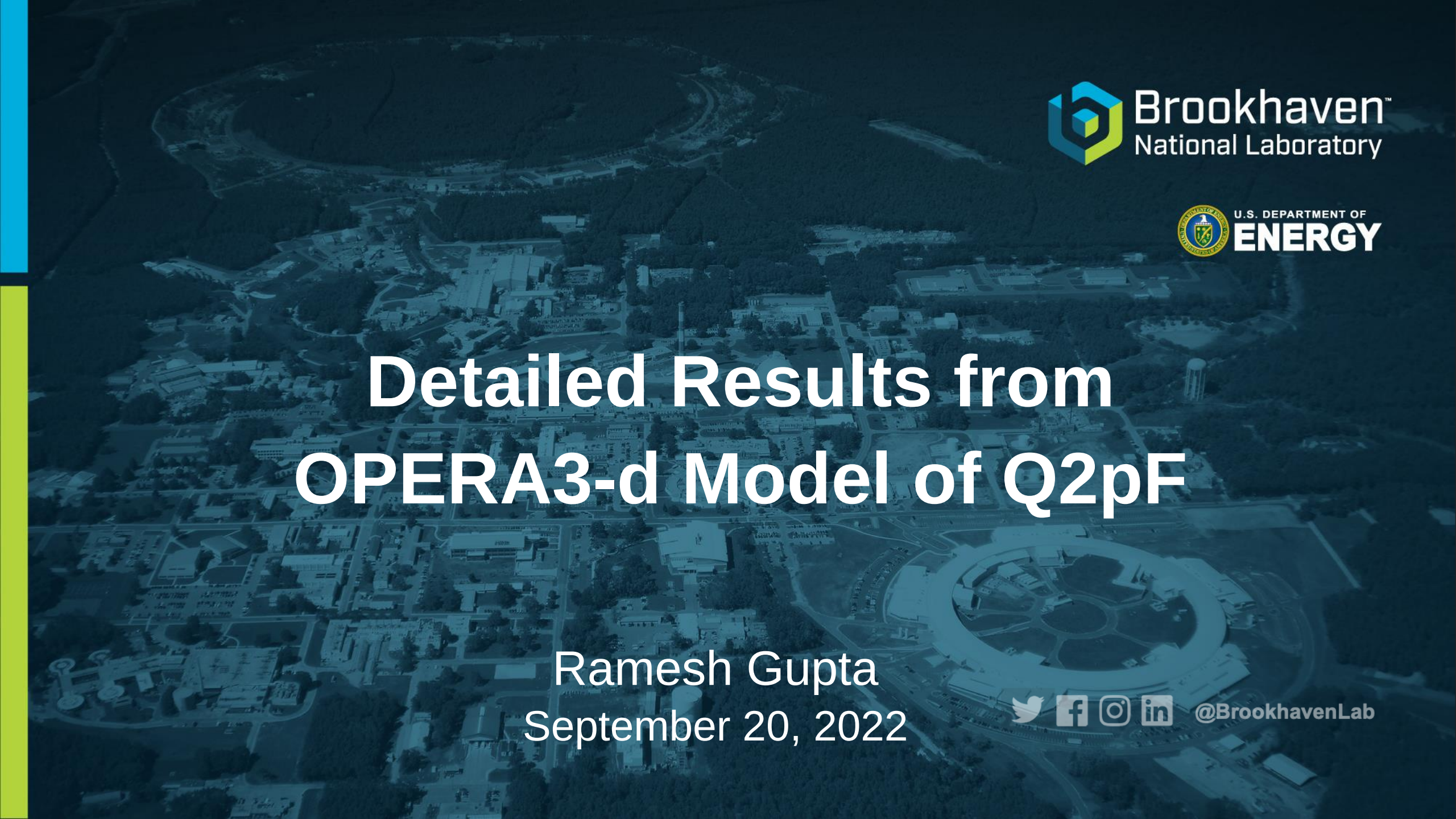

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U.S. DEPARTMENT OF ENERGY

Detailed Results from OPERA3-d Model of Q2pF

Ramesh Gupta

September 20, 2022

@BrookhavenLab

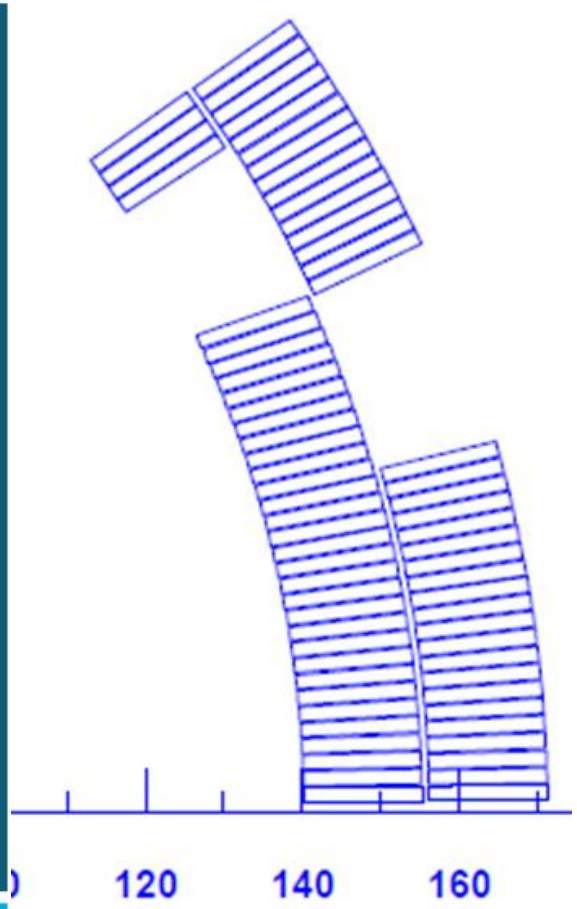
Overview

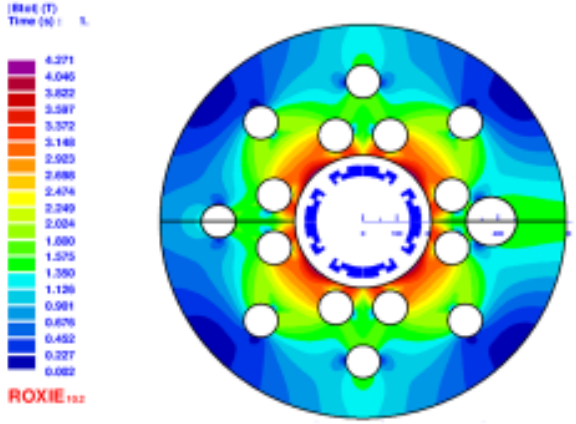
- OPERA3d model for coil optimized with ROXIE and realistic yoke with most features (including various holes and angular separation between proton and electron beam) present
- Calculations performed for non-linear iron as a function current with a scaling factors of 0.1 to 1.4, in a step of 0.1 of nominal current (8.5 kA)

- Detailed analysis of OPERA3d model for
  - ➢ Peak field in the coil, including location
  - ➢ Magnetic length and field fall-off in the ends as a function of current
  - ➢ Harmonics along the magnet length as a function of current

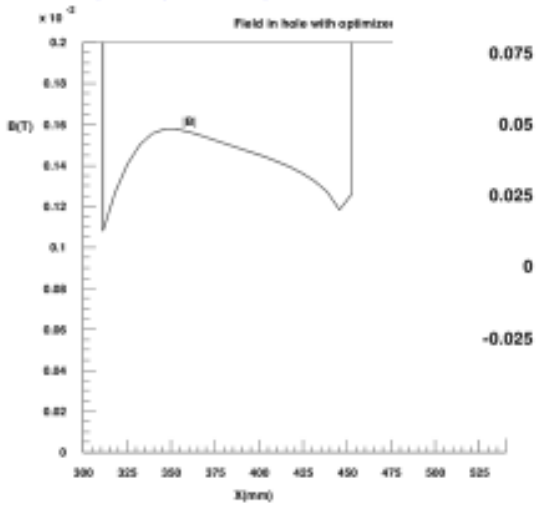
2-d Cross-section (optimization and analysis)

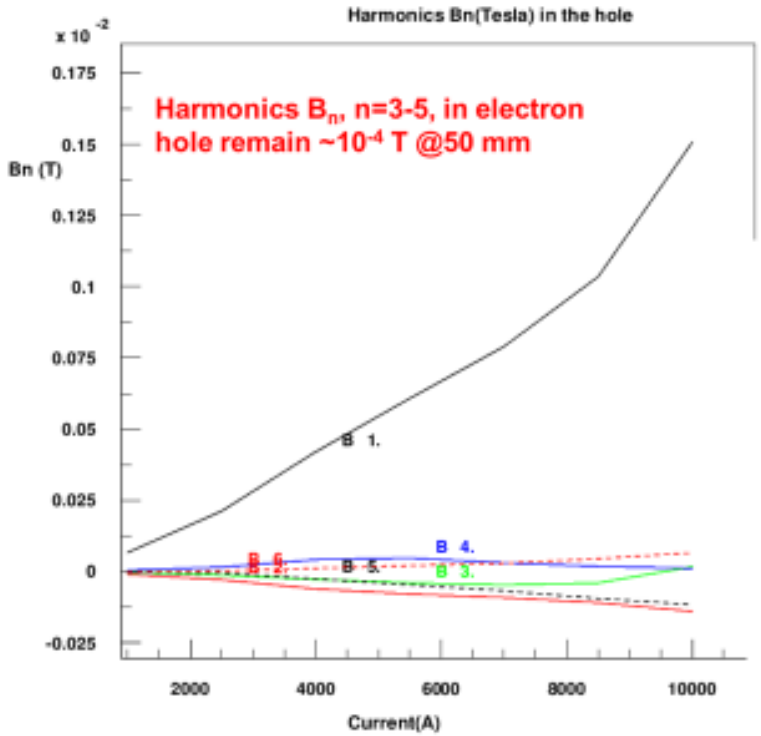
Field Harmonics with symmetric 2K He Holes at IP End

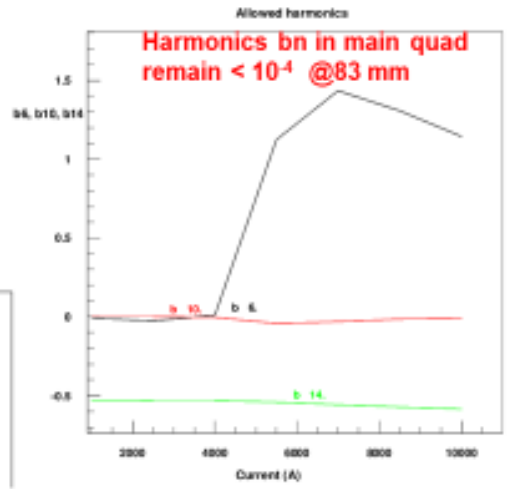


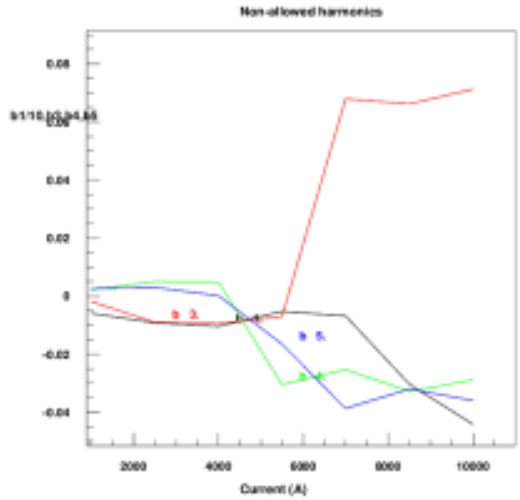


Field at 10 kA (design ~8.5 kA)









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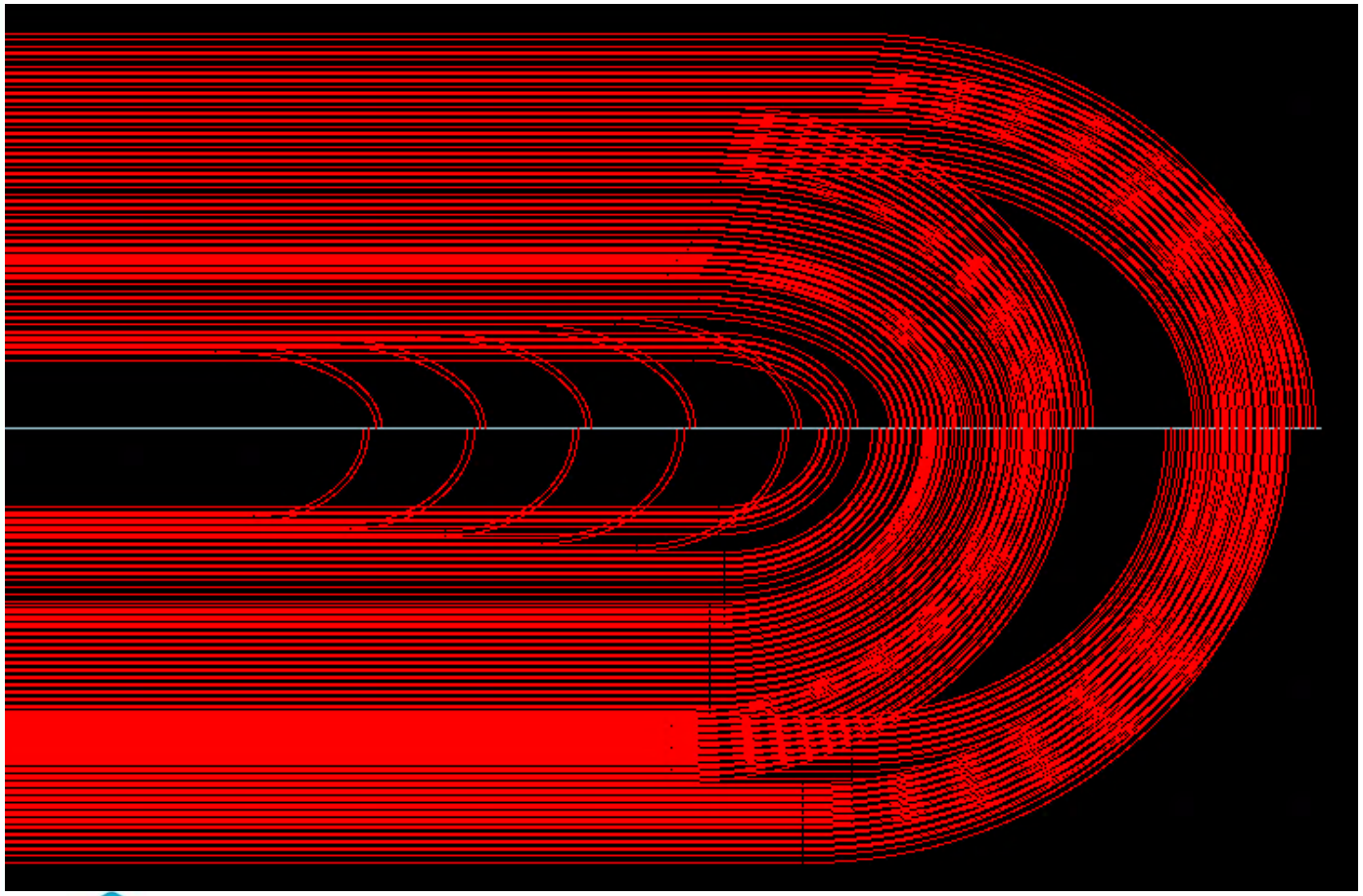
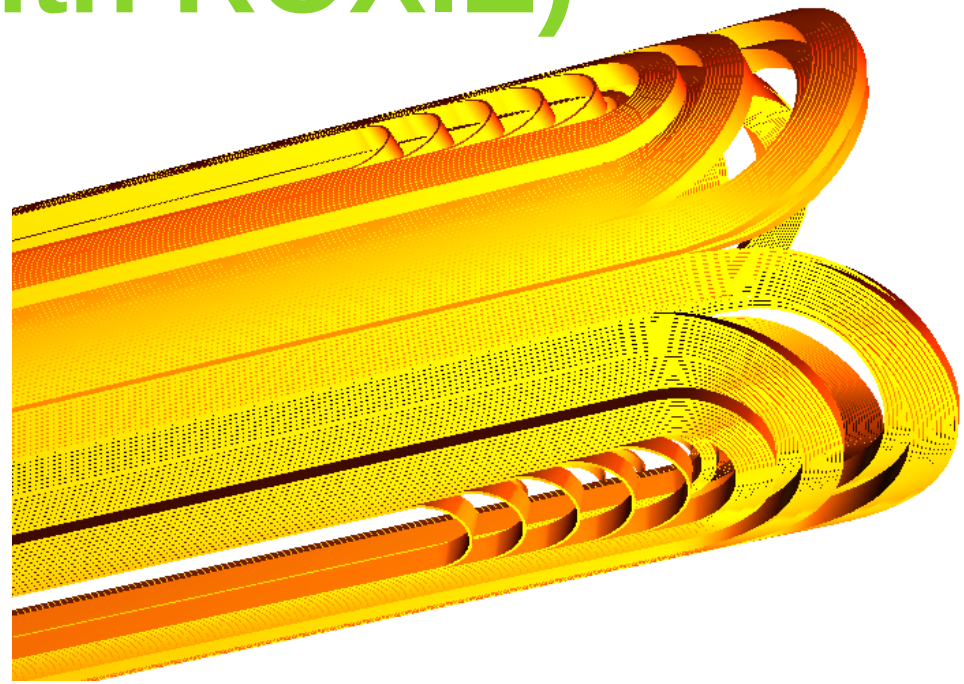
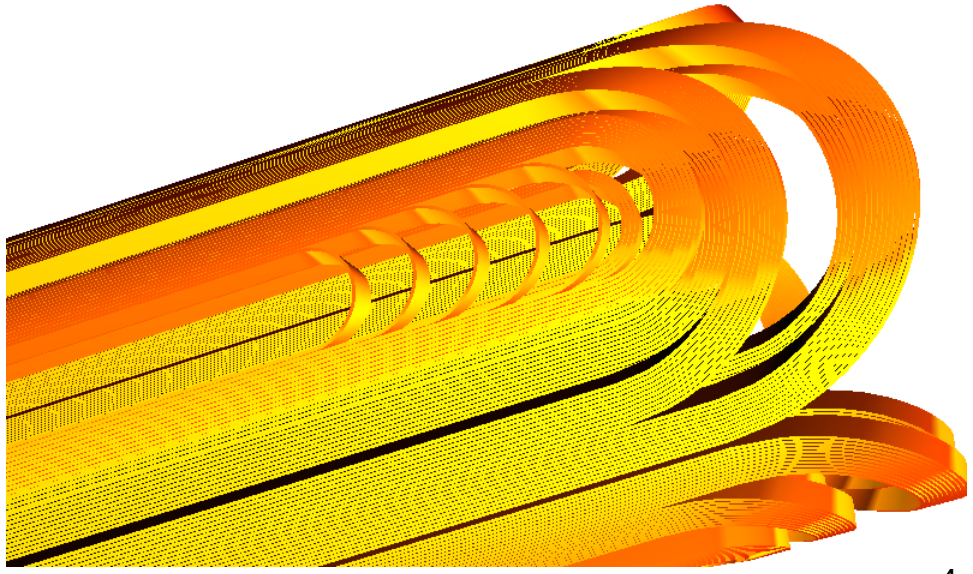
Results from OPERA3d Models of Q2pF
September 20, 2022
3

Optimized Coil Ends (with ROXIE)







Peak Field in the Ends

- Peak field in the body (including self field) : 6.94 T (7.05 T, without fine sub-division)
- **Peak field in the ends (including self field): 7.03 T**
  - **This is very close to the field in cross-section**

```
MARGIN CALC (USING JC-FIT):
BLOCK NUMBER ..........................................        11
PEAK FIELD IN CONDUCTOR   70 (T) ......................    7.0305
CURRENT IN CONDUCTOR  70 (A) ..........................  -8500.0000
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................   -886.0233
PERCENTAGE ON THE LOAD LINE ...........................     66.6742
QUENCHFIELD (T) .......................................     10.5446
TEMPERATURE MARGIN TO QUENCH (K) ......................      3.0966
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     27.2859
```

Analysis of the Optimized End Geometry (with ROXIE)

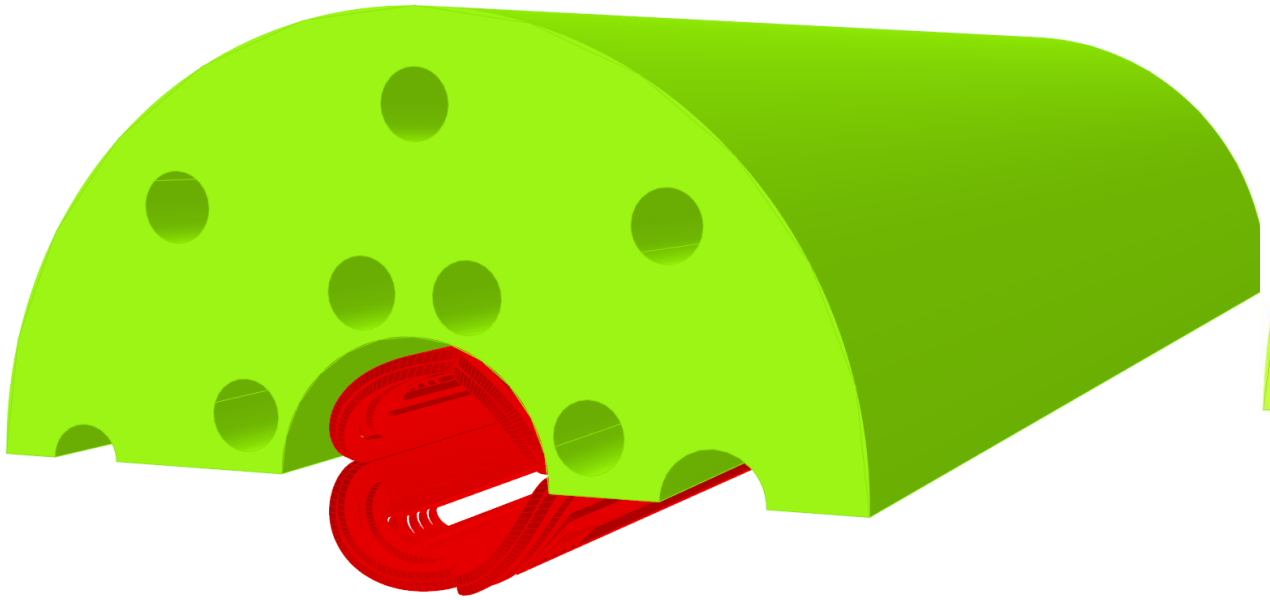
These results to be checked with other codes (OPERA3d, COMSOL?)

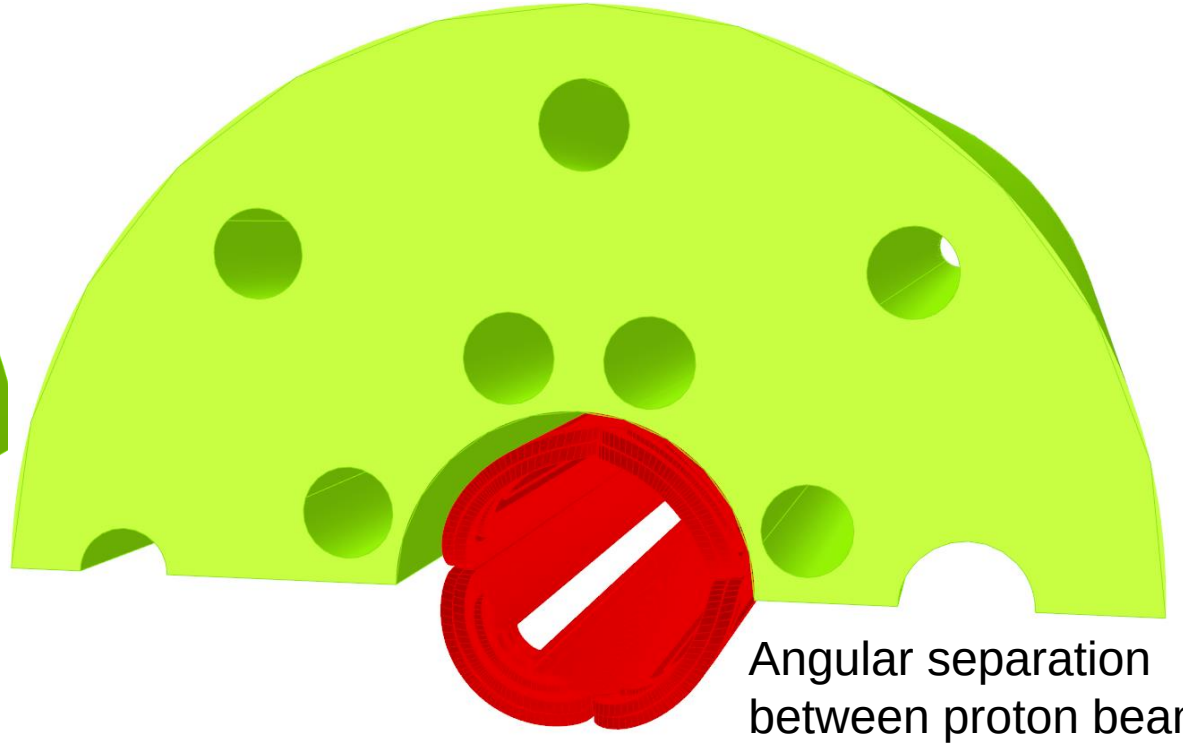

```
3D REFERENCE MAIN FIELD (T) ..........................      3.4693
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ...............     41.7991
MAGNETIC LENGTH (mm) .................................   1740.8142

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:     -0.08940
b 7:     -0.00000  b 8:     -0.00000  b 9:     -0.00000
b10:     -0.20210  b11:      0.00000  b12:      0.00000
b13:     -0.00000  b14:     -0.52138  b15:     -0.00000
b16:     -0.00000  b17:     -0.00000  b18:      0.01153
```

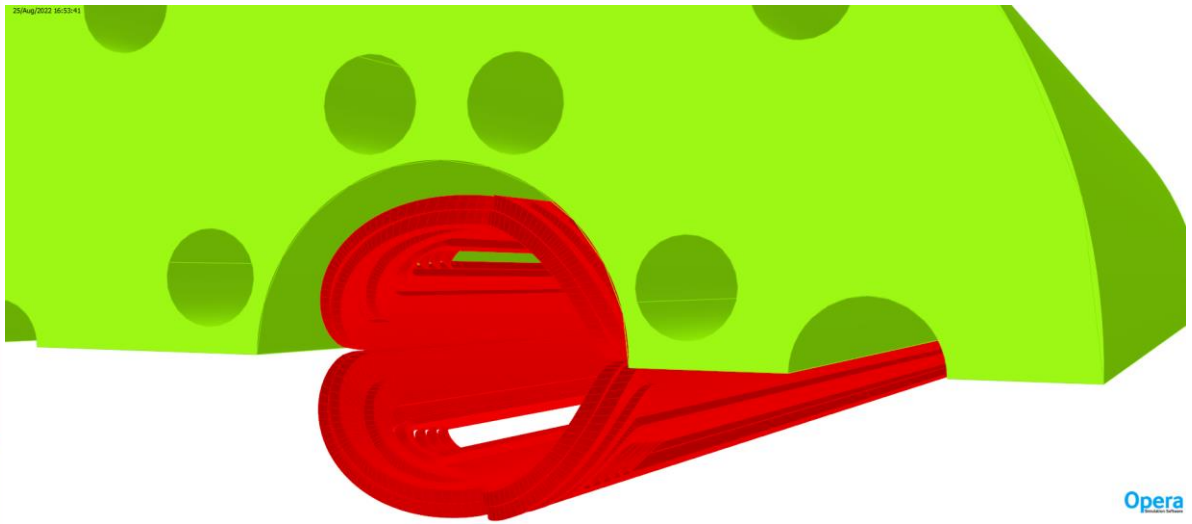
Mirror Iron Assumed

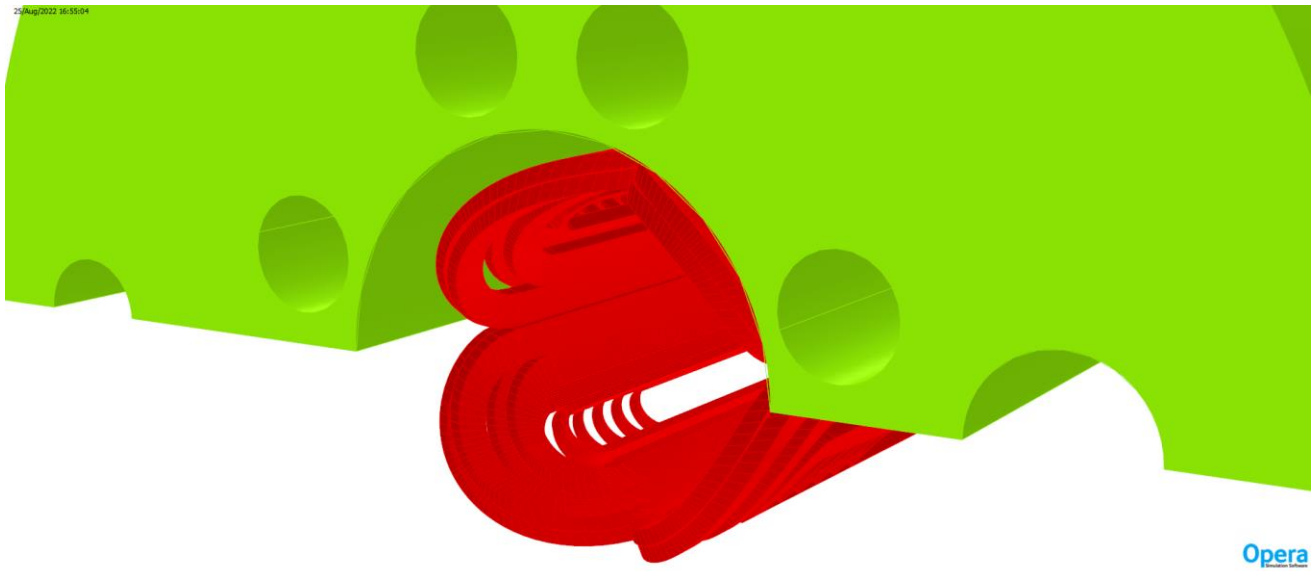
OPERA3d Model



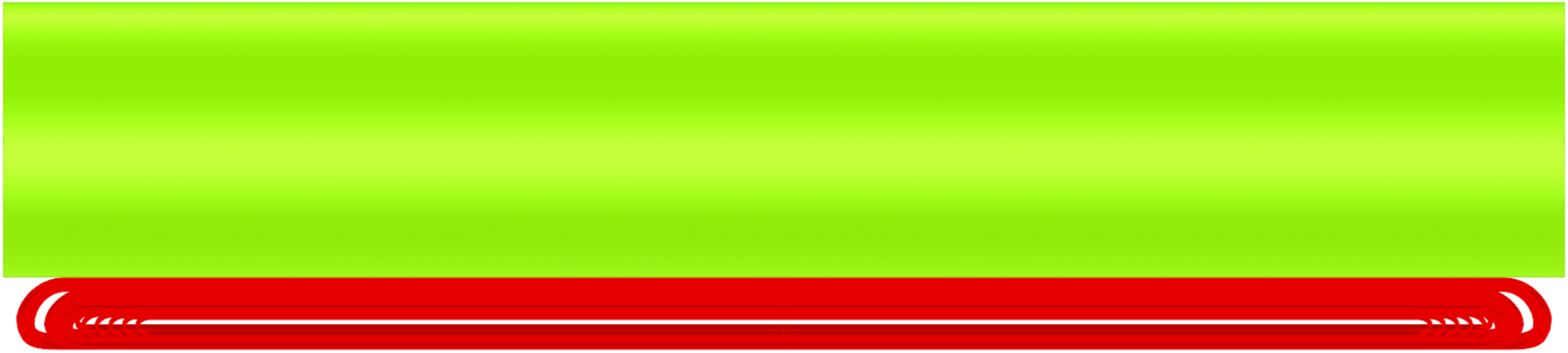


Angular separation between proton beam and electron beam





Views at the Ends in the OPERA3d Model



Ends optimized to reduce peak field and harmonics

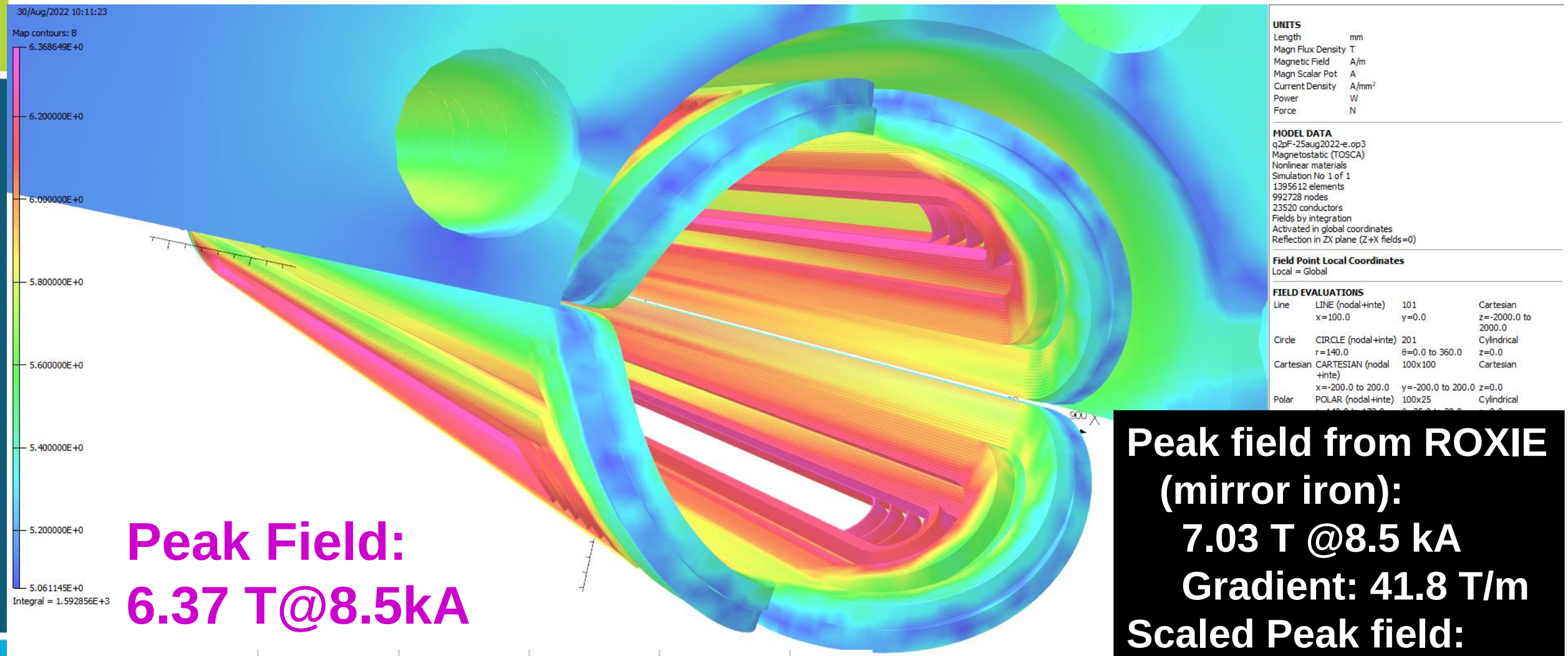
Left side

Right side

Peak Field in the Magnet Ends

Calculation of Peak Field with OPERA3d (non-linear iron)

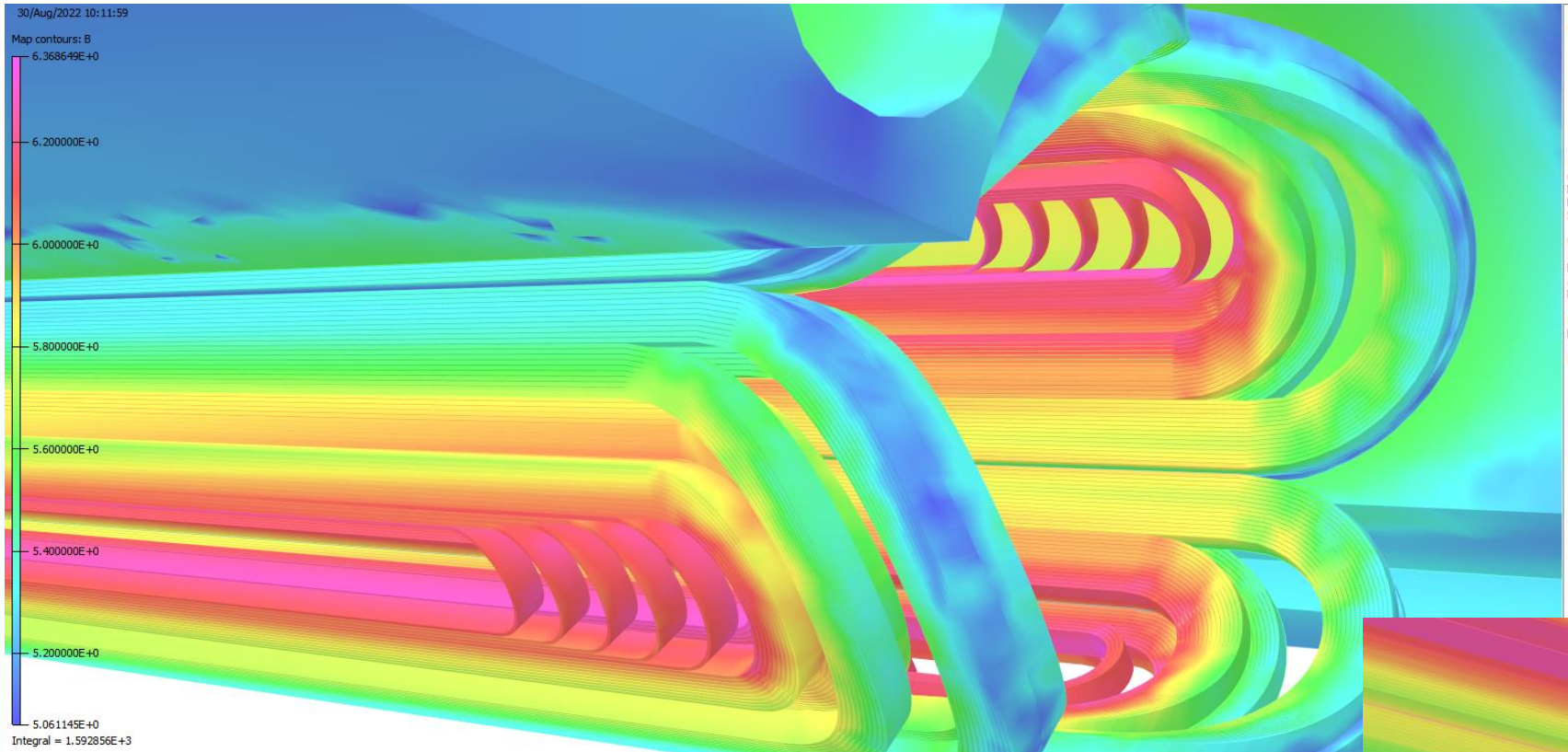
Integration method for the coil field to assure a reasonable accuracy



Peak Field:
6.37 T@8.5kA

Gradient @ center	38.218	T/m

Peak field from ROXIE (mirror iron):
7.03 T @8.5 kA
Gradient: 41.8 T/m
Scaled Peak field:
6.42 T for 38.2 T/m



UNITS

Length	mm
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/mm²
Power	W
Force	N

MODEL DATA

q2pF-25aug2022-e.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
1395612 elements
992728 nodes
23520 conductors
Fields by integration
Activated in global coordinates
Reflection in ZX plane (Z+X fields=0)

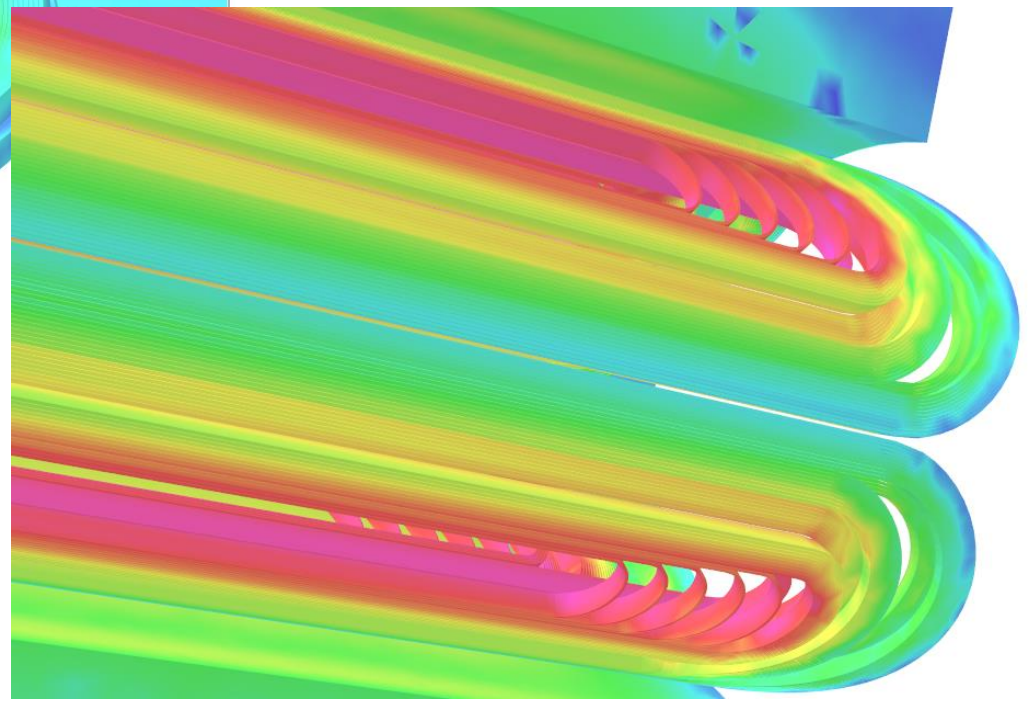
Field Point Local Coordinates

Local = Global

FIELD EVALUATIONS

Line	LINE (nodal+inte)	101	Cartesian
	x=100.0	y=0.0	z=-2000.0 to 2000.0
Circle	CIRCLE (nodal+inte)	201	Cylindrical
	r=140.0	θ=0.0 to 360.0	z=0.0
Cartesian	CARTESIAN (nodal +inte)	100x100	Cartesian
	x=-200.0 to 200.0	y=-200.0 to 200.0	z=0.0
Polar	POLAR (nodal+inte)	100x25	Cylindrical
	r=140.0 to 173.0	θ=35.0 to 38.0	z=0.0

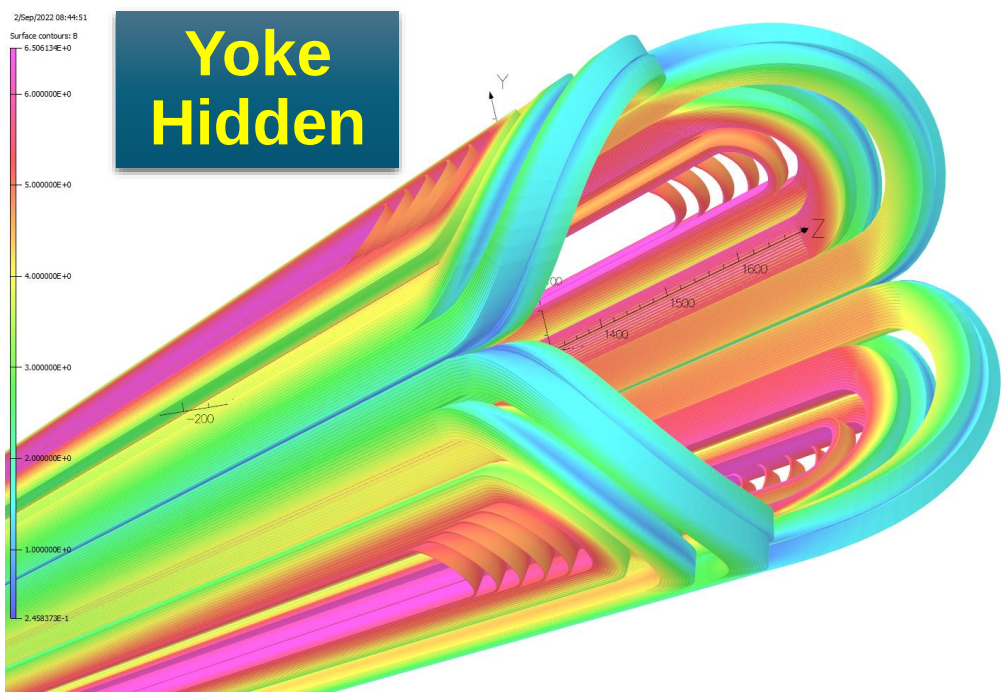
OPERA3d Views (1)

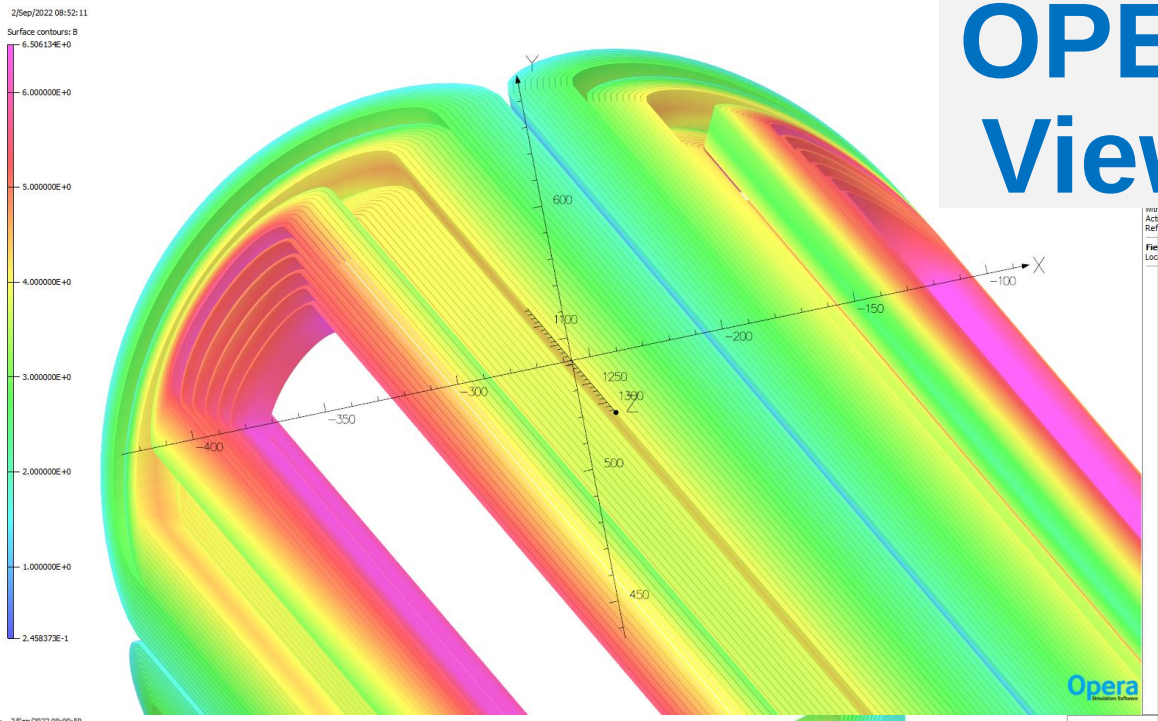


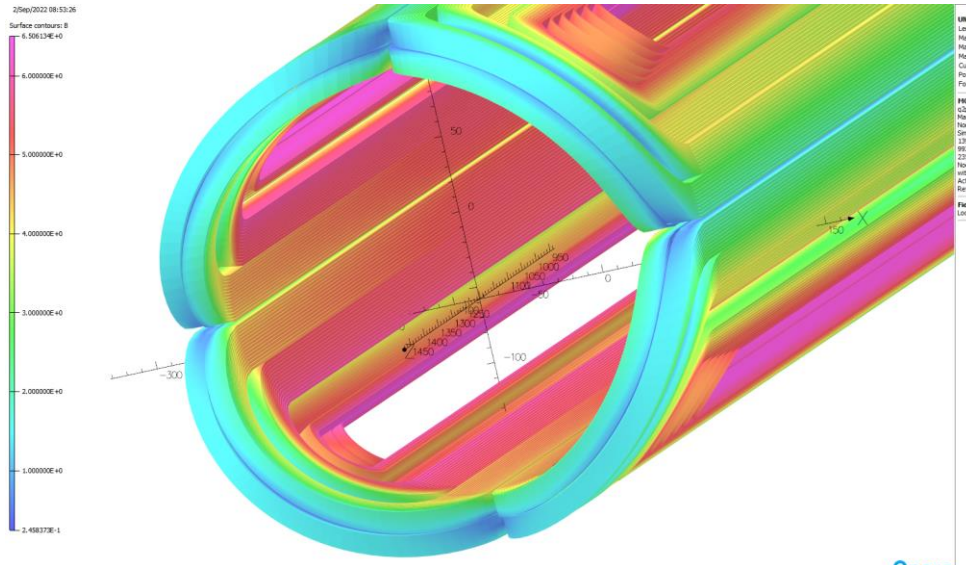
To check if the peak field in the ends is not too much over the peak field in the body of the magnet

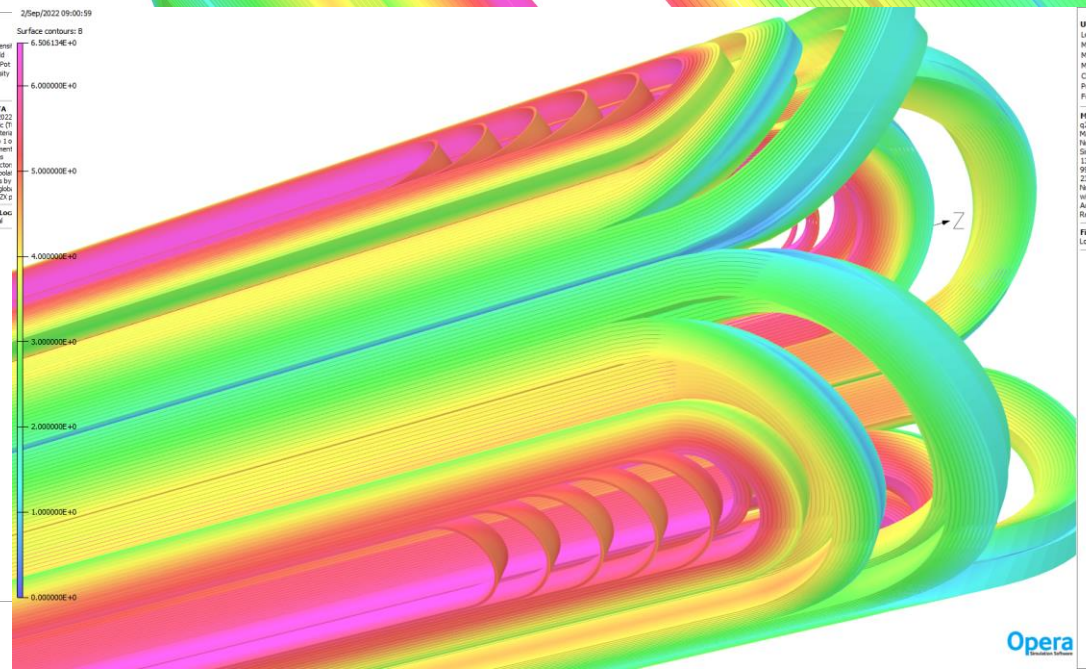
OPERA3d Views (2)

Yoke Hidden





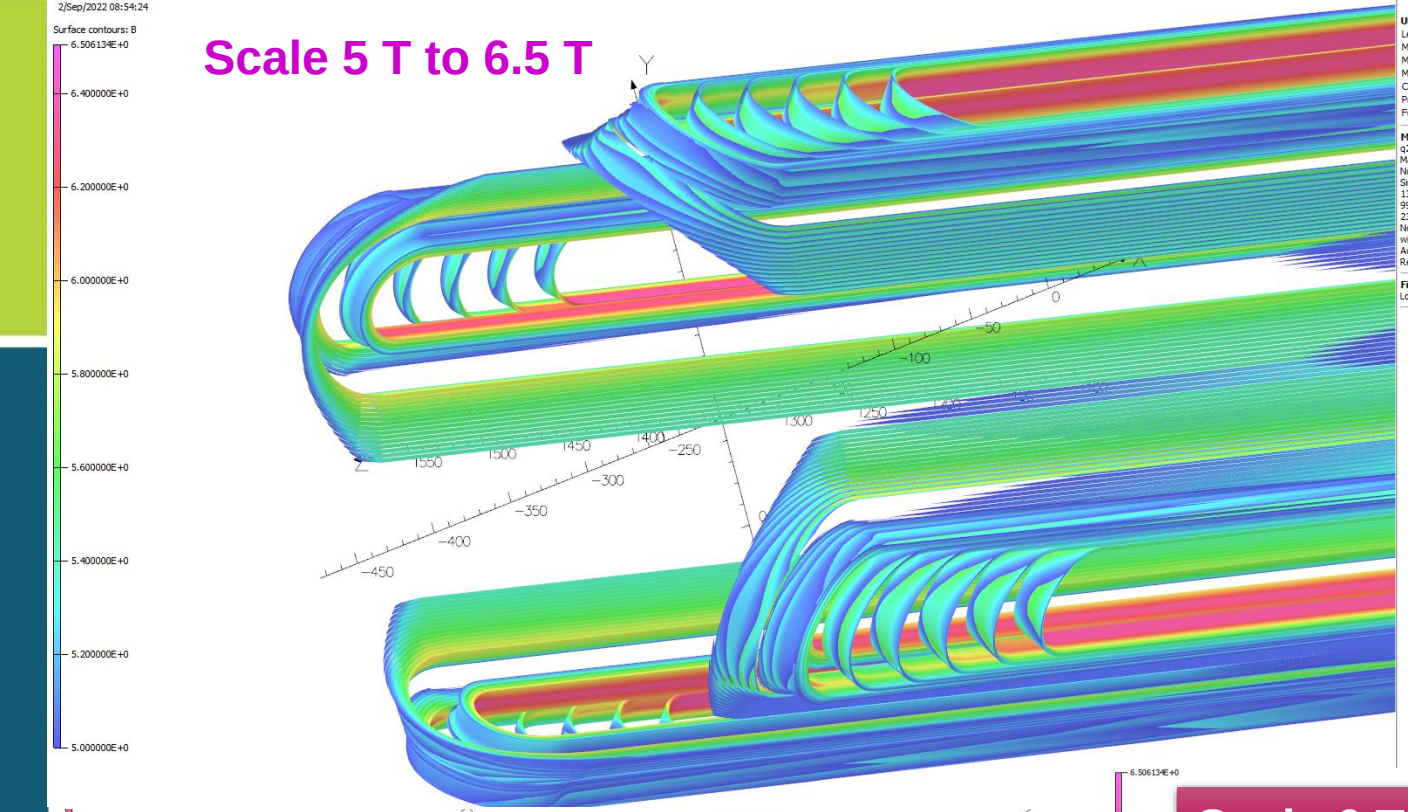


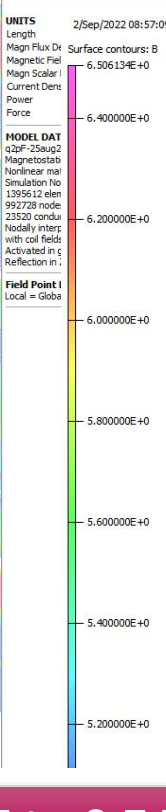


To check if the peak field in the ends is not too much over the peak field in the body of the magnet

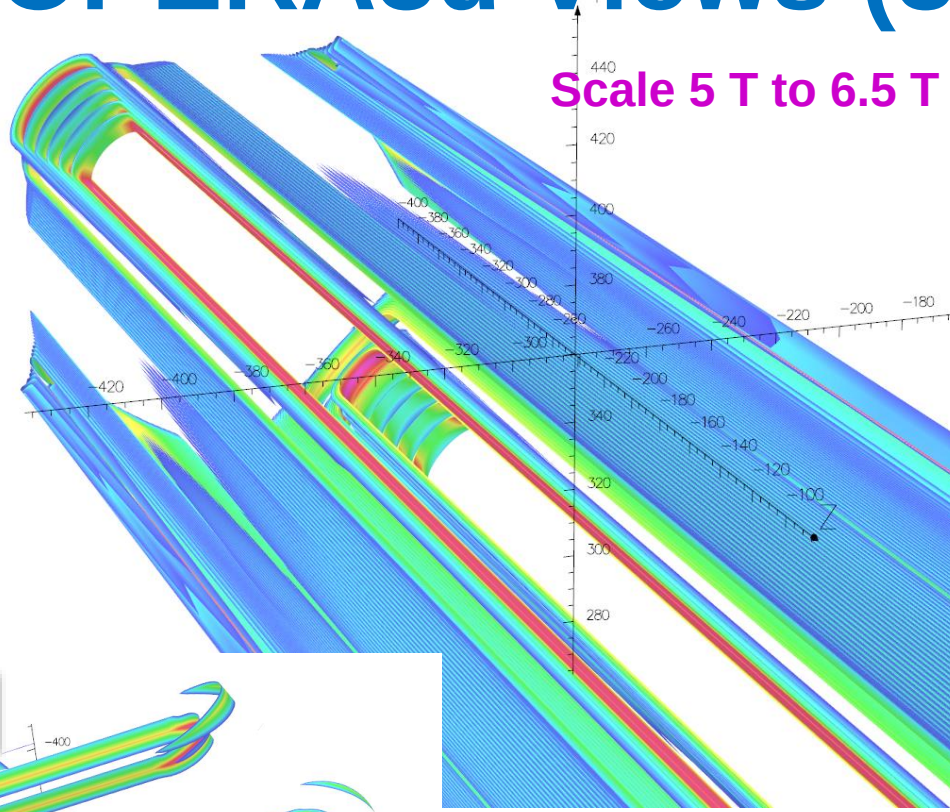
OPERA3d Views (3

Scale 5 T to 6.5 T

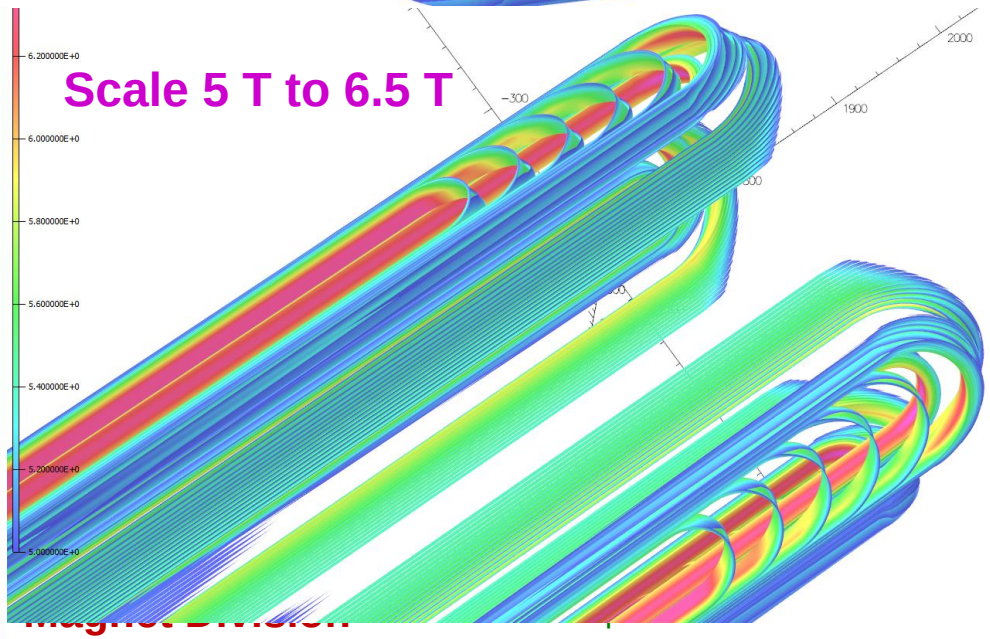




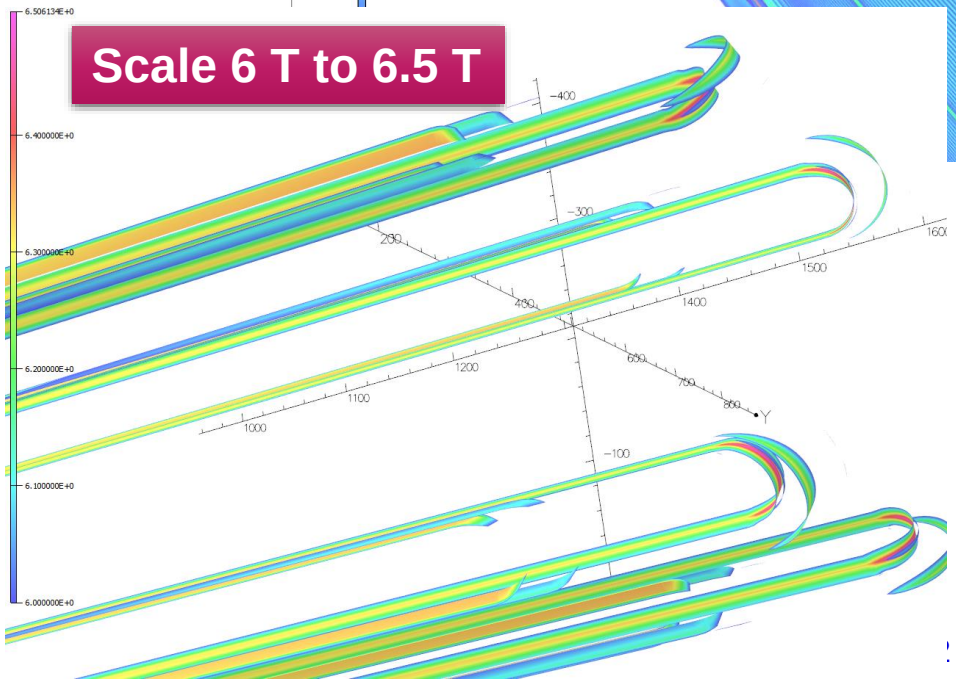
Scale 5 T to 6.5 T



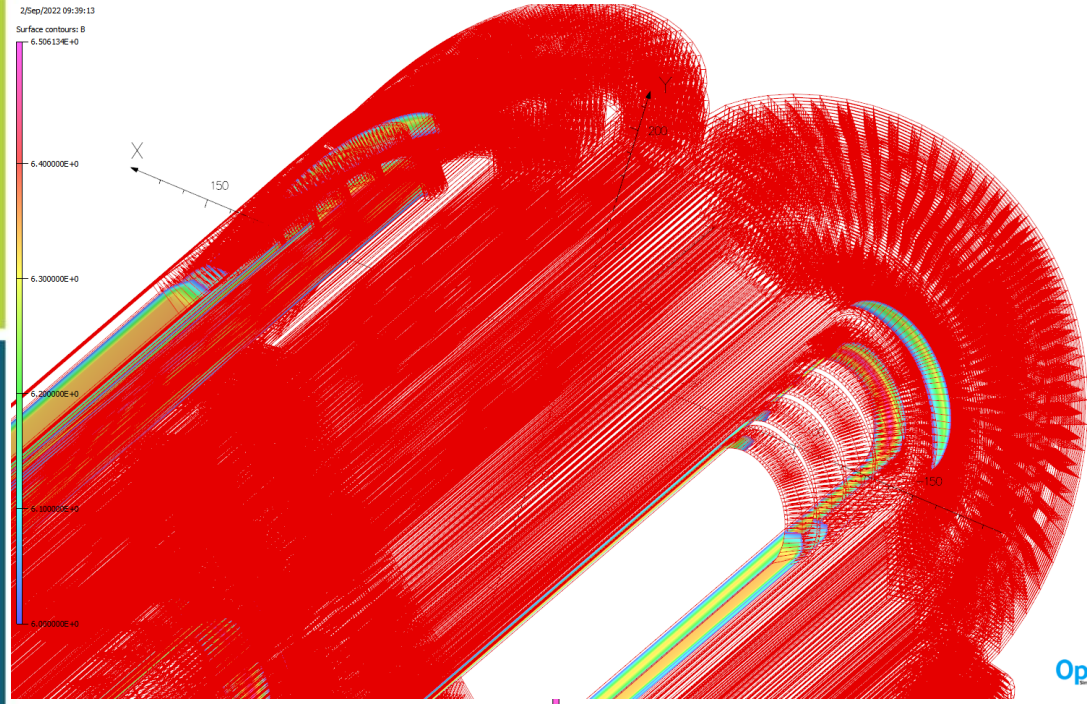
Scale 5 T to 6.5 T

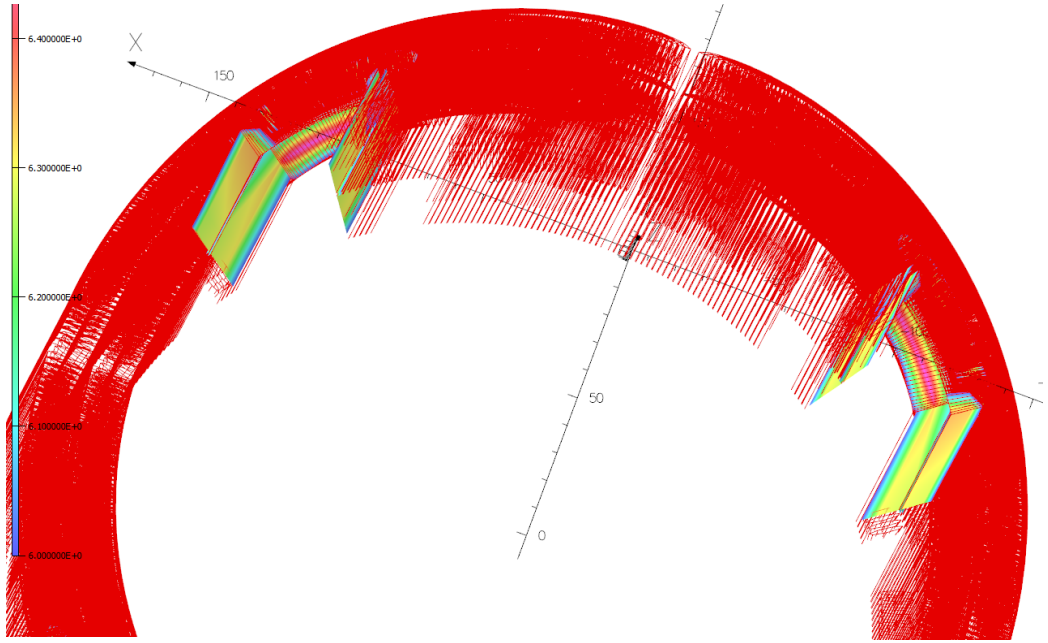


Scale 6 T to 6.5 T

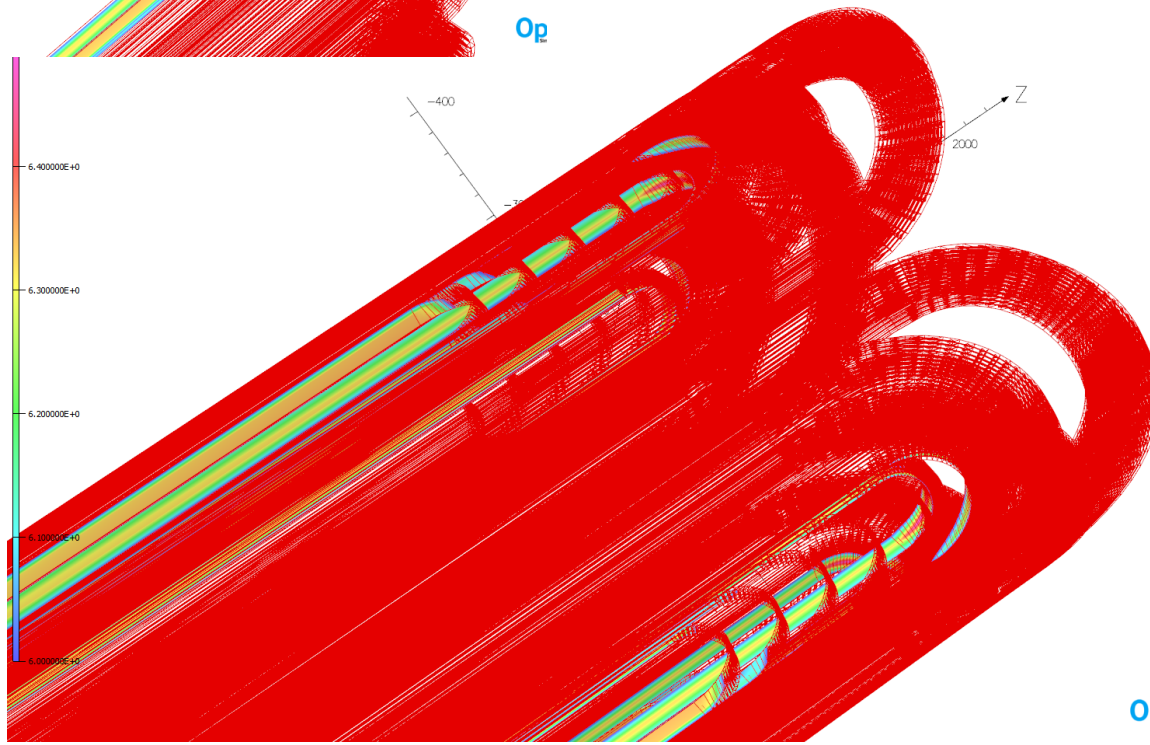


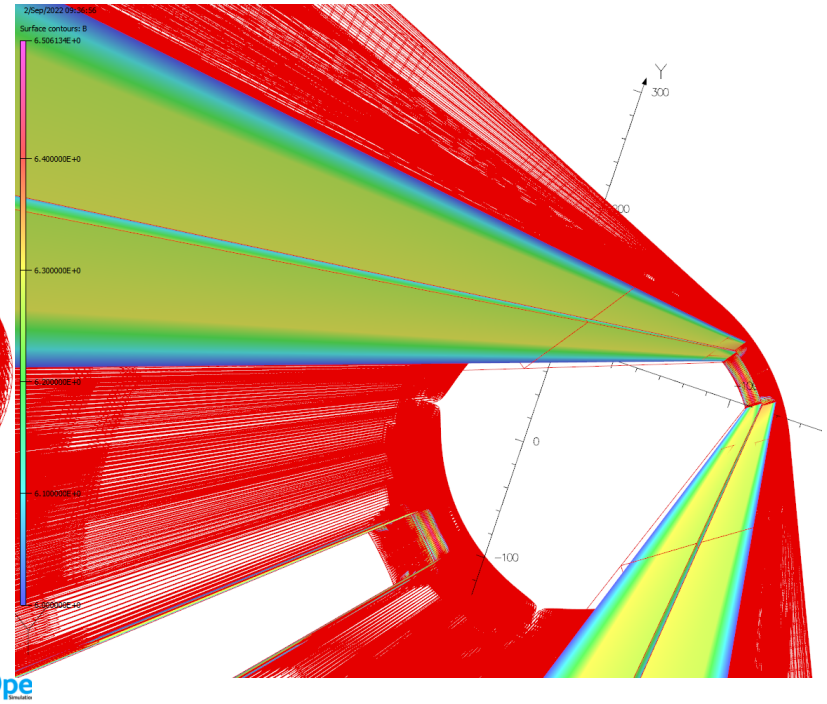
Locating the peak field. Seems to be on the inner layer. Not much above that in the body





OPERA3d Views (4) (with coil displayed in the background)



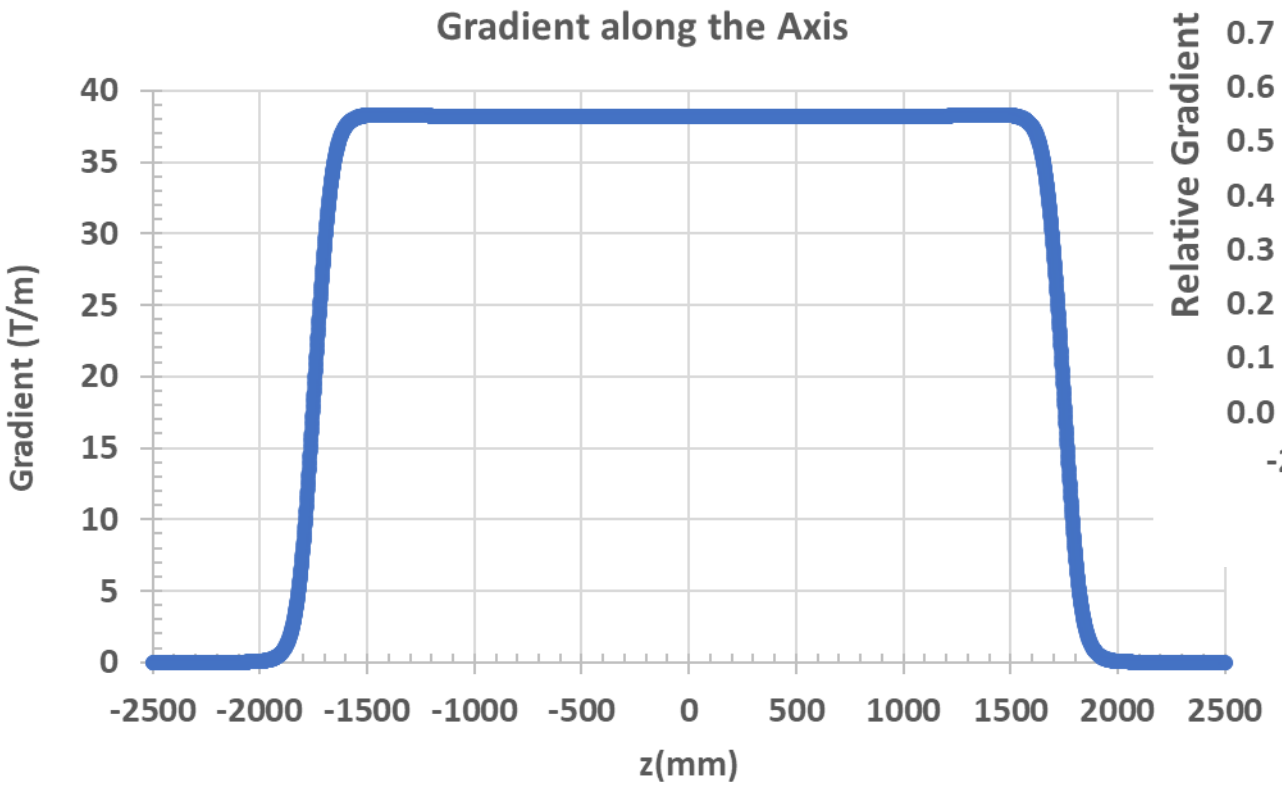


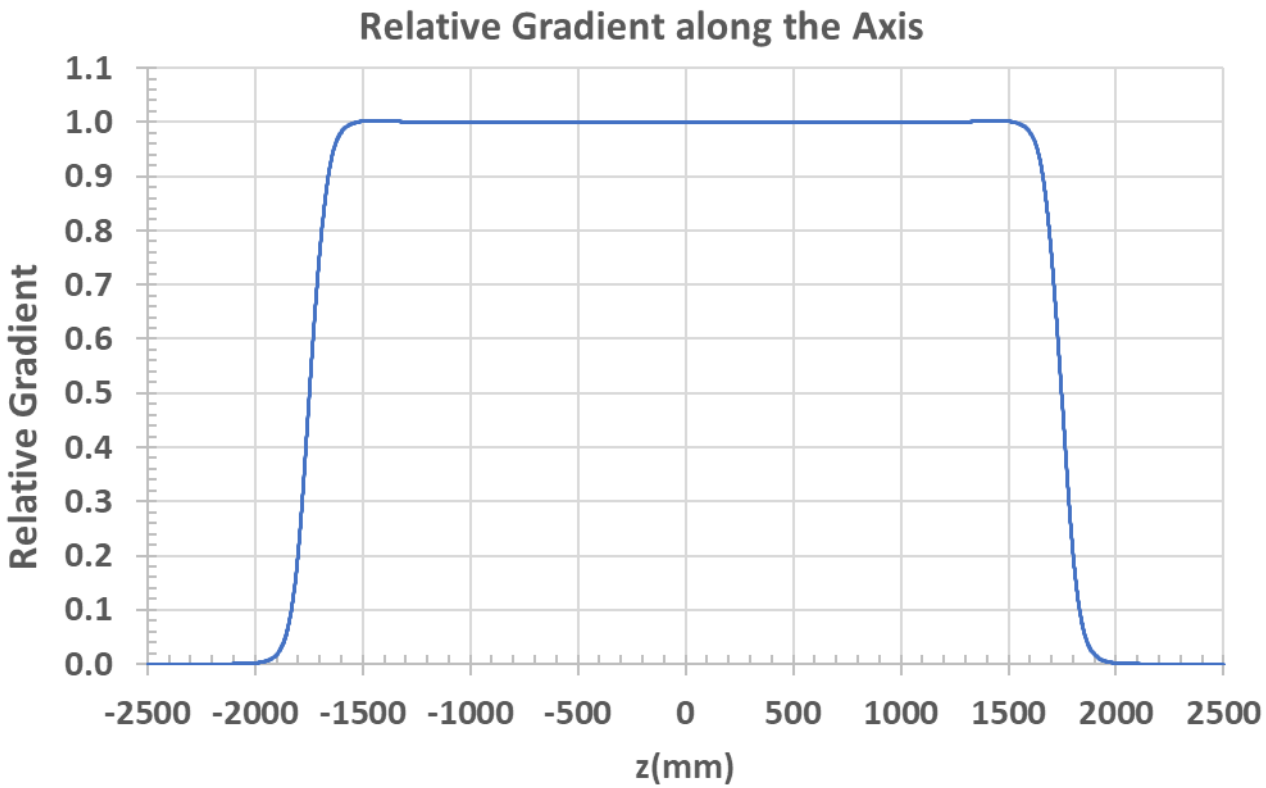
Magnetic Length and Fall-off of the Field in the Ends at Different Excitation

@8.5 kA

OPERA3d Calculations (1)

Gradient @ center	38.218	T/m
Integrated Gradient	133.55	Tesla
Magnetic Length	3.494	meter

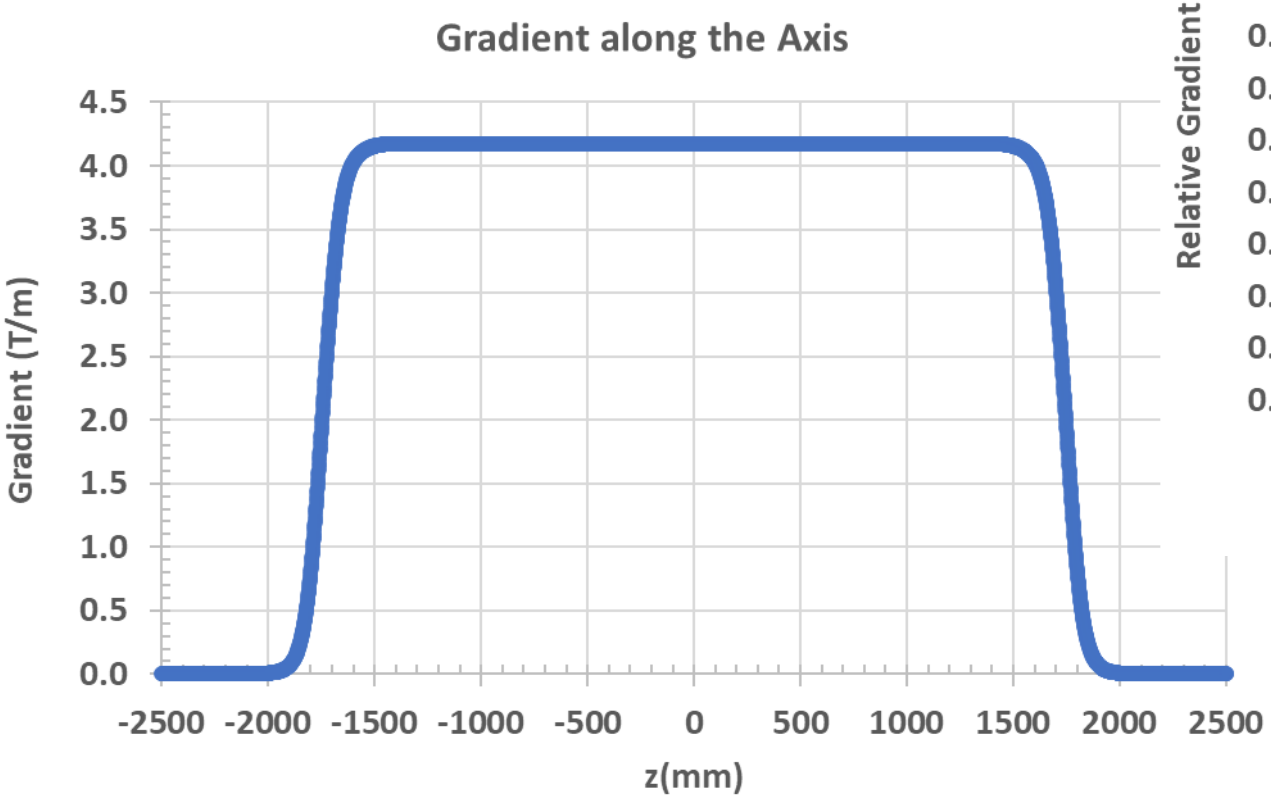


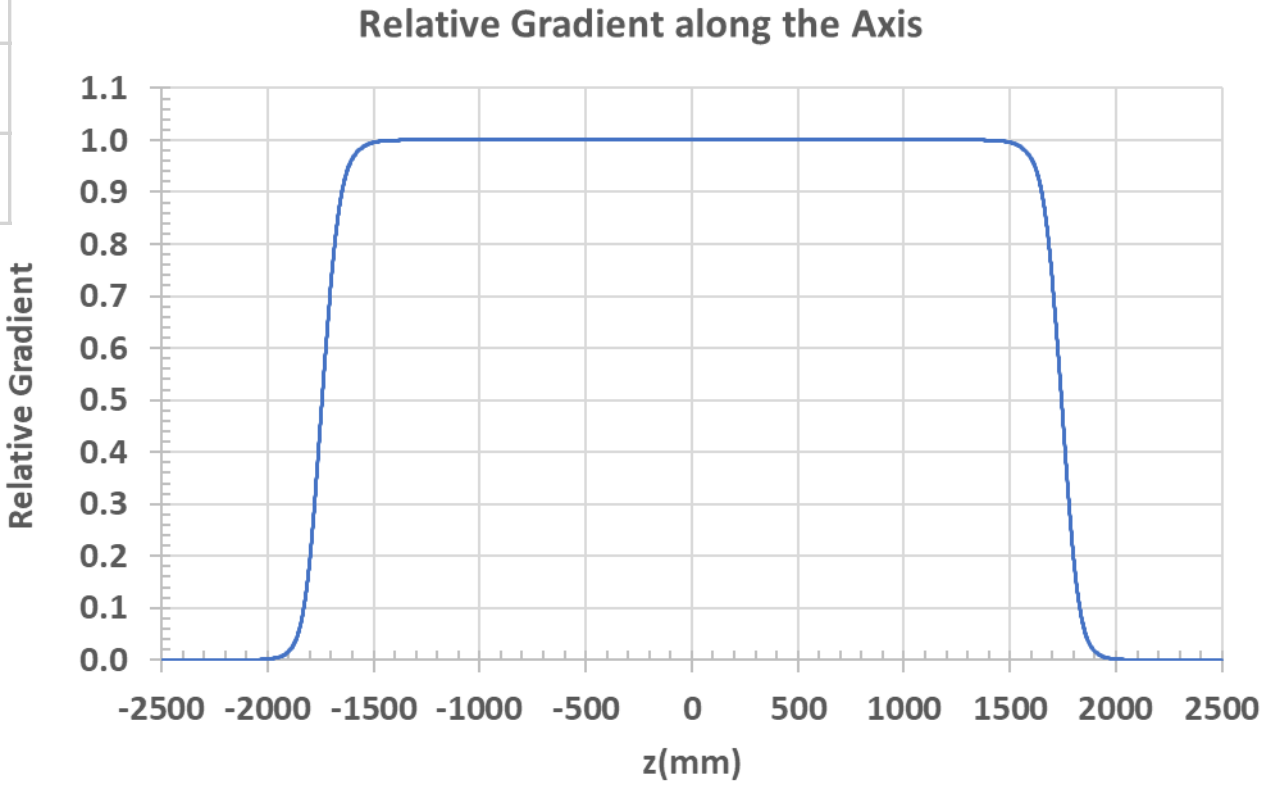


@0.85 kA (X=0.1)

OPERA3d Calculations (2)

Gradient @ center	4.174	T/m
Integrated Gradient	14.53	Tesla
Magnetic Length	3.482	meter



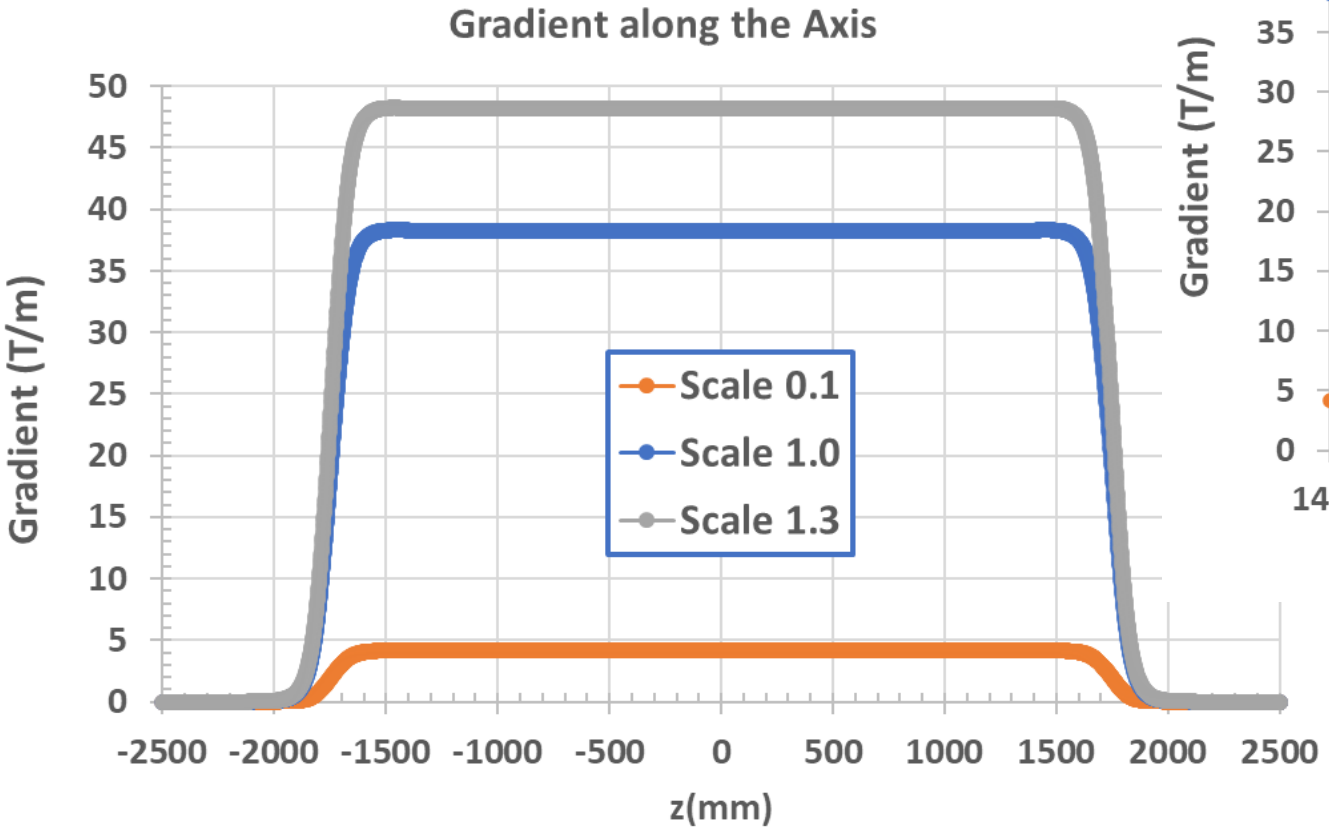


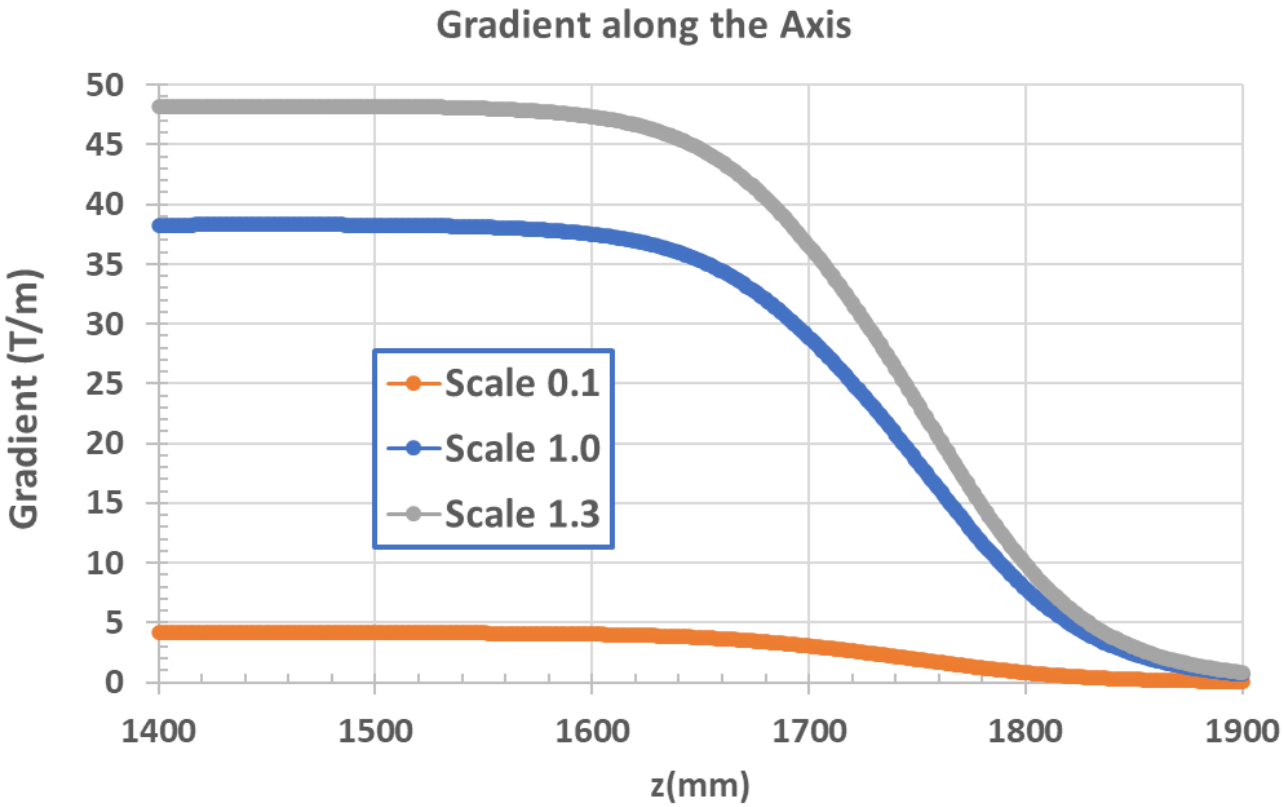
Notice a change in the magnetic length

Gradient @ center	38.218	T/m
Integrated Gradient	133.55	Tesla
Magnetic Length	3.494	meter

@8.5 kA (X=1)

OPERA3d Calculations (3)

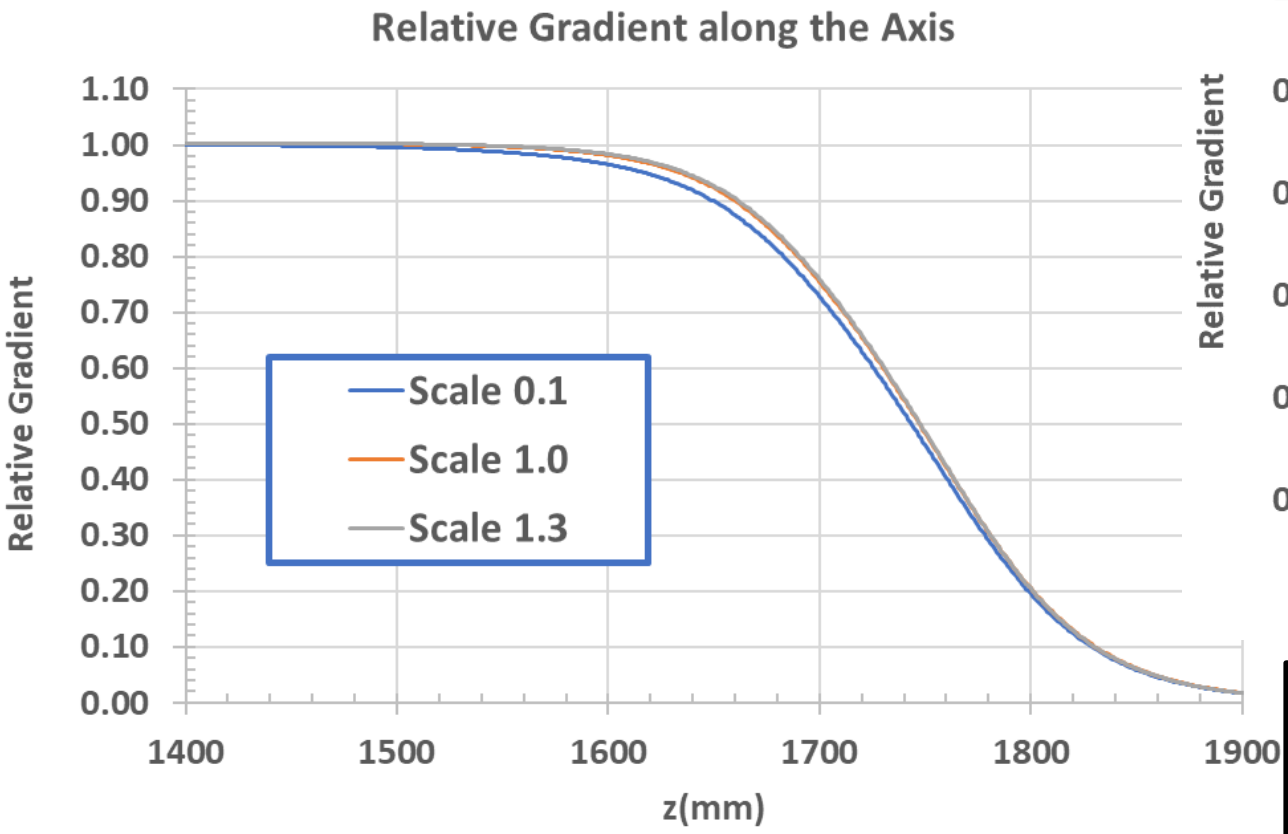


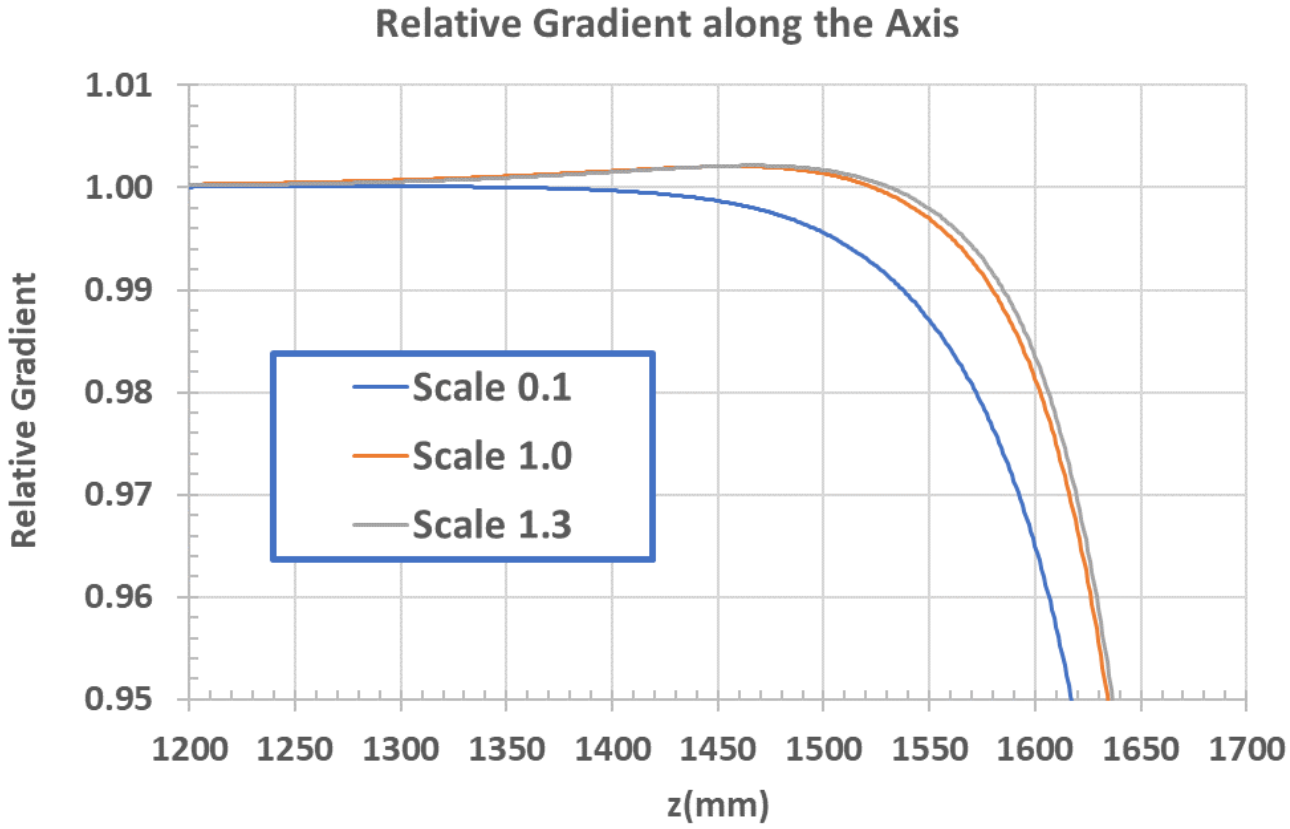


Scaled from 8.5 kA

OPERA3d Calculations (4)
(Gradient normalized to the value in the body)

Scaled from 8.5 kA

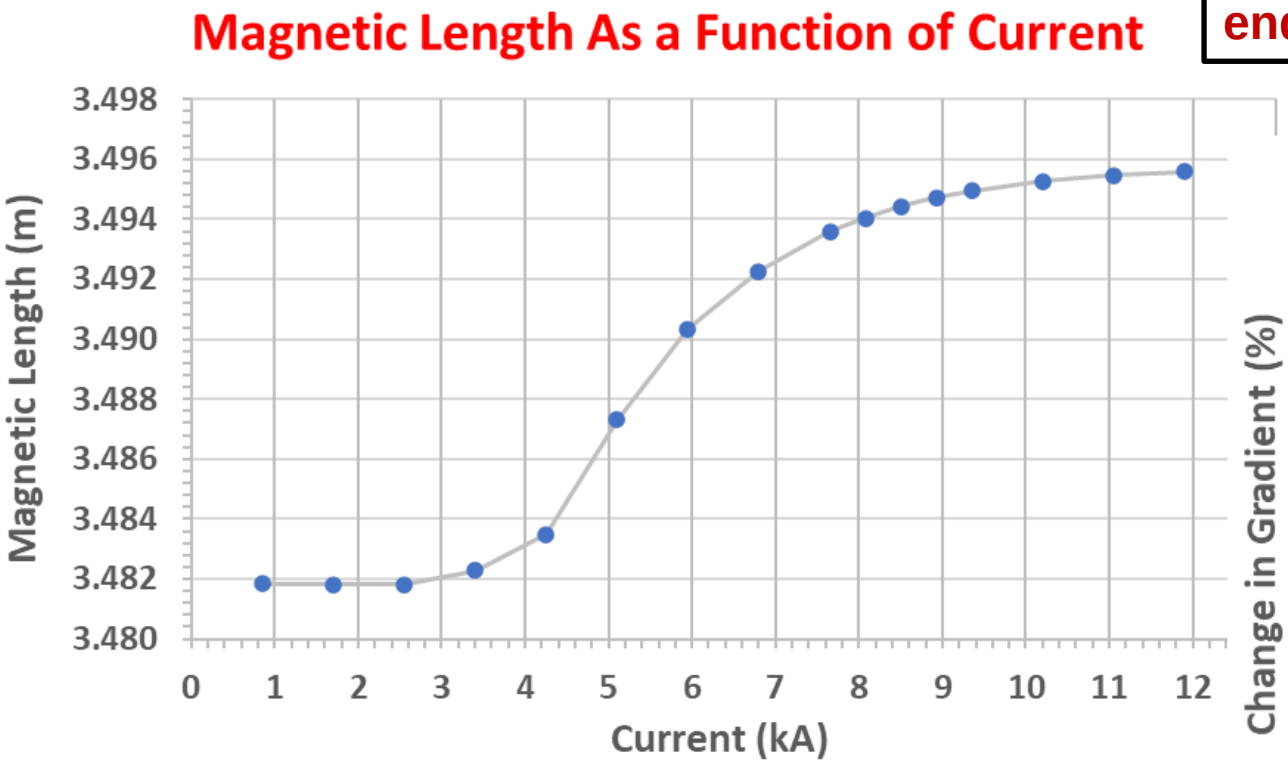


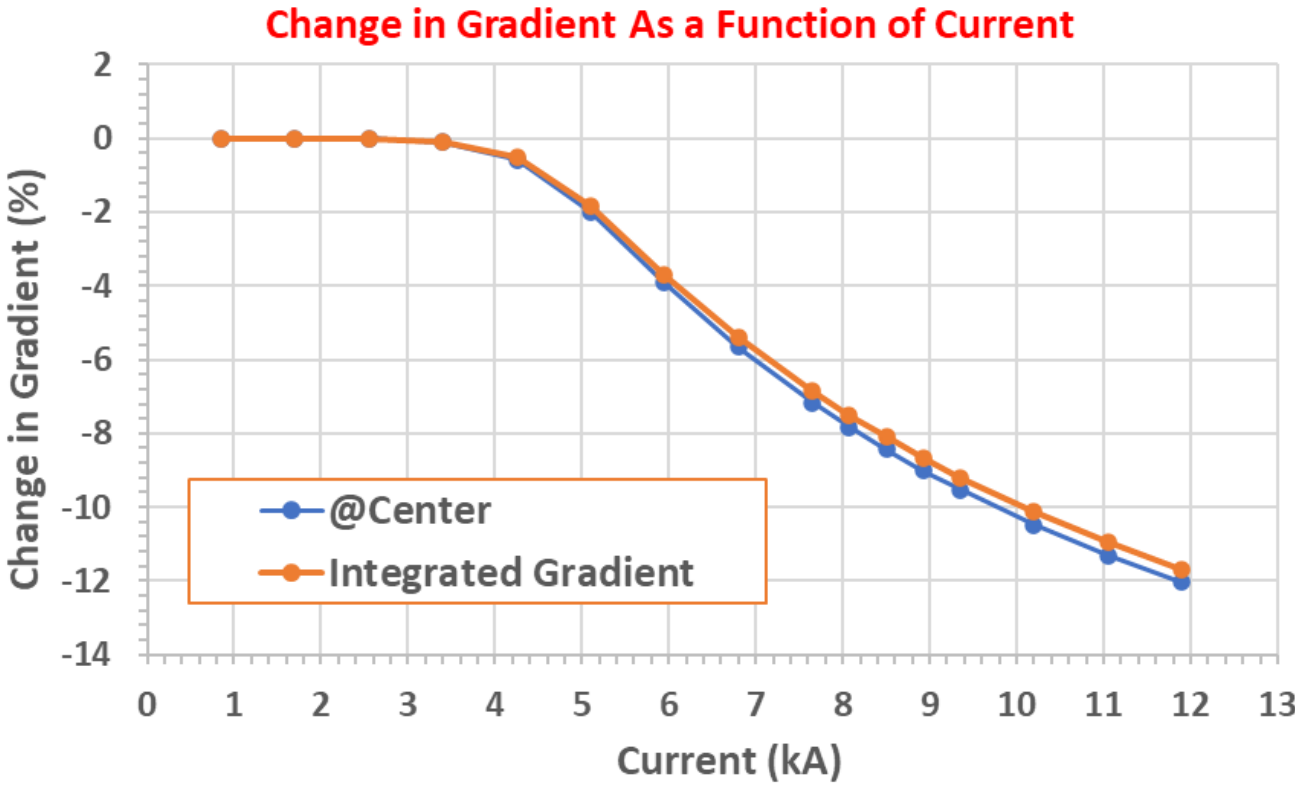


Note: An increase in effective length at high currents. That's because flux lines in yoke gets pushed out to ends which is not yet fully saturated while in body is

OPERA3d Calculations (5)
(Change in Effective Magnetic Length)

Note: An increase in effective length at high currents. That's because the flux lines in yoke gets pushed out to ends which is not yet fully saturated while in body it is

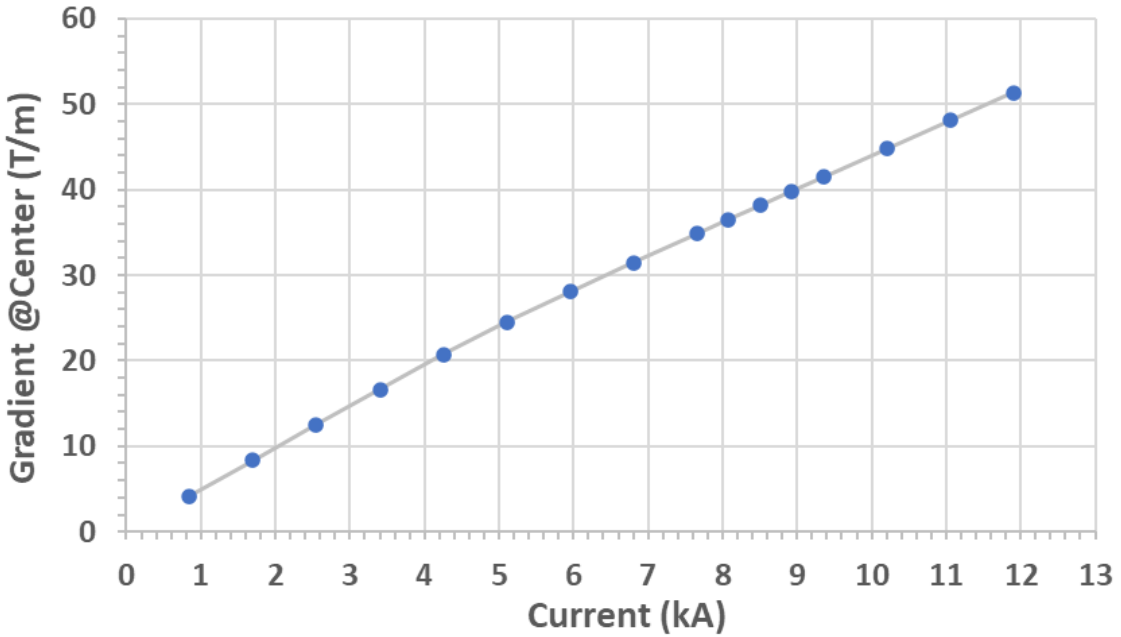




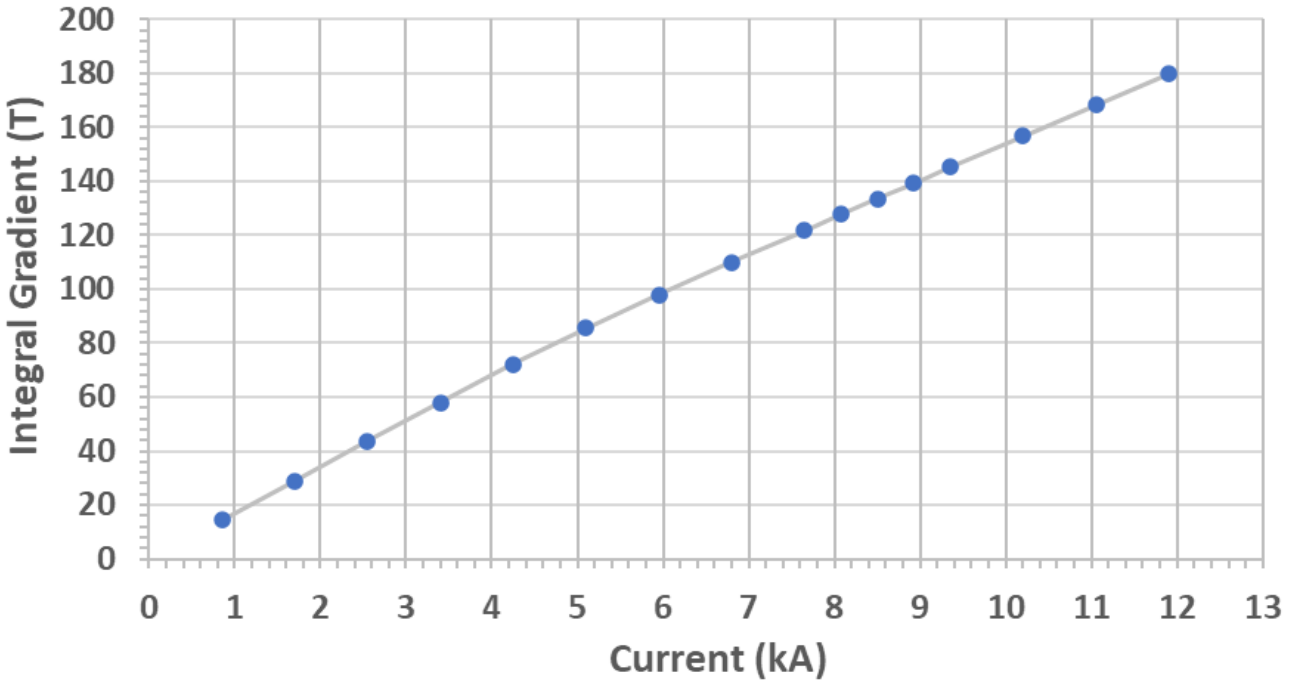
OPERA3d Calculations (6)

Scale		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95	1	1.05	1.1	1.2	1.3	1.4
Current	kA	0.85	1.7	2.55	3.4	4.25	5.1	5.95	6.8	7.65	8.075	8.5	8.925	9.35	10.2	11.05	11.9
Gradient @ center	T/m	4.174	8.348	12.521	16.678	20.749	24.545	28.070	31.499	34.875	36.550	38.218	39.880	41.538	44.840	48.128	51.404
Integrated Gradient	Tesla	14.533	29.065	43.597	58.078	72.279	85.595	97.974	110.005	121.840	127.707	133.550	139.370	145.171	156.727	168.229	179.687
Magnetic Length	meter	3.482	3.482	3.482	3.482	3.483	3.487	3.490	3.492	3.494	3.494	3.494	3.495	3.495	3.495	3.495	3.496
Transfer Function	T/m/kA	4.910	4.910	4.910	4.905	4.882	4.813	4.718	4.632	4.559	4.526	4.496	4.468	4.443	4.396	4.355	4.320
Integrated Transfer Function	T/kA	17.097	17.097	17.097	17.082	17.007	16.783	16.466	16.177	15.927	15.815	15.712	15.616	15.526	15.365	15.224	15.100
Change in TF	%	0	0.002	-0.002	-0.103	-0.576	-1.989	-3.925	-5.664	-7.159	-7.822	-8.434	-9.002	-9.528	-10.475	-11.301	-12.030
Change in ITF	%	0	0.001	-0.003	-0.090	-0.528	-1.835	-3.690	-5.381	-6.846	-7.499	-8.103	-8.665	-9.188	-10.129	-10.954	-11.683

Gradient As a Function of Current

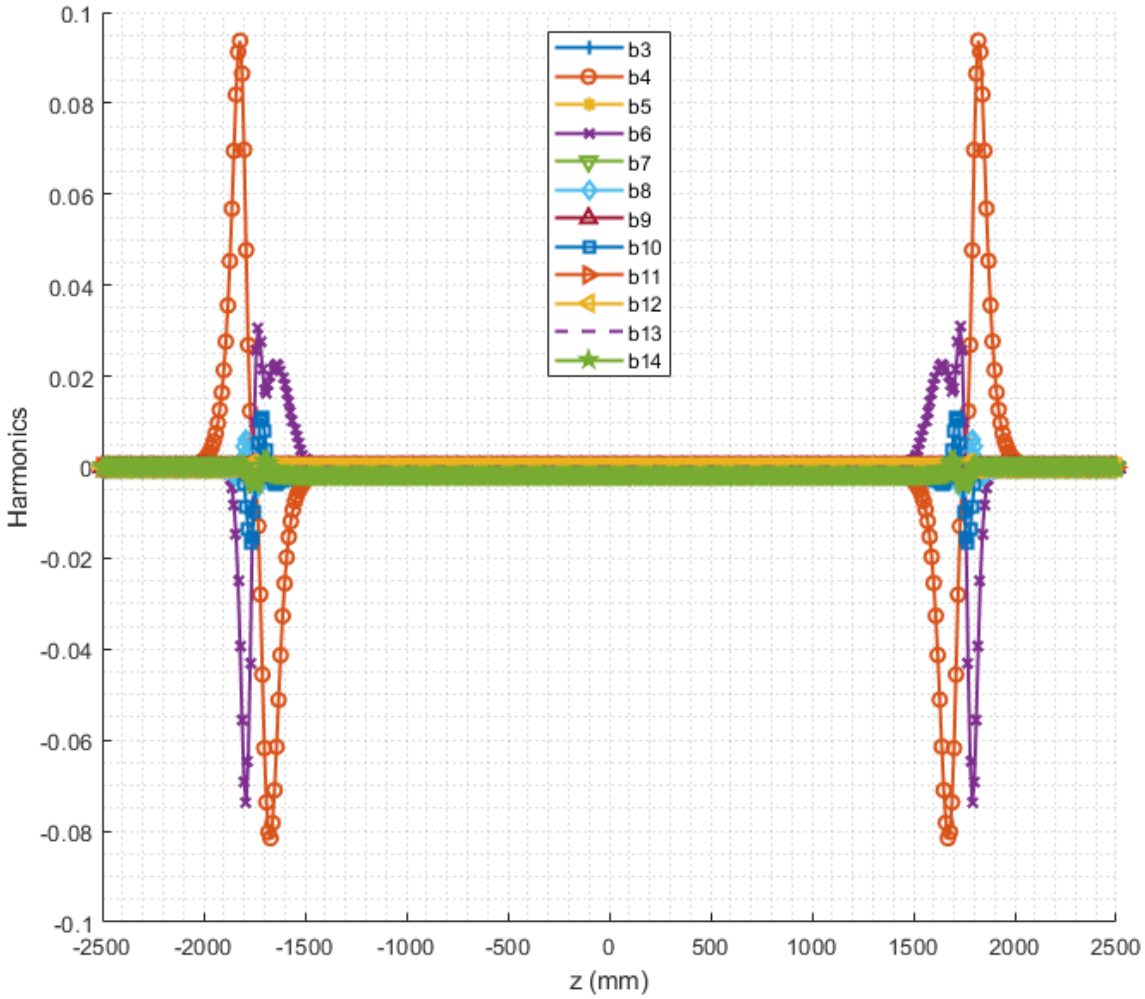


Integral Gradient As a Function of Current



Field Harmonics Integral and Local Variation Along the Axis at Different Excitation

Field Harmonics Along the Axis from OPERA3d at 8.5 kA (R=100 mm)



Tesla.Meter

	Bintegrated	Bintegrated_normalized
1	-0.000075181942410	-0.056263461075211
2	13.362480902036793	10000
3	0.000023024531717	0.017230731243597
4	0.000464056930494	0.347283512616857
5	-0.000024709142955	-0.018491433691162
6	0.000681847568507	0.510270191221260
7	0.000007583980080	0.005675577862652
8	0.000049237761469	0.036847769385237
9	0.000001467642652	0.001098330963445
10	-0.001333449316859	-0.997905498713160
11	-0.000000384123813	-2.874644427706261e-04
12	0.000004807661206	0.003597880693933
13	0.000000034910438	2.612571589112344e-05
14	-0.007018299871190	-5.252243144549428

Prime Unit

From Integral in Tesla.mm

Integral Harmonic Analysis of By
With Standard normalisation

Radius	Z1	Z2	Nz
100.0	-2500.0	2500.0	501.0

Order	A(n) Sine	B(n) Cosine
1	0.0	-0.080131631
2	1.784681E-13	13348.815276
3	-7.93366E-13	3.276125E-03
4	-3.17855E-13	0.4493765363
5	2.390401E-15	-0.025853542
6	-1.05553E-12	0.6544018569
7	-8.38545E-13	5.656591E-03
8	-1.63166E-12	0.0473328832
9	-4.75992E-13	6.077704E-04
10	-2.32249E-12	-1.329631599
11	-9.67382E-13	-3.48583E-04
12	1.245805E-12	4.666351E-03
13	-5.73861E-13	0.0207942551
14	-3.35004E-12	-7.032003009

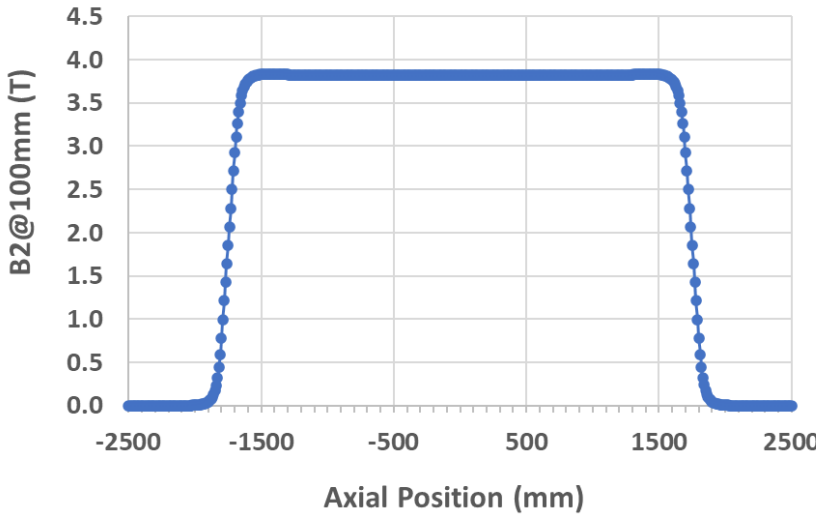
From Integral Prime Unit Normalized to 1

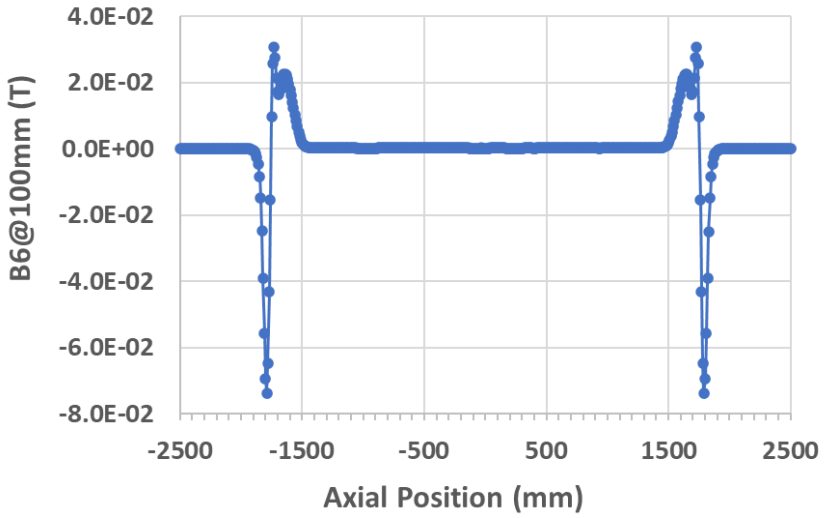
Integral Harmonic Analysis of By
With B_ref normalisation

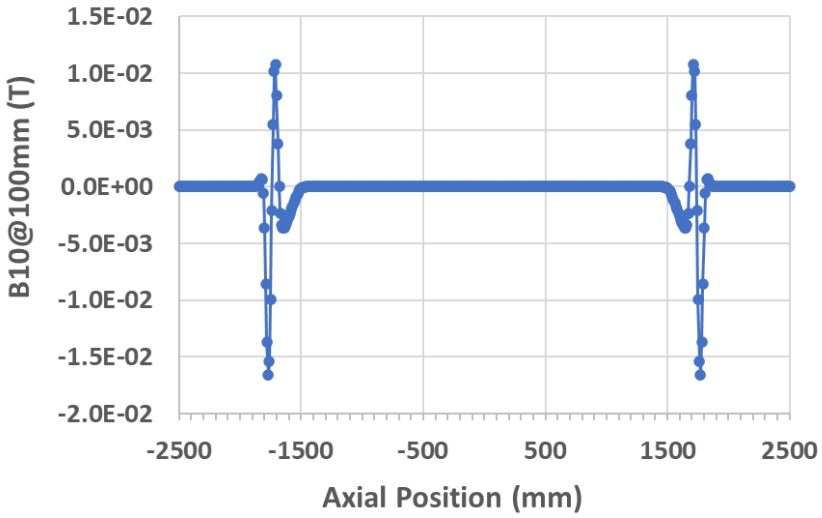
Radius	Z1	Z2	Nz
100.0	-2500.0	2500.0	501.0

Order	A(n) Sine	B(n) Cosine
1	0.0	-4.70112E-06
2	1.449232E-17	1.0
3	-1.30137E-17	1.029939E-06
4	-2.77545E-17	3.3324E-05
5	5.571918E-18	-1.96826E-06
6	-7.88904E-17	4.911349E-05
7	-6.60977E-17	5.532656E-07
8	-1.27164E-16	3.543308E-06
9	-3.52298E-17	6.569921E-08
10	-1.65716E-16	-9.96075E-05
11	-7.01948E-17	-2.52408E-08
12	1.003249E-16	3.500592E-07
13	-4.78382E-17	1.559448E-06
14	-2.43844E-16	-5.26786E-04

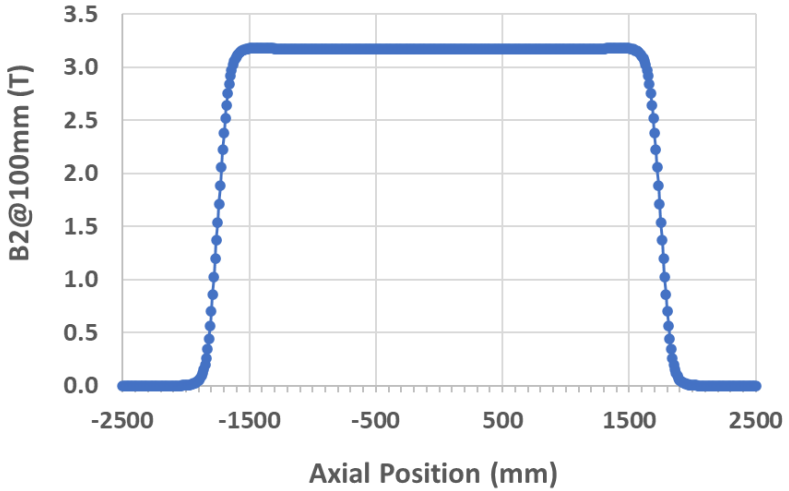
Field Harmonics Along the Axis from OPERA3d at 8.5 kA (R=100 mm)

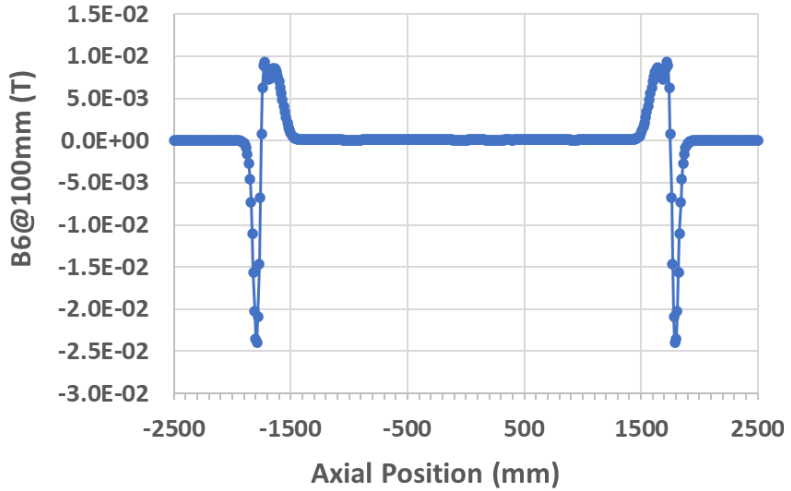


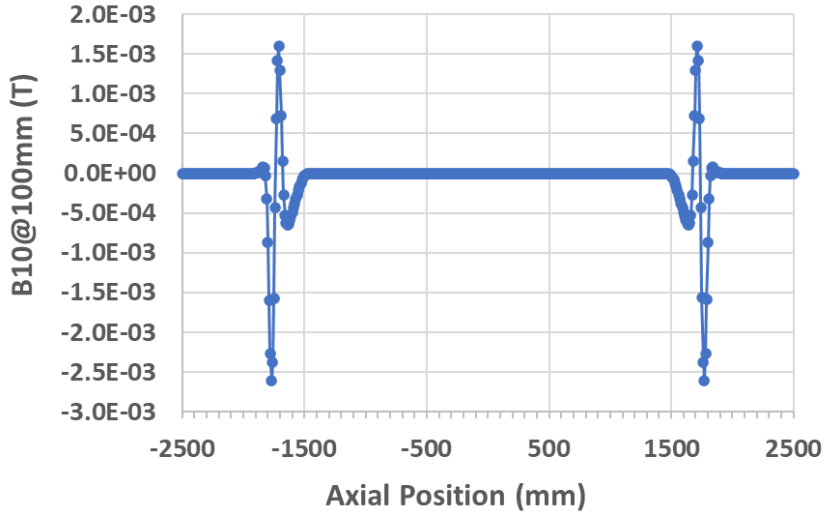




Field Harmonics Along the Axis from OPERA3d at 8.5 kA (R=83 mm)

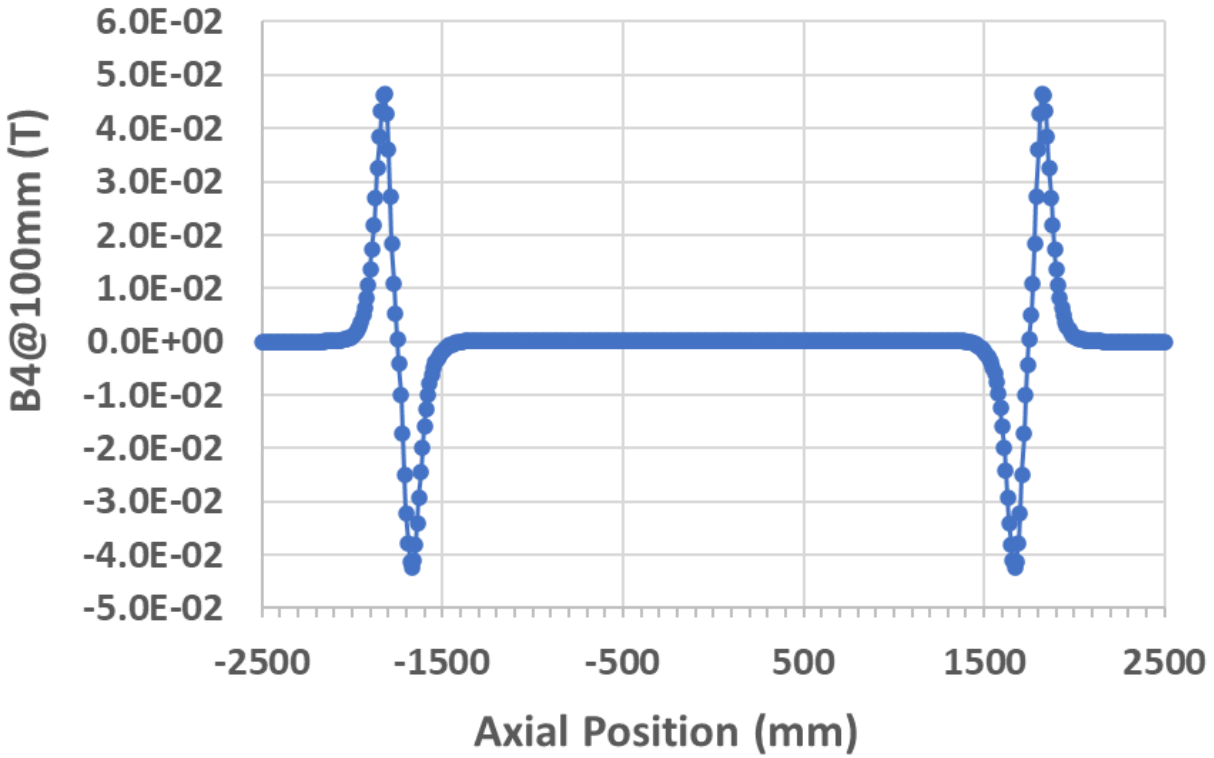


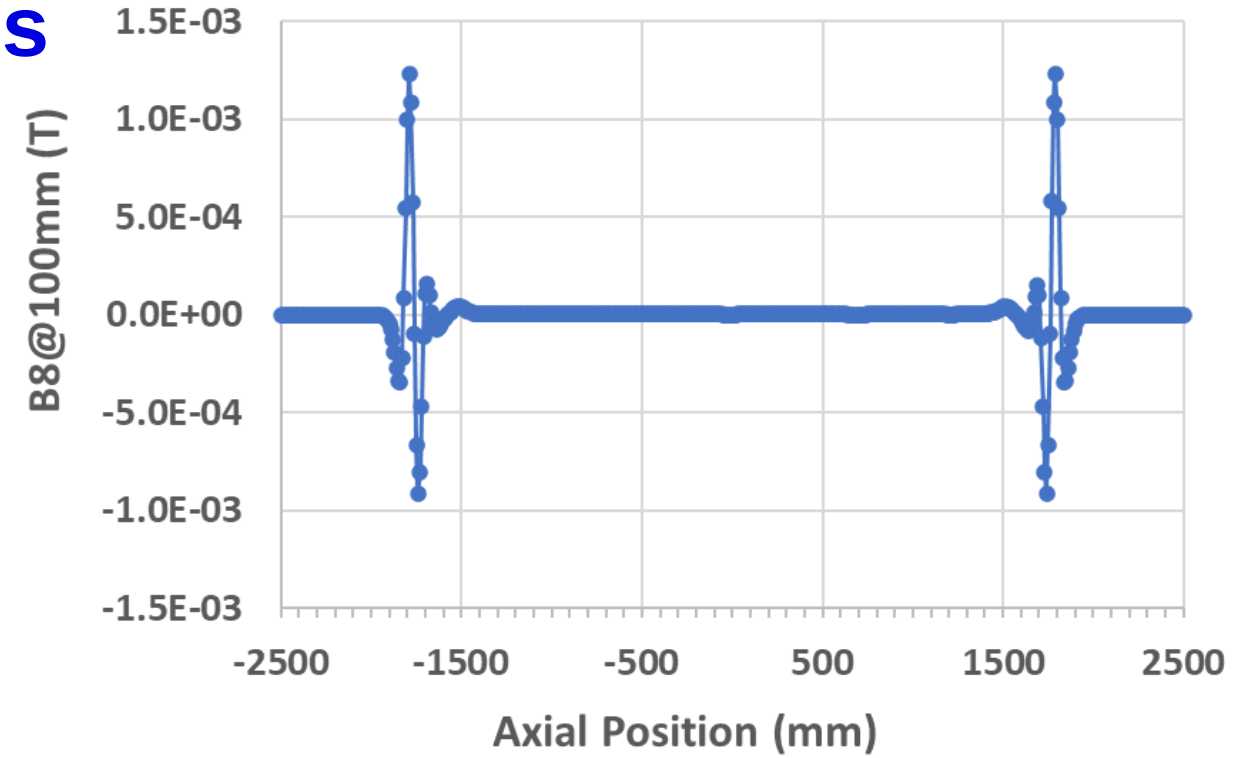




Field Harmonics from OPERA3d at 8.5 kA (R=83 mm)

Non-allowed harmonics across the length of the magnet





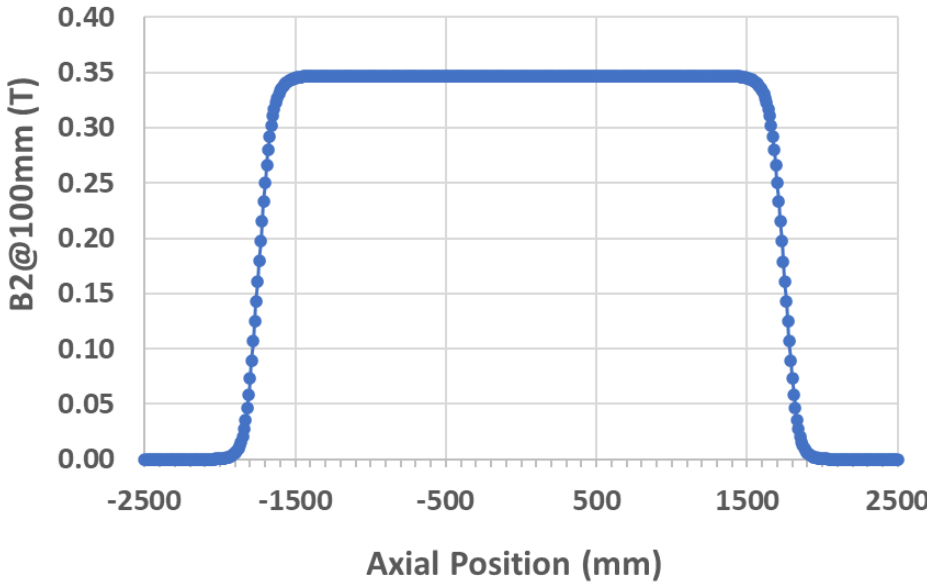
Is it real ?

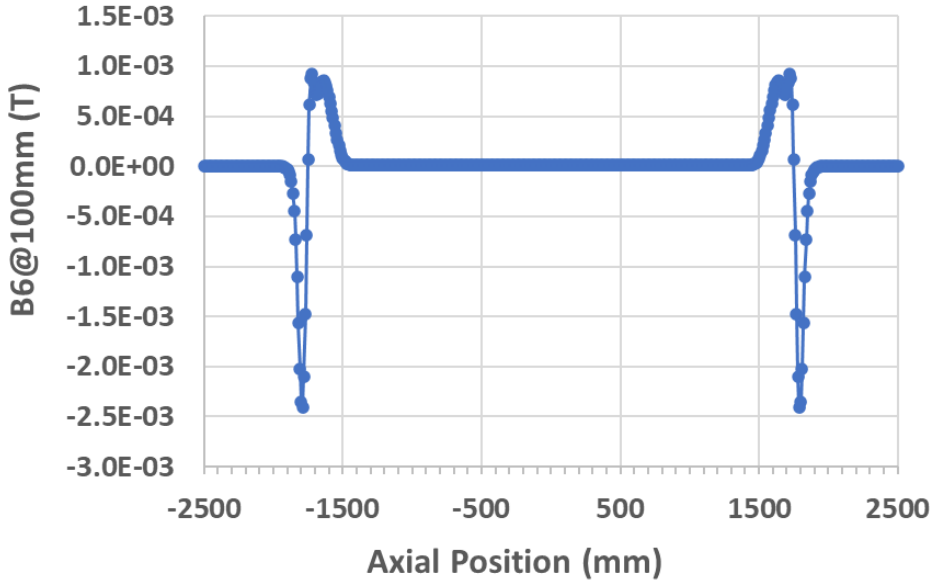
Either something happening at high fields or meshing or some coil description error!

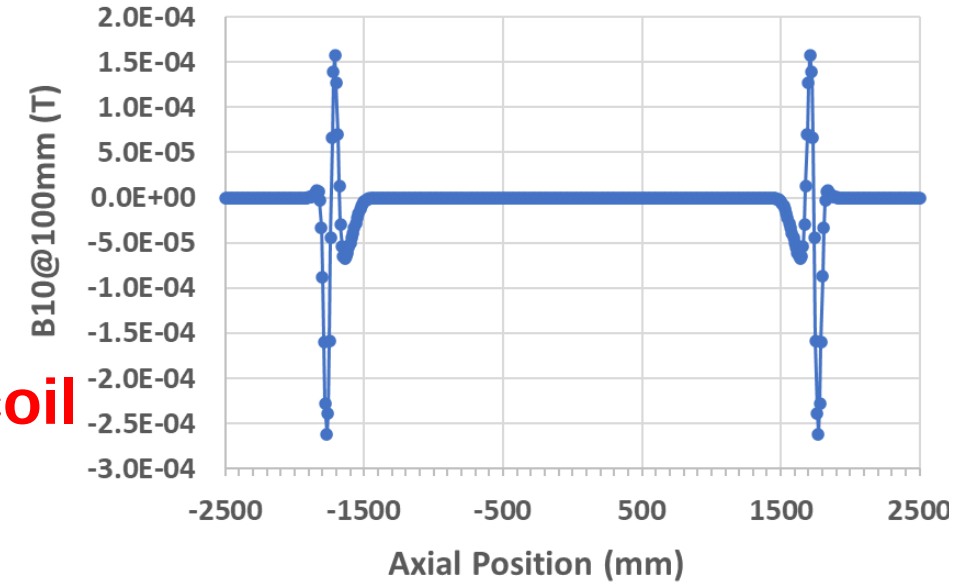
Field Harmonics from OPERA3d at 0.85 kA (R=83 mm)

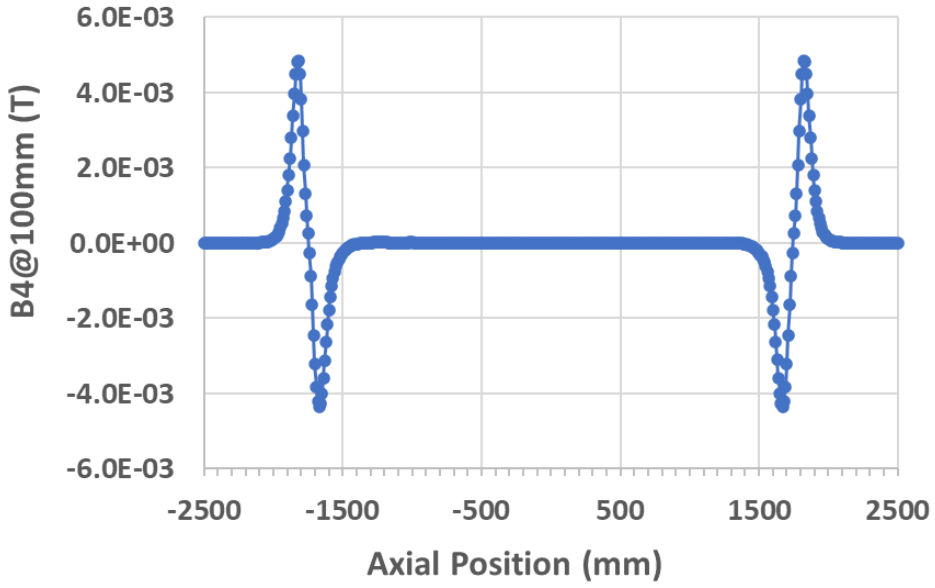
Check allowed (B2, B6 and B10) and Non-allowed Octupole harmonic (B4) along the length of the magnet at low fields

Doesn't look real since something is happening at low fields also. May be meshing or some coil description error!





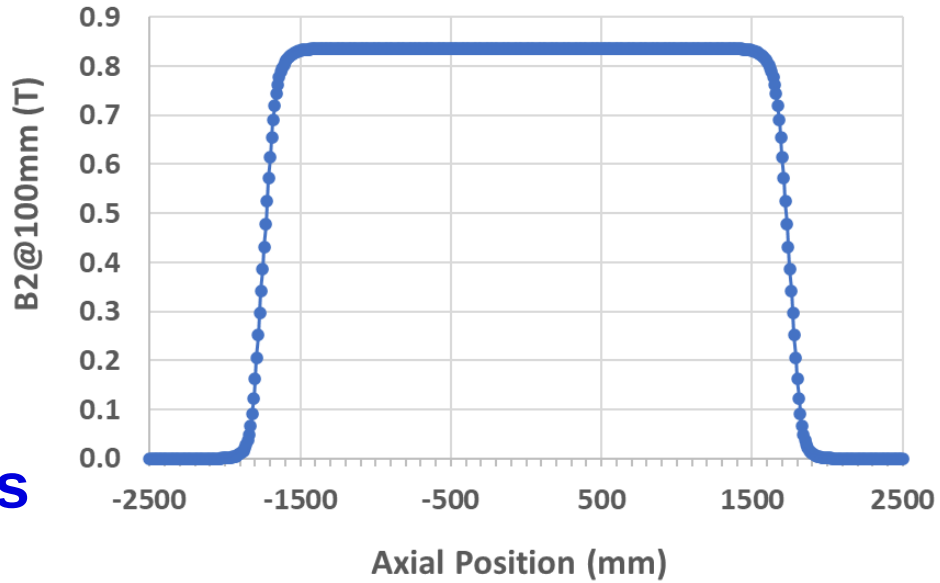


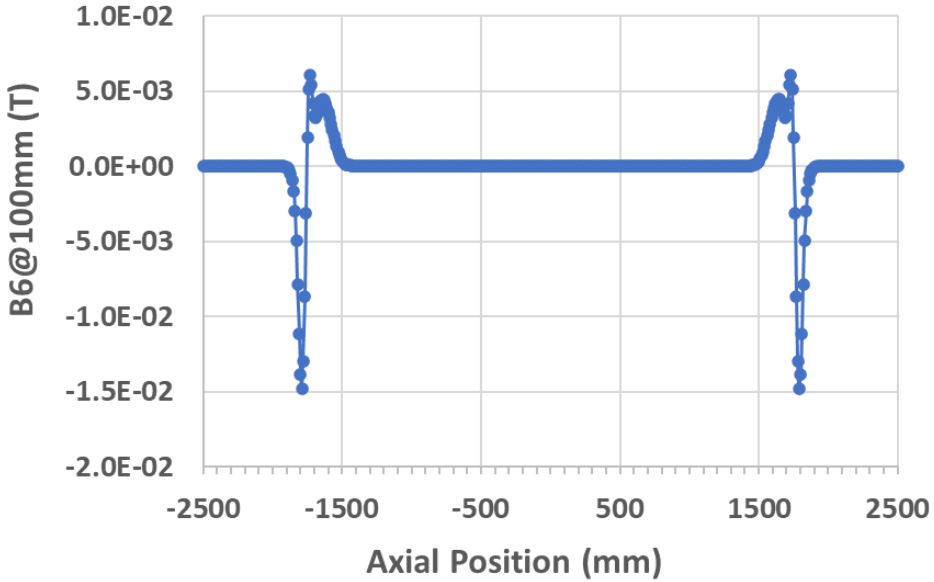


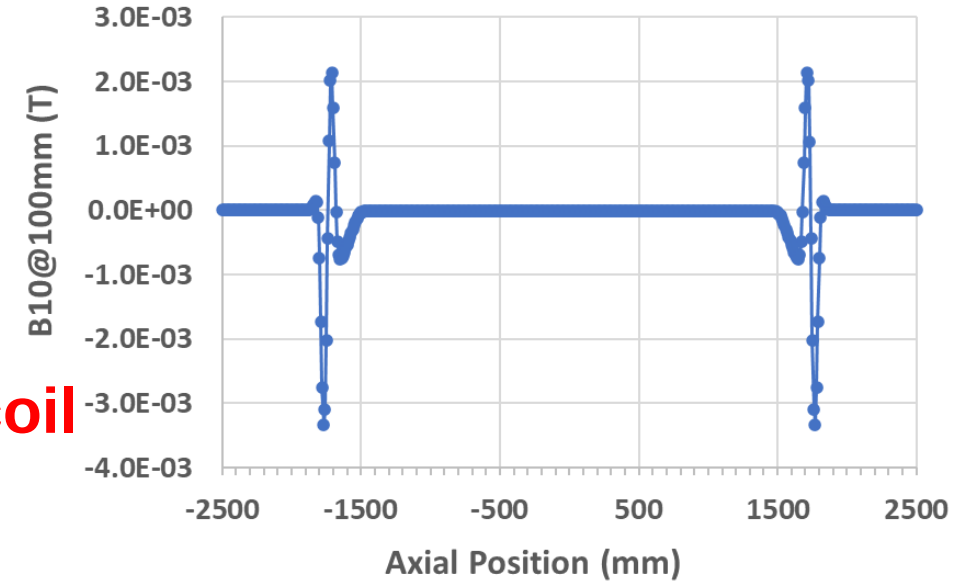
Field Harmonics from OPERA3d at 1.7 kA (R=83 mm)

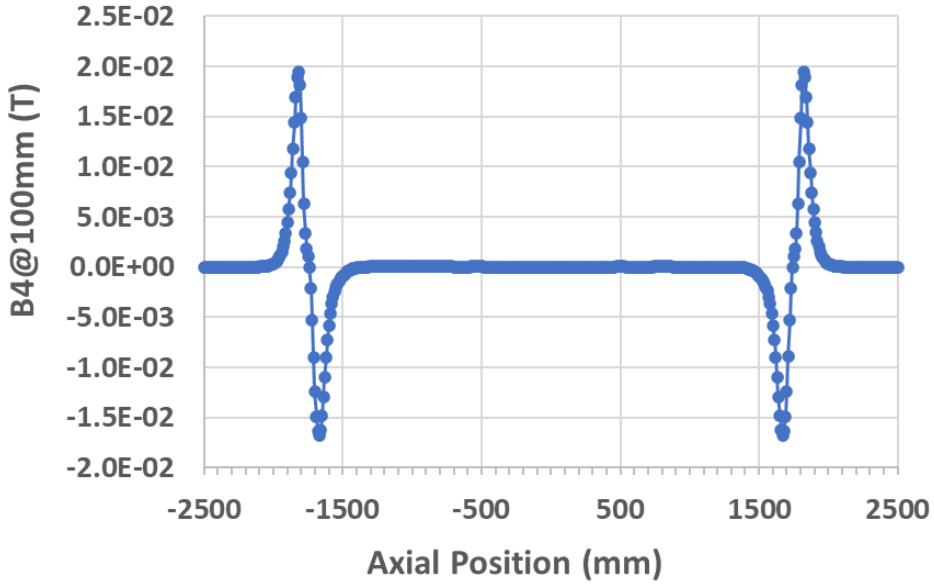
Check allowed (B2, B6 and B10) and Non-allowed Octupole harmonic (B4) along the length of the magnet at low fields

Doesn't look real since something is happening at low fields also. May be meshing or some coil description error!



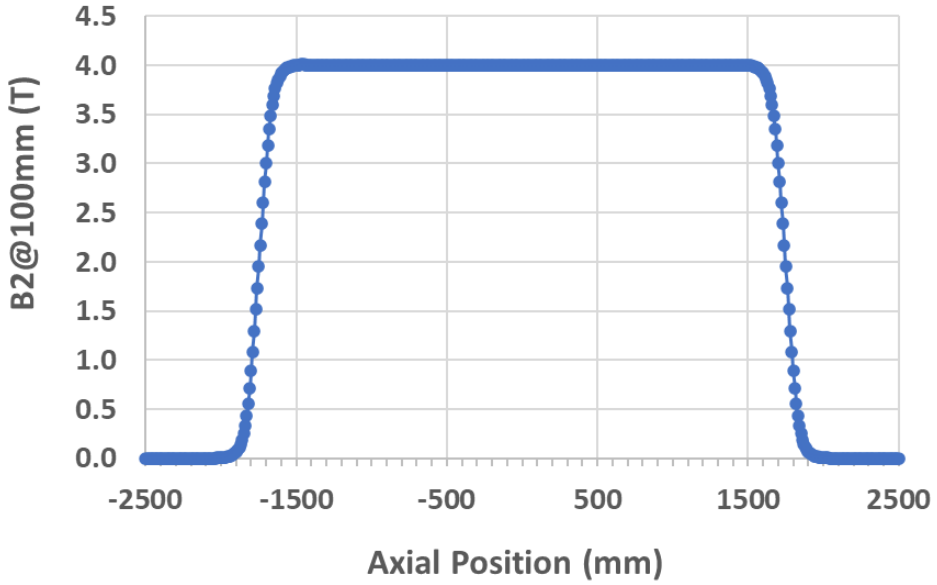


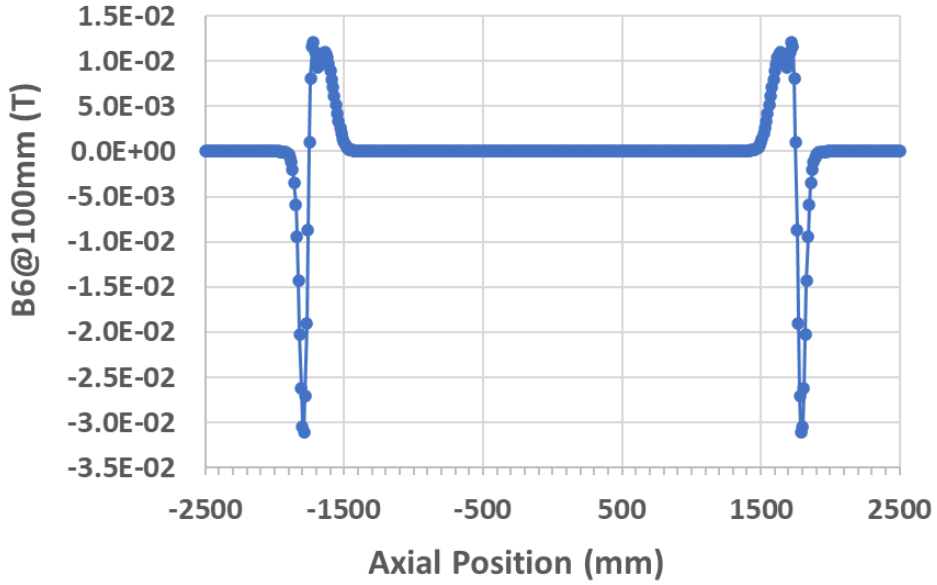


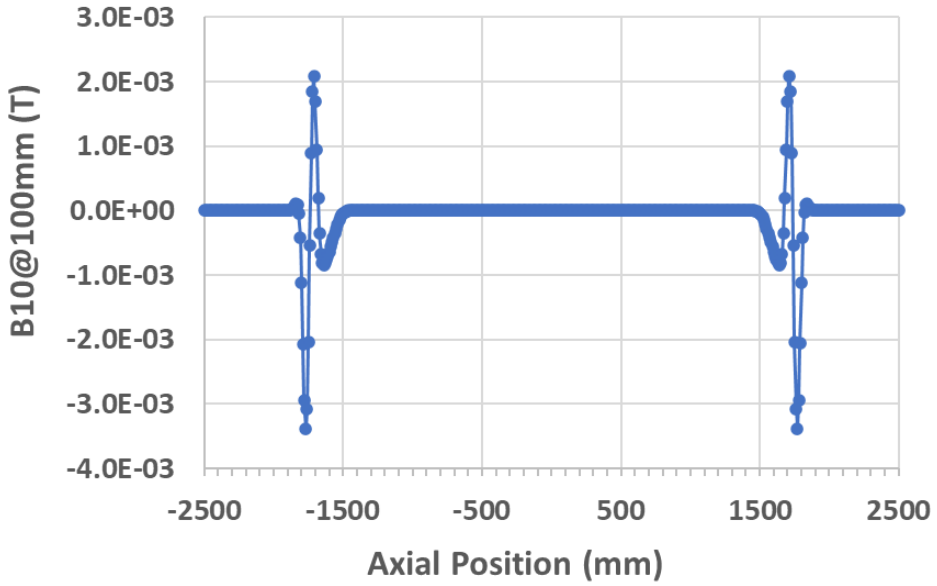


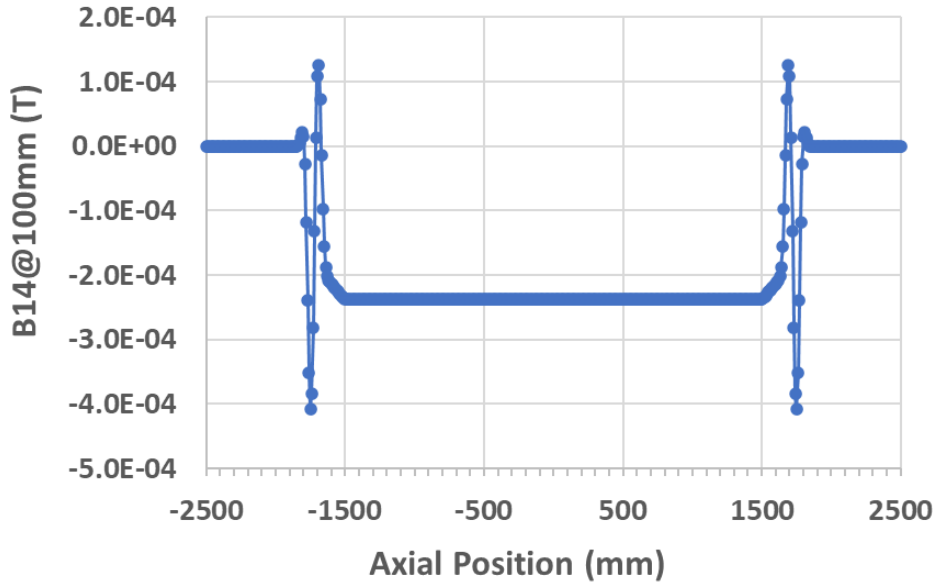
Field Harmonics from OPERA3d at 11.05 kA (R=83mm)

Allowed Harmonics









Summary

Extra Slides

Magnetic Length - Comparison from Initial Estimates

Initial estimates(4/13/2022): 3.66 m

Current value (8/23/2022): 3.58 m

Basic Parameters of the current Q2BpF Design

Parameters from pCDR:

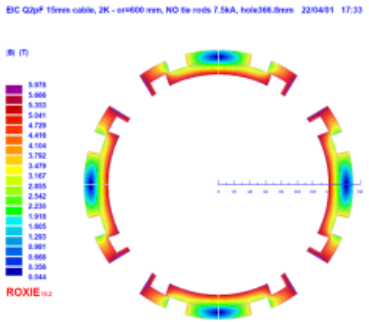
Table 6.6: Parameters Q2PF Magnet

Parameter	Value
Magnetic length [m]	3.8
Maximum gradient [T/m]	40.7
Aperture diameter (front) [m]	0.262
Aperture diameter (rear) [m]	0.262
Required field quality	1×10^{-4}
Physical length [m]	3.8
Physical width [m]	0.156
Physical height [m]	0.156
Superconductor type	NbTi
Conductor	Cable 20x2mm^2
Current density [A/mm^2]	512
Cu:Sc ratio	1.3
Temperature [K]	1.8
Peak field wire [T]	6.85
Magnetic energy [MJ]	3.0
Ampere turns [kA-t]	420
Number of turns	28
Current [A]	15000
Inductance [mH]	26.67
Margin loadline [%]	32

Parameters used in the current design:

- Gradient: 36 T/m (revised from pCDR, current 36.8 T/m)
- Physical Length: 3.8 m
- Coil inner radius: 140 mm
- Estimated effective length: 3.8 - 0.14 = ~3.66 m
- Estimated gradient in body: 36*3.8/3.66 = ~37.4 T/m
- Cable: 15 mm
  (LHC inner type)
- Cu/SC: 1.6
- Temperature: 2K

Design should be flexible to accommodate such changes



Q2pF Cross-section (15 mm cable @ 2K)

Integrated Harmonics (low enough)

```
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 .......................      300
LENGTH OF VIRTUAL COIL (mm) ......................   3000.0000
REFERENCE POSITION NUMBER ........................        10
MEASUREMENT TYPE ..................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................  0.5637E-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) .............................   1740.6647

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:     -0.08941
b 7:     -0.00000  b 8:     -0.00000  b 9:     -0.00000
b10:     -0.20212  b11:      0.00000  b12:      0.00000
b13:     -0.00000  b14:     -0.52143  b15:     -0.00000
b16:     -0.00000  b17:     -0.00000  b18:      0.01153
```

Reference field at 8500 A (mirror iron)

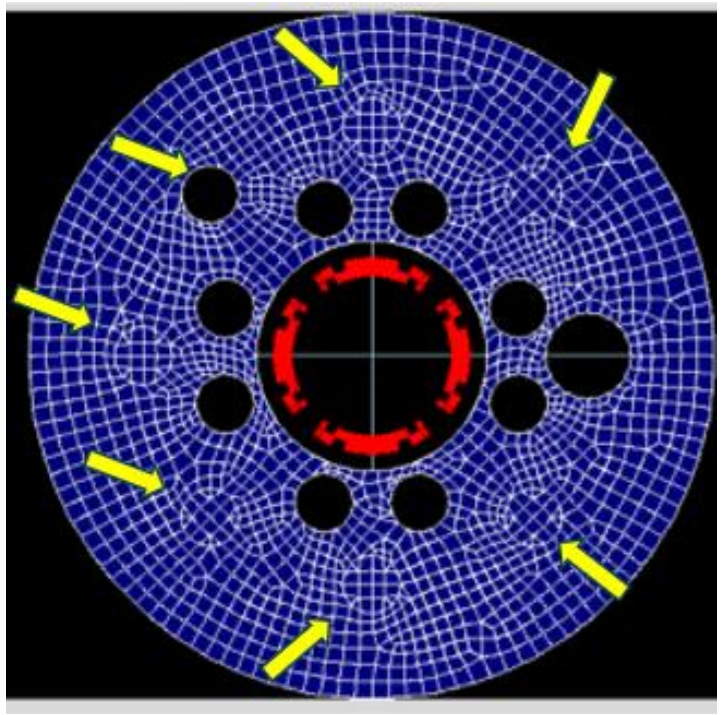
Magnetic length (mirror iron): 2X1.74 = 3.58 meter

Tip to tip coil length: ~3.65 meter

For reference: Magnet length in pCDR: 3.8 m

The two estimated values of magnetic lengths are close. New (current) value is a bit smaller than initial estimates since the overall coil length had to be a bit lower to make everything fit in the available slot length of 3.8 meter

Initial OPERA3d Models



ROXIE (2d)