Initial Design Studies for the Tapered Q1ABpF

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Date: December 4, 2025

Tapered Cosine Theta Coil Design Principle

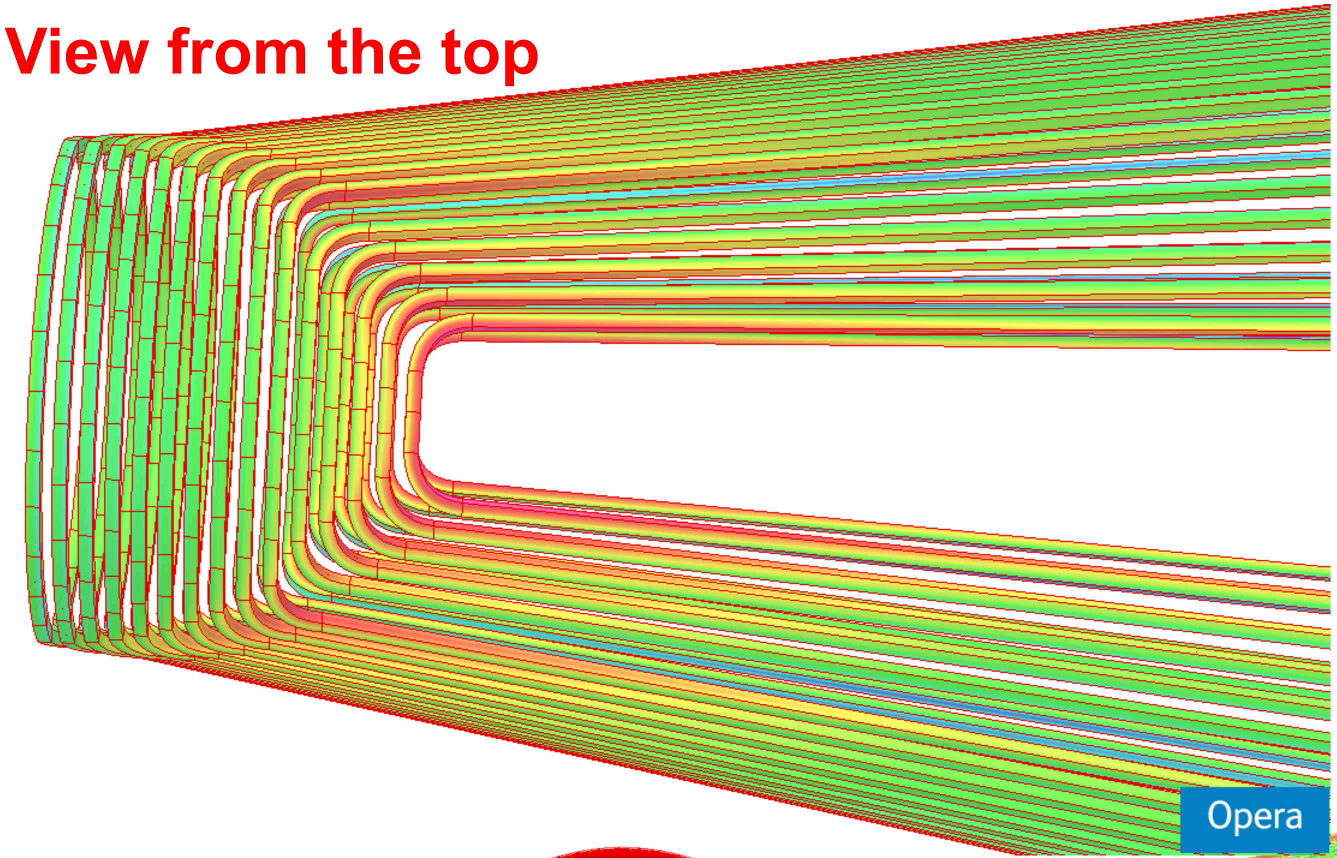
- Conventional Design Principle: to assure a good field quality, each wire maintains the same angular position while the coil radius is changing
- Issue: If the taper, i.e., the change in radius is large (as is the case in several EIC magnets), there will be a significant empty space between the turns on the far end, causing a large loss in field or field gradient
- Proposed remedy: Find configurations which minimize the empty space between the turns and pack as many turns as possible despite the taper
    - ➢ **If not, the loss becomes significant in critical high field magnets.**
    - ➢ **A few approaches have been explored to reduce this loss.**

✓ **Outcome: The basic approach which Vikas is pursuing is the best suited in the parameter set of Q1AbpF (may be with a few mods)**

Slides from an Earlier PBL/BNL Presentation

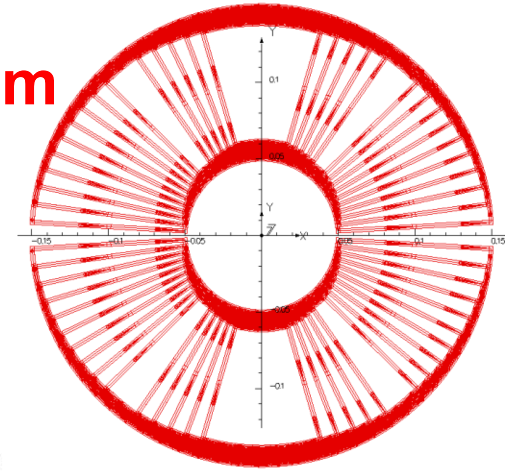
Conventional Design of a Tapered Cosine Theta Dipole

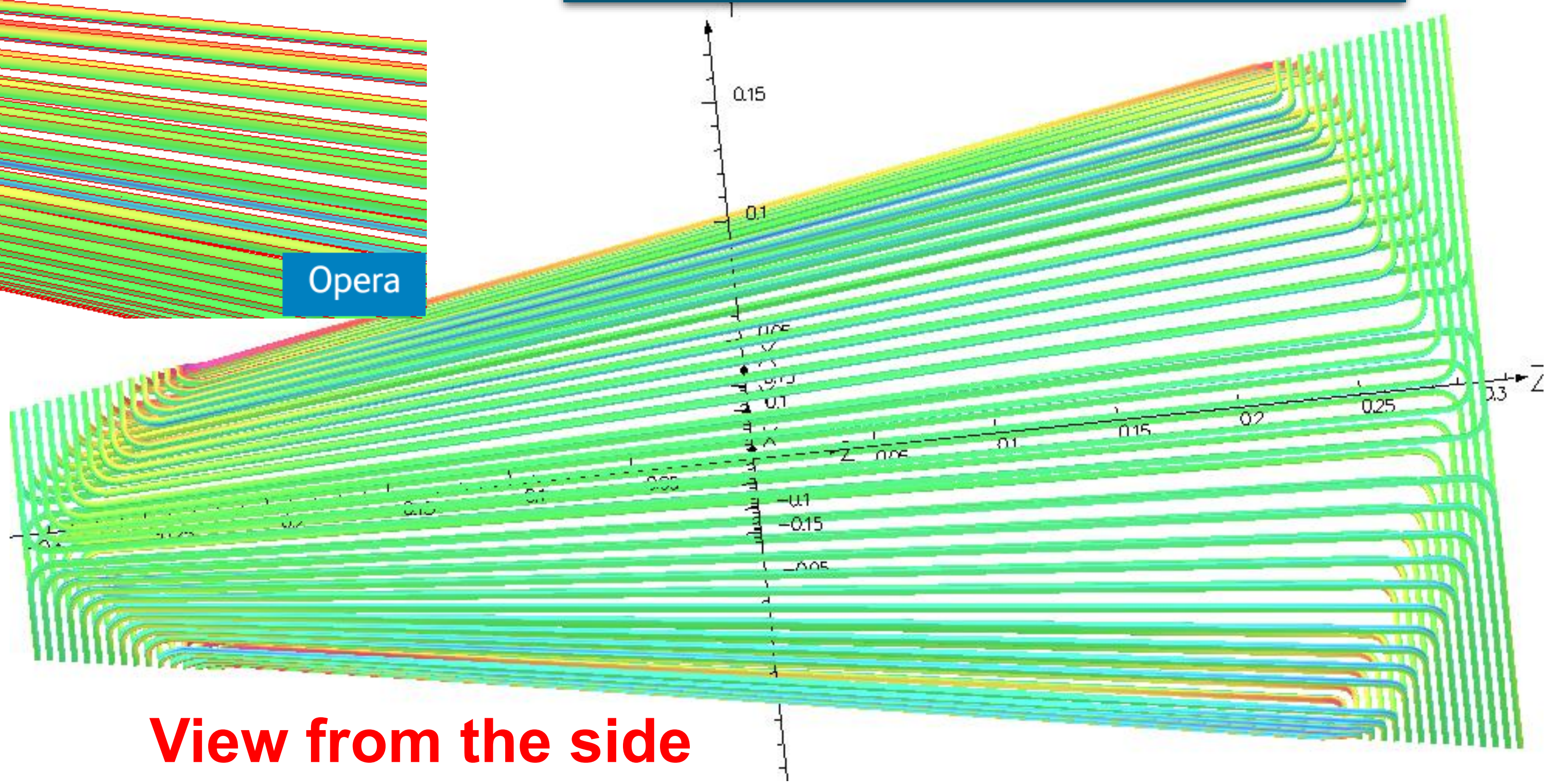
View from the top



Wire maintain their angular position while radii change

View from the end





View from the side

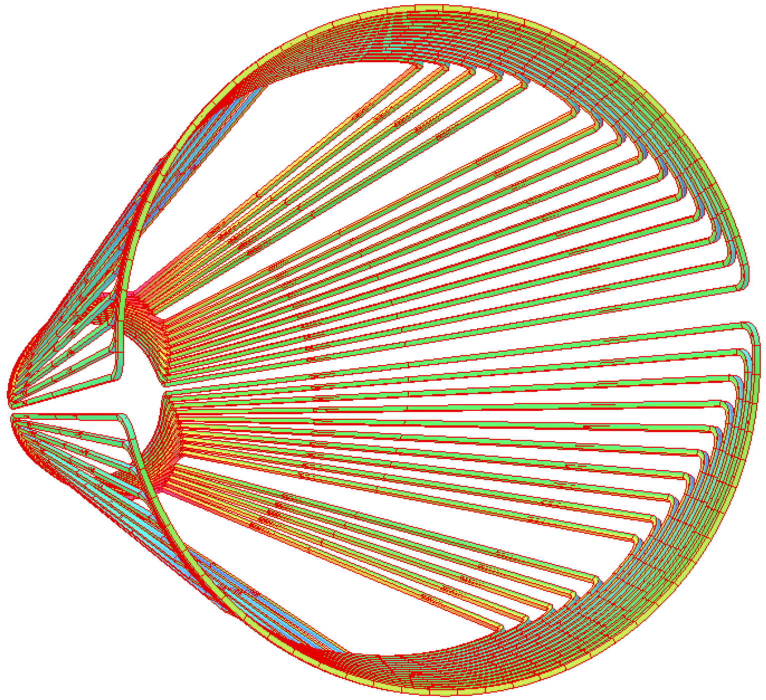
Positives and Negatives of the Conventional Cosine Theta Tapered Dipole

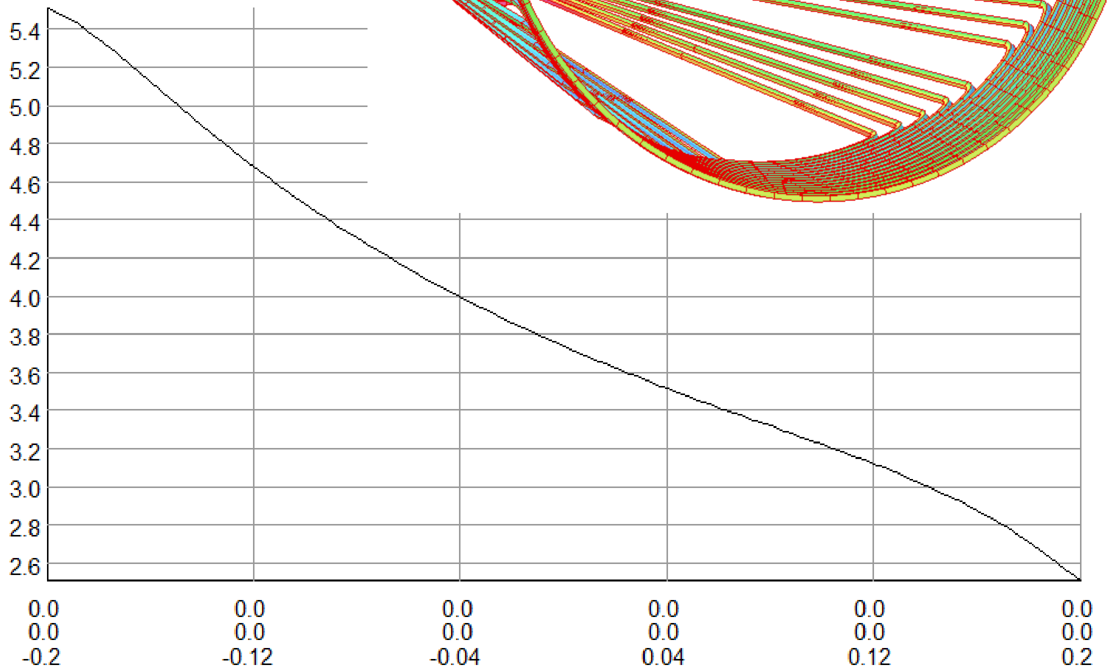
Positives:

- Design is simple to understand
- Good harmonics are assured

Negatives:

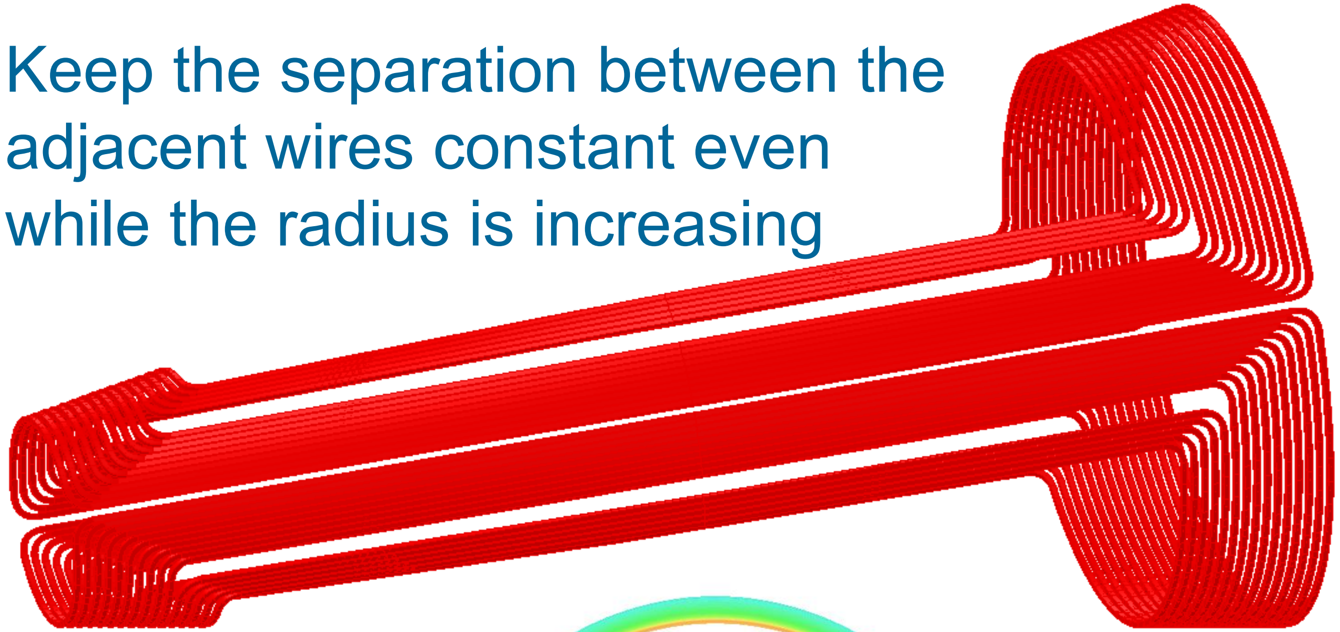
- Number of turns is limited by the side having smaller radius
- Field strength along the axis decreases as the radius increases

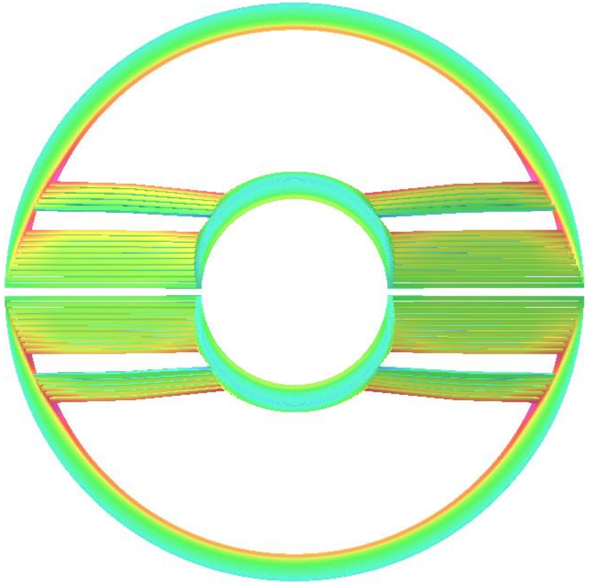




Proposed Design - Step #1

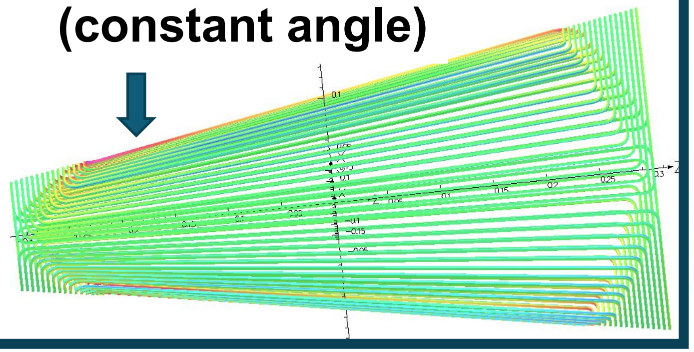
Keep the separation between the adjacent wires constant even while the radius is increasing

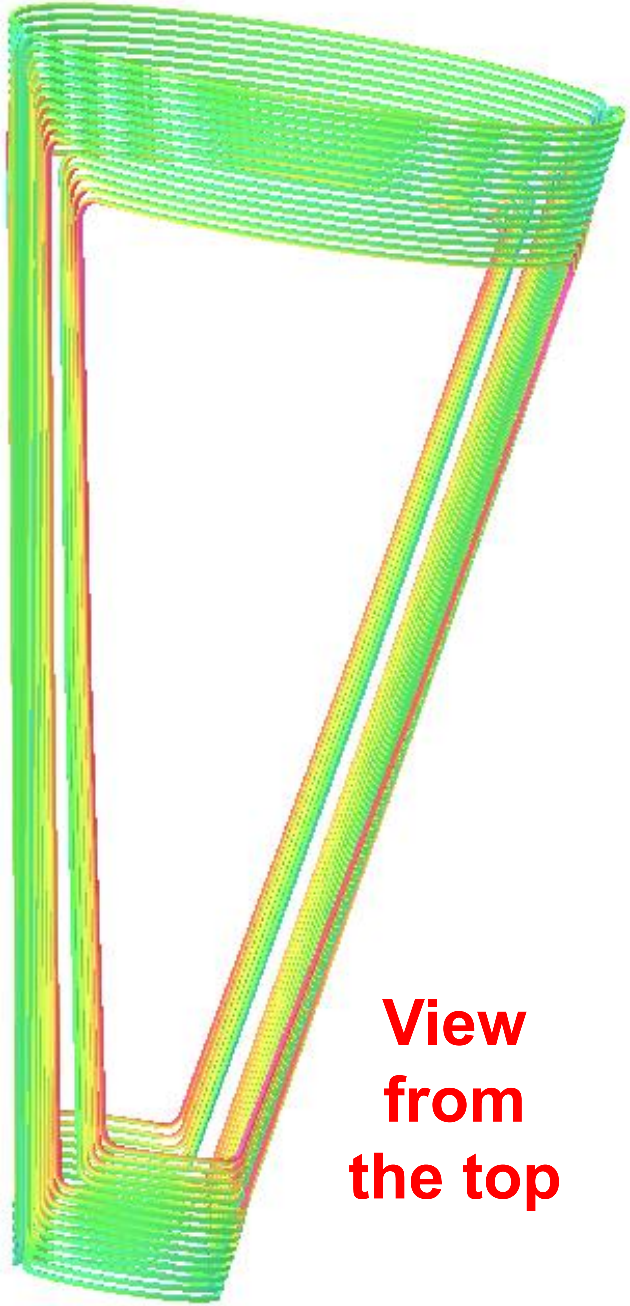




View from the end

Original case (constant angle)

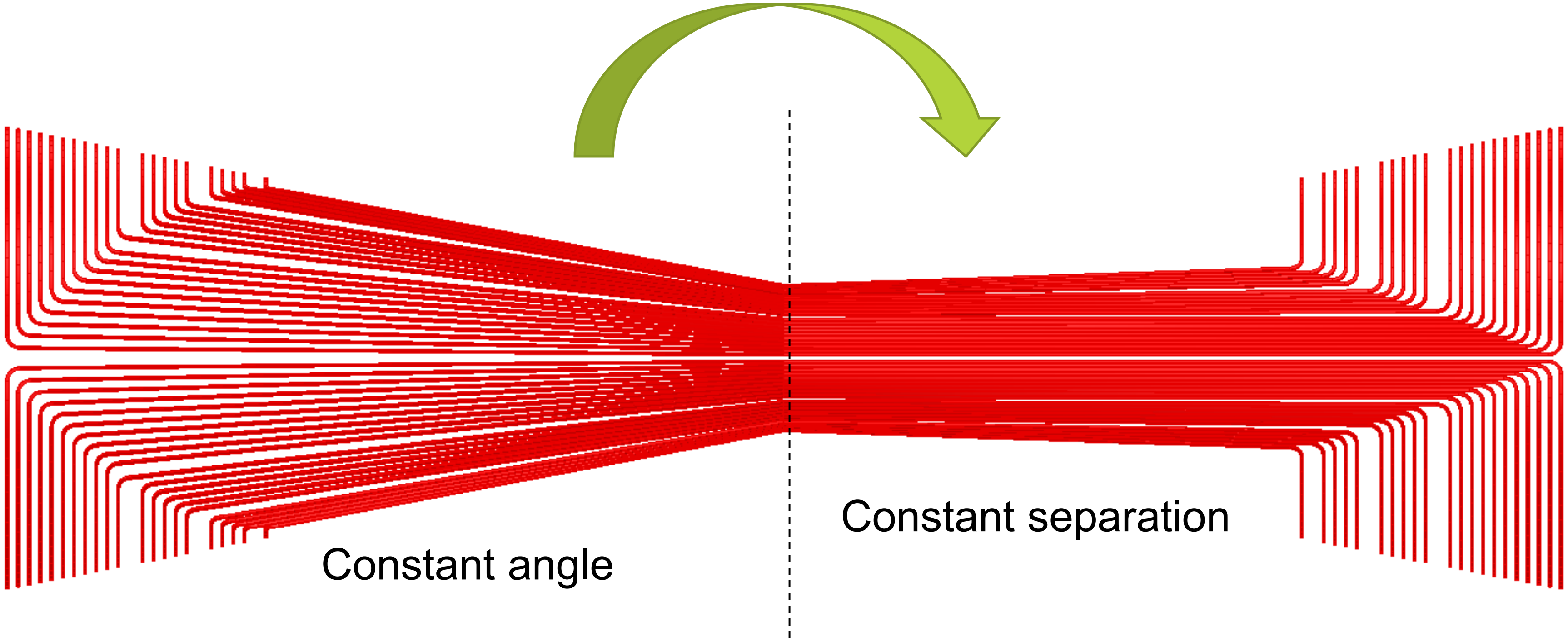


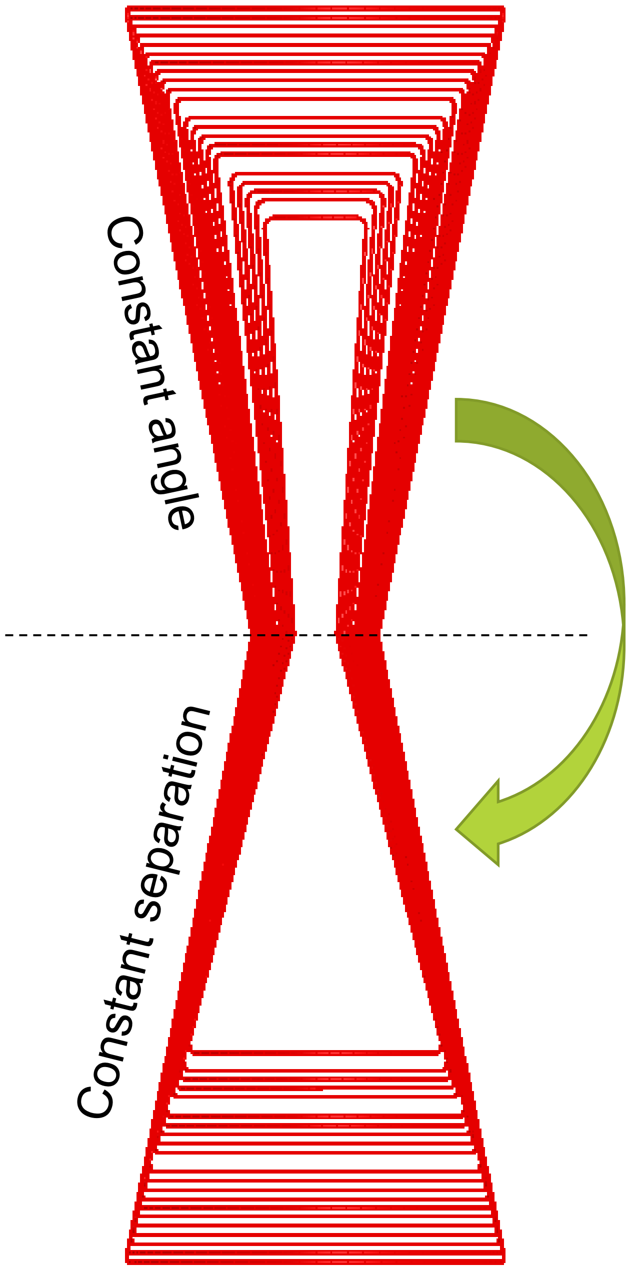


View from the top

Proposed Design – Step 1

Wind pattern with a "*<u>constant separation</u>*" *between the turns* along the length of the taper

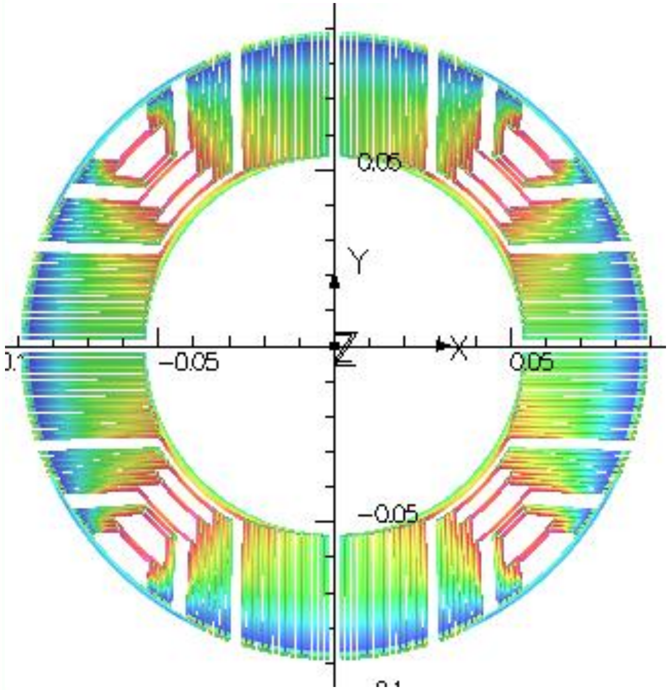


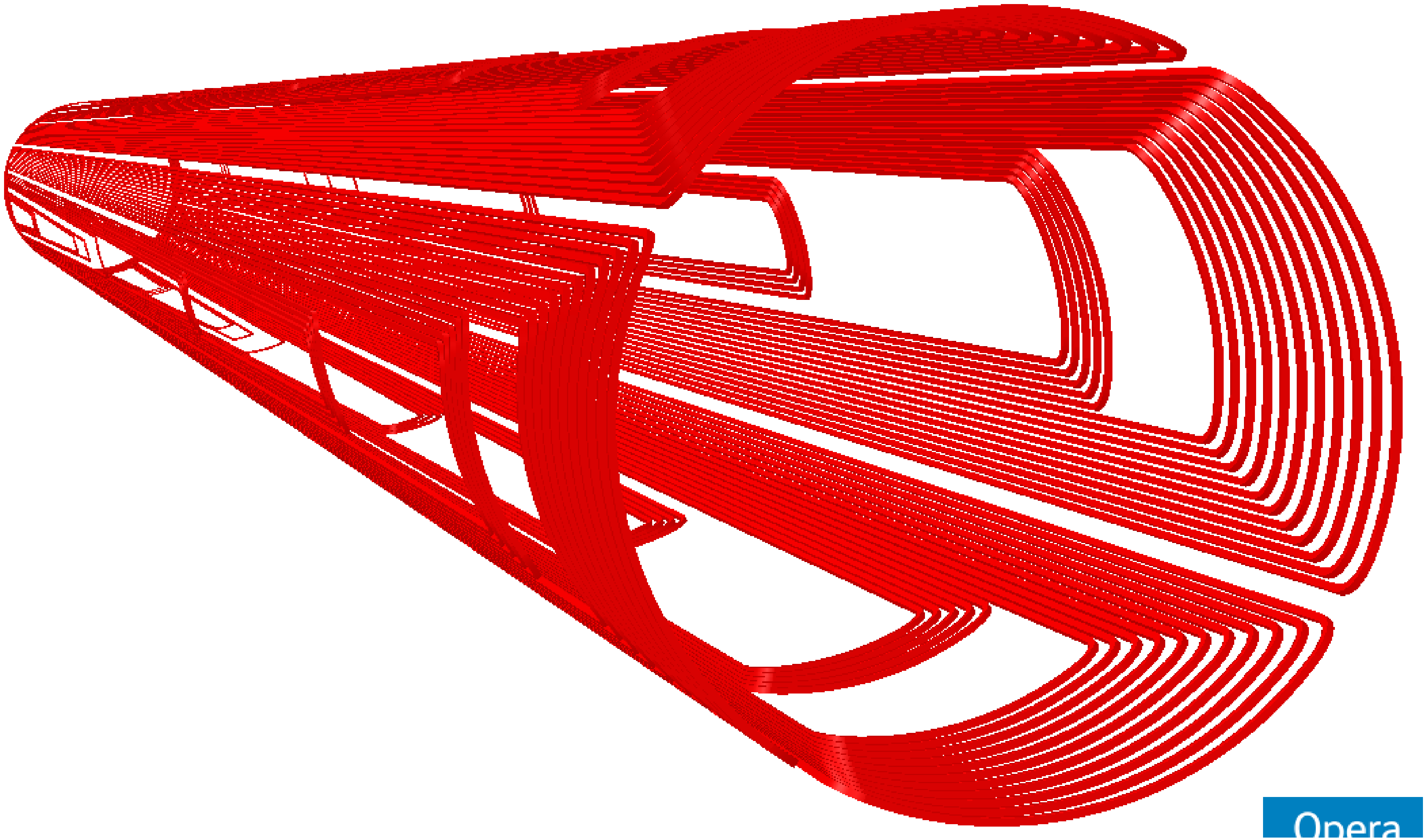


L= 3.5 m, Taper: 107.4 mm (IP) and 180.9 m (non-IP)

Proposed Design - Step #2

➢ **Add more turns (with increasing radius) in longitudinal space created in step #1**

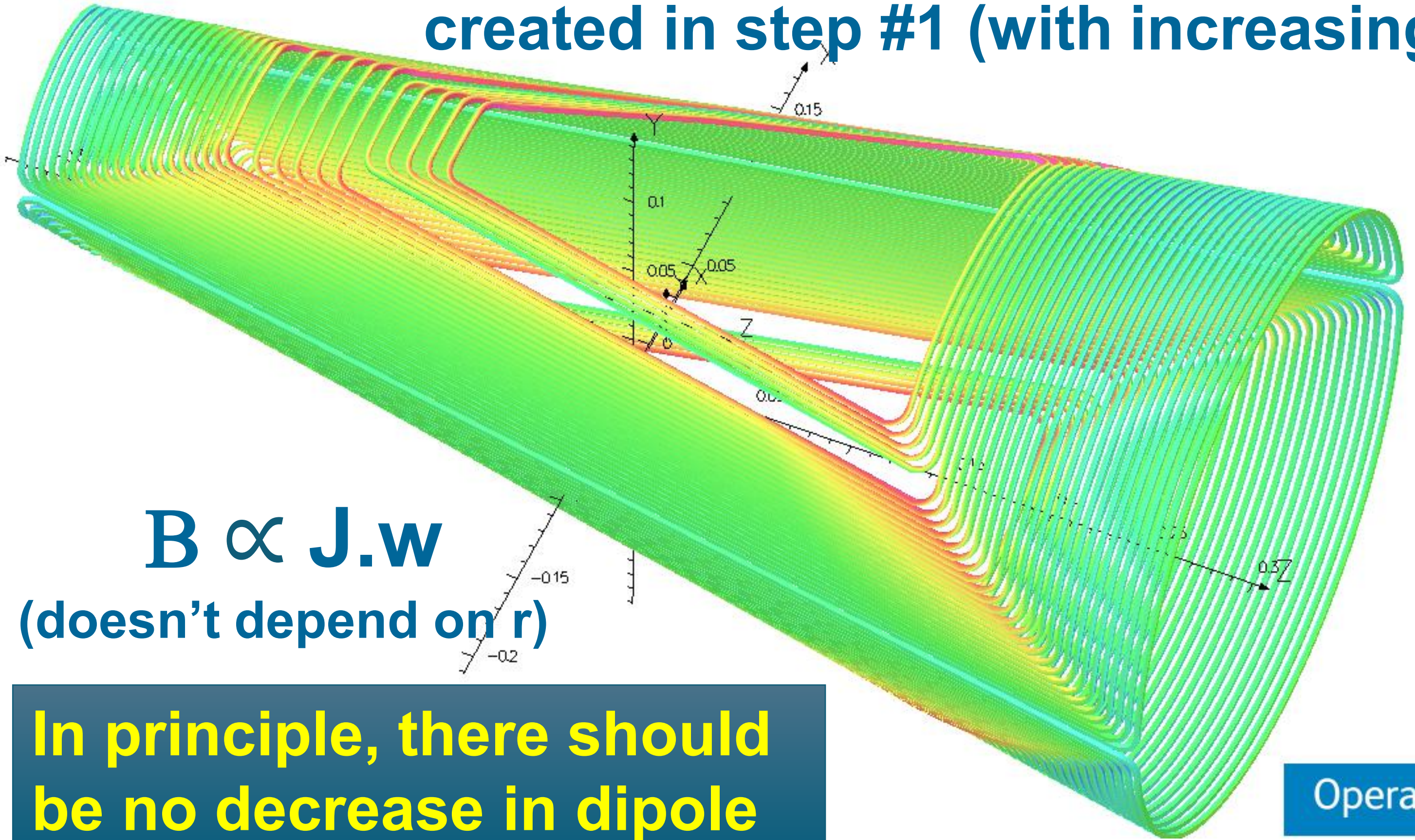




Proposed Design - Step #2

Constant Spacing

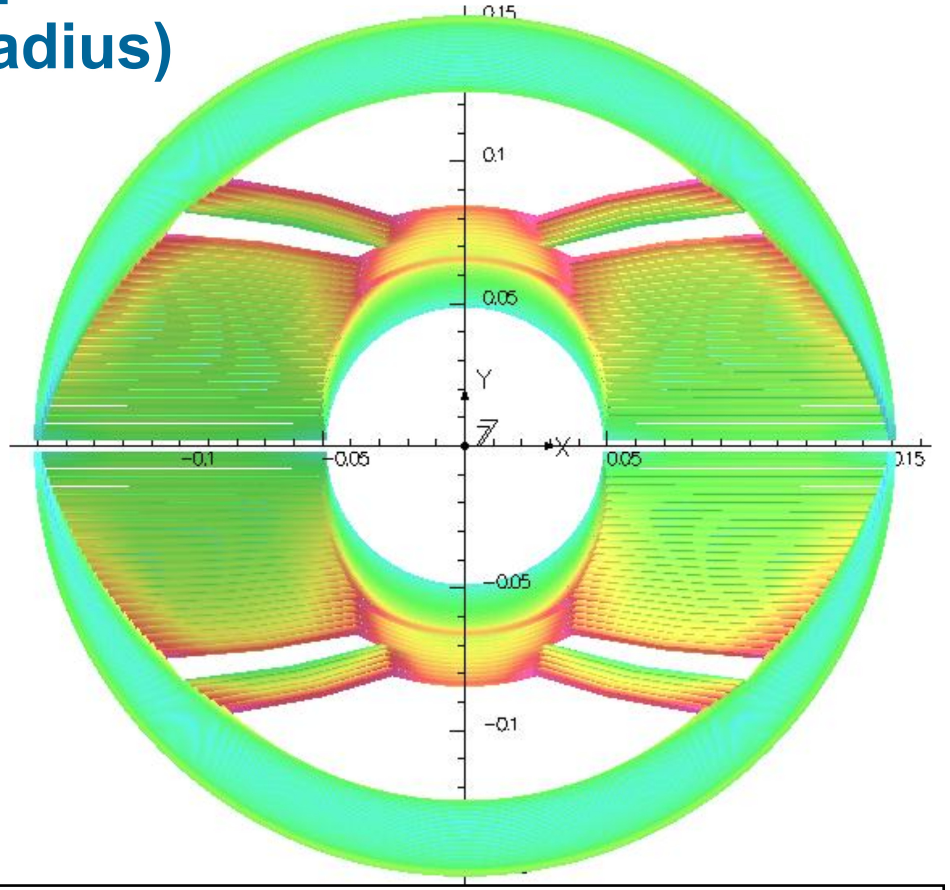
➤ Add more turns in the longitudinal space created in step #1 (with increasing radius)



$\mathrm{B} \propto$ **J.w**

(doesn't depend on r)

View from the end



In principle, there should be no decrease in dipole field strength for the same conductor width

Harmonics must be optimized carefully. They will vary locally but are made small when integrated over certain (small) length. **2-d harmonic definition is not valid.**

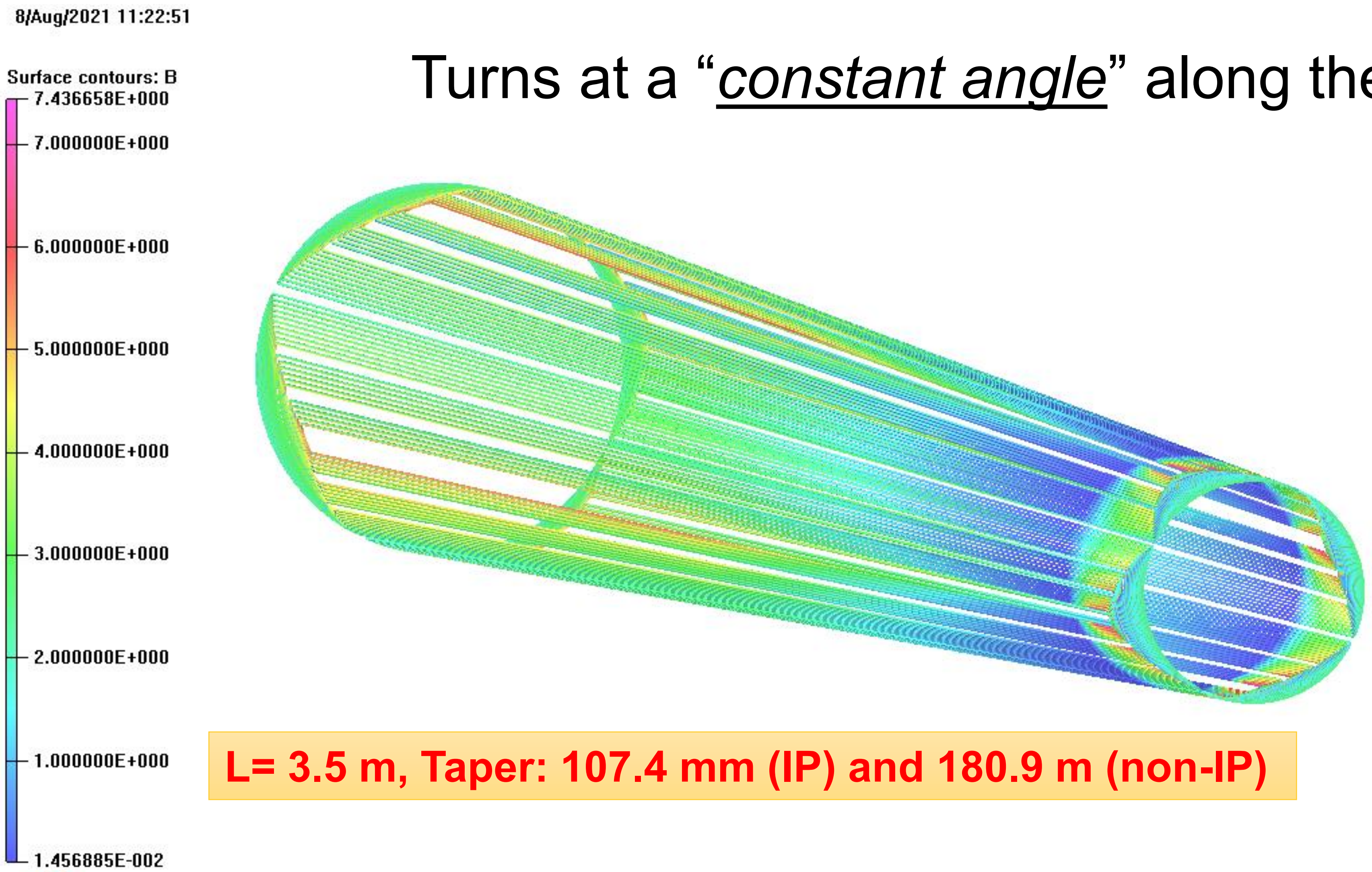
EIC Magnet to be evaluated for SBIR: Q1AB

(to see if there is any real advantage of this approach)

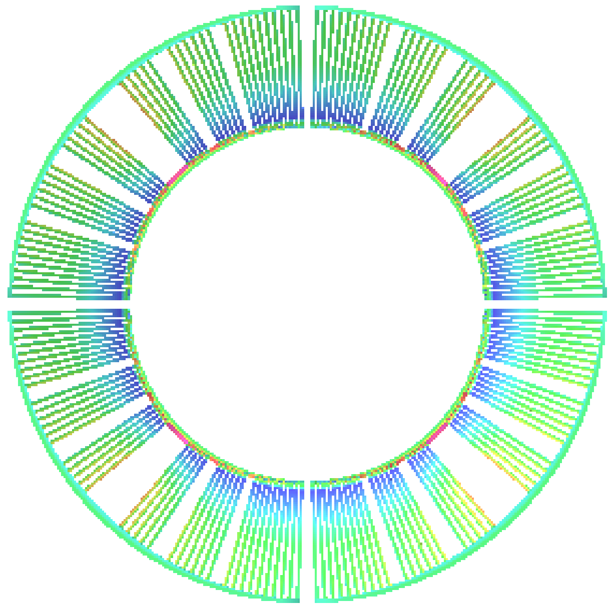
Parameters of the current design will be used

EIC Cosine Theta Tapered Quad Q1AB (conventional design)

Turns at a "*<u>constant angle</u>*" along the length of the taper



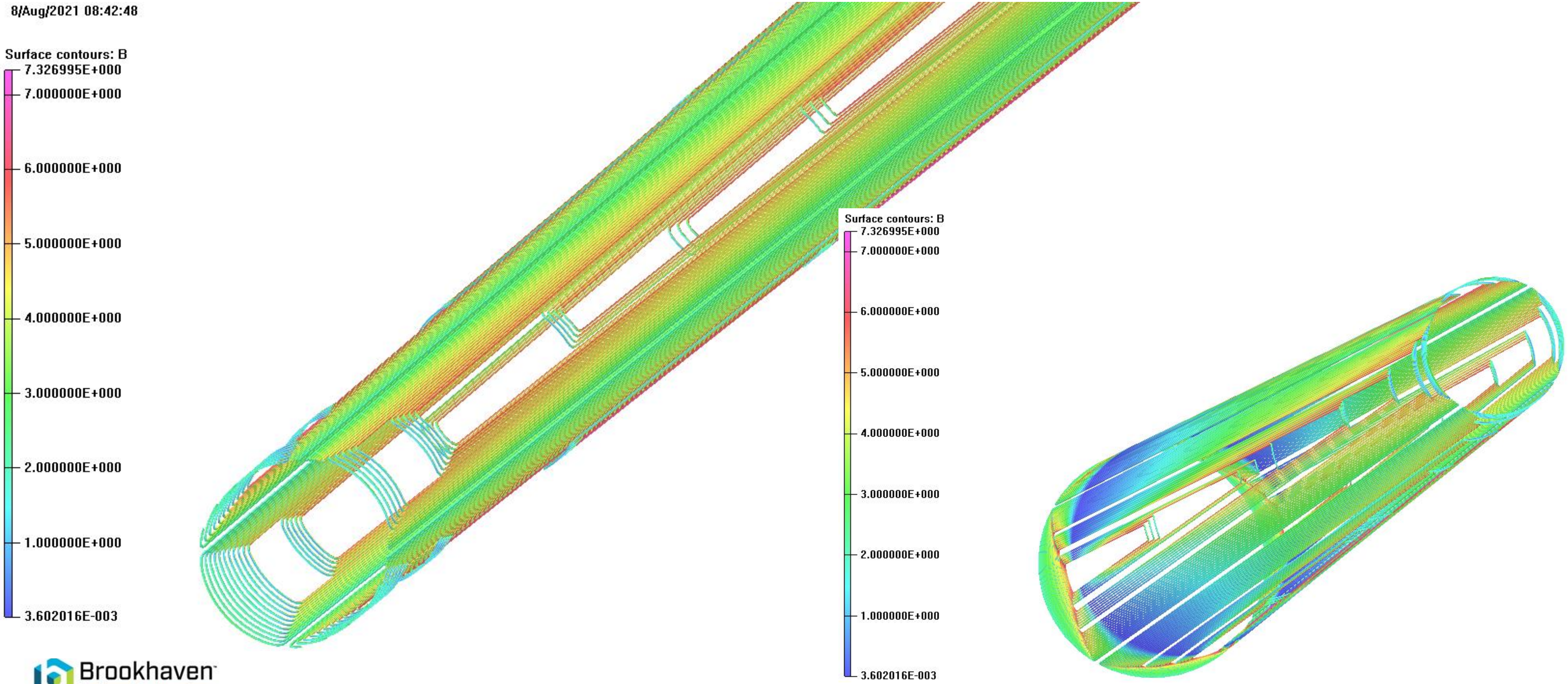
L= 3.5 m, Taper: 107.4 mm (IP) and 180.9 m (non-IP)



View from the end

Proposed Design - Step #2 (cont.)

- **Add more turns in longitudinal space created in step #1 (with increasing radius)**



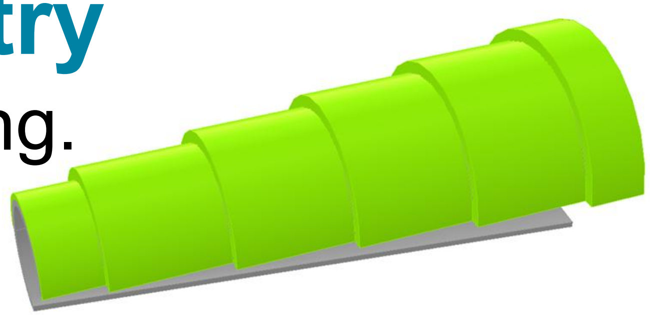
Q1ABpF – parameter specific optimization

- **Q1ABpF is a long magnet (length to aperture ratio)**
- **In this case, the relative gain from the optimum integral design to serpentine design are small.**
- **Therefore, if similar benefits can be found in a serpentine design, then that should be the design of choice.**
- **Above is what Vikas's design is primarily doing.**

Staircase Concept for a Tapered Coil Geometry

(individual coil layers are flat, not tapered, despite the overall geometry being tapered)

Staircase Concept for a Tapered Geometry



- EIC direct wind magnets have several layers of winding.
- In this concept, each layer is wound on a flat surface.
- It maintains a minimum tube thickness throughout.
- This may limit the length of an individual layers, depending on the place.
- Second layer is wound partially on the first layer. It begins from the start and goes further out - till the minimum tube thickness is hit again.
- Each double layer (or each coil set) is optimized for a good field quality.
- Once the maximum number of layers in the design is reached, then starting point of subsequent layers will shift axially.
- Layers at the two ends will have smaller length to maintain the same maximum number of layers across the length, if desired (not required).
- This creates a tapered geometry made of the flat coils, with empty space between the turns at far end essentially eliminated.

Views of the surface for winding coil on the Tapered Tube

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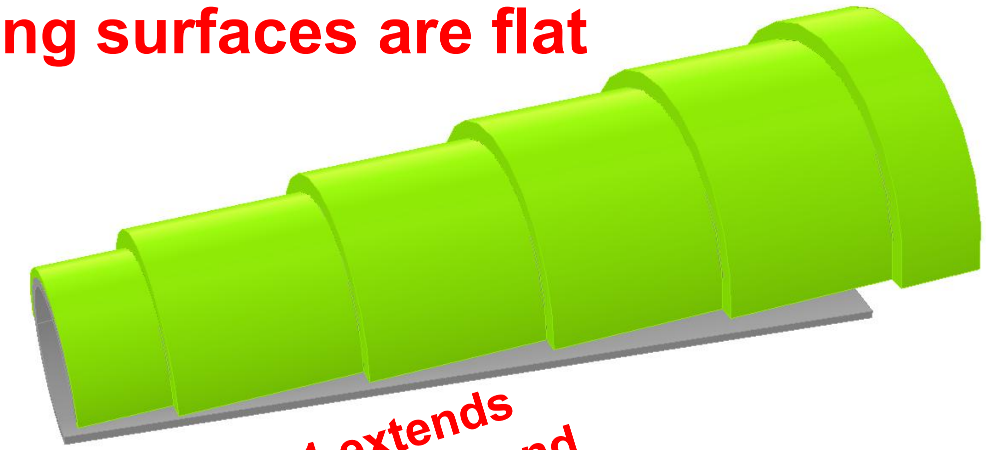
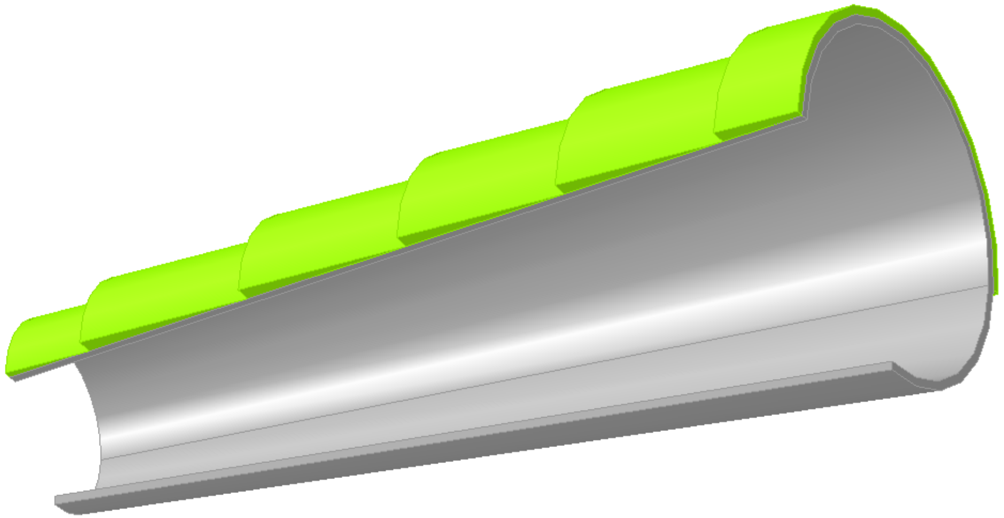
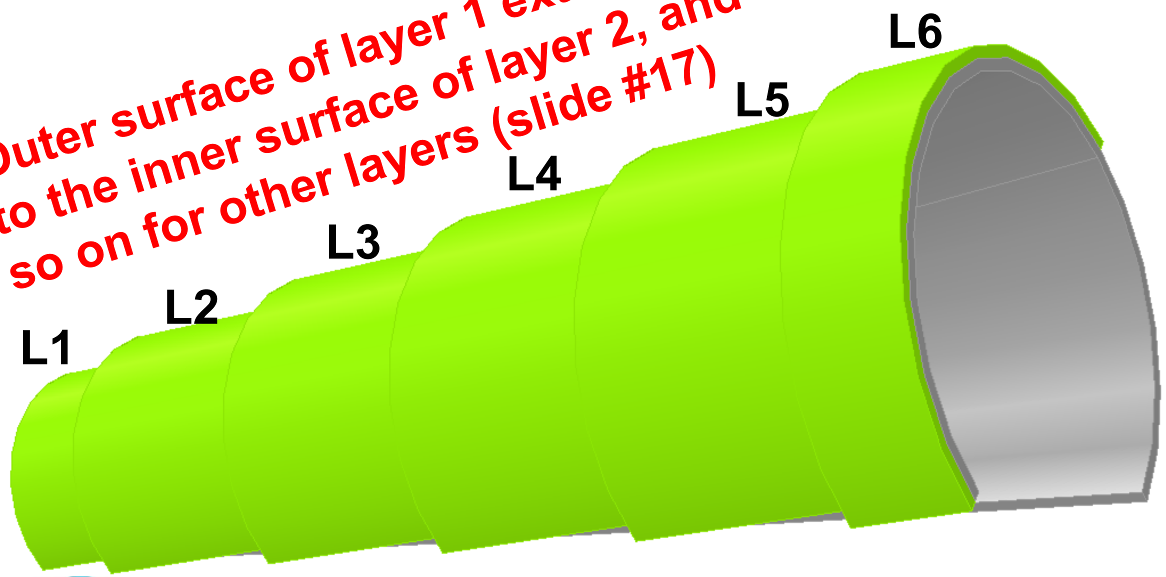
Tube is tapered but the winding surfaces are flat

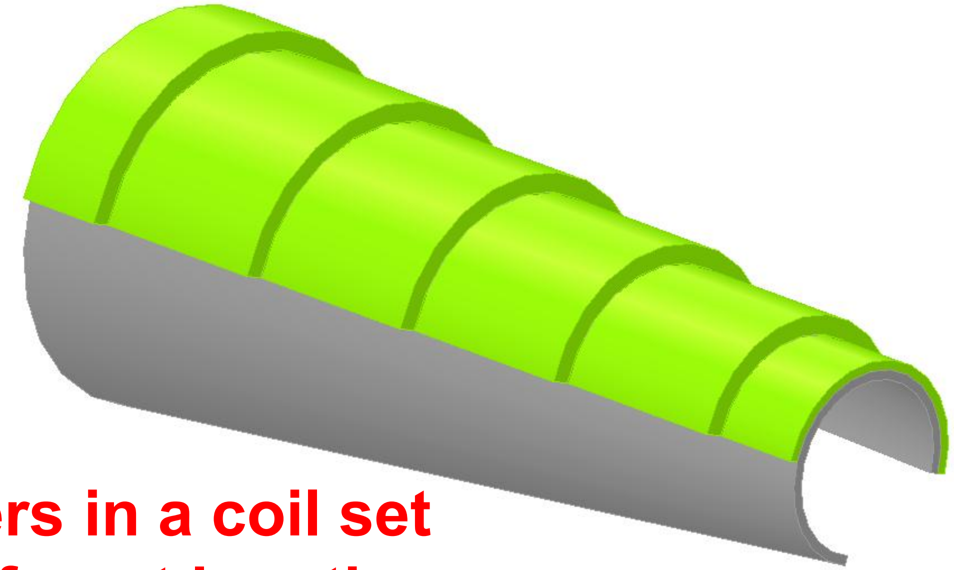




Opera

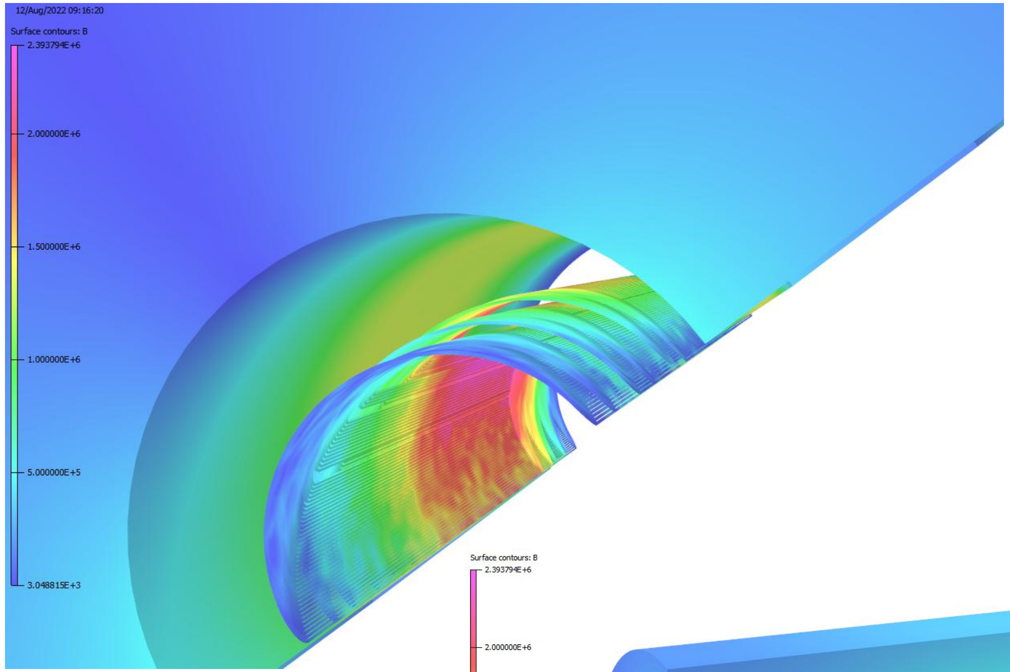
Outer surface of layer 1 extends to the inner surface of layer 2, and so on for other layers (slide #17)

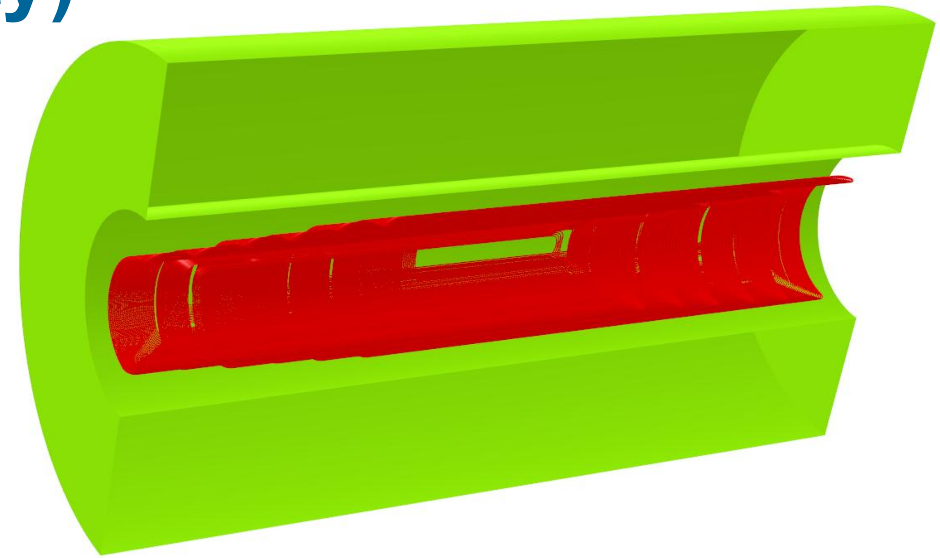


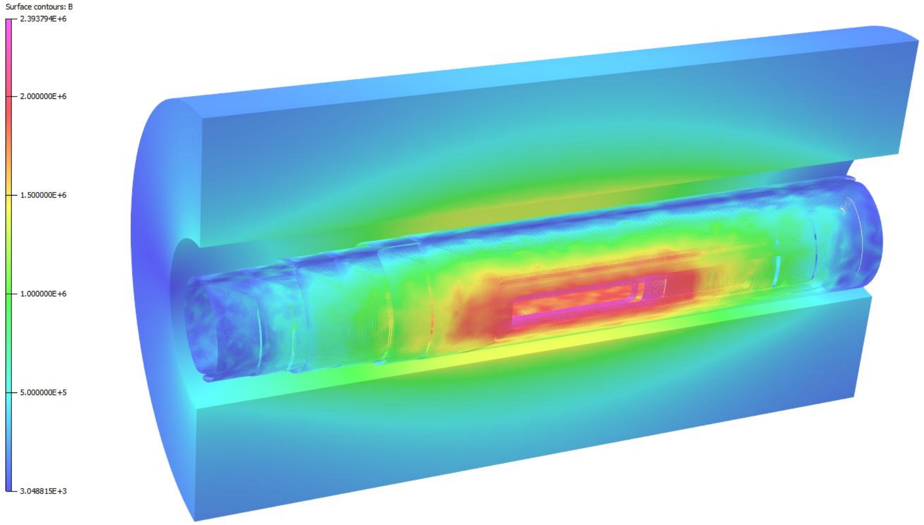


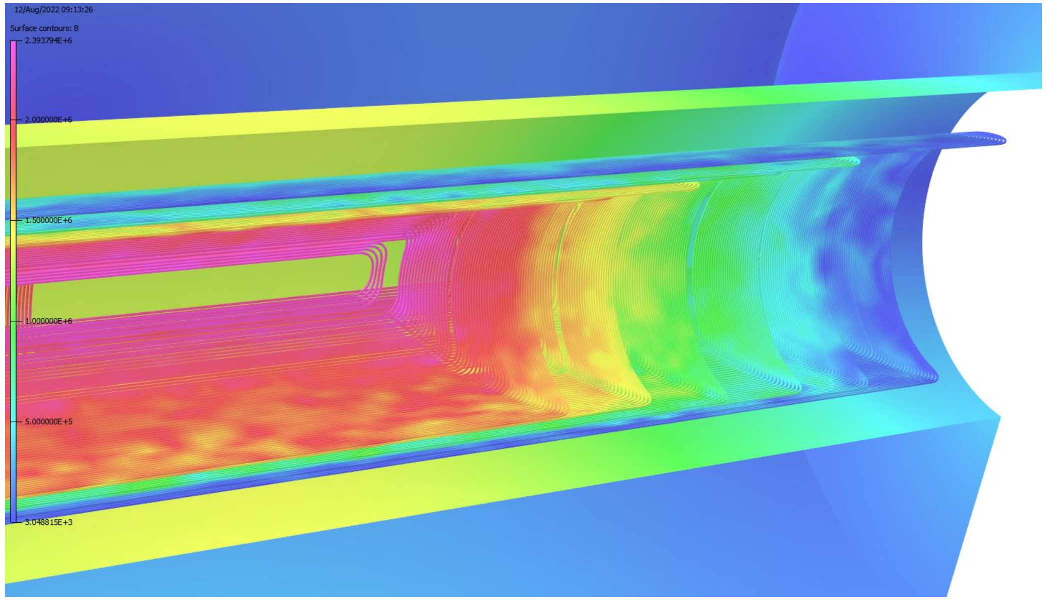
Two layers in a coil set have different lengths

Illustrations of the Windings in Yoke (starting of layers staggered for clarity)

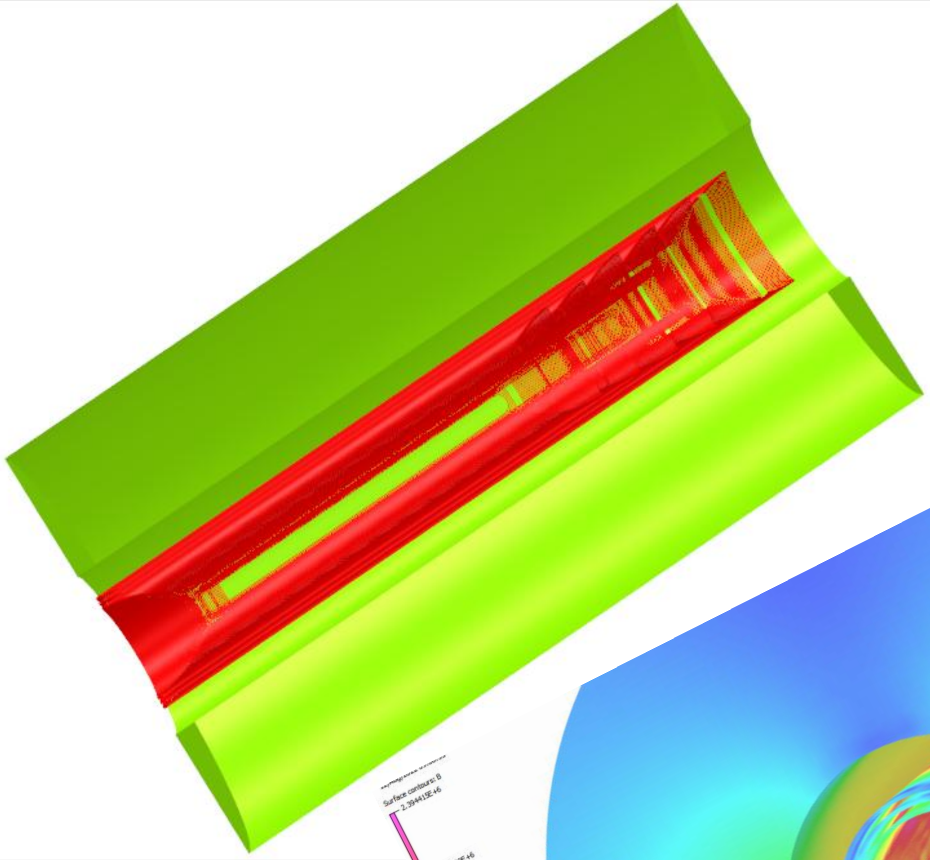


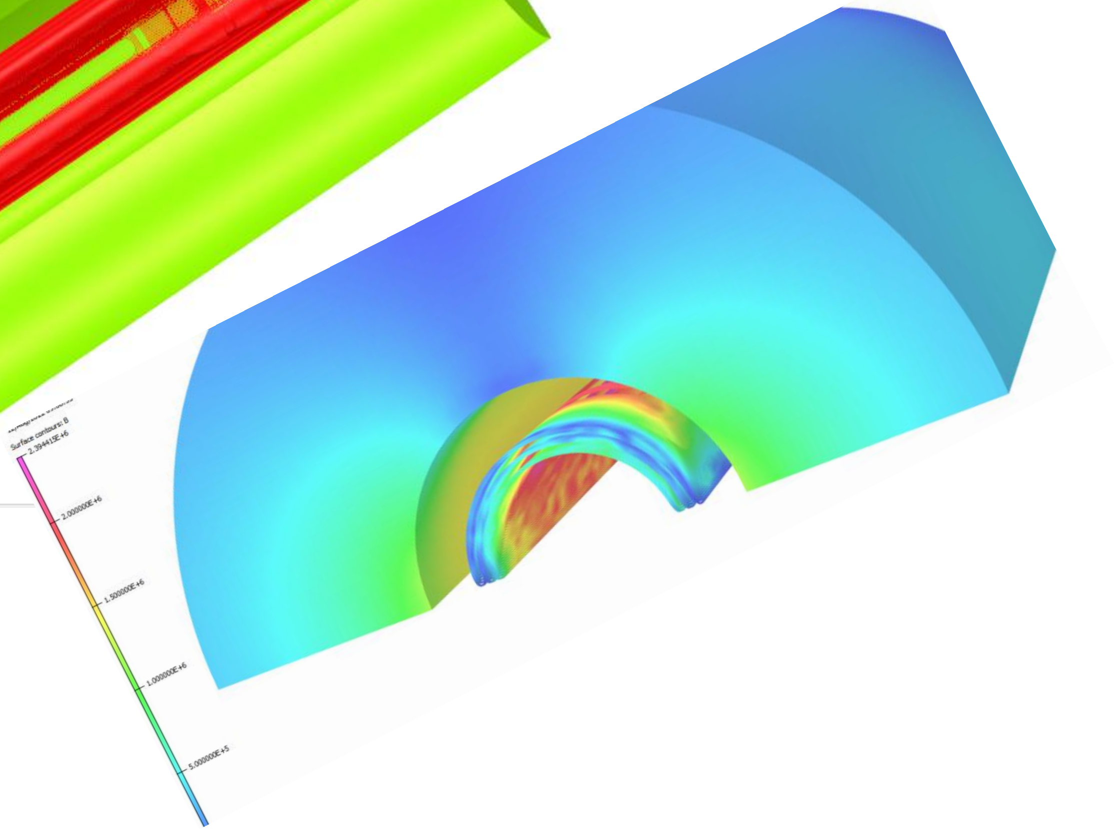


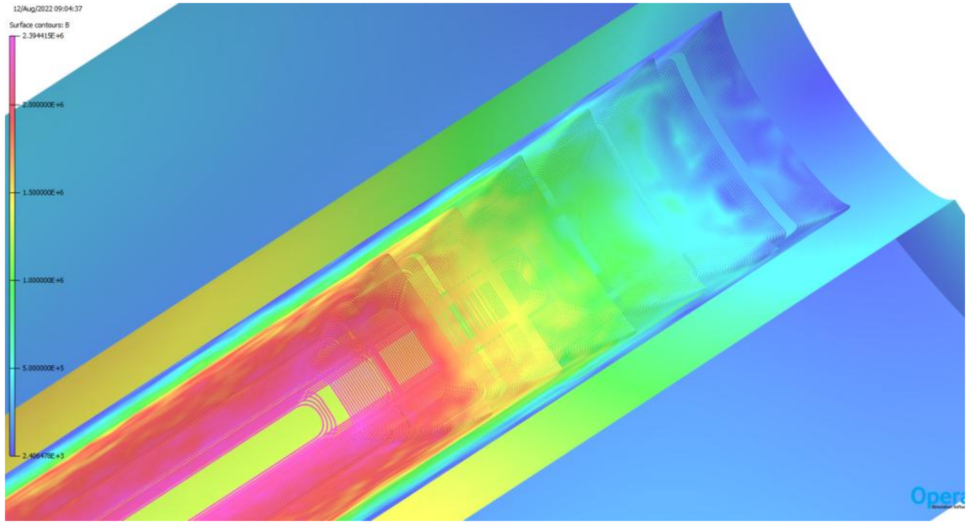


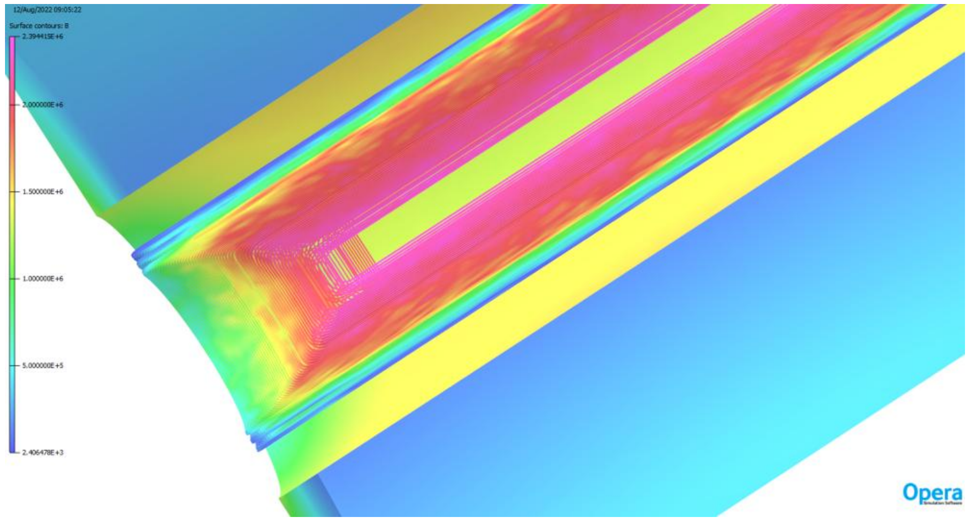


More Illustrations of the Windings in Yoke



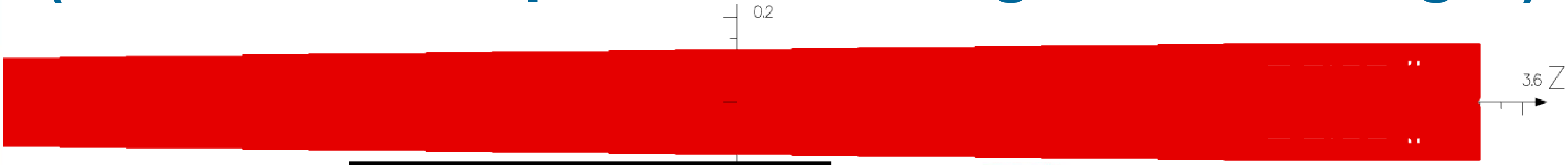




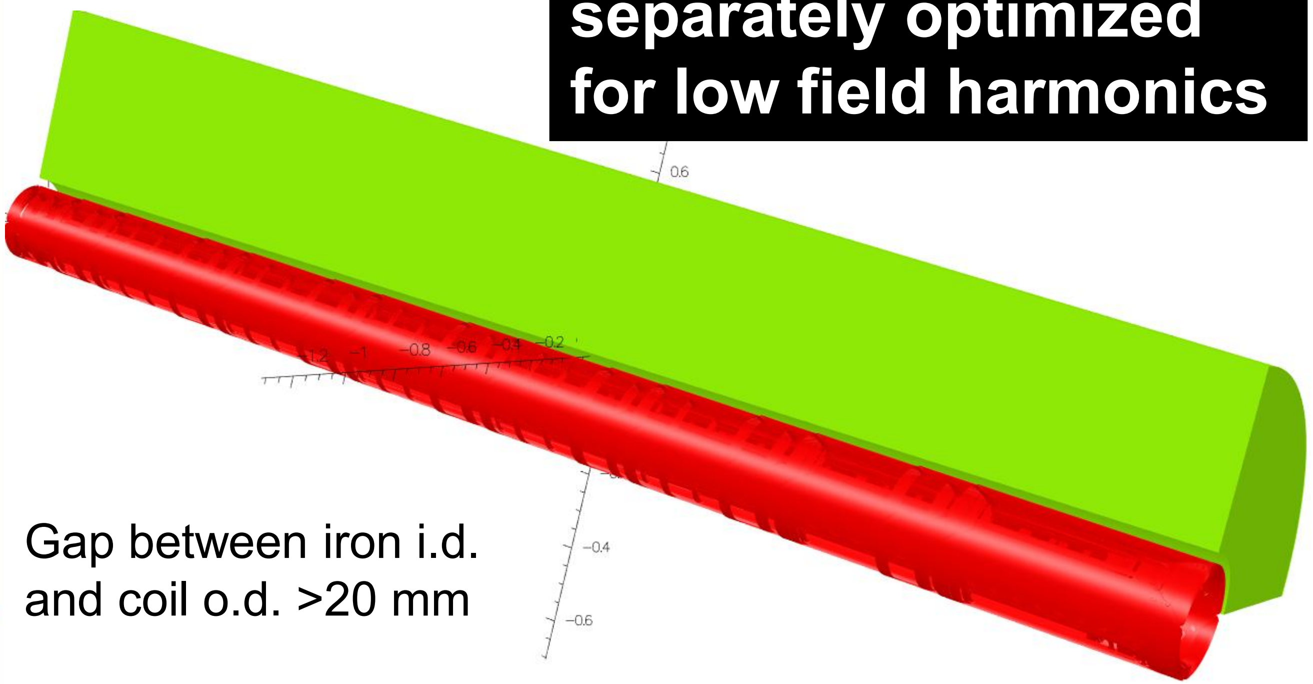


First Investigation of the Staircase Tapered Design for Q1ABpF

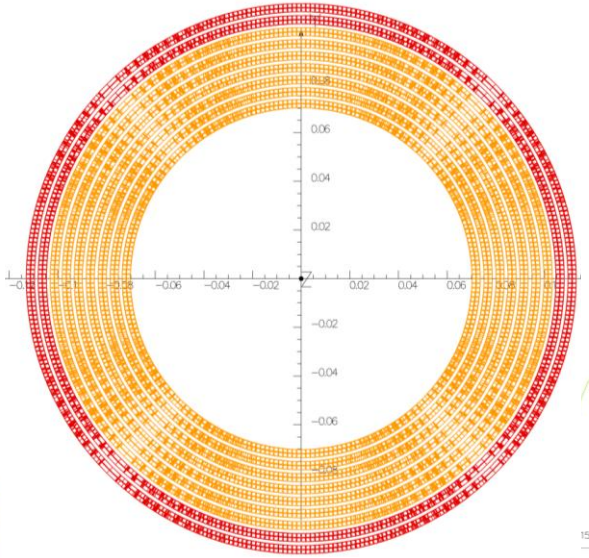
Initial Model of the Staircase Tapered Q1ApF (coil-set buildup: seven throughout the length)



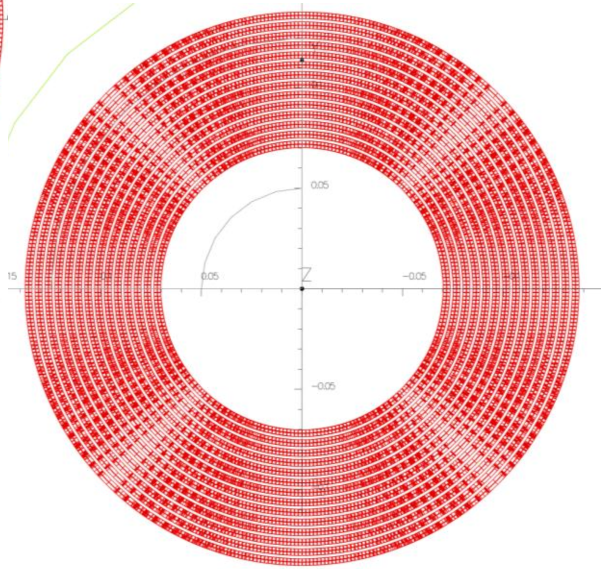
Each coil-set is separately optimized for low field harmonics



Gap between iron i.d. and coil o.d. >20 mm



View from the IP-side



View from the non-IP-side

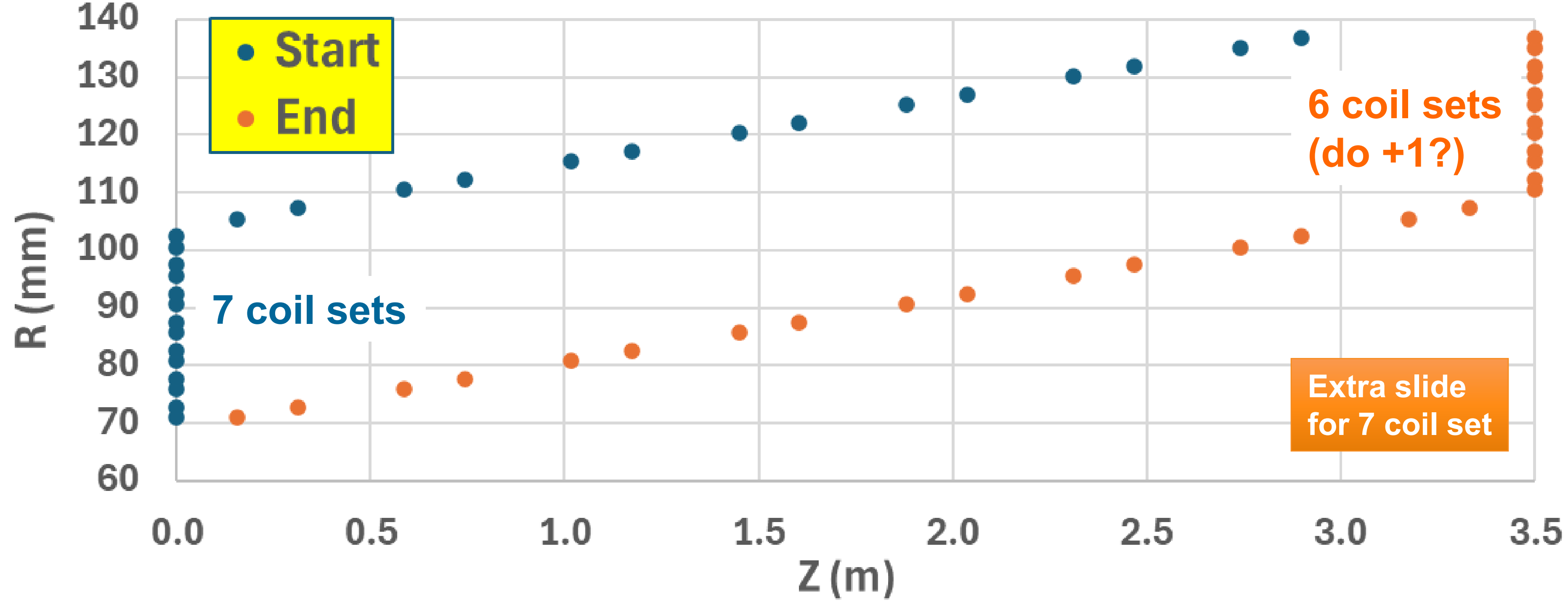
Staircase Design Details and Options
(Serpentine will also work and perhaps preferable)

Coil aligned to one end

Coil end in the middle

Layer #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
R(mm)	70.98	72.76	75.91	77.69	80.84	82.61	85.76	87.54	90.69	92.47	95.62	97.40	100.5	102.3	105.5	107.3	110.4	112.2	115.3	117.1	120.3	122.0	125.2	127.0	130.1	131.9	135.1	136.8
Zstart(m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0.31	0.59	0.74	1.02	1.17	1.45	1.60	1.88	2.04	2.31	2.47	2.74	2.90
Zend(m)	0.16	0.31	0.59	0.74	1.02	1.17	1.45	1.60	1.88	2.04	2.31	2.47	2.74	2.90	3.17	3.33	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
L(m)	0.16	0.31	0.59	0.74	1.02	1.17	1.45	1.60	1.88	2.04	2.31	2.47	2.74	2.90	3.17	3.33	2.91	2.76	2.48	2.33	2.05	1.90	1.62	1.46	1.19	1.03	0.76	0.60
L/R	2.2	4.3	7.7	9.6	12.6	14.2	16.9	18.3	20.7	22.0	24.2	25.3	27.3	28.3	30.1	31.0	26.4	24.6	21.5	19.9	17.1	15.5	12.9	11.5	9.1	7.8	5.6	4.4

- **When L/R > 4 in quadrupoles, relative gain of the Optimum Integral over the serpentine is small**



Initial (this) design: optimum integral

However, most coils are long so the penalty in going to serpentine is small.

- **Try serpentine**

Field Harmonics as Optimized by the *IntegralOpt*

Harmonics computed in each coil-set at a reference radius of 36 mm

@ the IP End

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.98572E-01	10000.0000
5	0.37289E-10	0.0000
9	-0.14253E-08	-0.0001
13	-0.24624E-06	-0.0250
17	-0.95927E-08	-0.0010
21	-0.12934E-08	-0.0001
25	0.11304E-09	0.0000
29	0.18494E-10	0.0000

In the Middle

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units
1	0.10244E+01	10000.0000
5	-0.56999E-04	-0.5564
9	-0.14420E-04	-0.1408
13	0.94365E-07	0.0009
17	0.66300E-09	0.0000
21	-0.13192E-10	-0.0000
25	-0.12432E-12	-0.0000
29	0.48257E-14	0.0000

Note:
US numbering of harmonics
(b5=>b6)

@ the Non-IP End

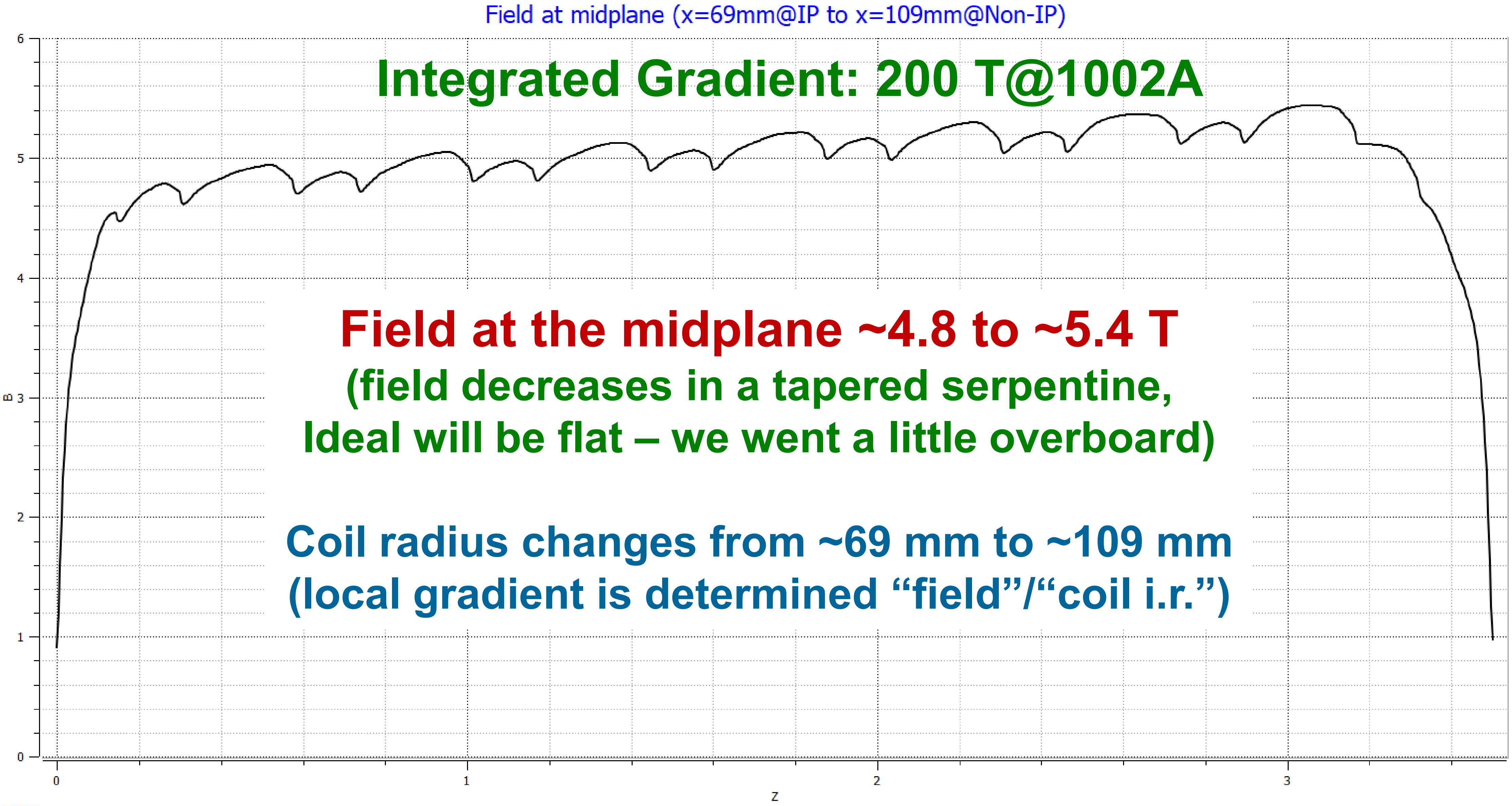
INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.18910E+00	10000.0000
5	0.76739E-11	0.0000
9	-0.57453E-08	-0.0003
13	0.23353E-09	0.0000
17	0.55430E-12	0.0000
21	-0.22878E-13	-0.0000
25	0.69997E-17	0.0000
29	0.70257E-18	0.0000

Harmonics, peak field and coil geometry, not fully optimized
(good enough for the first investigation)

Each double layer is optimized for a good field quality

Field at the Coil Midplane in the Initial Staircase Design



Integrated Gradient: 200 T@1002A

Field at the midplane ~4.8 to ~5.4 T

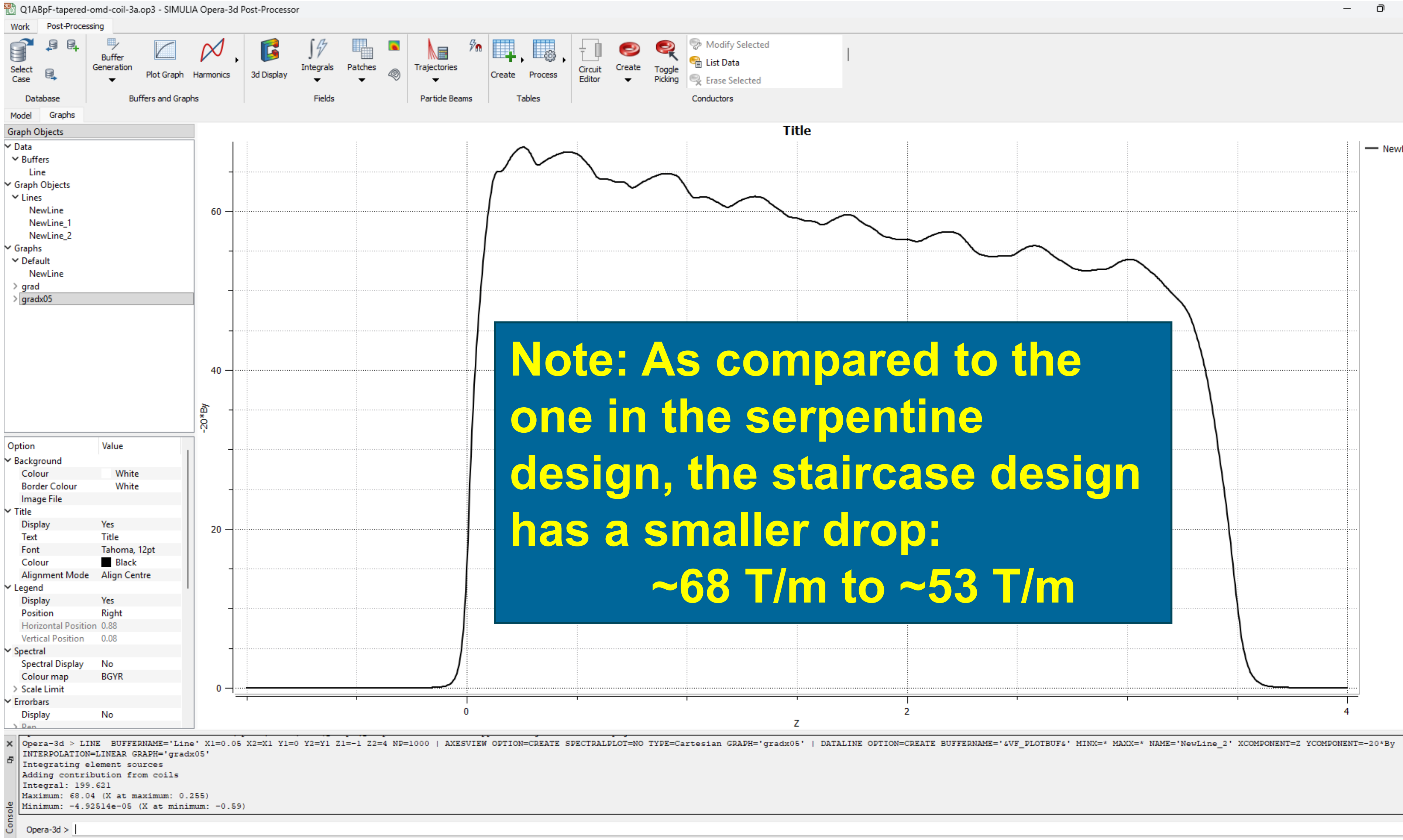
(field decreases in a tapered serpentine,
Ideal will be flat – we went a little overboard)

Coil radius changes from ~69 mm to ~109 mm
(local gradient is determined "field"/"coil i.r.")

Gradient Profile in the Staircase Design

Integrated Gradient: 200 T

Operating Current: 1002 A



Note: As compared to the one in the serpentine design, the staircase design has a smaller drop:
~68 T/m to ~53 T/m

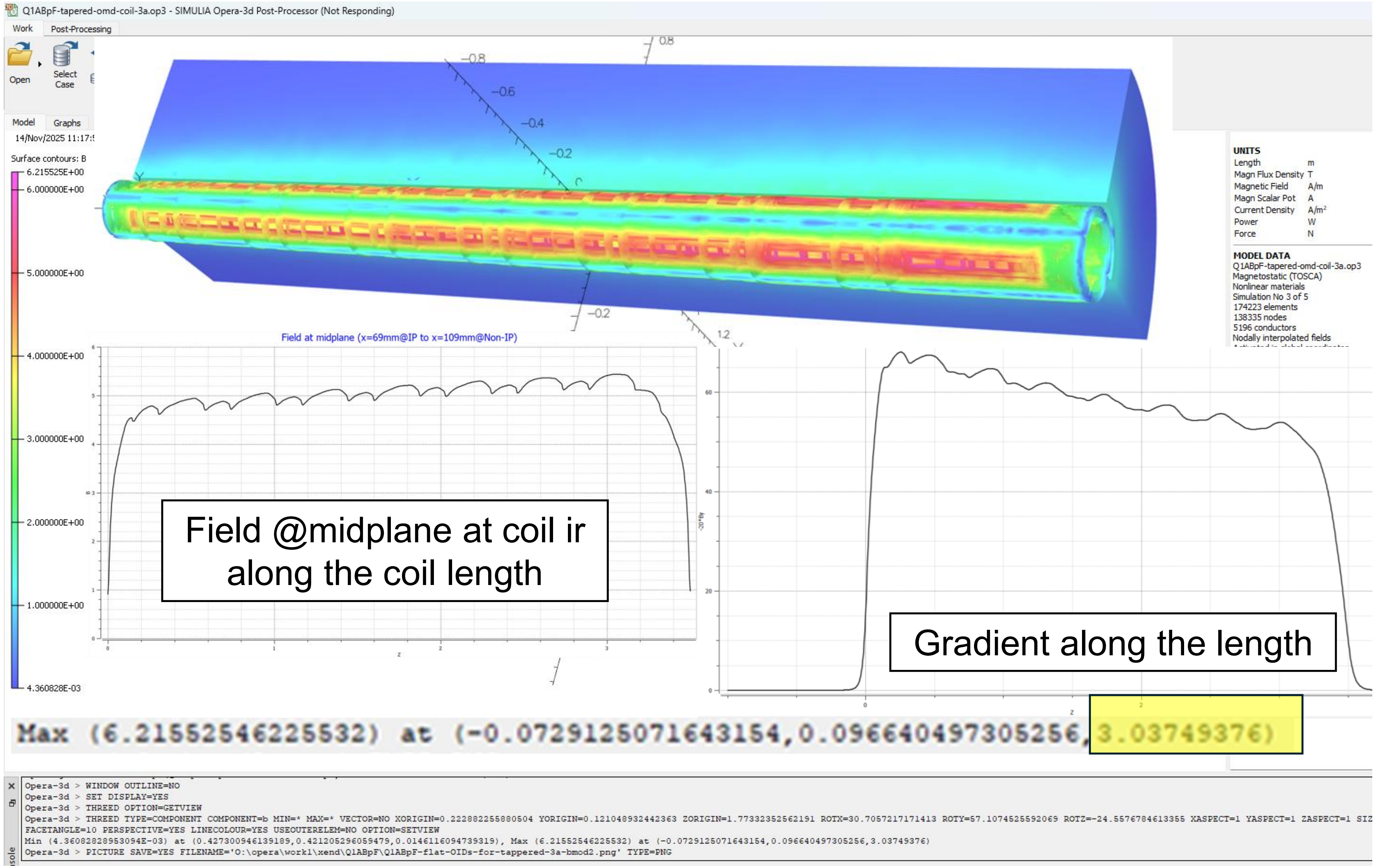
Peak Field in the Initial Staircase Design

Integrated Gradient:
200 T
Operating Current:
1002 A

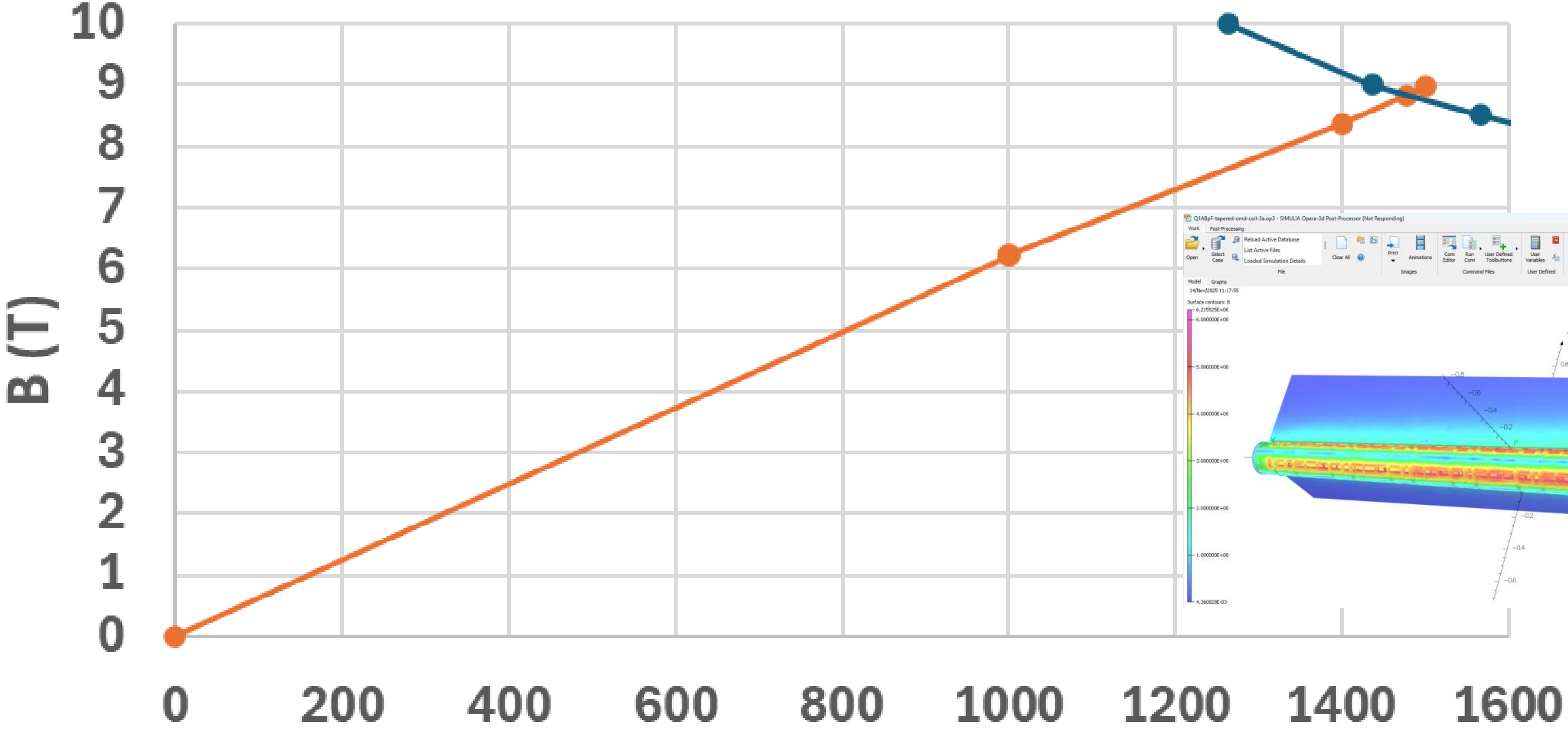
Peak Field: ~6.2 T
(not fully optimized)

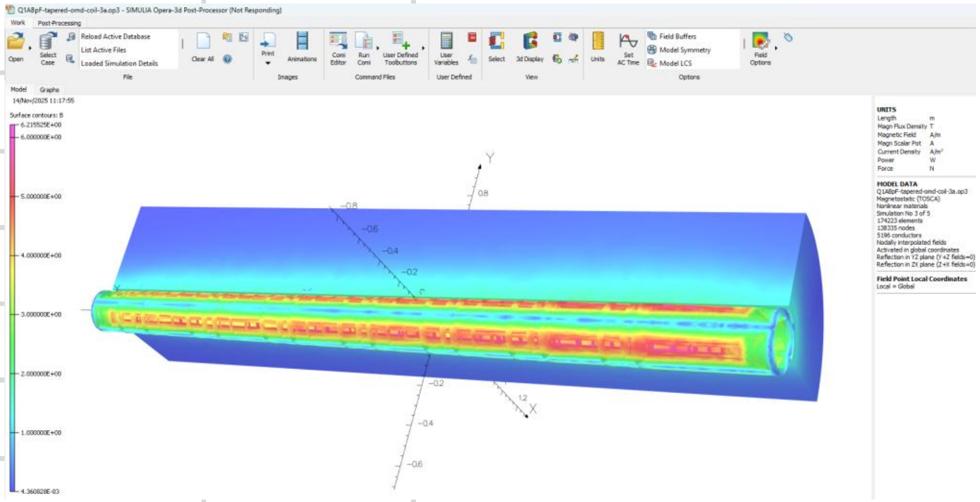
Maximum Field at the midplane: 5.4 T

Peak field enhancement
6.2/5.4=1.15
OK. Peak field should be lower for a flatter profile.



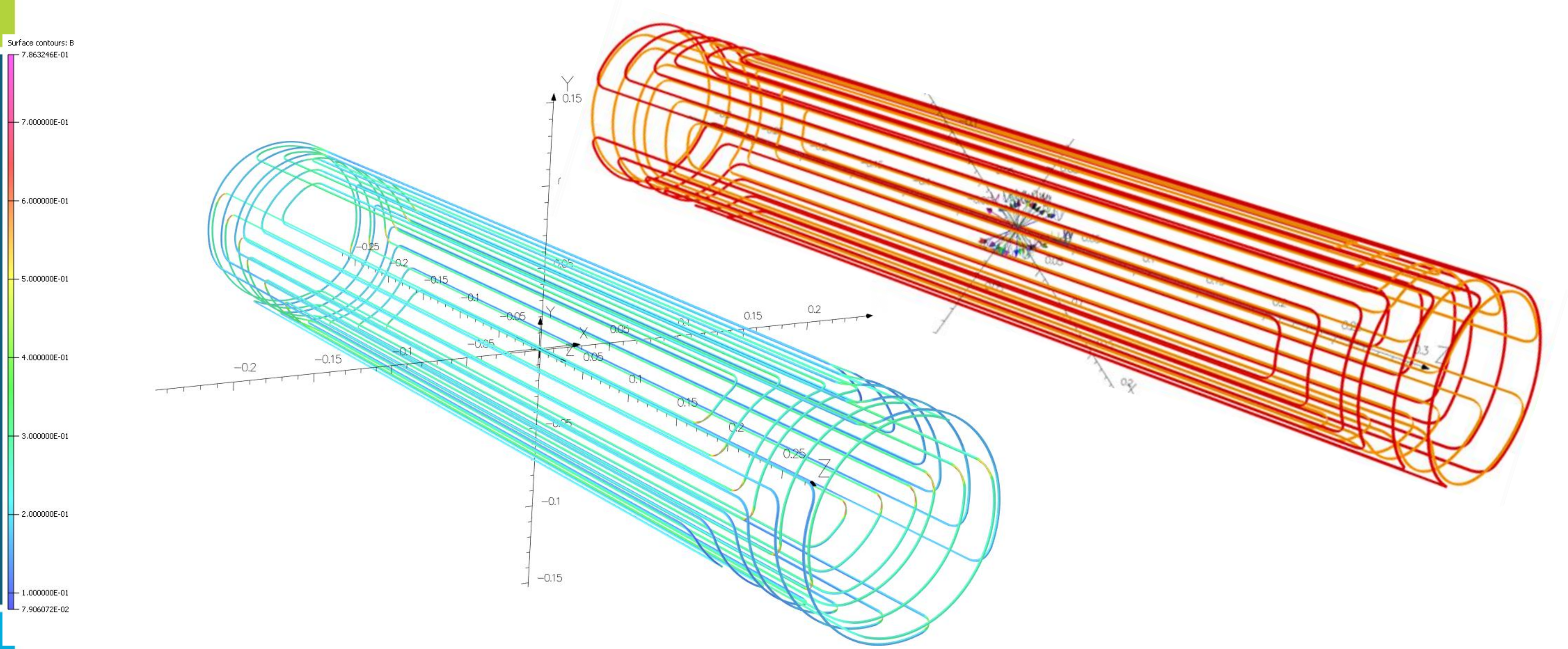
Load-line Margin in the Initial Staircase Design





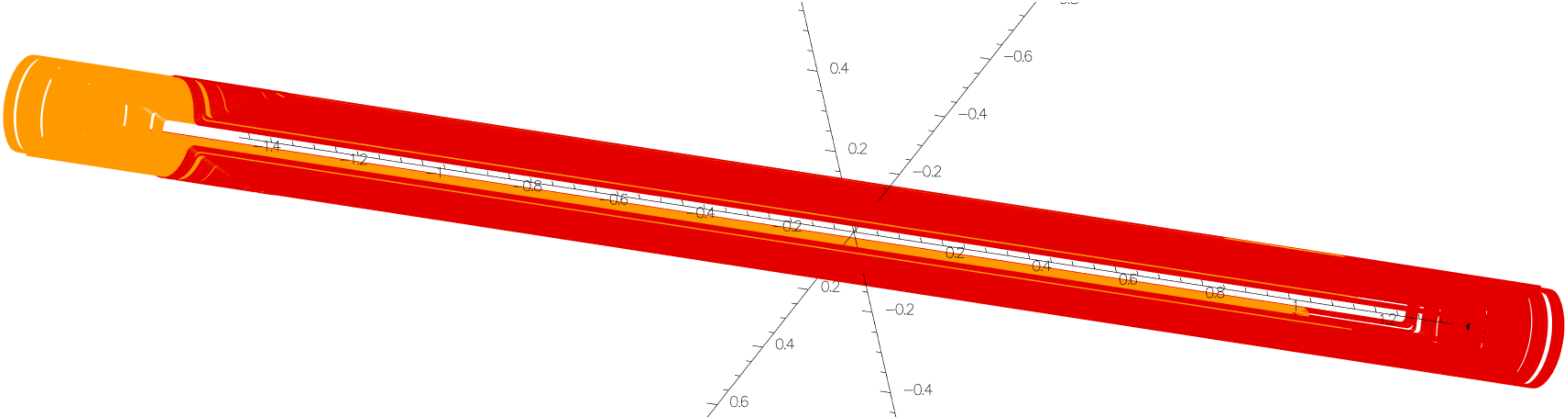
- ➢ **Computed Short Sample Current: 1478 A**
- ➢ **Current for 200 T Integrated Gradient: 1002 A**
- ➢ **Load-line fraction: 0.68 (a bit more is possible)**

Serpentine Coil Design with the *OptIntegral* Code (visual illustration of an example of a coil set-2 layers)



Serpentine Coil Design with the *OptIntegral* Code (one coil set of Q1ABpF optimized)

Each coil-set is separately optimized for low field harmonics



Start and end position of the two layers may be different

Summary

- In conventional tapered designs, there is a loss in gradient as conductors at the far end must be sparse to maintain the field quality. This shortcoming can be overcome in either a Tapered Design or in staircase design.
- In the first investigation, we found that as compared to the serpentine design, one can get the same integral field with a fewer coil-sets (7 instead of eight).
- Since Q1ABpF is a relatively long magnet, one can and should use the tapered serpentine design.
- Compare initial magnetic design concepts for the tapered Q1ABpF (double helix, tapered serpentine or its variation, staircase OID; tapered OID) and choose one to go in more detail.
- Perform cross talk. Mechanical analysis and quench studies on the selected one.

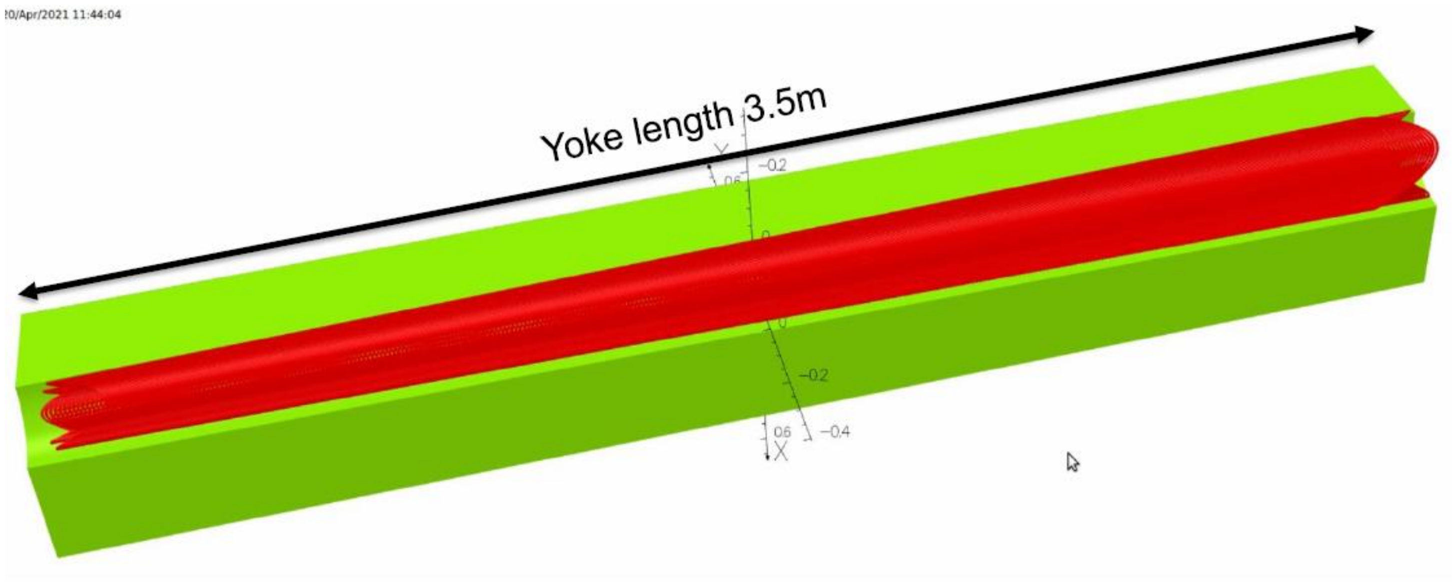
Extra Slides

EIC Tapered Coil Design – Double Helix (Holger Witte)

Overview Q1ABpF

BROOKHAVEN NATIONAL LABORATORY

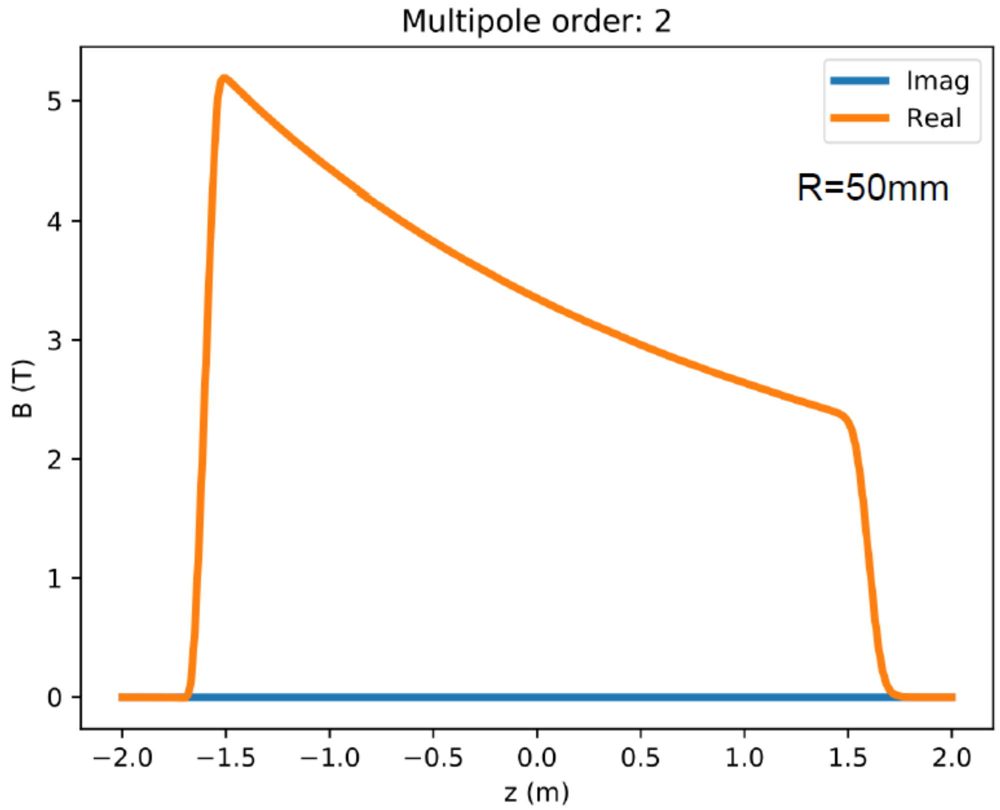
This may not be the latest design



Average gradient: 64T/m
Integrated (3.5m): 224T
(We need: 212T)

Using macroscopic conductor
Radial thickness: 20mm
Long. Packing fraction: 50%

20 April 2021 3

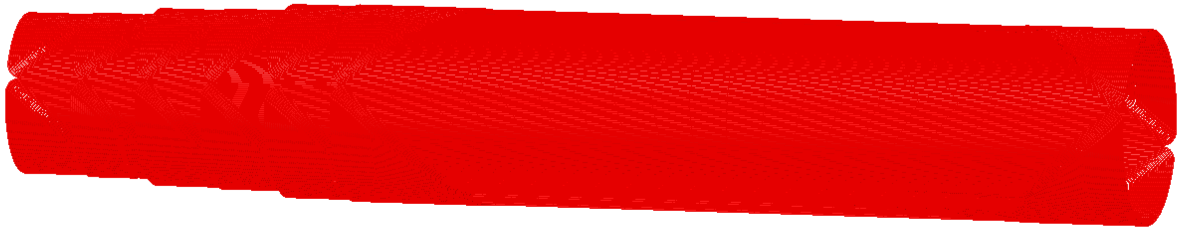


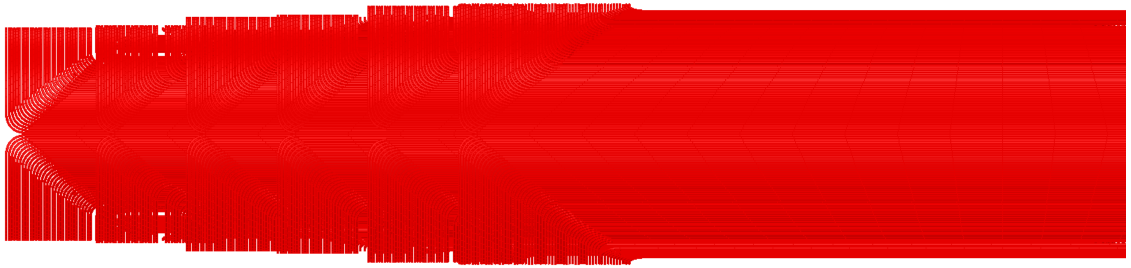
Initial Goals of the Staircase Investigation

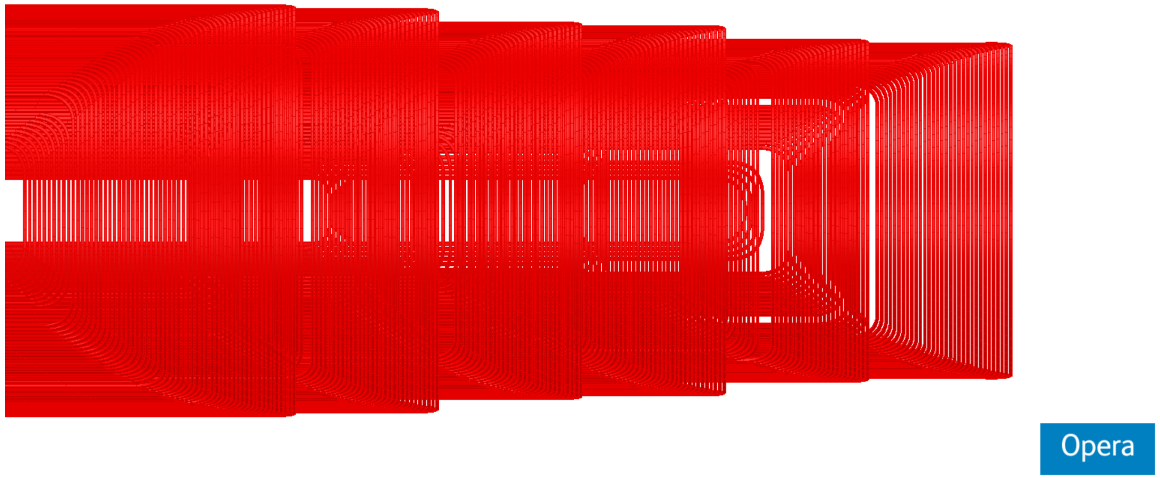
Perform initial investigation to see if there are benefits of the staircase tapered design in Q1ABpF for the same overall coil parameters as those used in the serpentine design:

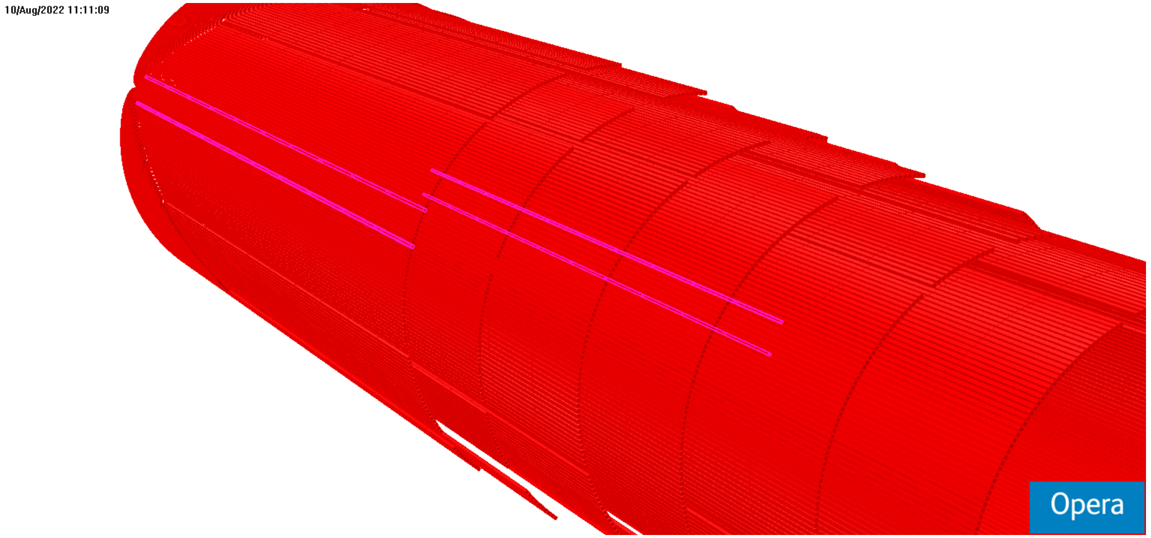
- Same wire/cable
- Same tapered tube inner radius and minimum tube thickness
- Similar margin (~65% on the load line)
- Same overall coil length (Q1ApF+Q1BpF)
- A fewer number of coil-set buildup – **7** instead of **8**

Illustrations of the Windings (starting of layers staggered for clarity)









Each double layer will be optimized for a good field quality