

EDIPO 2
Staggered racetracks
Mechanical 3D FEA

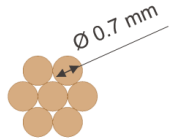
X. Sarasola

October 17th, 2024

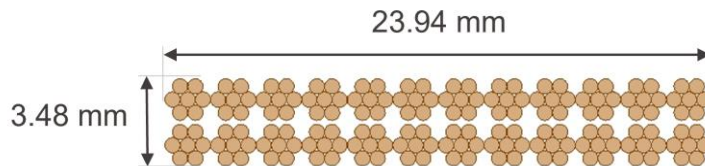
Cable design

- Bruker strand:
 - $j_{c,nc} = 2600 \text{ A/mm}^2$ at 12 T and 4.2 K
 - Cu:nCu = 1.0
- Same cable used for all coils

- First stage:



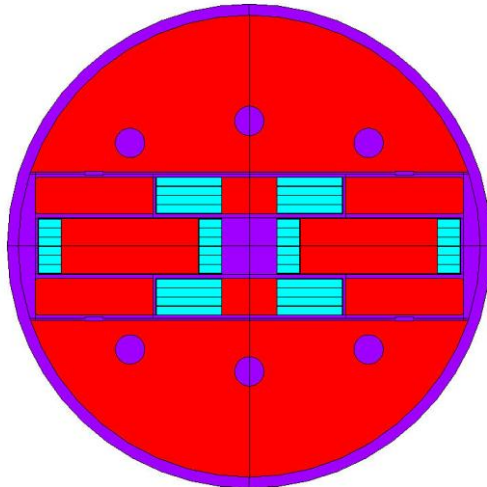
- Second stage: $24 \times (6+1)$, 0.7 mm



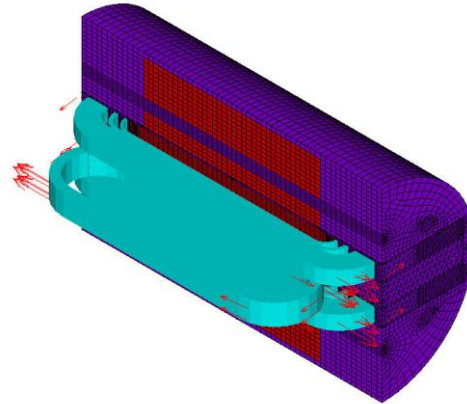
- Assumed insulation thickness: 0.2 mm

Magnet design

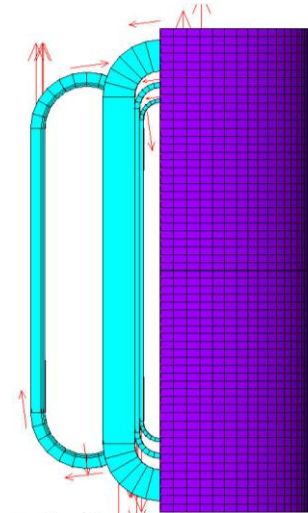
- 144×144 mm² aperture
- Two sets of flat racetrack coils:
 1. Side coils: one pair of coils, each made of 6 pancakes: 16 turns/pancake
 2. Vertical coils: one pair of coils, each made of 4 pancakes: 46 turns/pancake
- Iron parts in red: iron yoke limited to the straight section of the coils
- 50 mm wide spacers (**only vertical coils**)



EDIPO, magnetic 2D model



EDIPO, magnetic 3D model

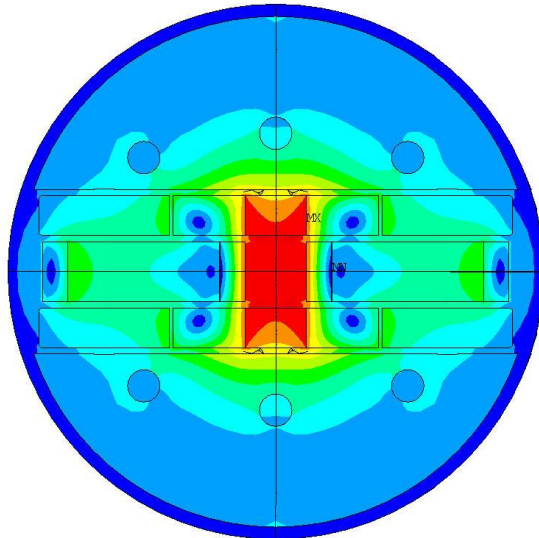


EDIPO, magnetic 3D model

Comparison 3D vs 2D

	3D	2D
I_{op} (85% $\times I_{ss}$)	17.359 kA	17.316 kA
$B_{center\ aperture}$	15.02 T	15.03 T
B_{coil}	15.05 T	15.07 T
E_{total}	20.6 MJ	11.4 MJ/m

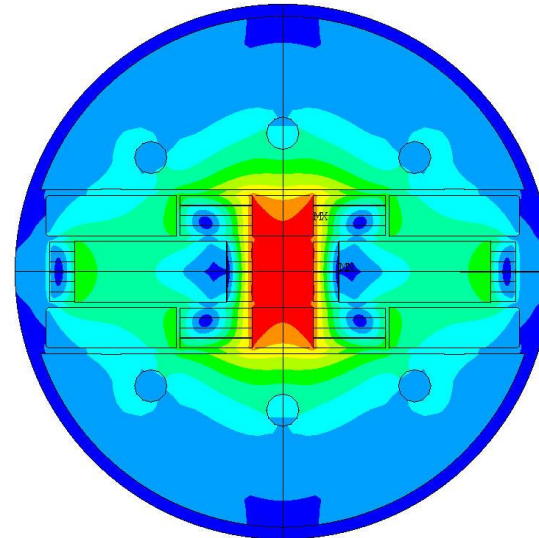
Magnetic 3D model



```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.013936
SMX =16.5466
1.8509
3.68786
5.52483
7.36179
9.19876
11.0357
12.8727
14.7096
16.5466
    
```

Magnetic 2D model



```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =5
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.01
SMX =16.55
0
1.83
3.67
5.5
7.33
9.17
11
12.83
14.67
16.5
    
```

EDIPO, magnetic 3D model

EDIPO, magnetic 2D model

Mechanical 3D FEA

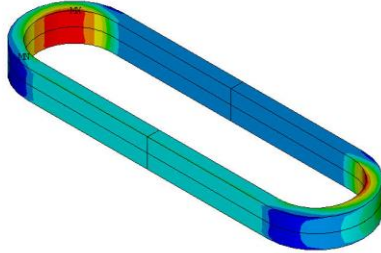
Stress in the ends of the vertical coils

(use of a reinforcing strip)

Equivalent Von Mises stress in the coils (reference)

Side coils

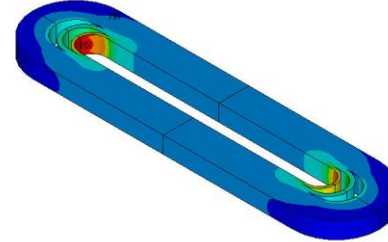
Cool-down



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =6
TIME=2
/EXPANDED
/SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002523
SMN =.197E+08
SMX =.530E+08
.197E+08
.234E+08
.271E+08
.308E+08
.345E+08
.382E+08
.419E+08
.456E+08
.493E+08
.530E+08
```

Vertical coils

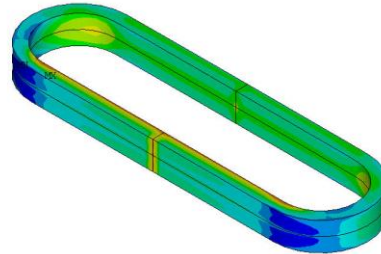
Cool-down



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =6
TIME=2
/EXPANDED
/SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003092
SMN =.715E+07
SMX =.760E+08
.715E+07
.148E+08
.225E+08
.301E+08
.378E+08
.454E+08
.531E+08
.607E+08
.684E+08
.760E+08
```

Cool-down (4.2 K)

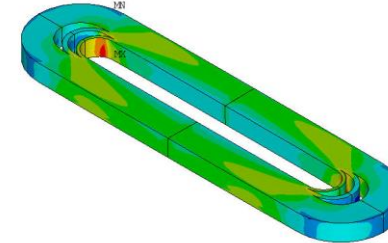
Nominal field



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
/SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =.758E+07
SMX =.895E+08
.758E+07
.167E+08
.258E+08
.349E+08
.440E+08
.531E+08
.622E+08
.713E+08
.804E+08
.895E+08
```

Cool-down (4.2 K)

Nominal field



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
/SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001918
SMN =.163E+08
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

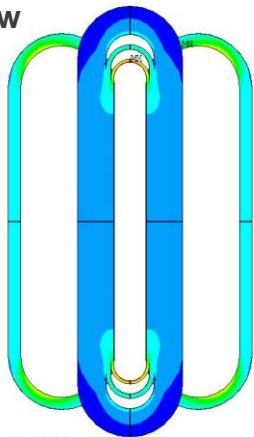
Nominal field

Nominal field

Equivalent Von Mises stress in the coils (reference)

Cool-down

Top view

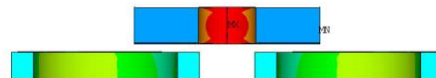


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =6
TIME=2
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003092
SMN =.715E+07
SMX =.760E+08
.715E+07
.148E+08
.225E+08
.301E+08
.378E+08
.454E+08
.531E+08
.607E+08
.684E+08
.760E+08
```

Cool-down (4.2 K)

Cool-down

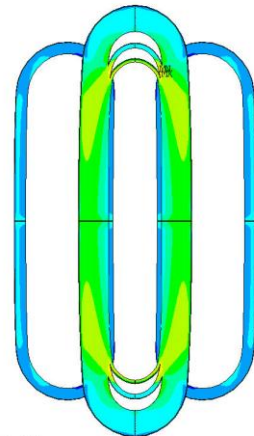
Front view



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =6
TIME=2
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003092
SMN =.715E+07
SMX =.760E+08
.715E+07
.148E+08
.225E+08
.301E+08
.378E+08
.454E+08
.531E+08
.607E+08
.684E+08
.760E+08
```

Cool-down (4.2 K)

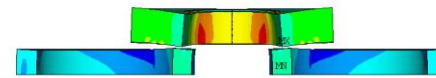
Nominal field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =.758E+07
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

Nominal field



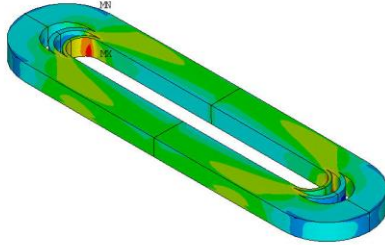
```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =.758E+07
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

Equivalent Von Mises stress (use of a 2 mm inner strip)

Nominal field

Vertical coils (ref)

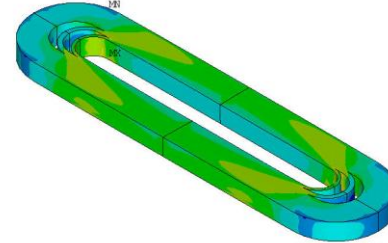


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001918
SMN =.163E+08
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

Nominal field

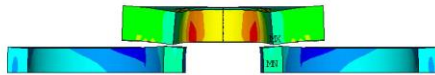
Vertical coils (inner strip)



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001891
SMN =.150E+08
SMX =.289E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

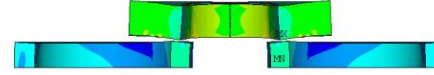
Nominal field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =.758E+07
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

Nominal field



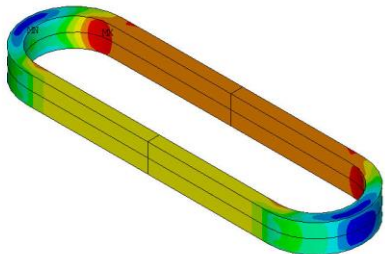
```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002239
SMN =.747E+07
SMX =.289E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

Strain along z in the coils

Side coils, nom. field

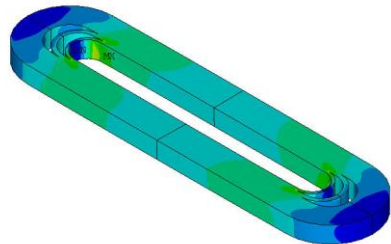
Reference



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =-.001472
SMX =.002293
-.001472
-.001053
-.635E-03
-.217E-03
.202E-03
.620E-03
.001038
.001456
.001875
.002293
```

Nominal field

Vert. coils, nom. field

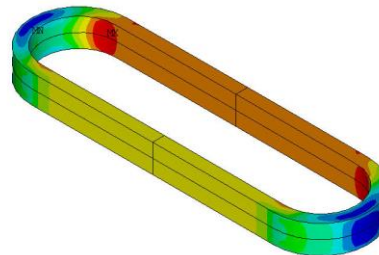


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001918
SMN =-.002504
SMX =.01358
-.002504
-.716E-03
.001071
.002858
.004645
.006432
.008219
.010006
.011793
.01358
```

Nominal field

Side coils, nom. field

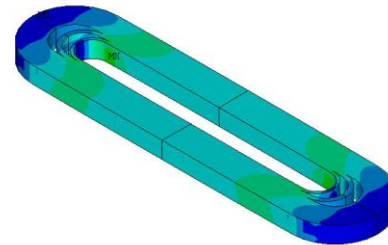
Inner strip



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002239
SMN =-.001469
SMX =.002305
-.001469
-.001049
-.630E-03
-.211E-03
.209E-03
.628E-03
.001047
.001466
.001886
.002305
```

Nominal field

Vert. coils, nom. field

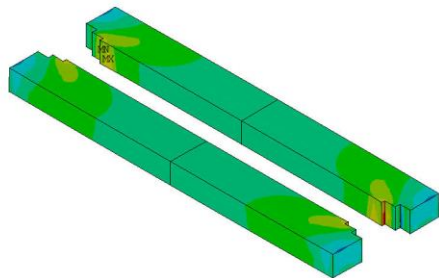


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001891
SMN =-.001894
SMX =.014031
-.001894
-.125E-03
.001644
.003414
.005183
.006953
.008722
.010492
.012261
.014031
```

Nominal field

Longitudinal strain in the vertical coils (reference)

ϵ_z (straight section)



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001891
SMN =-.001077
SMX =.008332
-.001077
-.316E-04
.001014
.002059
.003105
.00415
.005196
.006241
.007287
.008332
```

ϵ_θ (end 1)



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOY (AVG)
RSYS=24
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001419
SMN =.002944
SMX =.014031
.002944
.004176
.005408
.006639
.007871
.009103
.010335
.011567
.012799
.014031
```

Nominal field

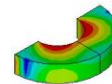
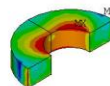
ϵ_θ (end 2)



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOY (AVG)
RSYS=25
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001124
SMN =.001121
SMX =.009066
.001121
.002004
.002886
.003769
.004652
.005535
.006418
.007301
.008183
.009066
```

Nominal field

ϵ_θ (end 3)



```
ANSYS 2022 R1.0z
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOY (AVG)
RSYS=26
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.00157
SMN =.312E-04
SMX =.003146
.312E-04
.377E-03
.723E-03
.001069
.001415
.001762
.002108
.002454
.0028
.003146
```

Nominal field

Nominal field

Mechanical 3D FEA

Mech prop of the winding pack

Sensitivity analysis

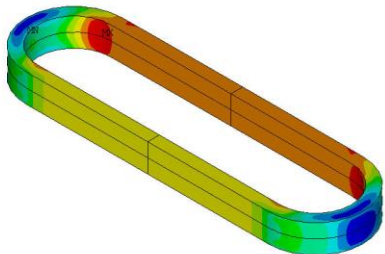
- Impregnated two-stage flat cable:
 - Assumption for EDIPO2: $E = 20$ GPa
- Impregnated Rutherford cable:
 - Assumption for FCC dipoles (and EDIPO2 in the past): $E = 25$ GPa
 - D. Schoerling
 - Model: $E = 20$ GPa
 - S. I. Bermudez et al., "Performance of a MQXF Nb3Sn Quadrupole Magnet Under Different Stress Level," doi: 10.1109/TASC.2022.3167369.
 - Measured: 32 to 37 GPa
 - O. Sacristan De Frutos et al., "Characterisation of the Mechanical Behaviour of Superconducting Cables Used in High Field Magnets From Room Temperature Down to 77K", <https://doi.org/10.18429/JACoW-IPAC2017-WEPVA112>, <http://jacow.org/ipac2017/papers/wepva112.pdf>, 2017.
 - Measured: 30 to 58 GPa
 - Vallone et. al., "A Review of the Mechanical Properties of Materials Used in Nb3Sn Magnets for Particle Accelerators," doi: 10.1109/TASC.2023.3248544.
 - Calculated:
 - D Arbelaez et al 2010 J. Phys.: Conf. Ser. 234 022002

E_s (GPa)	100 μm insulation			60 μm insulation		
	90	110	126	90	110	126
E_1 (GPa)	65.1	78.7	89.5	68.5	82.8	94.5
E_2 (GPa)	41.0	45.8	49.3	45.7	51.7	56.1
E_3 (GPa)	27.8	29.7	30.9	34.0	36.8	38.8
ν_{12}	0.34	0.34	0.34	0.34	0.34	0.34
ν_{23}	0.24	0.23	0.22	0.25	0.24	0.23
ν_{31}	0.14	0.12	0.11	0.16	0.14	0.13
μ_{12} (GPa)	19.4	22.0	23.8	20.5	23.5	25.7
μ_{23} (GPa)	13.7	14.9	15.6	15.2	16.8	17.8
μ_{31} (GPa)	14.8	16.1	17.0	16.8	18.8	20.2

Strain along z in the coils

E = 20 GPa

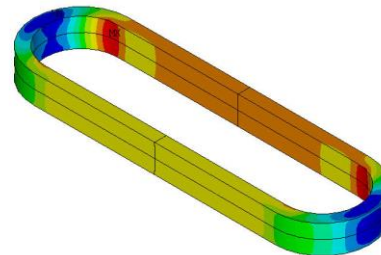
Side coils, nom. field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =-.001472
SMX =.002293
-.001472
-.001053
-.635E-03
-.217E-03
.202E-03
.620E-03
.001038
.001456
.001875
.002293
```

E = 50 GPa

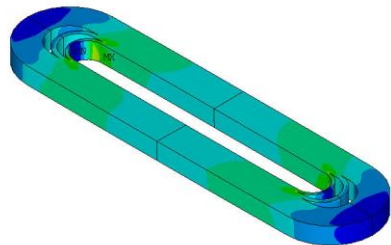
Side coils, nom. field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002271
SMN =-.921E-03
SMX =.002209
-.921E-03
-.573E-03
-.226E-03
.122E-03
.470E-03
.818E-03
.001166
.001513
.001861
.002209
```

Nominal field

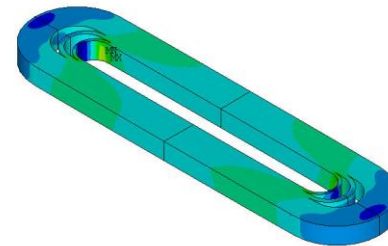
Vert. coils, nom. field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001918
SMN =-.002504
SMX =.01358
-.002504
-.716E-03
.001071
.002858
.004645
.006432
.008219
.010006
.011793
.01358
```

Nominal field

Vert. coils, nom. field



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
EPTOZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002415
SMN =-.001314
SMX =.008209
-.001314
-.256E-03
.802E-03
.00186
.002918
.003976
.005035
.006093
.007151
.008209
```

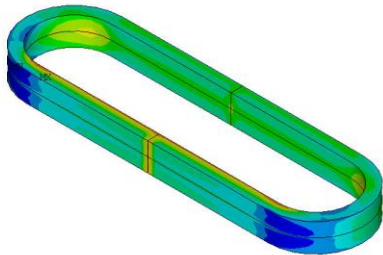
Nominal field

Nominal field

Equivalent Von Mises stress in the coils

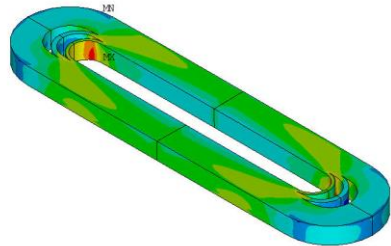
Side coils, nom. field

E = 20 GPa



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002237
SMN =.758E+07
SMX =.895E+08
.758E+07
.167E+08
.258E+08
.349E+08
.440E+08
.531E+08
.622E+08
.713E+08
.804E+08
.895E+08
```

Nominal field

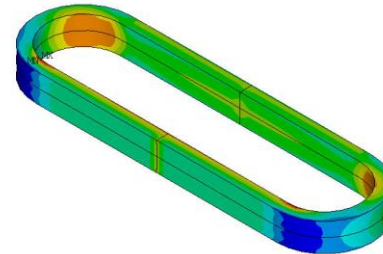


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001918
SMN =.163E+08
SMX =.276E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

Nominal field

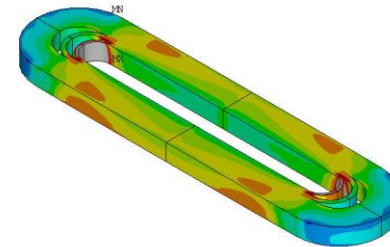
Side coils, nom. field

E = 50 GPa



```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002271
SMN =.333E+08
SMX =.144E+09
.333E+08
.456E+08
.579E+08
.702E+08
.824E+08
.947E+08
.107E+09
.119E+09
.132E+09
.144E+09
```

Nominal field

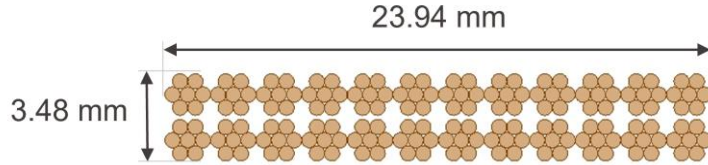


```
ANSYS 2022 R1.0;
Build 22.1
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =6
TIME=3
/EXPANDED
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002415
SMN =.137E+08
SMX =.425E+09
0
.222E+08
.444E+08
.667E+08
.889E+08
.111E+09
.133E+09
.156E+09
.178E+09
.200E+09
```

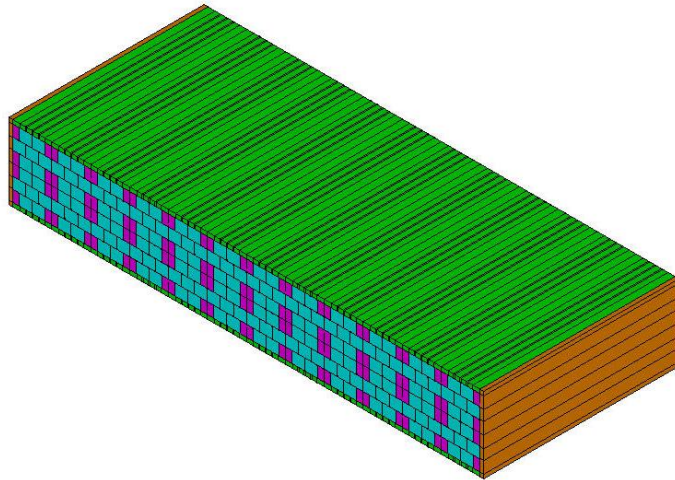
Nominal field

Vert. coils, nom. field

Homogeneized mechanical properties. Model

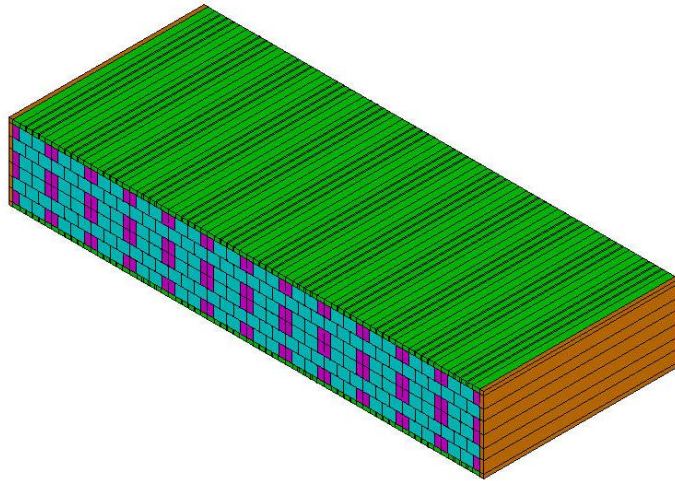
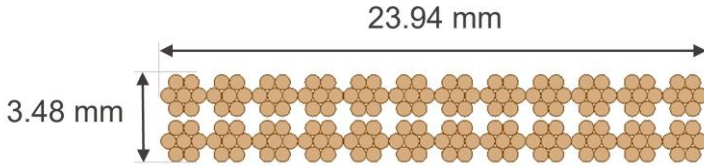


- Same material cross-sections:
 - Superconductor
 - Void fraction (~20%)
 - Insulation thickness: 0.2 mm
- Bonded contacts everywhere
- Assumed material properties at 4.2 K:



	E (GPa)	ν (-)	α $10^{-6}/K$
Nb ₃ Sn	125	0.37	7
Cu	118	0.36	17
Epoxy resin	2.4	0.4	50
G10	E1=12 GPa E2=20 GPa E3=20 GPa	$\nu_{12}=0.33$ $\nu_{23}=0.17$ $\nu_{13}=0.33$	$\alpha_1=24.7$ $\alpha_2=6.9$ $\alpha_3=6.9$

Homogeneized mechanical properties. Model



- Results:

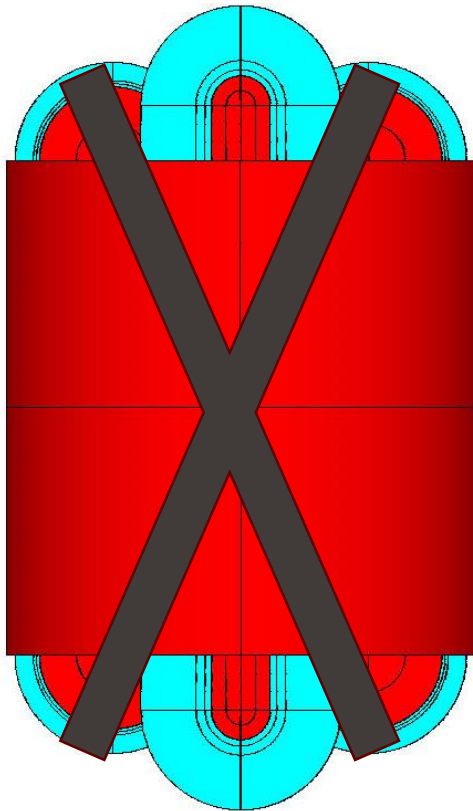
Prop	Value	Unit
E_x	52.7	GPa
E_y	50.6	GPa
E_z	86.5	GPa
ν_{xy}	0.22	-
ν_{yz}	0.22	-
ν_{xz}	0.22	-
α_x	19.2	$10^{-6}/K$
α_y	20.8	$10^{-6}/K$
α_z	18.9	$10^{-6}/K$

Magnetic 3D FEA

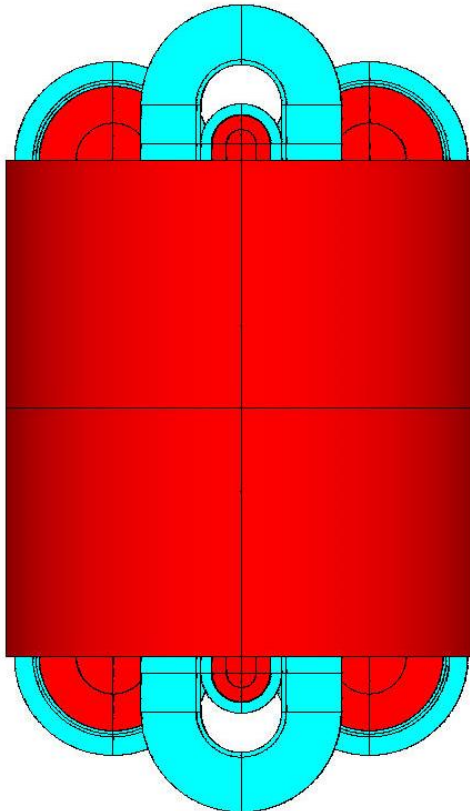
Use of end spacers

Use of end spacers

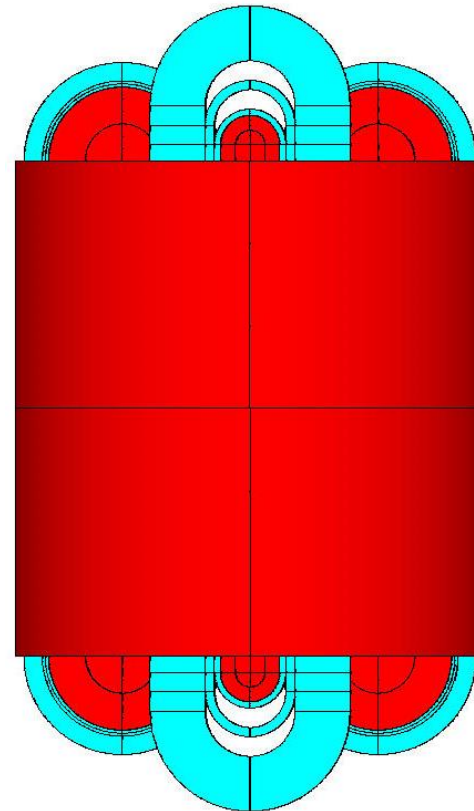
No end spacers
(B_{\max} in the ends)



One end spacer in vertical coils



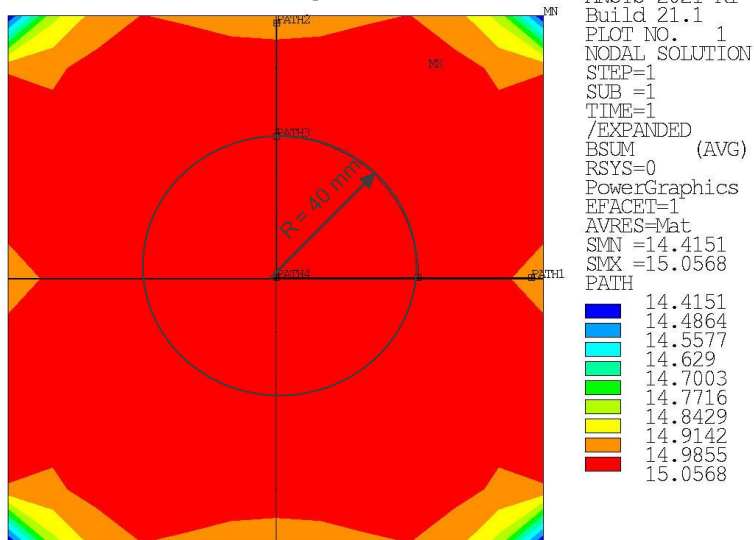
Two end spacers in vertical coils
(Ref)



Field in the aperture

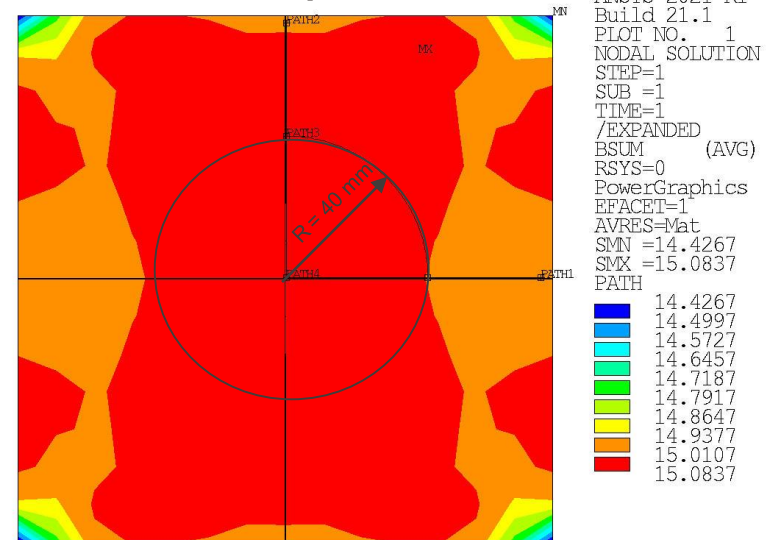
- B field plotted along 4 paths:
 - Path 1 along x axis of the aperture
 - Path 2 along y axis of the aperture
 - Path 3 around a circumference of $R=40$ mm
 - Path 4 along z axis (longitudinal axis of the aperture)

One end spacer



EDIPO, magnetic 3D model

Two end spacers

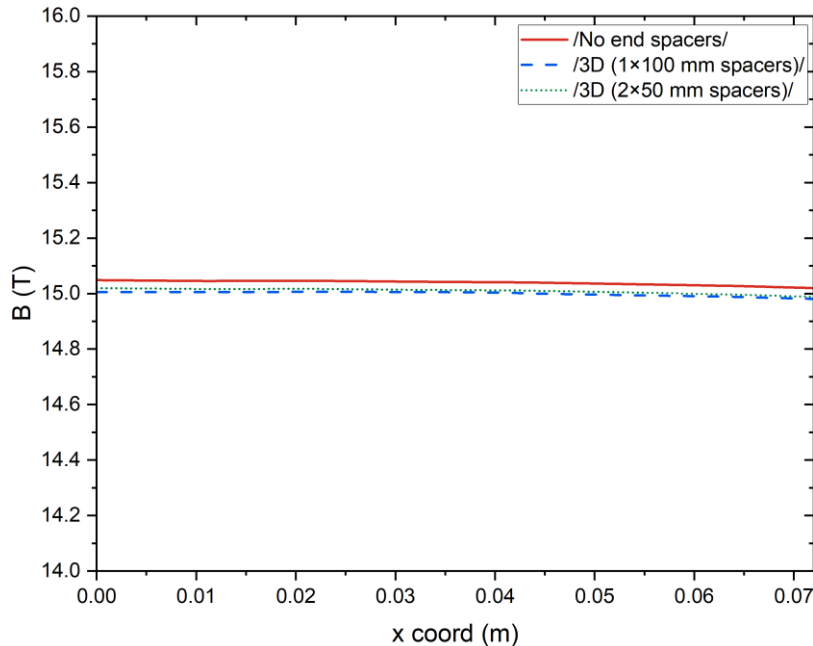


EDIPO, magnetic 3D model

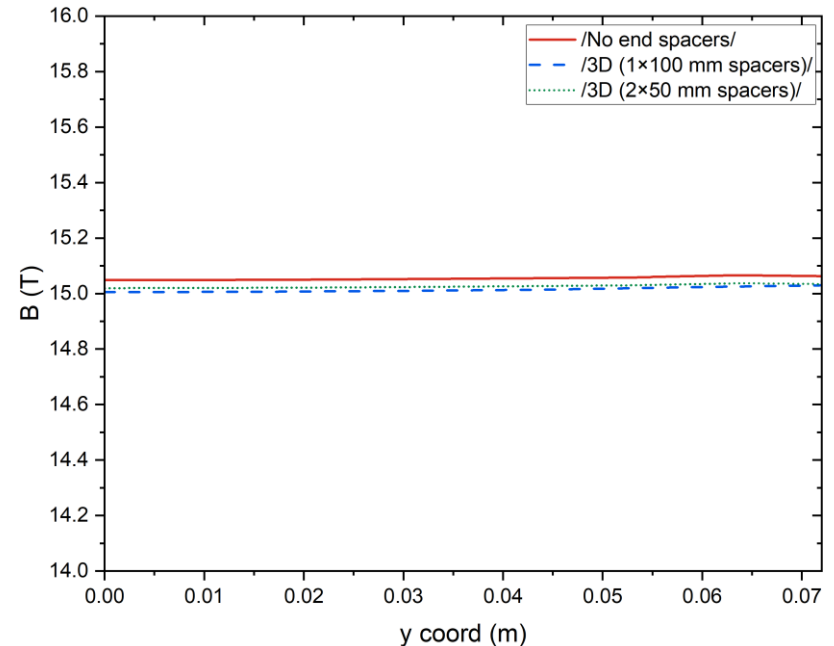
Field along paths 1 and 2

- The field uniformity along the x and y axes is identical in all cases
- In the cases with end spacers we lose ~ 0.02 T in the center of the aperture

Path 1 (x axis of the aperture)



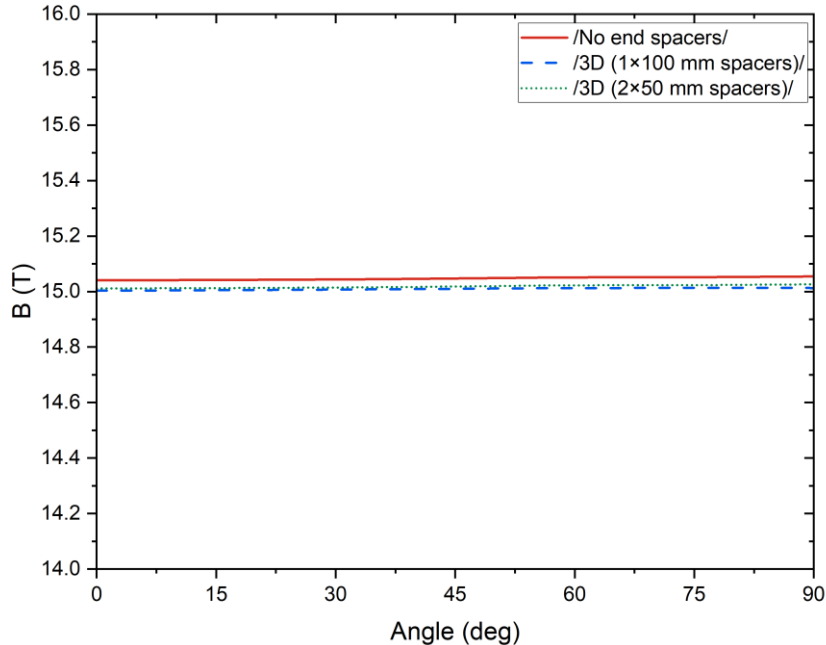
Path 2 (y axis of the aperture)



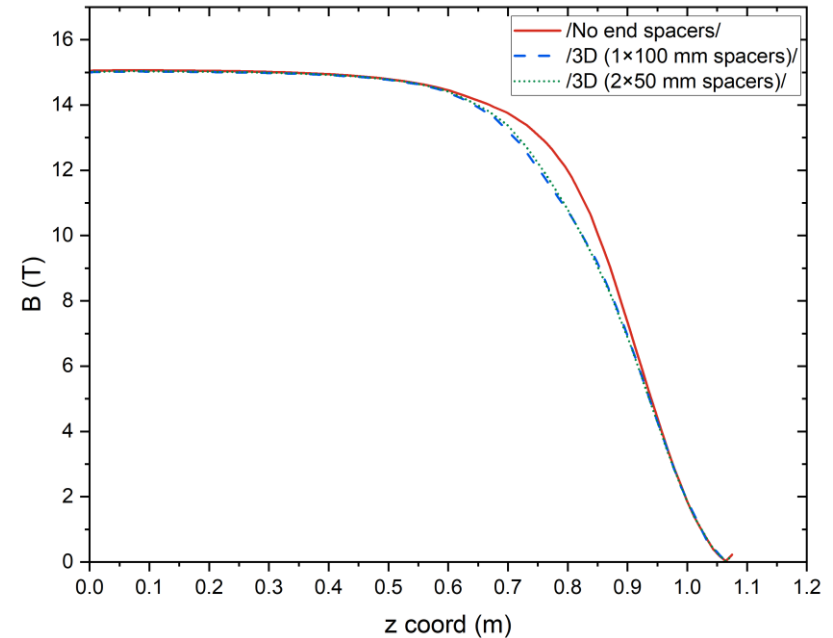
Field along paths 3 and 4

- The uniform field length along the longitudinal axis of the aperture (z axis) is not affected for $z < \pm 0.5$ m
- Almost identical profiles if one or two spacers are used

Path 3 (around circumference of $R=40$ mm)

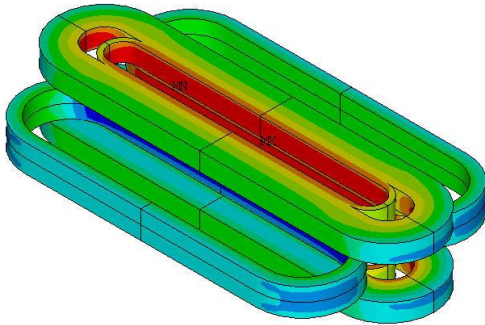


Path 4 (z axis of the aperture)



- In both cases, the peak field is in the straight section of the side coils:
 - One end spacer in the vertical coils: $B_{\max} = 15.03$ T, $B_{\text{bore}} = 15.005$ T
 - Two end spacers in the vertical coils: $B_{\max} = 15.05$ T, $B_{\text{bore}} = 15.02$ T

One end spacer

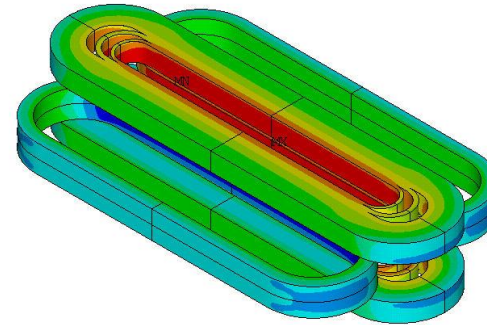


```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.004685
SMX =15.0325
.004685
1.67445
3.3442
5.01396
6.68372
8.35348
10.0232
11.693
13.3628
15.0325

```

Two end spacers



```

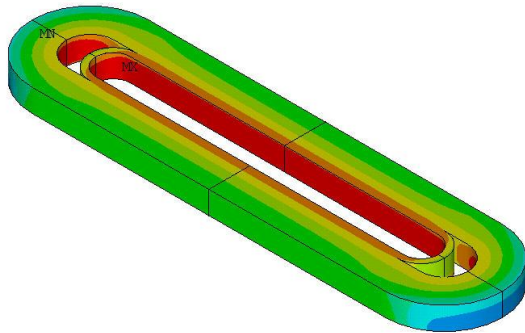
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.005986
SMX =15.0492
.005986
1.67745
3.34892
5.02038
6.69185
8.36331
10.0348
11.7062
13.3777
15.0492

```

B field in the vertical coils

- In the vertical coils, the presence of a second spacer shifts the peak field to the straight section:
 - One end spacer in the vertical coils: $B_{\max, \text{vert}} = 14.56 \text{ T}$
 - Two end spacers in the vertical coils: $B_{\max, \text{vert}} = 14.44 \text{ T}$

One end spacer

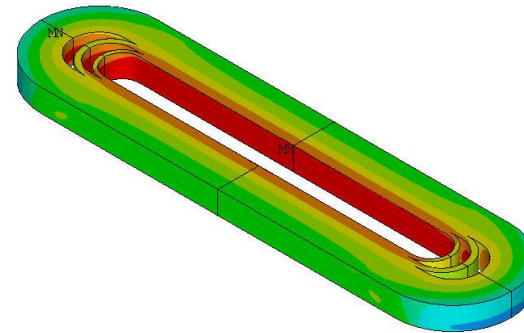


```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.524915
SMX =14.5652
.524915
2.08494
3.64497
5.205
6.76503
8.32506
9.88509
11.4451
13.0051
14.5652

```

Two end spacers



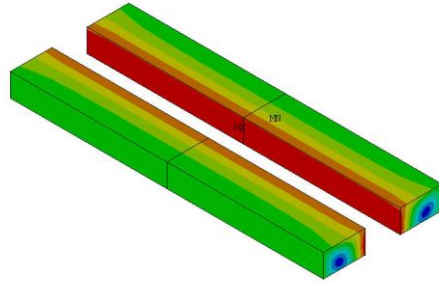
```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.144547
SMX =14.4438
.144547
1.73335
3.32215
4.91095
6.49975
8.08855
9.67735
11.2662
12.855
14.4438

```

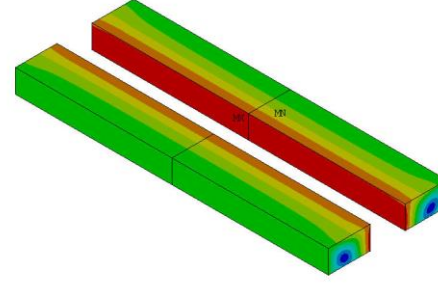
B field in the vertical coils: straight section vs ends

One end spacer, vertical coil, straight



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.684837
SMX =14.4411
.684837
2.21331
3.74178
5.27025
6.79872
8.32719
9.85566
11.3841
12.9126
14.4411
```

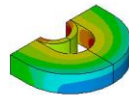
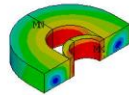
Two end spacers, vertical coil, straight



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.614354
SMX =14.4438
.614354
2.15095
3.68755
5.22415
6.76075
8.29735
9.83395
11.3706
12.9072
14.4438
```

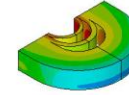
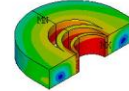
EDIPO, magnetic 3D model

One end spacer, vertical coil, ends



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.524915
SMX =14.5652
.524915
2.08494
3.64497
5.205
6.76503
8.32506
9.88509
11.4451
13.0051
14.5652
```

Two end spacers, vertical coil, ends



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.144547
SMX =14.4
.144547
1.72849
3.31243
4.89637
6.48031
8.06425
9.64819
11.2321
12.8161
14.4
```

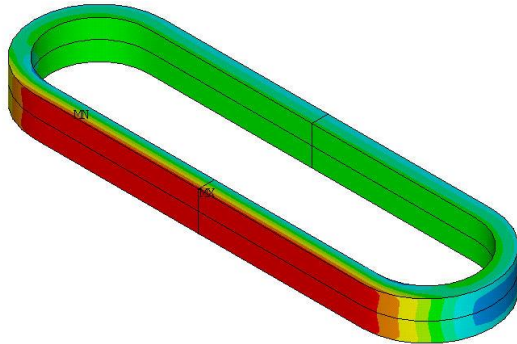
EDIPO, magnetic 3D model

EDIPO, magnetic 3D model

B field in the side coils

- In the side coils, the situation remains largely unchanged whether end spacers are used in the vertical coils or not:
 - One end spacer in the vertical coils: $B_{\max, \text{side}} = 15.03 \text{ T}$, $B_{\text{bore}} = 15.005 \text{ T}$
 - With end spacers in the vertical coils: $B_{\max, \text{side}} = 15.05 \text{ T}$, $B_{\text{bore}} = 15.02 \text{ T}$

One end spacer*



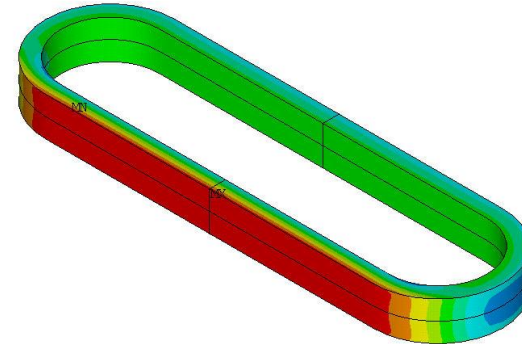
```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.004685
SMX =15.0325

```

15.0325
13.3628
11.693
10.0232
8.35348
6.68372
5.01396
3.3442
1.67445
.004685

Two end spacers*



```

ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.005986
SMX =15.0492

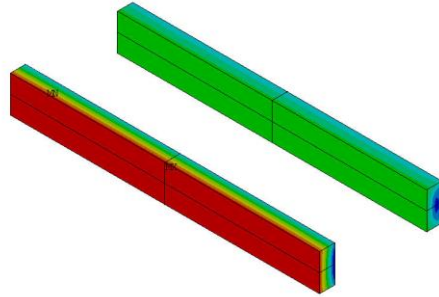
```

15.0492
13.3777
11.7062
10.0348
8.36331
6.69185
5.02038
3.34892
1.67745
.005986

*End spacers only in the vertical coils

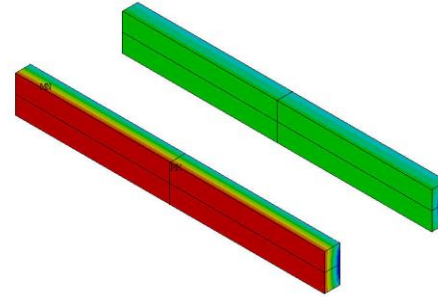
B field in the side coils: straight section vs ends

One end spacer*, side coil, straight



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.004685
SMX =15.0325
1.67445
3.3442
5.01396
6.68372
8.35348
10.0232
11.693
13.3628
15.0325
```

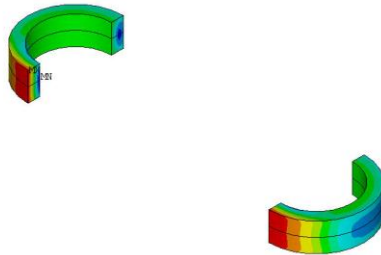
Two end spacers*, side coil, straight



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.005986
SMX =15.0492
1.67745
3.34892
5.02038
6.69185
8.36331
10.0348
11.7062
13.3777
15.0492
```

EDIPO, magnetic 3D model

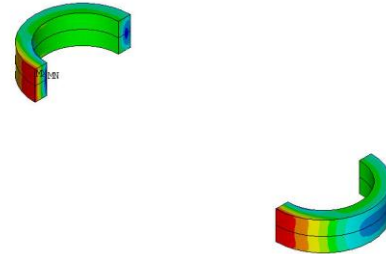
One end spacer*, side coil, ends



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.04826
SMX =14.2495
1.62617
3.20409
4.782
6.35992
7.93783
9.51575
11.0937
12.6716
14.2495
```

EDIPO, magnetic 3D model

Two end spacers*, side coil, ends



```
ANSYS 2021 R1
Build 21.1
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.021614
SMX =14.285
1.60644
3.19126
4.77608
6.3609
7.94573
9.53055
11.1154
12.7002
14.285
```

EDIPO, magnetic 3D model

*End spacers only in the vertical coils