Previous Studies on the Tapered Q1ABpF

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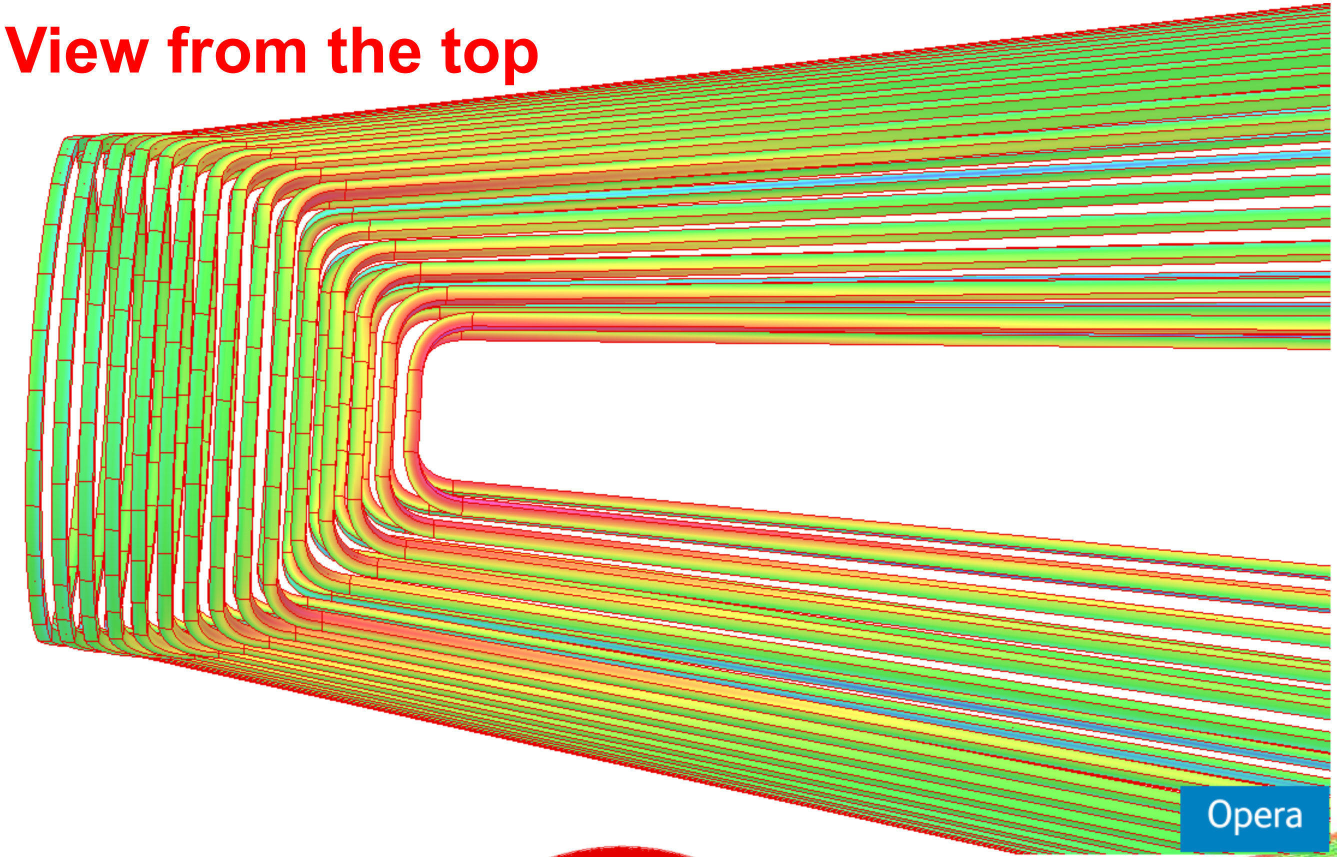
Background

- This brief presentation on a previous study performed on the tapered direct wind design using the direct wind technology with the optimum integral design.
- That study was performed for a SBIR/STTR proposal and with internal funding to support the case of the tapered direct wind option. To first order, conclusions should be similar whether it is (a) serpentine tapered design (current default), or (b) optimum integral tapered design with constant spacing (SBIR proposal #1), or (c) a set of staircase non-taper coils to effectively it tapered (SBIR proposal #2).
- This will be a brief presentation drawn from a previous one, with most slides moved to the “extra slide section”.

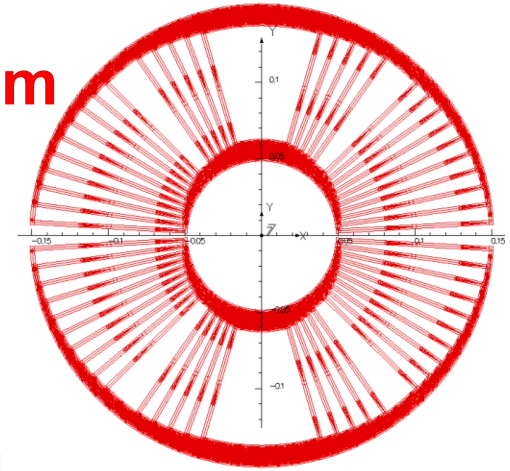
Conventional Design of a Tapered Cosine Theta Dipole

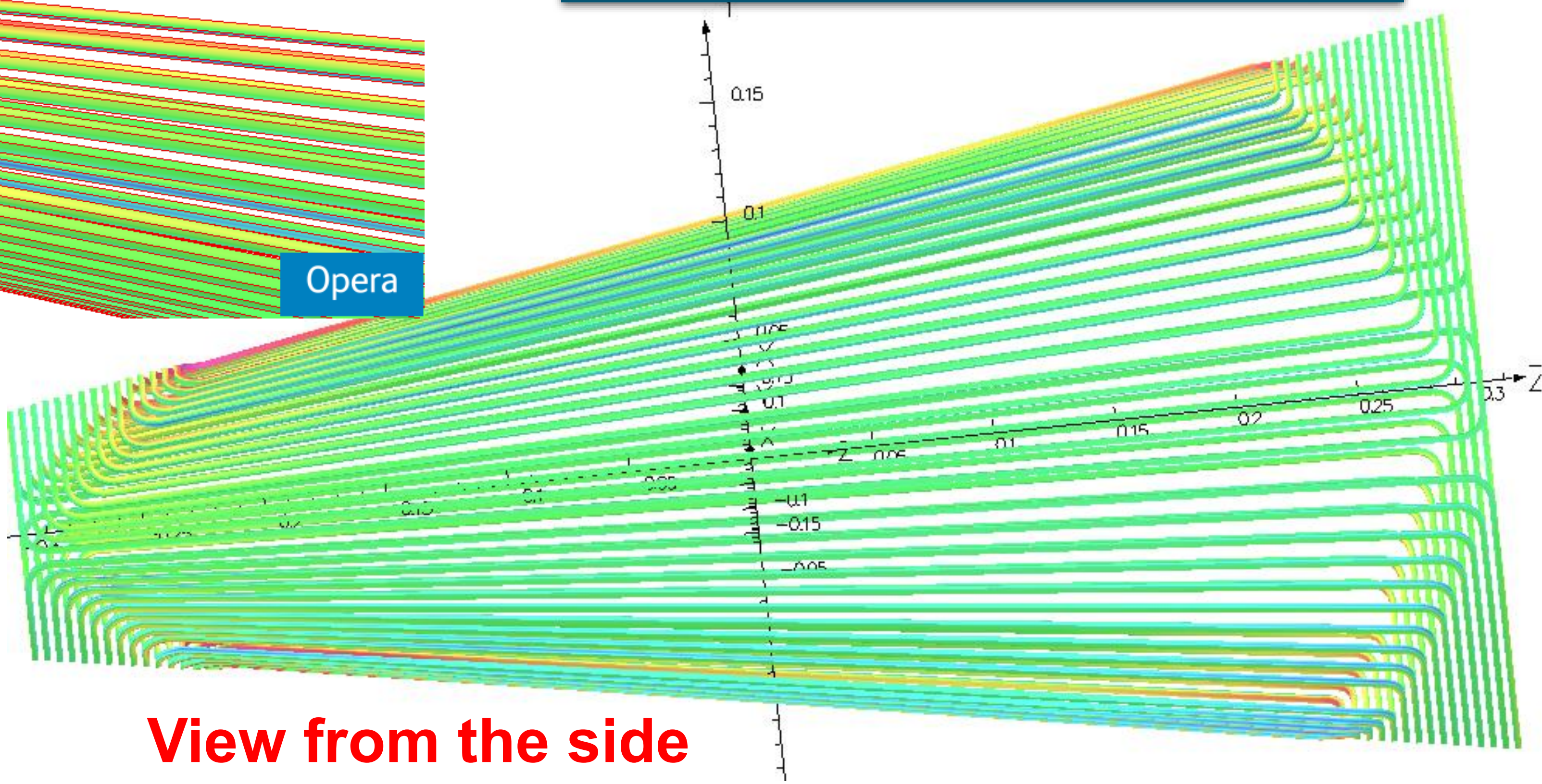
View from the top



Wire maintain their angular position while radii change

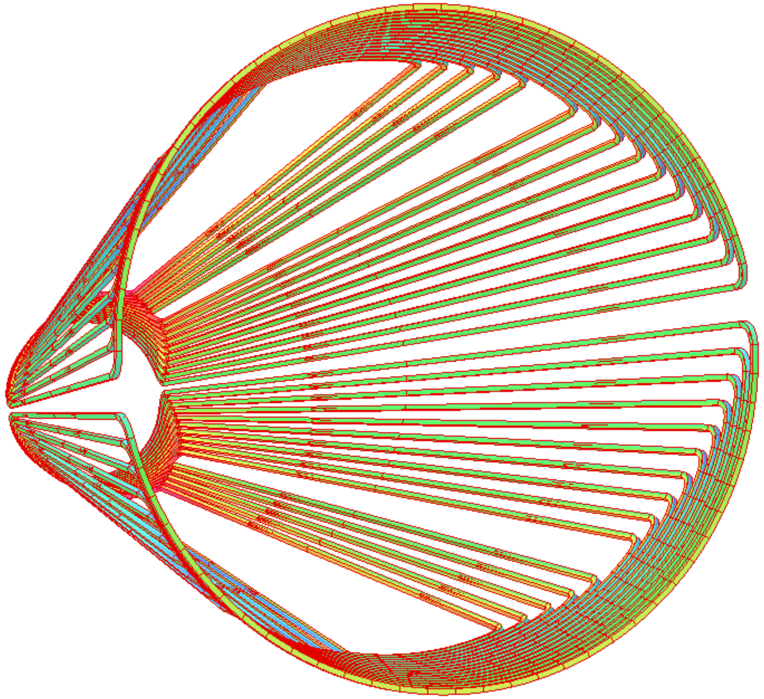
View from the end





View from the side

Positives and Negatives of the Conventional Cosine Theta Tapered Dipole

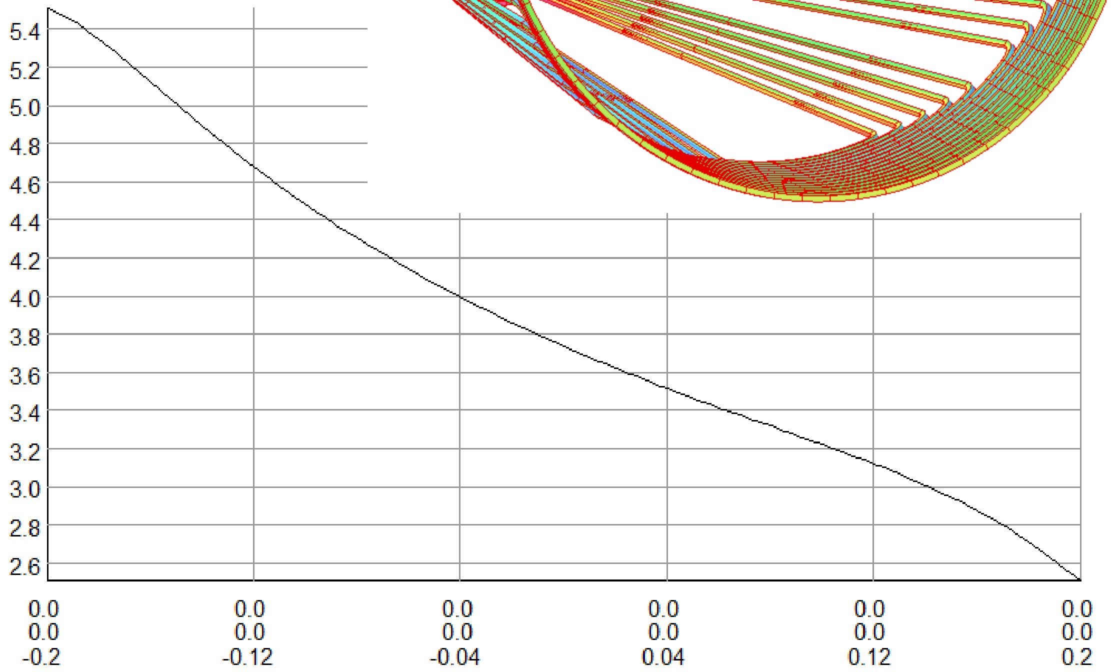


Positives:

- Design is simple to understand
- Good harmonics are assured as the angular position of wire remains the same

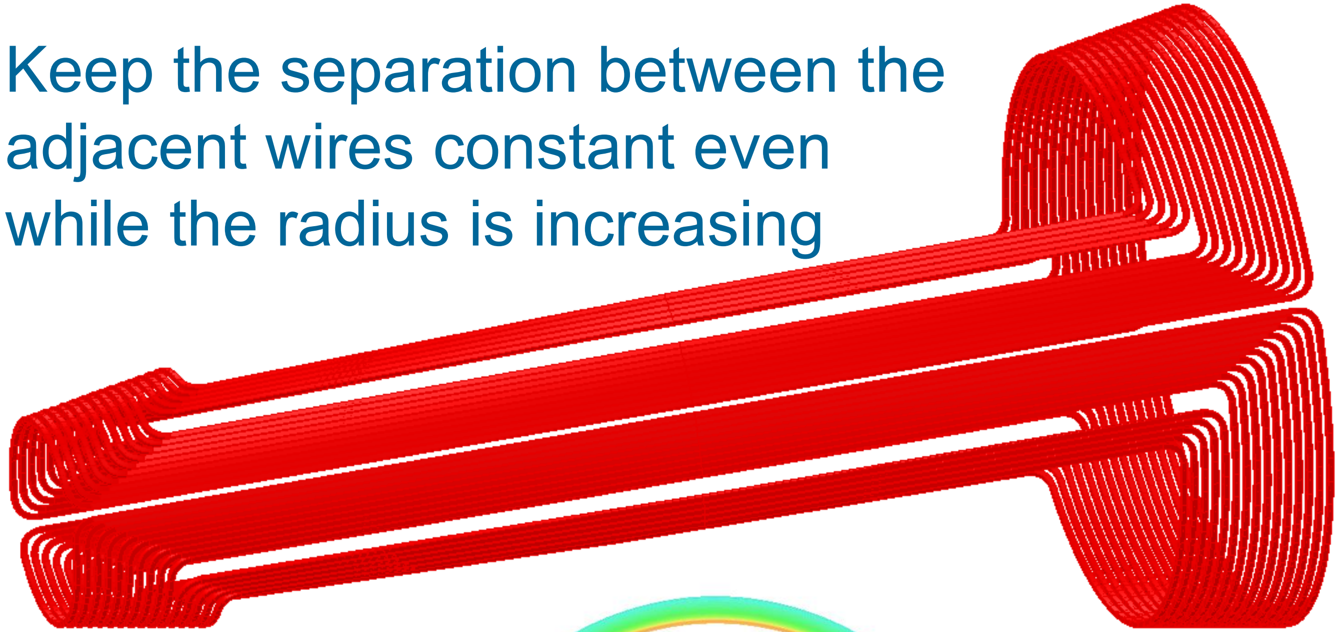
Negatives:

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

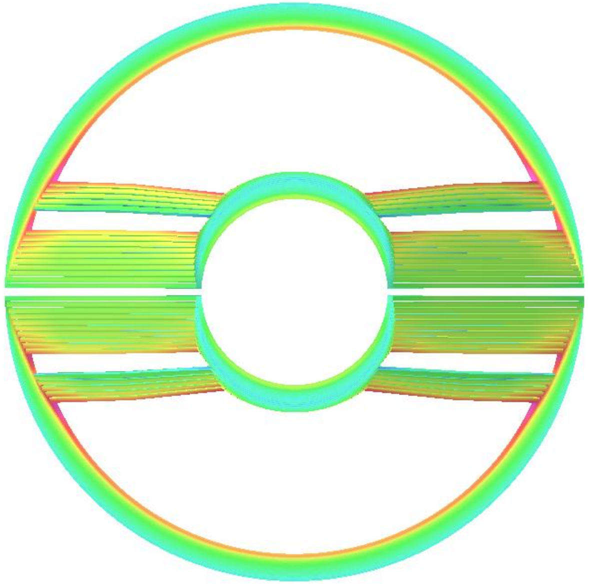


Proposed Design - Step #1

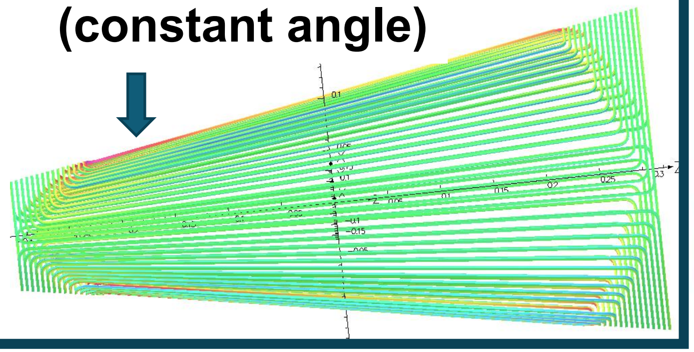
Keep the separation between the adjacent wires constant even while the radius is increasing



View from the end



Original case (constant angle)



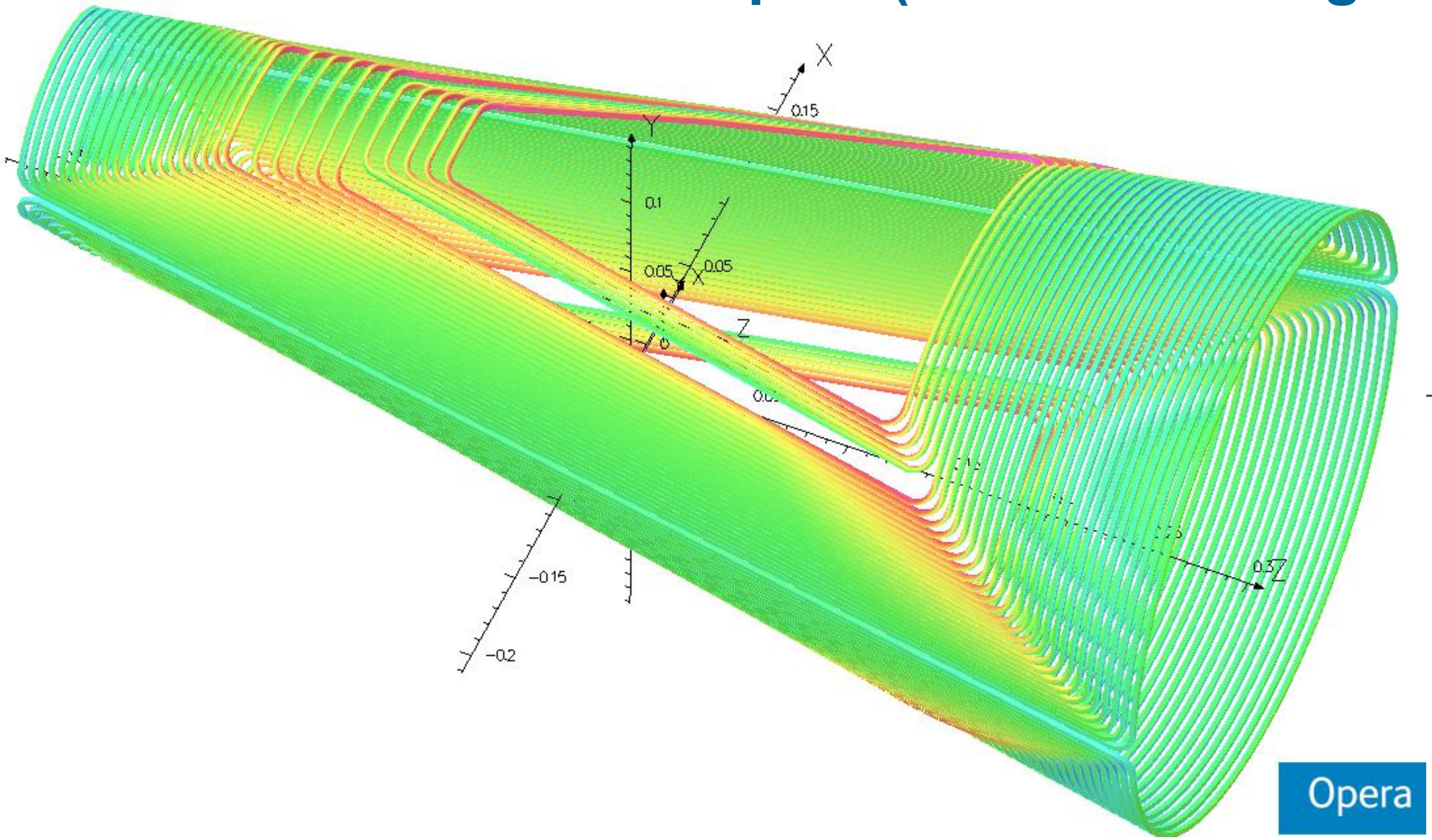
View from the top

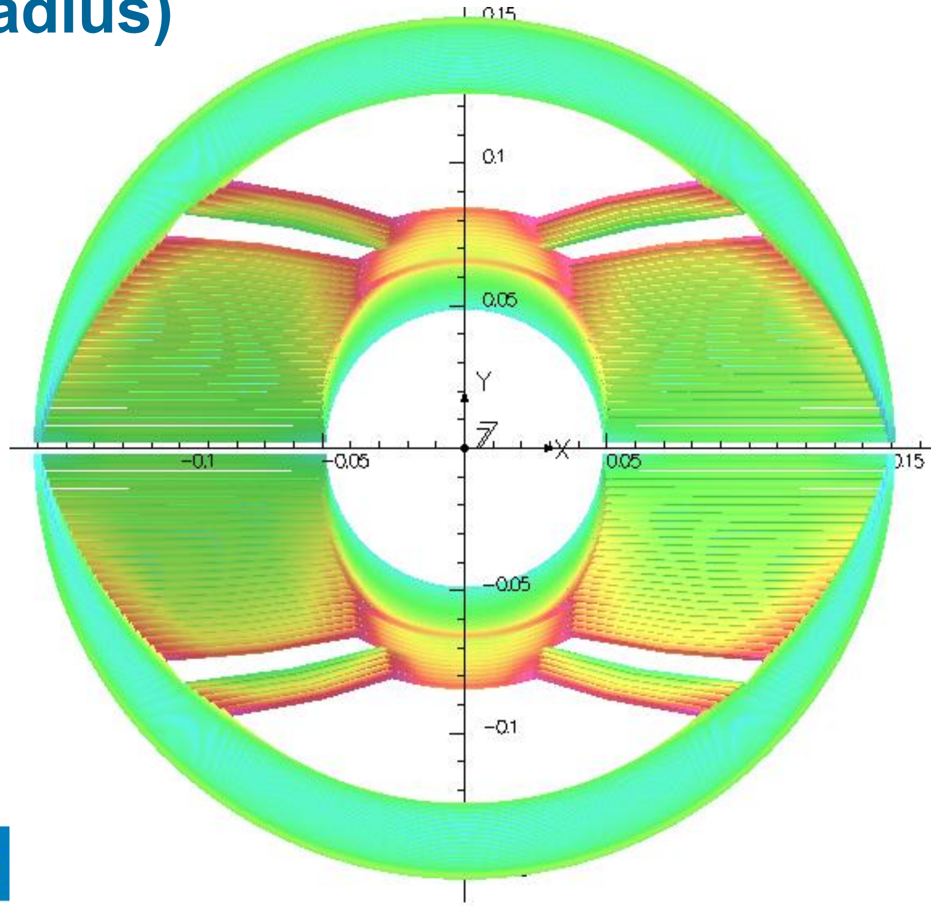
Note: field quality will no longer be good, if done nothing.

Proposed Design - Step #2

View from the end

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

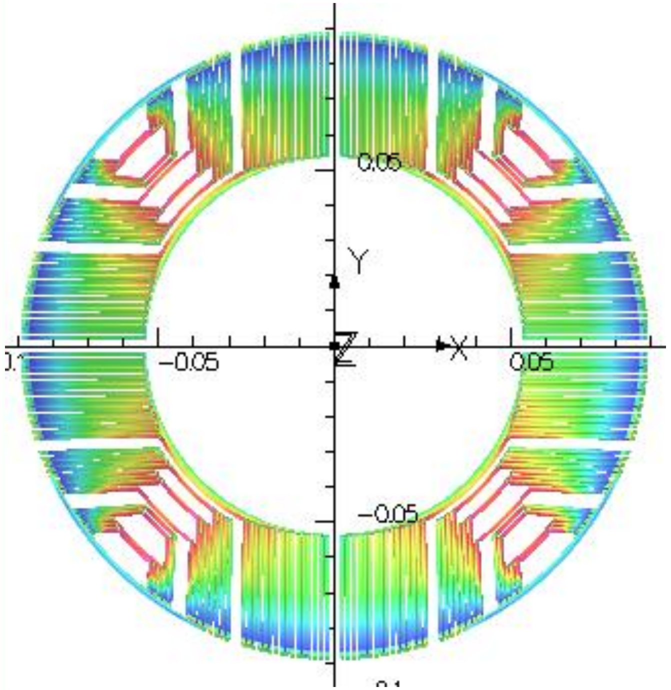


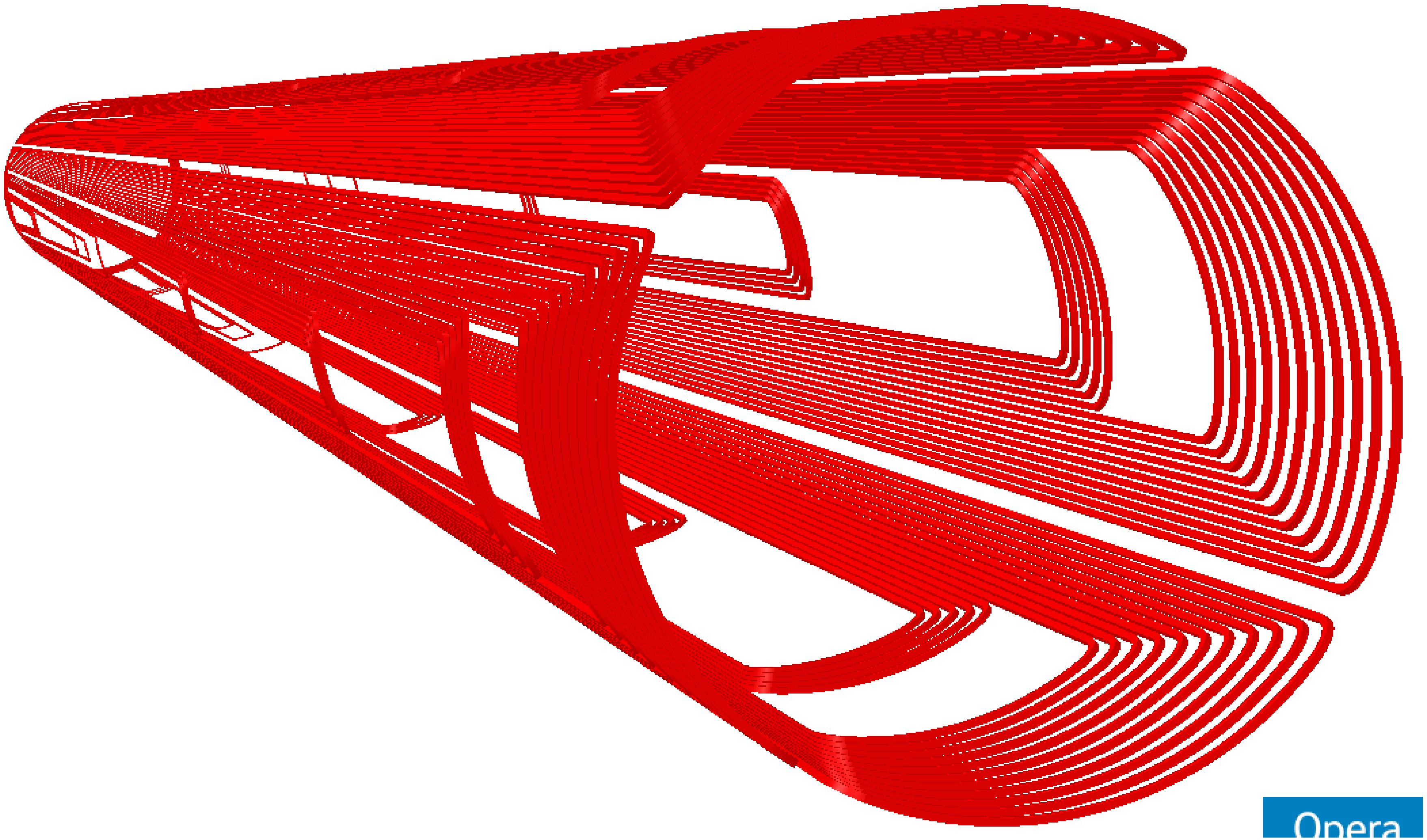


The additional turns will be used to increase the field and to optimize the field harmonics.

Design Concept for Q1ABPF After Step #2

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





Staircase Concept for a Tapered Coil Geometry

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

Views of the surface for winding coil on the Tapered Tube

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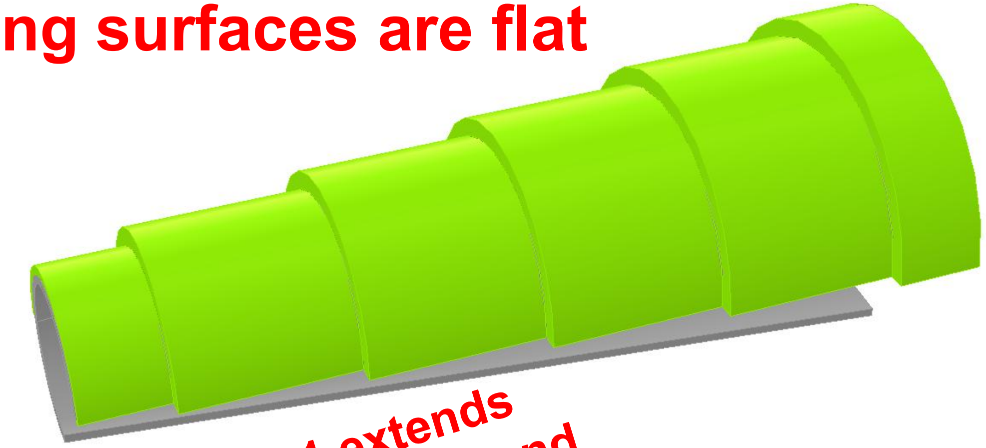
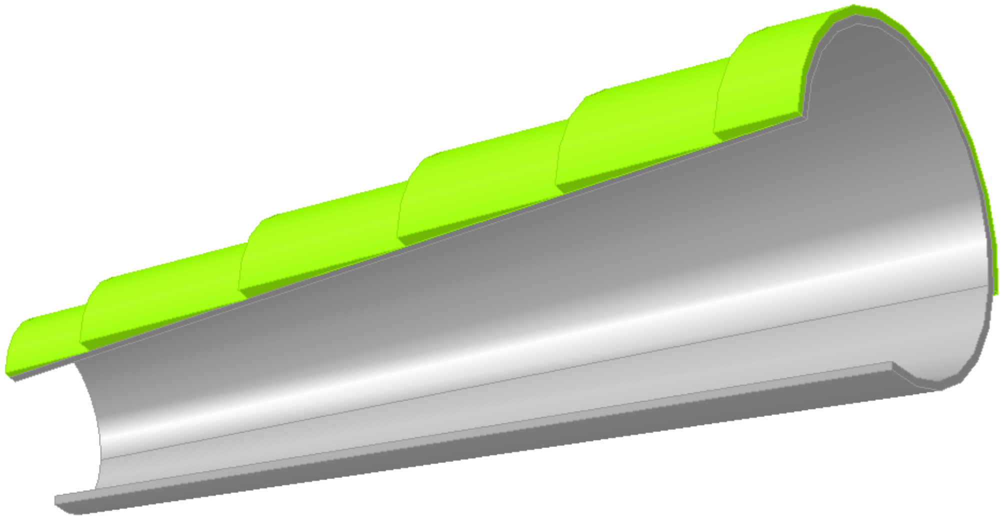
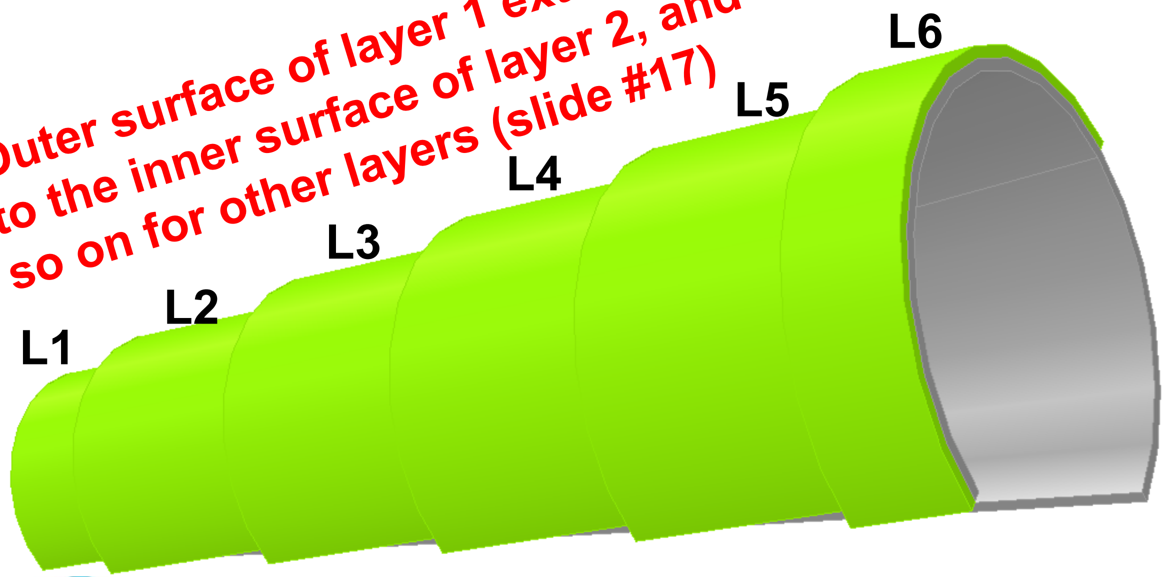
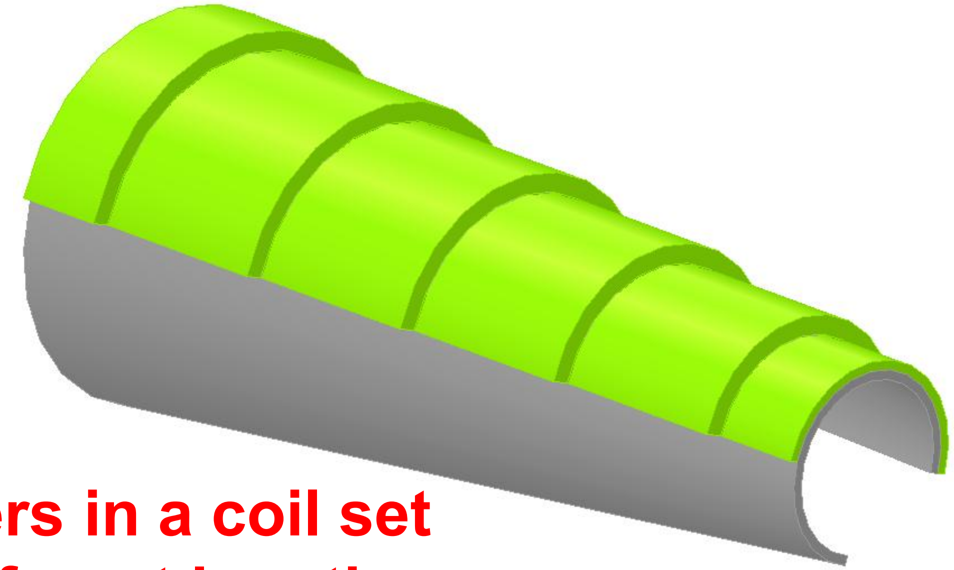
Tube is tapered but the winding surfaces are flat





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

Staircase Investigation

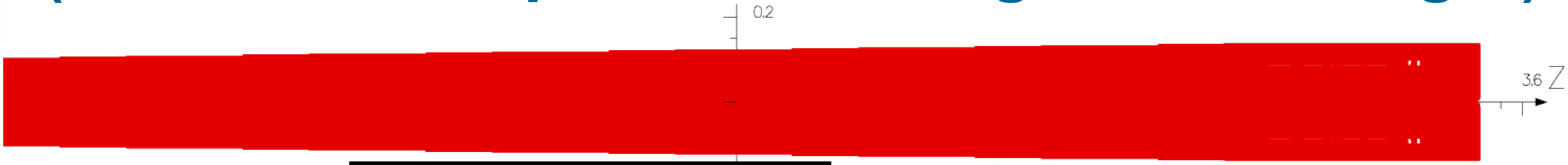
(performed for original design, before 10% reduction in radius)

Key assumptions are the same as in then Q1ABpF serpentine design:

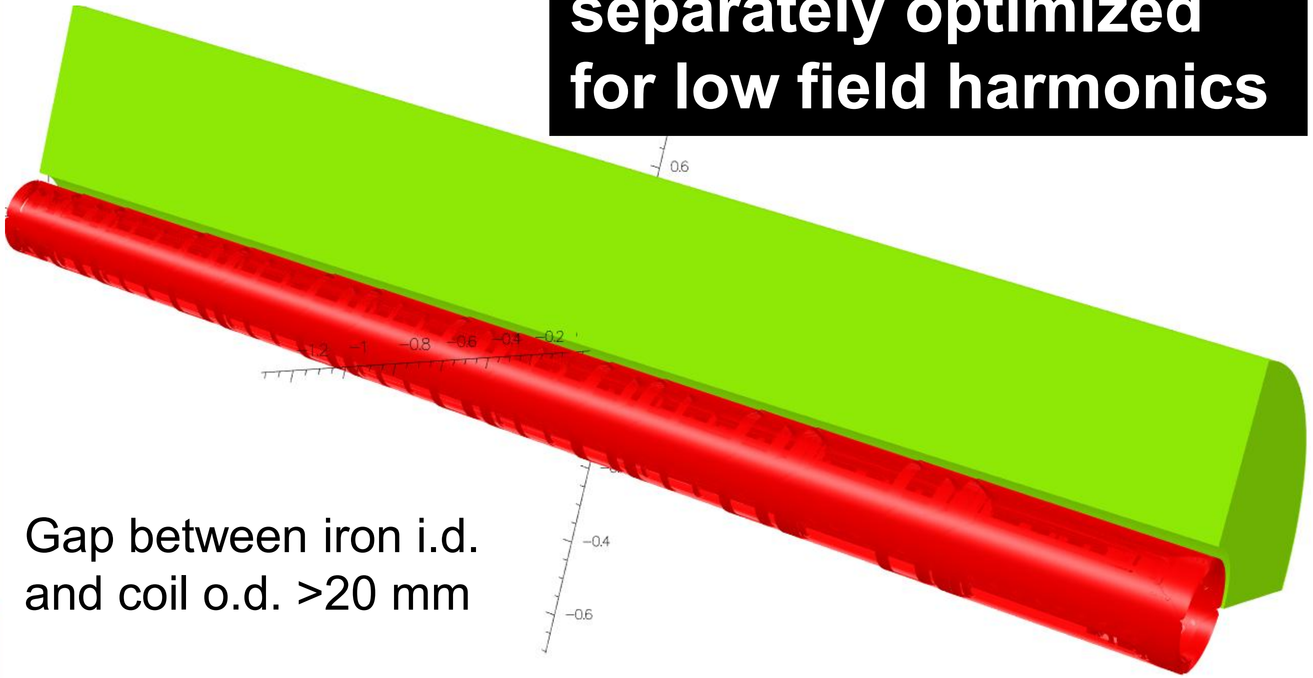
- ➢ Same wire/cable
- ➢ Same tapered tube inner radius and minimum tube thickness
- ➢ Same overall coil length (Q1ApF+Q1BpF)

❑ **The target is to see if one can get 65%-70% load line fraction with low field harmonics in a quick investigation.**

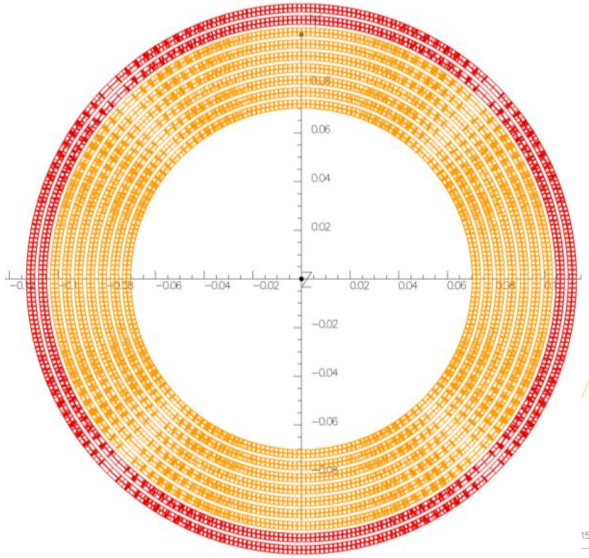
Initial Model of the Staircase Tapered Q1ApF (coil-set buildup: seven throughout the length)



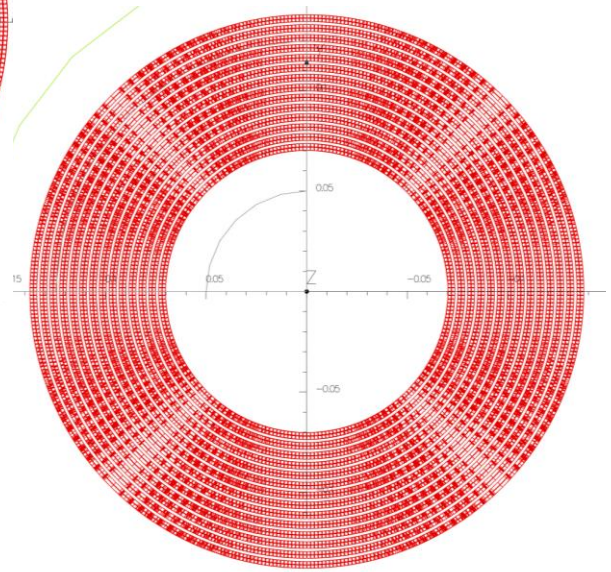
Each coil-set is separately optimized for low field harmonics



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)

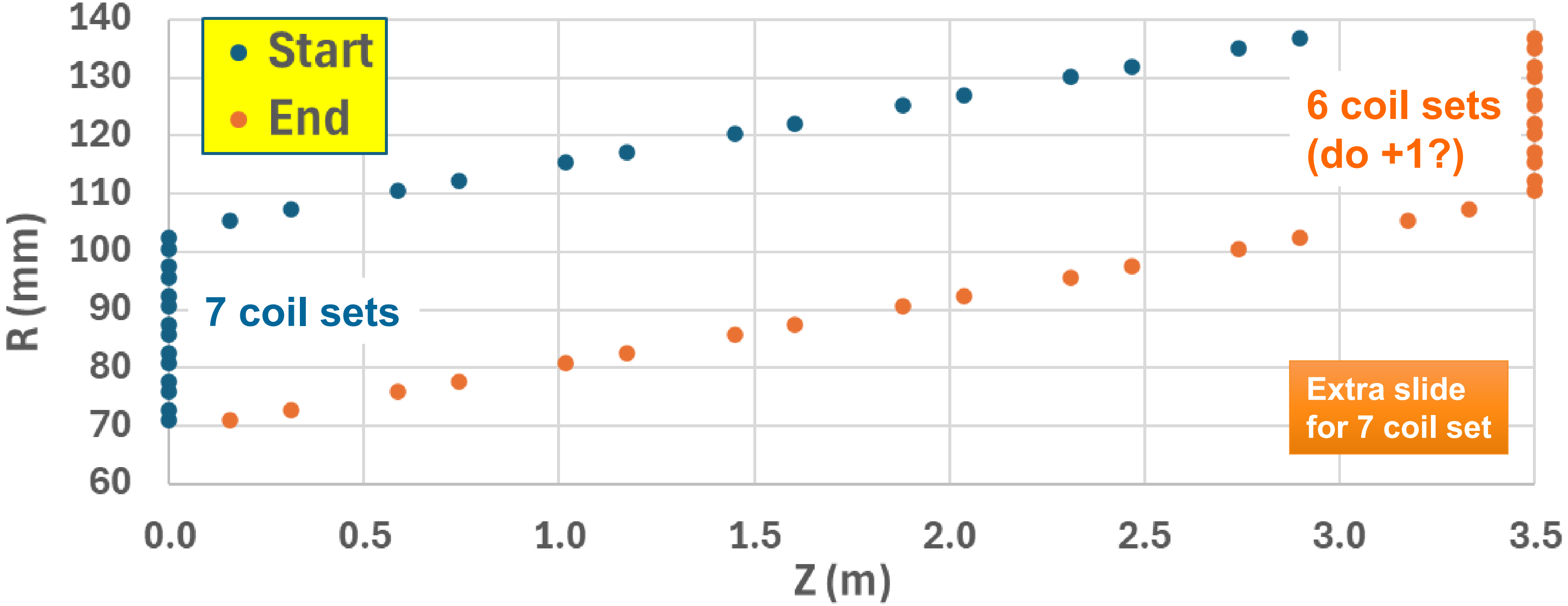
Coil aligned to one end

Coil end in the middle

Layer #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
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
Zstart(m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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
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
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

Layer #	15	16	17	18	19	20	21	22	23	24	25	26	27	28
R(mm)	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)	0.16	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)	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)	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	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

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

@ 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

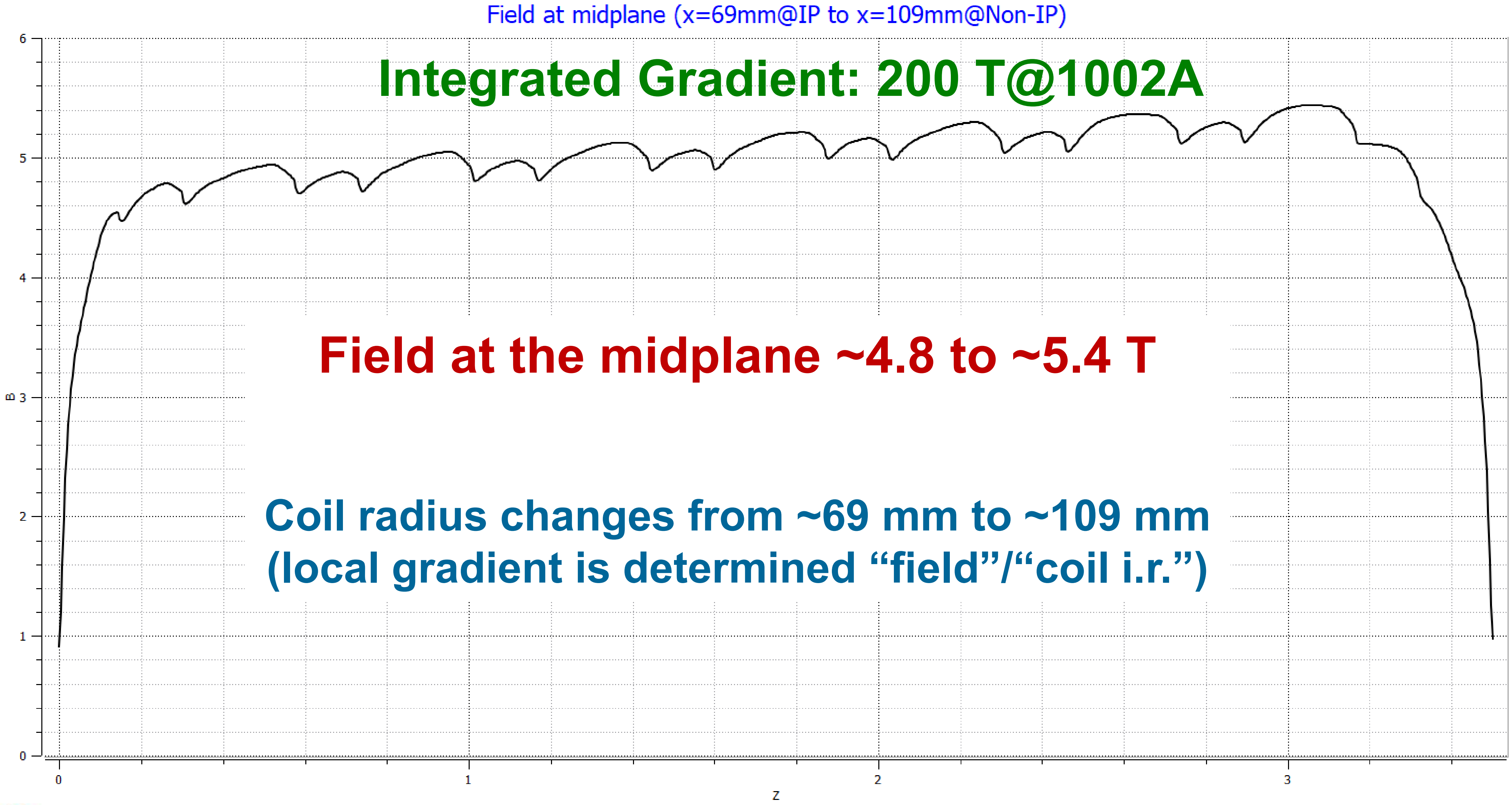
@ the Non-IP End

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)

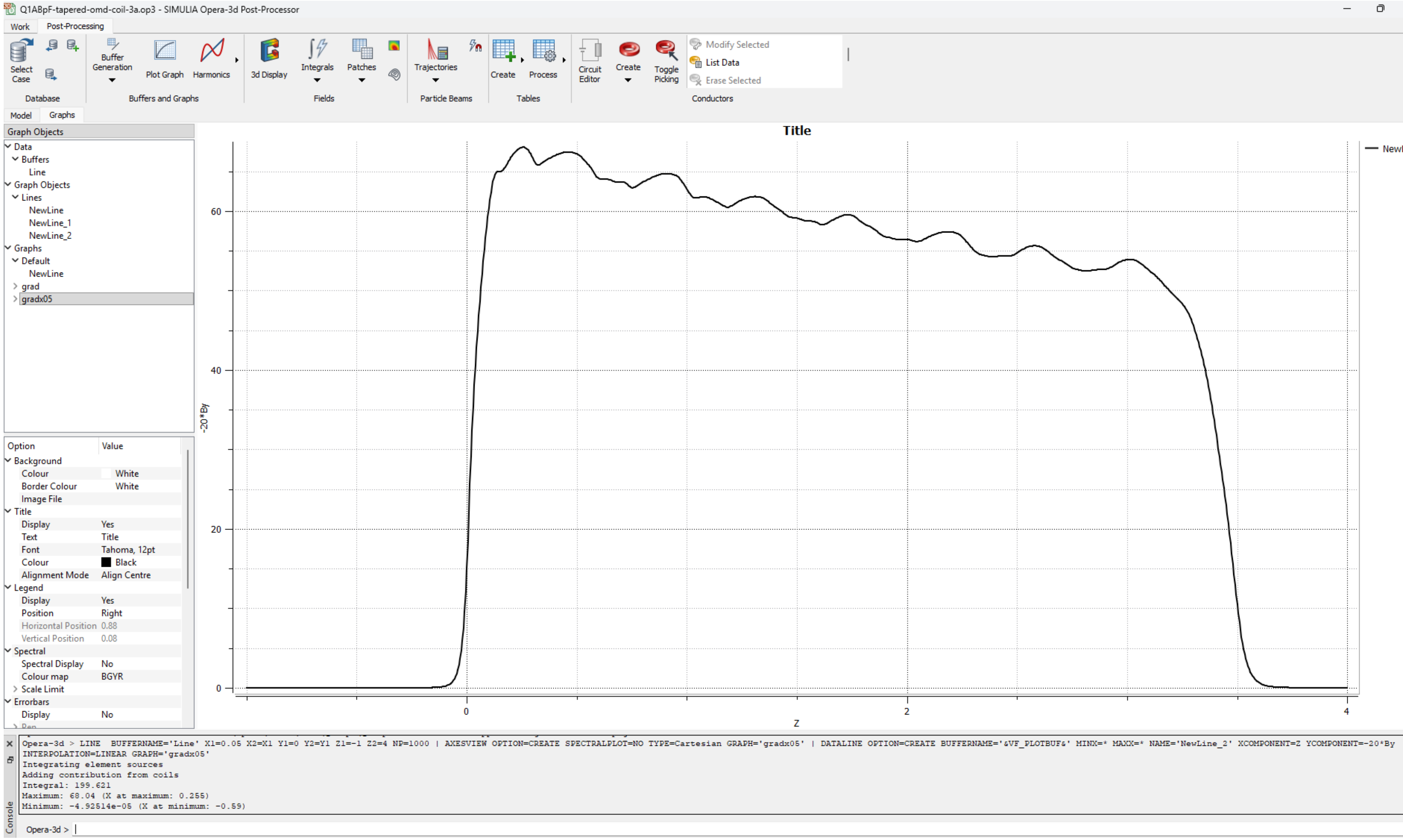
Field at the Coil Midplane in the Initial Staircase Design



Gradient Profile in the Staircase Design

Integrated Gradient: 200 T

Operating Current: 1002 A



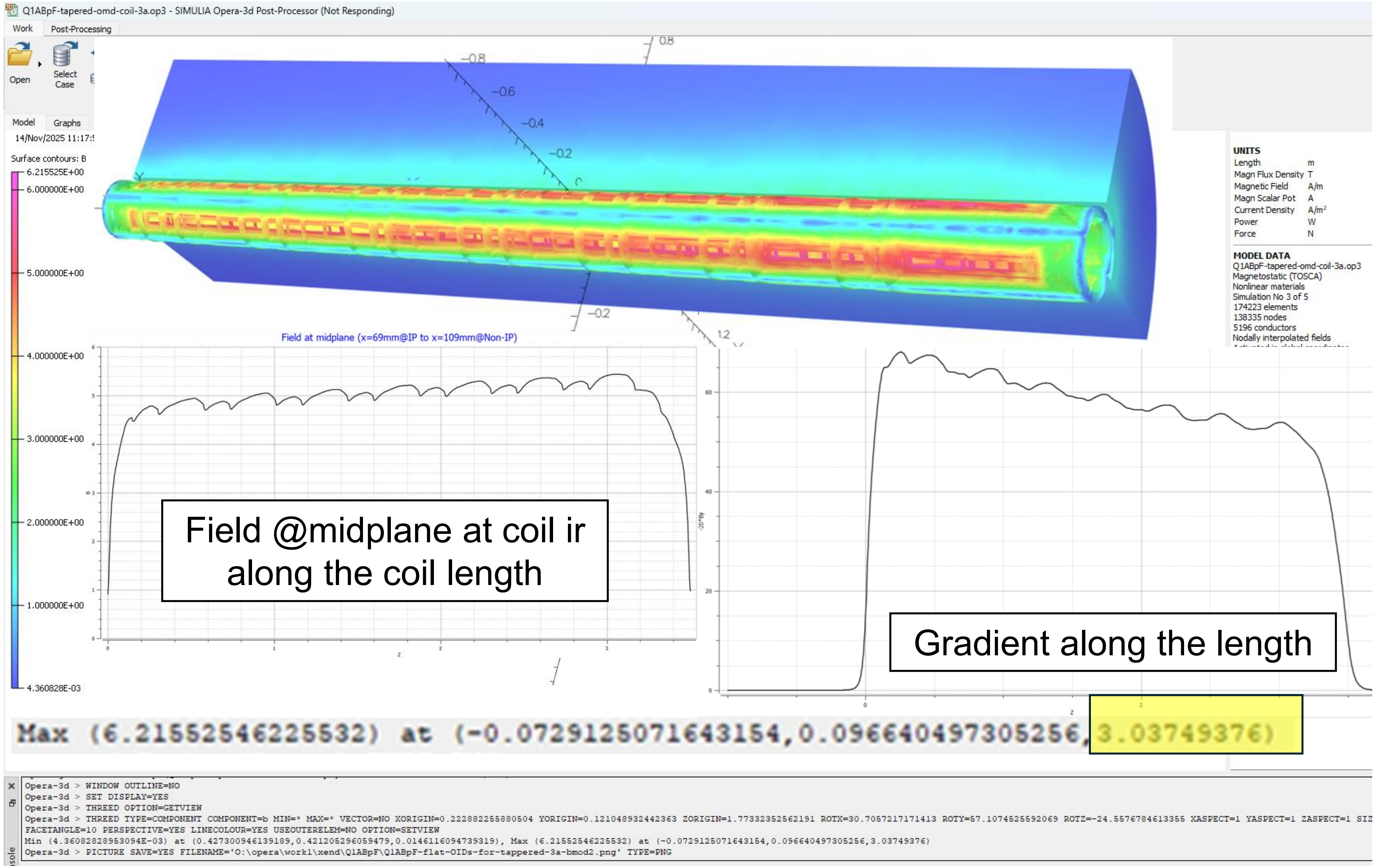
Peak Field in the Initial Staircase Design

Integrated Gradient:
200 T
Operating Current:
1002 A

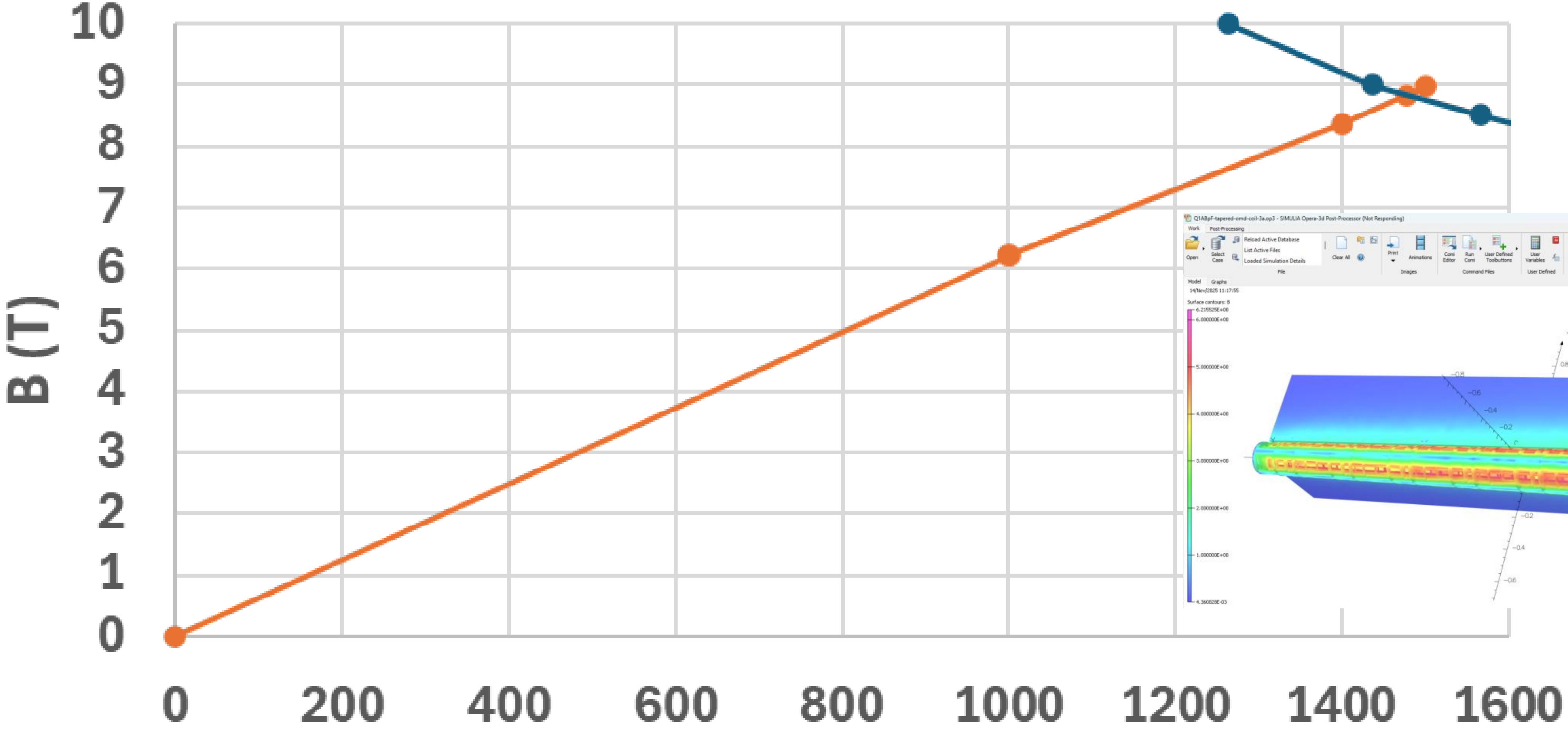
Peak Field: ~6.2 T
(not fully optimized)

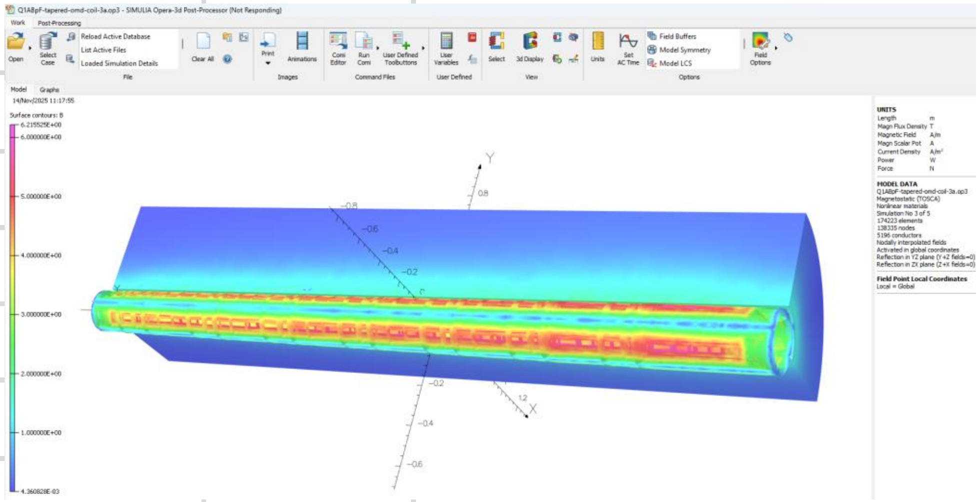
Maximum Field at the midplane: 5.4 T

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)**

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 optimum integral design or in a staircase optimum integral design or in a tapered serpentine design.
- In terms of margin, even in the first preliminary design, tapered staircase design is at the load-line fraction of ~67% (65% should be possible with a bit more optimization).
- Since most of the coils are long, one should be able to use the serpentine coils without much loss in integrated gradient.
- This work should be considered as an initial proof-of-principle investigative work to show that can one obtain the desired load line fraction margin with good field quality in a tapered design.
- The answer seems encouraging for a tapered direct wind solution irrespective of the details of the design. Serpentine geometry is preferable for a variety of reasons.

Extra Slides

Tapered Cosine Theta Coil Design Principle

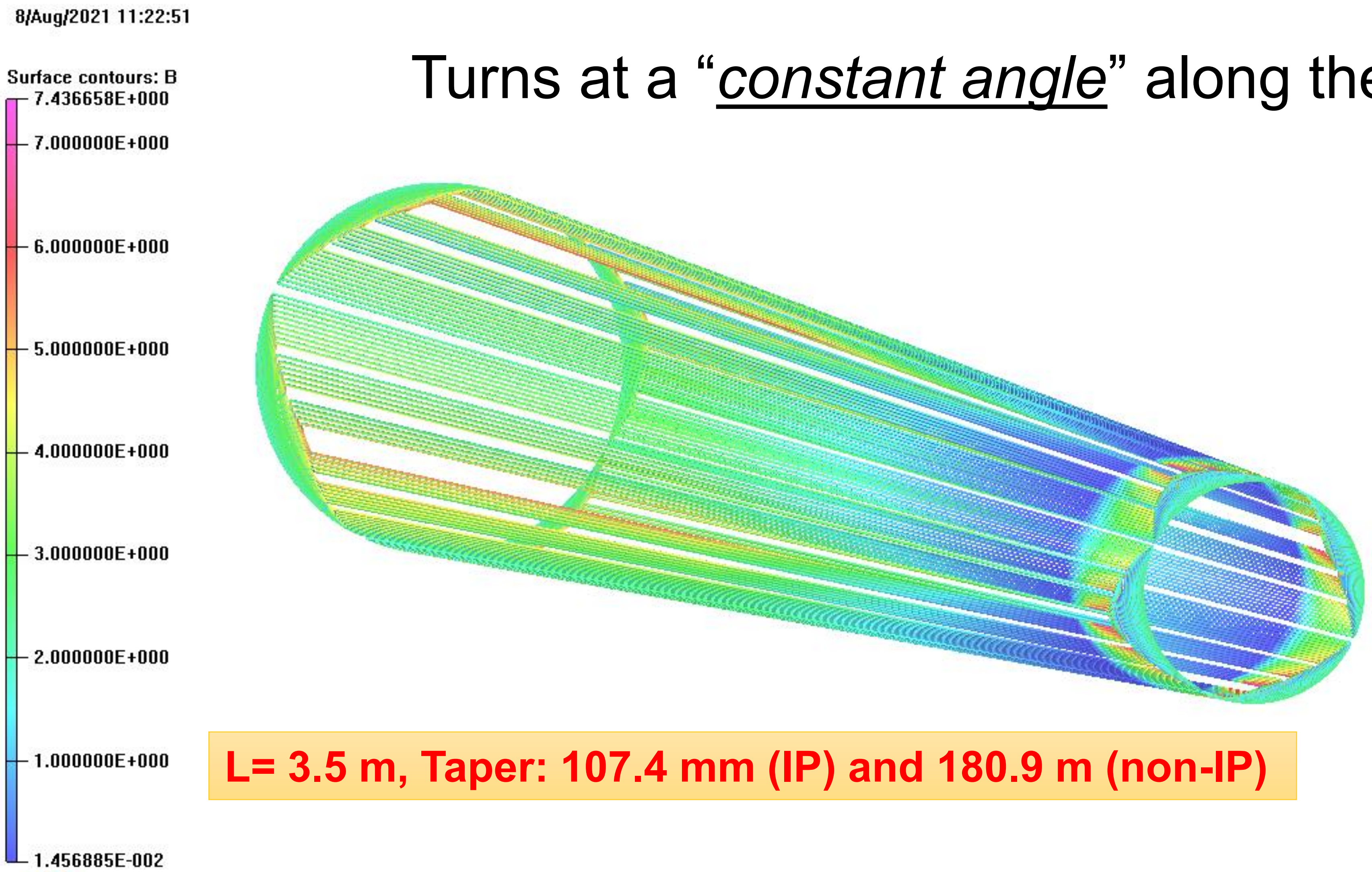
- Conventional Design Principle: to assure a good field quality, each wire maintains the same angular position while the coil radius is changing
- Issue: If the taper, i.e., the change in radius is large (as is the case in several EIC magnets), there will be a significant empty space between the turns 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.**
  - ➢ **Explanation: Why the basic approach being followed by Vikas is the best suited in the parameter set of Q1AbpF (may be with a few mods)**

Tapered Cosine Theta Coil Design Principle

- Conventional Design Principle: to assure a good field quality maintain the same angular position of each wire while the coil radius is changing
- Issue: If the taper or the change in radius is large (as is the case in the several EIC magnets), there will be a significant empty space (white space) between the turns causing a large loss in field or field gradient
- Proposed Principle: A configuration which minimizes the white space between the turns and pack as many turns as possible despite a taper

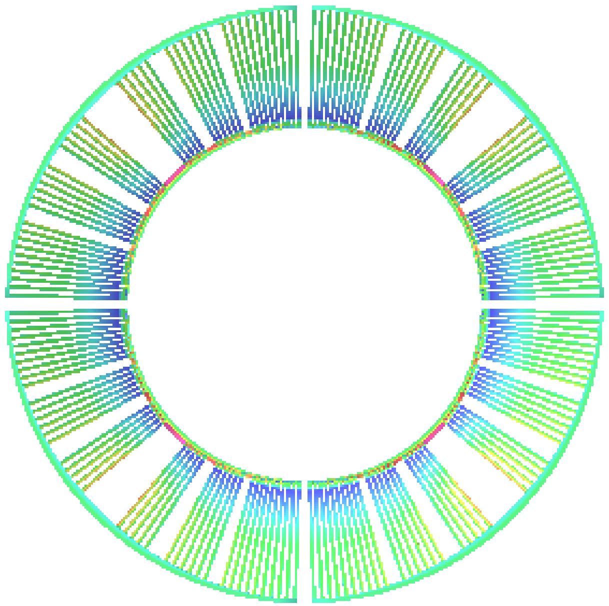
➢ **Next few slides will explain the proposed concept/principle (illustrated first for the dipole and then for the quadrupole)**

EIC Cosine Theta Tapered Quad Q1AB (conventional design)



Turns at a "*constant angle*" along the length of the taper

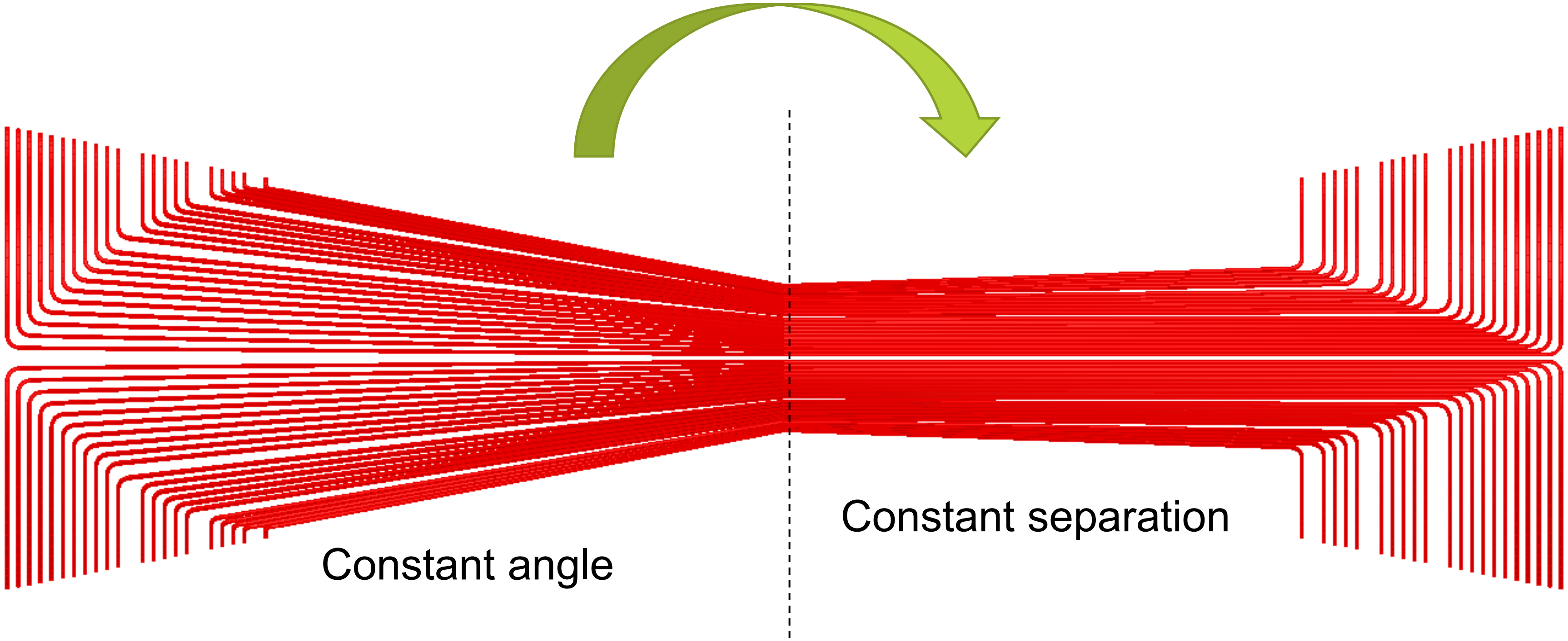
L= 3.5 m, Taper: 107.4 mm (IP) and 180.9 m (non-IP)

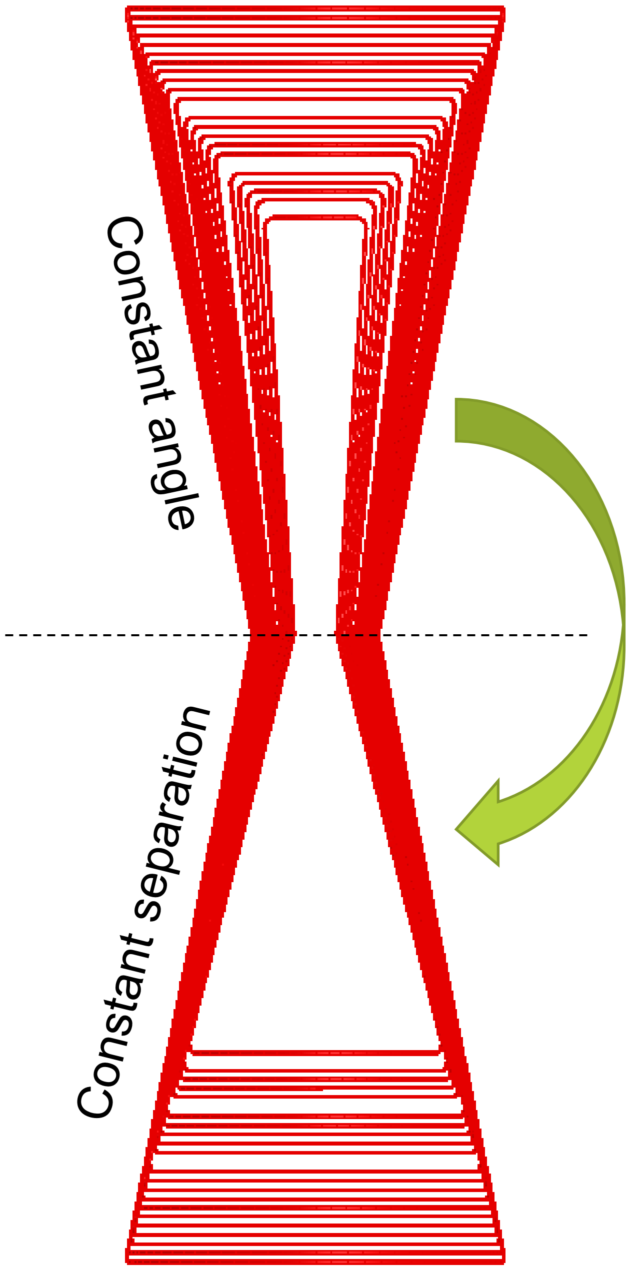


View from the end

Proposed Design – Step 1

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

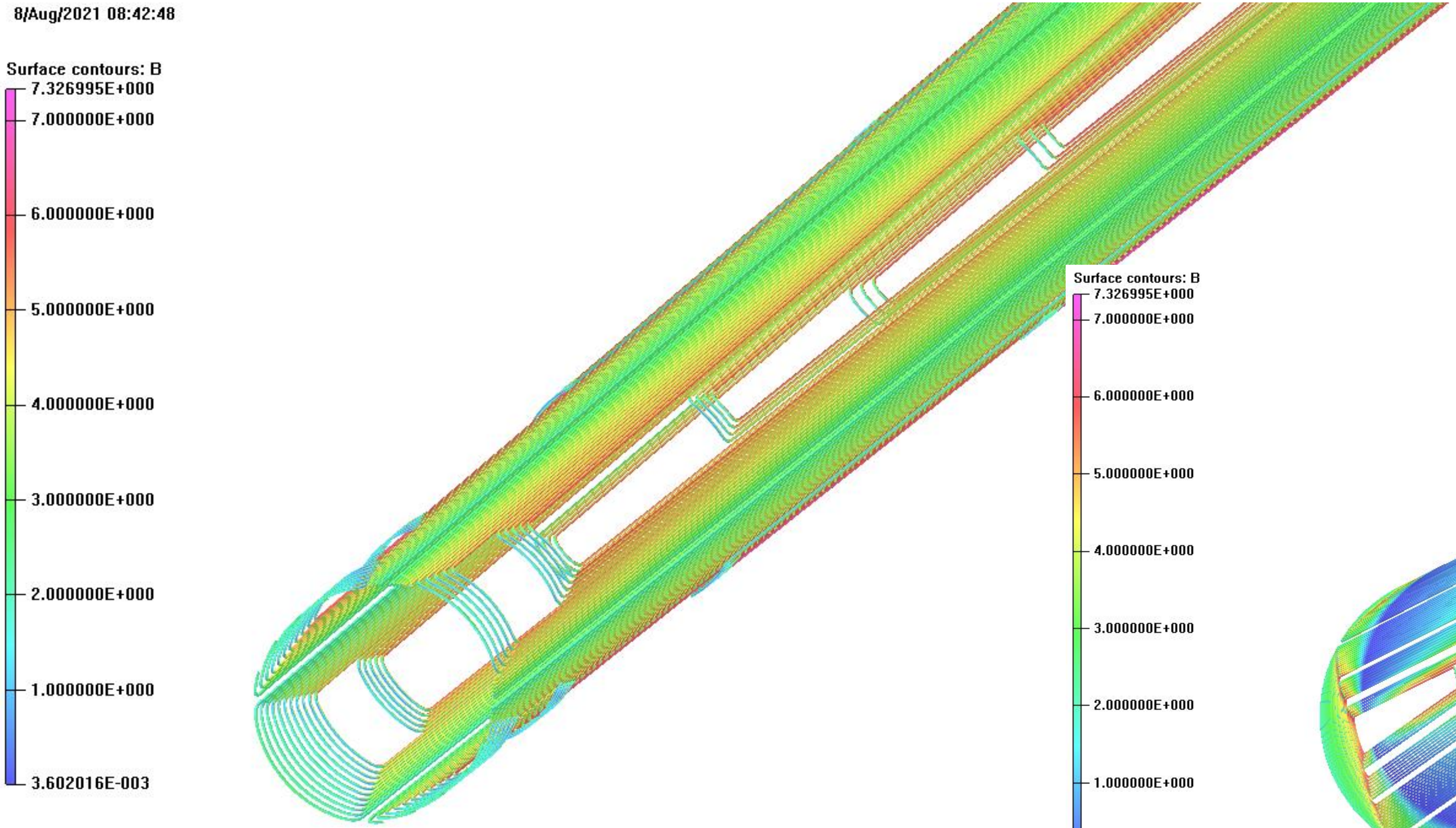


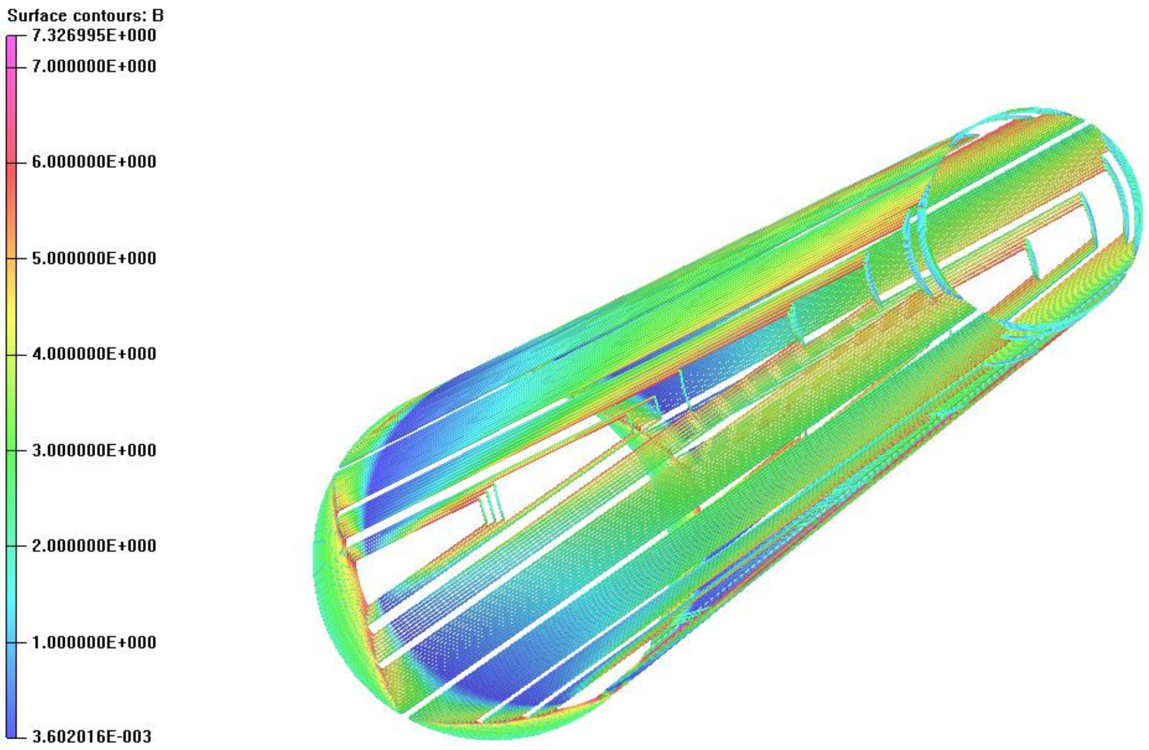


L= 3.5 m, Taper: 107.4 mm (IP) and 180.9 m (non-IP)

Proposed Design - Step #2 (cont.)

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

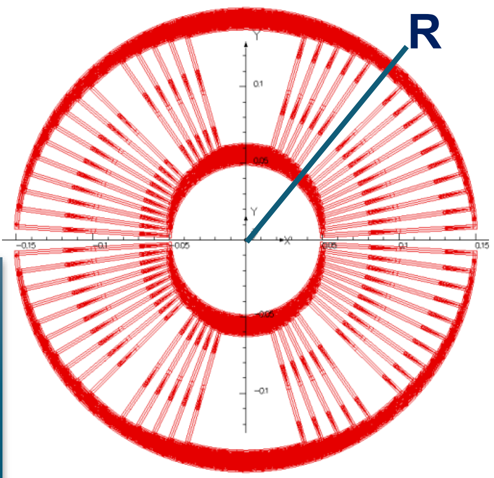




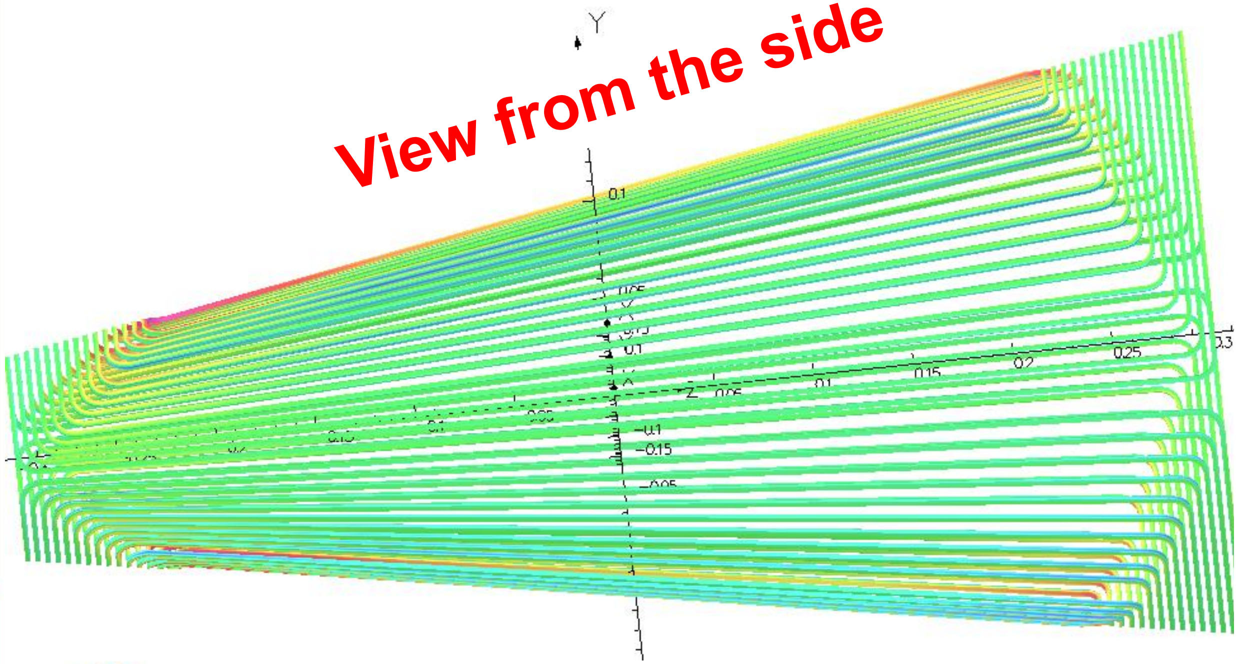
Conventional Design of a Tapered Cosine Theta Dipole

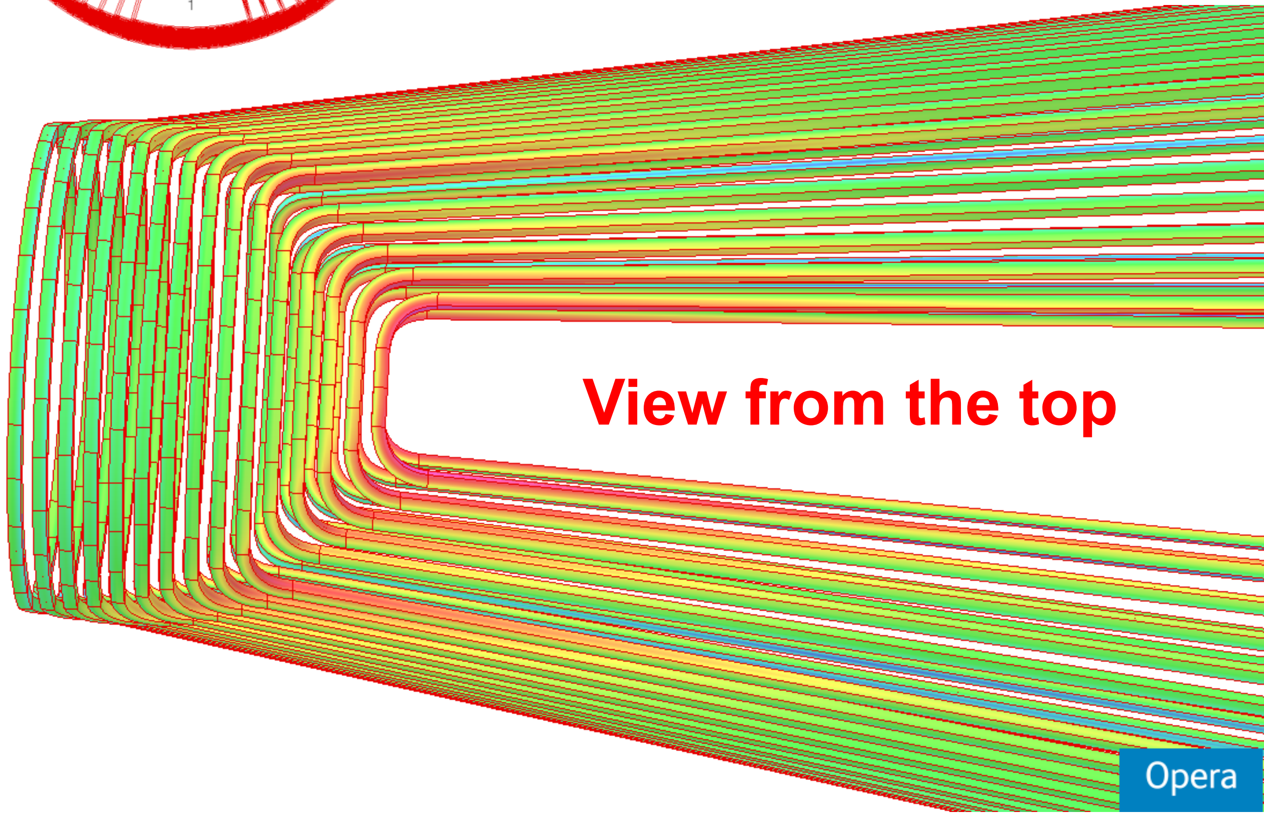
Wires maintain their angular position even when radius is changing (harmonics will not change)

View from the end



One side of the taper is at the i.d. and the other side at the o.d. Note: The angular position doesn't change. However, non-productive space is increased on far side.

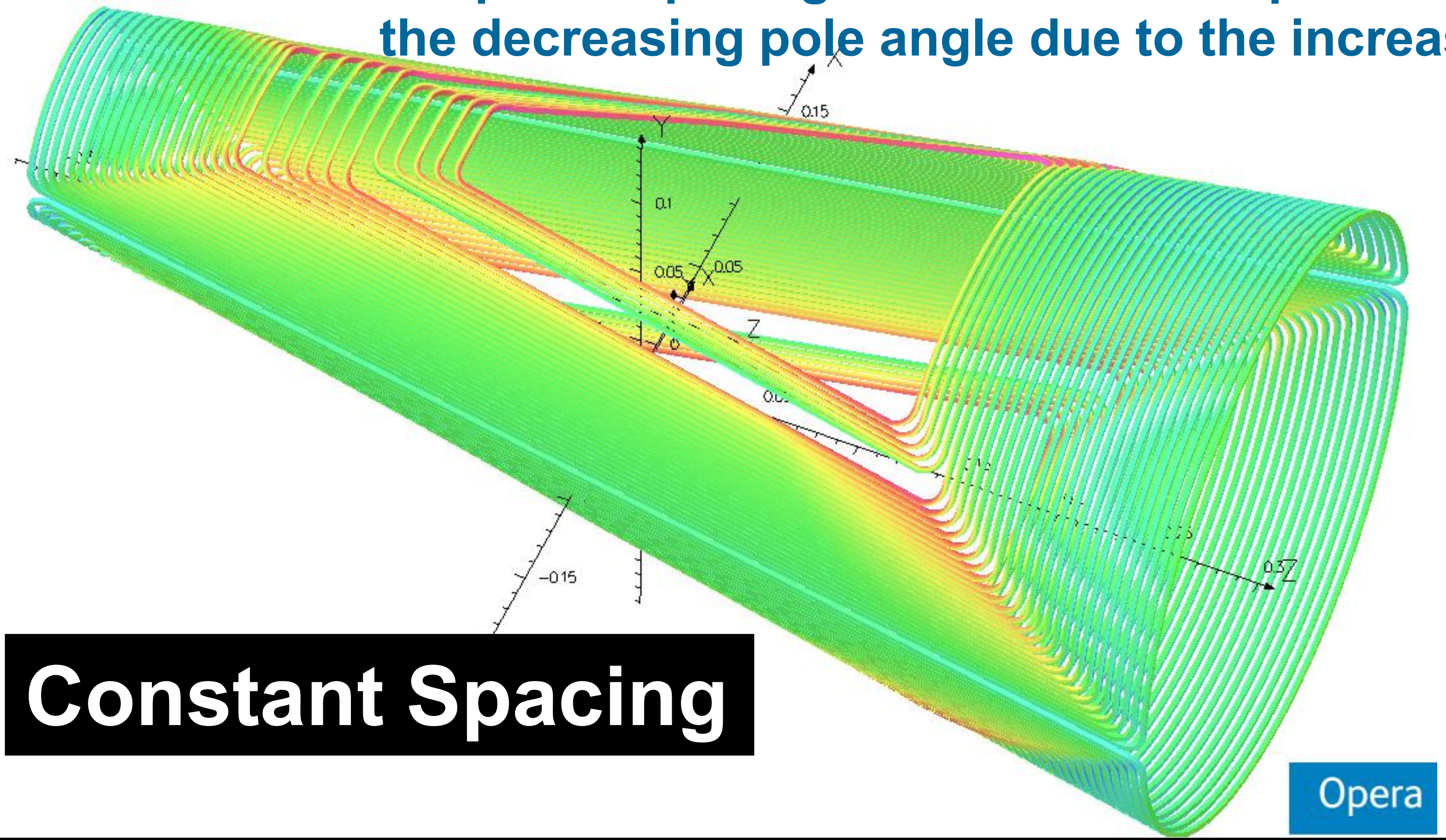




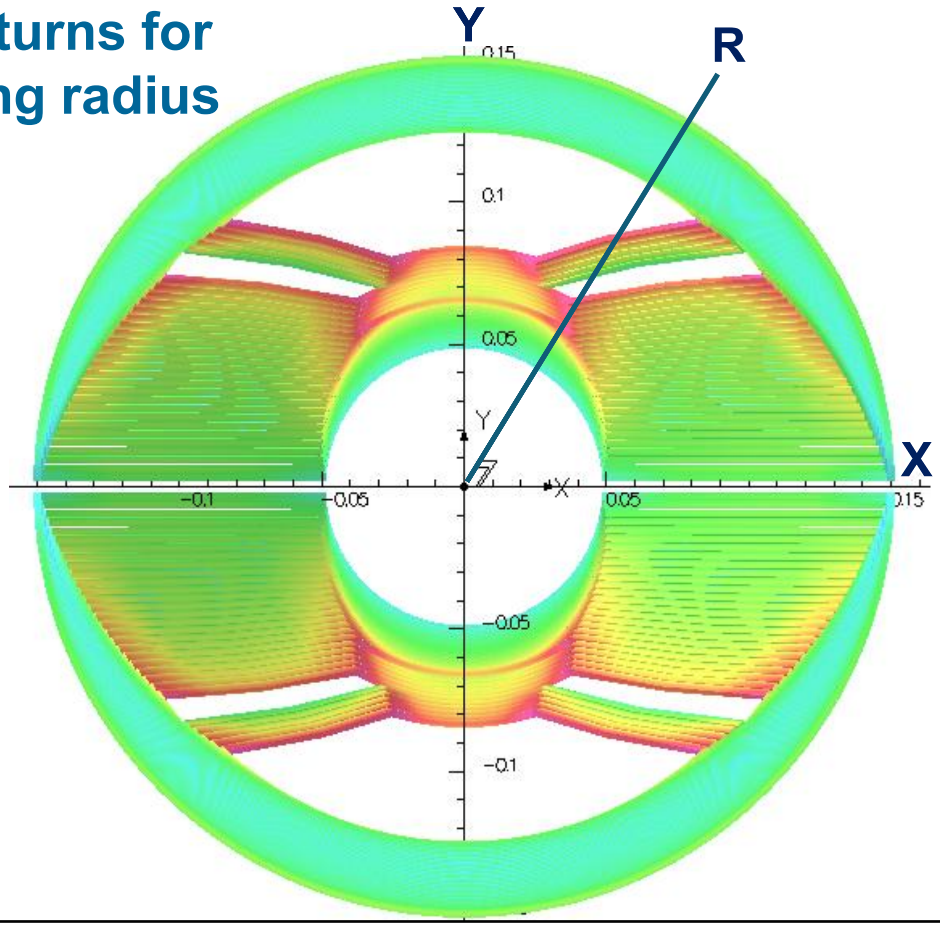
One Approach (explored earlier – not to be discussed here)

✓ **Tapered Optimum Integral Design**

- ➢ **Keep turn spacing constant and keep adding turns for the decreasing pole angle due to the increasing radius**

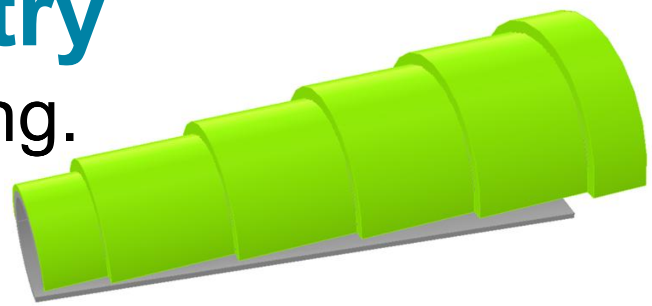


View from the end



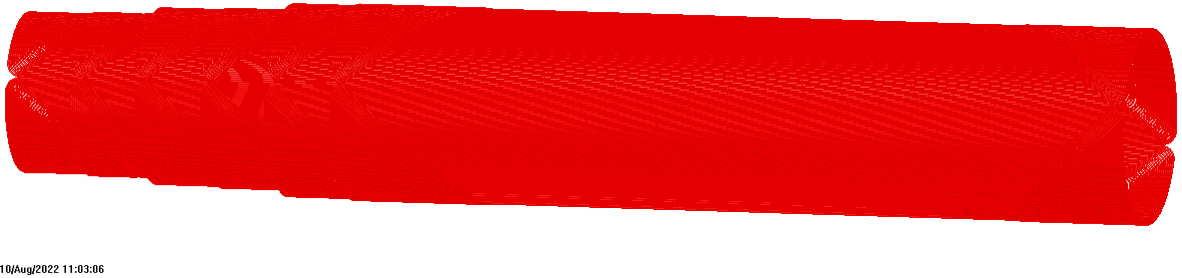
Harmonics must be optimized carefully. They will vary locally but are made small when integrated over certain (small) length. Is that OK? 2-d harmonic definition is not valid.

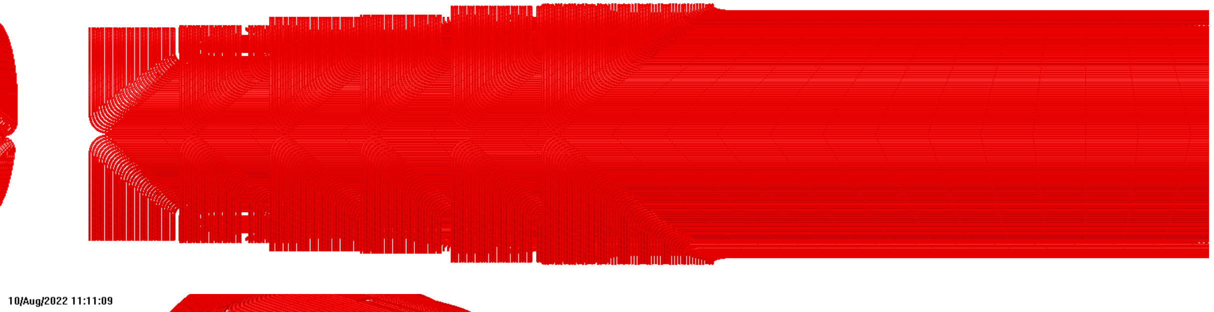
Staircase Concept for a Tapered Geometry

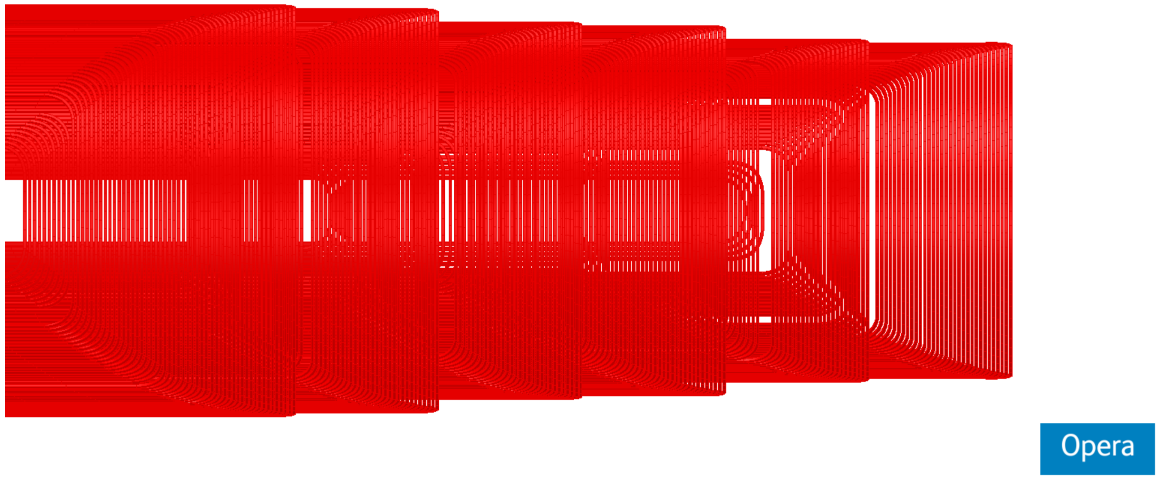


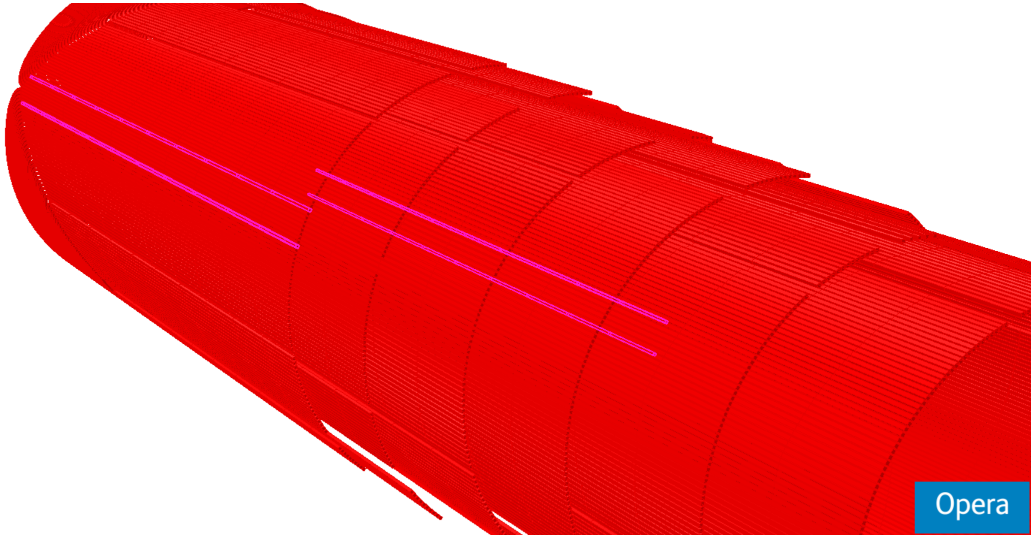
- EIC direct wind magnets have several layers of winding.
- In this concept, each layer is wound on a flat surface.
- It maintains a minimum tube thickness throughout.
- This may limit the length of an individual layers, depending on the place.
- Second layer is wound partially on the first layer. It 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. More info follows.

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



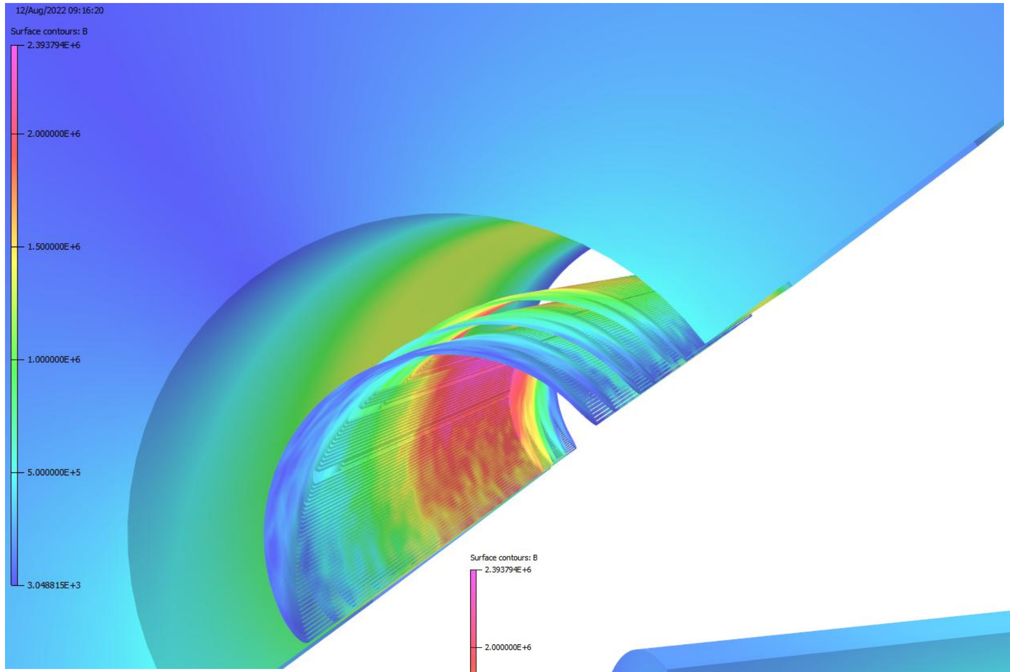


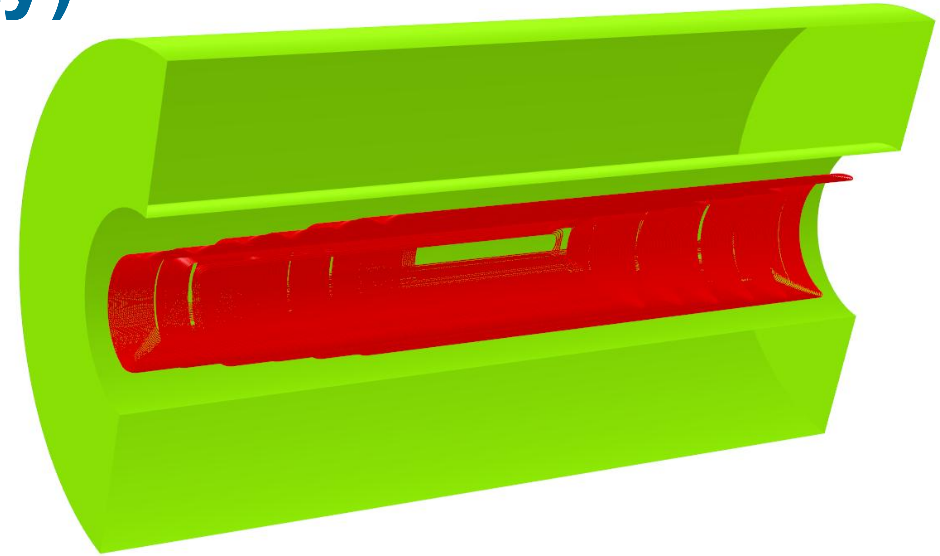


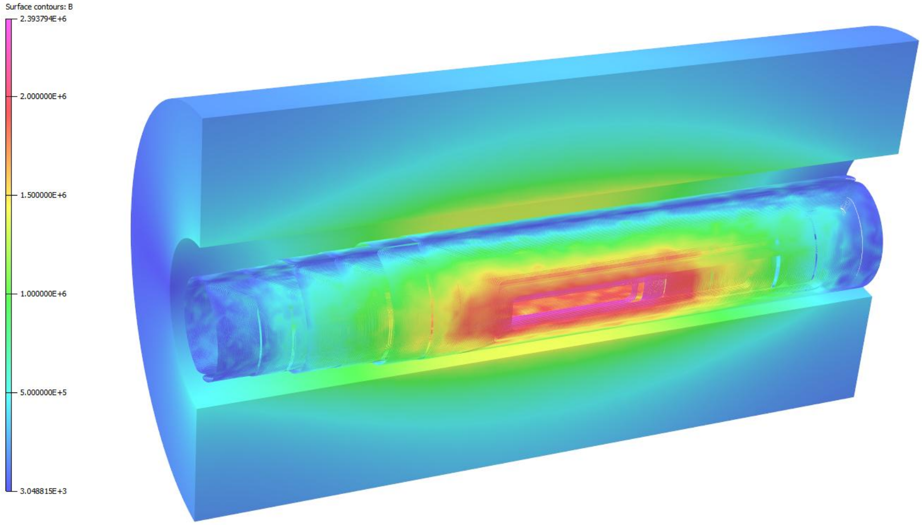


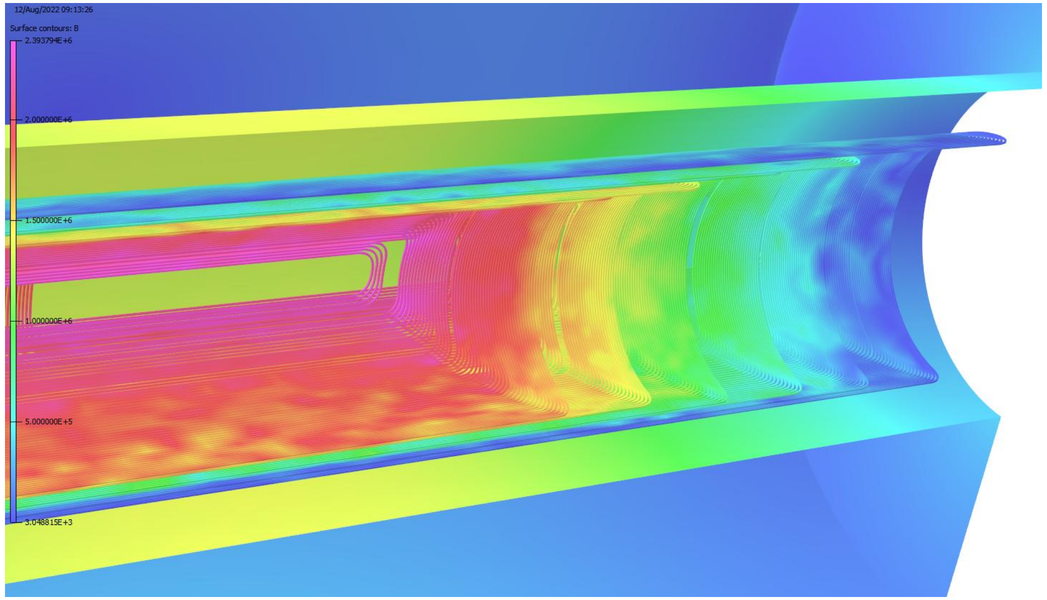
Each double layer will be optimized for a good field quality

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

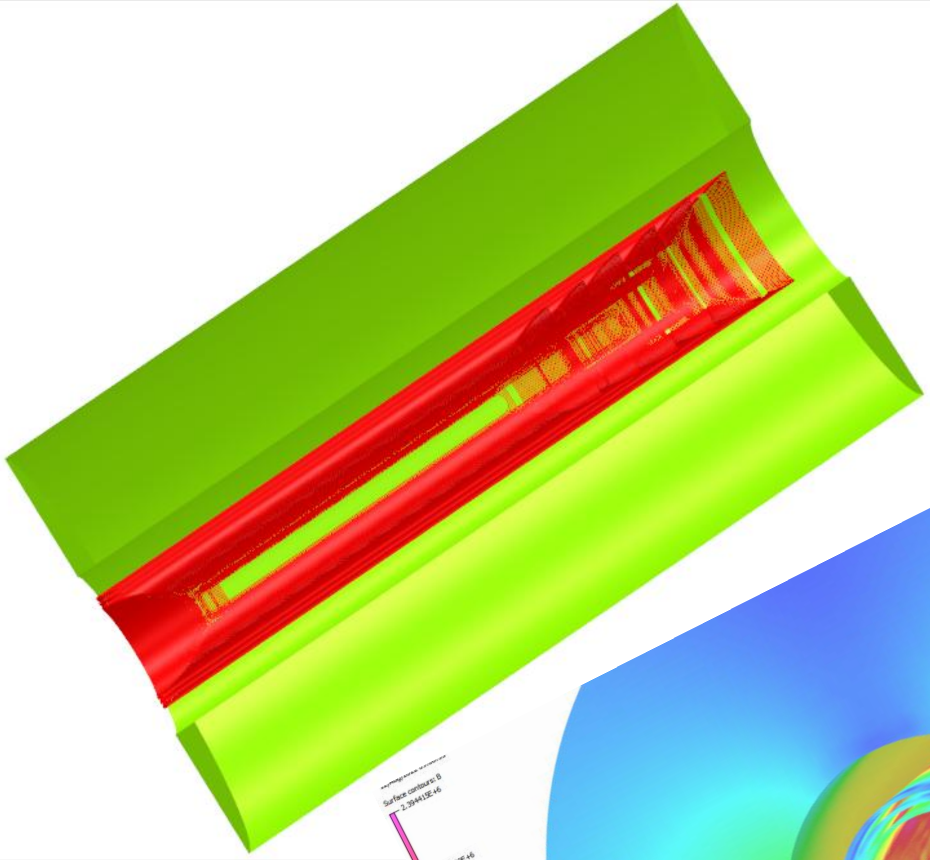


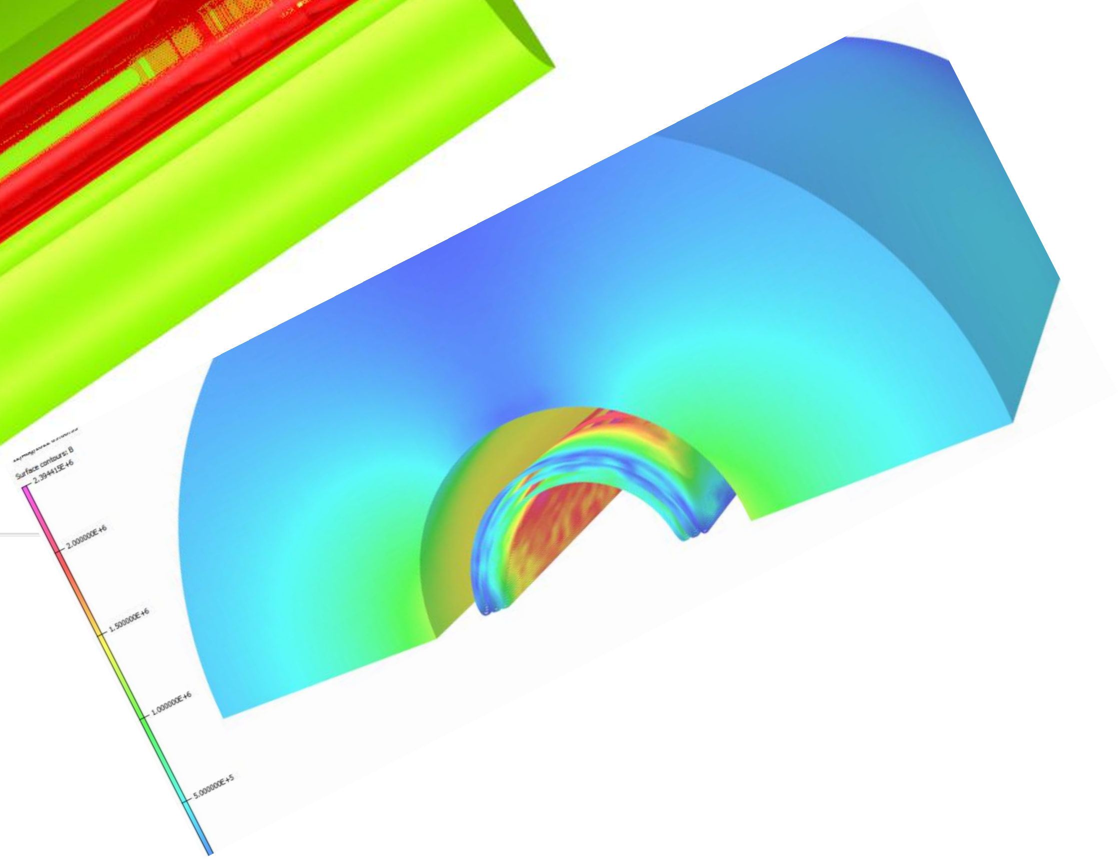


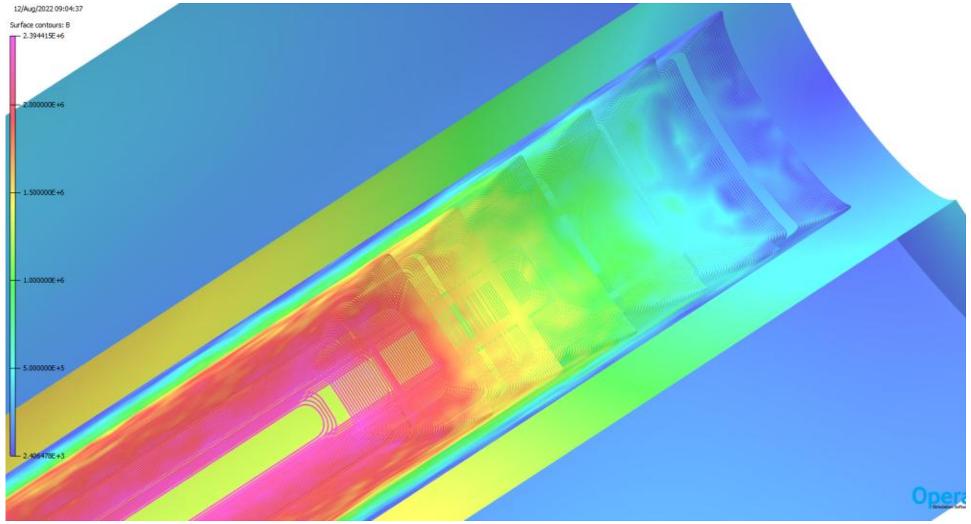


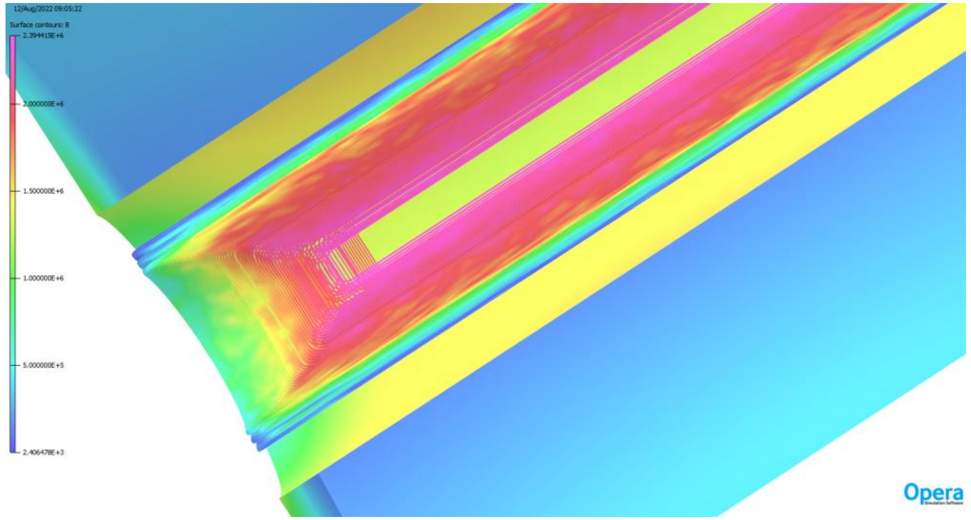


More Illustrations of the Windings in Yoke

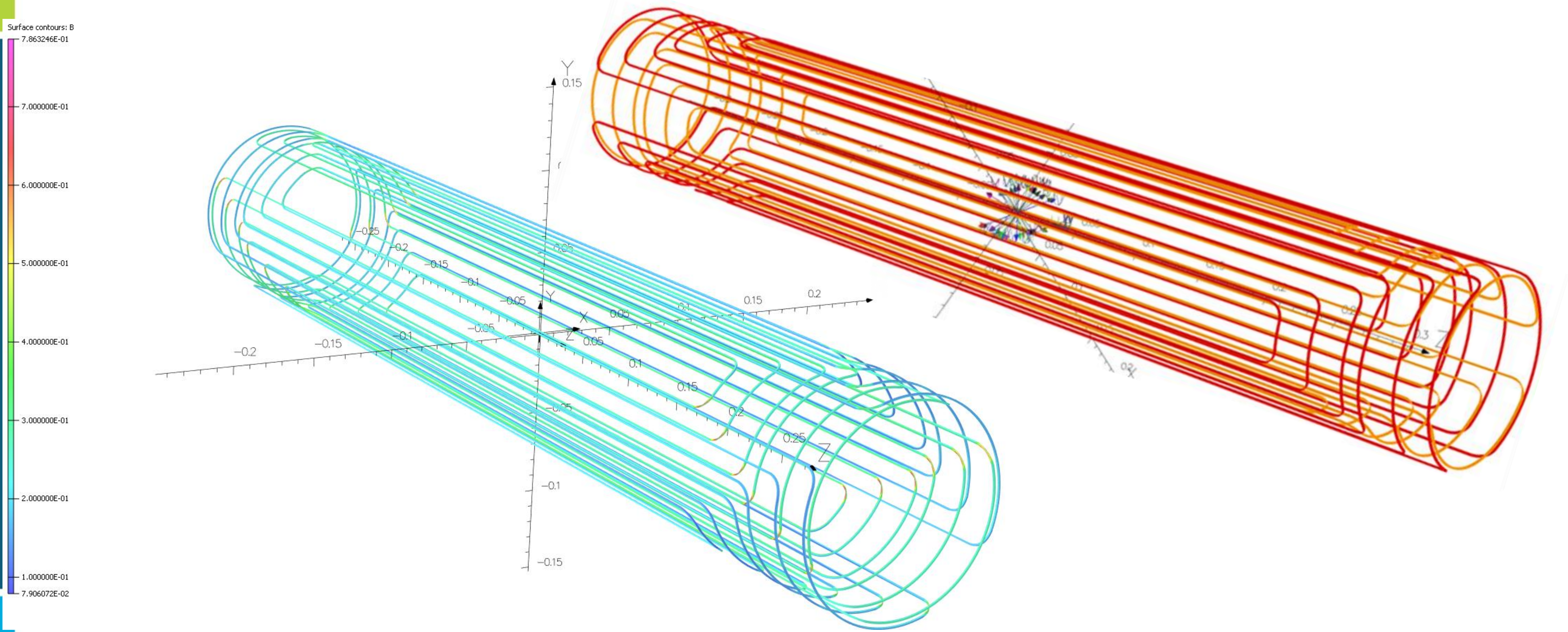






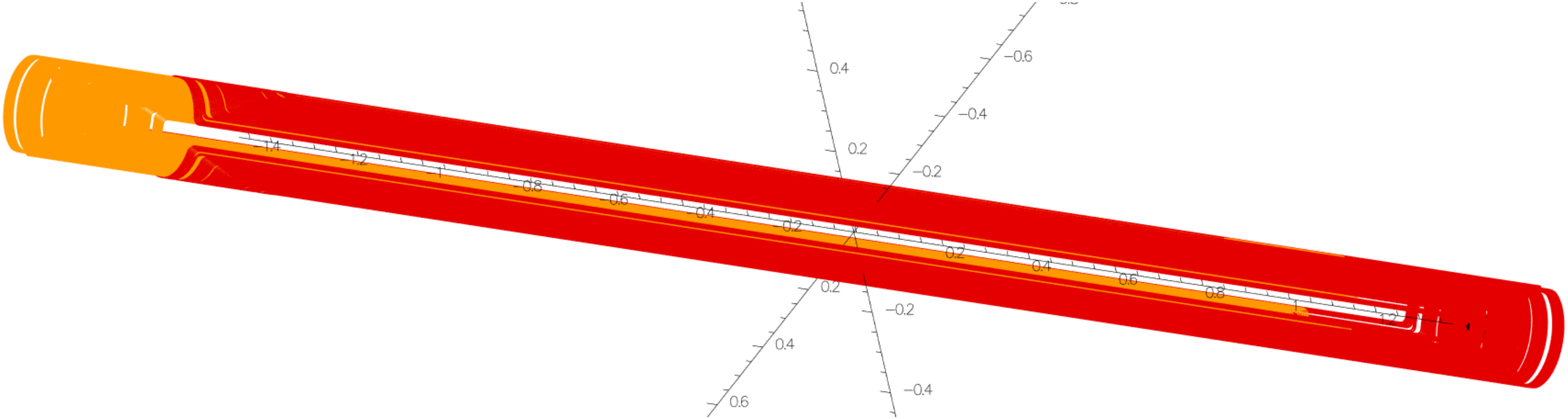


Serpentine Coil Design with the *OptIntegral* Code (visual illustration of an example of a coil set-2 layers)



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

More Extra Slides

EIC Tapered Coil Design – Double Helix (Holger Witte)

Overview Q1ABpF

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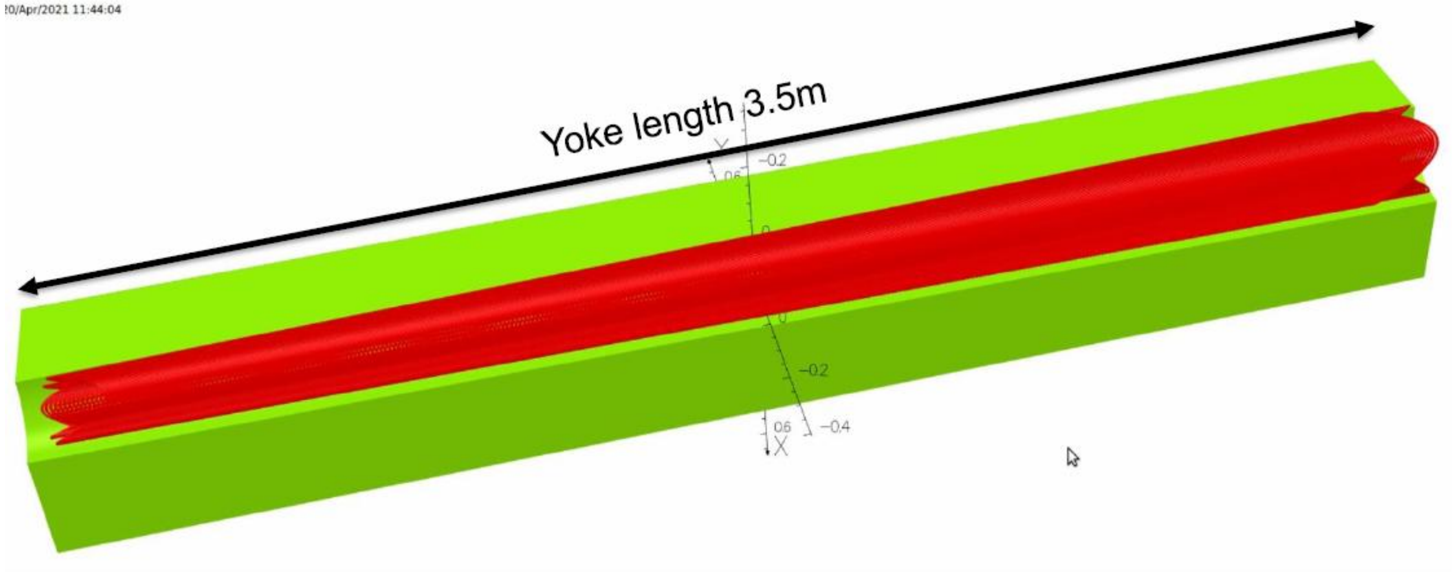
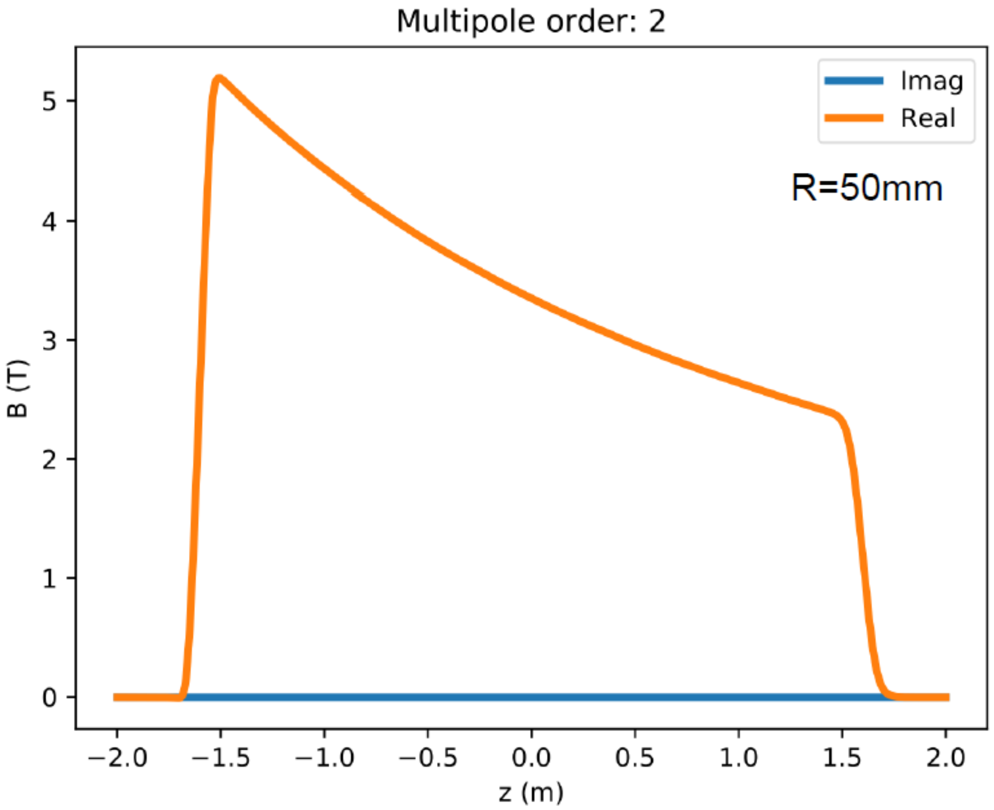


This may not be the latest design



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

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

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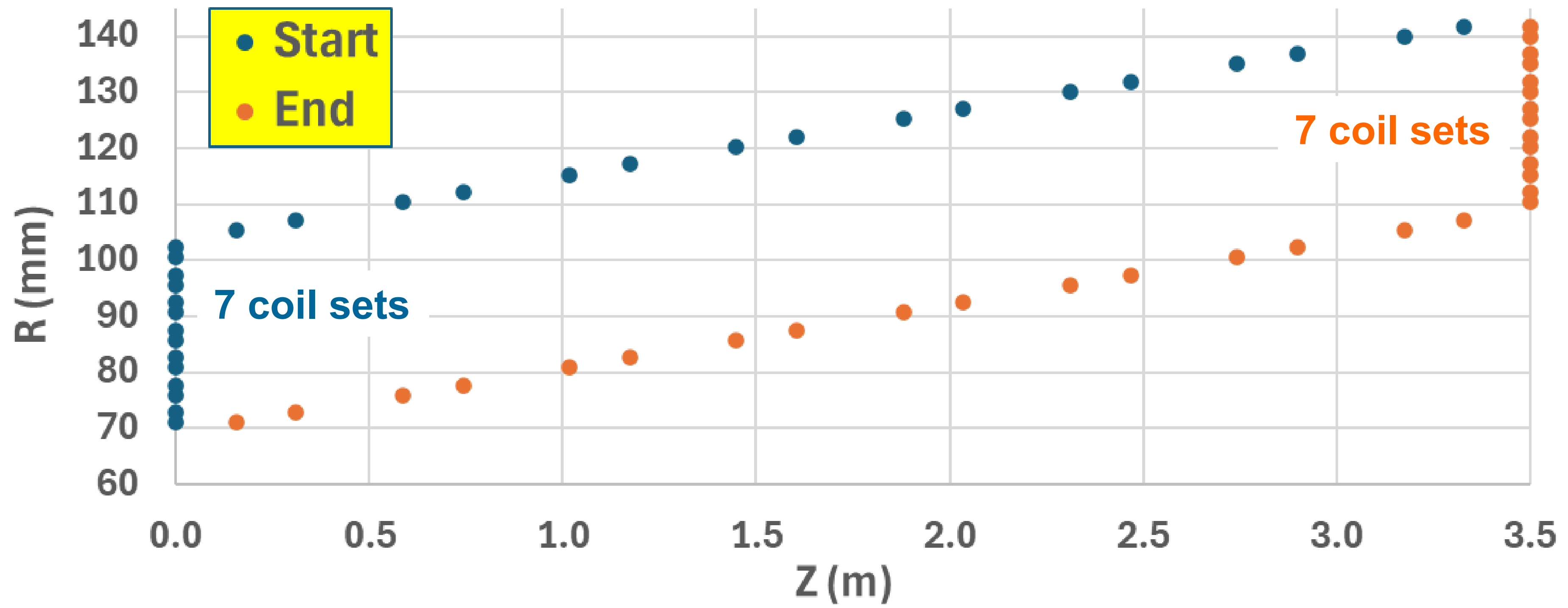
Staircase Design Details and Options
(Serpentine will also work and perhaps preferable)

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	L29	L30	Layer #
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	140.0	141.8	R(mm)
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	3.17	3.33	Zstart(m)
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	3.5	3.5	Zend(m)
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	0.33	0.17	L(m)
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	2.3	1.2	L/R

- 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**

Gradient Profile when polarity is made opposite between the two halves of the coil sets (7 positive, 7 negative)

Such an option is interesting if we wish to turn it into two quads with lower gradient and opposite polarity.

Make appropriate selection in choosing number of layers for two coil sets