B1pF & B1apF Cross-sections

Ramesh Gupta
Superconducting Magnet Division

Sept 22, 2020

(This concludes the 1st round of 2-d design work)

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

Overview

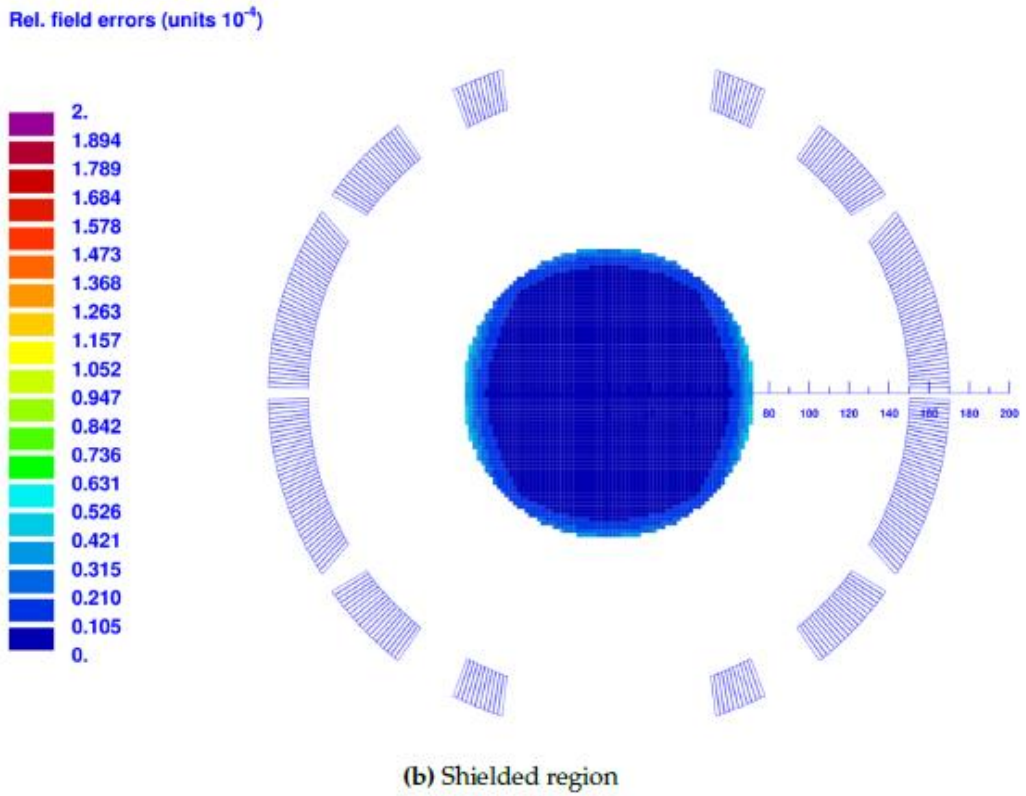
- Cross-sections of B1pF and B1apF
- Based on cables that can be easily procured
- Two series of designs with 36-strand cable
  - No key stone (rectangular)
  - Fully keystone for B1apF (same used in B1pF)
- Rectangular yoke retained; can be changed
- With all 2-d designs iterated, now we can proceed to 3-d

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



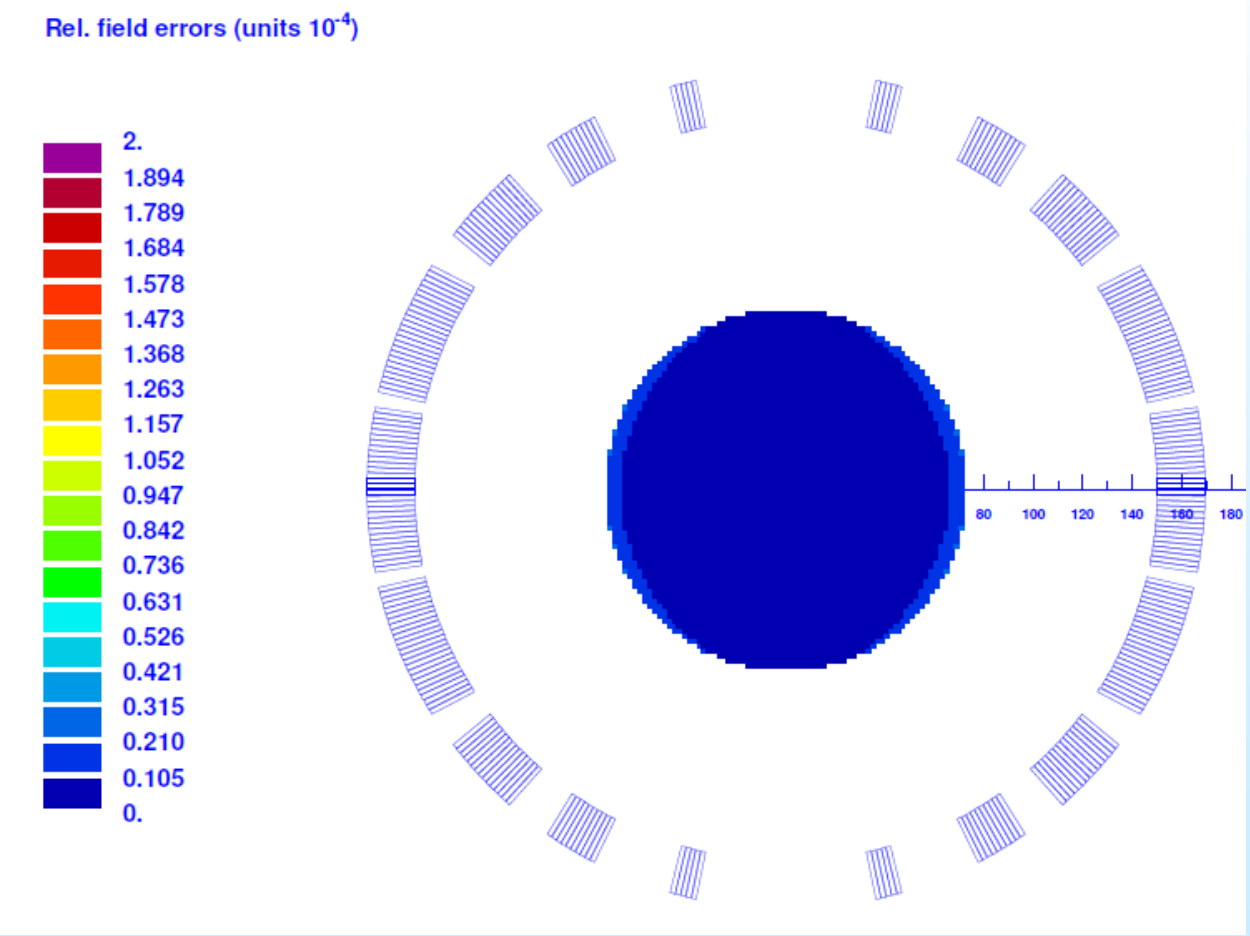
(b) Shielded region

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

B1pF with Keystone Cable (keystone chosen from B1apF)

- **Mechanically good cross-section**

- **Collar angle**
- **Wedge angles**



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**

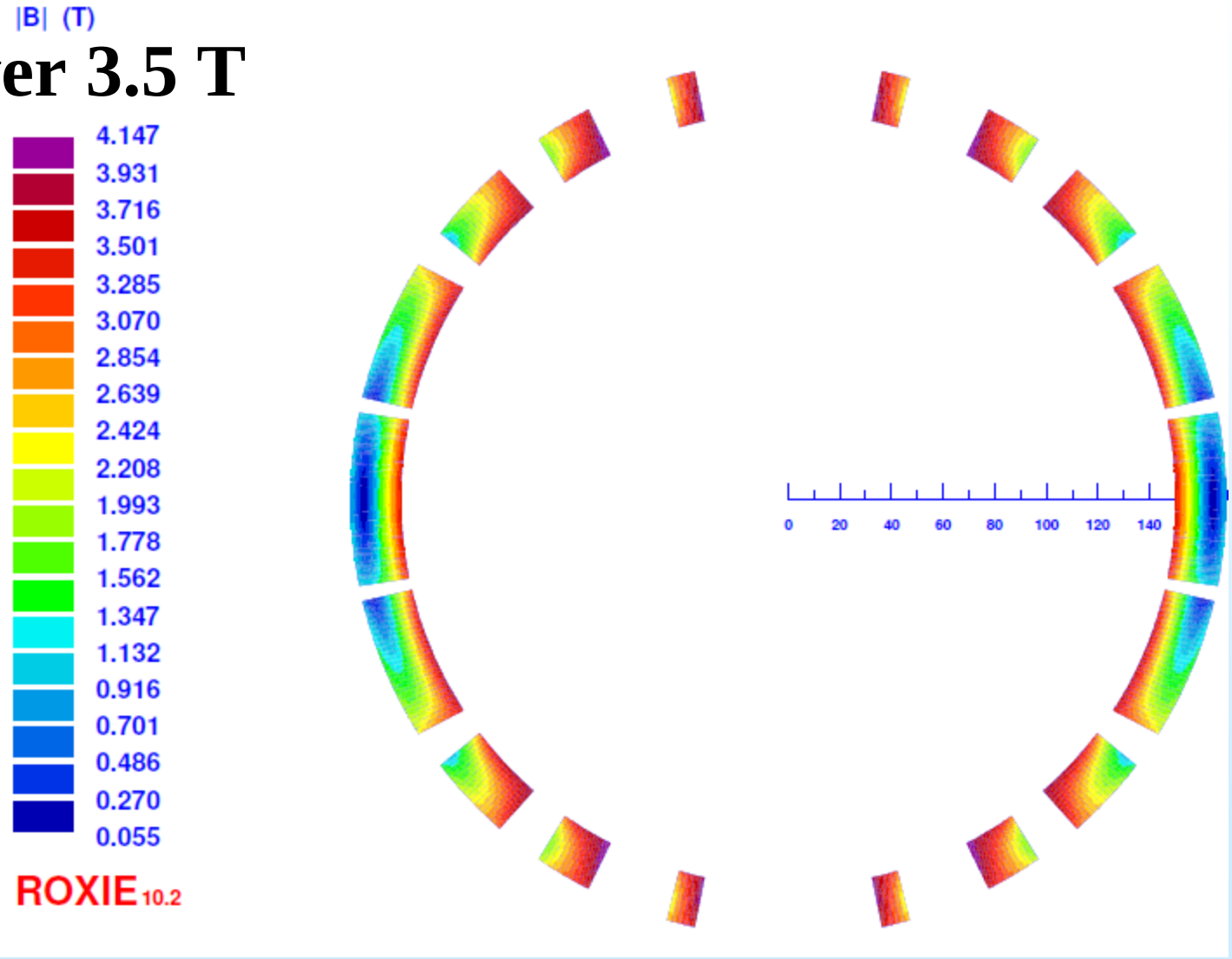
```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  280 (T) ......................      4.0120
CURRENT IN CONDUCTOR 280 (A) ..........................  -8050.0000
LOWEST FIELD IN CONDUCTOR  276 (T) ....................      2.3731
SUPERCONDUCTOR CURRENT DENSITY (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

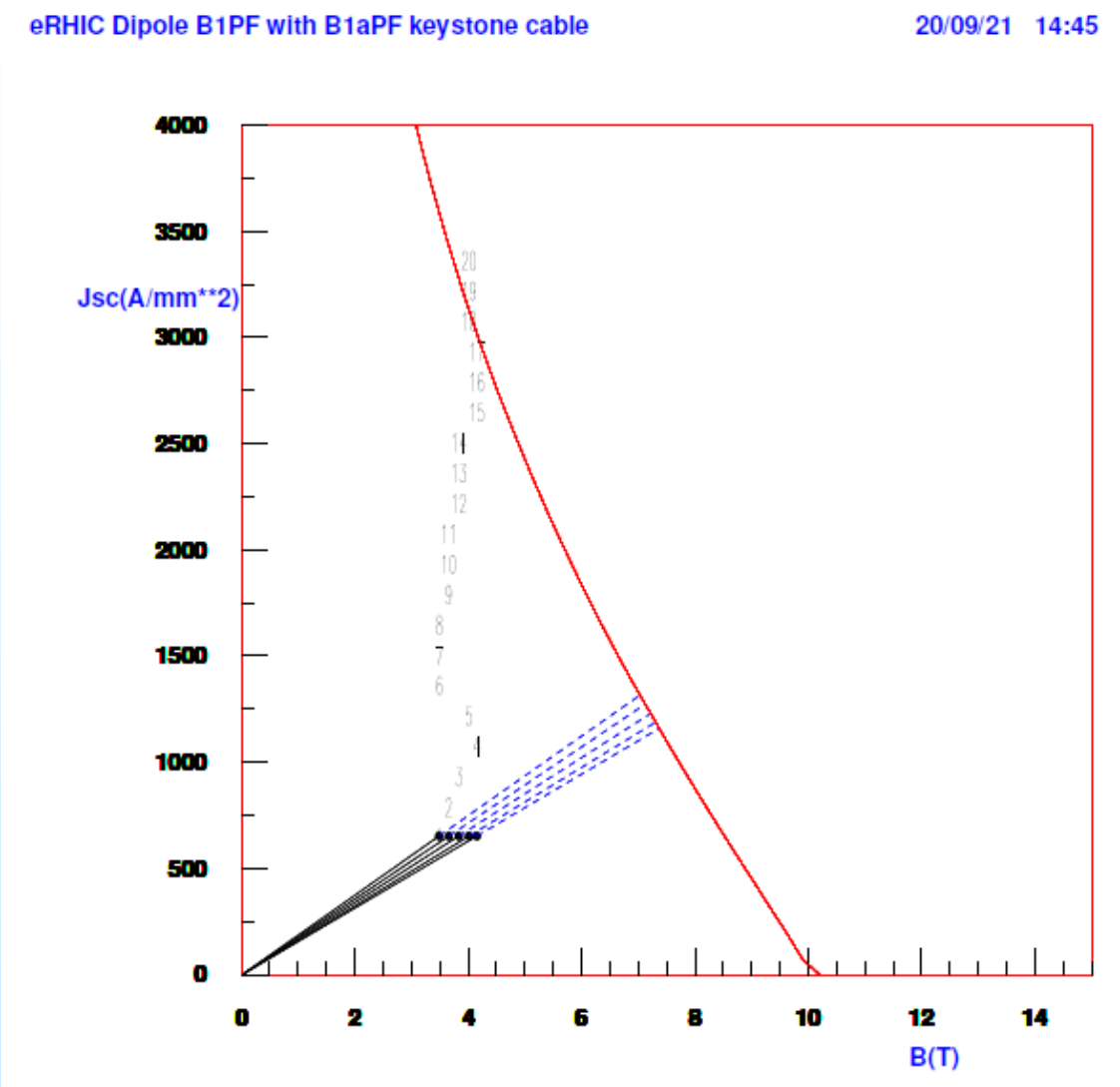
Peak field enhancement

~18%



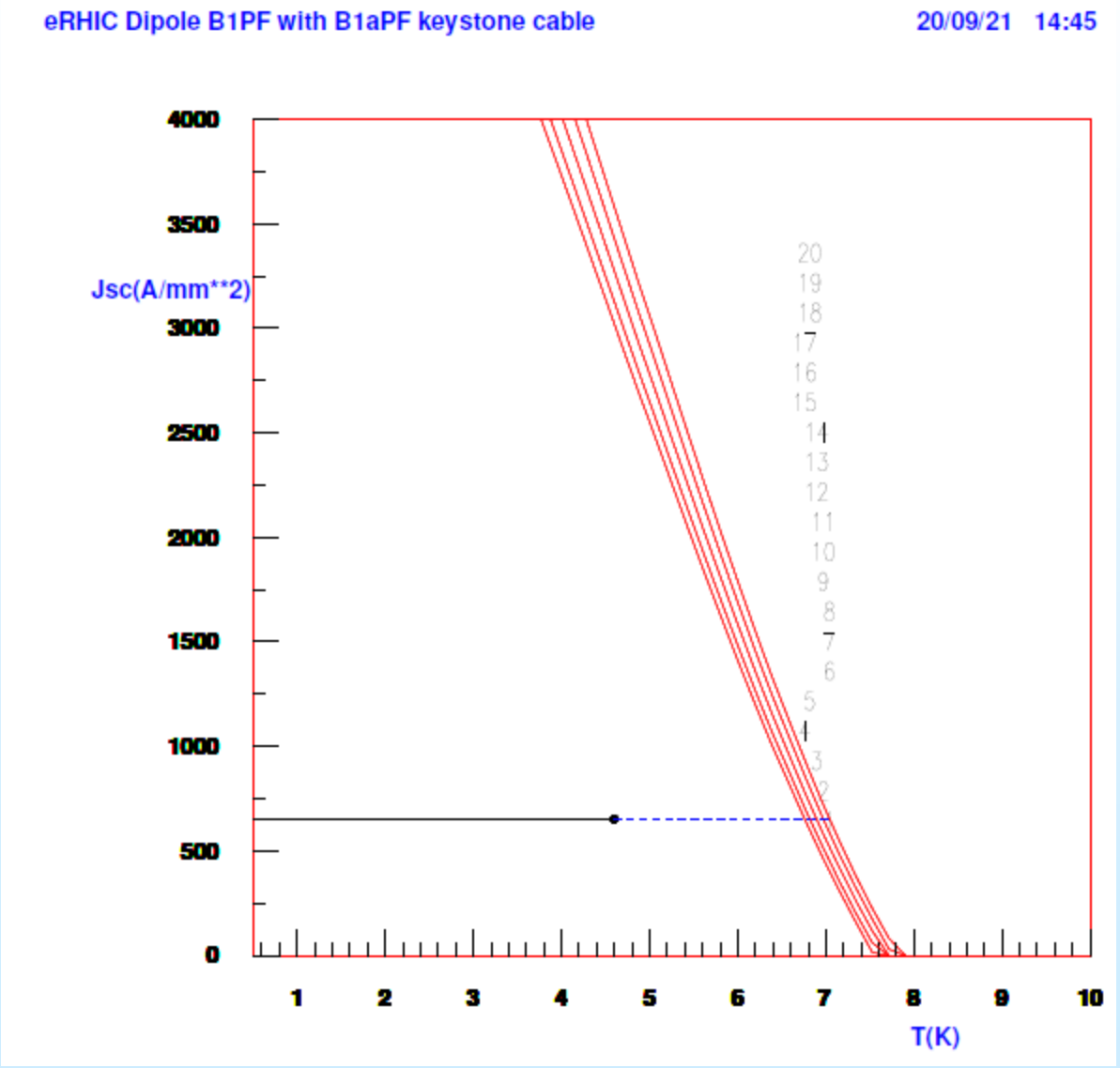
Very Good Overall Margin

Over 70% field margin



Temperature Margin over 4.6 K

Over 2.1 K Temperature Margin

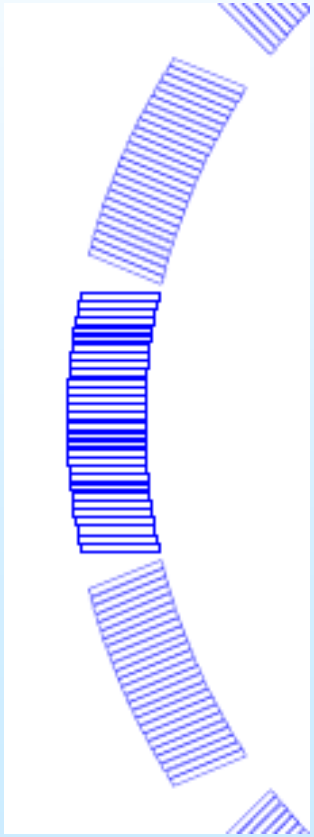


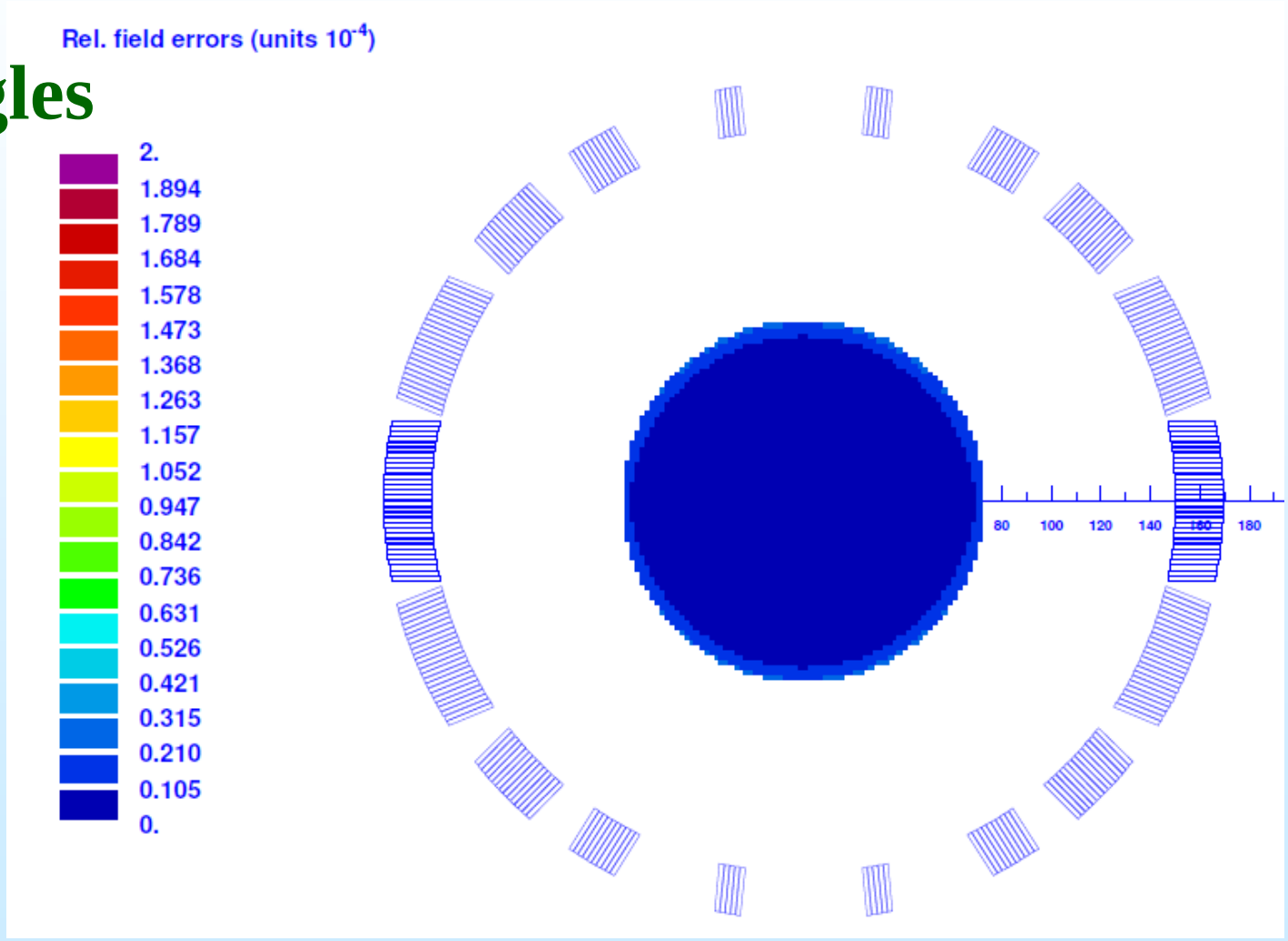
B1pF at 4.6 K with No-keystoned (rectangular cable) with 36 strands

B1pF with no-keystone Cable (no-keystone - rectangular)

- **A reasonably good cross-section mechanically**

➢ **Wedge angles**





Good Field Quality
B1pF with No-keystoned Cable

- **All field harmonics small (3.4 T @ 8.17 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 .......................  0.1481E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .........................................    3.497004
MAGNET STRENGTH (T/(m^(n-1)) ...........................      3.4970

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:     -0.00163
b 4:     -0.00000  b 5:      0.00021  b 6:      0.00000
b 7:      0.00489  b 8:     -0.00000  b 9:     -0.01759
b10:      0.00000  b11:     -0.21616  b12:     -0.00000
b13:      0.06202  b14:     -0.00000  b15:     -0.00015
b16:      0.00000  b17:      0.00559  b18:     -0.00000
b19:      0.00010  b20:      0.00000  b
```

Good Margin (B=3.4T, T=4.6K) B1pF with No-keystoned Cable

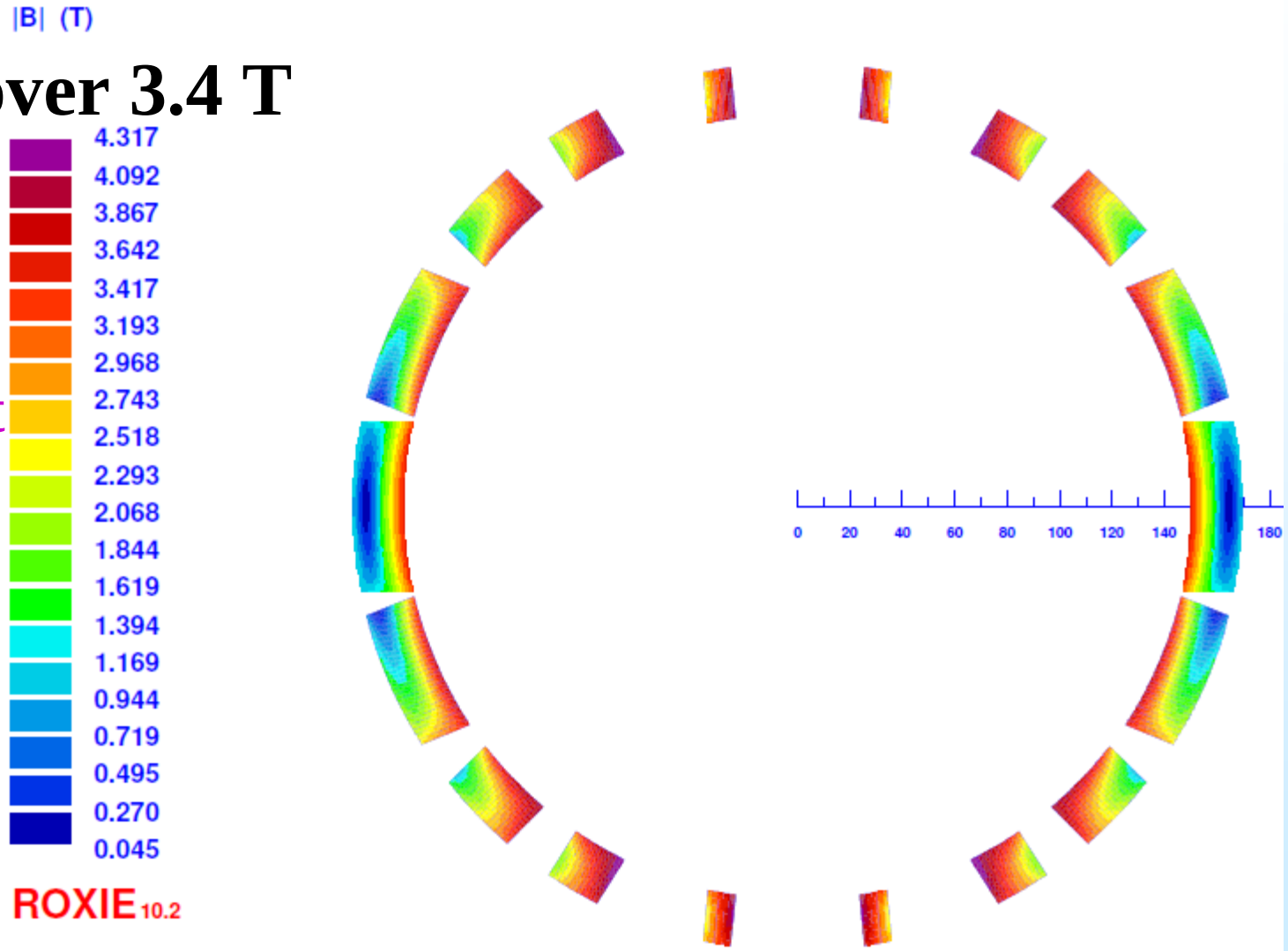
- **Very healthy margin in cross-section @4.6 K**
  - ✓ **>70% field margin, >2.1 K temperature margin**

```
BLOCK NUMBER ..........................................          20
PEAK FIELD IN CONDUCTOR  280 (T) ......................      4.1499
CURRENT IN CONDUCTOR 280 (A) ..........................   -8400.0000
LOWEST FIELD IN CONDUCTOR  276 (T) ....................      2.4318
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    -681.0218
COPPER CURRENT DENSITY (A/MM2) ........................    -425.6386
PERCENTAGE ON THE LOAD LINE ...........................      56.9585
QUENCHFIELD (T) .......................................      7.2859
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.1273
PERCENTAGE OF SHORT SAMPLE CURRENT ....................      22.5480

MAXIMUM LOADLINE IN BLOCK    4 (%) ....................      58.6509
MINIMUM TEMPERATURE MARGIN IN BLOCK    4 (T) .........      2.0540
```

Peak Fields

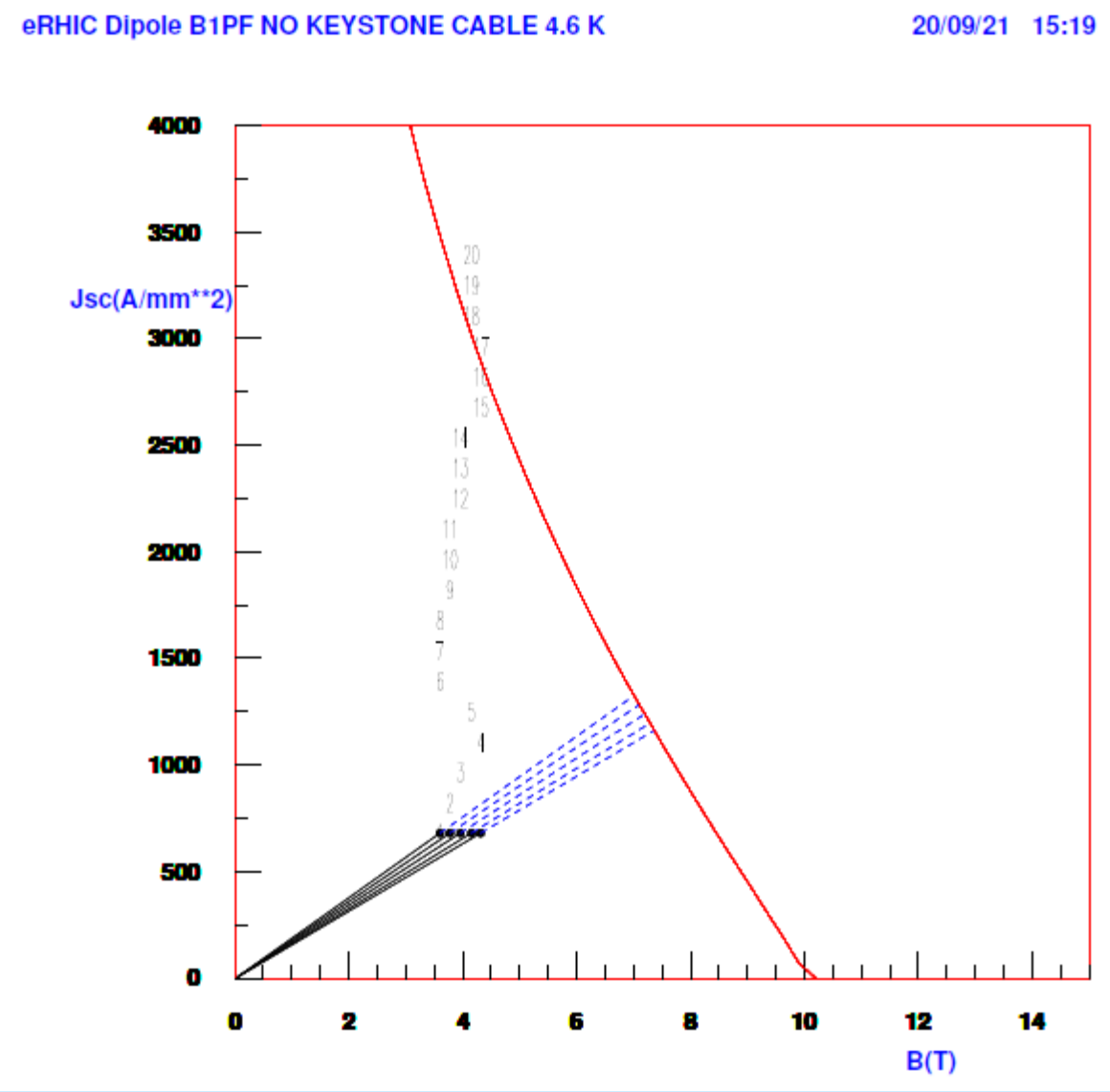
Peak field over 3.4 T

Peak field enhancement ~26% (higher)



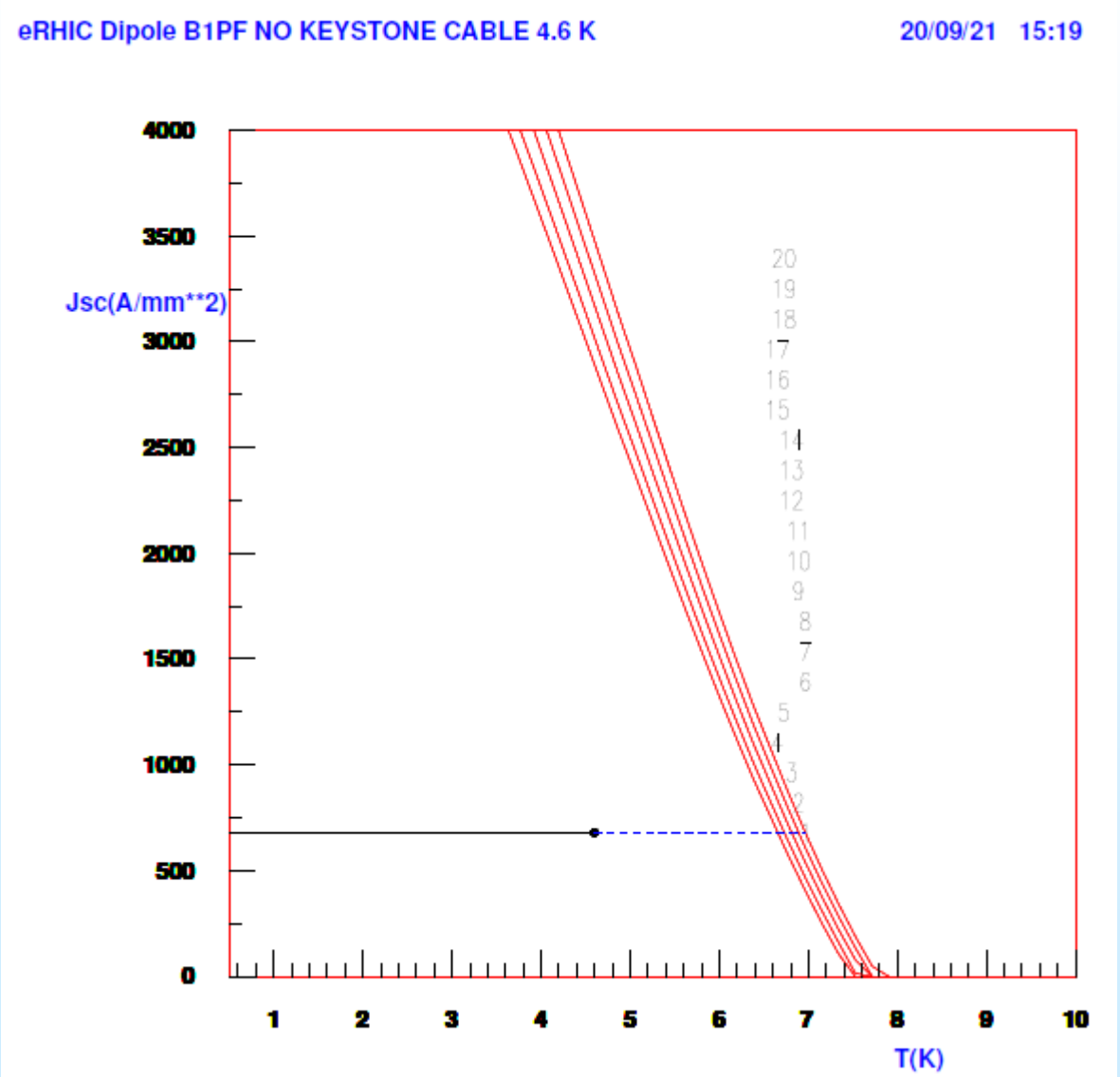
Very Good Overall Margin

Over 70% field margin



Temperature Margin over 4.6 K

Over 2.1 K Temperature Margin



Overview

Overview

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

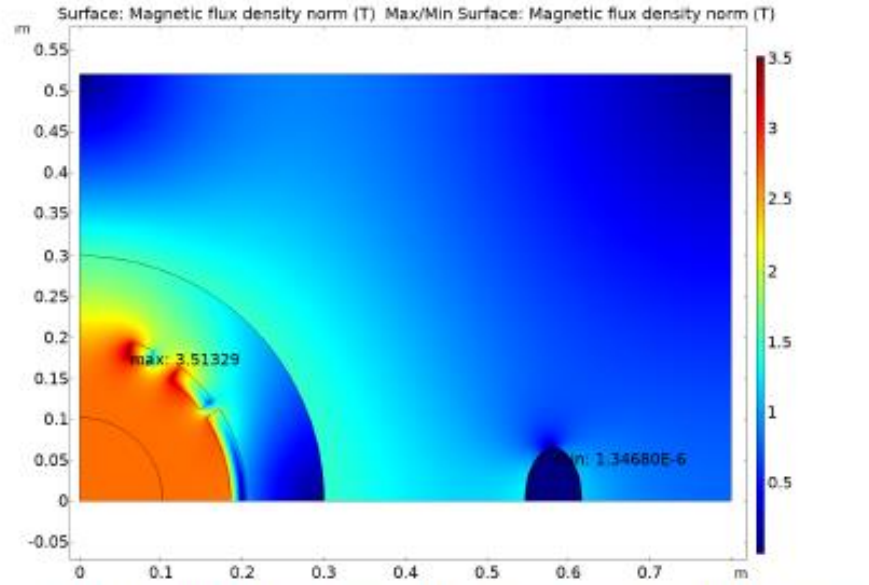
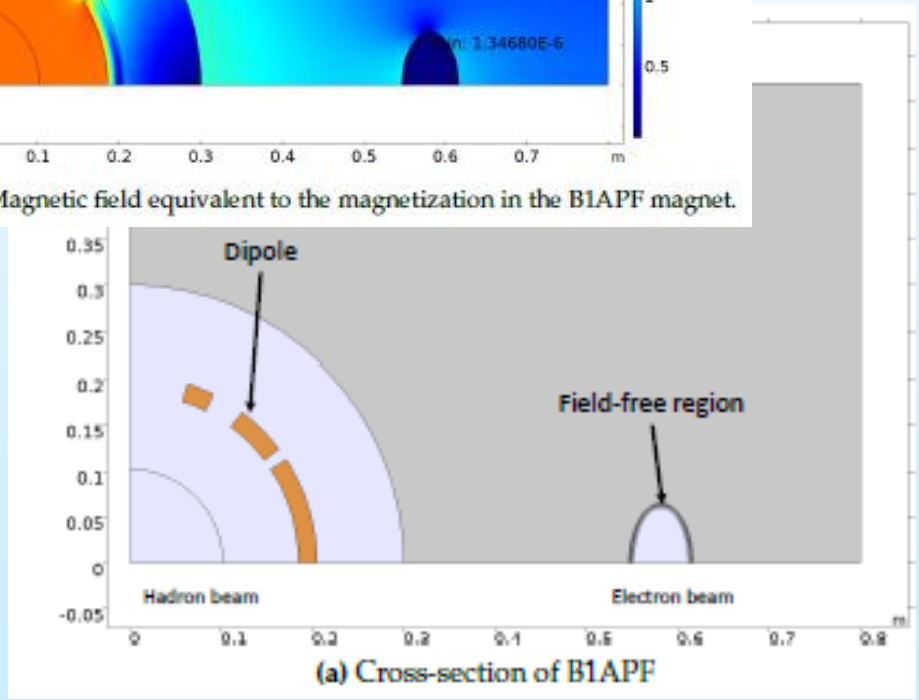


Figure 6.39: Magnetic field equivalent to the magnetization in the B1APF magnet.



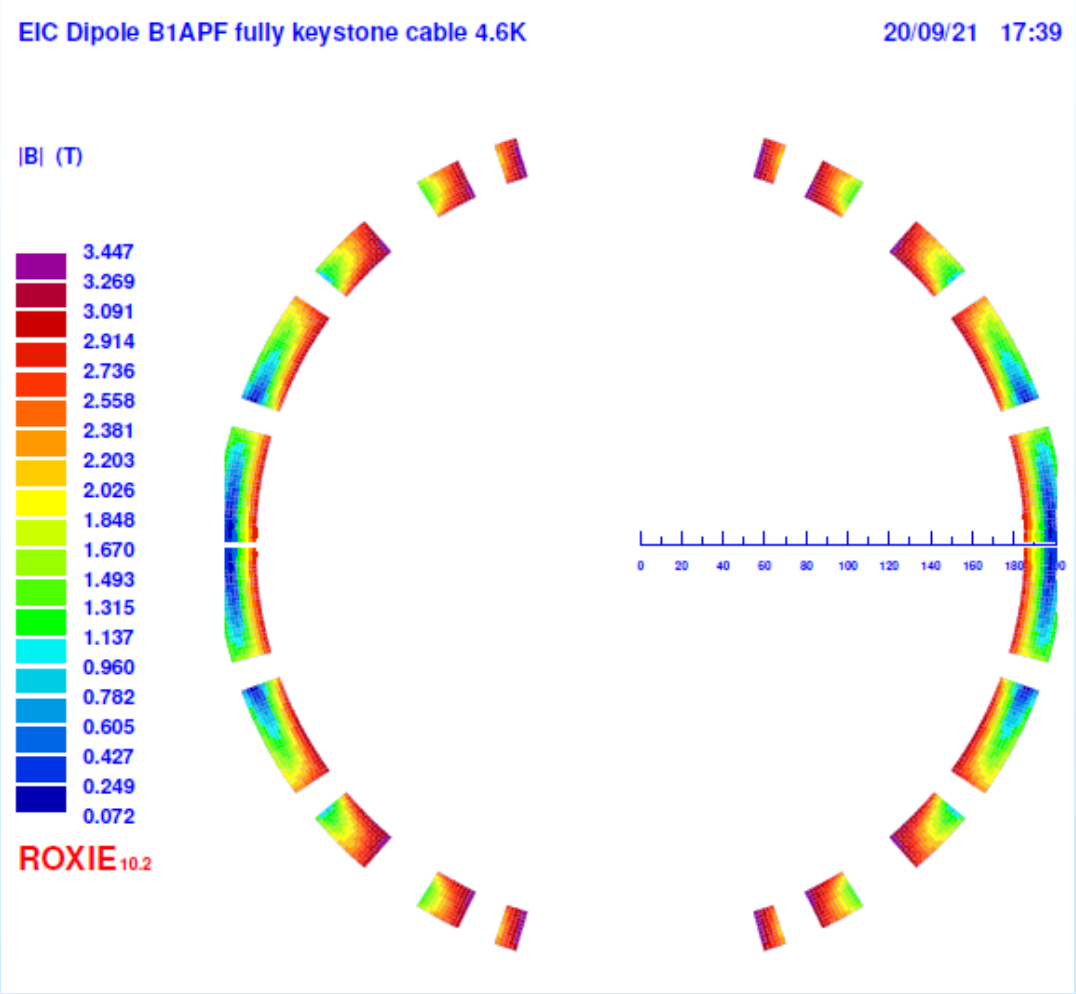
(a) Cross-section of B1APF

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

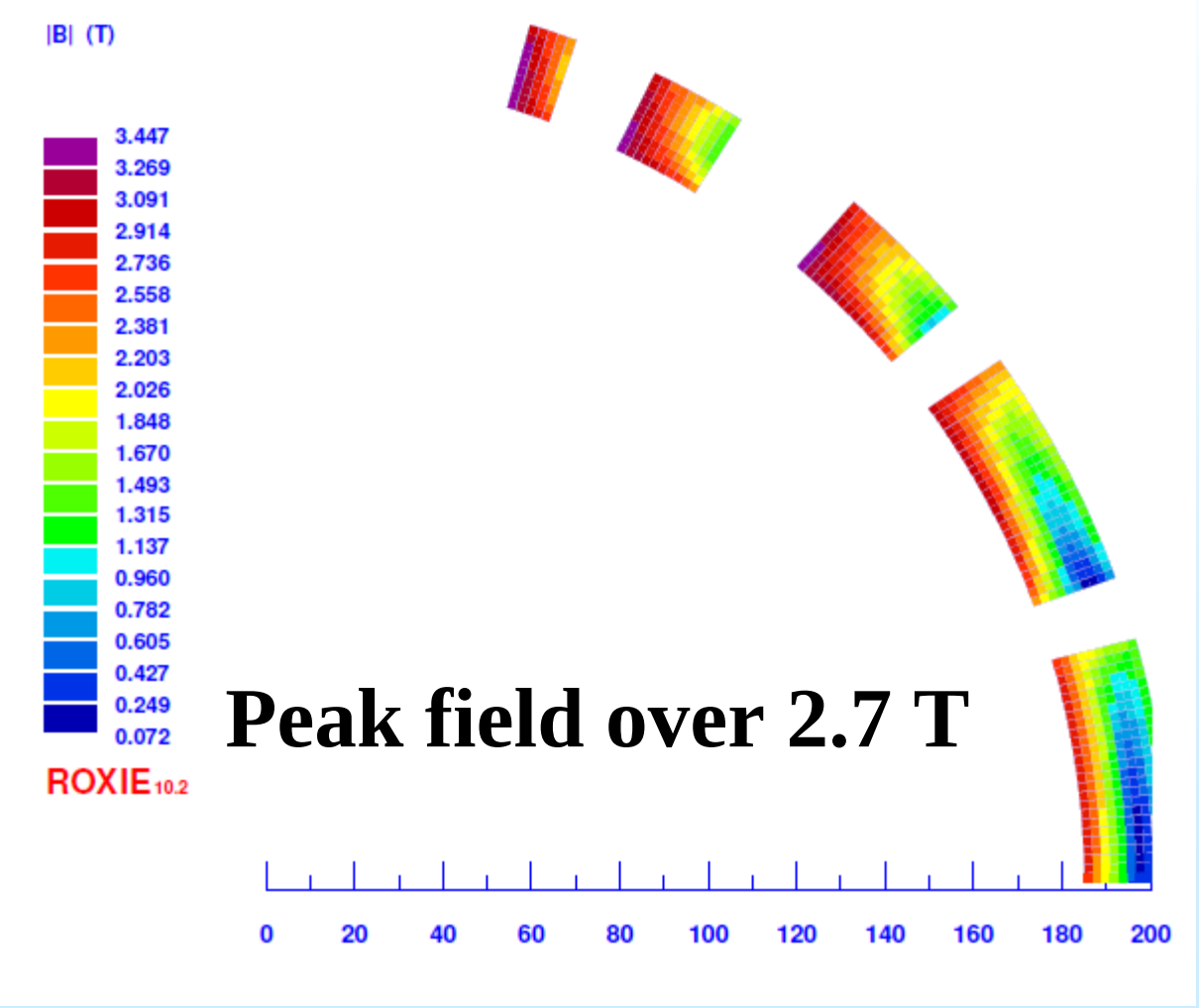
- **Very healthy margin in cross-section @4.6 K**
  - ✓ **~110% field margin, >2.5 K temperature margin**

```
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

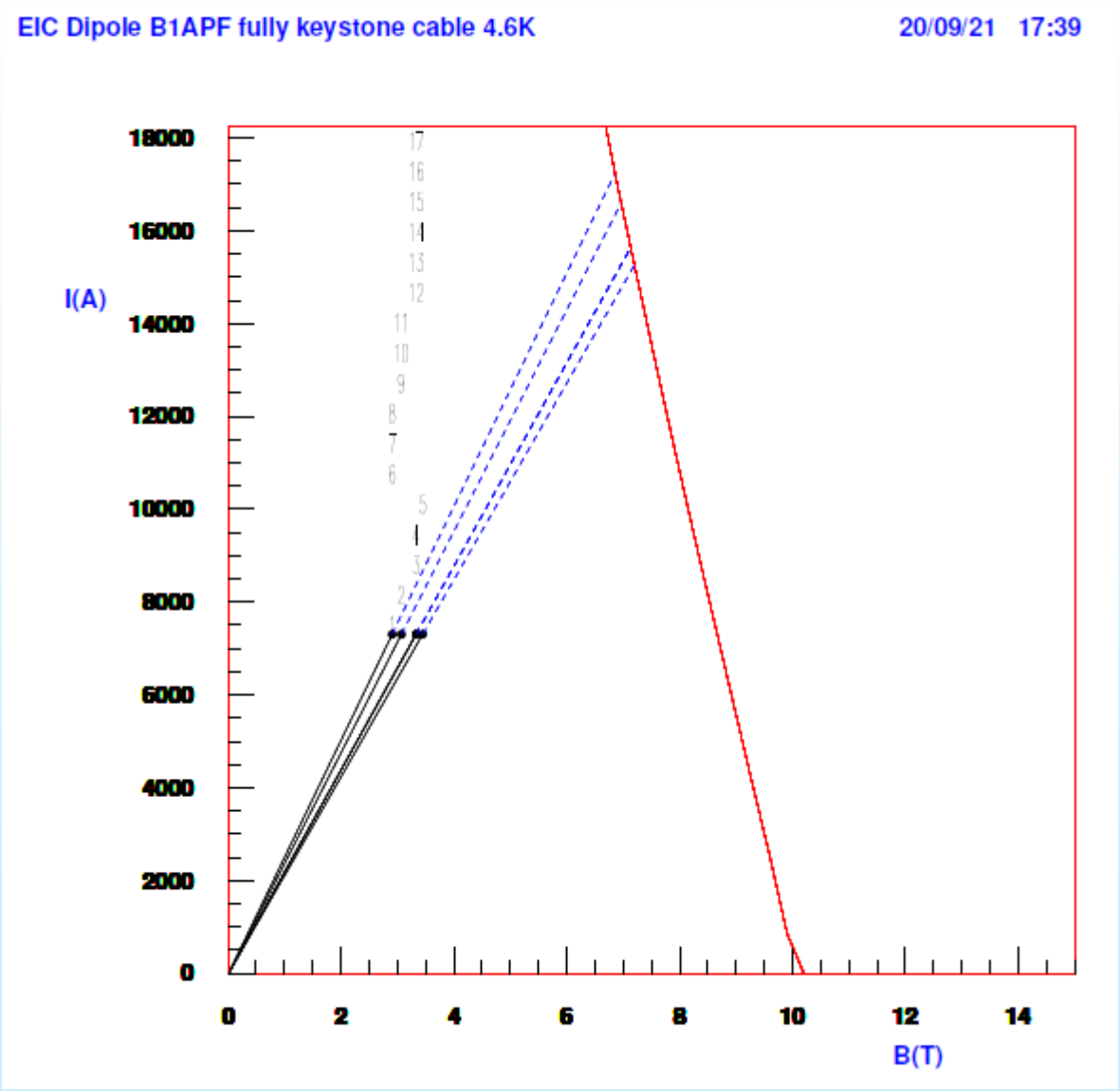
Peak field enhancement ~25%

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



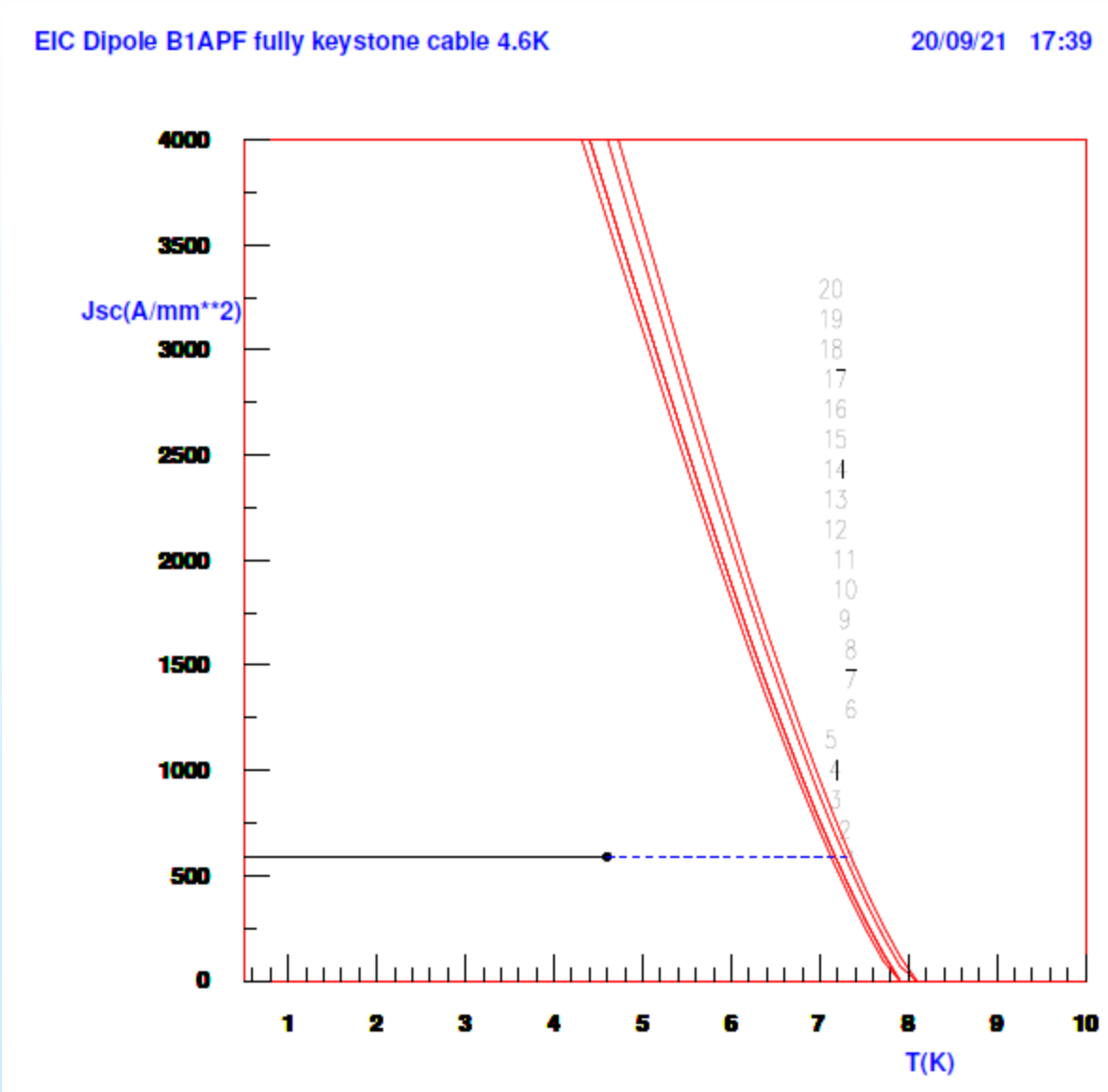
Very Good Overall Margin

About 110% field margin



Temperature Margin over 4.6 K

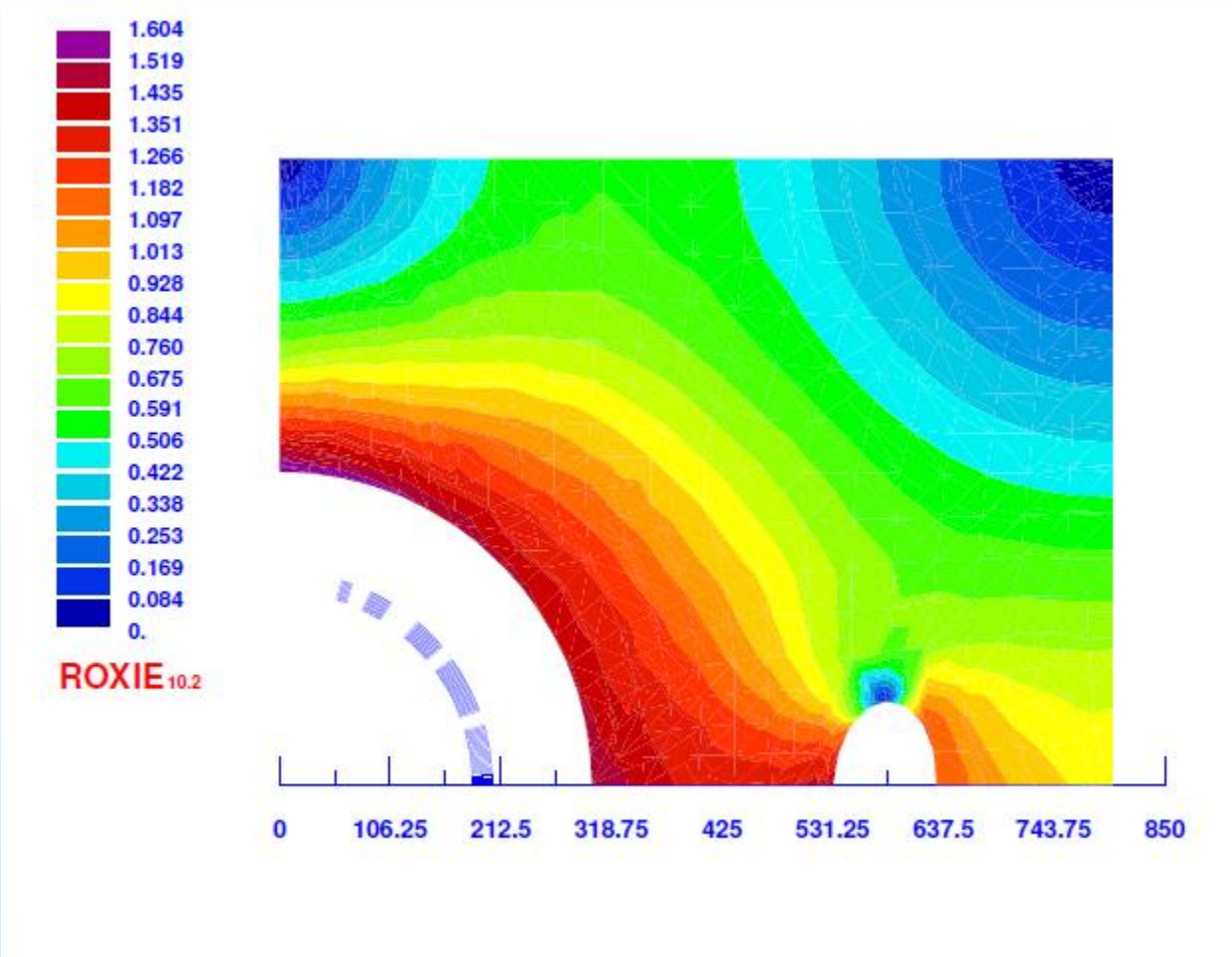
Over 2.5 K Temperature Margin



Some thoughts on the non-circular iron yoke

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

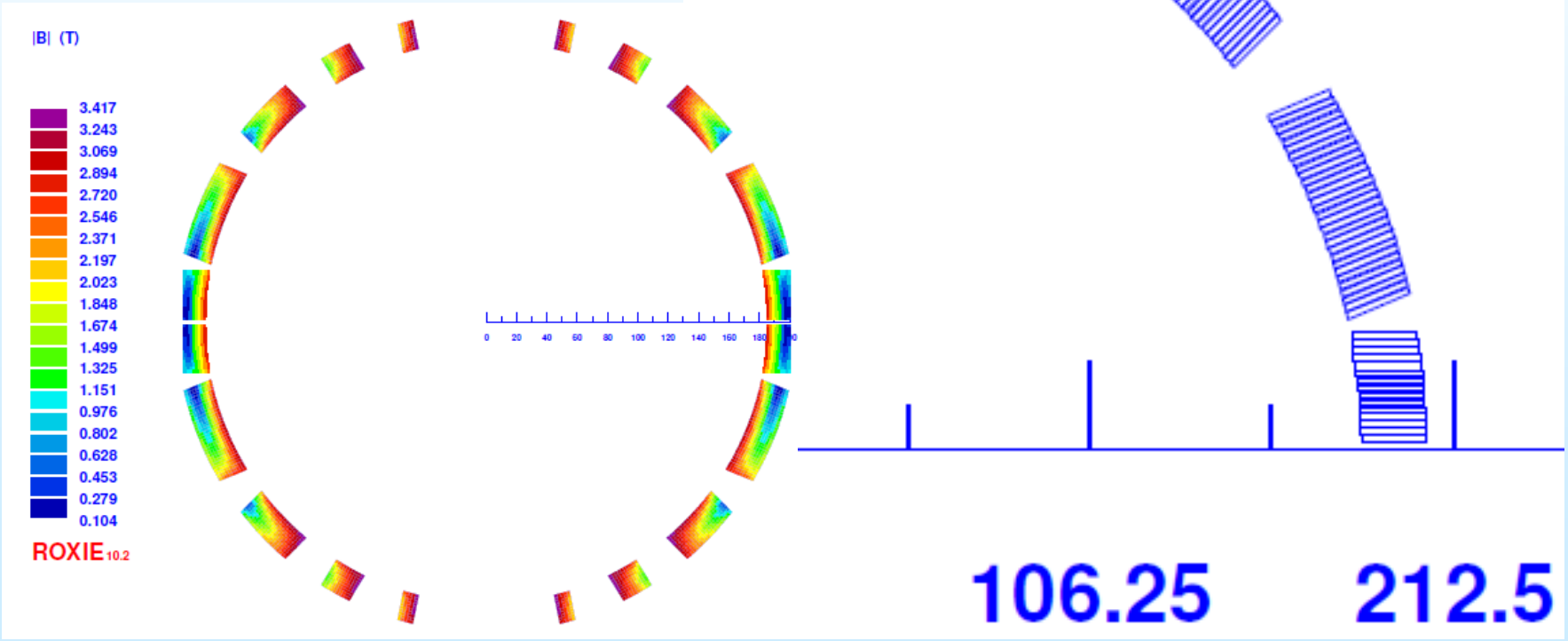
Put extra warm iron outside the coldmass



B1ApF at 4.6 K with No-keystoned (rectangular cable) with 36 strands

B1ApF with no-keystone Cable (no-keystone - rectangular)

- **A reasonably good cross-section mechanically**
  - ➢ **Collar**
  - ➢ **Wedge angles**



Good Field Quality B1ApF with No-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 .....................   0.1276E-05
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .........................................     2.698351
MAGNET STRENGTH (T/(m^(n-1)) ...........................       2.6984

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.00006
b 4:     -0.00000  b 5:     -0.00125  b 6:     -0.00000
b 7:     -0.01985  b 8:      0.00000  b 9:     -0.18040
b10:     -0.00000  b11:     -0.05690  b12:      0.00000
b13:     -0.01146  b14:      0.00000  b15:      0.00378
b16:     -0.00000  b17:      0.00114  b18:      0.00000
b19:      0.00003  b20:     -0.00000  b
```

Good Margin (B=3.4T, T=4.6K) B1pF with No-keystoned Cable

- **Very healthy margin in cross-section @4.6 K**
  - ✓ **>105% field margin, >2.5 K temperature margin**

```
BLOCK NUMBER ..........................................          16
PEAK FIELD IN CONDUCTOR  295 (T) ......................      3.4179
CURRENT IN CONDUCTOR 295 (A) ..........................   7300.0000
LOWEST FIELD IN CONDUCTOR  286 (T) ....................      1.4077
SUPERCONDUCTOR CURRENT DENSITY (A/MM2) ................    591.8404
COPPER CURRENT DENSITY (A/MM2) ........................    369.9003
PERCENTAGE ON THE LOAD LINE ...........................     47.5880
QUENCHFIELD (T) .......................................      7.1824
TEMPERATURE MARGIN TO QUENCH (K) ......................      2.5360
PERCENTAGE OF SHORT SAMPLE CURRENT ....................     16.2221

MAXIMUM LOADLINE IN BLOCK   16 (%) ....................     47.5880
MINIMUM TEMPERATURE MARGIN IN BLOCK    4 (T) .........      2.5360
```

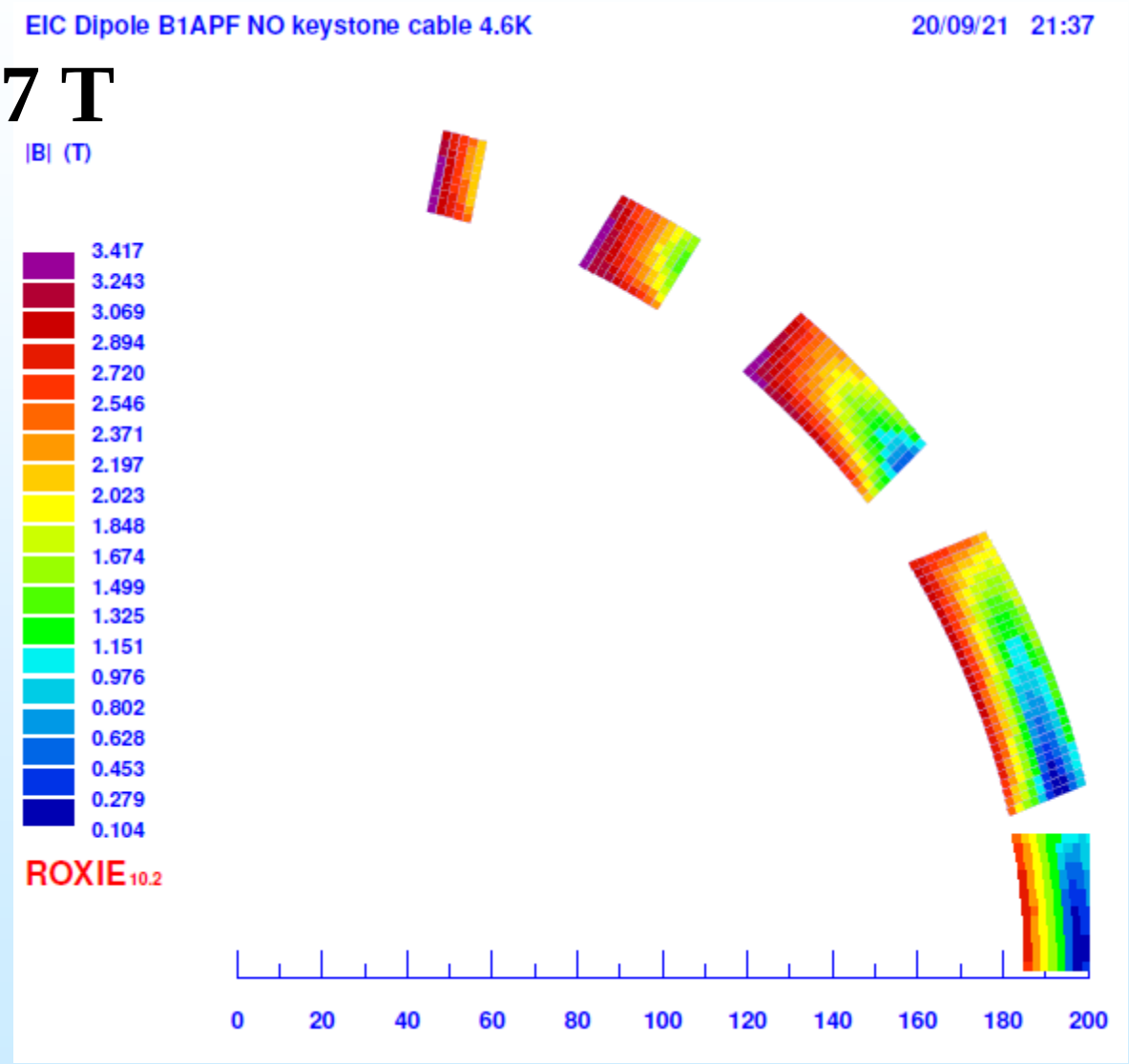
Peak Fields

Peak field over 2.7 T

Peak field enhancement

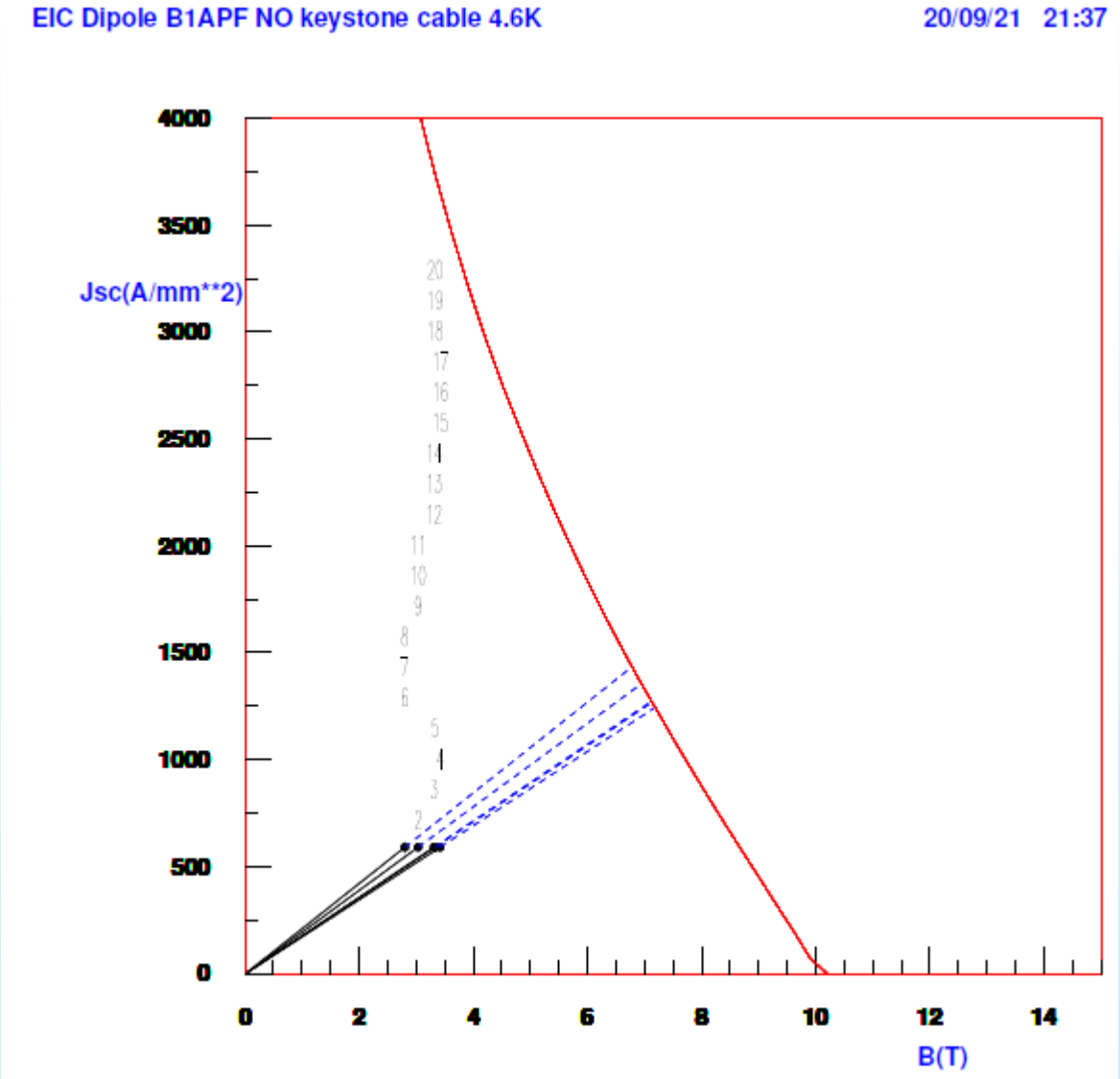
~26%

(higher)



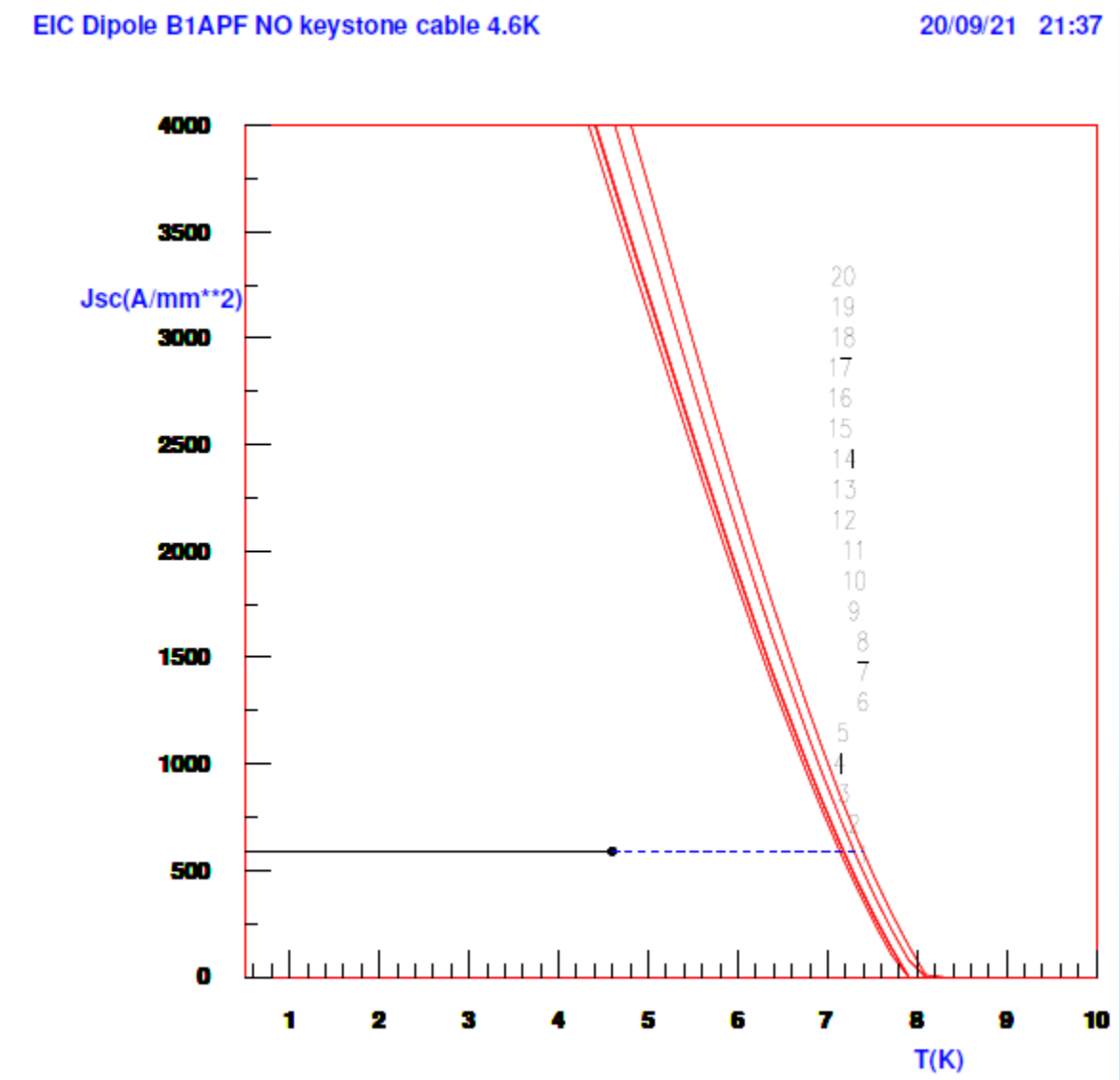
Very Good Overall Margin

Over 105% field margin



Temperature Margin over 4.6 K

Over 2.5 K Temperature Margin



Summary

- All 2-d designs of cable magnets completed (B1pf and B1apF just presented were the last one)
- All are based on the cables that can be easily procured
- Two series of designs with 36-strand cable based on (a) No key stone (rectangular) and (b) based on fully keystone for B1apF
- Rectangular yoke retained; can be changed
- With all 2-d designs iterated, now we can proceed to 3-d (Q2pF partially performed)