

Combined Function O1D B0pF (moving from PoP to optimized design)

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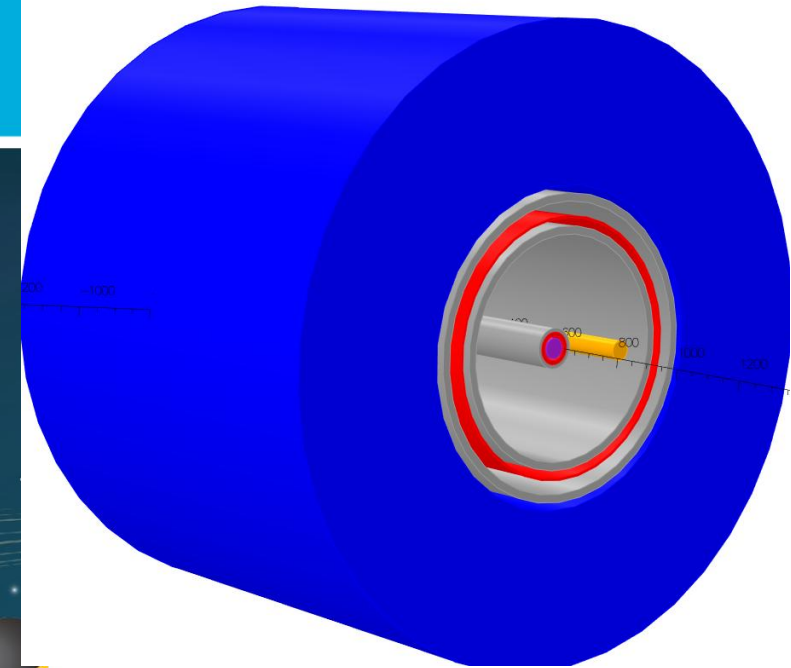
Electron-Ion Collider



Components of the Updated B0pF Combined Function OID

- Warm iron proposal (as discussed earlier)
- Progress on continuous double-layer winding with no splices
- Major upgrade in the software for optimizing combined function optimum integral design
- Individually optimized eight layers with lower field harmonics and lower peak fields
- Performance of 2-layer, 4-layer, 6-layer and 8-layer designs (no to commit to 8-layer design now as the margins are large)

Warm Iron Tubular Cryostat for Any Design of B0pF

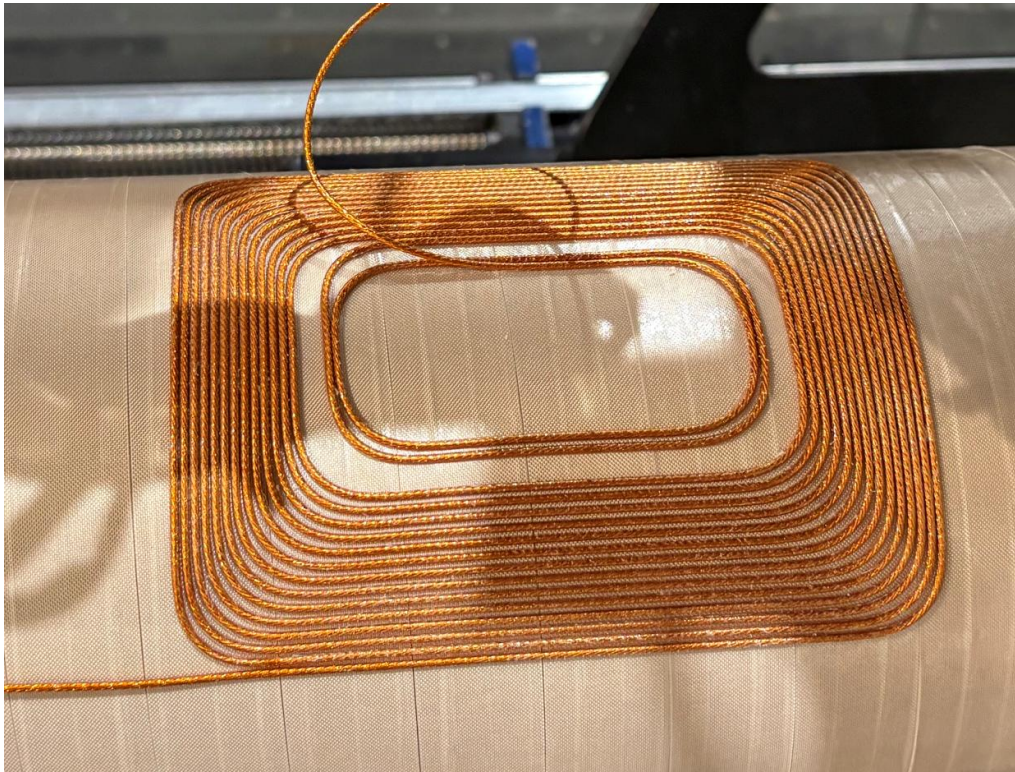


- B0pF superconducting coils inside the tubular cryostat.
- Example: RIA with warm iron yoke. Space taken by cryostat is relatively small in such a large magnet.



- Smaller area to cool
- Easier to reduce weight (doesn't have to be circular) and transport
- Easier to iterate yoke design after measurement, if desired
- Should reduce overall cost

Progress in continuous double-layer OID winding (no splices)



1st quadrant of the 1st layer wound
midplane to pole
(instead of typical pole to pole in OID)



- Substrate placed **along the length** after filling gaps with fiberglass spacers and blue epoxy
- **Substrate glues strongly for winding next layer**
- 1st quadrant of 2nd layer wound
- Temporary spacer holder for winding removed

Progress in continuous double-layer OID winding (no splices)

- Ready for winding 1st layer of 2nd quadrant
- Proud and happy technician



Feedback to design:

- Make end of the 2nd layer smaller by one-wire (negligible impact)
- May need $\frac{1}{2}$ wire per quadrant extra space at midplane (a small fraction of ~ 200 turns)



Upgrade in Optimum Integral Design Code

Basic formulation and optimization approach:

(very different from the other codes, making it very fast as compared to others, dramatically faster for 3-d)

Philosophical goal: $I(\theta) \cdot L(\theta) = I_o \cdot L_i(\theta) \propto I_o \cdot L_o \cdot \cos(n\theta)$

For no wedges or end spacer, function is linear ==> Modulate it to cos theta

- **Full-length midplane turn defines the length of the magnet
(essentially no loss due to magnet ends)**

Expression for 2-d harmonics b_n :

for a line current located at (a, ϕ)

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

Integral field 3-d harmonics (B_n):

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

Harmonics are directly computed and optimized, as necessary; essentially no difference between 2d and 3d)

How Optimum Integral Design code differs from most other 3-d codes in computing and optimizing integral harmonics

- Most codes first compute field (or vector potential) along the length at several places and then compute and integrate field harmonics and then optimize them.
- Optimum integral code directly computes integral harmonics of interest by integrating the value from each conductor. Iron is included as the image current.
- This is an order of magnitude faster. The formulae are valid when the field is 2-d or when it is integrated over the entire length. Cylindrical part of the conductor (going from the lead end to return end) does not contribute to field harmonics. A section of the conductor which connects straight-section to cylindrical part (small in most direct wind magnets), is approximated with a set of line currents.
- **Chi square (χ^2) function is minimized for a set of n-harmonics with chosen weightage to each of those n harmonics.**
$$\chi^2 = \sum_i \mathbf{w}_i \cdot (\mathbf{C}_i^2 - \mathbf{D}_i^2),$$

where C_i is the computed value of the i^{th} parameter, D_i is the design value of the i^{th} parameter and w_i the weight for the i^{th} parameter.
- The downside is that it doesn't do anything else – like peak field, field in the aperture, etc., etc., etc..
- To overcome that limitation to carry out the design process efficiently, we create output files which are input for OPERA (or RAT) and those calculations are performed there.

INPUT Files for Optimum Integral Design

“Old Fashion Input”
(working on the modern
way of doing things)

.X01 and .X07 files

```

30pF CF Layer#2 1.4 mm wire 1.27m
1 W1E 0. 0. 0. 1.
2 N1E 15. 0. 40. 89.
3 B1E 0. 0. 0. 9.
4 W2E 2.56 0.1 0. 3.6
5 N2E 15. 0. 5. 50.
6 B2E 0.0 0.0 0. 0.1
7 W1F 2.42 0.1 0. 3.5
8 N1F 14. 0. 40. 89.
9 B1F 0. 0. 0. 1.
10 W2F 2.33 0.1 0. 3.4
11 N2F 13. 0. 5. 50.
12 B2F 0.0 0.0 0. 0.1
13 W1G 3.16 0.1 0. 3.6
14 N1G 11. 0. 40. 89.
15 B1G 0. 0. 0. 9.
16 W2G 1.02 0.1 0. 2.6
17 N2G 9. 0. 5. 50.
18 B2G 0.0 0.0 0. 0.1
19 W1H 2.12 0.1 0. 2.6
20 N1H 7. 0. 40. 89.
21 B1H 0. 0.0 0. 1.
22 W2H 0.8 0.1 0. 2.9
23 N2H 6. 0. 5. 50.
24 B2H 0.2 0.01 0.1 0.3
25 S1E 0 0. 0. 20.
26 T1E 15. 0. 4. 79.
27 E1E 0. 0.0 0. 0.09
28 S2E 0.09 0.1 0. 30.
29 T2E 15. 0. 0. 39.
30 E2E 0.0 0. 0. 1.0
31 S1F 0.09 0.1 0. 30.
32 T1F 14. 0. 4. 59.
33 E1F 0. 0.0 0. 1.
34 S2F 0.09 0.1 0. 30.
35 T2F 13. 0. 0. 49.
36 E2F 0.0 0.0 0. 1.
37 S1G 0.09 0.1 0. 30.
38 S1G 0.09 0.1 0. 30.
39 S1G 0.09 0.1 0. 30.
40 S1G 0.09 0.1 0. 30.
41 S1G 0.09 0.1 0. 30.
42 S1G 0.09 0.1 0. 30.
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111 S1G 0.09 0.1 0. 30.
112 S1G 0.09 0.1 0. 30.
113 S1G 0.09 0.1 0. 30.
114 S1G 0.09 0.1 0. 30.
115 S1G 0.09 0.1 0. 30.
116 S1G 0.09 0.1 0. 30.
117 S1G 0.09 0.1 0. 30.
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121 S1G 0.09 0.1 0. 30.
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124 S1G 0.09 0.1 0. 30.
125 S1G 0.09 0.1 0. 30.
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153 S1G 0.09 0.1 0. 30.
154 S1G 0.09 0.1 0. 30.
155 S1G 0.09 0.1 0. 30.
156 S1G 0.09 0.1 0. 30.
157 S1G 0.09 0.1 0. 30.
158 S1G 0.09 0.1 0. 30.
159 S1G 0.09 0.1 0. 30.
160 S1G 0.09 0.1 0. 30.
161 N23 11. 0. 5. 50.
162 B23 0.0 0.0 0. 0.1
163 W14 -0.79 0.1 -4. 0.
164 N14 9. 0. 40. 89.
165 B14 0. 0.0 0. 1.
166 W24 -0.78 0.1 -5. 0.
167 N24 9. 0. 5. 50.
168 B24 0.0 0.0 0. 0.1
169 S11 0 0. 0. 20.
170 T11 18. 0. 4. 79.
171 E11 0. 0.0 0. 10.
172 S21 0.09 0. 0. 50.
173 T21 18. 0. 0. 39.
174 E21 0.0 0. 0. 1.0
175 S12 0.09 0.0 0. 5.
176 T12 16. 0. 4. 59.
177 E12 0. 0.0 0. 1.
178 S22 0.09 0. 0. 50.
179 T22 15. 0. 0. 49.
180 E22 0.0 0.0 0. 1.
181 S13 0.09 0. 0. 20.
182 T13 13. 0. 4. 29.
183 E13 0. 0.0 0. 0.09
184 S23 0.09 0. 3. 50.
185 T23 11. 0. 0. 29.
186 E23 0.0 0. 0. 1.0
187 S14 9.9 0. 0. 20.
188 T14 9. 0. 4. 49.
189 E14 0. 0. 0. 1.
190 S24 9.9 0. 5. 50.
191 T24 9. 0. 0. 39.
192 E24 0.00 0.0 0. 3.0
CALL FCN 3.
SIMPLEX
CALL FCN 3. 1.
END RETURN
    
```

4 layers
represent
4 quadrant

(192 input parameters, not
all optimized together)

OUTPUT Files for Optimum Integral Design

```

LAYER NO., X-SECTION TURNS, END-TURNS:      1   90   90
LAYER NO.   BLOCK NO.   TURN NO.   WEDGE (DEGREE)   C2C-BODY (DEG)
  1           1           15           0.00000           0.00000
  1           2           15           0.00003           0.00000
  1           3           14           2.51165           0.00000
  1           4           13           2.42313           0.00000
  1           5           11           3.25189           0.00000
  1           6           9            0.01475           0.00000
  1           7           7            2.33108           0.00000
  1           8           6            0.90990           0.21045
LAYER NO.   BLOCK NO.   TURN NO.   END-SPACER (MM)   C2C-END (MM)
  1           1           15           0.00000           0.00000
  1           2           15           27.88913           0.00000
  1           3           14           27.46401           0.00000
  1           4           13           24.92583           0.00000
  1           5           11           24.25830           0.00000
  1           6           9            14.61209           0.00000
  1           7           7            19.12535           0.00000
  1           8           6            48.46177           3.90139
LAYER NO., X-SECTION TURNS, END-TURNS:      2   90   90
LAYER NO.   BLOCK NO.   TURN NO.   WEDGE (DEGREE)   C2C-BODY (DEG)
  2           1           6            5.58668           0.19905
  2           2           7            0.01937           0.00000
  2           3           9            0.95966           0.00000
  2           4           11           1.11014           0.00000
  2           5           13           2.11091           0.00000
  2           6           14           0.09008           0.00000
  2           7           15           0.00029           0.00000
  2           8           15           0.85056           0.00000
LAYER NO.   BLOCK NO.   TURN NO.   END-SPACER (MM)   C2C-END (MM)
  2           1           6            48.46177           3.90139
  2           2           7            19.12535           0.00000
  2           3           9            14.61209           0.00000
  2           4           11           24.25830           0.00000
  2           5           13           24.92583           0.00000
  2           6           14           27.46401           0.00000
  2           7           15           27.88913           0.00000
  2           8           15           0.00000           0.00000

                                4           8           9           9.89032   (
TOTAL NUMBER OF TURNS =                               398
CHI SQUARE =      1.9417652624688344
INTEGRATED FIELD HARMONICS :
No.   Bn (T.m)   bn*10^4 (units)   bn (des)   weight
  0   -0.32809E-01   -7429.8618   -7400.0000   2.0000
  1    0.44158E-01   10000.0000    0.0000    0.0000
  2    0.10337E-06    0.0234    0.0000    6.0000
  3   -0.20413E-05   -0.4623    0.0000    8.0000
  4    0.37790E-06    0.0856    0.0000    8.0000
  5   -0.88335E-06   -0.2000    0.0000    4.0000
  6    0.64188E-07    0.0145    0.0000    1.0000
  7    0.37709E-07    0.0085    0.0000    1.0000
  8   -0.15653E-08   -0.0004    0.0000    0.0000
  9    0.73949E-09    0.0002    0.0000    0.0000
 10    0.52535E-10    0.0000    0.0000    0.0000
 11    0.10397E-10    0.0000    0.0000    0.0000
 12    0.11948E-11    0.0000    0.0000    0.0000
 13   -0.27225E-12   -0.0000    0.0000    0.0000
 14    0.16027E-13    0.0000    0.0000    0.0000
 15    0.11261E-14    0.0000    0.0000    0.0000
 16    0.61690E-15    0.0000    0.0000    0.0000
 17   -0.33110E-16   -0.0000    0.0000    0.0000
 18    0.47239E-17    0.0000    0.0000    0.0000
 19    0.25069E-17    0.0000    0.0000    0.0000
 20   -0.32866E-18   -0.0000    0.0000    0.0000
 21   -0.88661E-21   -0.0000    0.0000    0.0000
 22    0.41199E-20    0.0000    0.0000    0.0000
 23    0.24075E-20    0.0000    0.0000    0.0000
 24   -0.16171E-21   -0.0000    0.0000    0.0000
 25   -0.19909E-22   -0.0000    0.0000    0.0000
 26    0.55788E-24    0.0000    0.0000    0.0000
 27   -0.73455E-25   -0.0000    0.0000    0.0000

```

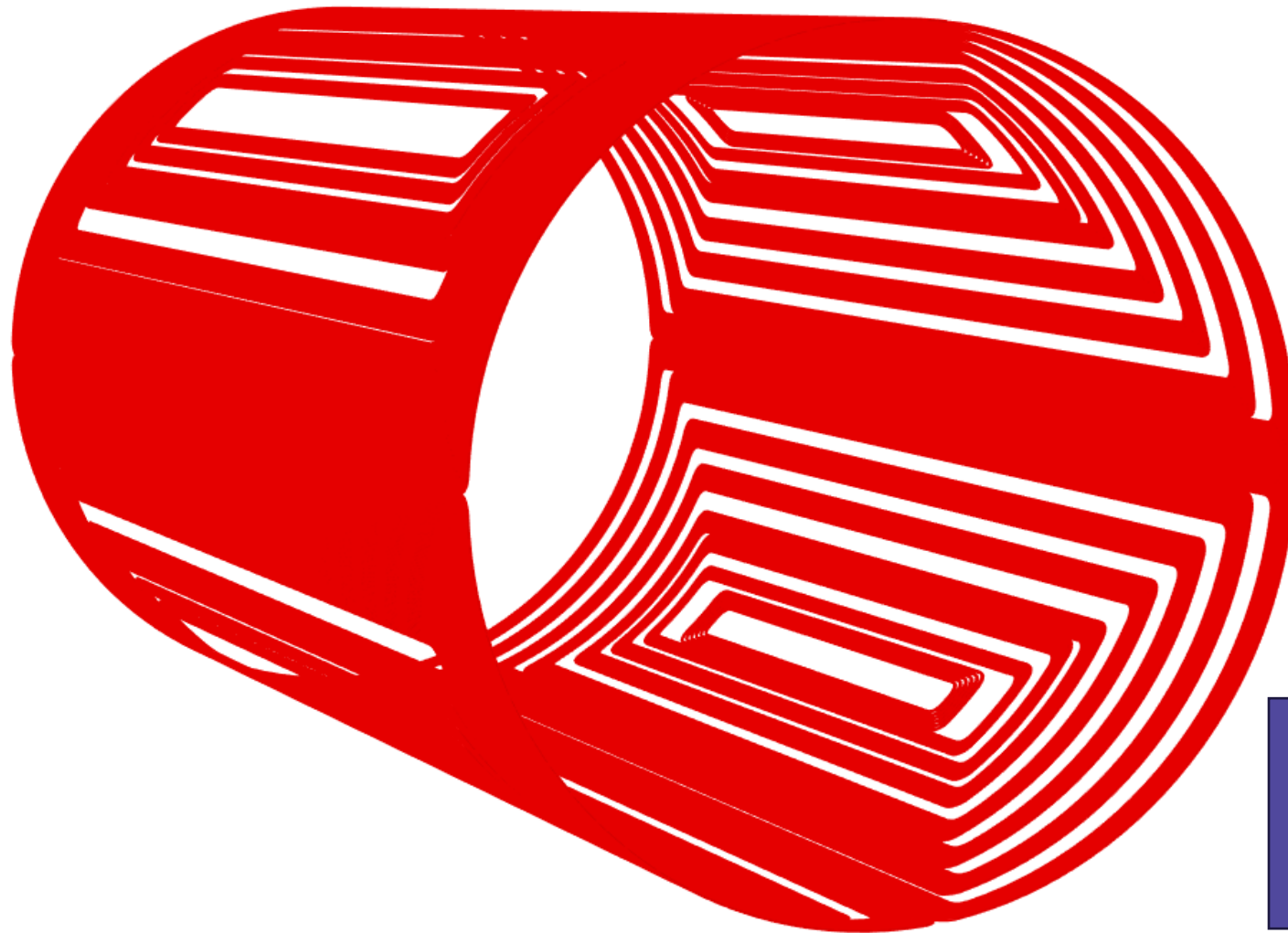
And many other files like input to other programs, such as files to wind coil downstairs and input to opera3d, etc.

Latest Upgrade

To allow four quadrants to work in sink while being optimized such as wedges, turn to turn spacing, end spacers.

Some work required to make sure that all four quadrants connect properly, particularly in case when the end spacers vary (optimization of end and body together is the key part of the optimum integral design).

See the difference between left side and right side (both in the body and in the end)



Summary of Results

The analysis is completed for 2-layer, 4-layer, 6-layer and 8-layer designs.

Field quality is better than before.

Margins are a little higher (not fully analyzed)

