# E uro C ir C ol

## 2nd Review of the EuroCircol WP5

## Block coil: electromagnetic

CEA

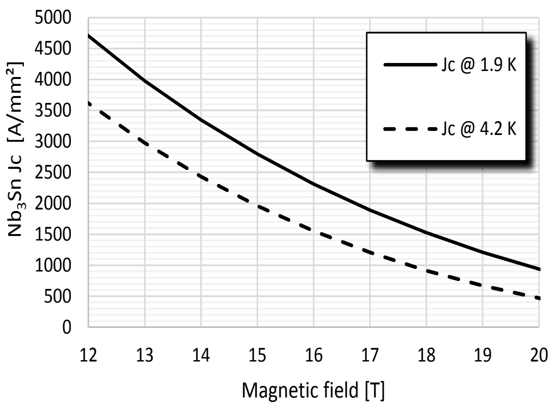
CERN, 9 oct 2017

# EuroCirCol main specifications

- Magnet:

| Parameter | Value | Unit |
|---|---|---|
| Nonimal field magnitude | 16 | T |
| Aperture diameter | 50 | mm |
| Operating temperature | 1.9 | K |
| Inter-beam distance (at cold) | ≤ 204 | mm |
| Margin on the load-line @ 1.9 K | 14 | % |
| Hotspot temperature (105% $I_{nom}$) | 350 | K |
| Peak voltage to ground (105% $I_{nom}$) | 1200 | V |

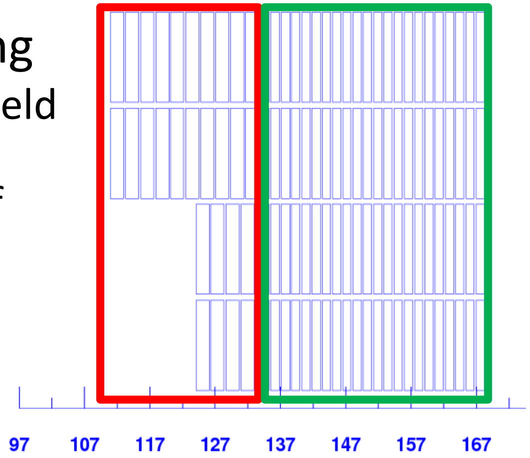
- $Nb_3Sn$ conductors:

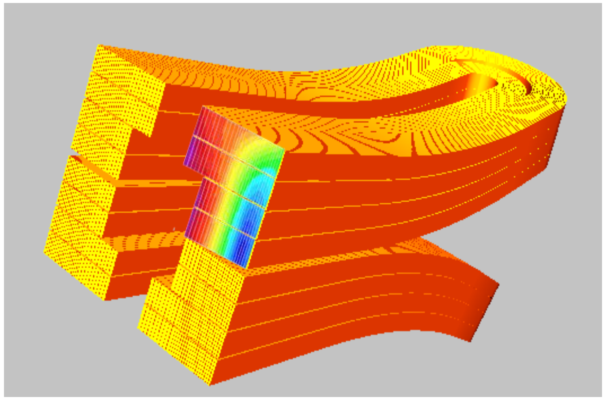



| Parameter | Value | Unit |
|---|---|---|
| Critical current density @ 16 T, 1.9 K - 4.2K | 2315 - 1500 | A/mm² |
| Strand diameter | ≤1.2 | mm |
| Copper/non-Copper ratio | ≥ 0.8 | adim |
| Cabling degradation | 3 | % |
| Cable thickness increase over HT | 3 | % |
| Cable width increase over HT | 1 | % |

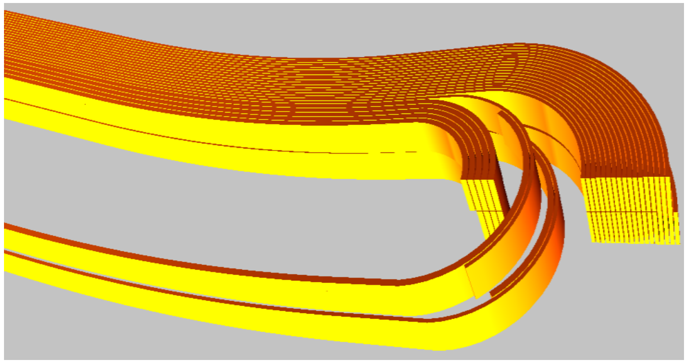
# Block coil - grading

- Conductor savings -> grading
  - Two cables: High and Low field regions
  - Reduction of the amount of conductor by ~50%

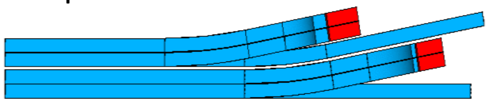


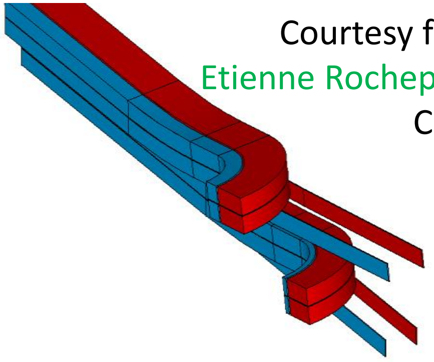



- How to make it real?
  - Internal splices: practical attempts going on at **CERN** and the Applied Superconductivity Group at the Swiss Plasma Center, **PSI** (Switzerland)



- External splices:





Courtesy from
Etienne Rochepault
CERN

# Block coil - 2D emag -conductor

Rectangular cable:

| PARAMETER | Values | | Unit |
|---|---|---|---|
| Strand diameter | 1.1 | 0.7 | mm |
| Number of strands | 21 | 34 | adim |
| Unreacted width | 12.47 | 12.47 | mm |
| Unreacted thickness | 1.94 | 1.23 | mm |
| Reacted width | 12.6 | 12.6 | mm |
| Reacted thickness | 2.00 | 1.27 | mm |
| Copper/non-Copper ratio | 0.8 | 2.0 | adim |
| Insulation thickness | 0.15 | 0.15 | mm |
| Bare cable compaction | 11.8 | 12.0 | % |
| Packing factor | 85.4 | 88.2 | % |
| Transposition pitch | 93 | 93 | mm |

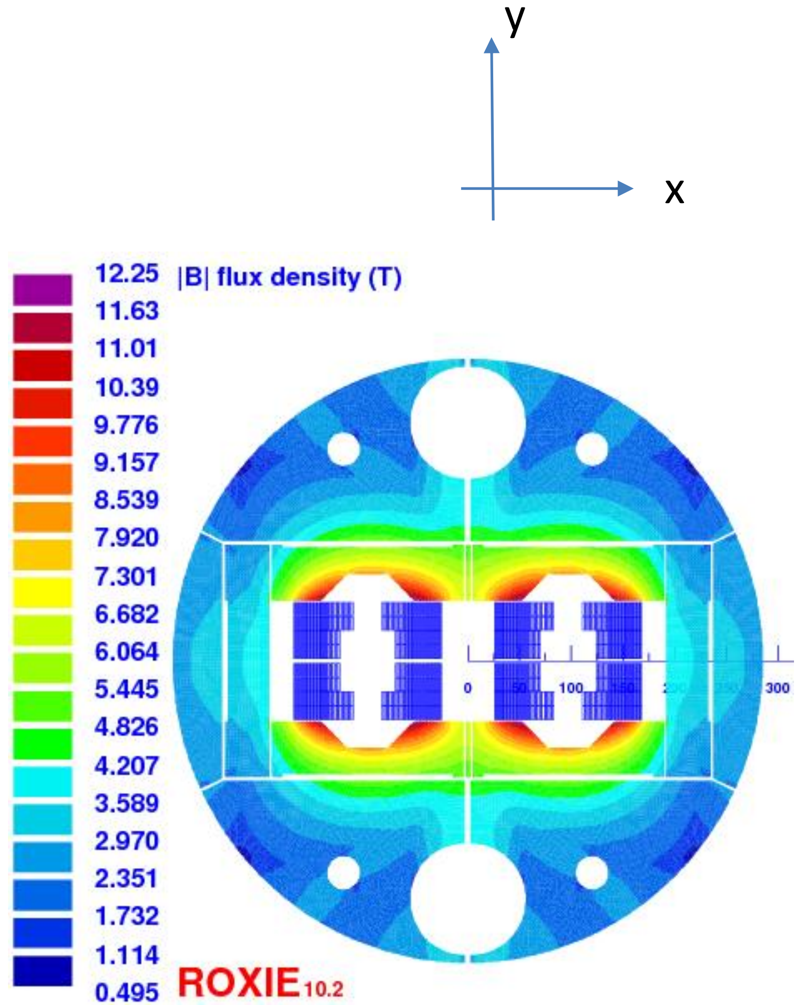
J. Fleiter: Rutherford cable design approach and experience at CERN (here)

| Parameter | Unit | **11 T RRP for LS2** | **11 T PIT for LS2** | **MQXF (PIT and RRP)** | **FRESCA2** | **ERMC** | **SMC** |
|---|---|---|---|---|---|---|---|
| Number of strands | (-) | 40 | 40 | 40 | 40 | 40 | 18 |
| Strands diameter | mm | 0.70 | 0.70 | 0.85 | 1.0 | 1.0 | 1.0 |
| Cable bare width | mm | 14.70 | 14.70 | 18.15 | 20.9 | 20.9 | 10 |
| Cable bare thickness | mm | 1.250 | 1.250 | 1.525 | 1.82 | 1.82 | 1.81 |
| **Keystone angle** | ° | **0.79** | **0.50** | **0.40** | **0.0** | **0.0** | **0.0** |
| **Thin edge compaction*** | **%** | **17.95** | **15.3** | **14.02** | **9.0** | **9.0** | **9.5** |
| Thick edge compaction* | % | 3.48 | 6.13 | 6.57 | | | |
| Transposition pitch | mm | 100 | 100 | 109 | 120 | 120 | 63 |
| SS Core width (thickness) | mm | | 12 (0.0025) | | NO | 14 (0.0025) | NO |

# Block coil - 2D electromagnetism

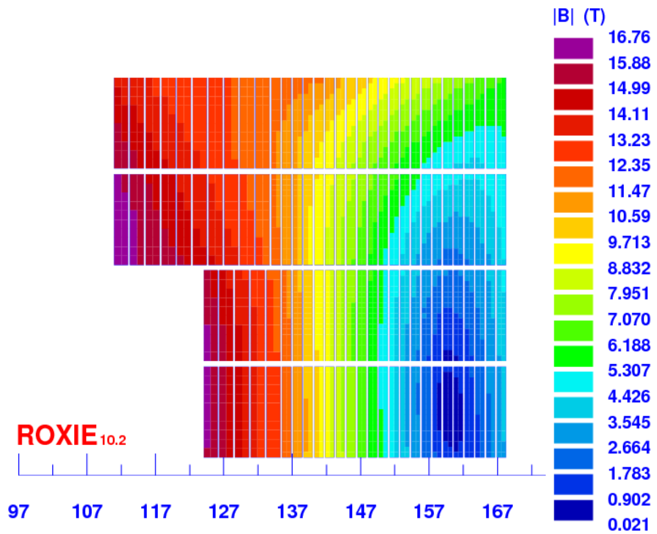
| PARAMETER | [MT2017] | Unit |
|---|---|---|
| Nominal current | 10000 | A |
| Peak field | 16.76 | T |
| Loadline margin | 13.86 | % |
| Inductance (2 apertures) | 50.2 | mH/m |
| Stored energy (2 apertures) | 2647 | kJ/m |
| Horizontal force / ½ pole | -8269/+7636 | kN/m |
| Vertical force / ½ pole | -3535/-2960 | kN/m |
| Inter-beam distance | 194 | mm |
| Yoke diameter | 570 | mm |
| Bore tip thickness | 1.4 | mm |
| Mid-plane shim | 2.35 | mm |
| Hotspot | 329* | K |
| Voltage to ground | 870* | V |
| Number of turns HF cable per layer | 2x5+2x10 | adim |
| Number of turns LF cable per layer | 2x21+2x22 | adim |
| Area of conductor (2 apertures) | 137.9 | $cm^2$ |
| Total weight** | 7860 | tons |

**given as an indication for 4578 dipoles, 14.3 m long each, and a conductor density of 8700 $kg/m^3$.

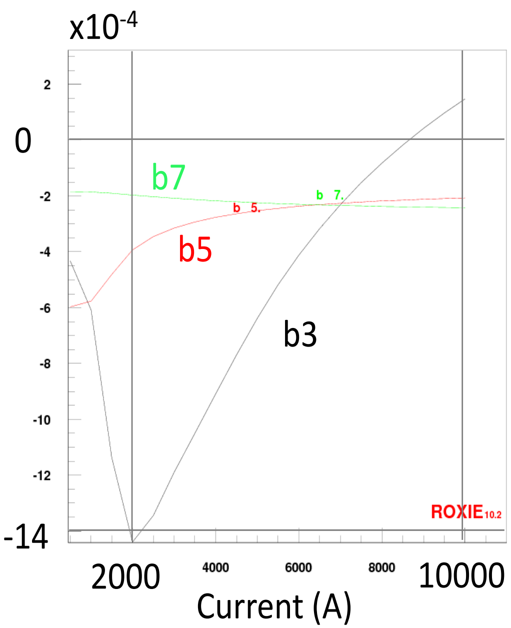


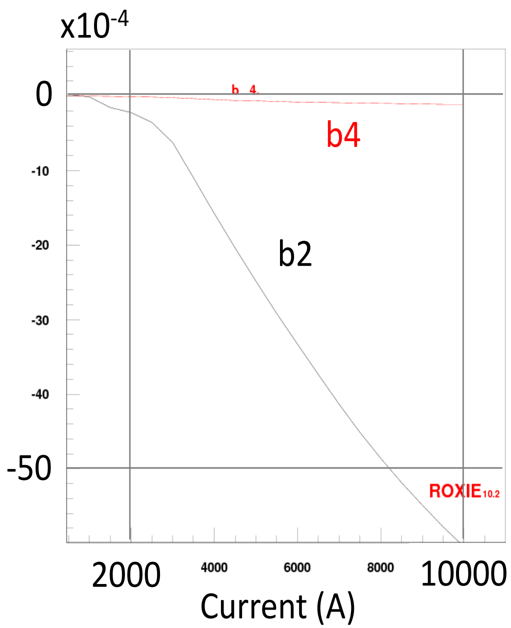
# Block coil - 2D electromagnetism

- Harmonics at nominal in units (spec < 3 units)
  - b3 = 1.5
  - b5 = -2.0
  - b7 = -2.5
  - b2 = -60.0




- From injection at 1 T to 16 T →

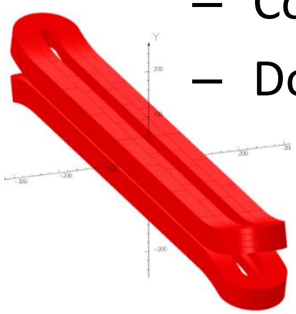


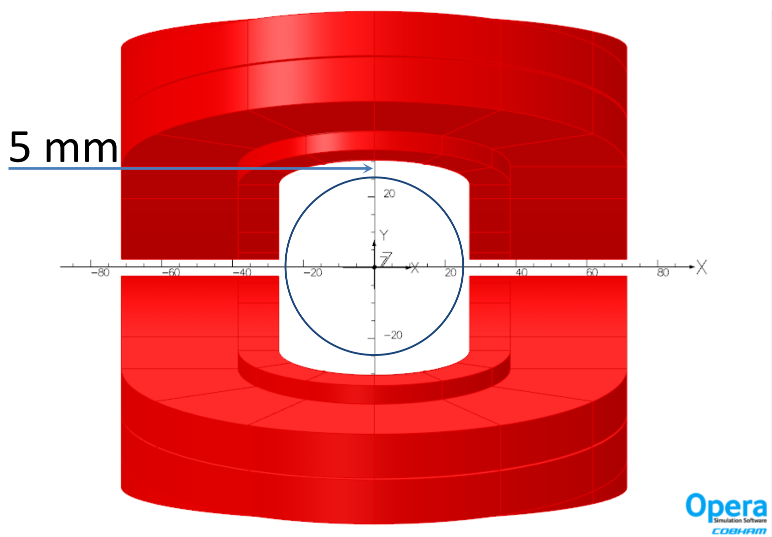



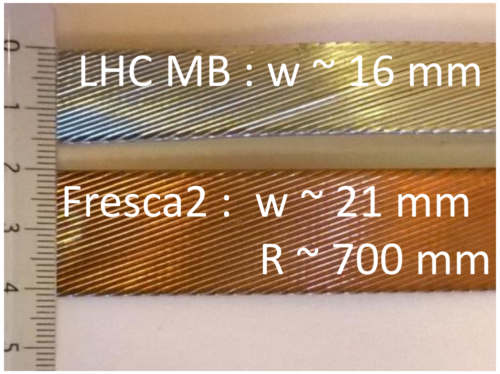

| inter beam [mm] | 194 | 204 | 250 |
|---|---|---|---|
| b2 [units] at nominal (yoke Φ = 750 mm) | 31 | 27 | 12 |
| b2 [units] at nominal (yoke Φ = 600 mm) | | 46 | |
| b2 [units] at nominal (yoke Φ = 570 mm) | 60 | | |

# Block coil - 3D ends

- Assumptions:
  - Return ends – 1000 mm straight section
  - Hardway bend : Rmin = 450 mm in upper layer (w = 12.6 mm)
    - Strain 13.8 mm/m (HD2: 30.6 mm/m HD3: 12.4 mm/m Fresca2: 15.3 mm/m)
  - Coil-to-aperture y-direction: 5 mm
  - Double pancake end

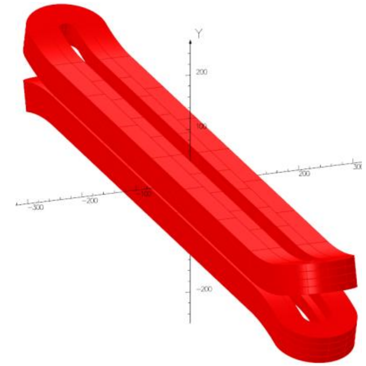




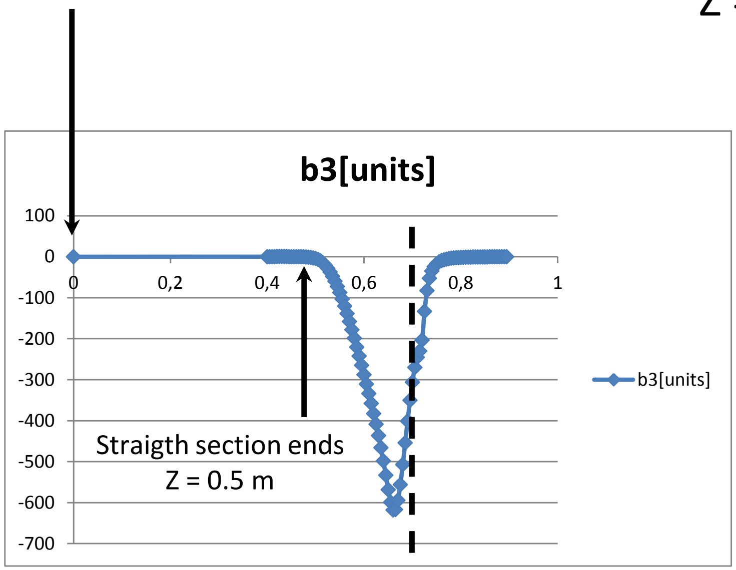



# * = integration over 0.5 m

- b3* = -128 units (~ -10 units in the 2D)



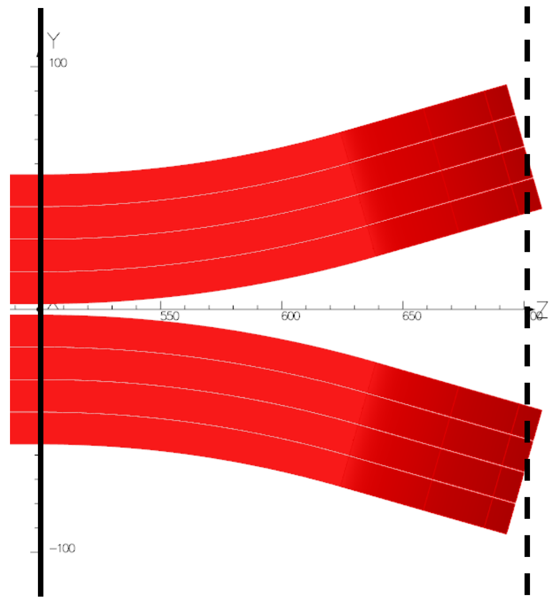

Magnet center
z = 0.0 m




Straigth section ends

Z = 0.5 m

Z = 0.7 m



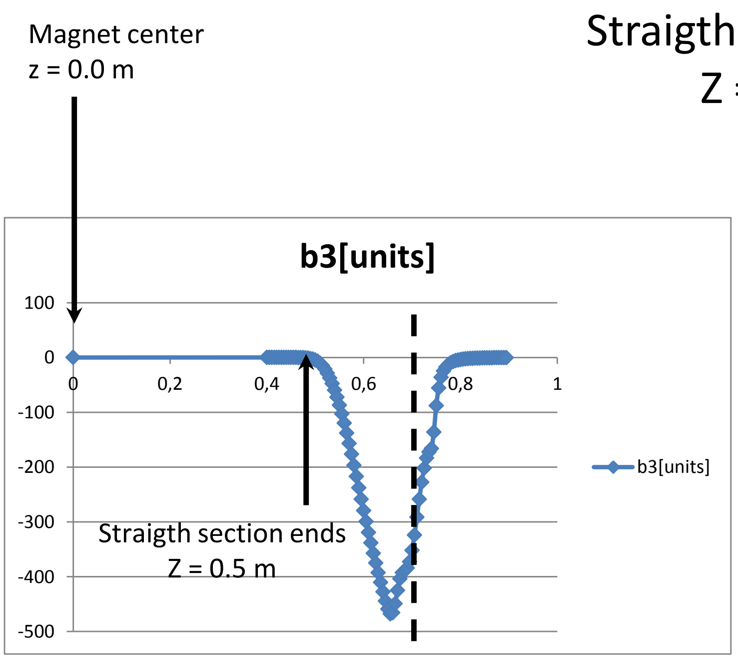

Conductor-to-conductor length = 1.414 m

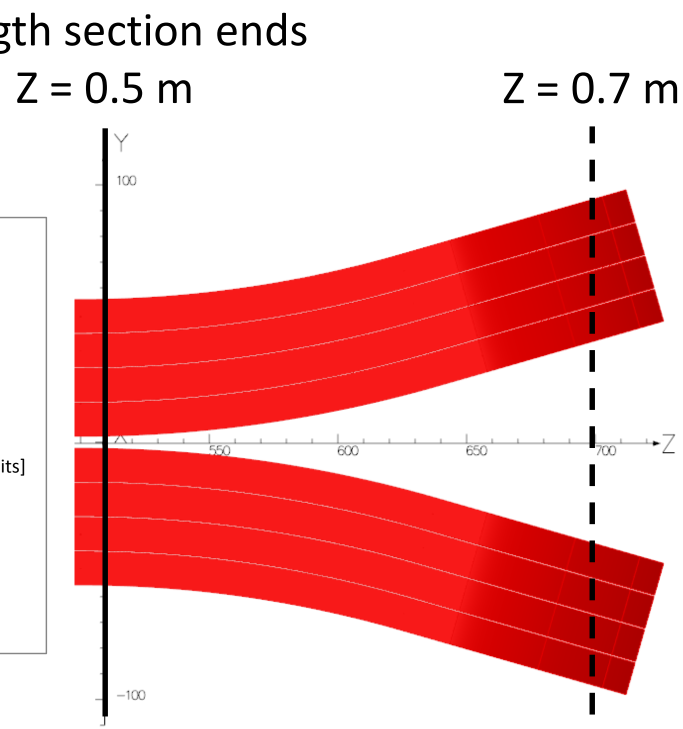
$$b_3^* = \frac{1}{\Delta z_0} \int_{z_0}^{z_0+\Delta z_0} b_3(z)\,dz$$

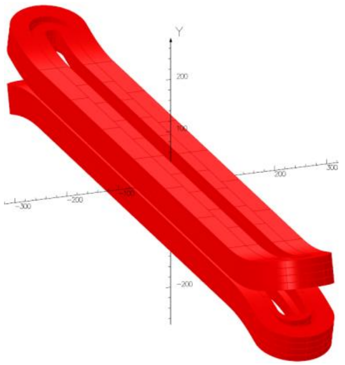
$$b_3(z) = \frac{B3(z)}{B1(z=0)} * 1e-4$$

# 20 mm gap HF-LF

- b3* = -124 units (~ -10 units in the 2D)



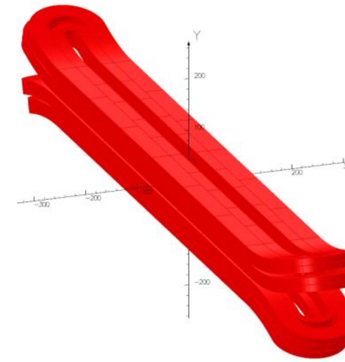
Conductor-to-conductor length = 1.453 m
(+19.5 mm/end)

$$b_3^* = \frac{1}{\Delta z_0}\int_{z_0}^{z_0+\Delta z_0} b_3(z)dz$$

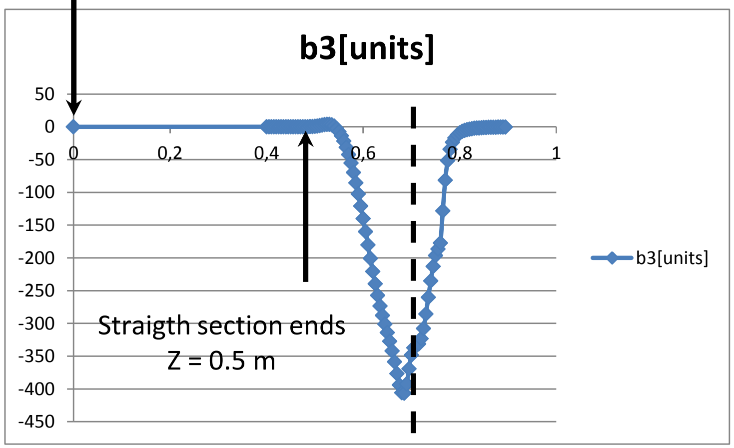
$$b_3(z) = \frac{B3(z)}{B1(z=0)} * 1e-4$$

# Z_low + 25 mm

- b3* = -104 units (~ -8 units in the 2D)



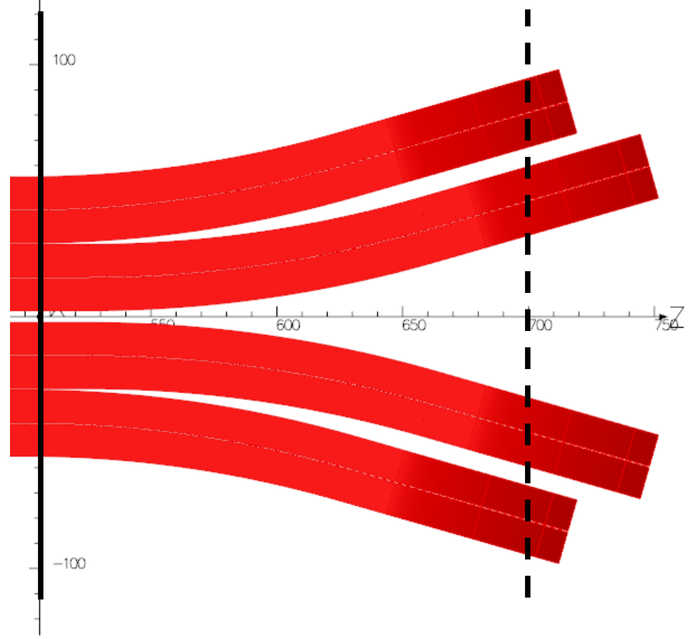

Magnet center
z = 0.0 m




Straigth section ends

Z = 0.5 m

Z = 0.7 m



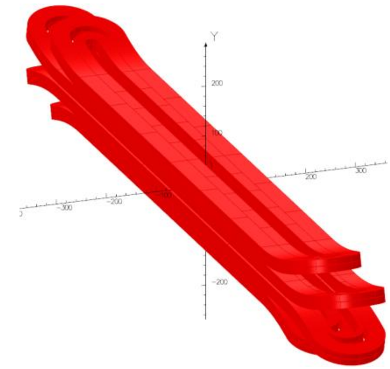

Conductor-to-conductor length = 1.503 m
(+25 mm/end)

$$b_3{*} = \frac{1}{\Delta z_0} \int_{z_0}^{z_0+\Delta z_0} b_3(z)\,dz$$

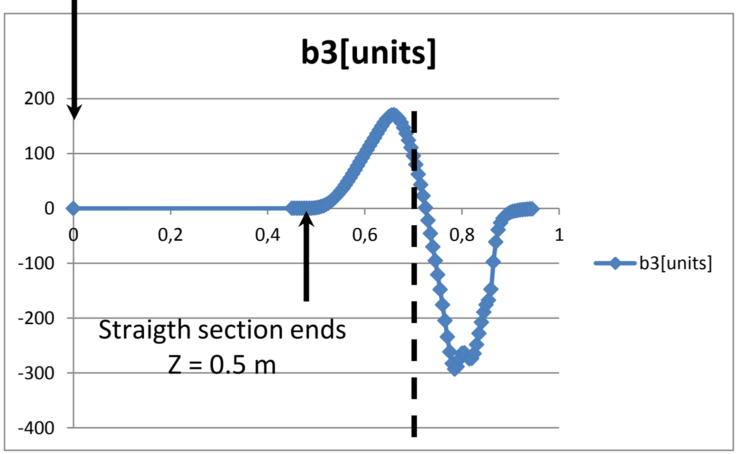
$$b_3(z) = \frac{B3(z)}{B1(z=0)} * 1e-4$$

# Z_low + 25 mm + 100 mm

- b3* = -20 units (~ -1.5 units in the 2D)



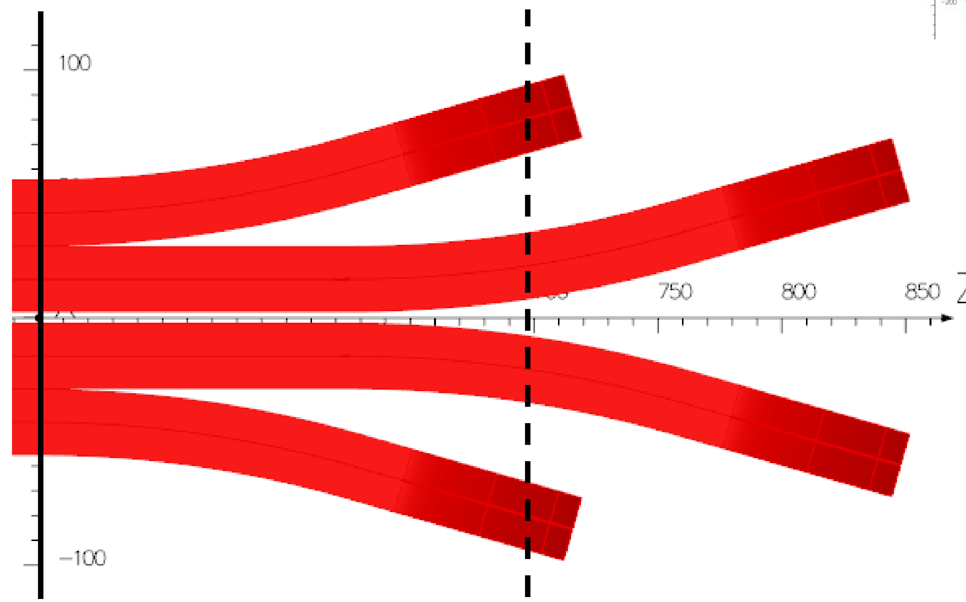
Magnet center
z = 0.0 m




Straigth section ends

Z = 0.5 m

Z = 0.7 m



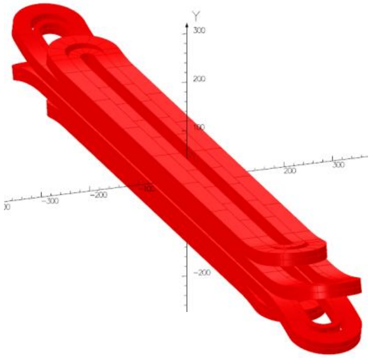

Conductor-to-conductor length = 1.703 m
(+100 mm/end)

$$b_3^* = \frac{1}{\Delta z_0} \int_{z_0}^{z_0+\Delta z_0} b_3(z)\,dz$$

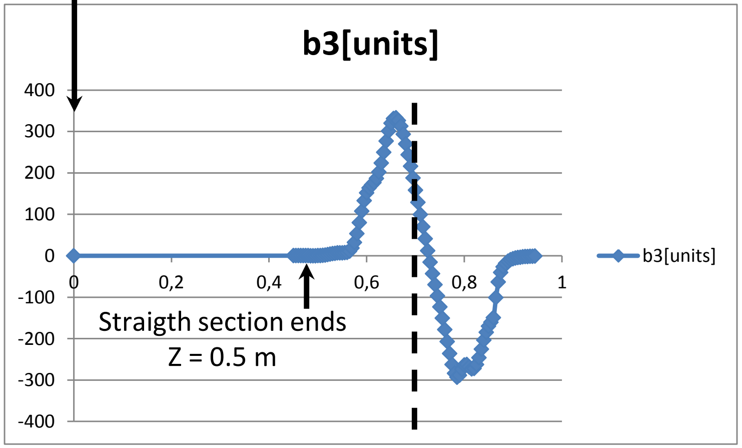
$$b_3(z) = \frac{B3(z)}{B1(z=0)} * 1e-4$$

# Angle_high 10° (wrt 16°)

- b3* = 1.6 units (~ -0.1 units in the 2D)



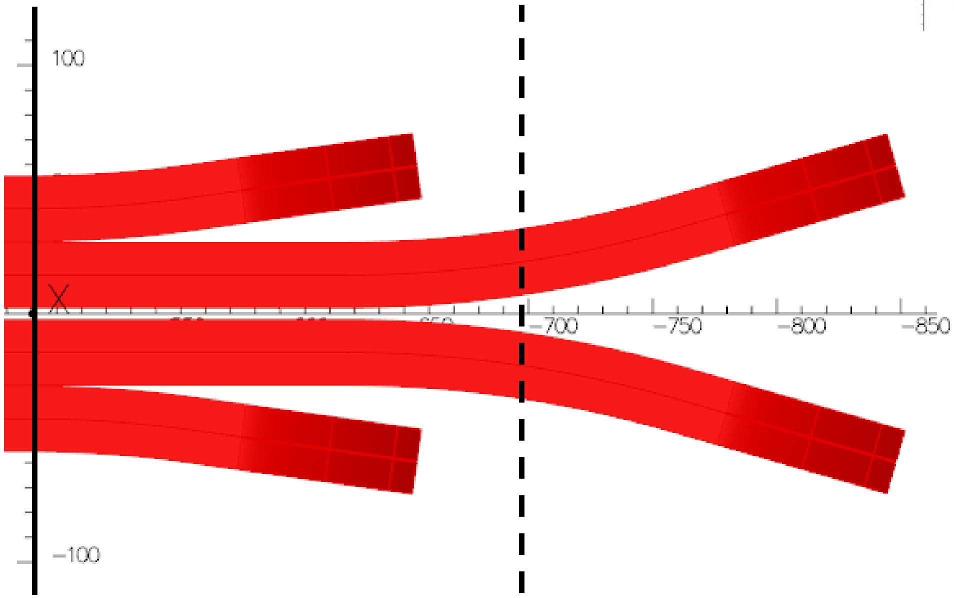
Magnet center
z = 0.0 m




Straigth section ends

Z = 0.5 m

Z = 0.7 m



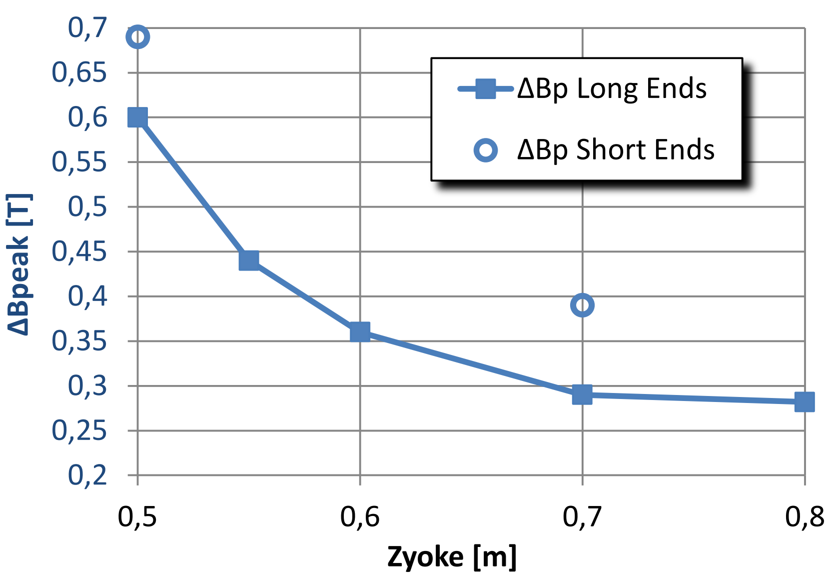

Conductor-to-conductor length = 1.703 m
(+0 mm/end)

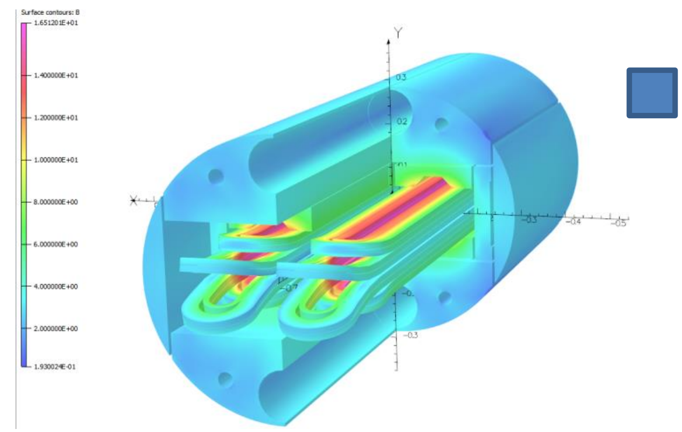
$$b_3^* = \frac{1}{\Delta z_0} \int_{z_0}^{z_0+\Delta z_0} b_3(z)\,dz$$

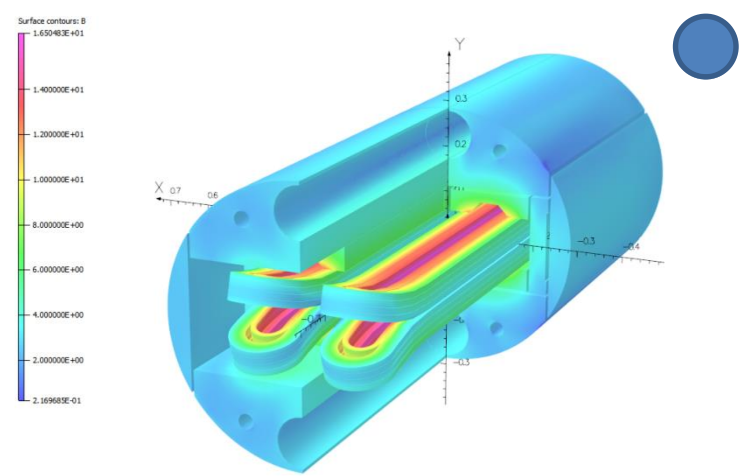
$$b_3(z) = \frac{B3(z)}{B1(z=0)} * 1e-4$$

# Bpeak

- Long vs Short Ends (zpad = 0.5 m = straight part)



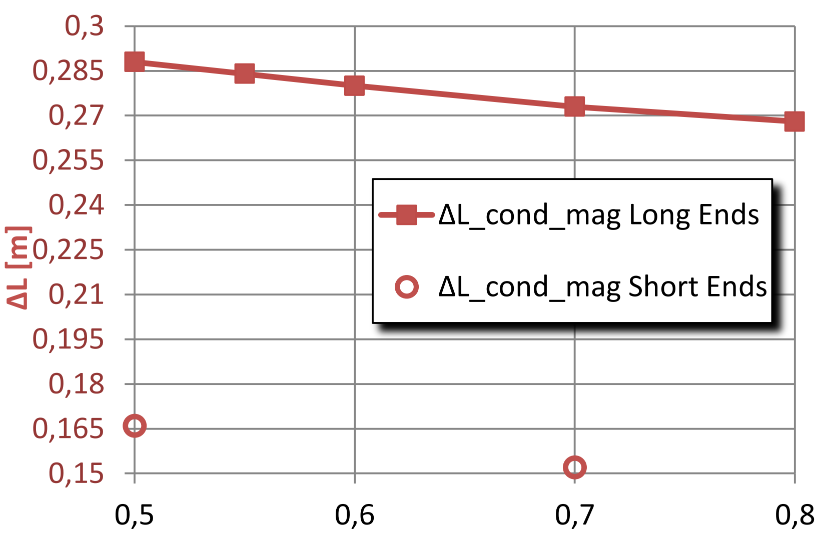



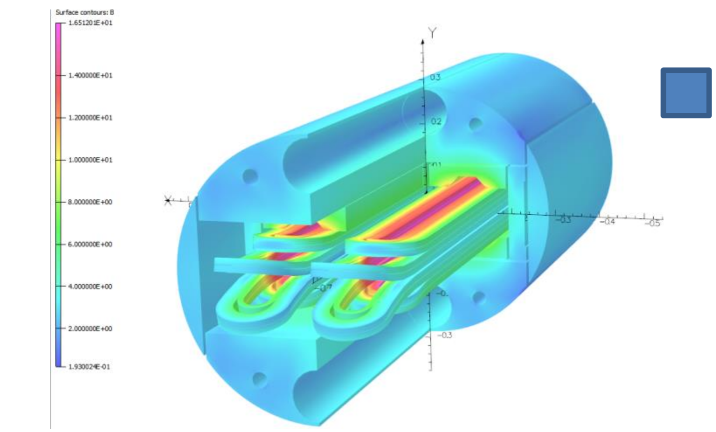


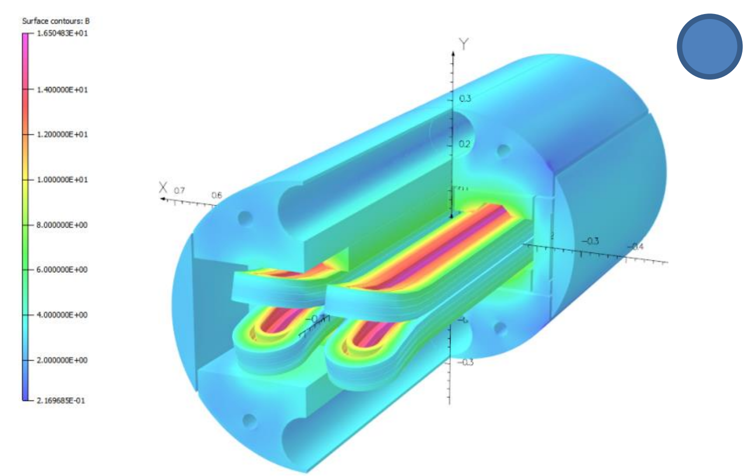
$\Delta B_{peak} = B_{peak\ straight\ section} - B_{peak\ ends}$

# Lmag

- Long vs Short Ends (zpad = 0.5 m = straight part)



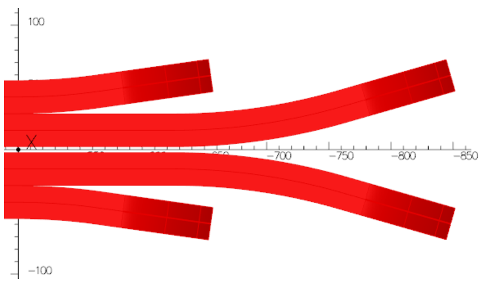



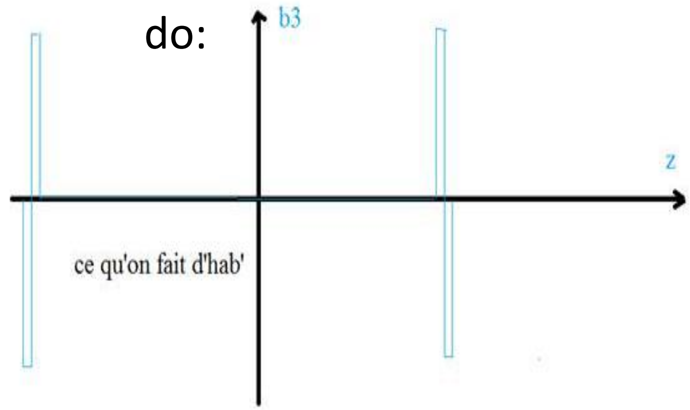


$\Delta L = L_{cond\text{-}to\text{-}cond} - L_{mag}$

# Field quality

What we usually do:




No straight section length effect

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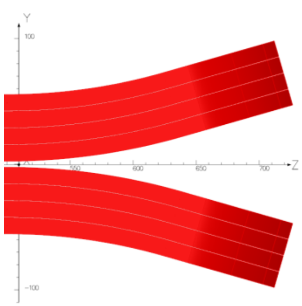
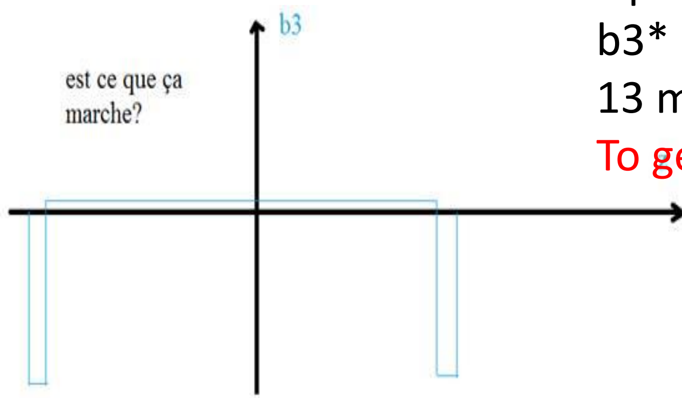
Is that feasible?






Optimization depends on the SS length

b3* = -130 units over 1 m

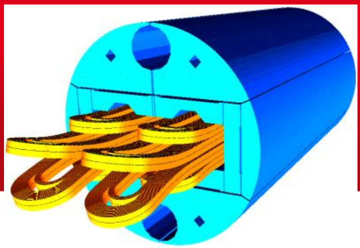
13 m of ss x 10 units = 130 units

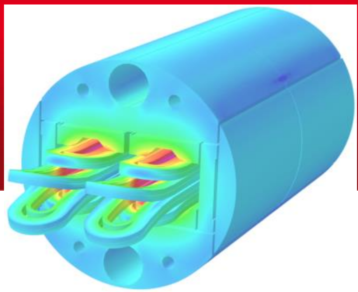
To get more compact ends:

# CONCLUSION

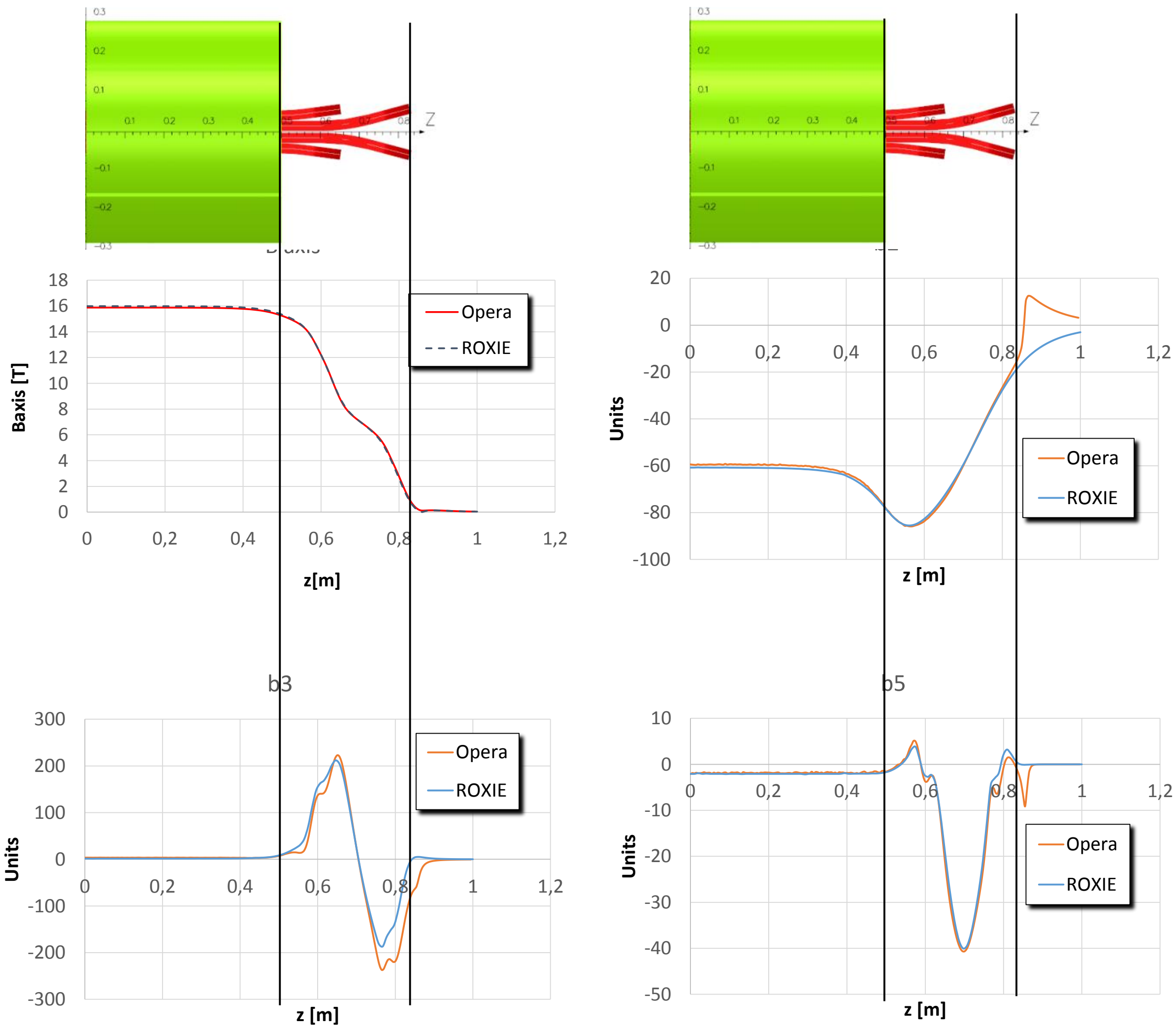
- A 3D double aperture electromagnetic model has been developped
- Field quality 2D, Hotspot, Voltage to ground: ok
- Still some interrogation for the ends mainly:
  - Input from splice tests are needed.
  - End design: compact vs field quality 3D
  - Iteration with the mechanics still pending

# Roxie Opera Xcheck

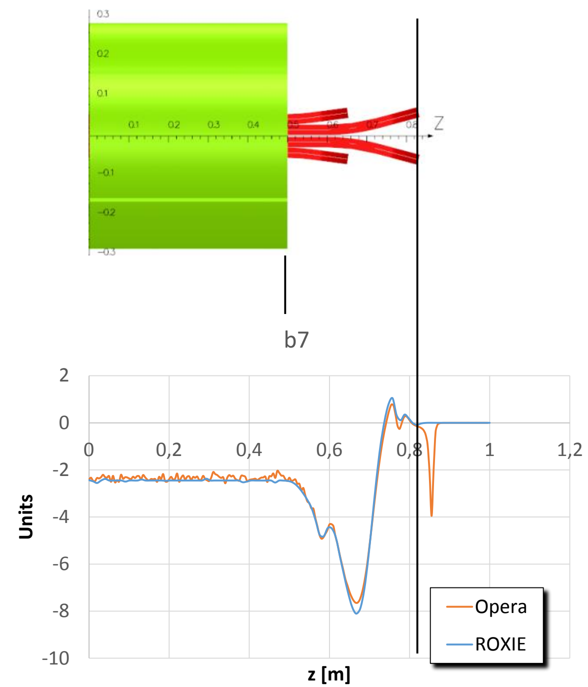




- Simulation of one model:




Something to clarify in the way I calculate the harmonics in Opera…



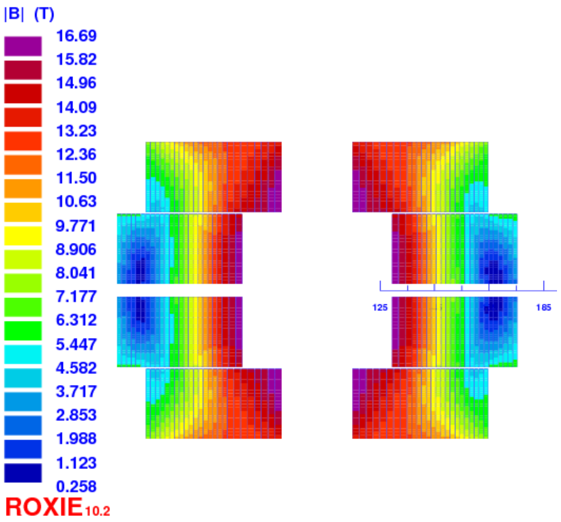
# Extra – Magnet and cable parameters

| PARAMETER | [ASC2016] | [MT2017] | Unit |
|---|---|---|---|
| Nominal current | 10930 | 10000 | A |
| Peak field | 16.81 | 16.76 | T |
| Loadline margin | 13.95 | 13.86 | % |
| Inductance (2 apertures) | 48.06 | 50.2 | mH/m |
| Stored energy (2 apertures) | 3016 | 2647 | kJ/m |
| Horizontal force / ½ pole | 8473 | 8269 | kN/m |
| Vertical force / ½ pole | 3572 | 3535 | kN/m |
| Inter-beam distance | 250 | 194 | mm |
| Yoke diameter | 800 | 570 | mm |
| Bore tip thickness | 6.3 | 1.4 | mm |
| Mid-plane shim | 1.45 | 2.35 | mm |
| Hotspot | 348 | 329* | K |
| Voltage to ground | 1065 | 870* | V |
| Number of turns HF cable per layer | 2x3+2x9 | 2x5+2x10 | adim |
| Number of turns LF cable per layer | 2x22+2x23 | 2x21+2x22 | adim |
| Area of conductor (2 apertures) | 151.9 | 137.9 | $cm^2$ |
| Total weight** | 8652 | 7860 | tons |
| **given as an indication for 4578 dipoles, 14.3 m long each, and a conductor density of 8700 $kg/m^3$. | | | |

| PARAMETER | Values | | Unit |
|---|---|---|---|
| Strand diameter | 1.1 | 0.7 | mm |
| Number of strands | 21 | 34 | adim |
| Unreacted width | 12.47 | 12.47 | mm |
| Unreacted thickness | 1.94 | 1.23 | mm |
| Reacted width | 12.6 | 12.6 | mm |
| Reacted thickness | 2.00 | 1.27 | mm |
| Copper/non-Copper ratio | 0.8 | 2.0 | adim |
| Insulation thickness | 0.15 | 0.15 | mm |
| Bare cable compaction | 11.8 | 12.0 | % |
| Packing factor | 85.4 | 88.2 | % |
| Transposition pitch | 93 | 93 | mm |

# What to do with that?

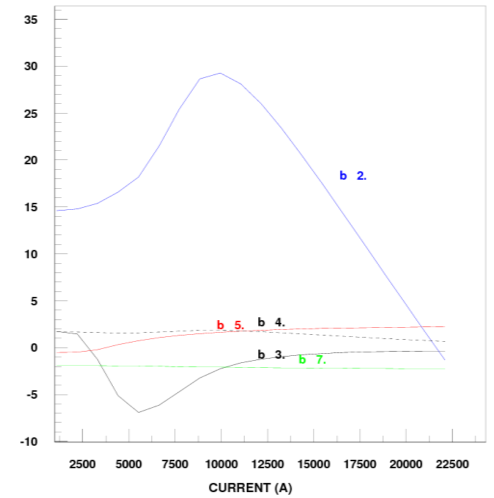
| Quantity | v8ari204 |
|---|---|
| strand diameter | 1.2 – 0.8 |
| nb of strands | 40 – 60 |
| width | 25.2 |
| thickness | 2.2 – 1.45 |
| Cu/nonCu | 0.8 – 1.6 |
| $I_{nom}$ | 22100 |
| $B_{peak}$ | 16.7 |
| LL margin (1.9 K) | 14.1 |
| Inductance diff. (2 ap) | 9.58 |
| Stored energy (2 ap) | 2457 |
| Nb of turns | 114 = 3+3+9+9 +22+22+23+23 |
| Fx & Fy (per ½-coil) | 7942 & -3242 |
| Hotspot | 340 |
| Bore thickness | 2.35 (-0.5 of insulation) |
| Midplane shim | 2.25 |
| LdxI (1 aperture) | 105 |
| I/Ic HF-LF | 0.45 – 0.59 |
| Conductor area (2 ap) | **133.9** |
| 4578 x 14.3 x 8.7 weight | **7626** |

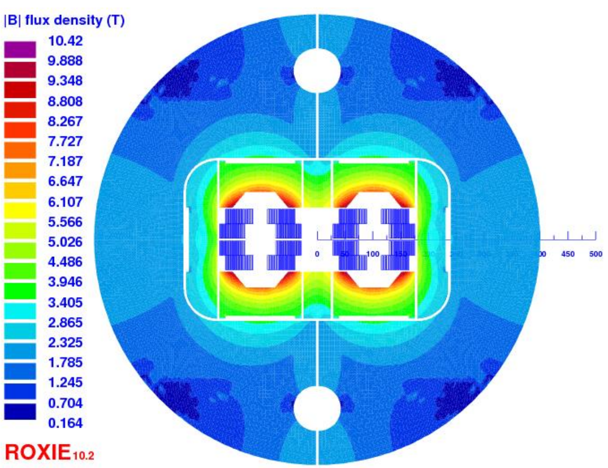



$F_{Lorentz}$/width = 178 MPa

$F_{Lorentz}$/width = 127 MPa

```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:    -1.32363  b 3:    -0.35508
b 4:      0.65195  b 5:     2.22602  b 6:     0.02648
b 7:     -2.25963  b 8:     0.00043  b 9:    -1.71440
```




Voltage
Splices
1 DP
Current
Cable

# Critical surface $Nb_3Sn$

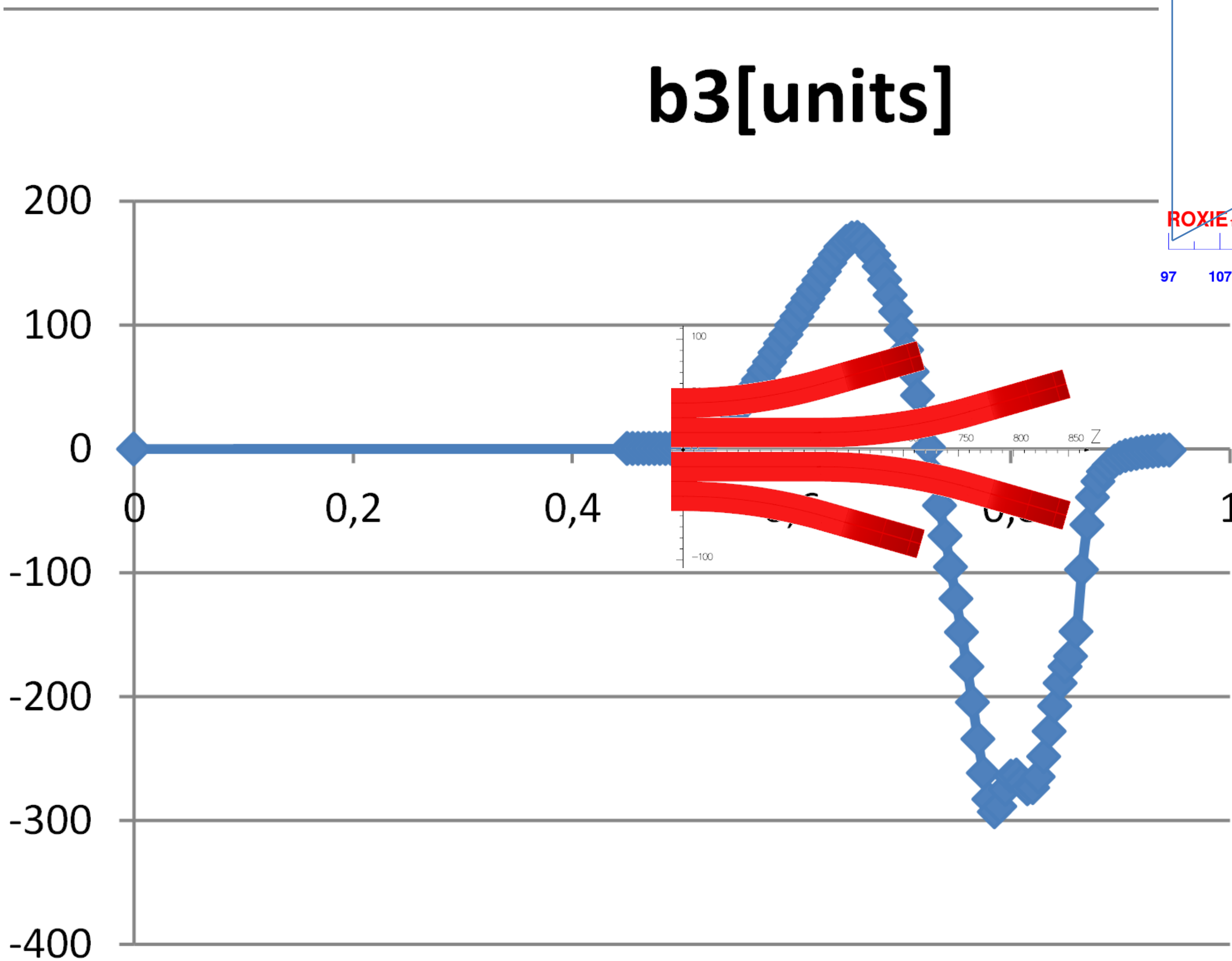
- Jc (1.9 K, 16 T) = 2245 A/mm²
- no cabling degr.
- C0 = 267845 AT/mm²

$$
\begin{cases}
J_c = \dfrac{C(t)}{B} b^{0.5} (1-b)^2 \\
B_{c2}(T) = B_{c20}(1-t^{1.52}) \\
C(t) = C_0 (1-t^{1.52})^{\alpha} (1-t^2)^{\alpha}
\end{cases}
$$

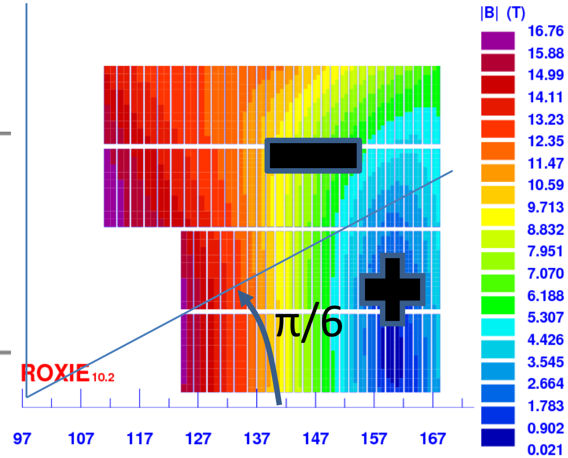
where $t = T/T_{c0}$ and $b = B/B_{c2}(t)$ with $B$ the magnetic flux density on the conductors. $T_{c0}$ = 16 K, $B_{c20}$ = 29.38 T, $\alpha$ = 0.96, are fitting parameters computed from the analysis of measurements on the conductor.

- Similarly:
  - Jc (1.9 K, 16 T) = 2312 A/mm²
  - 3% cabling degr.
  - C0 = 275880 AT/mm²

# Field $b_3$



b3[units]
200
100
0
-100
-200
-300
-400
0
0,2
0,4
1
100
-100
750
800
850
Z

|B| (T)
16.76
15.88
14.99
14.11
13.23
12.35
11.47
10.59
9.713
8.832
7.951
7.070
6.188
5.307
4.426
3.545
2.664
1.783
0.902
0.021
π/6
ROXIE 10.2
97
107
117
127
137
147
157
167