Particle Beam Lasers

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Update on Optimum Integral Design and Winding Software for Serpentine Coils

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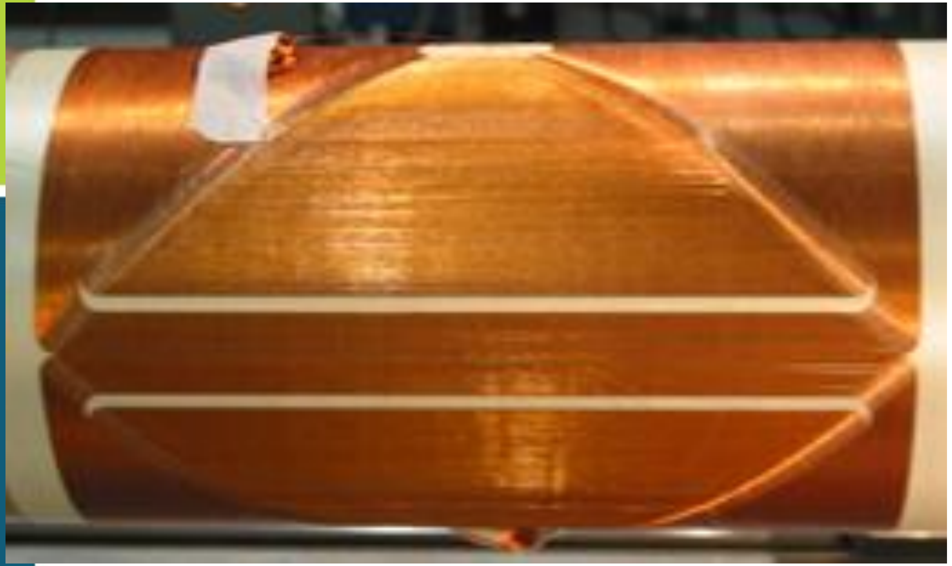
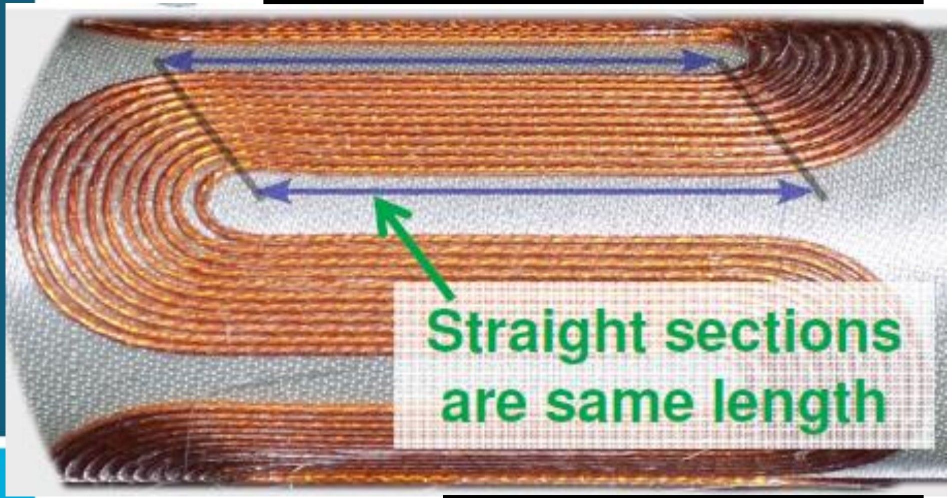
June 3, 2024

Note: The purpose of this presentation is not to discuss which design is better or how best to design a magnet. The purpose is to see if the software used in designing and winding optimum integral coil can be used to design and wind serpentine coil and to have an independent software to validate different designs.

Background



OPTIMUM INTEGRAL COIL

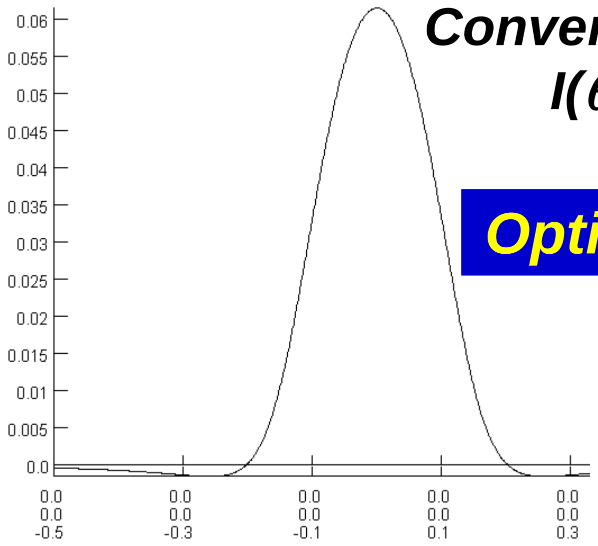


SERPENTINE COIL

- Several coils based on the optimum integral & serpentine designs have been wound (>10 each) using the direct wind technology (pics on left).
- For winding purposes, optimum and serpentine coils are almost the same on how wires are planted in the body and in the ends. Difference: direction of turn in two ends (same or opposite).
- A software was developed two decades ago to design and build an optimum integral dipole (the only direct wind magnet in a BNL accelerator).
- PBL/BNL has STTR on optimum integral B0ApF. Warm harmonic and 2 cold quench tests done.
- One key task: port and document coil designing and winding software to present system (done).
- The serpentine pattern is getting activated with ATRO internal funds (a relatively small task).

Optimum Integral Design Concept and Software

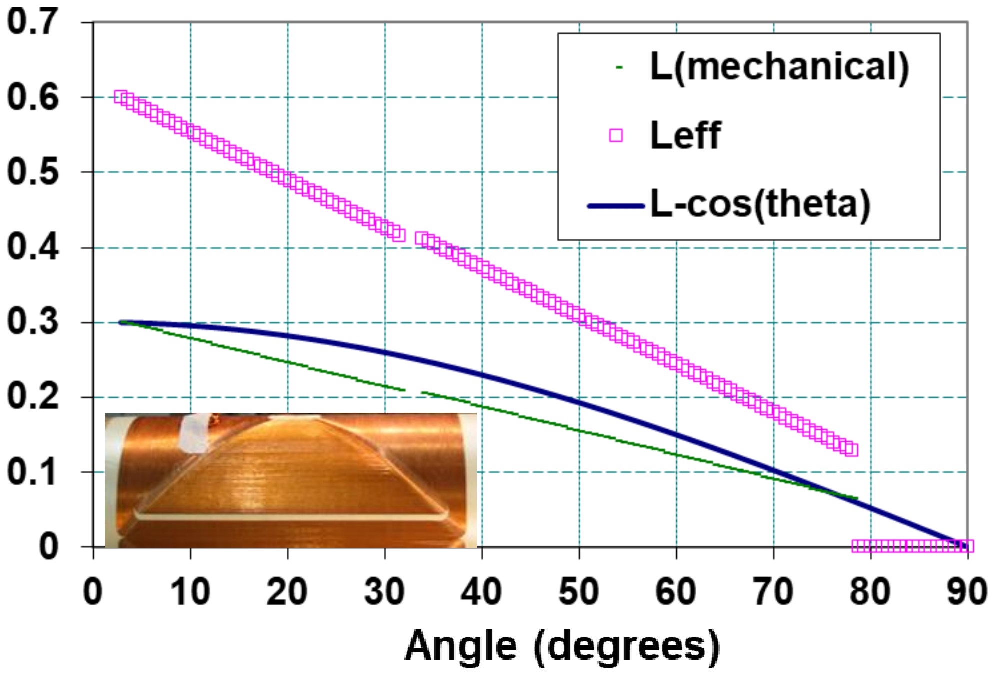
- In a conventional design process, we first optimize the “body” mimicking cos(θ) current distribution and then optimize the “ends” for low harmonics.
- Low peak fields (in the body and in the ends) are checked/optimized separately in select cases, since it takes too long.
- In short cos(nθ) magnets, there is little to no flat-top in the axial field profile.
- Therefore, “Body” and “Ends” can’t be treated <u>separately</u>.
- Optimum Integral design combines the to two together for a better optimization.



Conventional designs:
$I(\theta) = I_o \,.\, \cos(n\theta)$
(a 2-d design)

Optimum Integral:

$I(\theta) \,.\, L(\theta) =$
$I_o \,.\, L_i(\theta) \propto$
$I_o \,.\, L_o \,.\, \cos(n\theta)$
(a 3-d design)



Computation and Optimization of Integral Field and Field harmonics

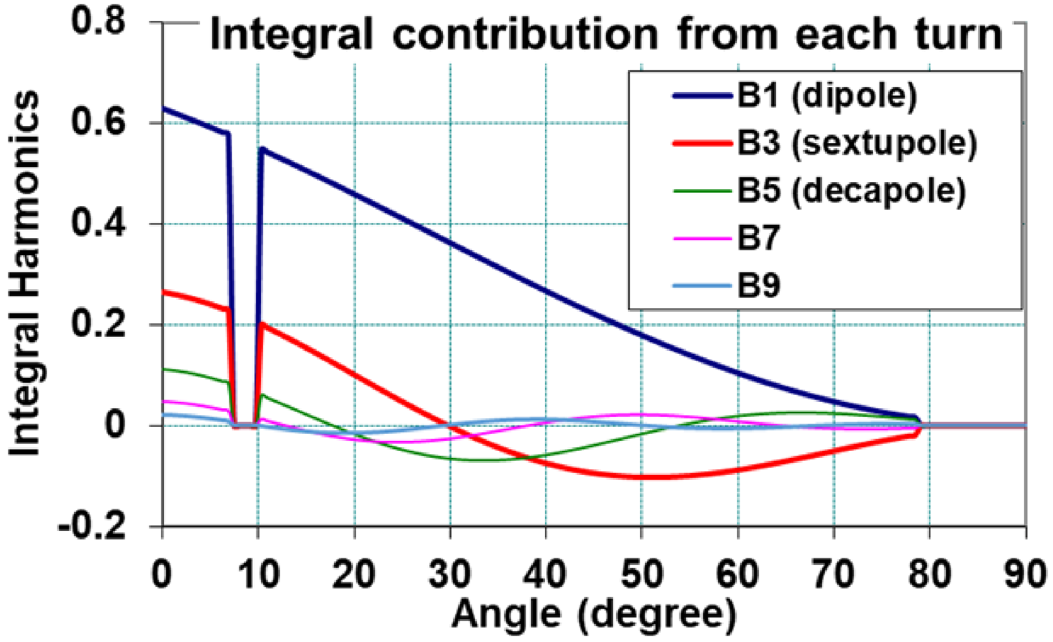
- Optimum Integral design optimization code computes harmonics in a very different way then most other codes
- Most 3-d code compute field or potential on a large number of circles along the z-axis, do harmonic analysis on them and then integrate them all. The coil itself gets divided in several segments. It takes a long time.
- Optimum integral code computes harmonic directly from a set of line currents. Given wire diameter to aperture ratio, line current is a good representation of the coil.
- Harmonic expressions are valid either for 2d (ideal serpentine) or when fully integrated (optimum integral).

for a line current located at (a, ϕ)

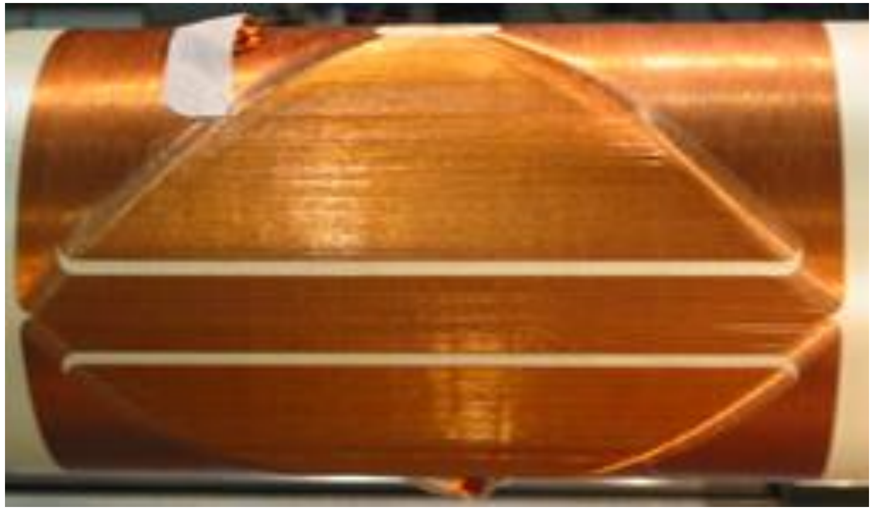
$$b_n = 10^4 \left(\frac{R_0}{a}\right)^n \cos\left[(n+1)\,\phi\right]$$

reference radius R_0

Integral harmonics B_n (Unit.m) are computed by multiplying bn from each turn by its length



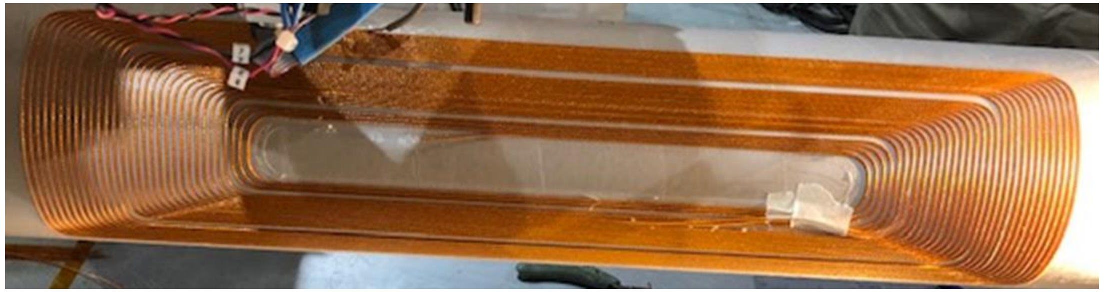
3-d harmonic calculations became two order of magnitude faster and made integral field optimization practical.

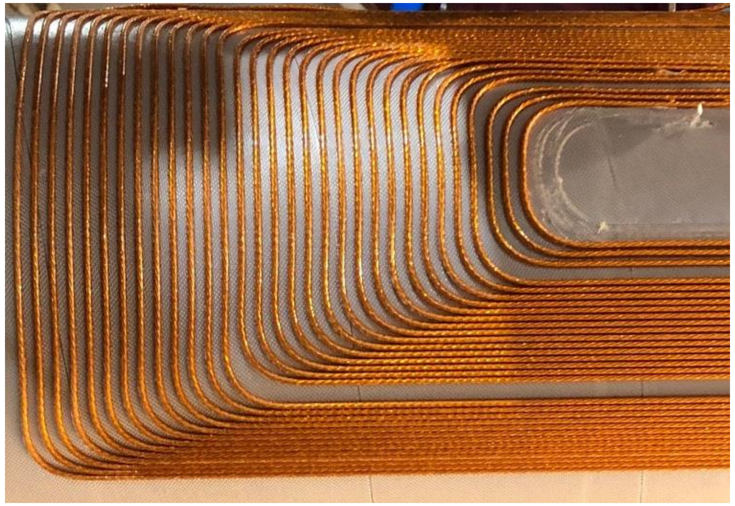


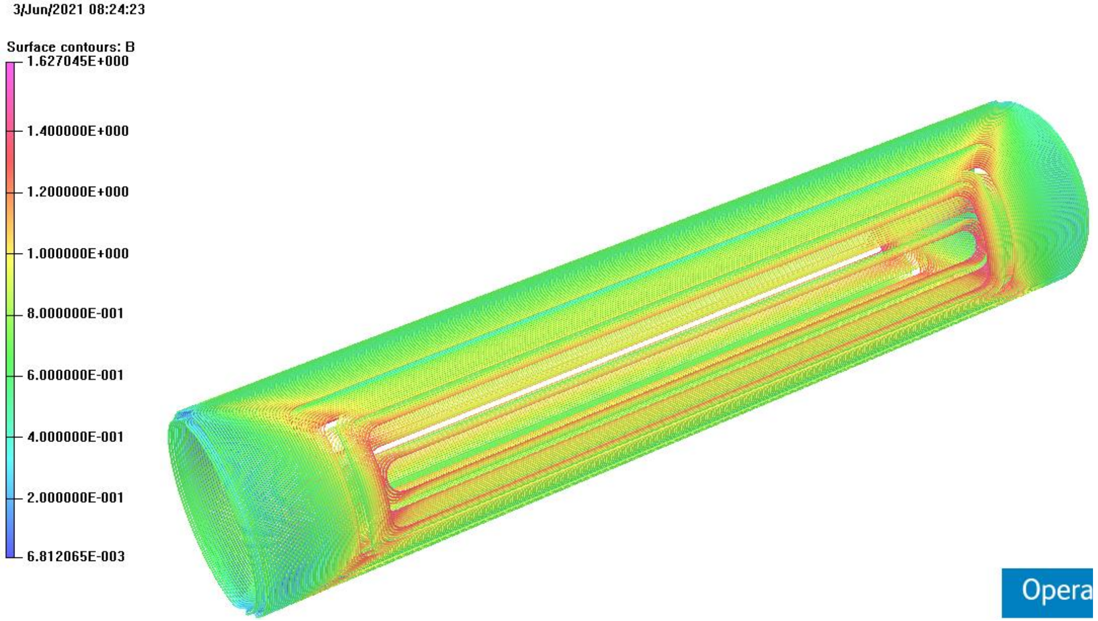
Approximation to the Rounded Section in the Ends

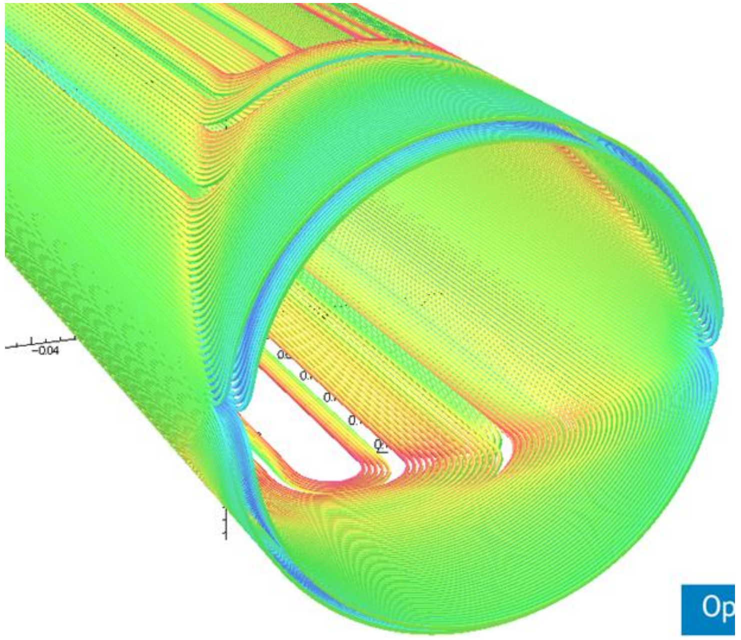
Formula presented in the last slide compute harmonics when wires are parallel to axis. Wires in the end section planted as solenoid don't contribute to harmonics. However, wires in the rounded section do.

- As such, this is a small section of the overall coil, and doesn't contribute much to harmonics.
- Program computes them by dividing this section into several sub-sections, each running current parallel to the z-axis.









Current Software – what it does and what it does not

- It computes and optimizes either (a) 3-d Integral harmonics or 2-d body (or serpentine) harmonics with the following parameters
  - Number of blocks in the body and in the ends (the two can be different)
  - Number of turns in each block (both in the body and in the ends)
  - Spacing between the blocks (both in the body and in the ends)
  - Spacing between turns in each block (both in the body and in the ends)
- Creates file that is used to drive the direct wind machine. Earlier it used legacy software but now it doesn’t. It has been used to wind optimum integral coils (many practice and ten actual) but not yet in serpentine. Works in simulation.
- It doesn’t do peak field calculations or field profile inside the magnet.
- However, it creates several output files, including OPERA3d model files, which are used to do the model calculations. Original code was written to optimize harmonics for both optimum integral and serpentine but not for creating files.
- With ATRO funds, the code is being updated to create serpentine files as well.

USER GUIDE TO THE SOFTWARE

First Release: January 7, 2024
This Release: April 28, 2024

IntegralOpt User Guide

Version 2a

Steve Kahn
Ramesh Gupta

History: The program, now called IntegralOpt, was originally written for VAX fortran by Ramesh Gupta (BNL) in 2004 for optimizing the optimum integral design. The optimum integral design was proposed by Ramesh Gupta in 2004 and used in designing and building a corrector dipole for AGS Helical magnet. The program was originally called MINXEND (for optimizing X-section and END design together, as per the optimum integral design approach, MIN refers to the use of CERN MINUIT routines for optimization). The program has now (2021-2024) been transported to Linux PC (first on Cygwin and now on Ubuntu) by Steve Kahn (now at PBL, was earlier at BNL) and by Ramesh Gupta as a part of Phase I and Phase II STTR and is being periodically updated. The manual was originally written by Steve Kahn.

Table 1: NAMELIST FCNX input variables.

Variable	Units	Default Value	Description
MAGTYPE	--	2	2 for Dipole; 4 for quadrupole; 3 for combine function
R0MM	mm	1.0	Reference Radius in mm
LAYERS	--	1	Total Number of Layers
RFEMM	mm	0	Iron Inner Radius in mm; If zero, No Iron
RBENDMM	mm	0	Bend Radius at Transition to End Sector
NBEND	--	10	Number of Points on Bend Curve
VC2CB*		.FALSE.	Flag to allow variable conductor spacing in body
VC2CE*		.FALSE.	Flag to allow variable conductor spacing in ends
ENDCONFIG*	--	2	0 for Straight Section; 1 for ½ body plus 1 end; 2 optimum integral end; 3 for serpentine* w/ SS
TAPER*		.FALSE.	Flag to indicate that the coils are tapered
TAPERTYPE*		0	?
MAXANGLE	degrees	0	Angle subtended at which a block is divided

***Features not yet fully implemented or tested**

Table 2: Variables on Layer Line

Layer Variable	Units
Number of Blocks in Layer Straight Section	--
Number of Blocks in Layer End Section	--
Straight Section Length	meters
Wire Diameter	mm
Layer Coil Radius	mm
Wire Current	A
Wire Insulation in End Section	mm
Wire Insulation in Straight Section	mm

Summary on the Status of the Software (details in next slide)

There are several parts of validating software. Here is the status:

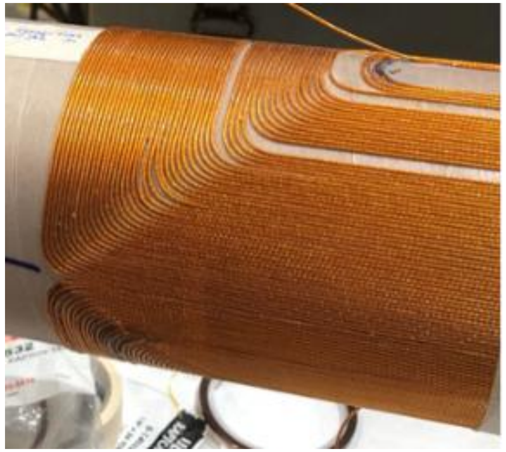
- **Field Harmonics (important as the approach is different from other codes) – validated for optimum integral in a 6-layer optimum integral STTR coil**
- **Winding coil – validated for the optimum integral coils. Not yet for the serpentine coil (though it looks ok pictorially)**
- **OPERA 3d Models – heavily checked for the optimum integral design. Created for the serpentine coils for dipoles, quadrupoles and sextupoles. They seems to look ok but needs to cross-checked and verified.**
- **Computation of peak field and field margins – software doesn't do these calculations but creates model for other codes which do. Phase I cold test show that coil reached its computed short sample of about.**

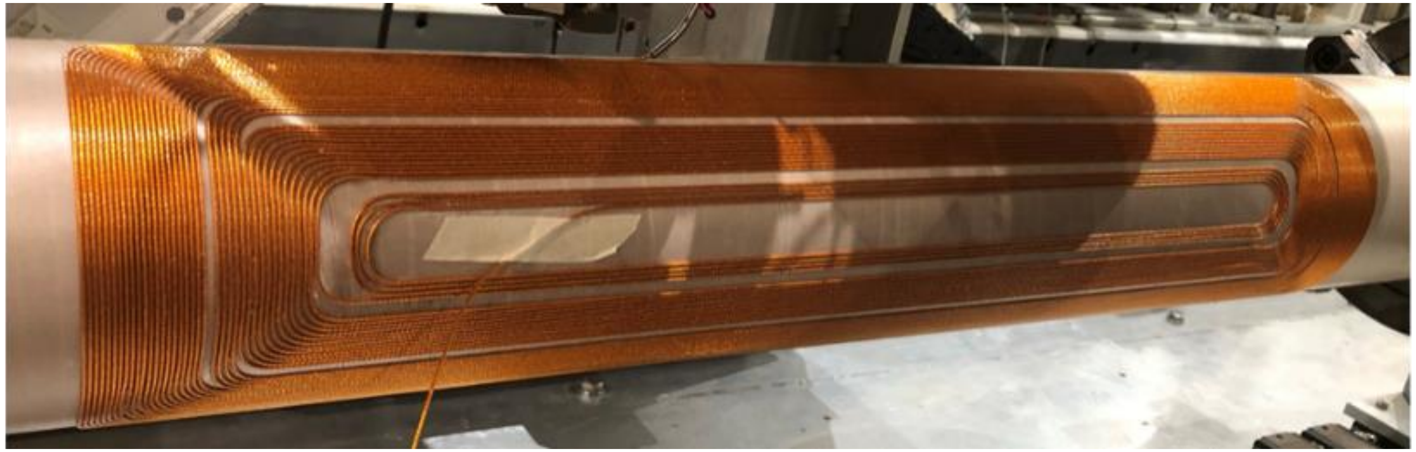
PBL/BNL STTR had a task of making this software available to others, including writing user manual. Both user manual and installers are available.

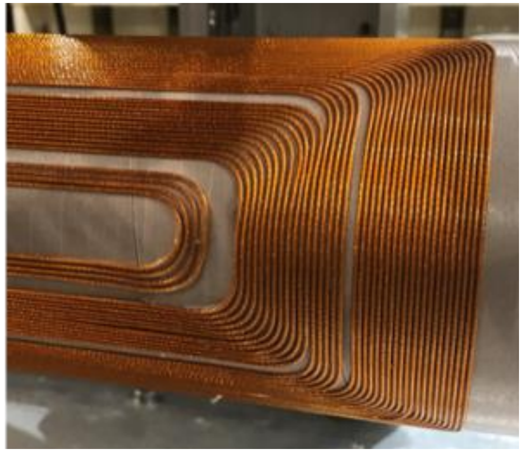
Optimum Integral Dipole - Phase I Coil (double layer)

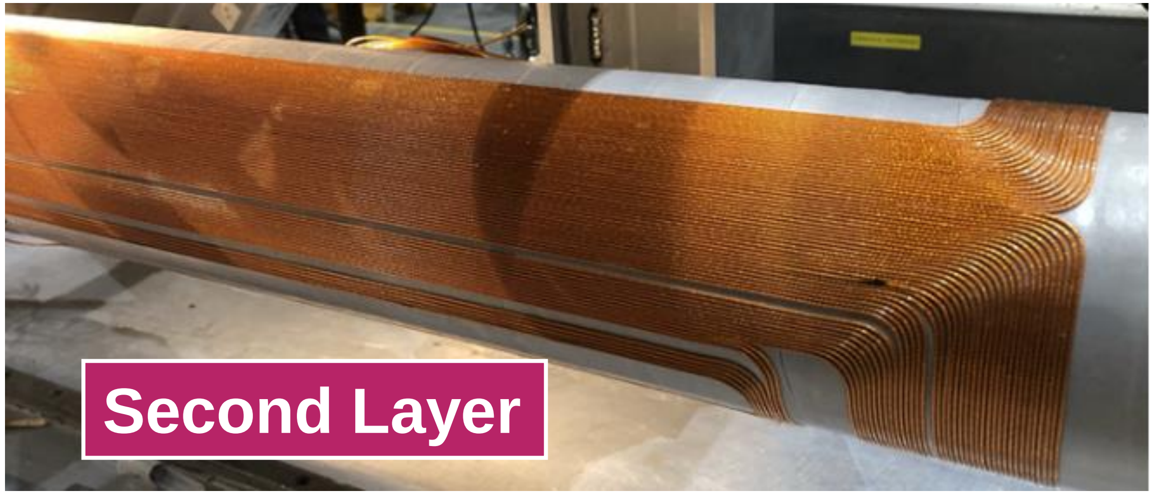
(validation of the winding without the legacy software)

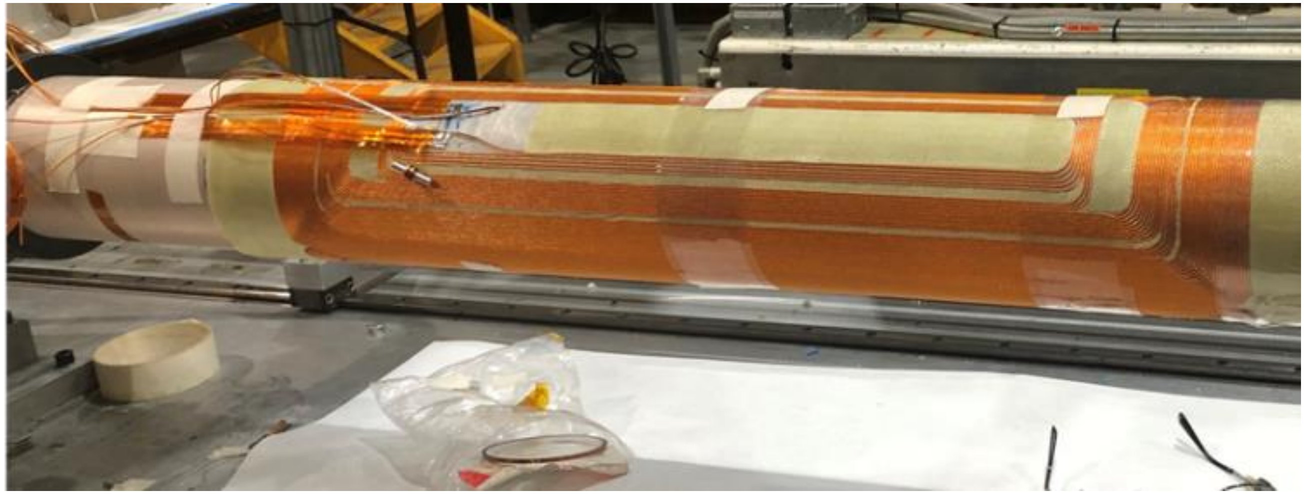
First Layer









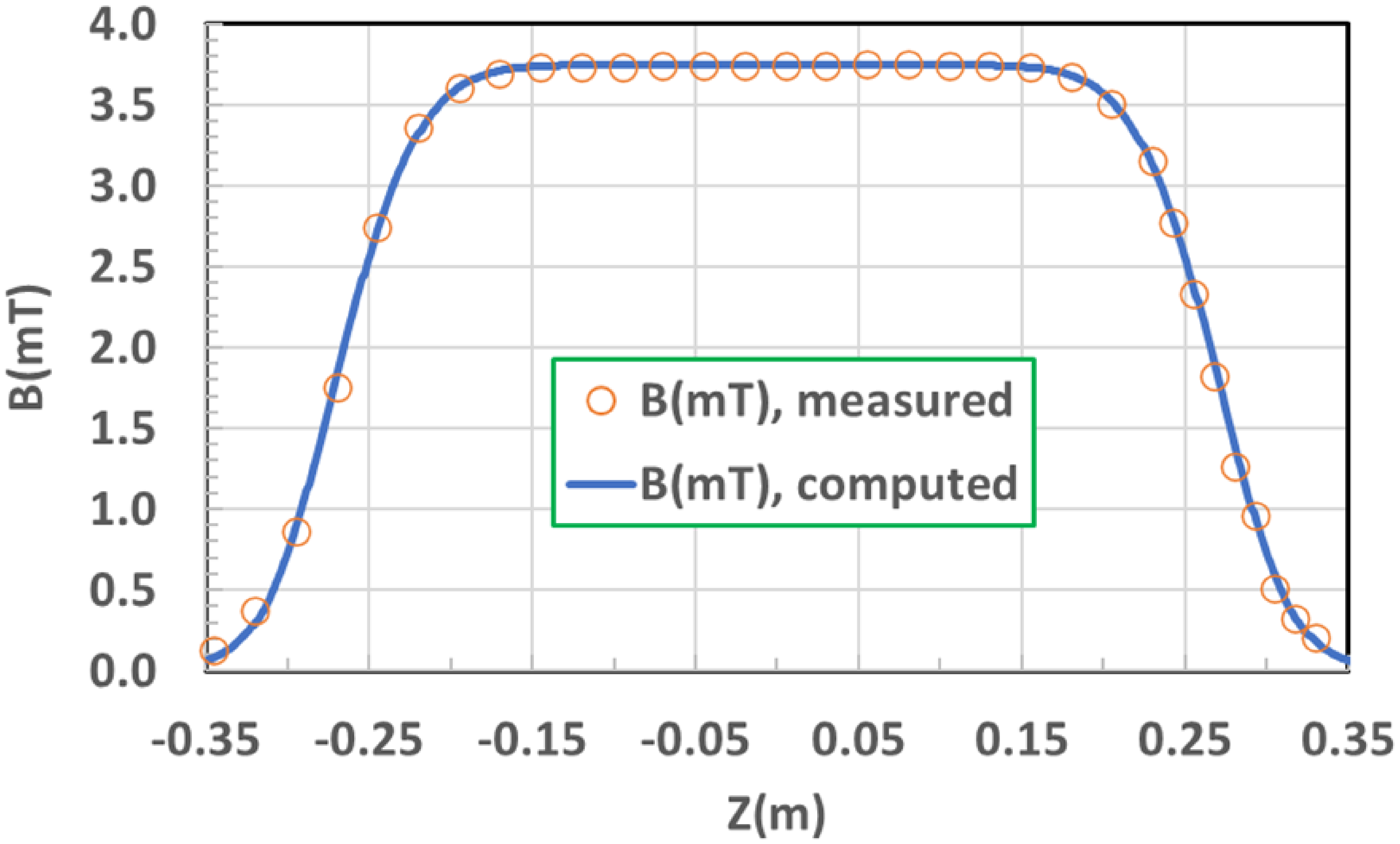


Midplane turns extended full length

Question: Will optimum integral design extend the magnetic length?
(validation in computing field profile with a OPERA3d model created)

Major motivation of the optimum integral design demonstrated

More on OPERA3d Models later



Field Quality Demonstration of the Design and of the Code

Main validation of the code:

Does it compute harmonics correctly?

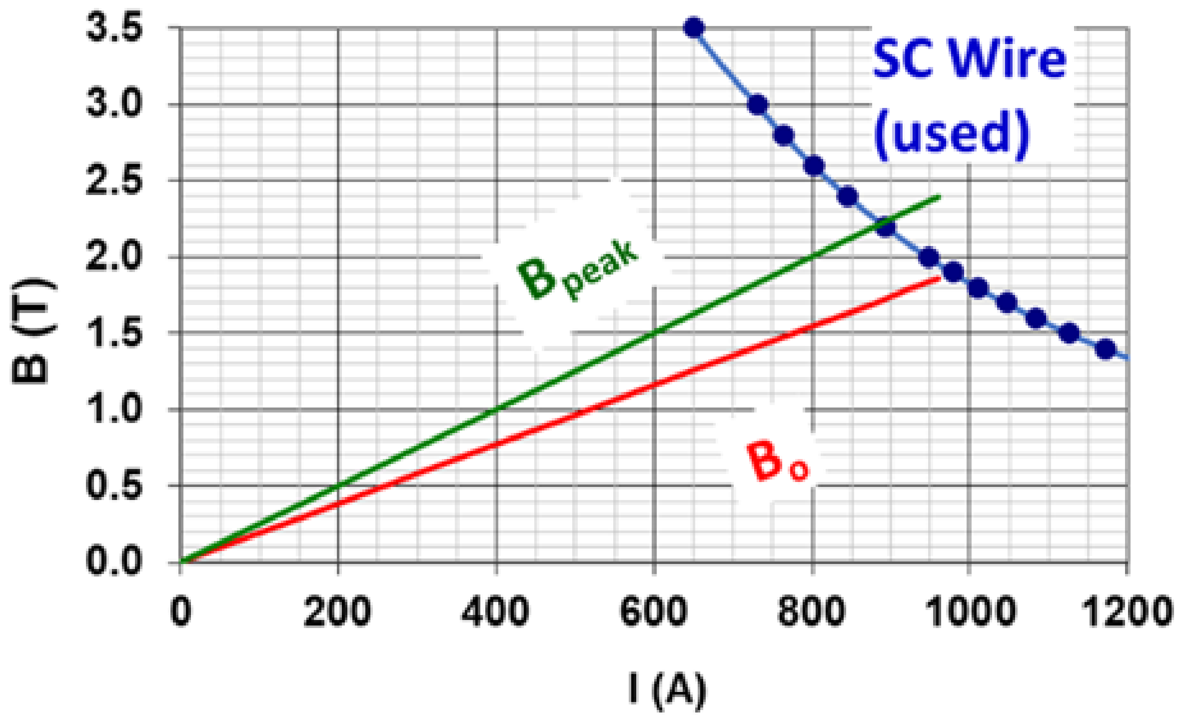
Warm harmonic Measured for the 6-layer coil

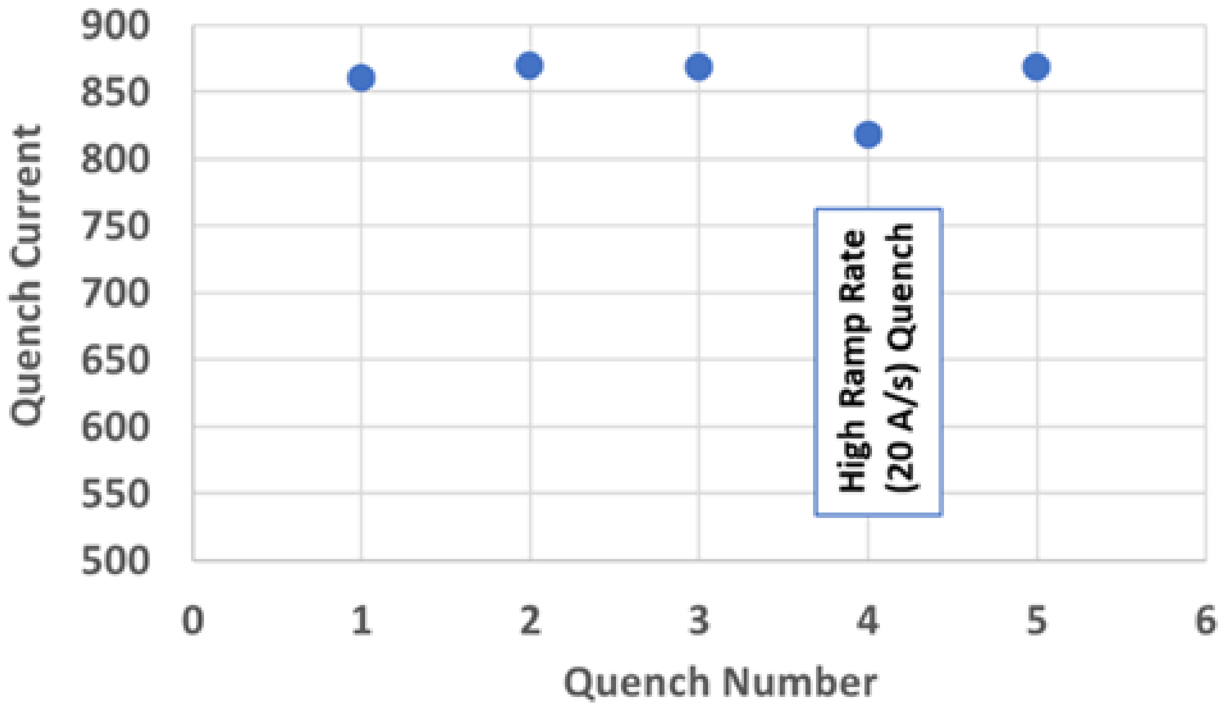
Optimum Integral Dipole 6-layer Design		
ITF (NO Fe)	1.860	mT.meter/A

Measured Integral Harmonics@31mm		
No.	bn	an
2	0.77	3.51
3	6.12	4.32
4	0.43	-0.98
5	0.93	0.50
6	0.20	-0.61
7	1.85	0.58
8	-0.02	0.22
9	-0.66	-0.19
10	0.02	-0.08
11	0.18	0.05
12	0.00	0.02

A good field quality despite several changes on the fly (as in any R&D project)

Question: Will the direct wind coil based on the optimum integral have a good quench performance? (validation of OPERA models)





B_o = ~1.7 T, B_{pk} = ~2.2 T, Coil i.d. = 114 mm

Answer: Quench performance remains excellent

(meets computed SS with no quench, validates OPERA models)

Examples of using the software to design optimum integral and serpentine coils

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Wire Current	A
Wire Insulation in End Section	mm
Wire Insulation in Straight Section	mm

Software for the Optimum Integral Design

- Initially developed for VAX FORTRAN.
- It was used to design and optimize optimum integral dipole for AGS
- The software has now been ported to PC and is being further upgraded

eic-pbl-PhII-L1cs.x01

```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,MAGTYPE=2,LAYERS=6,RFEMM=110,R0MM=38.,
      RBENDMM=10,NBEND=10 &end
 3 3 0.6 1.1 57. 500 0.4 0.20
 3 3 0.6 1.1 58.5 500 0.4 0.20
 2 2 0.6 1.1 62. 500 0.4 0.20
 2 2 0.6 1.1 63.5 500 0.4 0.20
 2 2 0.6 1.1 73. 500 0.4 0.20
 2 2 0.6 1.1 74.5 500 0.4 0.20
B2 0.  1.
B4 0.  2.
b6 0.  5.
b8 0.  7.
b10 0.  9.
b12 0.  9.
```

-Tube1-6lyr-n6a.X07

```
INNER Tube 6 LAYERS - New splices 3-6
  1 W11      0.      0.     0.     19.
  2 N11      37.     0.     20.    42.
  3 B11      0.      0.     0.     9.
  4 W21      3.5     0.     1.     3.5
  5 N21      12.     0.     10.    20.
  6 B21      0.18    0.0    0.     0.2
  7 W31      4.      0.     2.     4.
  8 N31      4.      0.     3.     5.
  9 B31      0.51    0.0    0.     0.8
 10 S11      0       0.     0.     20.
 11 T11      32.     0.     4.     29.
 12 E11      0.      0.0    0.     10.
```

INPUT Files

A few of many output files

LAYER NO.	BLOCK NO.	TURN NO.	WEDGE(DEGREE)	C2C-BODY(DEG)
1	1	57	0.00000	0.00000
1	2	12	5.08455	0.22859
1	3	4	1.00841	0.00000
LAYER NO.	BLOCK NO.	TURN NO.	END-SPACER(MM)	C2C-END(MM)
1	1	47	0.00000	0.00000
1	2	22	0.03448	0.00239
1	3	4	2.00373	0.12796
LAYER NO.	BLOCK NO.	TURN NO.	WEDGE(DEGREE)	C2C-BODY(DEG)
2	1	47	0.00000	0.00000
2	2	27	1.00500	0.01948
2	3	4	4.31012	0.00001
LAYER NO.	BLOCK NO.	TURN NO.	END-SPACER(MM)	C2C-END(MM)
2	1	52	0.00000	0.00000
2	2	22	0.00138	0.00125
2	3	4	11.48548	1.39409
LAYER NO.	BLOCK NO.	TURN NO.	WEDGE(DEGREE)	C2C-BODY(DEG)
3	1	47	0.00000	0.00000
3	2	17	2.25399	0.03786
3	3	9	7.49249	0.01186
LAYER NO.	BLOCK NO.	TURN NO.	END-SPACER(MM)	C2C-END(MM)
3	1	32	0.00000	0.00000
3	2	37	0.00180	0.00476
3	3	4	5.19675	0.20025
LAYER NO.	BLOCK NO.	TURN NO.	WEDGE(DEGREE)	C2C-BODY(DEG)
4	1	52	0.00000	0.00000
4	2	22	3.23338	0.00920
4	3	4	1.44408	0.13169
LAYER NO.	BLOCK NO.	TURN NO.	END-SPACER(MM)	C2C-END(MM)
4	1	22	0.00000	0.00000
4	2	50	0.00014	0.00000
4	3	6	2.01384	0.22288

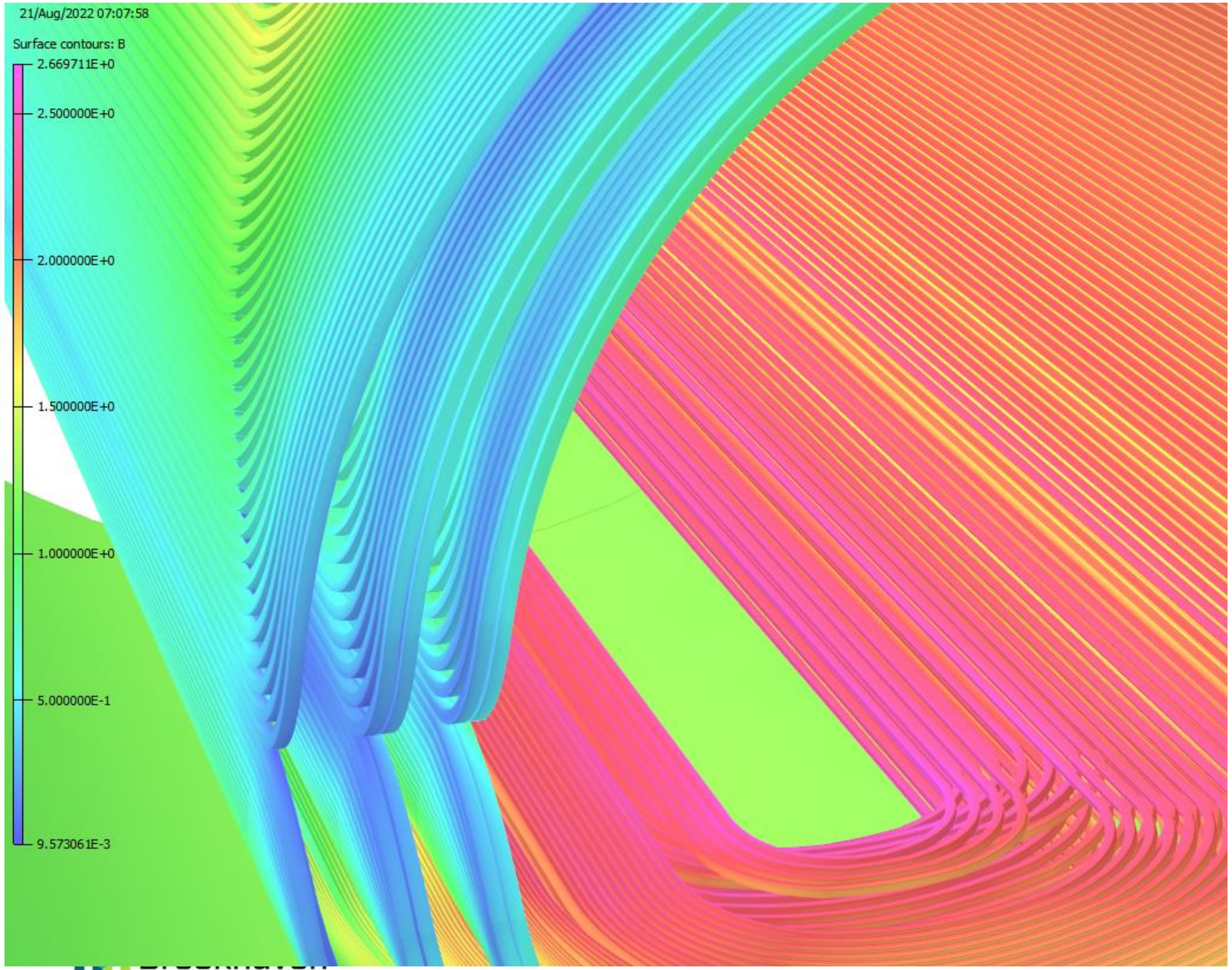
eic-pbl-PhII-L1cs.x01 | eic-pbl-PhII-L2cs.x01 | eic-pbl-PhII-L1cs.X11 | eic-pbl-PhII-L1cs.X31

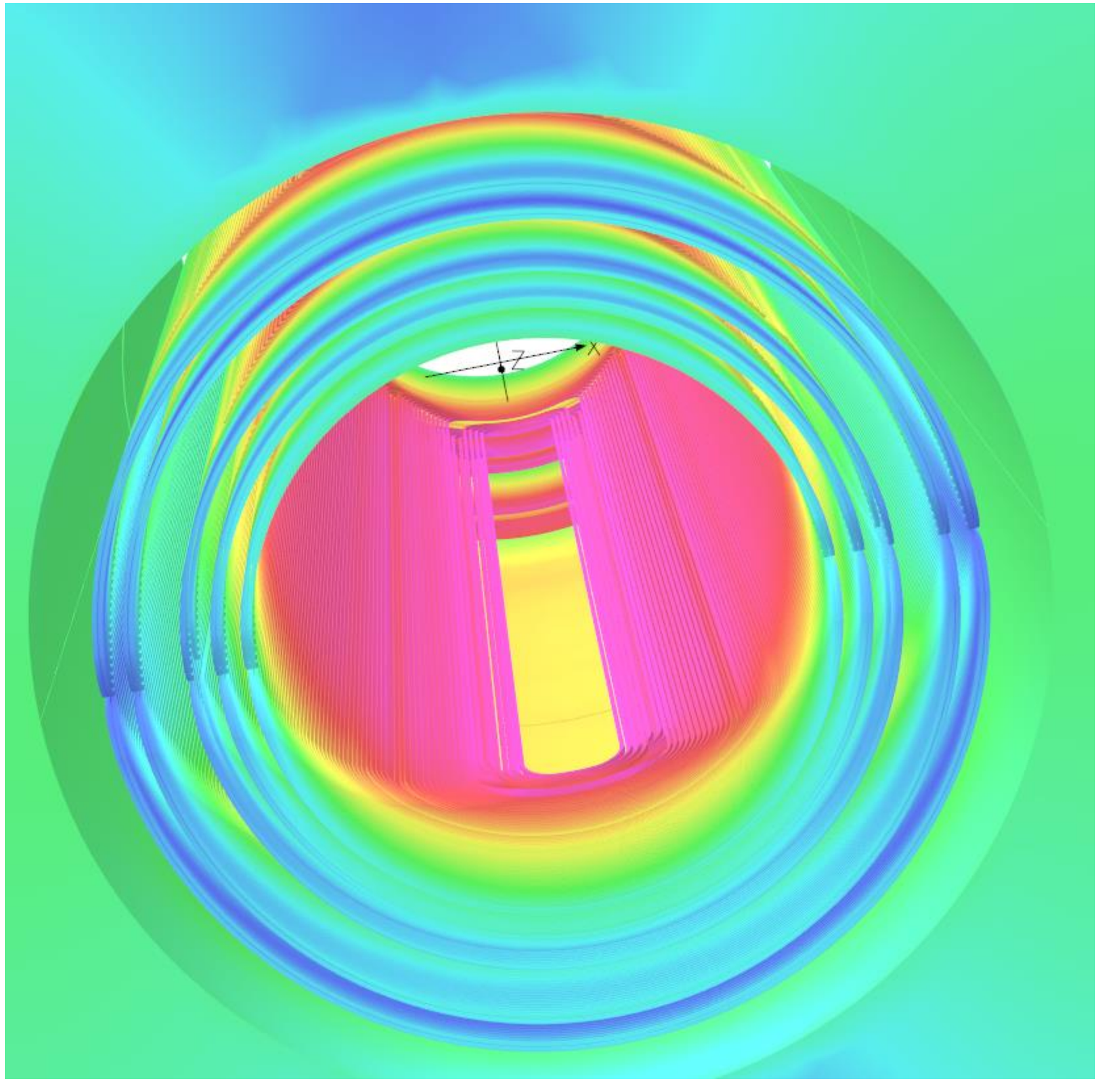
LAYER	TURN	RADIUS(MM)	ANGLE(DEG)	TURN-LENGTH(M)	X(MM)	Y(MM)
1	1	56.513	0.65337	0.600000	56.996	0.650
1	2	56.513	1.96012	0.597000	56.967	1.950
1	3	56.513	3.26686	0.594000	56.907	3.248
1	4	56.513	4.57361	0.591000	56.818	4.545
1	5	56.513	5.88036	0.588000	56.700	5.840
1	6	56.513	7.18710	0.585000	56.552	7.131
1	7	56.513	8.49385	0.582000	56.375	8.419
1	8	56.513	9.80059	0.579000	56.168	9.703
1	9	56.513	11.10734	0.576000	55.932	10.981
1	10	56.513	12.41409	0.573000	55.667	12.254
1	11	56.513	13.72083	0.570000	55.373	13.520
1	12	56.513	15.02758	0.567000	55.051	14.779
1	13	56.513	16.33432	0.564000	54.699	16.031
1	14	56.513	17.64107	0.561000	54.319	17.274
1	15	56.513	18.94781	0.558000	53.911	18.508
1	16	56.513	20.25456	0.555000	53.475	19.733
1	17	56.513	21.56130	0.552000	53.011	20.947
1	18	56.513	22.86805	0.549000	52.520	22.151
1	19	56.513	24.17480	0.546000	52.001	23.343
1	20	56.513	25.48154	0.543000	51.455	24.523
1	21	56.513	26.78829	0.540000	50.883	25.690
1	22	56.513	28.09503	0.537000	50.284	26.843
1	23	56.513	29.40178	0.534000	49.658	27.983
1	24	56.513	30.70852	0.531000	49.007	29.108
1	25	56.513	32.01527	0.528000	48.331	30.218
1	26	56.513	33.32202	0.525000	47.629	31.313
1	27	56.513	34.62876	0.522000	46.903	32.391
1	28	56.513	35.93551	0.519000	46.152	33.452
1	29	56.513	37.24226	0.516000	45.377	34.496
1	30	56.513	38.54900	0.513000	44.578	35.521
1	31	56.513	39.85575	0.510000	43.757	36.529
1	32	56.513	41.16249	0.507000	42.912	37.517
1	33	56.513	42.46924	0.500258	42.045	38.486
1	34	56.513	43.77598	0.496888	41.157	39.435
1	35	56.513	45.08273	0.493518	40.247	40.363
1	36	56.513	46.38948	0.490148	39.316	41.271
1	37	56.513	47.69622	0.486778	38.364	42.156
1	38	56.513	52.50296	0.483408	34.697	45.223

Output files created for OPERA3d, etc.

Models of Year 1 and Year 2 Magnets

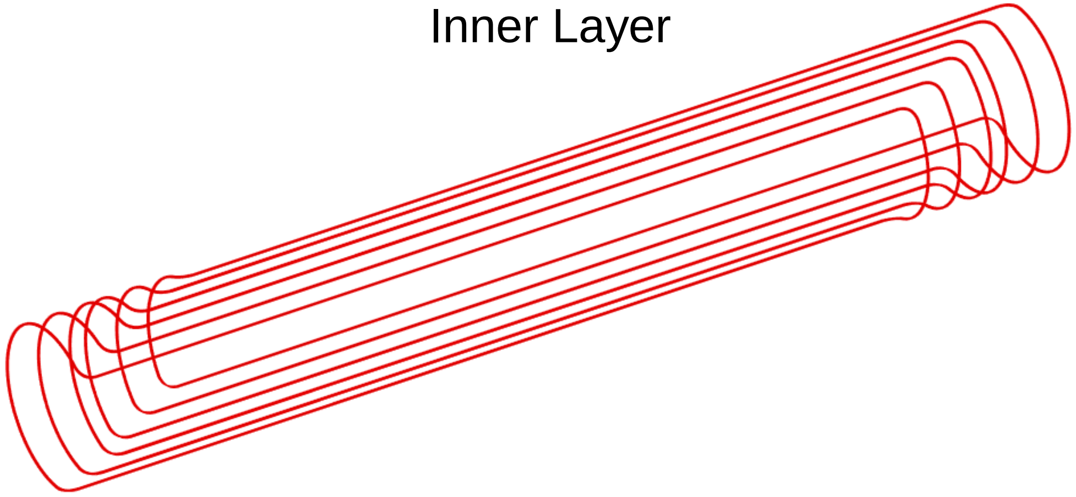
Ignore curvature at the ends and avoid modelling individual wire. Each coil (or section of coil) becomes a two-part structure – one for the body and another for the end (or a series of them).



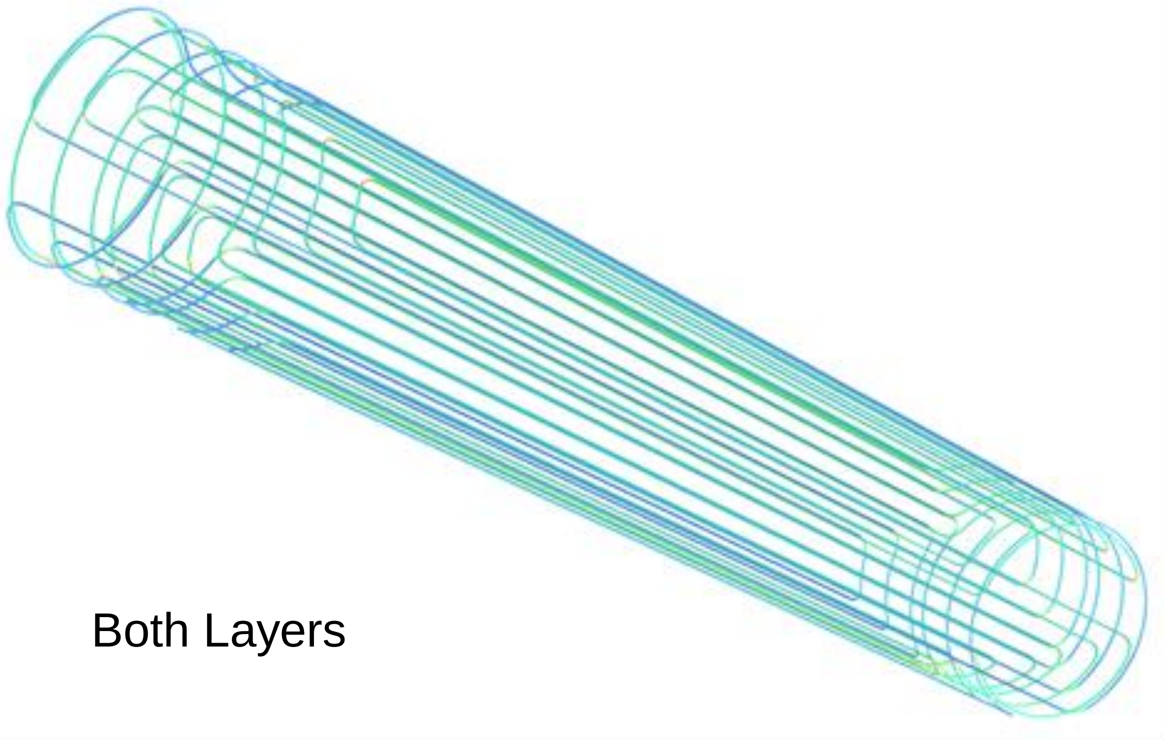


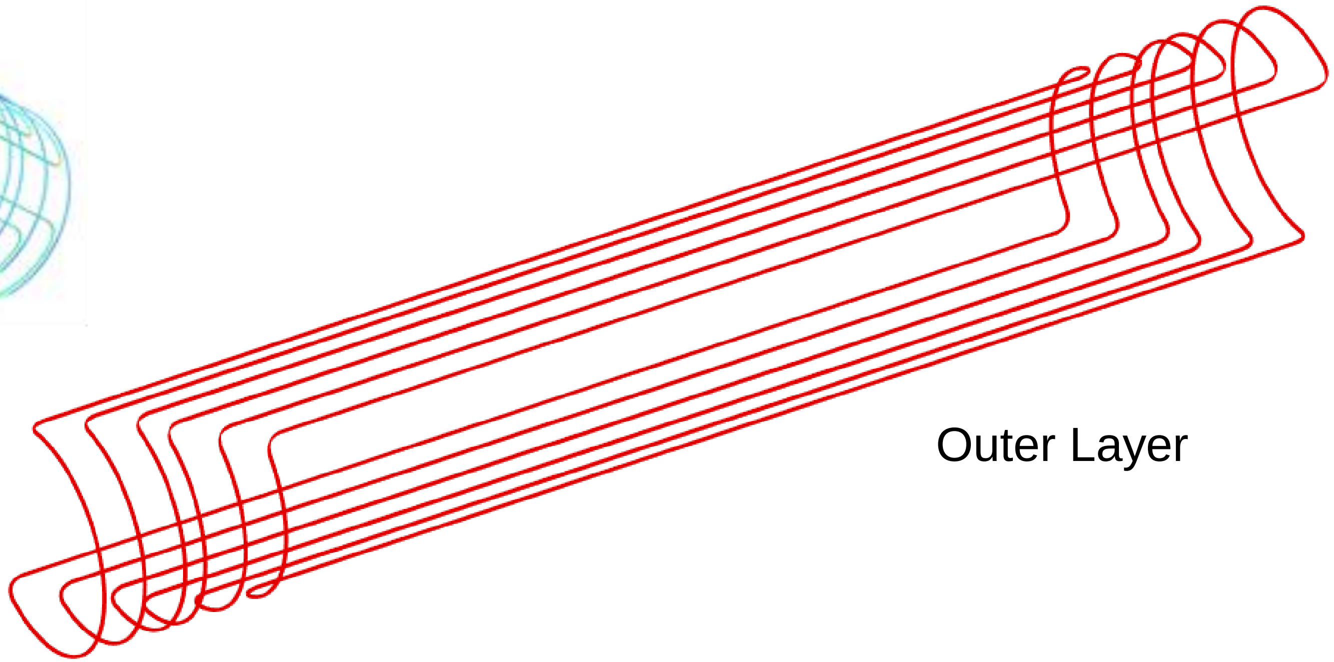
Two Layer Serpentine Dip

Inner Layer



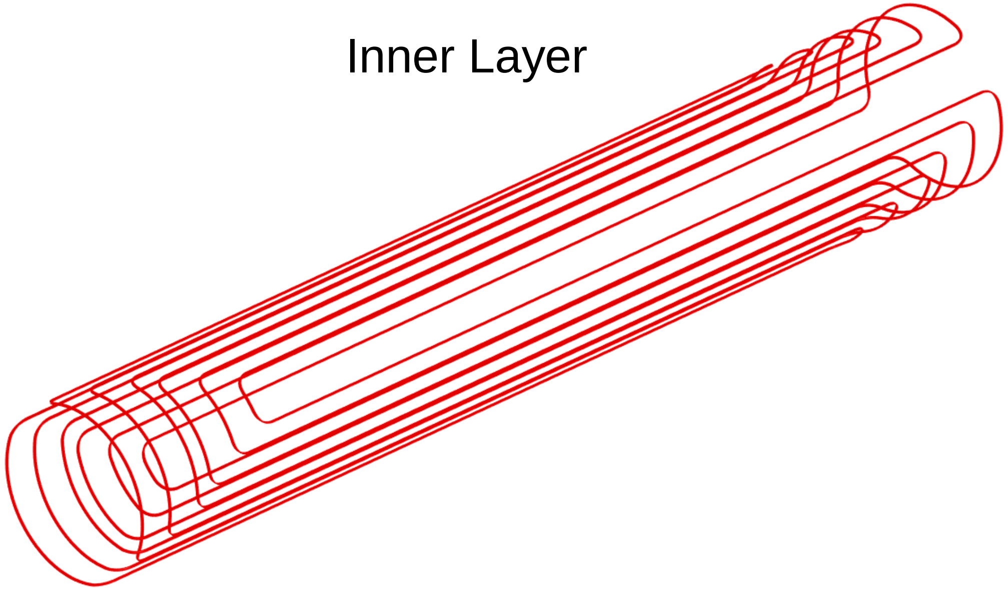
Both Layers

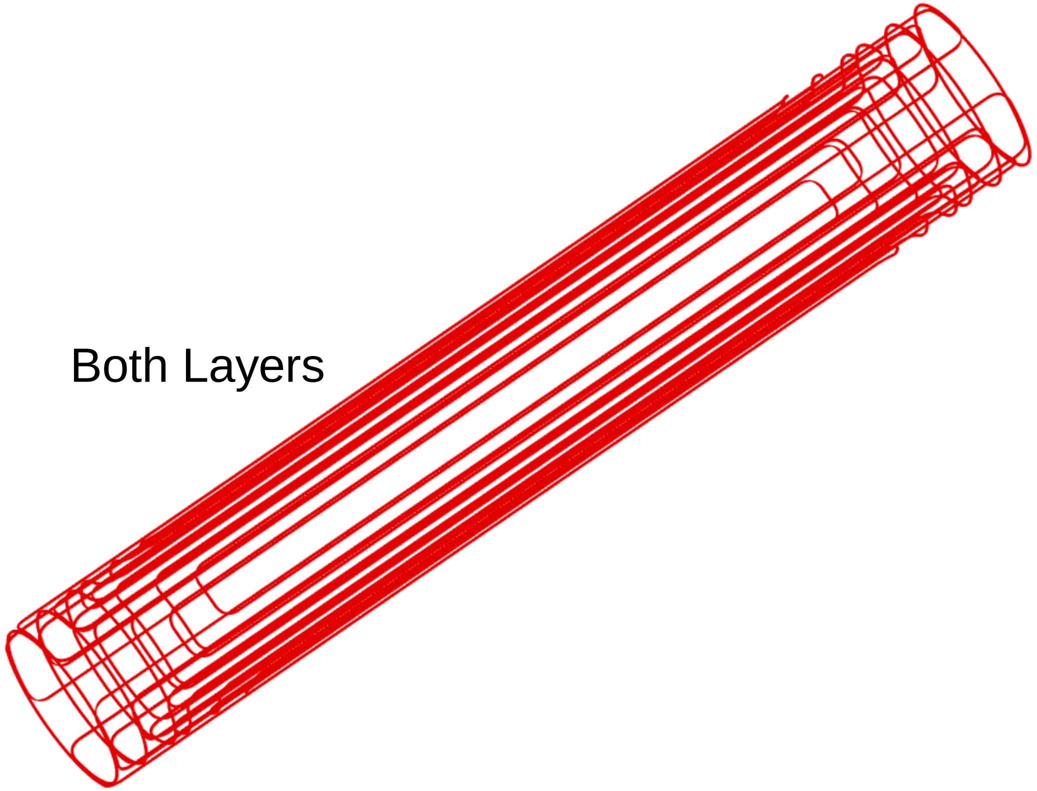


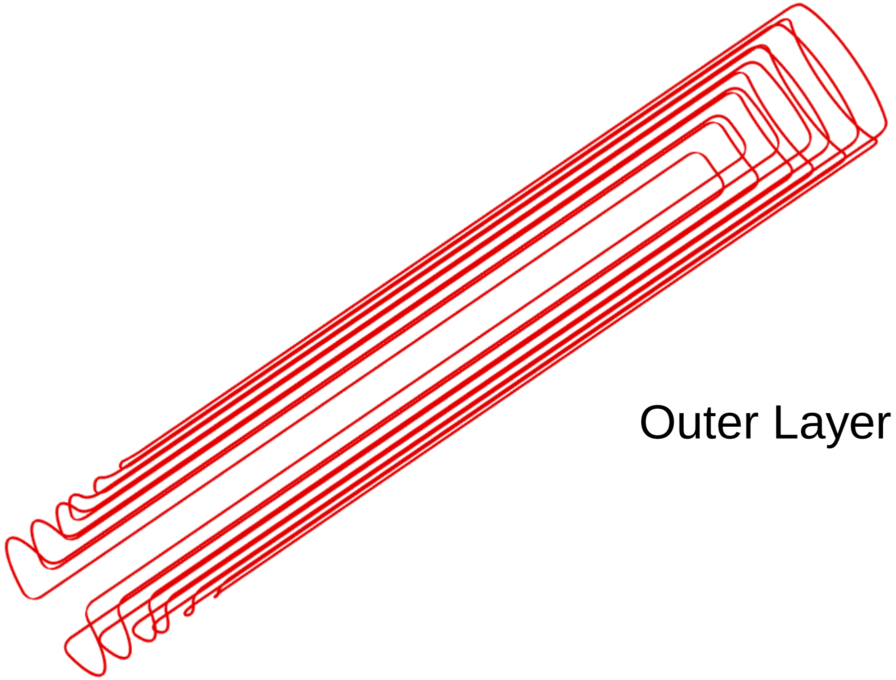


Outer Layer

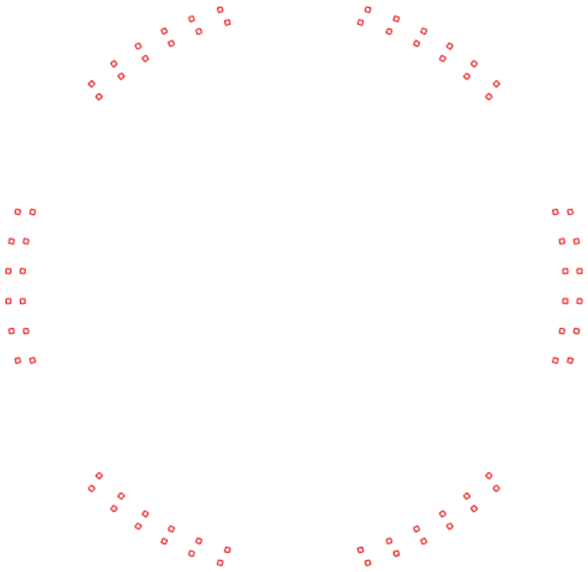
Two Layer Serpentine Quad



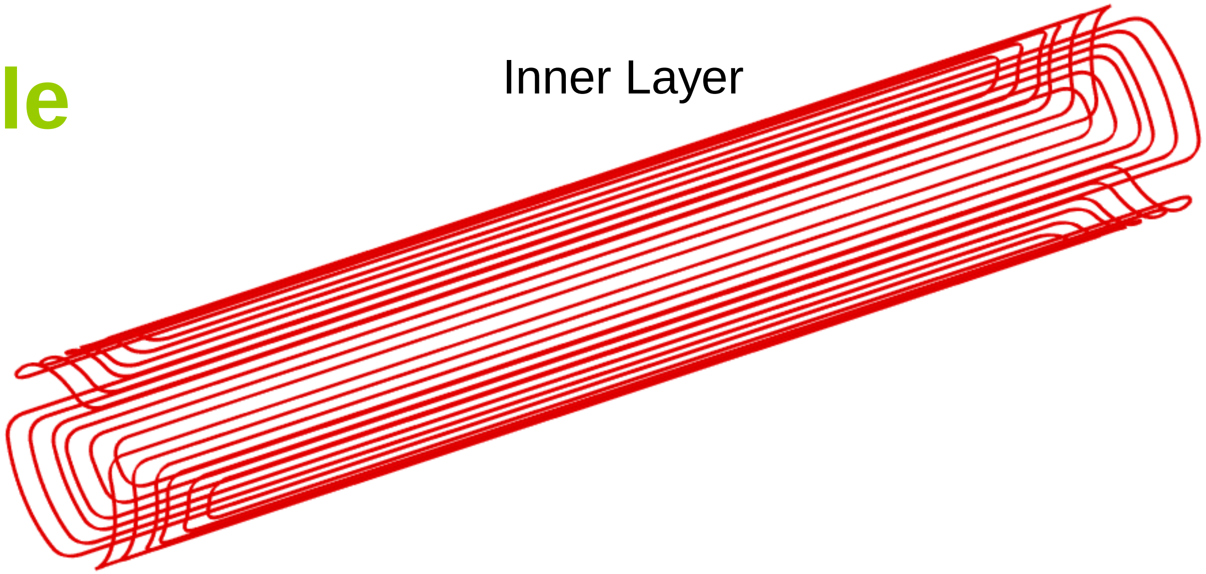




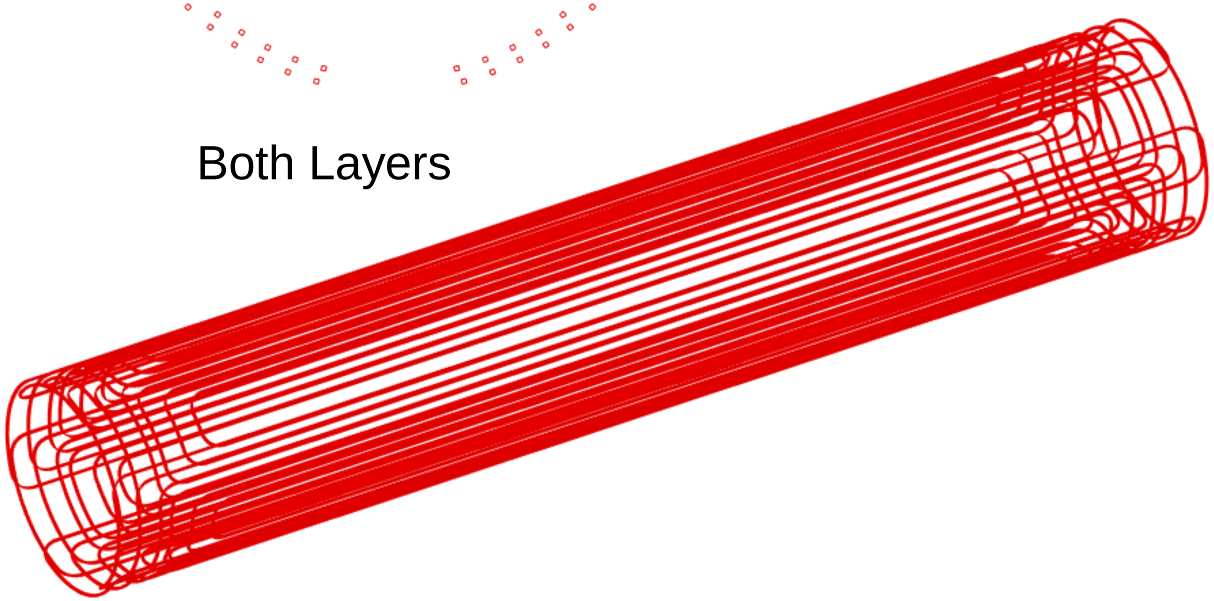
Two Layer Serpentine Sextupole

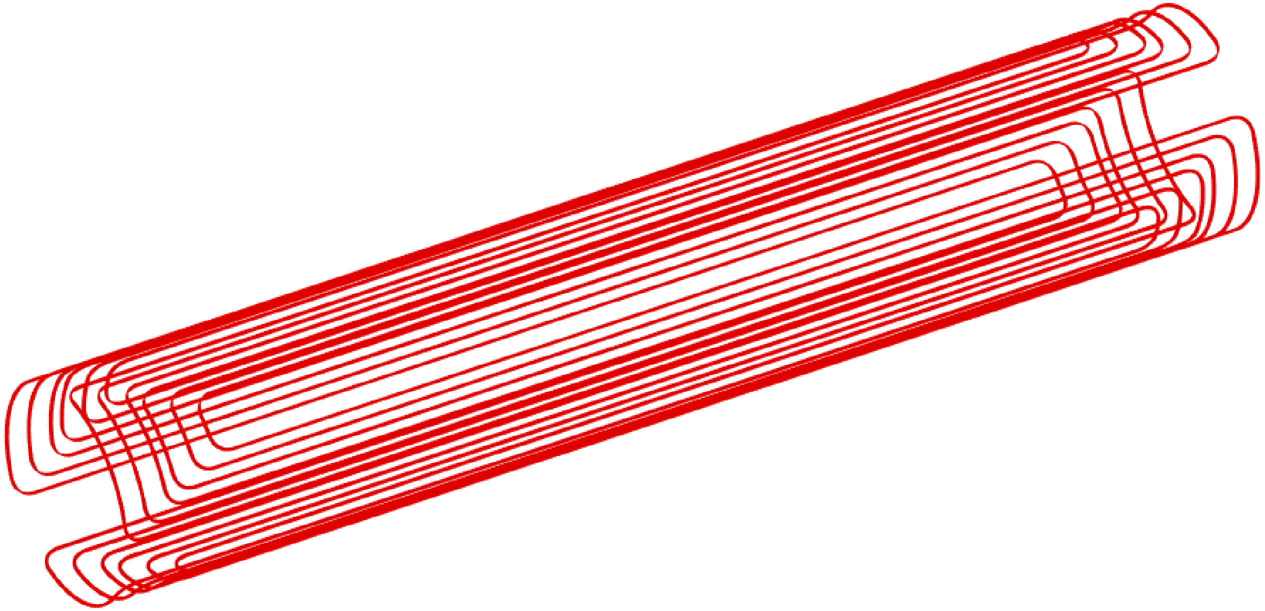


Inner Layer



Both Layers





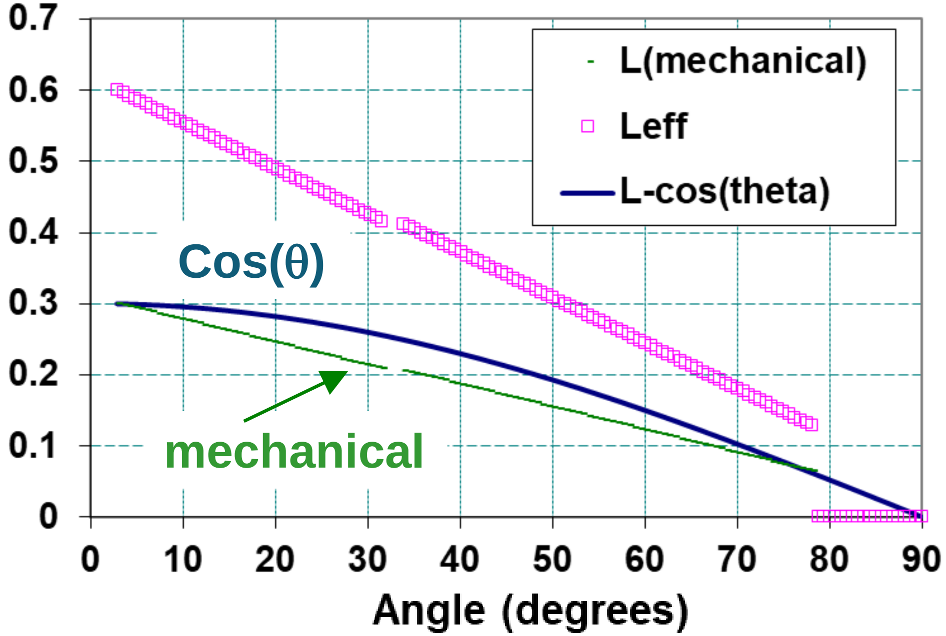
Extra Slides

Basic Principle of the Optimum Integral Design

In conventional designs, all turns of the straight section have the same length and the fill factor is approximated azimuthally as:

$$I(\theta) = I_o \, . \, cos(n\theta)$$

...and then ends are optimized separately. Note: turns near midplane, which contribute most to field don't extend full length (a significant loss in field produced)

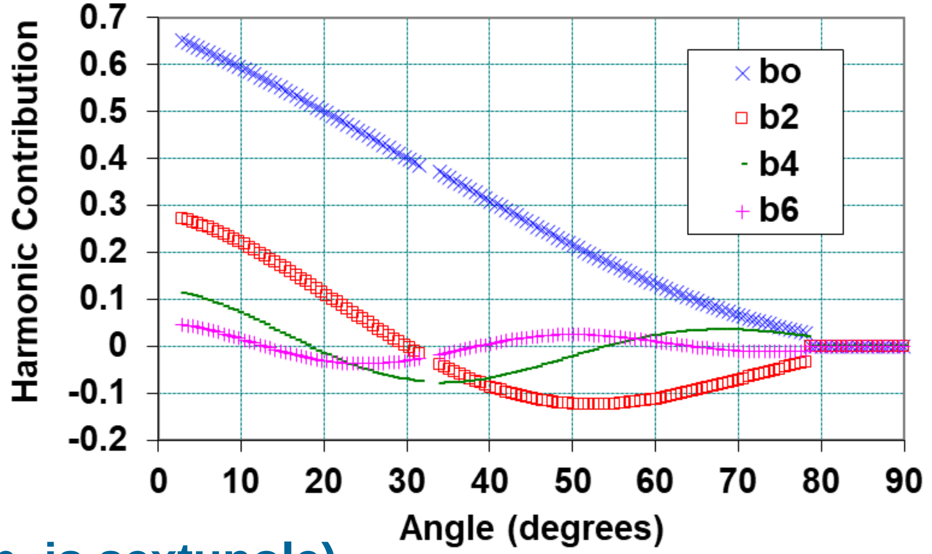


In the optimum integral design, midplane turns extend full coil length and contribute maximum to the field.

The cosine theta azimuthal distribution is obtained in an integral sense, i.e., not in "$I(\theta)$", but in "$I(\theta) \, . \, L(\theta)$":

$$I(\theta) \, . \, L(\theta) = I_o \, . \, L_i(\theta) \propto I_o \, . \, L_o \, . \, cos(n\theta)$$

Plus, packing can be increased in the body of the magnet



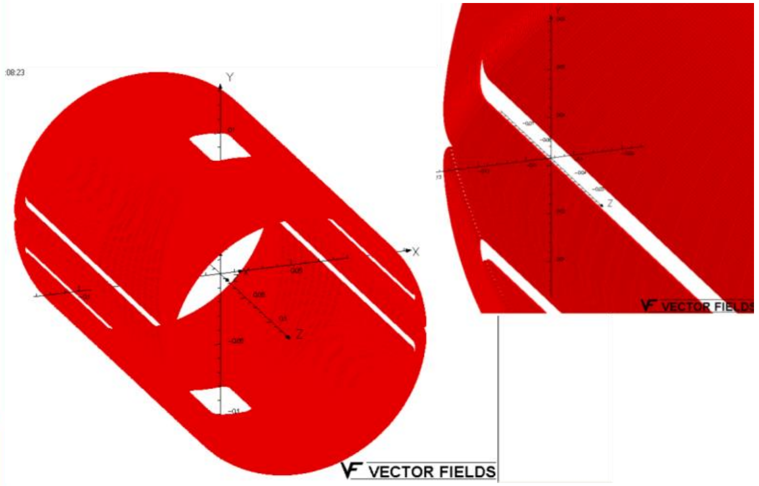
(b_2 is sextupole)

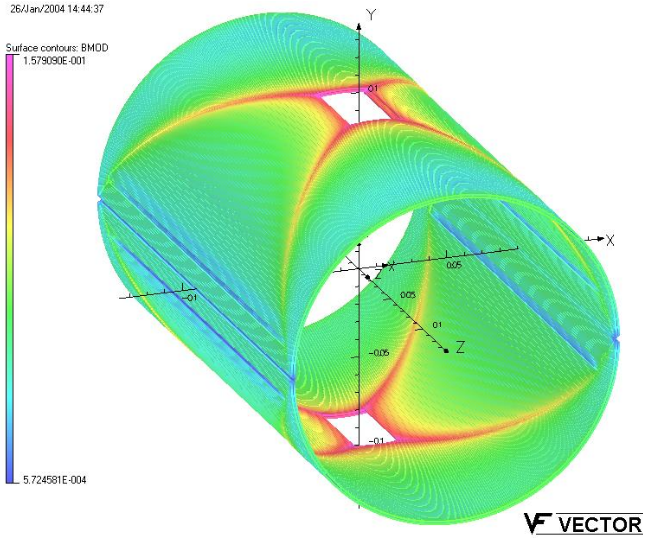
First Use of the Optimum Integral Design: AGS Corrector Dipoles

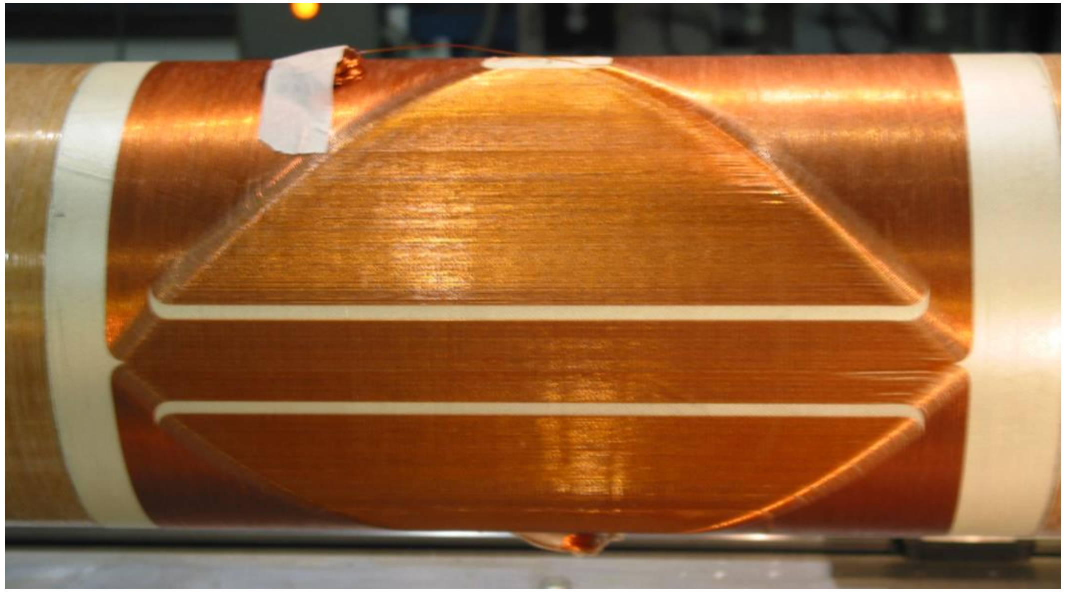
- **Note: Almost the full use of available azimuthal and axial space by the conductor (very high fill factor).**
- **Some space is needed for the leads at the pole. That, and a small azimuthal spacer was sufficient to modulate a natural variation in length for I_o.L.cos(θ) to obtain field quality needed in corrector magnets**

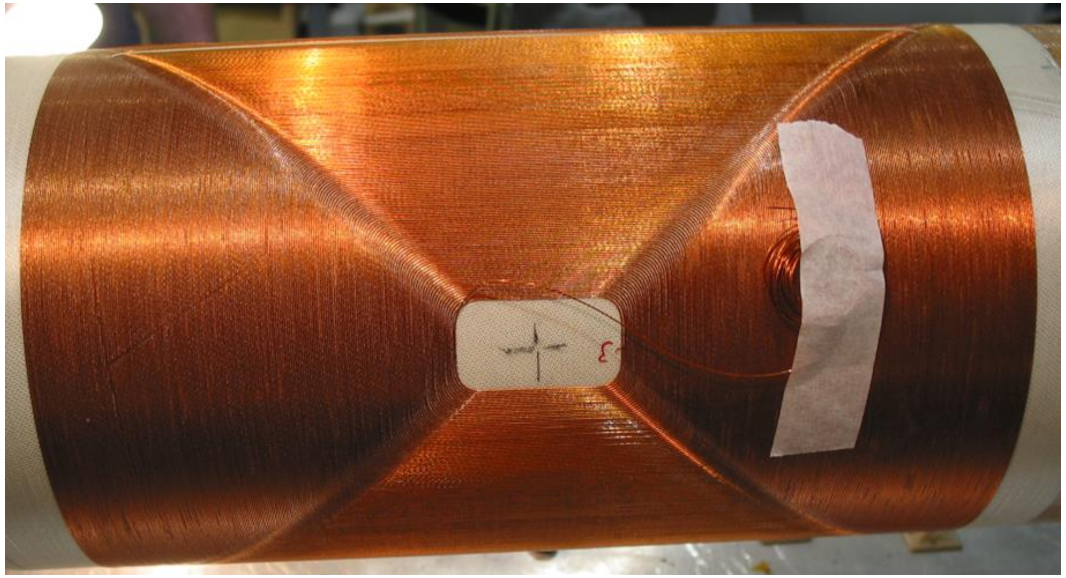
COMPUTED INTEGRAL FIELD HARMONICS IN THE AGS CORRECTOR DIPOLE DESIGN AT A REFERENCE RADIUS OF 60 MM. THE COIL RADIUS IS 90.8 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

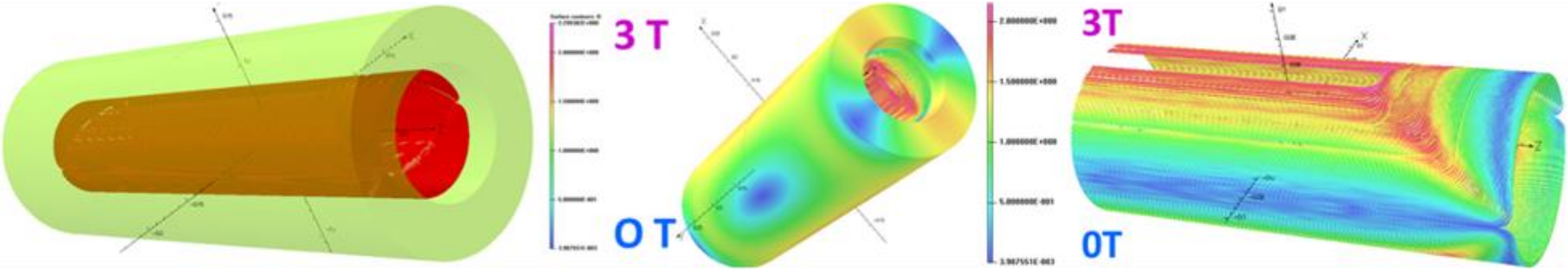


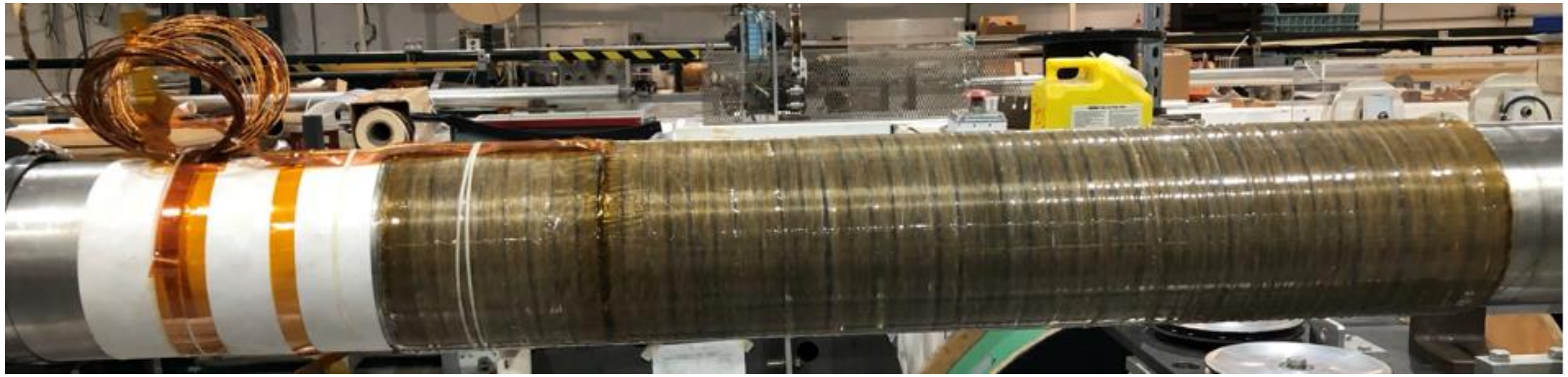






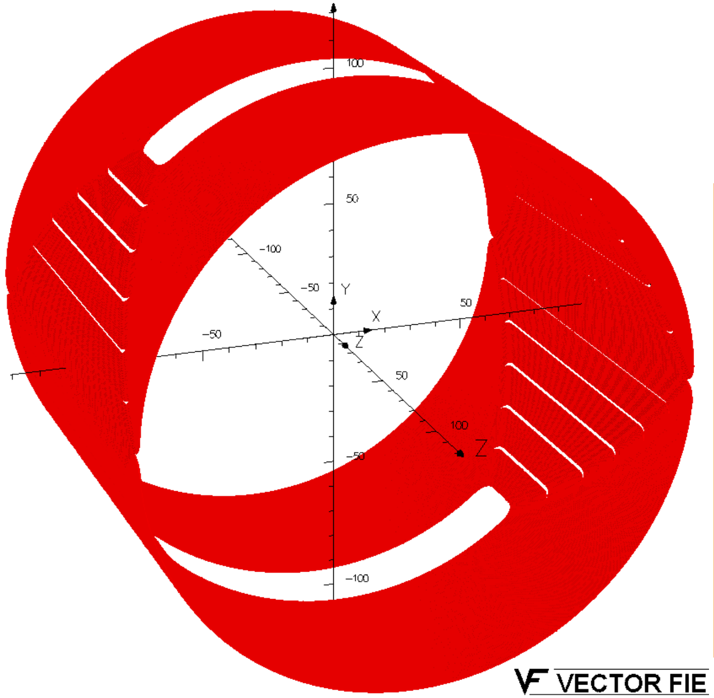
Phase I Optimum Integral Dipole
(As Designed and As Built)





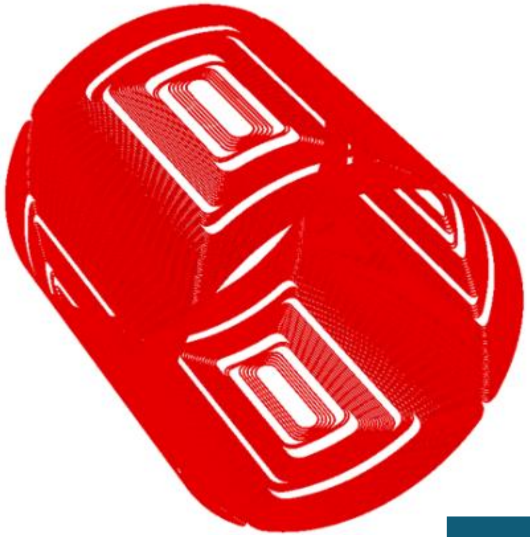
Opening A New Parameter Space with the Optimum Integral Design
(not considered practical for superconducting magnets before)

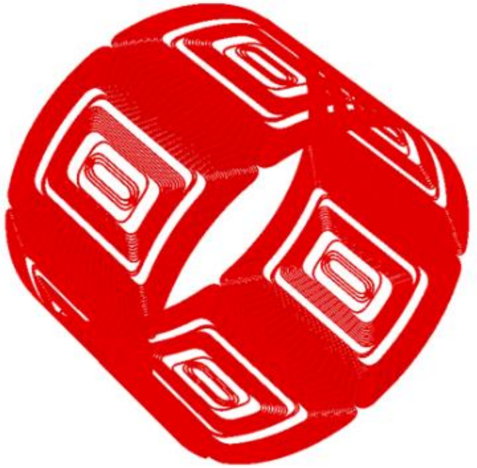
- **High field quality dipoles with coil length less than the coil diameter**
- **Quadrupole magnets with coil length less than the coil radius**
- **Sextupole magnets with coil length less than 2/3 of the coil radius**



Model of a short length dipole based on the Optimum Integral Design.

Coil length 175 mm; coil diameter 200 mm.





COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

Can the optimum integral design be useful in EIC?