Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Progress in Q2pF End Design

Ramesh Gupta

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Background

- Previous Q2pF Ends were designed for a different cross-section, with different number of turns & with a slightly different cable. This is the first go at the Ends for cross-section with perfectly symmetric wedges.
- The attempt will be to satisfy the same goals as in the earlier design:
  - ➢ Peak field in Ends remain close to the 2-d peak field in the X-section.
  - ➢ Small integrated harmonics.
  - ➢ End turn layout should be as vertical as possible at pole (kept 70^{o} in all cases) and layout looking visually reasonable before printing 3-d parts to try different variations. We will follow the useful experience from the single turn winding test of B1pF.

LHC Style Cable used in Quad & Dipole (based on full keystone for Q2pF and B1ApF)

EIC

LHC

Cable Geometry

No	Name	height	width_i	width_o	ns	transp.	degrd	Comment
1	EICLHCB	15.1	1.816	1.984	28	115	5	LHC IN KEYSTOE FOR EIC DIPOLE
1	EICLHCQ	15.1	1.79	2.01	28	115	5	LHC IN KEYSTONE FOR EICIR QUAD
1	EICLHC01	15.1	1.786	2.014	28	115	5	LHC CABLE KEYSTOR FOR EIC 4.2K
2	EIC3642	19.4	1.773	2.027	36	115	3	EIC 36 STRAND 04.2K
3	EIC3618	19.4	1.773	2.027	36	115	3	EIC 36 STRAND 01.8K
4	EIC3642A	19.4	1.788	2.012	36	115	3	EIC 36 STRAND 04.2K 2 Layers
5	CABLE01	15.1	1.736	2.064	28	115	5	MB INNER LAYER,STR01
6	CABLE02	15.1	1.362	1.598	36	100	5	MB OUTER LAYER,STR01
7	SINGLE	0.94	0.94	0.94	1	0	0	SINGLE STRAND
8	GSI1CAB	9.74	1.061	1.271	30	74	0	GSI001 (RHIC) CABLE
9	GSI001	9.73	1.111	1.321	30	74	0	GSI001 following Wanderer
10	20MMCABLE	20	1.736	2.172	37	0	0	20mm cable
11	20MMCBNOK	20	13.8	13.8	280	0	0	7x20mm cable, no keystone
12	20MMCAB2	20	1.8	2	37	0	0	20 mm cable 2

Cable Definition

No	Name	Cable Geom.	Strand	Filament	Insul	Trans	Quench Mat.	T_o	Comment
1	EICLHCB2K	EICLHCB	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR QUAD B2K
2	EICLHCQ2K	EICLHCQ	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR DIPOLE 6
3	LHCIN42K	EICLHC01	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	4.2	LHC INNER FOR EIC 04.2K
4	YELLONIN	CABLE01	STR01	NBTII	ALLPOLYIL	TRANS1	NONE	1.9	V6-1 DESIGN DIPOLE INNER
5	YELLONOU	CABLE02	STR02	NBTIO	ALLPOLYOL	TRANS1	NONE	1.9	V6-1 DESIGN DIPOLE OUTER

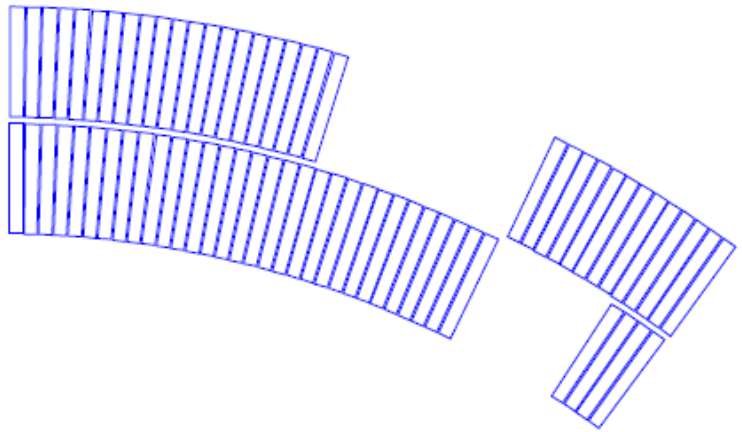
Keystone angle for cable width << coil readius		
	Q2pF	B1ApF
Cable height	15.1	15.1
Cable mid-thickness	1.9	1.9
Insul (one side)	0.12	0.12
Coil i.r.	140	185
Avg Rad	147.55	192.55
dt	0.2190	0.1678
Width_i	1.790	1.816
width_o	2.010	1.984

Note: Keystones are reduced for EIC

Cables considered for EIC: "EICLHCB2K" and "EICLHCQ2K" (EICLHCB and EICLHCQ)
Similar to LHC inner: "YELLONIN" (CABLE01)

Updated (current) Design Uses "Q" cable, instead of "B" cable

Design with Perfectly Symmetric Wedges (with EIC "Q" cable)



Looks good mechanically

2-d Field Harmonics

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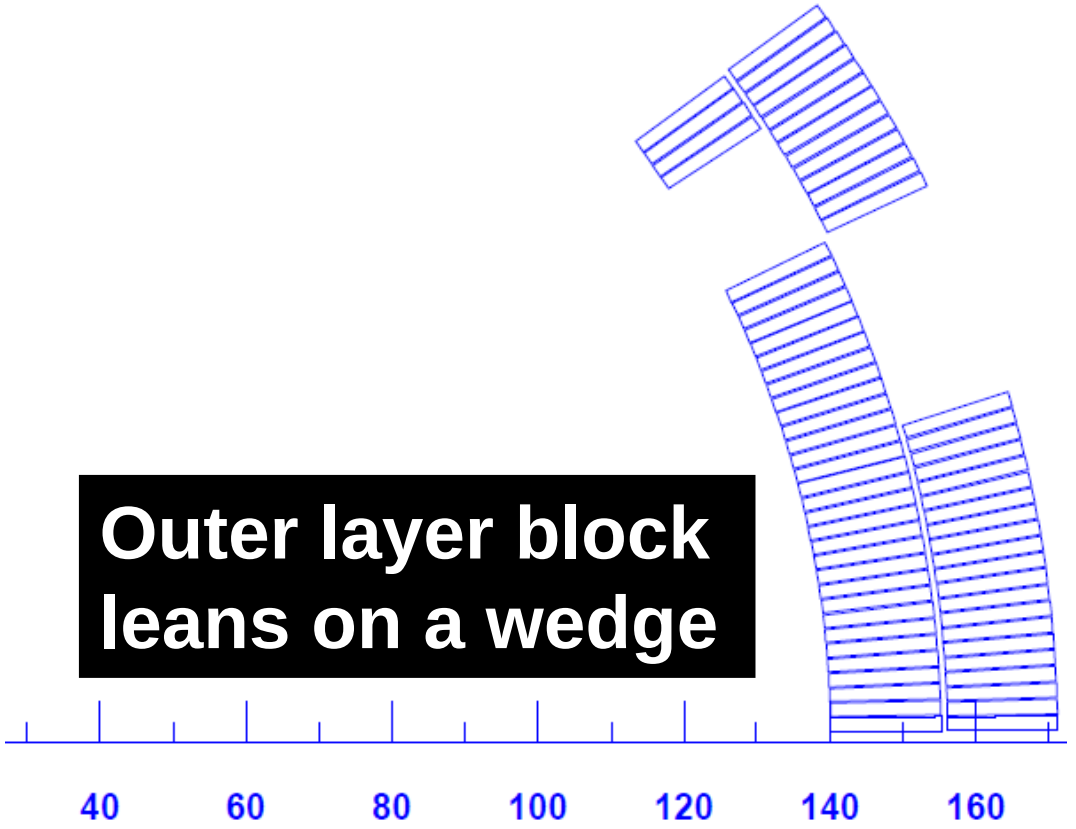
HARMONIC ANALYSIS NUMBER ..............................          1
MAIN HARMONIC ..........................................          2
REFERENCE RADIUS (mm) ..................................      83.0000
X-POSITION OF THE HARMONIC COIL (mm) ...................       0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ...................       0.0000
MEASUREMENT TYPE ..................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................... 0.6776E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

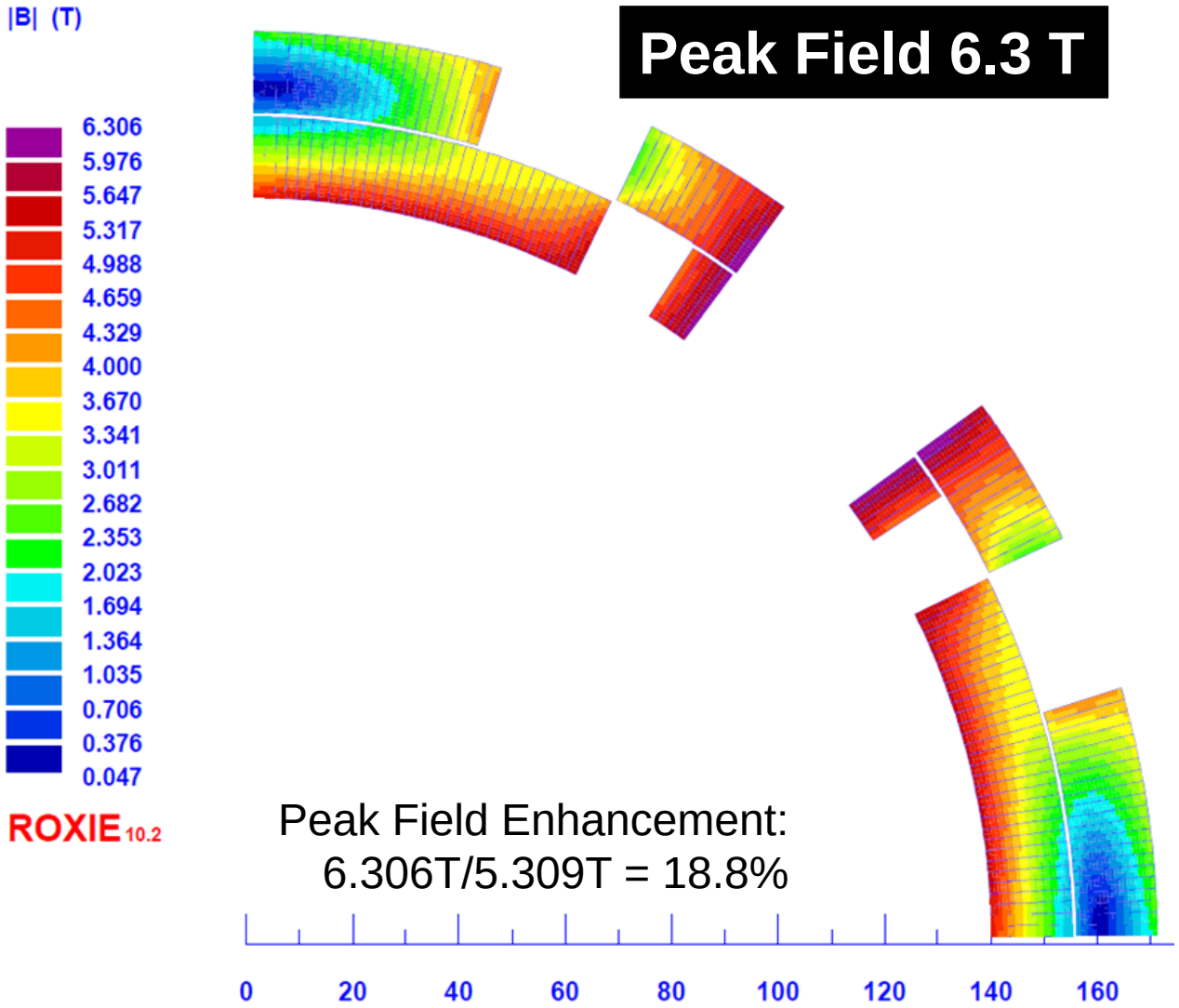
MAIN FIELD (T) .........................................   3.147502
MAGNET STRENGTH (T/(m^(n-1)) ...........................   37.9217

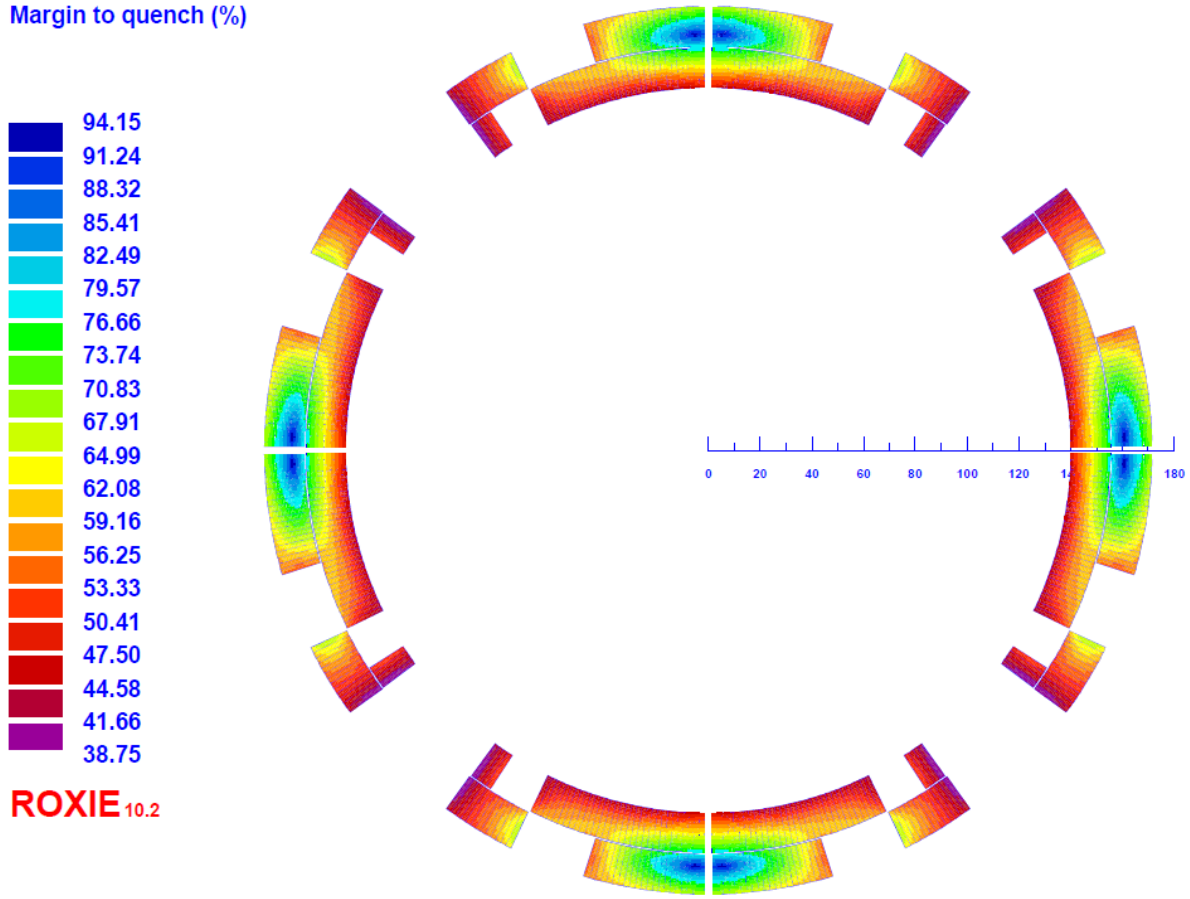
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.14254  b 2:  10000.00000  b 3:      0.00250
b 4:     -0.01577  b 5:      0.02641  b 6:     -0.10295
b 7:     -0.00201  b 8:     -0.00094  b 9:      0.00065
b10:     -0.40774  b11:     -0.00011  b12:      0.00000
b13:     -0.00002  b14:     -0.46484  b15:      0.00000
b16:     -0.00000  b17:     -0.00000  b18:      0.00550
```



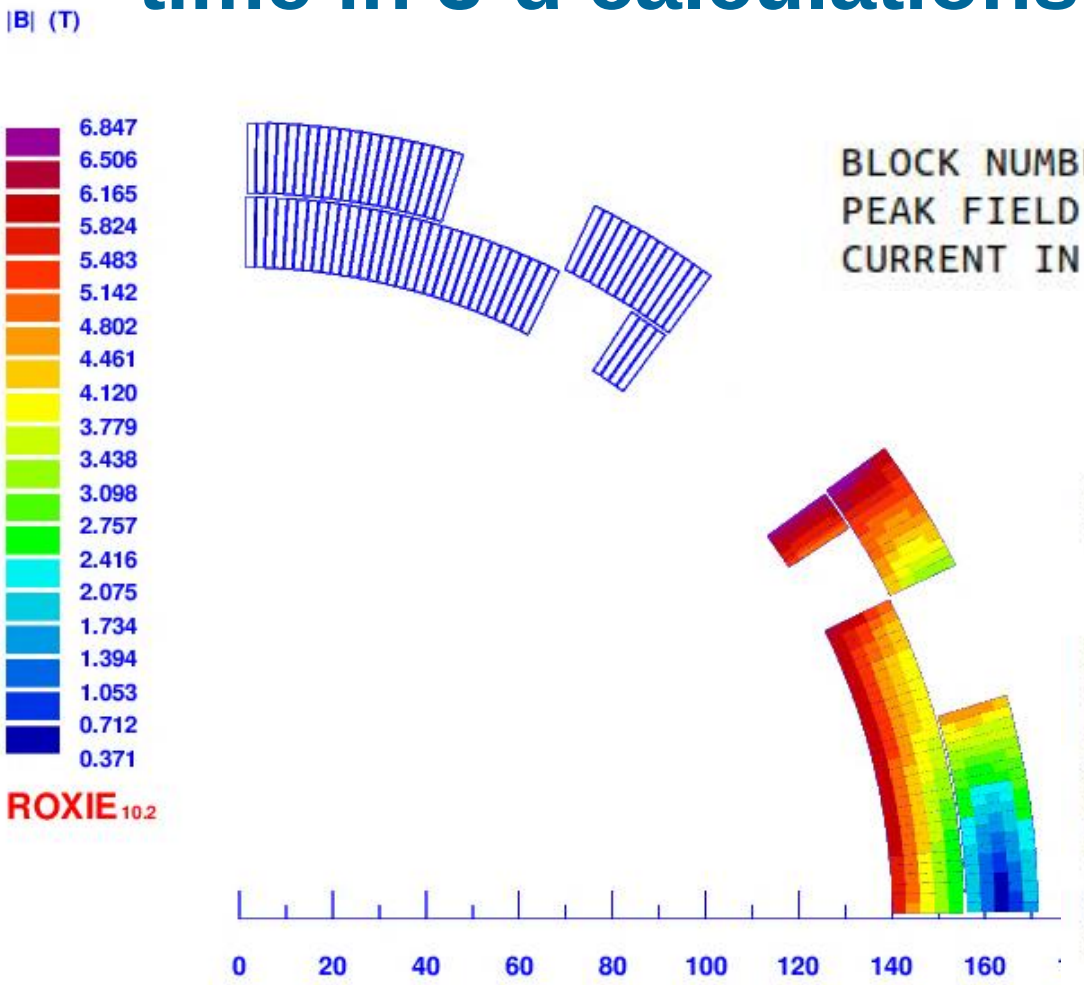
Outer layer block leans on a wedge

Peak Field and Margin in Q2pF Cross-section





Field and Peak Field in X-section for Mirror Iron (to save time in 3-d calculations while comparing with 2-d fields)

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BLOCK NUMBER ..........................................          11
PEAK FIELD IN CONDUCTOR   69 (T) ......................      6.8470
CURRENT IN CONDUCTOR  69 (A) ..........................   -8500.0000
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MAXIMUM LOADLINE IN BLOCK   11 (%) ..................      65.3012
MINIMUM TEMPERATURE MARGIN IN BLOCK   11 (T) .......      3.1931
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```
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
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ......................  0.6812E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))
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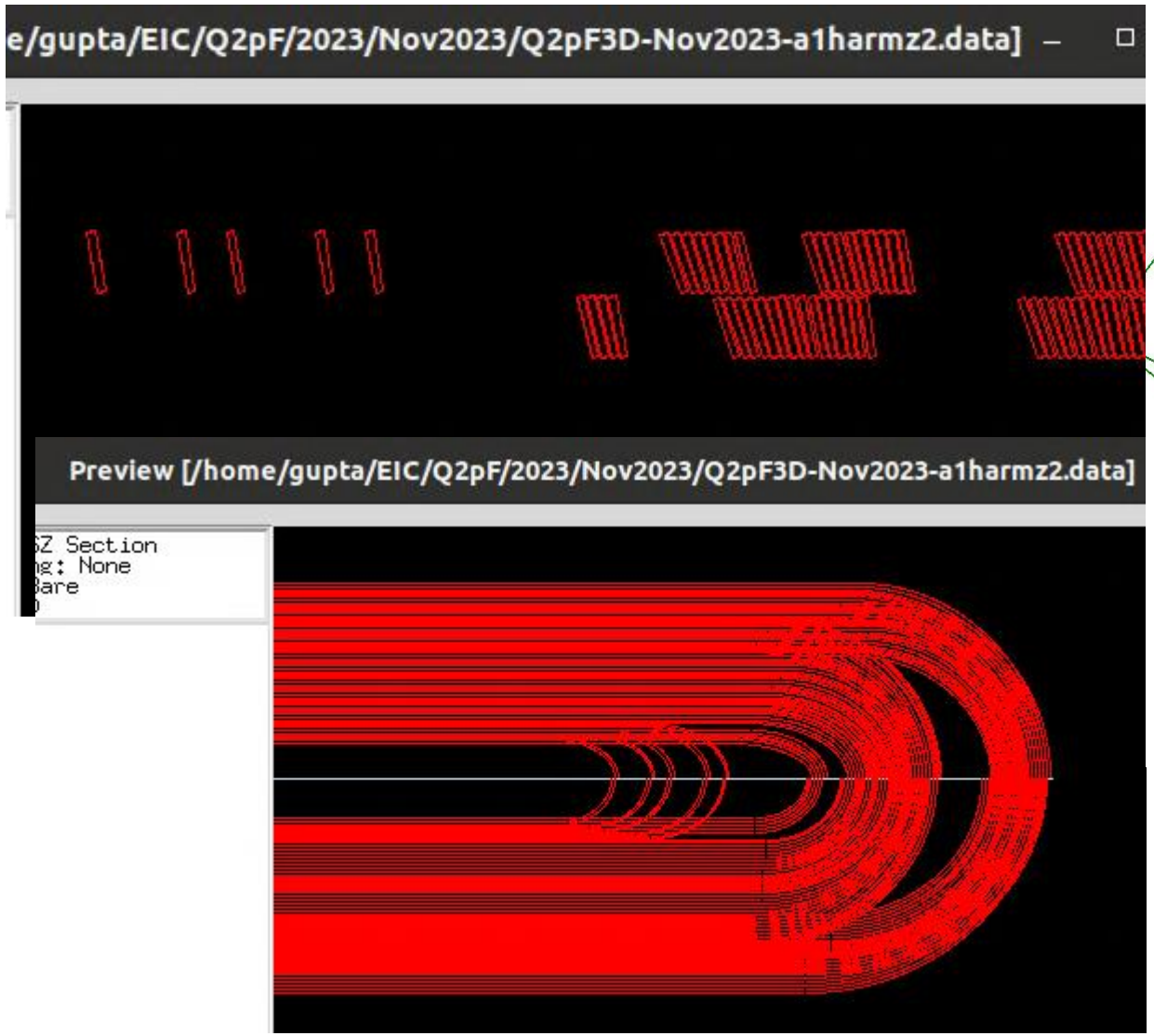
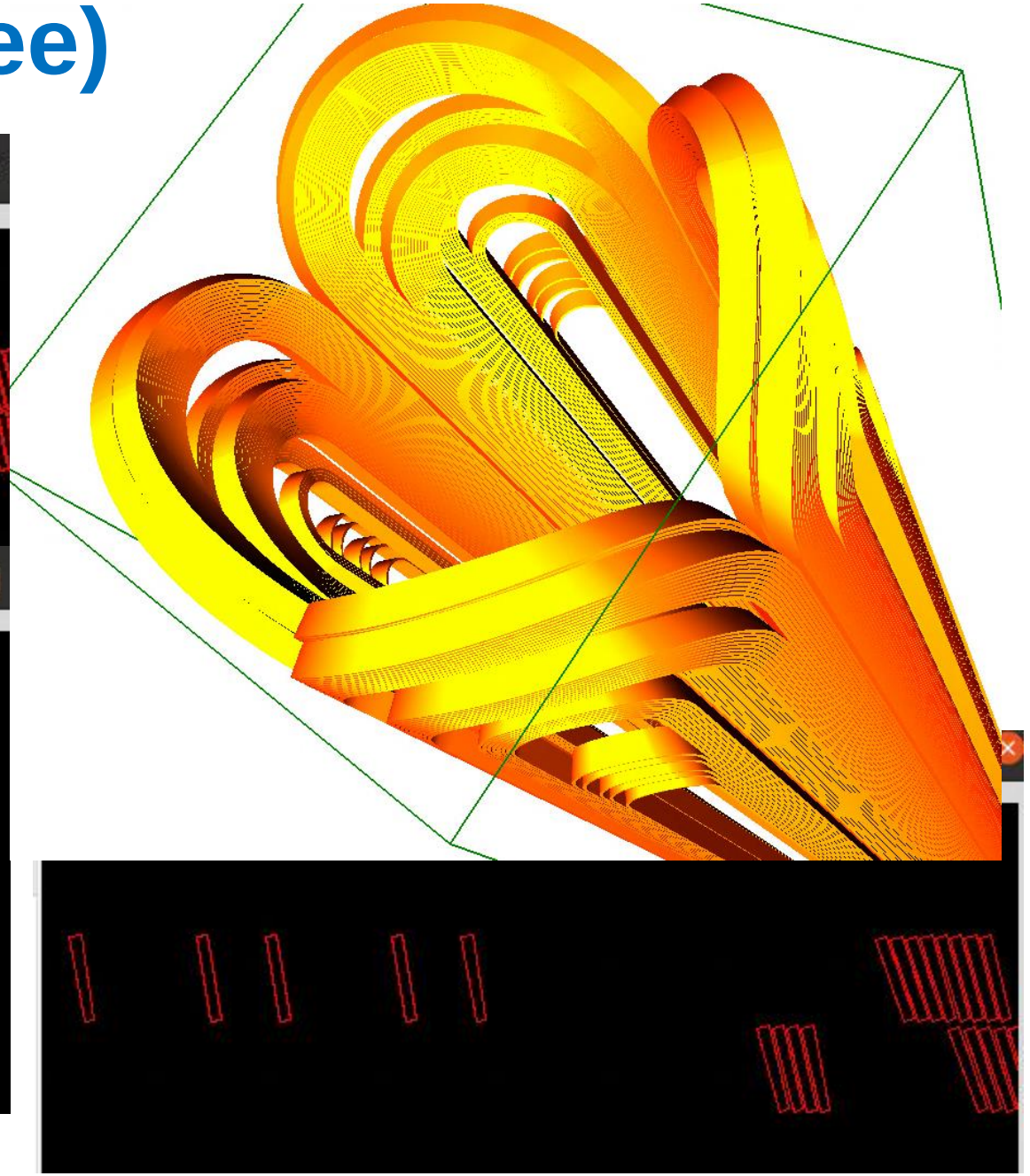
MAIN FIELD (T) ........................................      3.438369
MAGNET STRENGTH (T/(m^(n-1)) ..........................      41.4261
```

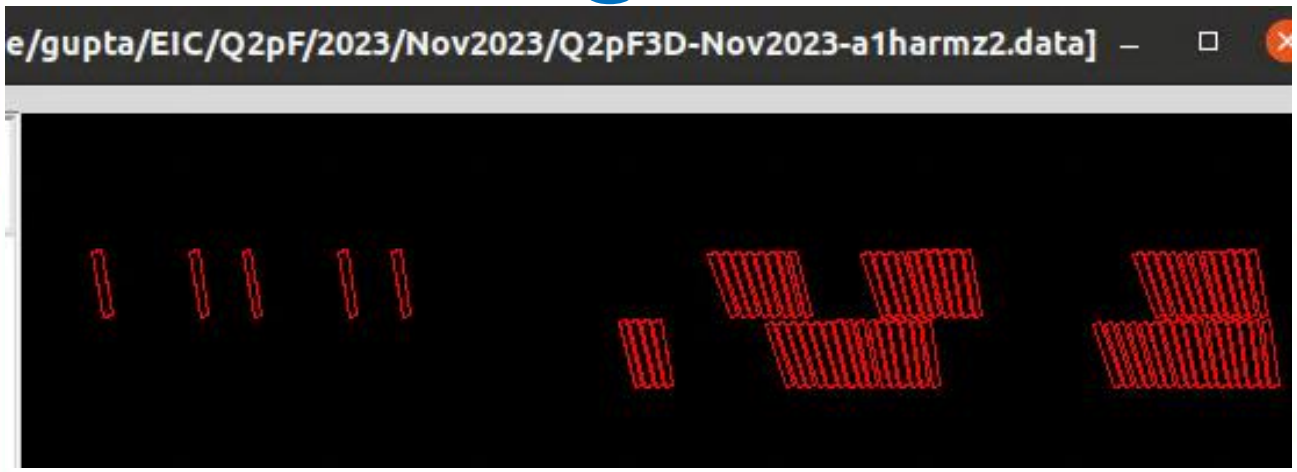
Peak Field for actual iron: 6.3 T

End Design #1 (70 degree)





End Design #1



Reasonable start:

- Field harmonics: not too large
- Peak field: 6.95 T (Vs 6.85T in 2-d)
- Tilt Angle 70 degree

About ~1.9% higher peak field than that in x-section

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MARGIN CALC (USING JC-FIT):
BLOCK NUMBER ..........................................          11
PEAK FIELD IN CONDUCTOR   69 (T) ......................      6.9503
CURRENT IN CONDUCTOR  69 (A) ..........................   -8500.0000
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -886.0233
PERCENTAGE ON THE LOAD LINE ...........................      66.0740
QUENCHFIELD (T) .......................................      10.5189
TEMPERATURE MARGIN TO QUENCH (K) ......................       3.1389
PERCENTAGE OF SHORT SAMPLE CURRENT ....................      26.8483

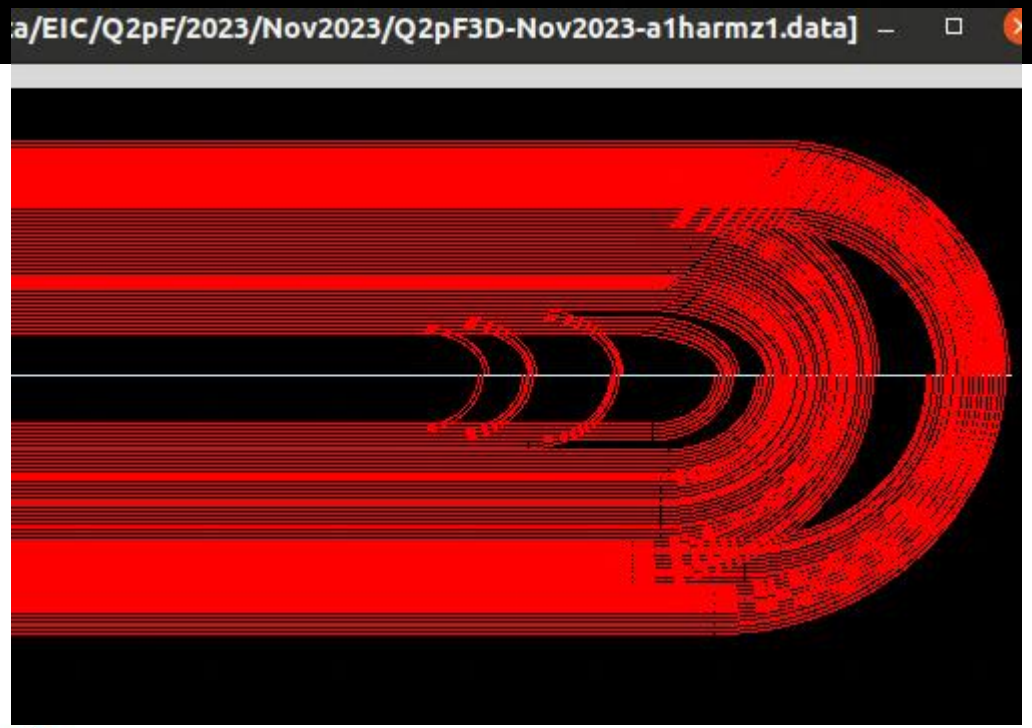
FORCES (N) IN COIL ENDS
CONDUCTOR  FX          FY          FZ        FPAR        FPER
  69    49479.701  -68505.087    1372.501    100.339   85229.112
SUMM    49479.701  -68505.087    1372.501    100.339   85229.112

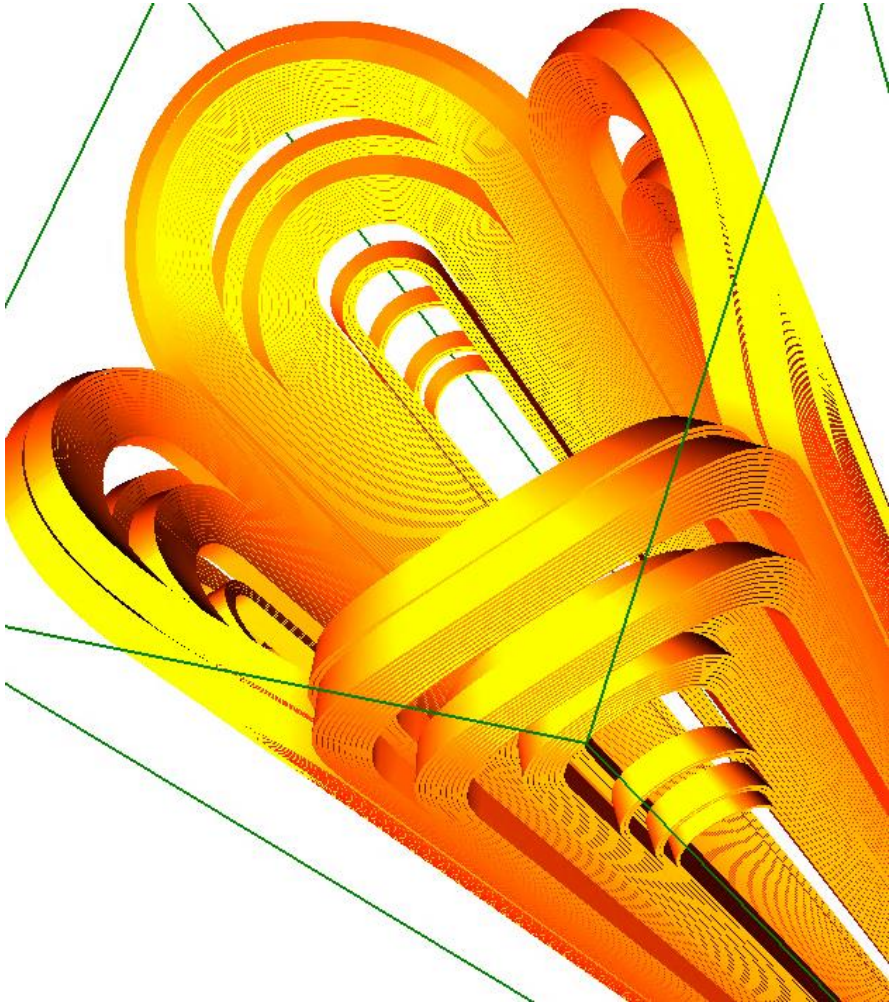

HARMONIC ANALYSIS NUMBER ..............................          1
MAIN HARMONIC .........................................          2
REFERENCE RADIUS (mm) .................................       83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..................        0.0000
Y-POSITION OF THE HARMONIC 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 ......................  0.5231E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

3D REFERENCE MAIN FIELD (T) ...........................      3.4387
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ................     41.4295
MAGNETIC LENGTH (mm) ..................................   1725.4061

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:      0.12018
b 7:      0.00000  b 8:     -0.00000  b 9:      0.00000
b10:     -0.64588  b11:      0.00000  b12:      0.00000
b13:     -0.00000  b14:     -0.42942  b15:     -0.00000
b16:     -0.00000  b17:      0.00000  b18:      0.00205
```

End Design #2 (70 degree)





End Design #2

Reasonable start:

- Field harmonics: not too large
- Peak field: 6.952T (Vs 6.85T in 2-d)
- Tilt Angle 70 degree

About ~1.9% higher peak field than that in x-section; about the same as in the previous design.

```
MARGIN CALC (USING JC-FIT):
BLOCK NUMBER ..........................................          11
PEAK FIELD IN CONDUCTOR   69 (T) ......................      6.9518
CURRENT IN CONDUCTOR  69 (A) ..........................   -8500.0000
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -886.0233
PERCENTAGE ON THE LOAD LINE ...........................      66.0855
QUENCHFIELD (T) .......................................      10.5194
TEMPERATURE MARGIN TO QUENCH (K) ......................       3.1381
PERCENTAGE OF SHORT SAMPLE CURRENT ....................      26.8566

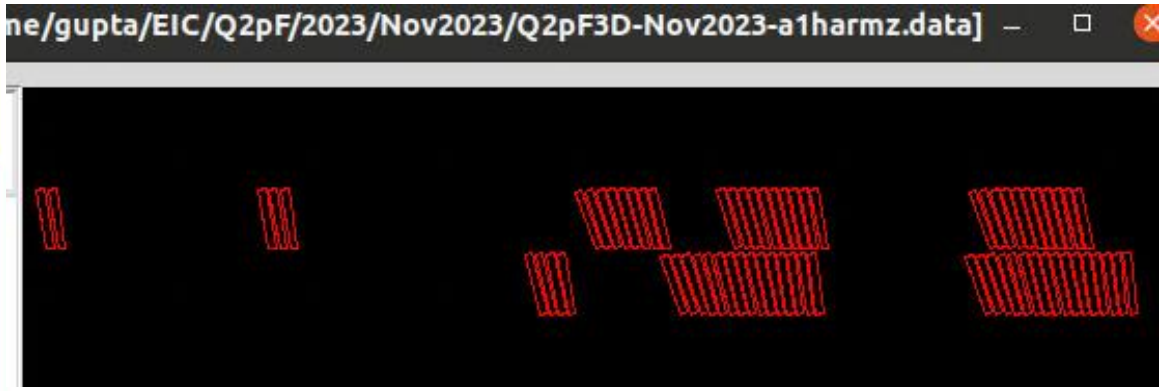
FORCES (N) IN COIL ENDS
CONDUCTOR  FX          FY          FZ        FPAR        FPER
  69    49480.650  -68506.113    1374.552    100.122   85231.765
SUMM    49480.650  -68506.113    1374.552    100.122   85231.765

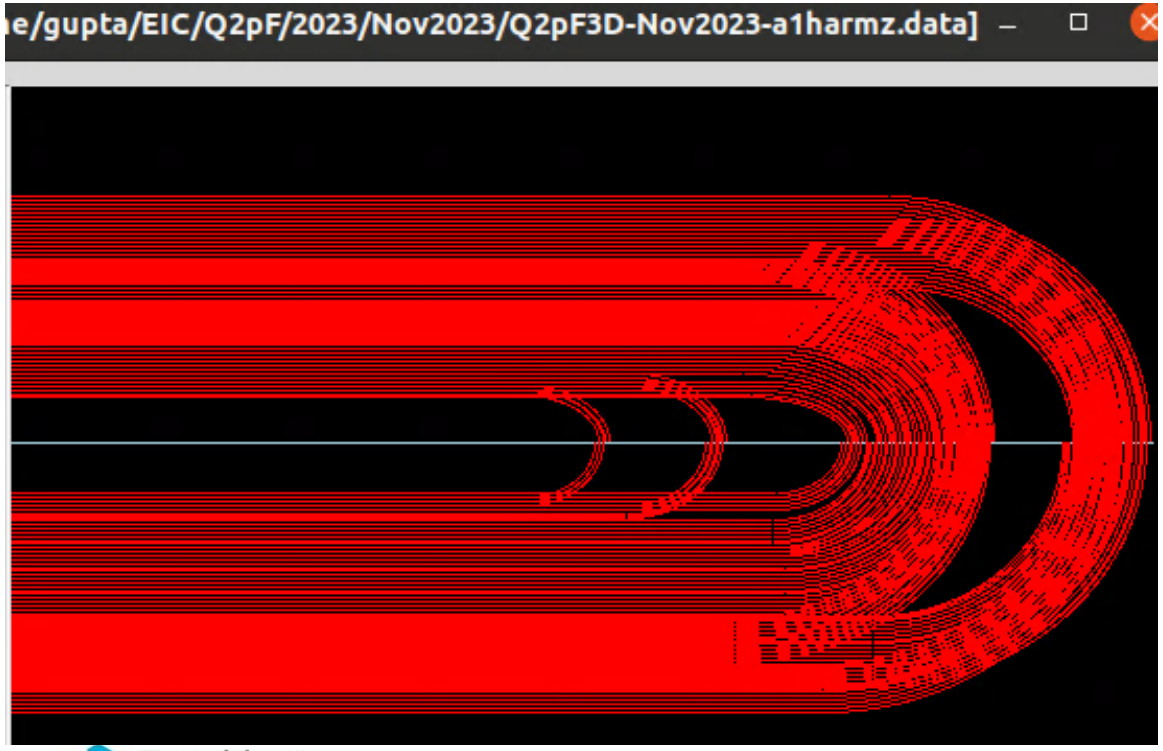

HARMONIC ANALYSIS NUMBER ..............................          1
MAIN HARMONIC .........................................          2
REFERENCE RADIUS (mm) .................................       83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..................        0.0000
Y-POSITION OF THE HARMONIC 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 ......................   0.5231E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

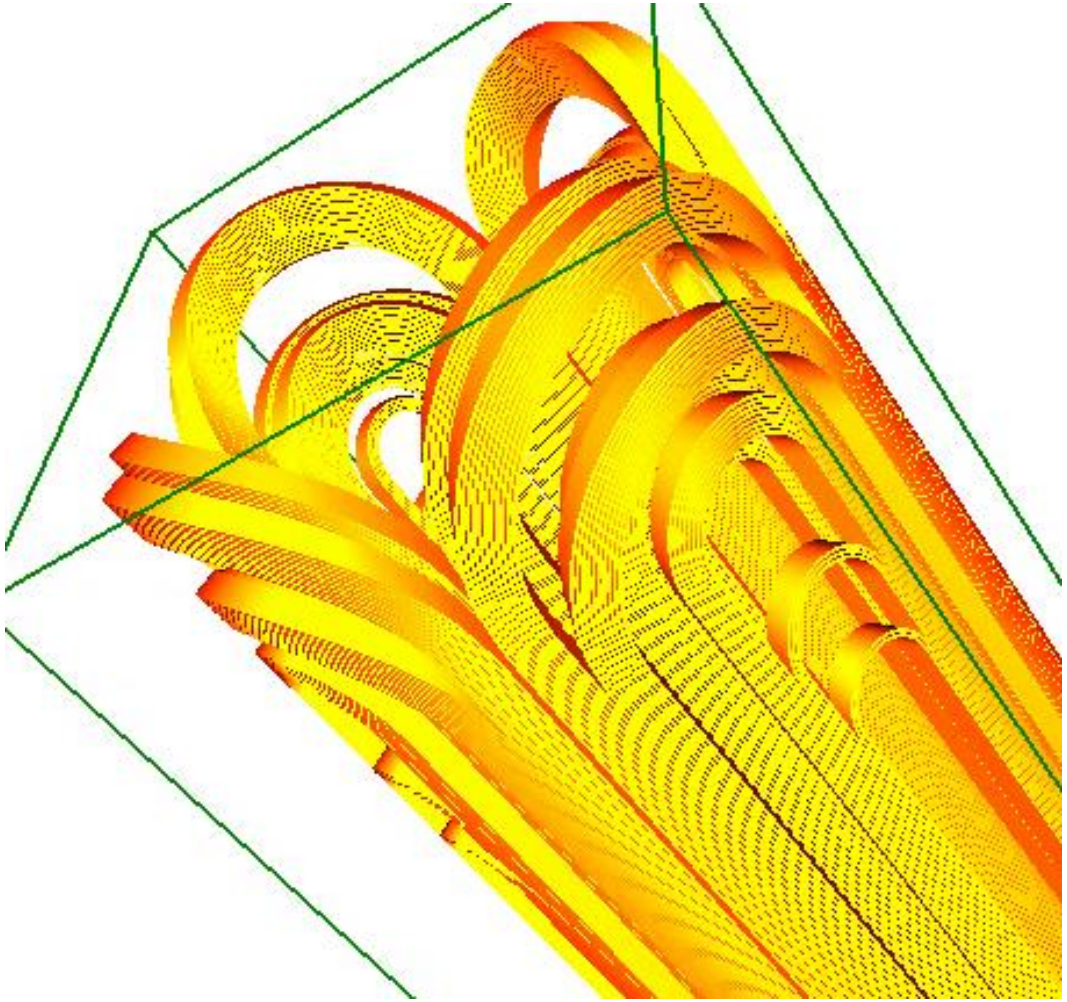
3D REFERENCE MAIN FIELD (T) ...........................       3.4387
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ................      41.4295
MAGNETIC LENGTH (mm) ..................................    1725.8457

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:       0.13001
b 7:      -0.00000  b 8:     -0.00000  b 9:      -0.00000
b10:      -0.64371  b11:      0.00000  b12:       0.00000
-  Q2pF3D-Nov2023-a1harmz1.output   99% L11068  (Fundamental)
```

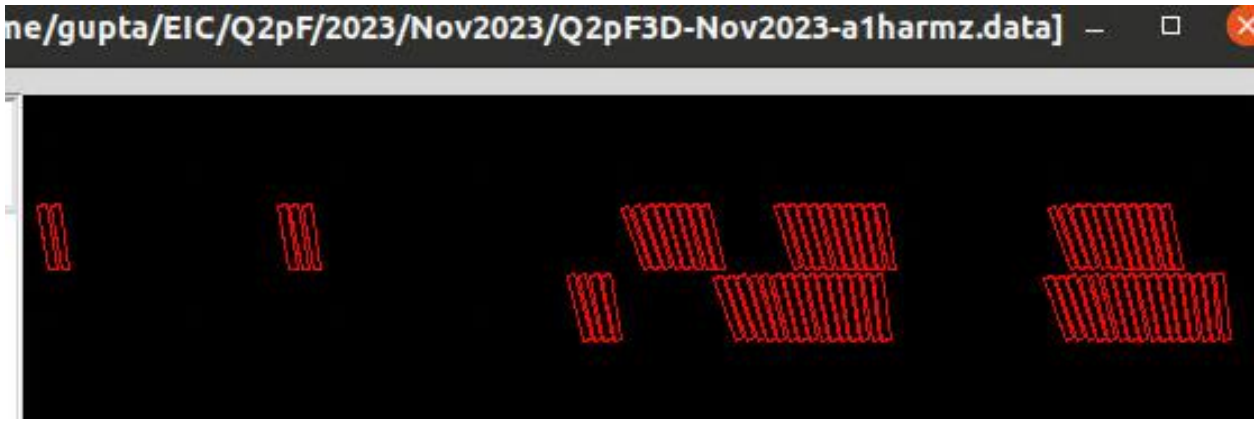
End Design #3 (70 degree)







End Design #3



Reasonable start:

- Field harmonics: not too large
- Peak field: 6.977 T (Vs 6.85T in 2-d)
- Tilt Angle 70 degree

About ~1.9% higher peak field than that in x-section; 0.2% higher peak field than in the other design.

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MARGIN CALC (USING JC-FIT):
BLOCK NUMBER ..........................................          11
PEAK FIELD IN CONDUCTOR   69 (T) ......................      6.9771
CURRENT IN CONDUCTOR  69 (A) ..........................   -8500.0000
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -886.0233
PERCENTAGE ON THE LOAD LINE ...........................      66.2747
QUENCHFIELD (T) .......................................      10.5275
TEMPERATURE MARGIN TO QUENCH (K) ......................       3.1248
PERCENTAGE OF SHORT SAMPLE CURRENT ....................      26.9936

FORCES (N) IN COIL ENDS
CONDUCTOR  FX          FY          FZ        FPAR        FPER
  69    49498.493  -68518.152    1400.887    102.559   85268.624
SUMM    49498.493  -68518.152    1400.887    102.559   85268.624


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 ......................  0.5237E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

3D REFERENCE MAIN FIELD (T) ...........................      3.4387
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ................     41.4295
MAGNETIC LENGTH (mm) ..................................    1721.7836

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:      -0.03053
b 7:      -0.00000  b 8:     -0.00000  b 9:       0.00000
b10:      -0.66259  b11:      0.00000  b12:       0.00000
b13:      -0.00000  b14:     -0.43020  b15:      -0.00000
 Q2pF3D-Nov2023-a1harmz.output   99% L11102  (Fundamental)
```

Summary

- There is no large increase in the peak fields in the ends over the body (an important part of this exercise). It is only 2% above the 2-d peak. Overall peak enhancement (2-d or 3-d is ~21%).
- Field harmonics looks ok as a good starting point (<1 unit).
- Peak field and harmonics will be further optimized together with the turn layout based on the initial single turn winding trials.
- A 70-degree vertical tilt angle should be possible.