A preliminary study of the target and capture channel for the Muon Collider

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SUMMARY

1. Starting from the hybrid solution of US-MAP [1-3] with 5 resistive coils and 19 SC coils (2.4 m bore) we compute for such design field on axis, field on coils, stresses etc.
   - Field on axis follows B-formula by Sayed-Berg [4] with wider plateau @ 20 T
   - Coils stresses/fields seems manageable
   - Large bore ➔magnetic energy (~3 GJ) and global forces
   - Coupling forces between resistive and SC coil set to be managed carefully

2. We develop an alternative solution with 18 SC coils (HTS), 1.2 m constant bore and engineering current density similar to (1) (i.e. max(J_E)≈40 A/mm^2):
   - Field on axis within 1% accuracy Sayed-Berg formula over 16 m channel length
   - Magnetic energy < 1 GJ
   - Advantages brought by HTS and smaller bore! However its feasibility needs verification (shielding?)

REFERENCES

1. R.J. Weggel, N. Souchlas, H.G. Kirk, V.B. Graves, K.T. McDonald, A TARGET MAGNET SYSTEM FOR A MUON COLLIDER AND NEUTRINO FACTORY, TUPS053 Proceedings of IPAC2011, San Sebastián, Spain
2. R.J. Weggel, N. Souchlas, H.K. Sayed, J.S. Berg, H.G. Kirk, X. Ding, V.B. Graves, K.T. McDonald, DESIGN OF MAGNETS FOR THE TARGET AND DECAY REGION OF A MUON COLLIDER/NEUTRINO FACTORY TARGET TUPFI073 Proceedings of IPAC2013, Shanghai, China
3. C. Rogers, Overview of target, capture and cooling complex, https://indico.cern.ch/event/1147941/
4. H.K. Sayed and J. S. Berg, Optimized capture section for a muon accelerator front end, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 070102 (2014)

HYBRID (NC+SC) DESIGN (US-MAP): Field, Forces and Stresses

Magnet	z_{min} (cm)	Δz (cm)	r_{min} (cm)	Δr (cm)	I (A/mm^2)
RC1	-131.3	47.3	17.8	30.24	16.56
RC2	-84	86.2	17.8	30.88	16.56
RC3	2.1	56.2	17.8	30.25	16.56
RC4	58.3	57	17.8	16.6	16.56
RC5	115.3	43.5	21.88	7.96	16.56
SC1	-222.6	169.4	120	75.85	23.22
SC2	-53.1	26.1	120	54	0
SC3	-27.1	327.1	120	54.07	23.1
SC4	310	65	110	1.16	29.96
SC5	385	65	100	20.76	33.31
SC6	460	65	90	6.4	35.85
SC7	535	65	80	8.71	38.21
SC8	610	65	70	5.61	40
SC9	685	65	60	6.06	40
SC10	760	65	50	4.72	40
SC11	835	65	45	4.6	40
SC12	910	65	45	4.42	40
SC13	985	65	45	4.31	40
SC14	1060	65	45	3.85	40
SC15	1135	65	45	3.83	40
SC16	1210	65	45	3.51	40
SC17	1285	65	45	3.53	40
SC18	1360	65	45	3.44	40
SC19	1435	140	45	3.24	40

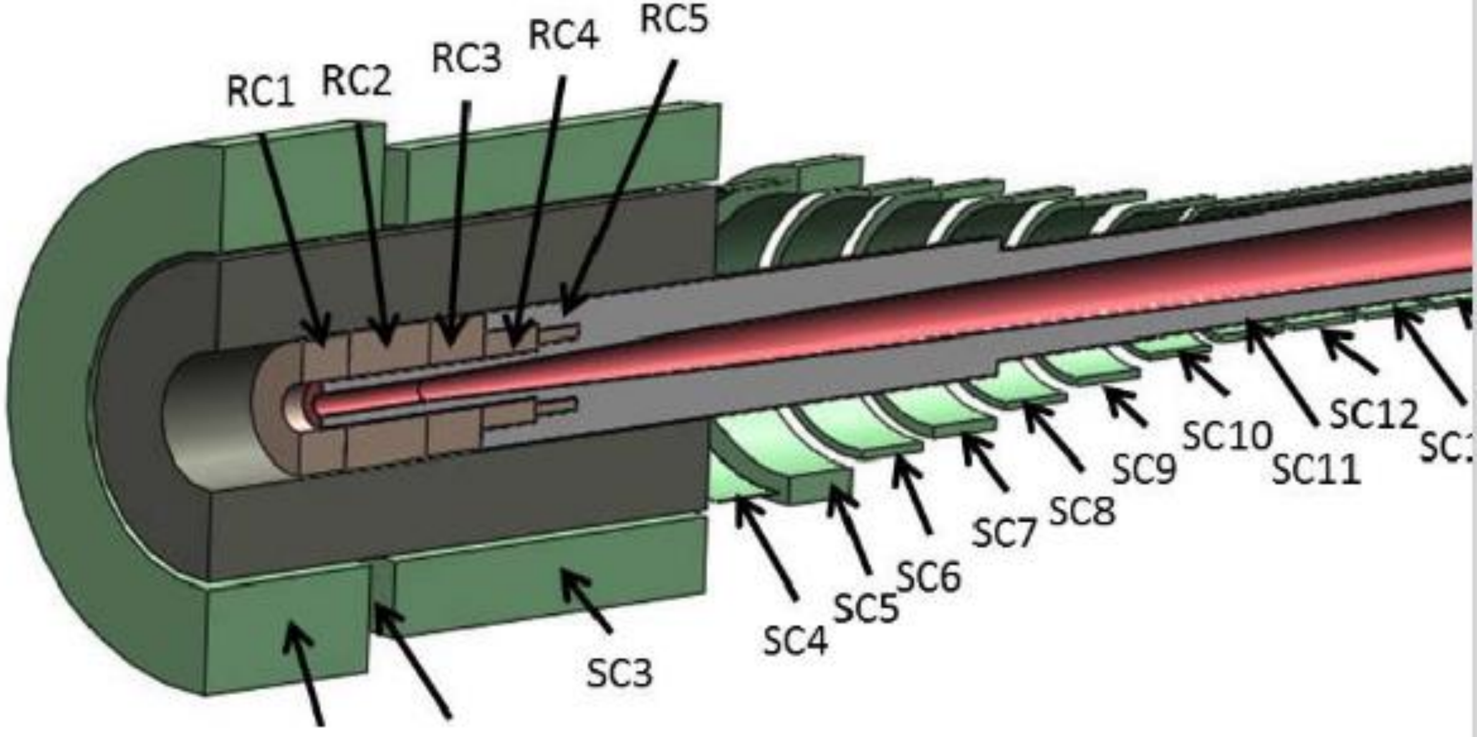
INPUT DATA

Resistive coils (5):

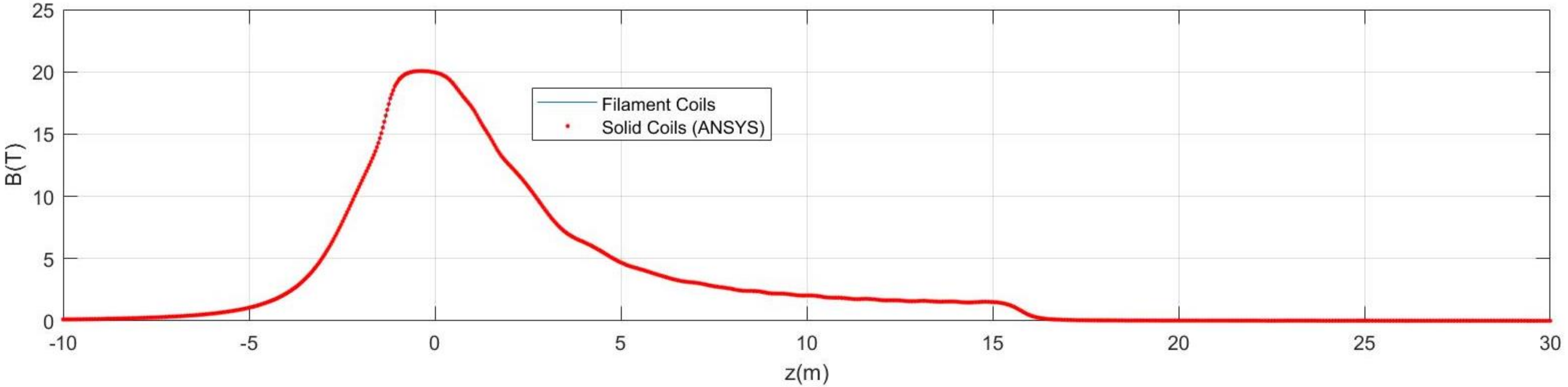
$R_{min} = 0.178$ m

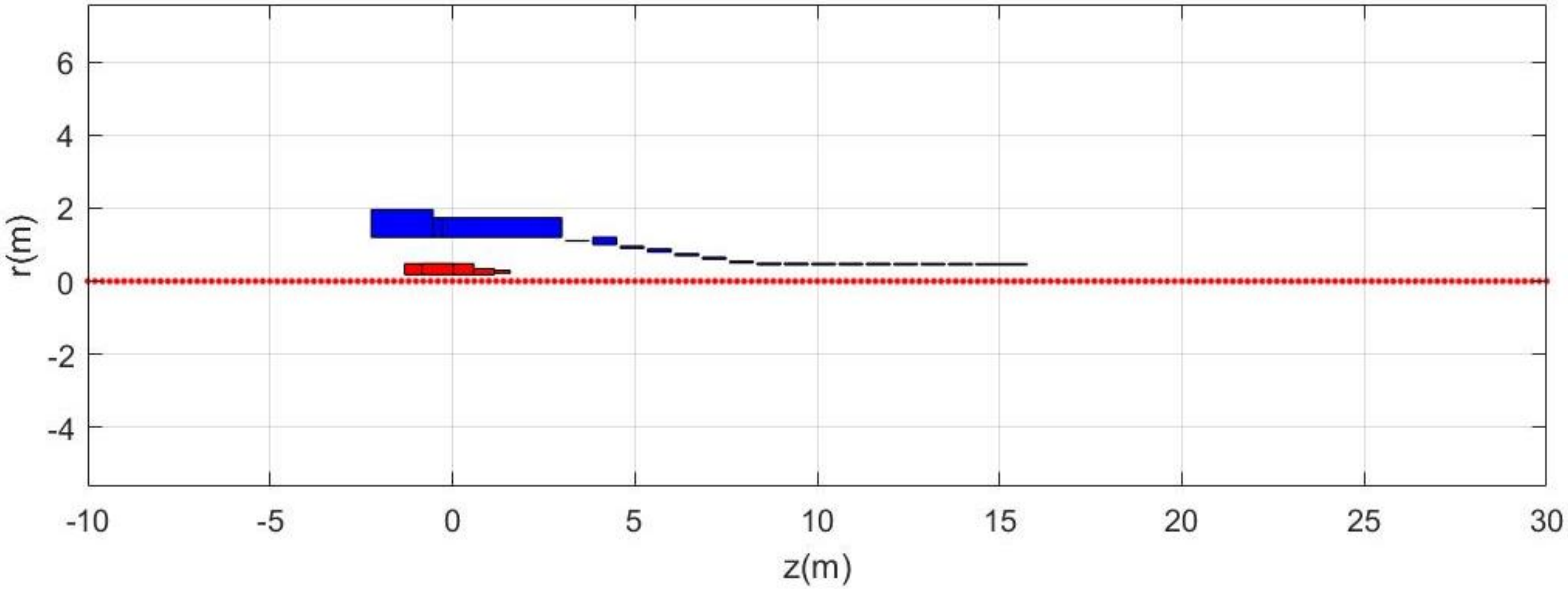
Superconducting coils (19):

$R_{min}^{(HF)} = 1.2$ m

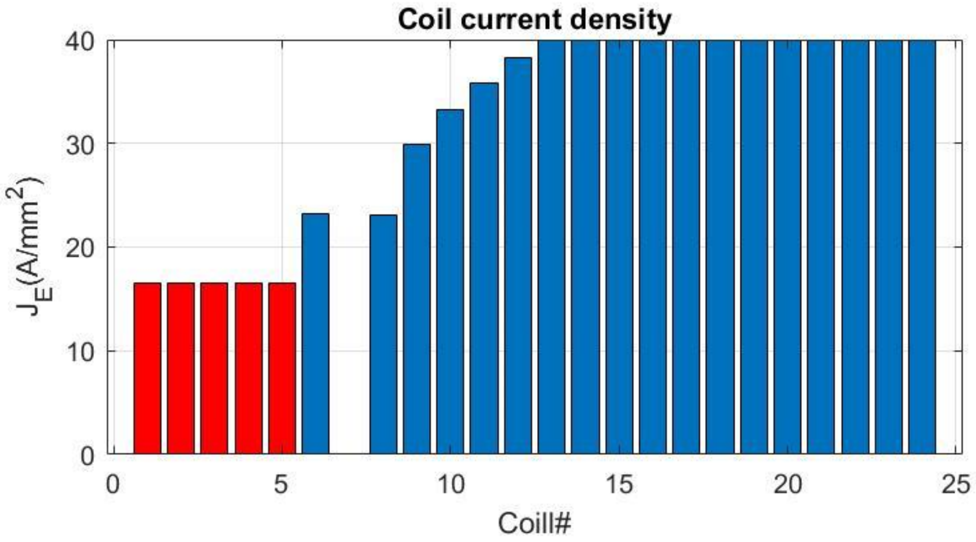


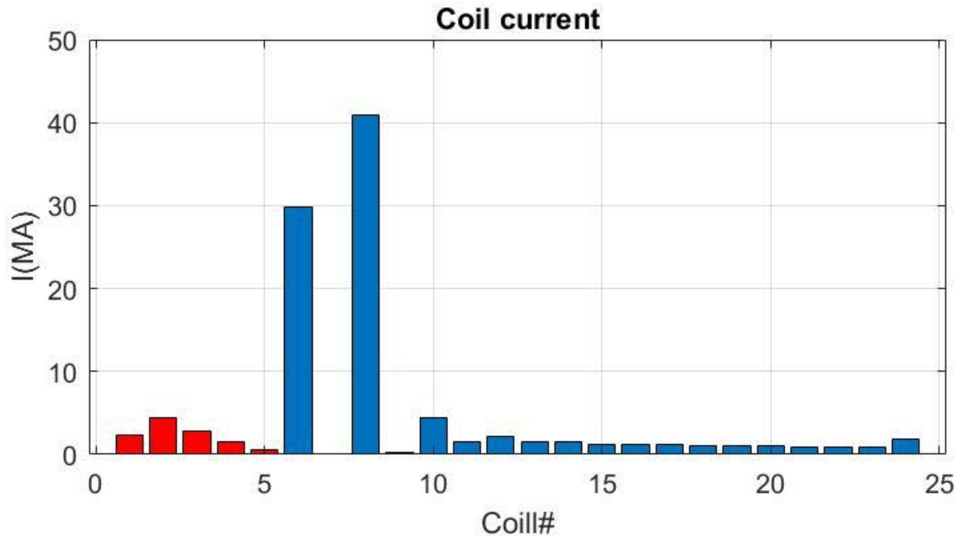
FIELD ON AXIS

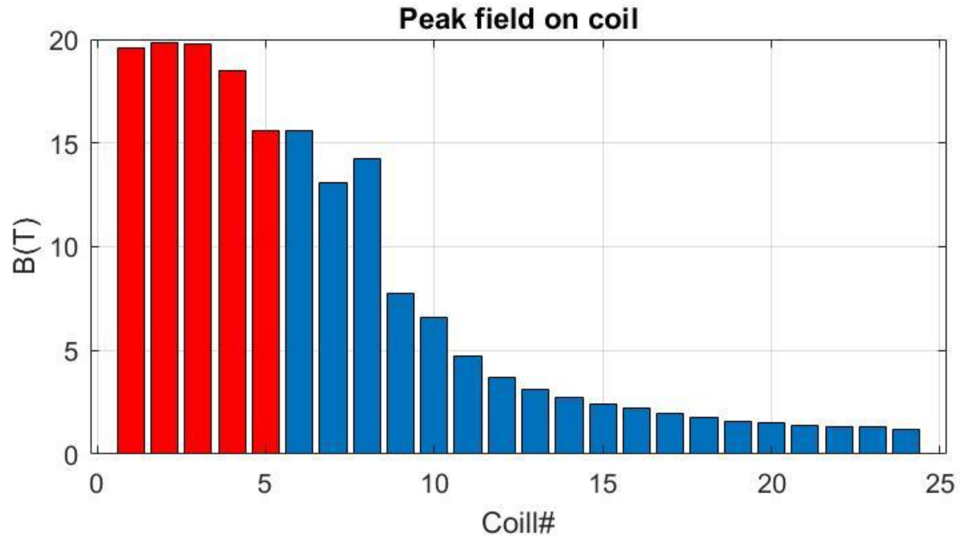


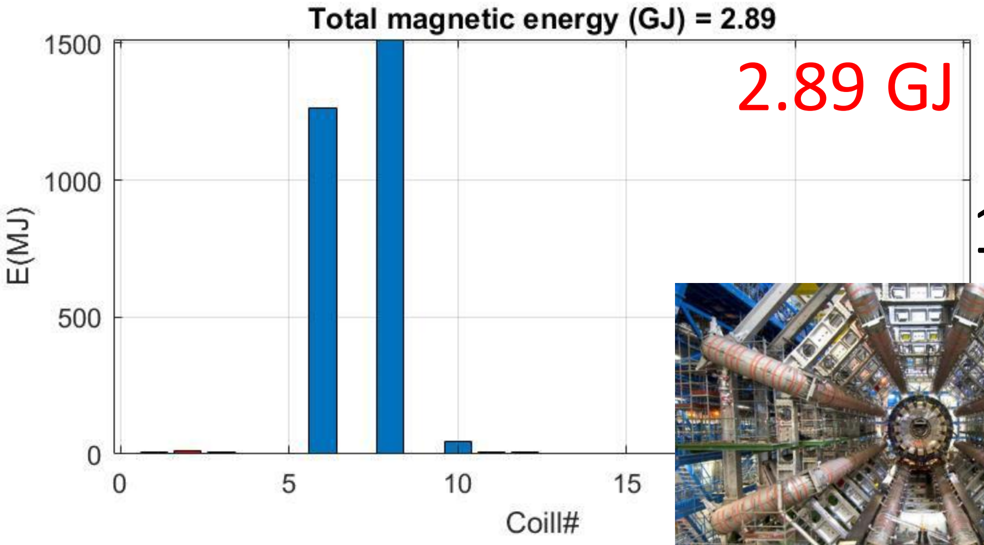


CURRENTS AND MAGNETIC ENERGY



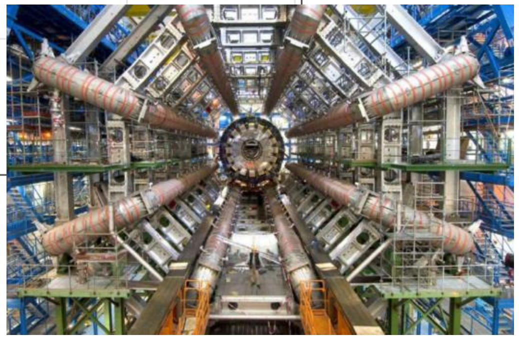






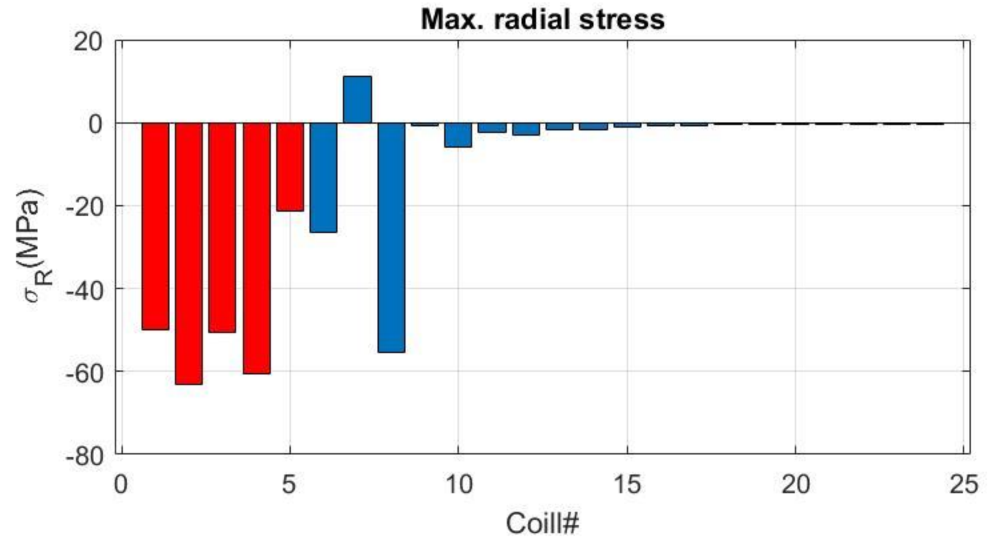
2.89 GJ

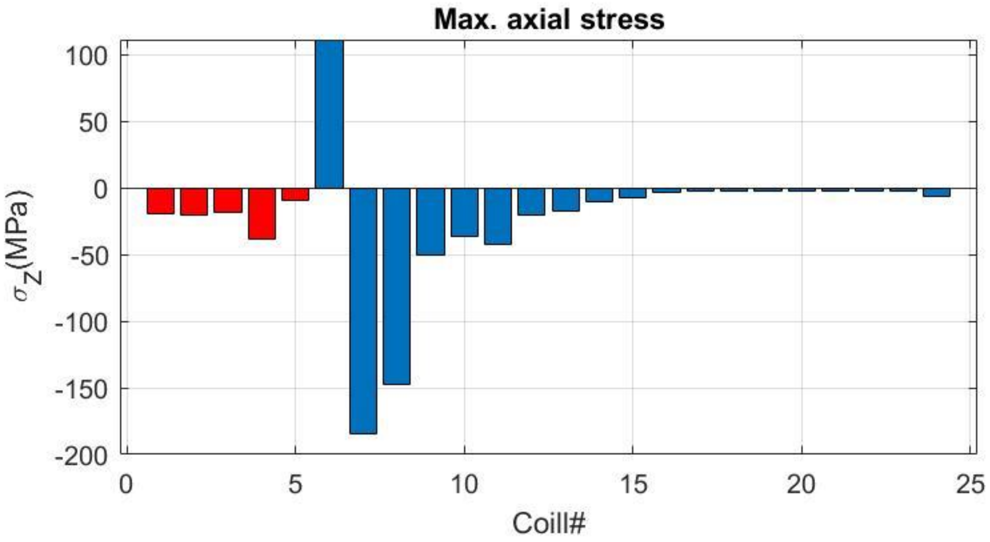
1.05 GJ

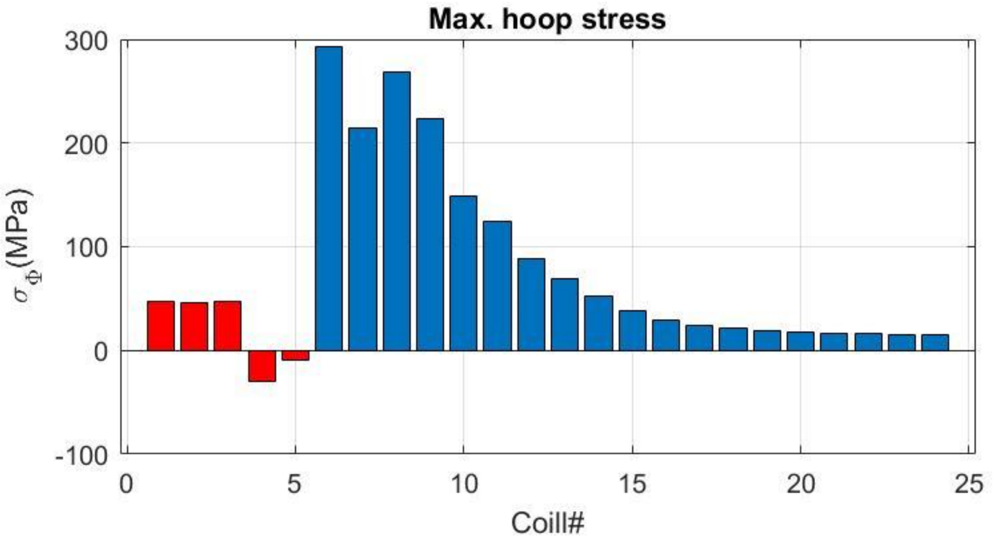


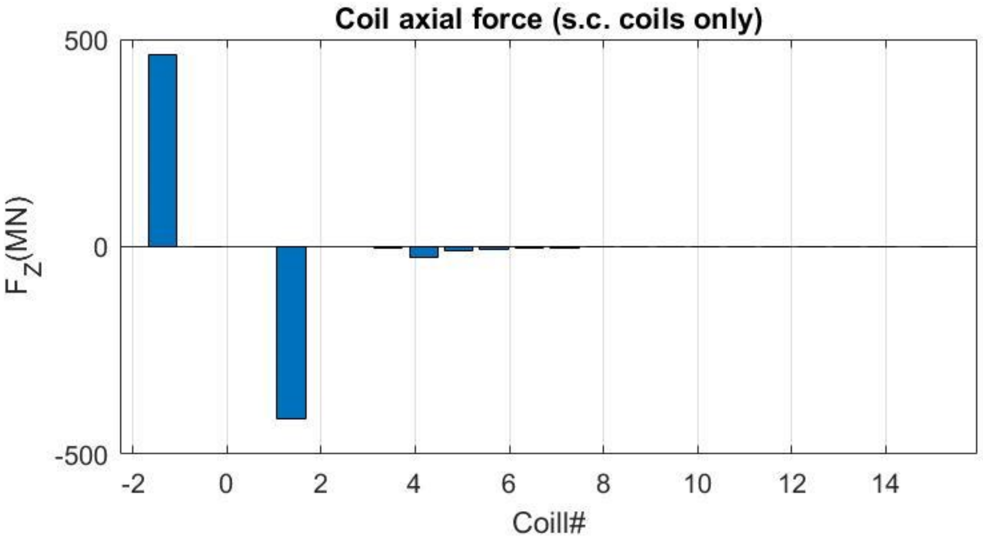
ATLAS main toroid

SMEARED STRESSES AND AXIAL FORCE

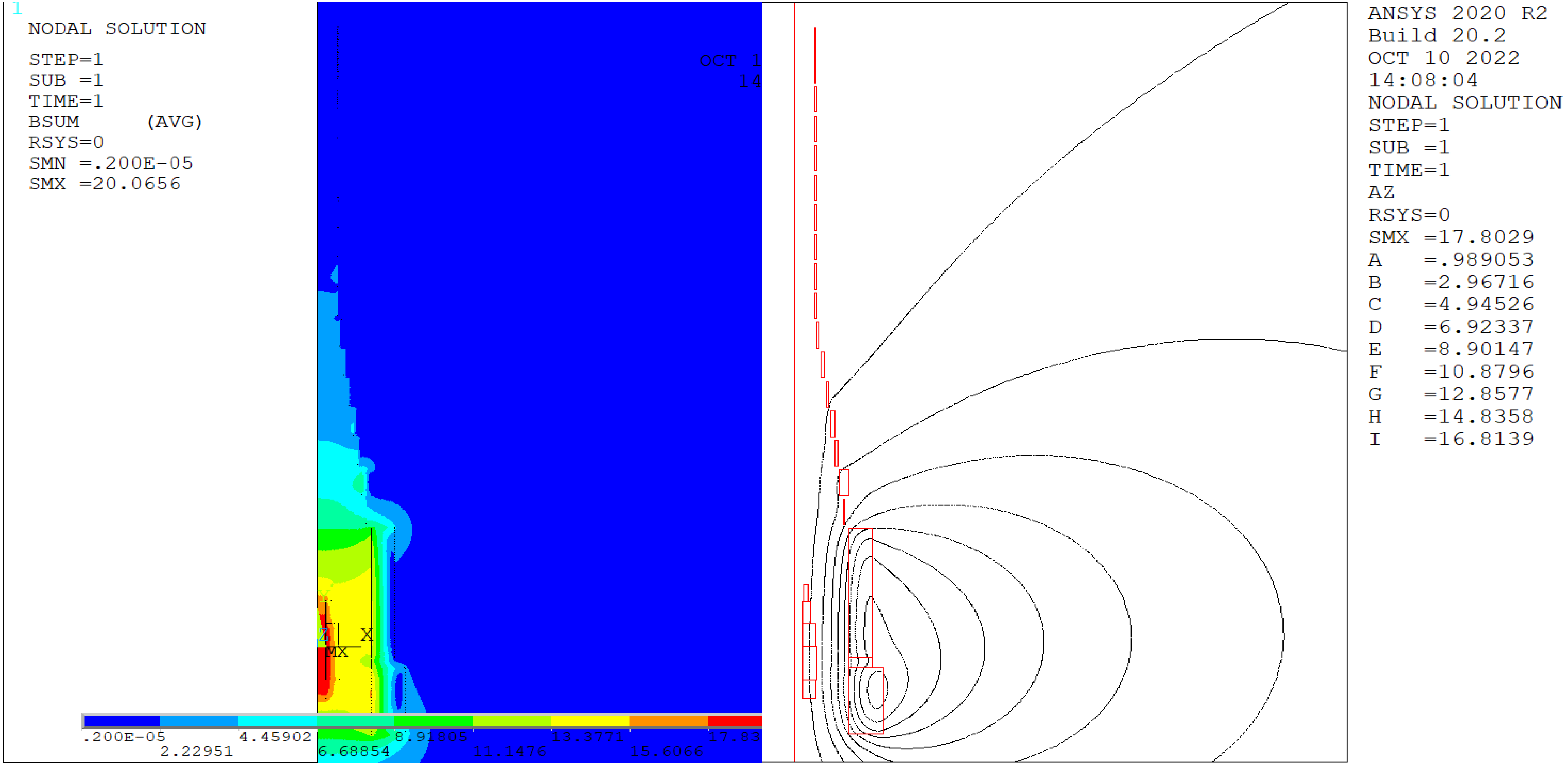


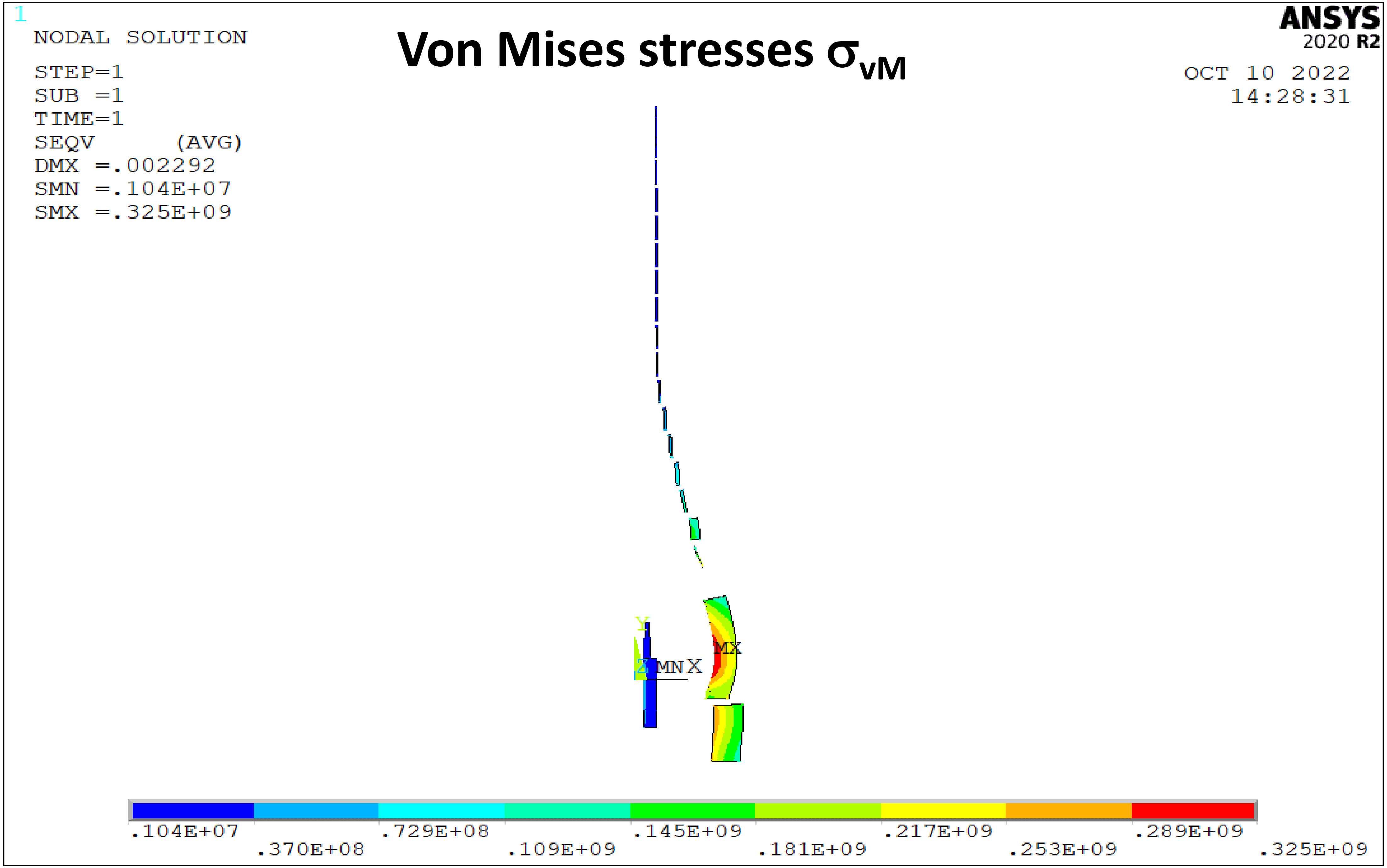






FIELD AND VECTOR POTENTIAL





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SMX =.325E+09
OCT 10 2022
14:28:31
Y
Z
MN
X
MX
.104E+07
.370E+08
.729E+08
.109E+09
.145E+09
.181E+09
.217E+09
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.289E+09
.325E+09

STRESSES


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OCT 10 2022
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Hoop stresses
σφ
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MN
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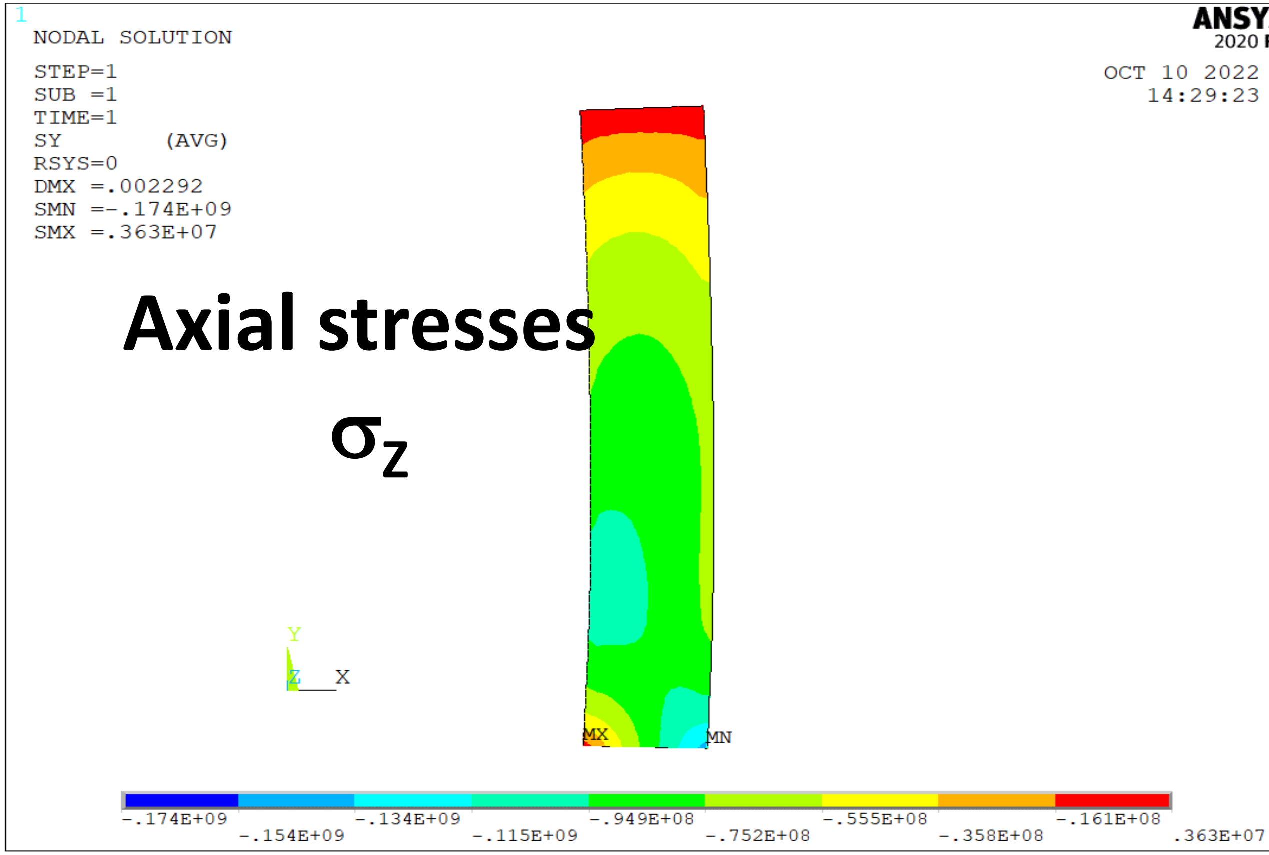
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-.161E+08
.363E+07

OUTPUT DATA

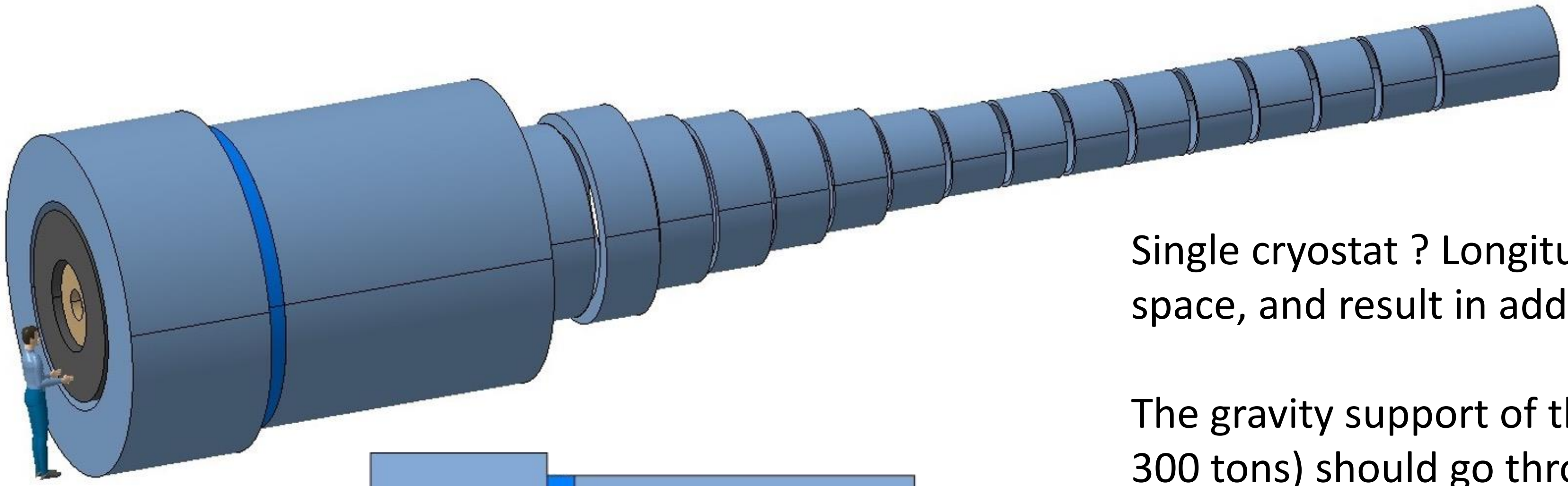
	Max B (T)	F_R (N)	Fz (N)	Max S_R (Pa)	Max S_Z (Pa)	Max S_φ(Pa)
Coil1	19.66	7.75E+07	4.20E+06	-5.65E+07	-2.41E+07	4.90E+07
Coil2	19.91	1.50E+08	2.08E+05	-5.32E+07	-2.88E+07	5.02E+07
Coil3	19.87	9.39E+07	-2.07E+06	-6.44E+07	-3.04E+07	4.95E+07
Coil4	18.59	4.05E+07	-1.30E+06	-7.64E+07	-3.63E+07	-3.34E+07
Coil5	15.88	1.34E+07	-5.35E+05	-3.30E+07	-1.47E+07	-1.43E+07
Coil6	15.33	1.54E+09	4.64E+08	-2.66E+07	1.14E+08	2.96E+08
Coil7	12.98	0.00E+00	0.00E+00	1.11E+07	-1.85E+08	2.10E+08
Coil8	13.84	2.14E+09	-4.14E+08	7.63E+07	-1.74E+08	2.70E+08
Coil9	7.79	8.07E+06	-2.59E+06	-2.18E+07	-4.34E+07	2.23E+08
Coil10	7.16	1.07E+08	-2.64E+07	-5.25E+06	-3.36E+07	1.52E+08
Coil11	5.02	2.66E+07	-8.57E+06	-1.22E+06	-4.04E+07	1.25E+08
Coil12	4.16	2.69E+07	-5.75E+06	-1.28E+06	-1.88E+07	9.10E+07
Coil13	3.32	1.33E+07	-2.74E+06	-9.30E+05	-1.53E+07	7.10E+07
Coil14	2.94	1.07E+07	-1.67E+06	-8.98E+05	-9.19E+06	5.29E+07
Coil15	2.55	6.18E+06	-7.66E+05	-7.64E+05	-6.78E+06	3.92E+07
Coil16	2.18	4.79E+06	-2.95E+05	-6.64E+05	-4.09E+06	2.96E+07
Coil17	1.84	3.98E+06	-1.57E+05	-5.79E+05	-3.23E+06	2.46E+07
Coil18	1.71	3.53E+06	-1.47E+05	-5.33E+05	-3.21E+06	2.22E+07
Coil19	1.58	2.85E+06	-1.04E+05	-4.37E+05	-2.63E+06	1.99E+07
Coil20	1.51	2.66E+06	-7.65E+04	-4.17E+05	-2.62E+06	1.85E+07
Coil21	1.41	2.27E+06	-5.70E+04	-3.52E+05	-2.22E+06	1.71E+07
Coil22	1.39	2.19E+06	-3.05E+04	-3.46E+05	-2.19E+06	1.64E+07
Coil23	1.34	2.04E+06	-4.42E+04	-3.24E+05	-2.20E+06	1.57E+07
Coil24	1.29	3.63E+06	-4.53E+05	4.67E+05	-6.91E+06	1.50E+07

Peak hoop stress:300 MPa

Peak axial force: 464 MN

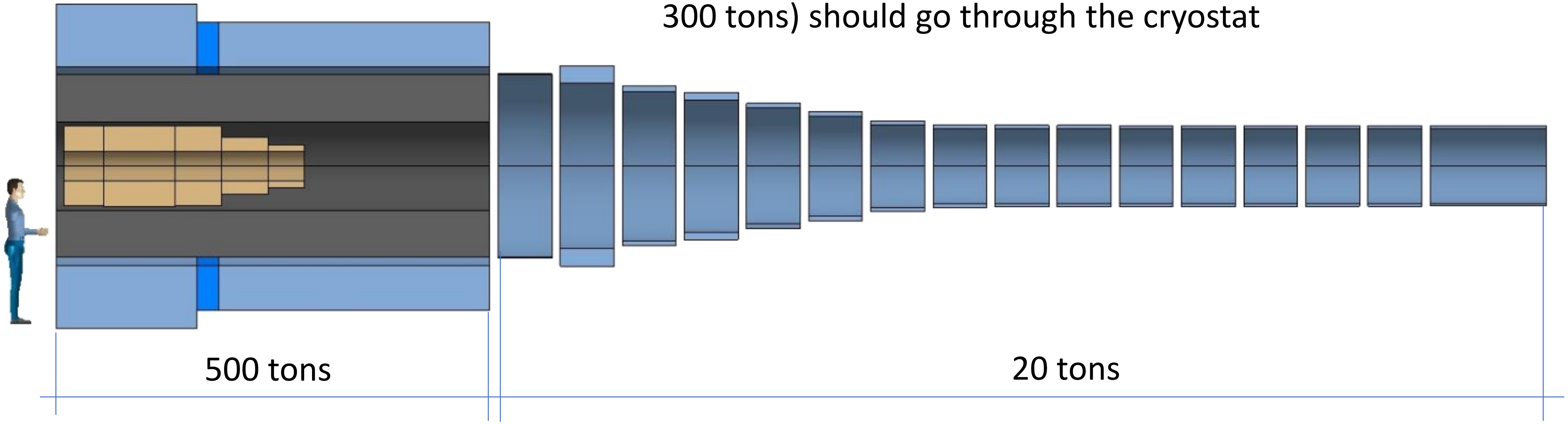
Cumulative axial force: ±464 MN

A 3D VIEW AND SOME ISSUES



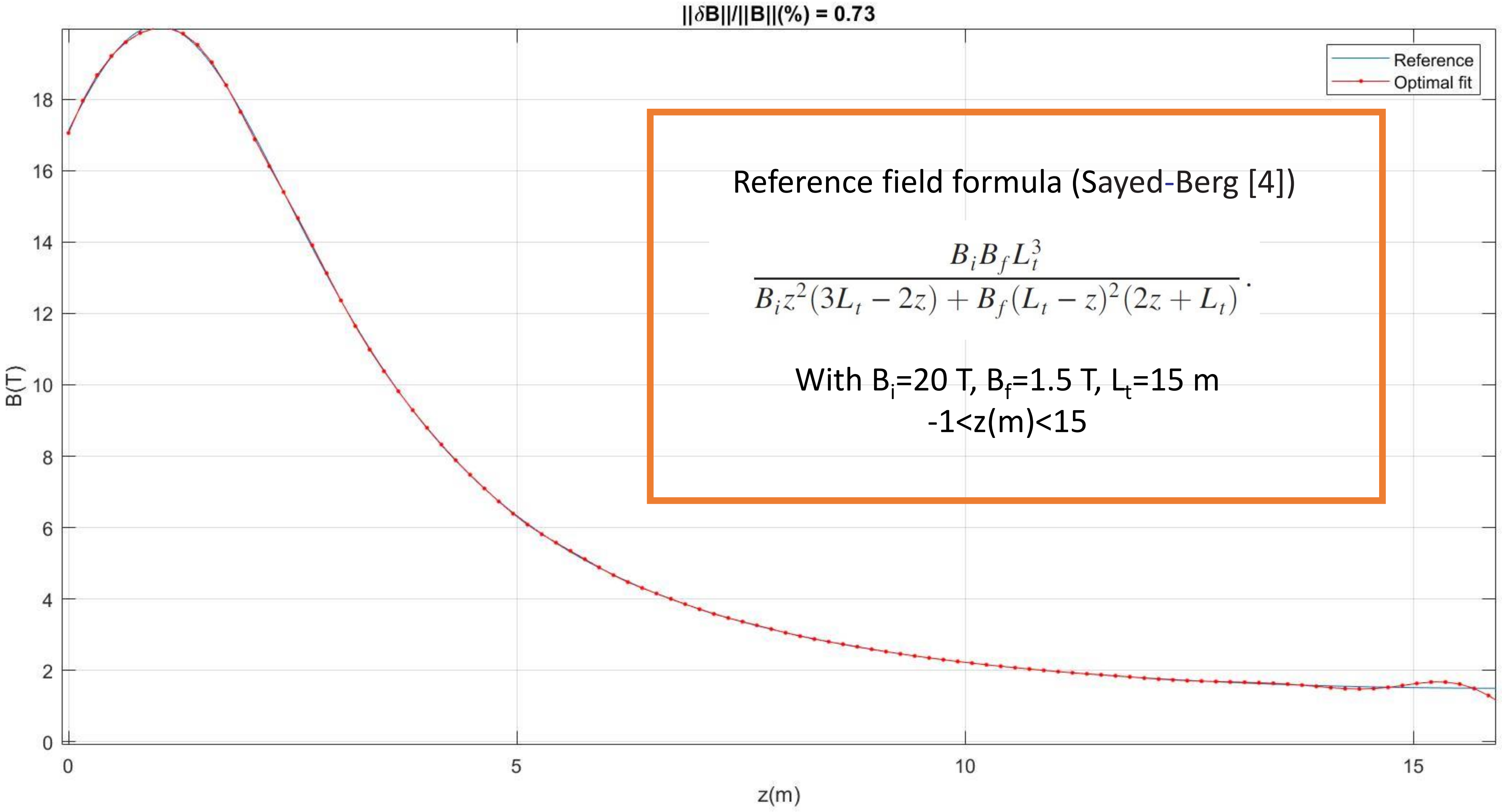
Single cryostat ? Longitudinal forces are significant, require space, and result in additional heat loads

The gravity support of the warm radiation shield (approx 300 tons) should go through the cryostat



HTS (PRELIMINARY) DESIGN:
Field, Forces and Stresses

OPTIMAL FIT OF FIELD ON AXIS



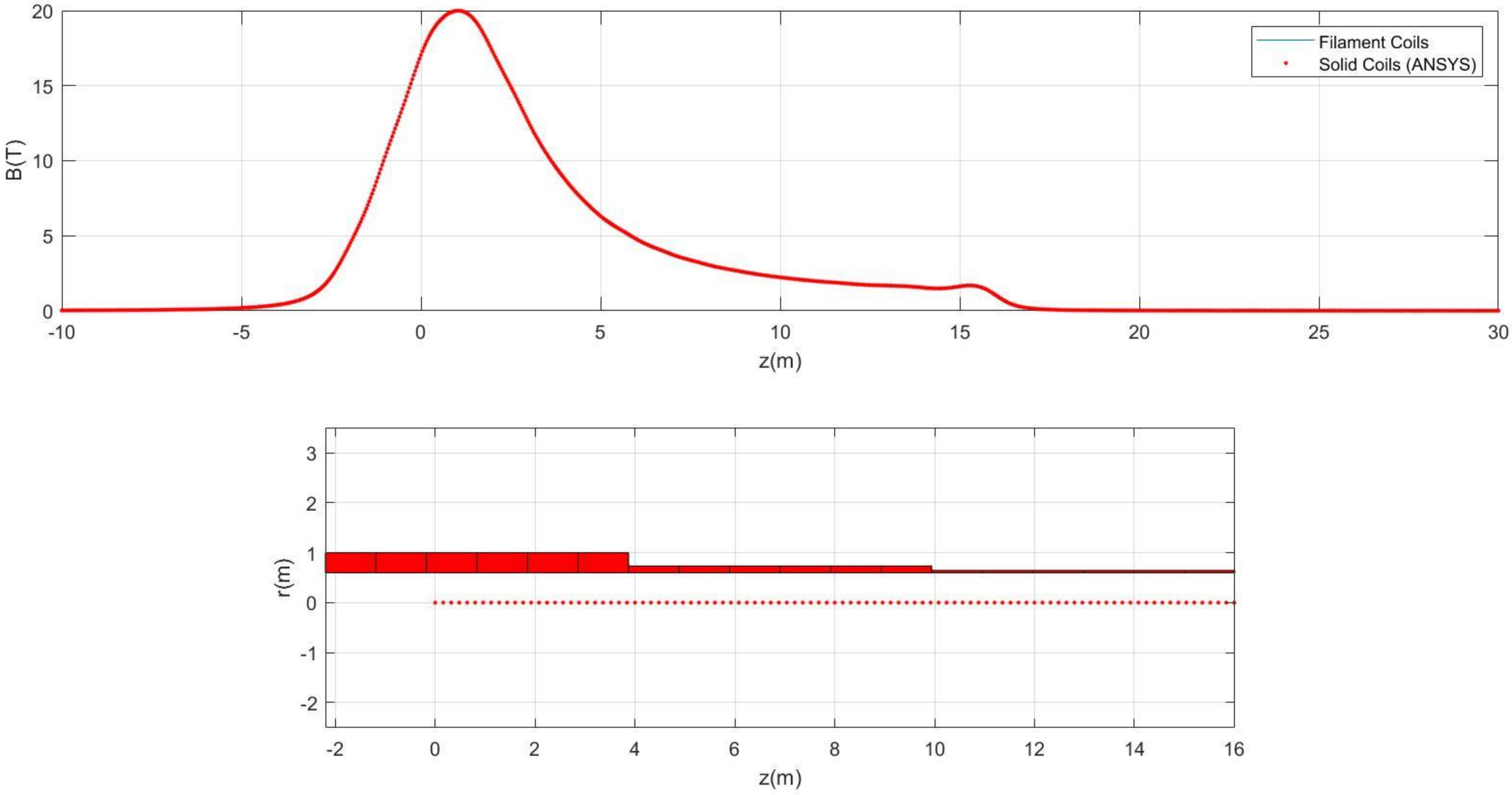
Reference field formula (Sayed-Berg [4])

$$\frac{B_i B_f L_t^3}{B_i z^2 (3L_t - 2z) + B_f (L_t - z)^2 (2z + L_t)}.$$

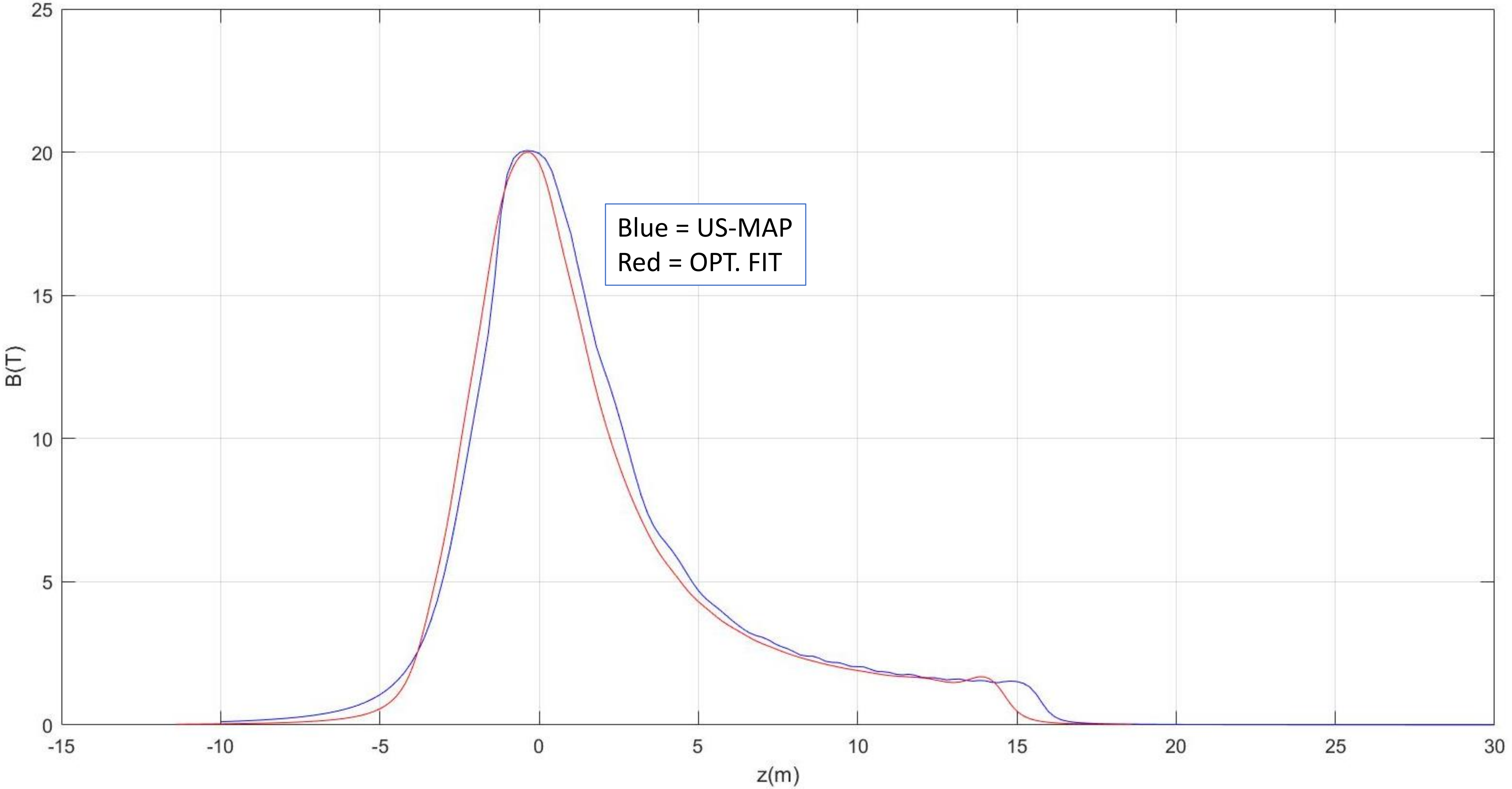
With B_i=20 T, B_f=1.5 T, L_t=15 m

$-1<z(m)<15$

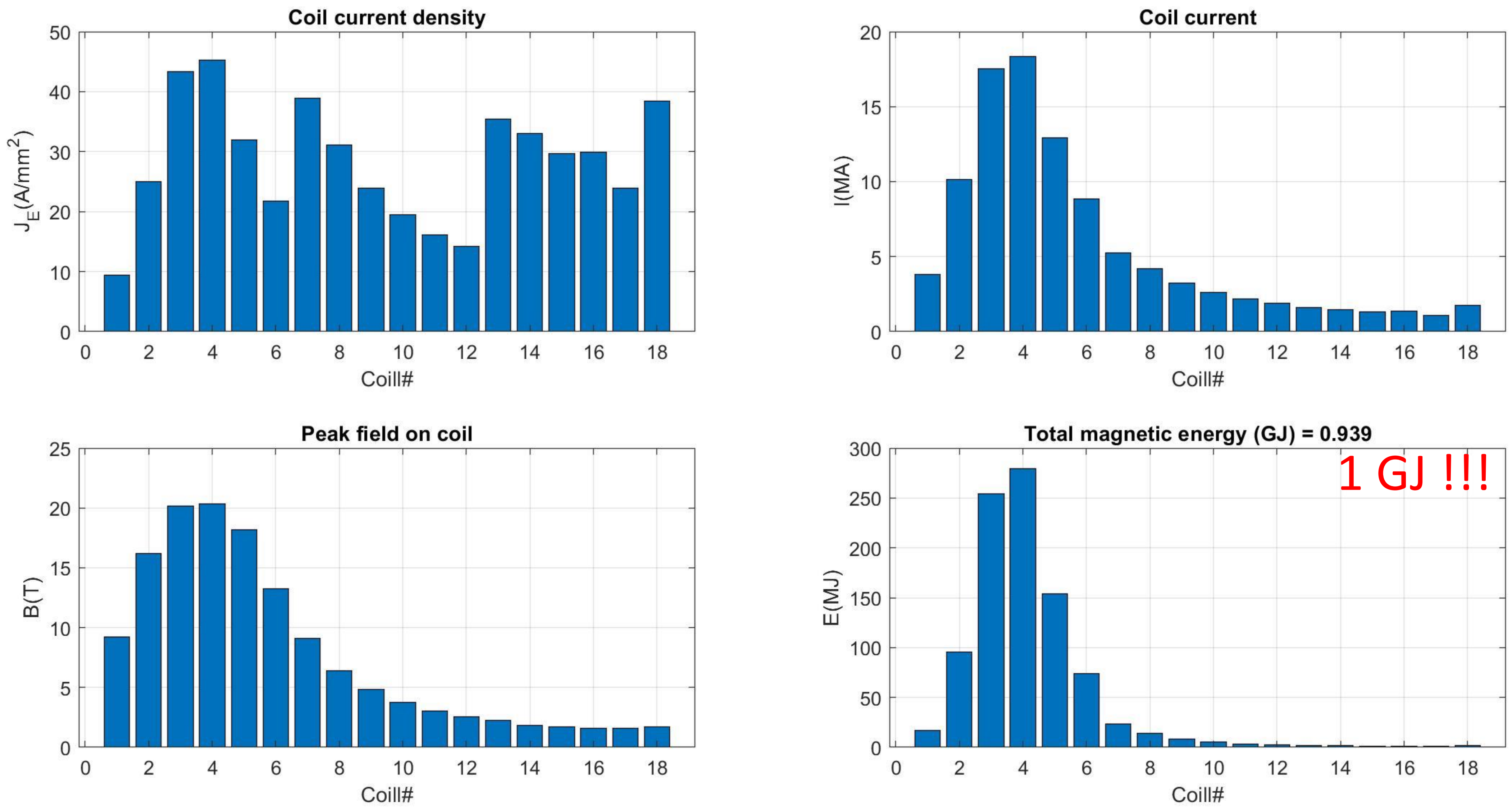
FIELD ON AXIS



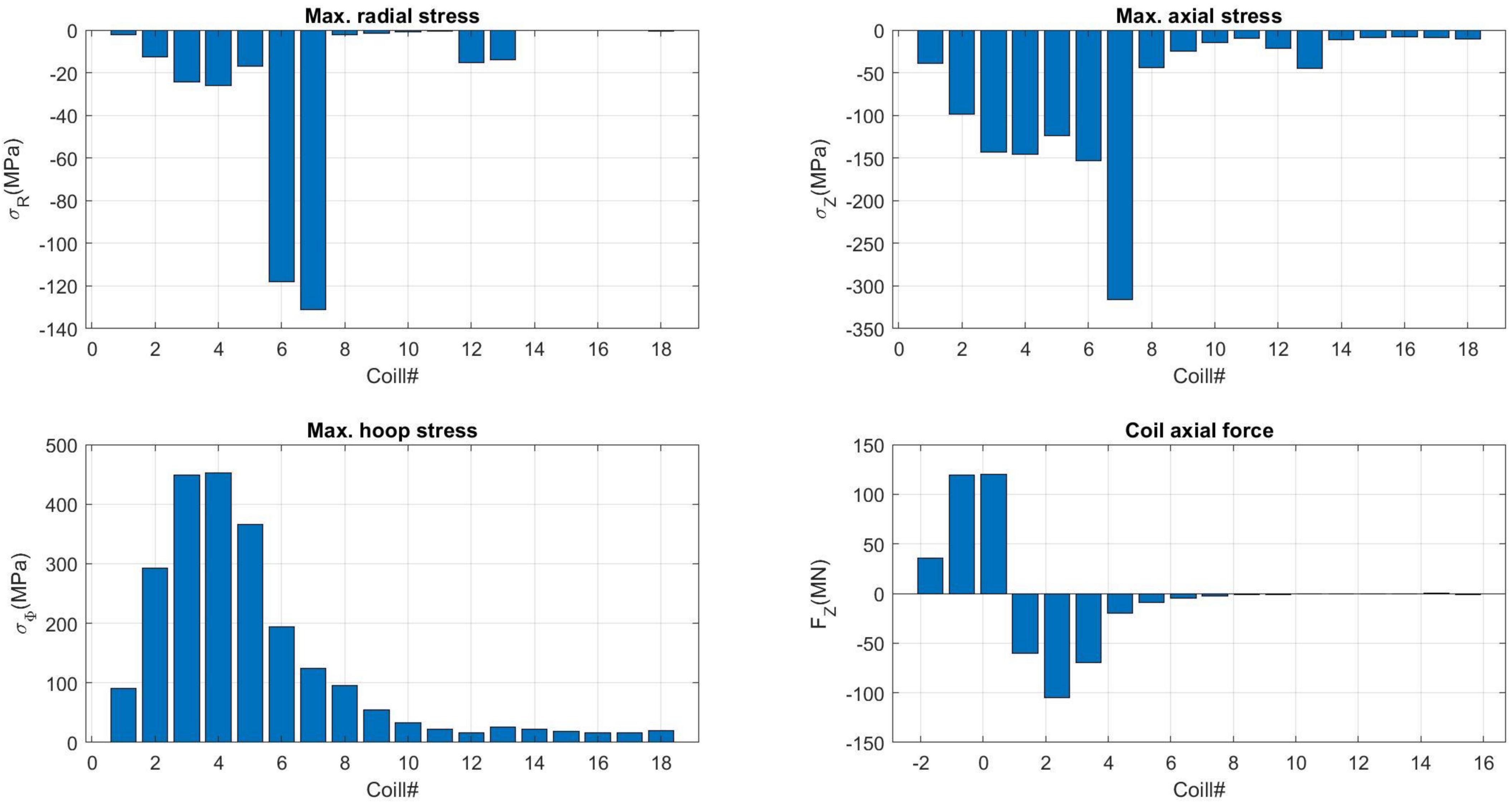
COMPARE FIELD ON AXIS



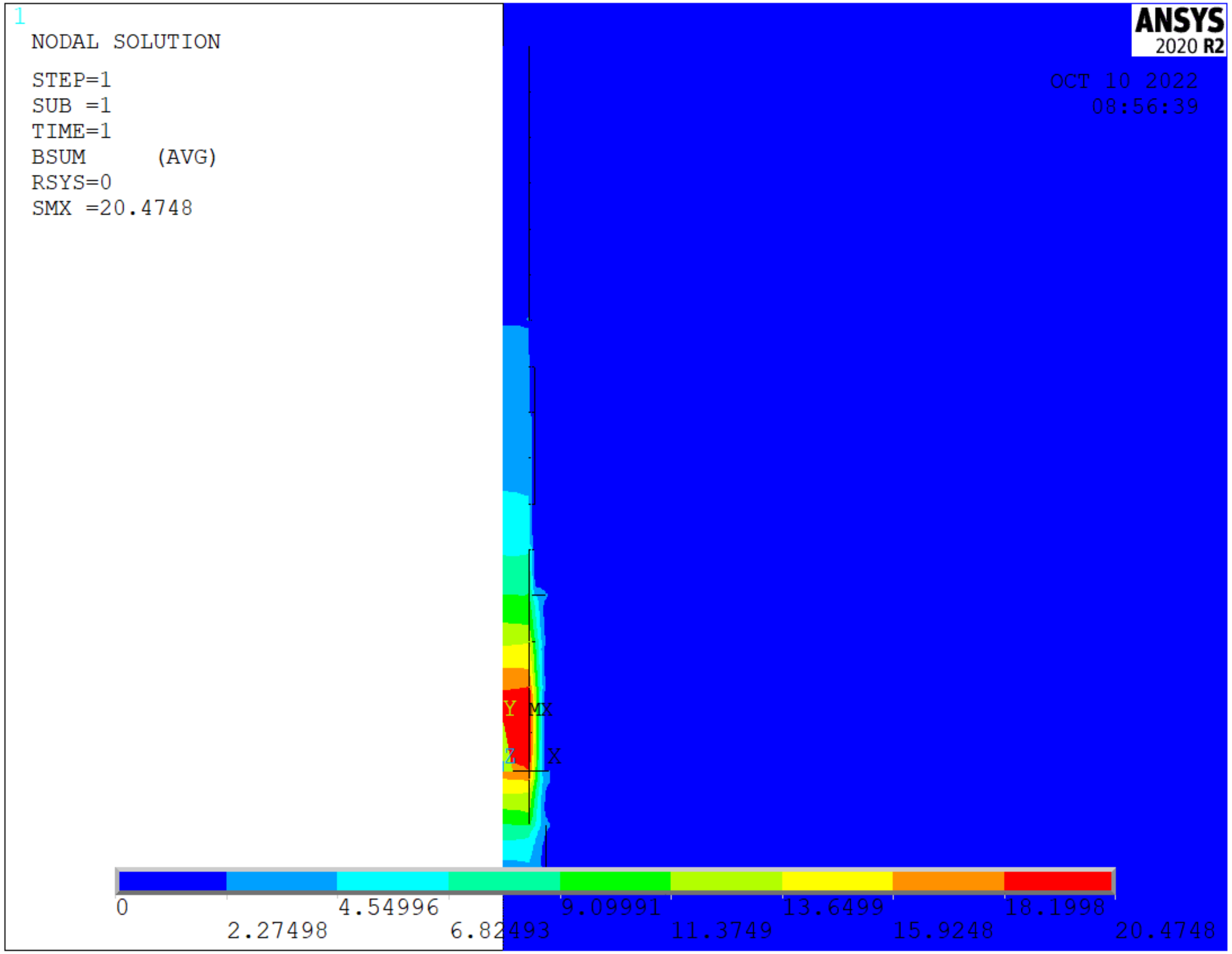
CURRENTS AND MAGNETIC ENERGY

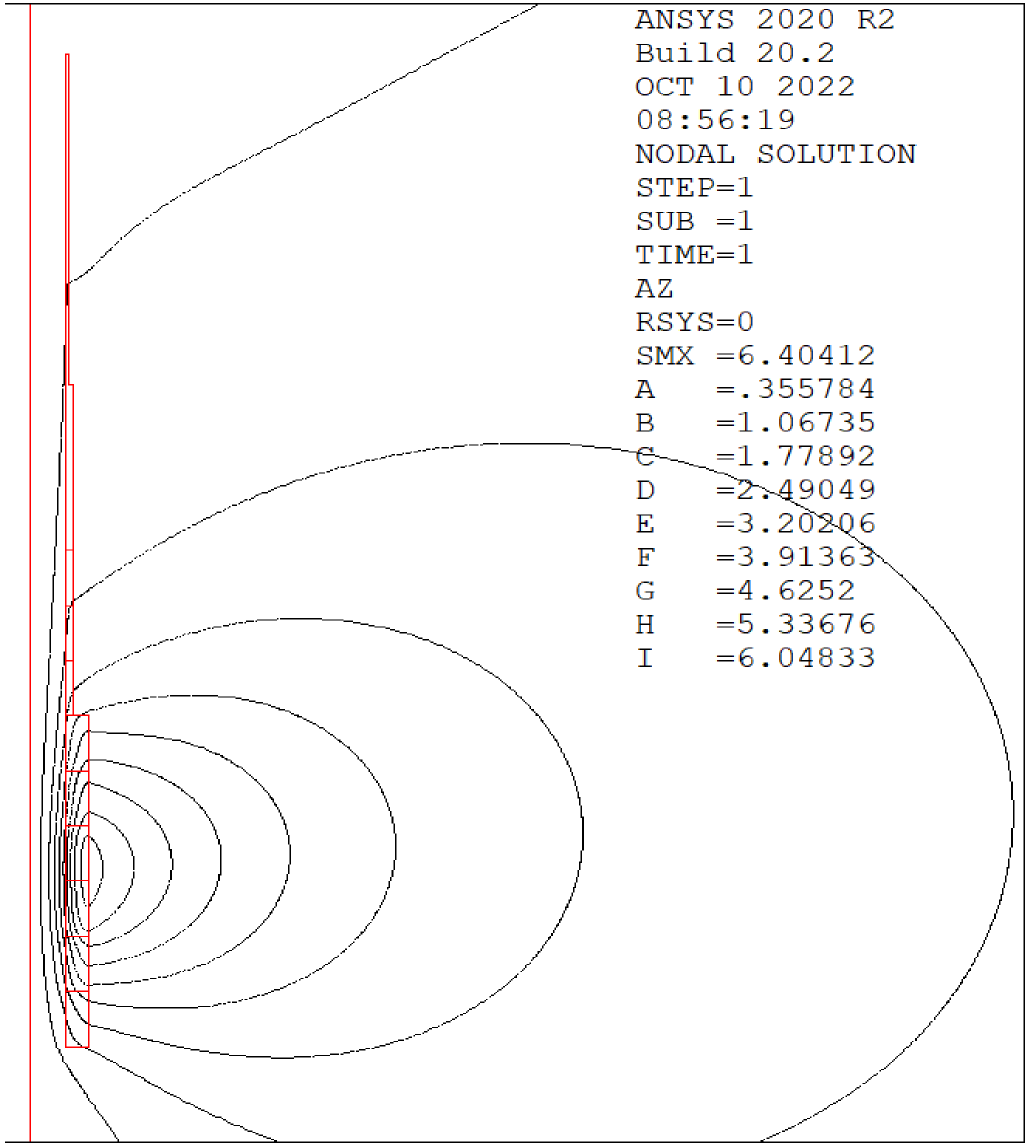


SMEARED STRESSES AND AXIAL FORCE

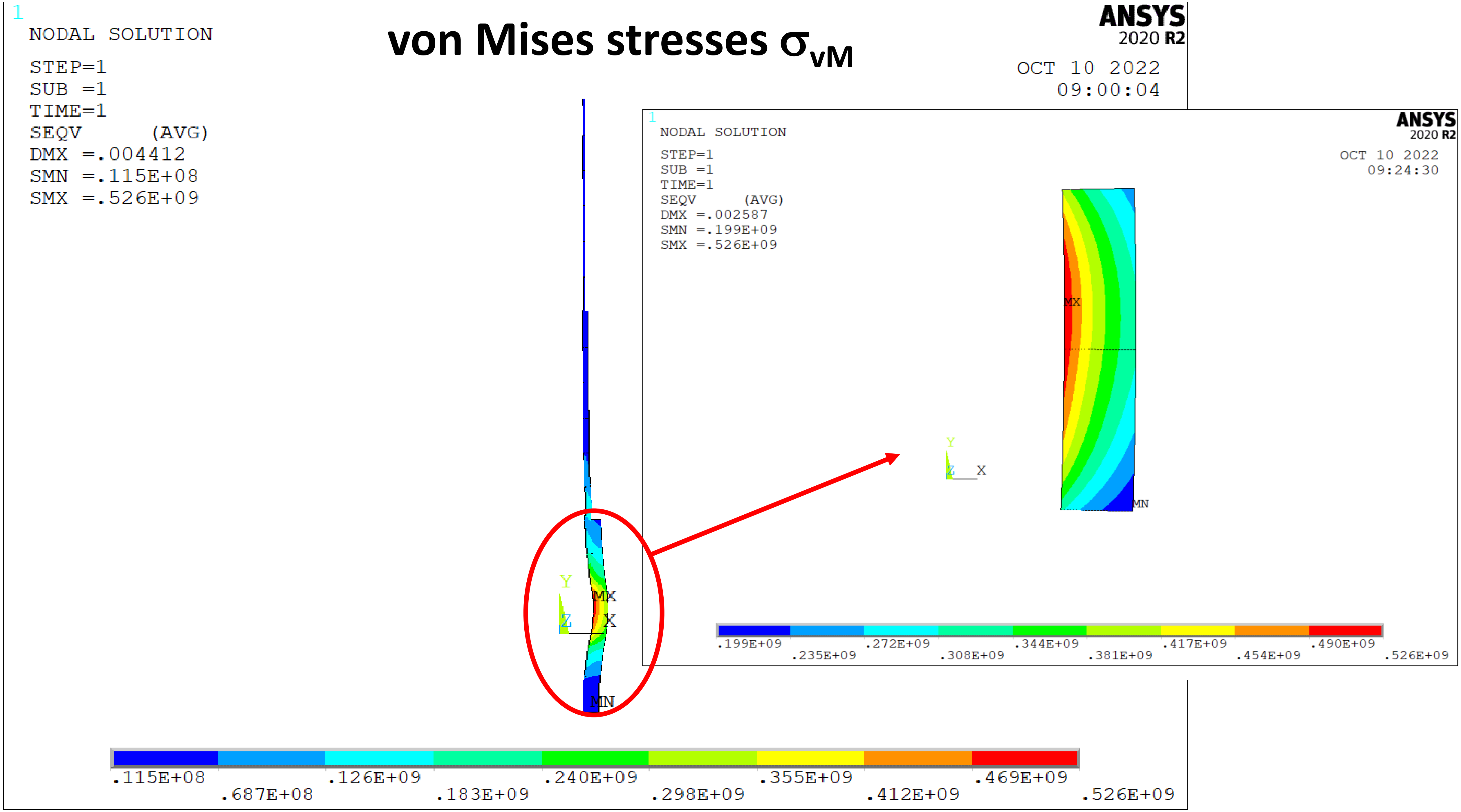


FIELD AND VECTOR POTENTIAL

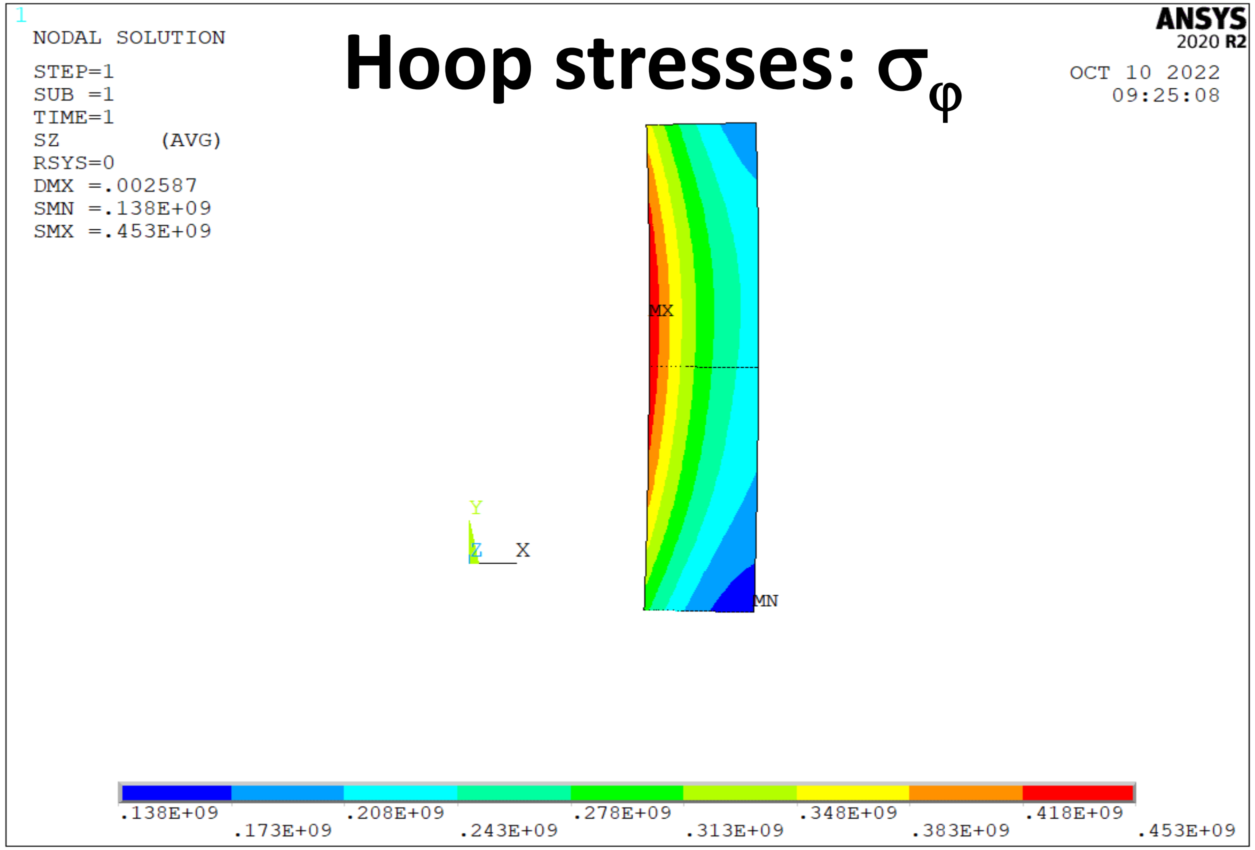




von Mises stresses σ_{vM}



STRESSES



Hoop stresses: σ_φ
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SMX =.453E+09
OCT 10 2022
09:25:08
MX
MN
Y
Z X
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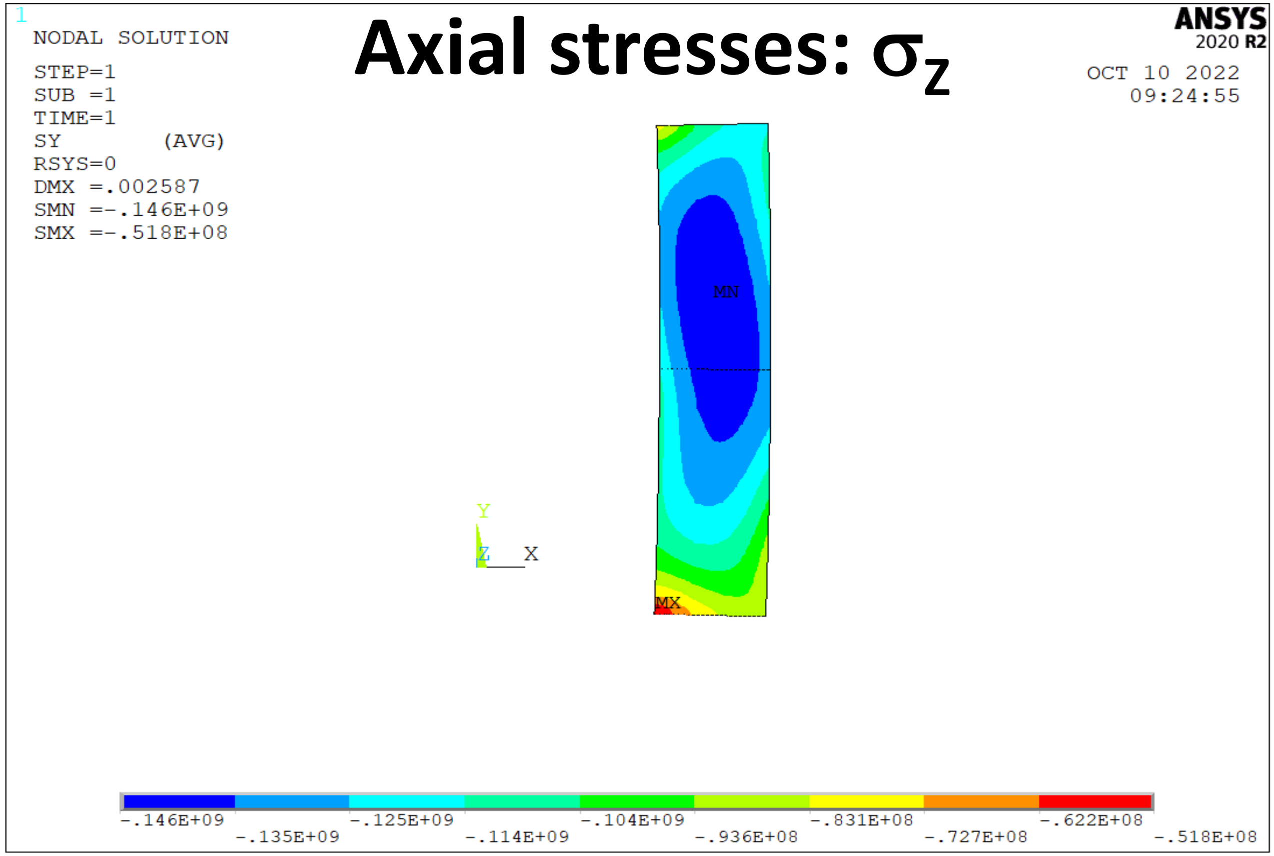

Axial stresses: σ_z
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OCT 10 2022
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Z X
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-.622E+08
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COILS OUTPUT DATA

	Rc(m)	Zc(m)	DR(m)	DZ(m)	I(MA)
Coil1	0.800	-1.694	0.400	1.012	3.820
Coil2	0.800	-0.682	0.400	1.012	10.124
Coil3	0.800	0.329	0.400	1.012	17.535
Coil4	0.800	1.341	0.400	1.012	18.321
Coil5	0.800	2.353	0.400	1.012	12.916
Coil6	0.800	3.365	0.400	1.012	8.825
Coil7	0.667	4.376	0.133	1.012	5.250
Coil8	0.667	5.388	0.133	1.012	4.203
Coil9	0.667	6.400	0.133	1.012	3.227
Coil10	0.667	7.412	0.133	1.012	2.621
Coil11	0.667	8.424	0.133	1.012	2.173
Coil12	0.667	9.435	0.133	1.012	1.909
Coil13	0.622	10.447	0.044	1.012	1.591
Coil14	0.622	11.459	0.044	1.012	1.485
Coil15	0.622	12.471	0.044	1.012	1.335
Coil16	0.622	13.482	0.044	1.012	1.343
Coil17	0.622	14.494	0.044	1.012	1.077
Coil18	0.622	15.506	0.044	1.012	1.728

Coil mass 111 tons

FIELD, FORCES AND SMEARED STRESSES

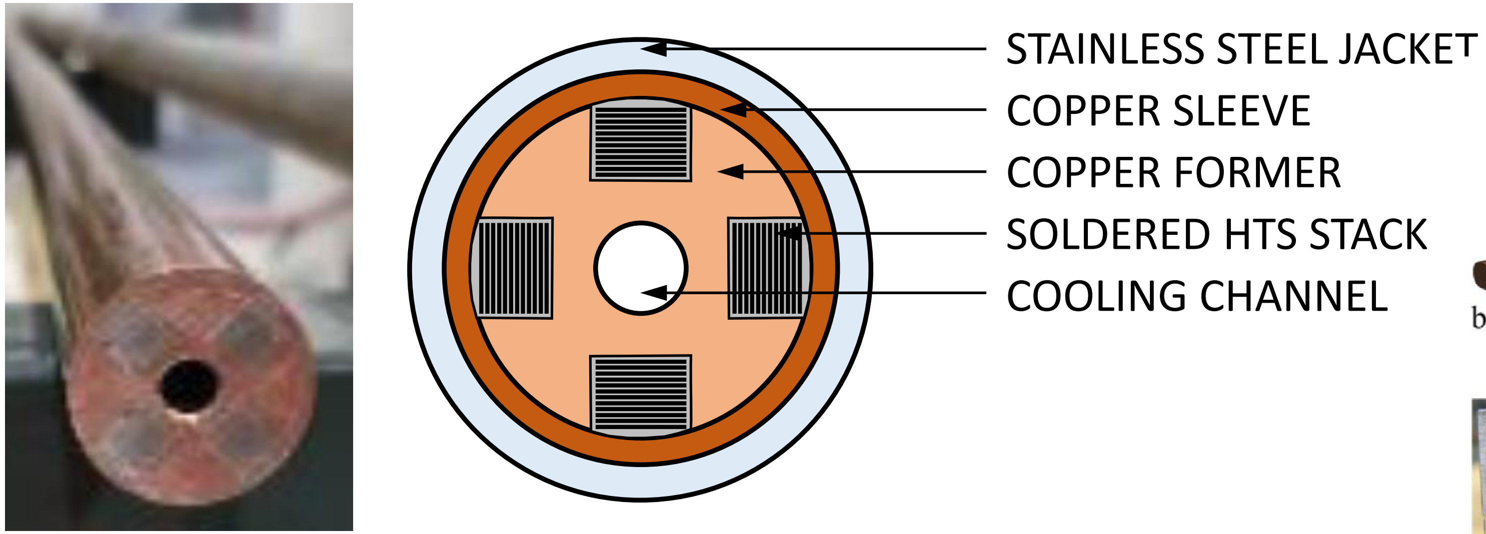
	Max B (T)	F_R (N)	Fz (N)	Max S_R (Pa)	Max S_Z (Pa)	Max S_φ(Pa)
Coil1	9.23	5.51E+07	3.57E+07	-2.04E+06	-3.93E+07	9.11E+07
Coil2	16.22	2.80E+08	1.19E+08	-1.26E+07	-9.83E+07	2.93E+08
Coil3	20.14	6.99E+08	1.20E+08	-2.42E+07	-1.43E+08	4.49E+08
Coil4	20.34	7.71E+08	-6.04E+07	-2.61E+07	-1.46E+08	4.53E+08
Coil5	18.16	4.46E+08	-1.05E+08	-1.68E+07	-1.24E+08	3.66E+08
Coil6	13.25	2.12E+08	-6.95E+07	-1.18E+08	-1.53E+08	1.94E+08
Coil7	9.08	9.62E+07	-1.96E+07	-1.31E+08	-3.16E+08	1.24E+08
Coil8	6.39	5.12E+07	-8.76E+06	-2.25E+06	-4.39E+07	9.52E+07
Coil9	4.84	2.96E+07	-4.54E+06	-1.44E+06	-2.48E+07	5.43E+07
Coil10	3.76	1.90E+07	-2.45E+06	-9.13E+05	-1.48E+07	3.29E+07
Coil11	3.05	1.29E+07	-1.40E+06	-6.20E+05	-9.77E+06	2.17E+07
Coil12	2.56	9.28E+06	-1.08E+06	-1.54E+07	-2.18E+07	1.64E+07
Coil13	2.24	6.97E+06	-5.23E+05	-1.38E+07	-4.46E+07	2.64E+07
Coil14	1.86	5.56E+06	-3.30E+05	-3.01E+05	-1.10E+07	2.28E+07
Coil15	1.69	4.52E+06	-1.79E+05	-2.50E+05	-9.15E+06	1.87E+07
Coil16	1.58	4.27E+06	-2.31E+05	-2.47E+05	-7.73E+06	1.64E+07
Coil17	1.59	3.14E+06	1.35E+05	-2.44E+05	-8.78E+06	1.63E+07
Coil18	1.74	4.97E+06	-1.22E+06	-4.17E+05	-1.03E+07	2.02E+07

Peak hoop stress: 453 MPa

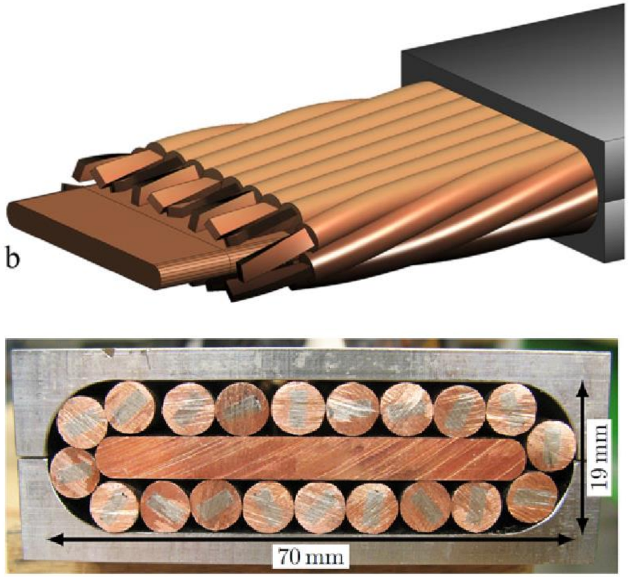
Peak axial force: 120 MN

Cumulative force: ±275 MN

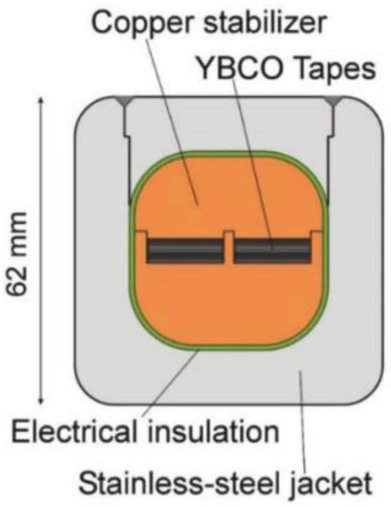
SUPERCONDUCTOR OPTIONS



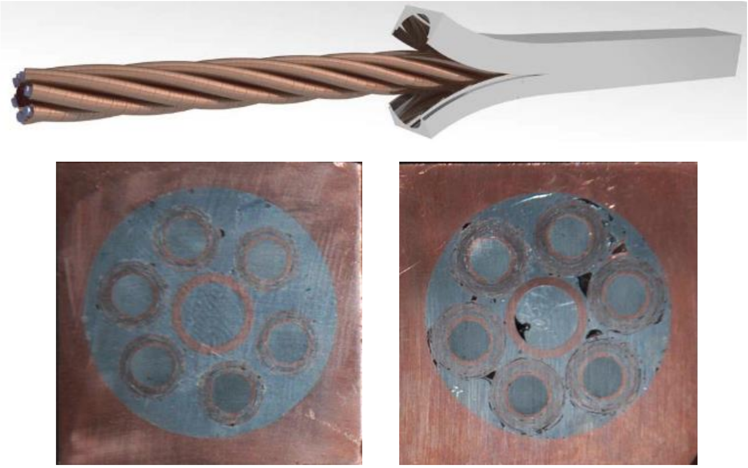
M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Zachary S Hartwig et al 2020 Supercond. Sci. Technol. 33 11LT01



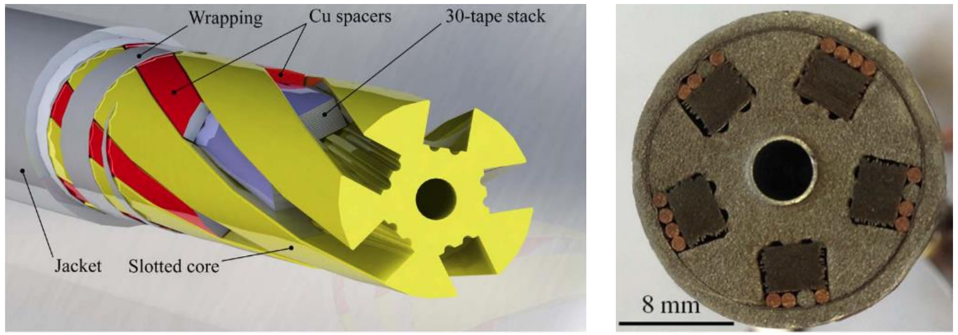
D. Uglietti et al 2015 Supercond. Sci. Technol. 28 124005



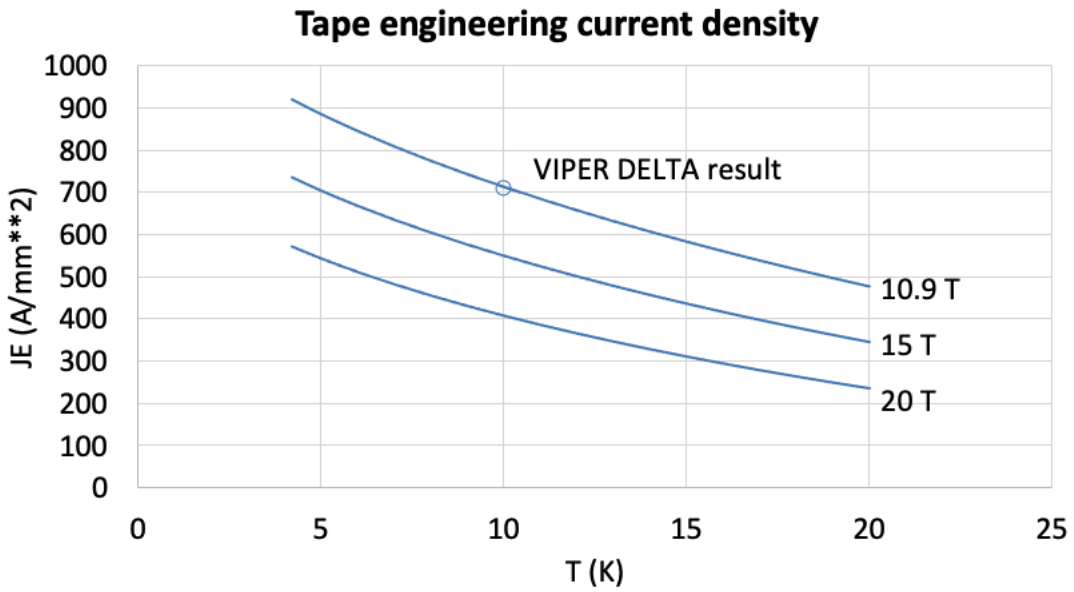
Y. Nagato et al., Nucl. Fus., 55 (2015) 053021

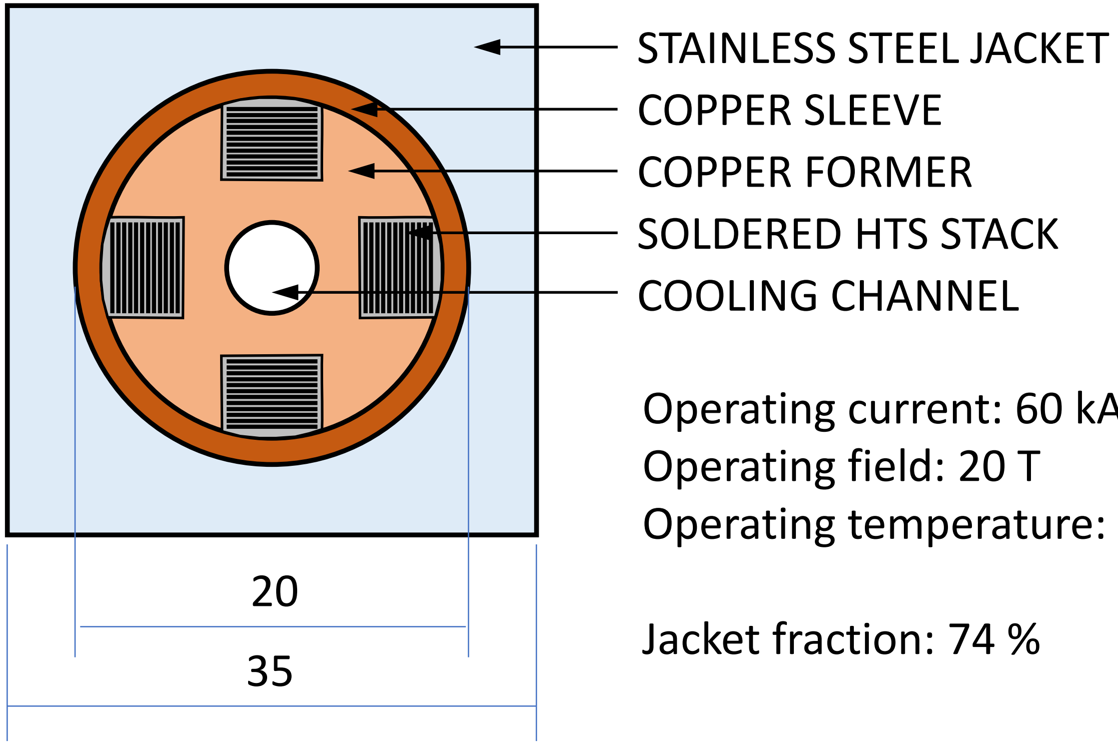


T. Mulder et al., IEEE TAS, 26 (2016), 4803605



G. Celentano et al., IEEE TAS, 24 (2014), 4601805





Operating current: 60 kA
Operating field: 20 T
Operating temperature: 20 K

Jacket fraction: 74 %

MUCOL TARGET SOLENOID CABLE		
Copper diameter	0.02	(m)
Hole diameter	0.006	(m)
Jacket outer dimension	0.035	(m)
HTS stack width	0.006	(m)
HTS stack thickness	0.006	(m)
number of stacks	4	(-)
A non-Cu	0.000144	(m^2)
A hole	0.000028	(m^2)
A Cu	0.000142	(m^2)
A Jacket	0.000911	(m^2)
A cable	0.001225	(m^2)
f non-Cu	0.12	(-)
f Cu	0.12	(-)
f Jacket	0.74	(-)
JE non-Cu (20 K 20 T)	400	(A/mm^1)
JE cable (20 K, 20 T)	47	(A/mm^1)
JE Cu (20 K, 20 T)	406	(A/mm^1)

Conclusions

- There are many magnetic configurations that provide a suitable B(s) profile in the target and capture section. We explored one possible choice based on:
  - Modular magnetic configuration (constant bore, identical coil geometry) to simplify the magnet
  - Use of HTS to provide the desired field, avoiding the resistive insert, and operating at temperature higher than liquid helium (virtual increase in COP by a factor 4)

- We found that the system mass and stored magnetic energy can be reduced (by a factor 2), as well as the cumulative attractive force between coils (by a factor 1.75)

- This looks interesting enough to follow-up. The suitability of this variant needs to be studied further, integrating beam, target, shielding, cryogenic and vacuum requirements