Main Goals of D2 Magnetic Design

Baseline specifications and performance targets (CERN):

- Aperture: 105 mm
- Inter-beam distance: 186 mm  
  (note this is different from 192 mm nominal LHC)
- Target operating point on load-line: 70%
- Integrated field: 35 T.m
- Magnetic length: below 10 m
  (there is interest in a shorter magnet, say around 8 m, if possible)
BNL has designed, built and delivered 80 mm D2 magnets. However, there are major differences in this design:

- Significantly larger aperture (105 mm instead of 80 mm)
  - over 31% more flux for similar overall yoke and cryostat
- Smaller spacing (186 mm instead of 188 mm)
  - less iron (21 mm instead of 48) between two apertures for more flux makes cross-talk at higher field a particular challenge
Iron Yoke for 2-in-1 Dipole  
(with field in the same vs. opposite direction)

Right-half of the x-section

- Like LHC main dipole, LHC insertion D2 is also a 2-in-1 dipole.

- In main ring dipoles, however, the field in two apertures is in opposite direction allowing one side to provide return flux path to the other.

- This is not the case in D2 since the field is in the same direction. This means that the flux on one aperture must return on the same side.

- Reducing cross-talk due to proximity of two apertures (quadrupole harmonic, etc.) and other harmonics arising from the insufficient iron at midplane is the major challenge.

- In 80 mm D2 we were able to overcome this by the unique oblate yoke design developed at BNL. Let’s examine this in 105 mm which has more flux and less spacing.
Impact of Relative Polarity (1)

Field in the opposite direction
(LHC main dipoles)

Field in the same direction
(D2 dipoles)

Field lines return from the other half

Field lines can’t return from the other half
Impact of Relative Polarity (2)

Field in the opposite direction (LHC main dipoles)

Field is low between two apertures (no saturation)

Field in the same direction (D2 dipoles)

Field is large between two apertures (high saturation)

20 mm SS collar (as in previous BNL D2)
Impact of Relative Polarity (3)

Field in the opposite direction
(LHC main dipoles)

Field is low between the two apertures (no saturation)

Field in the same direction
(D2 dipoles)

Field is large between the two apertures (high saturation)
Impact of Relative Polarity (3)

Field in the opposite direction (LHC main dipoles)

Field in the same direction (D2 dipoles)

Field is lower at the center of the magnet and in the return yoke

Field is higher at the center of the magnet and also in the return yoke
Impact of Relative Polarity on Transfer Function

Insufficient yoke iron in 105 mm aperture D2.

See @quench:
(a) Field at midplane between two apertures (~3 T)
(b) Field on cryostat wall - unusually high (~2 T)
Leakage field is so high that if you wrap a good amount of extra iron on cryostat wall, you get 1.3 T over there.
Impact of Relative Polarity on Quad Harmonic (cross-talk)

Large cross-talk due to insufficient iron in D2 at midplane between the two apertures.
Impact of Relative Polarity on Sextupole Harmonic

Significantly larger saturation induced sextupole (b3) in D2. Positive in the first case due to a larger pole saturation, negative in second case due to larger midplane saturation.

Field in the same direction

Field in the opposite direction
Impact of Relative Polarity on Octupole Harmonic (cross-talk)

Large cross-talk due to insufficient iron in D2 at midplane between the two apertures.
Impact of Relative Polarity on Other Harmonics

Design field ~3.5 T
A quick review (3 slides only) of what we did and what we got in 80 mm LHC D2

(we did manage a good field quality in those magnets)

References


LHC 80 mm D2 in Cryostat

- 80 mm aperture
- RHIC dipole coil
- Oblate Yoke
The low field transfer function is 0.6345 T/kA for all the three cases. Fig. 3 shows the change in transfer function (from the low field value) in the right aperture as a function of the dipole field in this aperture. For a given

Fig. 2: Field lines calculated using OPERA-2D at 3.77 T (6kA) in the right aperture, with 15% more current in the left aperture

Fig. 4: Saturation behavior of the quadrupole term
Measured Harmonics in 80 mm D2
(6 measured, 2 shown)

- Small saturation-induced quad, some sextupole
- 6 KA gives ~3.6 T
Initial Optimization of the Magnetic Design of 105 mm D2 Dipole

1. Coil cross-section

2. Yoke cross-section
Coil Cross-section Design

- The aperture of RHIC insertion dipole D0 is 100 mm. This is very close to 105 mm.
- RHIC D0 is a fully optimized and proven design. Several (all – no prototype) good field quality magnets have been built and all except one spare are being used in the interaction region which requires good field quality.
- Therefore, a reasonable starting point could be to scale and tweak the coil design of RHIC D0.
- RHIC 100 mm D0 had 40 turns in five blocks. Allow 42 turns in five blocks of the 105 mm LHC D2 coil.
- Use ROXIE to fine tune the coil cross-section.
### Parameters of RHIC 100 mm D0 Dipole

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil ID</td>
<td>100 mm</td>
</tr>
<tr>
<td>Coil OD</td>
<td>120 mm</td>
</tr>
<tr>
<td>Number of turns per pole</td>
<td>40</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3.6 m</td>
</tr>
<tr>
<td>Iron inner diameter</td>
<td>139.4 mm</td>
</tr>
<tr>
<td>Iron outer diameter</td>
<td>310 mm</td>
</tr>
<tr>
<td>Shell thickness</td>
<td>6.35 mm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.6 K</td>
</tr>
<tr>
<td>Design current</td>
<td>5.0 kA</td>
</tr>
<tr>
<td>Design field</td>
<td>3.5 T</td>
</tr>
<tr>
<td>Quench current</td>
<td>7.4 kA</td>
</tr>
</tbody>
</table>
LHC 105 mm D2 Coil Cross-section (optimized with ROXIE)

LHC D2 - 105 mm using RHIC Cable

|B| (T)

4.620
4.380
4.140
3.900
3.661
3.421
3.181
2.941
2.702
2.462
2.222
1.982
1.743
1.503
1.263
1.023
0.784
0.544
0.304
0.064

ROXIE^{10.2}
105 mm D2 Coil Harmonics @35 mm (2/3 coil radius, not 17 mm)

Optimization with ROXIE

REFERENCE RADIUS (mm) .............................................. 35.0000
X-POSITION OF THE HARMONIC COIL (mm) ....................... 0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ....................... 0.0000
MEASUREMENT TYPE ........................................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ...................... 0.2045E-02
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .................................................. -4.109409
MAGNET STRENGTH (T/(m^(n-1))) ................. -4.1094

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:  0.00000  b 3:  0.03316
b 4:  0.00000  b 5:  0.03930  b 6:  0.00000
b 7:  0.14095  b 8:  0.00000  b 9:  0.14324
b10:  0.00000  b11:  0.48417  b12:  0.00000
b13:  0.39692  b14:  0.00000  b15:  -0.20657
b16:  0.00000  b17:  -0.35482  b18:  0.00000
b19:  0.07375  b20:  0.00000

➢ Harmonics (specially higher order terms) are much smaller @17 mm
Flexible Coil Cross-section in LHC D2
(Could do the same as done in 100 mm RHIC Dipole)

- Simple techniques (midplane + pole shims) produced accelerator grade field quality in the very first magnet (field errors ~1 part in $10^4$ up to 60% coil radius).
- This flexibility in the design allowed easy harmonic tuning during the production without changing coil or yoke.
- It resulted in good field quality magnets - average error <1 part in $10^4$ up to ~80% of coil radius (almost entire vacuum pipe).

Much faster and much cheaper than conventional iterations
Yoke Cross-section Investigations

Major Challenge
Maximum Estimate of Cross-talk

- OK, so iron is bad. It saturates. Get rid of it. This also gives the max cross-talk.
- Quadrupole term becomes ~400 units. Getting rid of this and other harmonics will make a funny and inefficient coil cross-section. This not practical.

No iron (except in cryostat)
Variation in Collar Width

- So more iron is needed. Add it within the same envelop.
- What if SS collar thickness is reduced from 20 mm for extra iron (mechanical structure becomes complicated).

<table>
<thead>
<tr>
<th>Collar (mm)</th>
<th>B@~5.5kA</th>
<th>db2@35mm</th>
<th>db3@35 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mm</td>
<td>3.54</td>
<td>37</td>
<td>-54</td>
</tr>
<tr>
<td>10 mm</td>
<td>3.82</td>
<td>36</td>
<td>-33</td>
</tr>
<tr>
<td>5 mm</td>
<td>3.98</td>
<td>38</td>
<td>+29, -4</td>
</tr>
</tbody>
</table>

More iron gives a significantly higher field for the same current and it also reduces the saturation induced harmonics $b_2$, $b_3$, etc. (compare $b_2$ at the same field)
10 mm collar

Component: BMOD

3.12434E-03 3.342427651 6.681730963
20 mm collar
25 mm collar

UNITs
Length:mm
Flux density:T
Field strength:A m⁻¹
Potential:Wb m⁻¹
Conductivity:S m⁻¹
Source density:A mm²
Power:W
Force:N
Energy:J
Mass:kg

MODEL DATA
Ihc-d2-105mm-r25.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 9 of 9
Scale factor:7.0
61969 elements
124340 nodes
125 regions

Component: BMOD
3.17182E-03  3.140465383  6.277758948
Managing Saturation to Minimize Saturation-induced Harmonics

- Saturation-induced harmonics are created when the field in iron near the aperture varies as a function of angle at high fields.
- See left-right difference and angular dependence of field
- Either removing saturating iron, or forcing a uniform saturation by holes, etc. should reduce the saturation-induced harmonics.
Iron removed between the two apertures.

Change in quad term becomes half but the absolute value becomes about 100 unit and $b_4$ becomes about 30 unit.

- Rest of the examples are for forcing saturation rather than removing.
Midplane cutout to balance saturation between the left and the right side (20 mm collar)

Quad term becomes about half (~16 unit) and $b_4 < 5$ units @ 35 mm.
But $b_3$ becomes large (about 100 units) due to larger midplane saturation.
5 mm collar with large cutout at midplane

Cross-talk becomes even smaller (b2 < 7 unit and b4 < 2 units @ 35 mm. But b3 becomes large (over 100 units) due to larger midplane saturation.
Several other cases are examined in the following slides but none has given yet a solution that has all small saturation induced harmonics
5 mm spacer with arc cutout
20 mm radially arc cutout
20 mm moon cutout

UNITS
- Length: mm
- Flux density: T
- Field strength: A/m
- Potential: V
- Conductivity: S/m
- Source density: A/mm²
- Power: W
- Force: N
- Energy: J
- Mass: kg

MODEL DATA
- lm-c-d2-105mm-120g5b.S
- T
- Quadratic elements
- XY symmetry
- Vector potential
- Magnetic fields
- Static solution
- Case 9 of 9
- Scale factor: 7.0
- 67399 elements
- 155200 nodes
- 131 regions

Component: BMOD
- 6.1382E-03
- 3.181771513
- 6.357404831

Opera
Cutout on both side #1
Cutout on both side #2
Discussion on Approach

• We are facing a challenging situation in going from 80 mm to 105 mm within the same yoke envelope when the flux is increased by over 31%. Moreover, the spacing between the two apertures is further reduced.

• There is a large difference in iron saturation between the left and the right and the pole and the midplane.

• With cutouts and holes, the right side of the aperture (at the midplane) can be forced to saturate evenly with the left side (reducing the cross-talk harmonics) but it increases the difference between pole and midplane saturation (increasing allowed harmonics).

• One can force pole saturation to increase to mitigate it.

• But we are facing a very highly saturating iron and significant fringe fields.
SUMMARY

• Large increase in flux (over 31% due to increase in coil aperture from 80 mm to 105 mm) makes yoke optimization very challenging.

• A number of techniques to reduce saturation induced harmonics have been attempted. However, so far none has produced a field quality that is typical for accelerator magnets.

• More work on optimization may continue but one should also consider alternatives:
  • Can one have a larger cryostat to allow more yoke iron?
  • Can one allow this magnet to have tens of units of harmonics?
  • Is a point optimization at high field advisable which may be influenced by iron properties (note that the saturation is high)?