Q2pF Cross-section for 2K Operation

Ramesh Gupta

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Brookhaven National Laboratory
U.S. Department of Energy

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

- Cross-section designed for the desired mechanical layout of turns and for some possible future adjustments in field harmonics (as per the discussion last week).
- Thickness for collar (yoke i.d.) as per the guidance from the mechanical analysis.
- Saturation-induced harmonics examined as a function of current for the entire range of EIC operation (41 GeV to 275 GeV – a factor of 6.7).
- Impact of large holes for “tie rods” near the yoke inner surface examined.
- Field in the hole for electron beam examined (magnitude and the harmonic analysis of the field inside to better examine impact of the field on beam dynamics).
- Required thickness for yoke evaluated for choosing yoke outer radius.

Basic Parameters of the current Q2BpF Design

Parameters from pCDR:

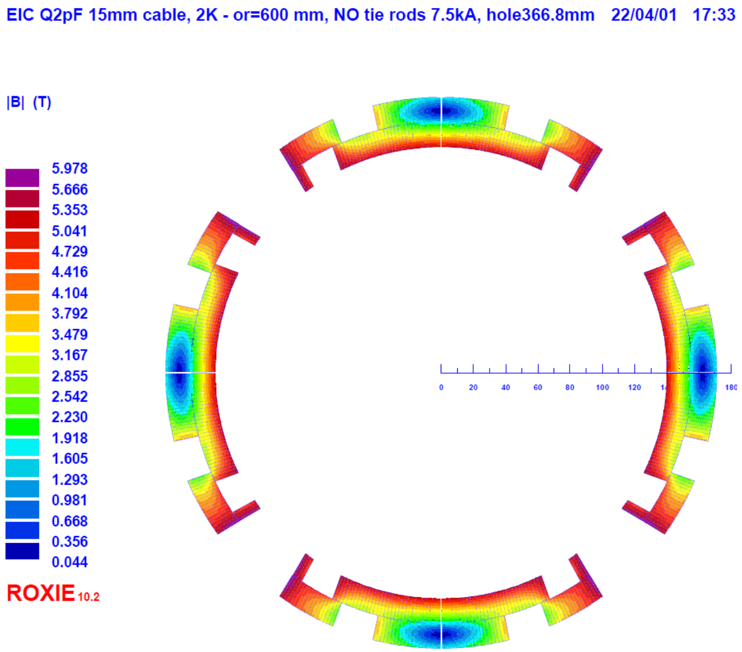
Table 6.6: Parameters Q2PF Magnet

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:

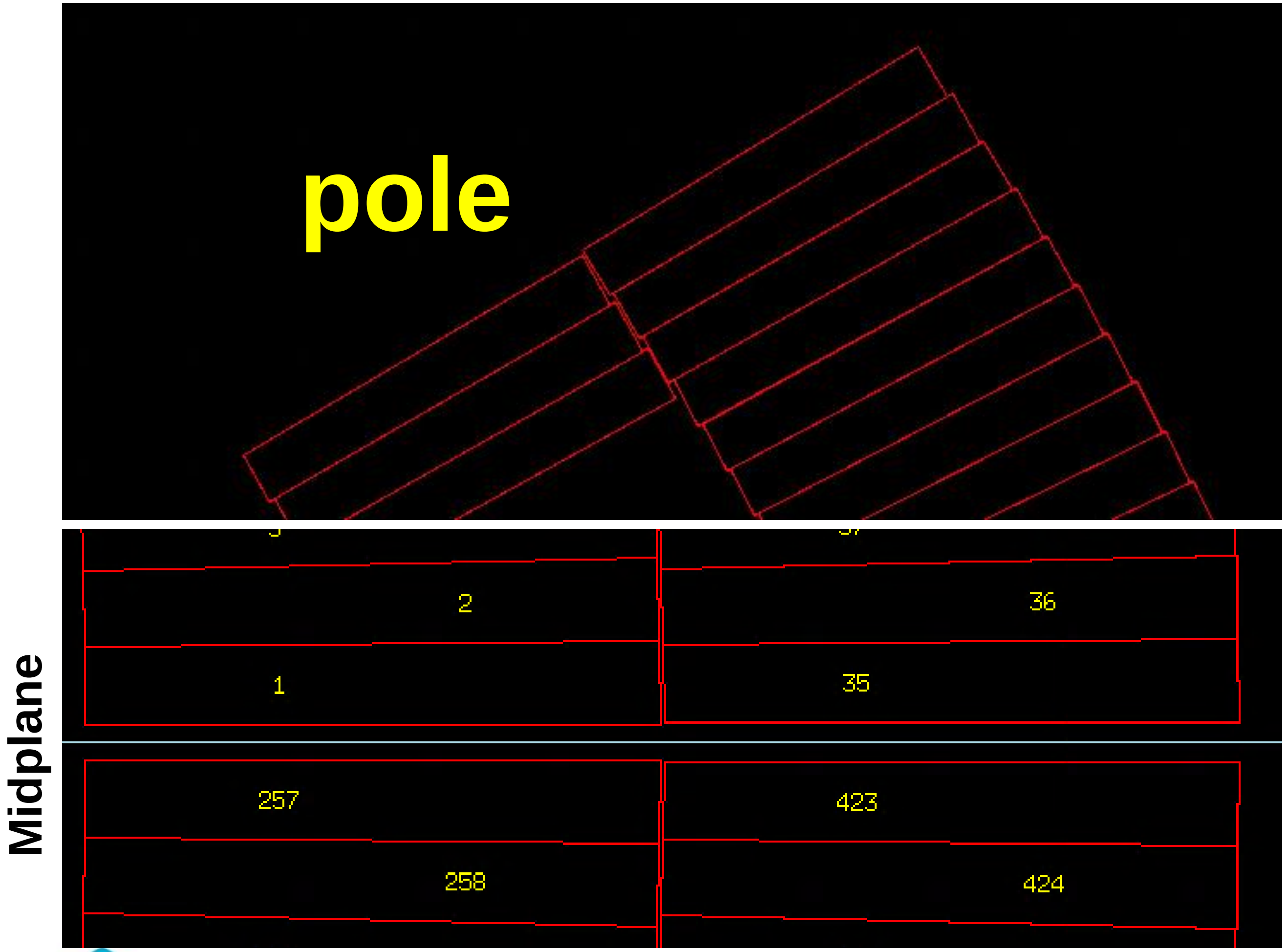
- Gradient: 36 T/m (revised from pCDR, current 36.8 T/m)
- Physical Length: 3.8 m
- Coil inner radius: 140 mm
- Estimated effective length: 3.8 - 0.14 = ~3.66 m
- Estimated gradient in body: 36*3.8/3.66 = ~37.4 T/m
- Cable: 15 mm
  (LHC inner type)
- Cu/SC: 1.6
- Temperature: 2K

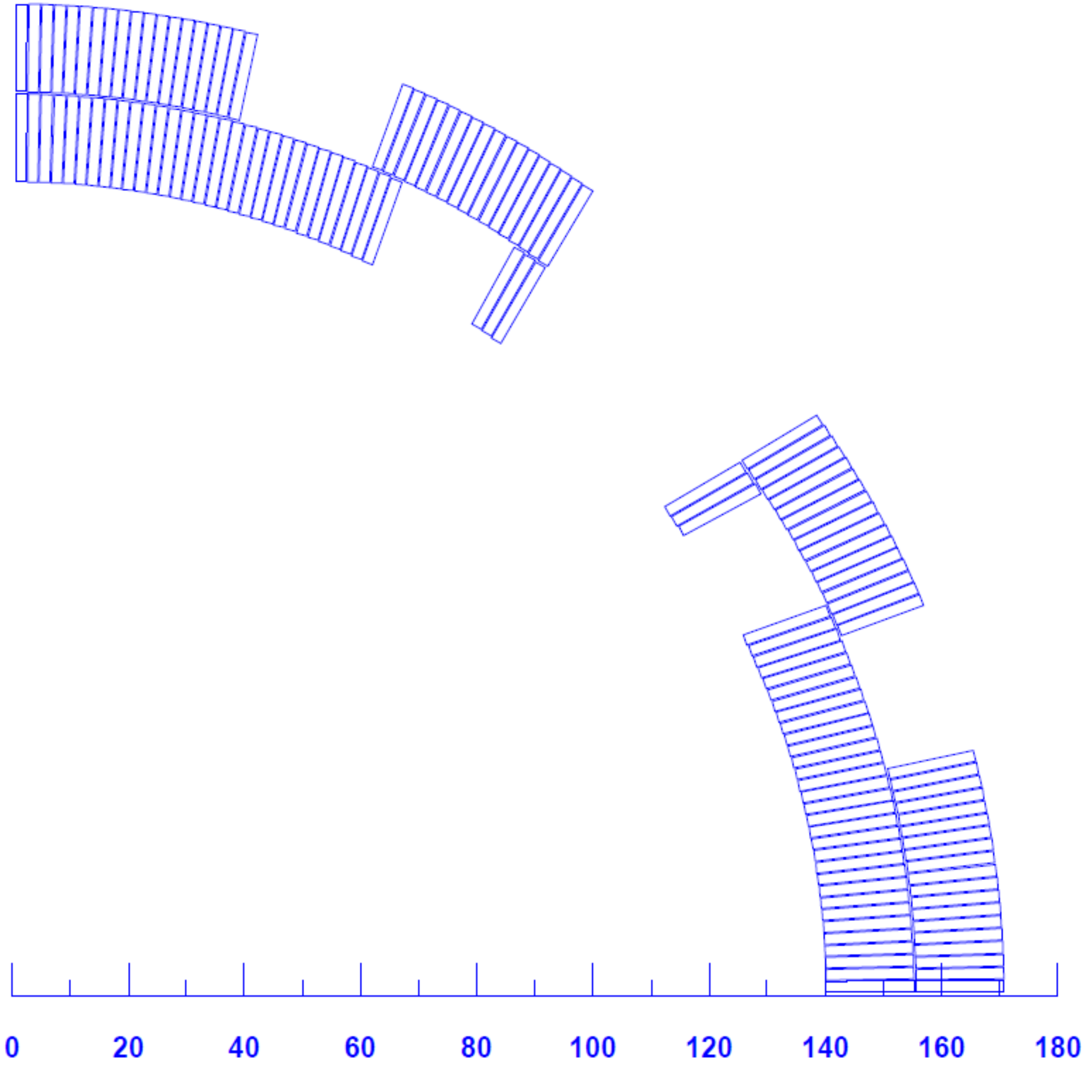
Design should be flexible to accommodate such changes



Optimization of Coil Geometry (pictorial)

- Angle for poles for collars, two aligned layers, wedges, gap at midplane





Optimization of Coil Geometry – ROXIE Input

Input to coil geometry

Xroxie [/home/gupta/EIC/Q2pF/2022/eic-Q2pF-600-7_7kA-NO-tie1

File Edit Display Run

Comment : EIC Q2pF 15mm cable, 2K - or=600 mm, NO tie rods 7.5kA, hole@366.8mm

Main Options

- 3D geometry (LEND)
- Endspacers (LWEDG)
- Time transient (LPE
- Quench simulation (LQUENCH)
- Optimization (LALGO)

Cable data path : /home/gupta/EIC/Q2pF/2022/roxie-eic.cadata Browse View file

2D Options

Block Data 2D

No	Type	NCab	X	Y	α	Current	Cable name	N1	N2	Im
1	Cos	31	140	0.2	0	-7717	EICLHCB2K	2	20	0
2	Cos	3	140	31.179	25.196	-7717	EICLHCB2K	2	20	0
3	Cos	19	155.5	0.2	0	-7717	EICLHCB2K	2	20	0
4	Cos	17	155.5	17	30	-7717	EICLHCB2K	2	20	0

Midplane half-gap = 0.2 mm (both layers)

Optimization algorithm : 1 Extrem

No	Xl	Xu	Xs	String	Act	N/a
1	3	9	8.0509	PHIR	2	2
2	25	33	28.6602	ALPHA	2	2
3	6	10	8.8426	PHIR	2	4
4	18	28	20.2614	ALPHA	2	4

Edit Cable Data [/home/gupta/EIC/Q2pF/2022/roxie-eic.cadata]

File Display

Insulation

No	Name	Radial	Azimut	Comment
1	BARE	0	0	BARE
2	ALLPOLYIL	0.15	0.12	POLYIMID MB INNER
3	ALLPOLYOL	0.15	0.13	POLYIMID MB OUTER
4	ALLPOLMQY	0.08	0.08	POLYIMID MQY,MQM
5	ALLPOLMQ	0.13	0.11	POLYIMID MQ

Cable parameters

Jc-Fit

Filament

Strand

No	Name	diam.	cu/sc	RRR	Tref	Bref	Jc@BrTr	dJc/dB	Comment
1	STREIC1	1.065	1.6	70	1.9	10	1591	500.34	EIC BRUKER-CERN SCALED.7%DEG
2	STR01	1.065	1.6	70	1.9	10	1433.3	500.34	MB INNER
3	STR02	0.825	1.9	80	1.9	9	1953	550.03	MB OUTER, MQ
4	WIRE3	0.93683	1.6	70	4.222	5	2640	606.8	MCS,MCD,MQT?
5	GSI1STRA	0.648	2.21	187	4.2	5.5	2495.24	583.898	GSI001 (RHIC) STRANDS

Transient

Quench Material Properties

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

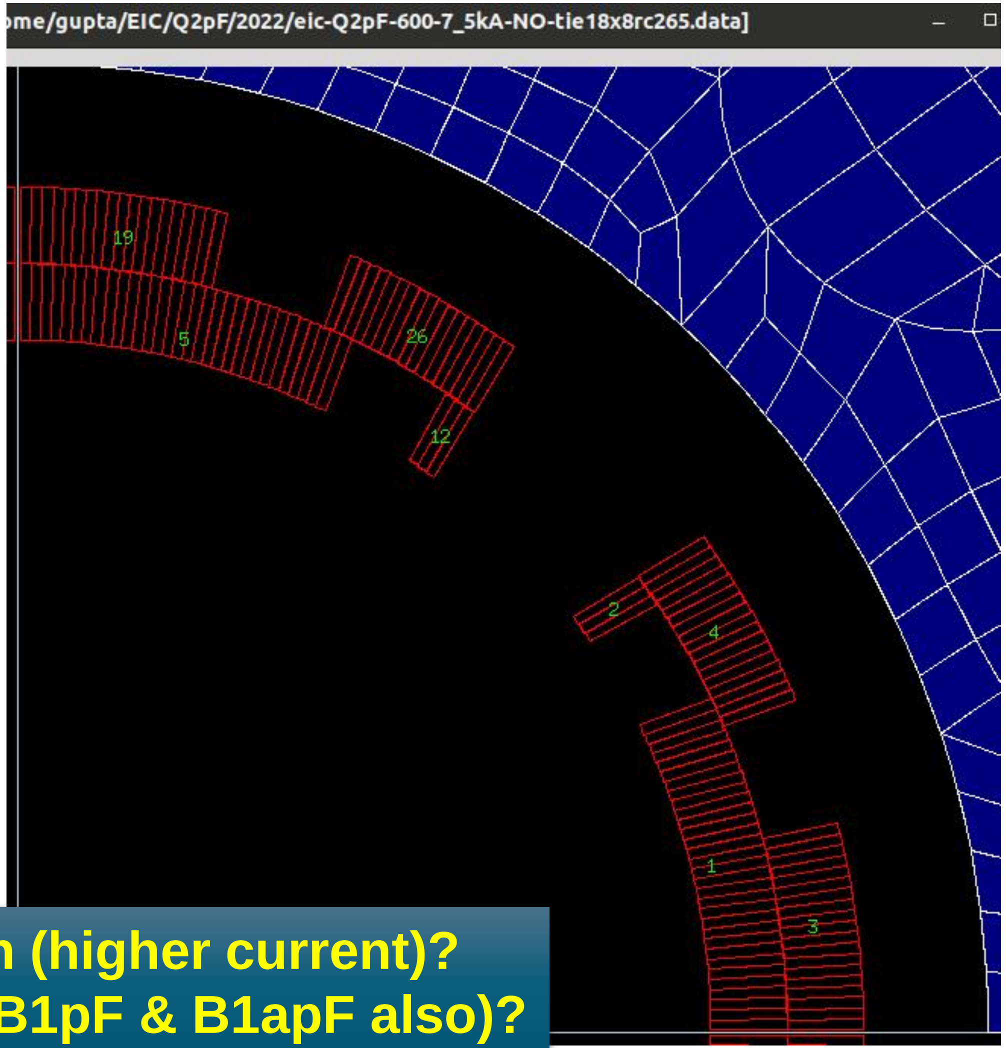
Cable Definition

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 @2
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

Quench Margin in the Current X-section of the Q2pF at 2 K (desired collar size, no tie rods)

MAIN FIELD (T)	3.104739
MAGNET STRENGTH (T/(m^(n-1))	37.4065

BLOCK NUMBER	29
PEAK FIELD IN CONDUCTOR 509 (T)	6.1311
CURRENT IN CONDUCTOR 509 (A)	-7717.0000
LOWEST FIELD IN CONDUCTOR 493 (T)	2.4084
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) .	-804.4049
COPPER CURRENT DENSITY (A/MM2)	-502.7531
PERCENTAGE ON THE LOAD LINE	58.6477
QUENCHFIELD (T)	10.4541
TEMPERATURE MARGIN TO QUENCH (K)	3.6548
PERCENTAGE OF SHORT SAMPLE CURRENT	20.7445



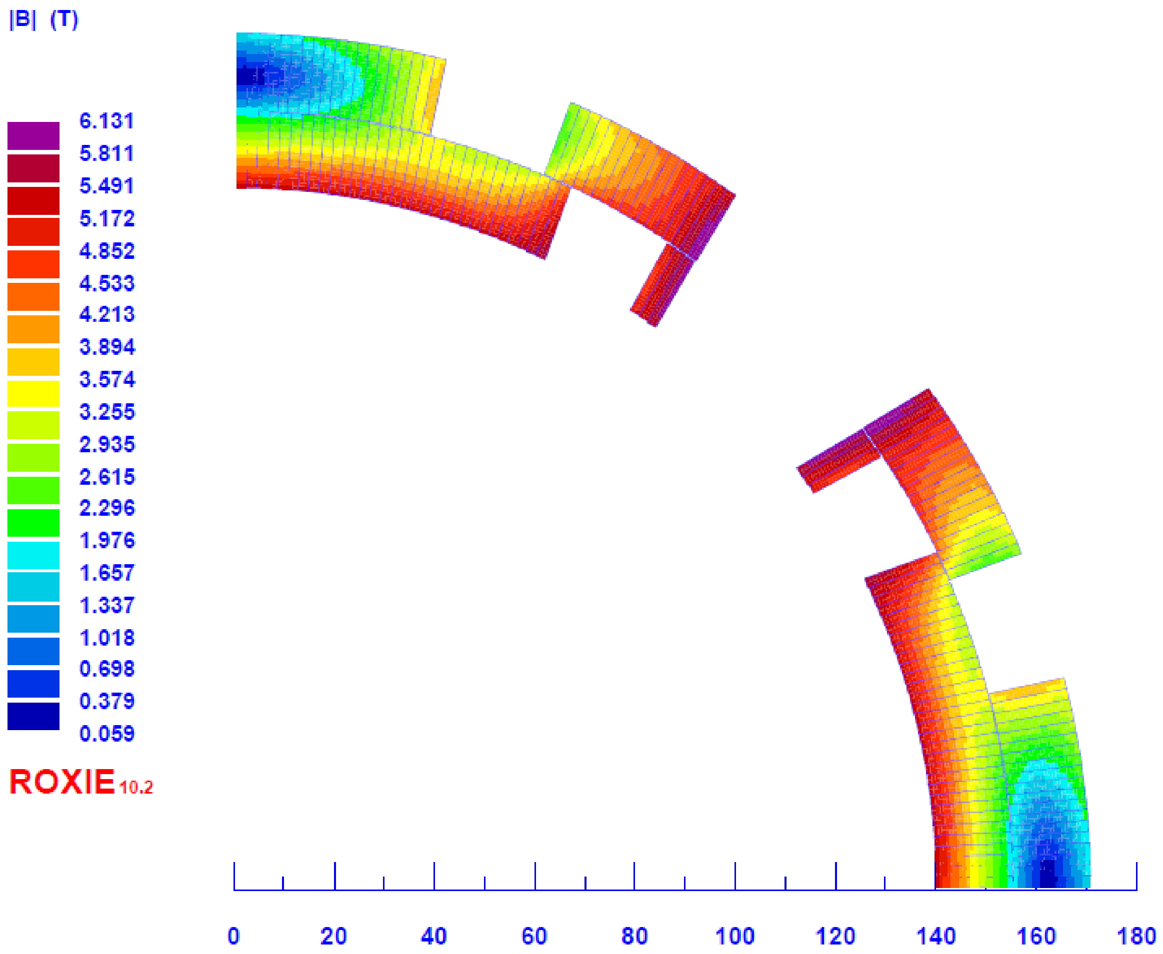
- Operational margin = 100/58.6 = ~70% (healthy margin)

Consider a single layer design (higher current)?
Or a narrower cable (same in B1pF & B1apF also)?

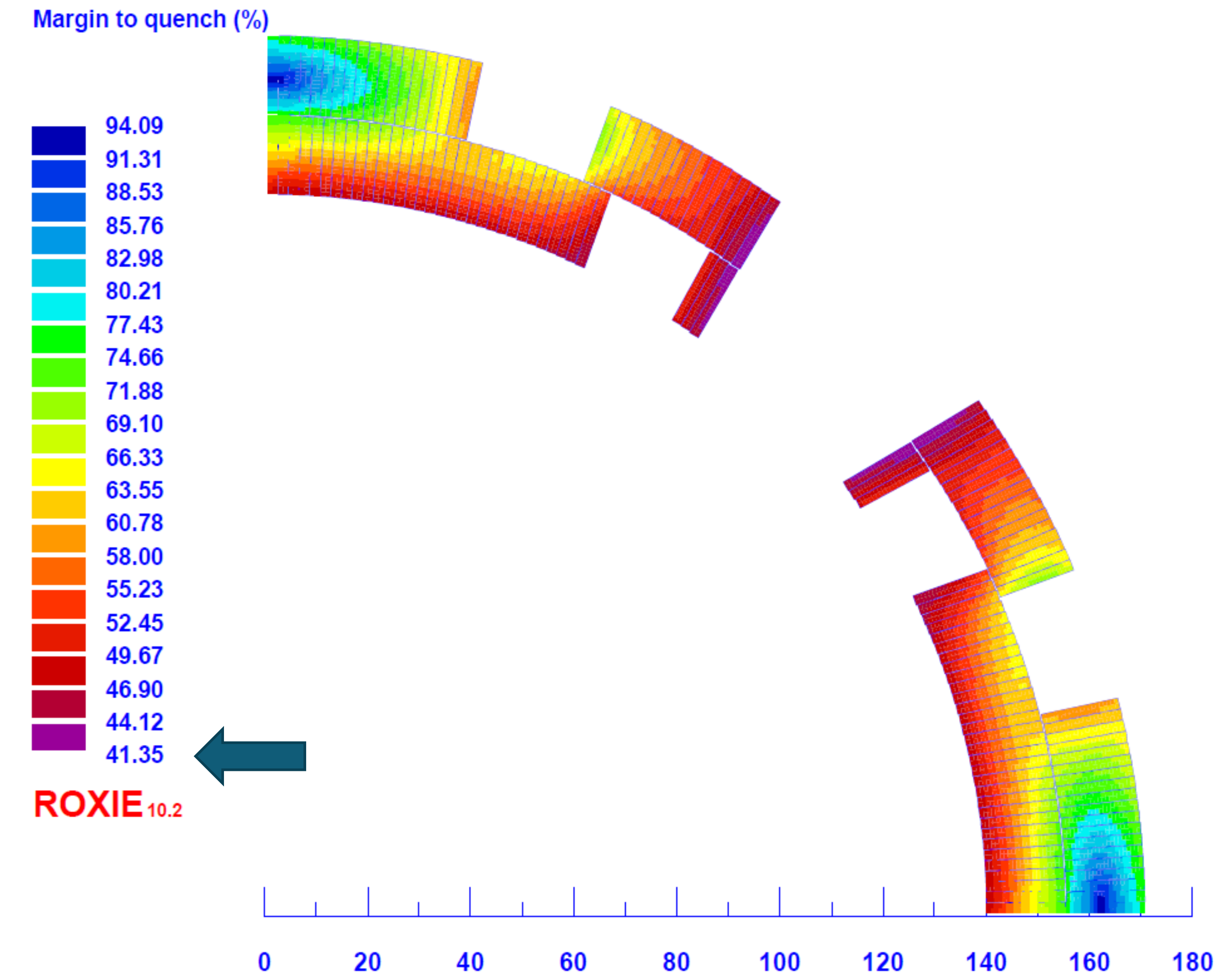
Quench Margin in the Current X-section of the Q2pF at 2 K (desired collar size, no tie rods)

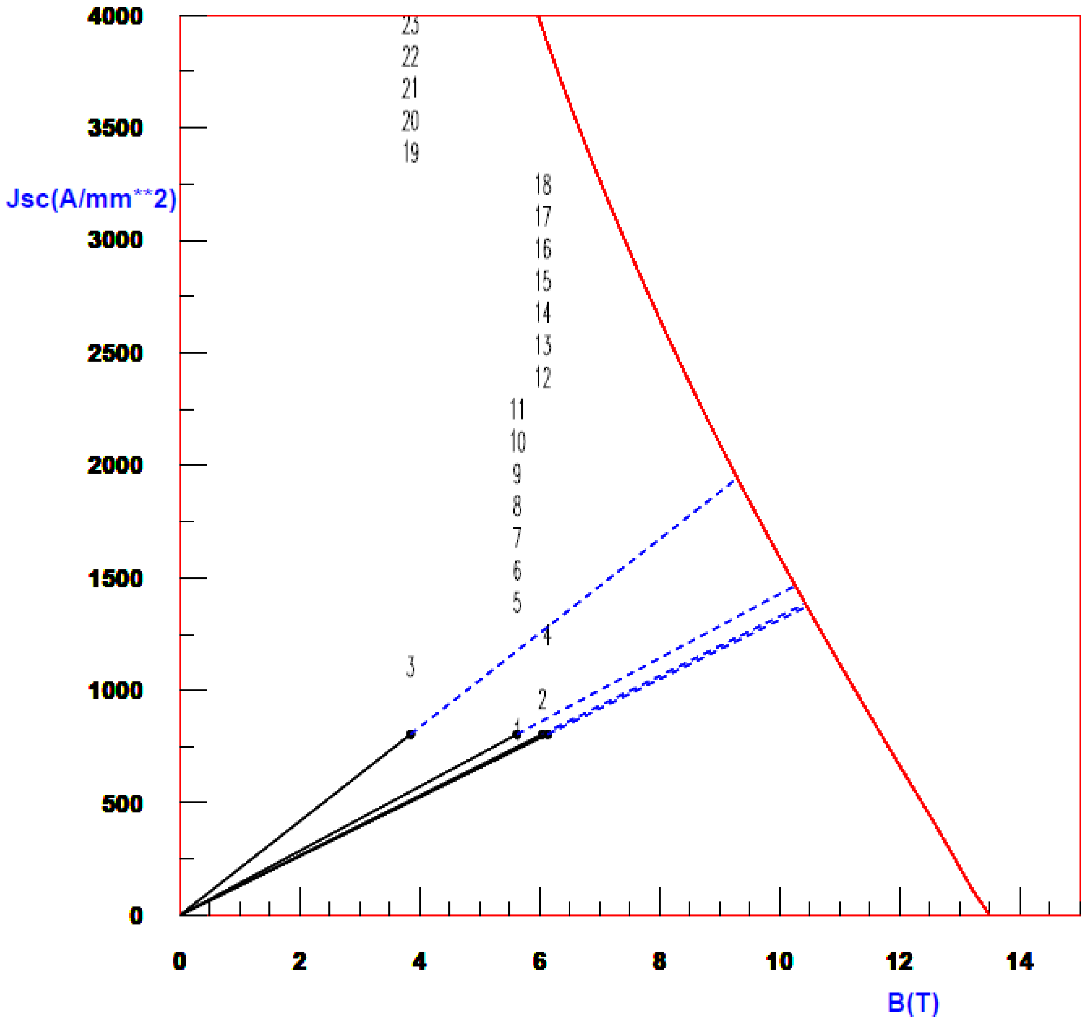
<u>**Peak Field Enhancement**</u>

- Field gradient = 37.4 T/m
- Coil Radius = 140 mm
- Computed midplane field at coil radius = 140 * 37.4 = 5.236 T
- Peak field enhancement = 6.131/5.236 = 17.1%



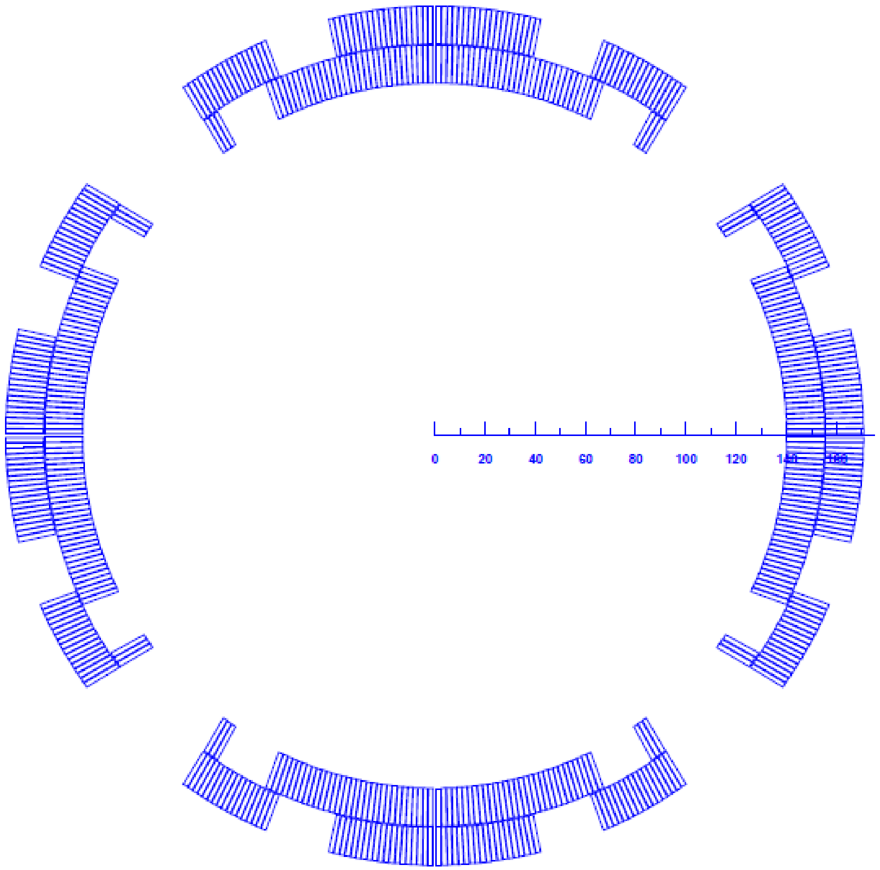
Quench Margin in the Current X-section of the Q2pF at 2 K (desired collar size, no tie rods)





Field Quality (Geometric Harmonics @1kA)

<u>GOAL</u>: Obtain low field harmonics in a geometry which is good mechanically (as per previous slides) at a field where persistent current induced or saturation induced harmonics are small (1kA)



7_7kA-NO-tie18x8rc265.output | Q2pF-28mar-a1cur1kA-1kA.output

```
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 ...................      0.5091E-05
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ......................................        0.422951
MAGNET STRENGTH (T/(m^(n-1)) .......................           5.0958

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.12739  b 2:  10000.00000  b 3:      0.02750
b 4:      0.00959  b 5:      0.00095  b 6:      0.08276
b 7:     -0.00197  b 8:     -0.00058  b 9:     -0.00024
b10:     -0.20165  b11:      0.00001  b12:      0.00001
b13:     -0.00000  b14:     -0.16068  b15:     -0.00000
b16:     -0.00000  b17:     -0.00000  b18:      0.02900
b19:      0.00000  b20:      0.00000  b
```

➢ **All geometric harmonics are small**

Saturation-induced Harmonics

(examine the impact of non-liner properties of iron at high fields)

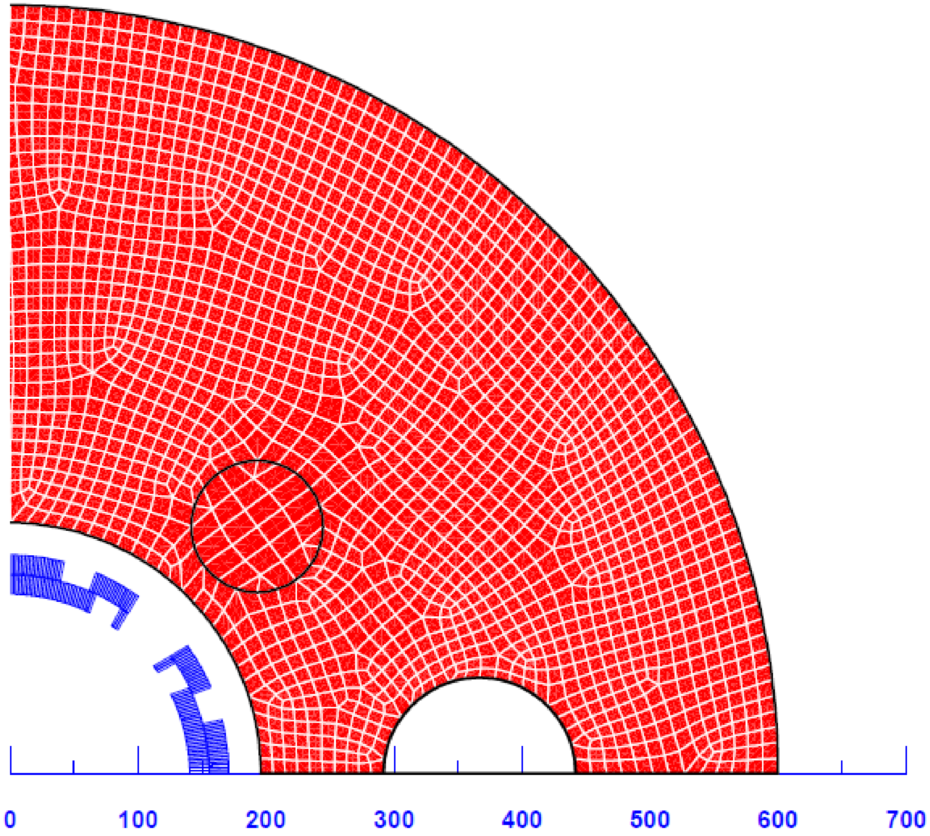
Current nominal operating range of EIC (Holger Witte): 41 GeV to 275 GeV
Minimum to Maximum Ratio: 1 to 6.7; Max. current: 7.7 kA (1.15 to 7.7 kA)

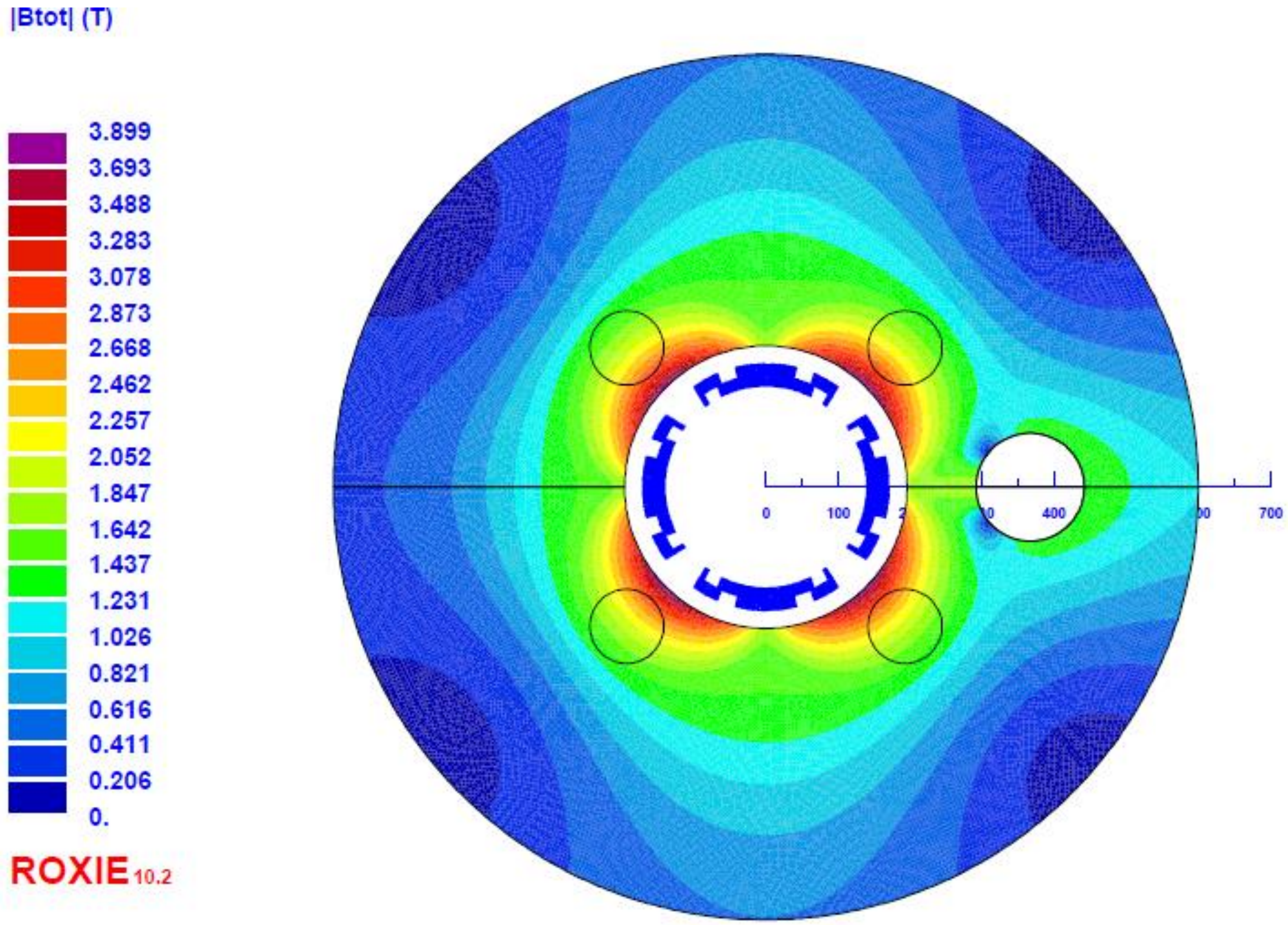
Persistent current induced harmonics will be of little concern (as in RHIC)

Evaluating the Impact of the Proposed Tie Rods

EIC Q2pF 15mm cable, 2K - or=600 mm, NO tie rods 7.5kA, hole366.8mm 22/04/02 10:43

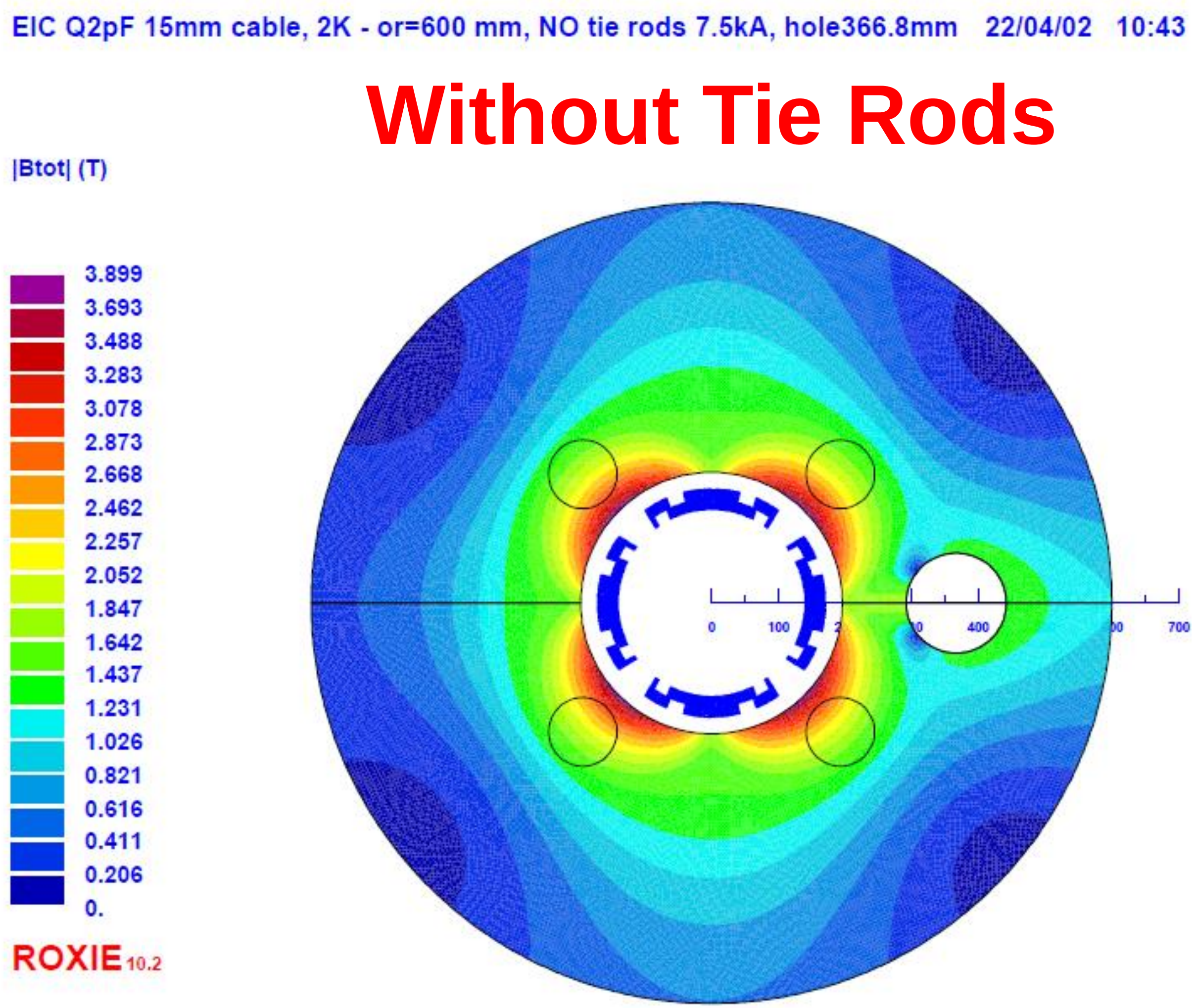
- Tie rods will have impact at high fields.
- Mesh to evaluate the impact of tie rods.
  Holes modeled for them - change iron to air.

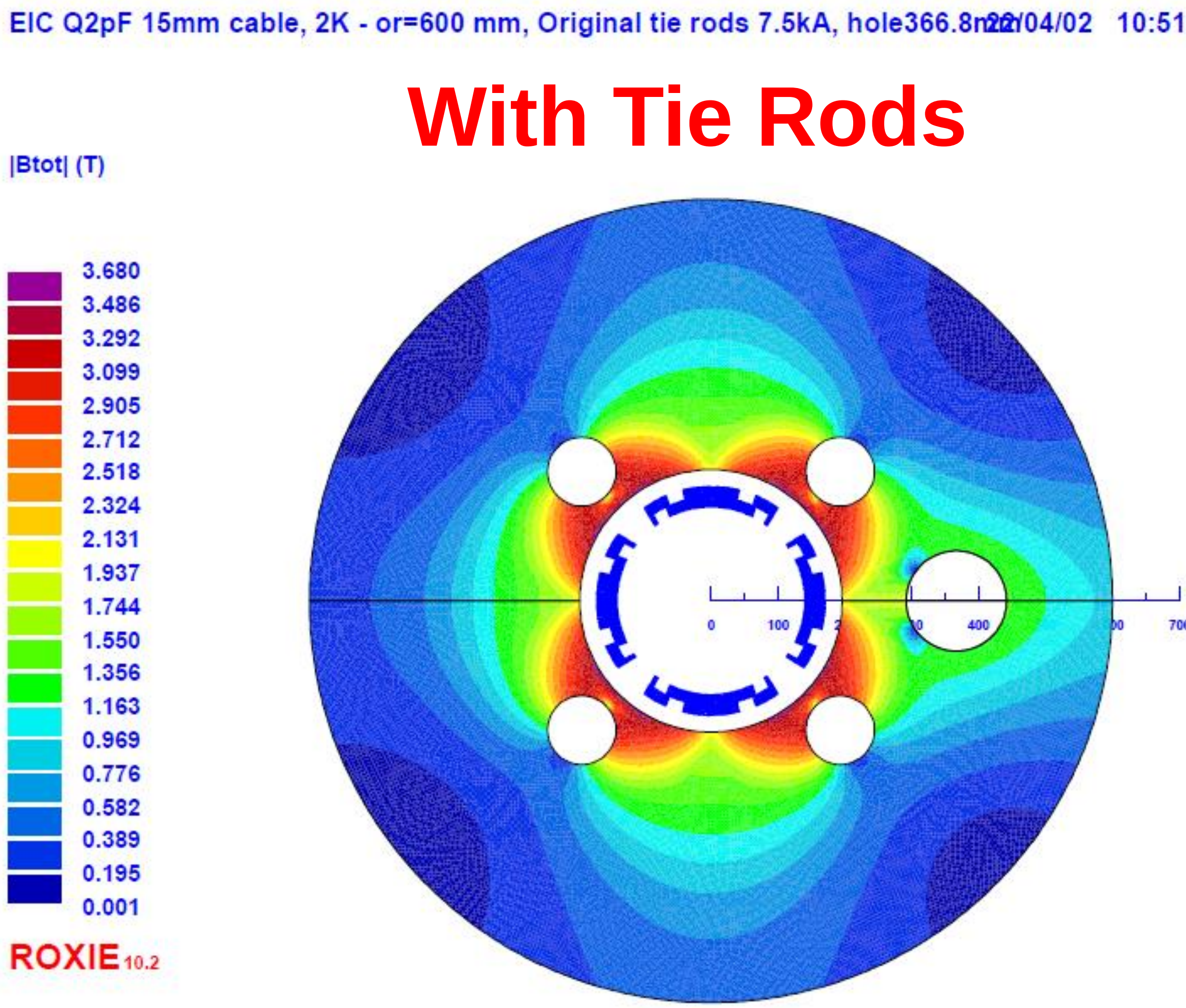




- ➢ Field Gradient @7.7 kA goes down from 37.4 T/m to 36.2 T/m (not surprising, given the location/size).
- ➢ This is significant (over 3.2%). *<u>However, it is more important to examine the impact on the harmonics.</u>*

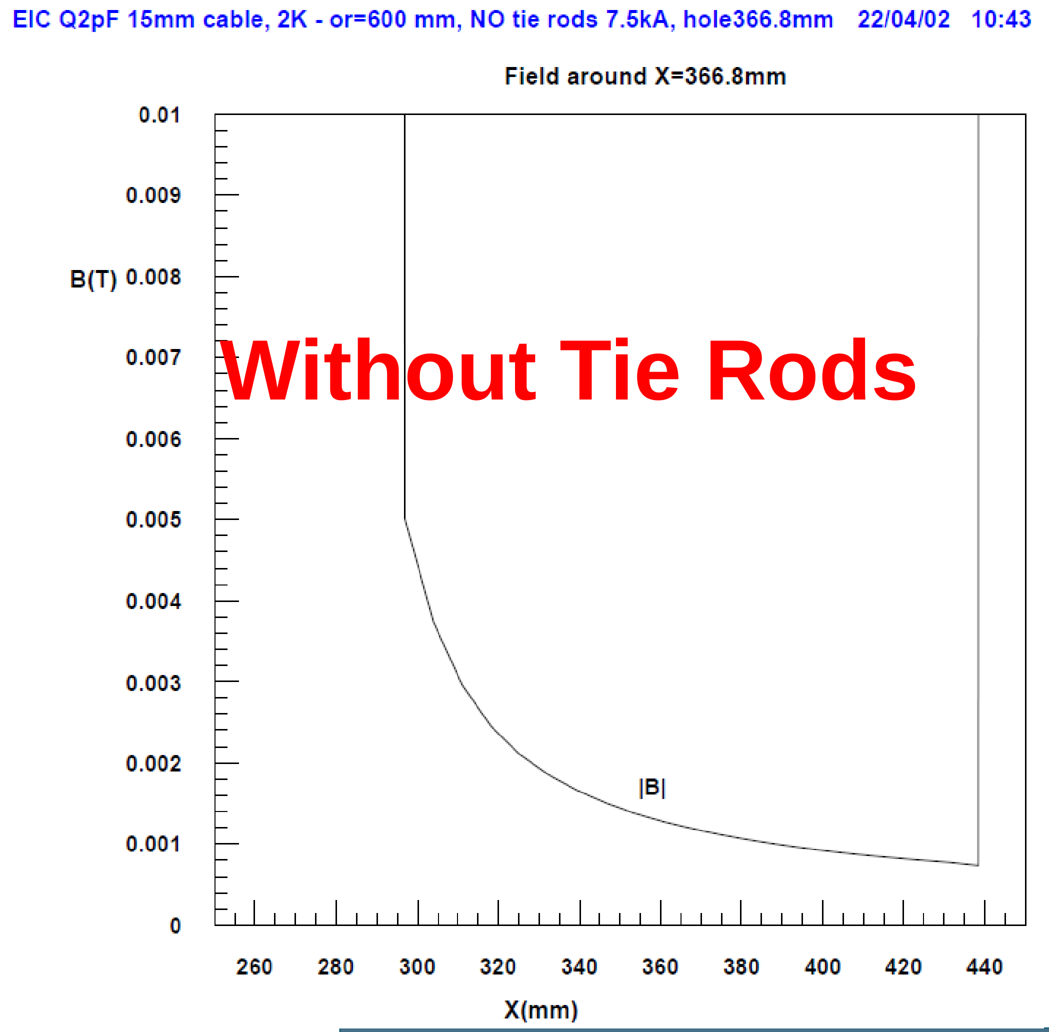
Impact of Tie Rods @7.7 KA (1)

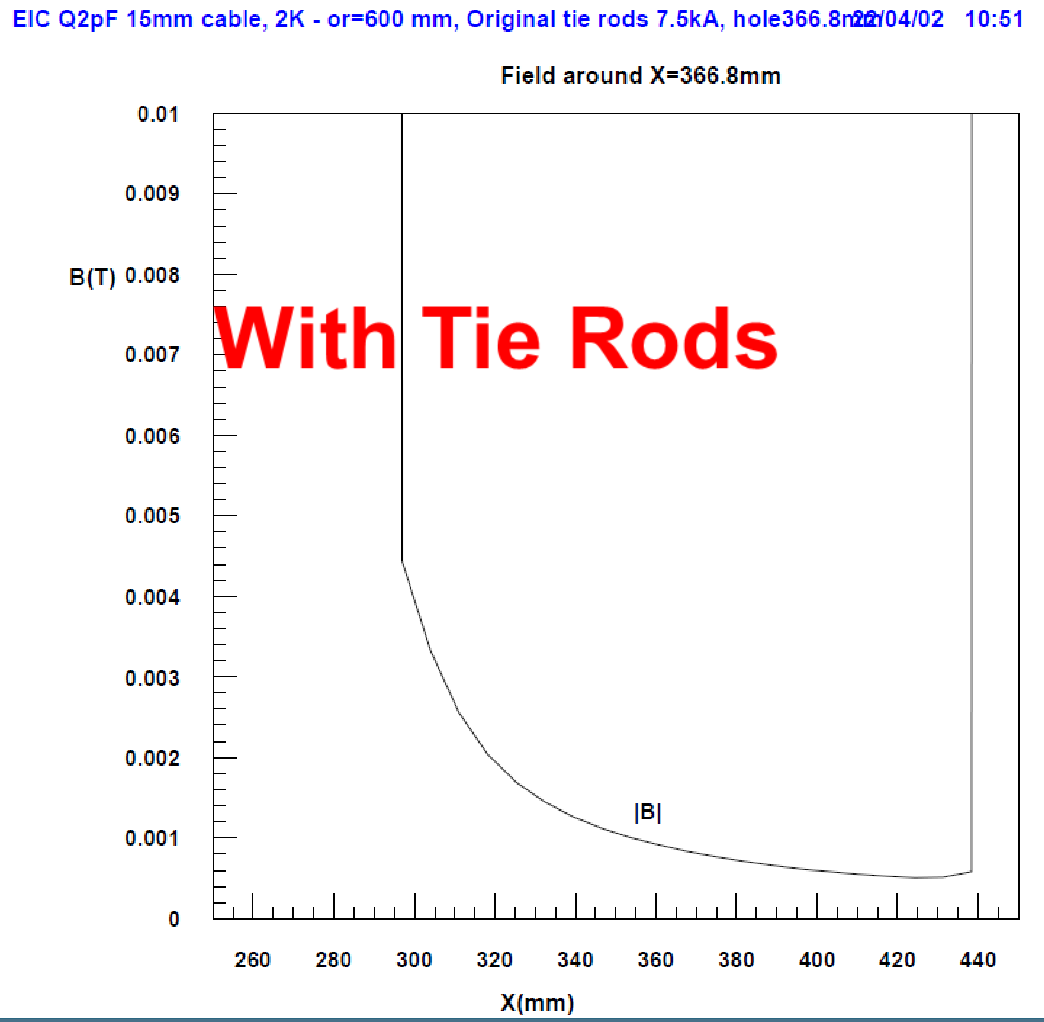




Tie Rods increase Saturation in pole region

Impact of Tie Rods @7.7kA (2)

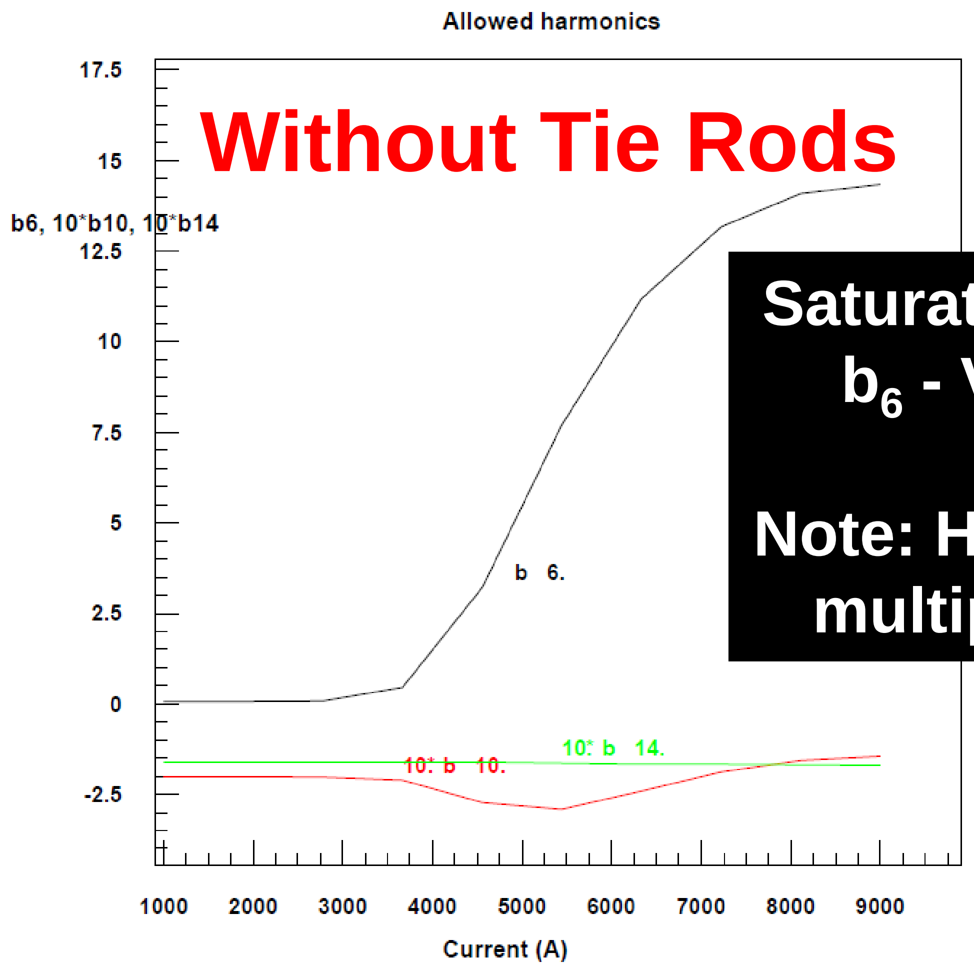




Little Impact on field in the hole for electron beam

Impact of Tie Rods on Allowed Harmonics Computed as a Function of Current

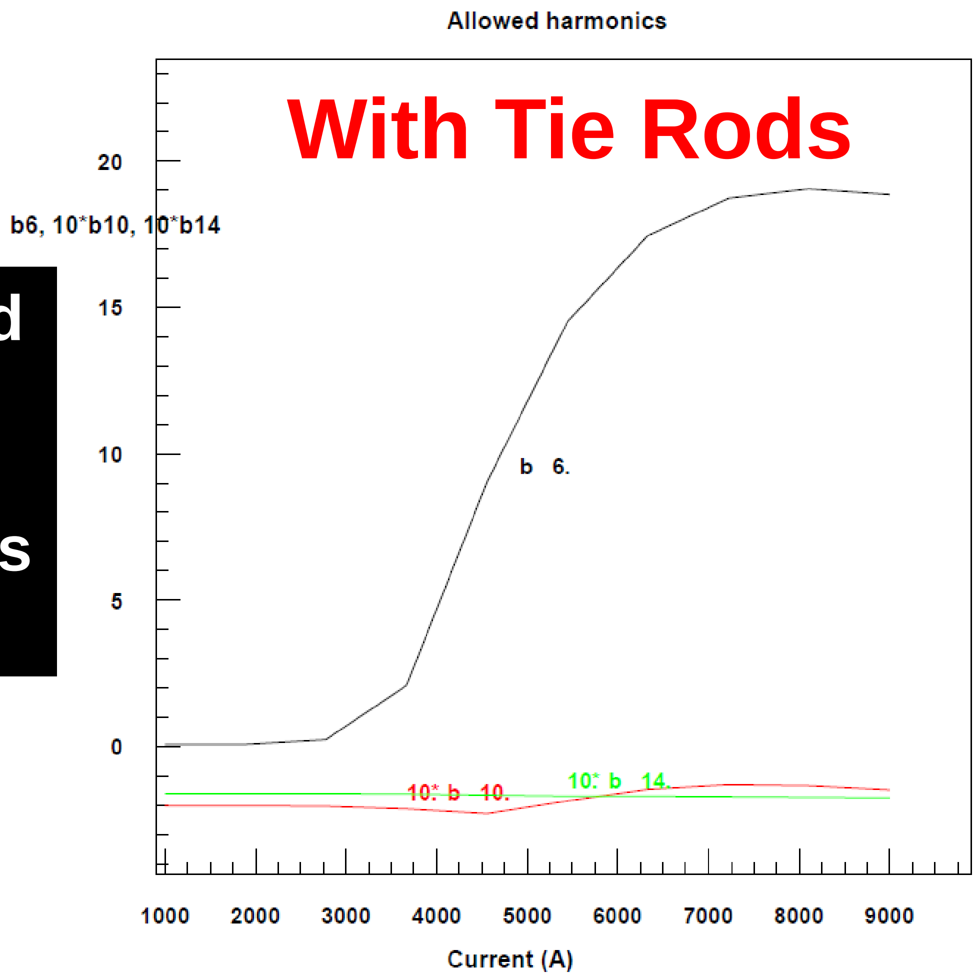
EIC Q2pF 15mm cable, 2K - or=600 mm, NO tie rods 1KA to 9KA 22/03/30 13:13



Saturation-induced b_6 - Very large

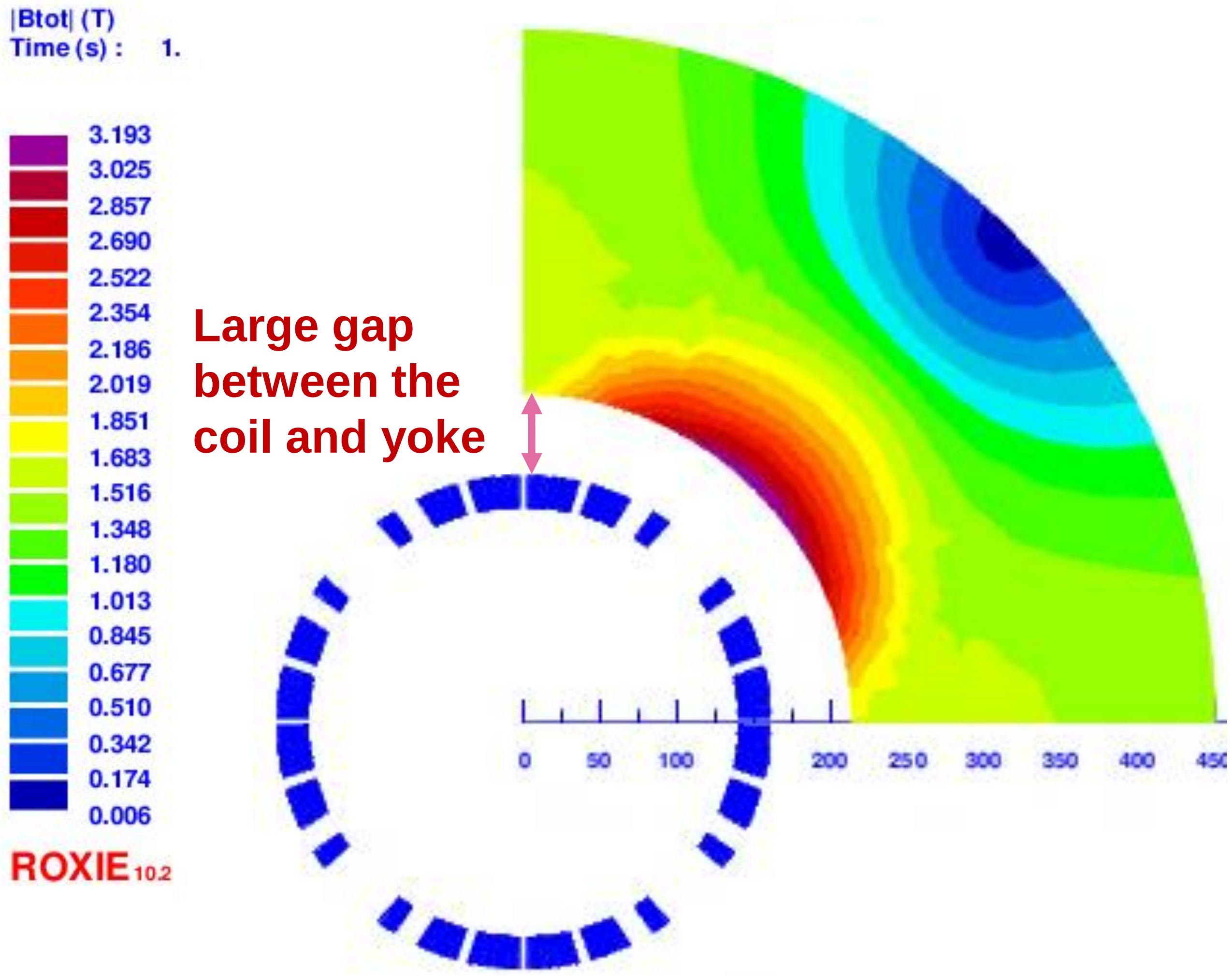
Note: Higher orders multiplied by 10

EIC Q2pF 15mm cable, 2K - or=600 mm, original tie rods 1KA to 9KA 22/04/02 13:29

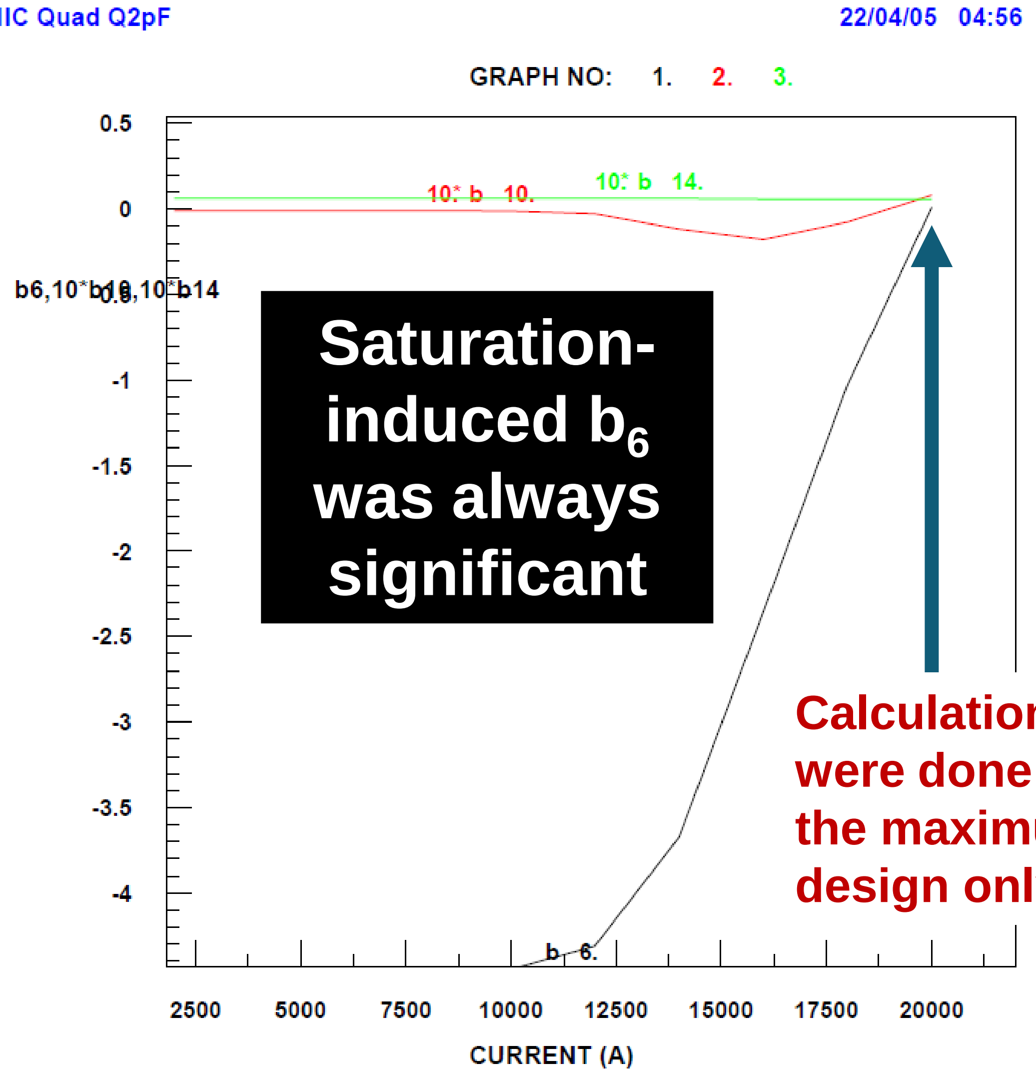


Tie Rods further increase b_6, little change in higher order

Saturation-induced Allowed Harmonics in Earlier 2 K Designs (Holger Witte 2020)



Large gap between the coil and yoke



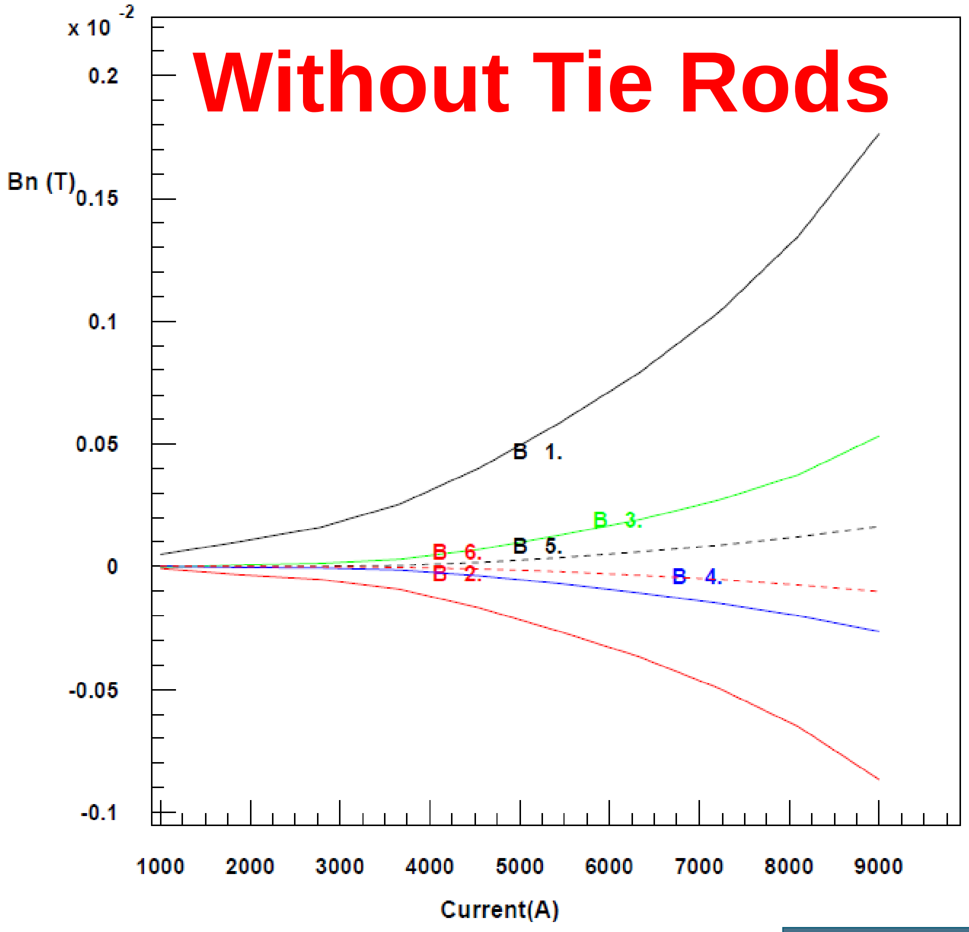
Saturation-induced b_6 was always significant

Calculations were done at the maximum design only

Measuring Impact of Cross-talk in Hole for e-beam with B_n Harmonics

(working with B_n should be a good way of communicating with accelerator physicists)

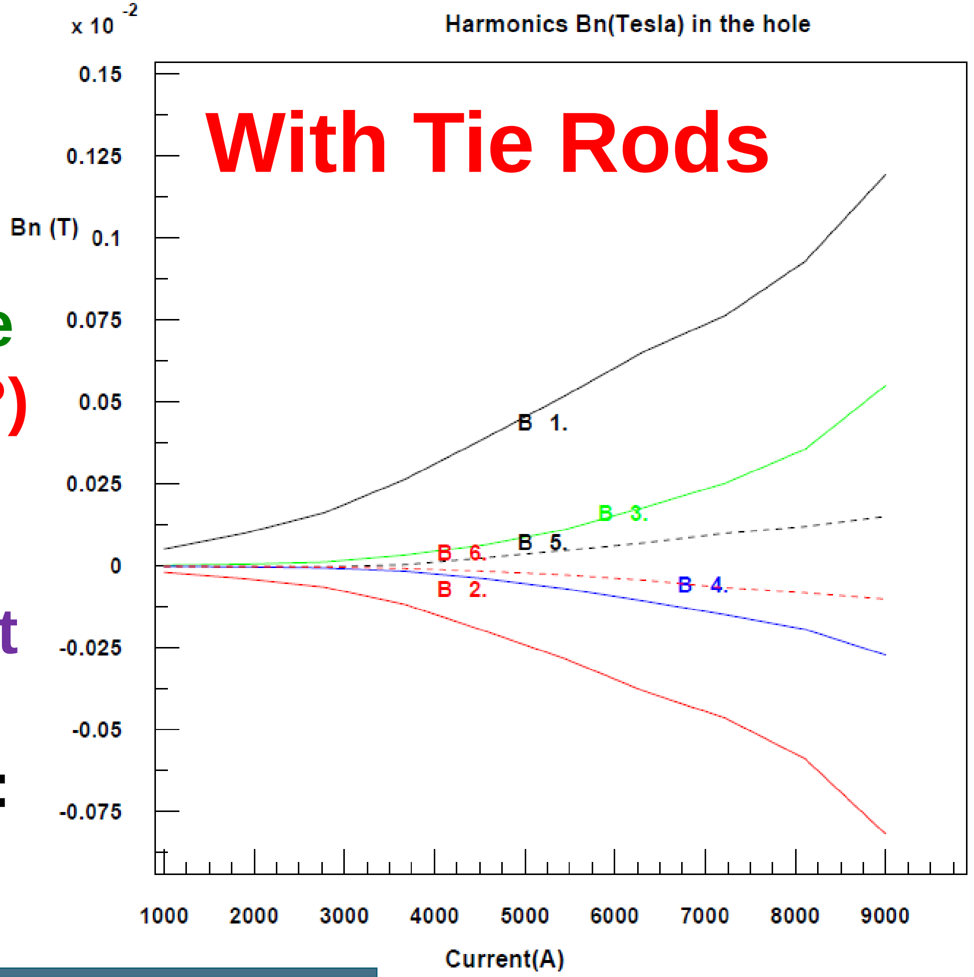
EIC Q2pF 15mm cable, 2K - or=600 mm, NO tie rods 1KA to 9KA 22/03/30 13:13



Harmonics @50 mm radius in r=75 mm hole (e-beam size?)

B1 shouldn't be an issue at this level. (most others: 10^{-3} or less)

EIC Q2pF 15mm cable, 2K - or=600 mm, original tie rods 1KA to 9KA 22/04/03 12:59



Minor impact of Tie Rods

Recap on the work presented so far on the Q2pF

- **We have a very good solution for coil geometry - mechanically good geometry with small field harmonics and some tunability. Also, enough space for collars.**

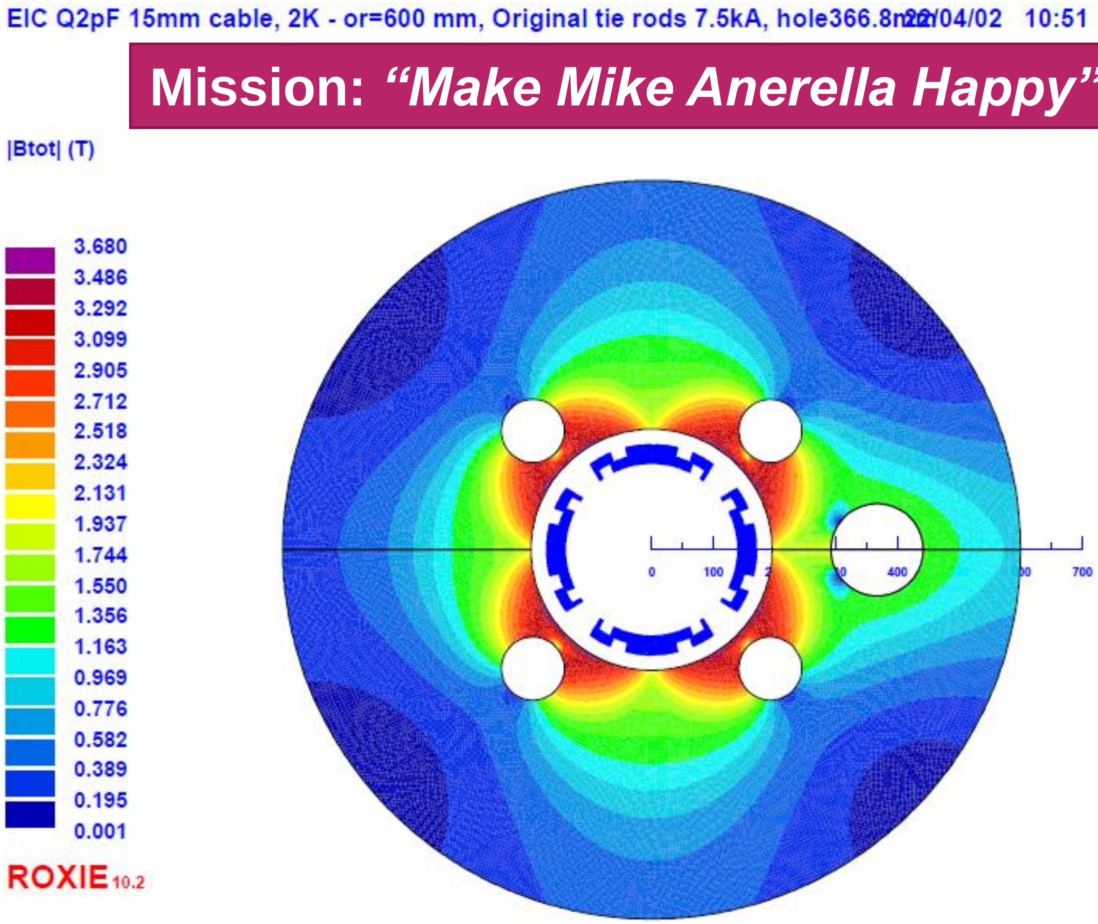
- However, the impact of non-linear yoke saturation needs to be taken care of.
- There is a larger decrease in transfer function due to tie rods from 5.1 T/m/kA@1kA
  - to 4.85 T/m/kA @7.7 kA (without tie rods), and 4.69 T/m/kA (with tie rods).
- Saturation-induced b_6 goes up from 13 units without tie rods to 16 units with tie rods.
- Moreover, there is still an issue with a large field in the hole for the electron beam.

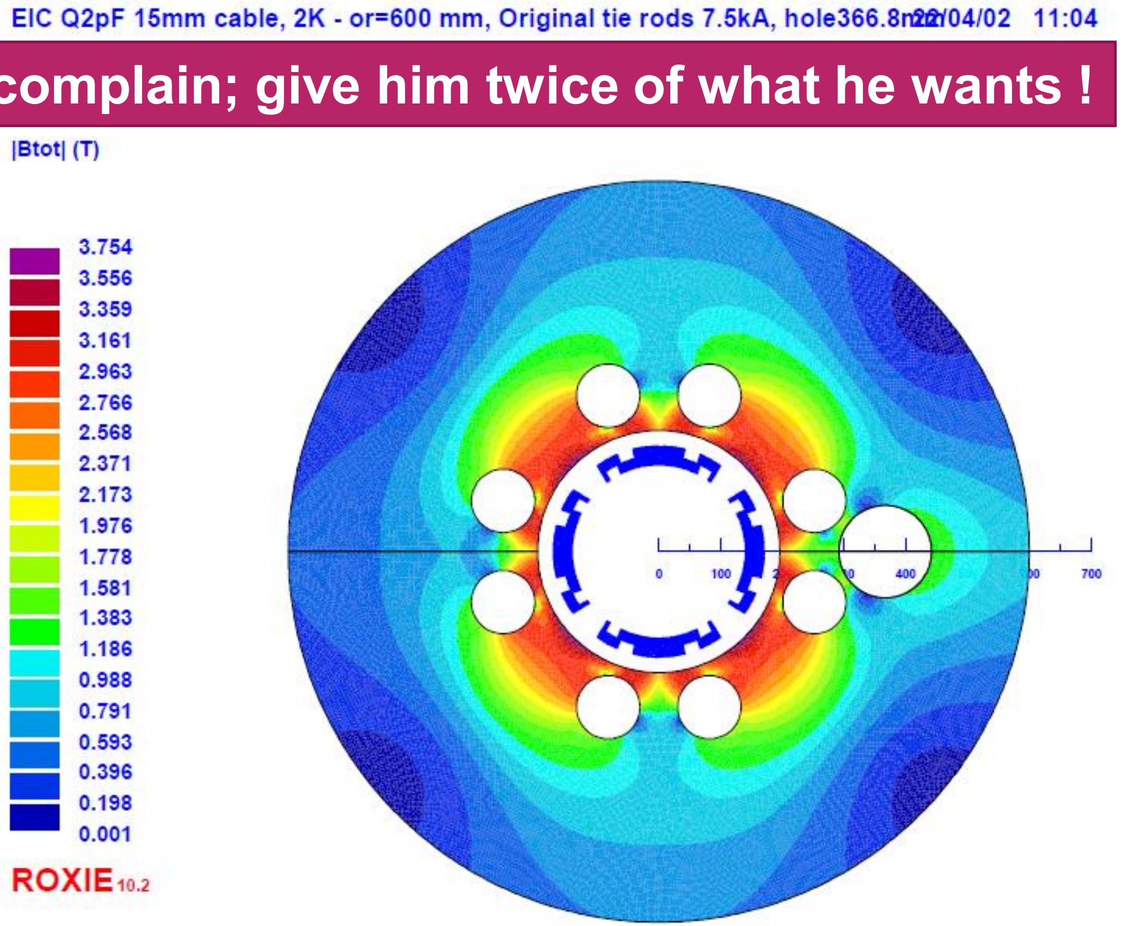
- **Is there a possibility to turn-around the situation, or look for another solution?**

Holes for Tie Rods – Turning them to an opportunity

- Strategy: Large holes for tie rods clearly make a significant impact on iron saturation. Let's try to make use of those large holes as a tool of opportunity!

Mission: *"Make Mike Anerella Happy"* – don't complain; give him twice of what he wants !

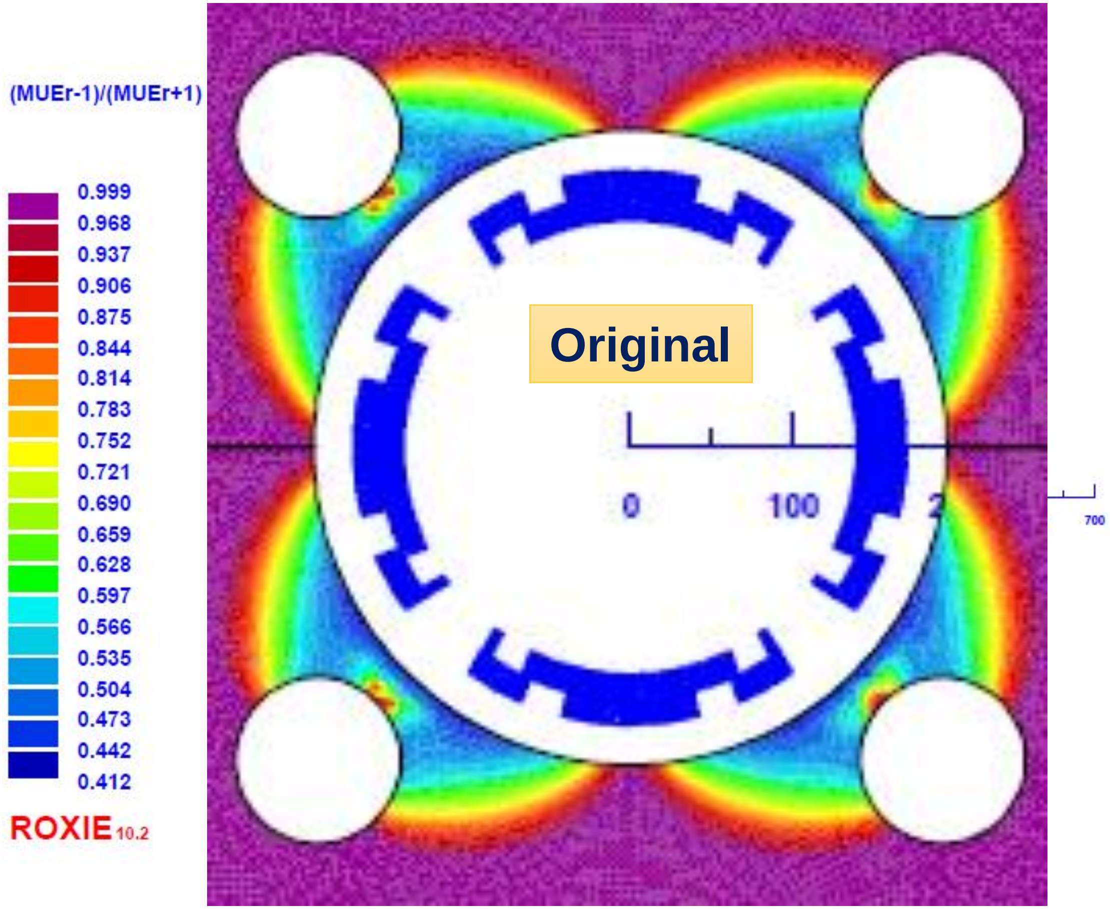


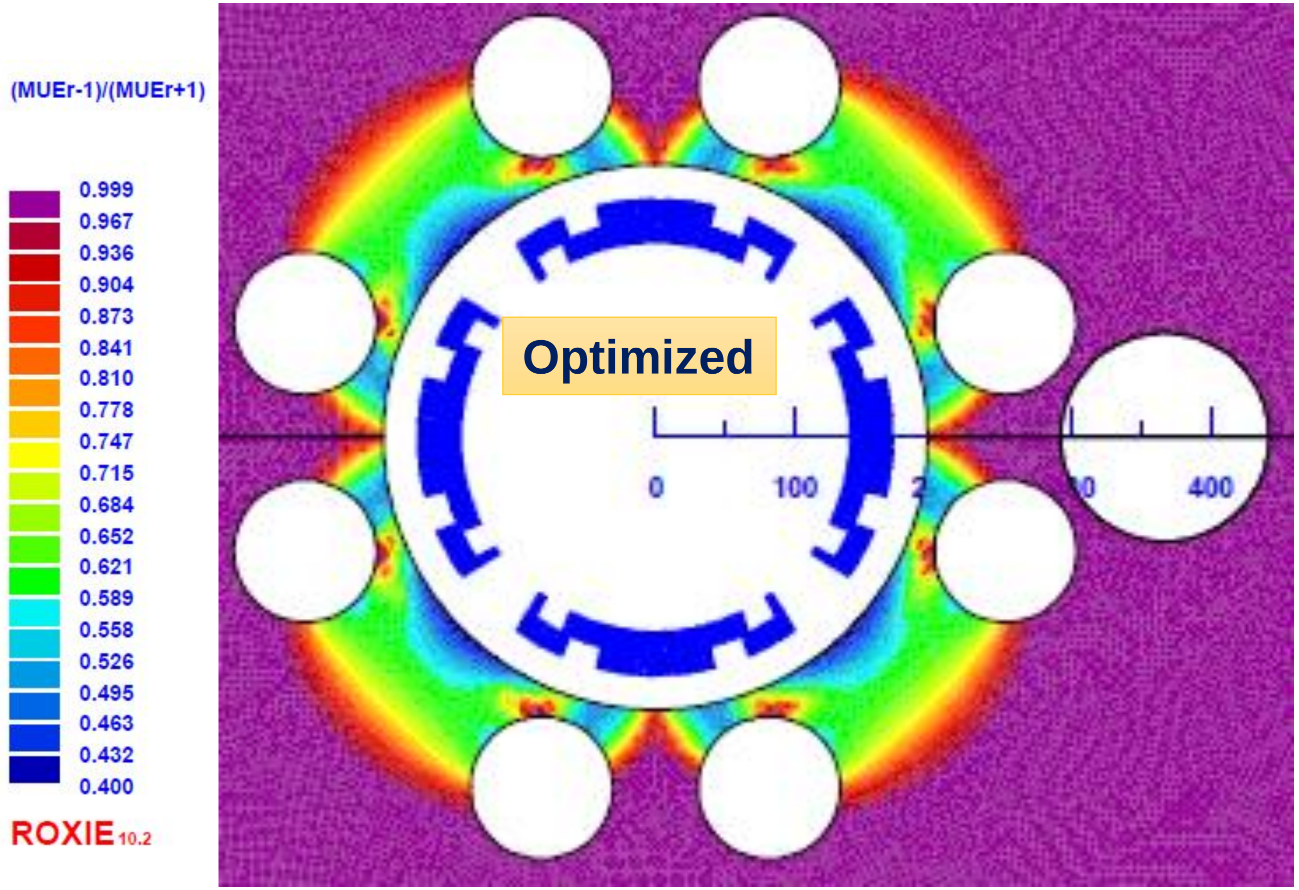


Note: Field in yoke iron at the aperture – it has become higher all around (more uniform)

Holes for Tie Rods – Turning them in to an opportunity

- Strategy: Large holes for tie rods clearly make a significant impact on iron saturation. Let's try to make use of those large holes as a tool of opportunity!

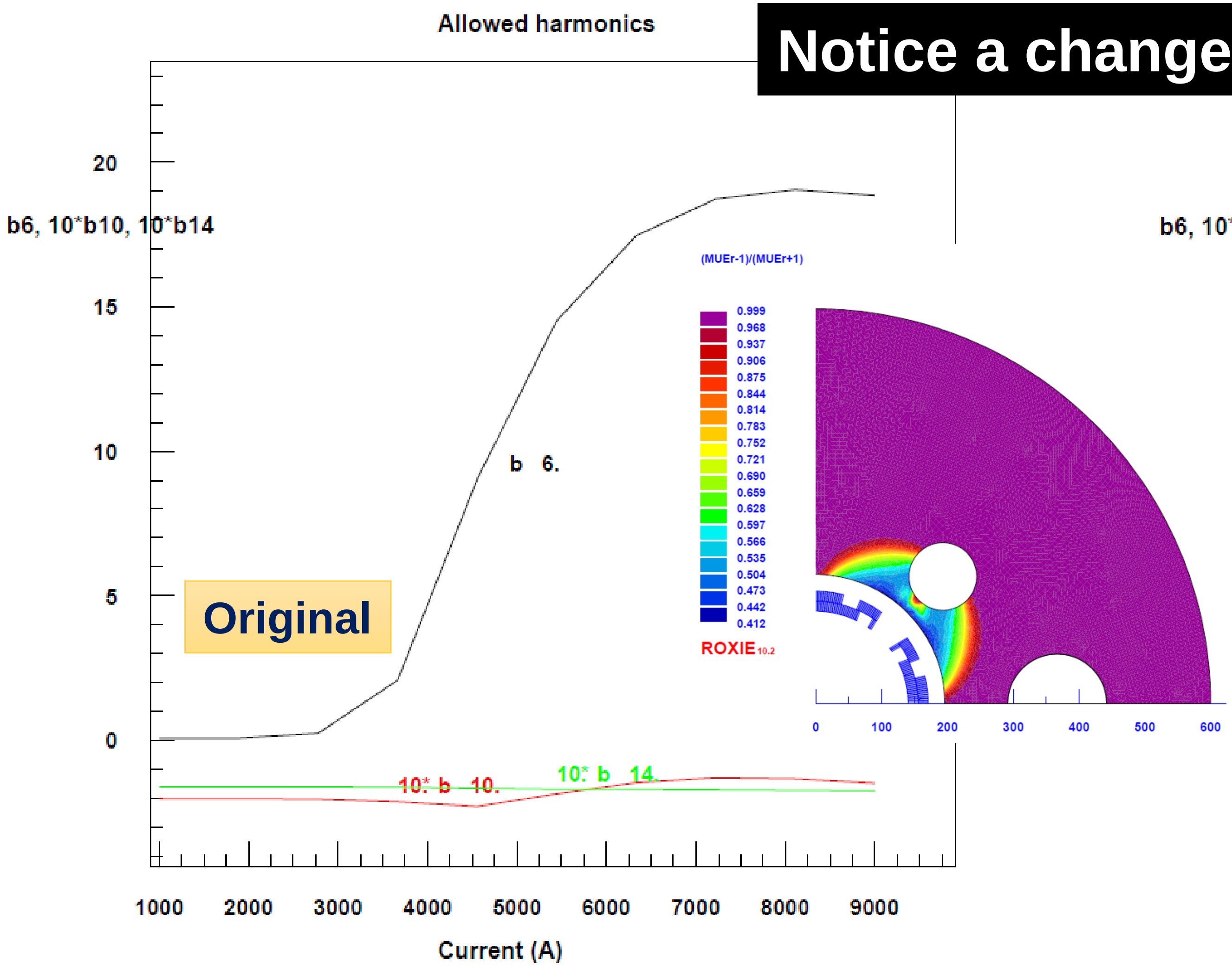


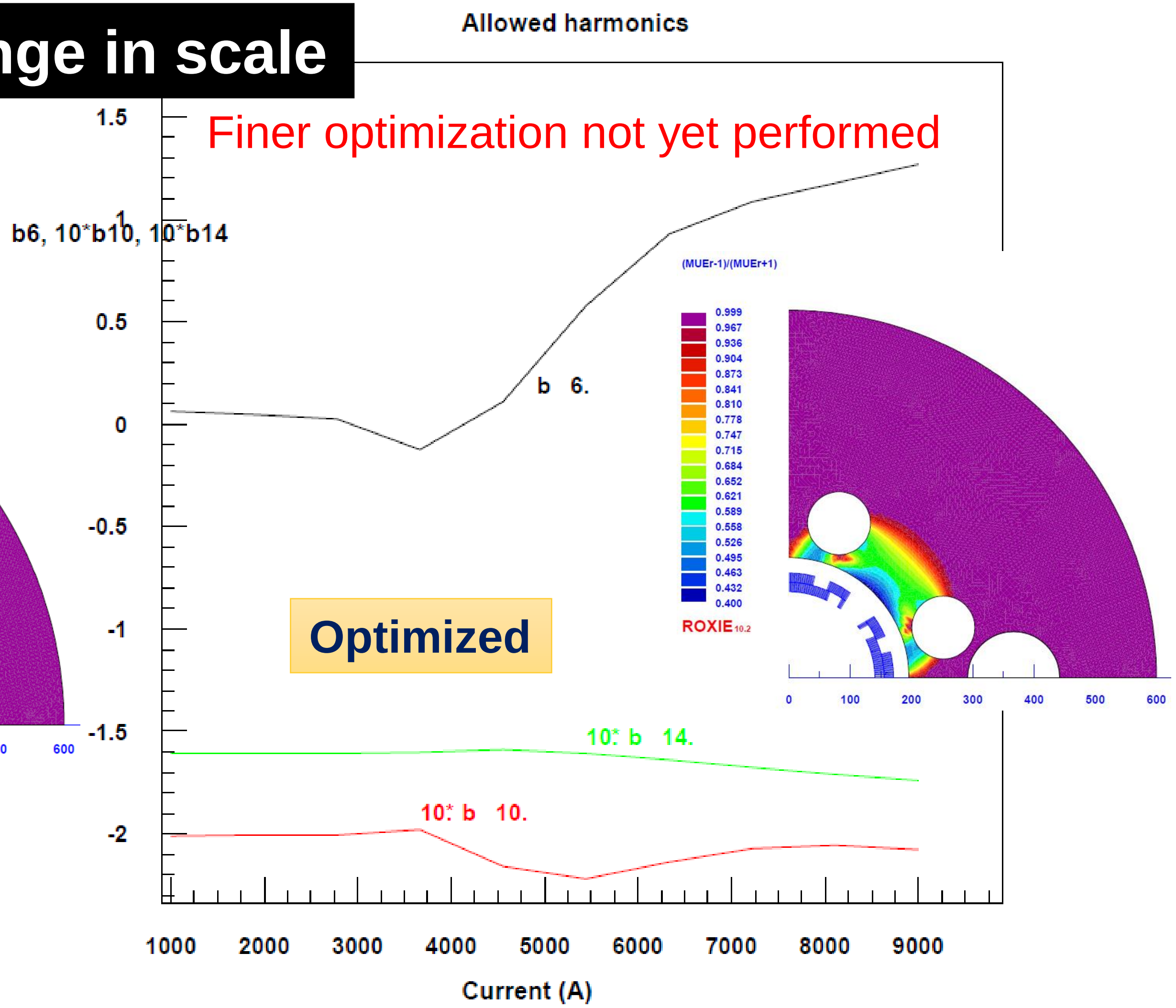


Note: $(\mu-1)/(\mu+1)$ in the yoke near i.r. has now become more uniform

Tie Rods to Reduce Saturation-induced Harmonics

Notice a change in scale



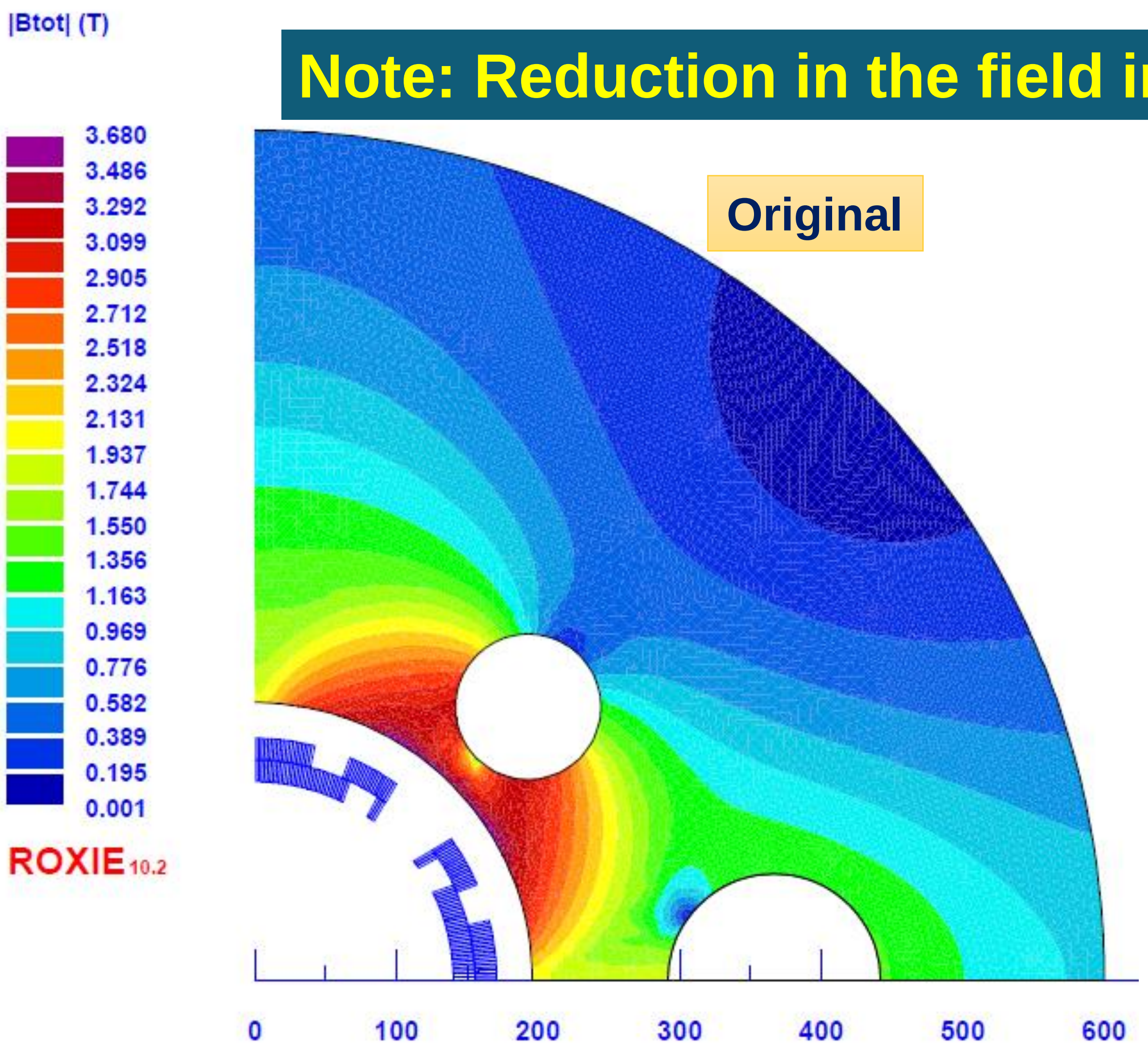


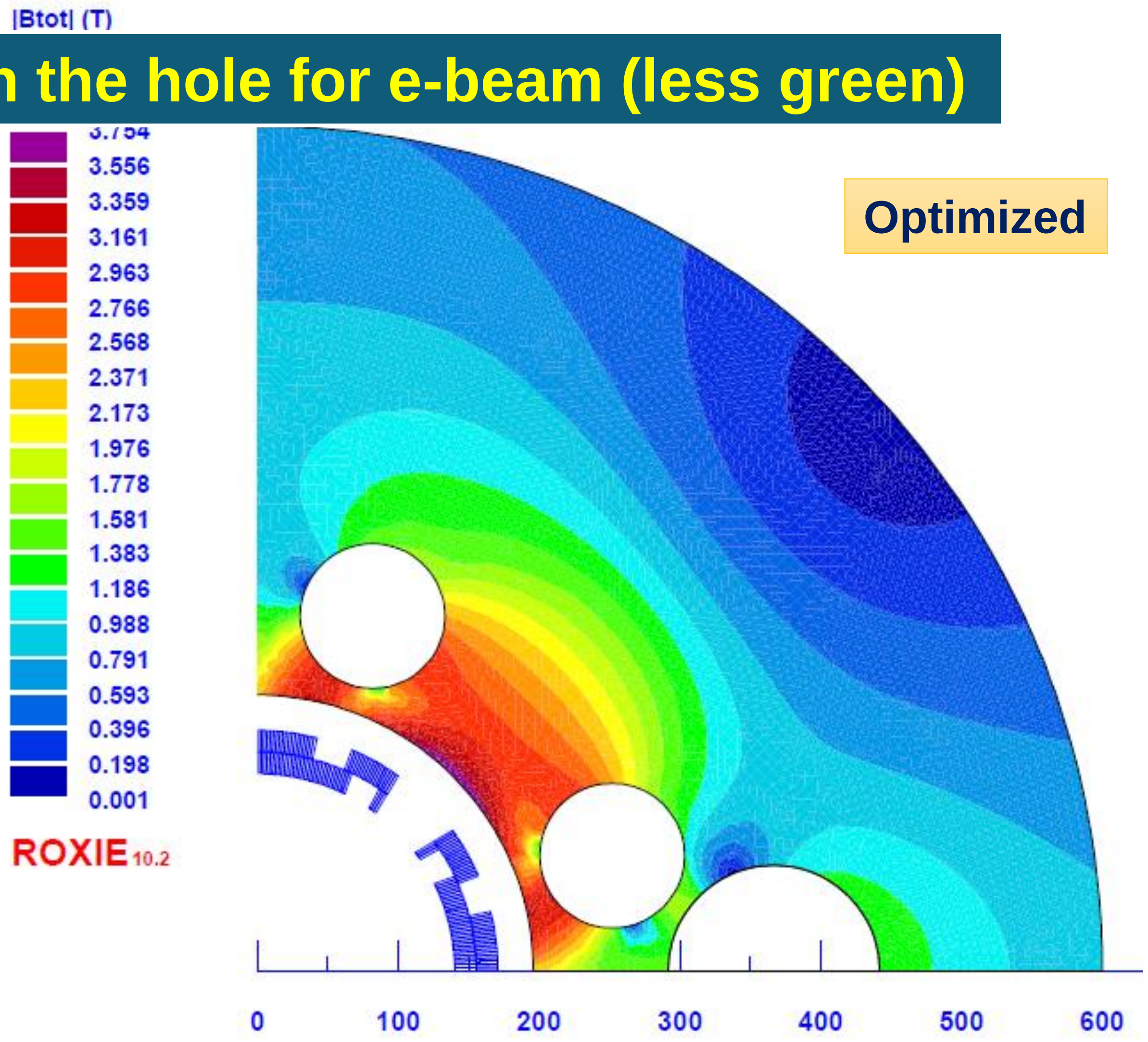
Optimized Iron: Major reduction in saturation induced allowed harmonics (order of magnitude)

Field Gradient @7.7 kA goes down from 36.2 T/m to 35.7 T/m for 2X holes (controlled saturation)

Tie Rods to Reduce Field in Hole for Electron beam

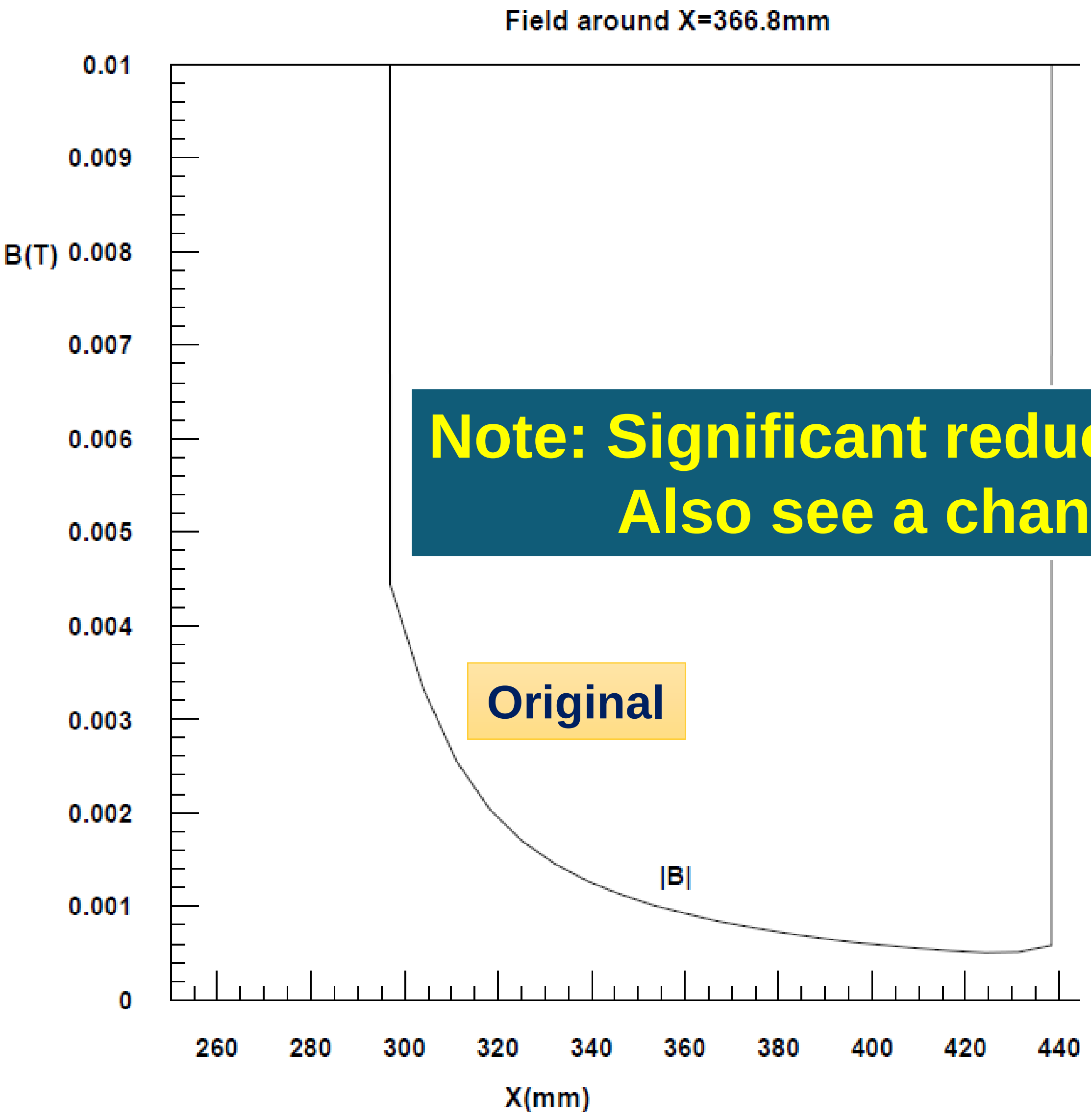
Note: Reduction in the field in the hole for e-beam (less green)

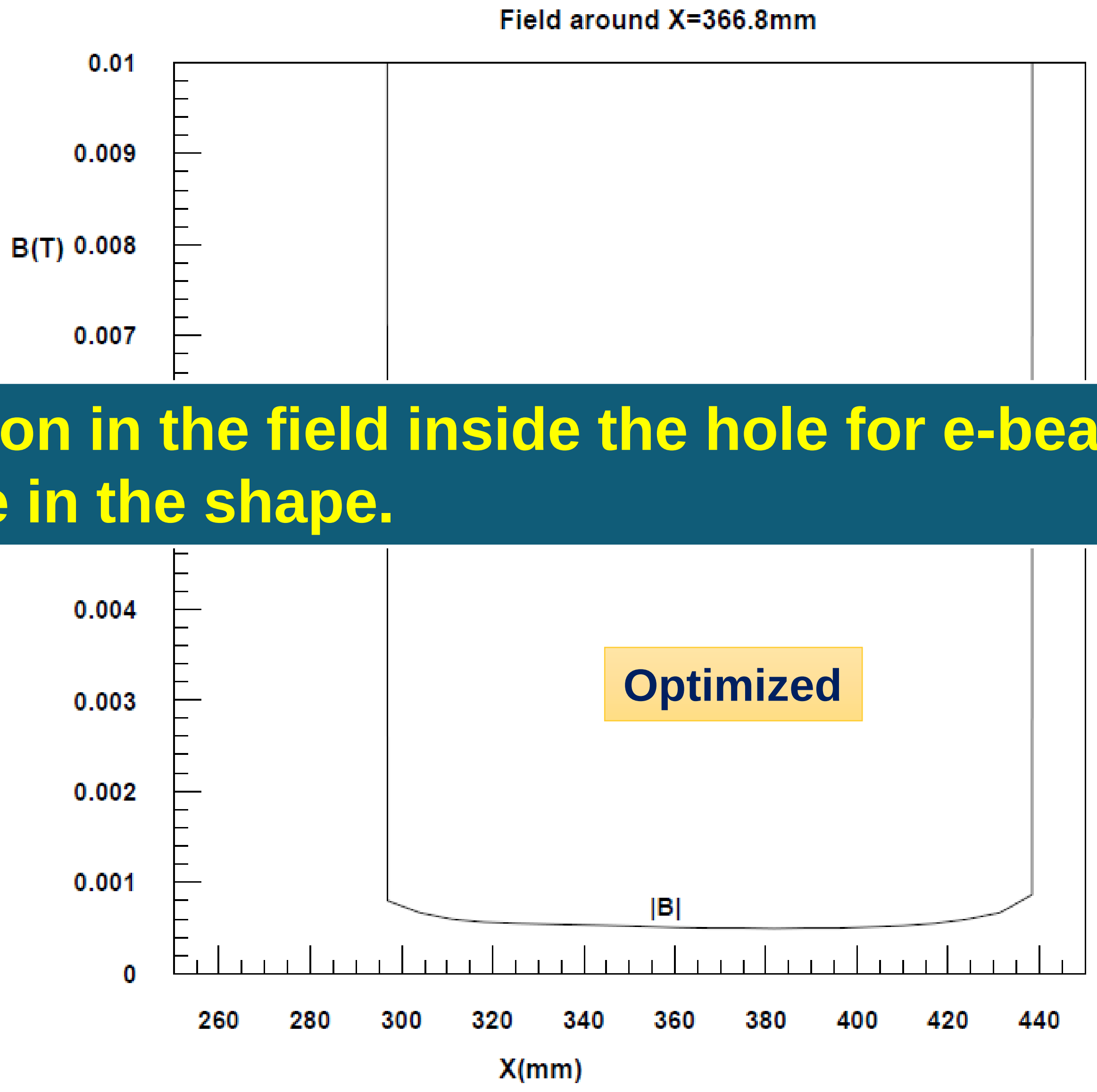




Finer optimization not yet preformed

Tie Rods to Reduce Field in Hole for Electron beam

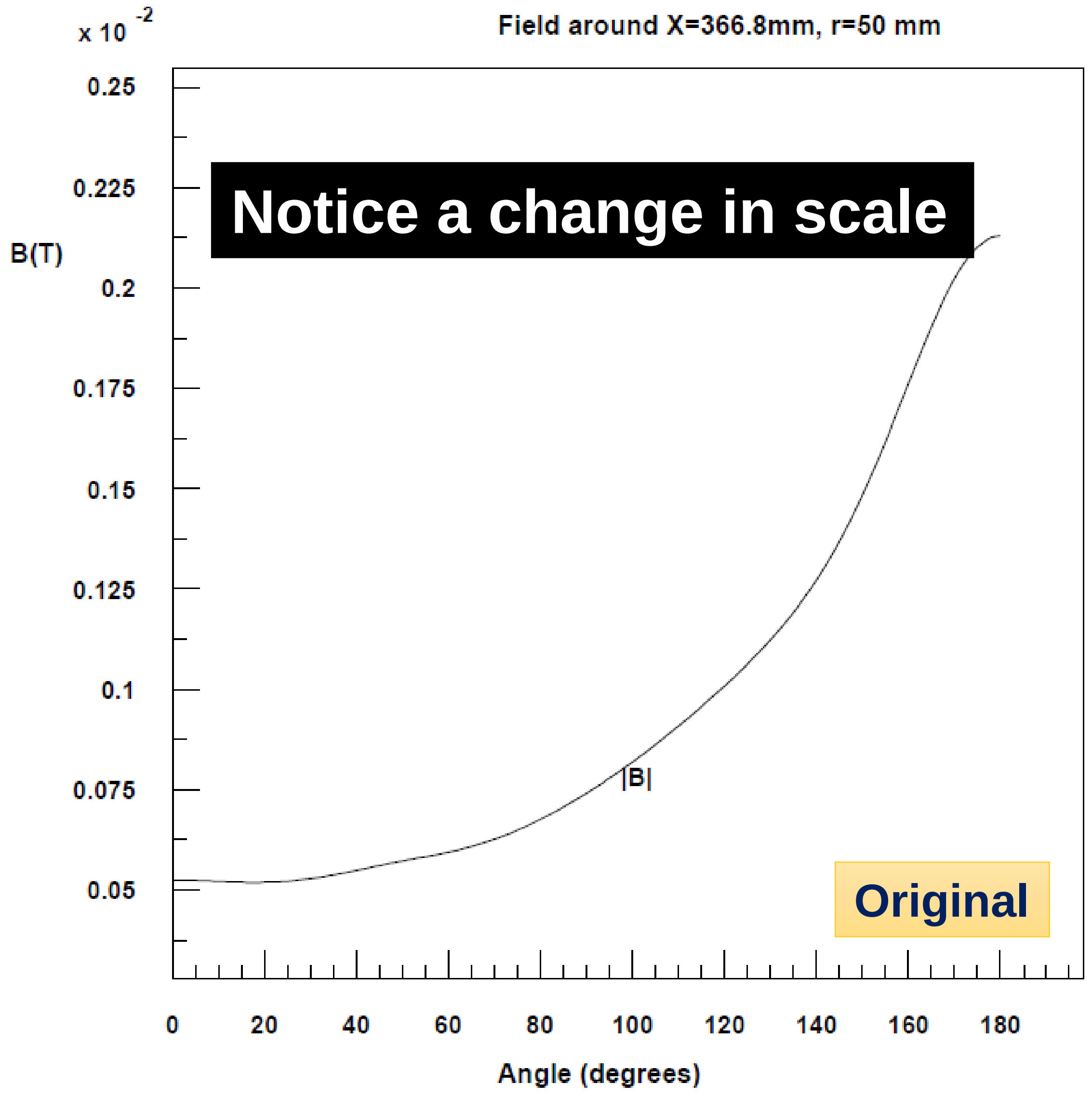


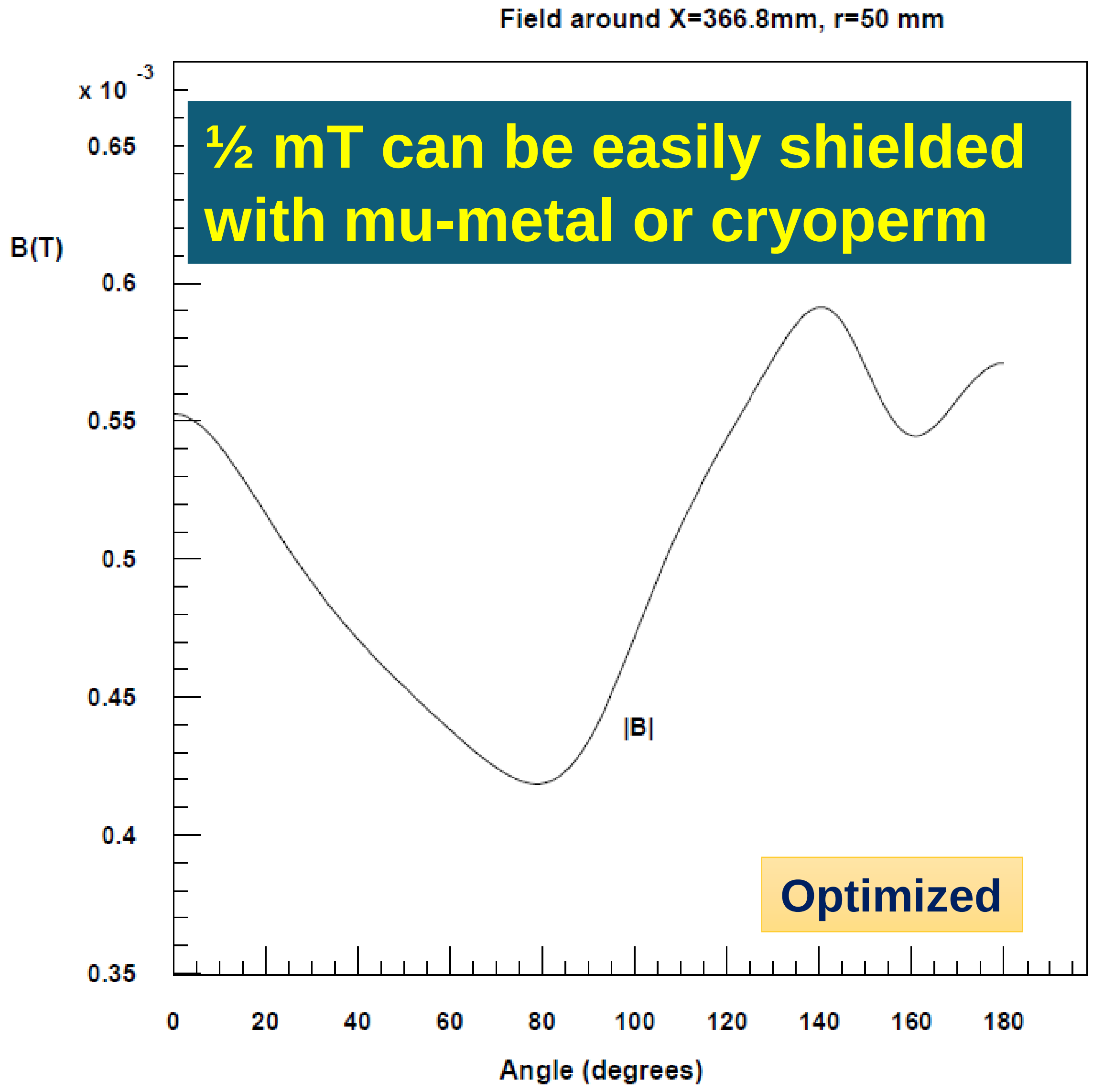


Note: Significant reduction in the field inside the hole for e-beam
Also see a change in the shape.

Finer optimization not yet preformed

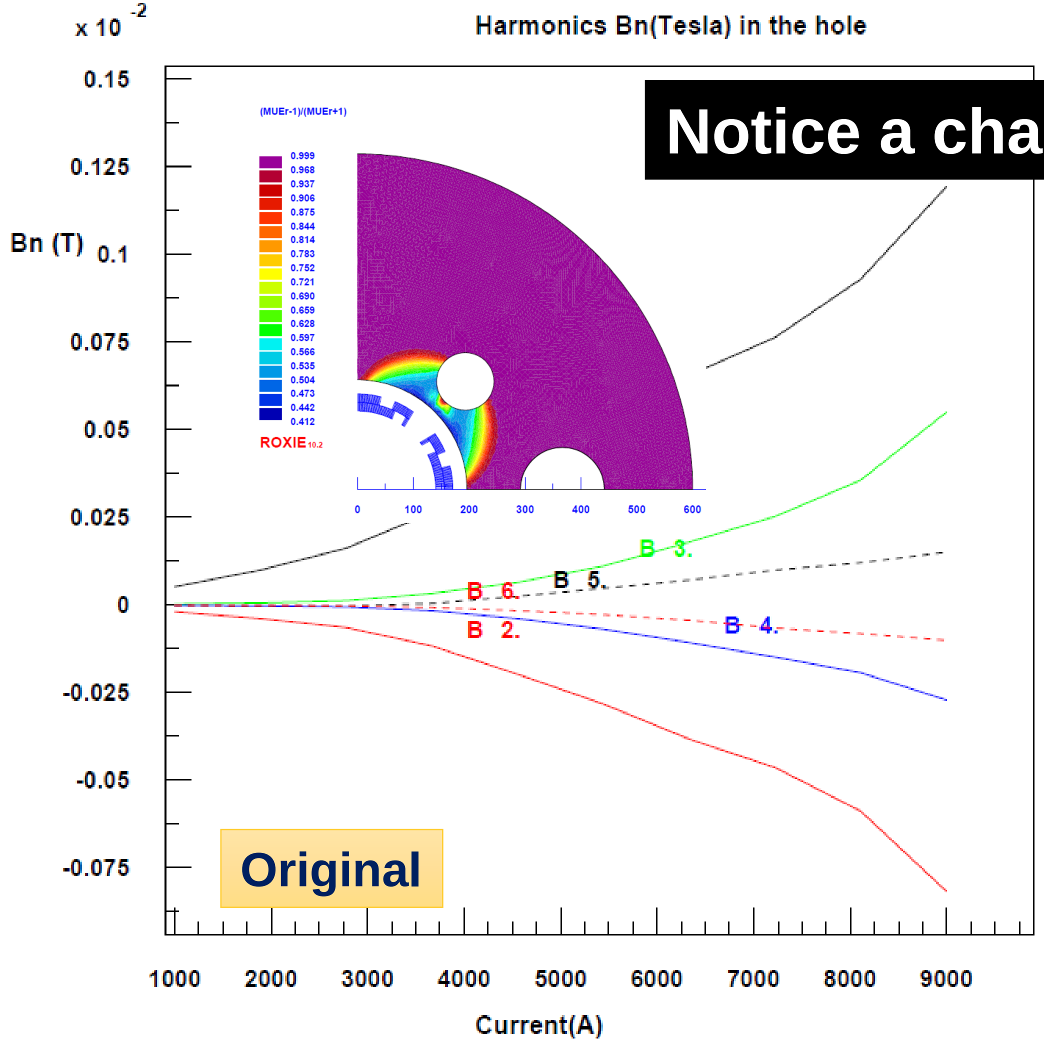
Field inside the e-beam Hole @50 mm radius





Finer optimization not yet preformed

Tie Rods to Reduce Field in Hole for Electron beam

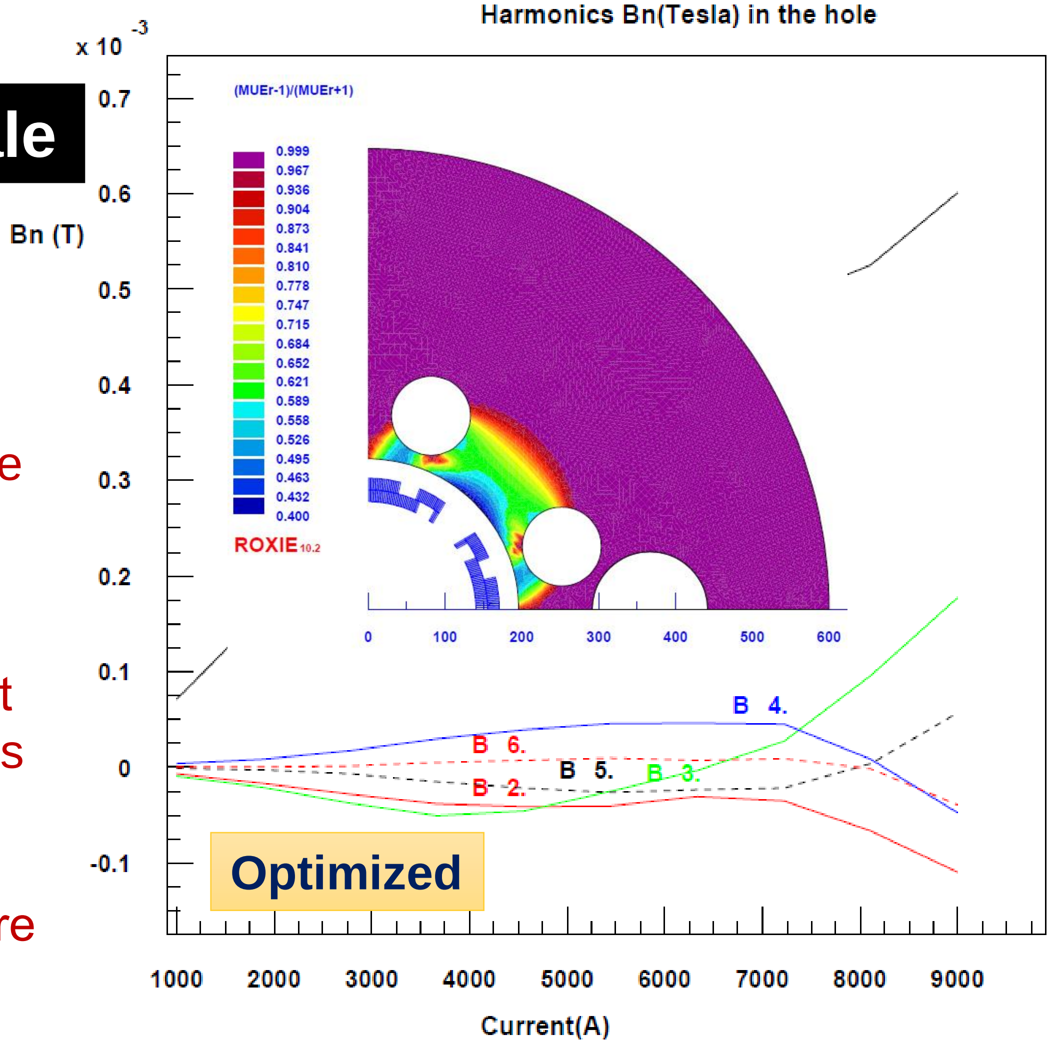


Notice a change in scale

Harmonics @50 mm (where is the e-beam?)

B_1 shouldn't matter at this field level.

Other B_n's are $<10^{-4}$



Optimized Iron: Major reduction in the field in the hole for e-beam

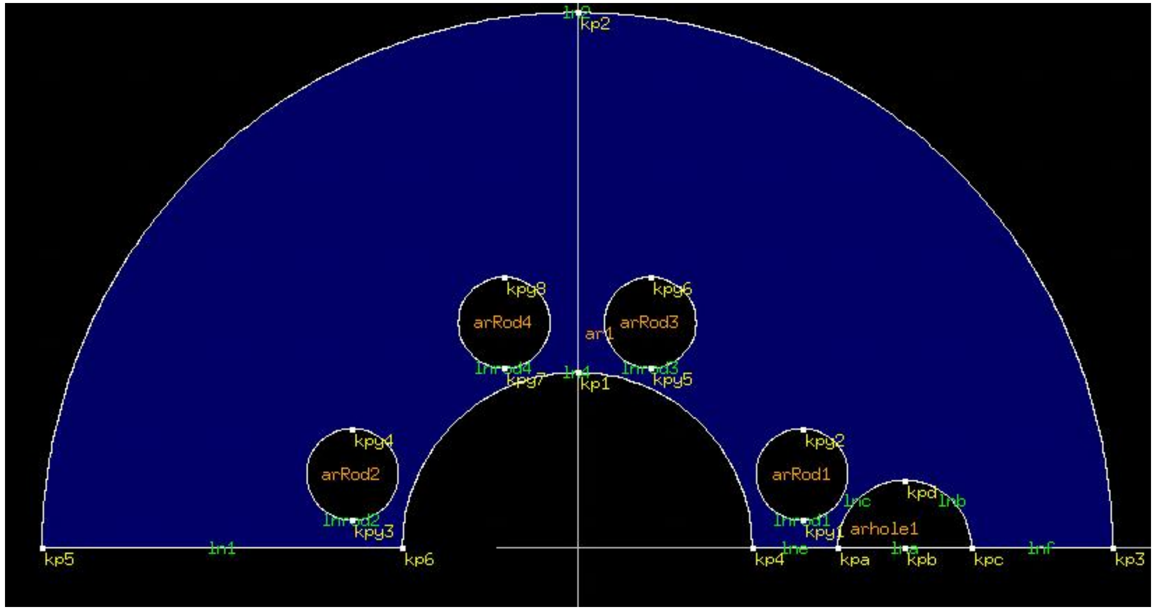
Finer optimization not yet preformed

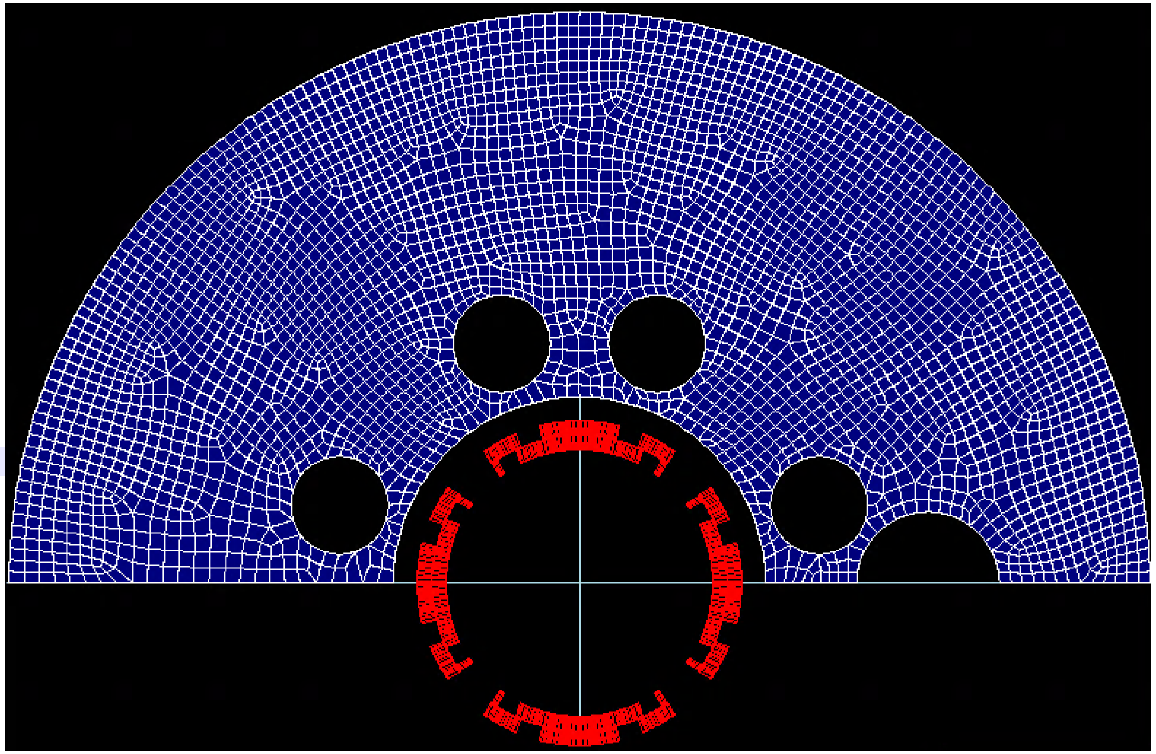
Parametric IRON File for ROXIE (can be used for any IR Quad)

```
HyperMesh;
--COMMENTS
--''

--VARIABLES
pi = 3.14159265;
ir = 0.196;
or = 0.60;
xh = 0.3668;
rh = 0.075;
rc = 0.265;
tc = 18;
ra = 0.0514;
xc = rc*Cos(tc/180*pi);
yc = rc*Sin(tc/180*pi);
-- xc = 0.19306;
-- yc = 0.19306;

--NODES
kp1 = [0,ir];
kp2 = [0.,or];
kp3 = [or,0];
kp4 = [ir,0];
kp5 = [-or,0];
kp6 = [-ir,0];
kpa = [xh-rh,0];
kpb = [xh,0];
kpc = [xh+rh,0];
kpd = [xh,rh];
kpy1 = [xc,yc-ra];
kpy2 = [xc,yc+ra];
kpy3 = [-xc,yc-ra];
kpy4 = [-xc,yc+ra];

kpy5 = [yc,xc-ra];
kpy6 = [yc,xc+ra];
kpy7 = [-yc,xc-ra];
kpy8 = [-yc,xc+ra];
```

```
--LINES
ln1 = HyperLine(kp5,kp6,"Line");
ln2 = HyperLine(kp5,kp3,"Arc",kp2);
ln4 = HyperLine(kp6,kp4,"Arc",kp1);
lna = HyperLine(kpa,kpc,"Line");
lnb = HyperLine(kpd,kpc,"Arc",rh);
lnc = HyperLine(kpa,kpd,"Arc",rh);
lne = HyperLine(kp4,kpa,"Line");
lnf = HyperLine(kpc,kp3,"Line");
lnrod1 = HyperLine(kpy1,kpy2,"Circle");
lnrod2 = HyperLine(kpy3,kpy4,"Circle");

lnrod3 = HyperLine(kpy5,kpy6,"Circle");
lnrod4 = HyperLine(kpy7,kpy8,"Circle");


--AREAS
ar1     = HyperArea(ln4,lne,lnc,lnb,lnf,ln2,ln1,BHiron1);
arhole1 = HyperArea(lnb,lnc,lna,BH_air);
arRod1 = HyperArea(lnrod1,BH_air);
arRod2 = HyperArea(lnrod2,BH_air);

arRod3 = HyperArea(lnrod3,BH_air);
arRod4 = HyperArea(lnrod4,BH_air);

--HOLES
HyperHoleOf(arRod1,ar1);
HyperHoleOf(arRod2,ar1);

HyperHoleOf(arRod3,ar1);
HyperHoleOf(arRod4,ar1);


--MESH
Lmesh(ln1,25);
Lmesh(ln4,50);
Lmesh(lne,10);
Lmesh(lnrod1,20);
Lmesh(lnrod2,20);
```

Need to give parameters of only one tie rod hole. Others are created for quad symmetry.

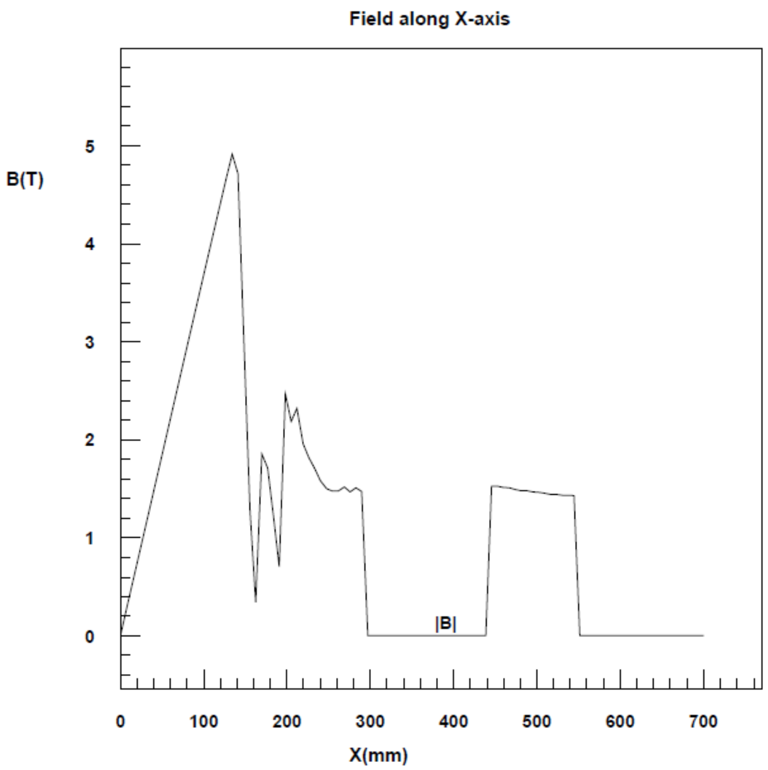


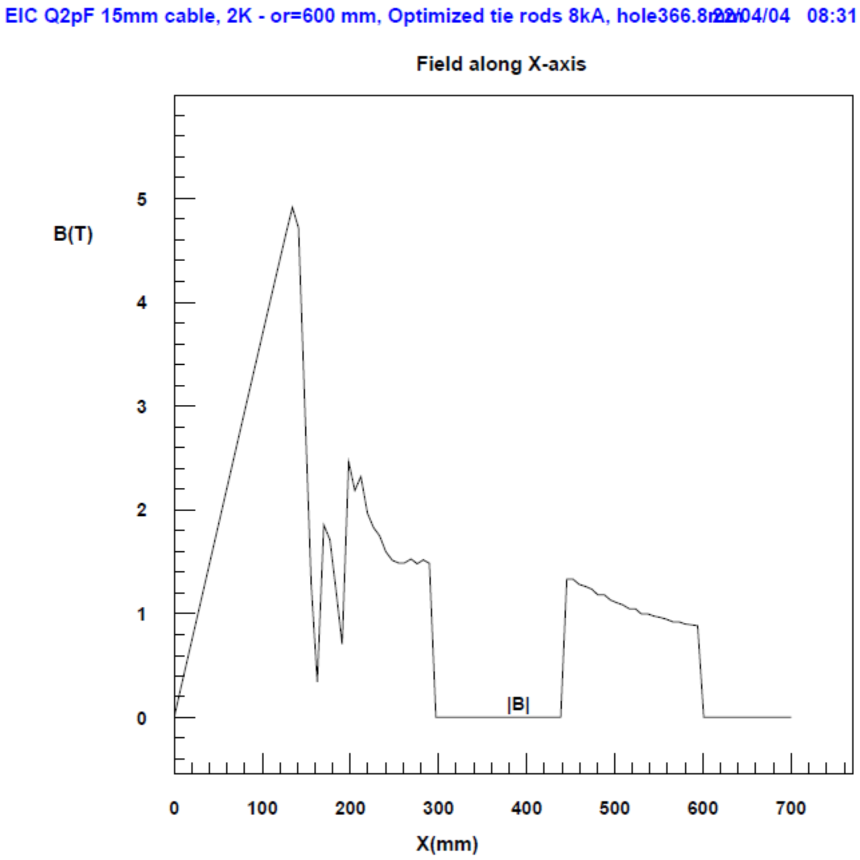


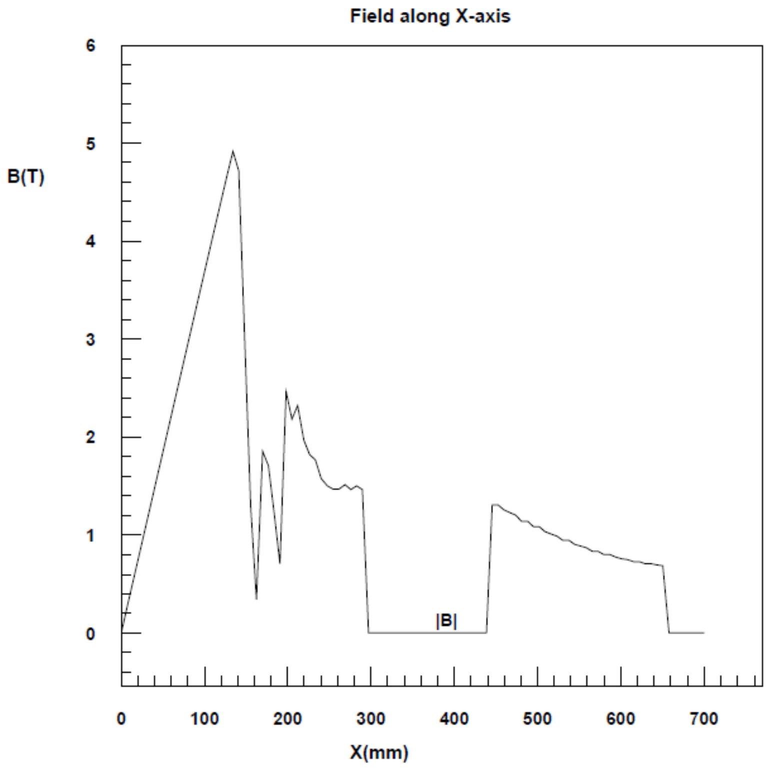
Choosing Yoke Outer Radius

Field on X-axis @I=8kA (gradient = 36.8 T/m)

Outer radius = 550 mm | **Outer radius = 600 mm** | **Outer radius = 650 mm**



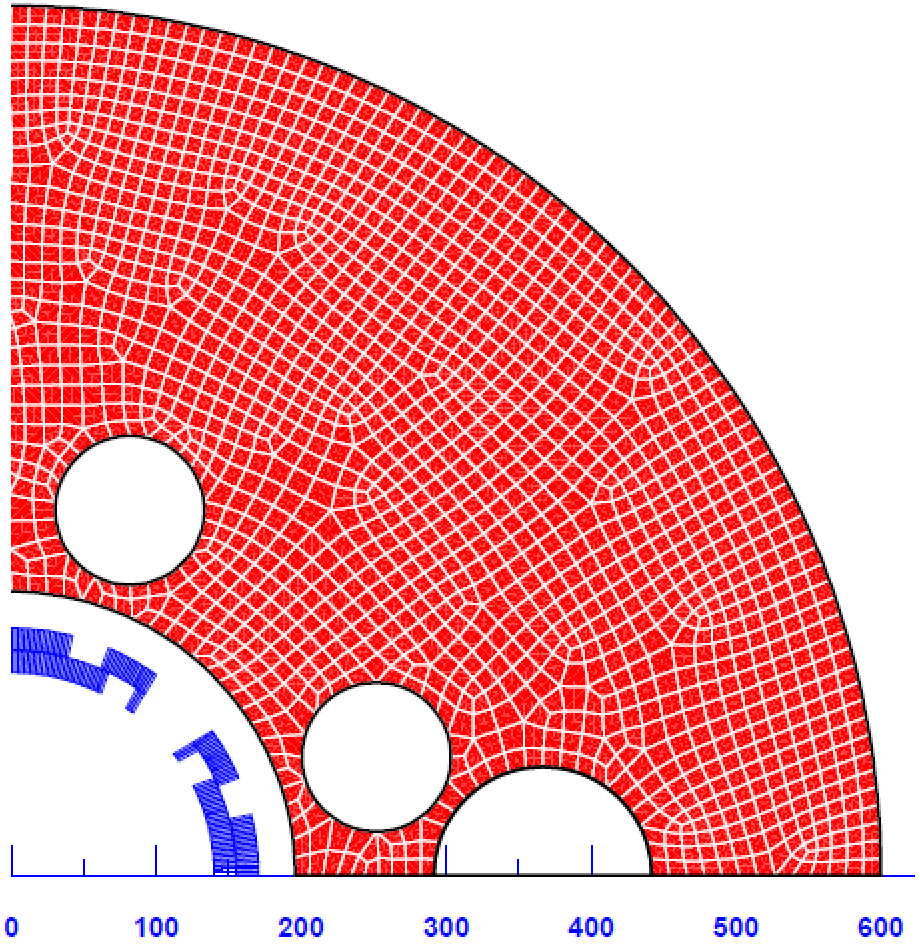




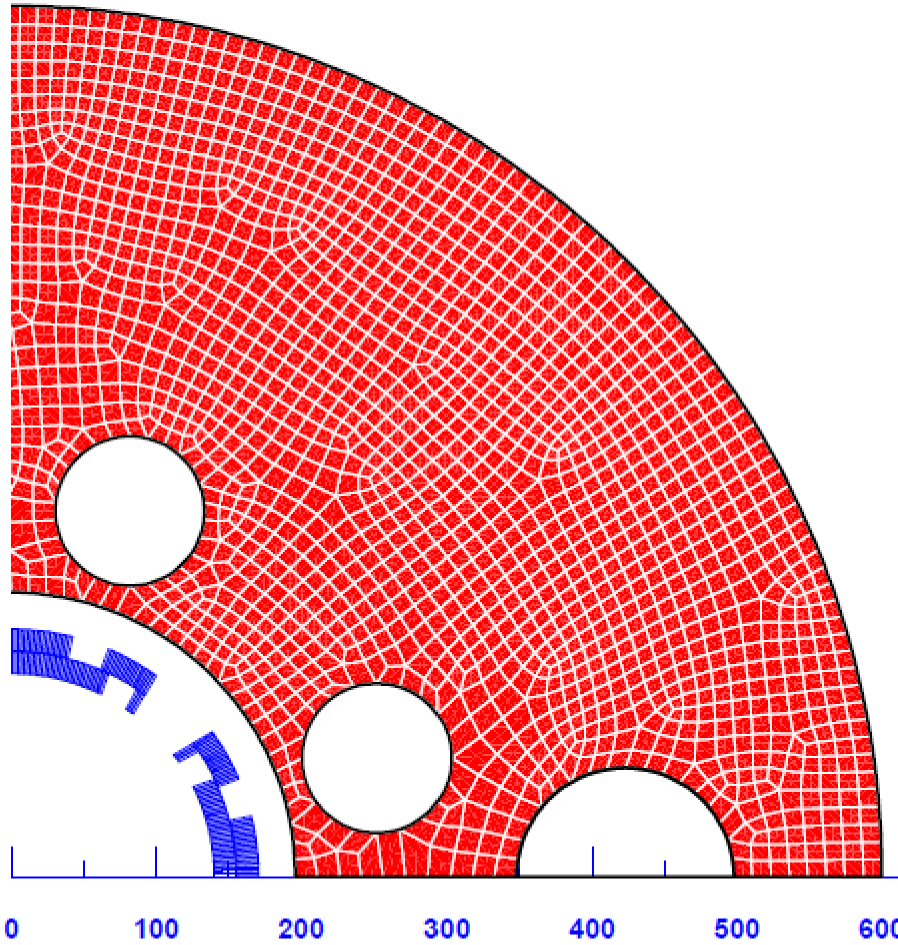
Outer radius of 600 mm is chosen

Holes for e-beam at two ends of the Q2pF

@366.28 mm from Q2pF center



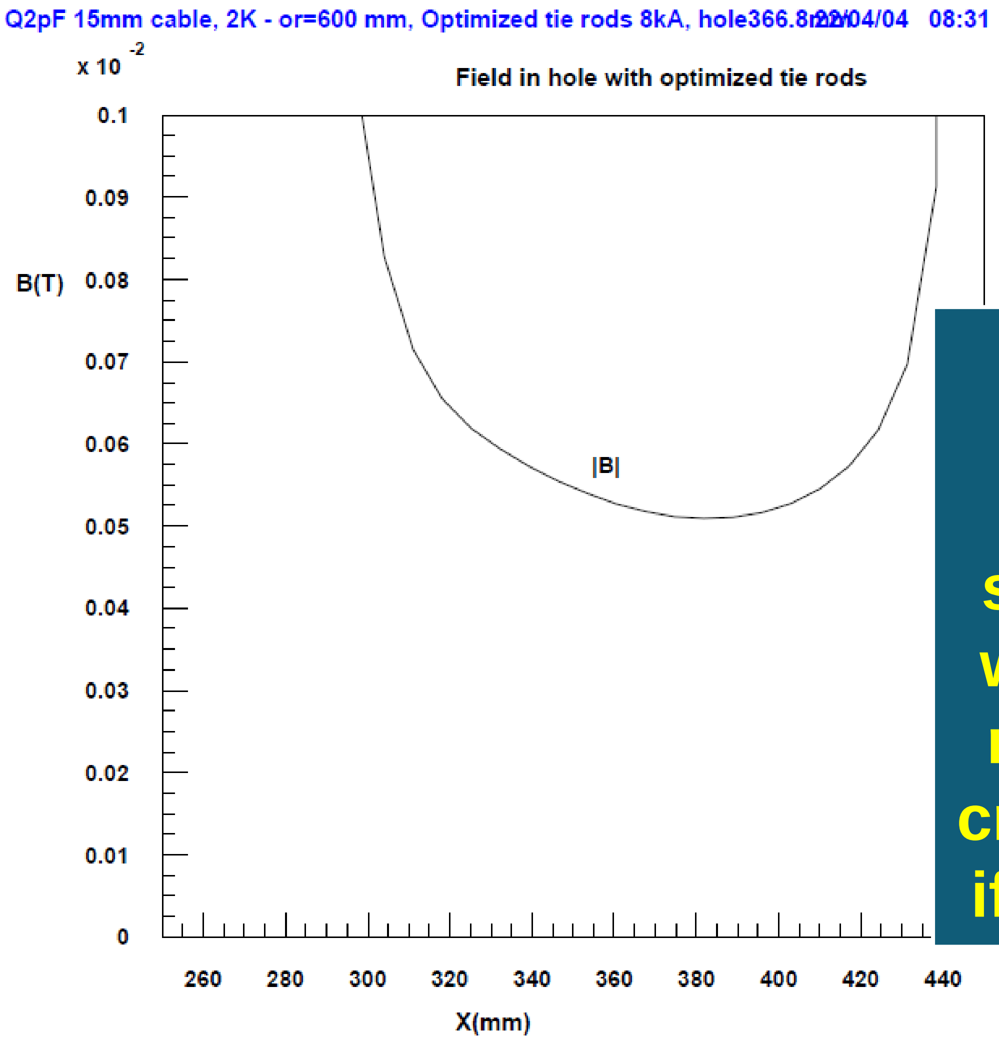
@423 mm from Q2pF center



New locations are a bit further out (less challenging). We are covering a large range.

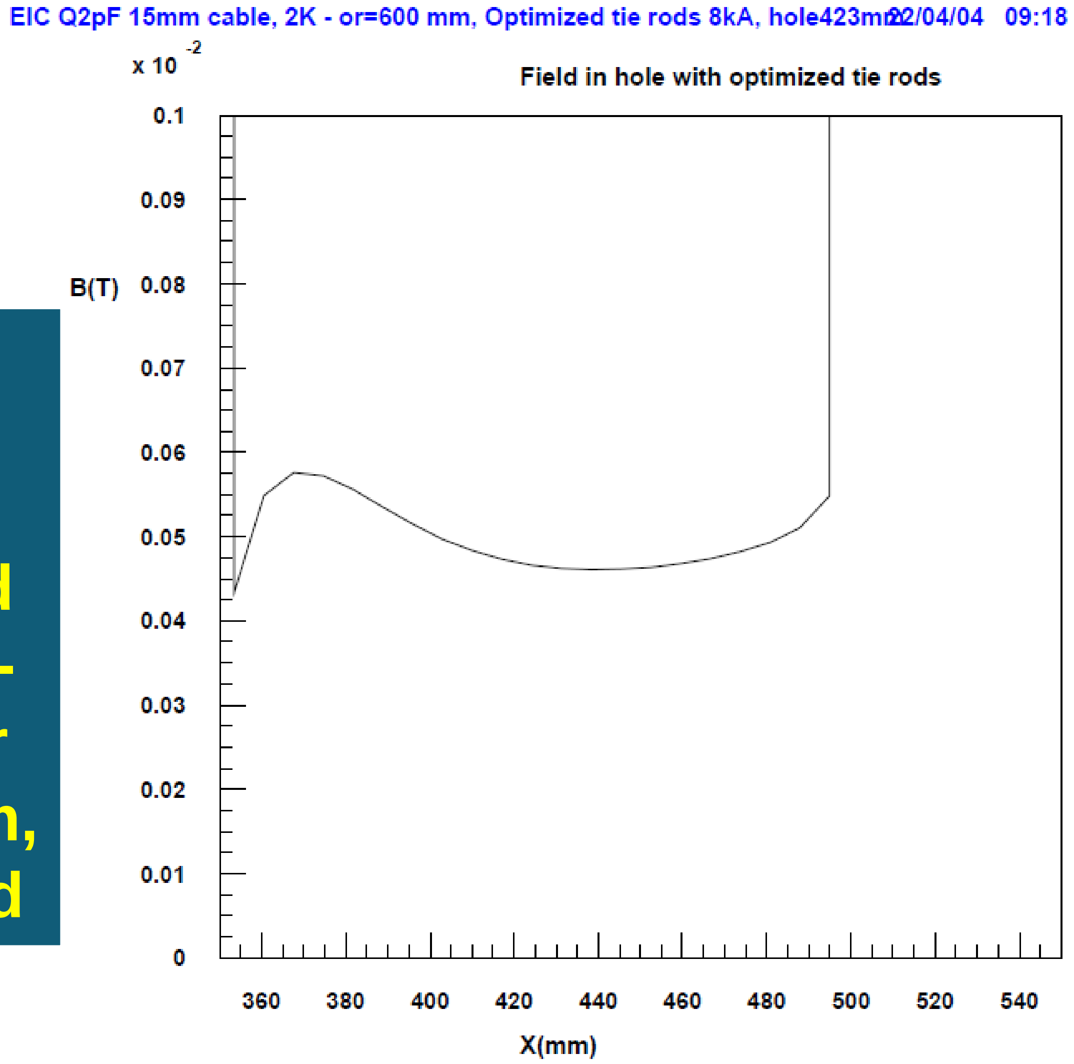
Holes for e-beam at two ends of the Q2pF

@366.28 mm from Q2pF center



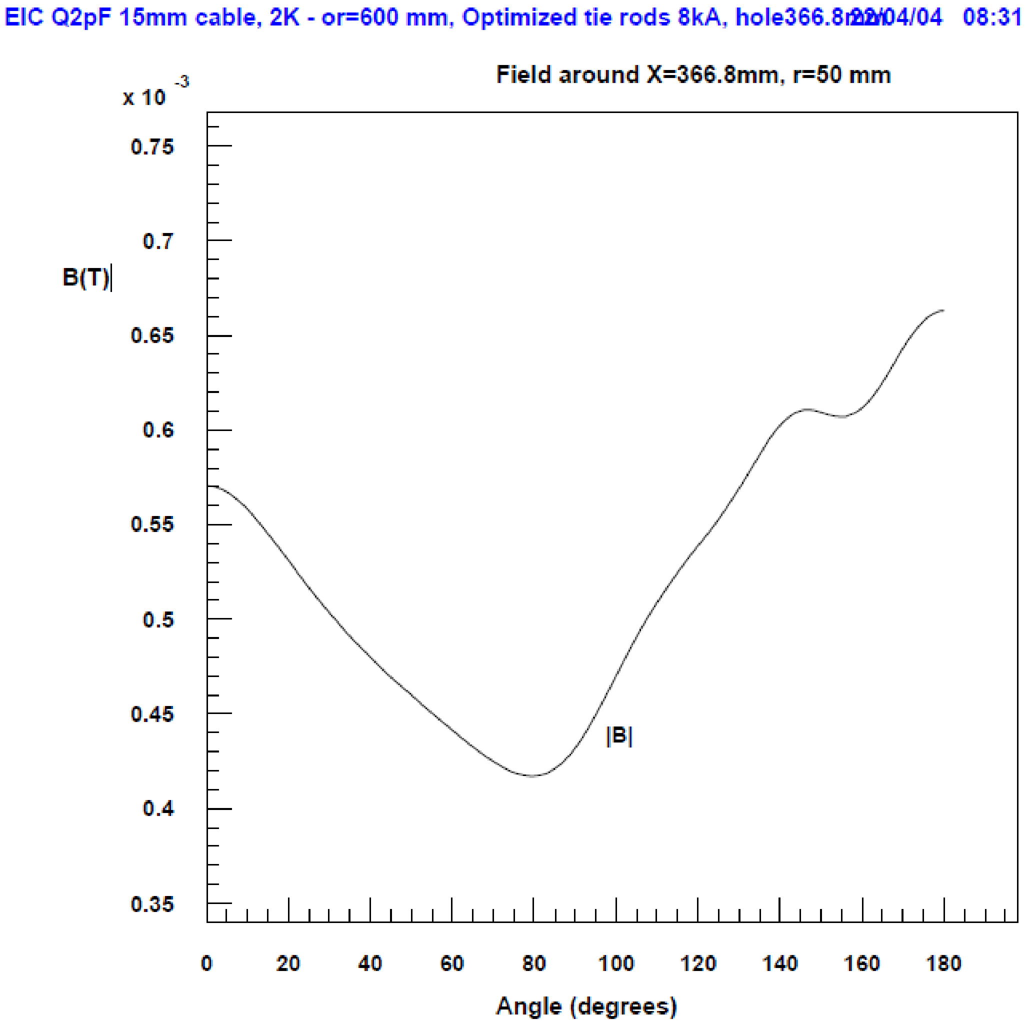
~½ mT can be easily shielded with mu-metal or cryoperm, if needed

@423 mm from Q2pF center



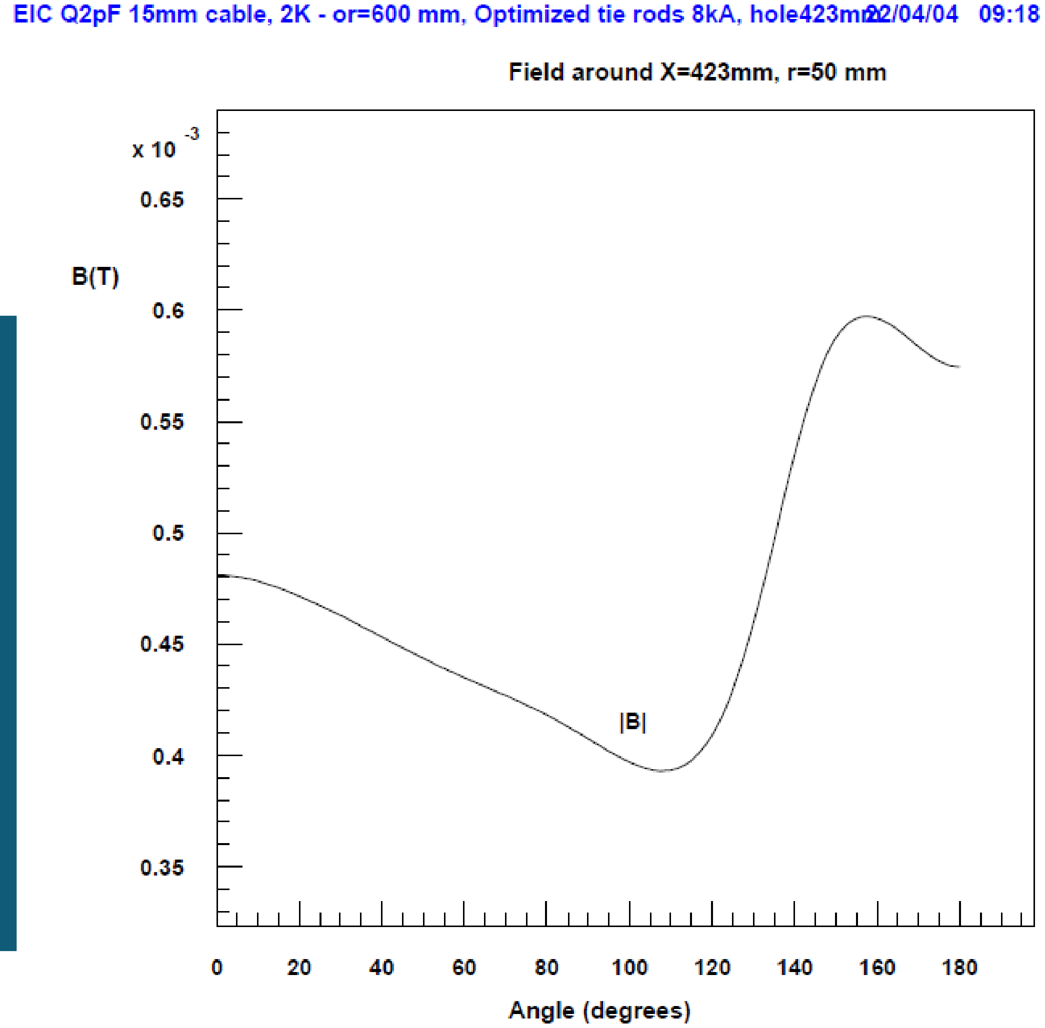
Holes for e-beam at two ends of the Q2pF field @r=50mm

@366.28 mm from Q2pF center

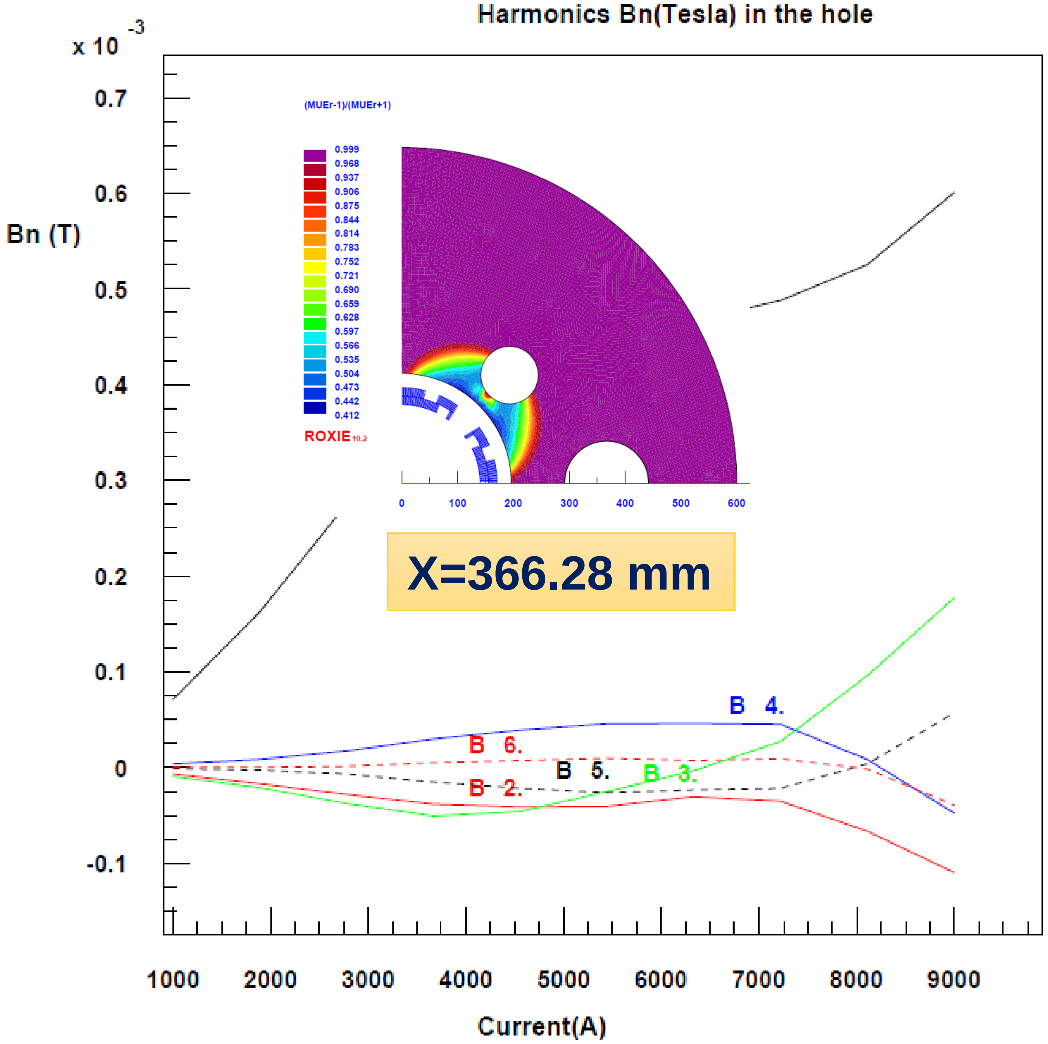


~½ mT can be easily shielded with mu-metal or cryoper, if needed

@423 mm from Q2pF center



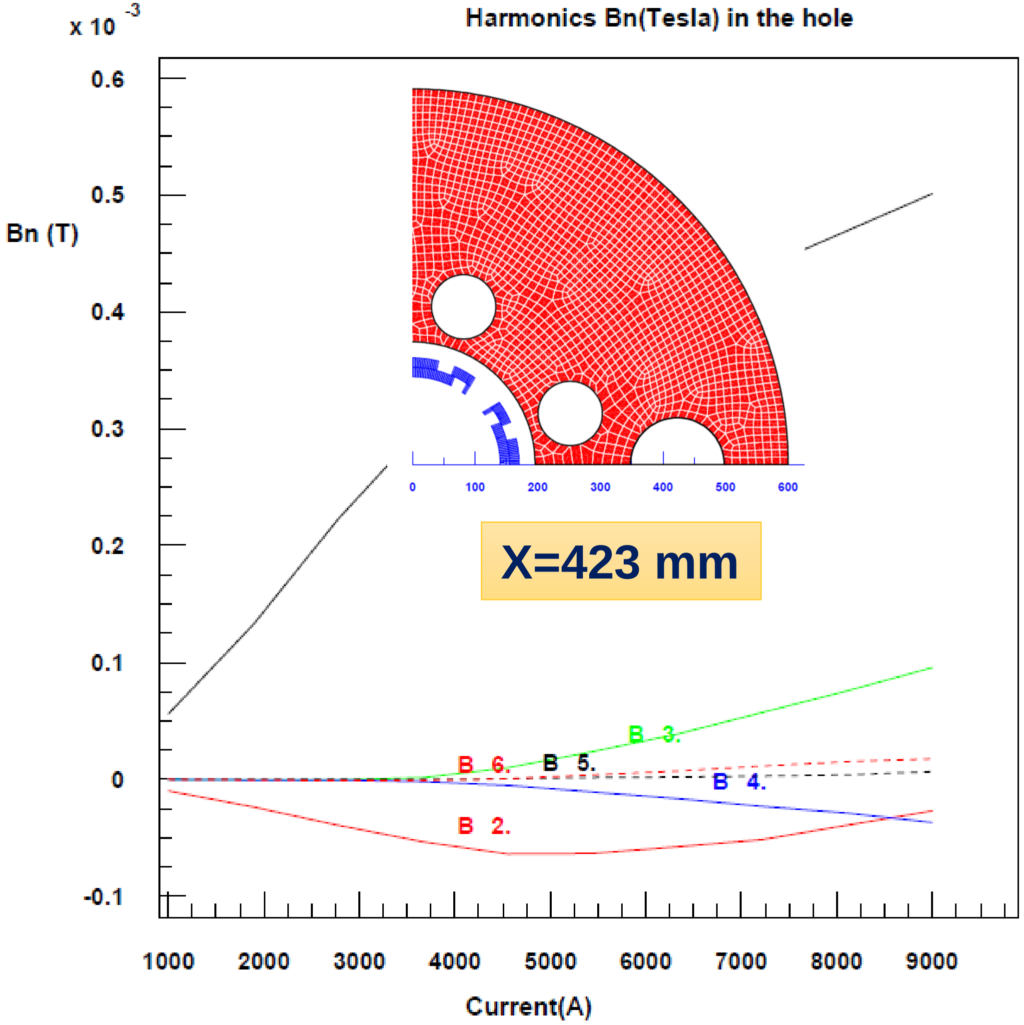
Tie Rods to Reduce Field in Hole for Electron beam



Harmonics @50 mm (where is the e-beam?)

B_1 shouldn't matter at this field level.

Other B_n's are $<10^{-4}$



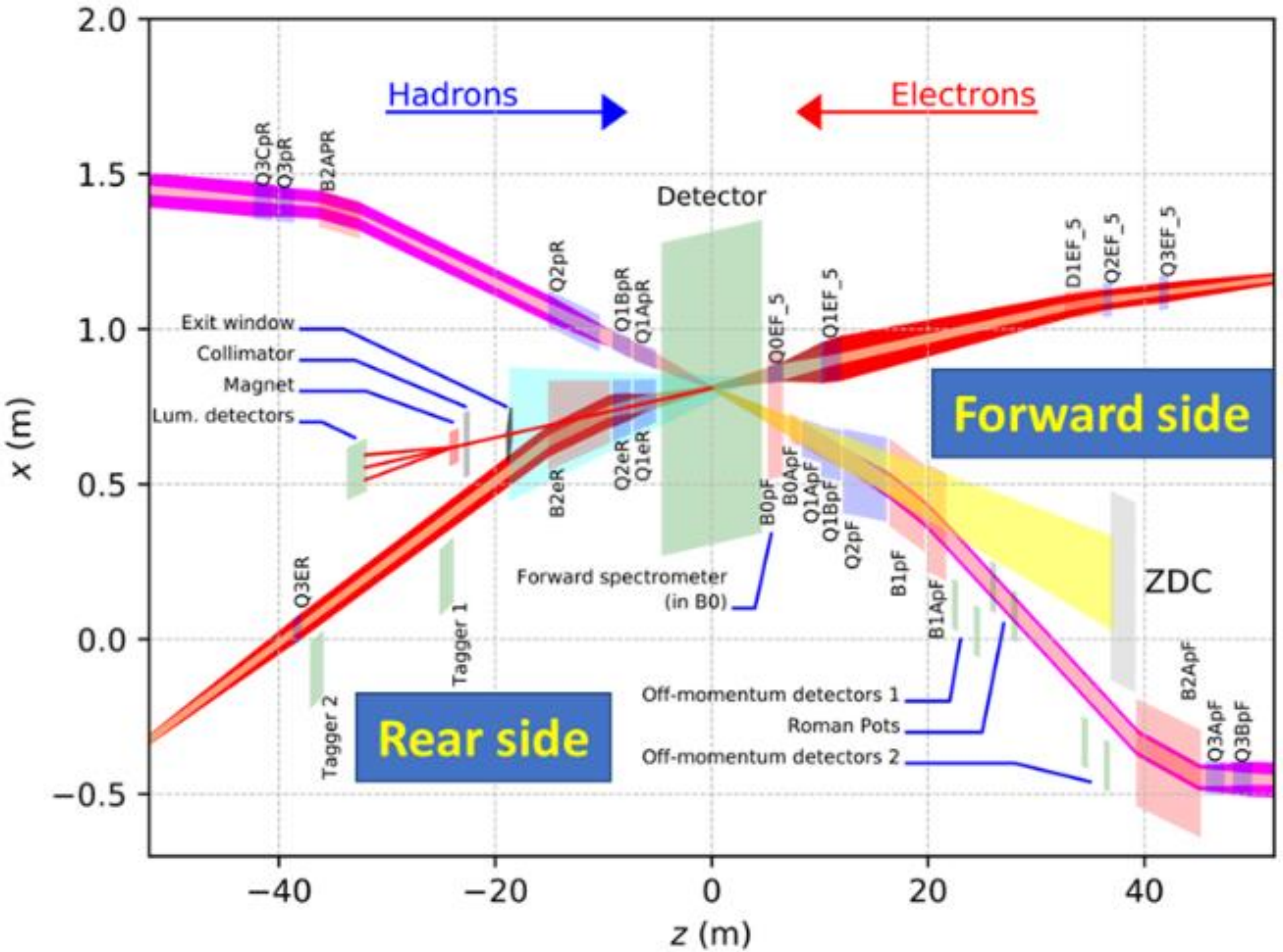
Optimized Iron: Major reduction in the field in the hole for e-beam

Finer optimization not yet preformed

Summary

- A reasonably good coil cross-section optimized. It has small geometric harmonics, good mechanically geometry, and has some tunability for adjusting harmonics.
- The cross-section has the collar thickness as requested by the initial mechanical analysis. A further increase can be accommodated, if needed.
- Operating margin is ~70%. Can be reduced, if desired, with a single layer design (higher current) or with a narrower cable which can also be used in B1pF & B1apF.
- Relatively large holes for tie rods near the yoke inner radius included. They have a large impact on saturation-induced harmonics. Location and number of those holes are used in reducing the impact of non-linear iron saturation on field quality.
- These holes are also used in reducing field in the hole for the electron beam.
- The field in the hole has become so low (~ ½ mT) that either the solution can be used as such (low B_n's) or can be further reduced with a mu-metal shield.
- B_n (not b_n) harmonic method is suggested to communicate with accelerator physicists so that they can examine the impact of these non-linearity on e-beam.

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
Q3ER
B2eR
Q2eR
Q1eR
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

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

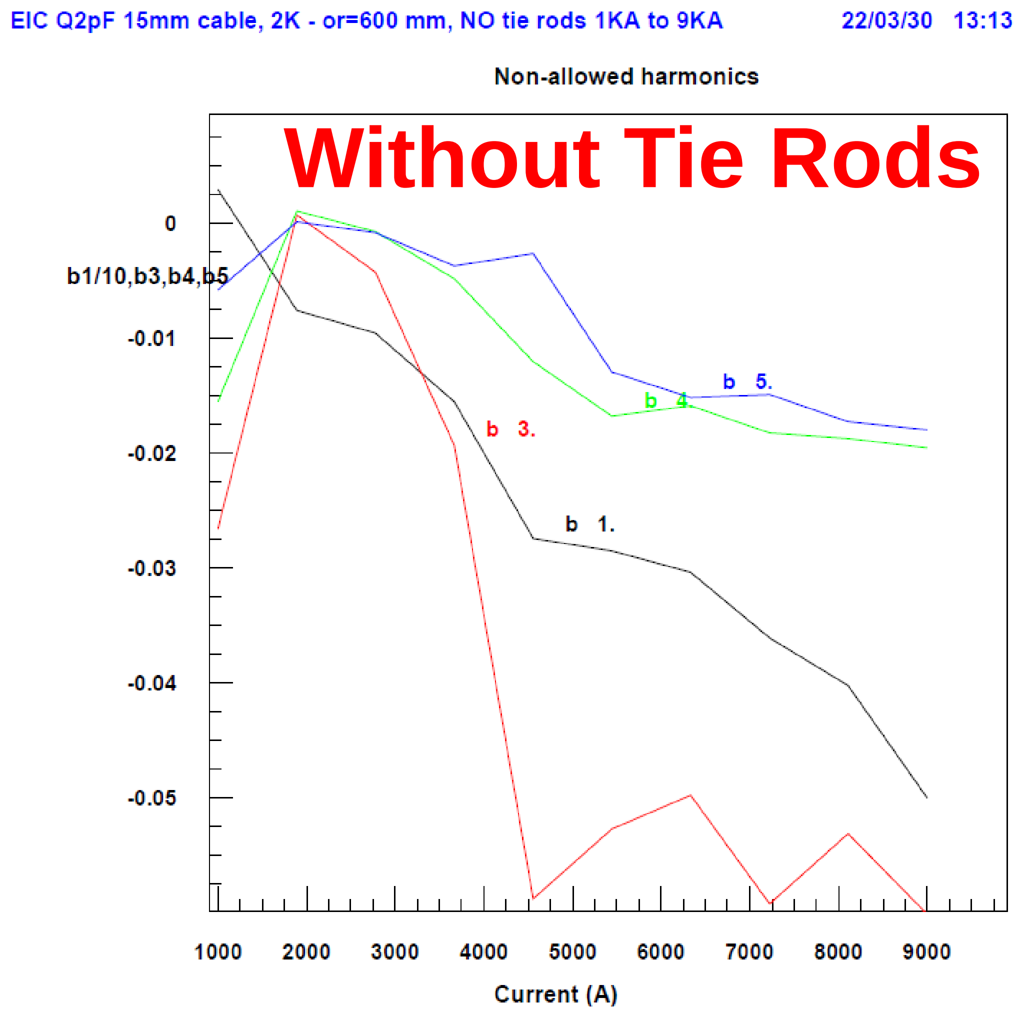
No	Name	Cable Geom.	Strand	Filament	Insul	Trans	Quench Mat.	T_o	Comment
1	EICLHCB2K	EICLHCB	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR QUAD @2K
2	EICLHCQ2K	EICLHCQ	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	2	LHC INNER FOR EIC IR DIPOLE @
3	LHCIN42K	EICLHC01	STREIC1	NBTII	ALLPOLYIL	TRANS1	NONE	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

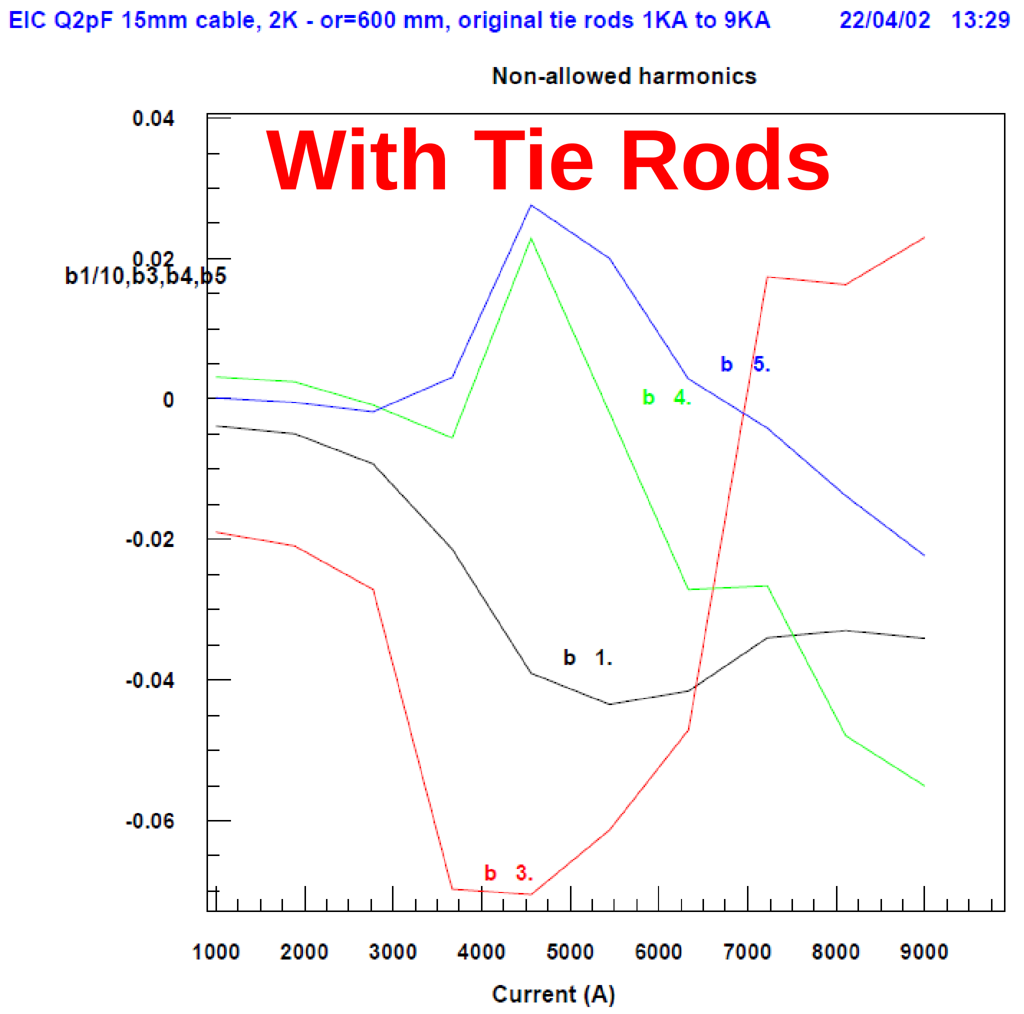
Keystone angle for cable width << coil readius		Q2pF	B1ApF
Cable height		15.1	15.1
Cable mid-thickness		1.9	1.9
Insul (one side)		0.12	0.12
Coil i.r.		140	185
Avg Rad		147.55	192.55
dt		0.2190	0.1678
Width_i		1.790	1.816
width_o		2.010	1.984

Note: Keystones are reduced for EIC

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

Impact on Non-allowed Harmonics in Q2pF





Small non-allowed harmonics (computational errors)