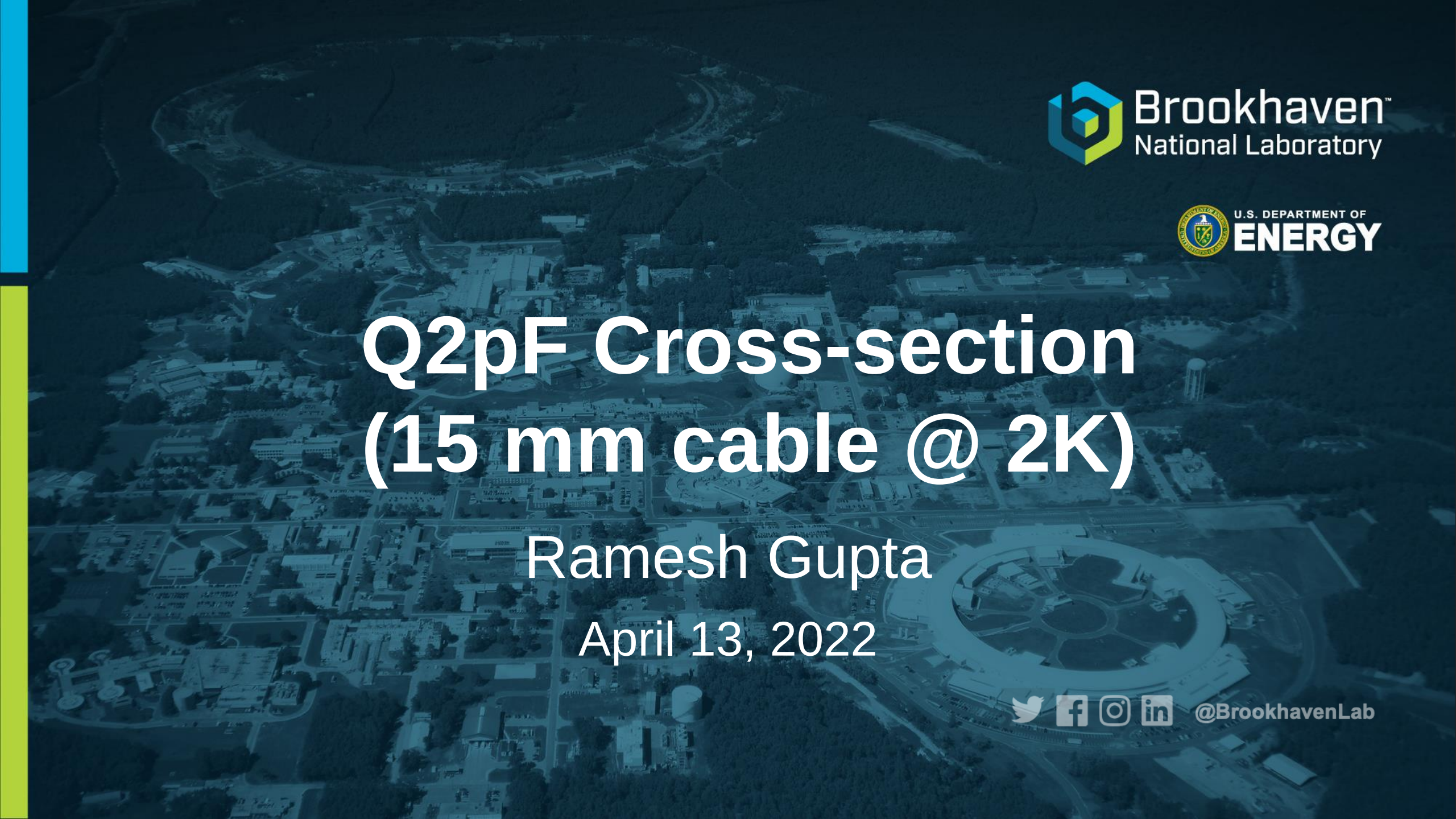


Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Q2pF Cross-section (15 mm cable @ 2K)

Ramesh Gupta

April 13, 2022

@BrookhavenLab

Status of the cross-section design of Q2pF for 2K operation

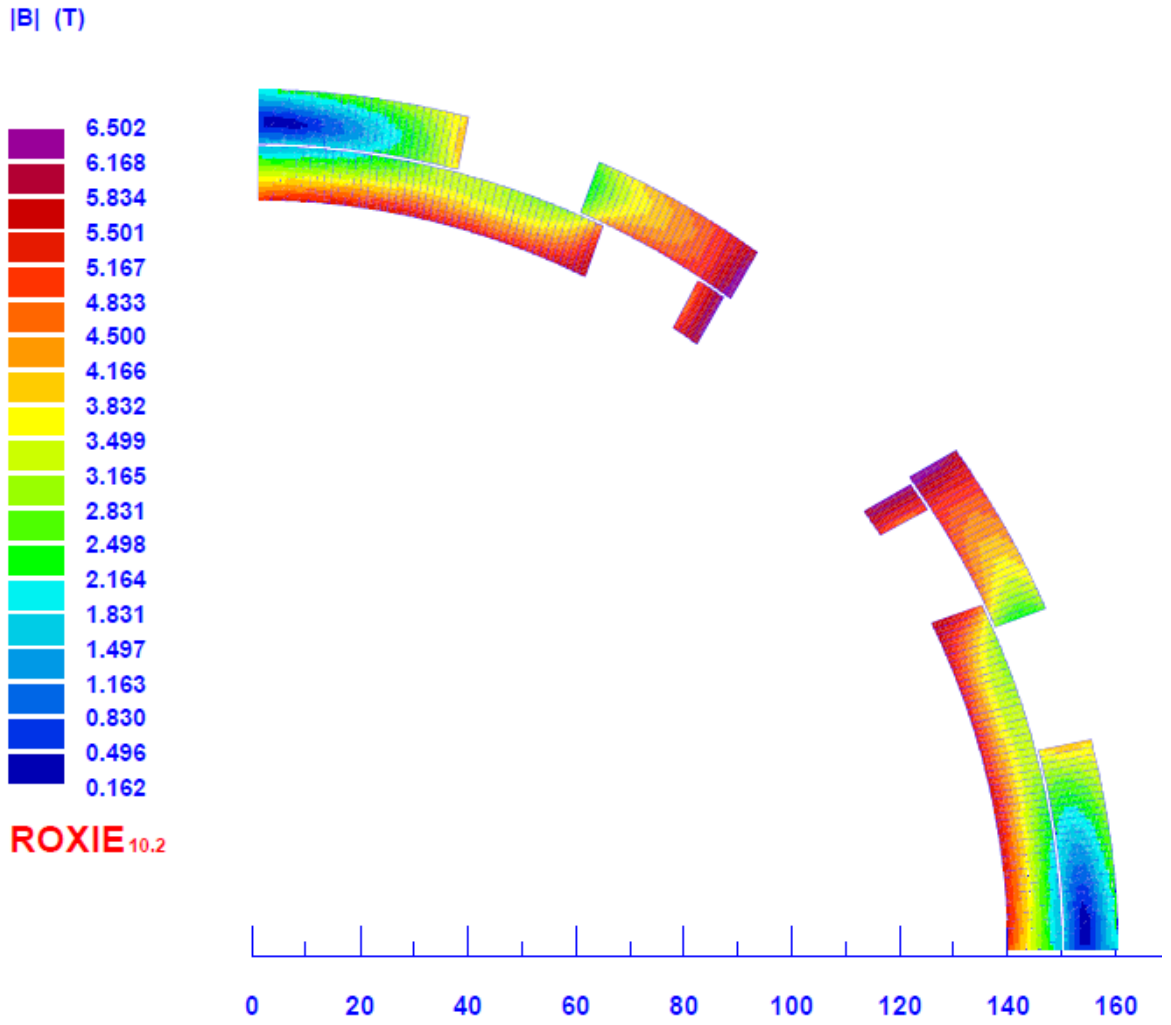
- Initial Optimization of Q2pF cross-section completed.
- RHIC ~10 m cable evaluated – not enough margin.
- Flexibility in the design space further increased to accommodate deviations in components for their impact on field quality and pre-stress on the coil.
- Collar thickness increased by 5 mm (to 30 mm) to allow more mechanical margin.
- Saturation-induced harmonics further reduced for the EIC design range of operation (41 GeV to 275 GeV – a factor of 6.7).
- Field and field harmonics remain low in the electron hole.
- Impact of additional holes for 2K cryo-system examined for holes at various location.
- Cross-section is available for further design and mechanical analysis.

Quench Margin with the 10 mm wide cable (RHIC-type cable) in Q2pF operating at 2 K

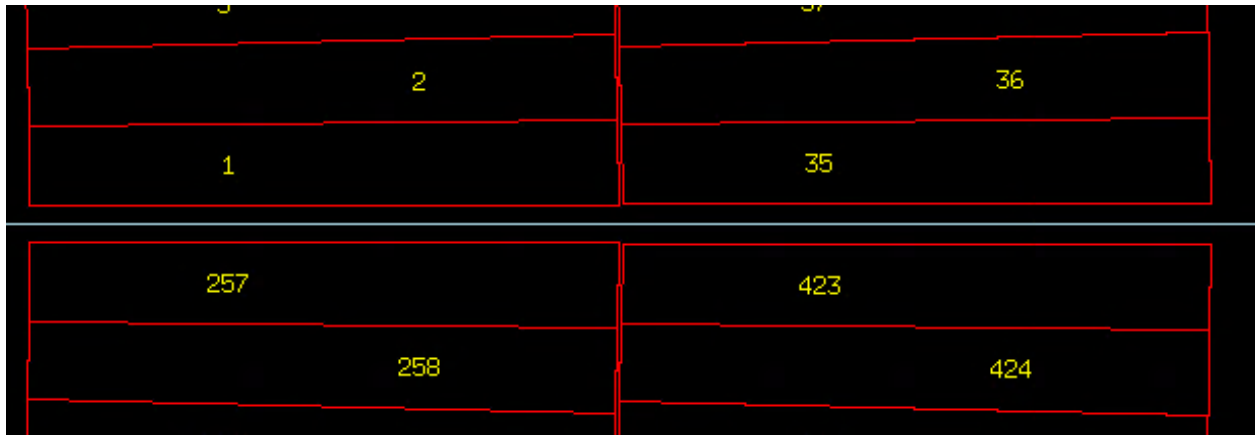
- Field quality good
- Field in electron hole low - good
- Margin reduced from over 50% to 10-15%
  - **NOT GOOD**
- Not acceptable for such a large and high field magnet with limited time for R&D.

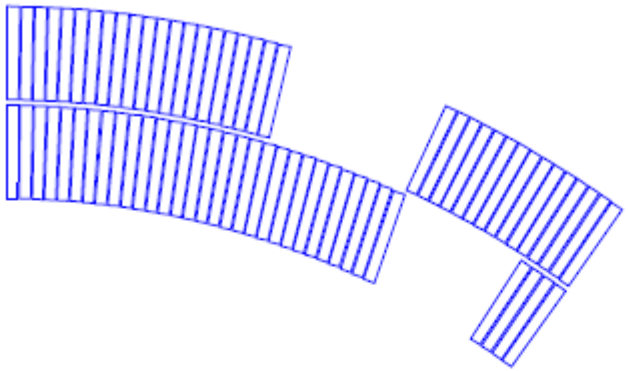
✓ ~15 mm cable should be retained for 2 K

➢ Another option: ~13 mm wide (RHIC insertion quad type). Not worthwhile for a one-off magnet for a relatively small difference

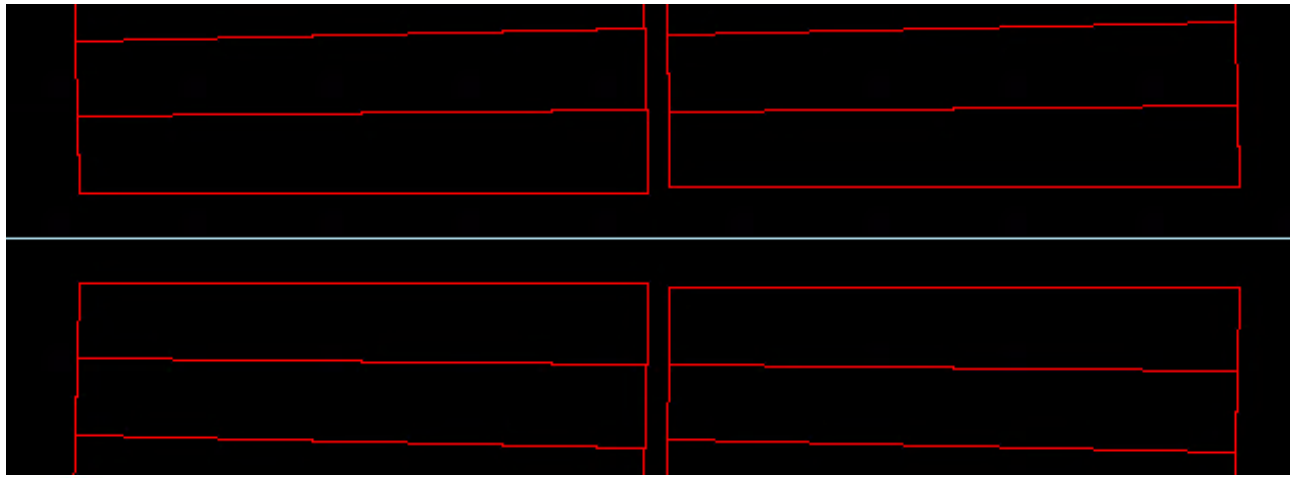


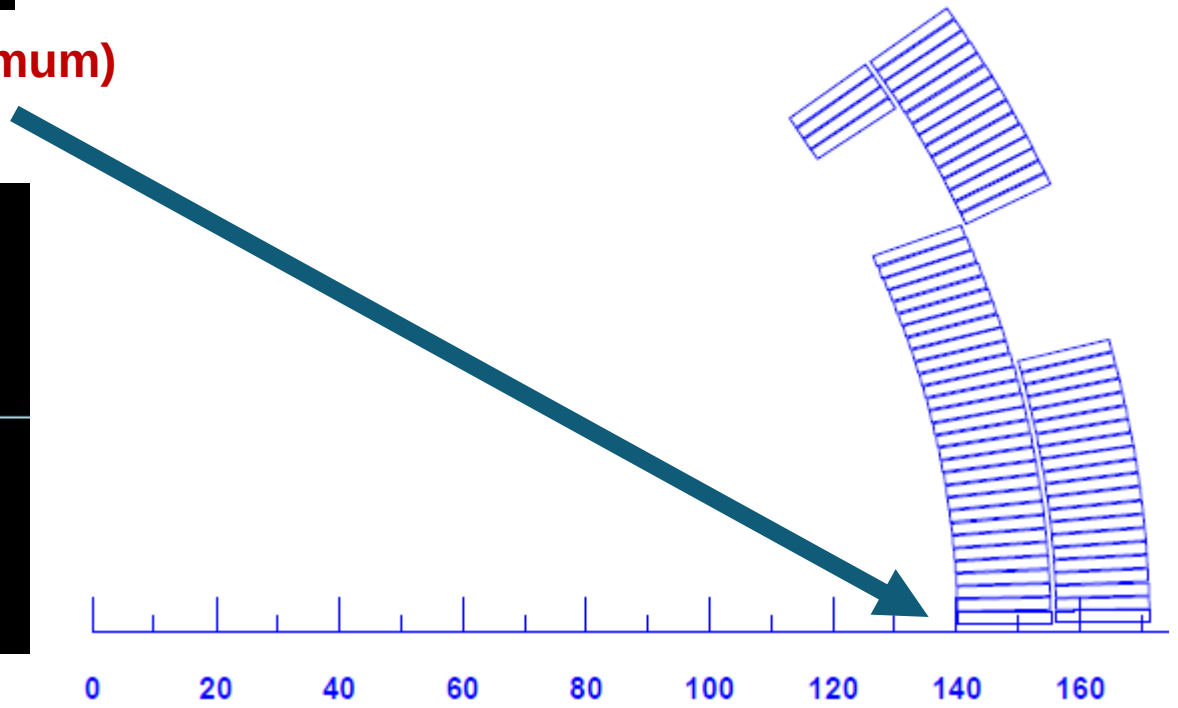
Increased Flexibility of Coil Geometry



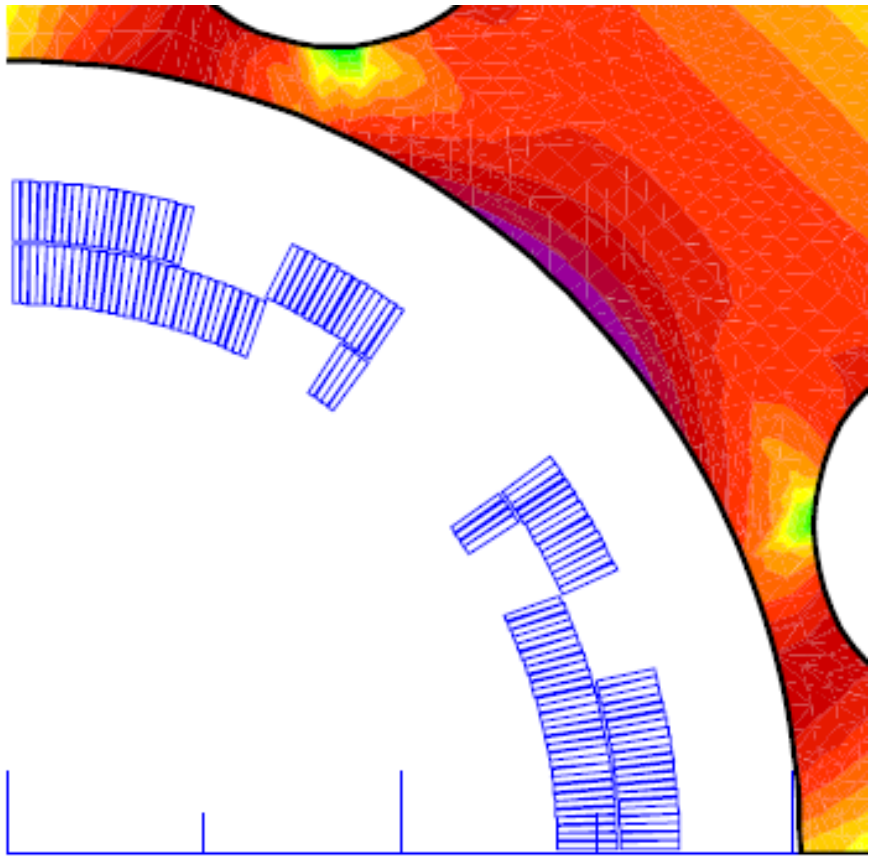


Midplane gap increased from +/-0.2 mm (+/- 0.1 mm minimum) to +/-0.5 mm to increase flexibility for such a large coil

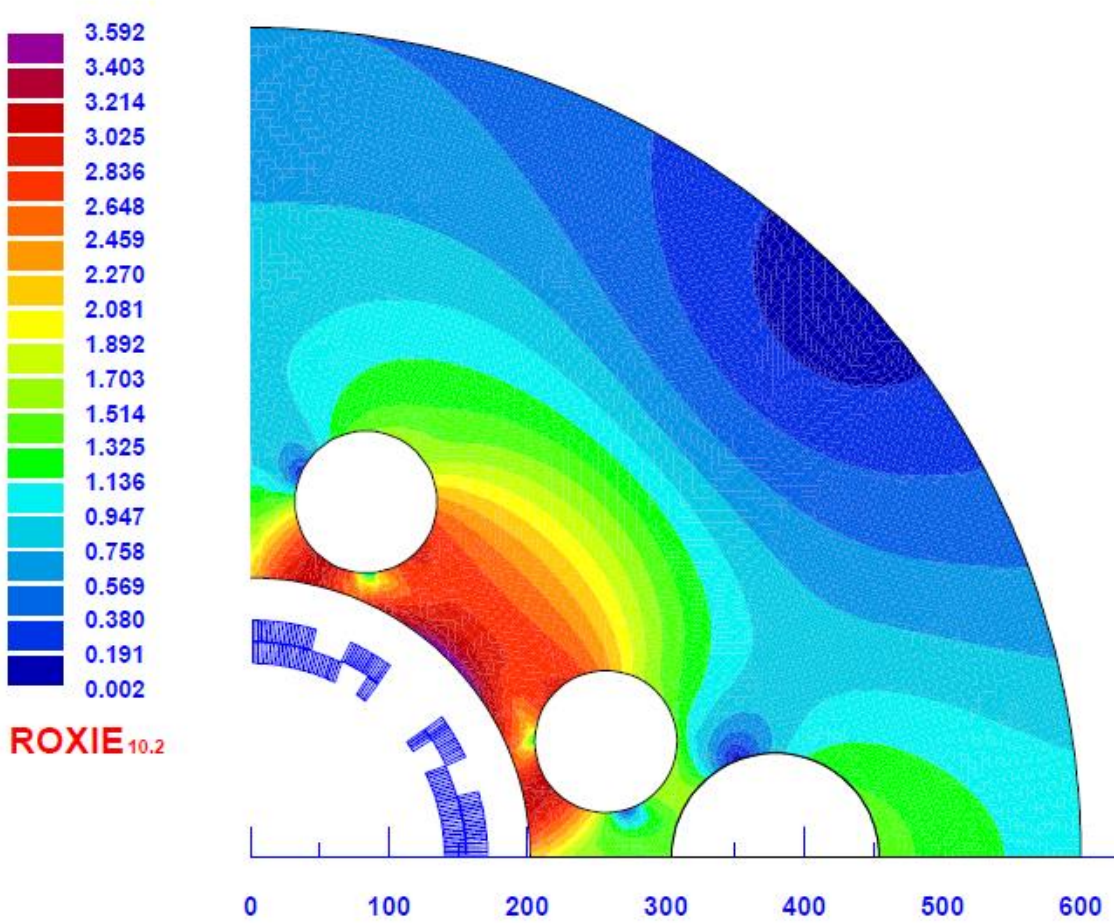




Allowing Larger Collar Thickness
(increased to 30 mm to assure enough space for thicker collar)

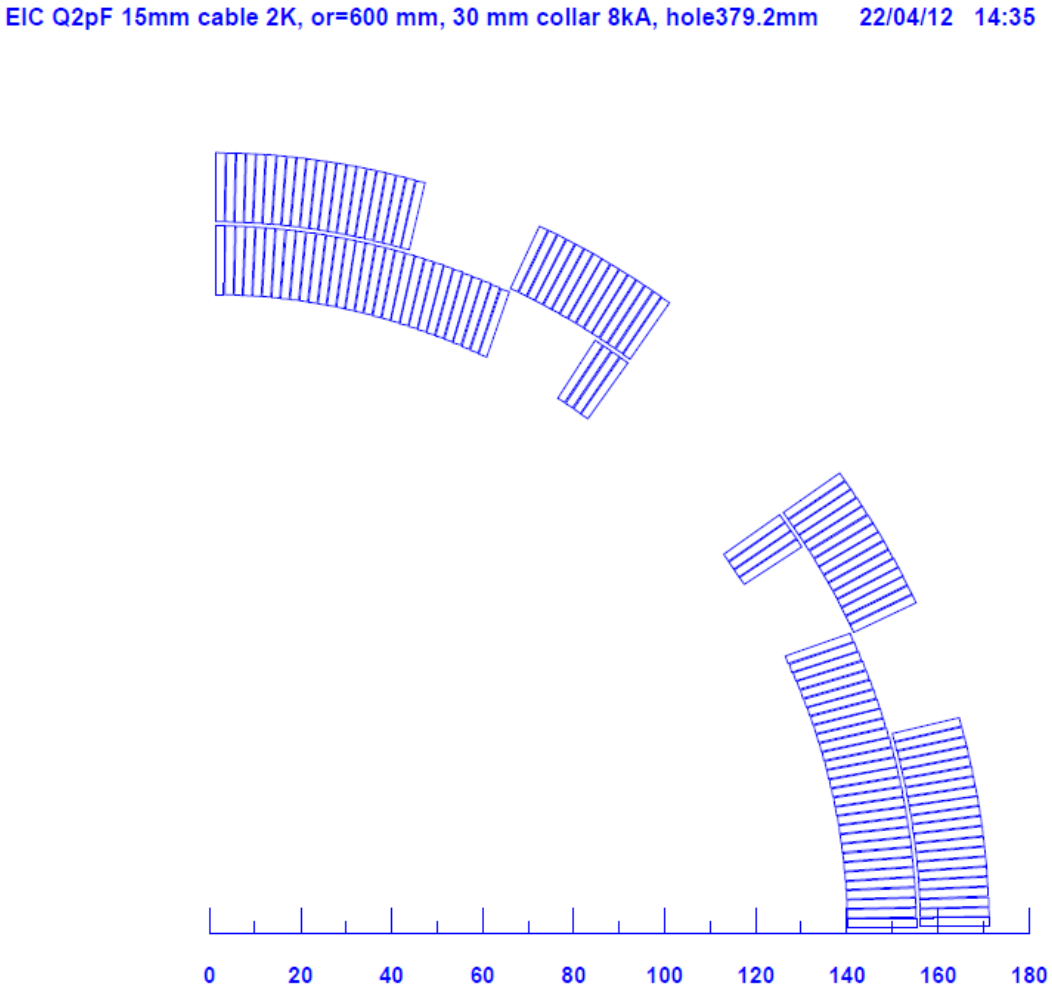


This should minimize future changes, as long as there is enough quench margin and acceptable cross-talk

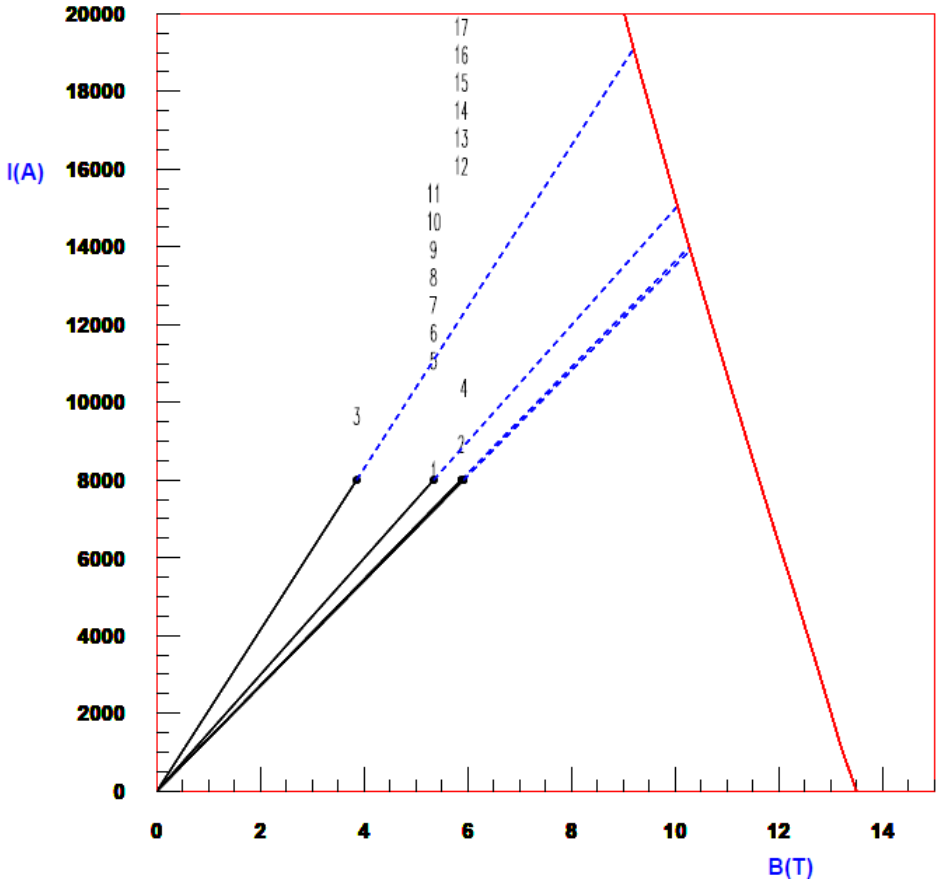


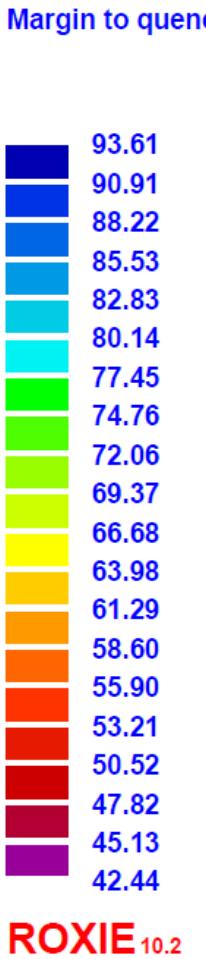
Coil Geometry Remains Good

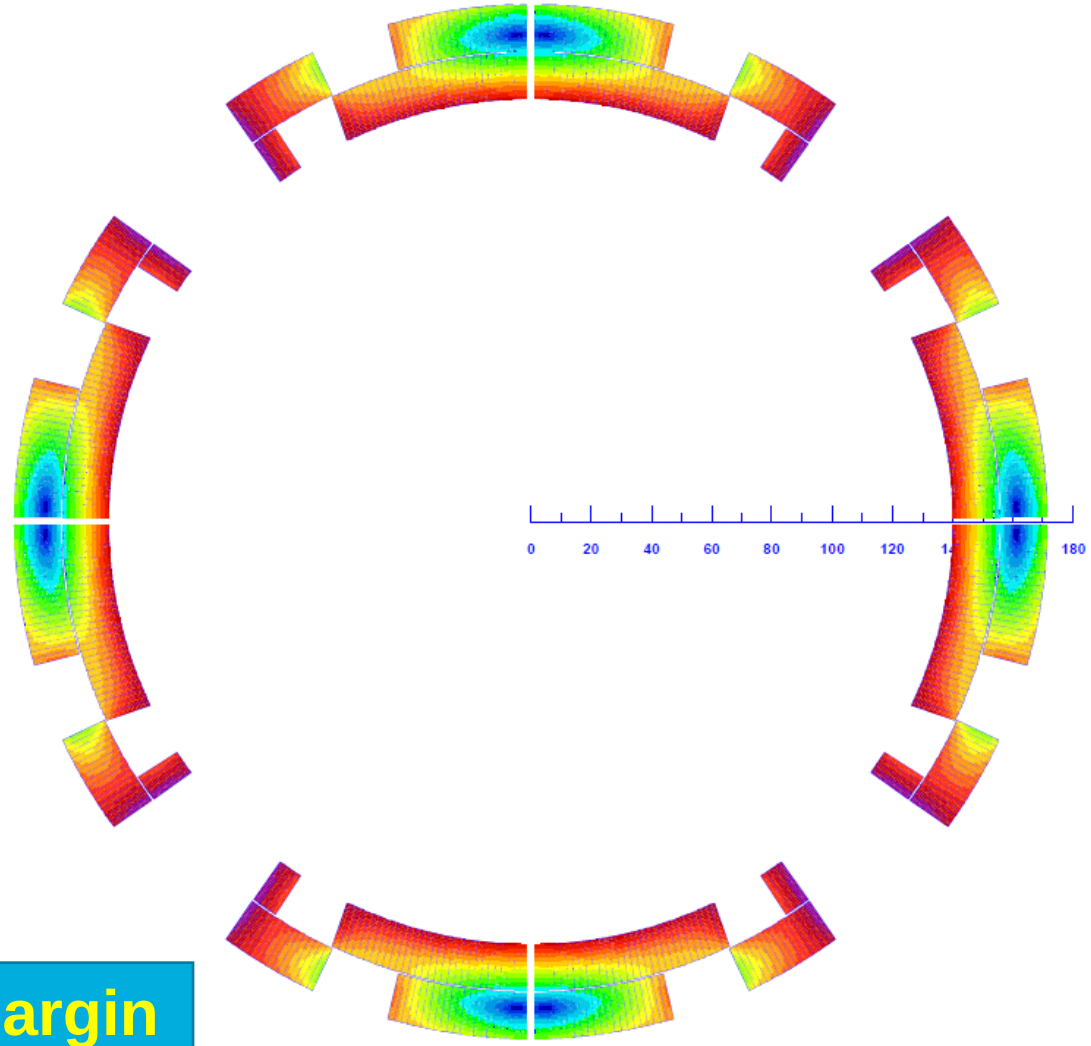
- The coil geometry remains good
- Two layers are properly aligned
- Pole angles are such that the collars can provide pre-stress
- Wedges are proper (outer side bigger than inner side so that they don't slip during collaring or energization



Quench Margin in the Current X-section of the Q2pF at 2 K (a very healthy margin)



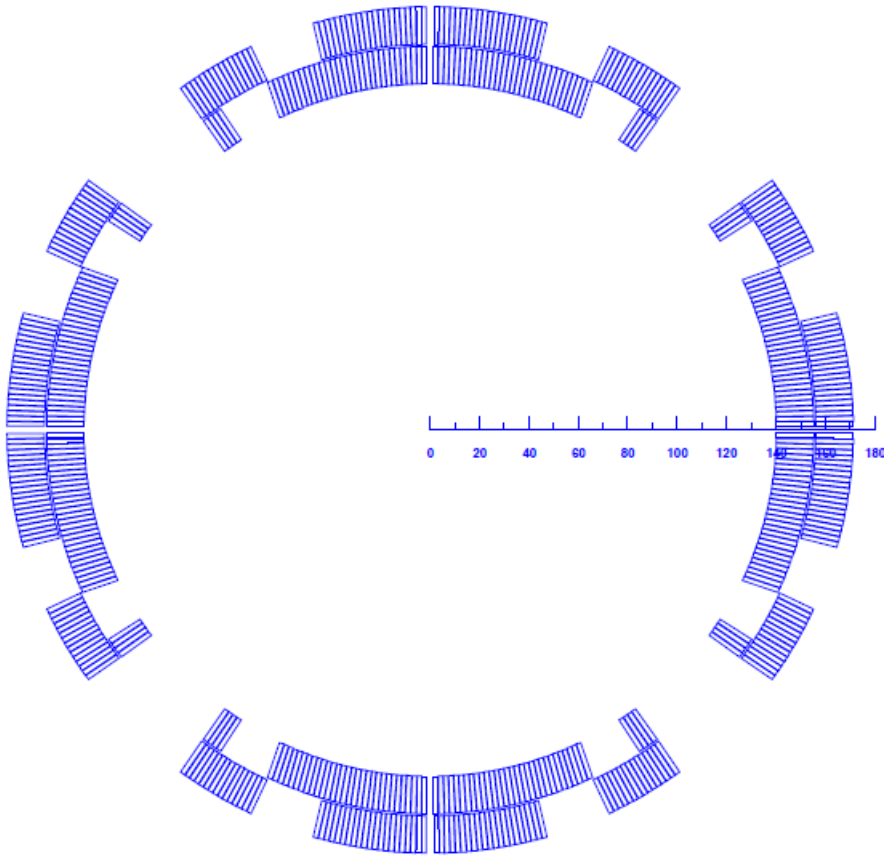




Need to check after 3-d, but a very healthy margin

Field Quality - Geometric Harmonics (@1kA)

GOAL: Obtain low field harmonics at a field where persistent current-induced or saturation induced harmonics are small (1kA), primarily geometric.



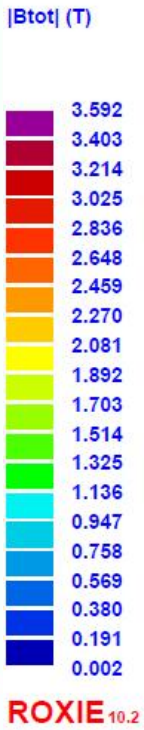

```
HARMONIC ANALYSIS NUMBER ..............................              1
MAIN HARMONIC .........................................              2
REFERENCE RADIUS (mm) .................................        83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..................         0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..................         0.0000
MEASUREMENT TYPE ..........................  ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ......................   0.1057E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ........................................    -0.408099
MAGNET STRENGTH (T/(m^(n-1)) ..........................      -4.9168

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:      -0.13185  b 2:  10000.00000  b 3:      -0.00388
b 4:       0.01480  b 5:     -0.00085  b 6:      -0.00623
b 7:      -0.00045  b 8:      0.00019  b 9:       0.00008
b10:       0.00051  b11:      0.00000  b12:       0.00000
b13:       0.00000  b14:     -0.53040  b15:      -0.00000
b16:      -0.00000  b17:     -0.00000  b18:       0.01442
b19:       0.00000  b20:      0.00000  b
```

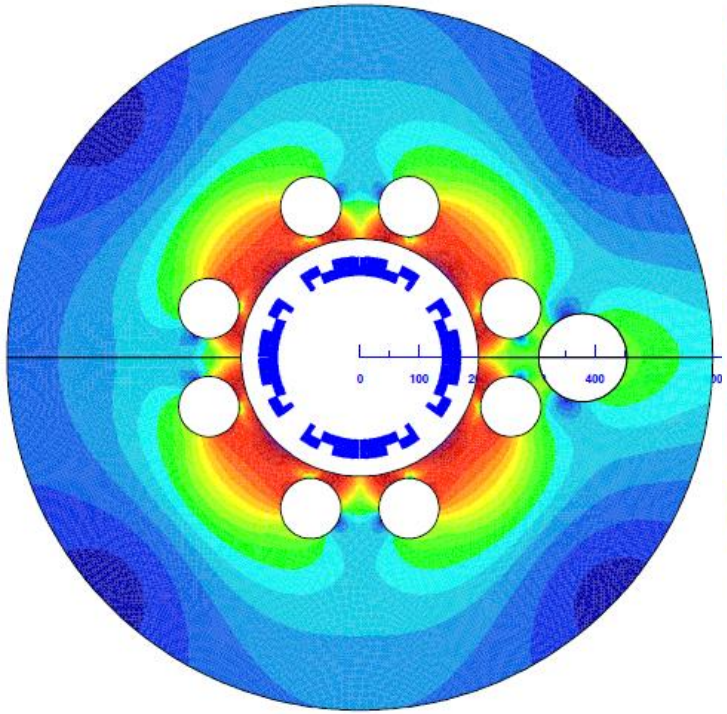
➢ **All geometric harmonics are small**

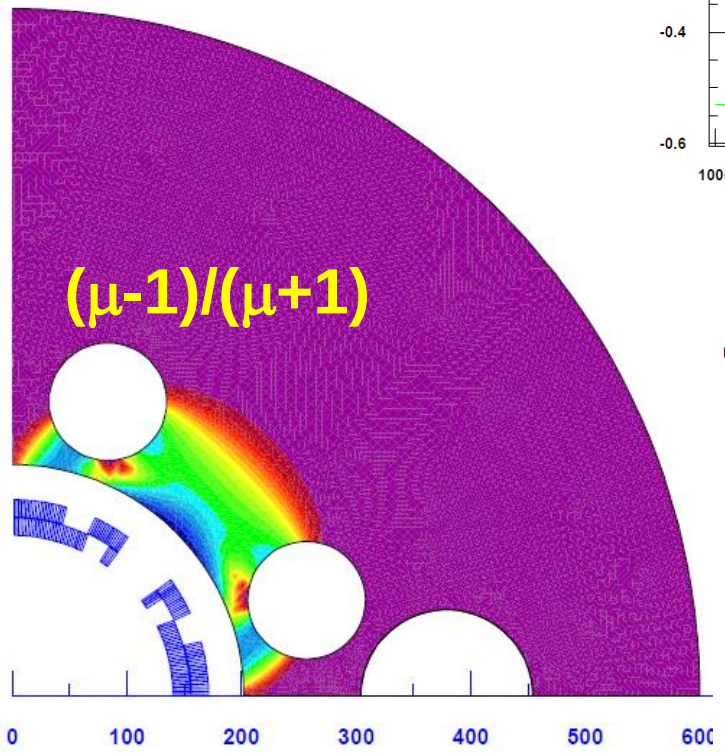
Field Quality - Saturation-induced Harmonics

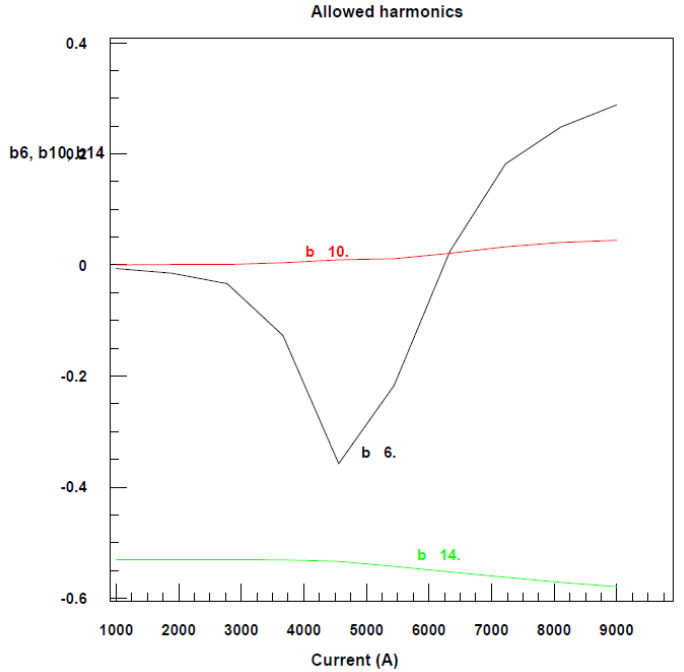
GOAL: Field quality should be good for the entire range of operation.
Reduce change in allowed harmonics as a function of current

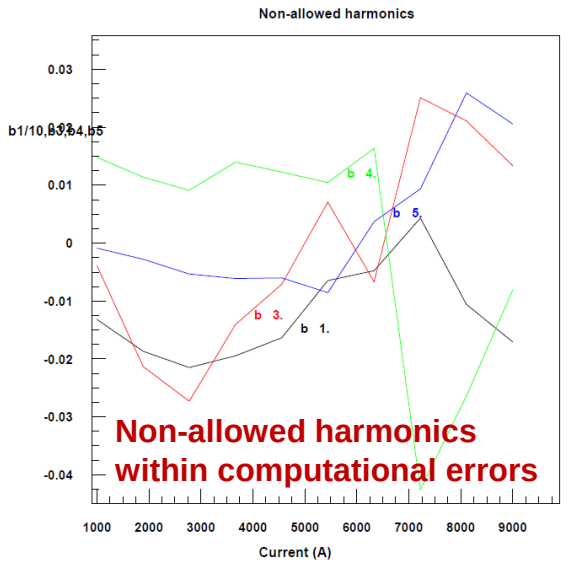
➢ Variation in allowed harmonics < +/- ½ unit





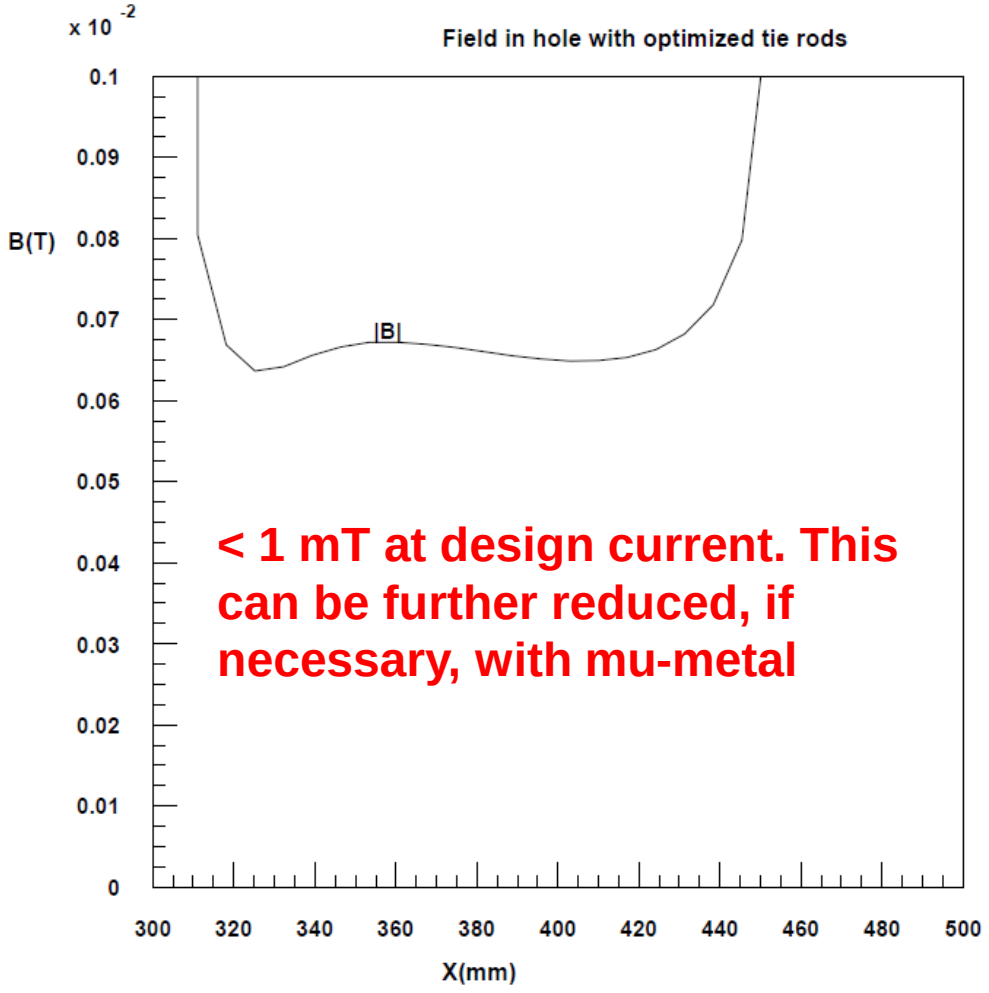




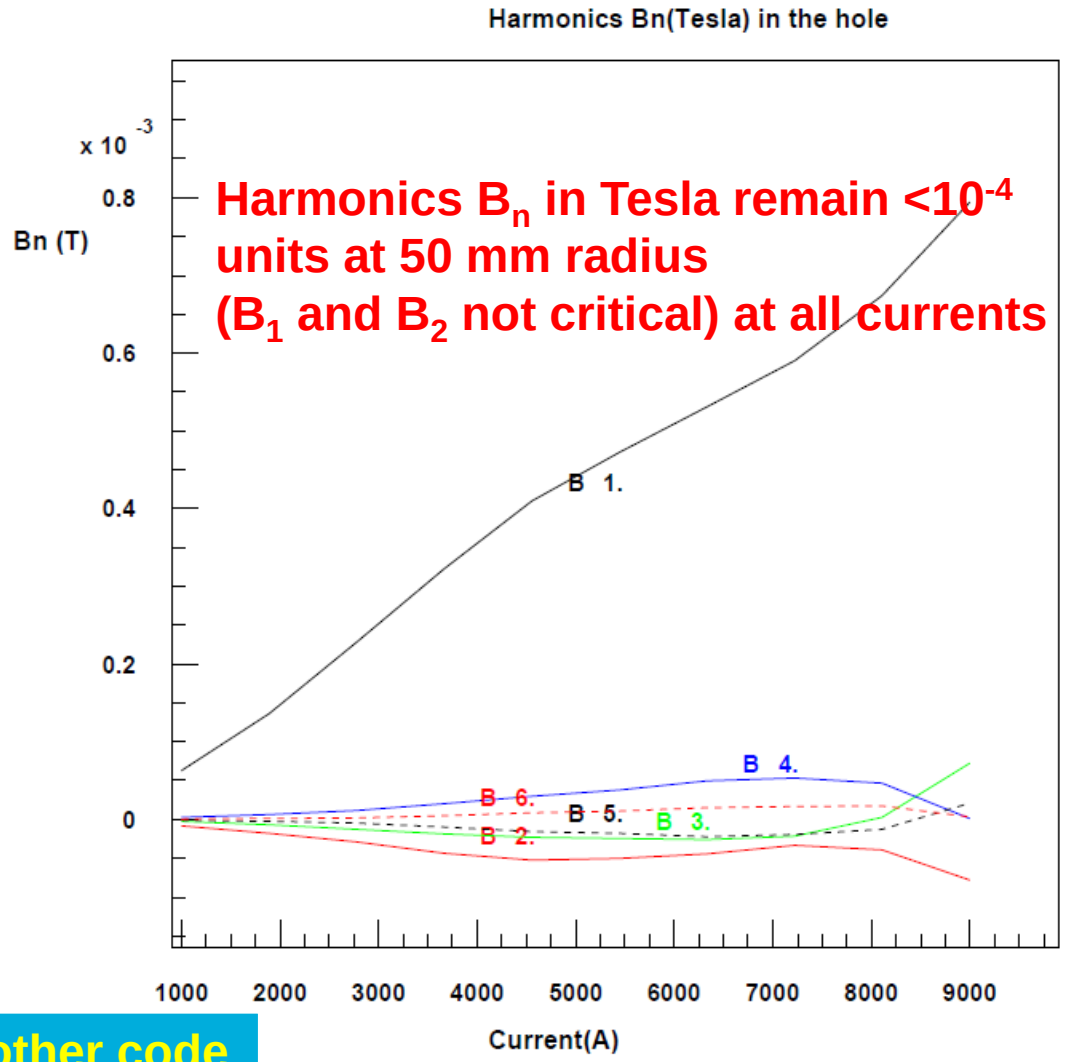


Non-allowed harmonics within computational errors

Field in the r=75 mm Hole (@379.2 mm) for e-beam (tie rod holes are used to reduce that)



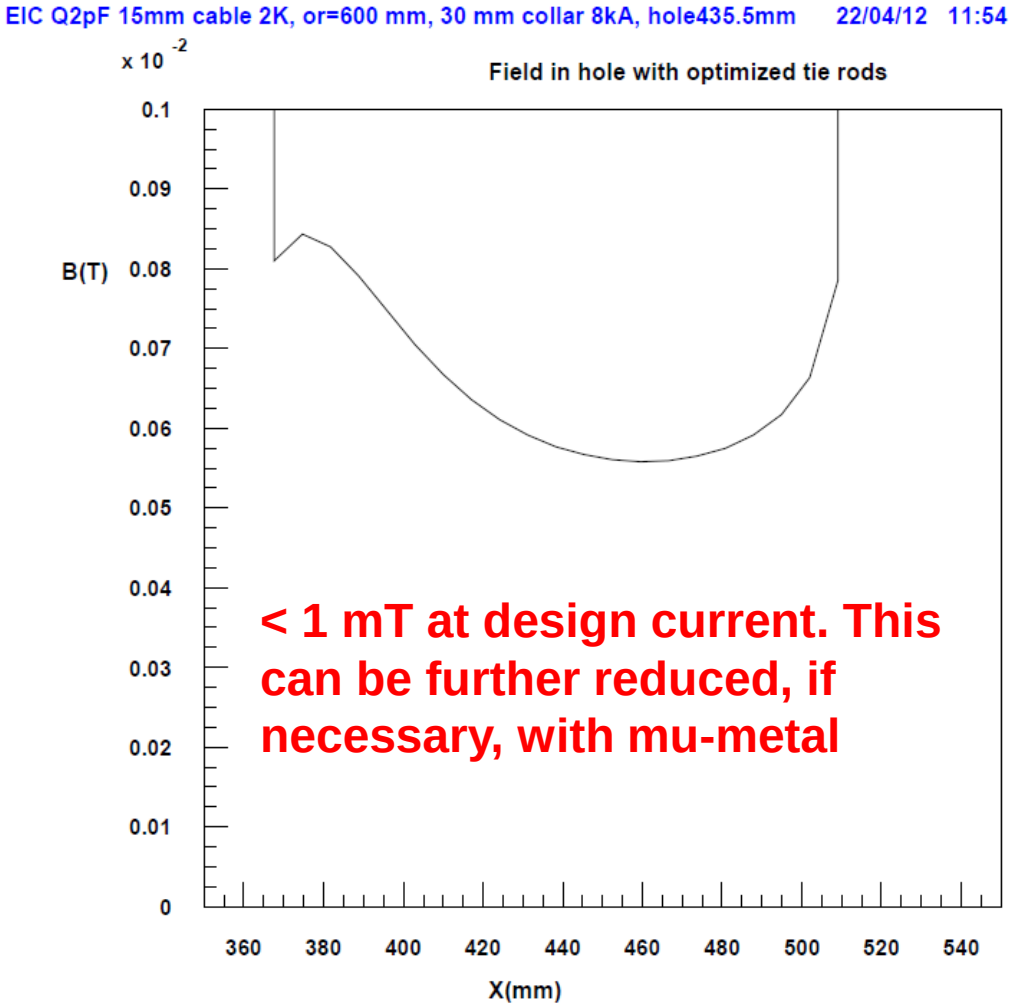
< 1 mT at design current. This can be further reduced, if necessary, with mu-metal



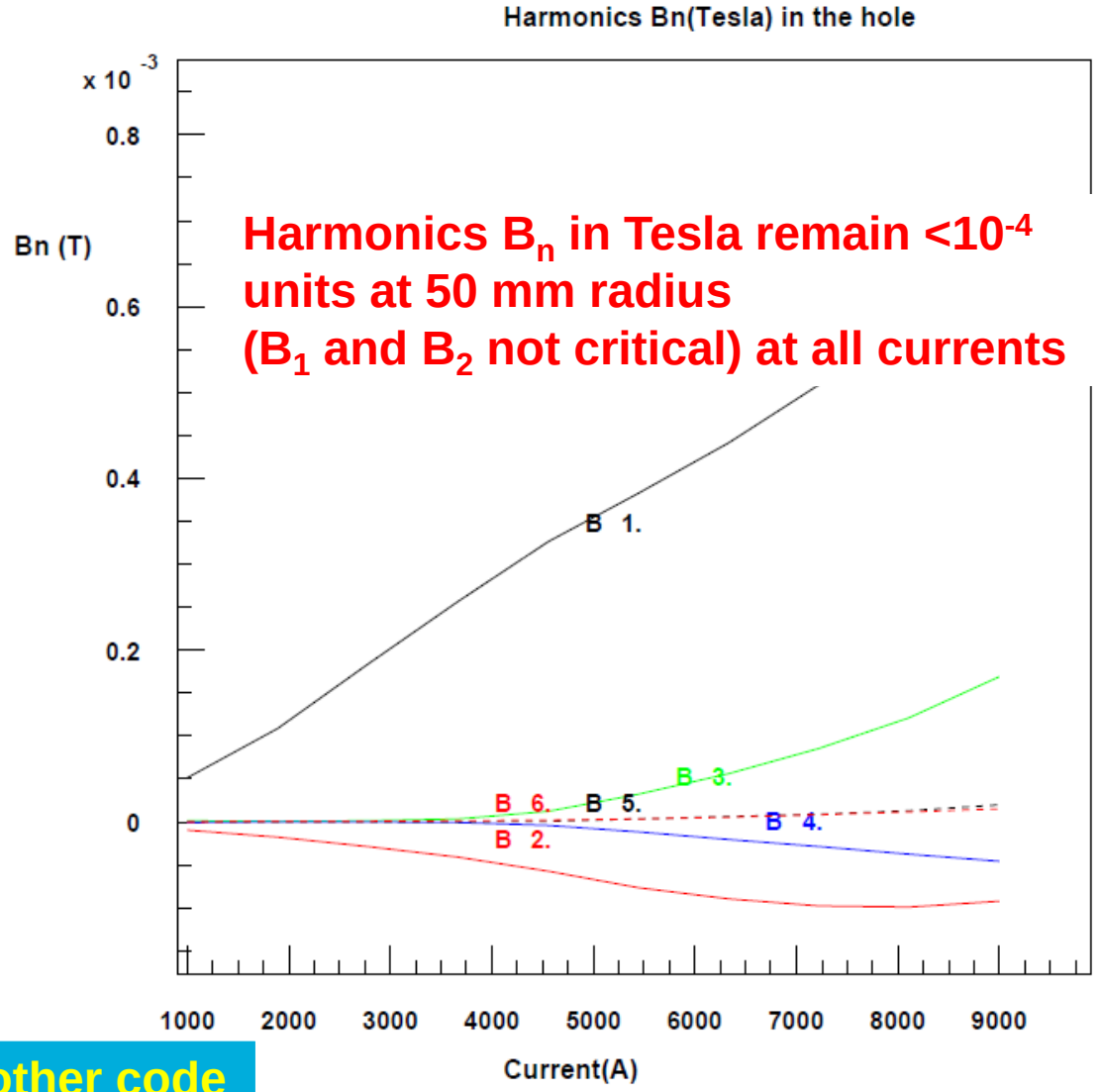
Harmonics B_n in Tesla remain $<10^{-4}$ units at 50 mm radius (B_1 and B_2 not critical) at all currents

Calculation should be checked with another code

Field in the r=75 mm Hole (@435.5 mm) for e-beam (tie rod holes are used to reduce that)



< 1 mT at design current. This can be further reduced, if necessary, with mu-metal



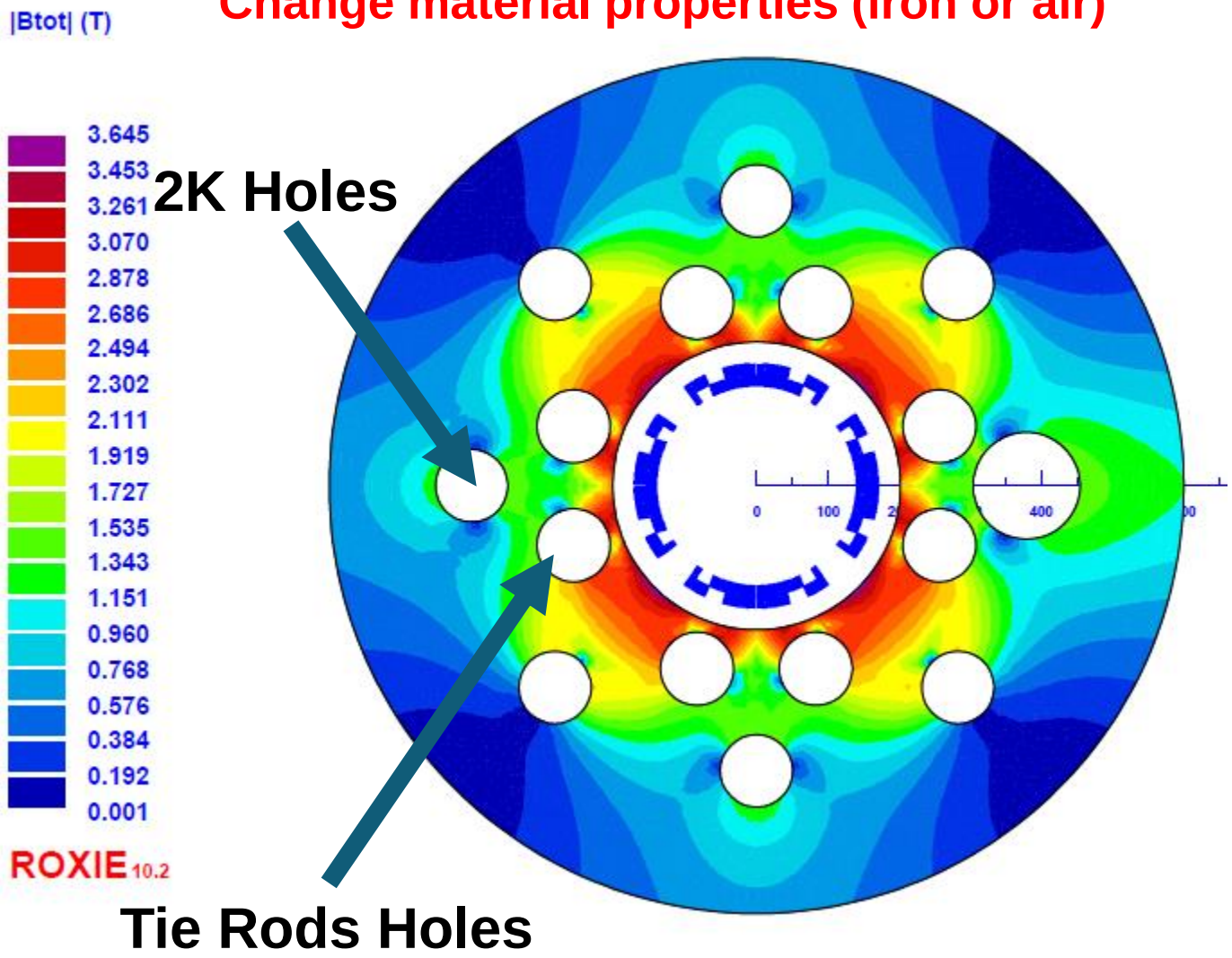
Harmonics B_n in Tesla remain $<10^{-4}$ units at 50 mm radius (B_1 and B_2 not critical) at all currents

Calculation should be checked with another code

Evaluating the Impact of Hole in Iron for 2K Plumping

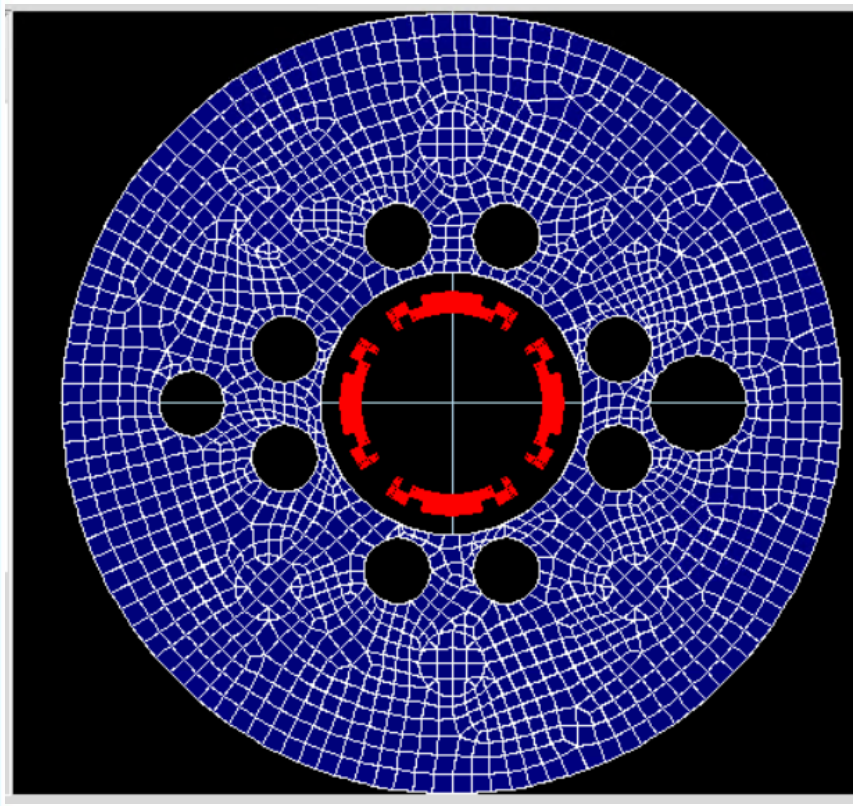
- More work is needed to determine the location and size
- To help ensure that it can be accommodated in the yoke, a magnetic design study is performed to find the impact of it for various possible locations.
- The impact on field quality (both for the proton beam and electron beam is computed.
- Hole size assumed: 4” diameter @r=400 mm. Need that big?

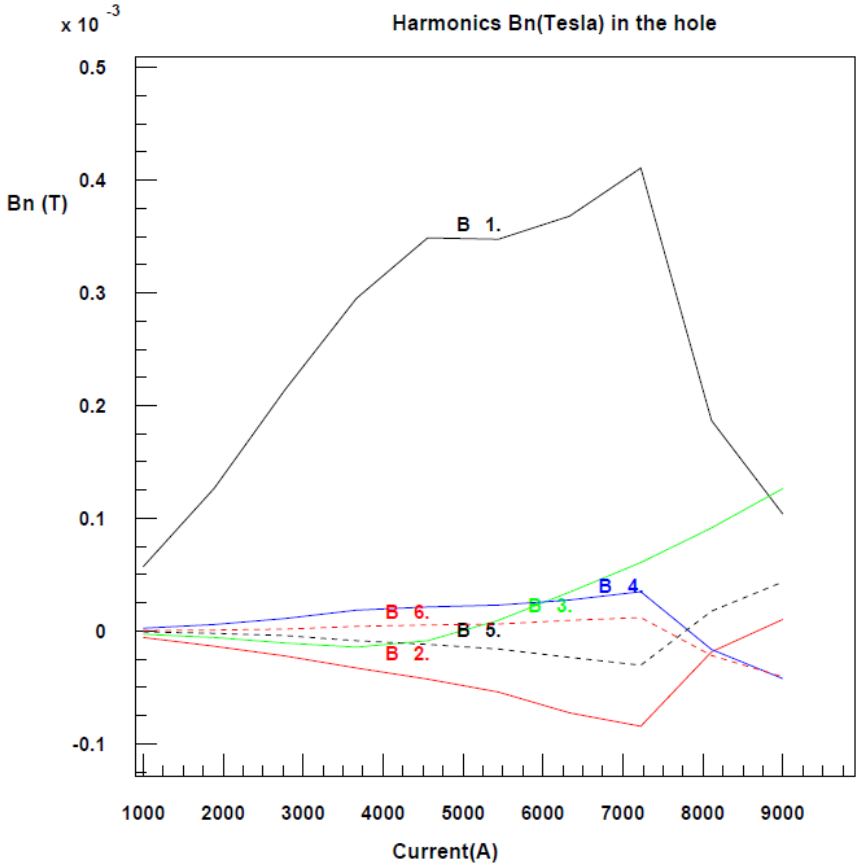
Swiss cheese model – all holes in the model
Change material properties (iron or air)

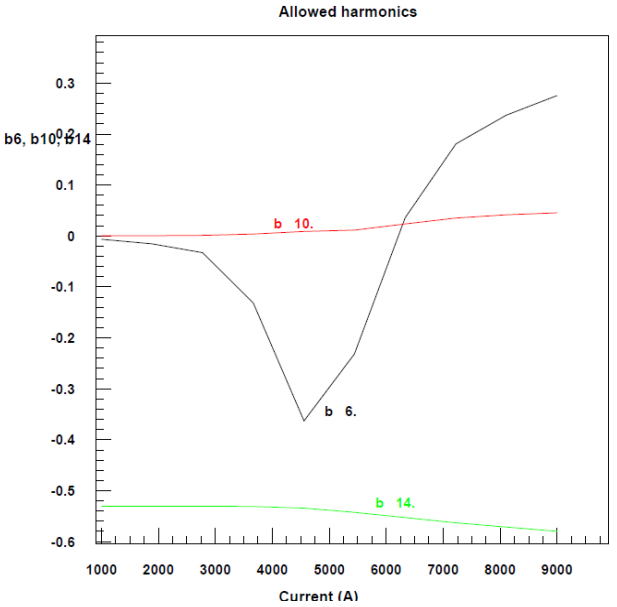


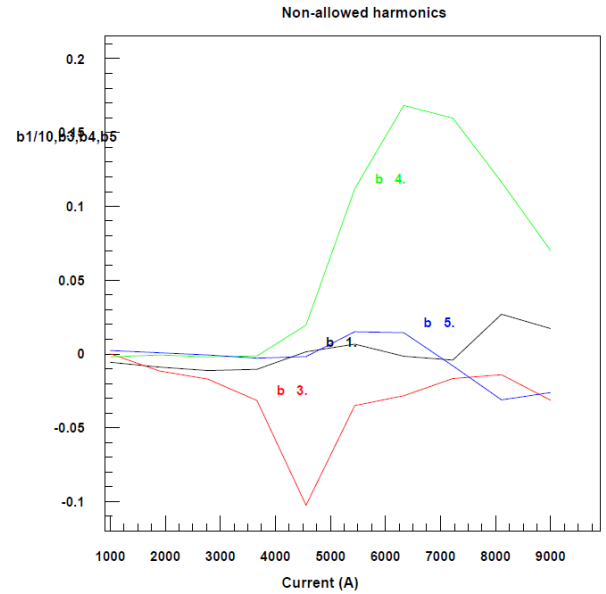
Impact of 4” diameter Hole in Iron @180°

- Harmonics (B_n) in electron hole remain < 10^{-4} T @50 mm
- Harmonics (bn) in main quad remain < 10^{-4} @83 mm





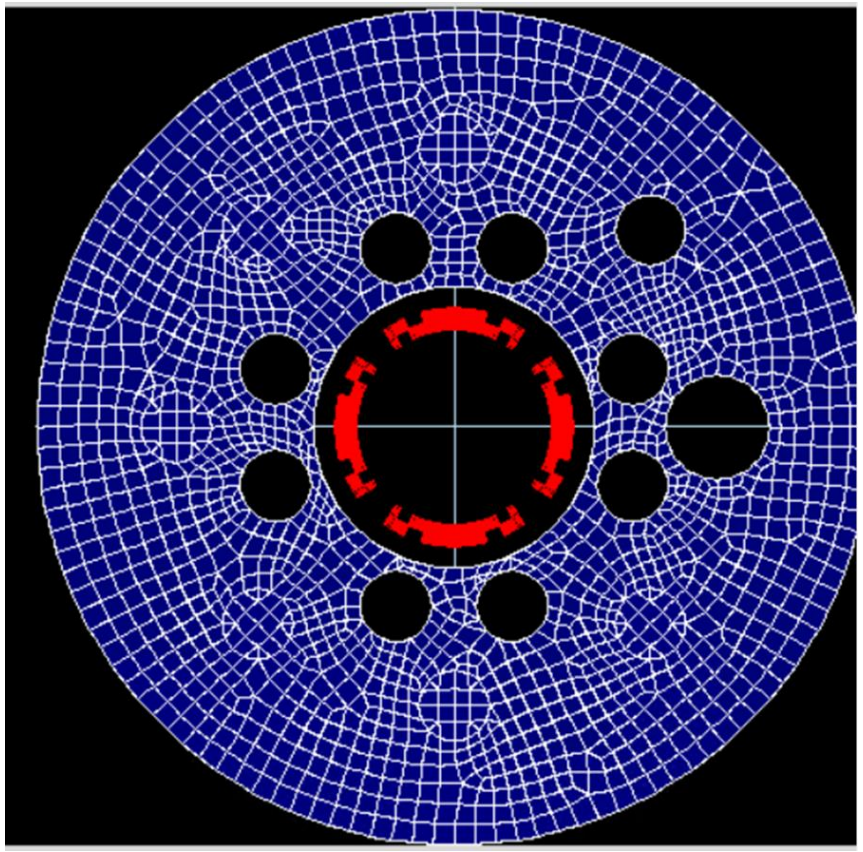


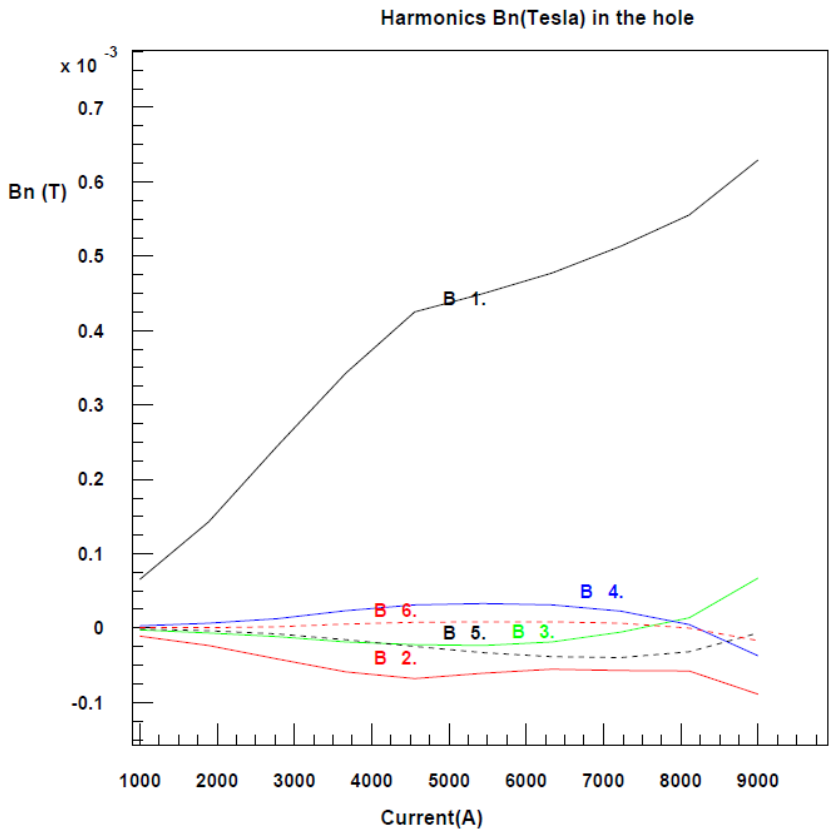


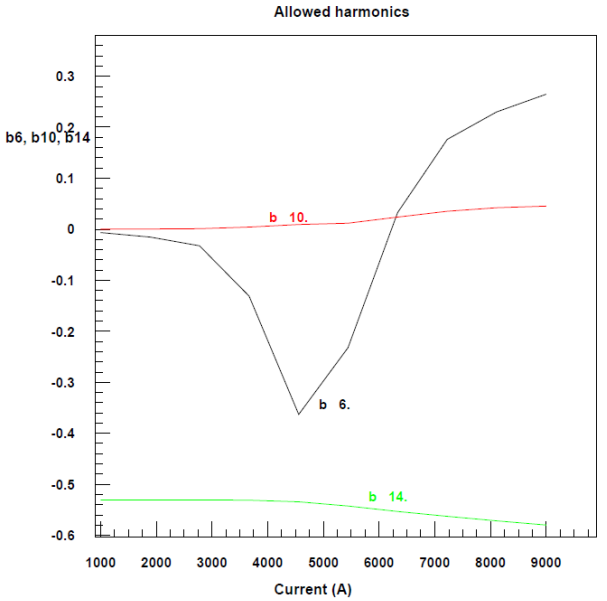
Harmonics of concern (B_3-B_6) < 10^{-4} T at 50 mm

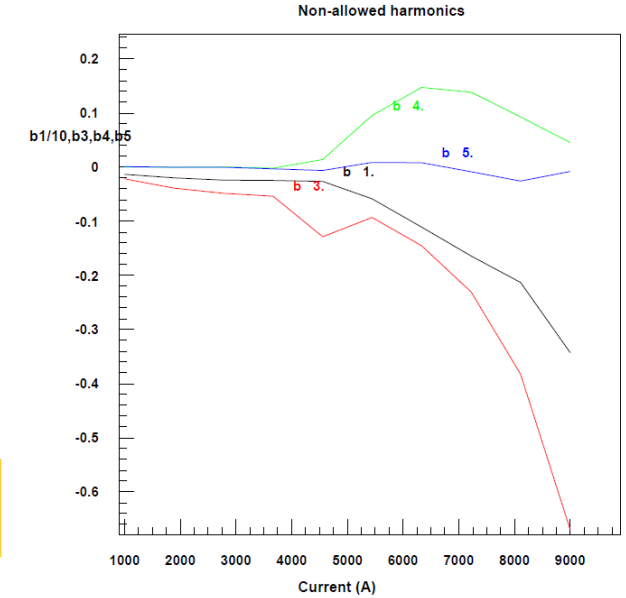
Impact of 4” diameter Hole in Iron @45º

- Harmonics (B_n) in electron hole remain < 10^{-4} T @50 mm
- Harmonics (bn) in main quad remain < 10^{-4} @83 mm





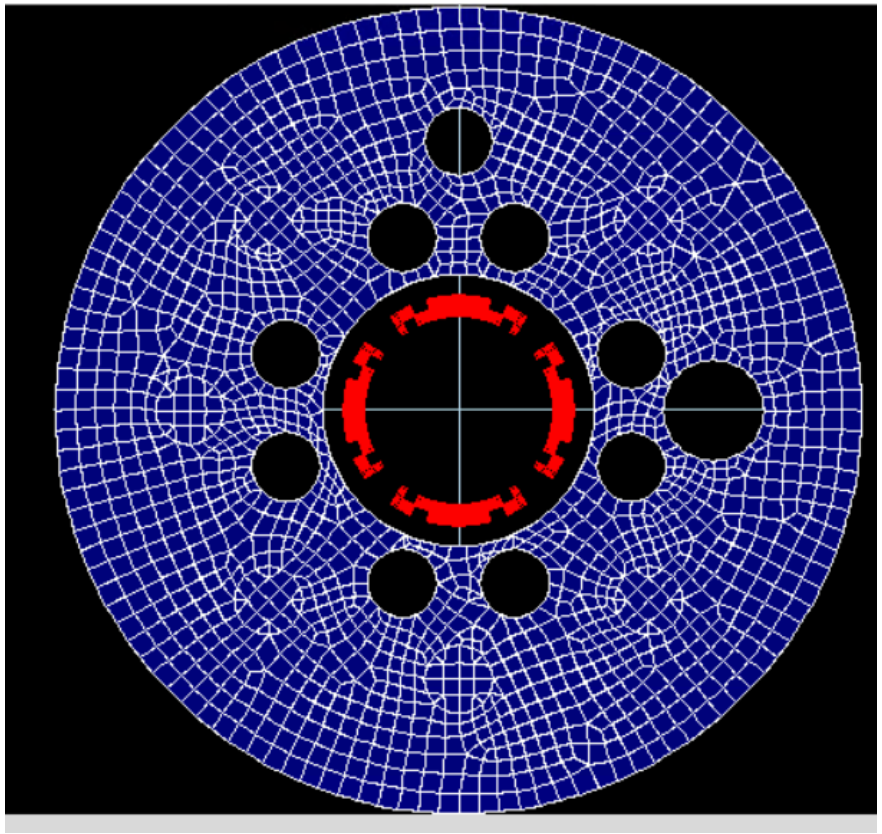


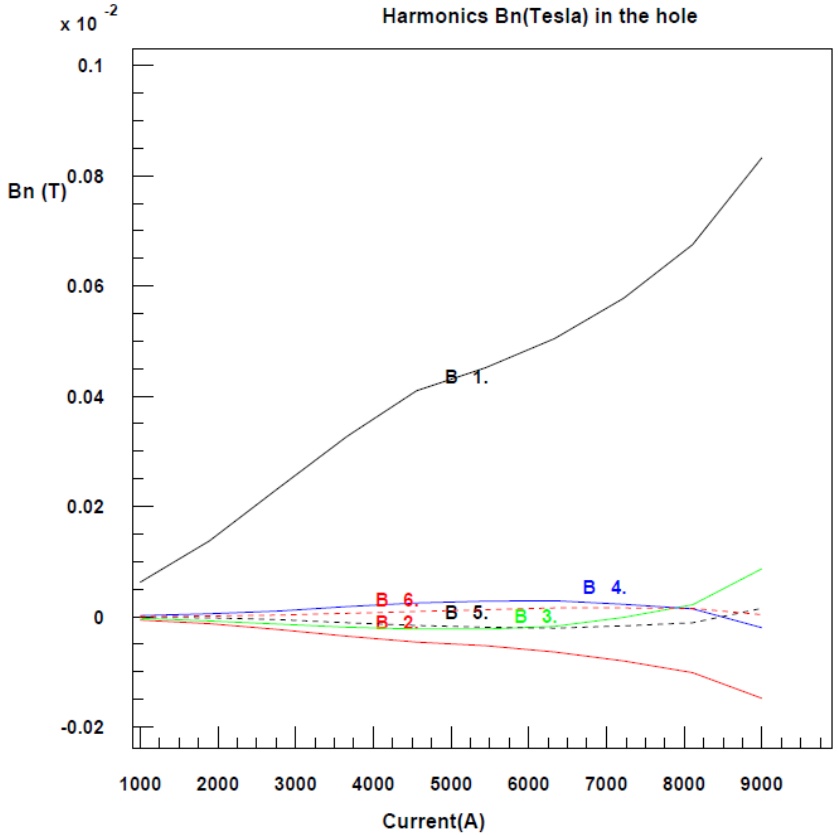


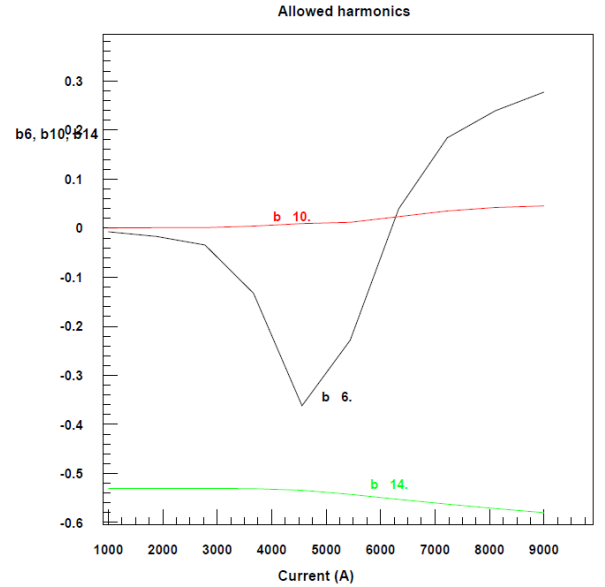
Harmonics of concern (B_3-B_6) < 10^{-4} T at 50 mm

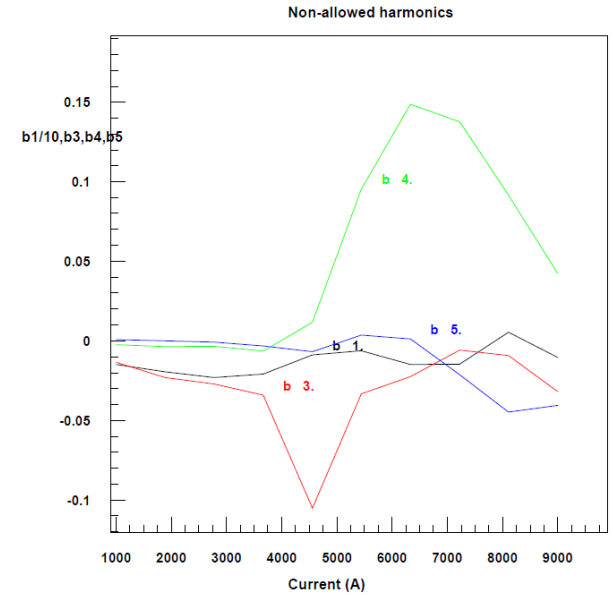
Impact of 4” diameter Hole in Iron @90º

- Harmonics (B_n) in electron hole remain < 10^{-4} T @50 mm
- Harmonics (bn) in main quad remain < 10^{-4} @83 mm





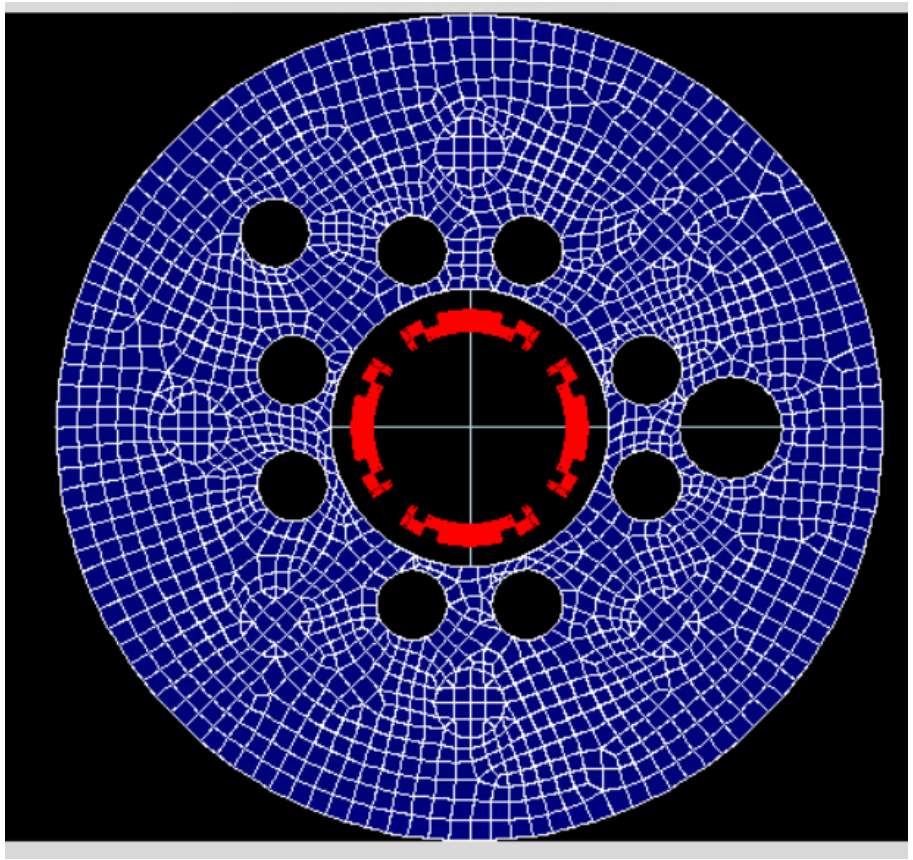


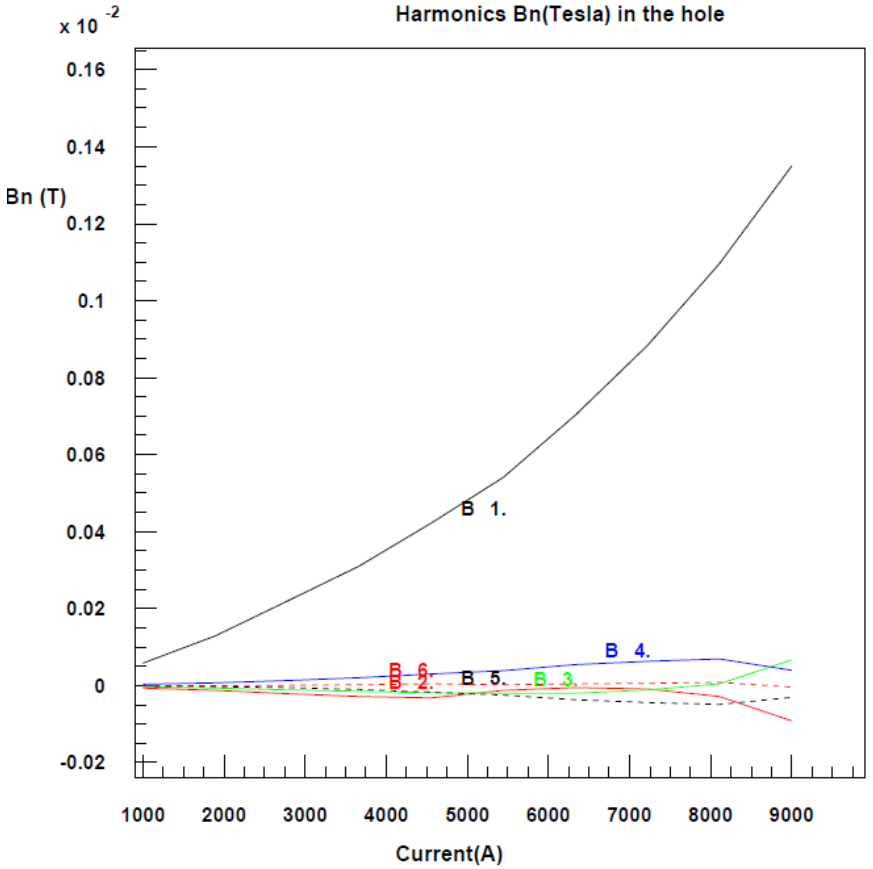


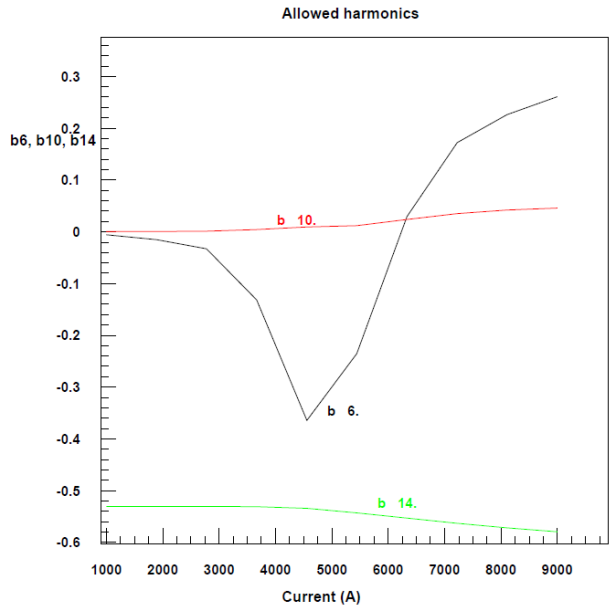
Harmonics of concern (B_3-B_6) < 10^{-4} T at 50 mm

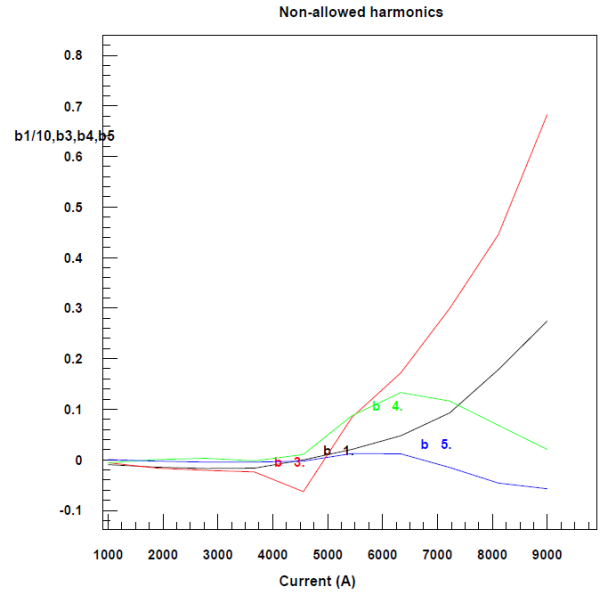
Impact of 4” diameter Hole in Iron @135°

- Harmonics (B_n) in electron hole remain < 10^{-4} T @50 mm
- Harmonics (bn) in main quad remain < 10^{-4} @83 mm







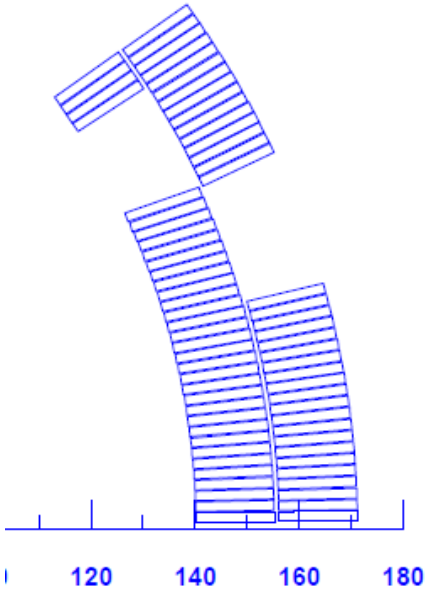


Harmonics of concern (B_3-B_6) < 10^{-4} T at 50 mm

Future Work

- Short term (within a week): Cross-check with other codes (COMSOL/OPERA) for low fields and low field harmonics in electron hole
- Medium term (with a few months, doesn't hold most other work): Internal details of yoke iron (holes for 2K helium, further optimization of field quality)
- Longer term (may not be needed): Coil cross-section iteration for dividing one big wedge in each layer to two for making them smaller and further reducing b_{14}

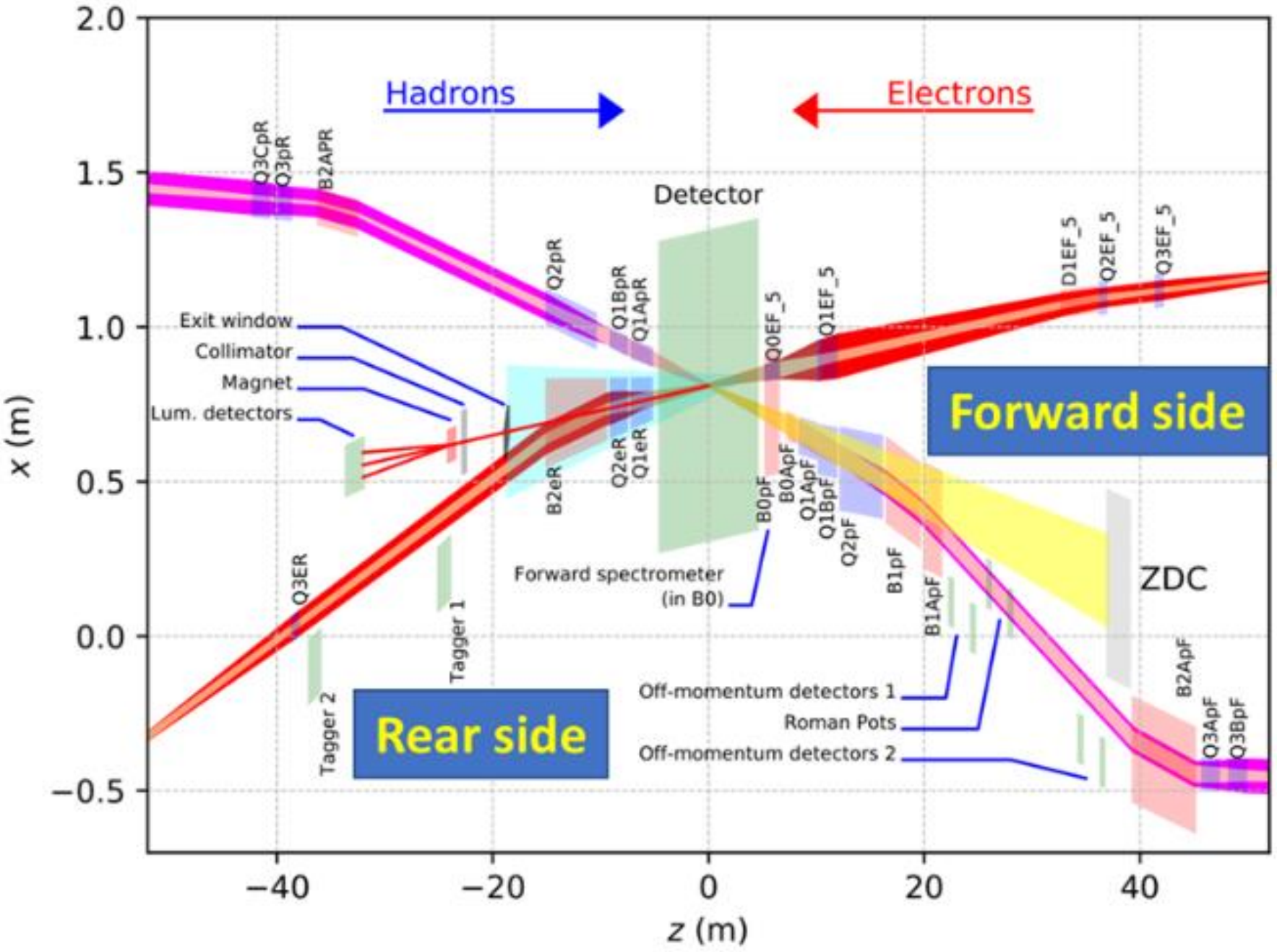
```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:      -0.13185   b 2:   10000.00000   b 3:      -0.00388
b 4:       0.01480   b 5:      -0.00085   b 6:      -0.00623
b 7:      -0.00045   b 8:       0.00019   b 9:       0.00008
b10:       0.00051   b11:       0.00000   b12:       0.00000
b13:       0.00000   b14:      -0.53040   b15:      -0.00000
b16:      -0.00000   b17:      -0.00000   b18:       0.01442
b19:       0.00000   b20:       0.00000   b
```



Summary and Conclusion

- Coil and overall cross-section of Q2pF has been sufficiently optimized and matured enough that the next phase of work can start
- Coil design seems to have good layout (wedges and poles)
- Allowable space for collar thickness increased to 30 mm
- Field quality in the main quad remains good (b_n <10^{-4} at r= 83 mm) for the entire operating range (low geometric and low saturation induced harmonics)
- Field errors (measured by B_n) in the electron holes remain low (B_n <10^{-4} at r=50 mm) for the entire operating range
- The flexibility in cross-section increased to allow wider adjustments from errors on parts and construction

Extra Slides


Hadrons
Electrons
Detector
Forward side
Rear side
ZDC
Exit window
Collimator
Magnet
Lum. detectors
Forward spectrometer
(in B0)
Off-momentum detectors 1
Roman Pots
Off-momentum detectors 2
Tagger 1
Tagger 2
Q3CpR
Q3pR
B2APR
Q2pR
Q1BpR
Q1ApR
Q0EF_5
Q1EF_5
D1EF_5
Q2EF_5
Q3EF_5
B2eR
Q2eR
Q1eR
Q3ER
B0pF
B0ApF
Q1ApF
Q1BpF
Q2pF
B1pF
B1ApF
B2ApF
Q3ApF
Q3BpF
x (m)
z (m)
2.0
1.5
1.0
0.5
0.0
−0.5
−40
−20
0
20
40

Basic Parameters of the current Q2BpF Design

Parameters from pCDR:

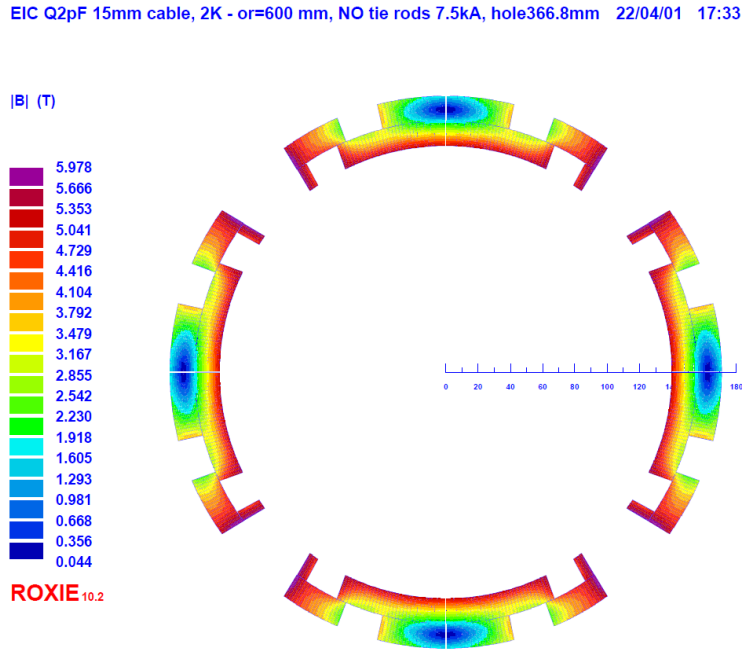
Table 6.6: Parameters Q2PF Magnet

Parameter	Value
Magnetic length [m]	3.8
Maximum gradient [T/m]	40.7
Aperture diameter (front) [m]	0.262
Aperture diameter (rear) [m]	0.262
Required field quality	1×10^{-4}
Physical length [m]	3.8
Physical width [m]	0.156
Physical height [m]	0.156
Superconductor type	NbTi
Conductor	Cable 20x2mm^2
Current density [A/mm^2]	512
Cu:Sc ratio	1.3
Temperature [K]	1.8
Peak field wire [T]	6.85
Magnetic energy [MJ]	3.0
Ampere turns [kA·t]	420
Number of turns	28
Current [A]	15000
Inductance [mH]	26.67
Margin loadline [%]	32

Parameters used in the current design:

- Gradient: 36 T/m (revised from pCDR, current 36.8 T/m)
- Physical Length: 3.8 m
- Coil inner radius: 140 mm
- Estimated effective length: 3.8 - 0.14 = ~3.66 m
- Estimated gradient in body: 36*3.8/3.66 = ~37.4 T/m
- Cable: 15 mm
  (LHC inner type)
- Cu/SC: 1.6
- Temperature: 2K

Design should be flexible to accommodate such changes



LHC Style Cable used in Quad & Dipole (based on full keystone for Q2pF and B1ApF)

EIC

LHC

Cable Geometry

No	Name	height	width_i	width_o	ns	transp.	degrd	Comment
1	EICLHCB	15.1	1.816	1.984	28	115	5	LHC IN KEYSTOE FOR EIC DIPOLE
1	EICLHCQ	15.1	1.79	2.01	28	115	5	LHC IN KEYSTONE FOR EICIR QUAD
1	EICLHC01	15.1	1.786	2.014	28	115	5	LHC CABLE KEYSTOR FOR EIC 4.2K
2	EIC3642	19.4	1.773	2.027	36	115	3	EIC 36 STRAND @4.2K
3	EIC3618	19.4	1.773	2.027	36	115	3	EIC 36 STRAND @1.8K
4	EIC3642A	19.4	1.788	2.012	36	115	3	EIC 36 STRAND @4.2K 2 Layers
5	CABLE01	15.1	1.736	2.064	28	115	5	MB INNER LAYER,STR01
6	CABLE02	15.1	1.362	1.598	36	100	5	MB OUTER LAYER,STR01
7	SINGLE	0.94	0.94	0.94	1	0	0	SINGLE STRAND
8	GSI1CAB	9.74	1.061	1.271	30	74	0	GSI001 (RHIC) CABLE
9	GSI001	9.73	1.111	1.321	30	74	0	GSI001 following Wanderer
10	20MMCABLE	20	1.736	2.172	37	0	0	20mm cable
11	20MMCBNOK	20	13.8	13.8	280	0	0	7x20mm cable, no keystone
12	20MMCAB2	20	1.8	2	37	0	0	20 mm cable 2

EIC

LHC

Cable Definition

No	Name	Cable Geom.	Strand	Filament	Insul	Trans	Quench Mat.	T_o	Comment
1	EICLHCB2K	EICLHCB	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR QUAD @2K
2	EICLHCQ2K	EICLHCQ	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR DIPOLE @
3	LHCIN42K	EICLHC01	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	4.2	LHC INNER FOR EIC @4.2K
4	YELLONIN	CABLE01	STR01	NBTII	ALLPOLYIL	TRANS1	NONE	1.9	V6-1 DESIGN DIPOLE INNER
5	YELLONOU	CABLE02	STR02	NBTIO	ALLPOLYOL	TRANS1	NONE	1.9	V6-1 DESIGN DIPOLE OUTER

Keystone angle for cable width << coil readius

	Q2pF	B1ApF
Cable height	15.1	15.1
Cable mid-thickness	1.9	1.9
Insul (one side)	0.12	0.12
Coil i.r.	140	185
Avg Rad	147.55	192.55
dt	0.2190	0.1678
Width_i	1.790	1.816
width_o	2.010	1.984

Note: Keystones are reduced for EIC

Cables considered for EIC: “EICLHCB2K” and “EICLHCQ2K” (EICLHCB and EICLHCQ)
Similar to LHC inner: “YELLONIN” (CABLE01)