Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Investigation of Q2pF Ends for Favorable Tilt Angles

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May 30, 2023

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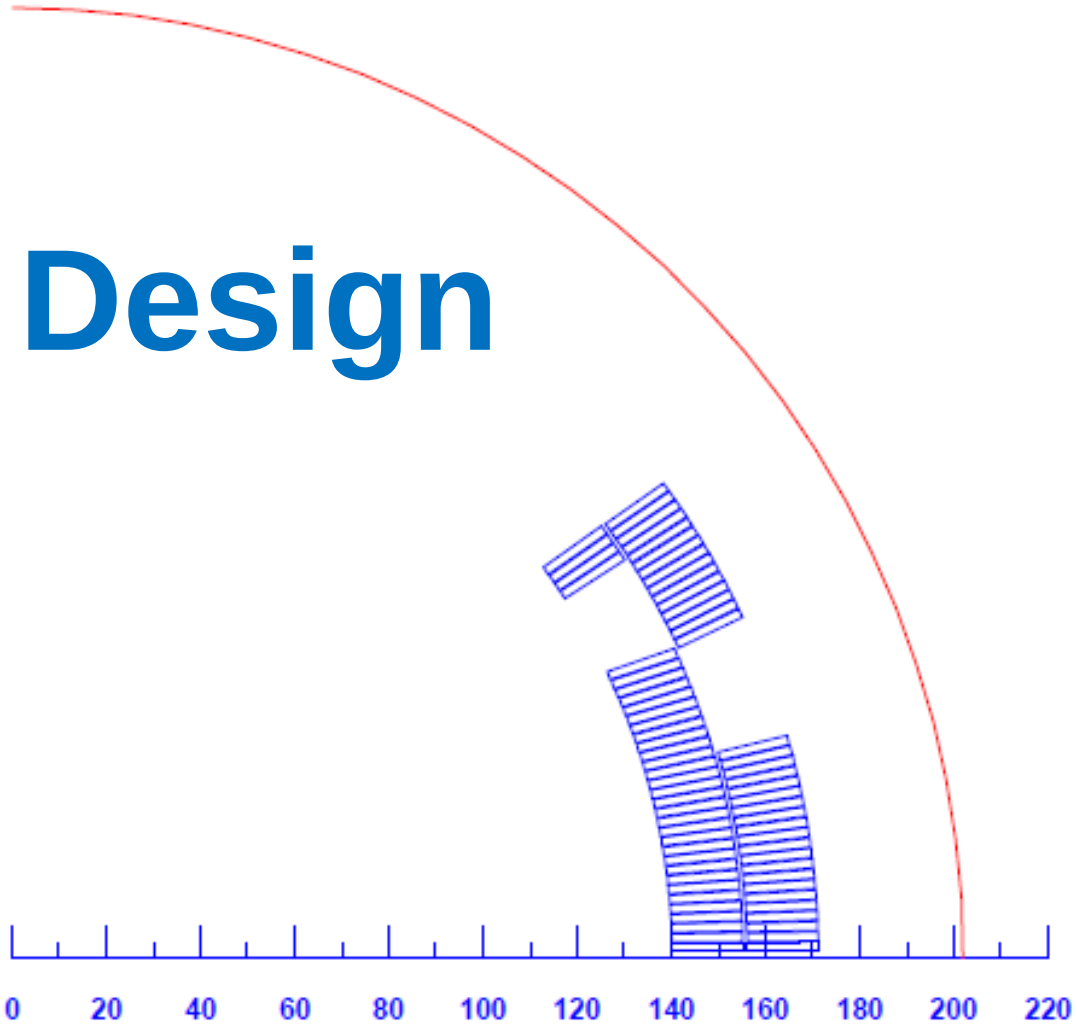
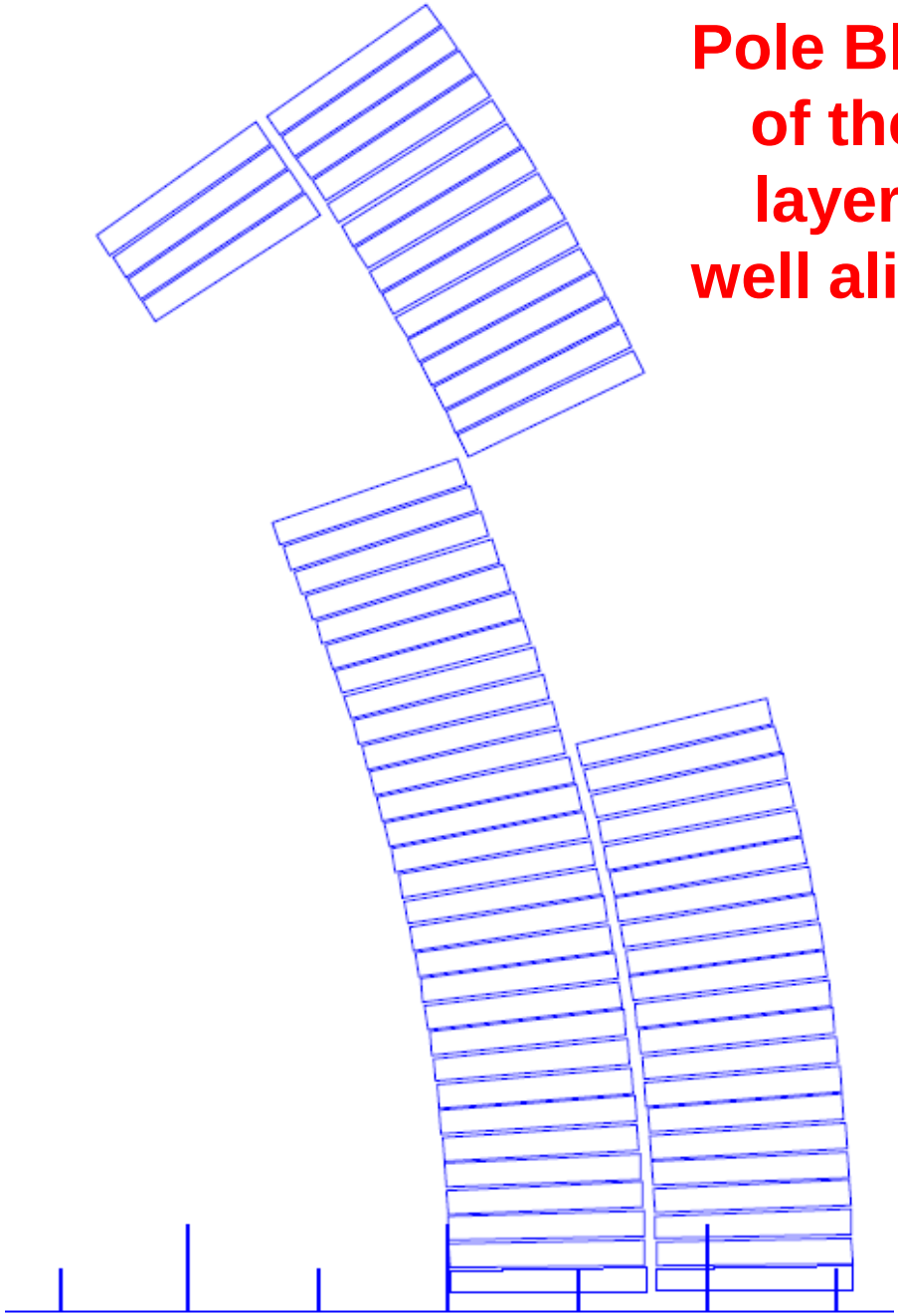
Design Goals : More Vertical Q2pF Ends

- Make this while satisfying the following other design criteria:
  - ➢ Peak field in the Ends remain within a few percentage of the 2-d peak field
    - ➢ **Important as (a) we don't want to lose any margin, and (b) the cable in the ends is less well supported than the cable in the body of the magnet**
  - ➢ Good field quality (small integrated harmonics in the Ends, as in straight section)

  Turns should be easy to wind. They should be easily kept in place with acceptable strain on the conductor. Take feedback and useful experience from the single turn test in B1pF. Follow a similar procedure. End turn layout should look reasonable from ROXIE and CAD models before printing 3-d parts.
- First round is done manually for developing a better understating. Detailed optimization to follow.
- One representative case each for 65 degrees tilt (25 degrees from vertical plane) and for 70 degrees tilt (20 degrees from vertical plane) will be presented today.

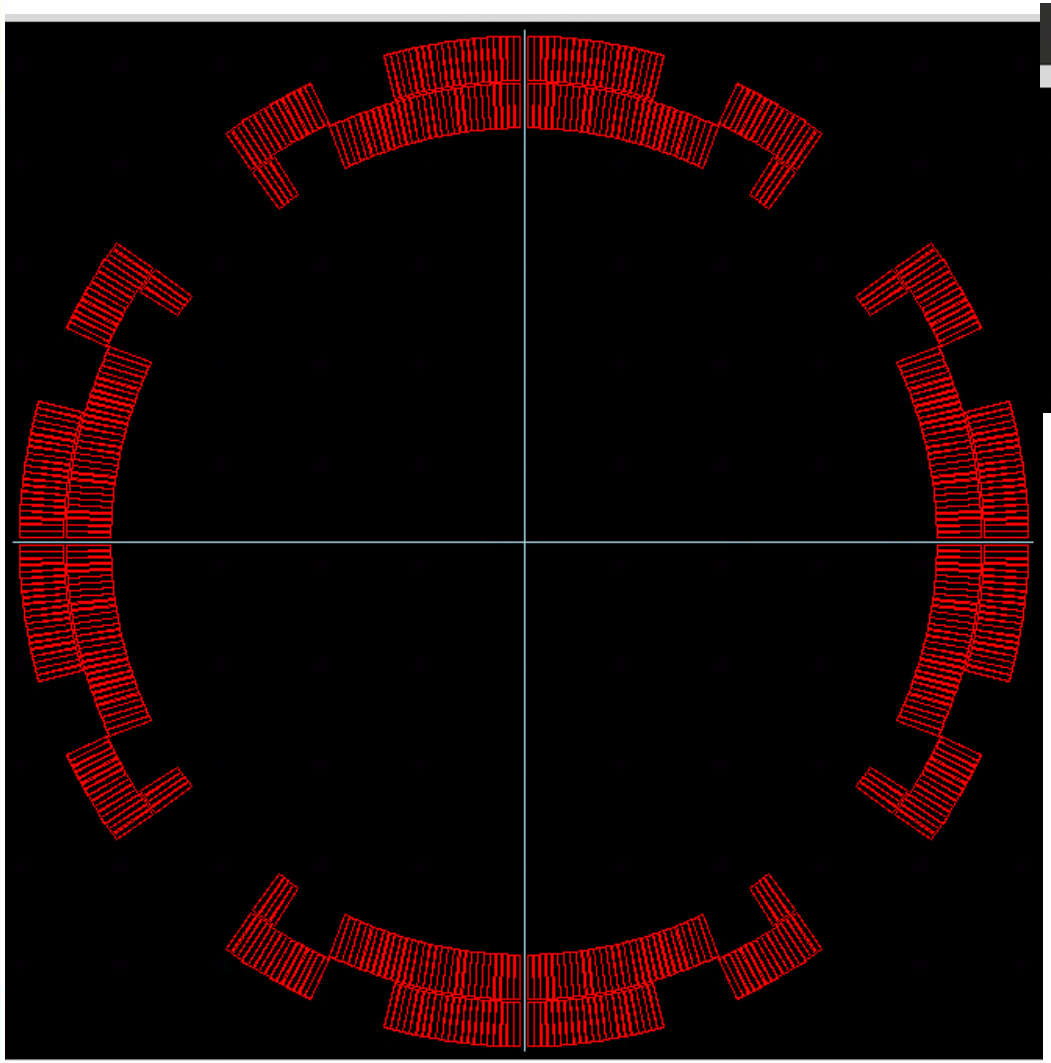
2-d Design

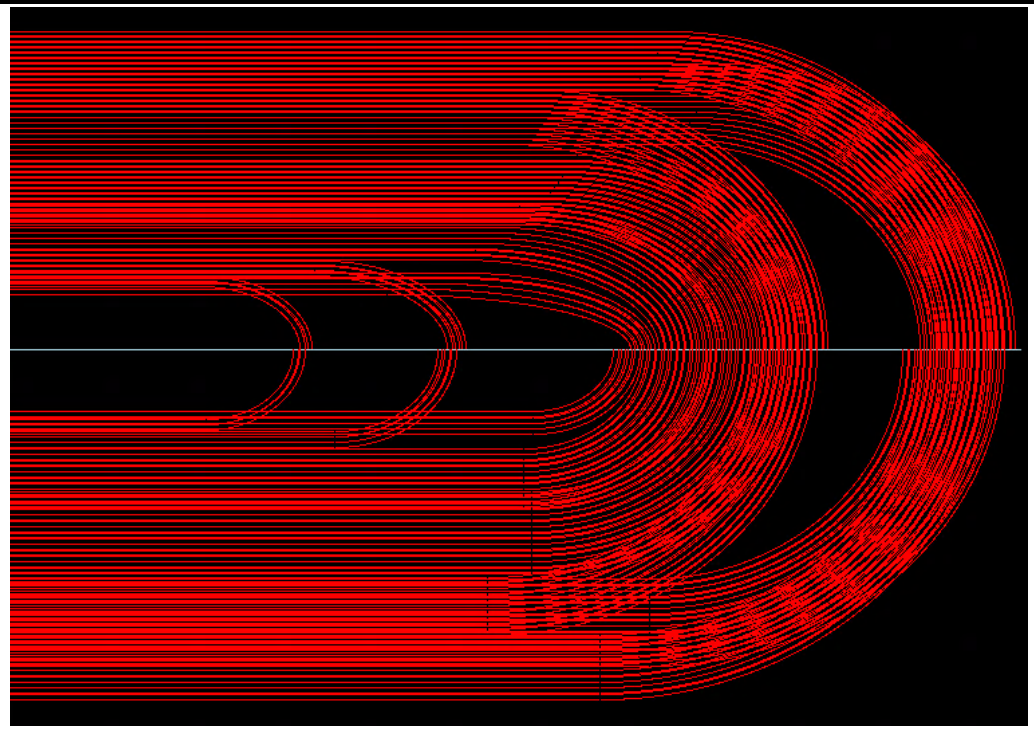




Pole Blocks of the two layers are well aligned

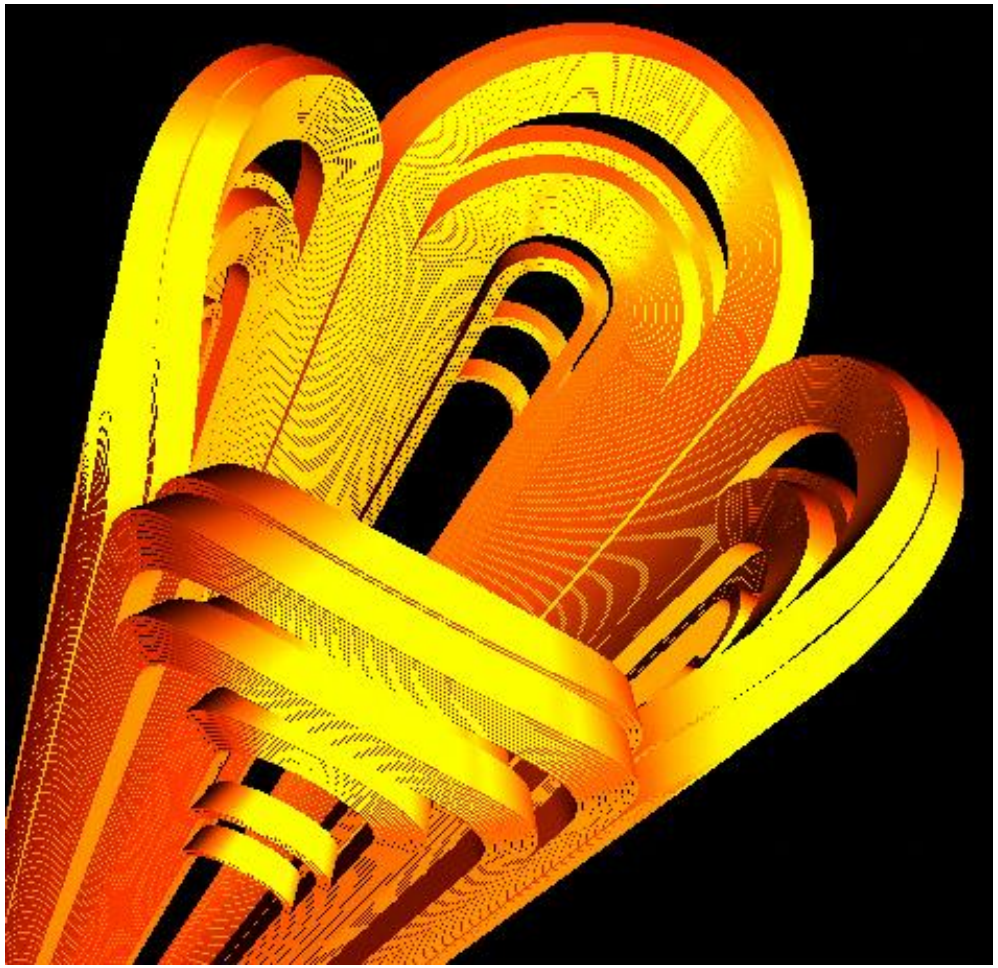
Initial Manually Optimized End Geometry (tilt angles 65 degrees or more, 25° from pole)

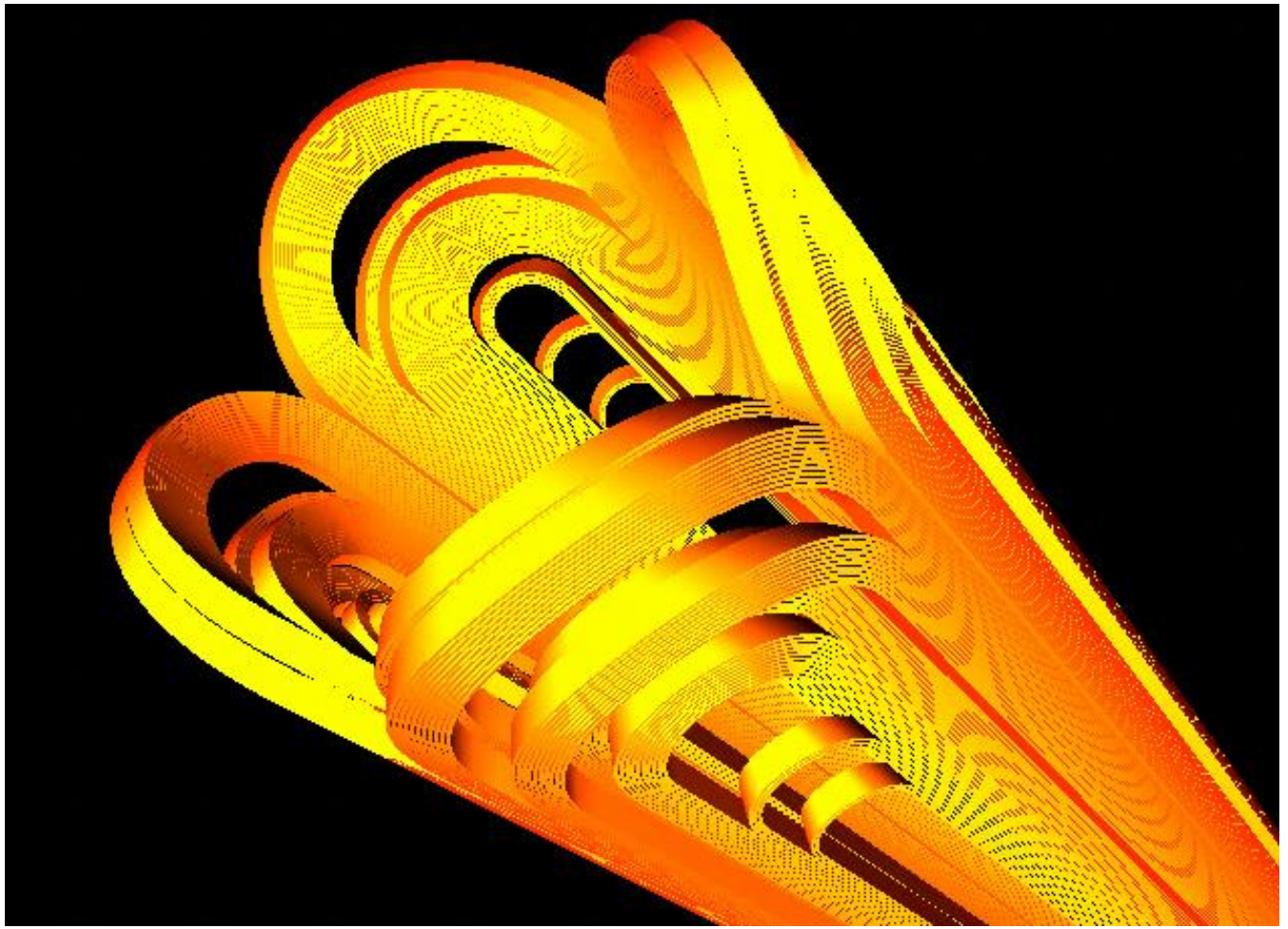




End Blocks of the two layers are well aligned

Views on Initial End Geometry (65º)

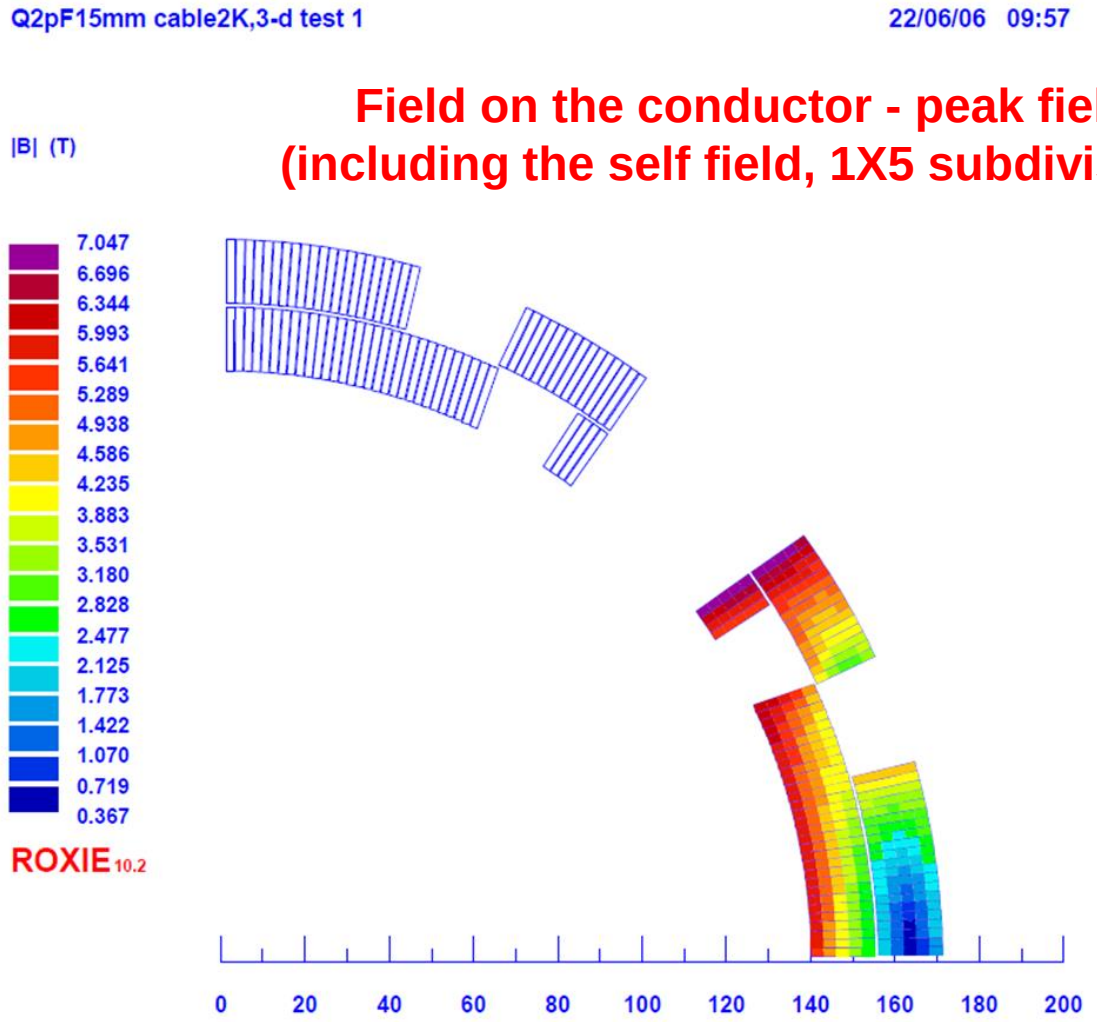




First Examine the Peak Field and Compare with the Body

Peak Field in the Body of the Magnet

Peak field in 2-d 7.047 T



Field on the conductor - peak field (including the self field, 1X5 subdivision)

Peak field enhancement: ~18%

Peak Field in the Ends (65º)

- **Peak field in the ends (including self field): 7.07 T; 2-d (Body) was 7.05 T**

  ✓**Peak field in the Ends is close to the field in cross-section**

```
MARGIN CALC (USING JC-FIT):
BLOCK NUMBER ..........................................          11
PEAK FIELD IN CONDUCTOR   70 (T) ..................... →     7.0716
CURRENT IN CONDUCTOR  70 (A) ..........................    -8500.0000
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ..............      -886.0233
PERCENTAGE ON THE LOAD LINE ...........................        66.9817
QUENCHFIELD (T) .......................................        10.5575
TEMPERATURE MARGIN TO QUENCH (K) ......................         3.0748
PERCENTAGE OF SHORT SAMPLE CURRENT ....................        27.5139
```

All other blocks have lower peak fields

Integrated Field Harmonics (65º)

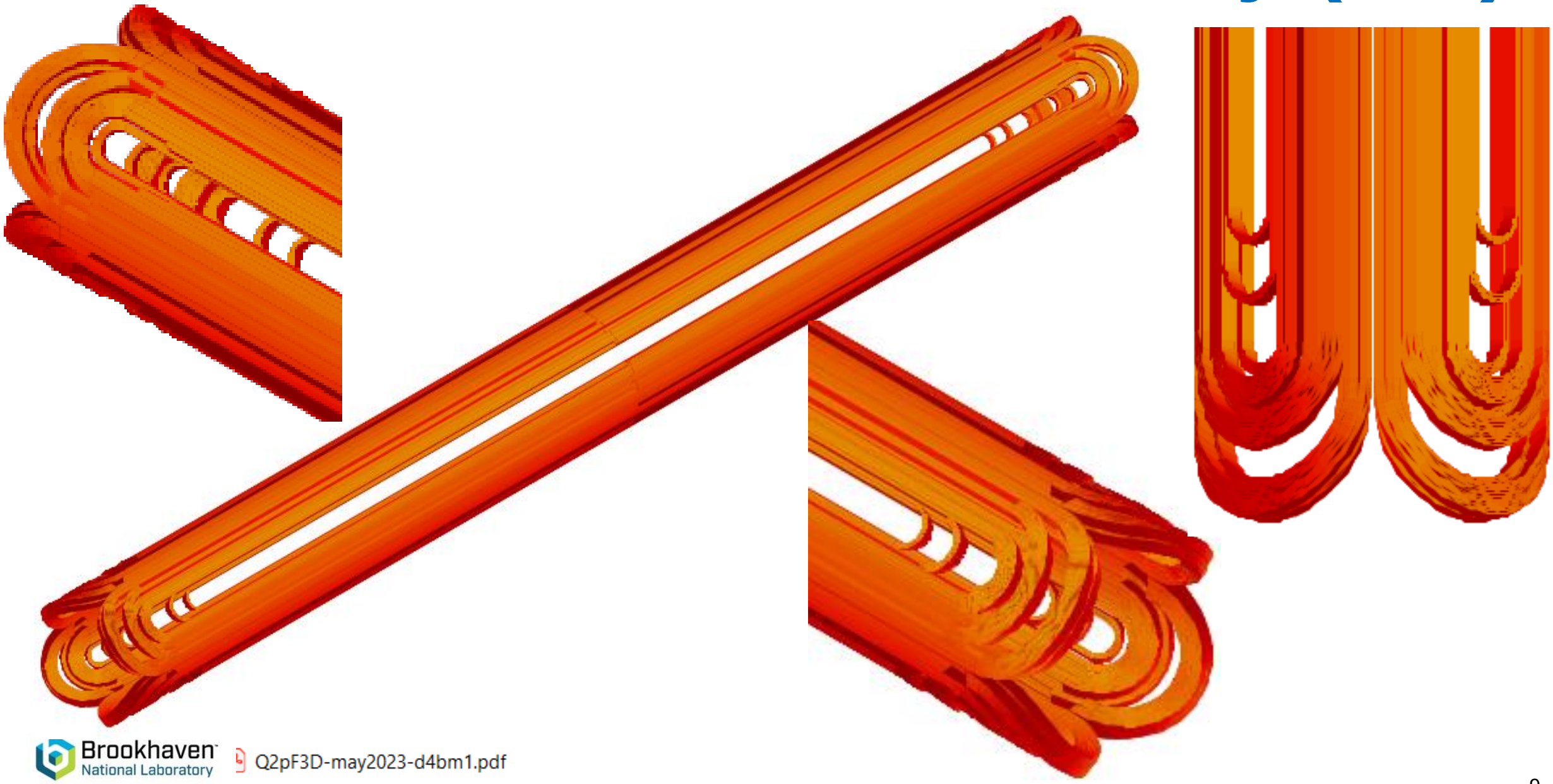
```
HARMONIC ANALYSIS NUMBER ..............................          1
MAIN HARMONIC .........................................          2
REFERENCE RADIUS (mm) .................................      83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..................       0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..................       0.0000
NUMBER OF ANALYSES ALONG Z ............................        500
LENGTH OF VIRTUAL COIL (mm) ...........................    2500.0000
REFERENCE POSITION NUMBER .............................         10
MEASUREMENT TYPE ..........................  ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ......................  0.6698E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

3D REFERENCE MAIN FIELD (T) ...........................      3.4693
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ................     41.7992
MAGNETIC LENGTH (mm) ..................................    1723.3571

NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
b 1:      0.00000  b 2:  10000.00000  b 3:      0.00000
b 4:      0.00000  b 5:     -0.00000  b 6:      0.14827
b 7:     -0.00000  b 8:     -0.00000  b 9:      0.00000
b10:     -0.21782  b11:      0.00000  b12:      0.00000
b13:     -0.00000  b14:     -0.52195  b15:     -0.00000
b16:     -0.00000  b17:      0.00000  b18:      0.01163
b19:     -0.00000  b20:     -0.00000  b
```

A reasonably good solution for manual optimization

Views on Initial End Geometry (65º)



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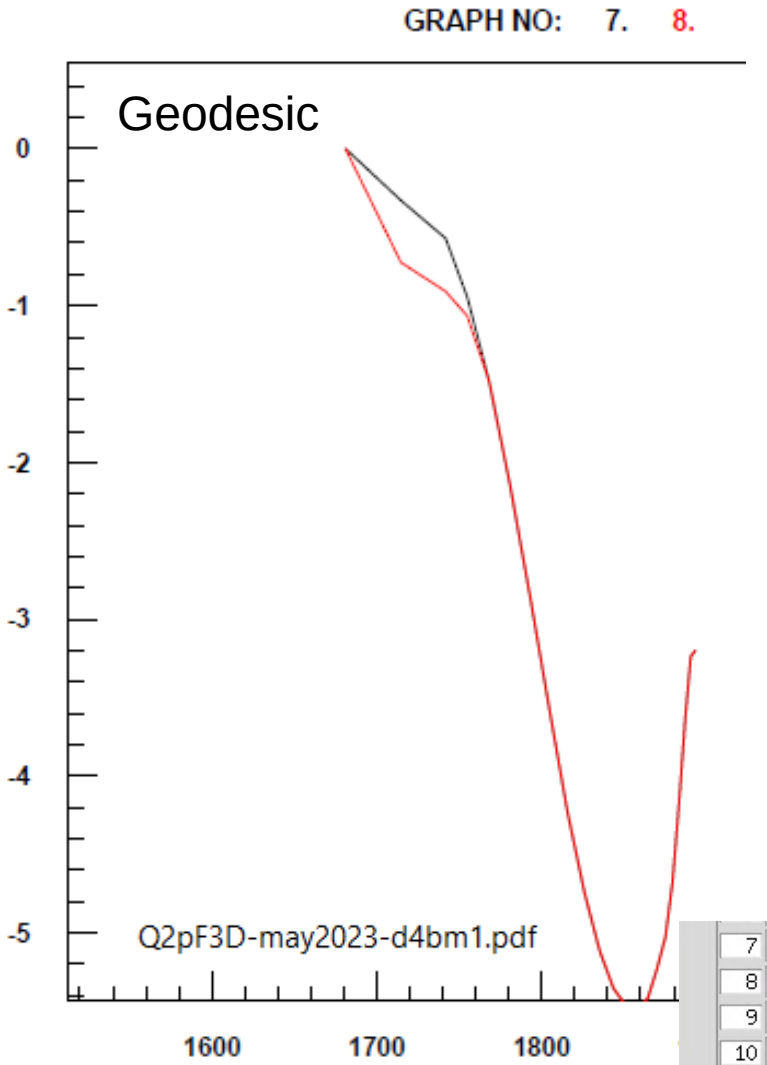
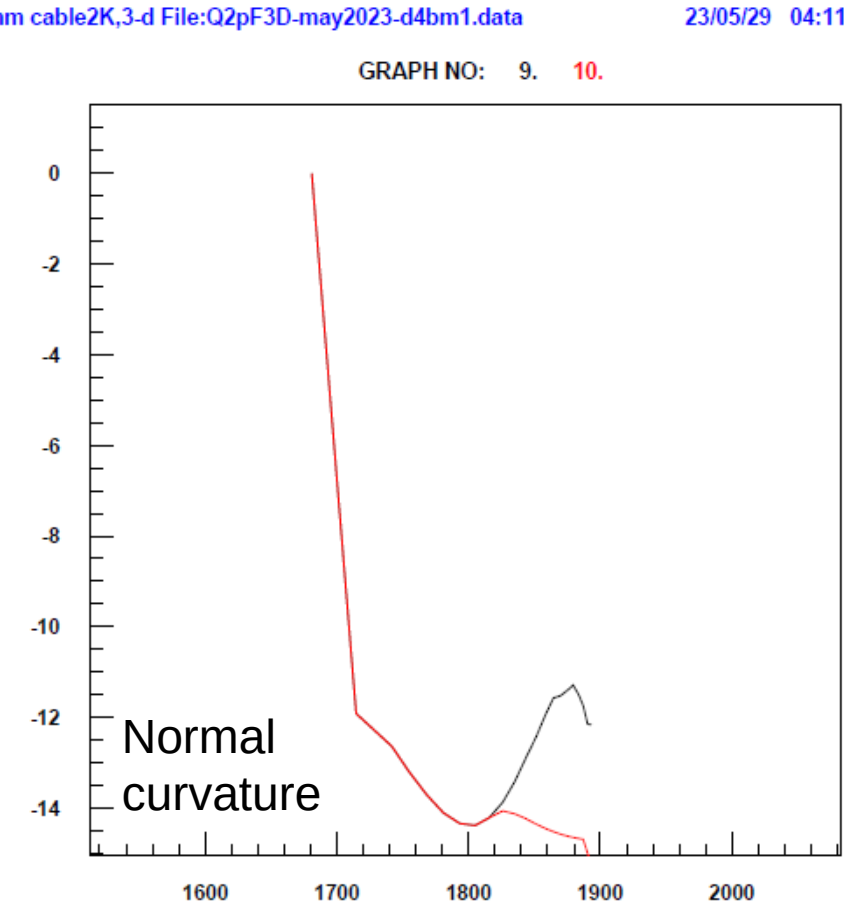
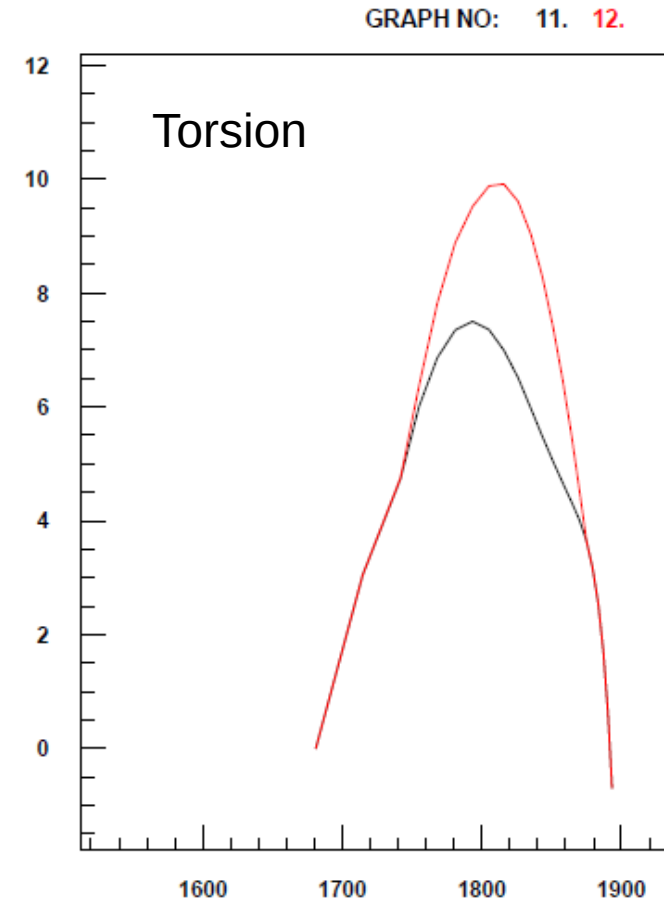
Q2pF3D-may2023-d4bm1.pdf

Mechanical Properties of the First turn of the Initial End Geometry for 65+ Degrees Tilt Angles







7	3D coil	ARCLC	0	0	CGEODE	1	0	7
8	3D coil	ARCLC	0	0	BGEODE	1	0	7
9	3D coil	ARCLC	0	0	CNORMA	1	0	8
10	3D coil	ARCLC	0	0	BNORMA	1	0	8
11	3D coil	ARCLC	0	0	CTORS	1	0	9
12	3D coil	ARCLC	0	0	BTORS	1	0	9

CTORS	Torsion
CNORMA	Normal curvature
CGEODE	Geodesic curvature
BTORS	Maximum torsion in block
BNORMA	Maximum normal curvature in block
BGEODE	Maximum geodesic curvature in block

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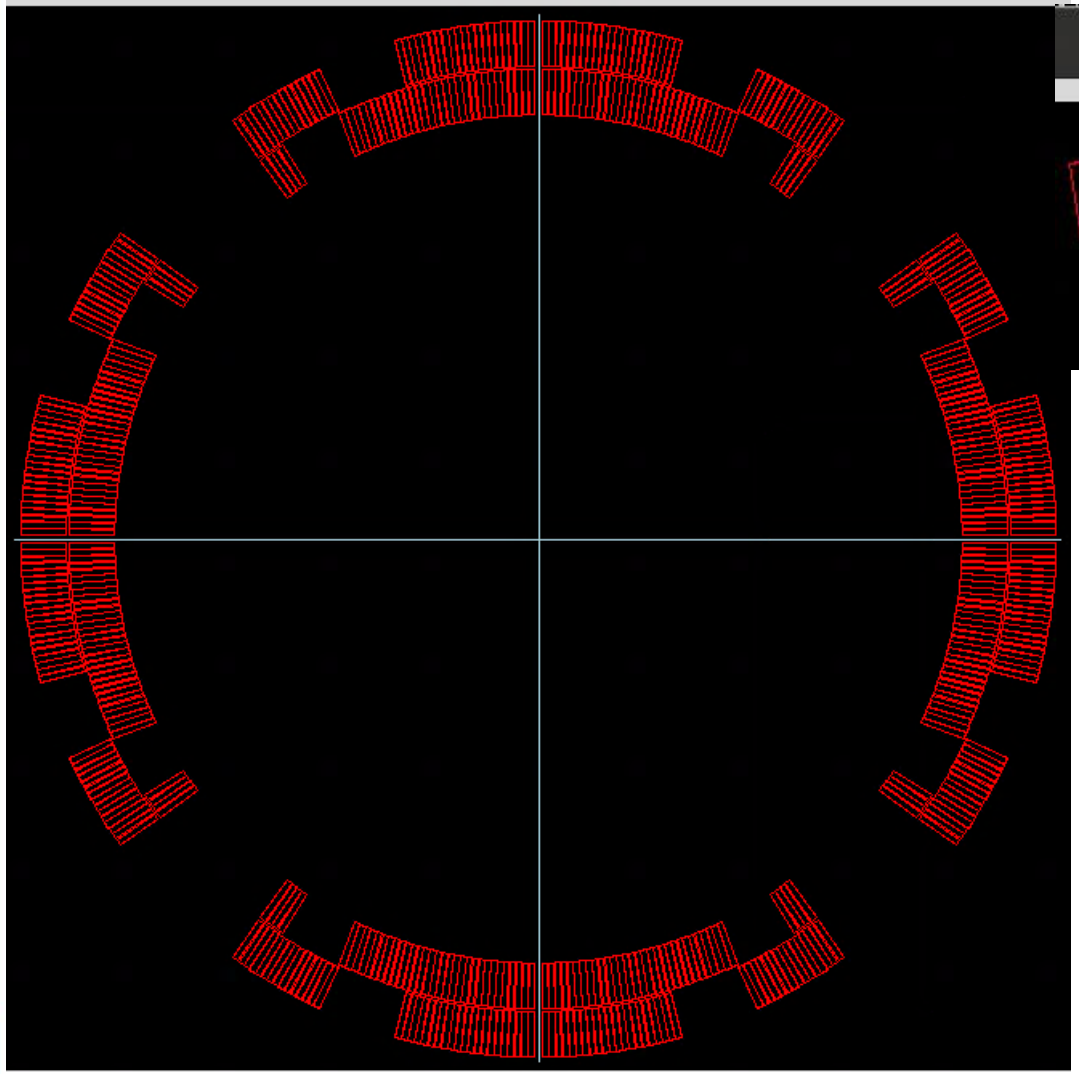
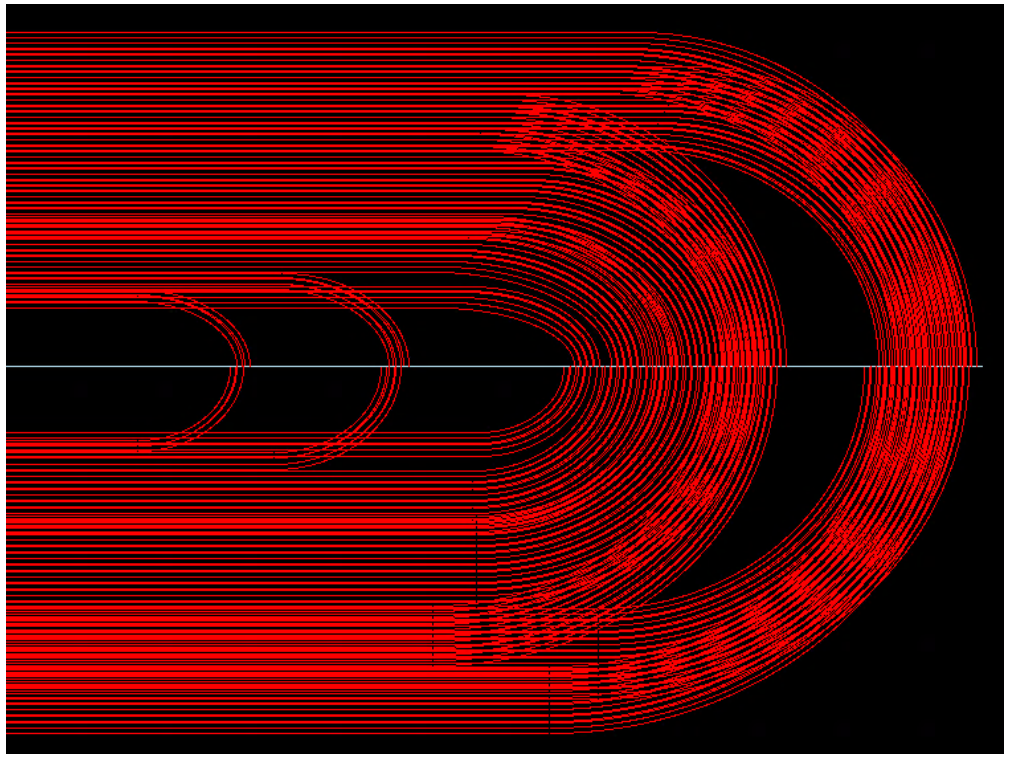
Tilt Angle of 70 degrees from midplane (20 degree from pole)

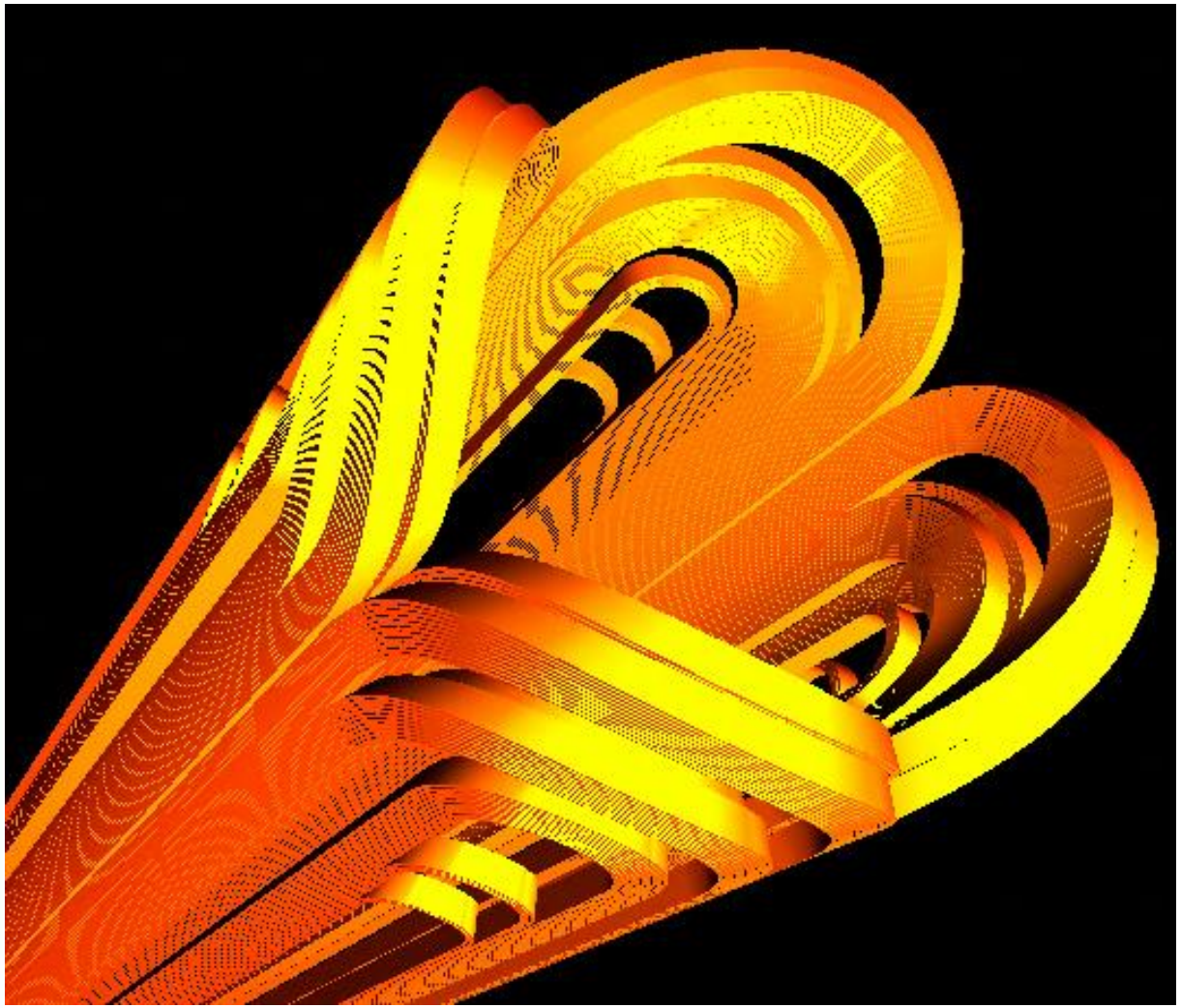
Initial Manually Optimized End Geometry (tilt angles 70 degrees or more , 20° from pole)

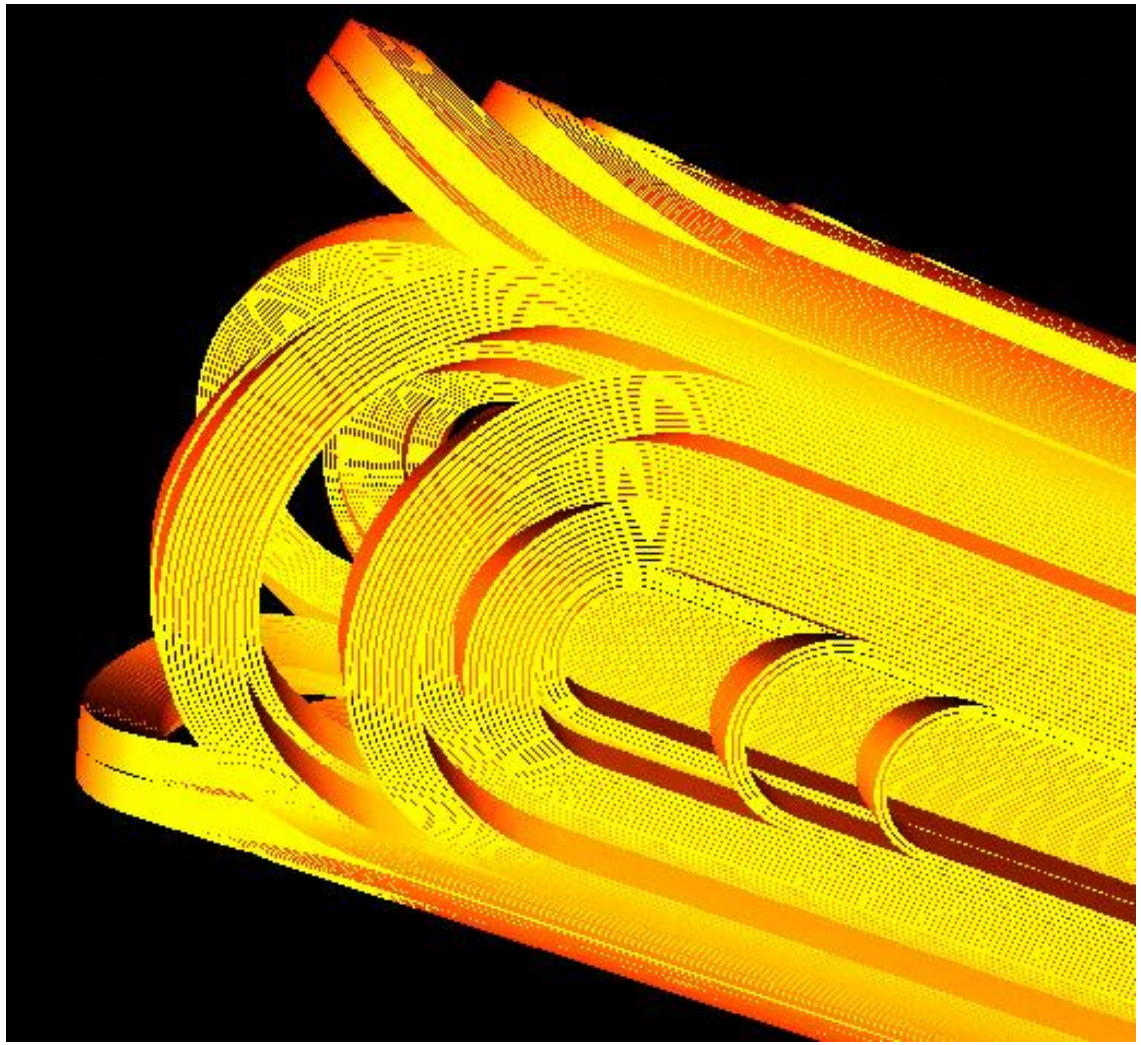




Ends of the two layers are well aligned

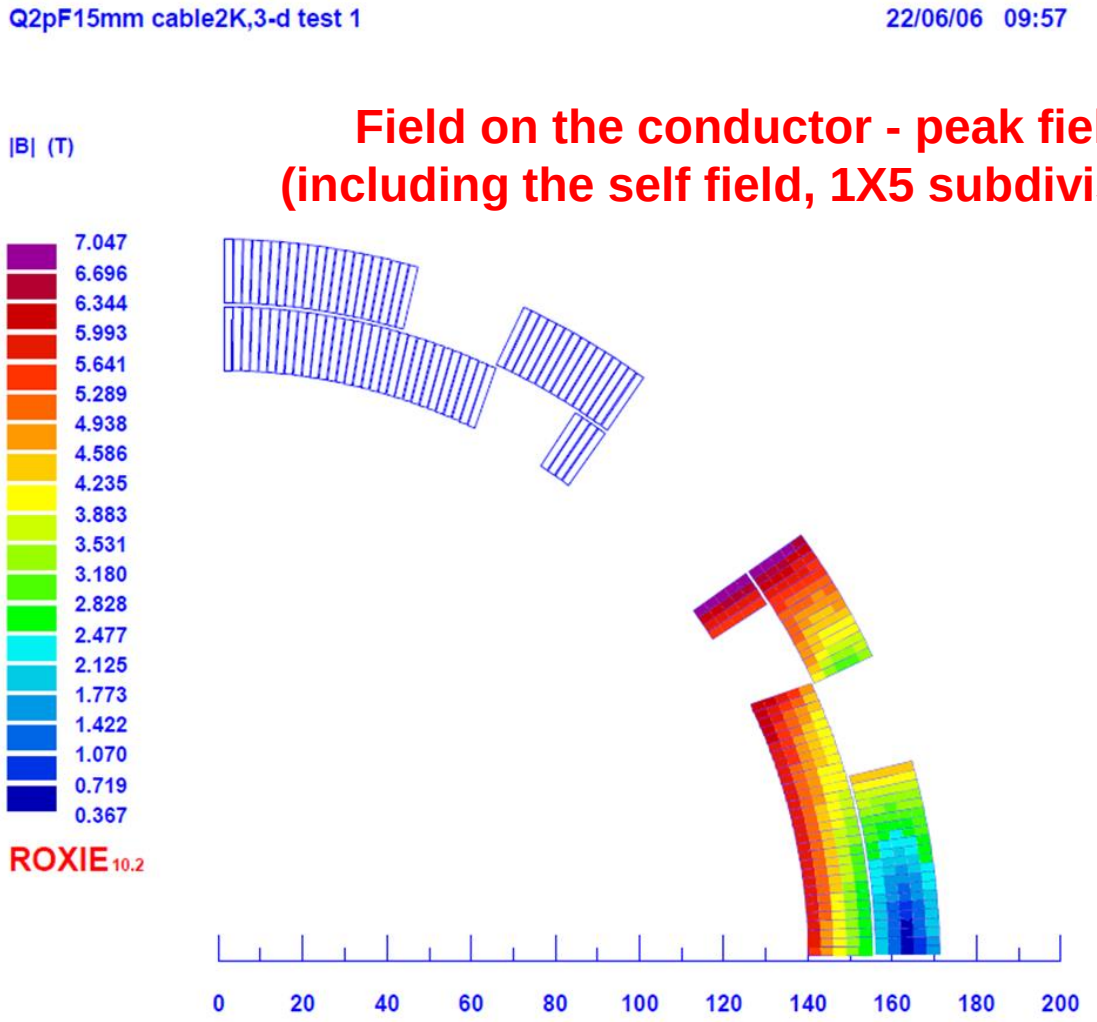
Views on Initial End Geometry (70º)





Peak Field in the Body of the Magnet

Peak field in 2-d 7.047 T



Field on the conductor - peak field (including the self field, 1X5 subdivision)

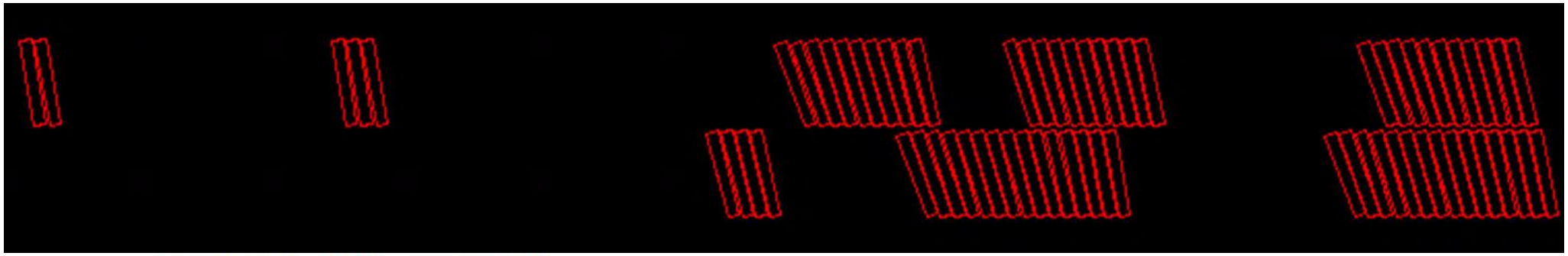
Peak Field in the Ends (70º)

- Peak field in the body (including self field) : 7.05 T
- **Peak field in the ends (including self field): 7.07 T**

✓**Peak field in the Ends is close to the field in cross-section**

```
RESULTS OF THE 3D PEAK FIELD CALCULATION
BLOCK NUMBER ..........................................        11

B  ABSOLUTE IN TESLA ..................................    7.0729
B  TRANSVERSAL TO CURRENT DIRECTION (T) ...............    7.0729
B  IN DIRECTION OF CURRENT (T) ........................   -0.0238
B  PARALLEL TO BROAD SIDE OF CABLE (T) ................    7.0280
B  PERPENDICULAR TO BROAD SIDE OF CABLE (T).............   -0.7887
NUMBER OF CONDUCTOR WITH PEAKFIELD .....................      70
```

All other blocks have lower peak fields



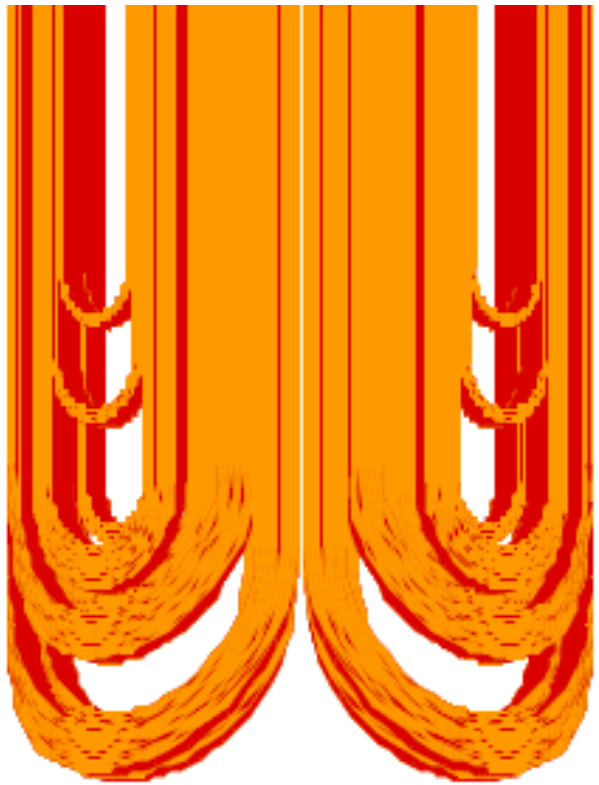
Integrated Field Harmonics (70°)

```
HARMONIC ANALYSIS NUMBER ..............................          1
MAIN HARMONIC .........................................          2
REFERENCE RADIUS (mm) .................................       83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..................        0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..................        0.0000
NUMBER OF ANALYSES ALONG Z ............................        500
LENGTH OF VIRTUAL COIL (mm) ...........................     2500.0000
REFERENCE POSITION NUMBER .............................         10
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ......................   0.6683E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

3D REFERENCE MAIN FIELD (T) ...........................        3.4693
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ................       41.7992
MAGNETIC LENGTH (mm) ..................................     1721.1688

NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
b 1:       0.00000  b 2:   10000.00000  b 3:       0.00000
b 4:       0.00000  b 5:       0.00000  b 6:      -0.01952
b 7:      -0.00000  b 8:      -0.00000  b 9:      -0.00000
b10:      -0.22372  b11:       0.00000  b12:       0.00000
b13:      -0.00000  b14:      -0.52159  b15:      -0.00000
b16:      -0.00000  b17:       0.00000  b18:       0.01163
b19:      -0.00000  b20:      -0.00000  b
--  Q2pF3D-may2023-c4c.output    90% L11100  (Fundamental)
```

Reasonably good (even better) solution for manual optimization

Views on Initial End Geometry (70º)

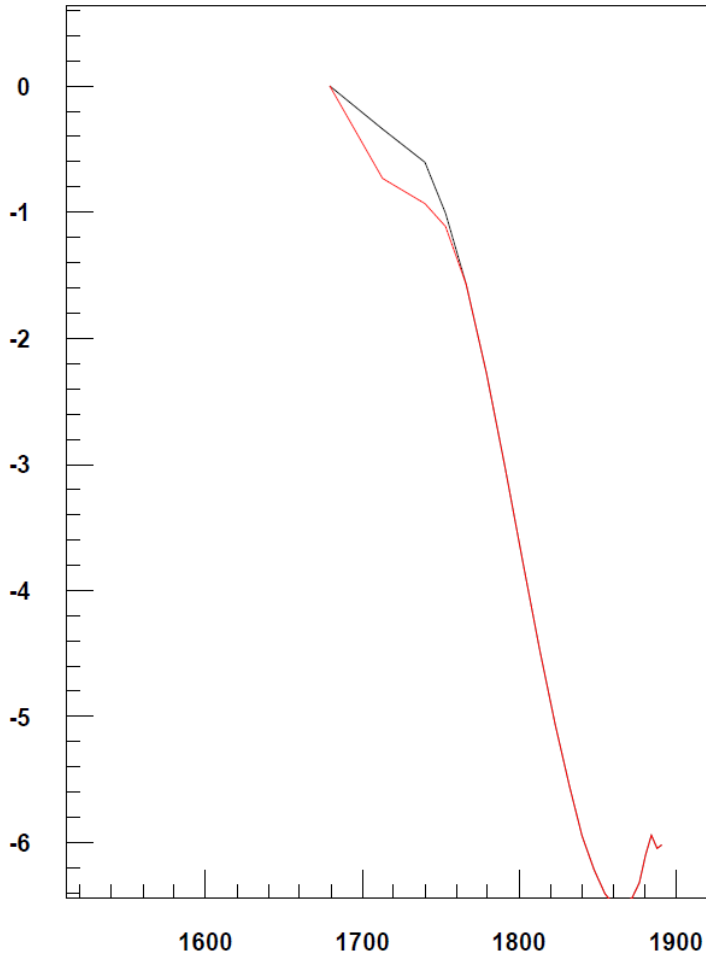
Q2pF3D-may2023-c4cm1.pdf -

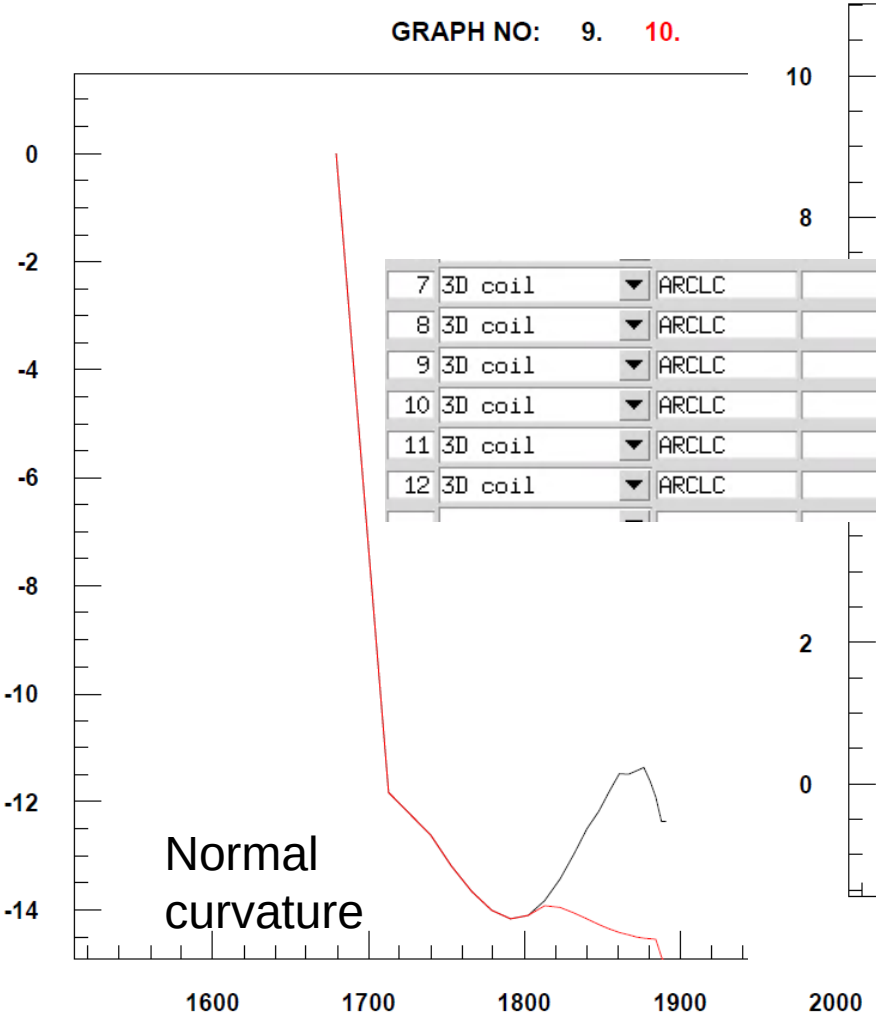


Q2pF3D-may2023-c4cm1.pdf -

Mechanical Properties of the Initial End Geometry for 70+ Degrees Tilt Angles

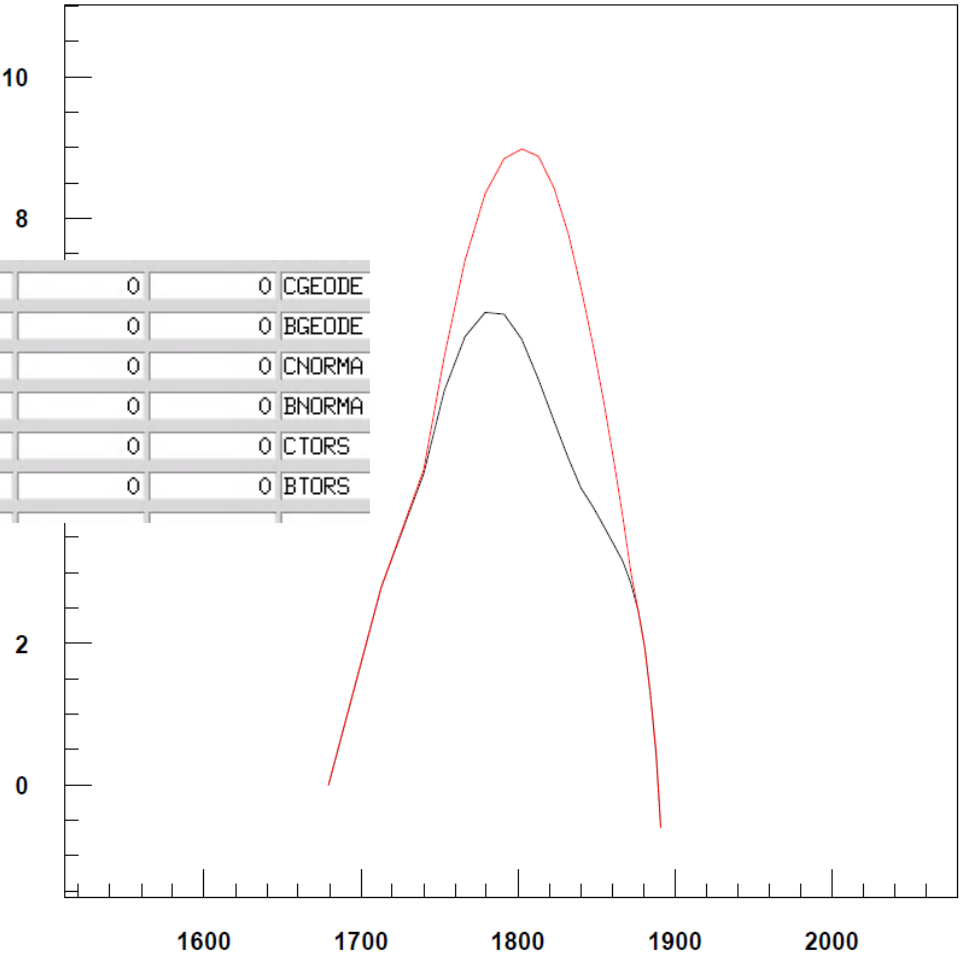
Geodesic





7	3D coil	ARCLC	0	0	CGEODE
8	3D coil	ARCLC	0	0	BGEODE
9	3D coil	ARCLC	0	0	CNORMA
10	3D coil	ARCLC	0	0	BNORMA
11	3D coil	ARCLC	0	0	CTORS
12	3D coil	ARCLC	0	0	BTORS

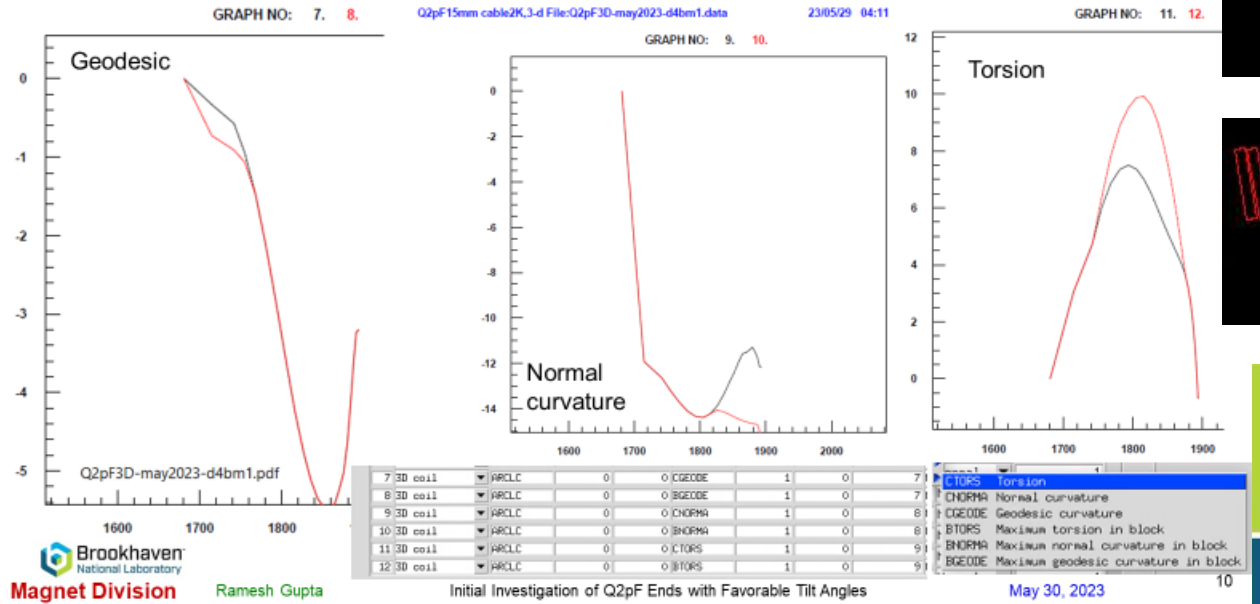
Torsion



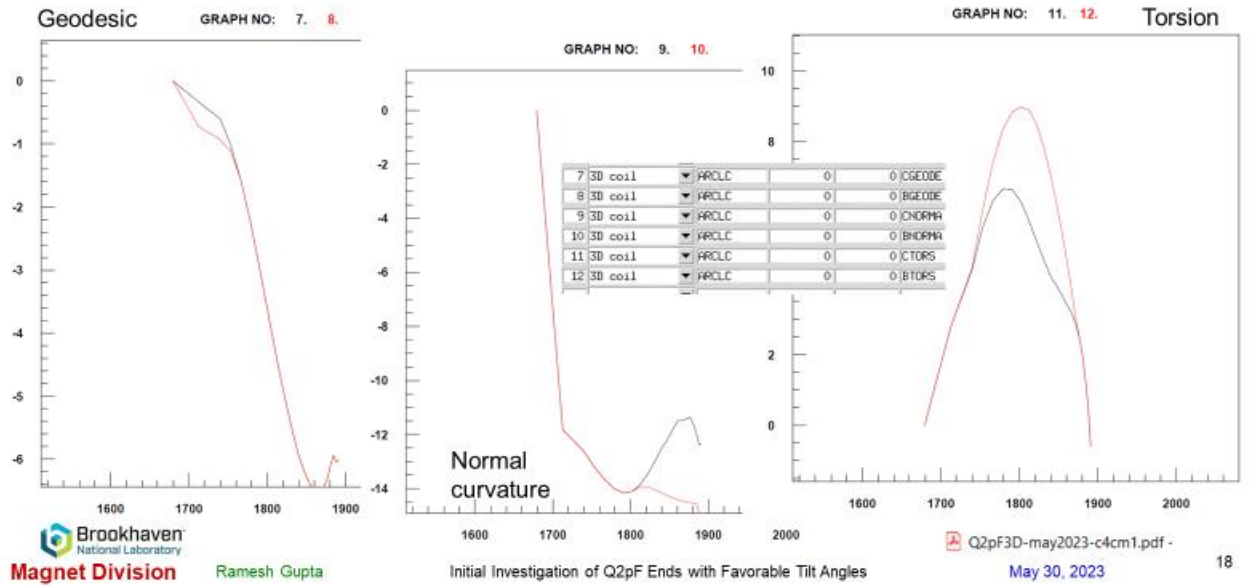
Q2pF3D-may2023-c4cm1.pdf -

Comparison between 65 degrees & 70 Degrees Tilt Angles

Mechanical Properties of the First turn of the Initial End Geometry for 65+ Degrees Tilt Angles



Mechanical Properties of the Initial End Geometry for 70+ Degrees Tilt Angles

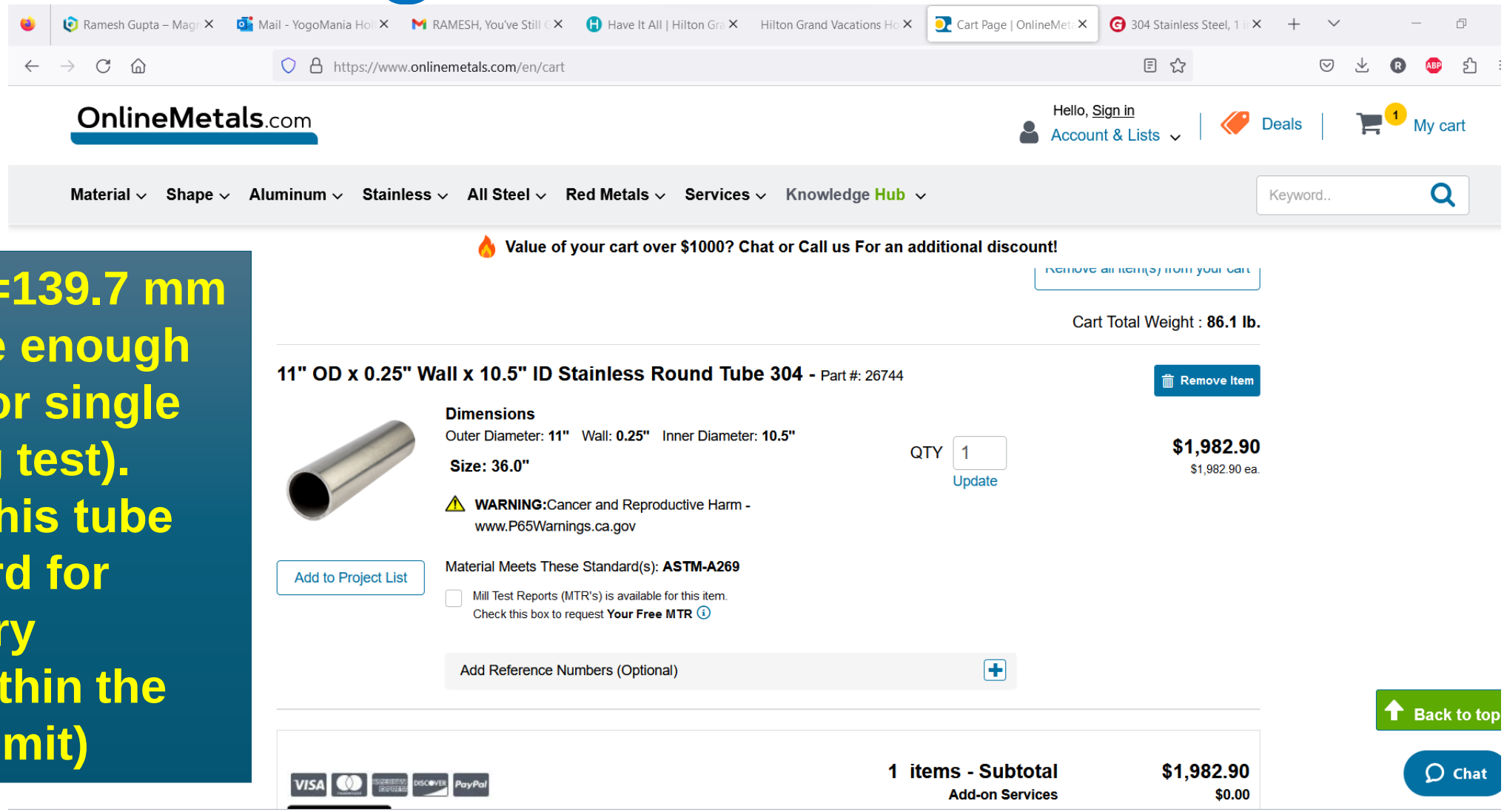


- **Both Ends have low peak fields and a good field quality**

NOT YET OPTIMIZED MECHANICALLY

About the right size tube available

11” dia ➔ r=139.7 mm (this is close enough to 140 mm for single turn winding test). Let’s order this tube on credit card for quick delivery ($amount within the credit card limit)

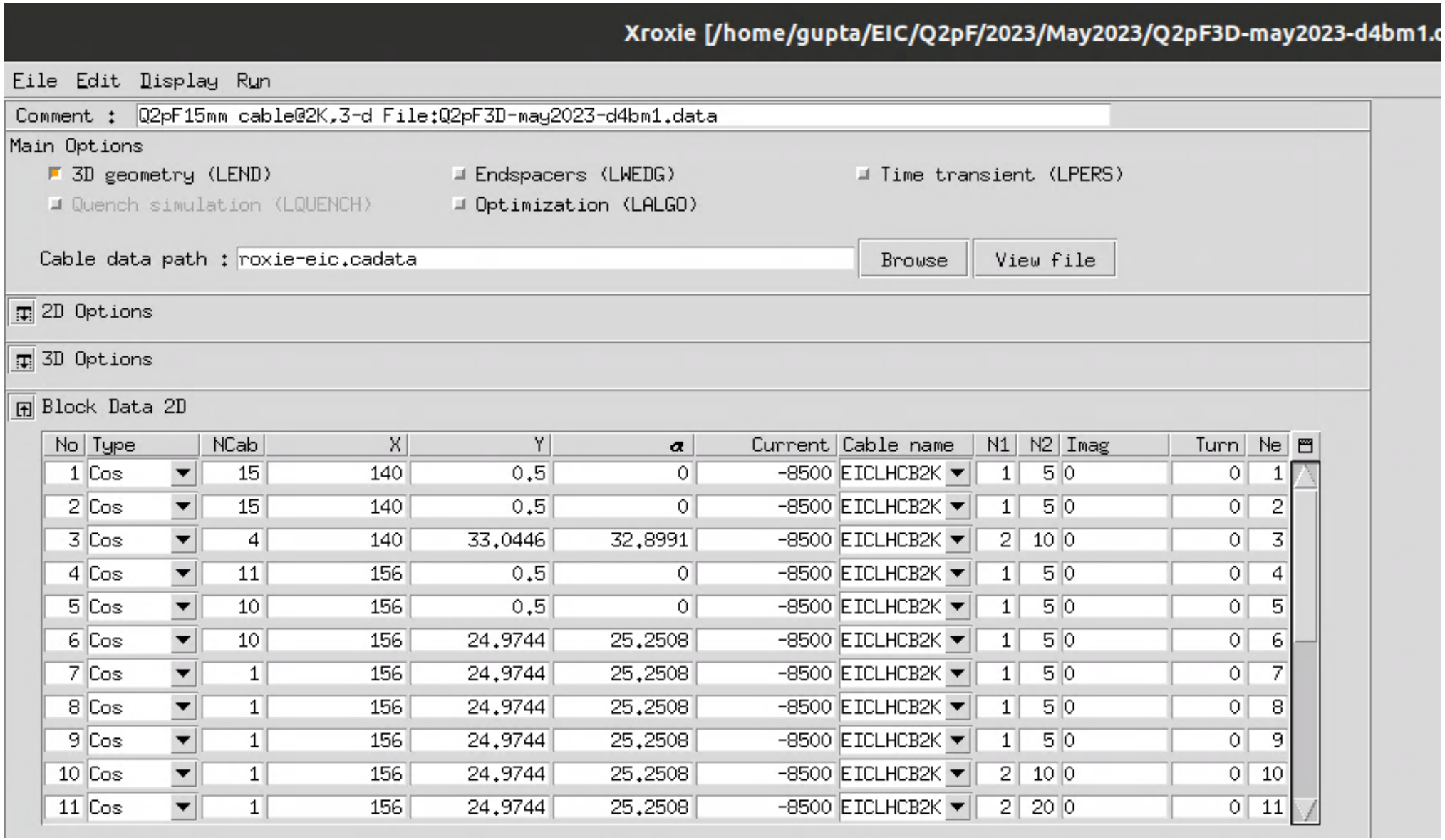


This is good enough to get idea from the single turn test on how turns are going to lay out to provide useful feedback.

Summary of Initial Look of the Manually Iterated End Design

- The results presented were developed manually for a systematic investigation to optimize a good mechanical and magnetic end design.
- This suggest that a more vertical tilt angle should be possible.
- There is no large increase in the peak fields in the ends over the body (important part of the exercise).
- Field harmonics look ok (within one unit) - may be further optimized.
- Tube with a size close to what we need has been located for inner layer. Let's order it on credit card for quick delivery to get started.
- Tube for the outer layer can also be ordered or made with SS sheet.
- Suggest that we do (limited) winding tests for both layers but limit the curing test to one layer only.

Cross-section (Block 2D Data) of Q2pF



No	Type	NCab	X	Y	α	Current	Cable name	N1	N2	Imag	Turn	Ne
1	Cos	15	140	0.5	0	-8500	EICLHCB2K	1	5	0	0	1
2	Cos	15	140	0.5	0	-8500	EICLHCB2K	1	5	0	0	2
3	Cos	4	140	33.0446	32.8991	-8500	EICLHCB2K	2	10	0	0	3
4	Cos	11	156	0.5	0	-8500	EICLHCB2K	1	5	0	0	4
5	Cos	10	156	0.5	0	-8500	EICLHCB2K	1	5	0	0	5
6	Cos	10	156	24.9744	25.2508	-8500	EICLHCB2K	1	5	0	0	6
7	Cos	1	156	24.9744	25.2508	-8500	EICLHCB2K	1	5	0	0	7
8	Cos	1	156	24.9744	25.2508	-8500	EICLHCB2K	1	5	0	0	8
9	Cos	1	156	24.9744	25.2508	-8500	EICLHCB2K	1	5	0	0	9
10	Cos	1	156	24.9744	25.2508	-8500	EICLHCB2K	2	10	0	0	10
11	Cos	1	156	24.9744	25.2508	-8500	EICLHCB2K	2	20	0	0	11

Input for beta 65 or more (magnetic)

Xroxie [/home/gupta/EIC/Q2pF/2023/May2023/Q2pF3D-may2023-d4b

File Edit Display Run

Comment : Q2pF15mm cable@2K,3-d File

Main Options

3D geometry (LEND) | Endspacers (LWEDG) | Time transient (LPERS)

Quench simulation (LQUENCH) | Optimization (LALGO)

Cable data path : roxie-eic.cadata | Browse | View file

2D Options

3D Options

Block Data 2D

Block Data 3D

Ne	Type	A	Bo	zo	Wi	Wo	Hwed	Horder
1	Diff. Geometry f	65	1.1	1140	0.28	0.28	15	2.2
2	Diff. Geometry f	65	1.2	1100	0.28	0.28	15	2.2
3	Diff. Geometry f	65	1.3	1670	0.28	0.28	15	2.3
4	Diff. Geometry f	65	1.1	1100	0.28	0.28	15	2
5	Diff. Geometry f	67	1.15	1150	0.28	0.28	15	2
6	Diff. Geometry f	65	1.2	1100	0.28	0.28	15	2
7	Diff. Geometry f	75	1.25	1530	0.28	0.28	15	2
8	Diff. Geometry f	75	1.25	1530	0.28	0.28	15	2
9	Diff. Geometry f	75	1.25	1530	0.28	0.28	15	2
10	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2
11	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2

No	Xl	Xu	Xs	String	Act	N/a
1	1100	1700	1652	Z0	2	3
2	1000	1700	1530	Z0	2	11
3	20	50	37	DZZR	2	1
4	10	40	23.7173	DZZR	2	2
5	10	60	37	DZZR	2	4
6	10	30	14.6026	DZZR	2	5
7	10	80	70.6626	DZZR	2	6
8	0	60	0.5	DZZR	2	7
9	0	60	0.5	DZZR	2	8
9	0	60	50	DZZR	2	9
10	0	50	0.5	DZZR	2	10
11	0	0	0	PHIR	2	2
12	0	0	0	ALPHR	2	2
13	0	0	0	PHIR	2	5
14	65	65	65	BETA	2	2
15	0	0	0	ALPHR	2	5
16	2	2	2	HORDER	2	2
17	0	0	0	PHIR	2	7-11
18	0	0	0	ALPHR	2	7-11

Xroxie [/home/gupta/EIC/Q2pF/2023/May2023/Q2pF3D-may2023-d4b.data]

Input for beta 70 degrees or more

Xroxie [/home/gupta/EIC/Q2pF/2023/May2023/Q2pF3D-may2023-c4cm1.

e Edit Display Run

mment : Q2pF15mm cable@2K,3-d File:Q2pF3D-23aug2022.data

n Options

3D geometry (LEND) | Endspacers (LWEDG) | Time transient (LPERS)

Quench simulation (LQUENCH) | Optimization (LALGO)

Cable data path : roxie-eic.cadata | Browse | View file

2D Options

3D Options

Block Data 2D

Block Data 3D

Ne	Type	A	Bo	zo	Wi	Wo	Hwed	Horder
1	Diff. Geometry f	70	1.1	1140	0.28	0.28	15	2.2
2	Diff. Geometry f	73	1.2	1100	0.28	0.28	15	2.2
3	Diff. Geometry f	75	1.3	1670	0.28	0.28	15	2.3
4	Diff. Geometry f	70	1.1	1100	0.28	0.28	15	2
5	Diff. Geometry f	72	1.15	1150	0.28	0.28	15	2
6	Diff. Geometry f	70	1.2	1100	0.28	0.28	15	2
7	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2
8	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2
9	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2
10	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2
11	Diff. Geometry f	80	1.25	1530	0.28	0.28	15	2

Design Variables

Optimization algorithm : 1 Extrem

No	Xl	Xu	Xs	String	Act	N/a
1	1100	1700	1651	Z0	2	3
2	1000	1700	1530	Z0	2	11
3	20	50	37	DZZR	2	1
4	10	40	23.7173	DZZR	2	2
5	10	60	37	DZZR	2	4
6	10	30	14.6026	DZZR	2	5
7	10	80	70.6626	DZZR	2	6
8	0	60	0.5	DZZR	2	7
9	0	60	0.5	DZZR	2	8
9	0	60	50	DZZR	2	9
10	0	50	0.5	DZZR	2	10
11	0	0	0	PHIR	2	2
12	0	0	0	ALPHR	2	2
13	0	0	0	PHIR	2	5
14	70	70	70	BETA	2	2
15	0	0	0	ALPHR	2	5
16	2	2	2	HORDER	2	2
17	0	0	0	PHIR	2	7-11
18	0	0	0	ALPHR	2	7-11

[/home/gupta/EIC/Q2pF/2023/May2023/Q2pF3D-may2023-c4cm1.data]

Input for mechanical plots

Graph

No	Type	X value	N/a	N/a	Y value	N/a	N/a	Plot number
1	3D coil	ARCLC	0	0	CGEODE	1	0	1
2	3D coil	ARCLC	0	0	BGEODE	1	0	2
3	3D coil	ARCLC	0	0	CNORMA	1	0	3
4	3D coil	ARCLC	0	0	BNORMA	1	0	4
5	3D coil	ARCLC	0	0	CTORS	1	0	5
6	3D coil	ARCLC	0	0	BTORS	1	0	6
7	3D coil	ARCLC	0	0	CGEODE	1	0	7
8	3D coil	ARCLC	0	0	BGEODE	1	0	7
9	3D coil	ARCLC	0	0	CNORMA	1	0	8
10	3D coil	ARCLC	0	0	BNORMA	1	0	8
11	3D coil	ARCLC	0	0	CTORS	1	0	9
12	3D coil	ARCLC	0	0	BTORS	1	0	9

3D Options

3D Fields & forces in coi

Additional bricks (LBRICK

More options :

No	String	Value
1	WRLWH	0

[/home/gupta/EIC/Q2pF/2023/May2023/Q2pF3D-may2023-c4cm1.data]

Plotting 3D

3D min. field in cond. (LROLER2) 3D max. field in cond. (LROLERP)

No	z-axis	Colour	4quad	View	Group	Field
1	3000	Colour	Yes	1 Isometric front	0	COIL SUN
2	3000	Colour	Yes	1 Isometric front	0	COIL B
3	3000	Colour	Yes	2 Isometric back	0	COIL SUN
4	3000	Colour	Yes	2 Isometric back	0	COIL B
5	3000	Colour	Yes	3 Isometric front	0	COIL SUN
6	3000	Colour	Yes	3 Isometric front	0	COIL B
7	4000	Colour	Yes	4 Top elevation	0	COIL SUN
8	4000	Colour	Yes	4 Top elevation	0	COIL B