EPFL

EDIPO 2
Staggered racetracks
Mechanical 3D FEA

X. Sarasola

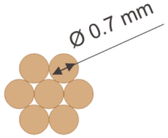
October 17th, 2024

SWISS
PLASMA
CENTER

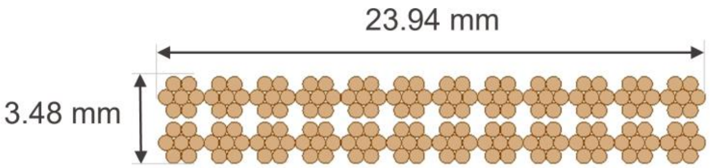
Cable design

- Bruker strand:
  - $j_{c,nc}$ = 2600 A/mm^2 at 12 T and 4.2 K
  - Cu:nCu = 1.0

- Same cable used for all coils
  - First stage:



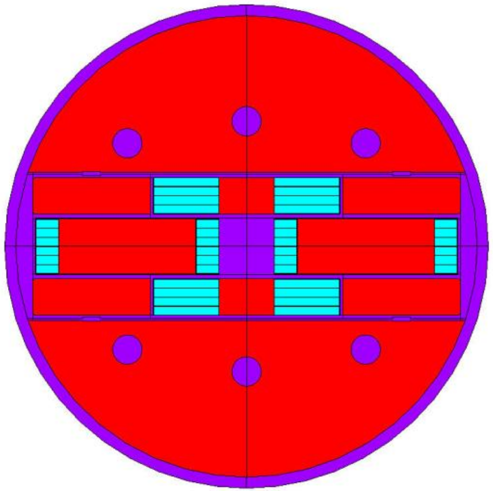
  - Second stage: 24×(6+1), 0.7 mm



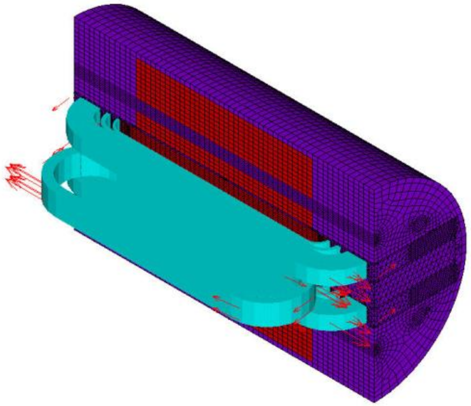
  - Assumed insulation thickness: 0.2 mm

Magnet design

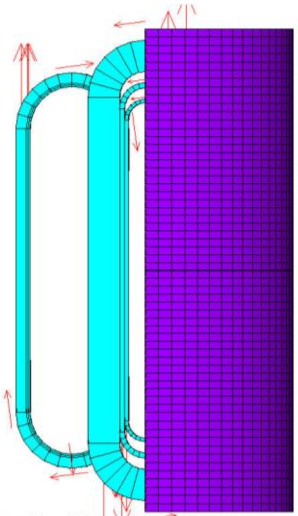
- 144×144 mm^2 aperture
- Two sets of flat racetrack coils:
  1. Side coils: one pair of coils, each made of 6 pancakes: 16 turns/pancake
  2. Vertical coils: one pair of coils, each made of 4 pancakes: 46 turns/pancake
- Iron parts in red: iron yoke limited to the straight section of the coils
- 50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



EDIPO, magnetic 2D model



EDIPO, magnetic 3D model

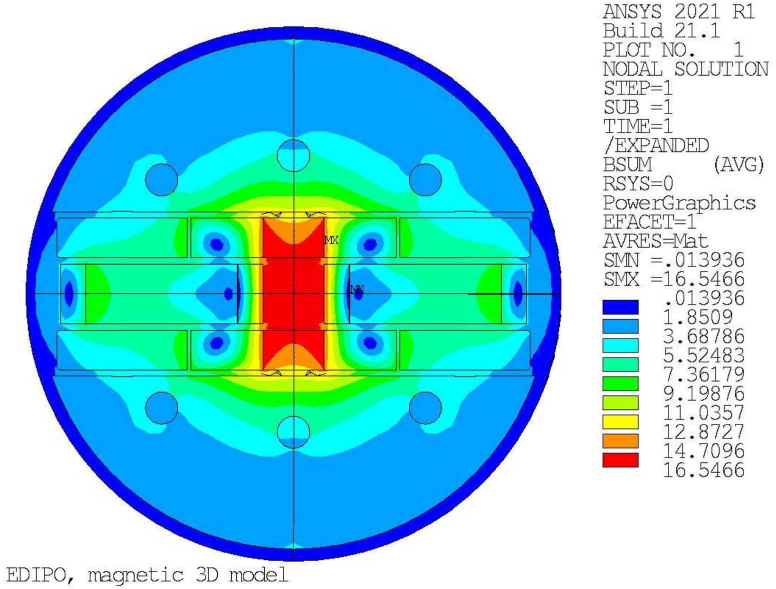


EDIPO, magnetic 3D model

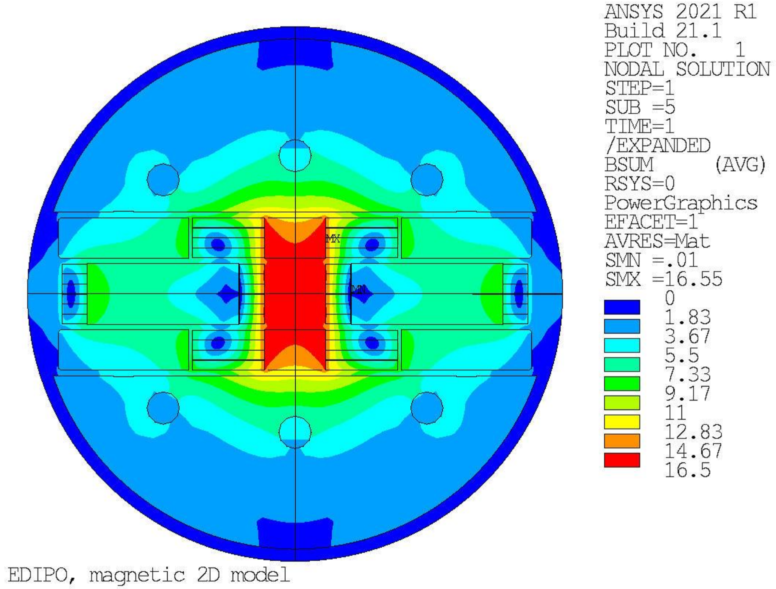
Comparison 3D vs 2D

	3D	2D
I_{op} (85%×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



Magnetic 2D model



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Mechanical 3D FEA
Stress in the ends of the vertical coils
(use of a reinforcing strip)

Equivalent Von Mises stress in the coils (reference)

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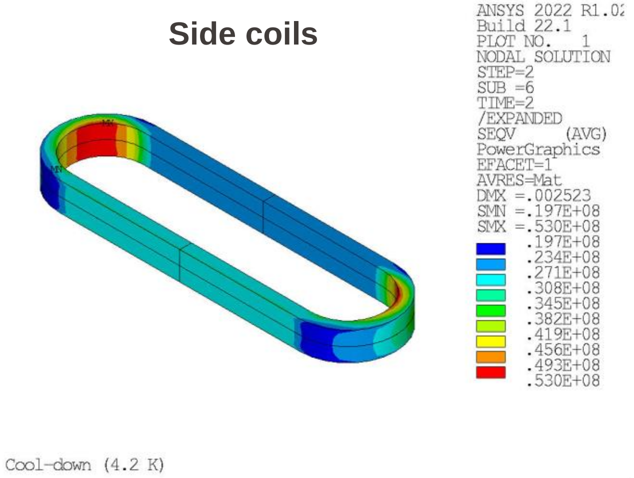
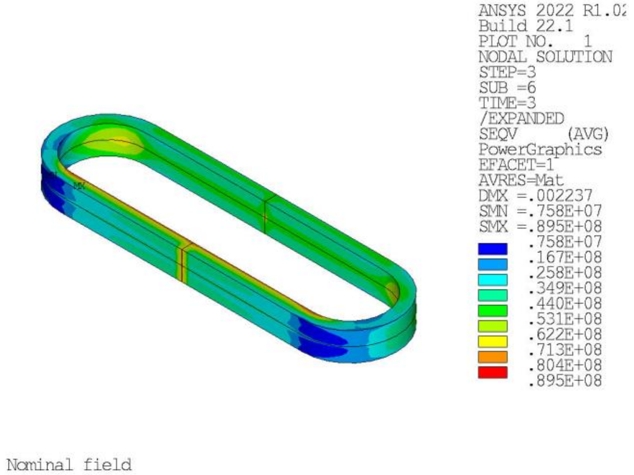
Side coils

Cool-down

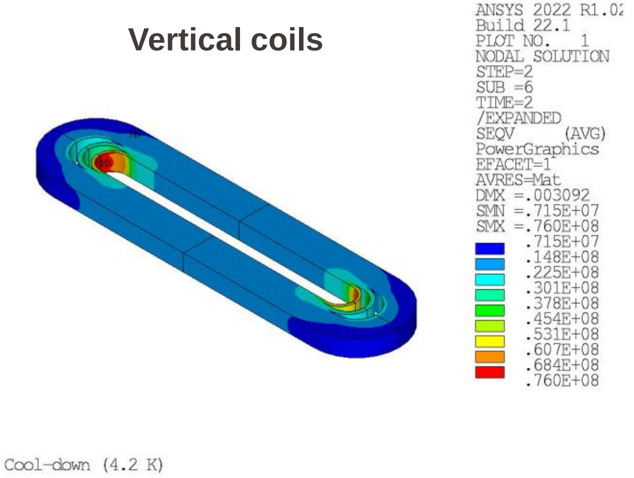


Nominal field

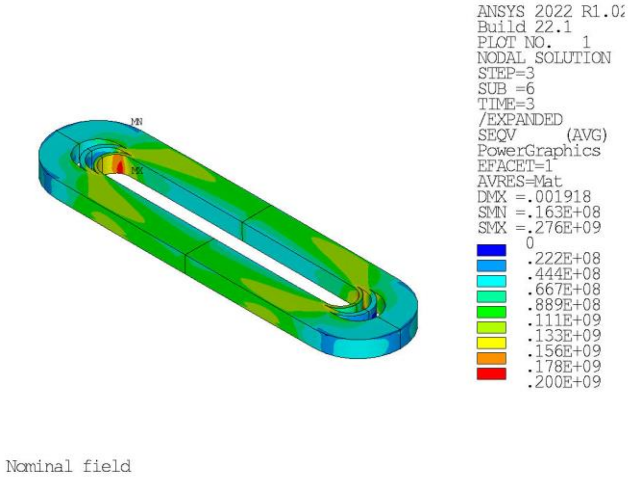


Vertical coils

Cool-down



Nominal field

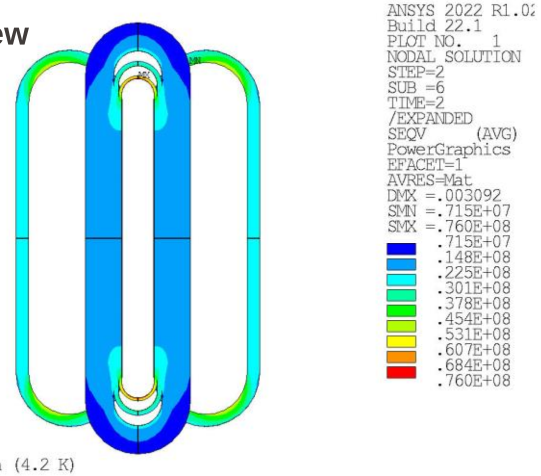


Equivalent Von Mises stress in the coils (reference)

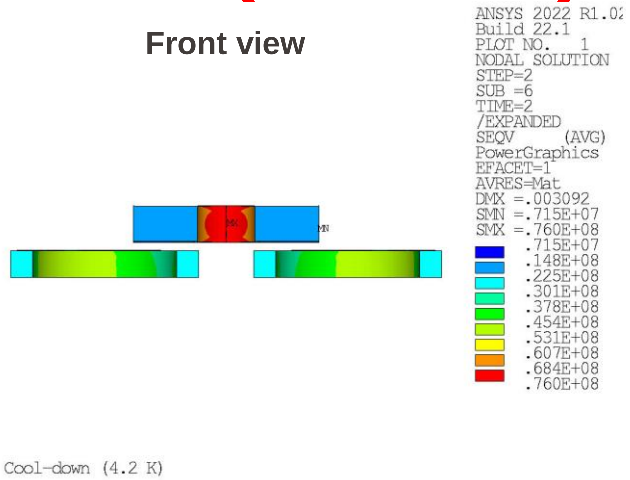
Top view

Front view

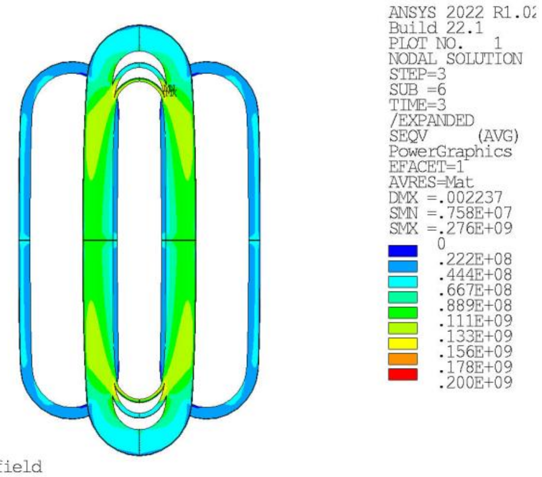
Cool-down



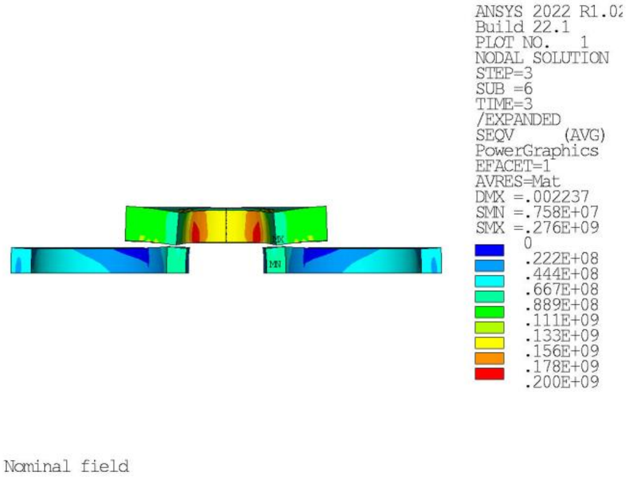
Cool-down



Nominal field



Nominal field



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

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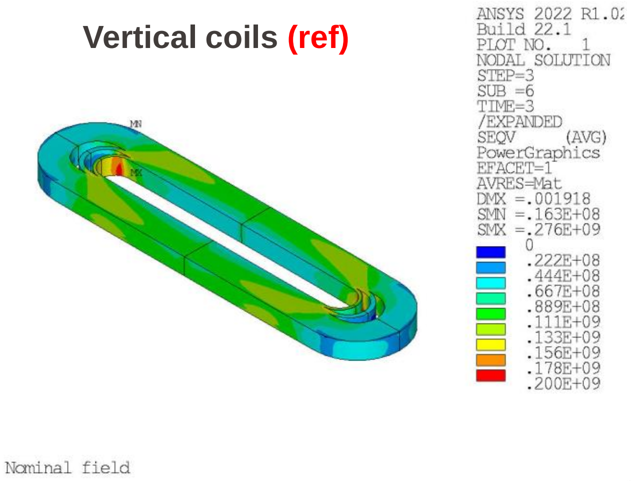
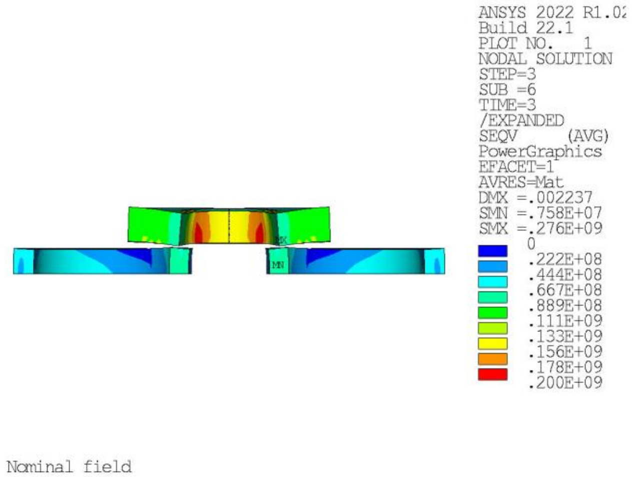
Vertical coils (ref)

Nominal field

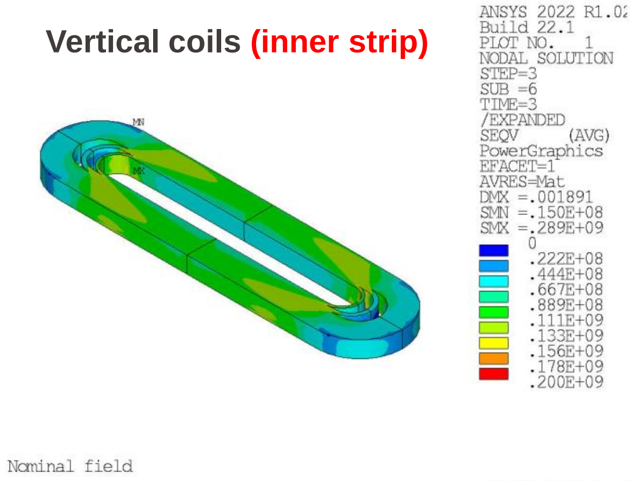


Nominal field

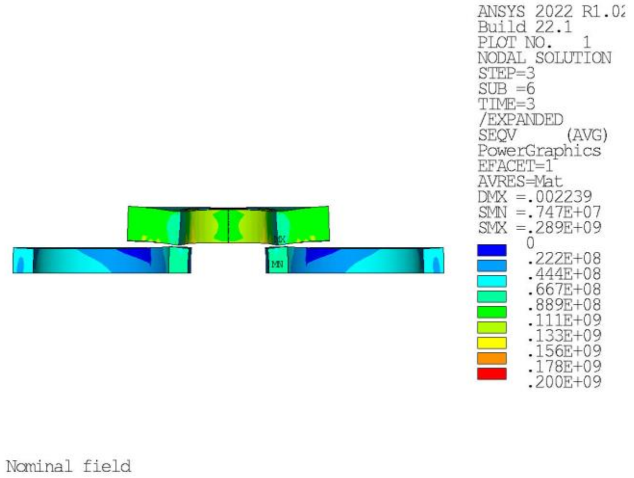


Vertical coils (inner strip)

Nominal field



Nominal field

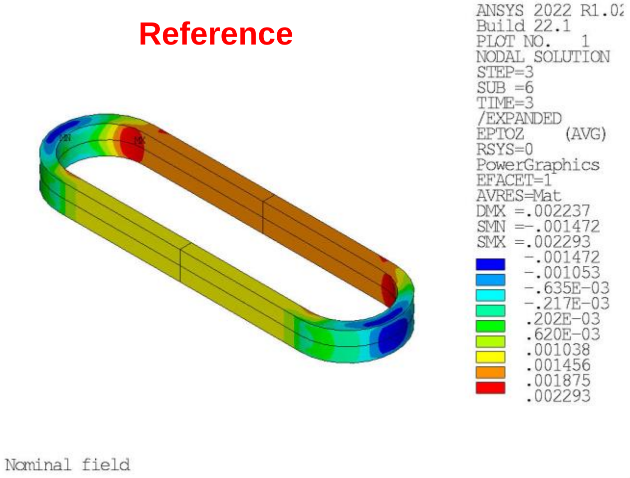


Strain along z in the coils

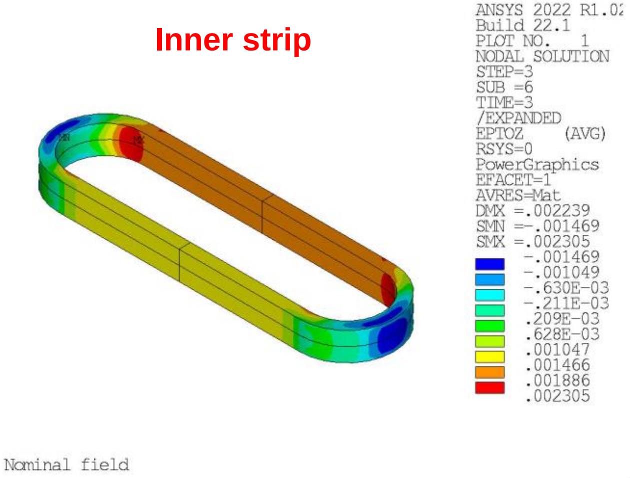
Reference

Inner strip

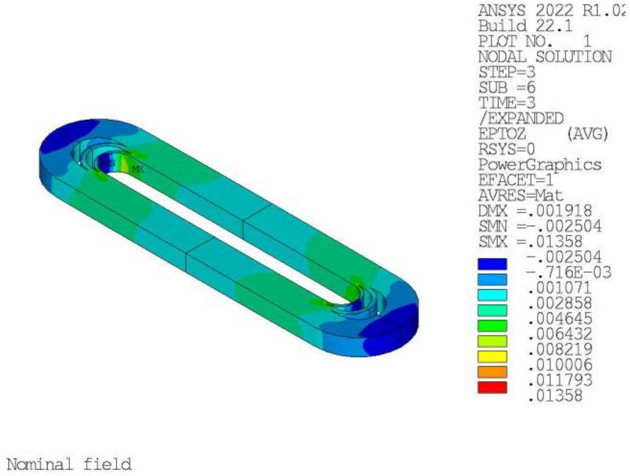
Side coils, nom. field



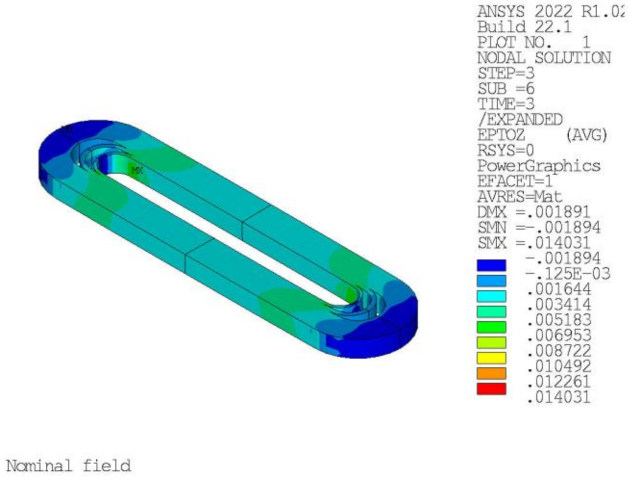
Side coils, nom. field



Vert. coils, nom. field

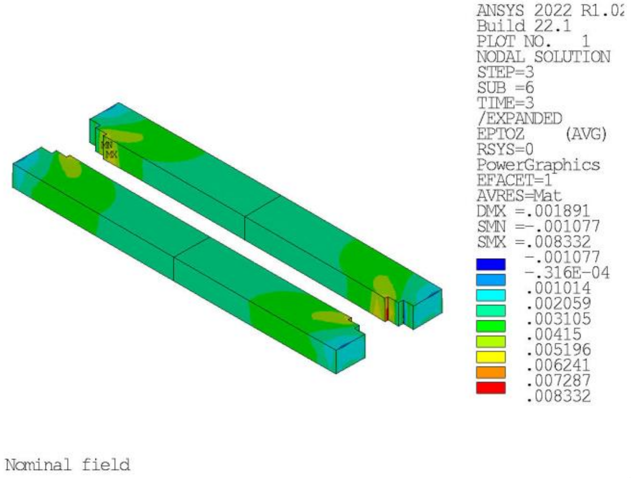


Vert. coils, nom. field

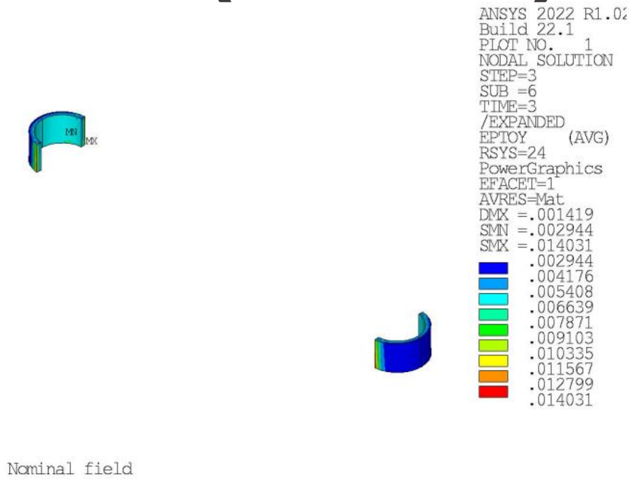


Longitudinal strain in the vertical coils (reference)

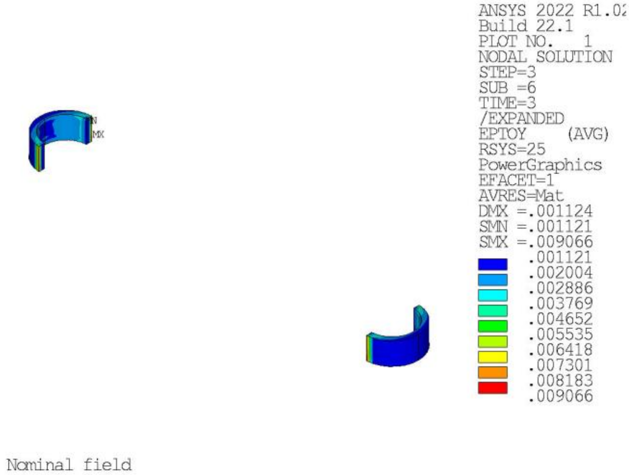
ε_z (straight section)



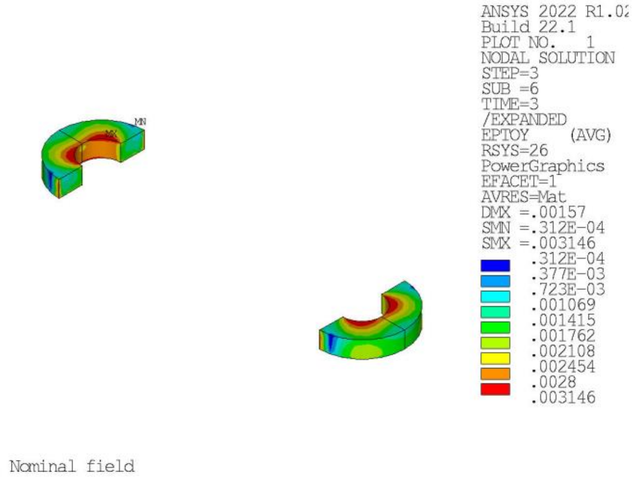
ε_θ (end 1)



ε_θ (end 2)



ε_θ (end 3)



Mechanical 3D FEA
Mech prop of the winding pack
Sensitivity analysis

Young's modulus

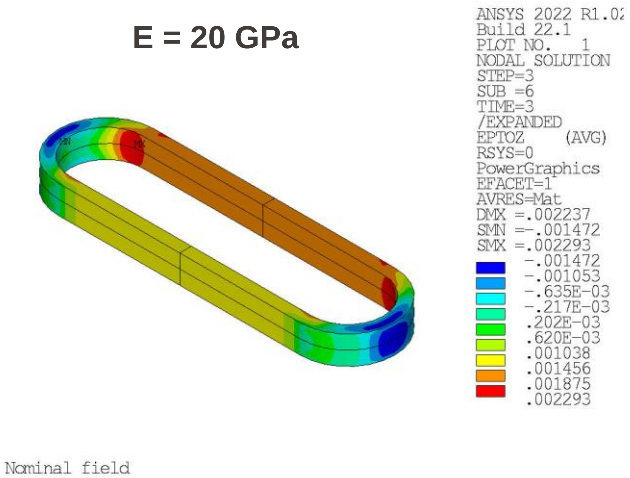
- Impregnated two-stage flat cable:
  - Assumption for EDIPO2: E = 20 GPa
- Impregnated Rutherford cable:
  - Assumption for FCC dipoles (and EDIPO2 in the past): E = 25 GPa
    - D. Schoerling
  - Model: E = 20 GPa
    - S. I. Bermudez et al., "Performance of a MQXF Nb3Sn Quadrupole Magnet Under Different 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

	100 μm insulation			60 μm insulation		
E_s (GPa)	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

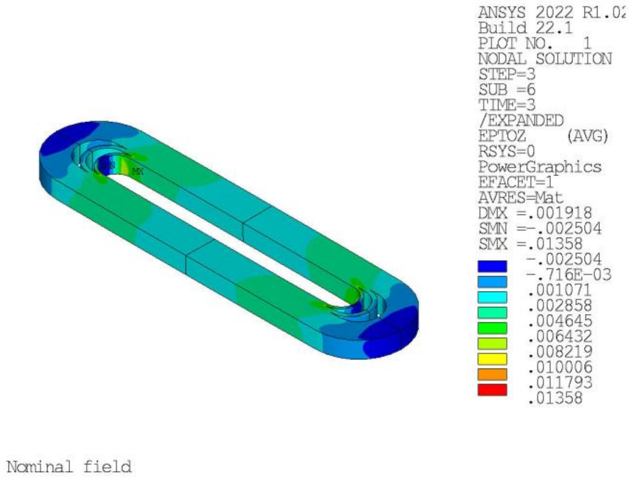
Strain along z in the coils

E = 20 GPa

Side coils, nom. field

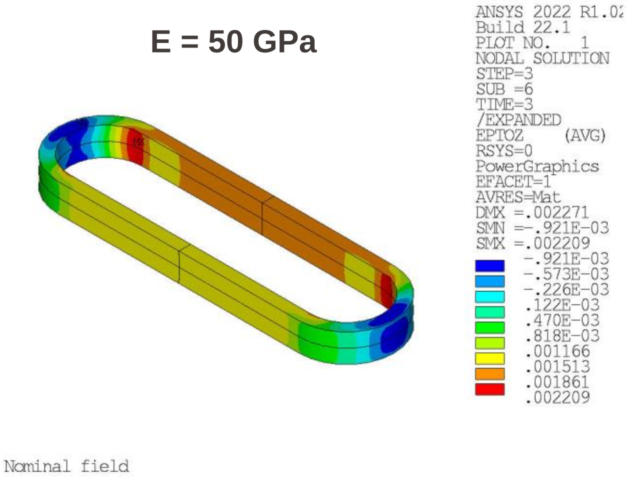


Vert. coils, nom. field

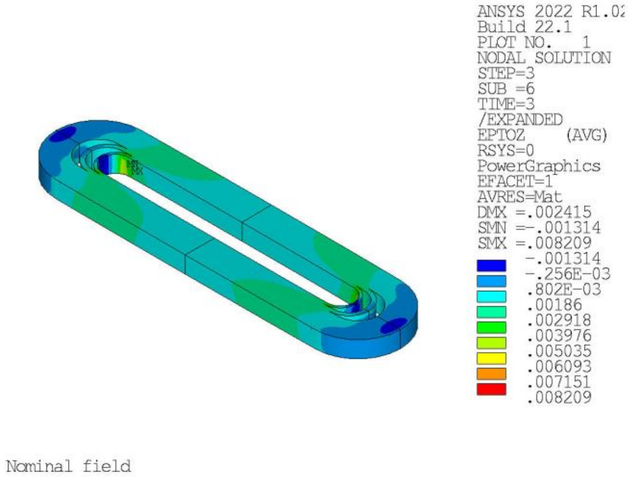


E = 50 GPa

Side coils, nom. field



Vert. coils, nom. field

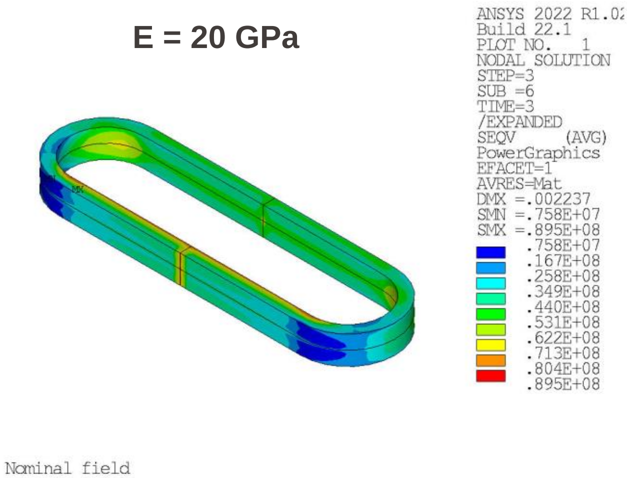


Equivalent Von Mises stress in the coils

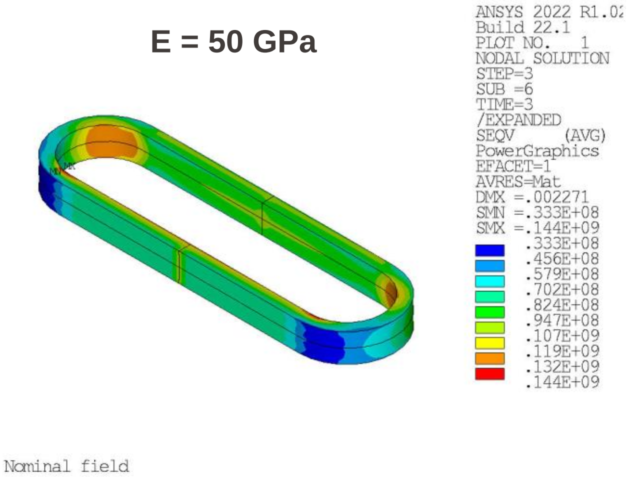
E = 20 GPa

E = 50 GPa

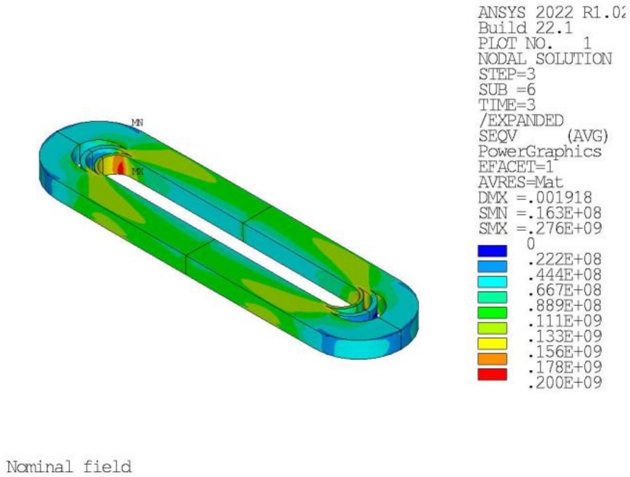
Side coils, nom. field



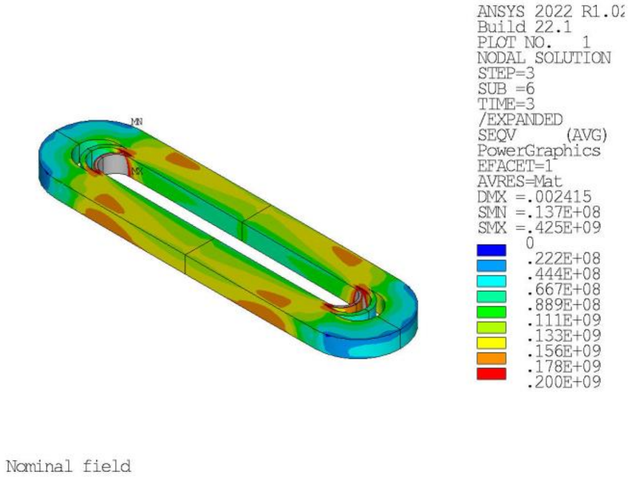
Side coils, nom. field



Vert. coils, nom. field



Vert. coils, nom. field



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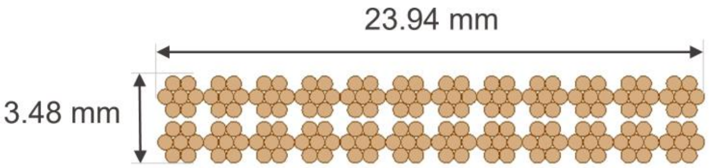
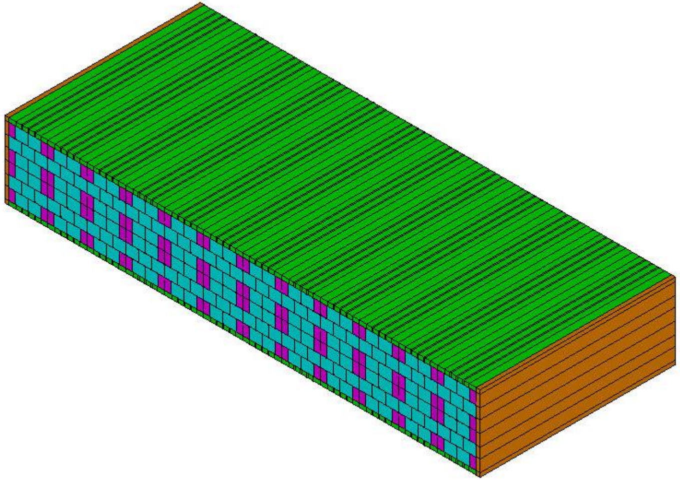
Homogeneized mechanical properties. Model

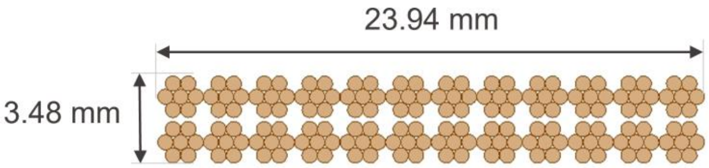


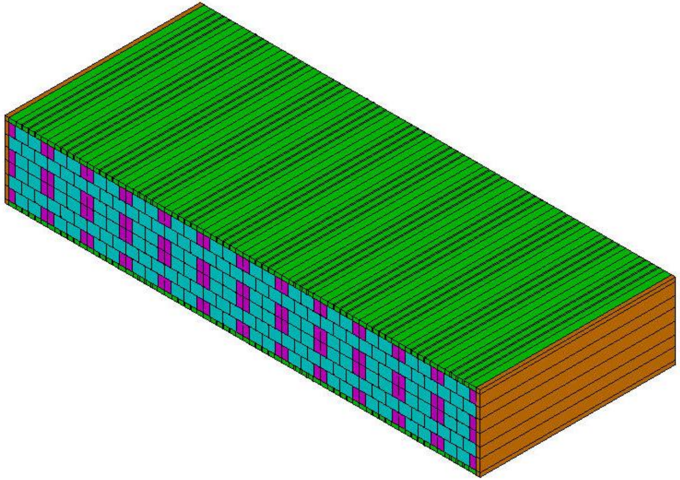


- Same material cross-sections:
  - Superconductor
  - Void fraction (~20%)
  - Insulation thickness: 0.2 mm
- Bonded contacts everywhere
- Assumed material properties at 4.2 K:

	E (GPa)	ν (-)	α 10^{-6}/K
Nb_3Sn	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	ν12=0.33 ν23=0.17 ν13=0.33	α1=24.7 α2=6.9 α3=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

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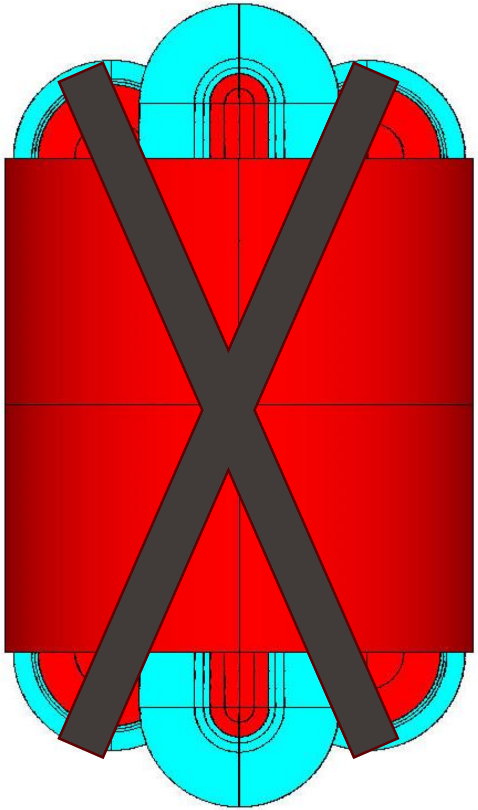
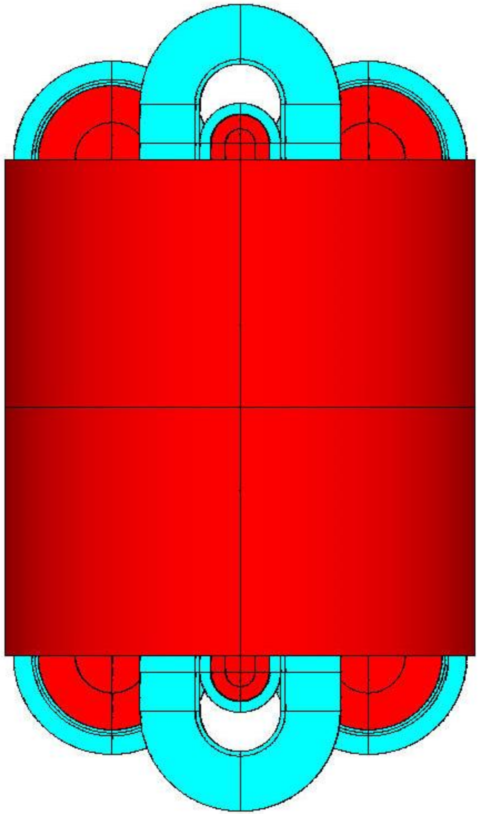
Magnetic 3D FEA
Use of end spacers

Use of end spacers

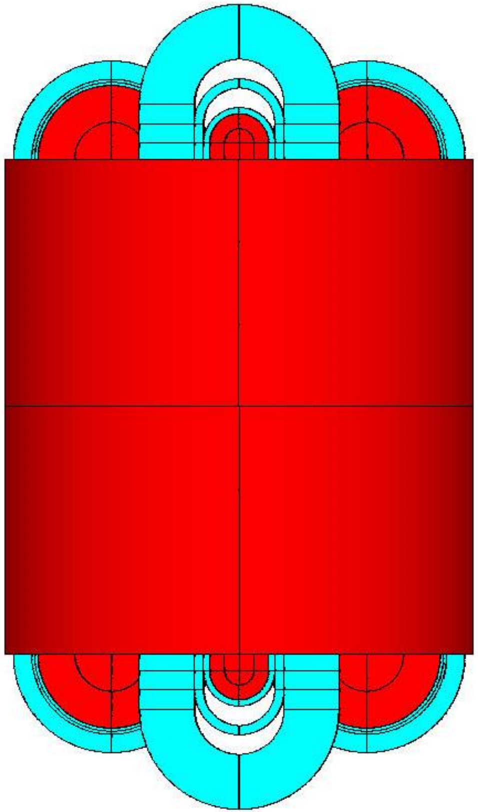
No end spacers
(B_{max} in the ends)



One end spacer in vertical coils



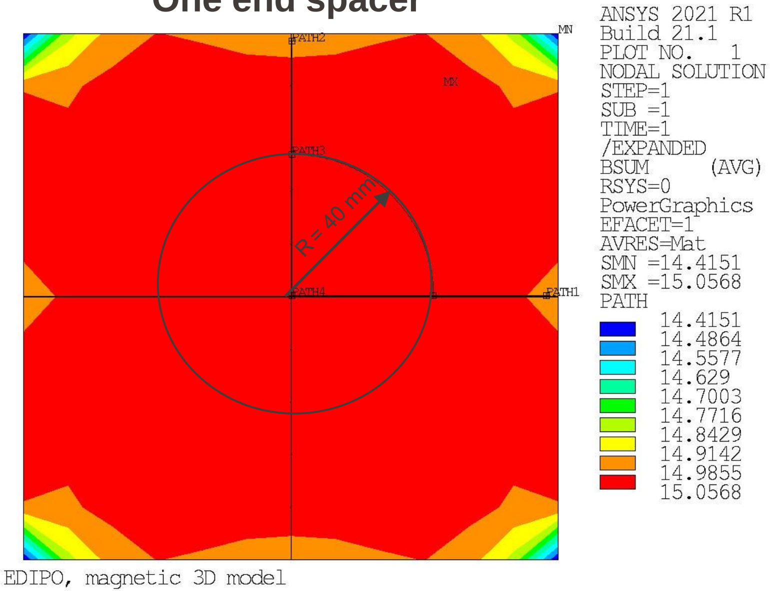
Two end spacers in vertical coils
(Ref)



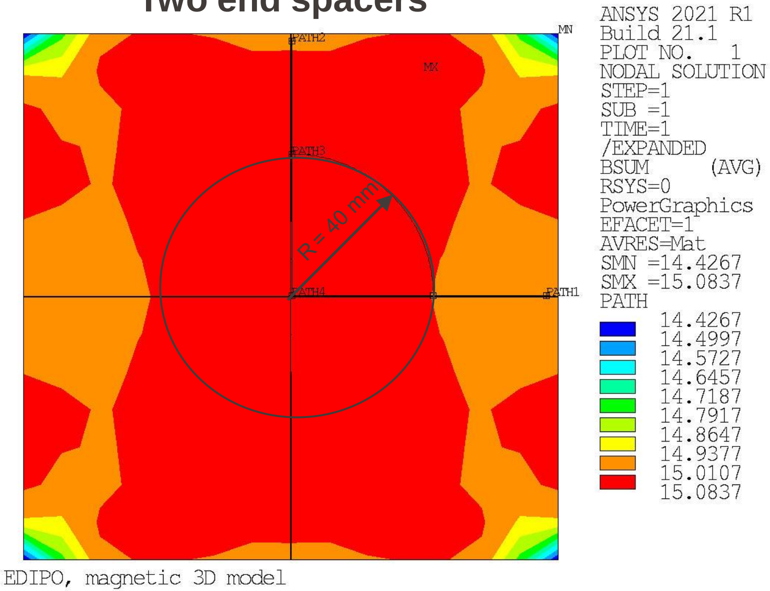
Field in the aperture

- 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



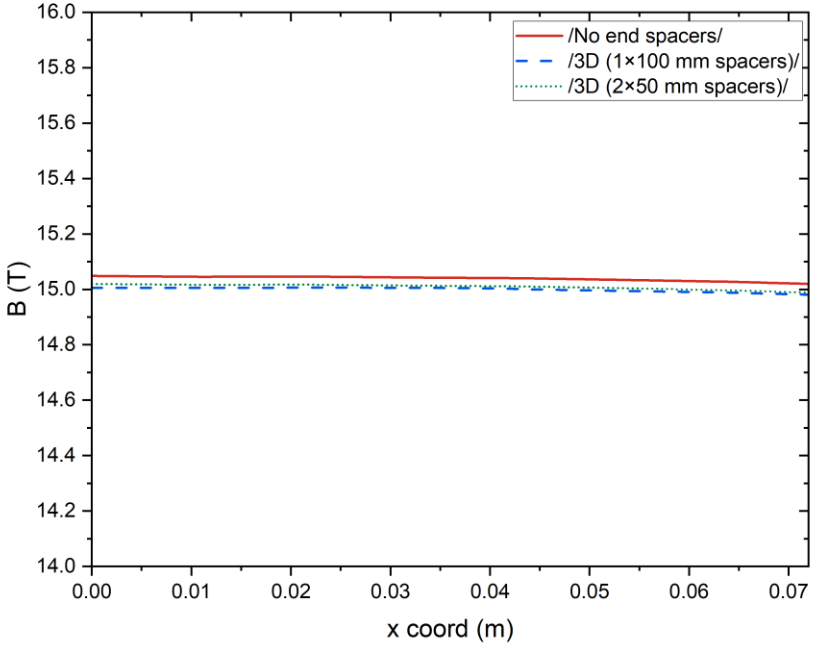
Two end spacers



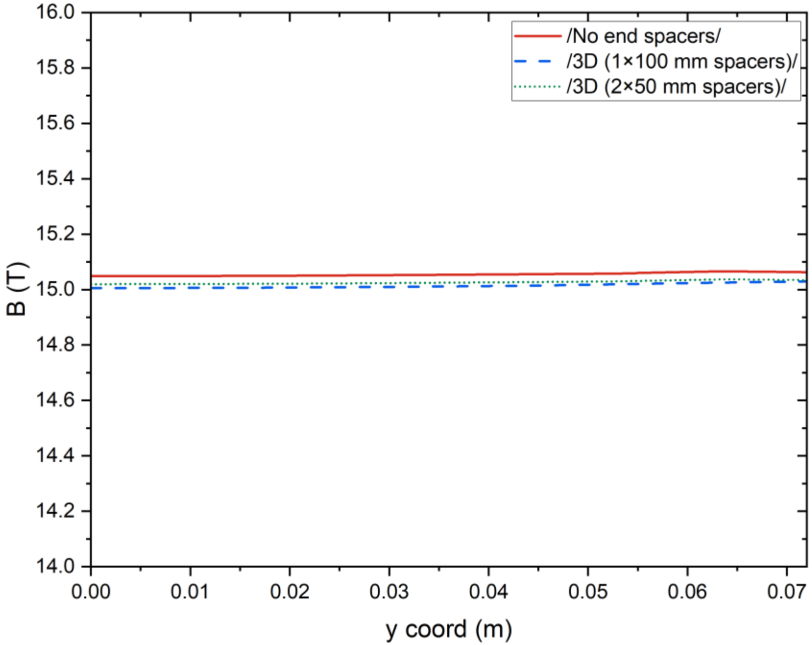
Field along paths 1 and 2

- 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)



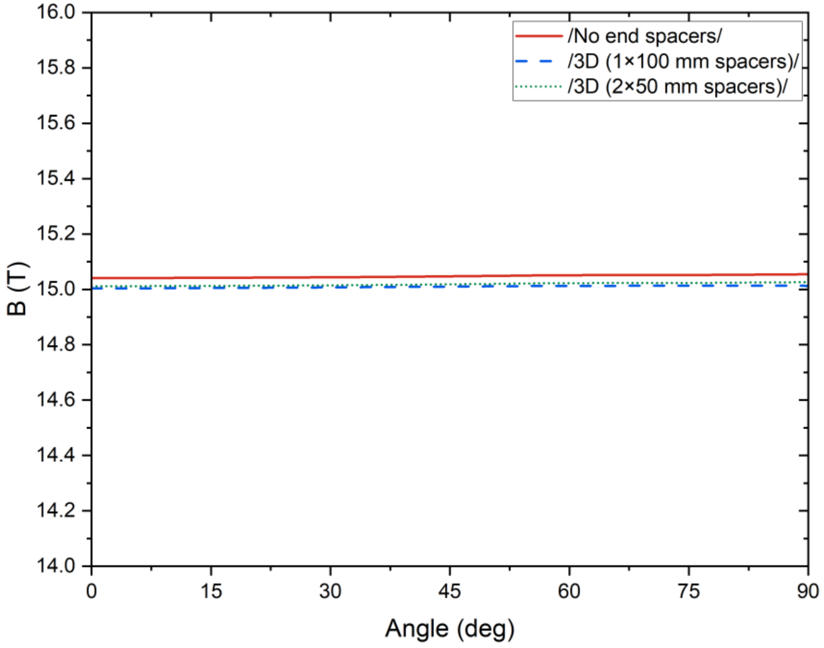
Path 2 (y axis of the aperture)



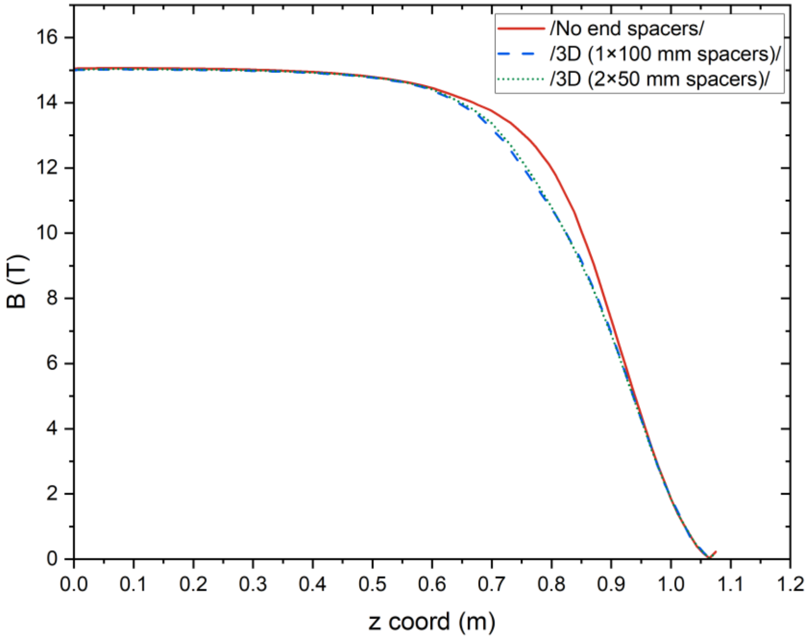
Field along paths 3 and 4

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

Path 3 (around circumference of R=40 mm)



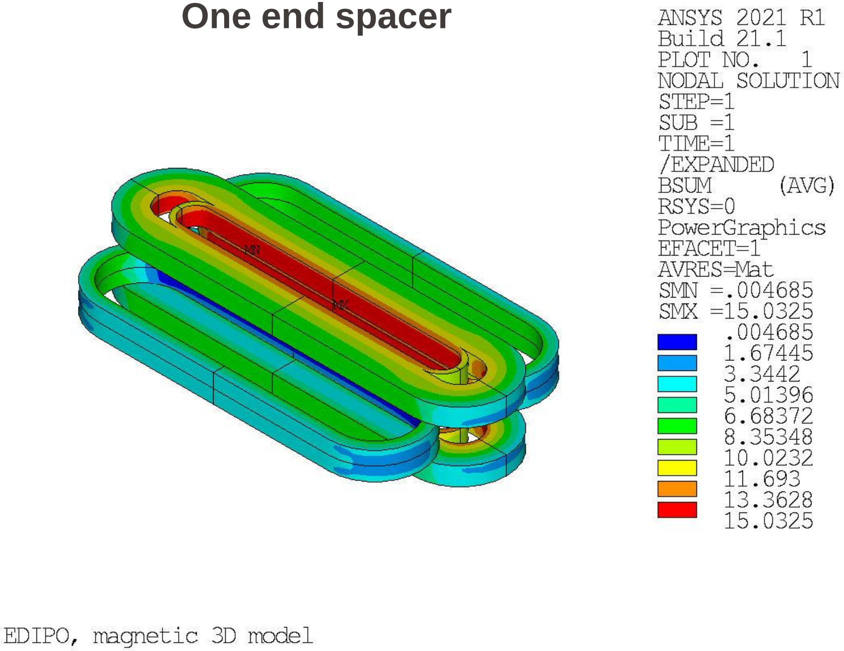
Path 4 (z axis of the aperture)



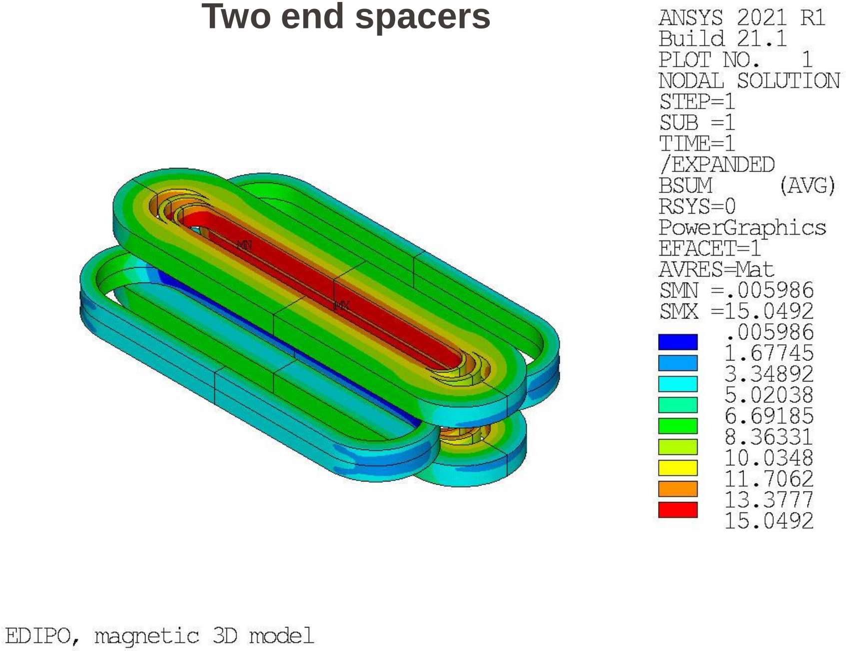
B field in the coils

- 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_{bore} = 15.005 T
  - Two end spacers in the vertical coils: B_{max} = 15.05 T, B_{bore} = 15.02 T

One end spacer



Two end spacers



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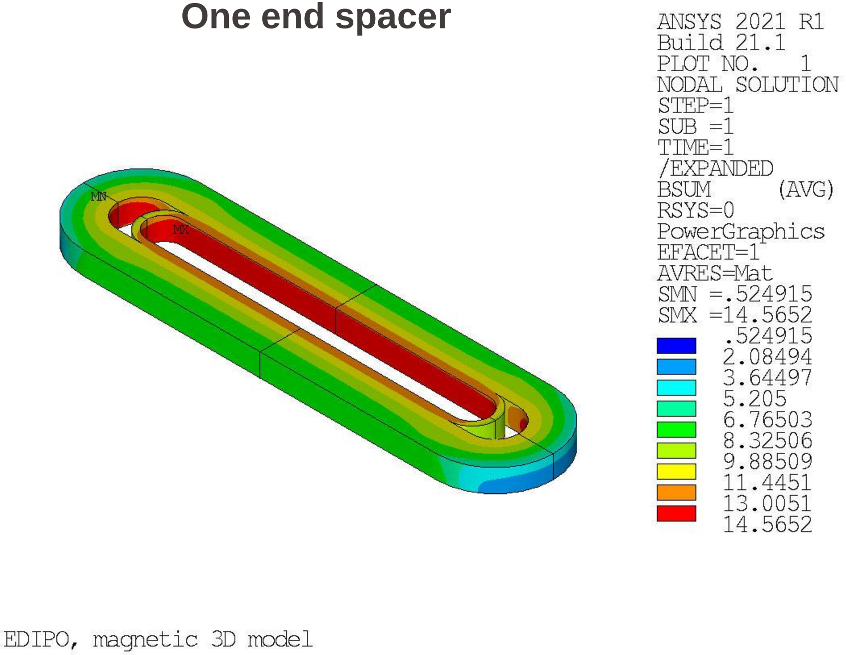
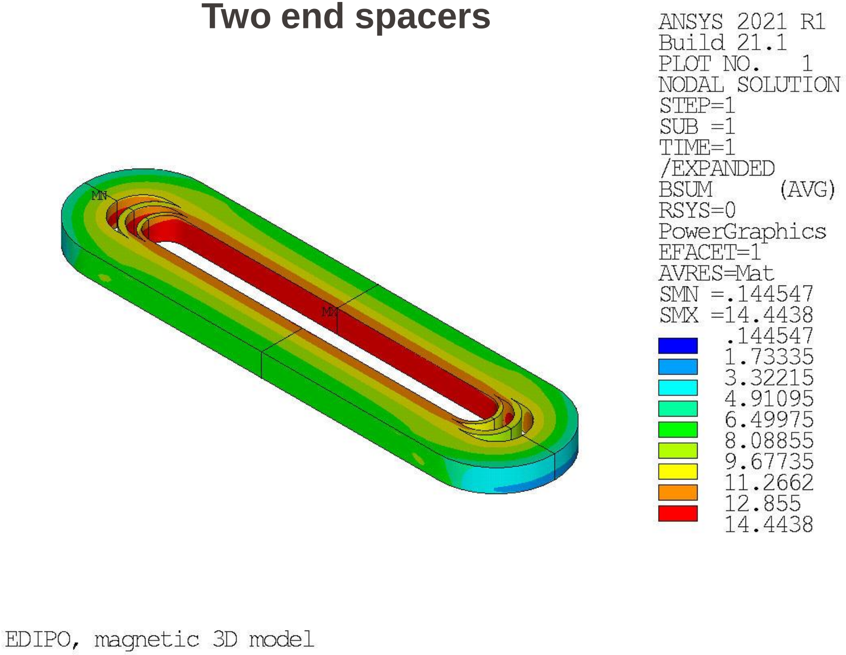
B field in the vertical coils

- 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: $B_{max,vert} = 14.56$ T
  - Two end spacers in the vertical coils: $B_{max,vert} = 14.44$ T

One end spacer



Two end spacers



B field in the vertical coils: straight section vs ends

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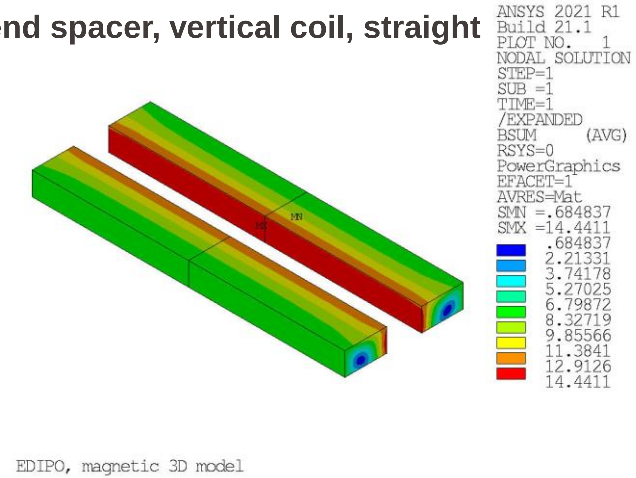
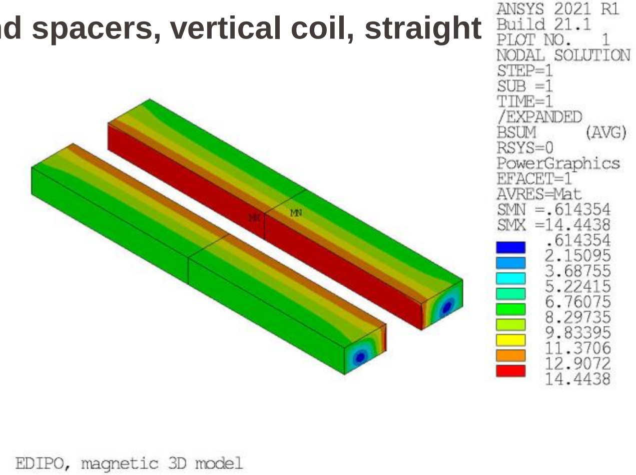
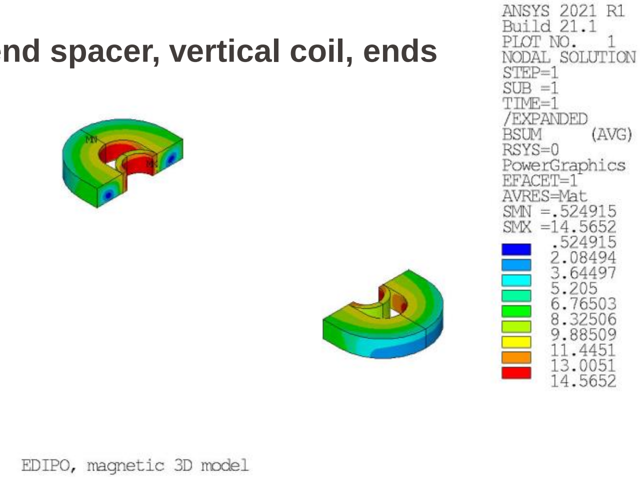
One end spacer, vertical coil, straight



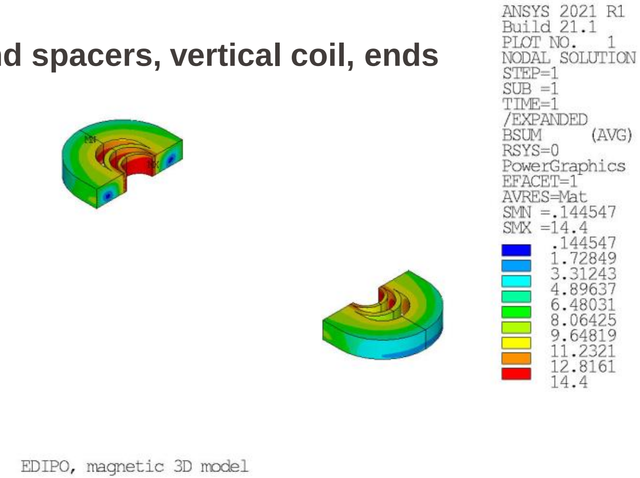
Two end spacers, vertical coil, straight



One end spacer, vertical coil, ends



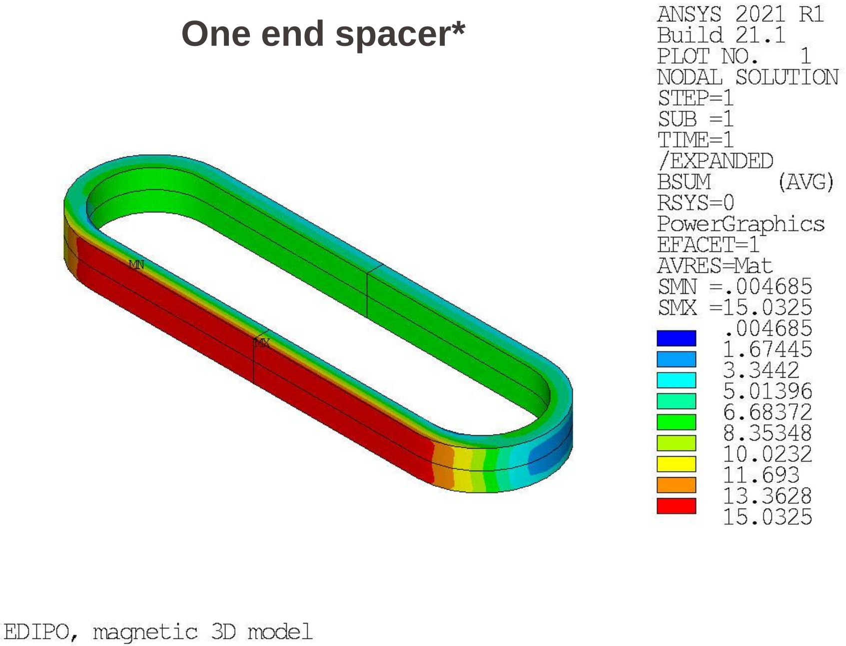
Two end spacers, vertical coil, ends



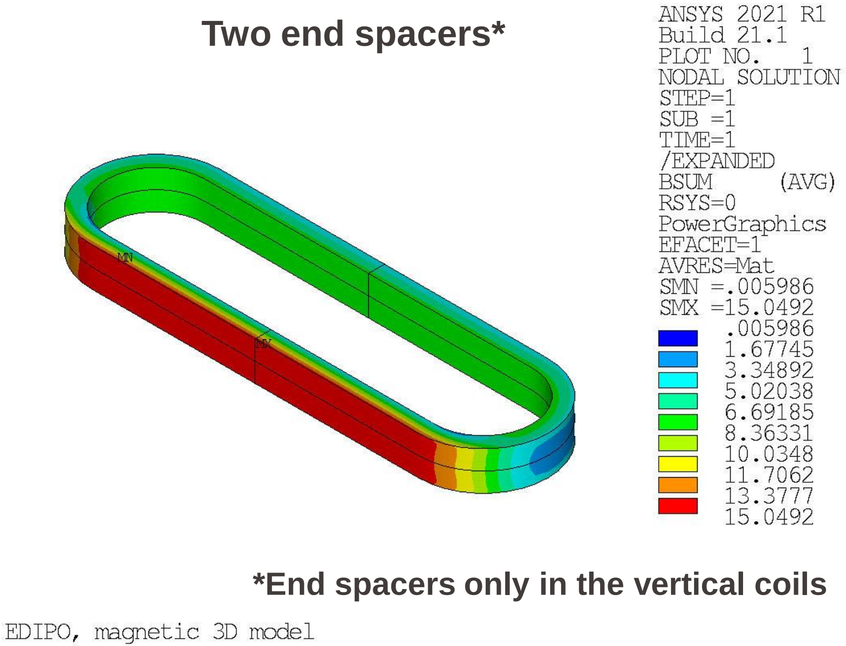
B field in the side coils

- 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: $B_{max,side}$ = 15.03 T, B_{bore} = 15.005 T
  - With end spacers in the vertical coils: $B_{max,side}$ = 15.05 T, B_{bore} = 15.02 T

One end spacer*



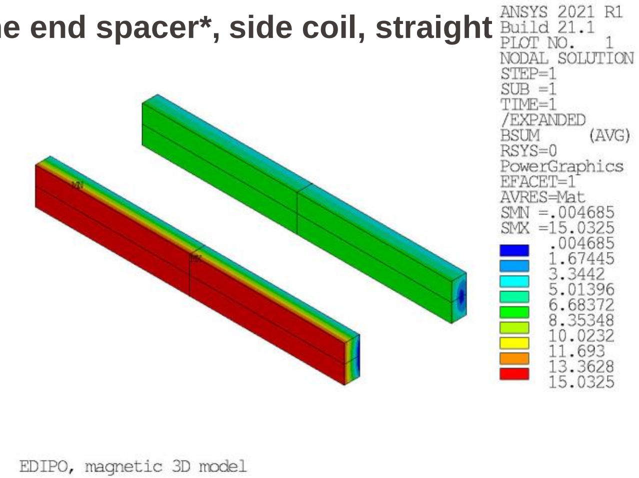
Two end spacers*



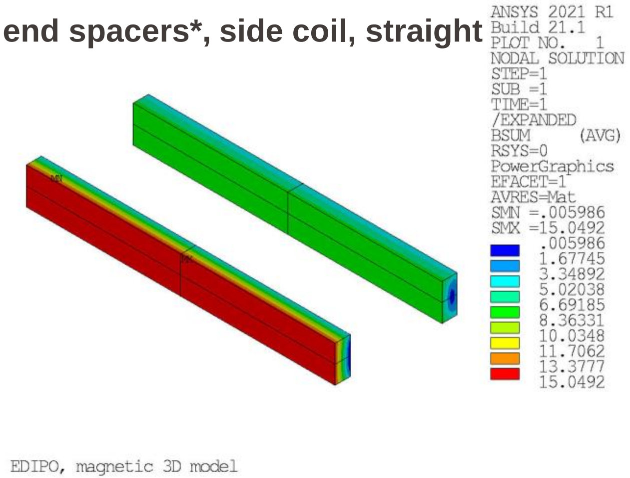
***End spacers only in the vertical coils**

B field in the side coils: straight section vs ends

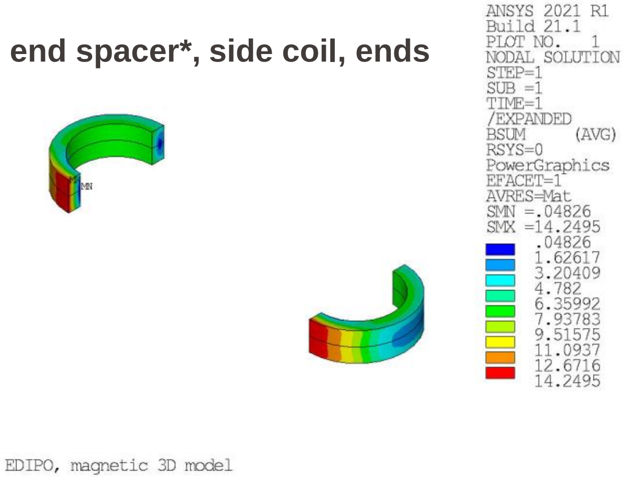
One end spacer*, side coil, straight



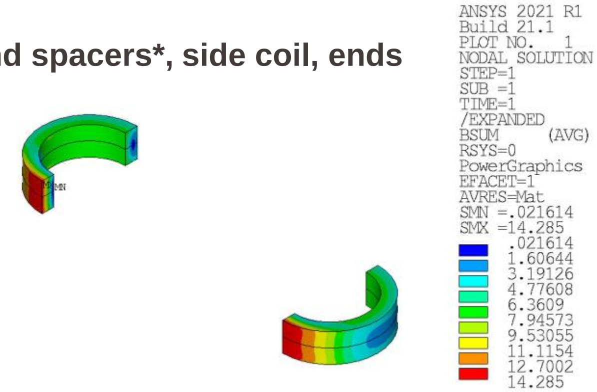
Two end spacers*, side coil, straight



One end spacer*, side coil, ends



Two end spacers*, side coil, ends



***End spacers only in the vertical coils**