Preliminary Analysis of the Target System Magnets

1. Version with a 6-T copper magnet insert
2. Version with a 6-T high-temperature superconductor insert
3. Deformations of the WC shield due to gravity.

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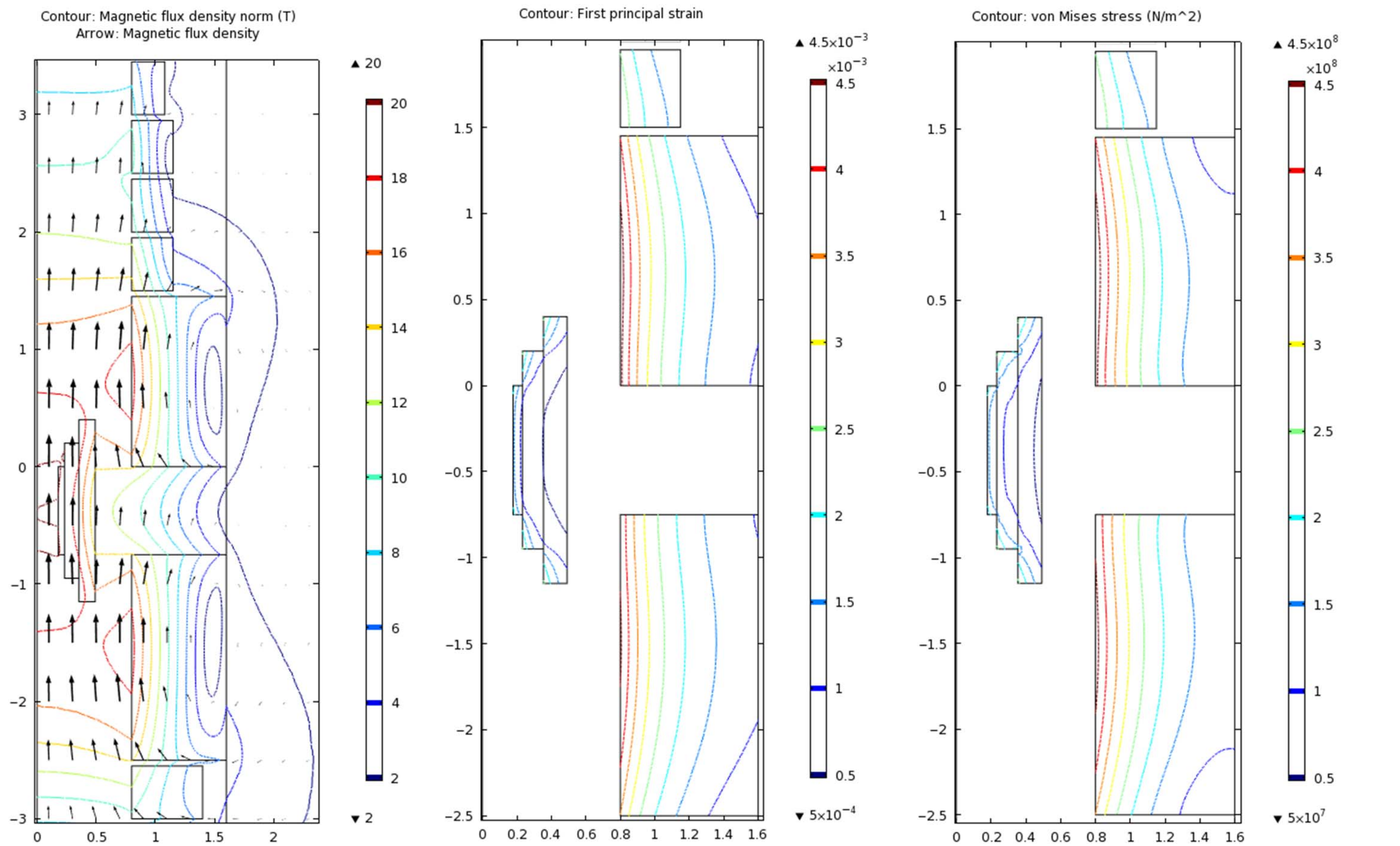
The IDS80d magnet configuration suffered from too high peak field in the superconducting magnets near the target, and from too high fields in these magnets if the 6-T copper magnet insert were to trip off.

A revised configuration, IDS80e, mitigates these issues.

IDS80d Beam is upwards



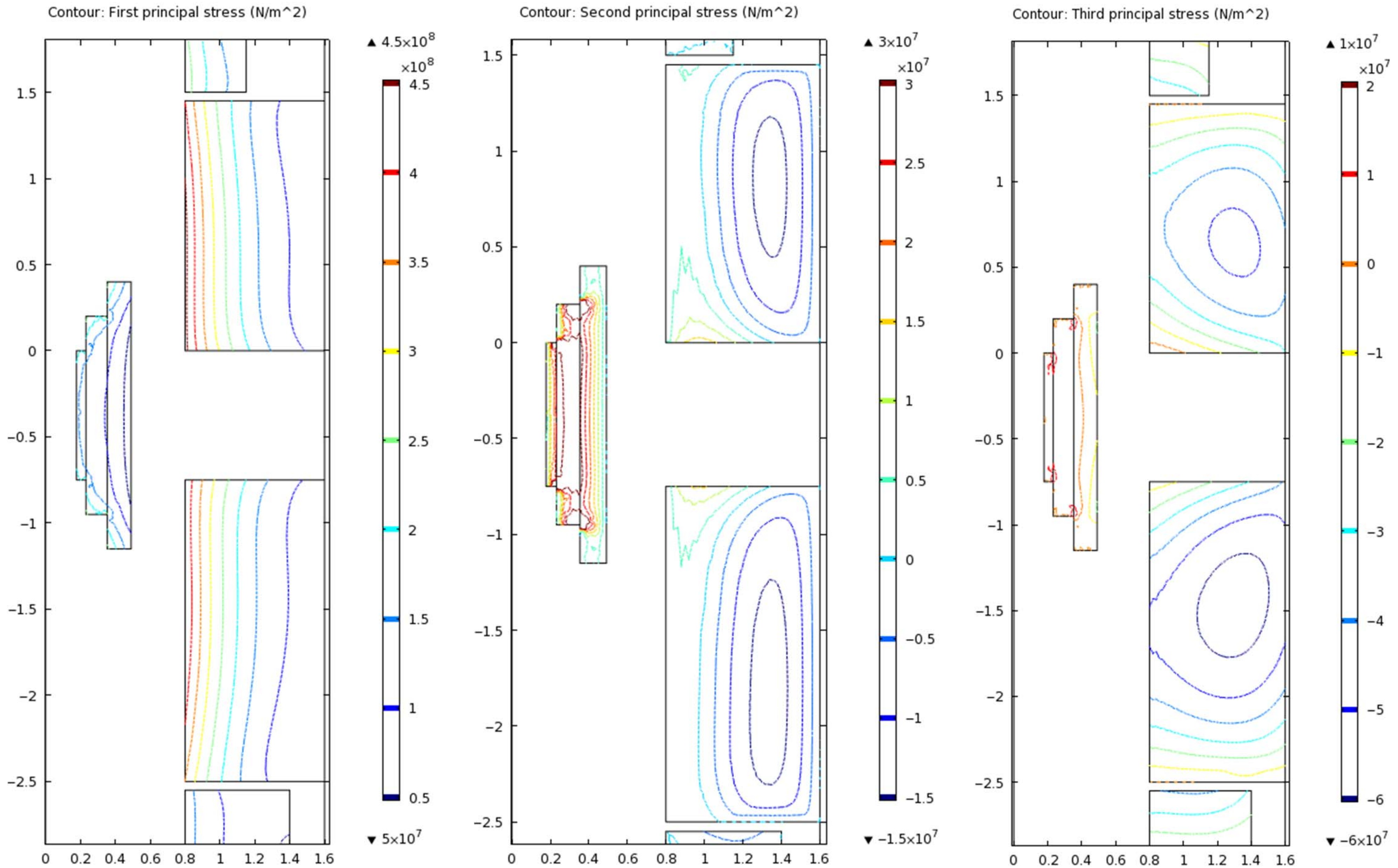
Upstream solenoids of 20 T, 2.3 GJ target magnet "ids80d".

Left: Windings cross section and field magnitude (contours) & direction (arrows). Innermost three solenoids are copper hollow conductor (B = 6 T; P = 8.8 MW); others shown are Nb_3Sn. B_{max} = 20.08 T; B = 20 T at z = 0, −34 cm, −43 cm & −74 cm.

Center: Hoop strain; ε_{max} = 0.463% if orthotropic Young's modulus components $\{E_\phi, E_r, E_z\}$ = {100, 20, 20} GPa.

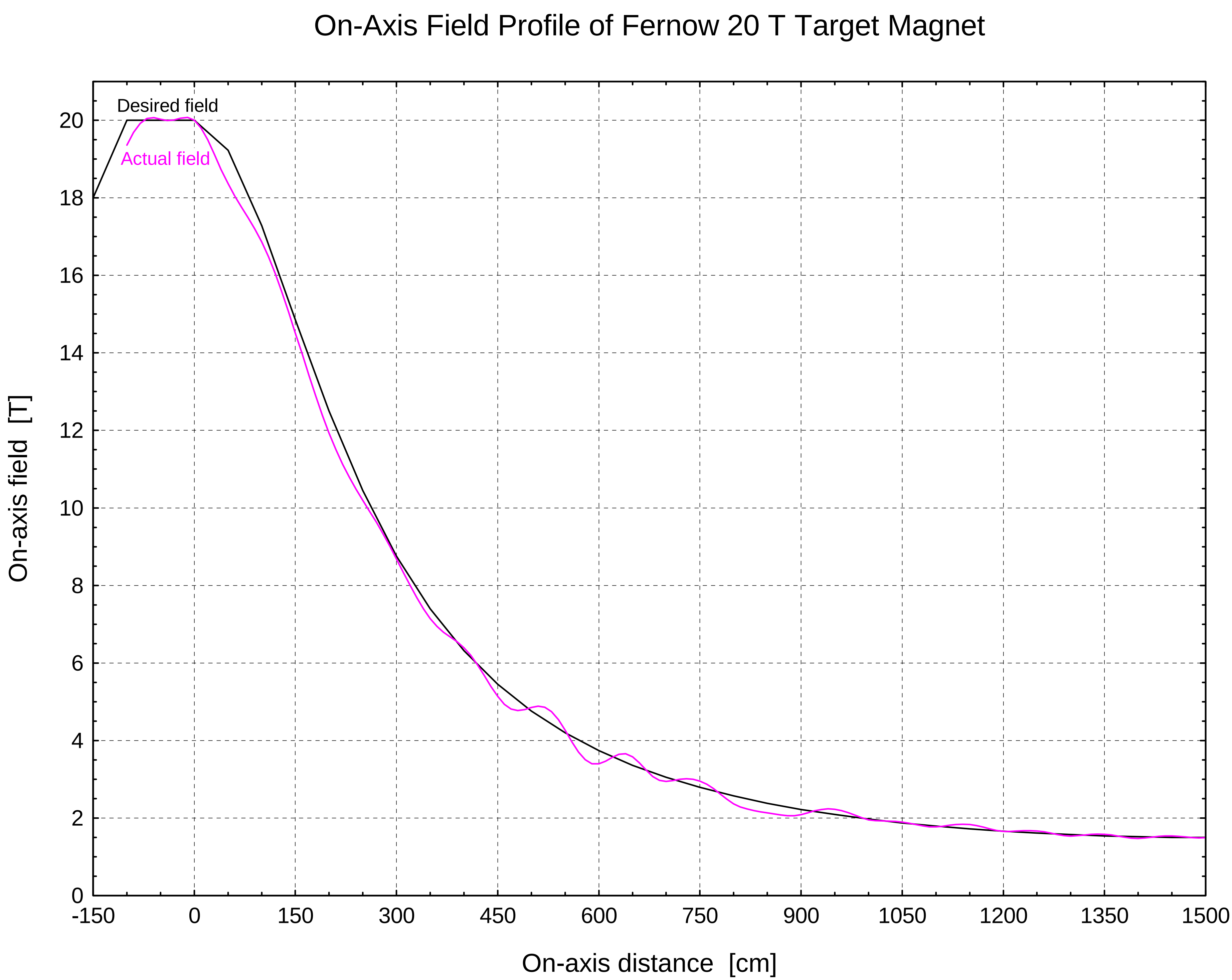
Right: von Mises stress, σ_{vM}; max. σ_{vM} = 473 MPa.

IDS80d   Beam is upwards

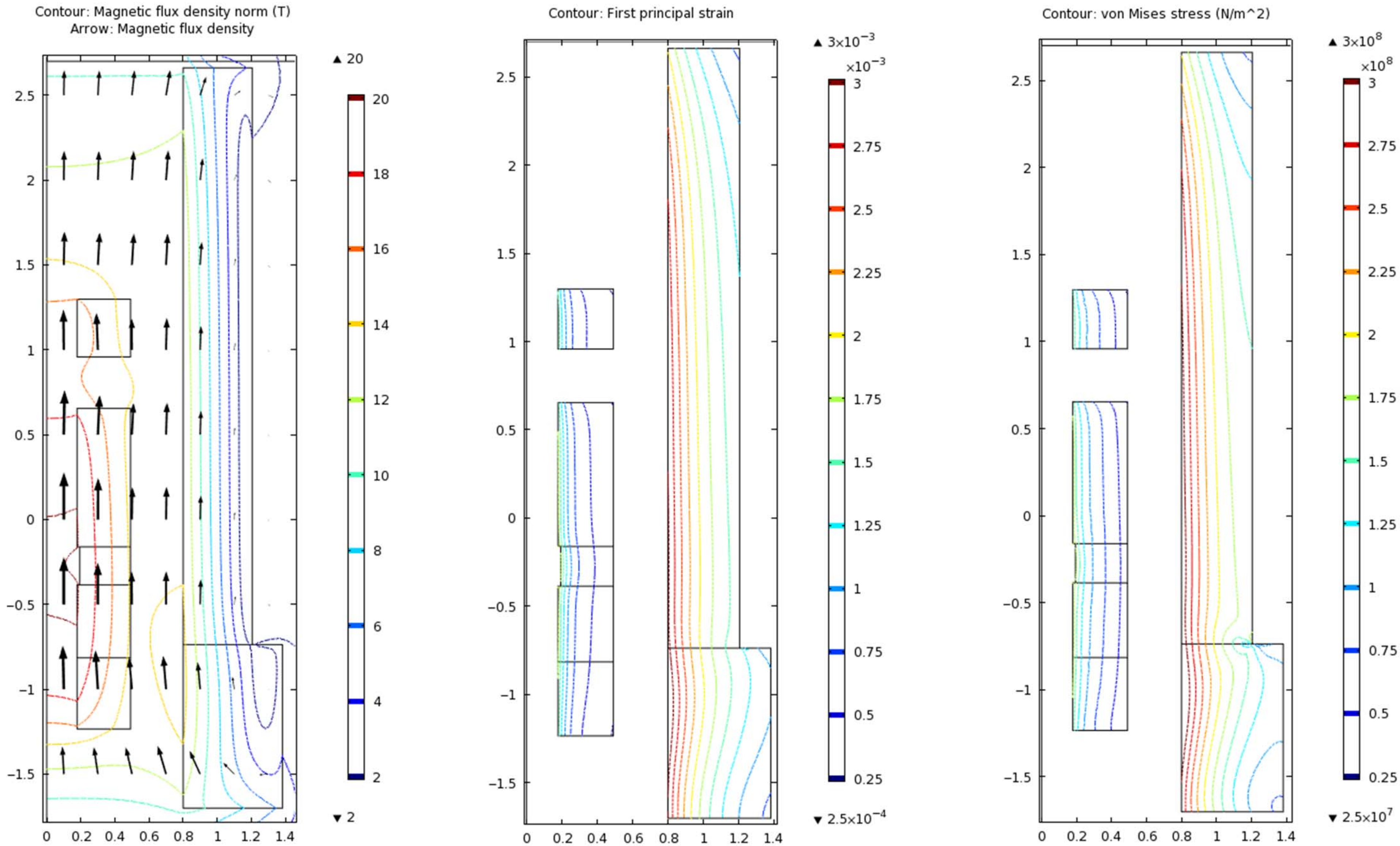


Principal stresses. Left: circumferential (hoop) stress, σ_ϕ; maximim σ_ϕ = 469 MPa.
Center: radial stress, σ_r.
Right: Axial stress, σ_z; max. compression = 62 MPa. Axial load on most-upstream Nb_3Sn solenoid is 162 MN (downstream direction); loads, in MN, on successive solenoids = {142, −66, −71, −22, −35, −36}.

IDS80d


On-Axis Field Profile of Fernow 20 T Target Magnet
Desired field
Actual field
On-axis field [T]
On-axis distance [cm]
0
2
4
6
8
10
12
14
16
18
20
-150
0
150
300
450
600
750
900
1050
1200
1350
1500

IDS80e with lower peak field in SC magnets   Beam is upwards



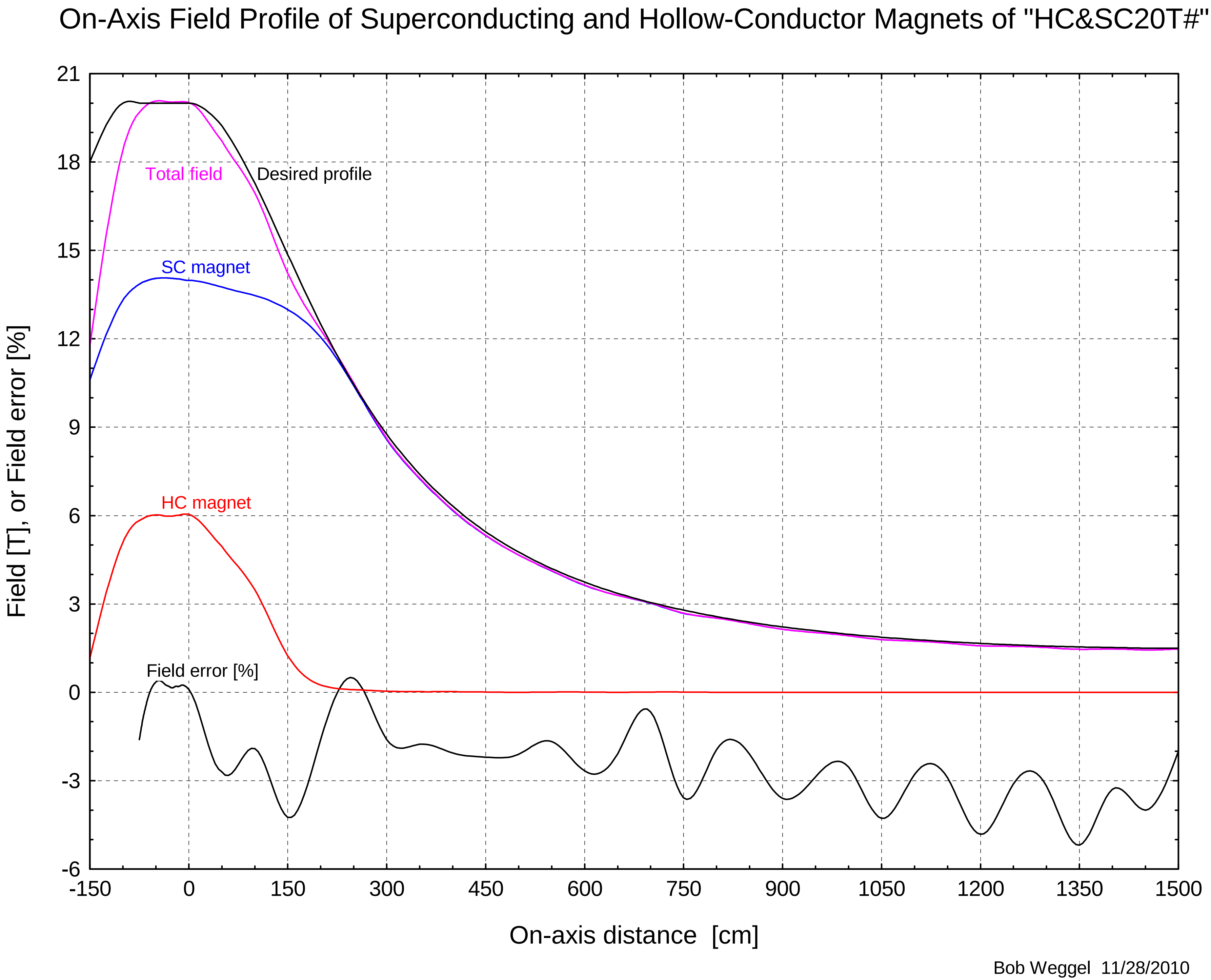
Upstream solenoids of HC&SC20T# target magnet with 6 T, 10.0 MW magnet of copper hollow conductor in 14 T SC magnet; magnetic energy = 1.18 GJ.

Left: Windings cross section and field magnitude (contours) & direction (arrows); maximum B_{SC} = 14.6 T.

Center: Hoop strain with orthotropic Young's modulus components $\{E_\phi, E_r, E_z\}$ = {100, 20, 20} GPa; ε_{max} = 0.326%.

Right: von Mises stress, σ_{vM}; max. σ_{vM} = 340 MPa.

IDS80e with lower peak field in SC magnets



Replacement of the 6-T copper magnet insert by a 6-T high temperature superconducting magnet could be attractive.

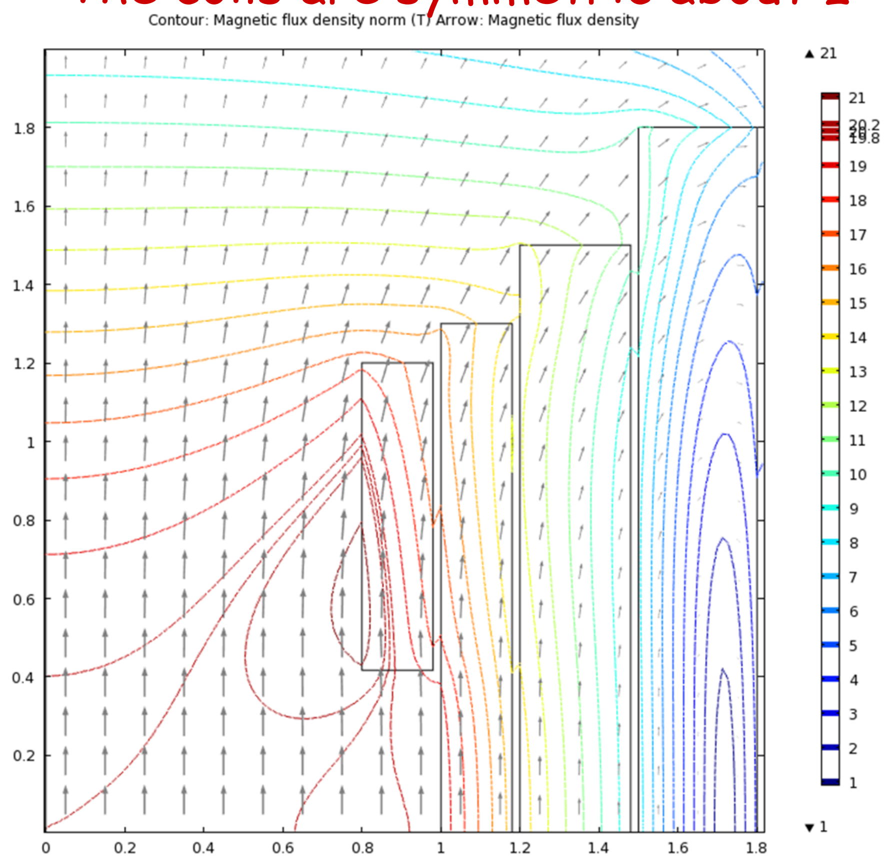
However, the peak stresses is the HTS coil would exceed the capability of any present conductor, ⇒ need significant conductor R&D before this option is viable.

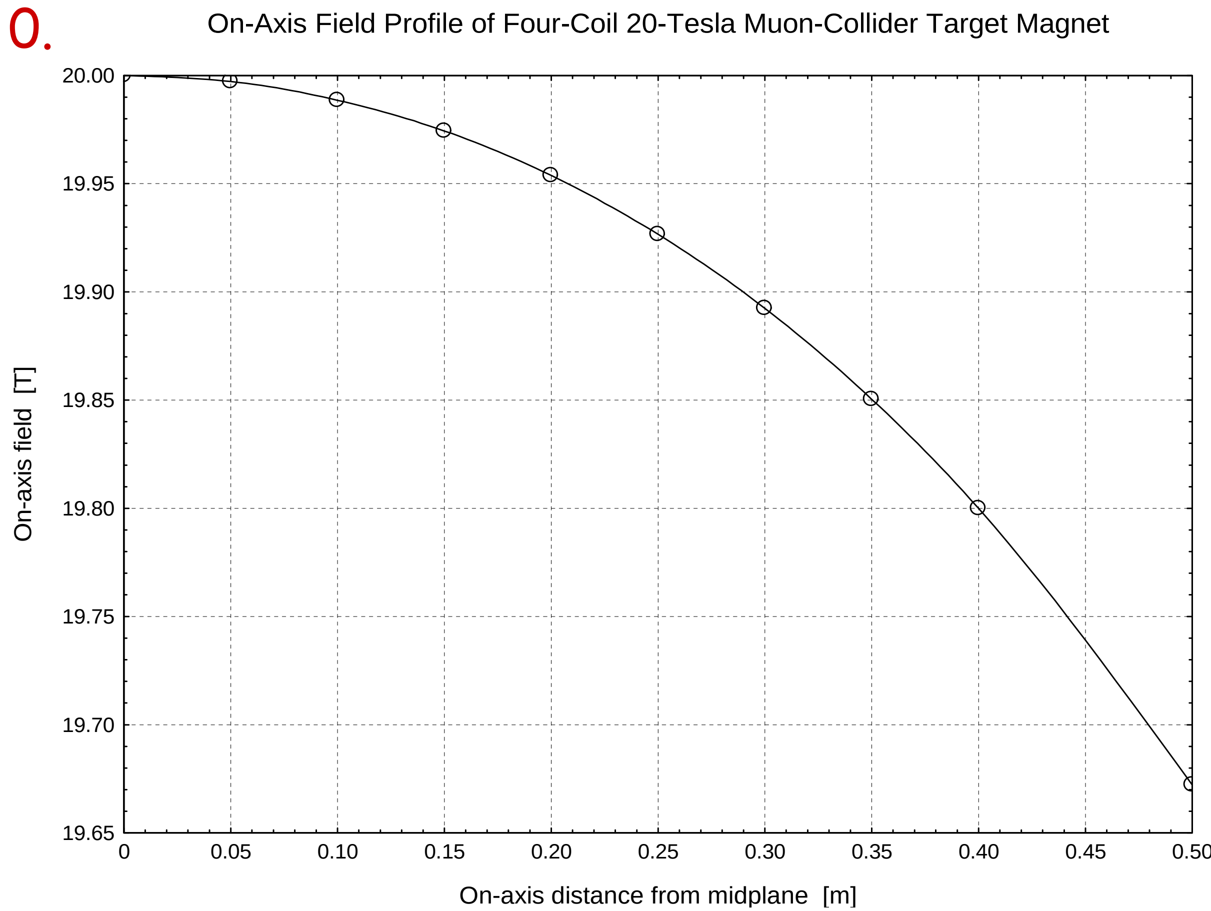
Four-Coil Magnet System near the Target

Inner 2 coils are HTS, 3rd is Nb_3Sn, 4th is NbTi

Beam is upwards.

The coils are symmetric about z = 0.





Four-coil 20-T pion-capture magnet. Annular spacing = 2 cm.

Inner HTS magnet: I.R. ≡ a_{11} = 80 cm; O.R. ≡ a_{21} = 98 cm; half length ≡ b_1 = 120 cm; half gap ≡ g_1 = 41.7 cm; coil current density ≡ j_1 = 23.4 A/mm^2; central field contribution ΔB_1 = 2 T; maximum ambient field B_1 = 21.5 T.

Outer HTS coil: a_{22} = 118 cm; b_2 = 130 cm; j_2 = 23.1 A/mm^2; ΔB_2 = 4 T; B_2 = 19.8 T.

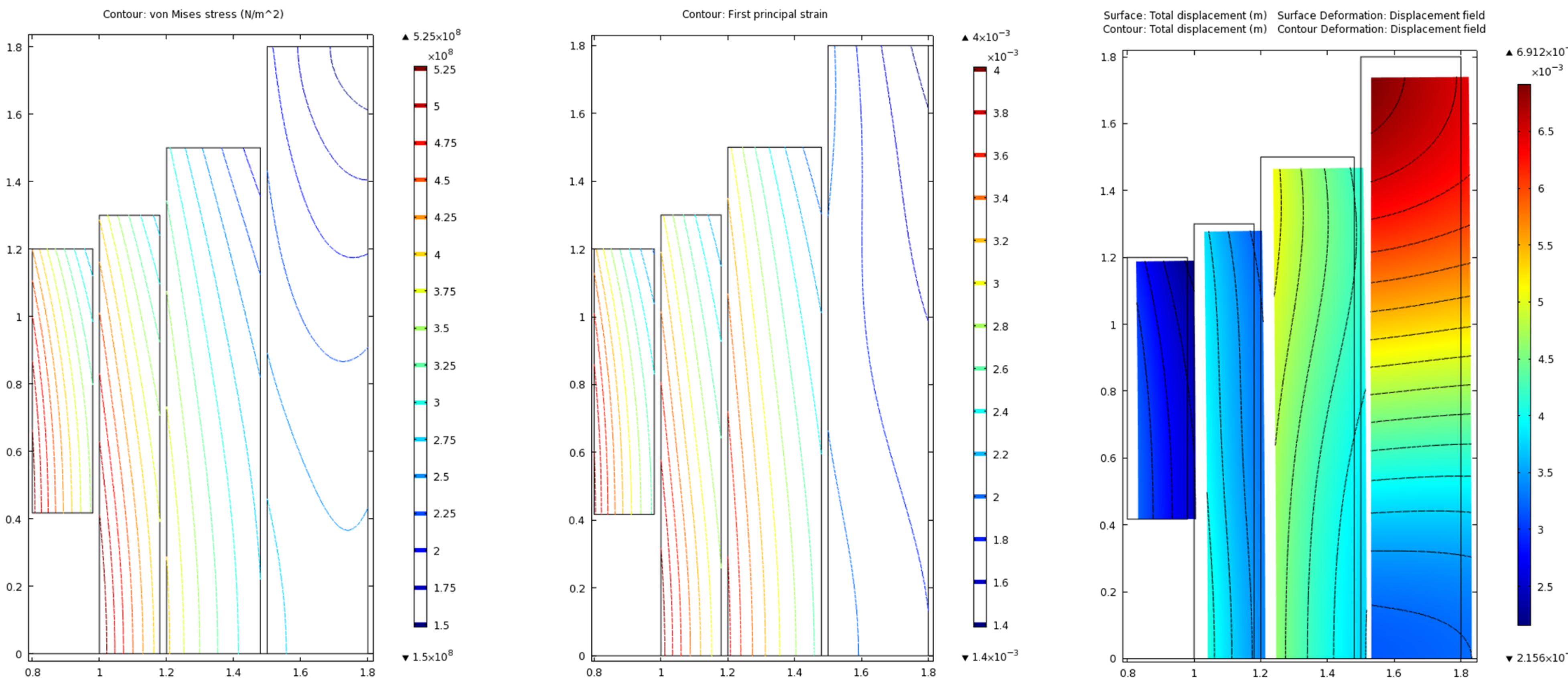
Nb_3Sn coil: a_{23} = 148 cm; b_3 = 150 cm; j_3 = 19.0 A/mm^2; ΔB_3 = 5 T; B_3 = 14.6 T.

NbTi coil: a_{24} = b_4 = 180 cm; j_4 = 32.4 A/mm^2; ΔB_4 = 9 T; B_4 = 10.8 T.

Left: First-quadrant cross section, field magnitude (contours) & direction (arrows).

Right: Field homogeneity is 1% over z = +/- 40 cm.

Stress, Strain and Deformation in Magnets of Slide 9



Stress, strain and deformation in magnets of slide 9 with orthotropic windings.

Young's moduli $\{E_r, E_\phi, E_z\}$ = {26, 130, 65} GPa in HTS coils and {20, 100, 40} GPa in LTS coils.

130 GPa derived from 50% Hastelloy of 220 GPa[13] + 25% copper of 80 GPa (320 MPa stress @ 0.4% strain) + 25% coolant & insulation (negligible stiffness).

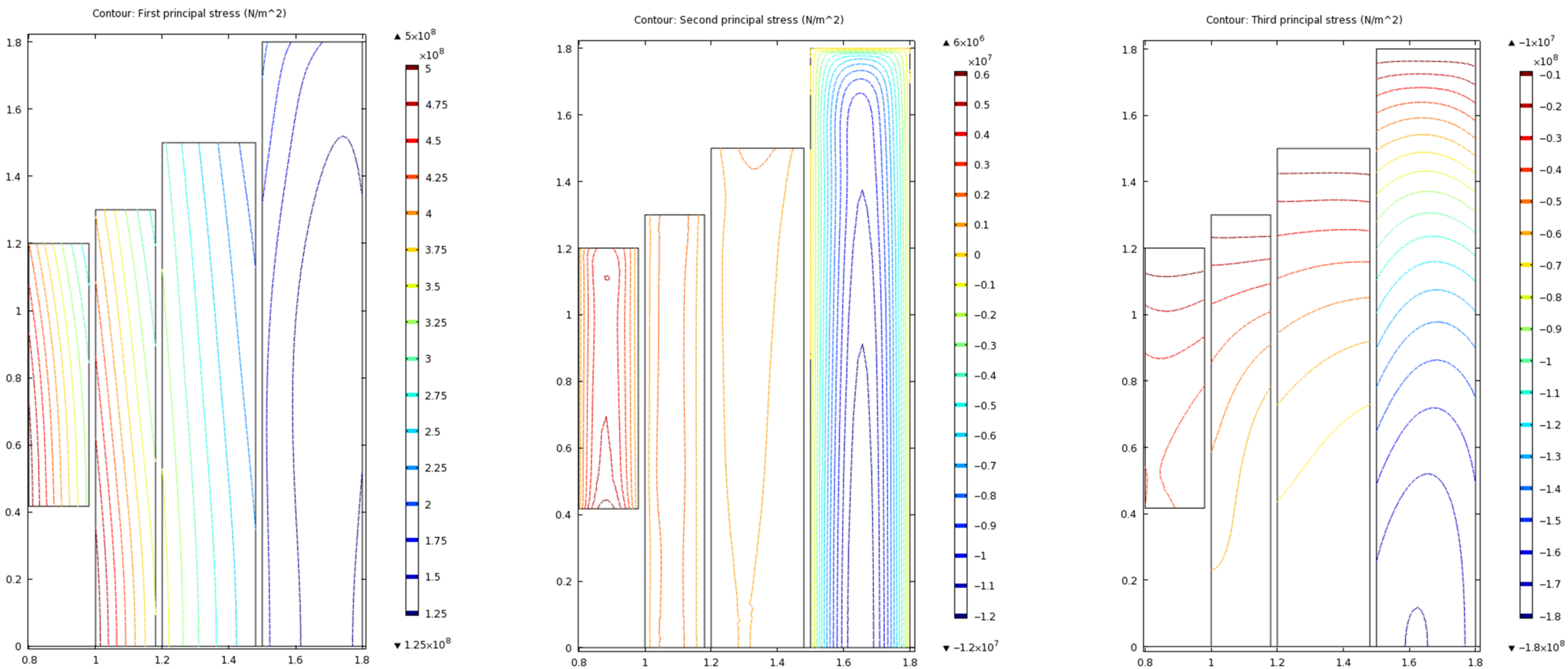
100 GPa derived from 35% steel of ~230 GPa[14] + 25% Cu + 40% residual for Nb_3Sn coil and, for NbTi coil, 20% steel + 40% Cu of ~135 GPa[15] + 40% residual.

Left: Von Mises stress, averaged locally over winding; maximum stress in consecutive coils = {535, 549, 406, 288} MPa.

Center: Hoop strain, ε_ϕ; max. percent = {0.40, 0.41, 0.38, 0.21}.

Right: Deformation (magnified tenfold) ranges from 2.2 mm to 6.9 mm; contour interval = 0.25 mm.

Principal Stresses in Magnets of Slide 9



Principal stresses in magnets of slide 9.

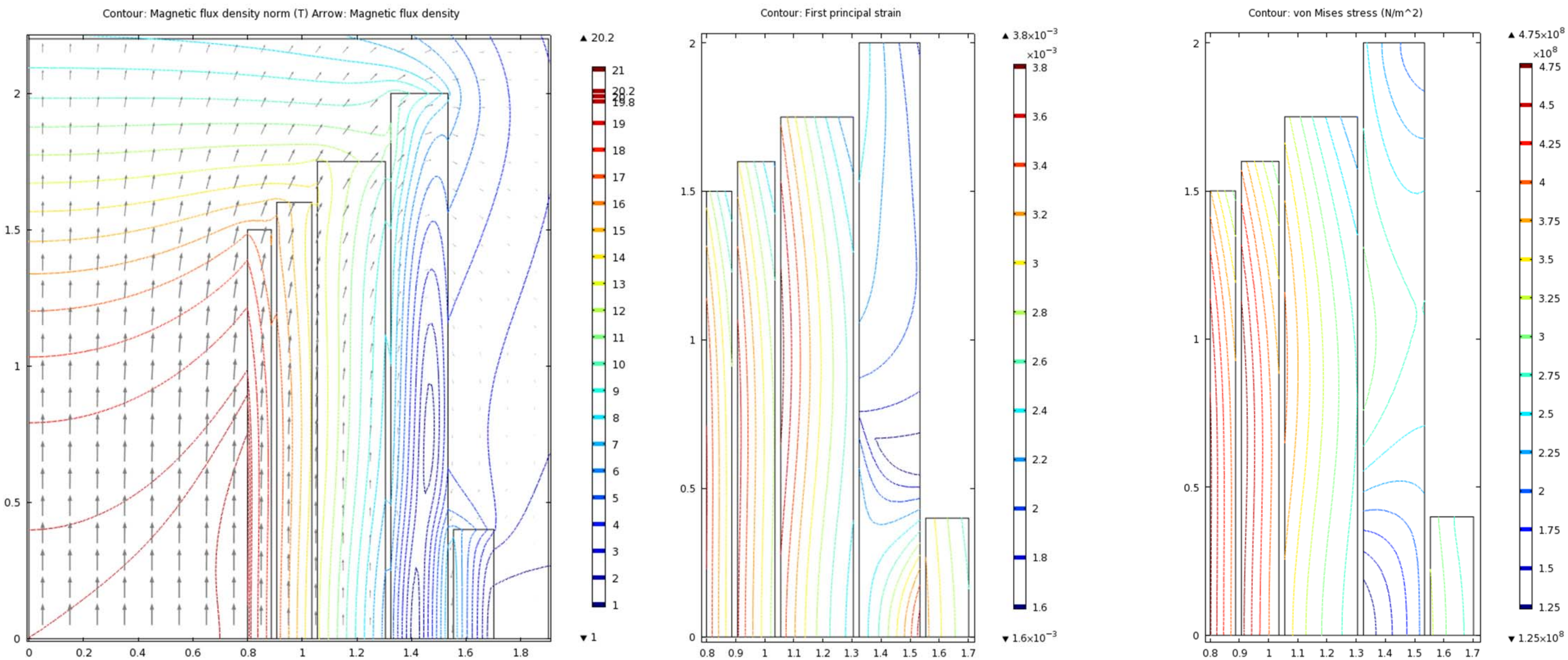
Left: Hoop stress σ_ϕ; max. MPa = {515, 516, 362, 159}.

Center: Radial stress σ_r; max. MPa = {6.5, 2.6, 1.6, −12.4}.

Right: Axial stress σ_z; max. MPa = {-49, −65, −78, −180}.

5-Coil Design with No Miplane Gap

Reversed Current in the 5th, Outer Coil



5-Coil design that eliminates midplane gap by use of reverse-current field-homogenization coil.

Inner HTS coil: a_{11} = 80 cm; a_{21} = 88.7 cm; b_1 = 150 cm; j_1 = 25.2 A/mm^2; ΔB_1 = 2.4 T; B_1 = 20.3 T.

Outer HTS coil: a_{12} = 90.7 cm; a_{22} = 103.5 cm; b_2 = 160 cm; j_2 = 26.1 A/mm^2; ΔB_2 = 3.6 T; B_2 = 17.7 T.

Nb_3Sn coil: a_{23} = 130.5 cm; b_3 = 175 cm; j_3 = 23.1 A/mm^2; ΔB_3 = 5 T; B_3 = 14.1 T.

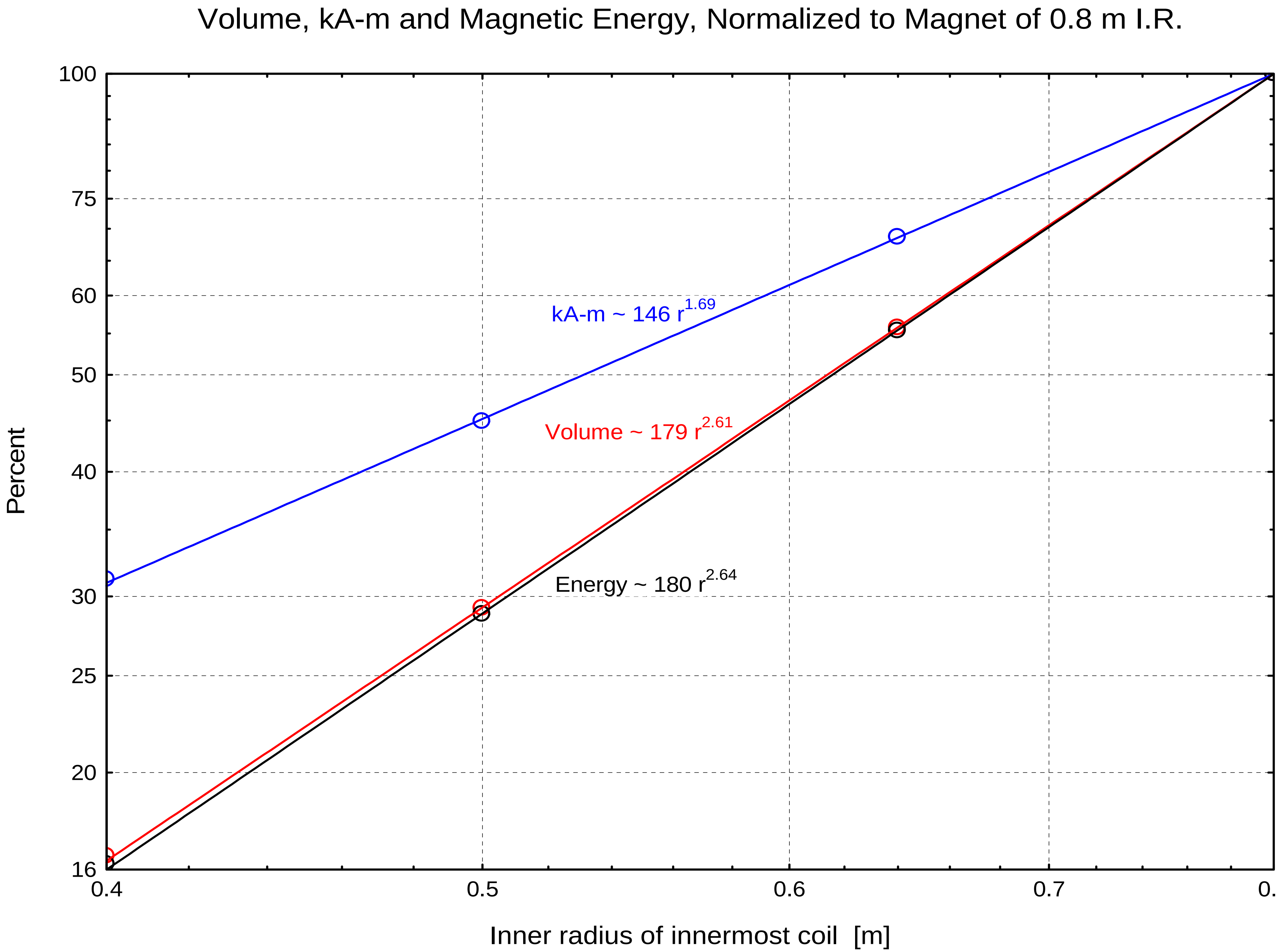
NbTi coil: a_{24} = 153.4 cm; b_4 = 200 cm; j_4 = 47.2 A/mm^2; ΔB_4 = 10.1 T; B_4 = 11.0 T.

Field-homogenizing coil: a_{25} = 170.2 cm; b_5 = 40 cm; $j_5 = -j_4$; ΔB_5 = −2.09 T; B_5 = 7.7 T.

Left: First-quadrant cross section and field magnitude (contours) & direction (arrows).

Center: Hoop strain ε_ϕ; max. percent ε_ϕ = {0.36, 0.37, 0.39, 0.37, 0.32}.

Right: von Mises stress; max. MPa = {480, 496, 406, 315, 328}.



Magnet volume, kiloampere-meters & magnetic energy *vs.* bore diameter.
Reducing the magnet bore by a factor of two would decrease its kA-m by a factor of three, and its volume and energy by a factor of six.

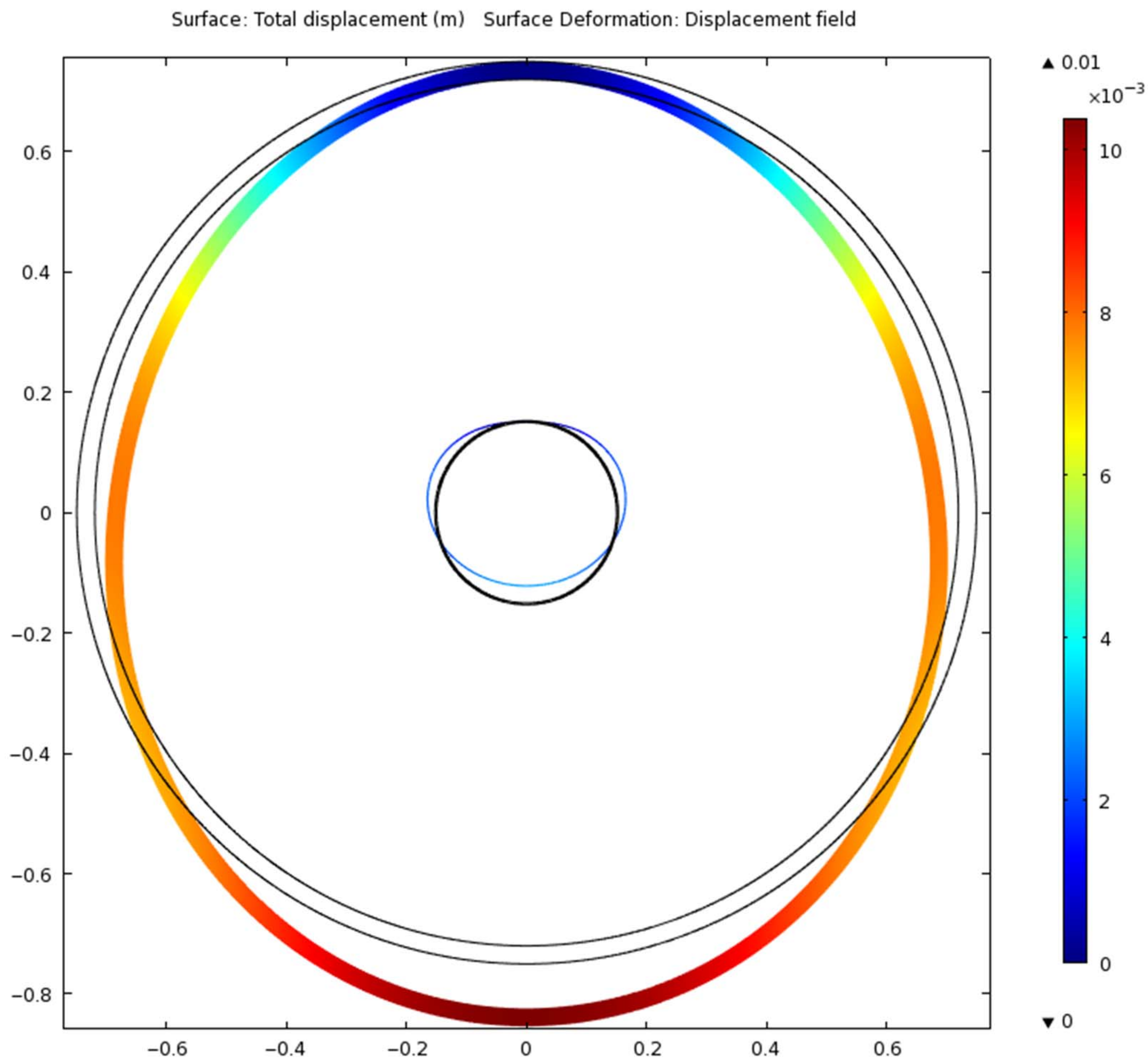
The WC shield weighs ~ 100 tons, and must be supported off the superconducting magnet cryostat.

The following models are "2-D" ⇒ no stiffening due to end disks or internal ribs.

The tungsten-carbide beads + water is modeled as a liquid.

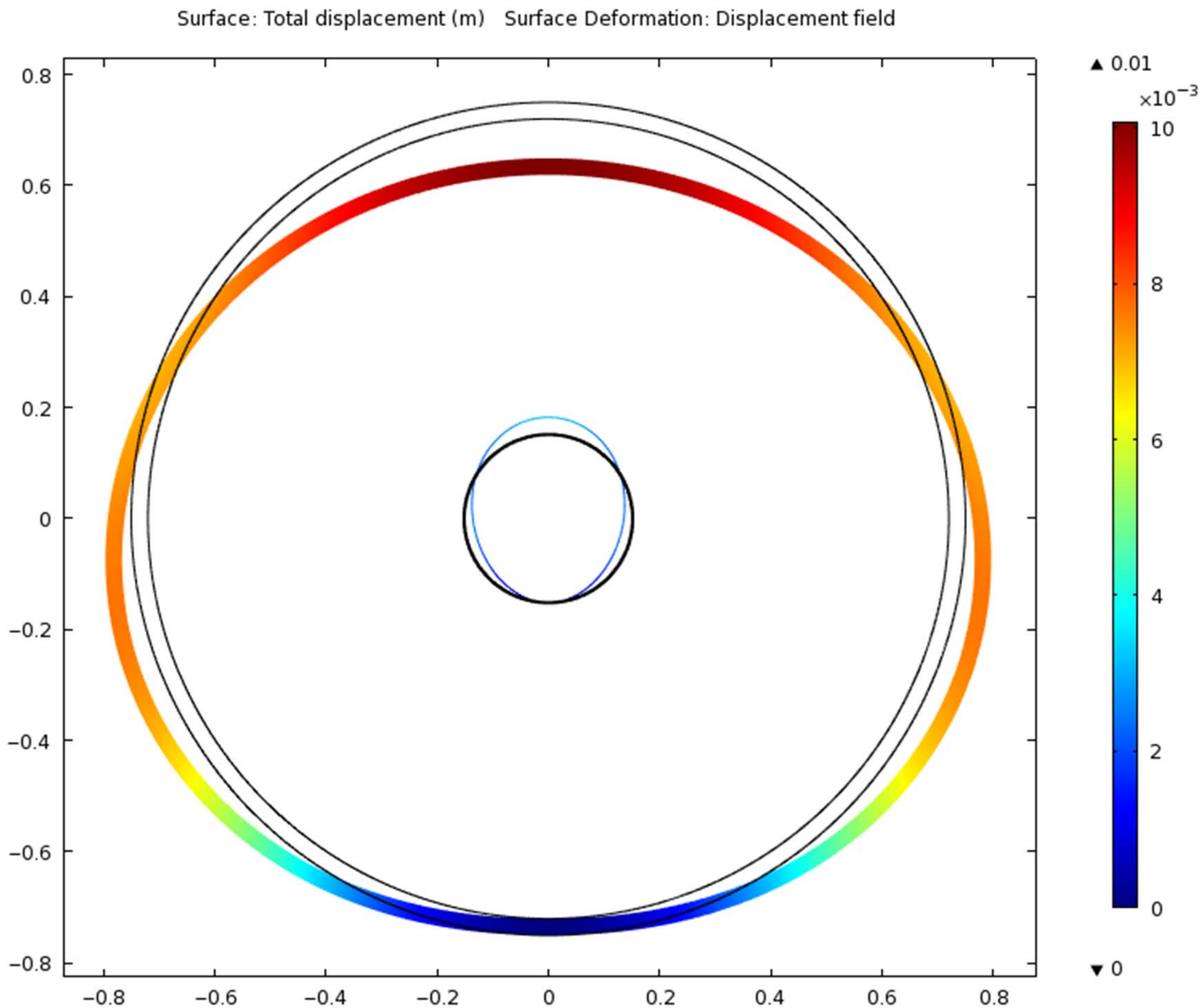
Even with 3-cm-thick walls, the deformations are of order 1 cm.

WC Shield, supported from Top 3-cm-thick walls
Approximate the WC as a liquid, so center tube "floats" upwards



Deformation, magnified tenfold, of horizontal steel cylinders, fixed at 12 o'clock, with annulus of 10 g/cm^3 fluid;
r_1 = 15 cm; dr_1 = 3 mm; r_2 = 72 cm; dr_2= 3 cm.

WC Shield, supported from Bottom   3-cm-thick walls
Approximate the WC as a liquid, so center tube "floats" upwards



Deformation, magnified tenfold, of horizontal steel cylinders, fixed at 6 o'clock, with annulus of 10 g/cm^3 fluid; r_1 = 15 cm; dr_1 = 3 mm; r_2 = 72 cm; dr_2= 3 cm.