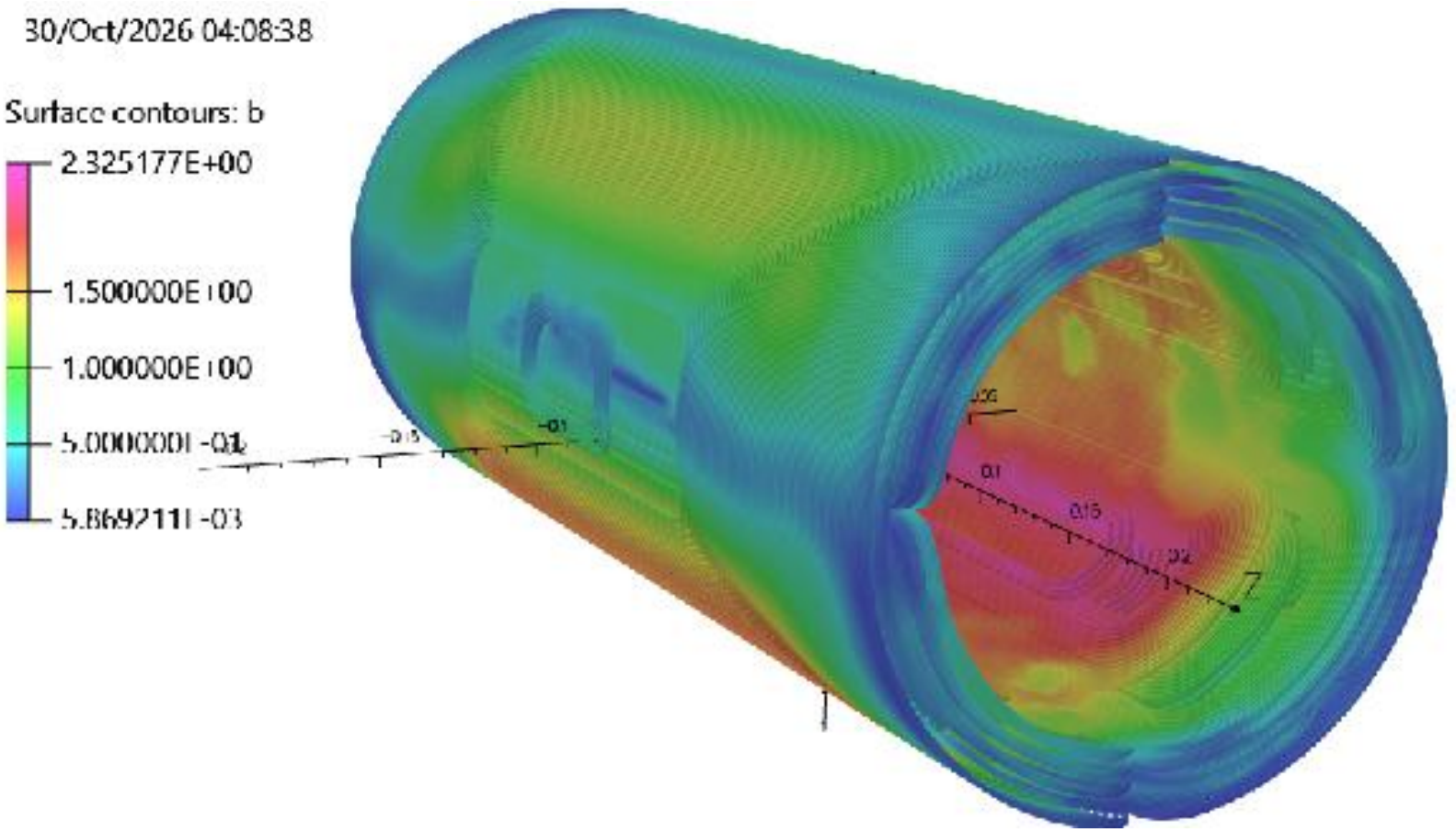
Bpeak=2.33 T

There will be off-centering forces on the coil.
They are likely to be small in this case.
Yoke will have forces in opposite direction.

- **Net force must be ZERO !**

All coils: normal quad (Q3pF), skew quad, and skew dipole

Bpeak=2.33 T



Currents to produce the design integrals:

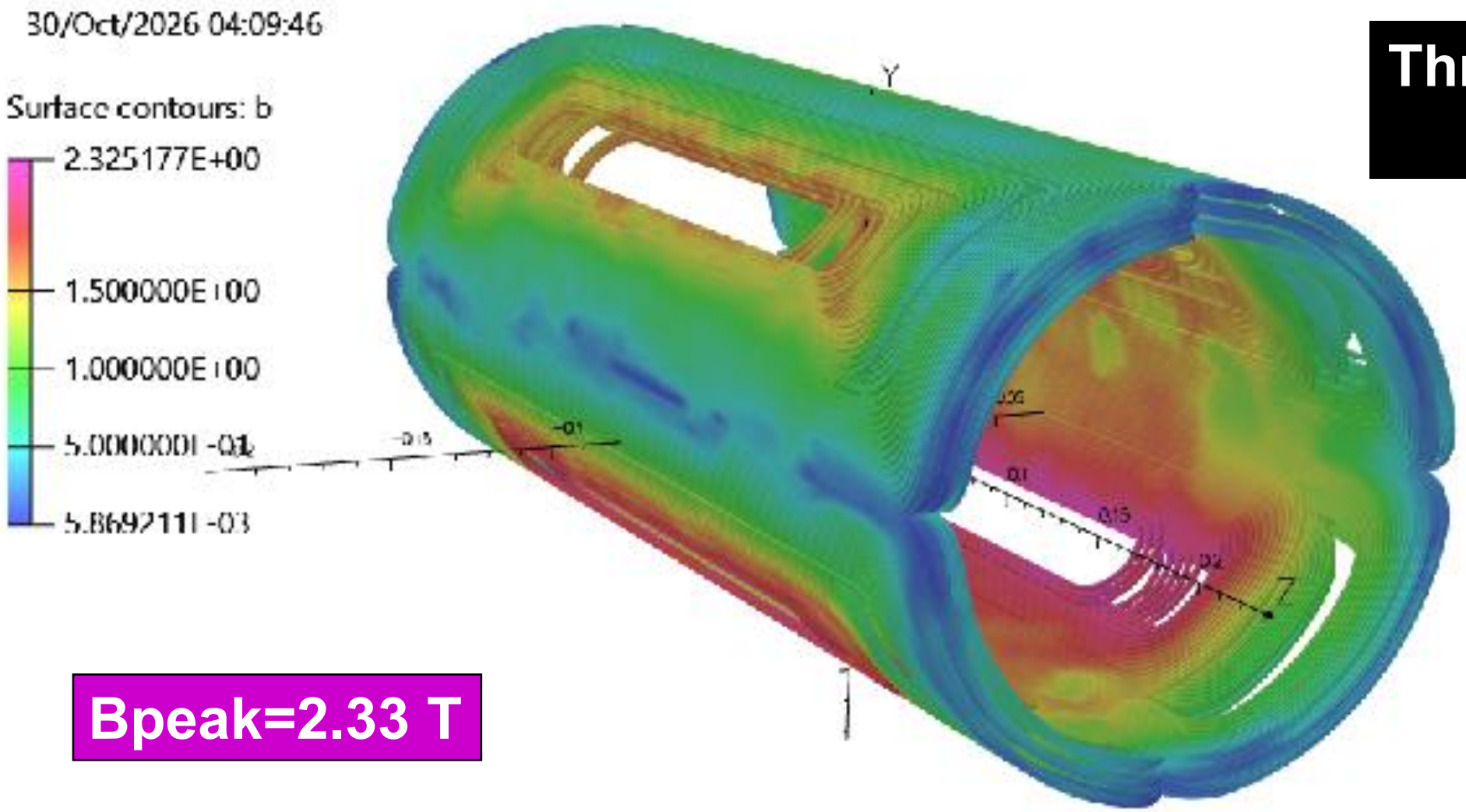
- **NQ (Q3pF): 643 A**
- **SQ (1lyr): 440 A**

(220 A for 2 layers in the same coil set)

- **SD (1lyr): ~460 A**

(230 A for 2 layers in the same coil set)

Field on the Normal Quad Q3pF (I = 643 A)

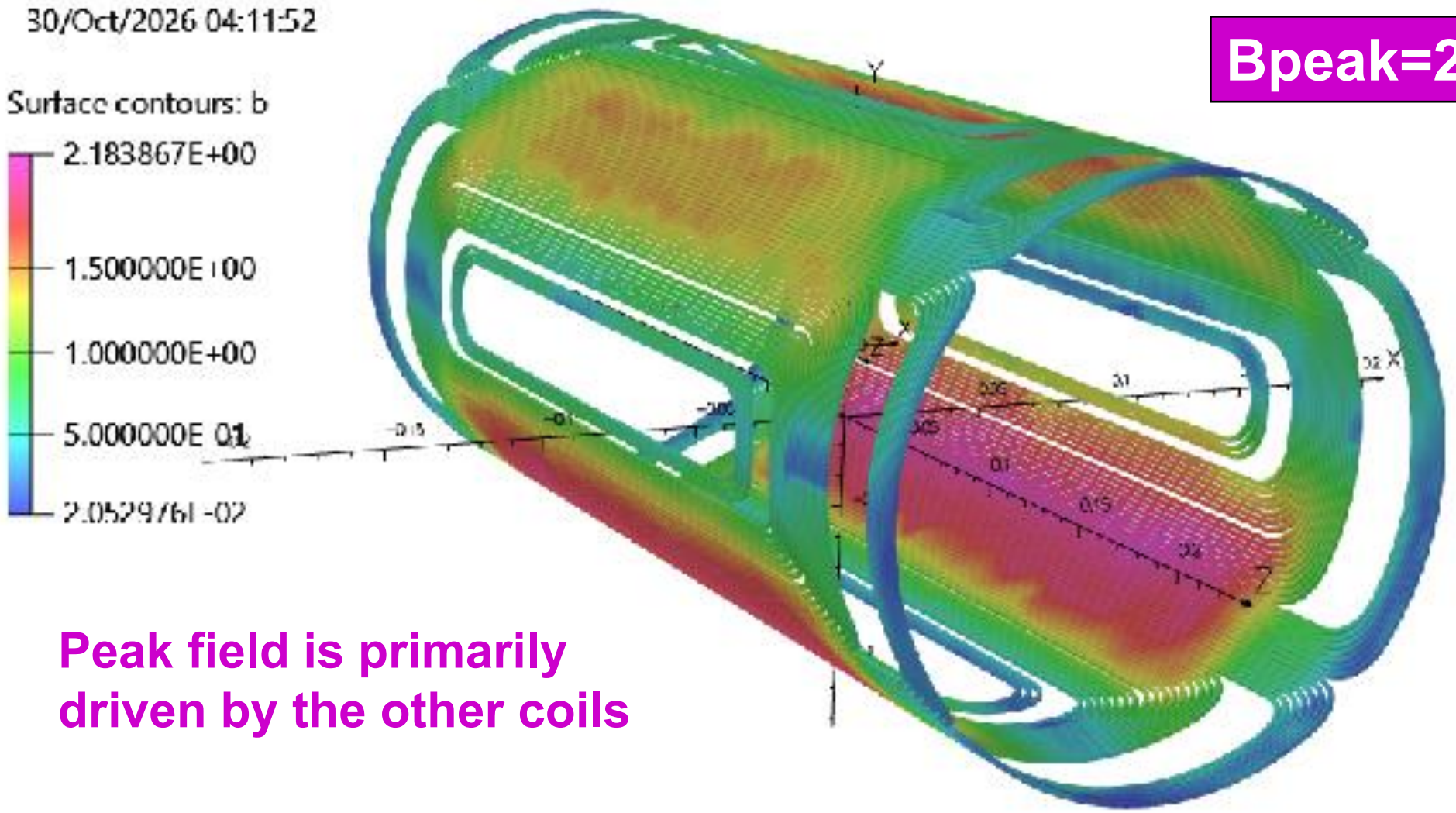


Three coil sets (6 layers)

Bpeak=2.33 T

All other coils are hidden even though they are powered at the maximum current (yoke is also hidden)

Coil Set 4 (skew quad corrector – 1-layer option, I = 440 A)



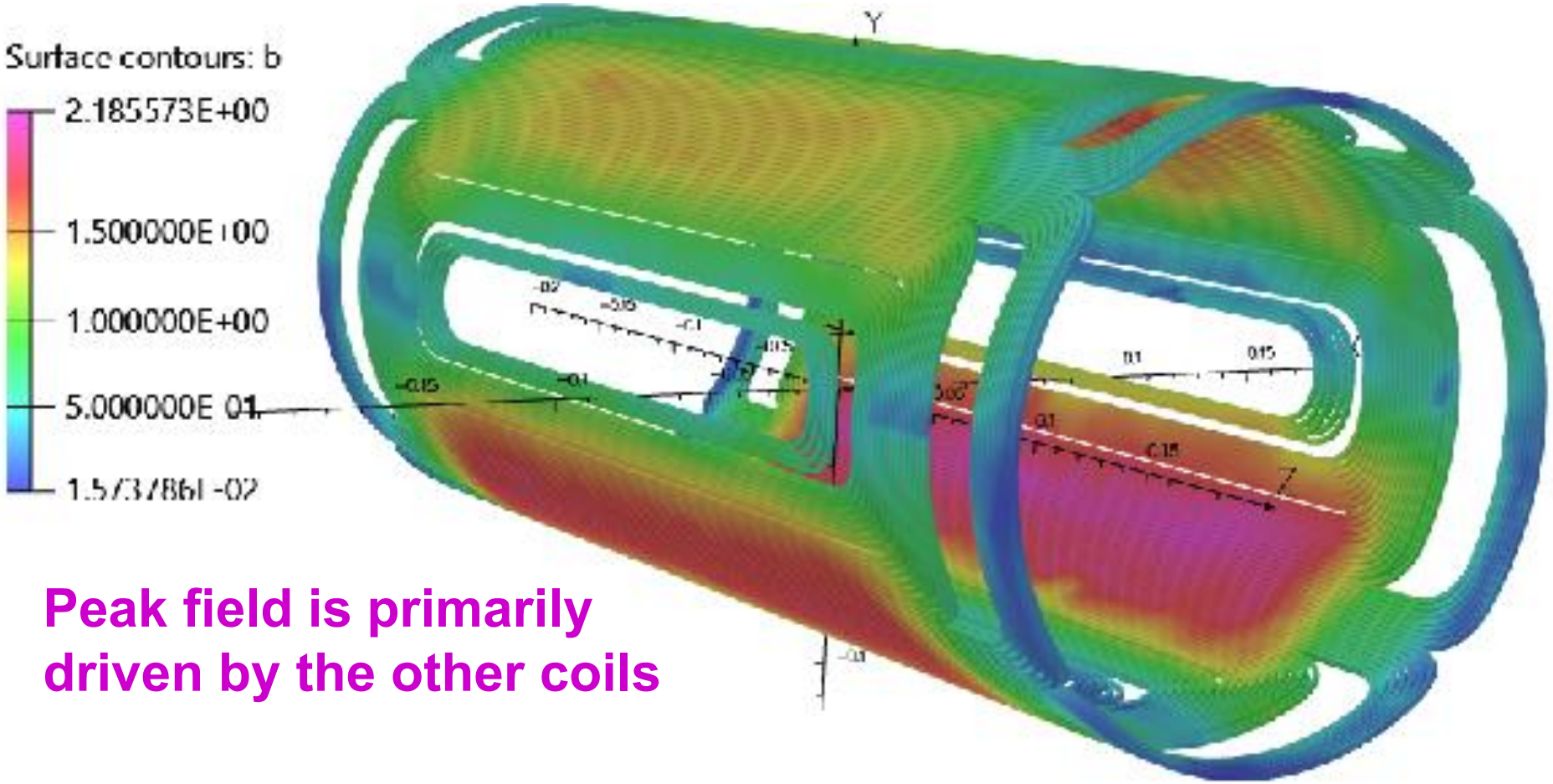
Bpeak=2.18 T

Peak field is primarily driven by the other coils

All other coils are hidden even though they are powered at the maximum current (yoke is also hidden)

Coil Set 4 (skew quad corrector – 2-layer option, I=220A)

Second layer in the same coil set doesn't add to the radial build up as it goes in the space taken by the leads (as such a single layer design is good enough)

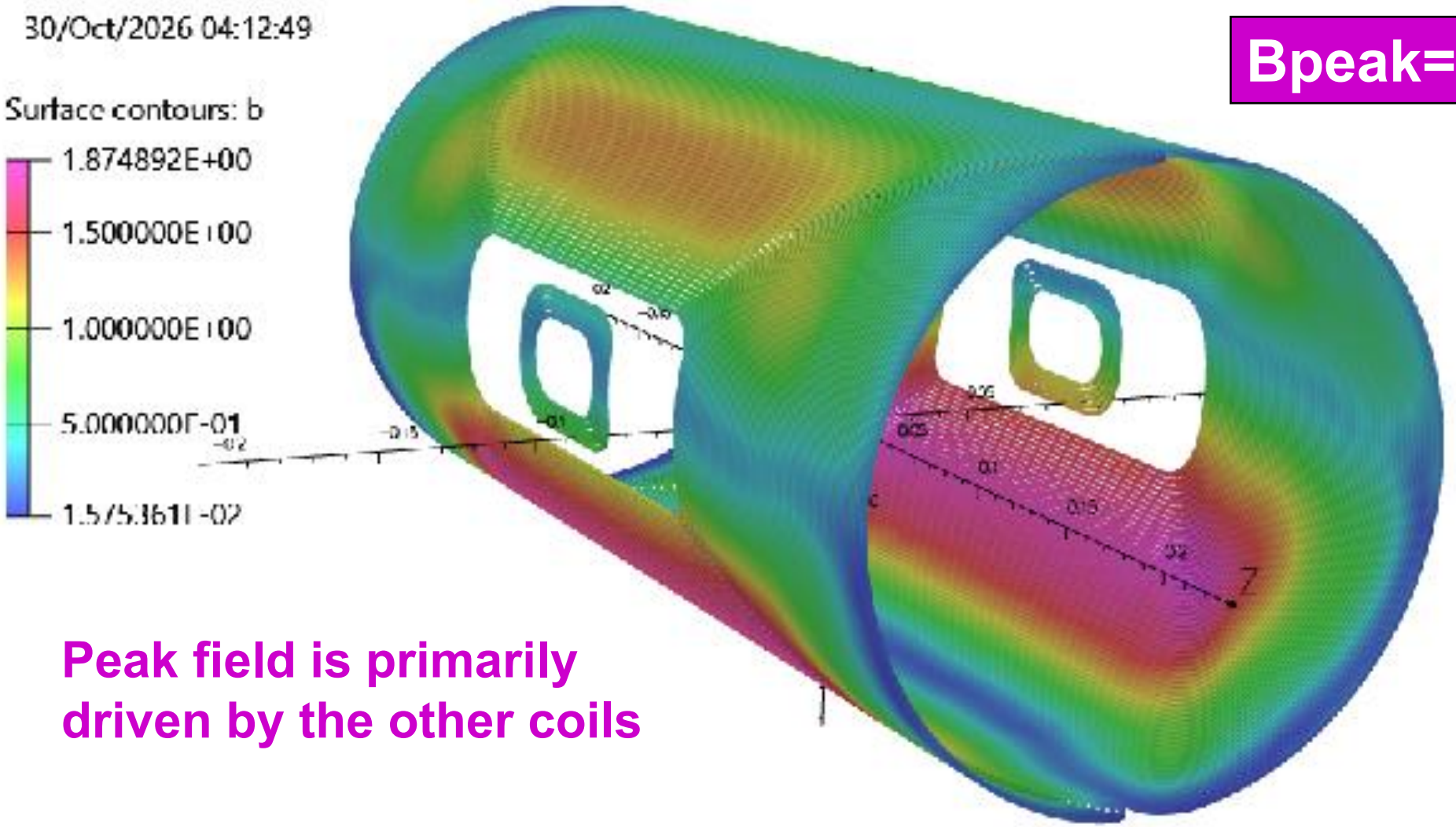


Peak field is primarily driven by the other coils

Bpeak=2.18 T

All other coils are hidden even though they are powered at the maximum current (yoke is also hidden)

Coil Set 5 (skew dipole corrector – 1-layer option, I=460A)



Bpeak=1.87 T

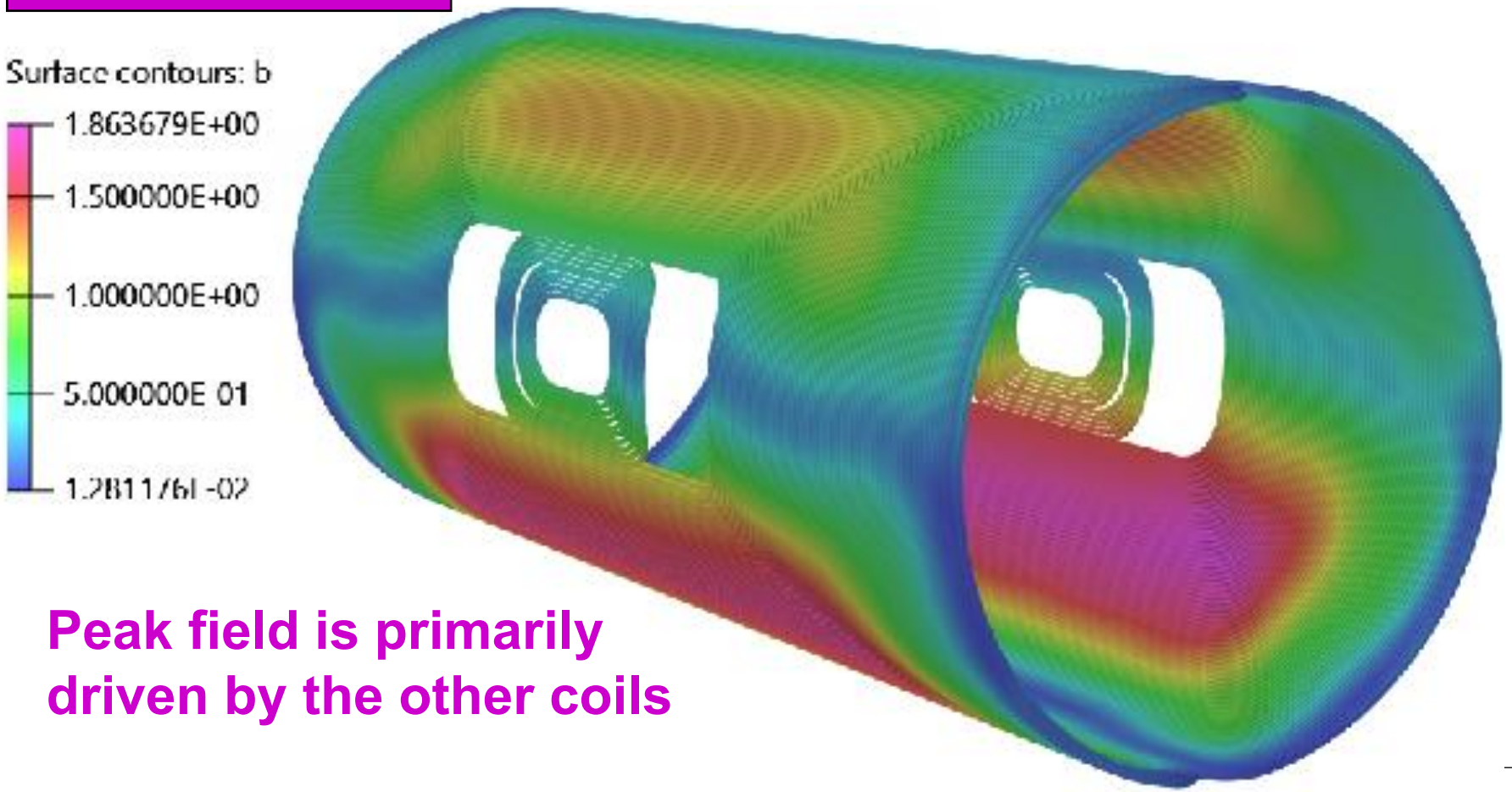
Peak field is primarily driven by the other coils

All other coils are hidden even though they are powered at the maximum current (yoke is also hidden)

Coil Set 5 (skew dipole corrector – 2-layer option, I=230A)

Second layer in the same coil set doesn't add to the radial build up as it goes in the space taken by the leads (as such a single layer design is good enough)

Bpeak=2.18 T



Peak field is primarily driven by the other coils

All other coils are hidden even though they are powered at the maximum current (yoke is also hidden)

Field Profile along the z-axis of the Skew Dipole (NOTE: NO FLAT-TOP FOR SUCH A SHORT MAGNET)

q3pf-NQNQNQ0-SQL0-SDL1-g-b2yoke614.op3 - SIMULIA Opera-3d Post-Processor

Work | Post-Processing

File | Print | Animations | Comi Editor | Run Comi | User Defined Toolbuttons | User Variables | Select | 3d Display | 3d Display Settings | Units | Set AC Time

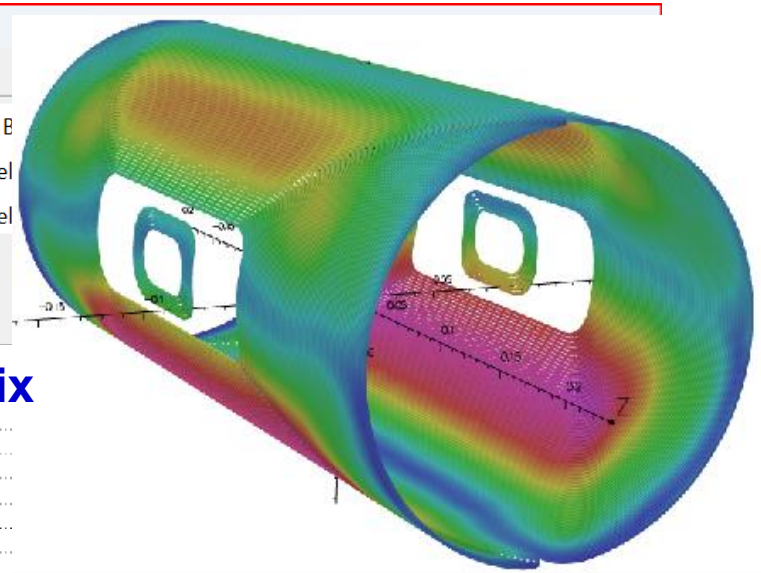
Images | Command Files | User Defined | View

Model | Graphs

Graph Objects

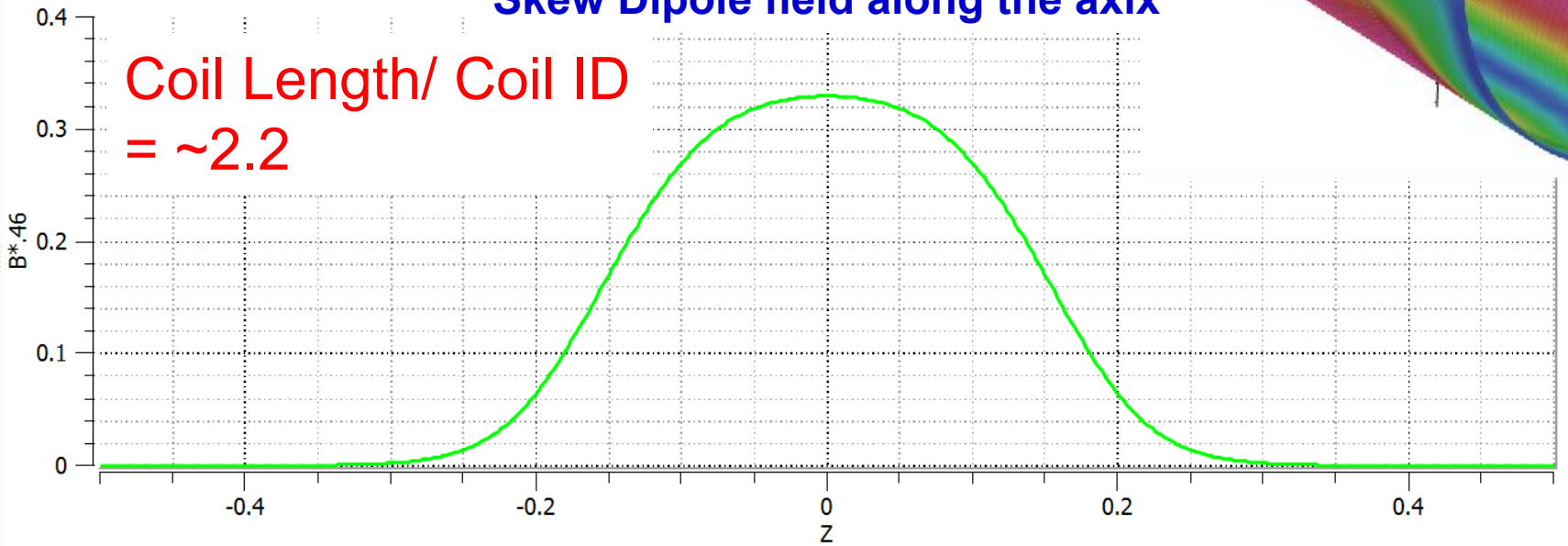
- Data
  - Buffers
    - Line
  - Graph Objects
    - Lines
      - grad-quad
      - Skew Dipole
  - Graphs
    - Default
      - Skew Dipole

Option	Value
Background	
Colour	White
Border Colour	White
Image File	
Title	
Display	Yes
Text	Skew Quad field al...
Font	Tahoma, 12pt
Colour	Blue



Skew Dipole field along the axix

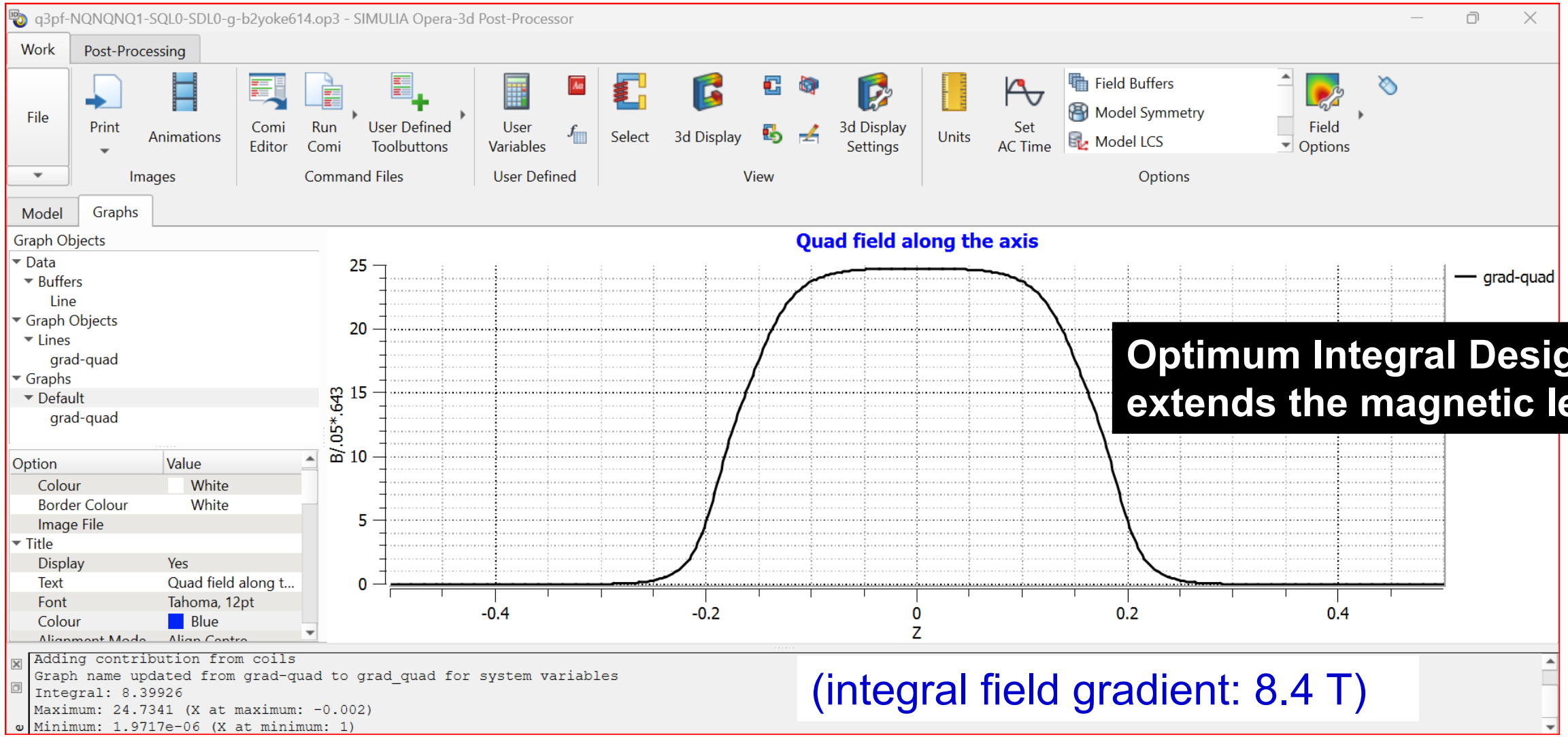
Coil Length/ Coil ID = ~2.2



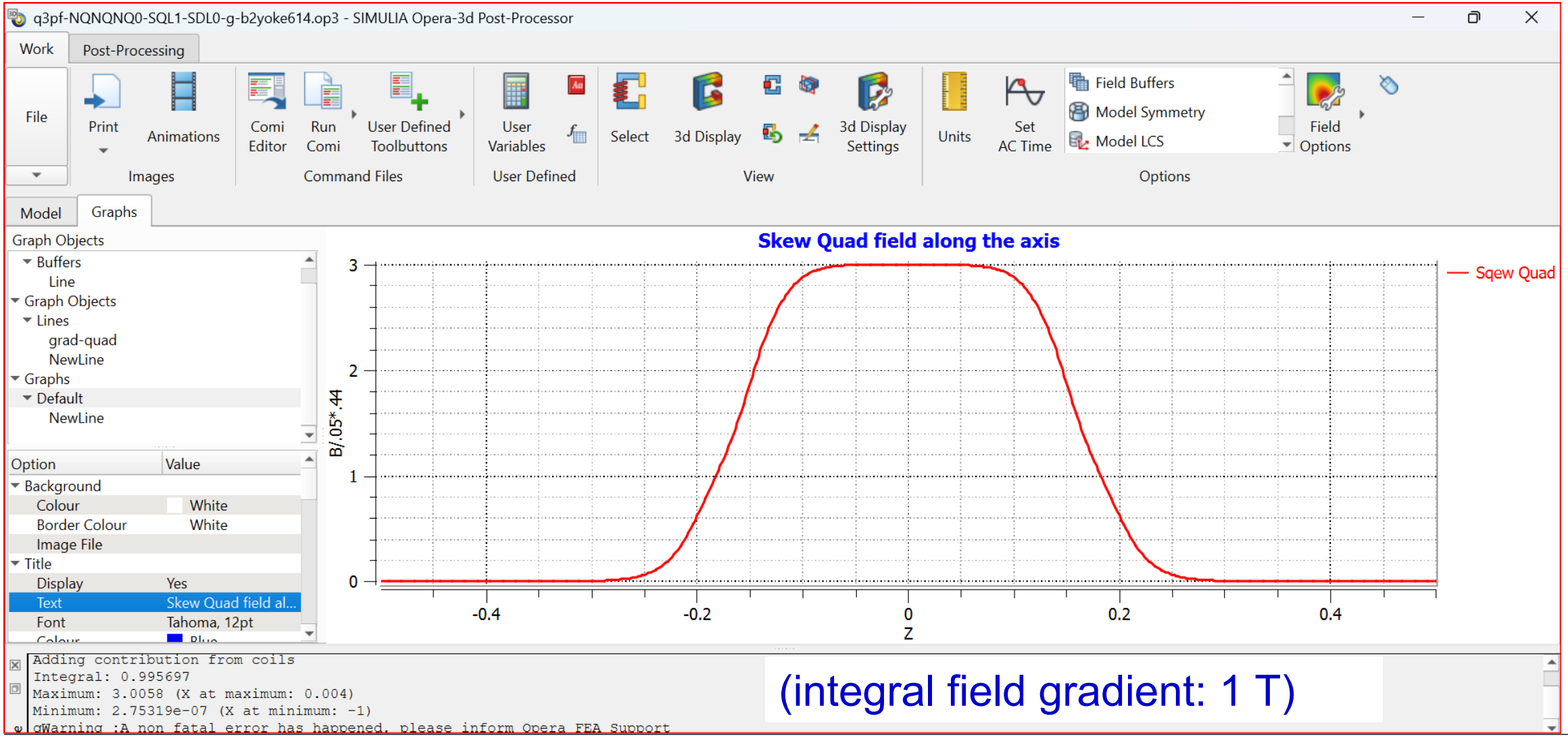
Graph name updated from Skew Dipole to Skew_Dipole for system variables
Integral: 0.100451
Maximum: 0.32944 (X at maximum: 0)
Minimum: 1.10275e-07 (X at minimum: -0.708)

(integral field of 0.1 T.m)

Field Profile along the z-axis of the Normal Quadrupole (normal quad needs maximum integral strength)



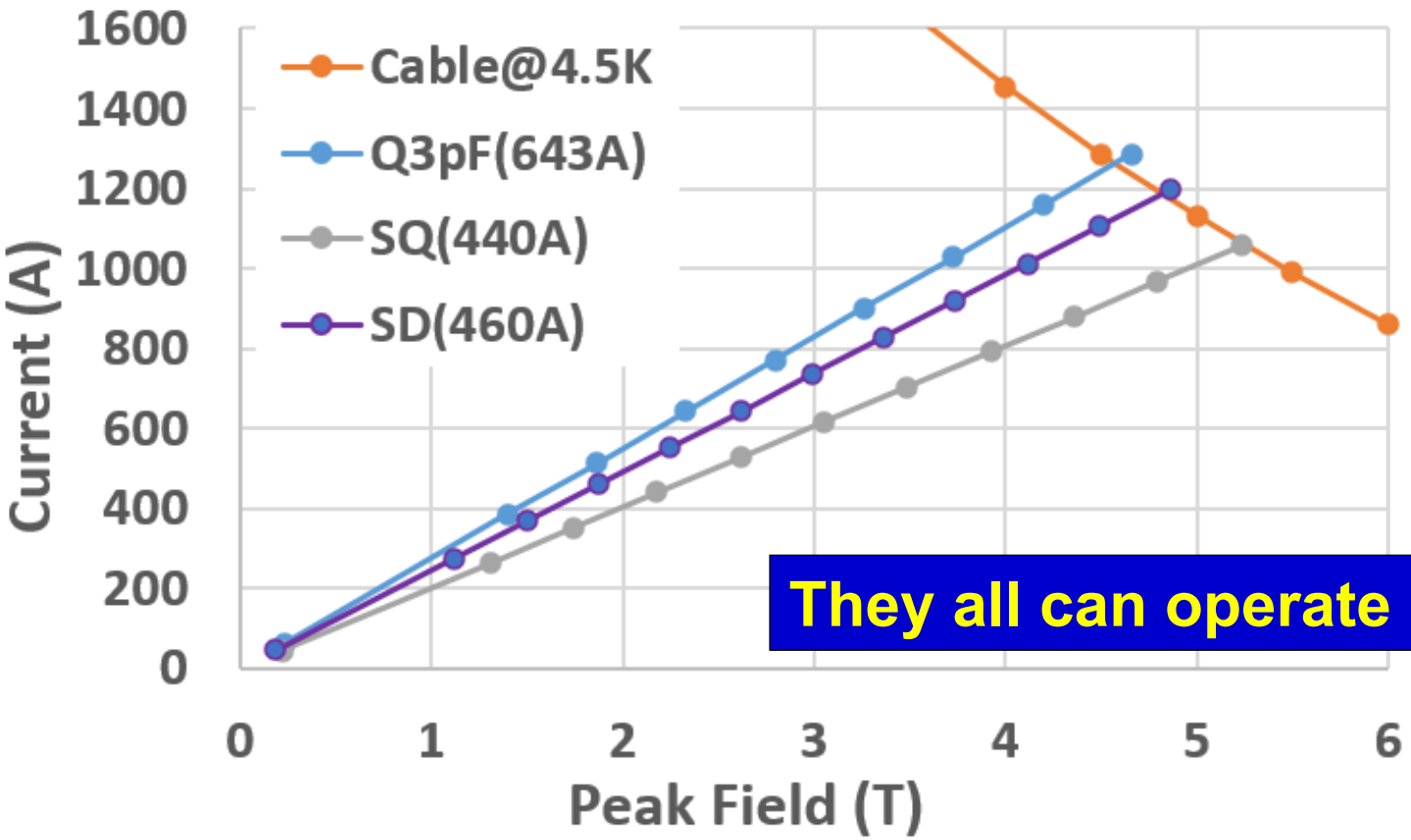
Field Profile along the z-axis of the Skew Quadrupole



(integral field gradient: 1 T)

Computed Quench Performance – Generous Margin (with field from all coils changing together)

***Margins are computed for all are powered at maximum and then all together operate at a load line fraction of 51%. Individual set will have even higher margin.**



I(NQ) = 643 A for 8.4 T, Iss = 1260A

- **Load line fraction*: 51%**

I(SQ) = 440 A for 1 T, Iss = 1060 A

- **Load line fraction*: 42%**

II(SD) = 460 A for 0.1 T.m, Iss =1180 A

- **Load line fraction*: 39%**

They all can operate at a much higher performance

(There is some discussion on increasing the diameter. That is ok for the margin. However, it might impact the self-protection)

RECAP: The Main Driver for this Design - Quench Protection

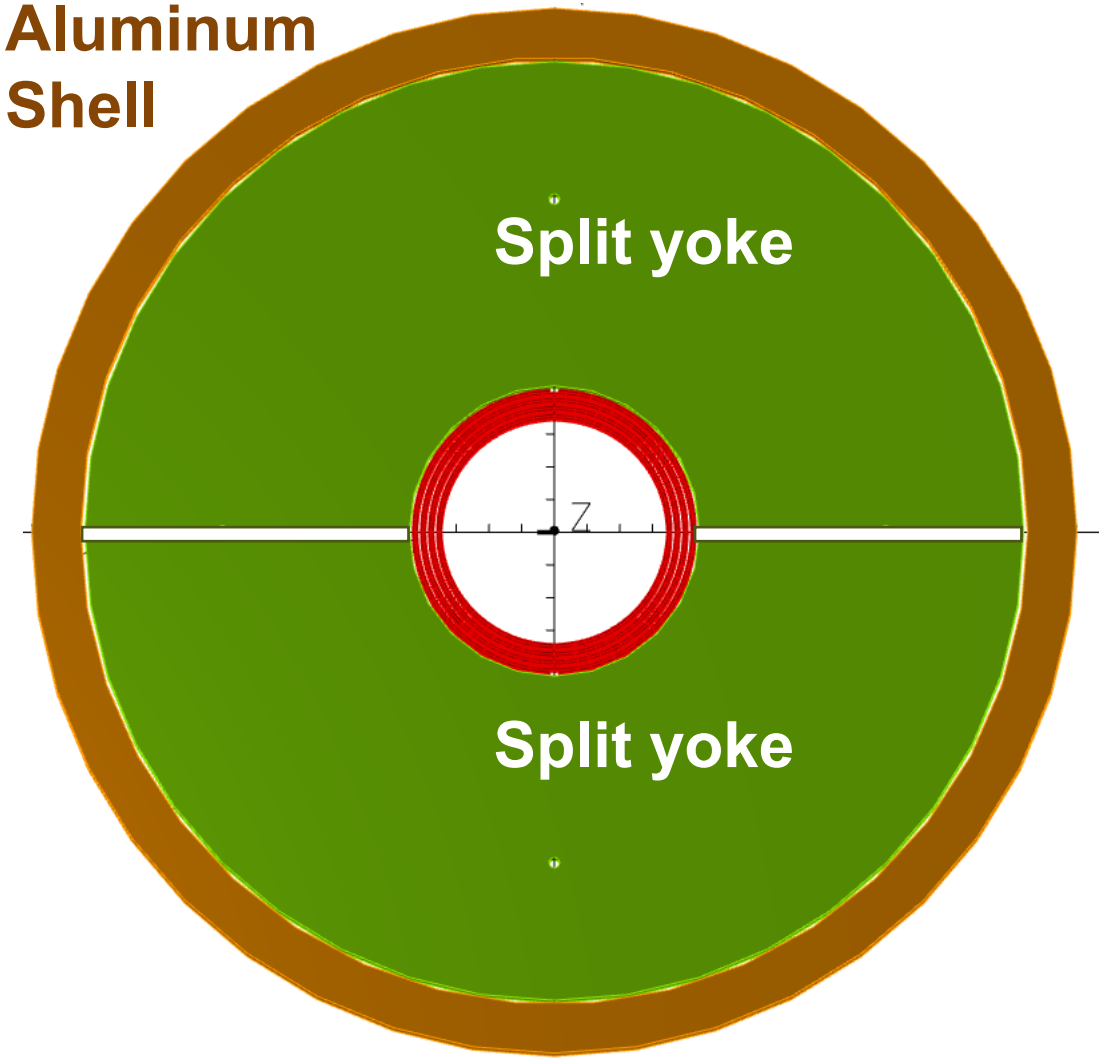
- Stored energy in Q3pF is significantly lower than in B0pF & B0ApF.
- While the cables used in B0pF, B0ApF and Q3pF are the same, the maximum current (and hence current density in copper at quench) is also significantly lower. e.g., B0pF: ~900 A, B0ApF: ~1200 A, Q3pF (new design): ~640 A and skew quad and dipole correctors (460 A).
- Some variations: In case the quench simulations show that the coils are not self protected, one can examine ESC coil or copper tube.
- The driver is to optimize the magnet system in an overall sense rather than just the number of layers or coil sets. Such an investigation should be done in the early phase of the design.

SUMMARY

- Design calculations confirm that the specified performance of superconducting Q3pF package, placed in the same cryostat as the B2pF, can be obtained with a 400 mm long multilayer-direct wind coils.
- Optimum integral design helps and increases the efficiency of short magnets.
- Design of the Q3pF package is optimized as a system (coil winding + quench protection). Number of coil sets in Q3pF is increased from minimum two to three to investigate if the need for external energy extraction can be eliminated (as in RHIC magnets). Skew quad and skew dipole require only a single layer of winding.
- The design and construction is expected to meet the field quality requirements.
- Design has generous quench margin for all three (Q3pF, skew quad, skew dipole).
- The design is ready to go for 2-d mechanical analysis. While 3-d analysis may be done later, 2-d analysis should be done for full 360 degrees (no symmetry).
- The design is ready for the quench analysis to see if self-protection works.

Older slide(s)

Strategies to deal with off-center forces (and to deal with large Lorentz forces in high field direct wind magnets)



Core Issue:

- Current direct wind designs keep a small gap between yoke and coil package.

This allows coil to move towards the iron, if not clamped at the ends. This still leaves a possibility of a bow when energized in the body of the magnet.

This may be acceptable in low field magnets where we don't take benefit of the yoke and shell.

We should consider, Aluminum shell and split yoke so that we have a tight fit when it cools down.

There are sign that the performance of OID and high field quad suffered from this.

Harmonics in quad seems to be coming due to this.

We can test this concept in OID or in high field quad.