EIC IR Magnet Design Summary (FY20)

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Cables

- **Magnet designs based on the cables that can be easily procured**
- **Two types of 36-strand cables**
  - **Same width and mid-thickness for both**
  - **Keystone #1 for B1apF and B1pF**
  - **Keystone #2 for quadrupoles**

Content

- These slides summarize the magnetic design work performed in FY20 on EIC IR cable magnets
- The main goal of this exercise was to develop magnetic designs such that all EIC IR magnets can operate at 4.2 K rather than 1.8 K
- Since the electron beam is very close to the proton beam, leakage field from the proton IR magnets must be low in the path traverse by the e-beam.
- Another goal was to develop designs based on the cables that can be easily procured (36-strand)

Q2pF

Overview

- **Design studies completed for now for Q2pF. Several cases examined but only the chosen one will be presented.**
- **Operation at 4.2K/4.6K. Peak field (margin), field quality and field in the electron beam region optimized.**
- **Strand/wire used: dia =1.065 mm, Cu/Sc =1.6.**
- **Cable: 19.4 mm wide (19.7 with insulation) with 36 strands, min thickness: 1.788 mm, max thickness: 2.012 mm.**

Chosen Cable Design (ROXIE)

Strand

No	Name	diam.	cu/sc	RRR	Tref	Bref	Jc@BrTr	dJc/dB	Comment
	STREIC1	1.065	1.6	70	1.9	10	1591	500.34	EIC BRUKER-CERN SCALED,7%DEGRA
1	STR01	1.065	1.6	70	1.9	10	1433.3	500.34	MB INNER
2	STR02	0.825	1.9	80	1.9	9	1953	550.03	MB OUTER, MQ

Cable Geometry

No	Name	height	width_i	width_o	ns	transp.	degrd	Comment
1	EIC3642A	19.4	1.788	2.012	36	115	3	EIC 36 STRAND @4.2K 2 Layers

Cable Definition

No	Name	Cable Geom.	Strand	Filament	Insul	_Trans	Quench Mat.	T_o	Comment
42	EIC3618	EIC3618	STREIC1	NBTII	ALLPOLYIL	NONE	NONE	1.8	EIC CABLE 36 STRAND, 1.8K
43	EIC3642	EIC3642	STREIC1	NBTII	ALLPOLYIL	NONE	NONE	4.2	EIC CABLE 36 STRAND, 4.2K
44	EIC3642A	EIC3642A	STREIC1	NBTII	ALLPOLYIL	NONE	NONE	4.2	EIC CABLE 36 STRAND, 4.2K
45	EIC3642B	EIC3642A	STREIC1	NBTII	ALLPOLYIL	NONE	NONE	4.6	EIC CABLE 36 STRAND, 4.6K

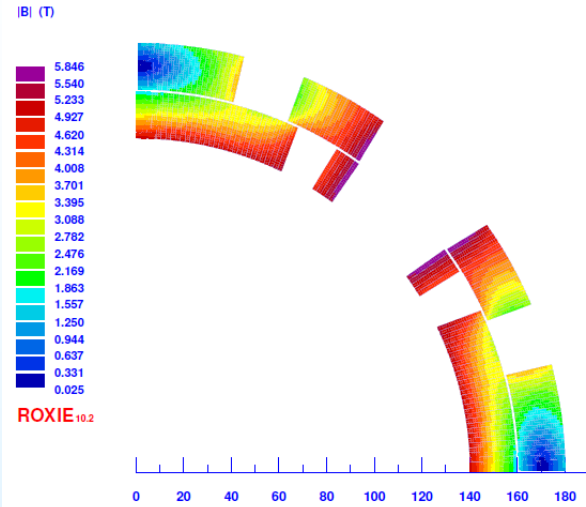
Strand dia =1.065 mm; 36 strands in cable

Cu/Sc =1.6, width 19.4 mm (bare)

Operating Temperature: 4.2 K / 4.6 K

Field Harmonics in Q2pF

A good field quality can be obtained with the restriction of designing the cross-section for a good mechanical design (all harmonics <1 unit)

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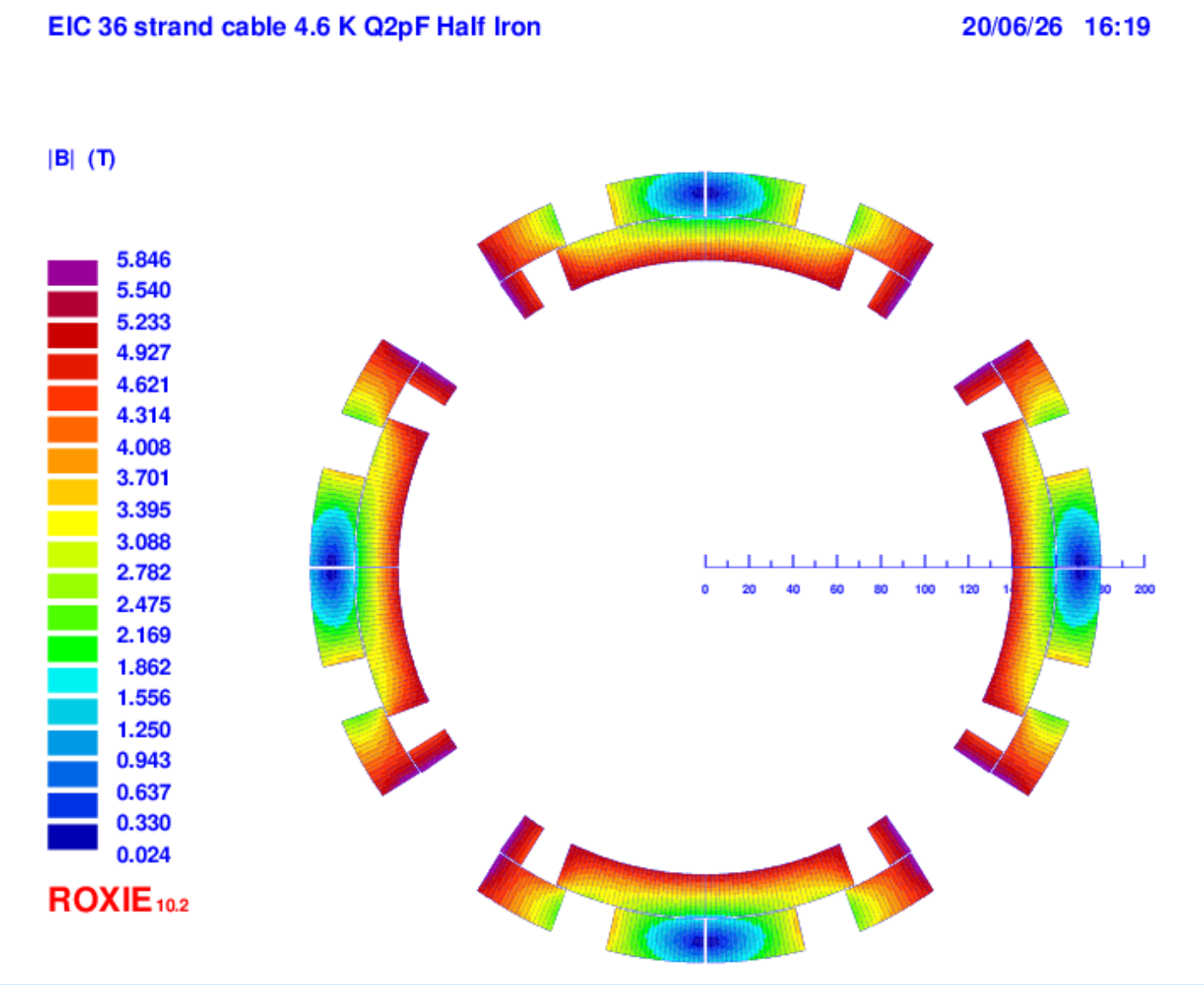
REFERENCE RADIUS (mm) ..............................        83.

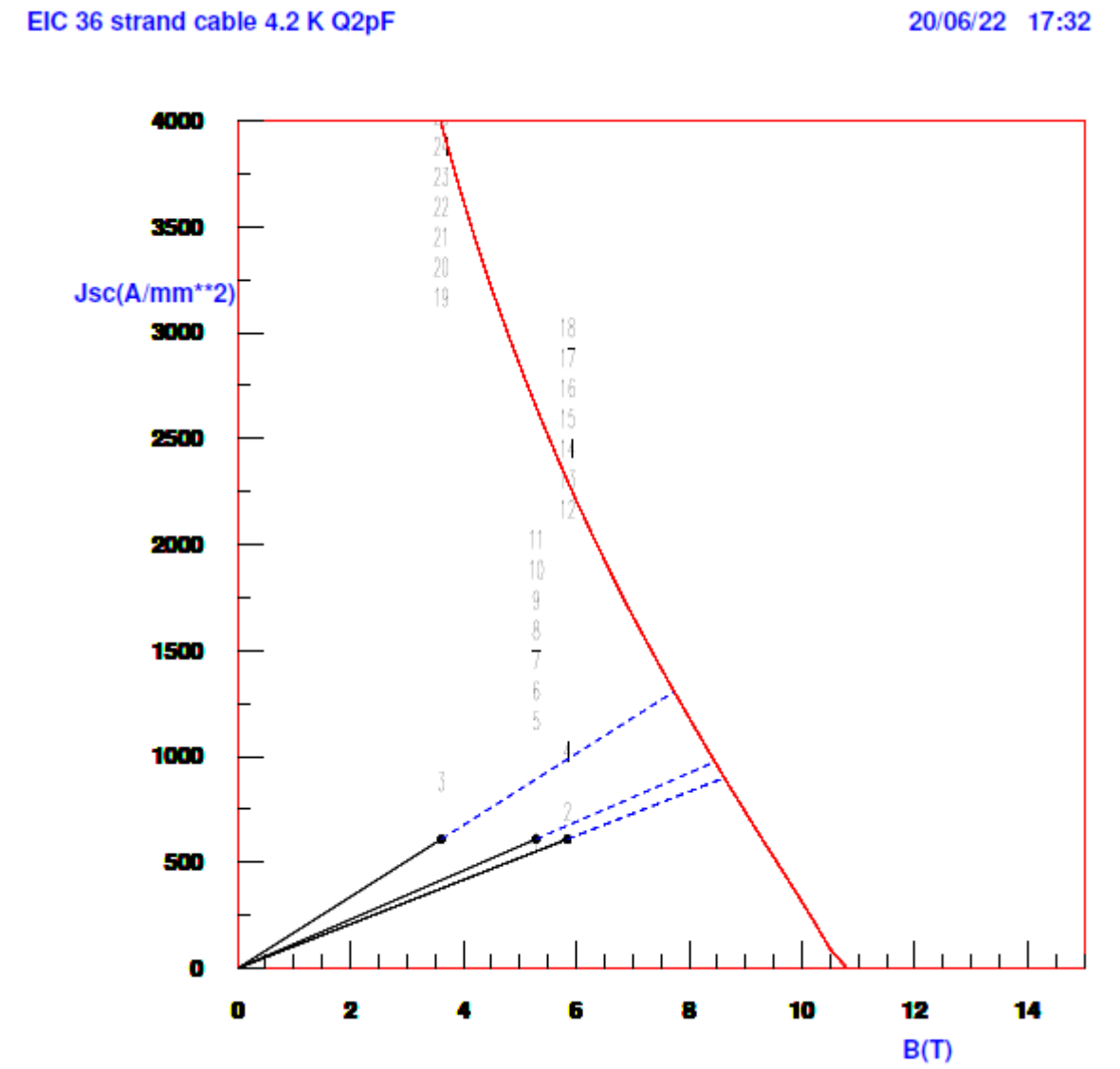
MAGNET STRENGTH (T/(m^(n-1)) .......................      36.0373

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:      -0.00000  b 2:  10000.00000  b 3:      -0.00000
b 4:      -0.04348  b 5:      0.00000  b 6:      -0.36357
b 7:       0.00000  b 8:     -0.00184  b 9:      -0.00000
b10:       0.62176  b11:     -0.00000  b12:      -0.00007
b13:       0.00000  b14:     -0.22463  b15:      -0.00000
b16:      -0.00000  b17:      0.00000  b18:       0.01234
```

Peak Fields in Q2pF

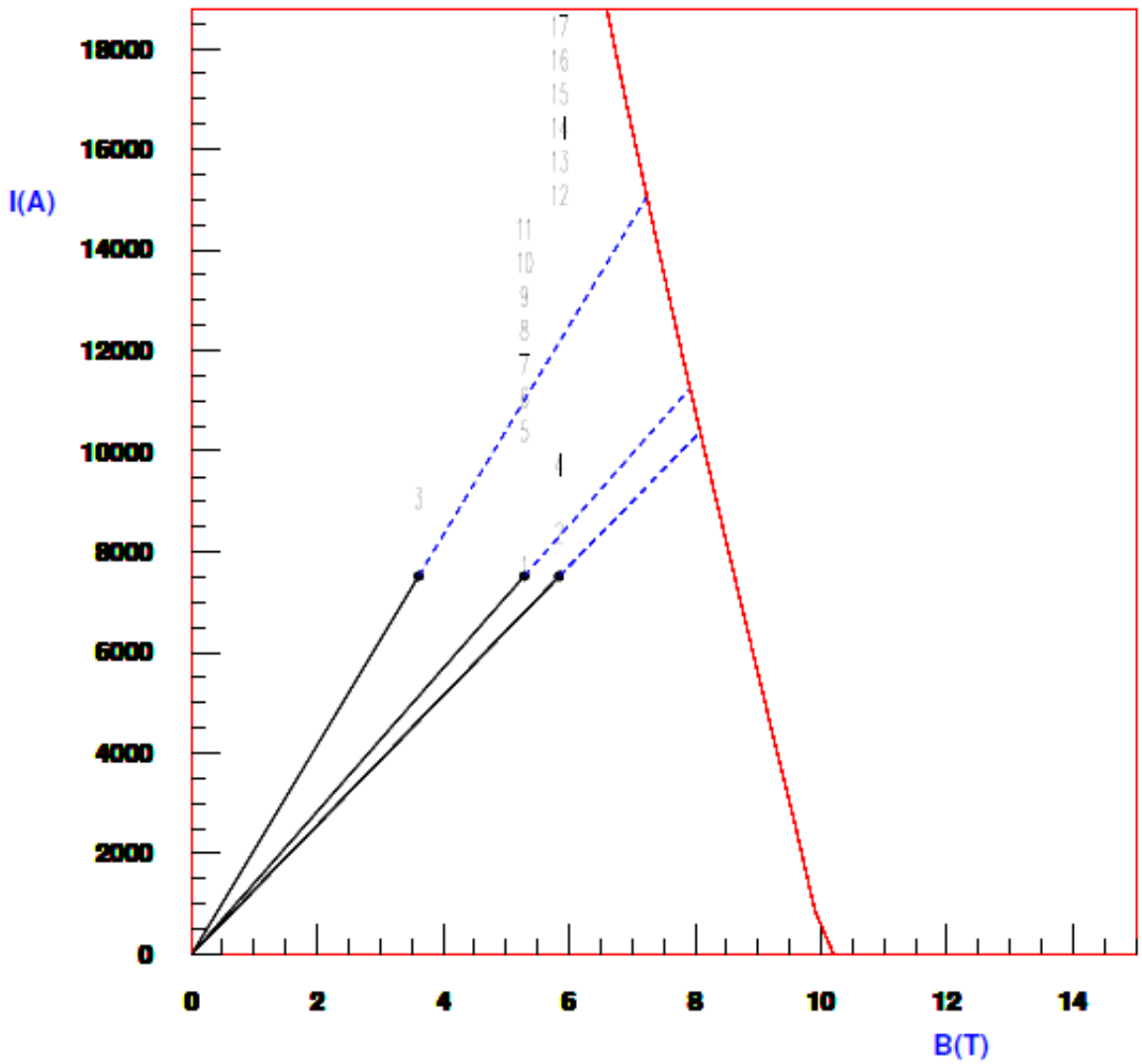


Field Margin at 4.2 K



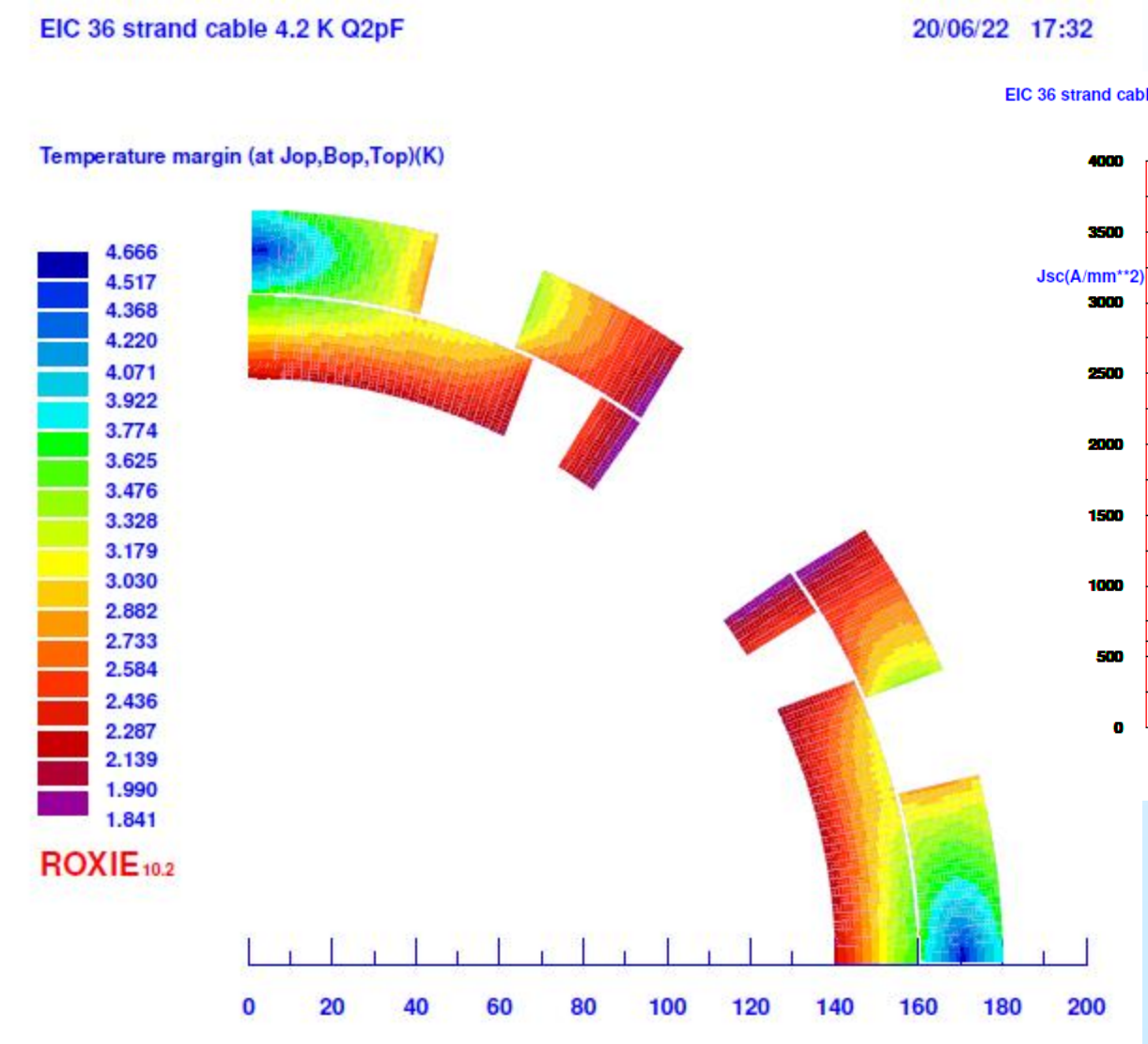
Healthy Margin: ~47% over 36 T/m at 4.2K (68% on loadline)

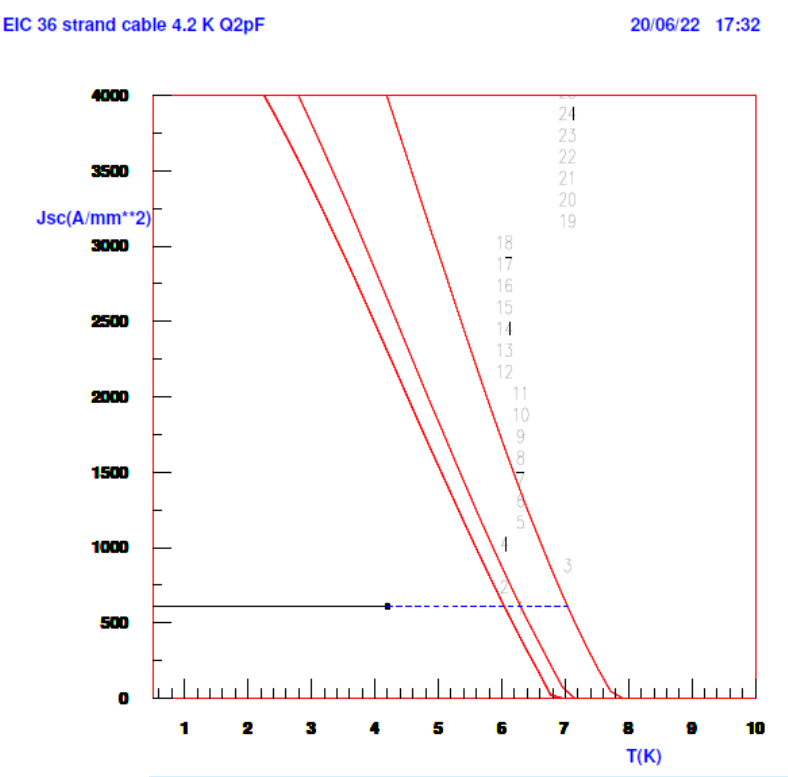
Field Margin at 4.6 K



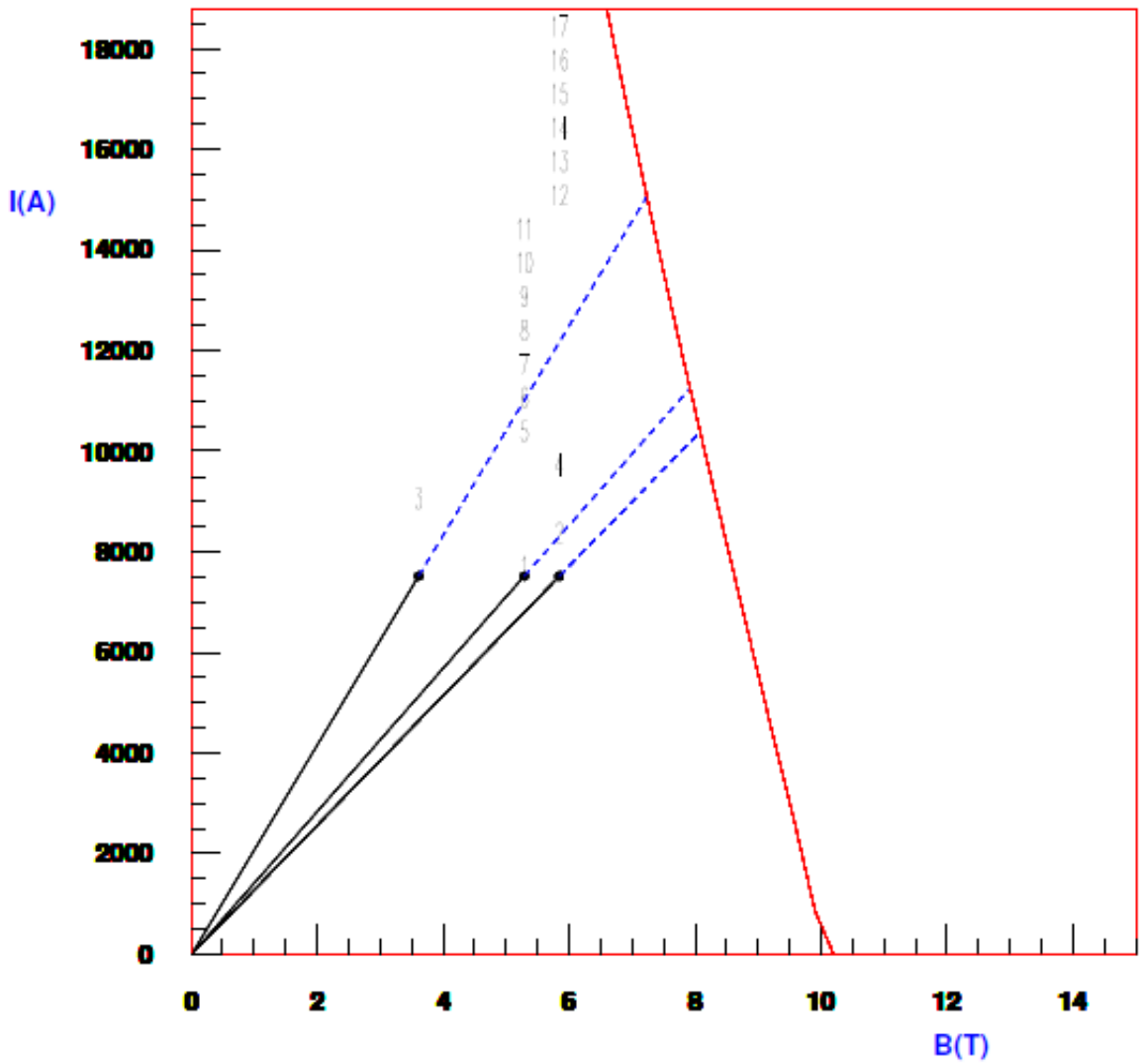
Healthy Margin: ~38% over 36 T/m at 4.6K (72% on loadline)

Temperature Margin at 4.2 K Over Different Blocks



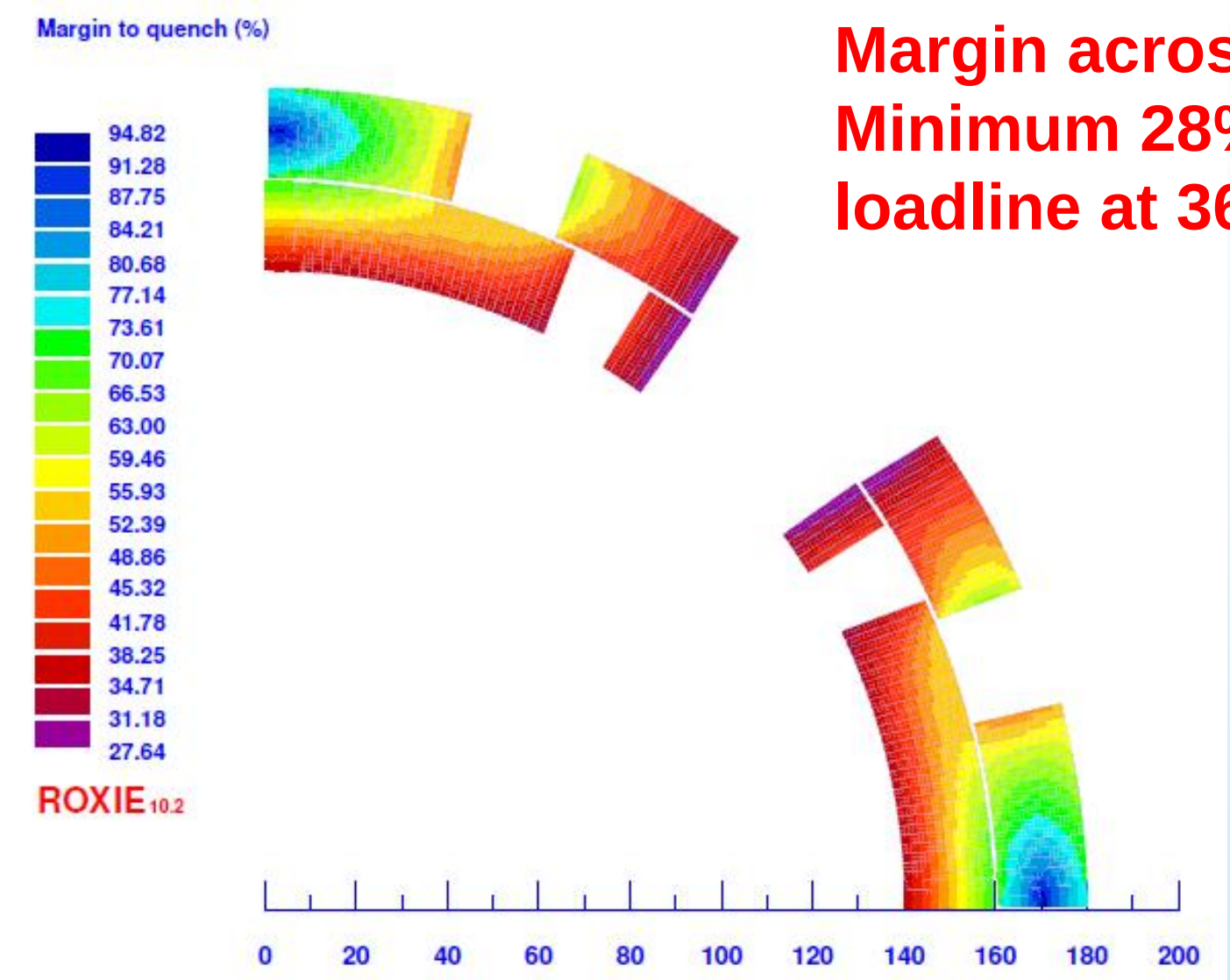


Field Margin at 4.6 K



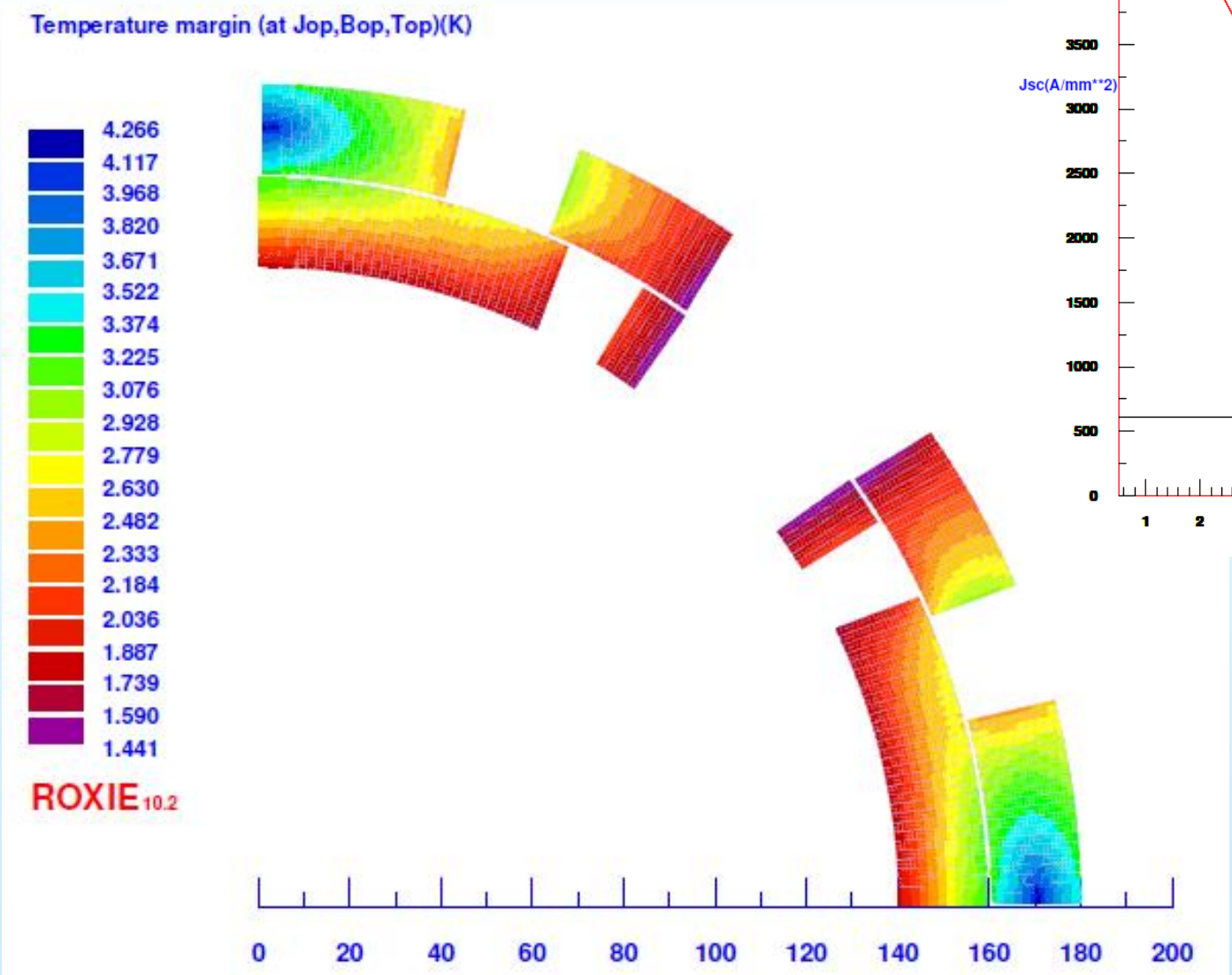
Healthy Margin: ~38% over 36 T/m at 4.6K (72% on loadline)

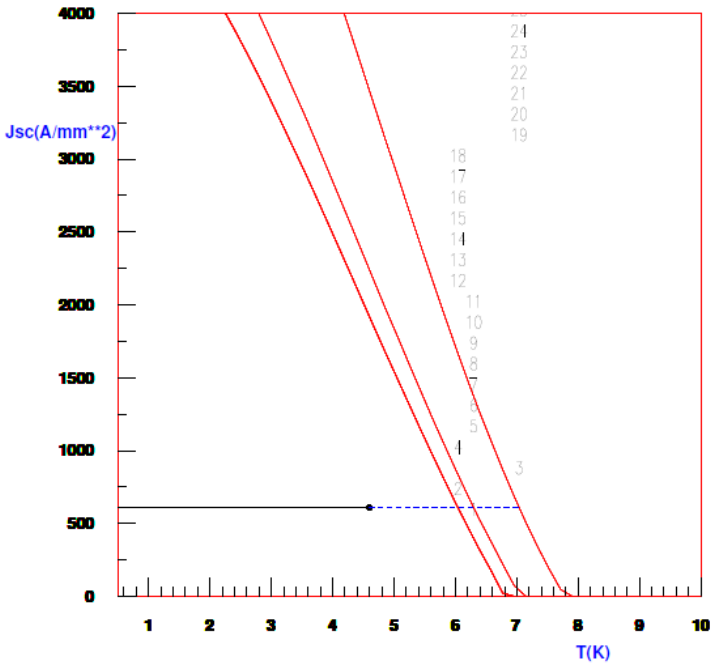
Field Margin at 4.6 K



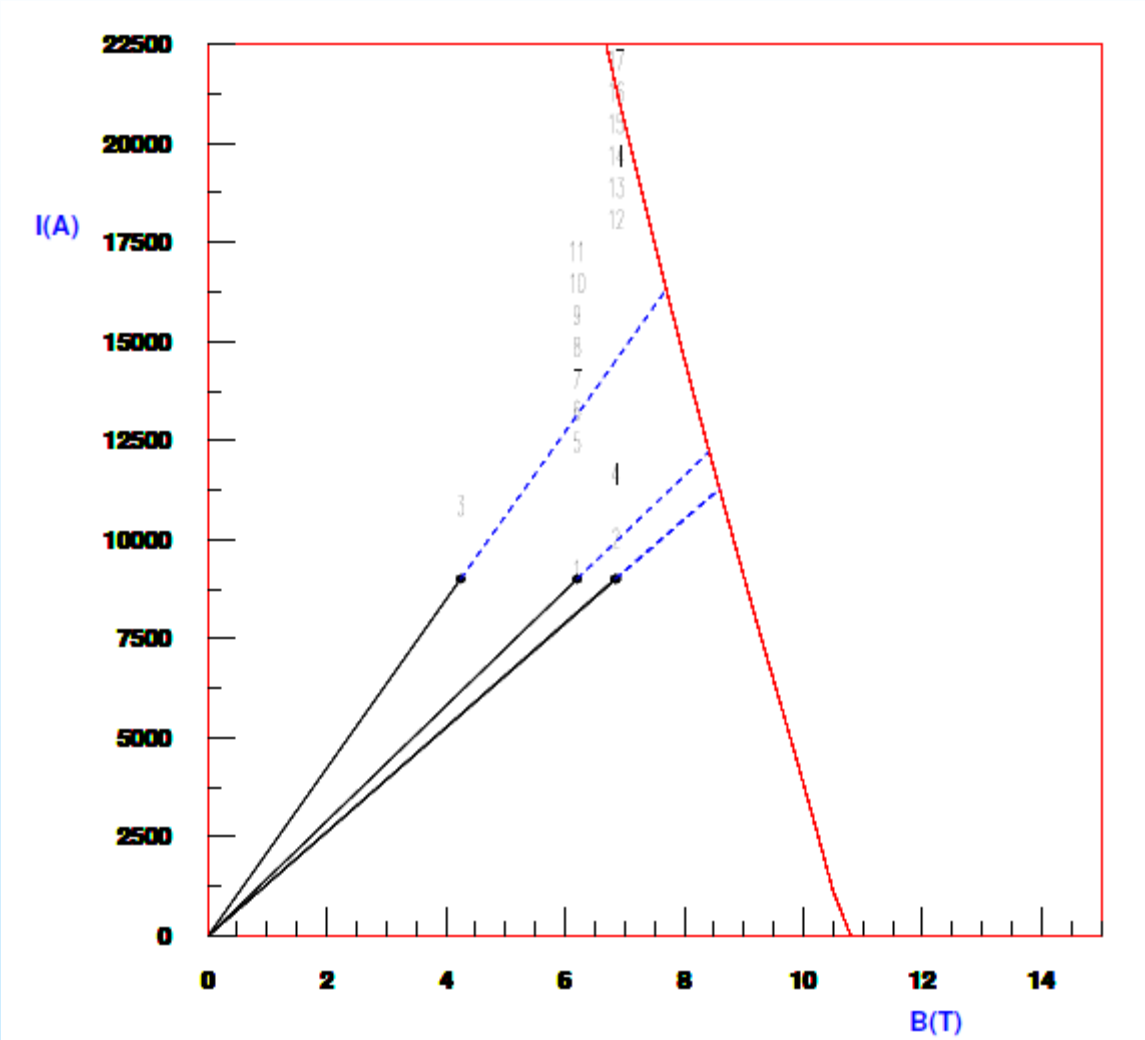
Margin across the coil: Minimum 28% on the loadline at 36 T/m @4.6 K

Temperature Margin at 4.6 K Over Different Blocks



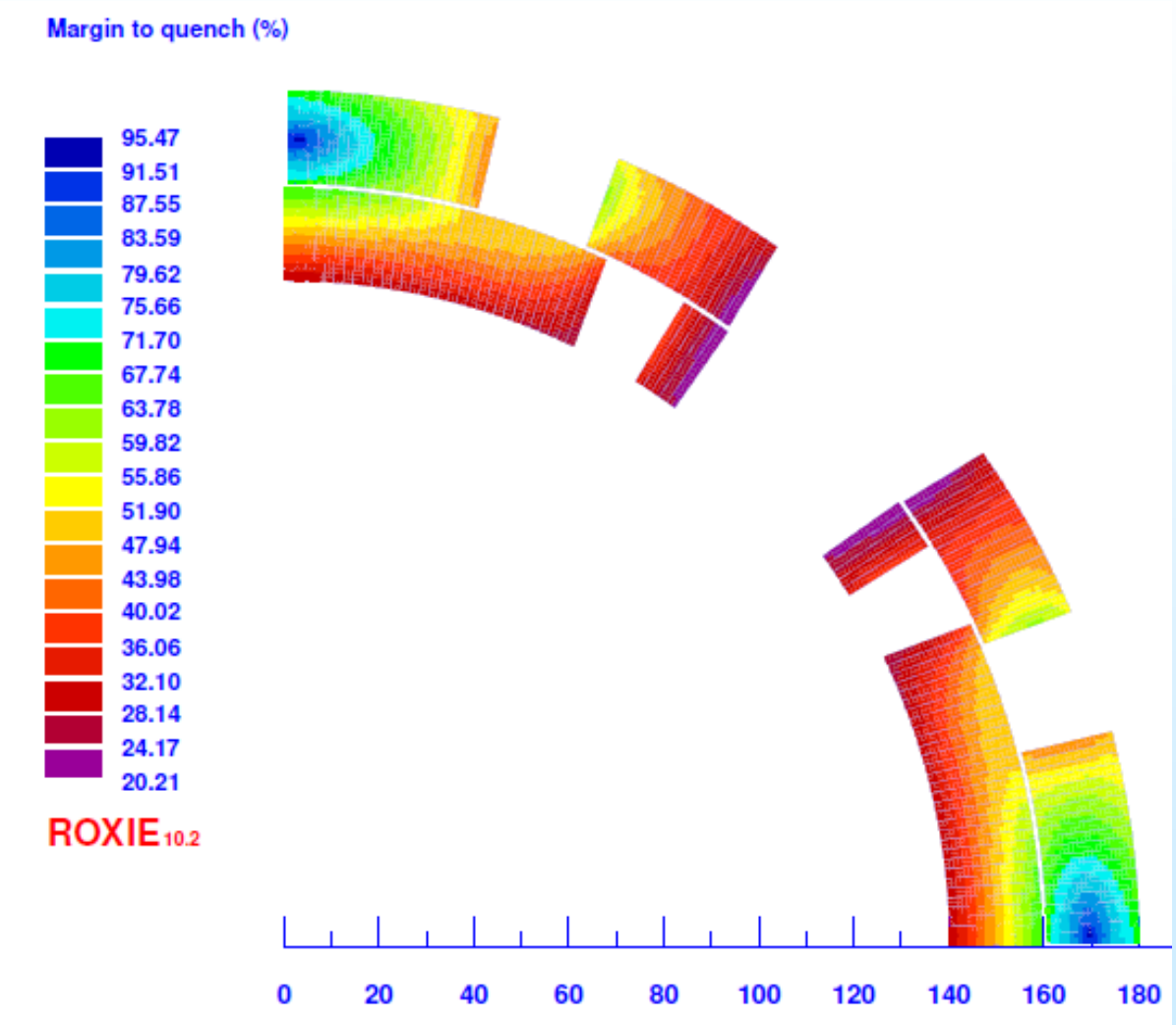


Field Margin at 4.2 K over 41 T/m



Significant Margin: ~25% over 41 T/m at 4.2K (9 kA) (80% on loadline)

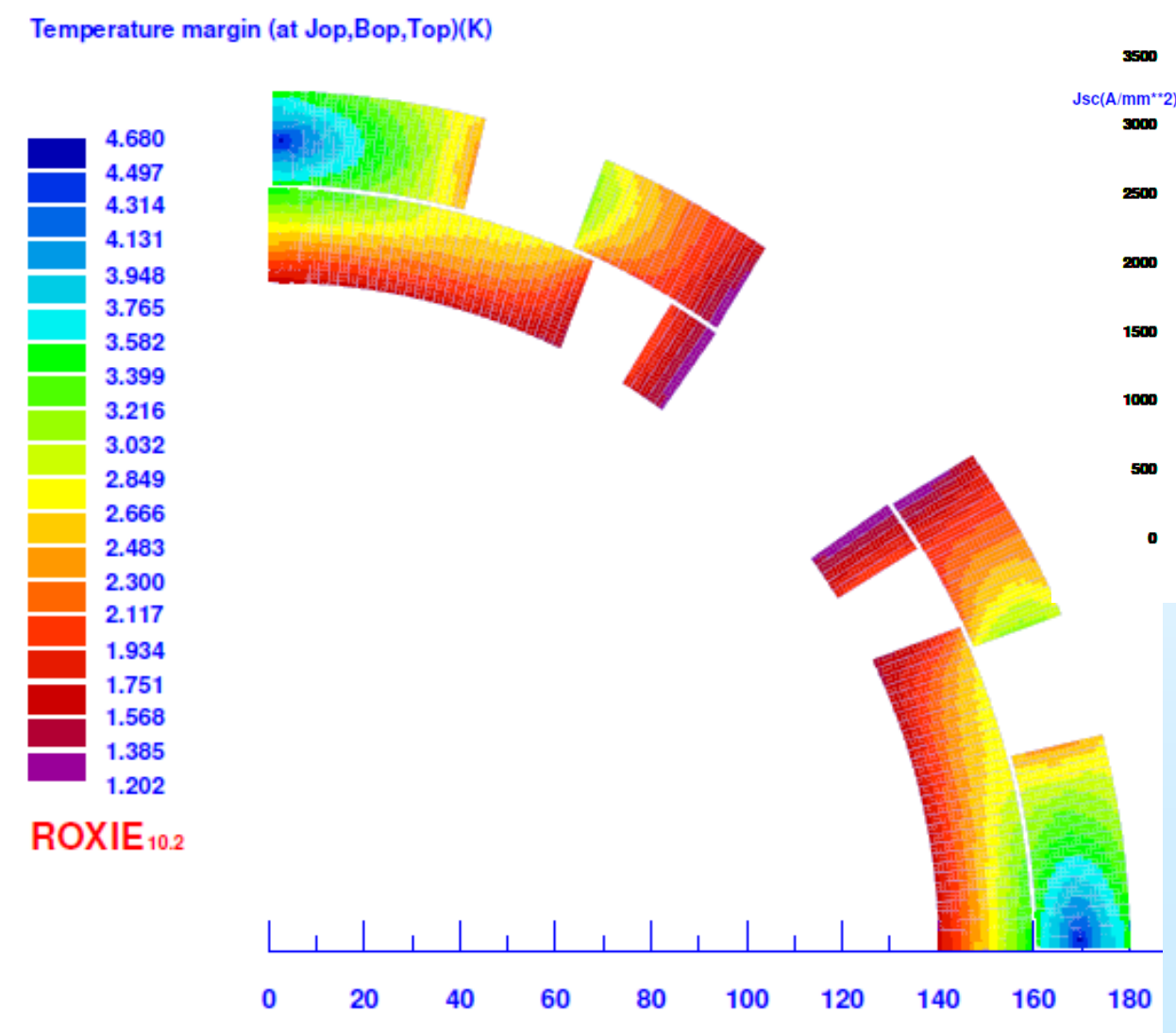
Field Margin over 41 T/m @4.2 K

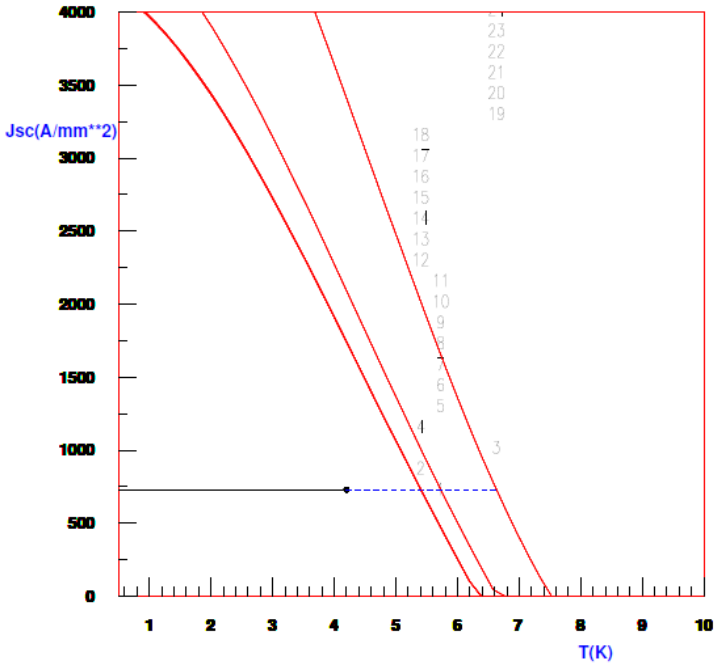


Margin across the coil: Minimum 20% on the loadline at 41 T/m at 4.2K

A Reasonable Margin: ~25% over 41 T/m at 4.2K (80% on loadline)

Temperature Margin over 41 T/m at 4.2 K Over Different Blocks

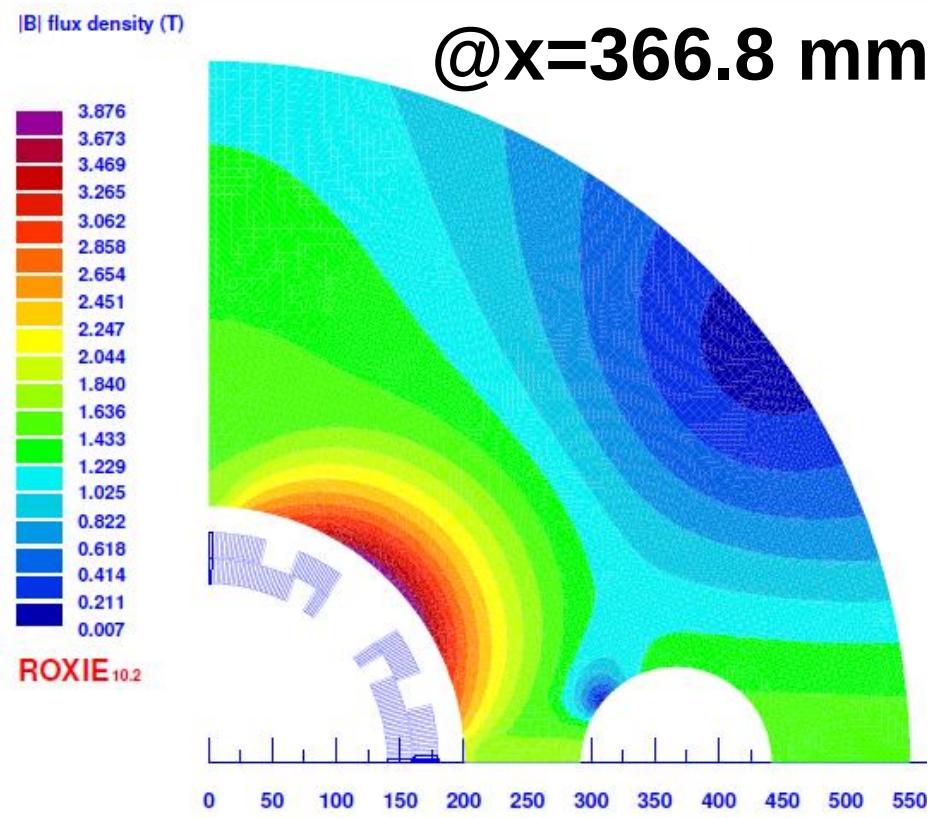


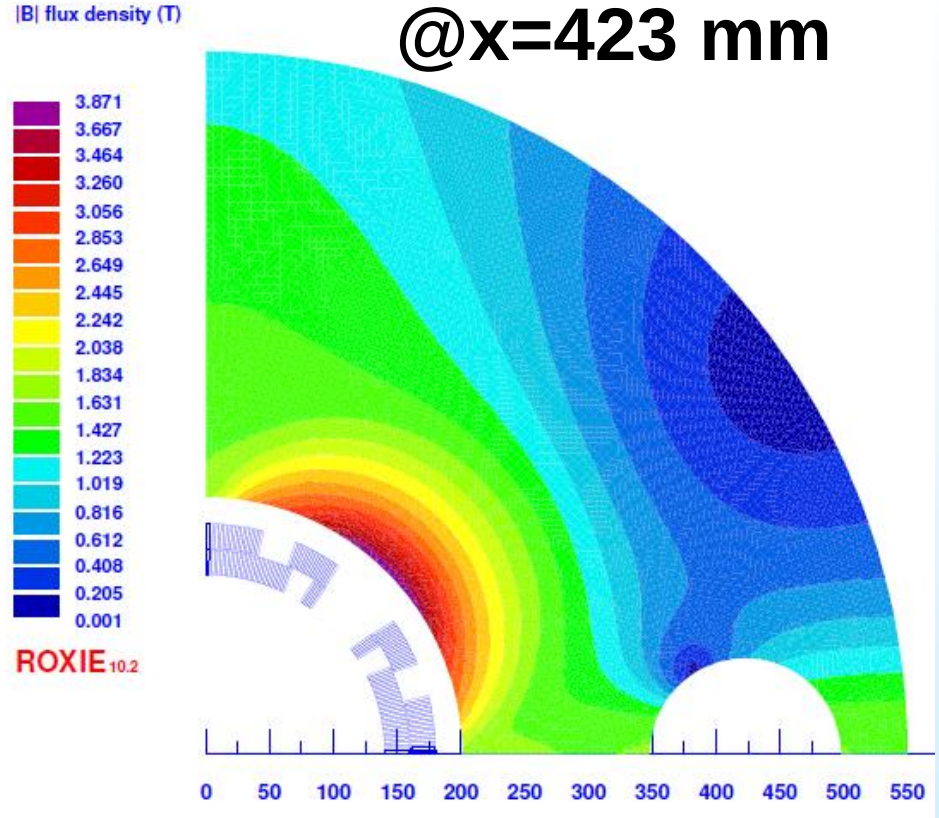


Extra layer reduced the space for the flux return and increased the field the electron beam region.

Field in the electron beam region can be reduced by increasing the yoke size

Two Positions of Holes in the Yoke





A total of five sets of files. 4.2 K and 4.6 K for two hole positions. Also one case at 41 T/m for completeness.

Q1BpF

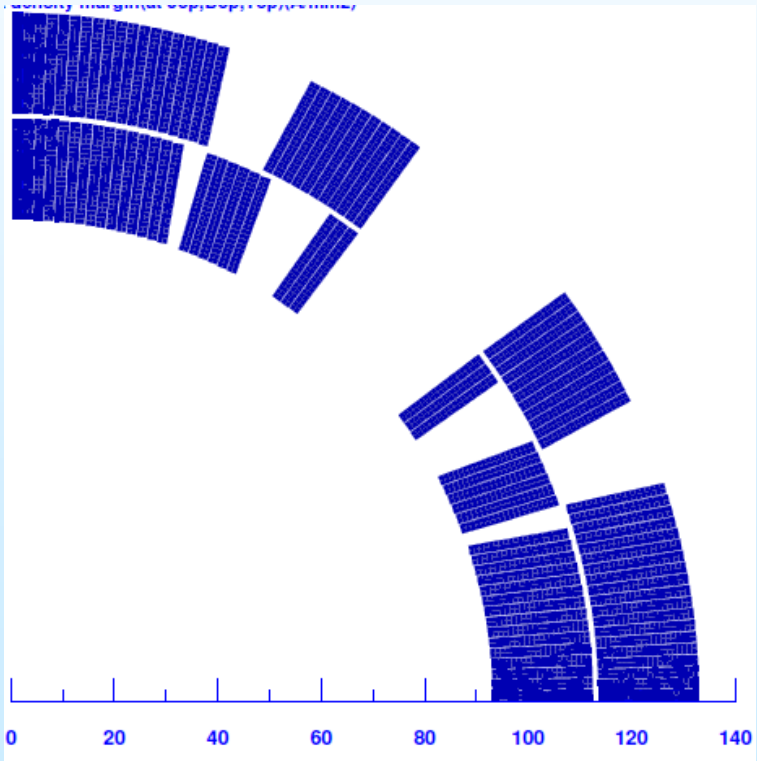
Overview

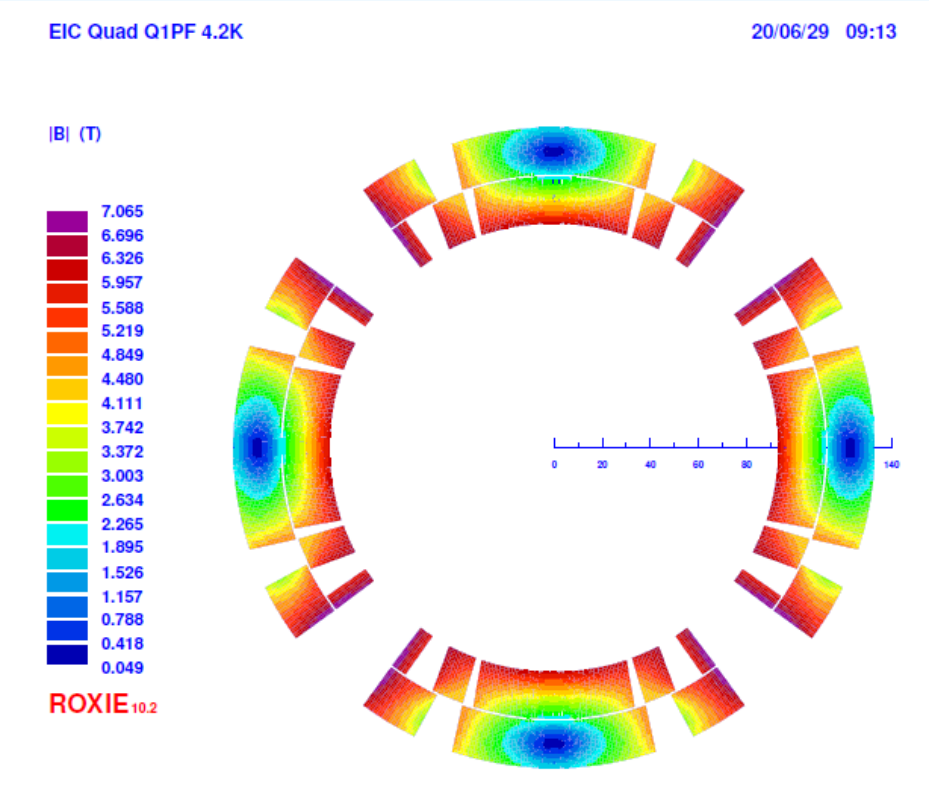
- Initial design studies of Q1BpF for a possible 4.2 K operation. Several cases examined but only one will be presented.
- Peak field (margin), field quality and field in the electron beam region are being optimized.
- The design consider several fronts - geometric, mechanical, magnetic design. Anis will continue on further optimization.
- Strand/wire used: dia =1.065 mm, Cu/Sc =1.3 (new) and 1.6.
- Cable: 19.4 mm wide (19.7 with insulation) with 36 strands, min thickness: 1.788 mm, max thickness: 2.012 mm (same as before).
- As mentioned during the last meeting, we will "try" to use this cable (and RHIC dipole type cable) for all EIC magnets.

Coil 2 Layers, Three wedges (2+1) 54 turns/pole (24 inner, 30 outer)

- **Poles of inner and outer layers aligned**
- **Coil poles have proper angles for collaring**
- **Two wedges in the inner to deal with keystone**

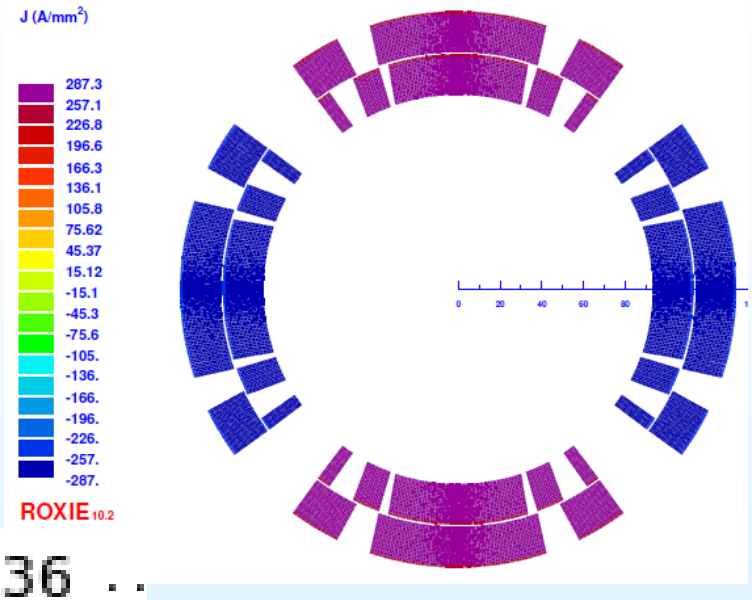
Coil radius: 93 mm (Q2B had 140 mm)





Field Harmonics in Q1BpF

A reasonably good field quality is obtained with a good mechanical design (coil radius 93 mm)
(all harmonics <1 unit)

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REFERENCE RADIUS (mm) . 36 ..
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Gradient 66.2 T/m at ~10 kA

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MAIN FIELD (T) ....................................     2.384284
MAGNET STRENGTH (T/(m^(n-1)) ......................      66.2301

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -3.92024  b 2:  10000.00000  b 3:     -0.40995
b 4:     -0.08318  b 5:     -0.02163  b 6:     -0.29828
b 7:     -0.00150  b 8:     -0.00033  b 9:     -0.00008
b10:      0.02322  b11:     -0.00001  b12:     -0.00000
b13:     -0.00000  b14:     -0.00054  b15:     -0.00000
b16:     -0.00000  b17:      0.00000  b18:     -0.00000
b19:      0.00000  b20:     -0.00000  b
```
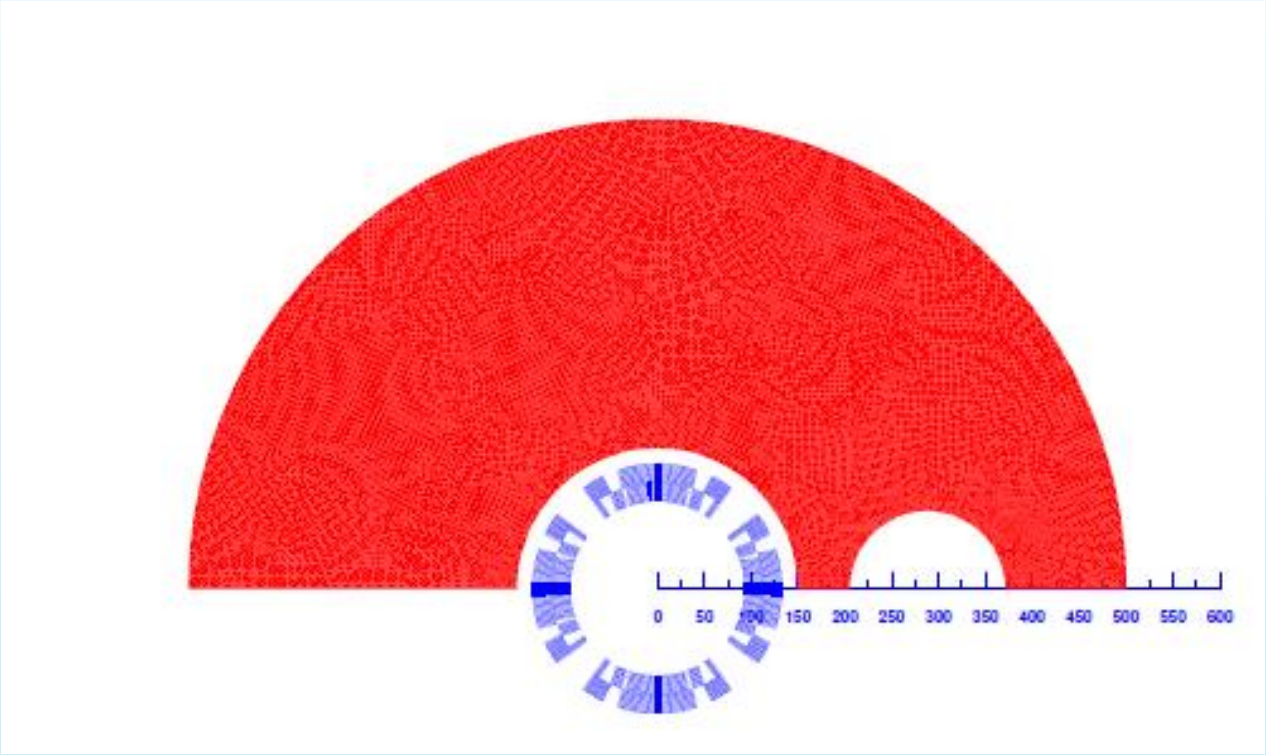
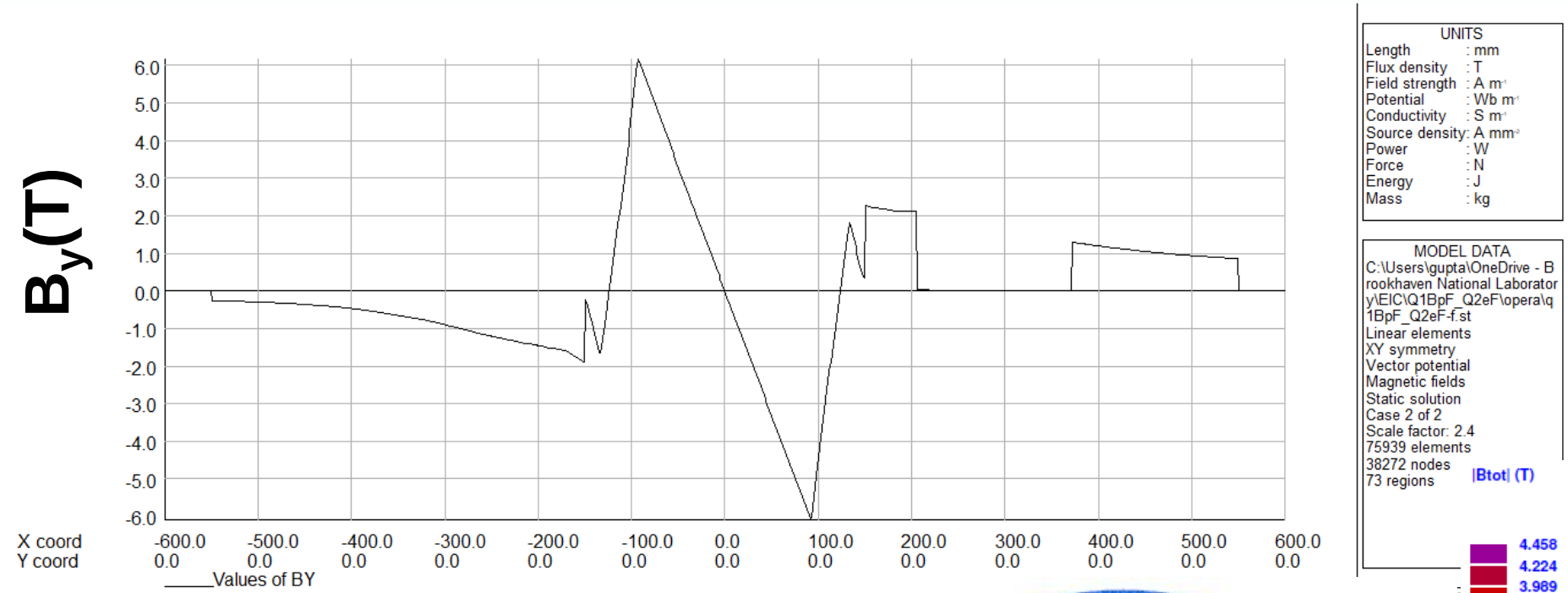

Iron Yoke – Current Design

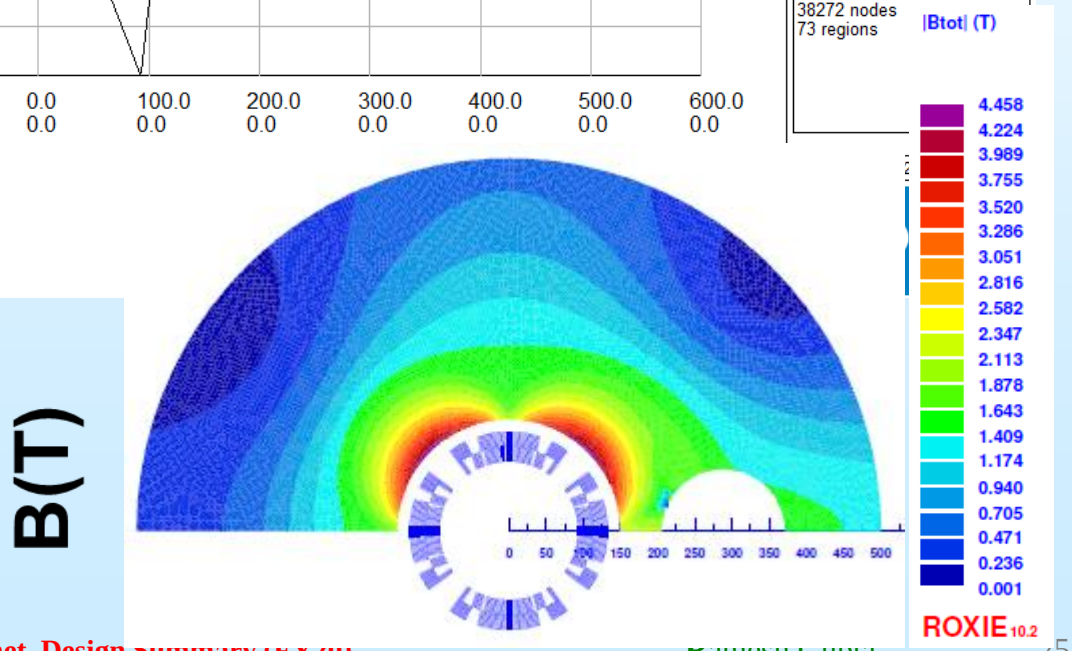
Yoke: ir = ~150 mm; or = 550 mm (or 500 mm)
Hole@ x = 288.3 mm to 312.5 mm
Radius of hole = 83 mm (63 mm for electron beam)
Collar width = ~20 mm for 66.2 T/m



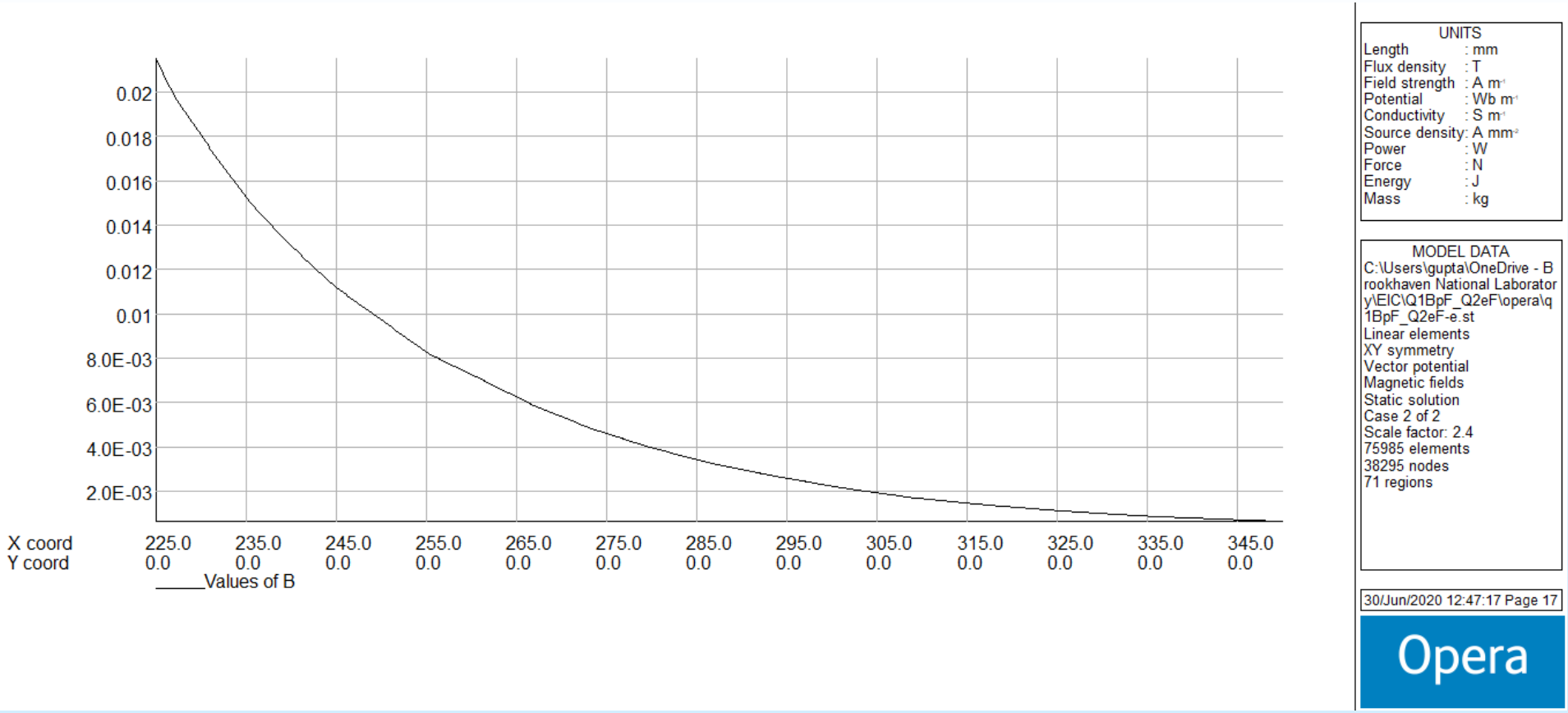
ROXIE

Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm





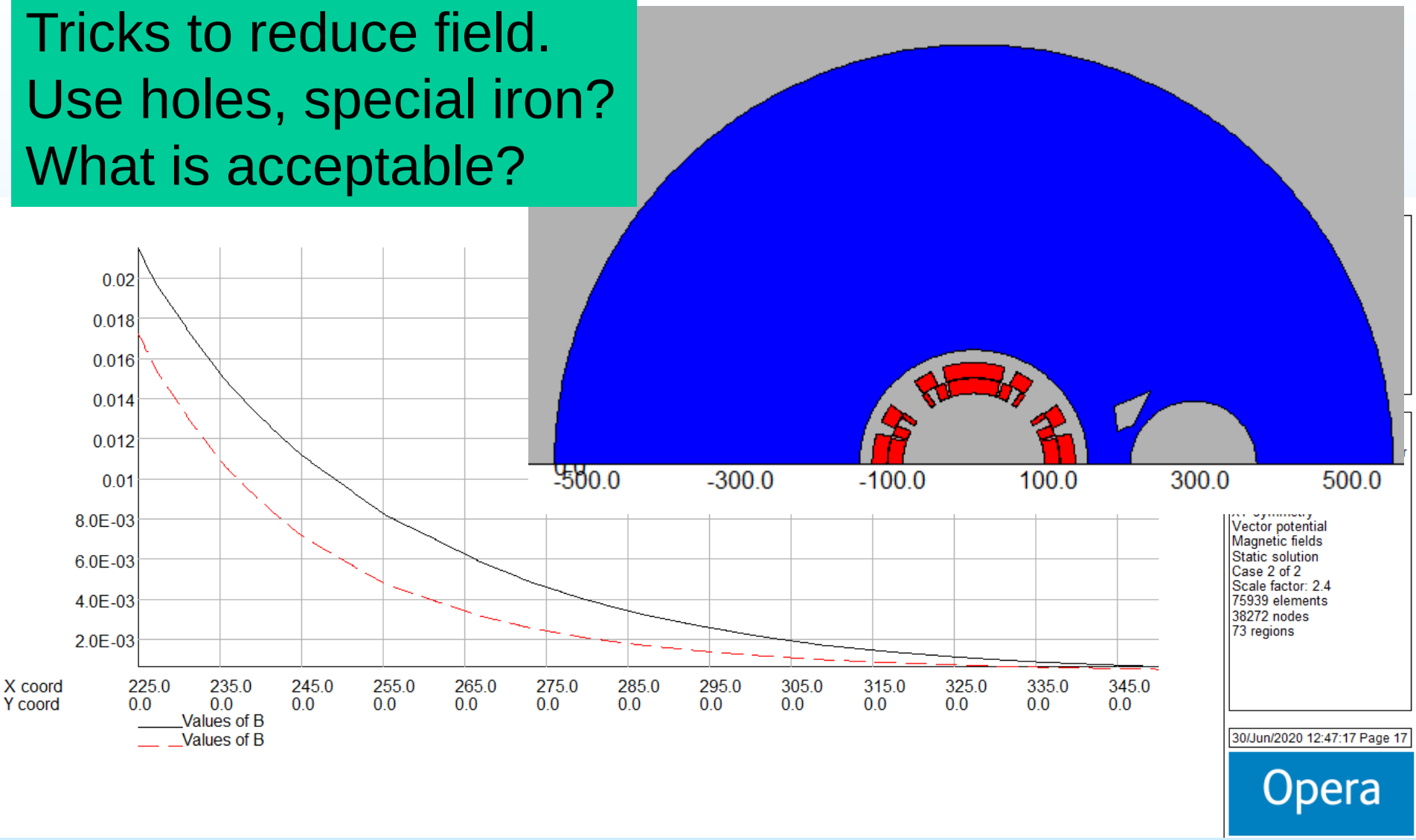
Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm



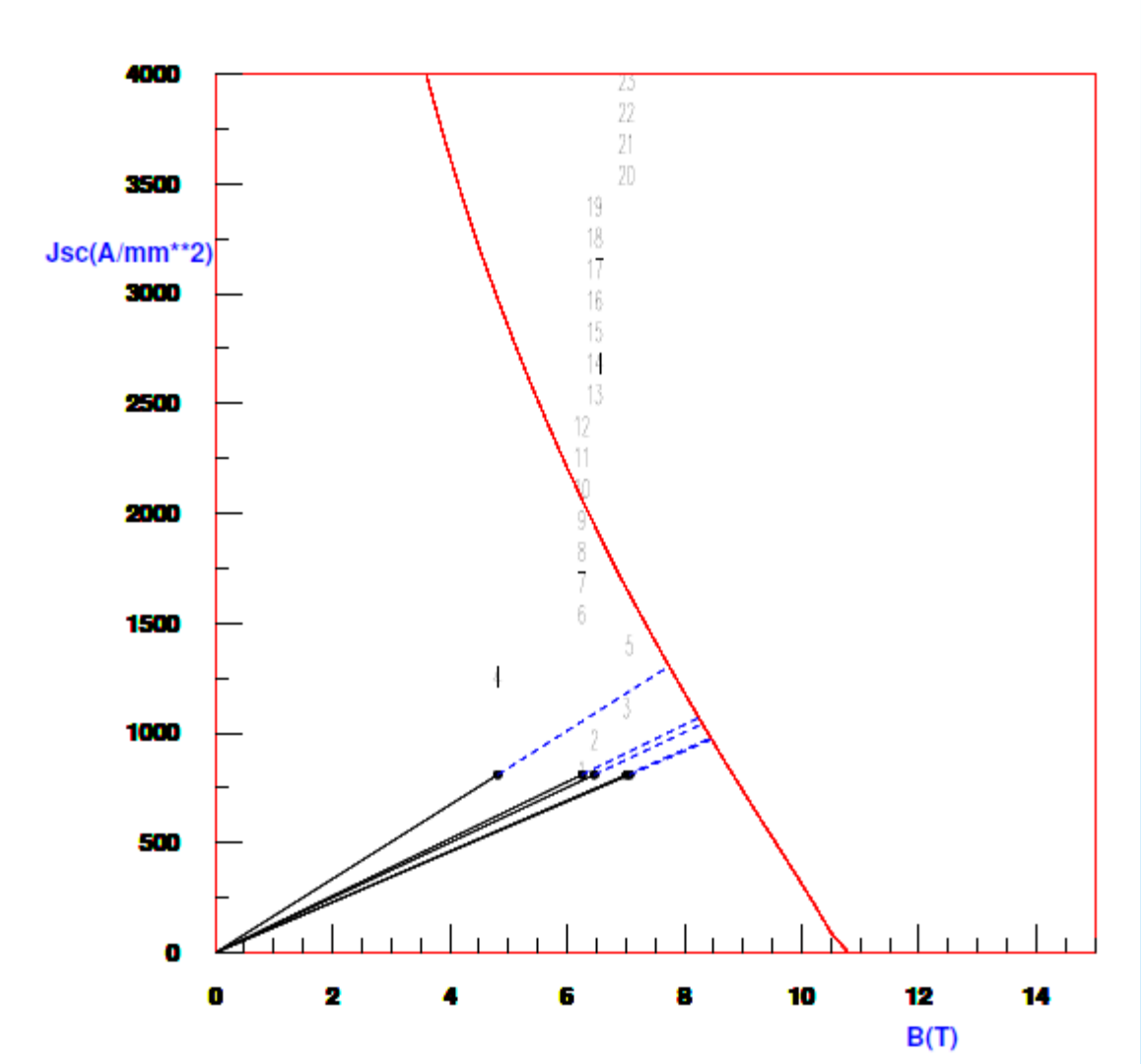
Initial Design. What is acceptable?

Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm

Tricks to reduce field.
Use holes, special iron?
What is acceptable?



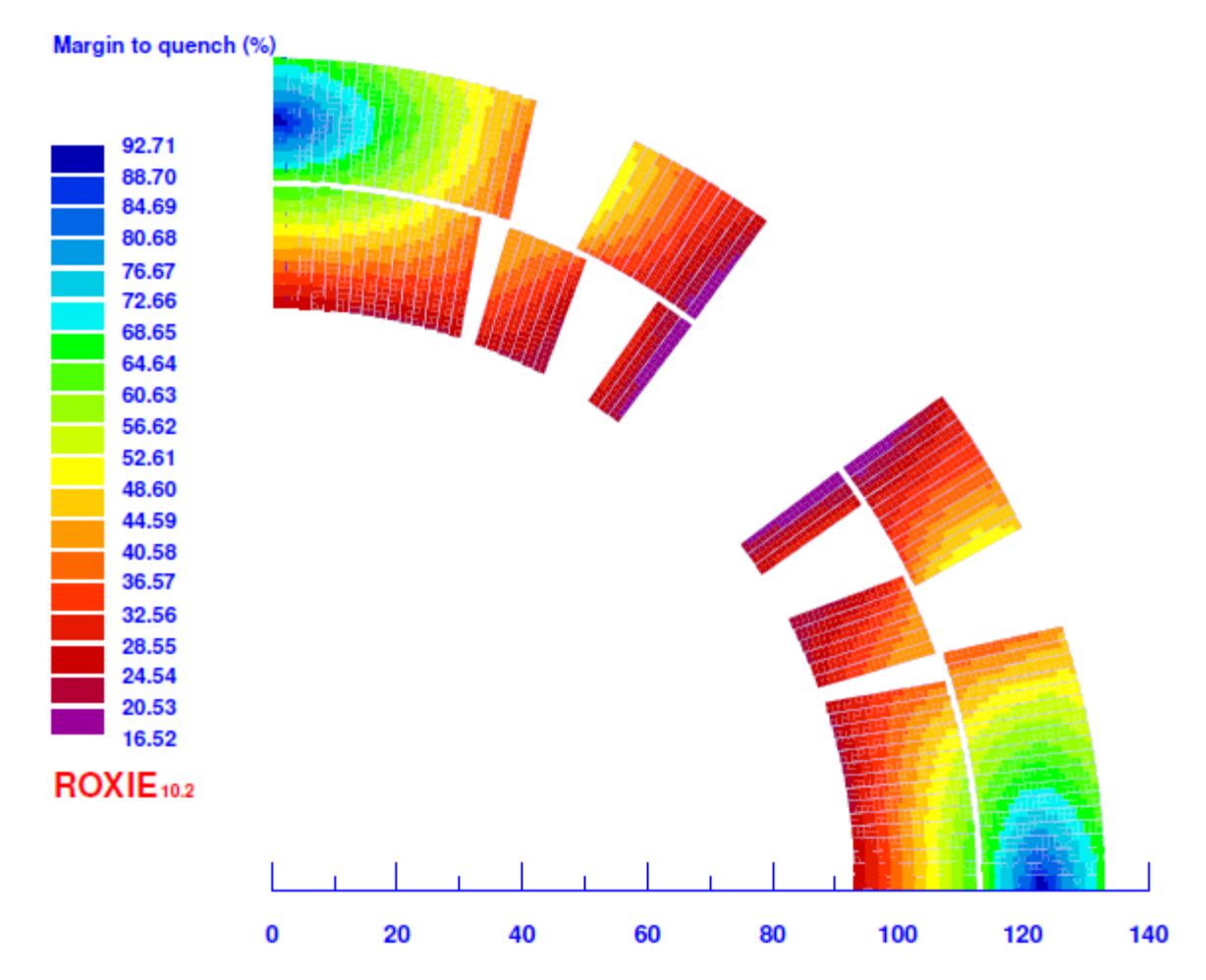
Field Margin at 4.2 K



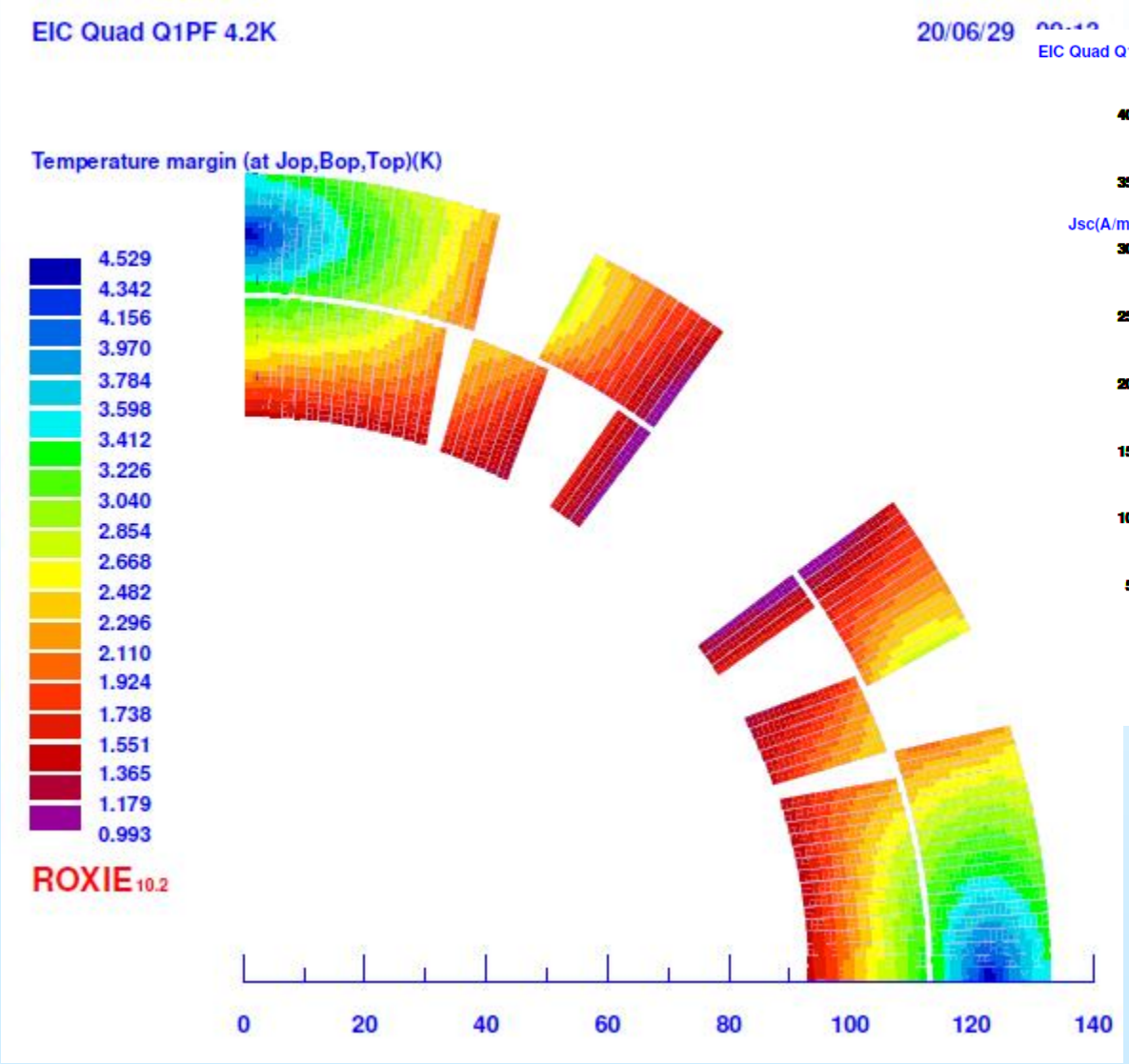
Healthy Margin: ~20% over 66.2 T/m at 4.2K

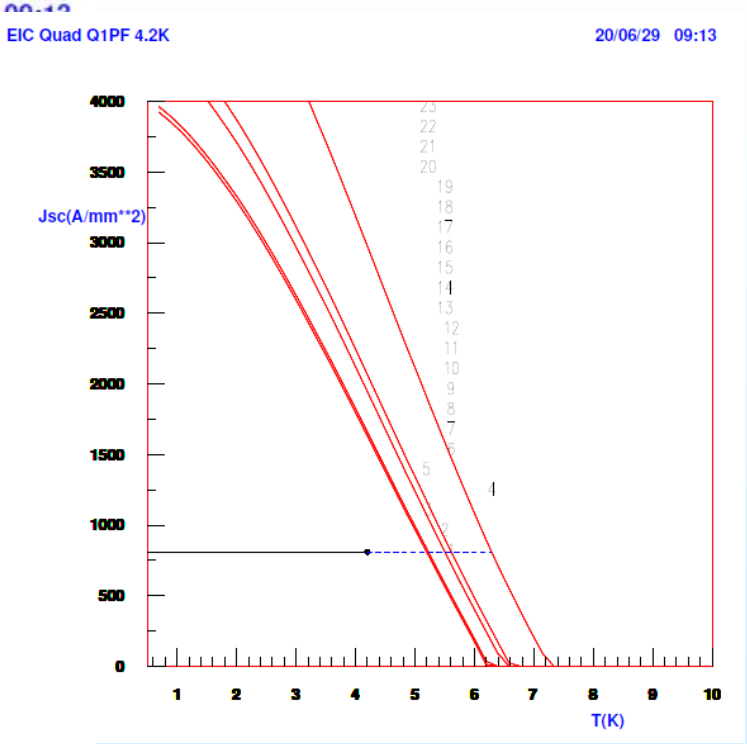
For Cu/Sc of 1.6 (83% on loadline)

Field Margin at 4.2 K

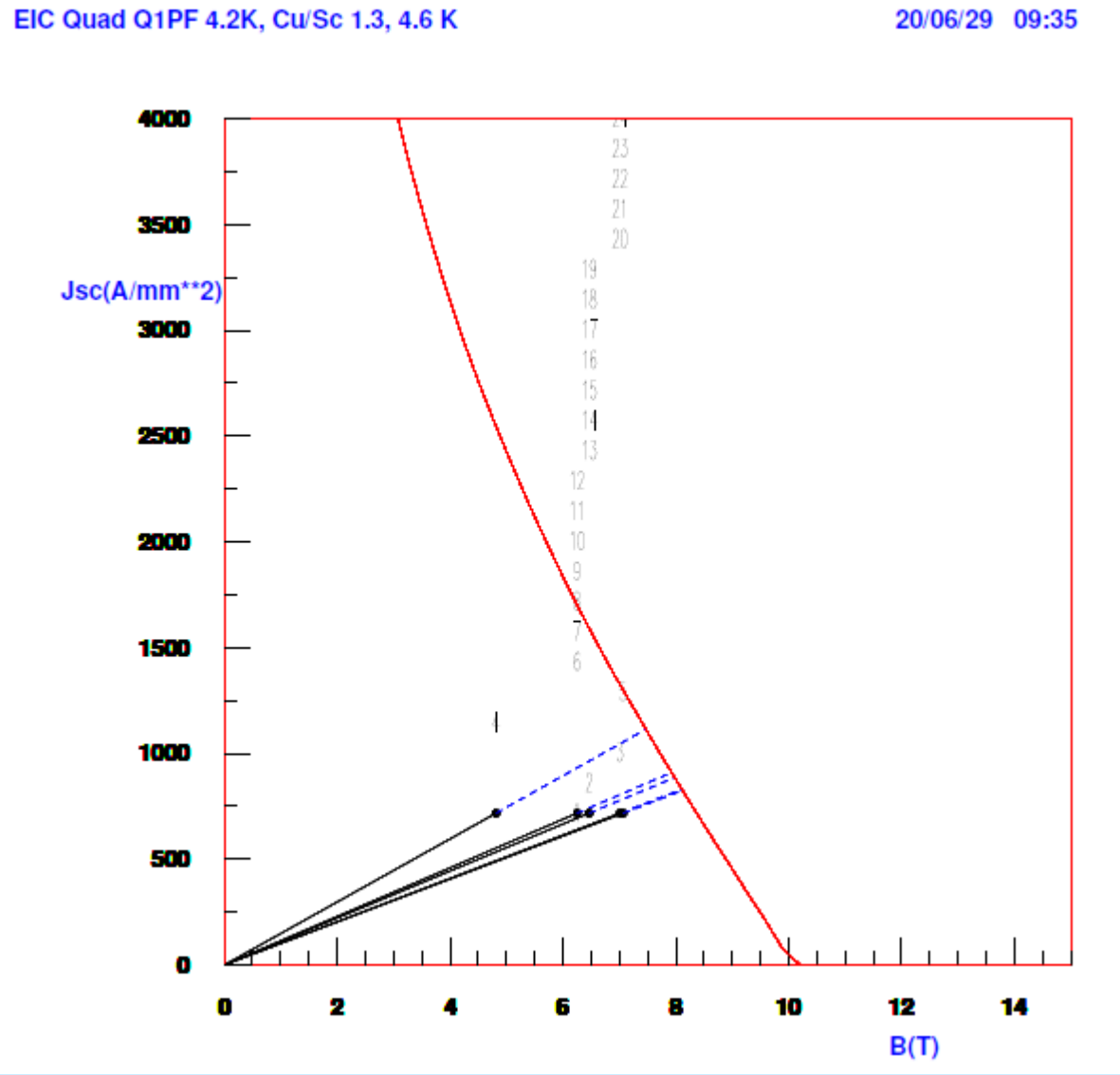


Temperature Margin at 4.2 K Over Different Blocks

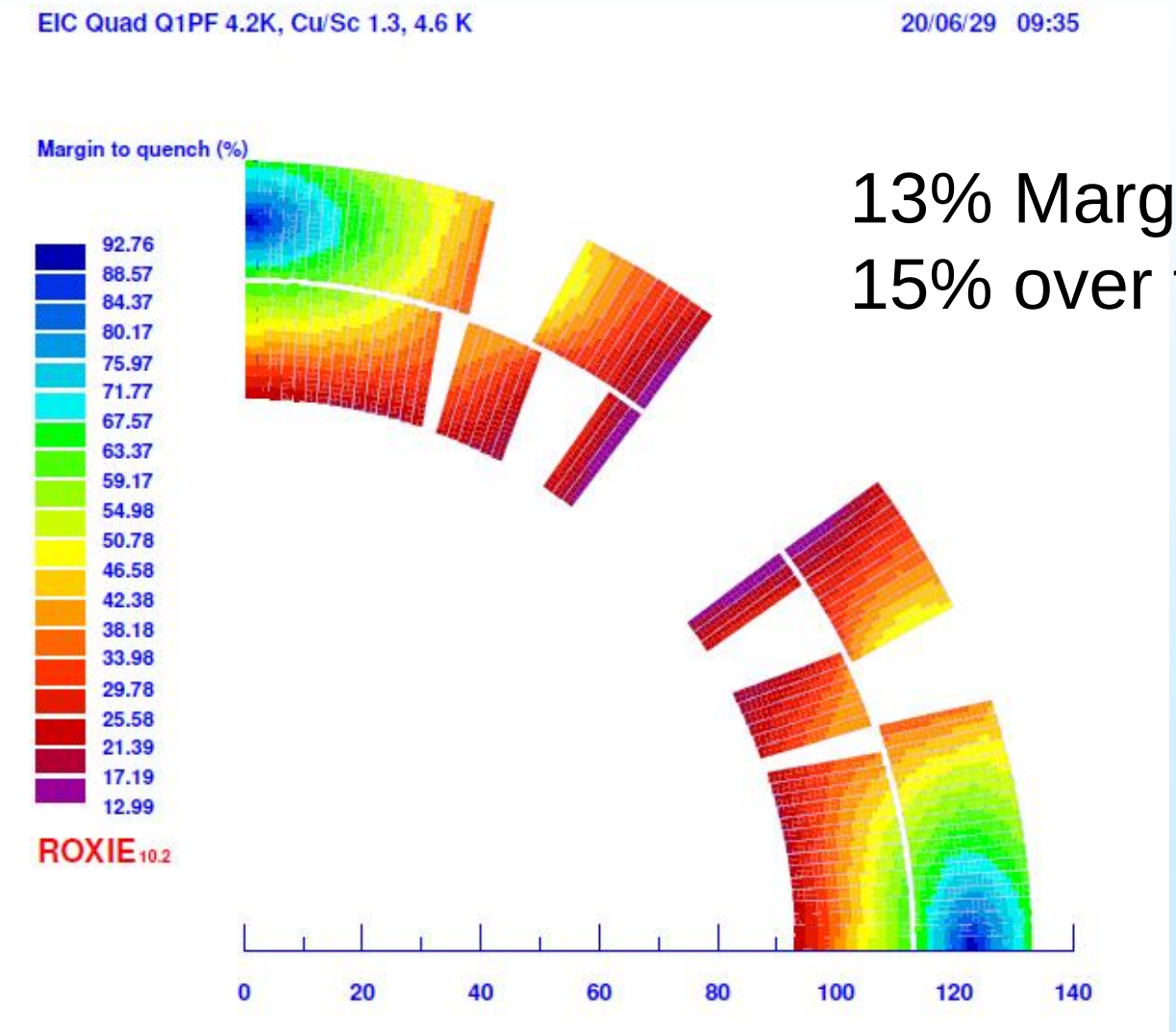




Field Margin at 4.6 K, Cu/Sc =1.3



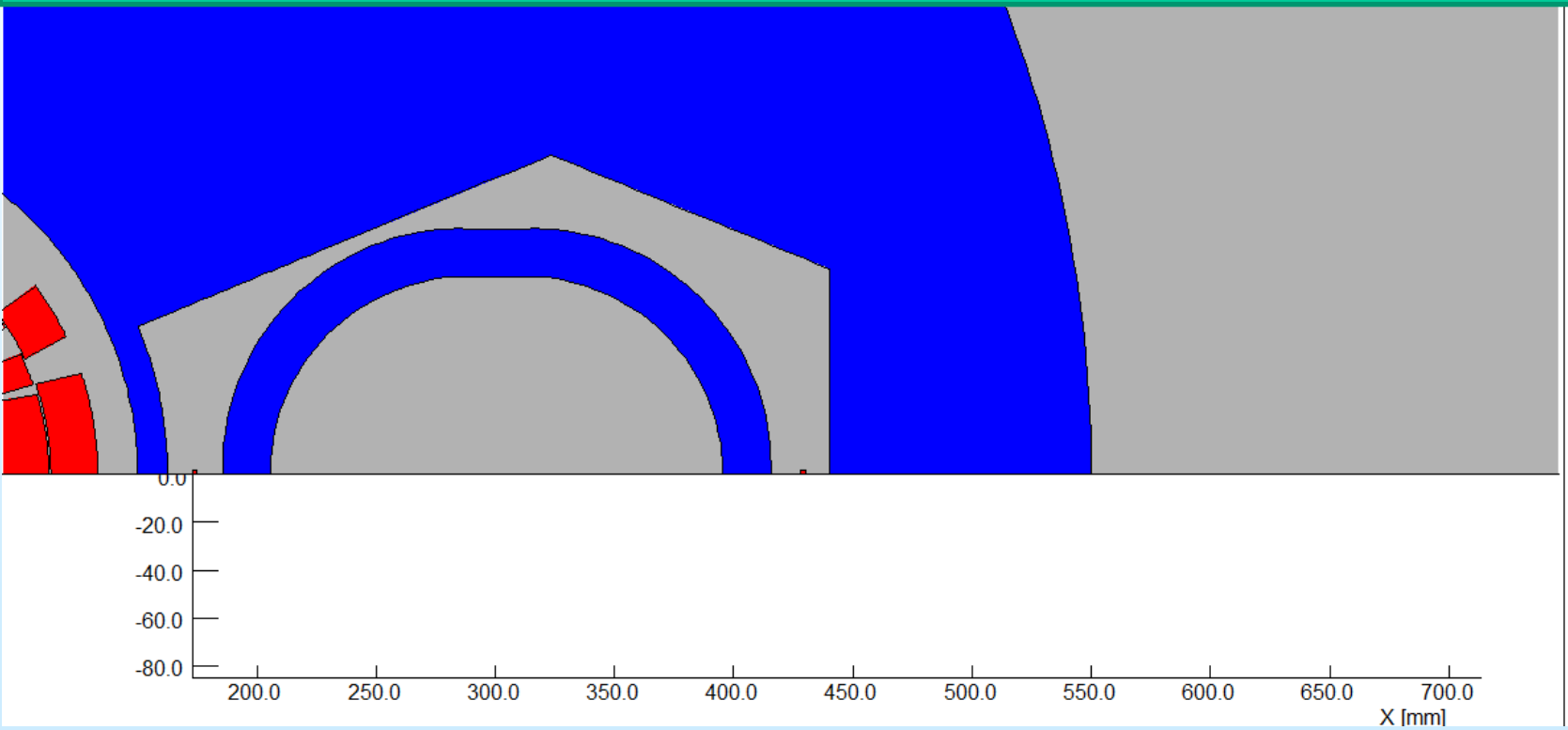
Field Margin at 4.6 K, Cu/Sc =1.3



13% Margin on the loadline
15% over the design field

Shielding Solution that Worked in Q1B

Path of flux lines navigated with cutout in yoke and small coils on the two side of yoke over e-beam region added to further navigate flux lines (and reduce saturation) to significantly reduce field in the e-beam region

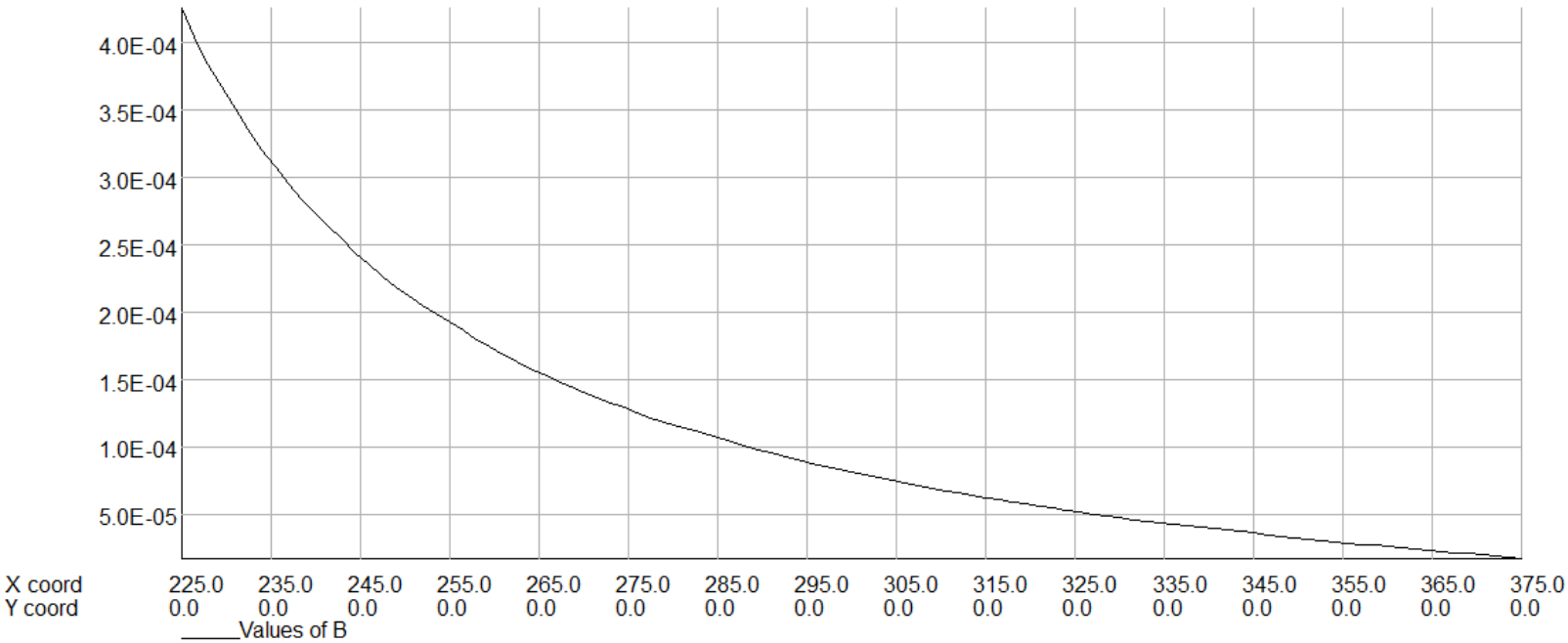


UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-06-30-gi1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
80713 elements
40666 nodes
82 regions

14/Jul/2020 12:09:52 Page 60

Two order of magnitude reduction in field in e-beam region of Q1B



UNITS
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Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
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MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-06-30-gi1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
80713 elements
40666 nodes
82 regions

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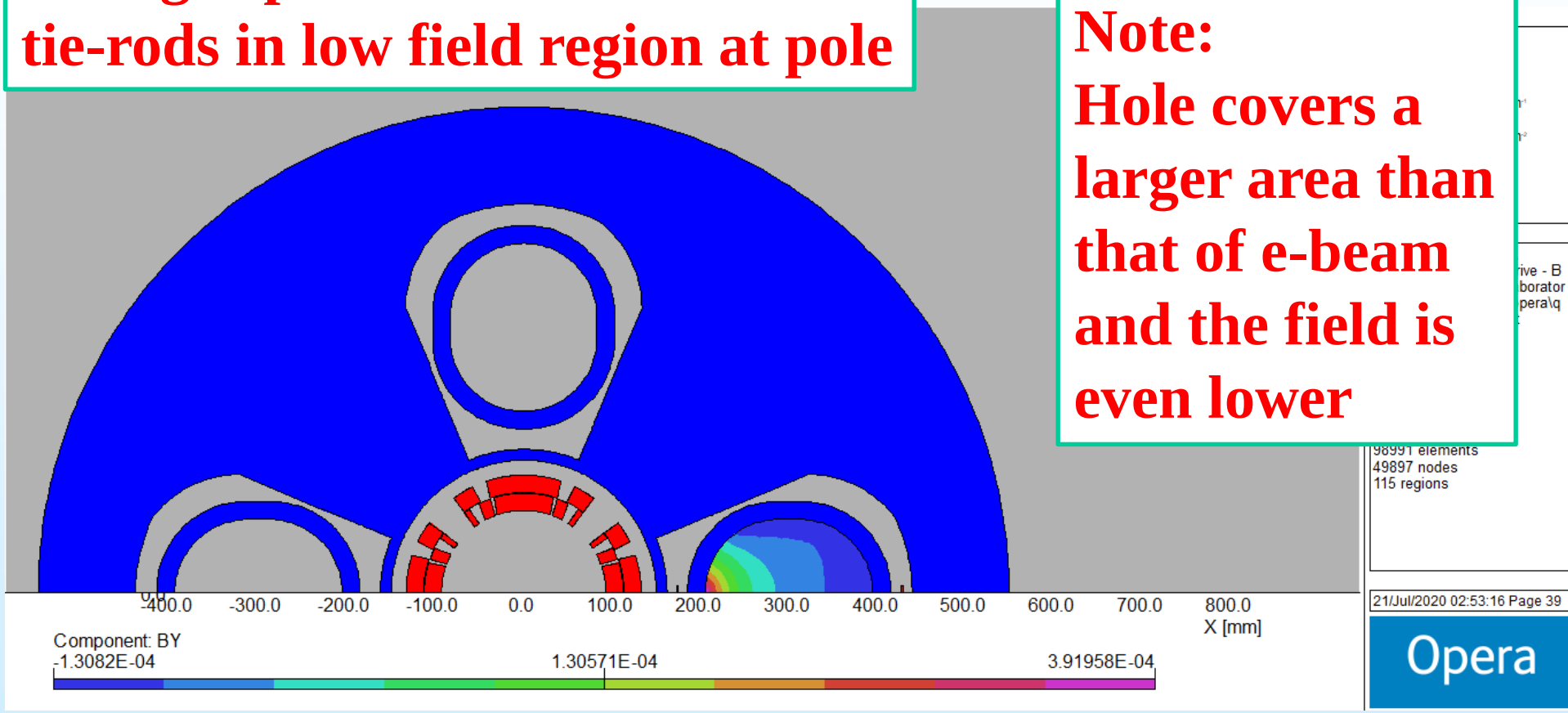
Opera

Such fields can be shield with mu-metal, etc.

Quadrupole Symmetric Yoke of Q1B

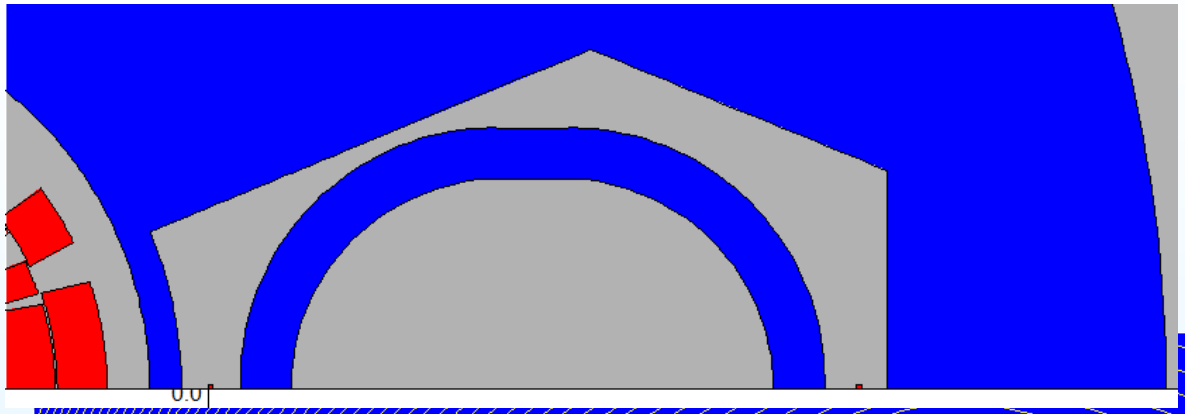
Enough space for holes for tie-rods in low field region at pole

Note: Hole covers a larger area than that of e-beam and the field is even lower

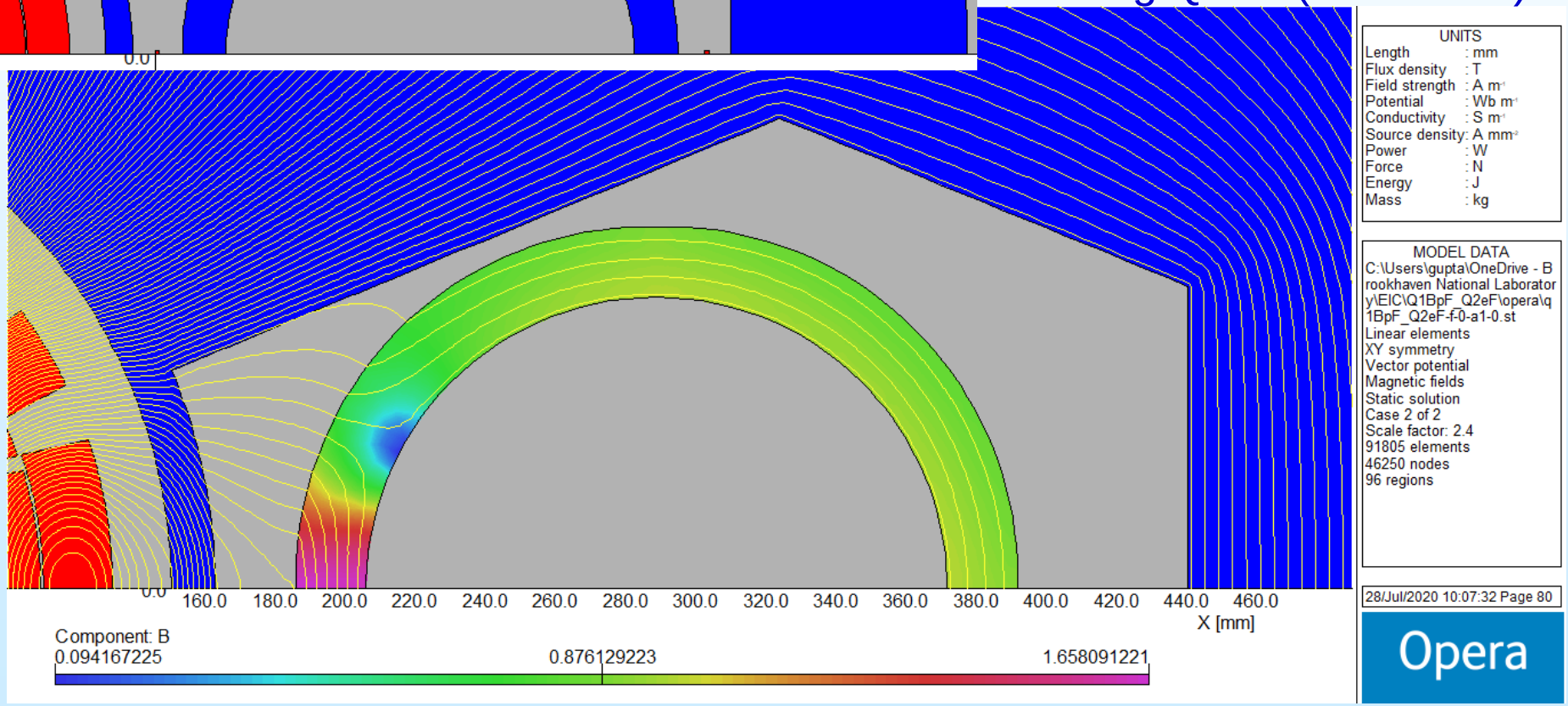


- It works. Field in the e-beam region ~10^{-4}
- But it may or may not be the best solution

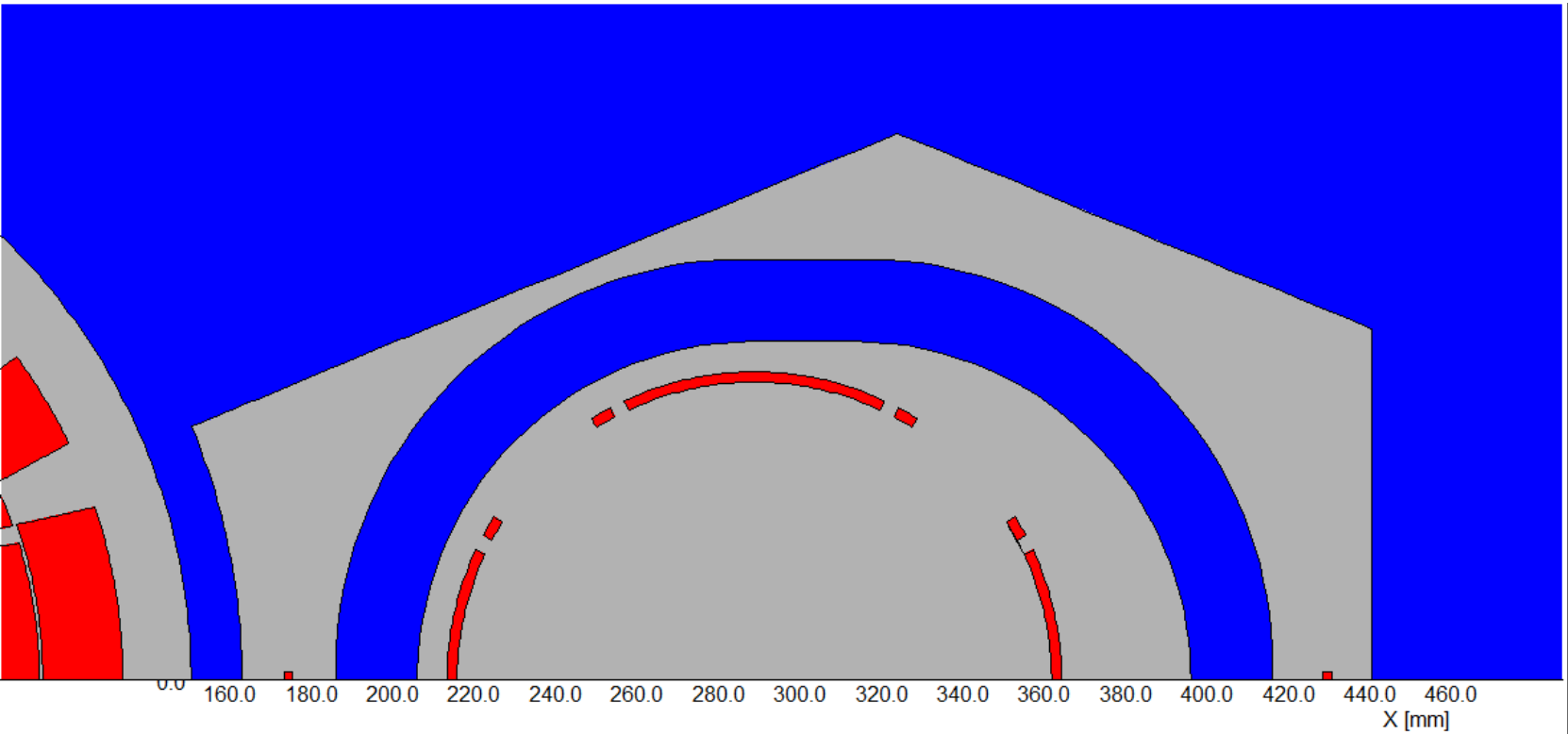
Q1BpF with Q1eF (need to remove flat-top)



Flat-top creates non-allowed harmonics and takes away iron from the return yoke. therefore, it is removed for inserting Q1eF (see below)



Q1BpF (Q1eF in flat-top yoke NOT GOOD)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-gi1-x1d.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
92805 elements
46758 nodes
96 regions

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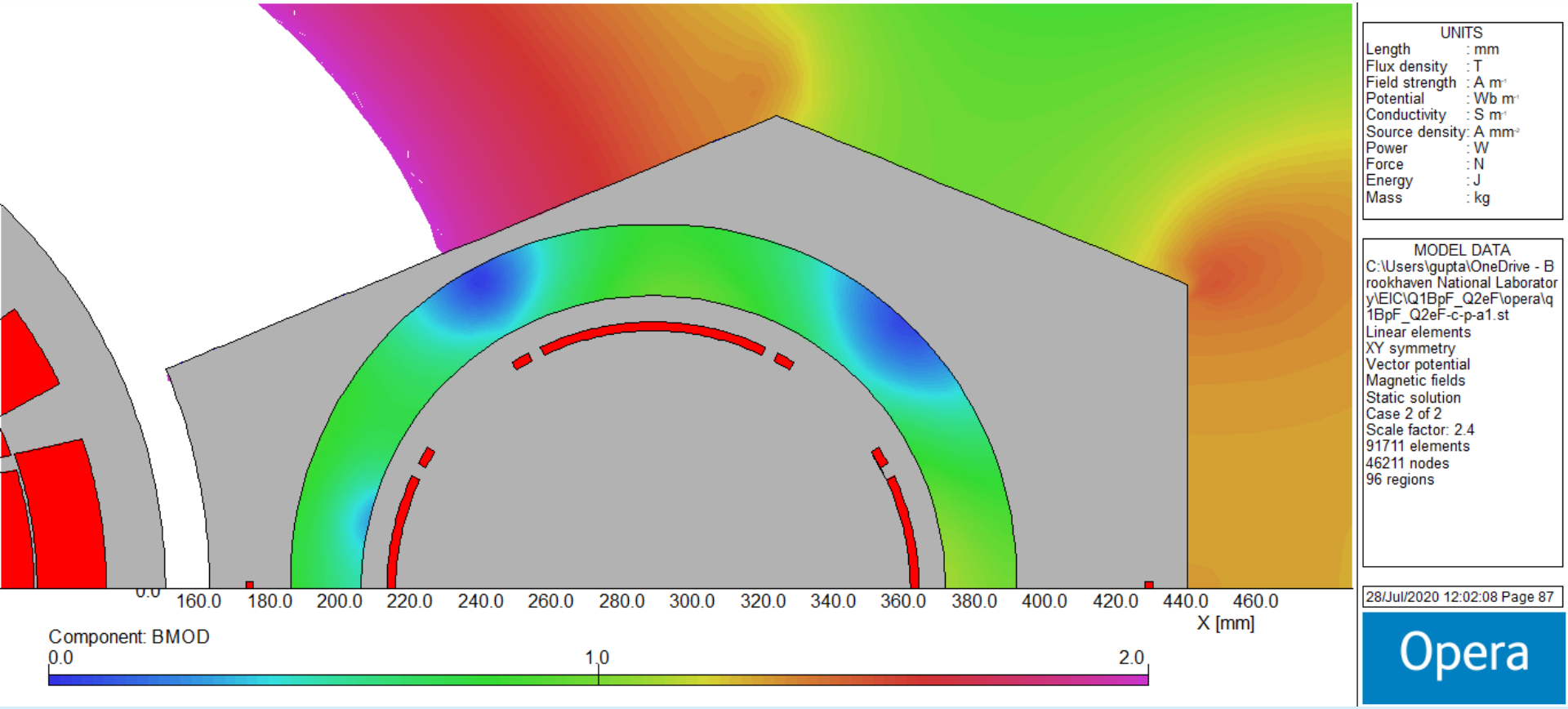
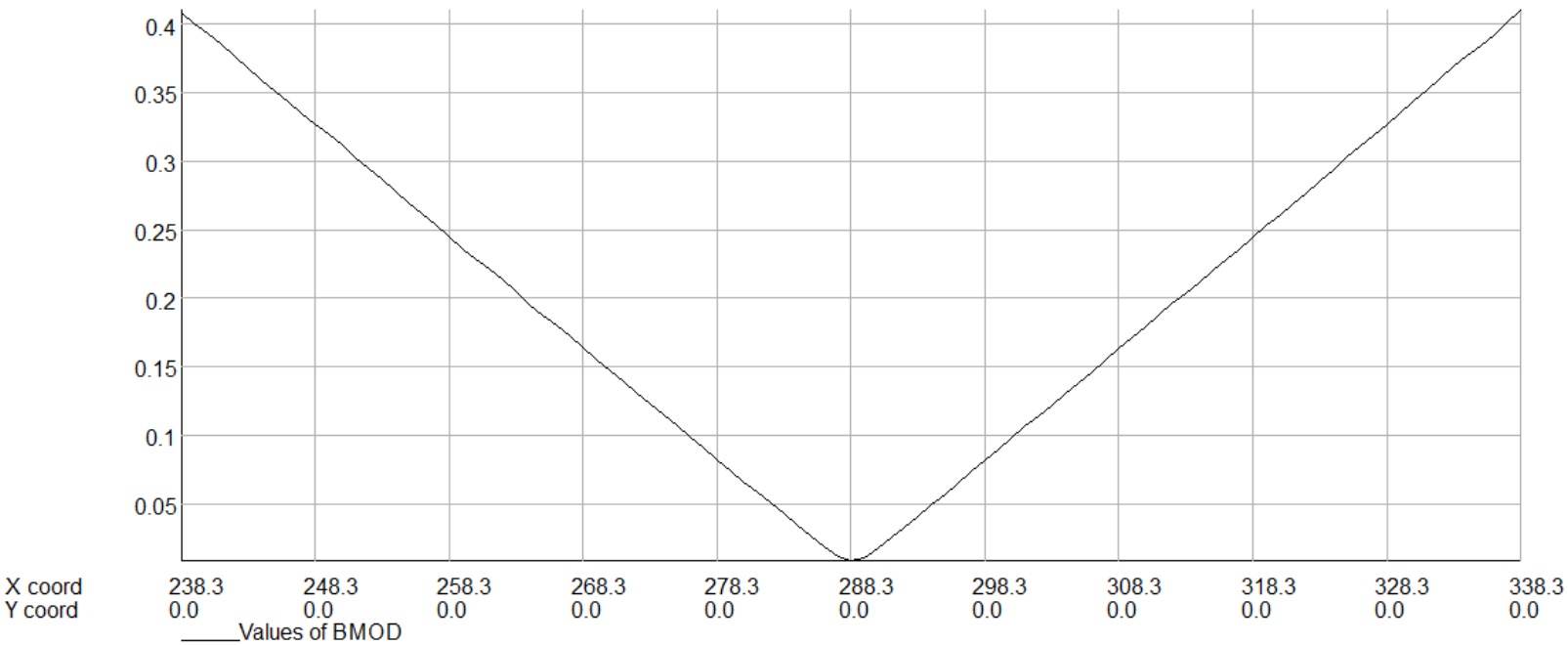
Opera

Q1BpF (Q1eF with one polarity)



Looks good as iron providing the shielding is not saturated

Q1BpF (Q1eF with one polarity)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-c-p-a1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91711 elements
46211 nodes
96 regions

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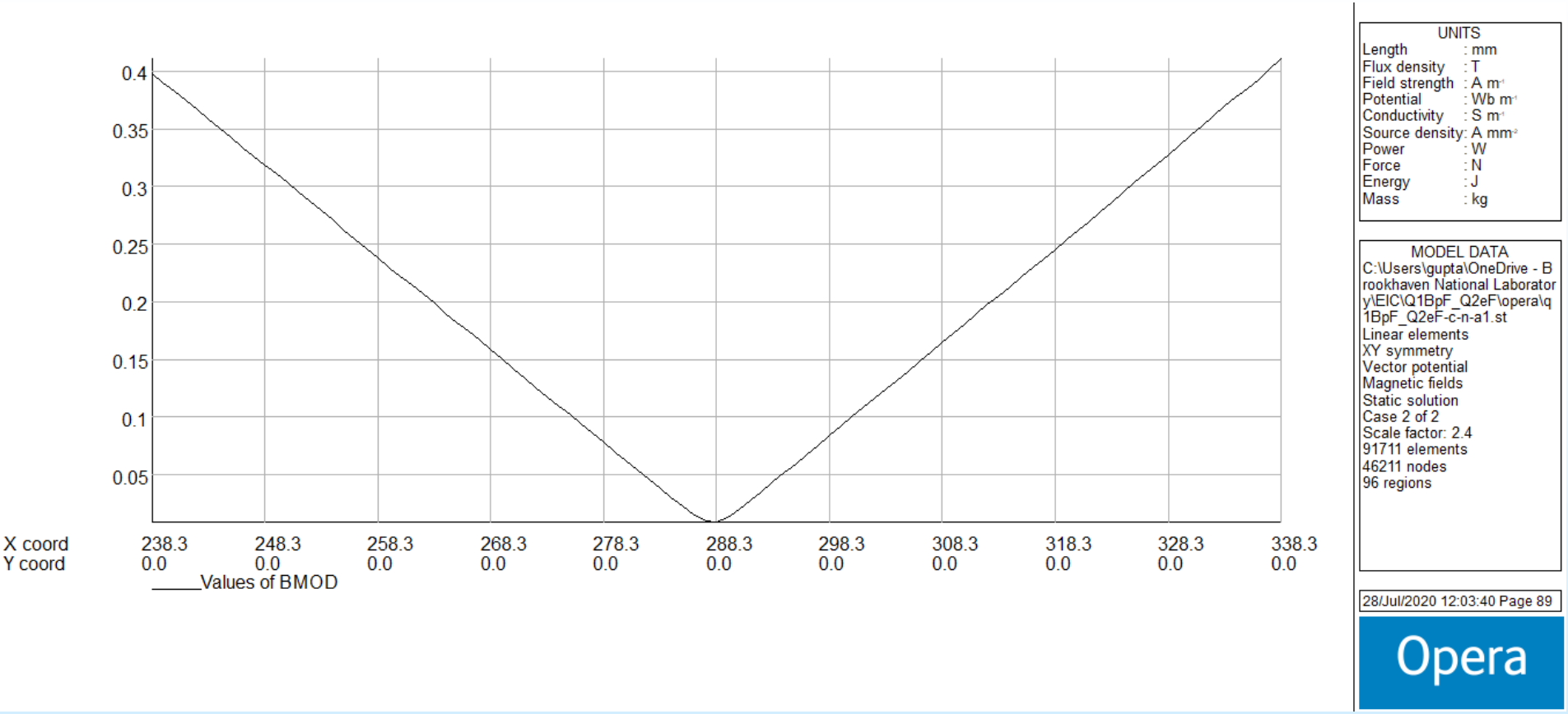
Opera

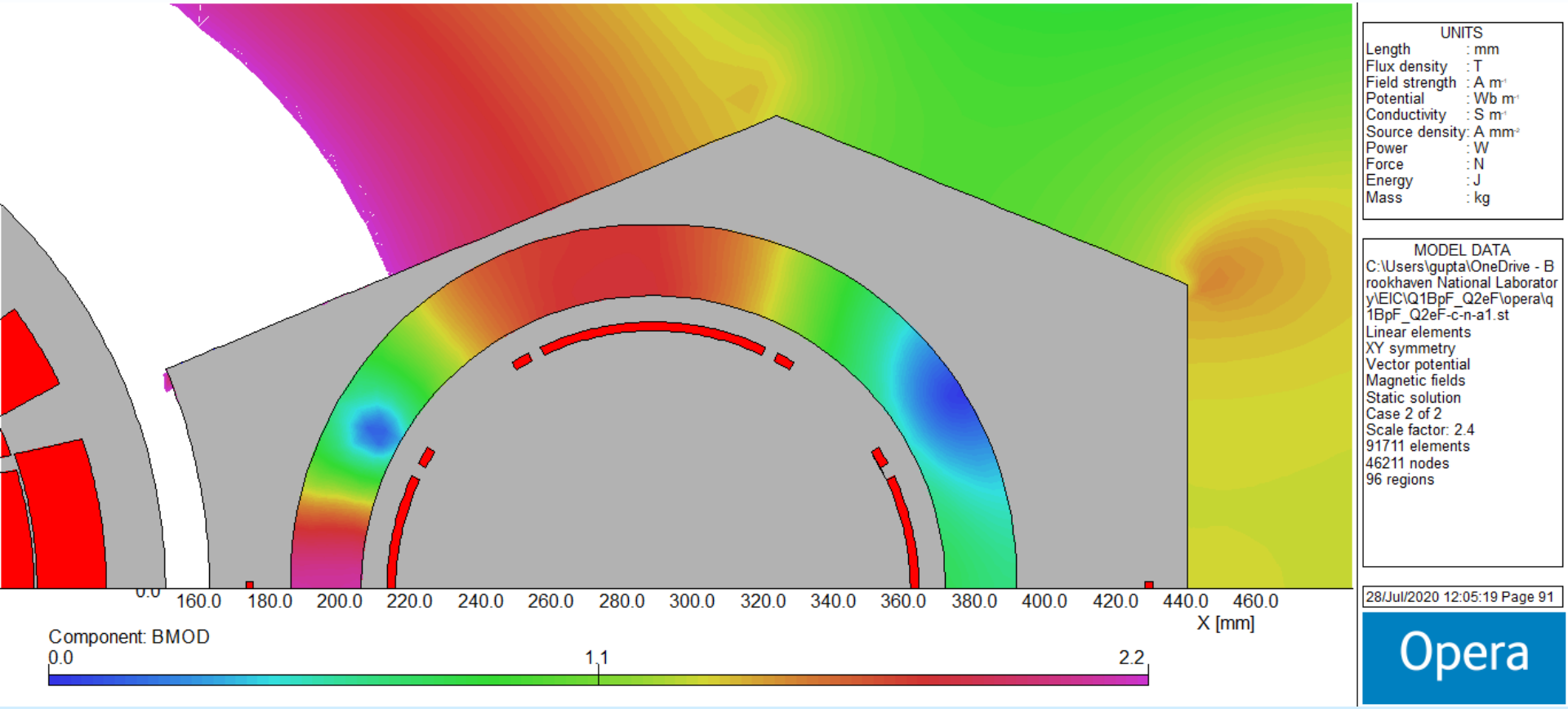
Looks good as gradient is symmetric around the center of Q1eF (x=288.3)

Q1BpF (Q1eF with opposite polarity)



Does NOT looks good as gradient is not symmetric around the center of Q1eF

Q1BpF (Q1eF with opposite polarity)

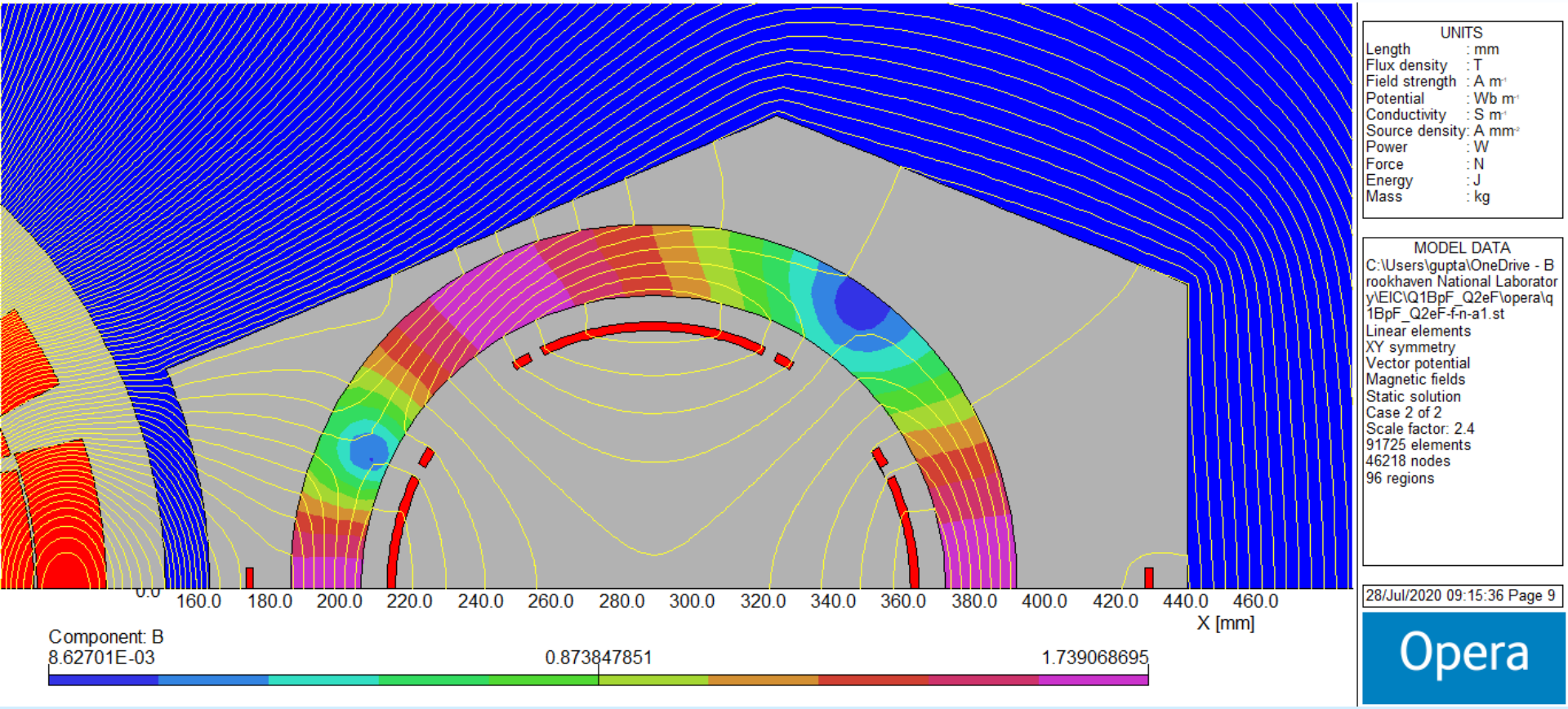


Does not look good as the iron providing the shielding is highly saturated on one side (>2T)

Solution

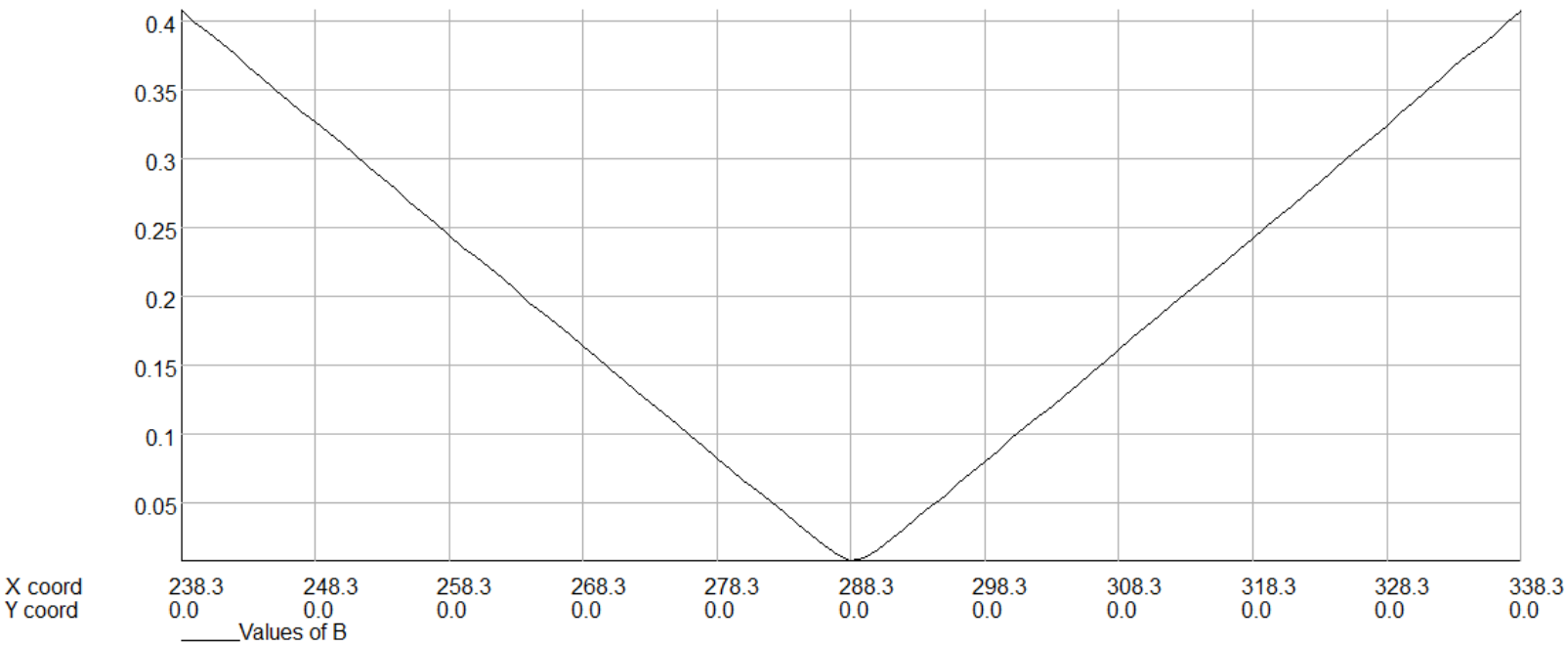
Use the technique that we recently invented (strengthen the coils around the iron to reduce saturation)

Q1BpF (Q1eF with opposite polarity AND stronger control coils)



Looks better as the iron providing the shielding is less saturated (1.7 T rather than over 2 T)

Q1BpF (Q1eF with opposite polarity AND stronger control coils)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-f-n-a1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91725 elements
46218 nodes
96 regions

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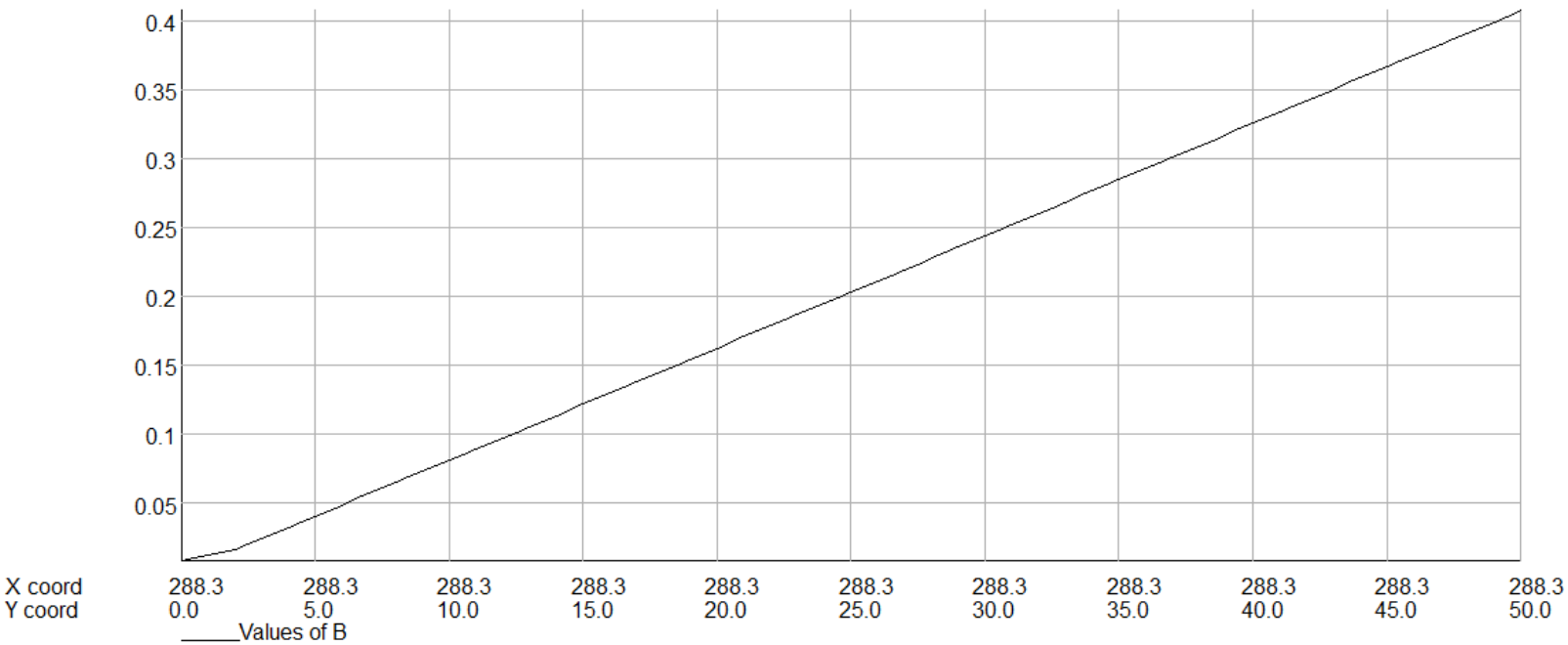
Opera

Still looks good as gradient is symmetric around the center of Q1eF (x=288.3)

Q1BpF (Q1eF with opposite polarity AND stronger control coils)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91725 elements
46218 nodes
96 regions

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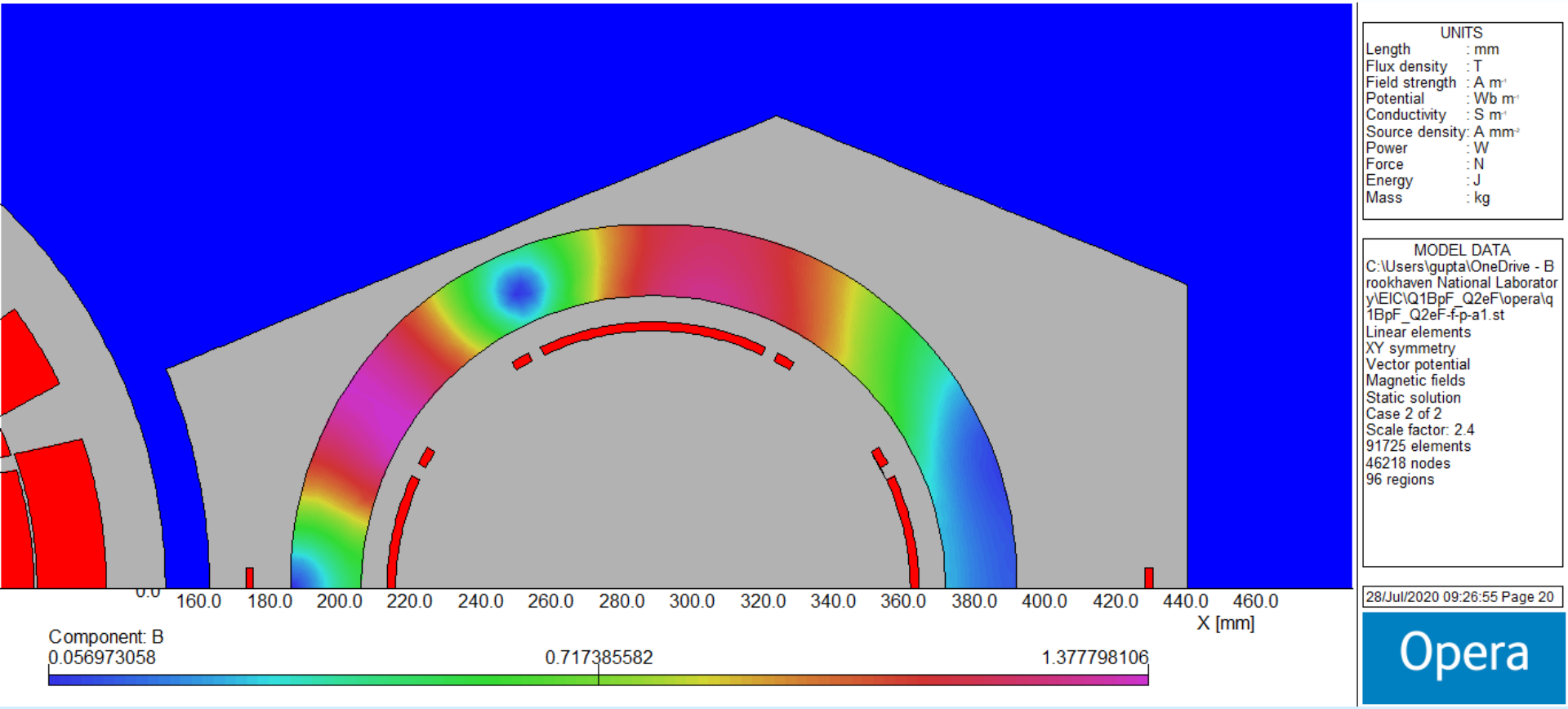
Opera

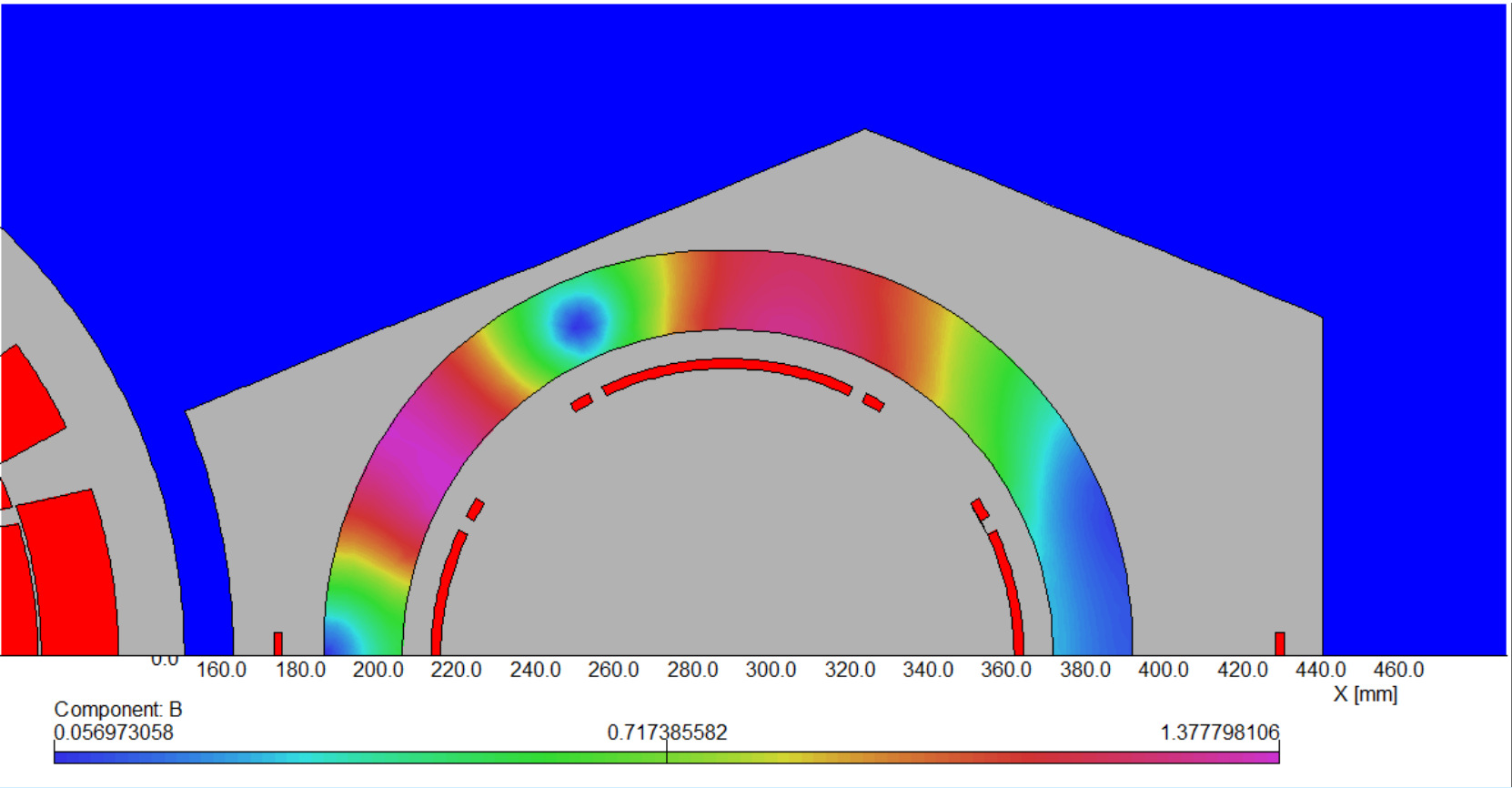
Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)

Q1BpF (Q1eF with good polarity AND stronger control coils)



Looks good as the iron providing the shielding is less saturated (1.3 T)

Q1BpF (Q1eF with good polarity AND stronger control coils)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-f-p-a1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91725 elements
46218 nodes
96 regions

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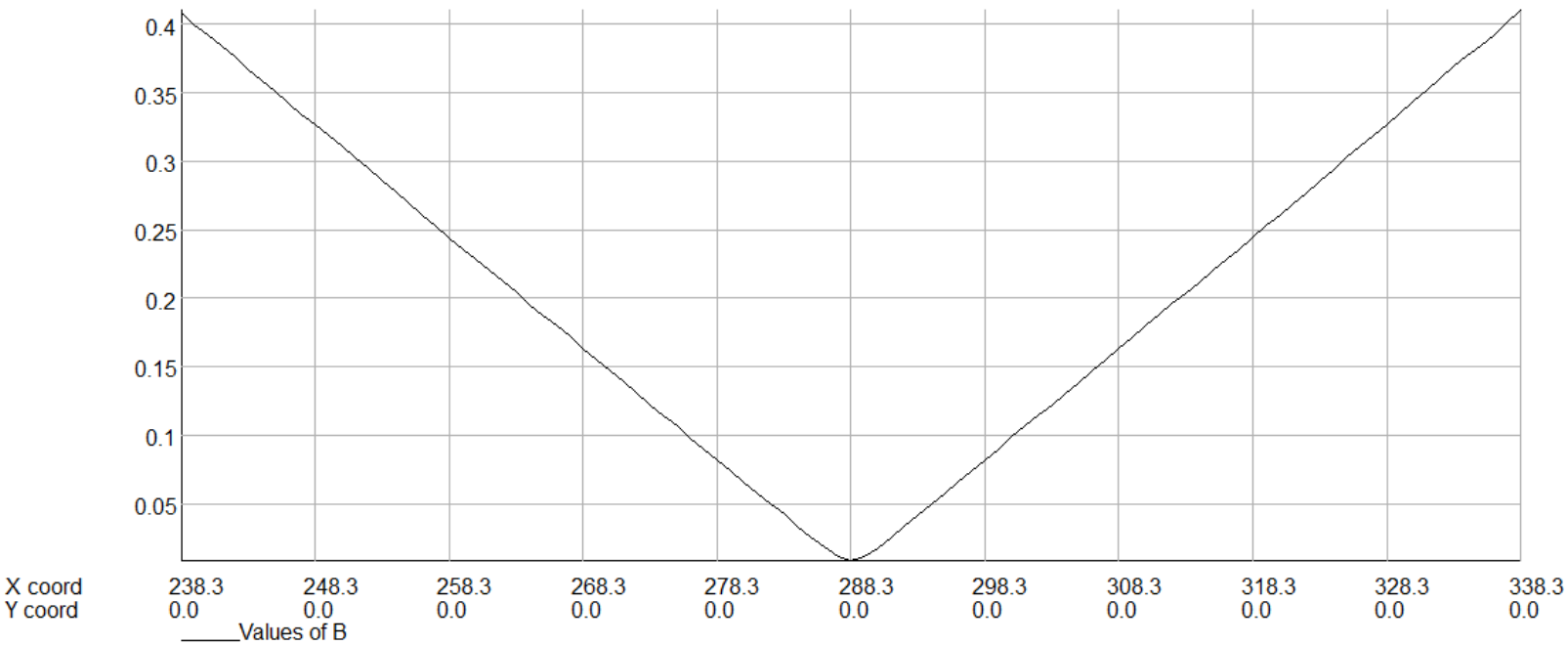
Opera

Q1BpF (Q1eF with good polarity AND stronger control coils)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

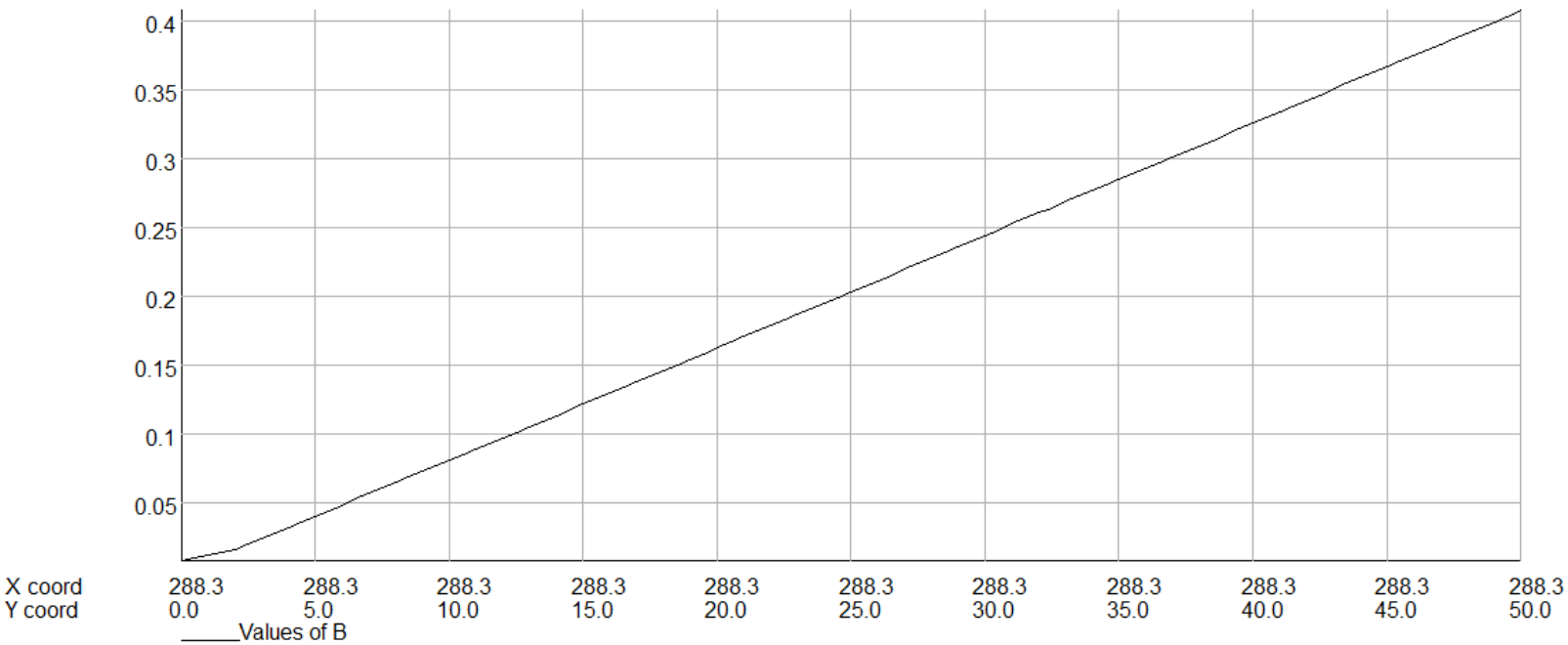
MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-f-p-a1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91725 elements
46218 nodes
96 regions

28/Jul/2020 09:21:50 Page 15

Opera

Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)

Q1BpF (Q1eF with good polarity AND stronger control coils)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-f-p-a1.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
91725 elements
46218 nodes
96 regions

28/Jul/2020 09:21:08 Page 14

Opera

Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)

Q1ApF

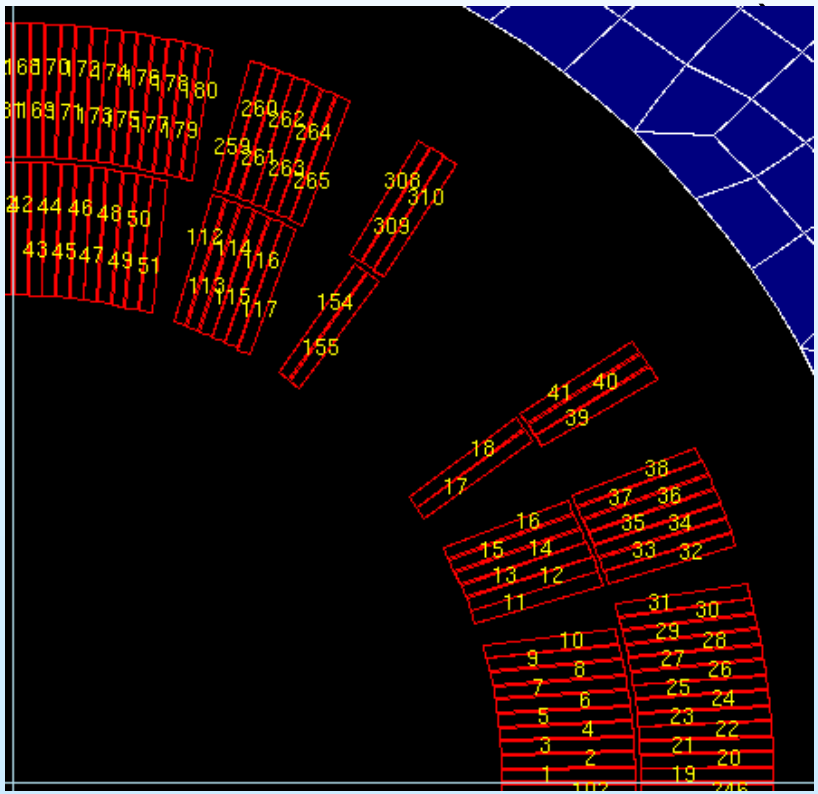
Overview

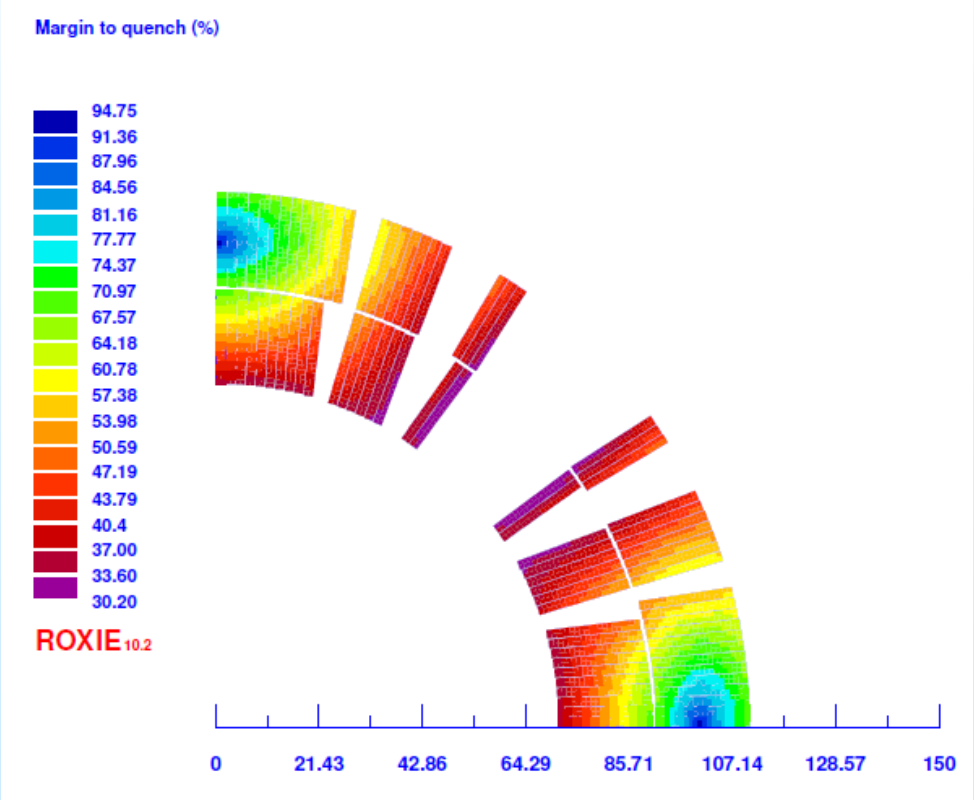
- Design studies of Q1ApF coil for a possible 4.2 K operation.
- Q1BpF yoke optimization to reduce field in electron beam region.
- Q1BpF coil redesign to increase margin for 4.2 K operation
- Several cases examined; only one each of above will be presented.
- In all cases, peak field (margin), field quality and field in the electron beam region are being optimized together.
- The design consider several fronts - geometric, mechanical, magnetic design. Anis will continue on further optimization.
- Strand/wire used: dia =1.065 mm, Cu/Sc =1.3 and 1.6.
- Use this cable (and RHIC dipole type cable) for all EIC magnets.
- Some thoughts on system optimization

Q1ApF Coil 2 Layers, Four wedges 41 turns/pole (18 inner, 23 outer)

- **Poles of inner and outer layers aligned**
- **Coil poles have proper angles for collaring**
- **Two wedges in each layer to deal with keystone**

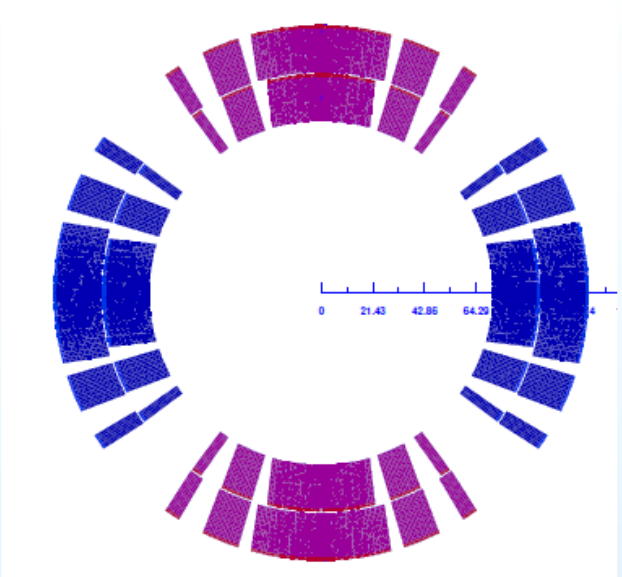
Coil radius: 71 mm (Q1B had 93 and Q2B had 140





Field Harmonics in Q1ApF

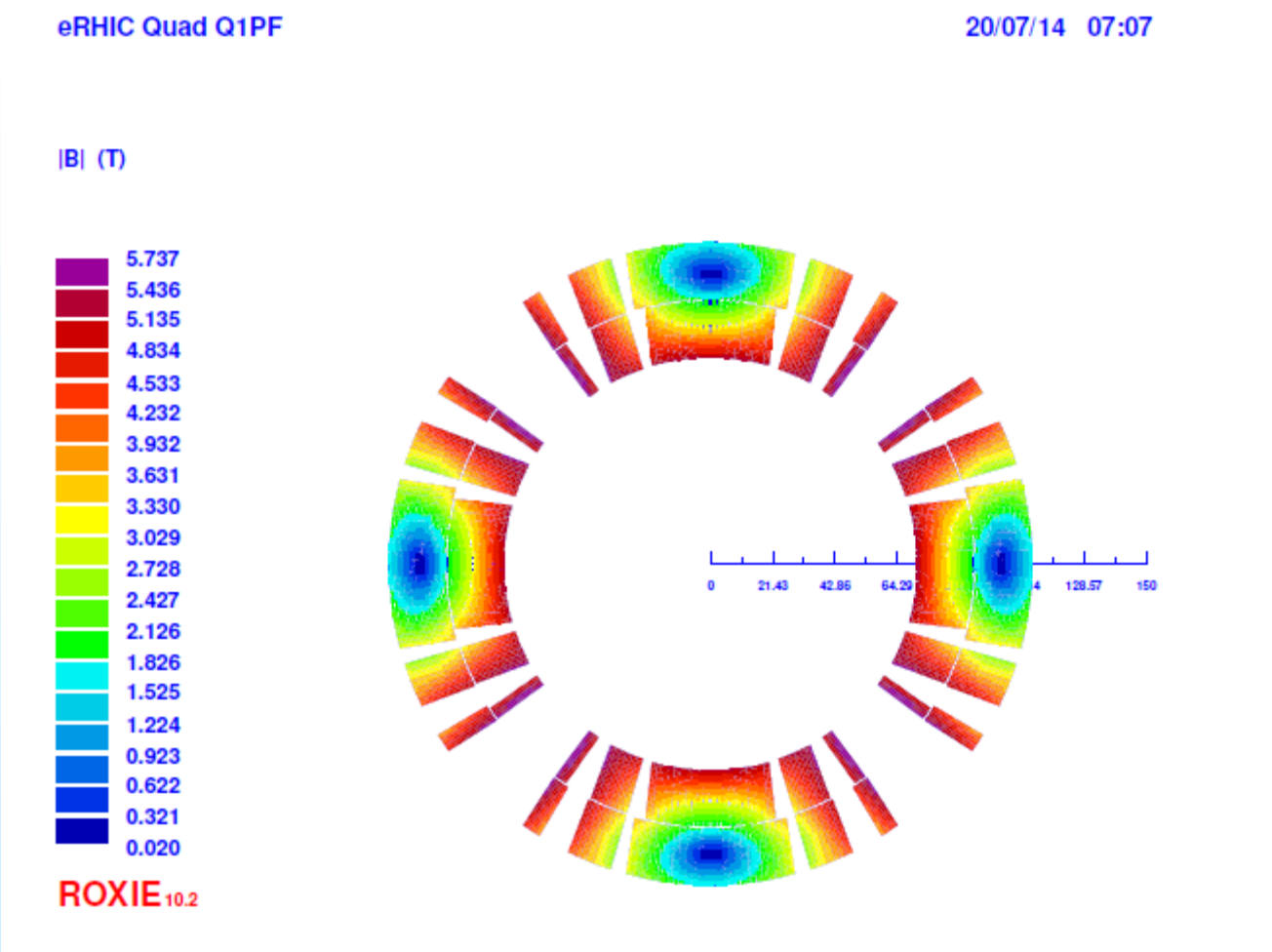
A reasonably good field quality is obtained with a good mechanical design (coil radius 71 mm)
(all harmonics <1 unit)



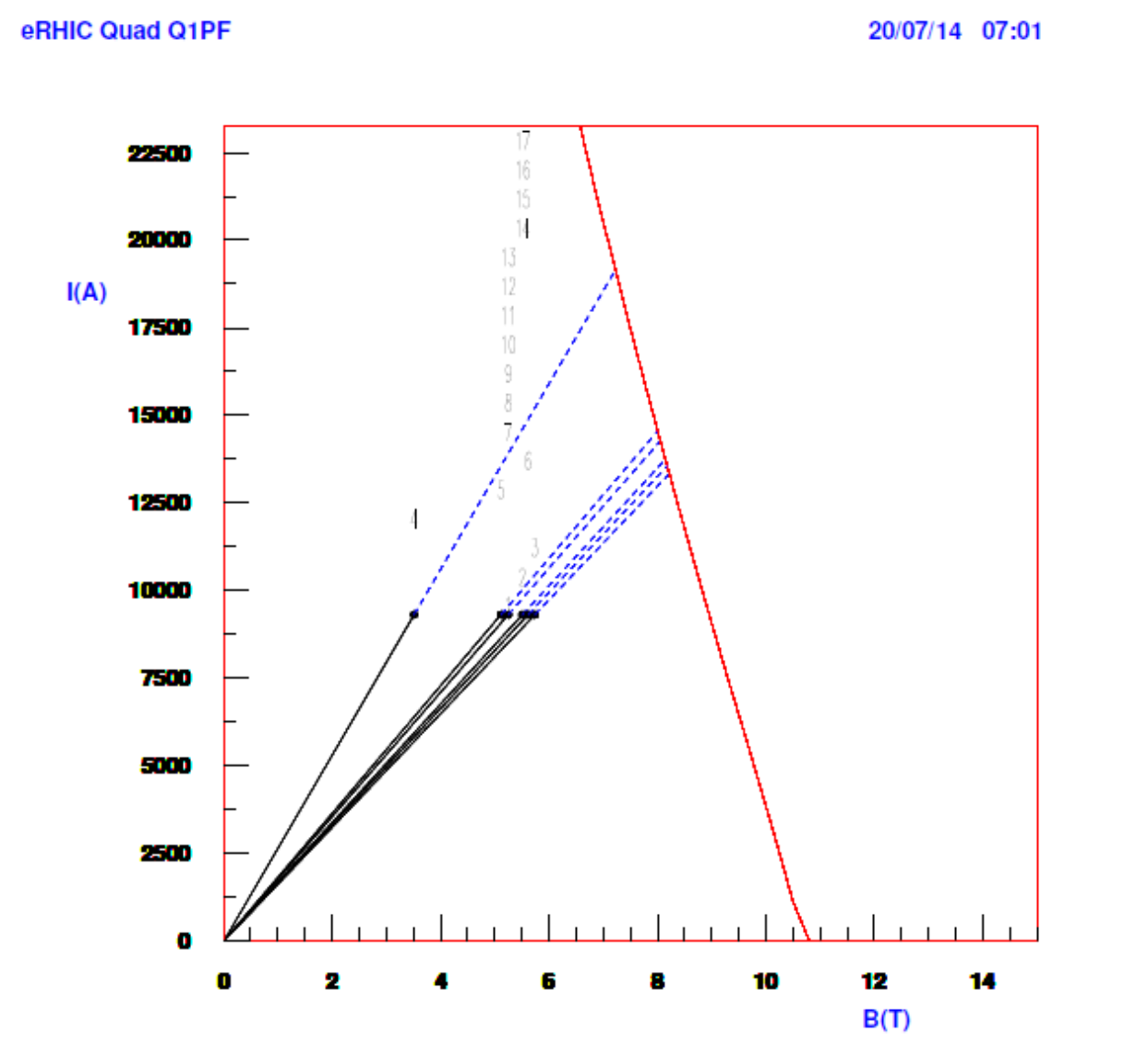
Gradient 72.6 T/m at ~9.3 kA

```
REFERENCE RADIUS (mm) ........ 36.0

MAGNET STRENGTH (T/(m^(n-1)) ......................      72.6821

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.77119  b 2:  10000.00000  b 3:     -0.17439
b 4:     -0.03551  b 5:     -0.01107  b 6:     -0.18329
b 7:     -0.00119  b 8:     -0.00028  b 9:     -0.00008
b10:      0.17361  b11:     -0.00001  b12:     -0.00000
b13:     -0.00000  b14:      0.04157  b15:     -0.00000
b16:     -0.00000  b17:      0.00000  b18:     -0.00097
b19:     -0.00000  b20:     -0.00000  b
```

Peak Fields in Q1ApF

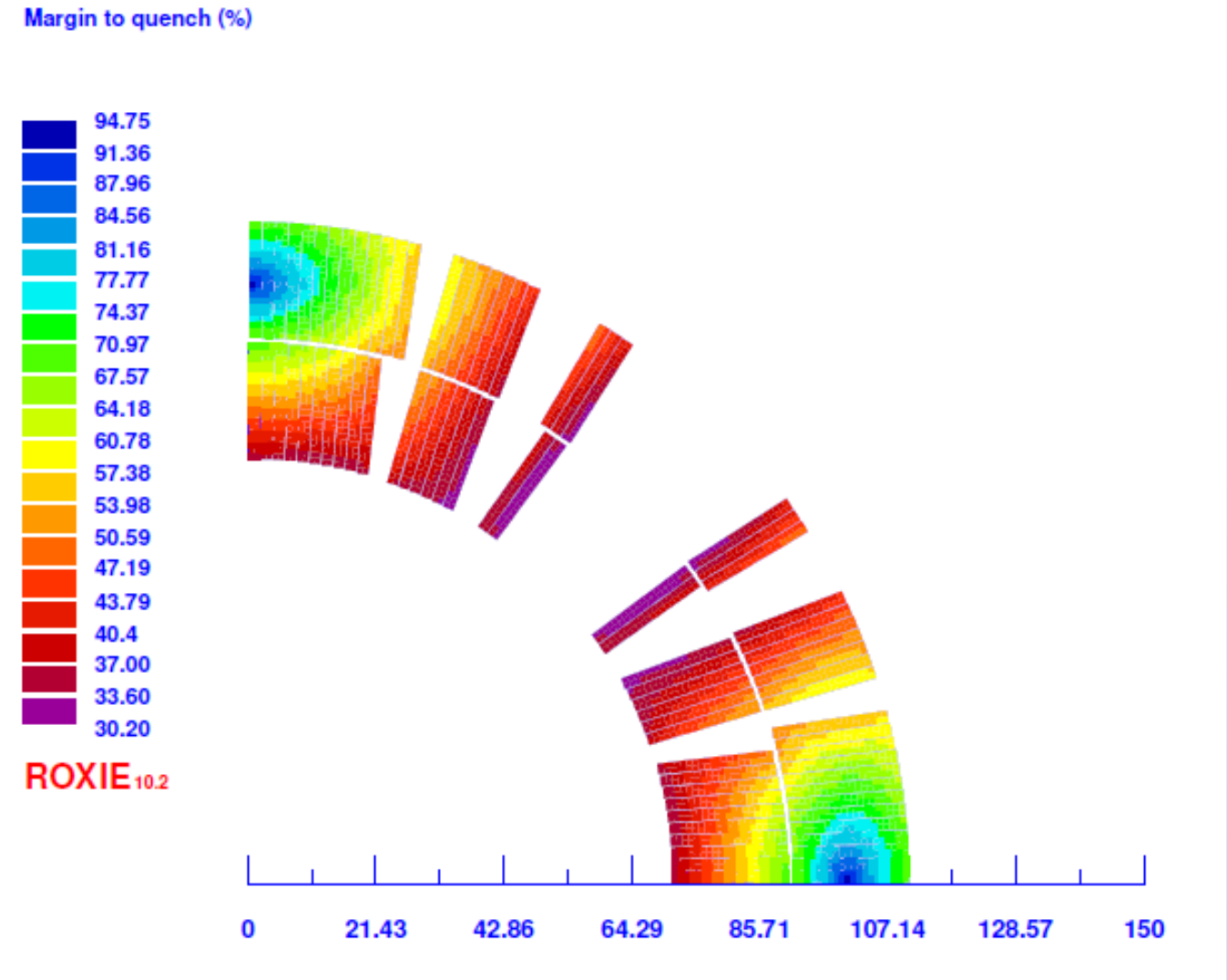


Field Margin at 4.2 K

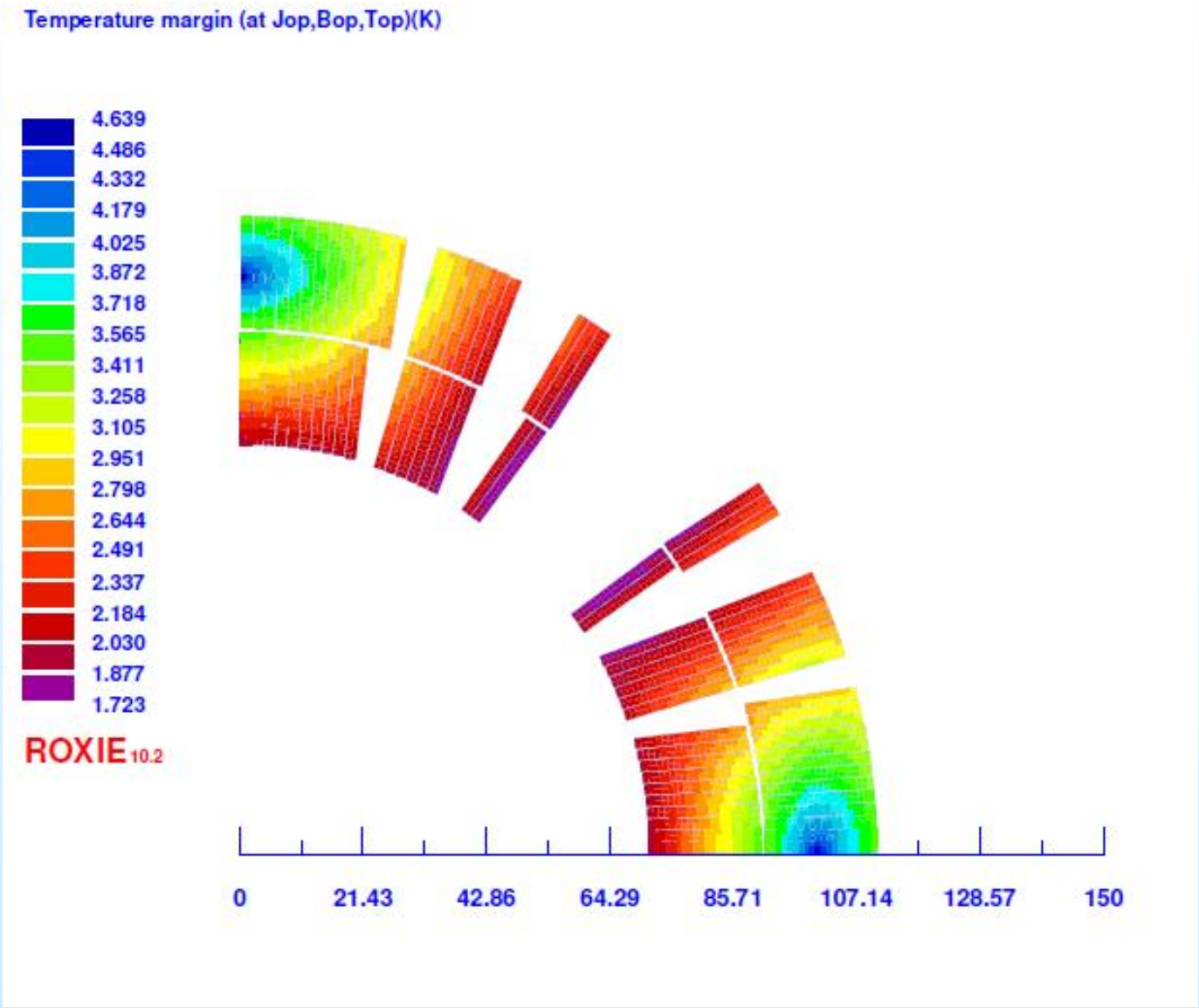


Very Good Margin

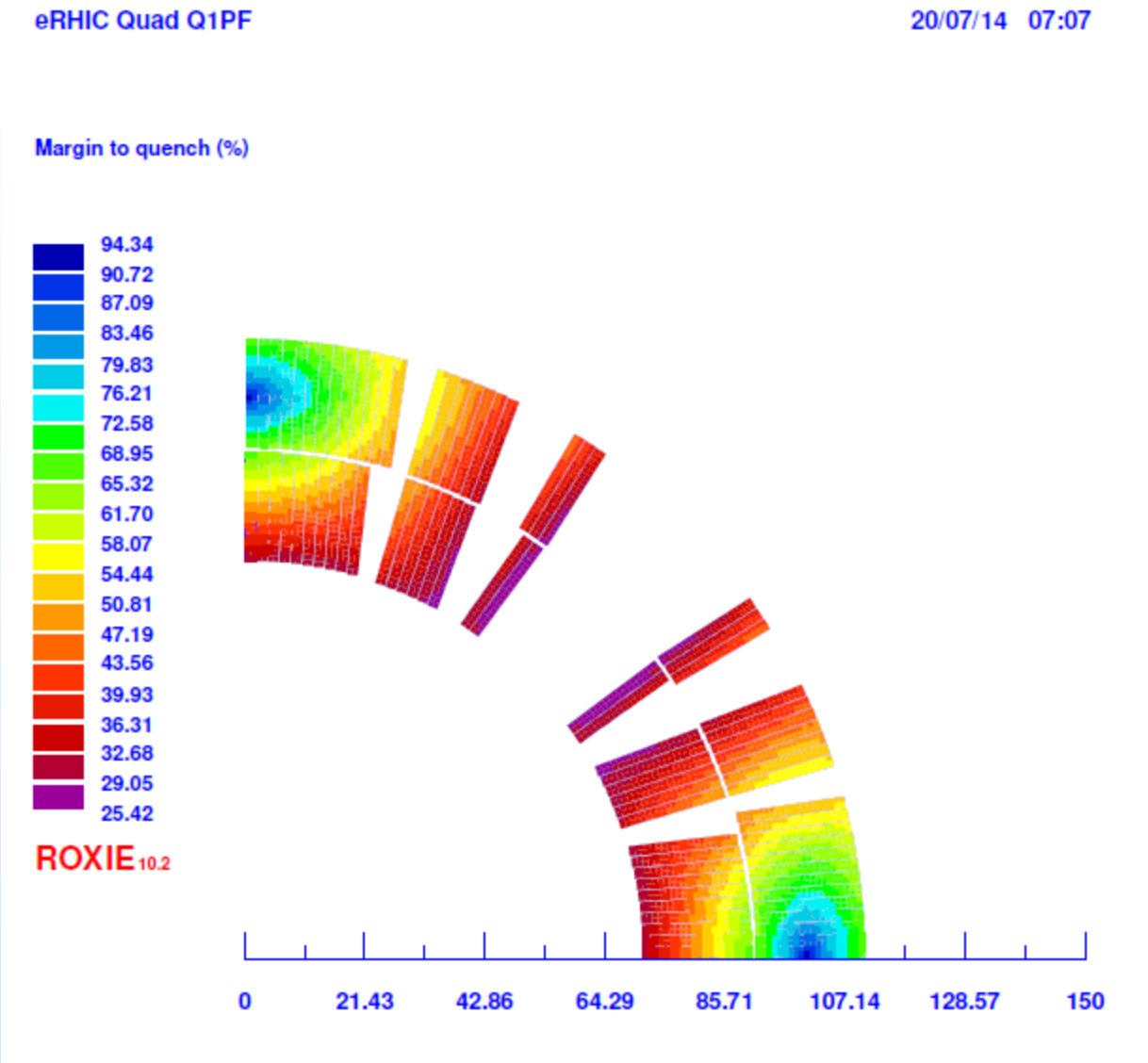
Field Margin at 4.2 K



Temperature Margin at 4.2 K Over Different Blocks

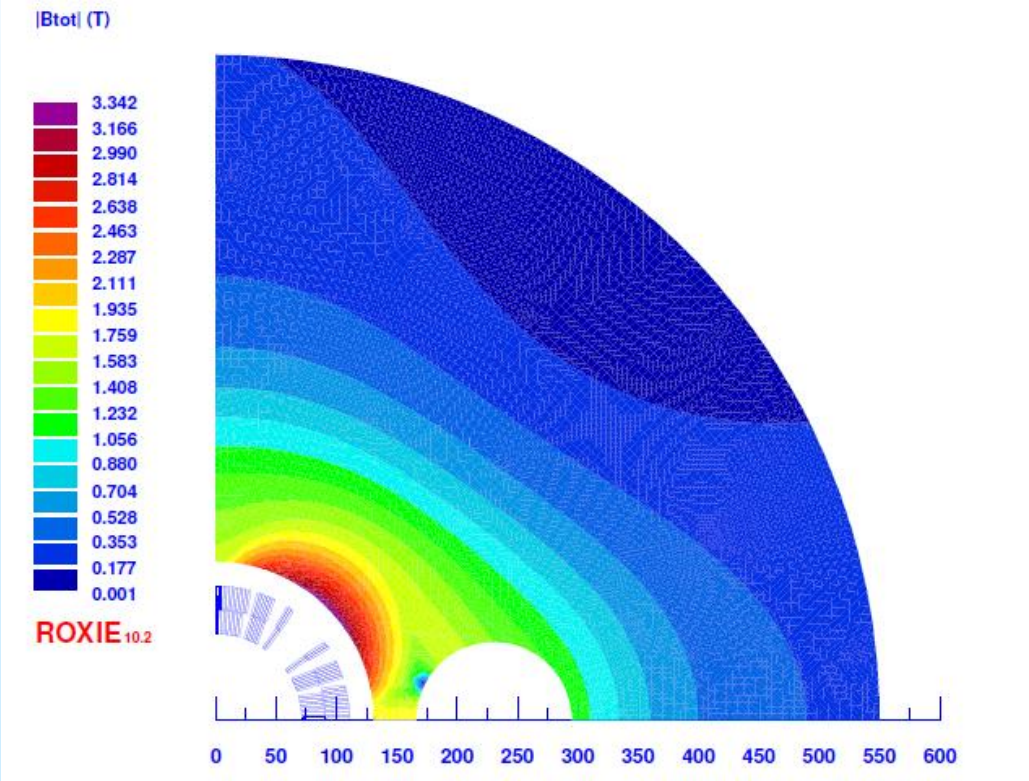


Field Margin at 4.6 K, Cu/Sc =1.6



Iron Yoke – Initial Design

Yoke: ir = ~131 mm; or = 550 mm (or 500 mm)
Hole@ x = 230.5 mm to 259 mm
Radius of hole = 44.6 & 58.4 mm (+20 mm for electron beam)
Collar width = ~20 mm

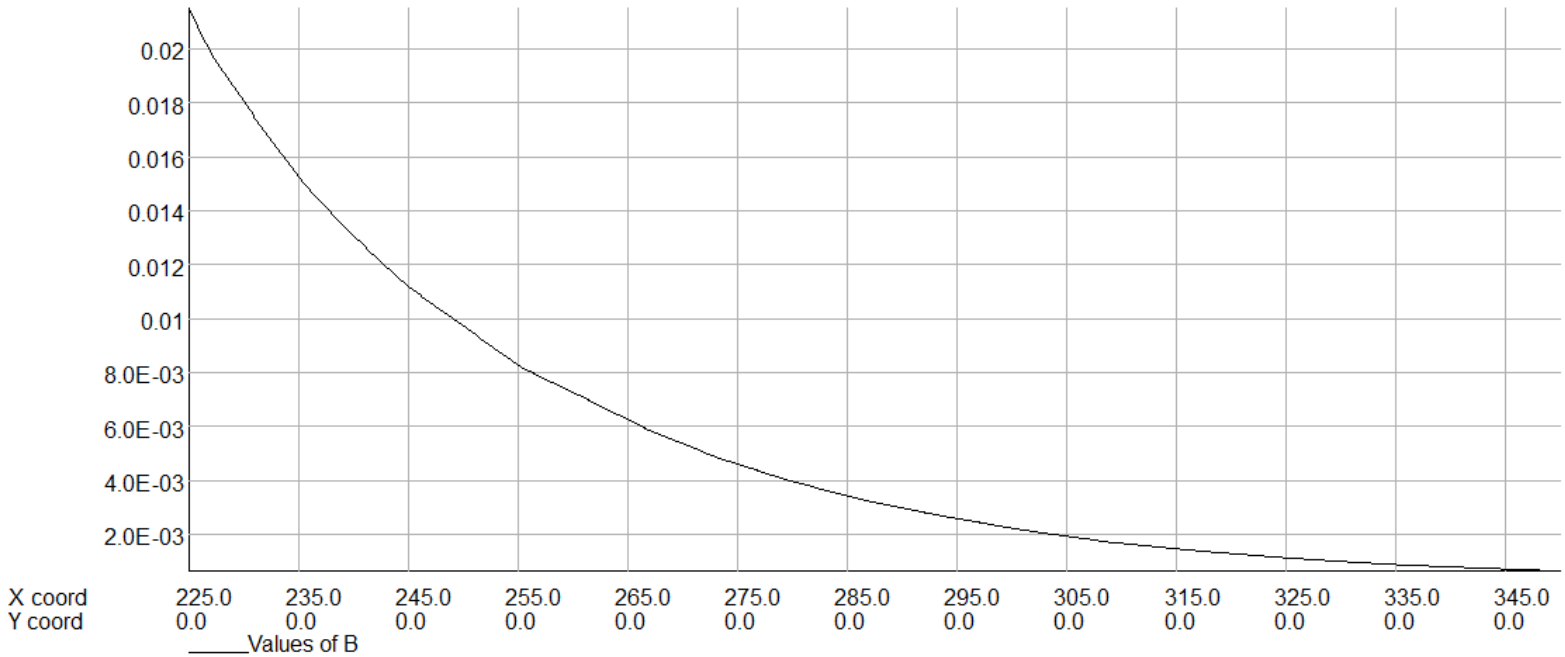


ROXIE

Iron Optimization to Reduce Field in the electron Beam Region

Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm

Shown a couple week ago (6/30/2020)
Field in electron Beam Region 0.02 T



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1BpF_Q2eF\opera\q1BpF_Q2eF-e.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
75985 elements
38295 nodes
71 regions

30/Jun/2020 12:47:17 Page 17

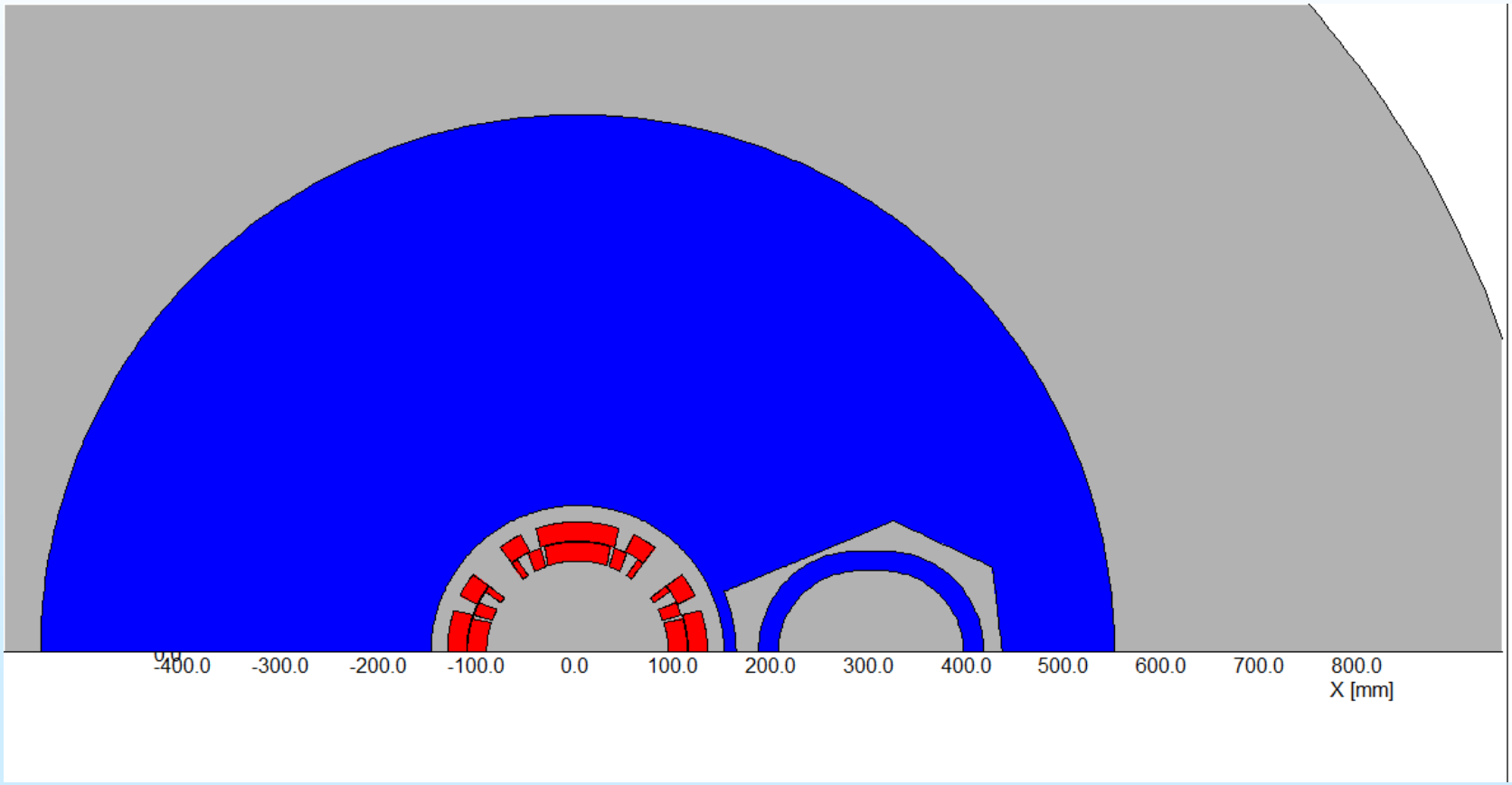
Opera

Several techniques from the first principle examined.

Only a couple of cases shown

Technique: Guide flux away from electron beam region

Provide circular shielding for electron and ion beam



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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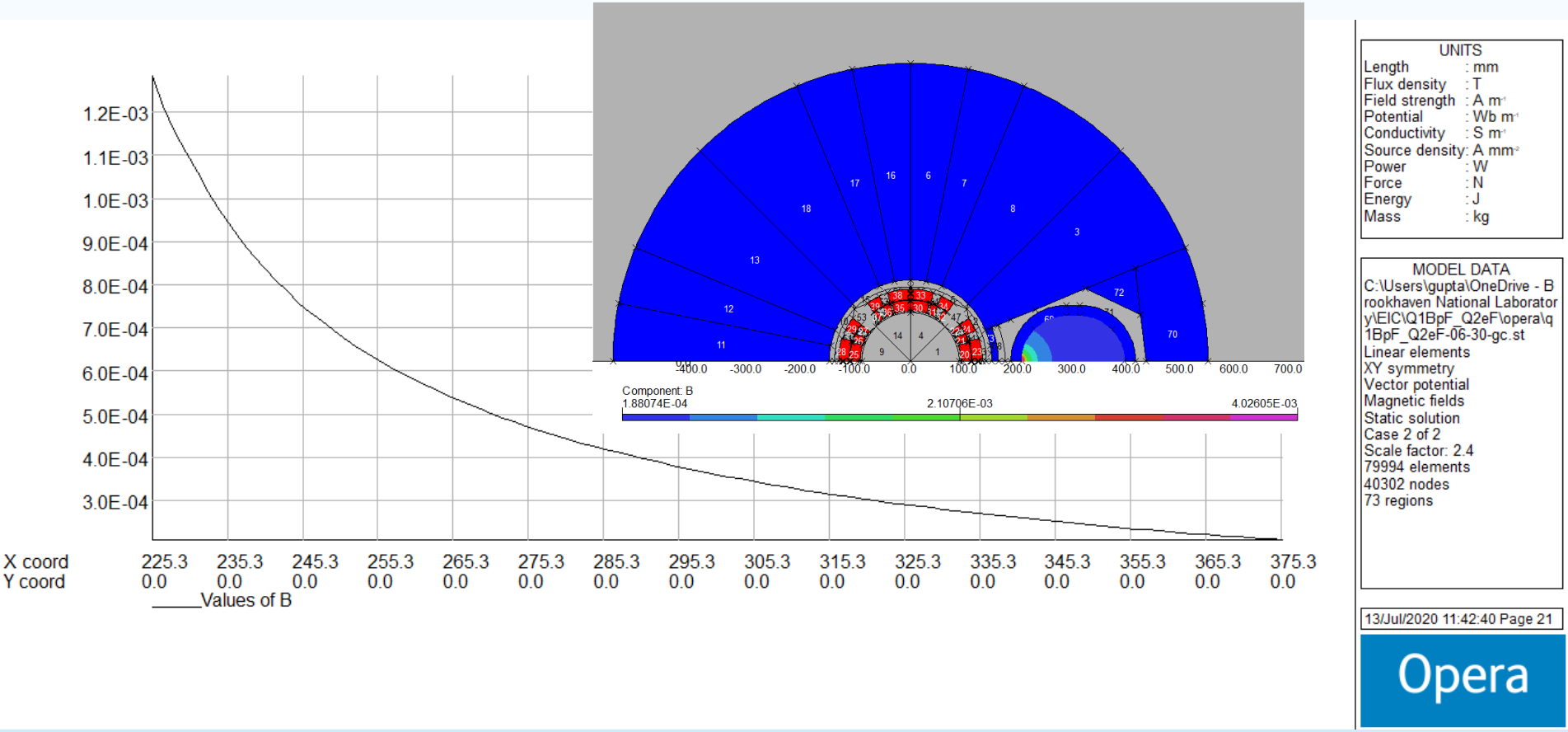
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
79994 elements
40302 nodes
73 regions

14/Jul/2020 11:57:29 Page 52

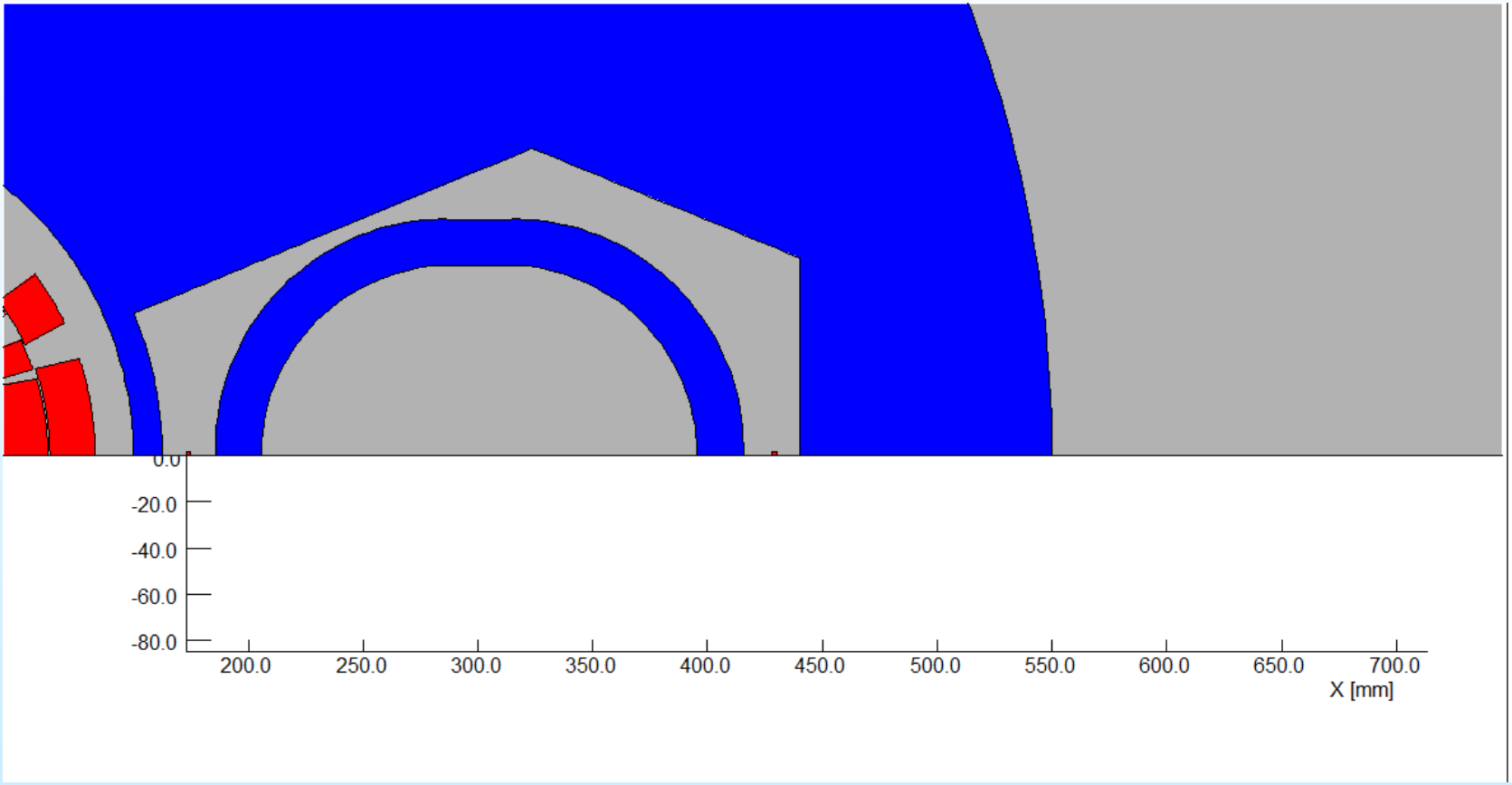
Opera

Over an order of magnitude reduction in field

This field can be shield with mu-metal, etc.



Further Reduction



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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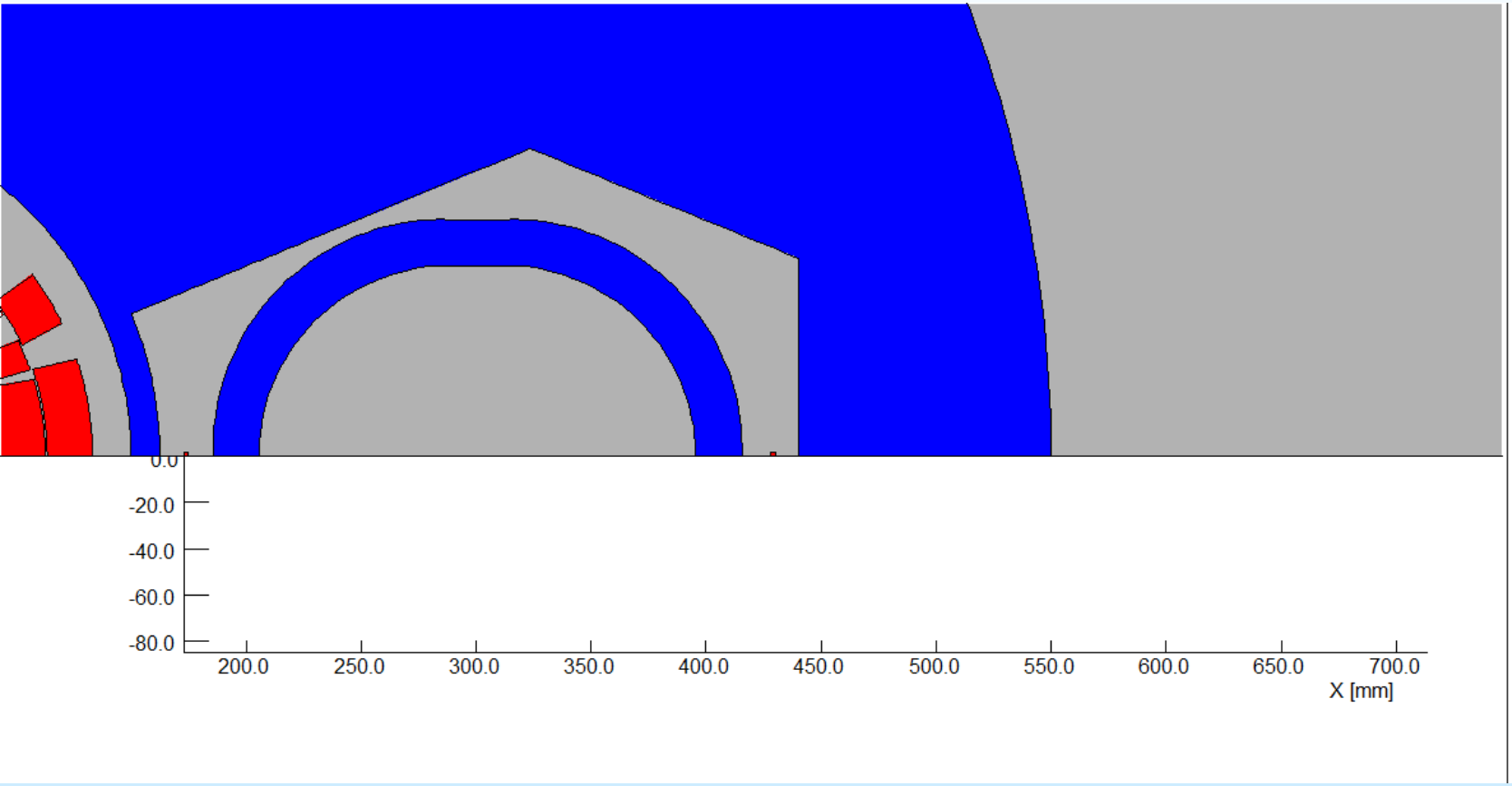
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
80713 elements
40666 nodes
82 regions

14/Jul/2020 12:09:52 Page 60

Opera

Shielding

Tiny current on the two side of circular yoke over e-beam (still shielding for electron and ion beam)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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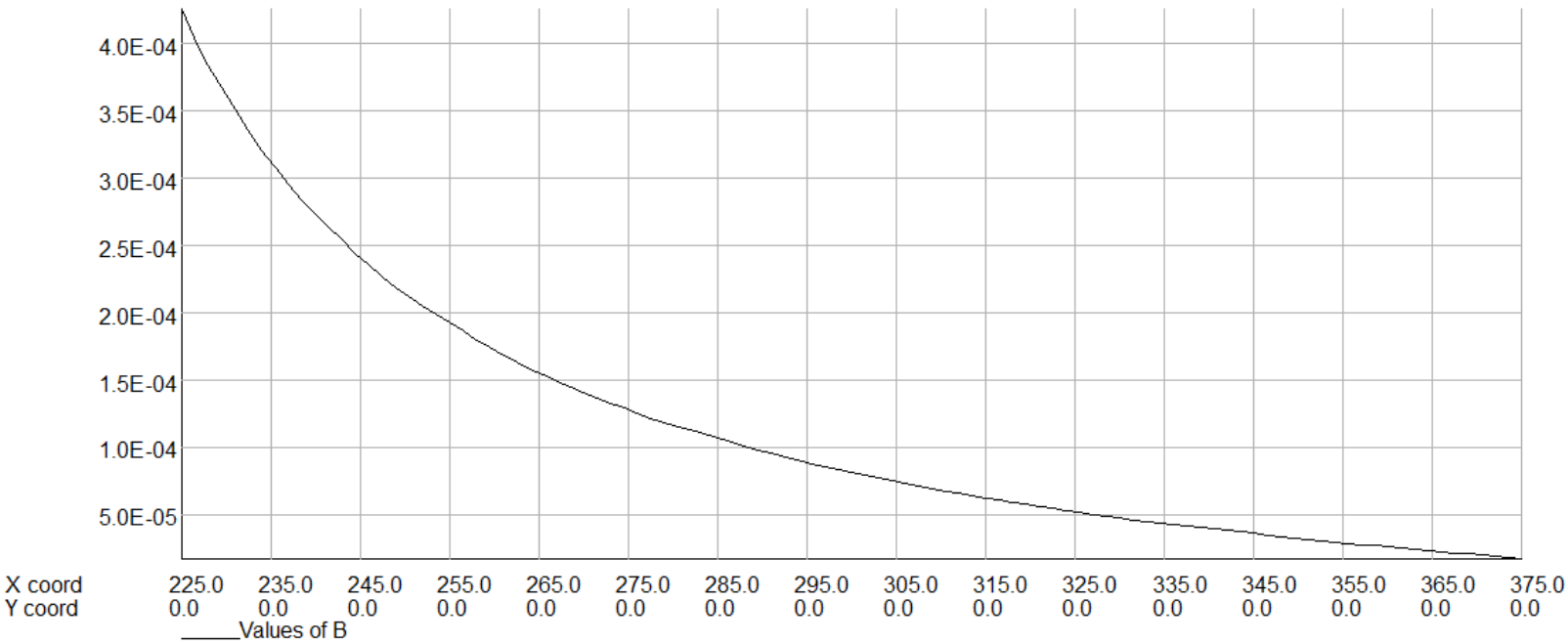
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
80713 elements
40666 nodes
82 regions

14/Jul/2020 12:09:52 Page 60

Opera

Two order of magnitude reduction

Tiny current on the two side of circular yoke over e-beam gives a solution (still shielding for electron and ion beam)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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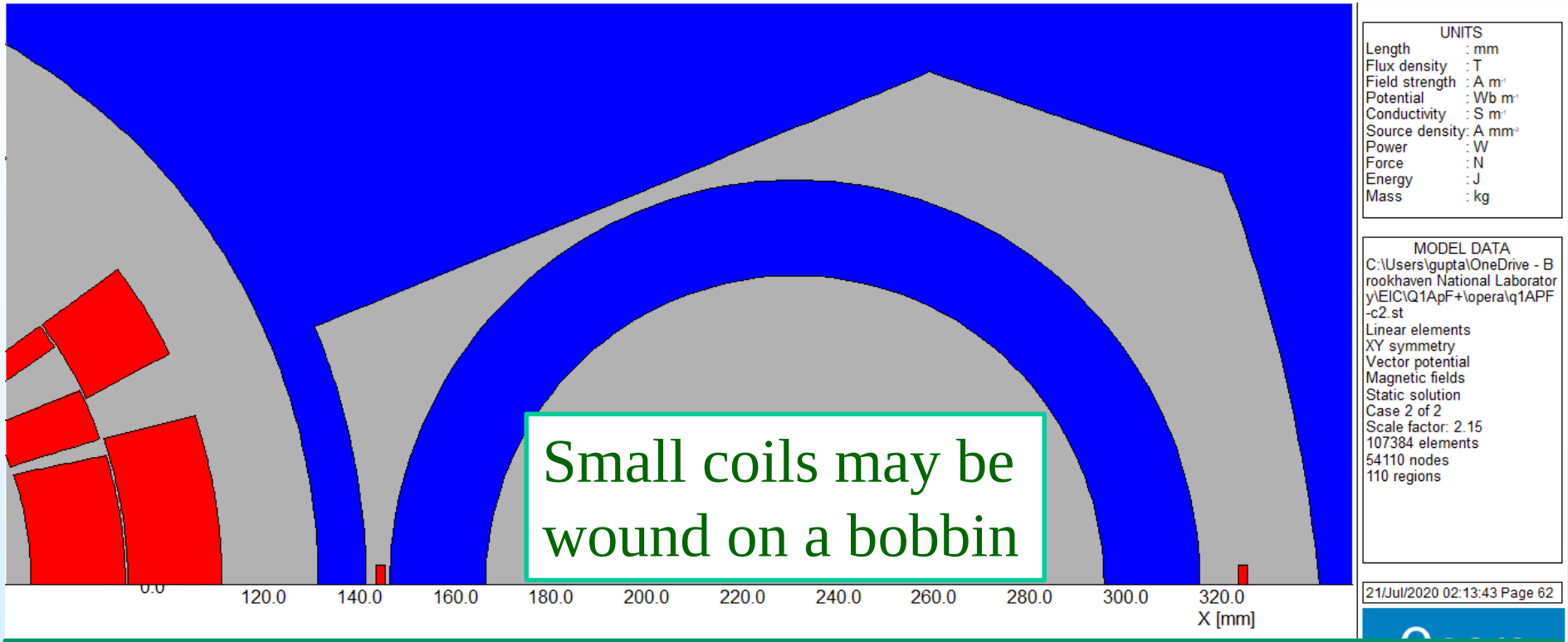
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.4
80713 elements
40666 nodes
82 regions

14/Jul/2020 12:13:54 Page 61

Opera

Yoke Design of Q1A for a low field e-beam region

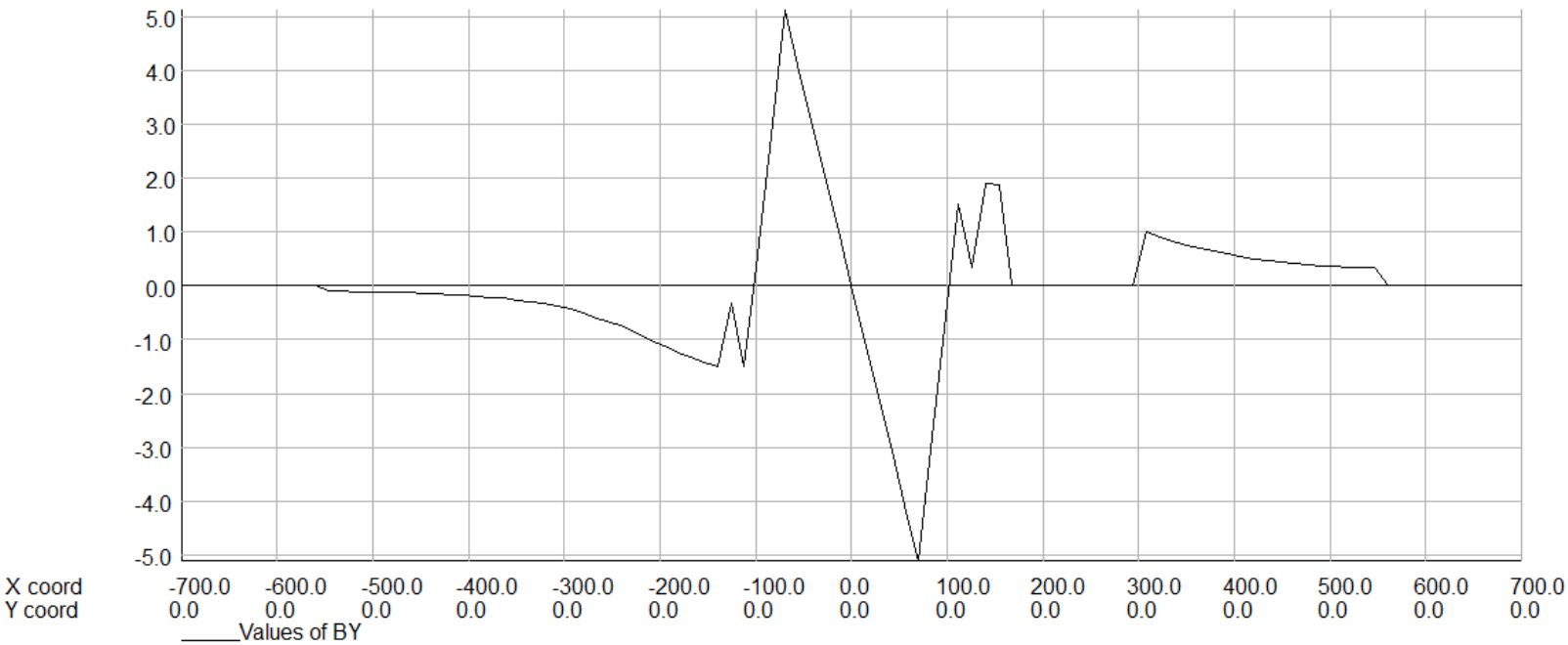
Optimized Q1A Yoke with Small Coil (same technique that worked in Q1B)



Small coils may be wound on a bobbin

Path of flux lines navigated with cutout in yoke and small coils on the two side of yoke over e-beam region added to further navigate flux lines (and reduce saturation) to significantly reduce field in the e-beam region

Original Case (nothing done)



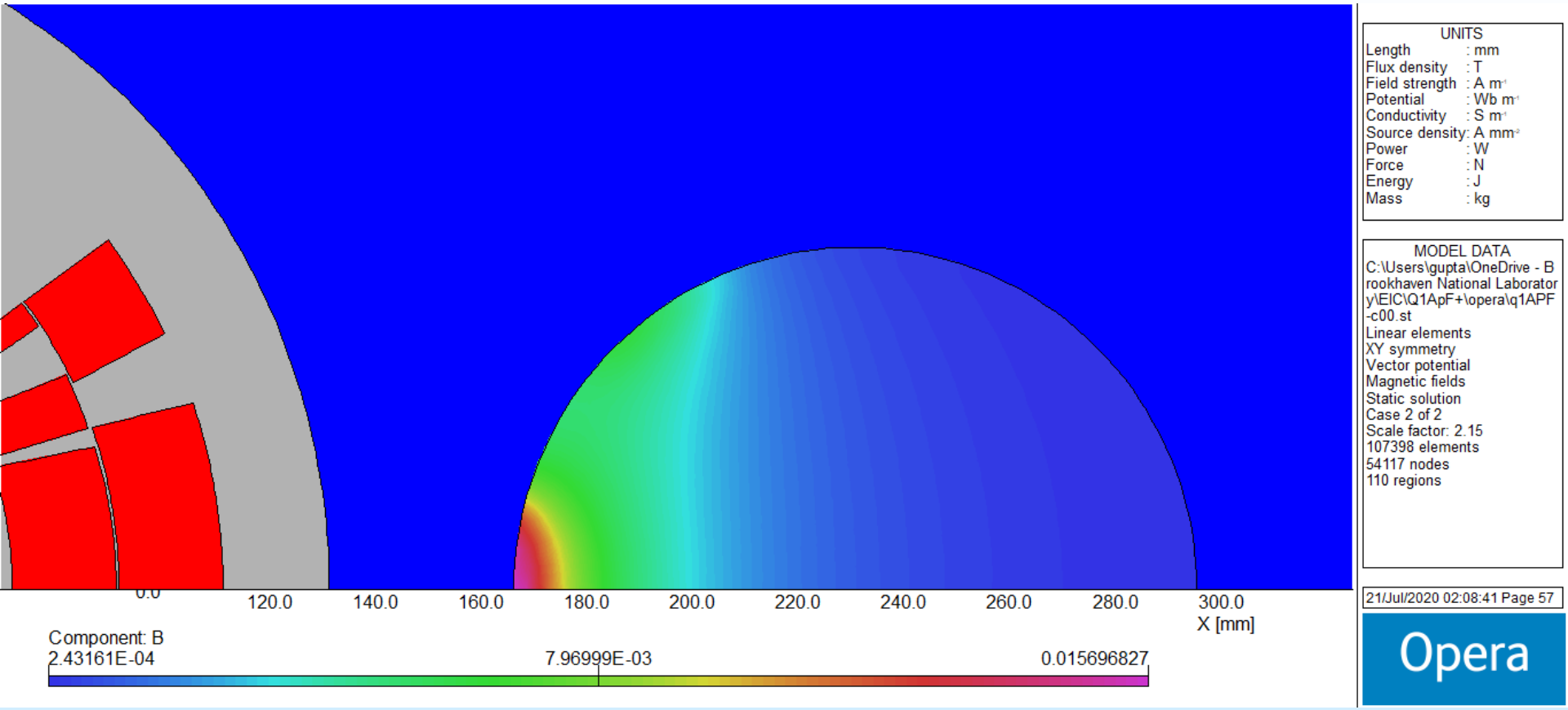
UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c00.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

21/Jul/2020 01:41:19 Page 26

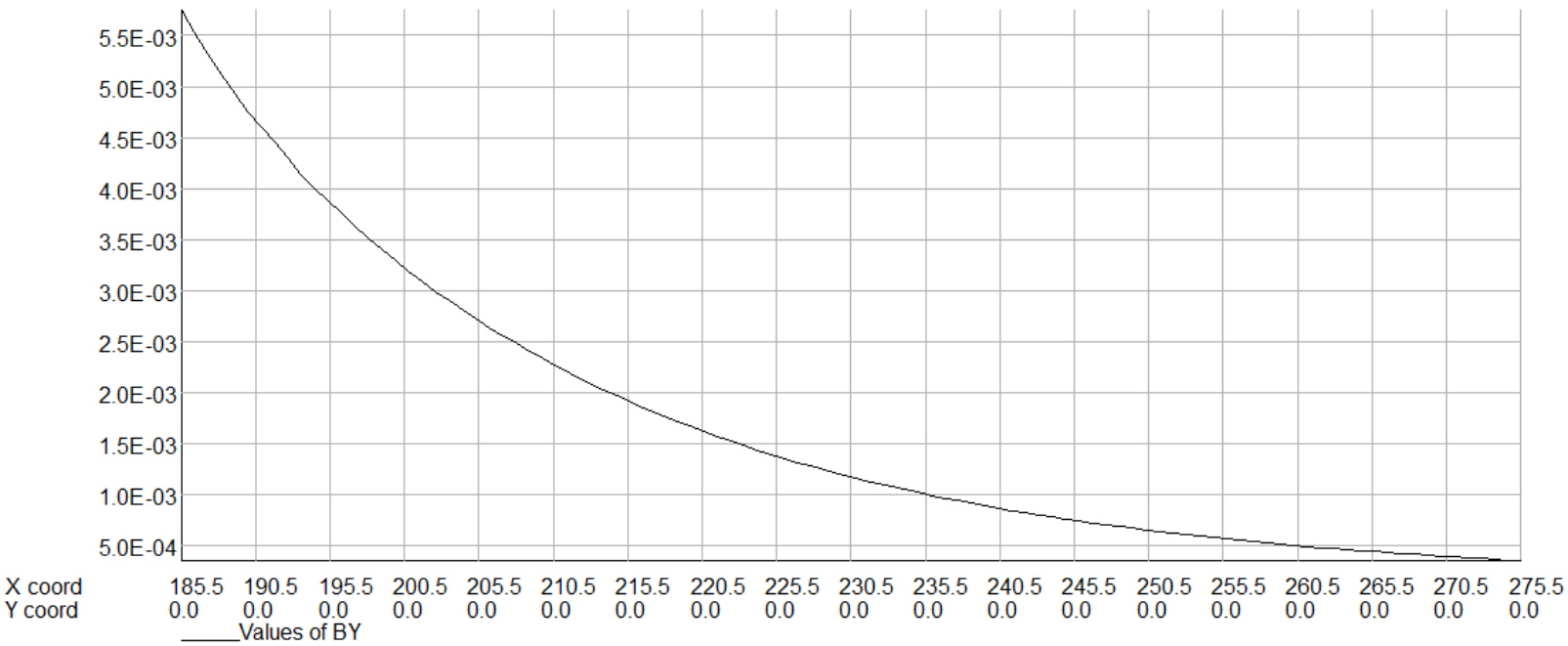
Opera

Original Case (nothing done)



Very high field in electron beam region

Original Case (nothing done)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

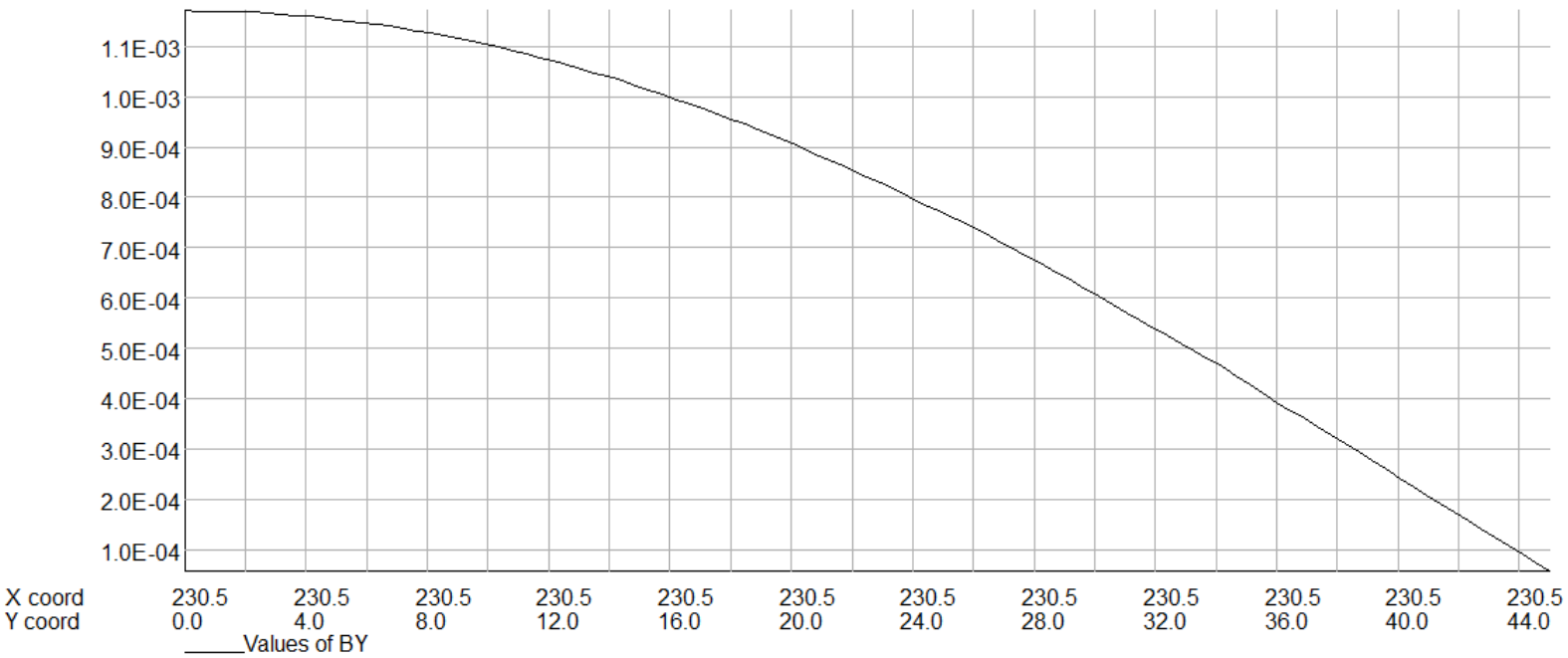
MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c00.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

21/Jul/2020 01:42:02 Page 27

Opera

Very high field in electron beam region

Original Case (nothing done)



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

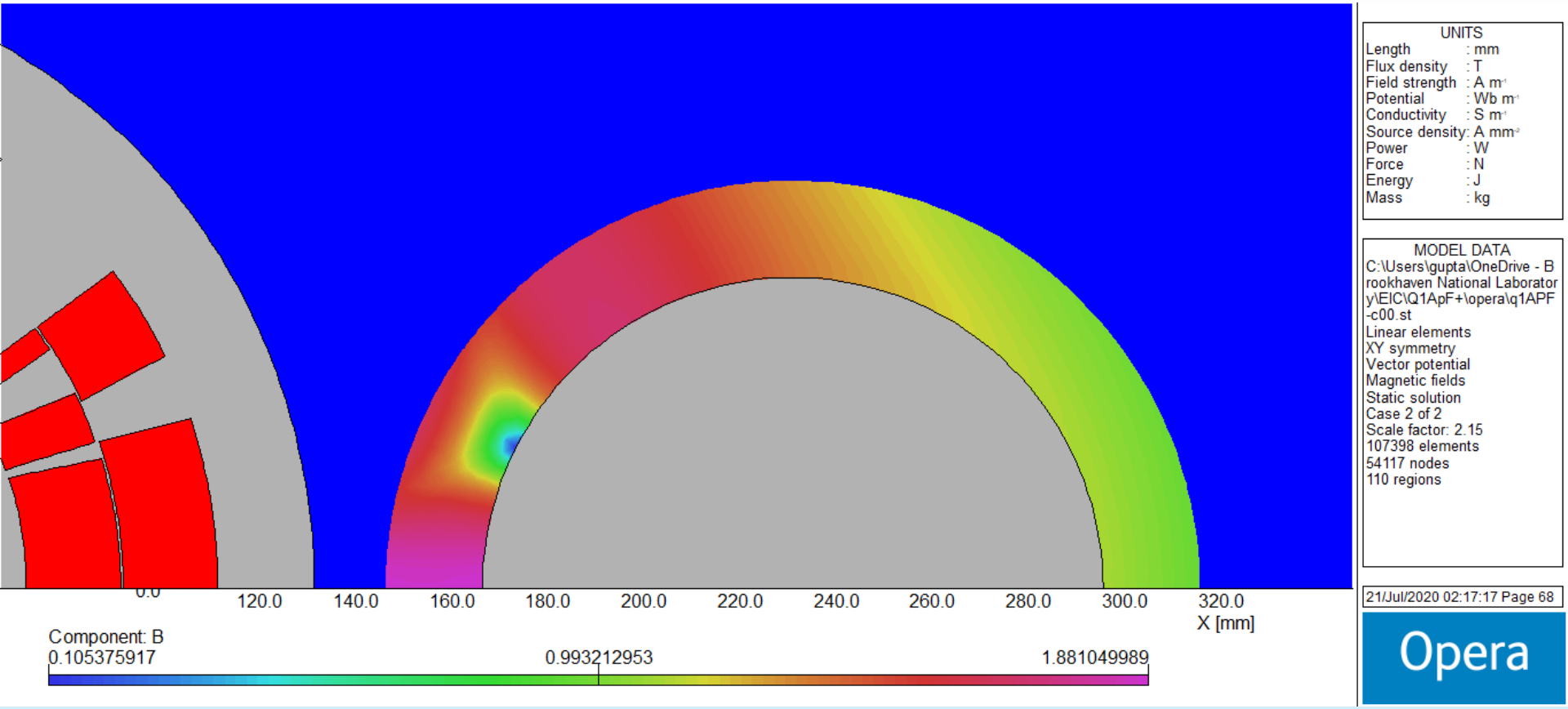
MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c00.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

21/Jul/2020 01:42:33 Page 28

Opera

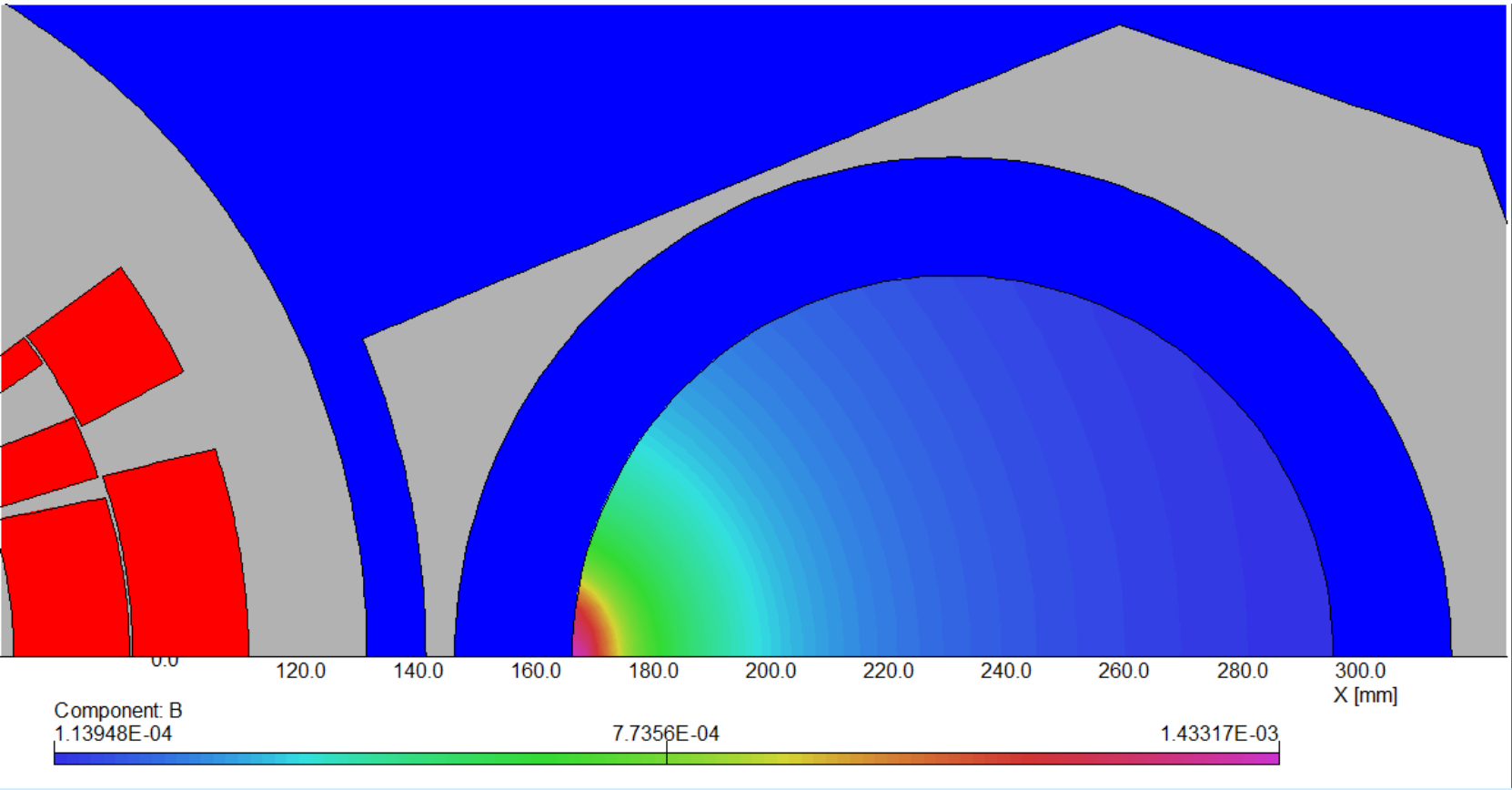
Very high field in electron beam region

Original Case (nothing done)

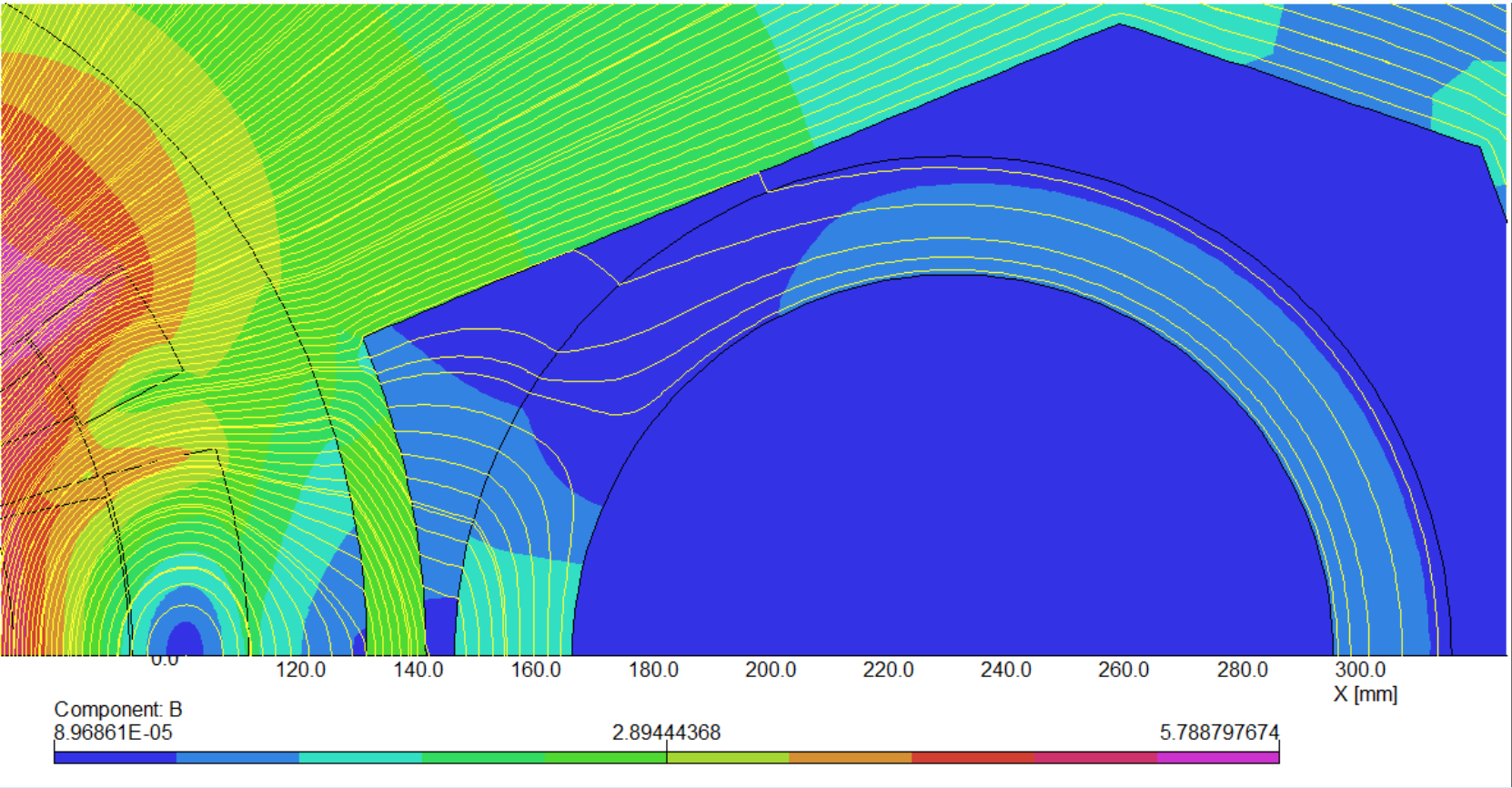


Yoke around electron beam region highly saturated

Cutout in the Yoke of Q1A



Cutout in the Yoke of Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c0.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

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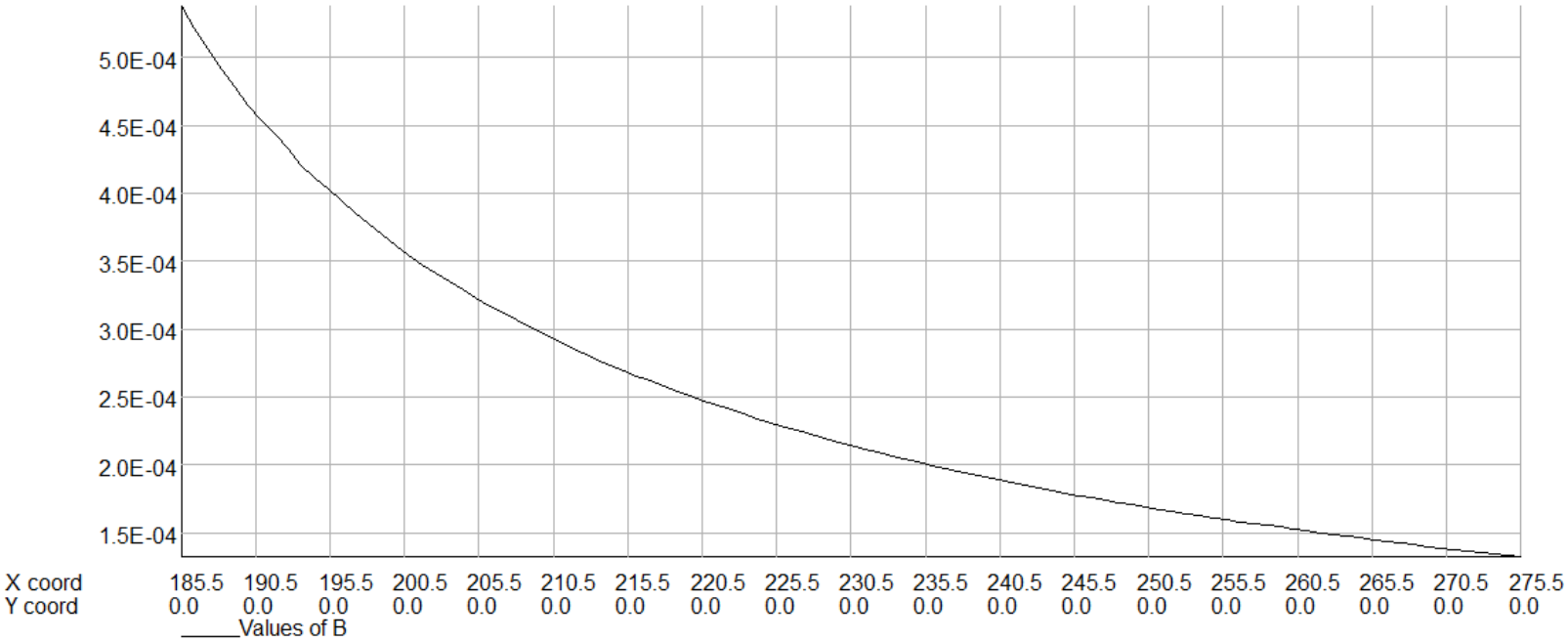
Opera

Cutout in the Yoke of Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

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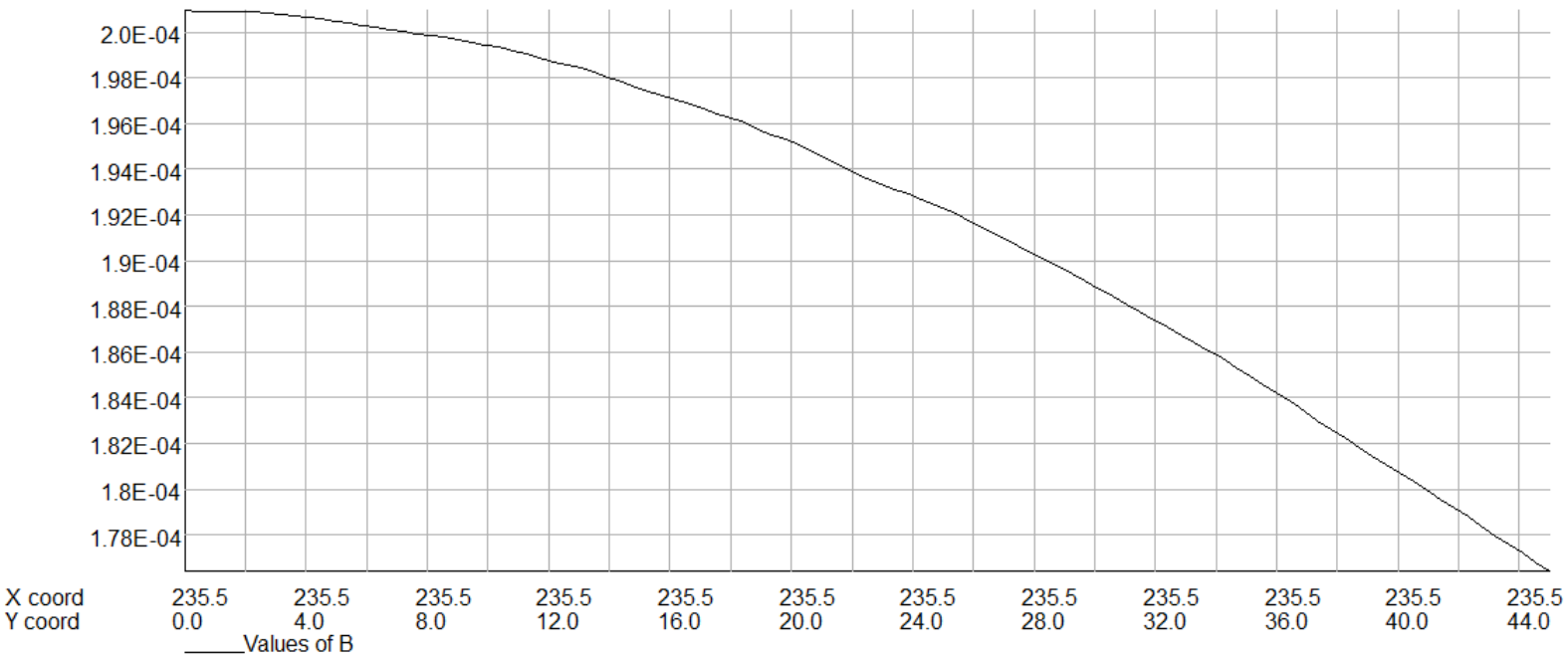
Opera

Cutout in the Yoke of Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c0.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

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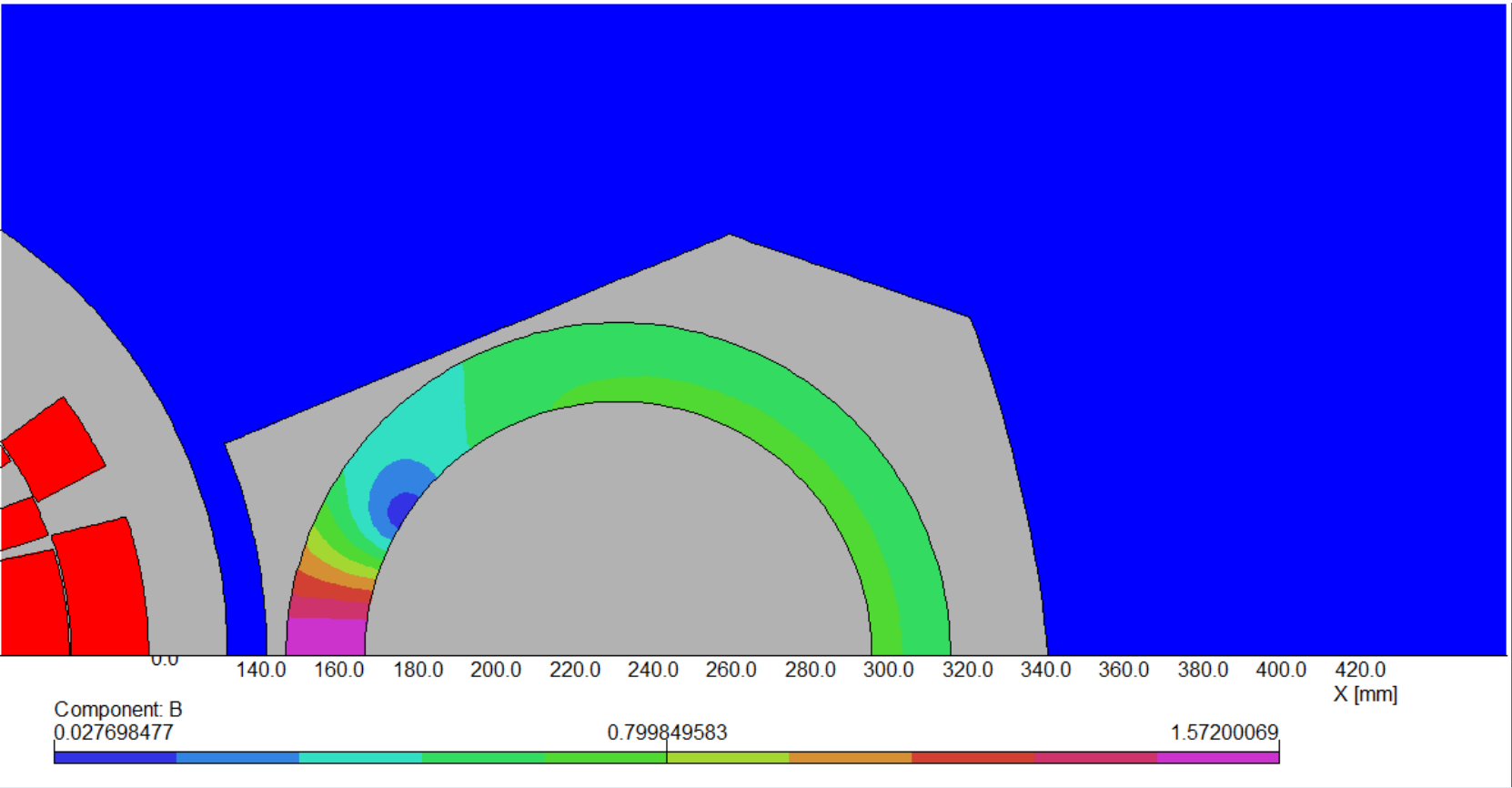
Opera

Cutout in the Yoke of Q1A

Cutout in the Yoke of Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c0.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

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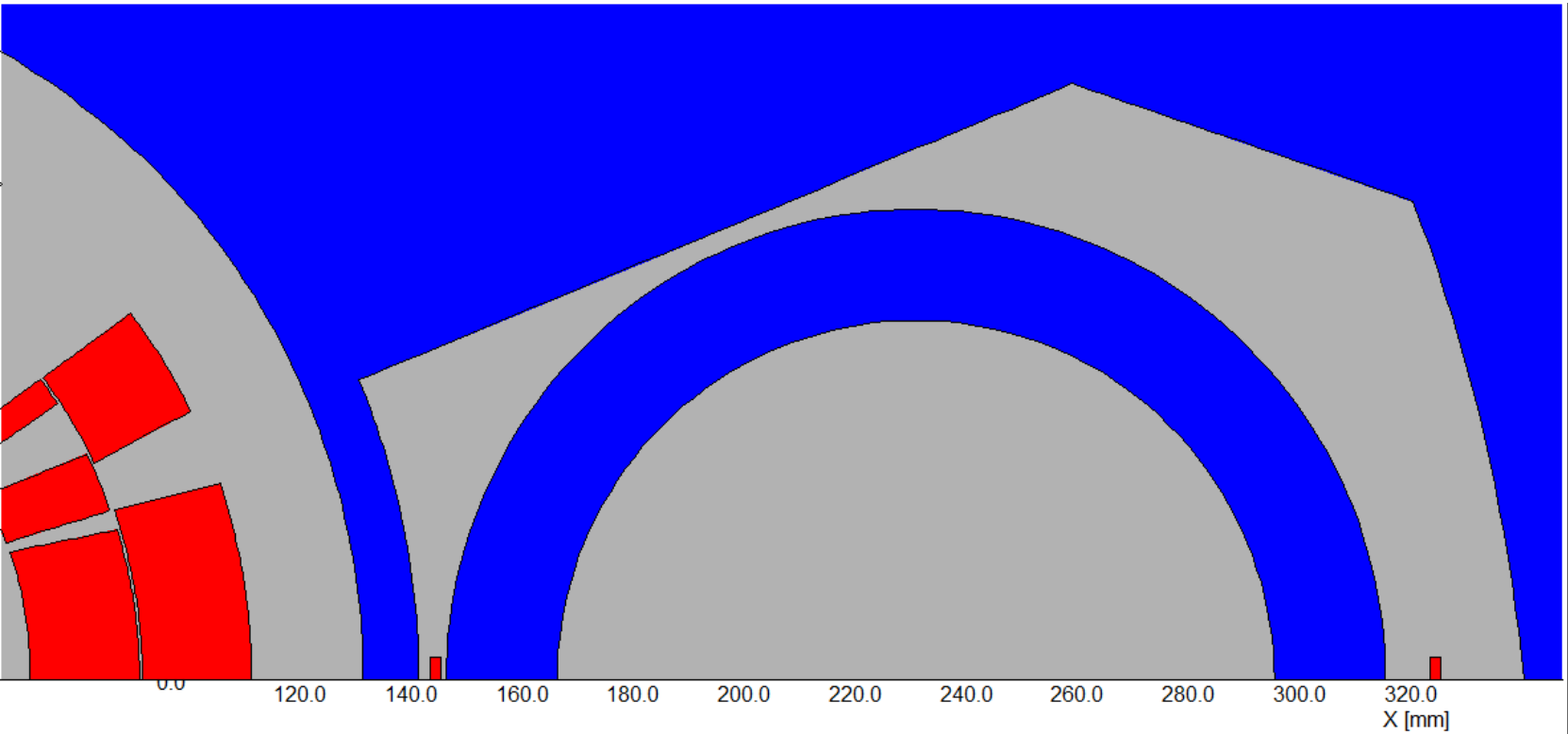
Opera

Cutout and Small Coil in Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
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Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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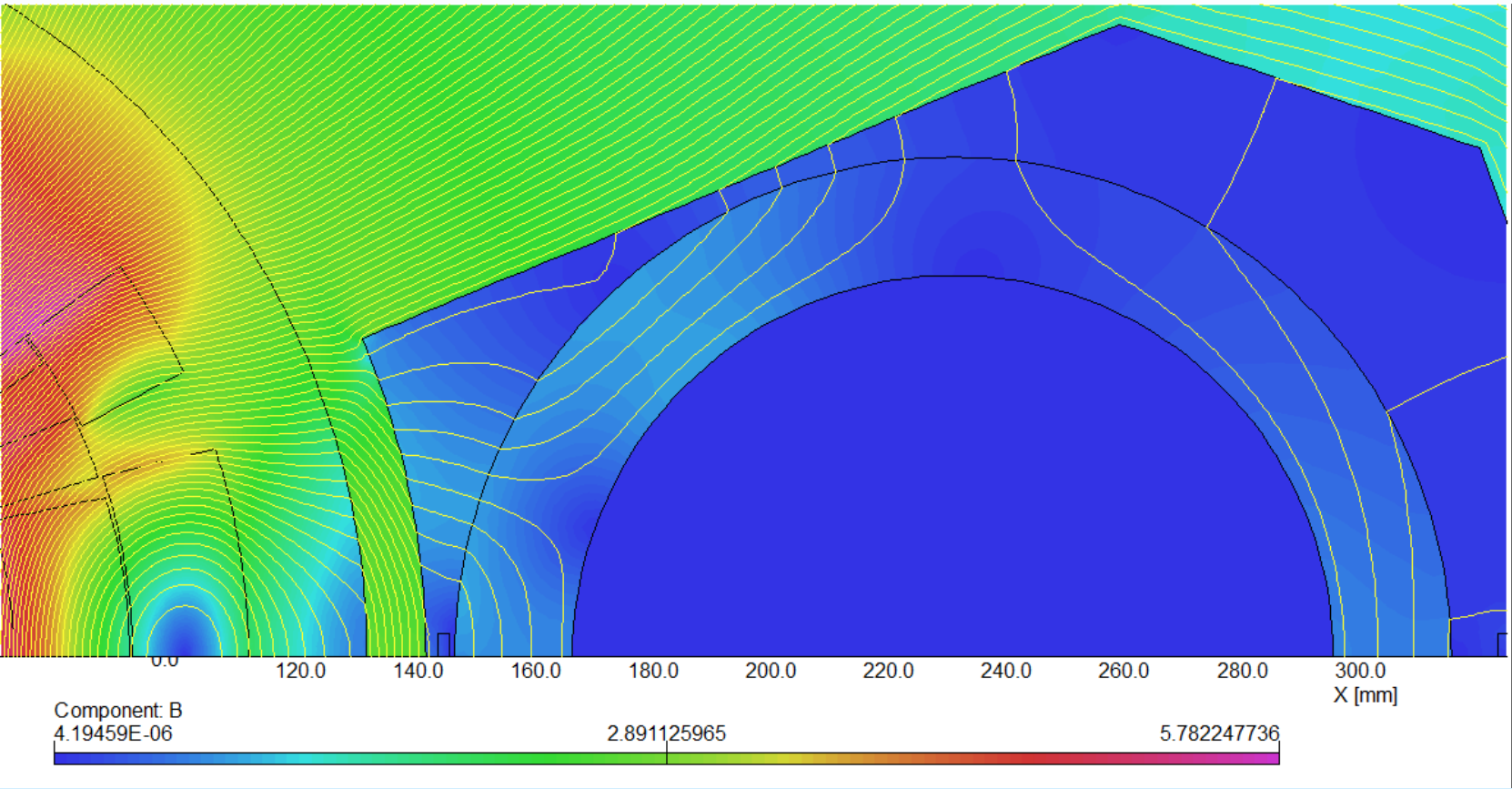
Opera

Cutout and Small Coil in Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c2.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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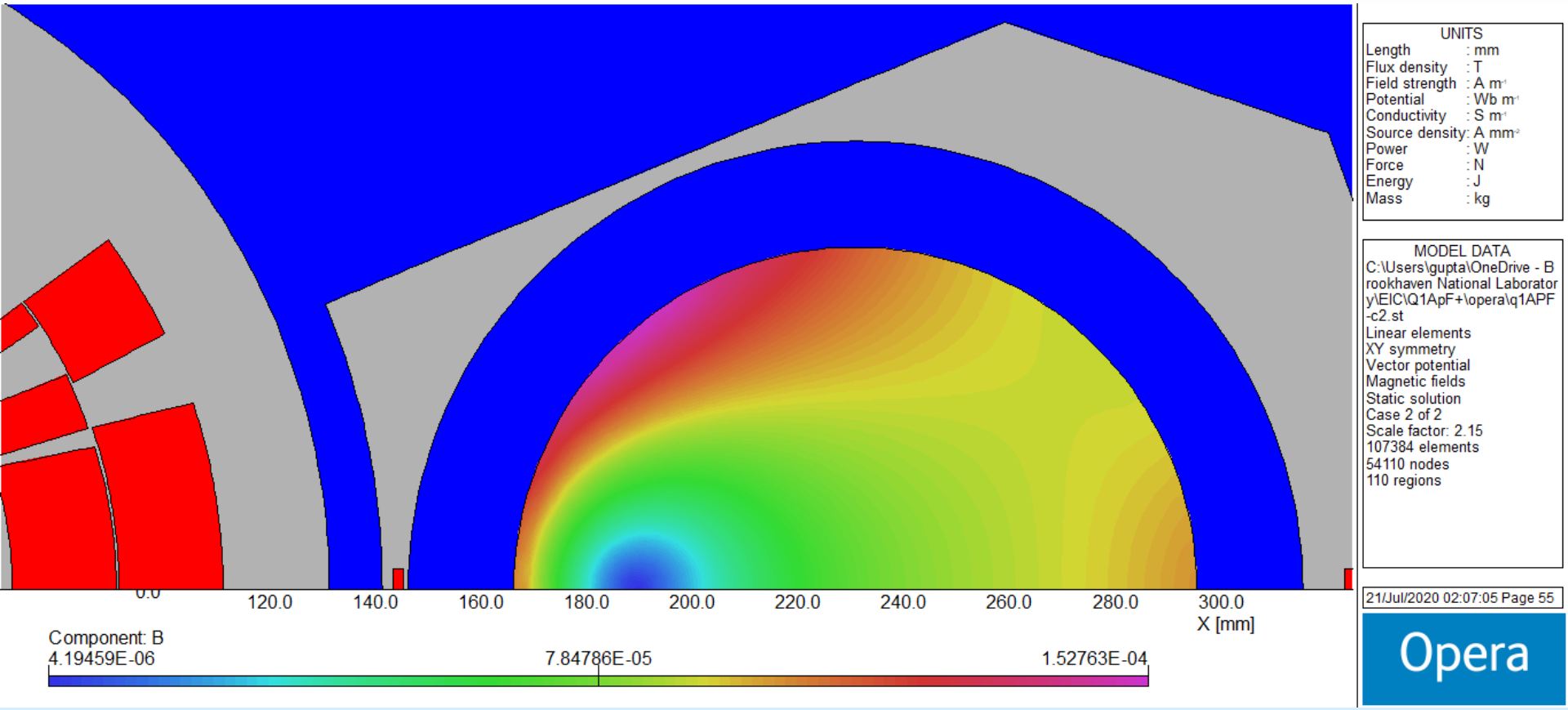
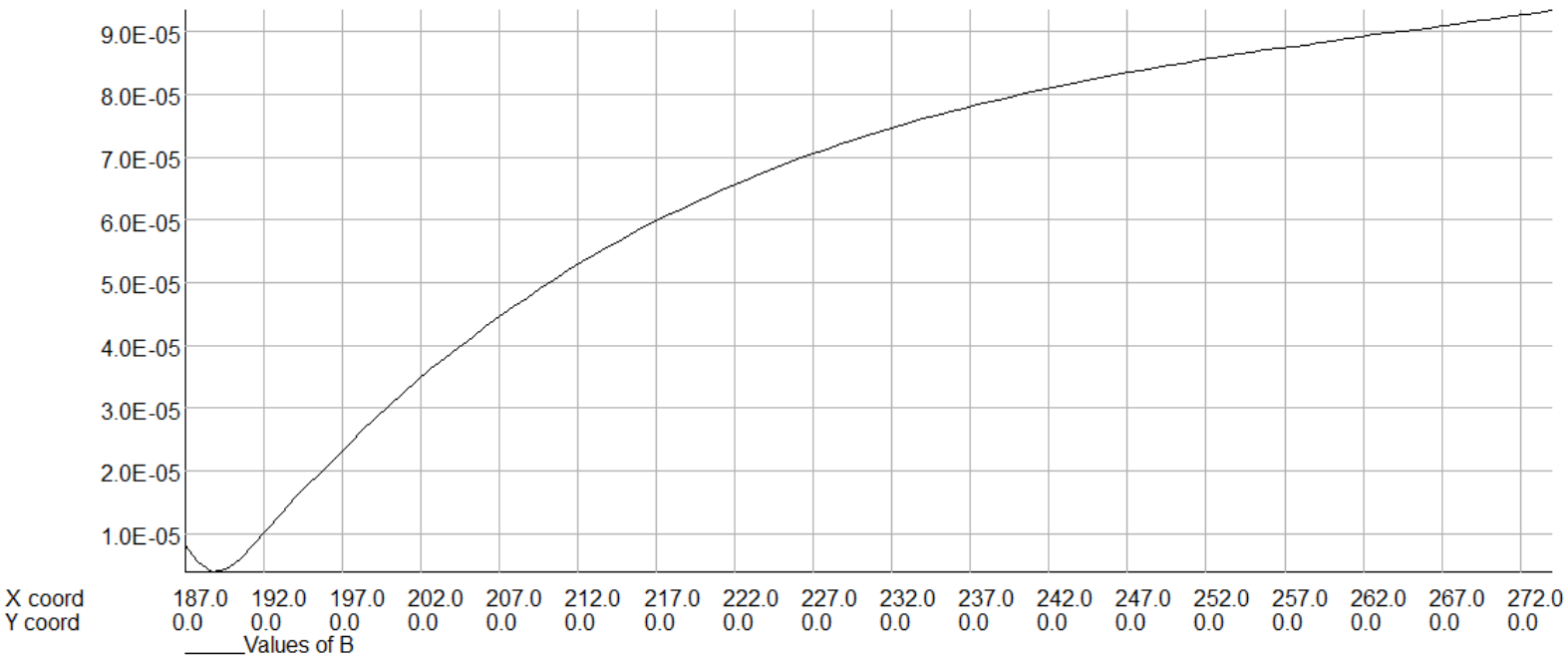
Opera

Cutout and Small Coil in Q1A



Cutout and Small Coil in Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c2.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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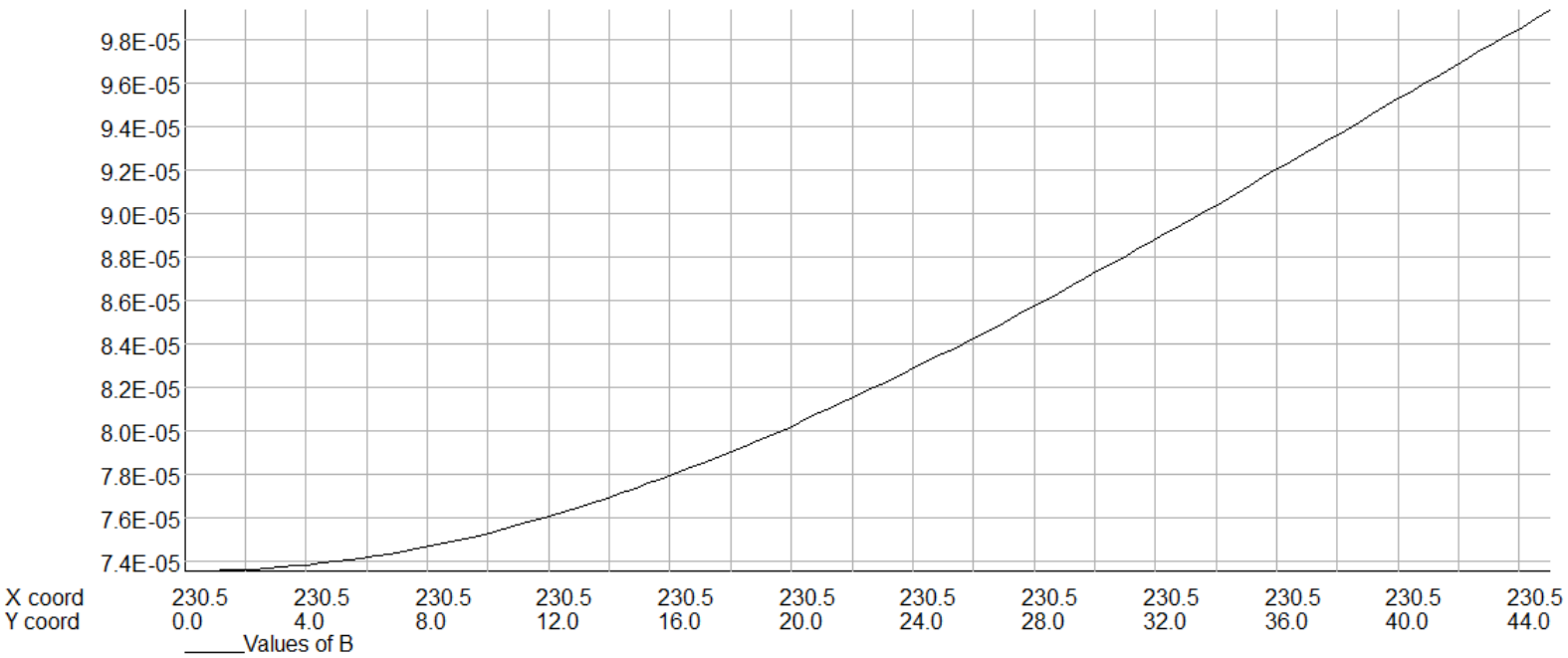
Opera

Cutout and Small Coil in Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c2.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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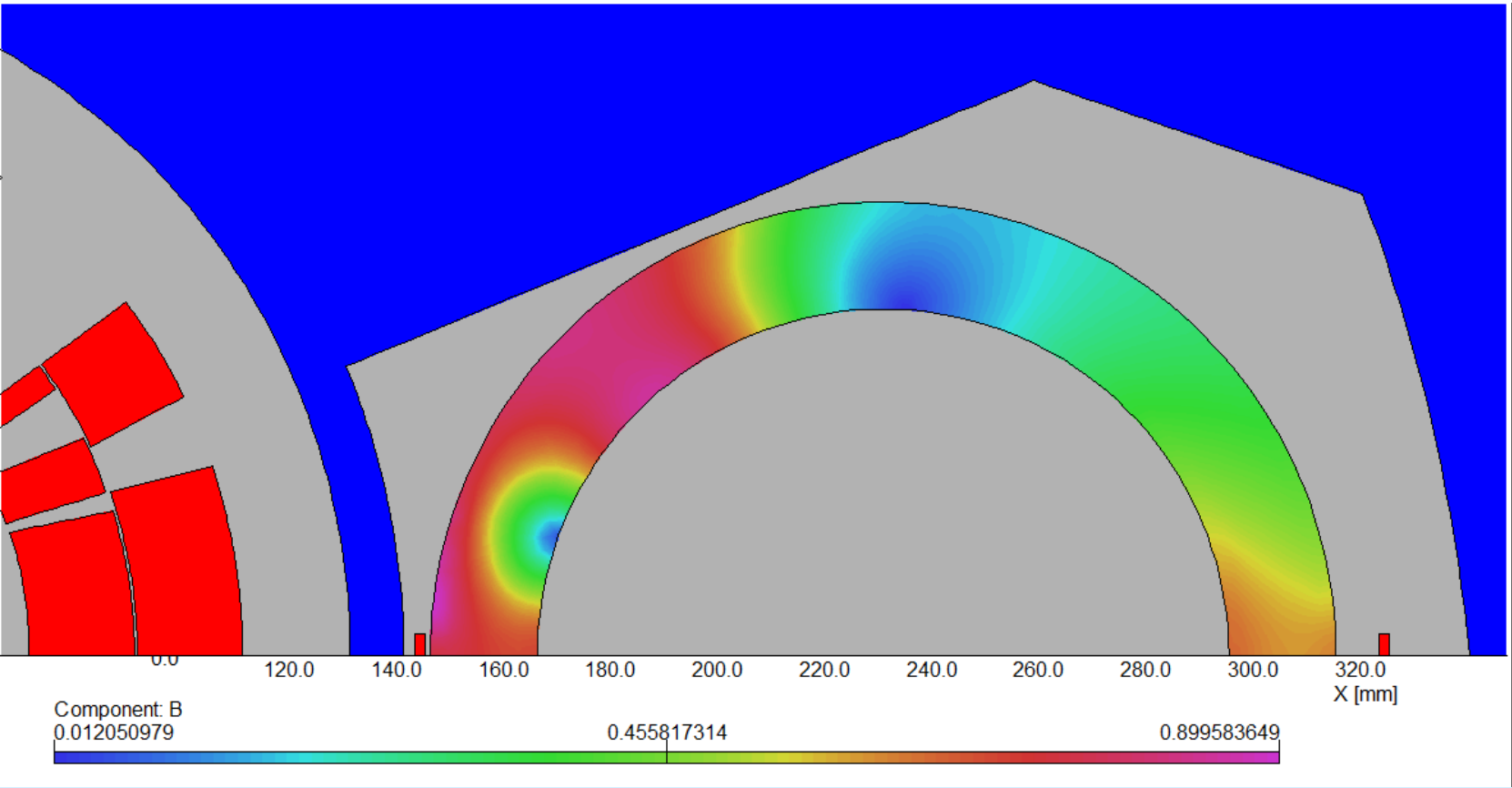
Opera

Cutout and Small Coil in Q1A



UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\EIC\Q1ApF+\opera\q1APF-c2.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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Opera

B1pF

Cable for B1pF and B1apF

- **Cross-sections of B1pF and B1apF are based on the cables that can be easily procured**
- **B1pF and B1apF are designed with 36-strand cable which is a fully keystone cable for B1apF. The same cable is used in B1pF**
- **Present designs retain the rectangular yoke as before; however, can be changed to circular**

Good Field Quality B1pF with Keystoned Cable

- **All field harmonics small (3.4 T @ 8.1 kA)**

```
MAIN HARMONIC ..........................................          1
REFERENCE RADIUS (mm) ..............................        73.0000
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 ....................   0.1501E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .......................................     3.390620
MAGNET STRENGTH (T/(m^(n-1)) ........................       3.3906

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     -0.00000  b 3:      0.00574
b 4:      0.00000  b 5:     -0.00729  b 6:      0.00000
b 7:     -0.01287  b 8:     -0.00000  b 9:     -0.12301
b10:      0.00000  b11:     -0.11449  b12:      0.00000
b13:      0.02768  b14:      0.00000  b15:      0.00780
b16:     -0.00000  b17:      0.00316  b18:      0.00000
b19:      0.00076  b20:      0.00000  b
```

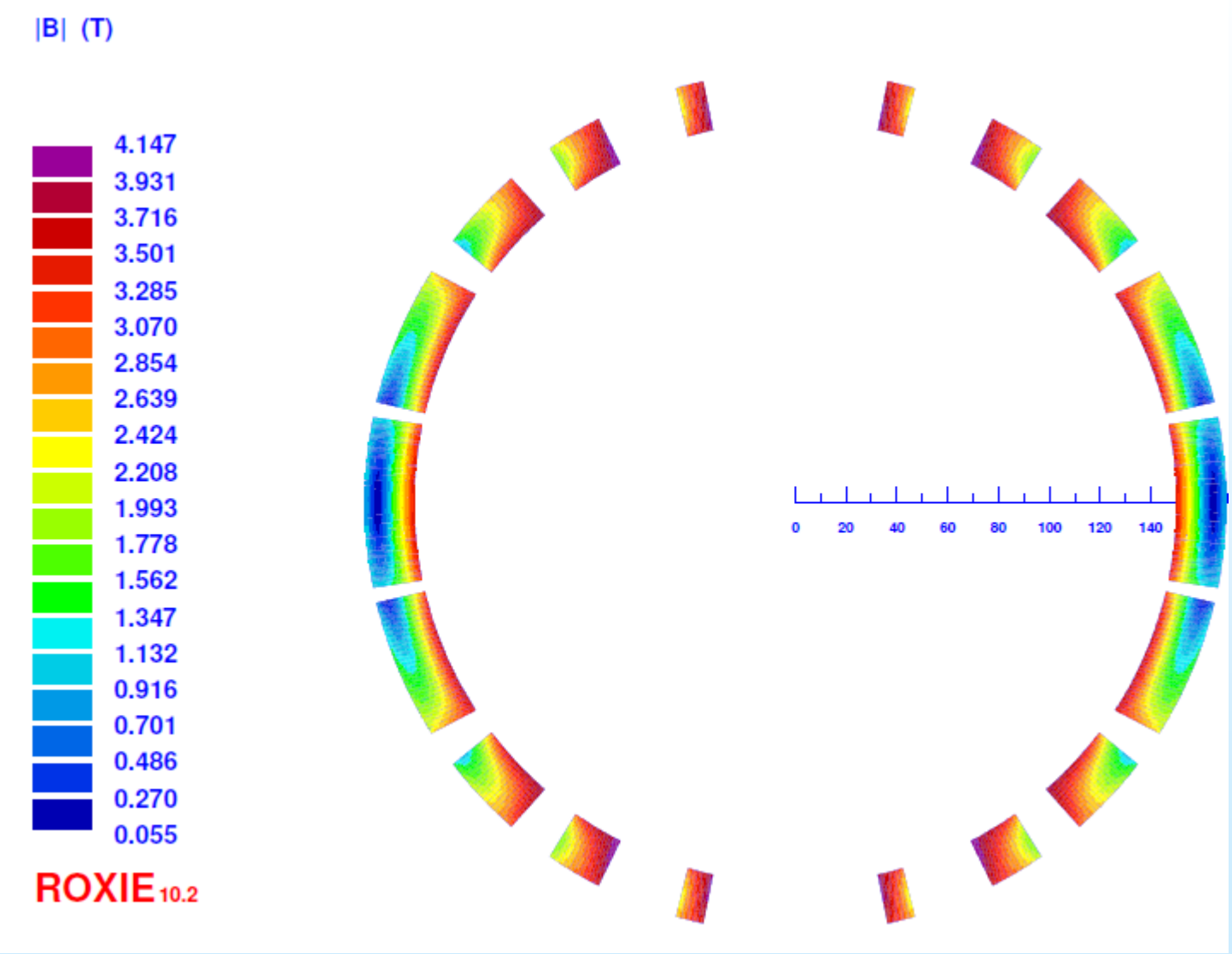
Good Margin (B=3.4T, T=4.6K) B1pF with Keystoned Cable

- **Very healthy margin in cross-section @4.6 K**
  - ✓ **>78% field margin, >2.2 K temperature margin**

```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  280 (T) ......................      4.0120
CURRENT IN CONDUCTOR 280 (A) ..........................   -8050.0000
LOWEST FIELD IN CONDUCTOR  276 (T) ....................      2.3731
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -652.6459
COPPER CURRENT DENSITY (A/MM2) ........................    -407.9037
PERCENTAGE ON THE LOAD LINE ...........................     54.9393
QUENCHFIELD (T) .......................................      7.3026
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.2178
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     20.8573

MAXIMUM LOADLINE IN BLOCK   15 (%) ....................     56.3052
MINIMUM TEMPERATURE MARGIN IN BLOCK    4 (T) ..........      2.1593
```

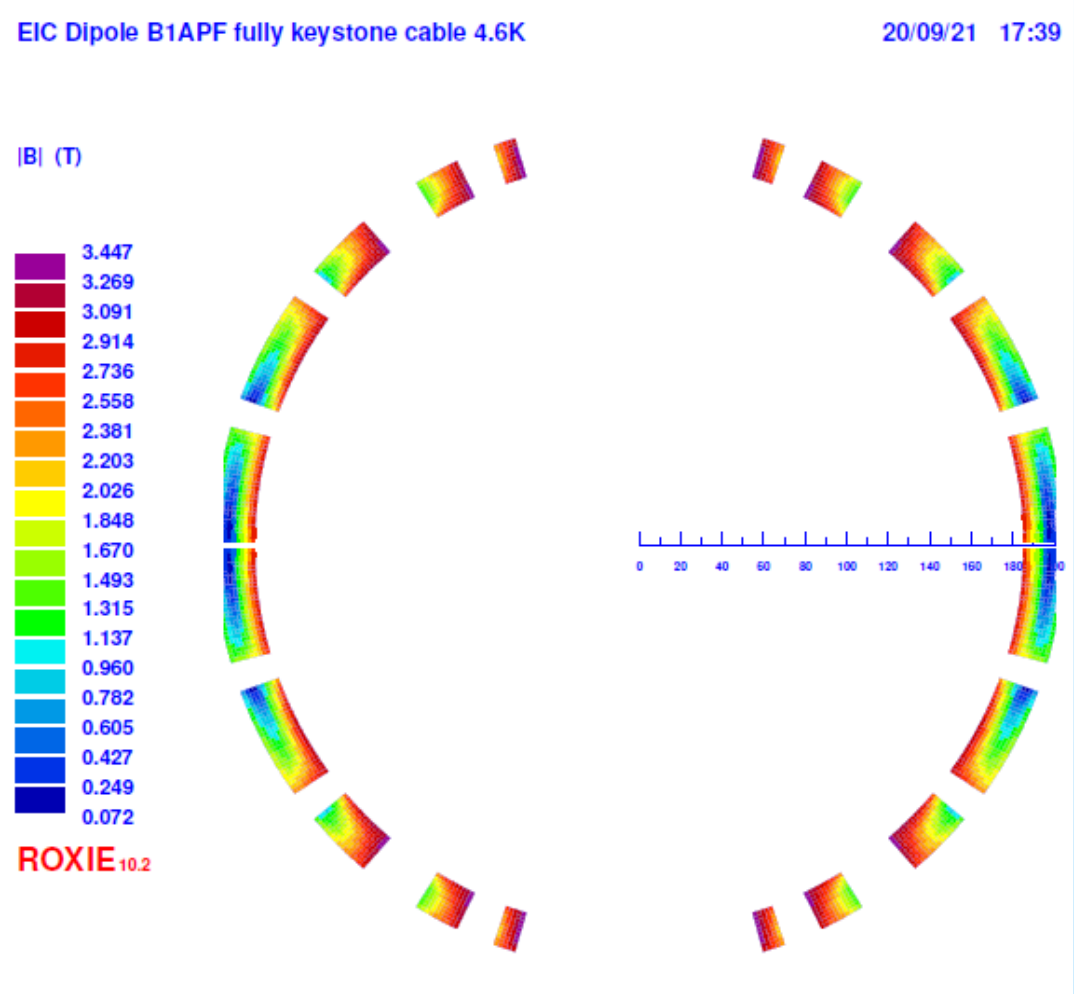
Peak Fields B1pF

Peak field enhancement ~18%



B1apF

B1apF with Keystone Cable (keystone chosen for B1apF)



Good Field Quality B1pF with Keystoned Cable

- **All field harmonics small (2.7 T @ 7.3 kA)**

```
MAIN HARMONIC ........................................          1
REFERENCE RADIUS (mm) ................................    80.0000
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 ....................  0.9843E-06
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .......................................  2.712609
MAGNET STRENGTH (T/(m^(n-1)) .........................    2.7126

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.00437
b 4:      0.00000  b 5:      0.00488  b 6:     -0.00000
b 7:      0.02281  b 8:     -0.00000  b 9:      0.07717
b10:     -0.00000  b11:      0.15408  b12:      0.00000
b13:     -0.00641  b14:      0.00000  b15:      0.00157
b16:     -0.00000  b17:      0.00016  b18:     -0.00000
b19:     -0.00021  b20:     -0.00000  b
```

Good Margin (B=2.7T, T=4.6K) B1pF with Keystoned Cable

- **Very healthy margin in cross-section @4.6 K**
  - ✓ **~110% field margin, >2.5 K temperature margin**

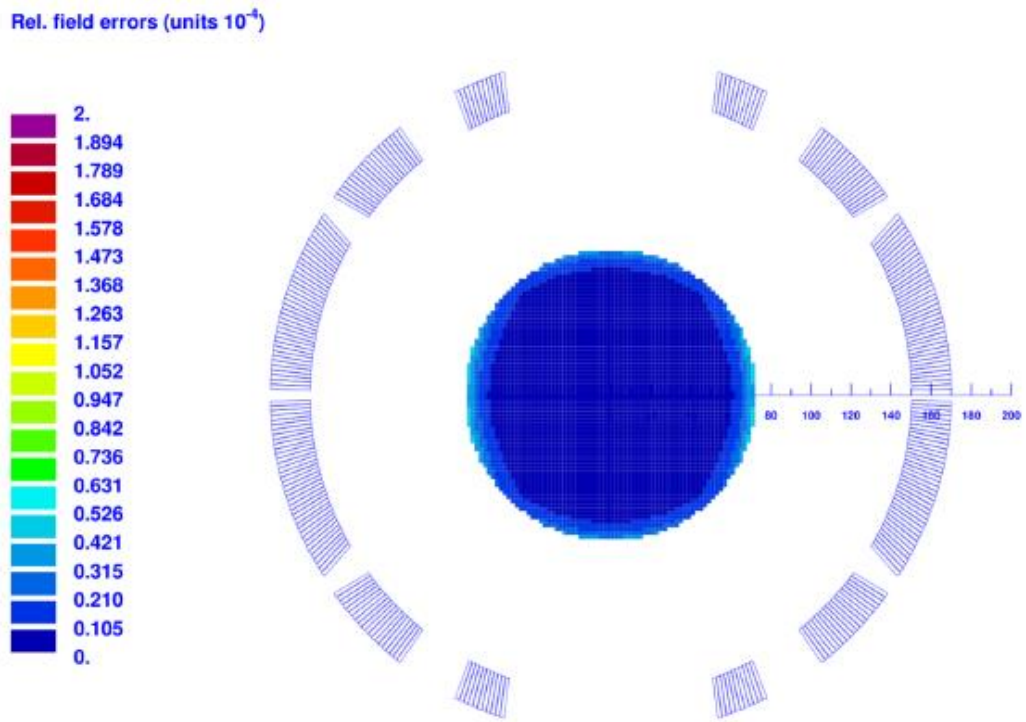
```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  320 (T) ......................      3.4471
CURRENT IN CONDUCTOR 320 (A) ..........................   -7300.0000
LOWEST FIELD IN CONDUCTOR  316 (T) ....................      2.1835
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -591.8404
COPPER CURRENT DENSITY (A/MM2) ........................    -369.9003
PERCENTAGE ON THE LOAD LINE ...........................     47.8841
QUENCHFIELD (T) .......................................      7.1989
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.5238
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     16.3463

MAXIMUM LOADLINE IN BLOCK    5 (%) ....................     47.8841
MINIMUM TEMPERATURE MARGIN IN BLOCK    5 (T) ..........      2.5238
```

B1pF

B1pF – pCDR parameters

Table 6.8: Parameters of the B1PF magnet.

Parameter	Value
Magnetic length [m]	3
Maximum dipole field [T]	3.4
Aperture [m]	0.262
Required field quality [%]	0.01
Coil width [m]	0.34
Coil height [m]	0.34
Superconductor Type	NbTi
Current density [A/mm^2]	241
Cu:Sc ratio	1.3
Temperature [K]	4.2
Peak field wire [T]	4.37
Magnetic energy [MJ]	1.36
Ampere turns [MA·t]	1.16
Margin loadline [%]	58



(b) Shielded region

Figure 6.34: Vertical magnetic field on the center plane for the hadron beam (a). Figure (b) shows the good field region.

Good Field Quality B1pF with Keystoned Cable

- **All field harmonics small (3.4 T @ 8.1 kA)**

```
MAIN HARMONIC ..........................................          1
REFERENCE RADIUS (mm) ..................................    73.0000
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 ......................  0.1501E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .........................................  3.390620
MAGNET STRENGTH (T/(m^(n-1)) ........................      3.3906

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     -0.00000  b 3:      0.00574
b 4:      0.00000  b 5:     -0.00729  b 6:      0.00000
b 7:     -0.01287  b 8:     -0.00000  b 9:     -0.12301
b10:      0.00000  b11:     -0.11449  b12:      0.00000
b13:      0.02768  b14:      0.00000  b15:      0.00780
b16:     -0.00000  b17:      0.00316  b18:      0.00000
b19:      0.00076  b20:      0.00000  b
```

Good Margin (B=3.4T, T=4.6K) B1pF with Keystoned Cable

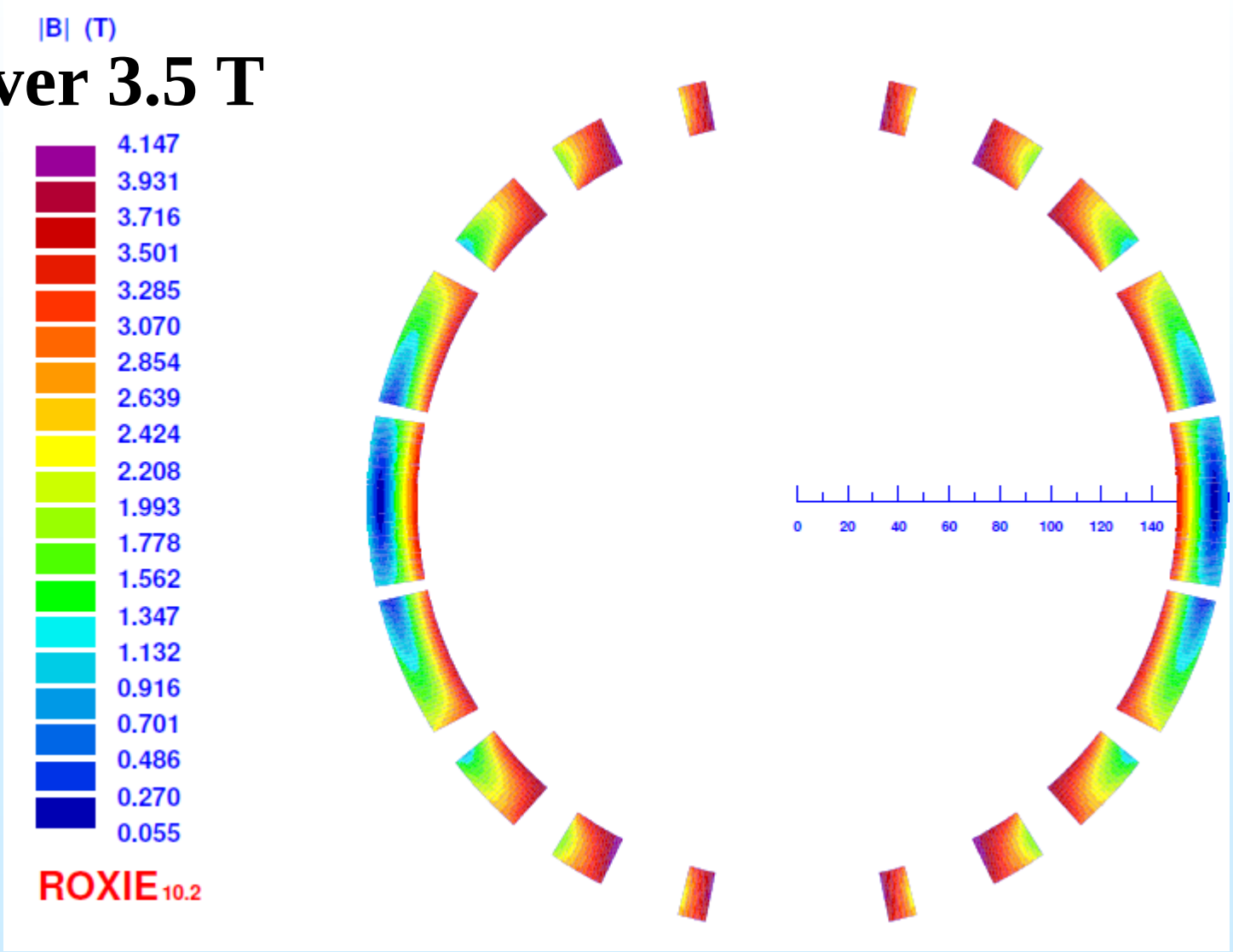
- **Very healthy margin in cross-section @4.6 K**
  - ✓ **>78% field margin, >2.2 K temperature margin**

```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  280 (T) ......................      4.0120
CURRENT IN CONDUCTOR 280 (A) ..........................   -8050.0000
LOWEST FIELD IN CONDUCTOR  276 (T) ....................      2.3731
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -652.6459
COPPER CURRENT DENSITY (A/MM2) ........................    -407.9037
PERCENTAGE ON THE LOAD LINE ...........................     54.9393
QUENCHFIELD (T) .......................................      7.3026
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.2178
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     20.8573

MAXIMUM LOADLINE IN BLOCK   15 (%) ....................     56.3052
MINIMUM TEMPERATURE MARGIN IN BLOCK    4 (T) ..........      2.1593
```

Peak Fields

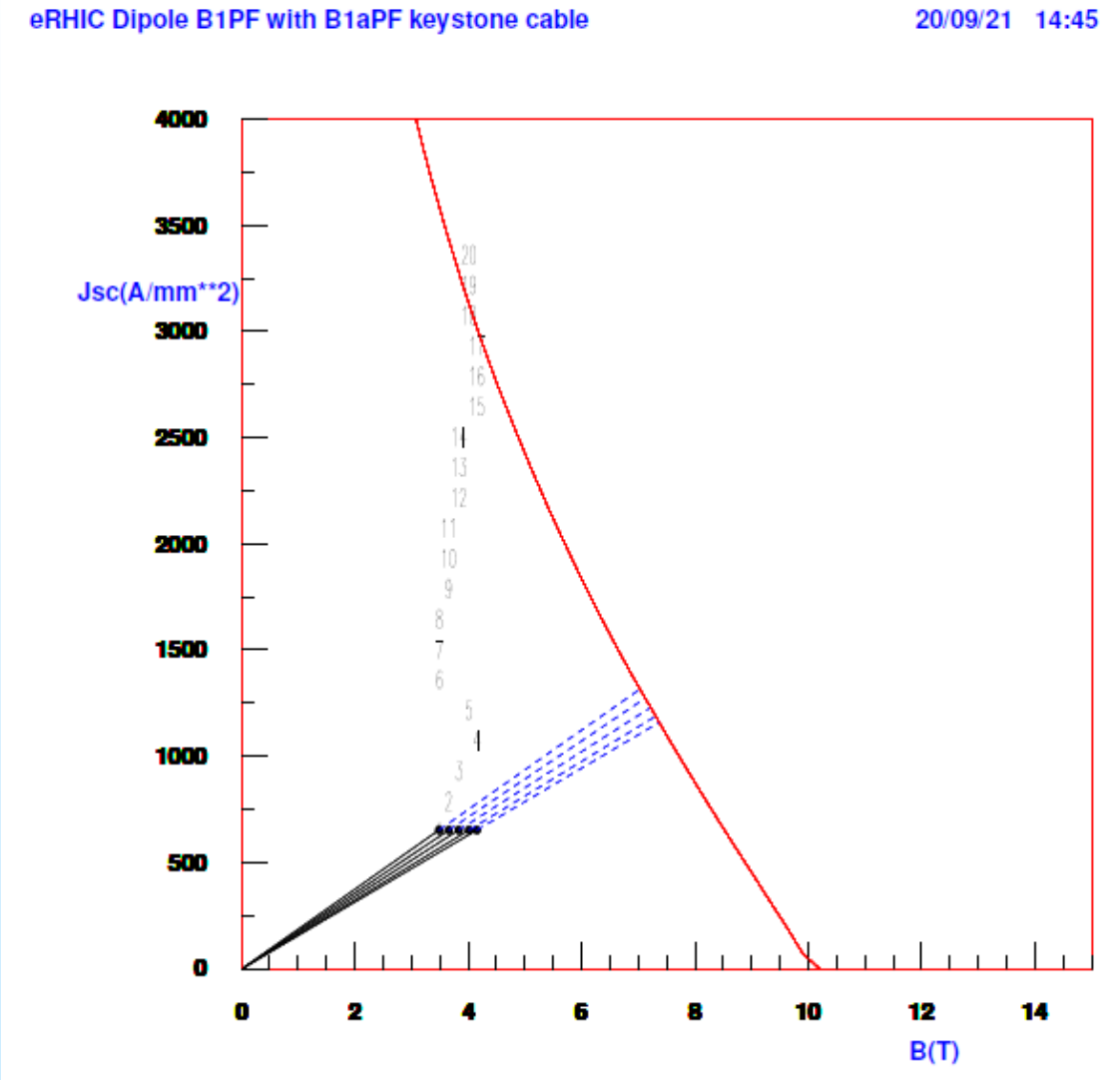
Peak field over 3.5 T

Peak field enhancement ~18%



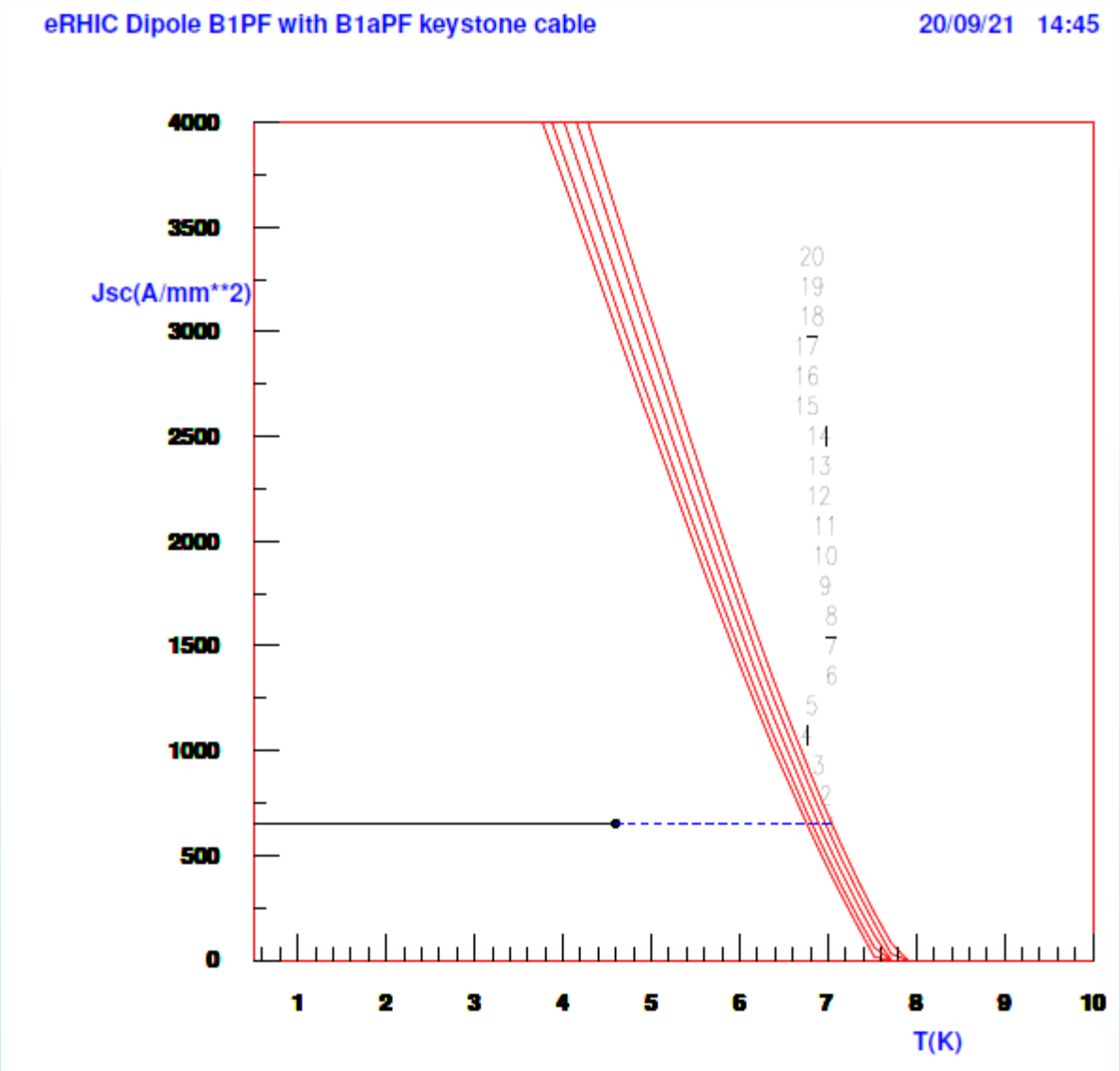
Very Good Overall Margin

Over 70% field margin



Temperature Margin over 4.6 K

Over 2.1 K Temperature Margin



B1apF

B1apF – pCDR parameters

Table 6.10: Parameters of the B1APF Dipole Magnet.

Parameter	Value
Magnetic length [m]	1.5
Maximum dipole field [T]	2.7
Aperture front [m]	0.3360
Aperture rear [m]	0.3360
Design field quality	1×10^{-4}
Physical length [m]	1.6
Physical width [m]	0.41
Physical height [m]	0.41
Superconductor type	NbTi
Conductor	Cable 20x2mm^2
Current density [A/mm^2]	148
Cu:Sc ratio	1.3
Temperature [K]	4.2
Peak field wire [T]	3.5
Magnetic energy [MJ]	0.717
Ampere turns [MA·t]	1.16
Number of turns	154
Current [A]	7670
Inductance [H]	0.024376
Margin loadline [%]	60

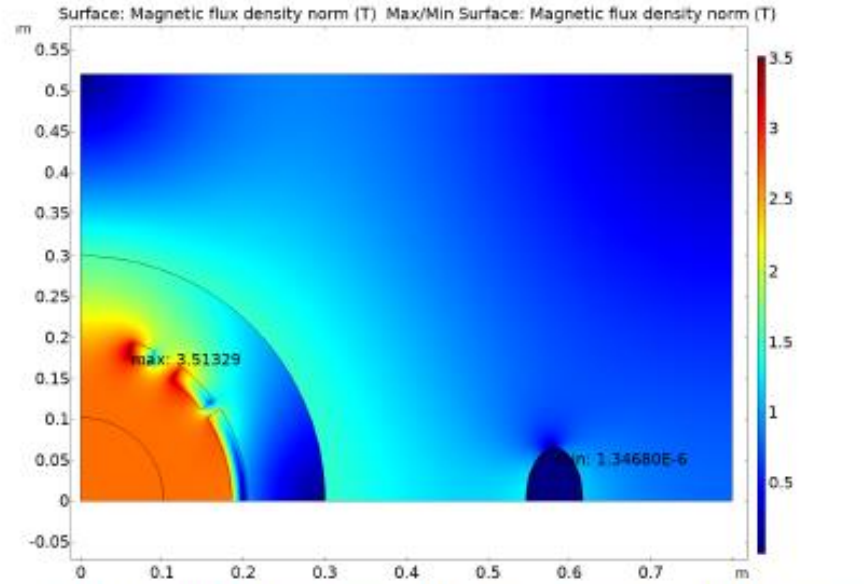
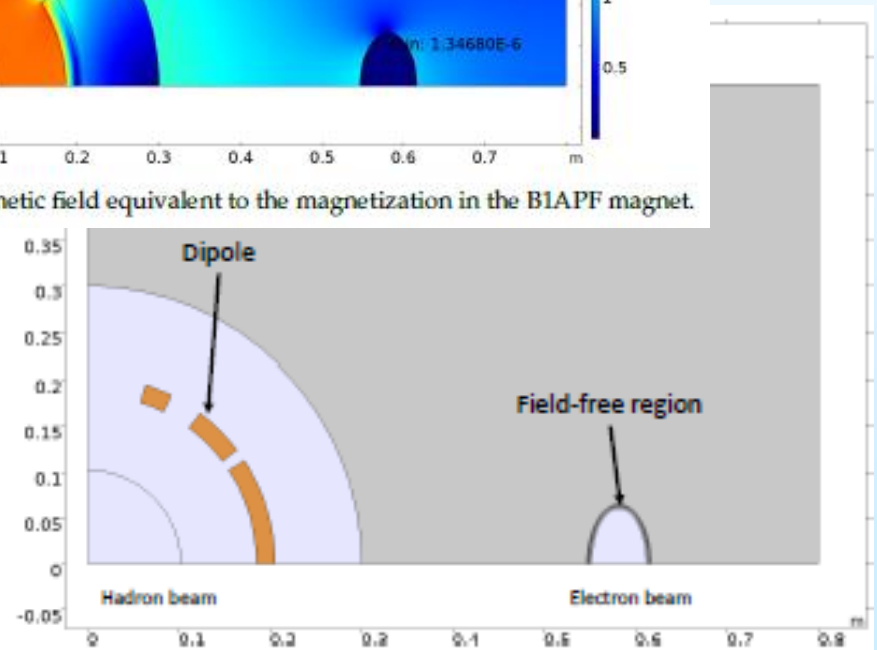


Figure 6.39: Magnetic field equivalent to the magnetization in the B1APF magnet.



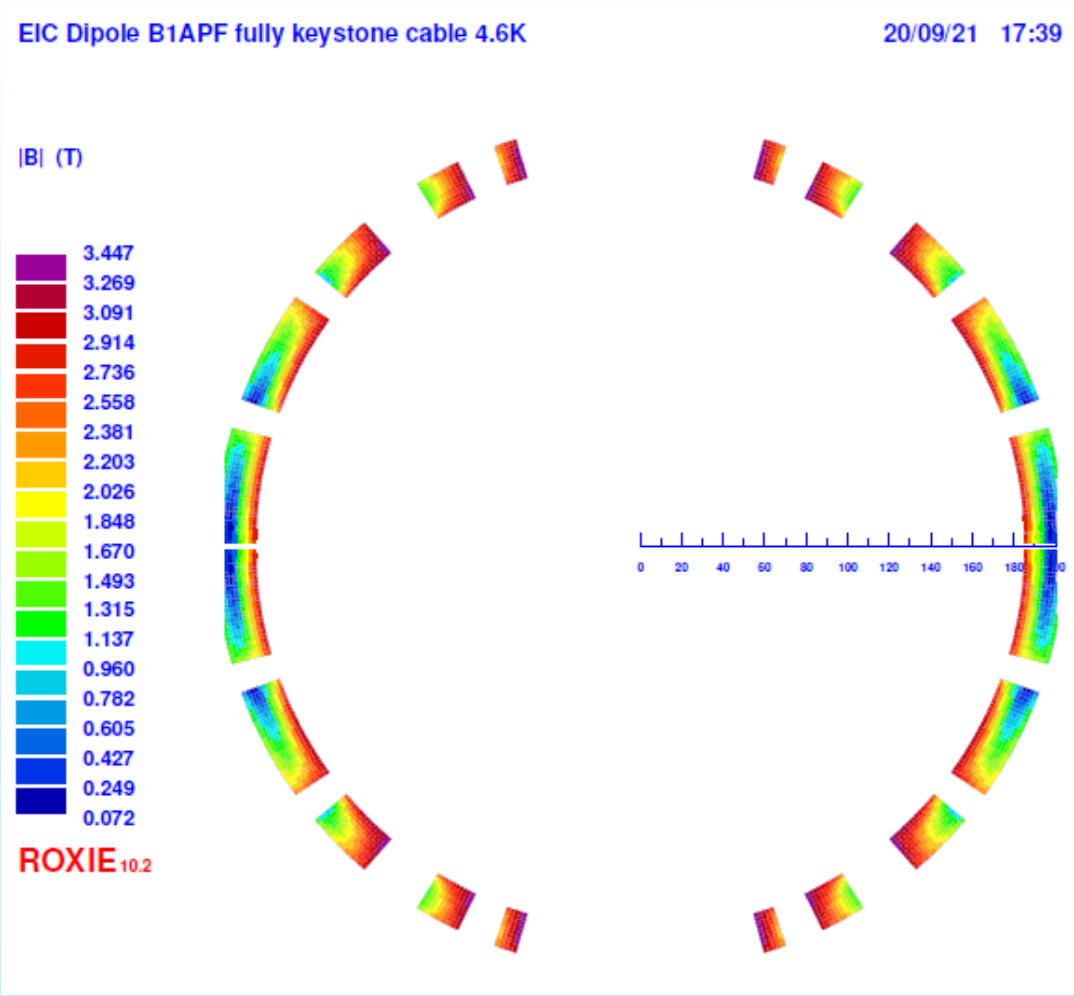
(a) Cross-section of B1APF

B1apF with Keystone Cable (keystone chosen for B1apF)

- **Mechanically good cross-section**

➢ **Collar angle**

➢ **Wedge angles**



Part of the coil missing because of the choice of scale

Good Field Quality B1pF with Keystoned Cable

- **All field harmonics small (2.7 T @ 7.3 kA)**

```
MAIN HARMONIC ........................................          1
REFERENCE RADIUS (mm) ................................    80.0000
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 ....................  0.9843E-06
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ......................................  2.712609
MAGNET STRENGTH (T/(m^(n-1)) ........................    2.7126

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.00437
b 4:      0.00000  b 5:      0.00488  b 6:     -0.00000
b 7:      0.02281  b 8:     -0.00000  b 9:      0.07717
b10:     -0.00000  b11:      0.15408  b12:      0.00000
b13:     -0.00641  b14:      0.00000  b15:      0.00157
b16:     -0.00000  b17:      0.00016  b18:     -0.00000
b19:     -0.00021  b20:     -0.00000  b
```

Good Margin (B=2.7T, T=4.6K) B1pF with Keystoned Cable

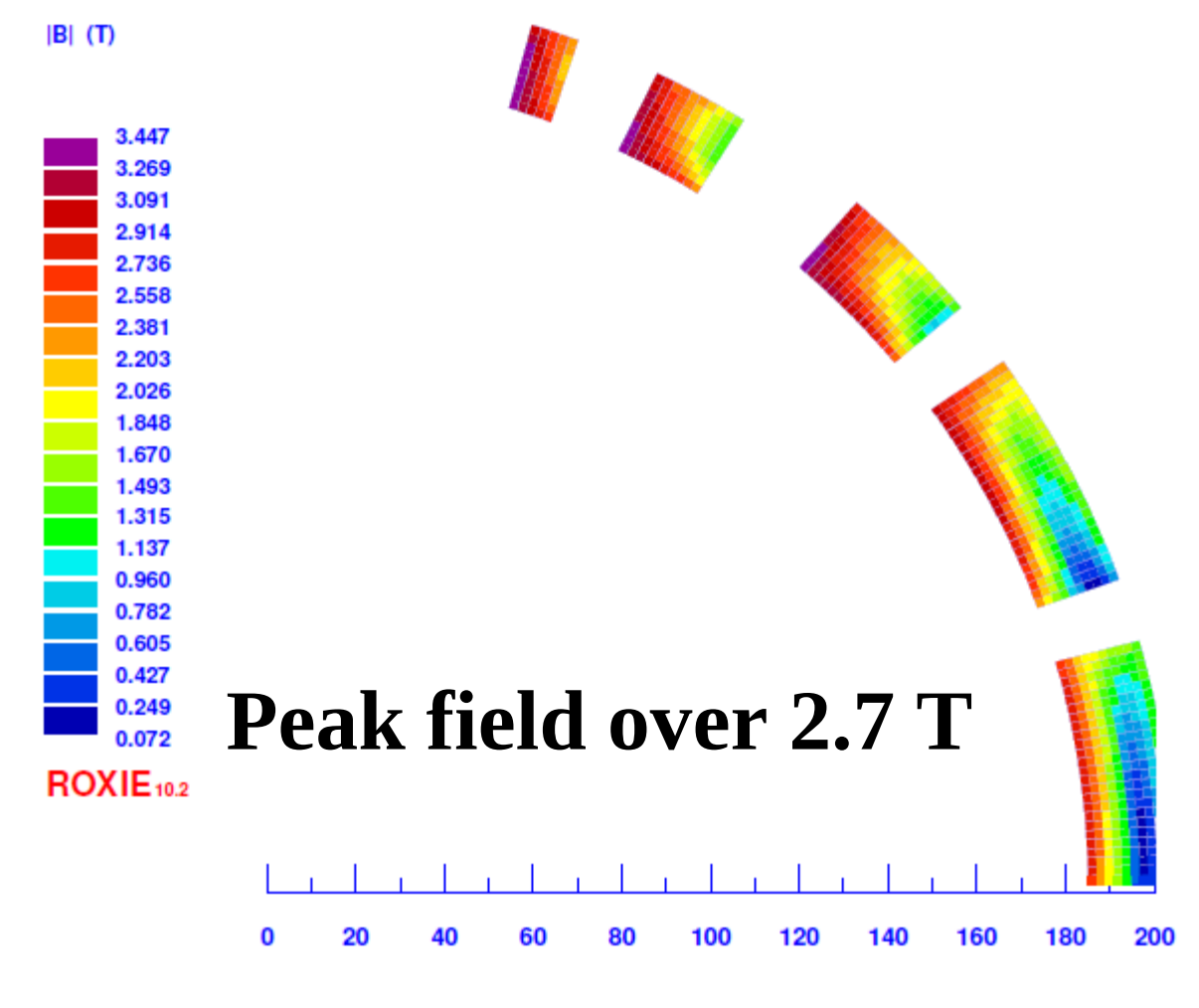
- **Very healthy margin in cross-section @4.6 K**
  - ✓ **~110% field margin, >2.5 K temperature margin**

```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  320 (T) ......................      3.4471
CURRENT IN CONDUCTOR 320 (A) ..........................   -7300.0000
LOWEST FIELD IN CONDUCTOR  316 (T) ....................      2.1835
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -591.8404
COPPER CURRENT DENSITY (A/MM2) ........................    -369.9003
PERCENTAGE ON THE LOAD LINE ...........................     47.8841
QUENCHFIELD (T) .......................................      7.1989
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.5238
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     16.3463

MAXIMUM LOADLINE IN BLOCK    5 (%) ....................     47.8841
MINIMUM TEMPERATURE MARGIN IN BLOCK    5 (T) ..........      2.5238
```

Peak Fields at 2.7 T

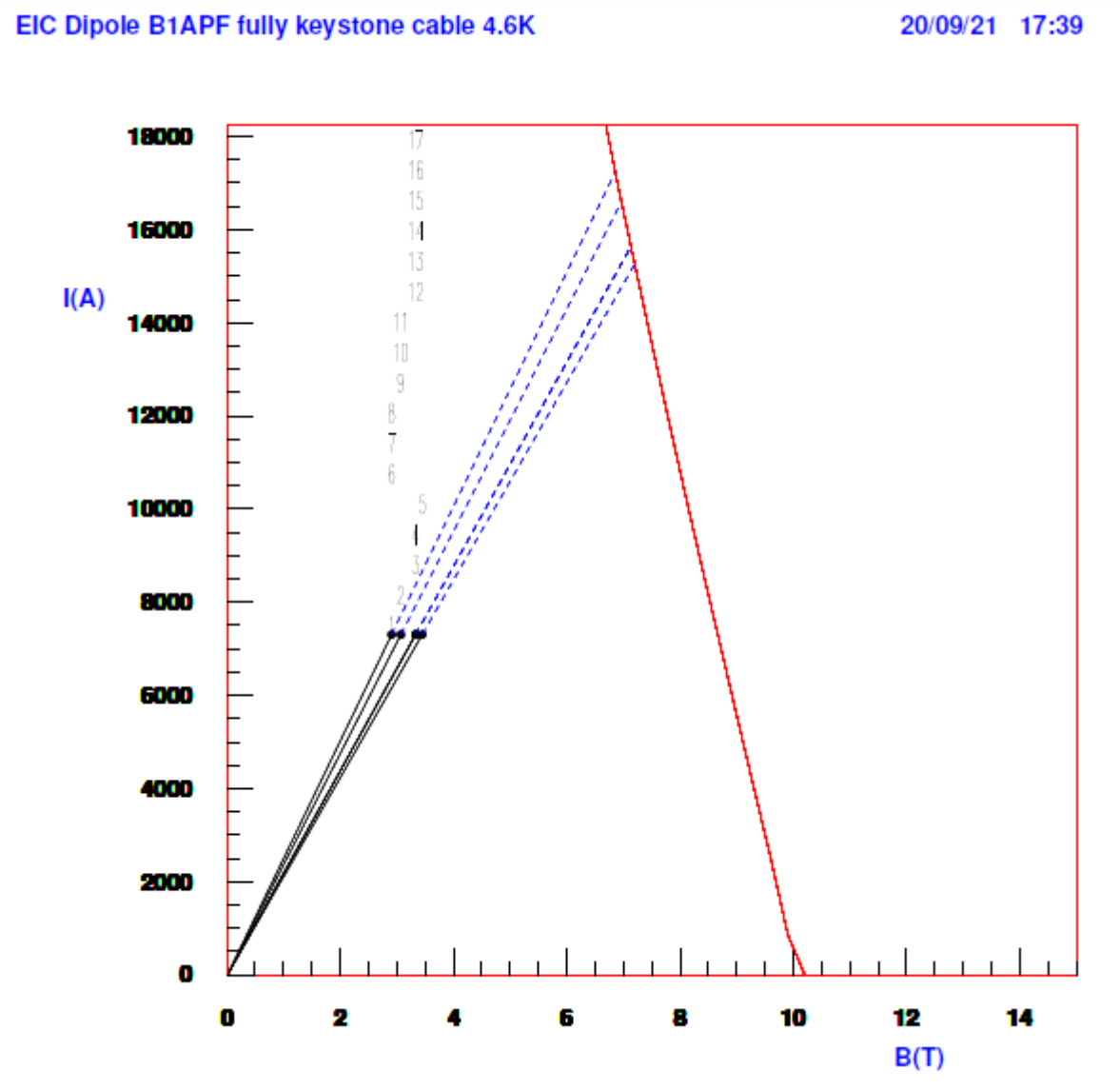
Peak field enhancement ~25%

(peak field cana be reduced in design iteration but already a very high margin)



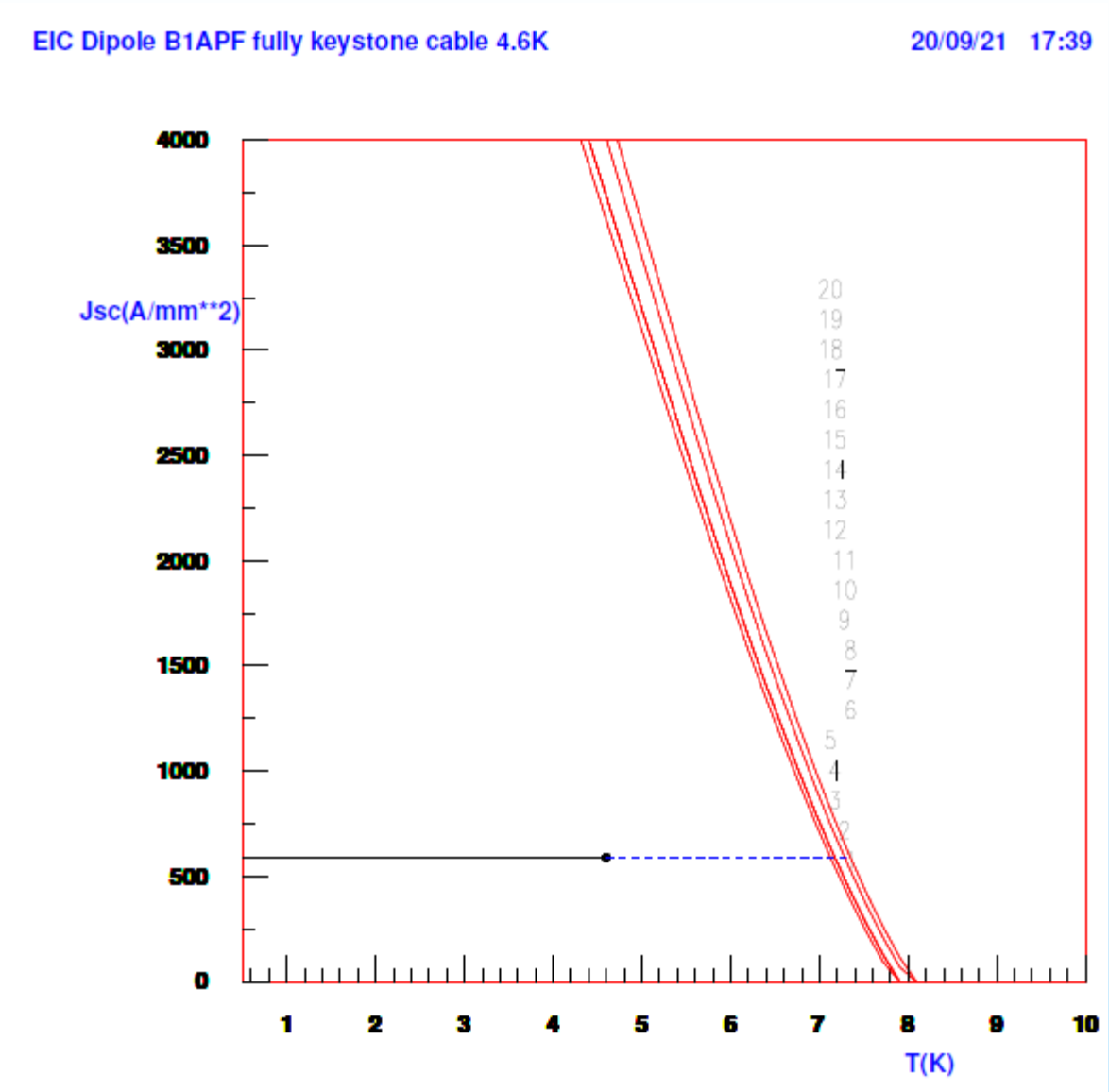
Very Good Overall Margin

About 110% field margin



Temperature Margin over 4.6 K

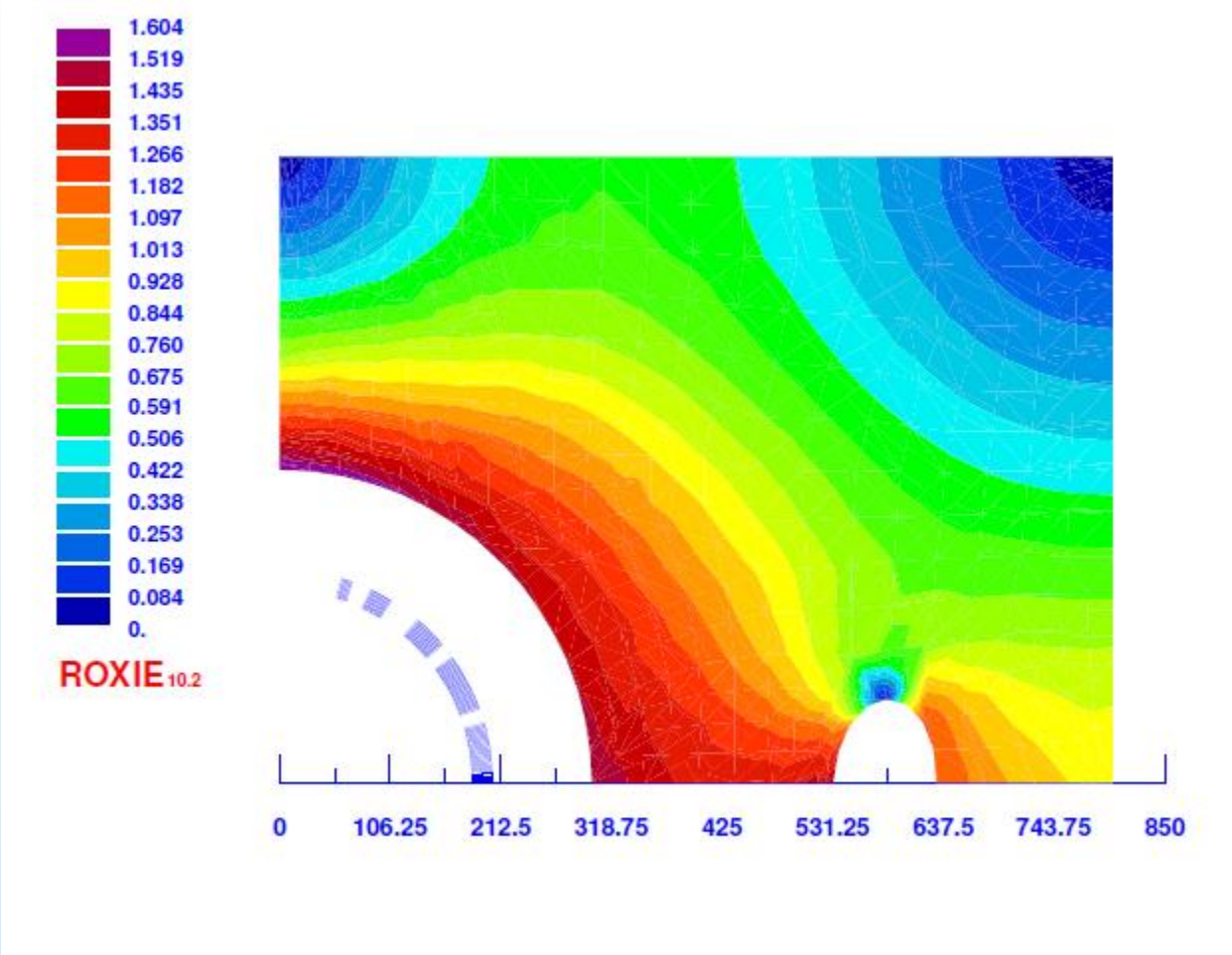
Over 2.5 K Temperature Margin



Some thoughts on the non-circular iron yoke

Coldmass can be circular even if yoke really has to be rectangular.

Put extra warm iron outside the coldmass



Summary

- Initial cross-section of cable all magnets developed for 4 K operation
- All cross-sections are based on the superconducting wire and cable designs that can be easily procured
- Two types of 36-strand cable used (a) Quad cable that is fully keystone for Q2BpF and (b) dipole cable which is fully keystone for B1apF
- Techniques developed to minimize fringe field from the proton/ion quad on the path of the electron beam, including cases when the quadrupole for electron beam were also present