High Field Solenoid

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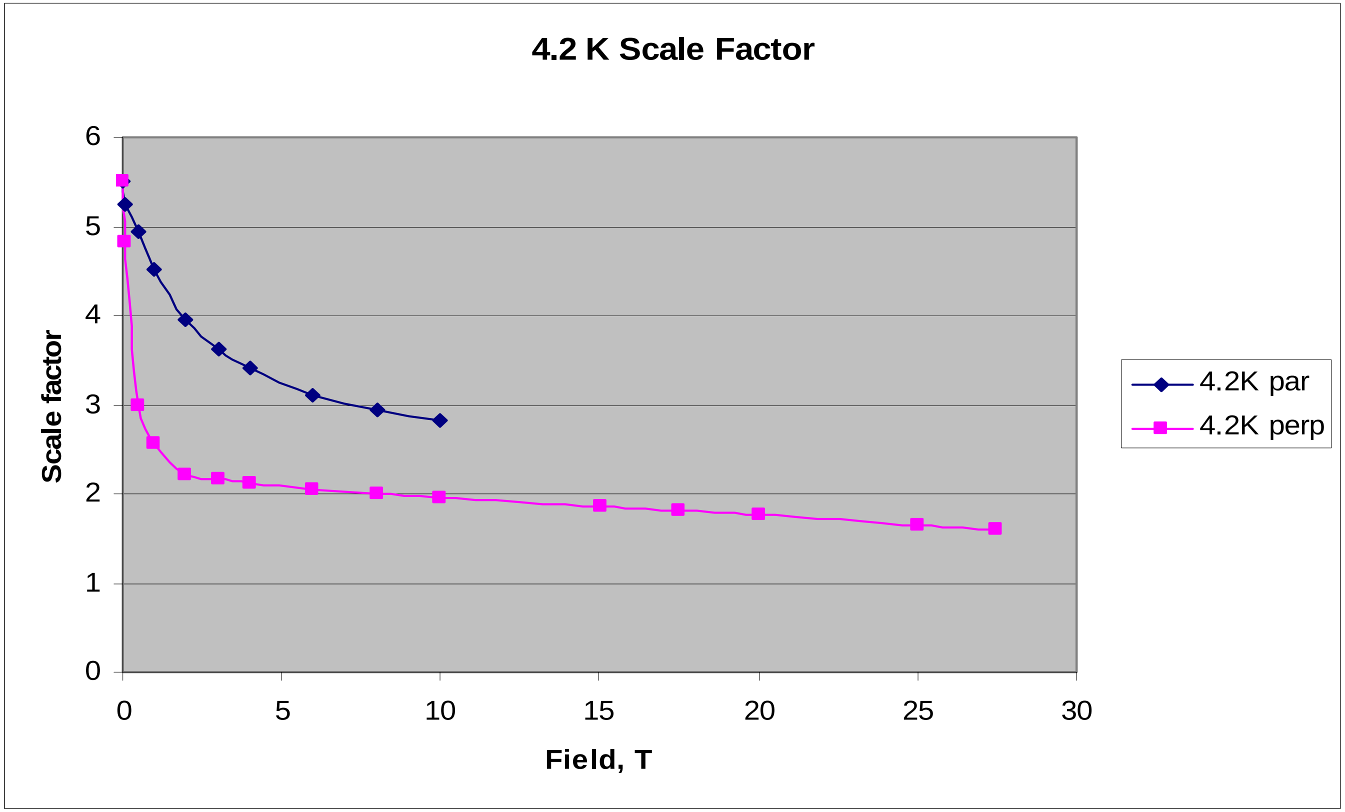
Properties of American Superconductor's High Temperature Superconductor Wire

Parameter	High Current Wire	High Strength Wire	Compression Tolerant Wire
J_e amp/mm^2	161	113	100
Thickness, mm	0.22	0.3	0.3
Width, mm	4	4.2	4.85
Max Tensile Strength (77^o K), MPa	65	300	280
Max Tensile Strain (77^{o}K)	0.10%	0.35%	0.30%
Max Compressive Strain (77^o K)			0.15%
Min Bend Radius, mm	50	25	25
Max Length, m	800	400	400
Spliceable	no	yes	yes

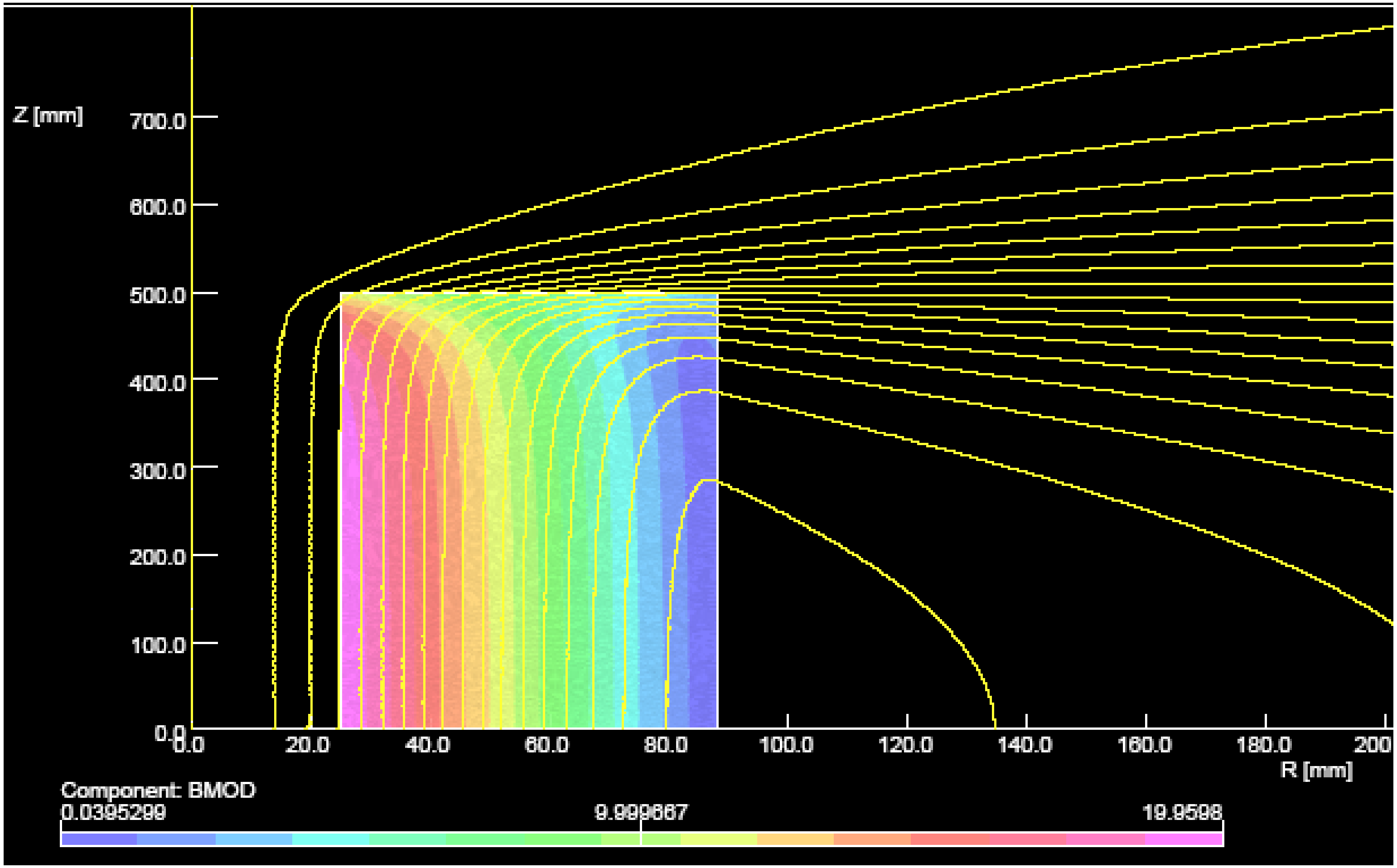
Current Carrying Capacity for HTS Tape in a Magnetic Field
Scale Factor is relative to 77ºK with self field



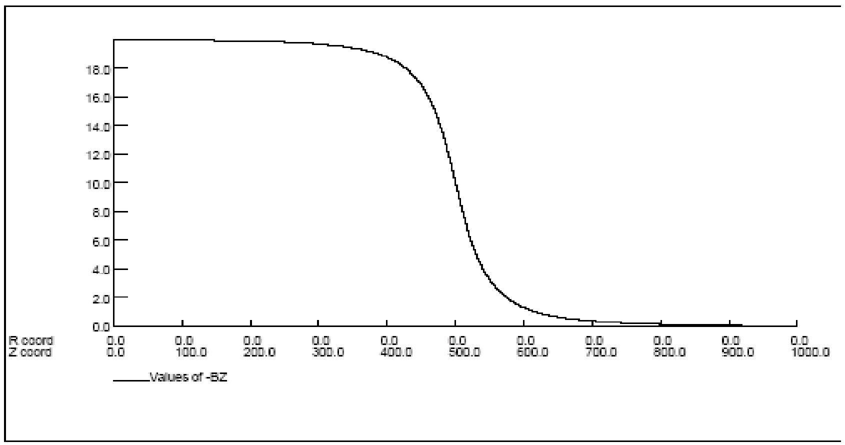
Building a High Field Solenoid from HTS Conductor

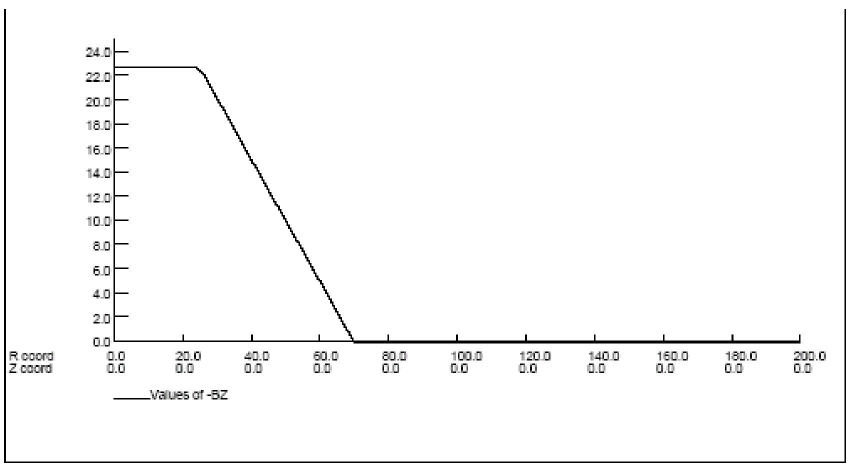
- We shall look at two examples to build a 20 Tesla solenoid.
  - One example is built entirely with HTS conductor.
  - The other is a hybrid solenoid with a HTS insert surrounded by a outsert solenoid made with Nb_3Sn conductor.
    - The hybrid design is chosen since HTS conductor is very expensive. Generating 14 T of the field with the less expensive Nb_3Sn makes the magnet more affordable.
- We have chosen the *high strength* HTS conductor.
  - The inner radius is the minimum bend radius: 25 mm
  - The current density is determined by the 20 T field needed on the inner surface: 254 amp/mm^2
  - The outer radius of the all HTS solenoid is determined by the total current necessary to make 20 T: 88 mm.

Case 1: Solenoid With All HTS



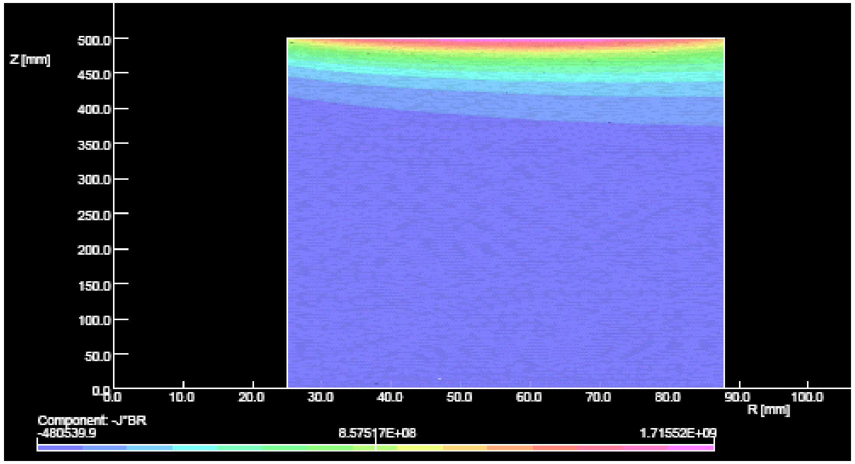
Case 1: Fields

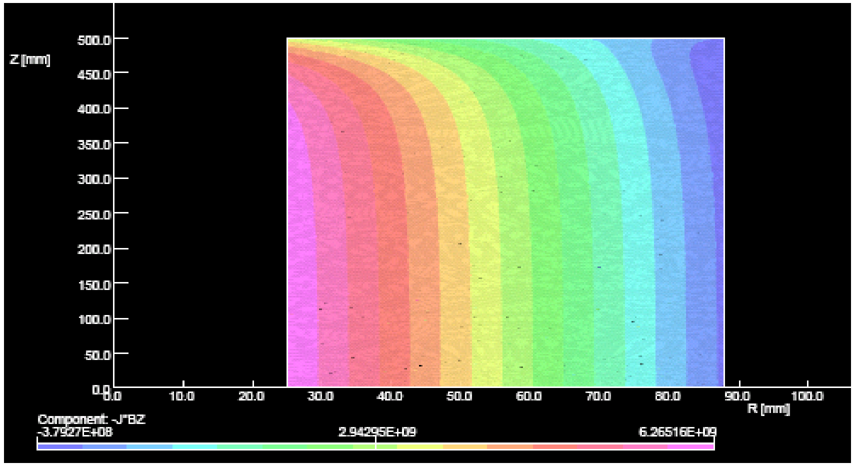




- Upper figure shows the B_z field along the solenoid axis.
- Lower figure shows the B_z field radially outword on the solenoid midplane.

Lorentz Force Density for HTS Solenoid





- The top figure shows the force density:

$$f_z = j \times B_r$$

  In most of this figure (the blue part) the force is compressive toward the center of the magnet. Near the end, the force is outward.

- The lower figure shows the force density:

$$f_r = j \times B_z$$

  – The radial force density is outward.

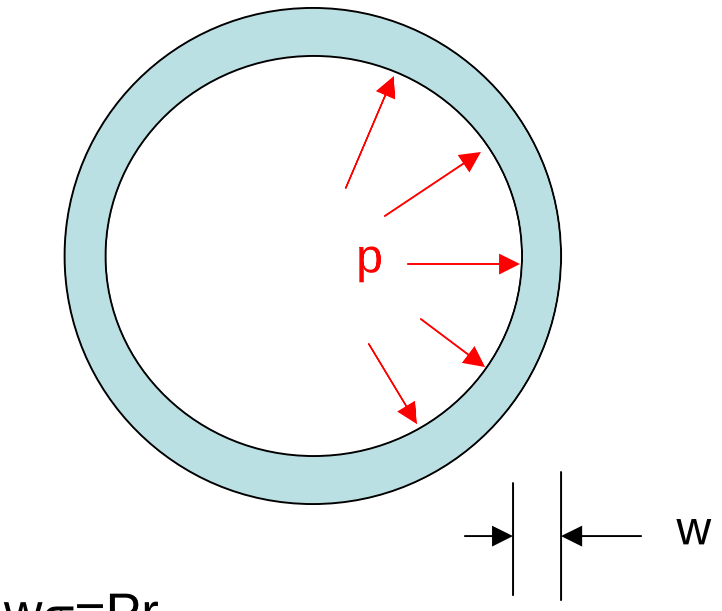
Case 1: Summary of Parameters

Parameter	Units	Value
Total Current	Amp-turns	1.6×10^{7}
Stored Energy	Joules	1.1×10^{6}
Total Radial Force	Newtons	4.3×10^{8}
Upper Half Axial Force	Newtons	-1.2×10^{6}
Central Field	Tesla	19.96
B_{eff} = ?Bdl/L	Tesla	20.02
R_{inner}	mm	25
R_{outer}	mm	88
Length	mm	1000
Maximum Stress	MPa	84.3

Maximum Stress determined by integrating radial force density.

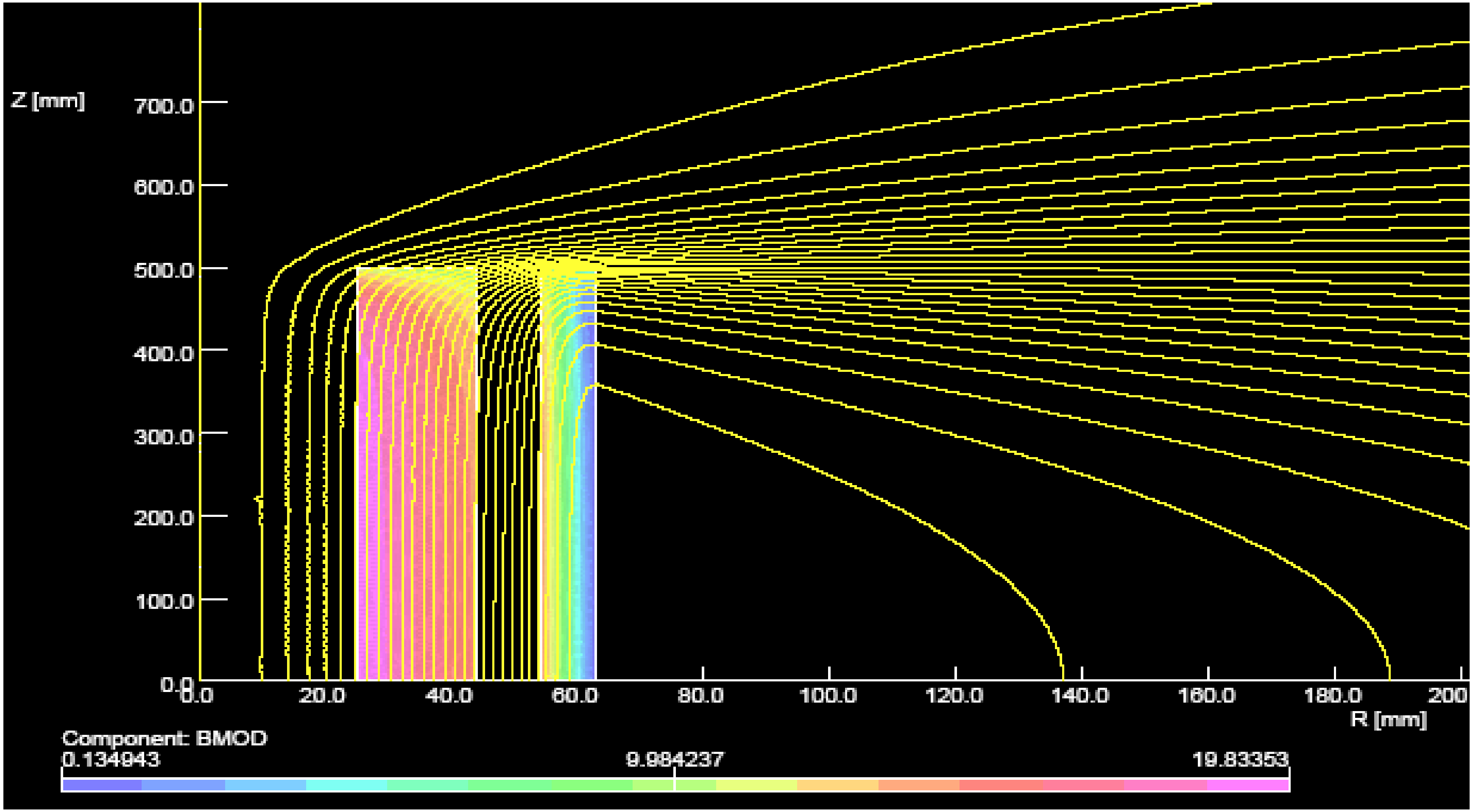
How Do We Constrain the Radial Force?

- Suppose we try to constrain the radial force with a stainless steel shell.
  - Stainless Steel 316 Tensile Strength: σ=460-860 MPa.
    - Choose σ=700 MPa.
  - Radial stress from superconductor: P =84 MPa
  - Superconductor outer radius: 88 mm.
  - The constraining shell needs to be at least 10.6 mm thick.
  - This is possible!

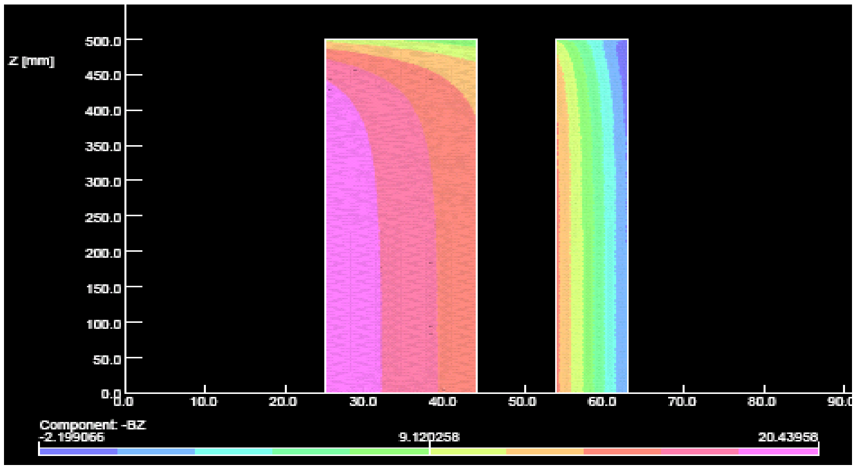


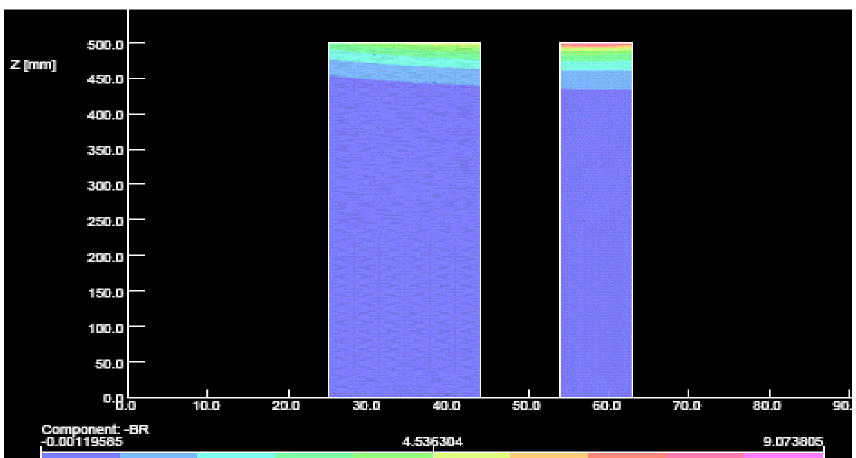
$w\sigma=Pr$

Case 2: Hybrid Magnet with Outer Nb_3Sn Coils and Inner HTS Coils



Hybrid Case with Outer Coils Made of Nb_3Sn and Inner Coils of HTS





- This case uses Nb_3Sn superconductor for the region where the field is less than 14 Tesla.
- The upper figure shows a contour plot of B_Z. The lower figure shows a contour plot of B_R.

Case 2: Summary of Parameters for Hybrid Magnet

Parameter	*Units*	*Inner*	*Outer*	*Total*
Total Current	Amp-turns	4.35×10^{6}	1.154×10^{6}	1.59×10^{6}
Stored Energy	Joules	1.51×10^{5}	9.26×10^{5}	1.076×10^{6}
Radial Force	Newtons	1.52×10^{7}	2.74×10^{7}	4.26×10^{7}
Upper Half Axial Force	Newtons	-1.57×10^{5}	-9.65×10^{5}	-1.156×10^{6}
Central Field	Tesla	5.45	14.39	19.83
$B_{eff}=\int B\,dl/L$	Tesla	5.45	14.43	19.88
R_{inner}	mm	25	54	25
R_{outer}	mm	44	63	63
Length	mm	1000	1000	1000
Stress	MPa	63.7	93.5	—

Maximum Stress determined by integrating radial force density.

Note that Inner and Outer Stored Energy are that part of the total energy associated to those coils. They are not that which comes from powering the coils separately.

Case 2 : Hybrid Magnet Radial Containment

- Based on the radial stress from the HTS we would require a stainless steel containment shell with thickness of 4 mm.
- Based on the radial stress from the Nb_3Sn we would require a stainless steel containment shell with thickness of 8.5 mm.

How High a Field Magnet Can We Make?

- We have estimates of what it will take to make a 20 Tesla magnet.
- Forces for these magnets scale as B^2.