Target and capture solenoids

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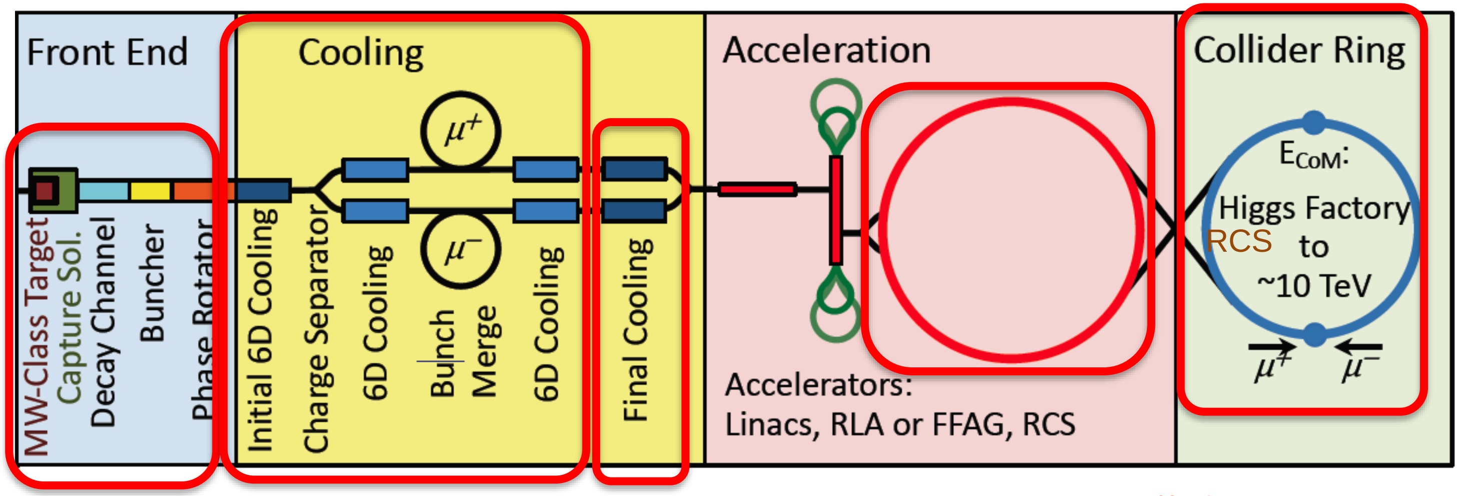
IMCC Annual Meeting, Orsay 19-22 June

Muon Collider magnet "specs"

Target solenoids
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD



Final Cooling solenoids
Field: > 40 T (ideally 60 T)
Bore: 50 mm
Length: ≈ 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

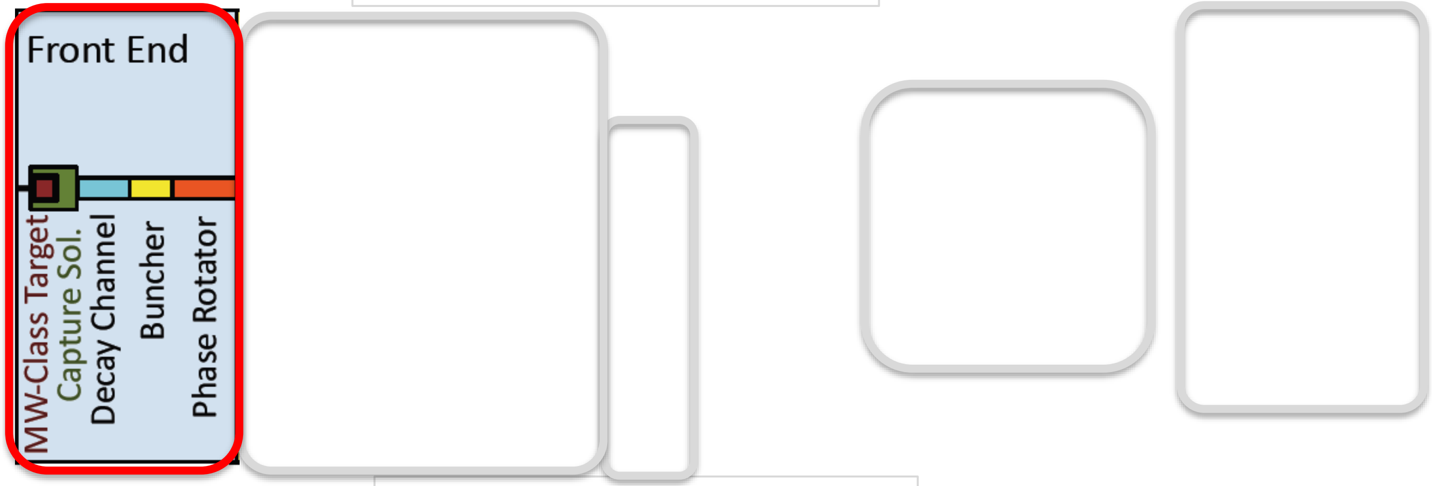
Collider ring magnets
Field: 16 T peak (IR 20 T)
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy

Target and Capture: Magnet specifications

MAGNET SPECS
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD



MAGNET TEAM
CERN (Antti, Carlotta, Luca)
F4E (Alfredo, Jose’, Pietro)

Final Cooling solenoids
Field: > 40 T (ideally 60 T)
Bore: 50 mm
Length: ≈ 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

Collider ring magnets
Field: 16 T peak (IR 20 T)
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy

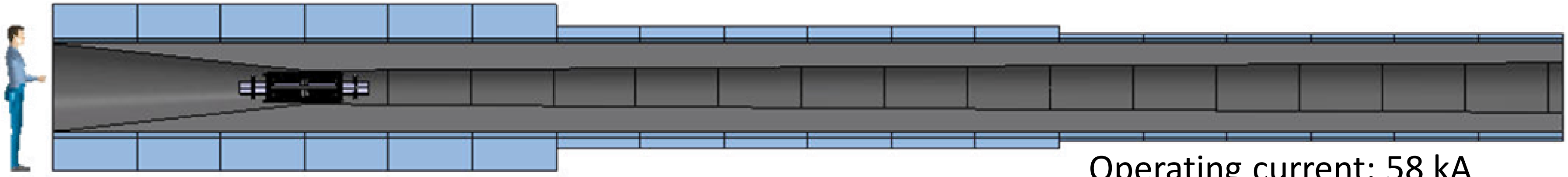
SUMMARY

- **Aim**

  Develop an alternative solution to the hybrid US-MAP [1-3] (5 resistive coils and 19 SC coils, 2.4 m bore ∅) made of HTS (23 SC coils, 1.2 m bore ∅)

- **Design highlights**
  - VIPER-like cable (HTS tapes, central cooling hole, steel jacket) with I_{max}≈61 kA
  - Set of 23 coils in 3 sections (300 mm gap between sections, 20 mm gap between coils)
    - Peak field on conductor 20.9 T, magnetic energy 1.1 GJ
    - Cable length ≈ 8.7 km, winding mass ≈ 115 t
  - Field on axis within 4% accuracy of Sayed-Berg formula over 16 m channel length
  - Stresses in structural elements within 316 LN limits (σ_Y≈1000 MPa)
  - Stresses in tapes being investigated to be minimized (t_{xy}≈30 MPa)
  - Coils operating at 20 K, ≈20 bar, ≈15 W pumping power, ≈150 W heat removal
  - High conductor stability (DT≥10 K!)
  - Detection & dump for quenches in low field/current most challenging (→long detection times) but seems compatible with hot-spot temperature limit (T_{HS} ≈ 150-200 K)

HTS-Based Target Solenoids: HTS Conductor

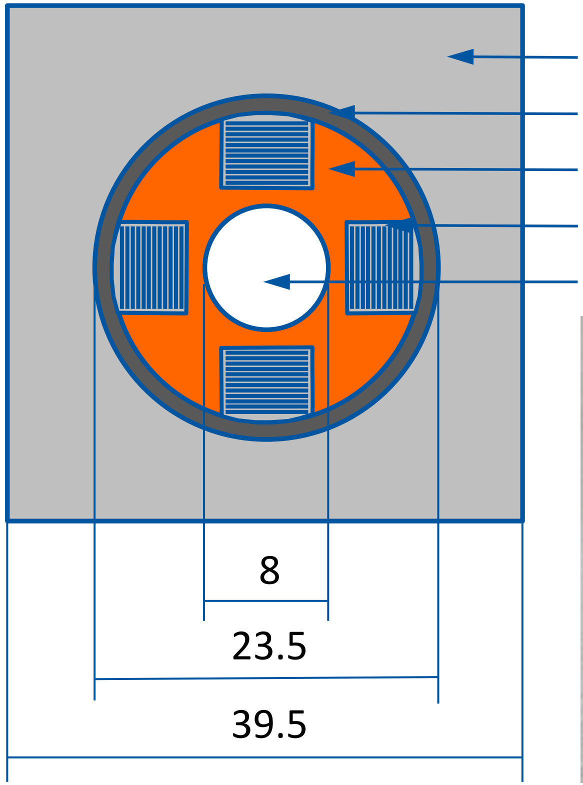


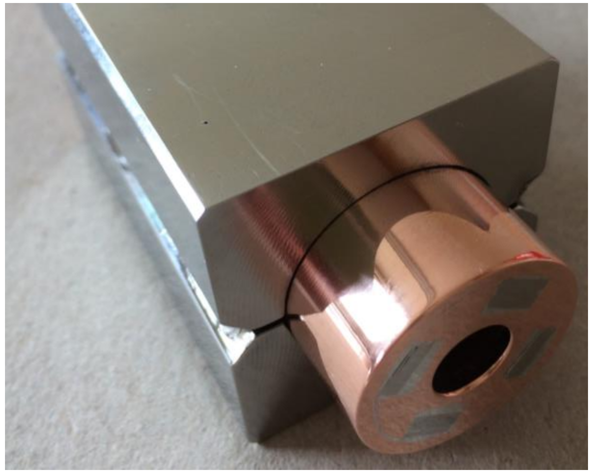
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

MIT “VIPER” conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

HTS conductor design



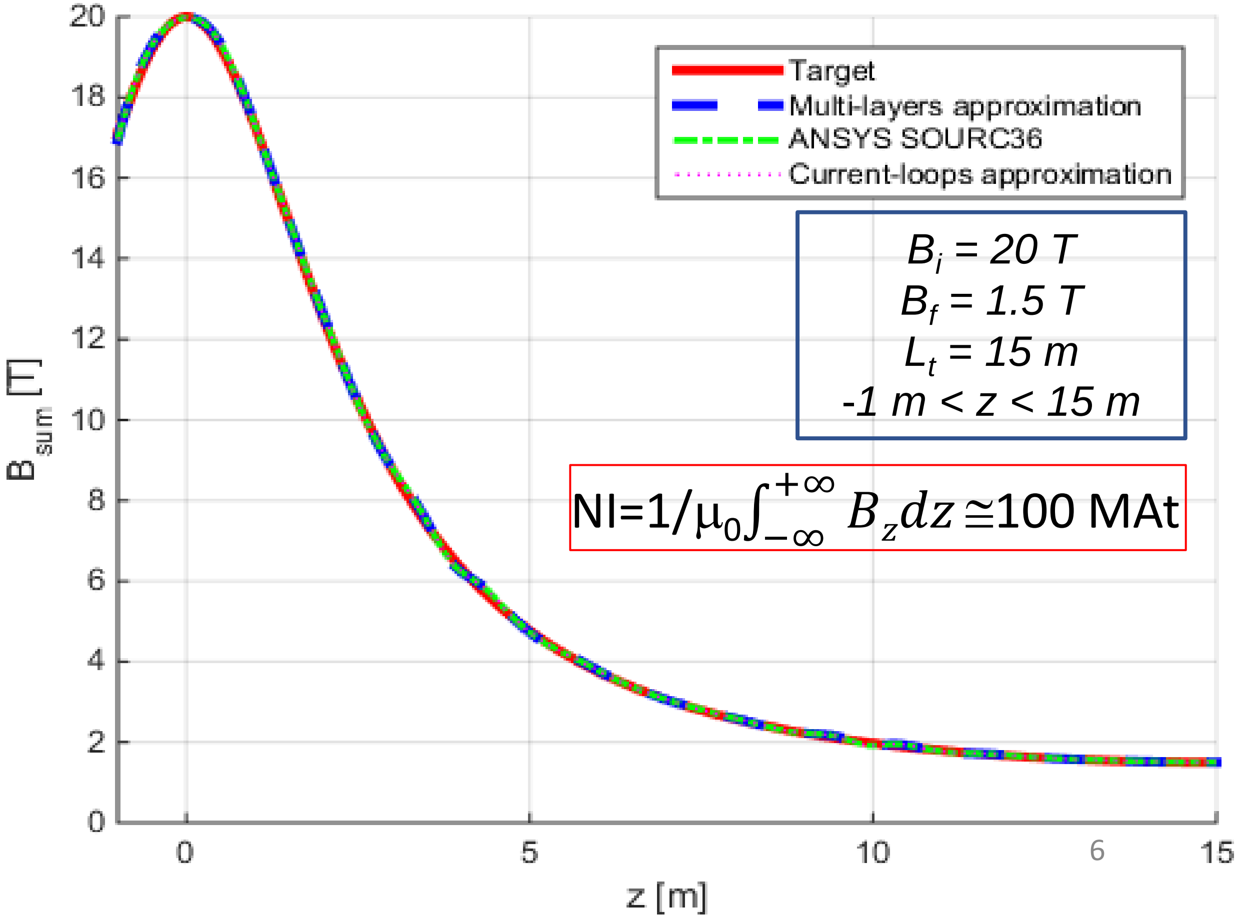


HTS-Based Target Solenoids: Field Profile and Coils Geometry

Reference field profile on axis

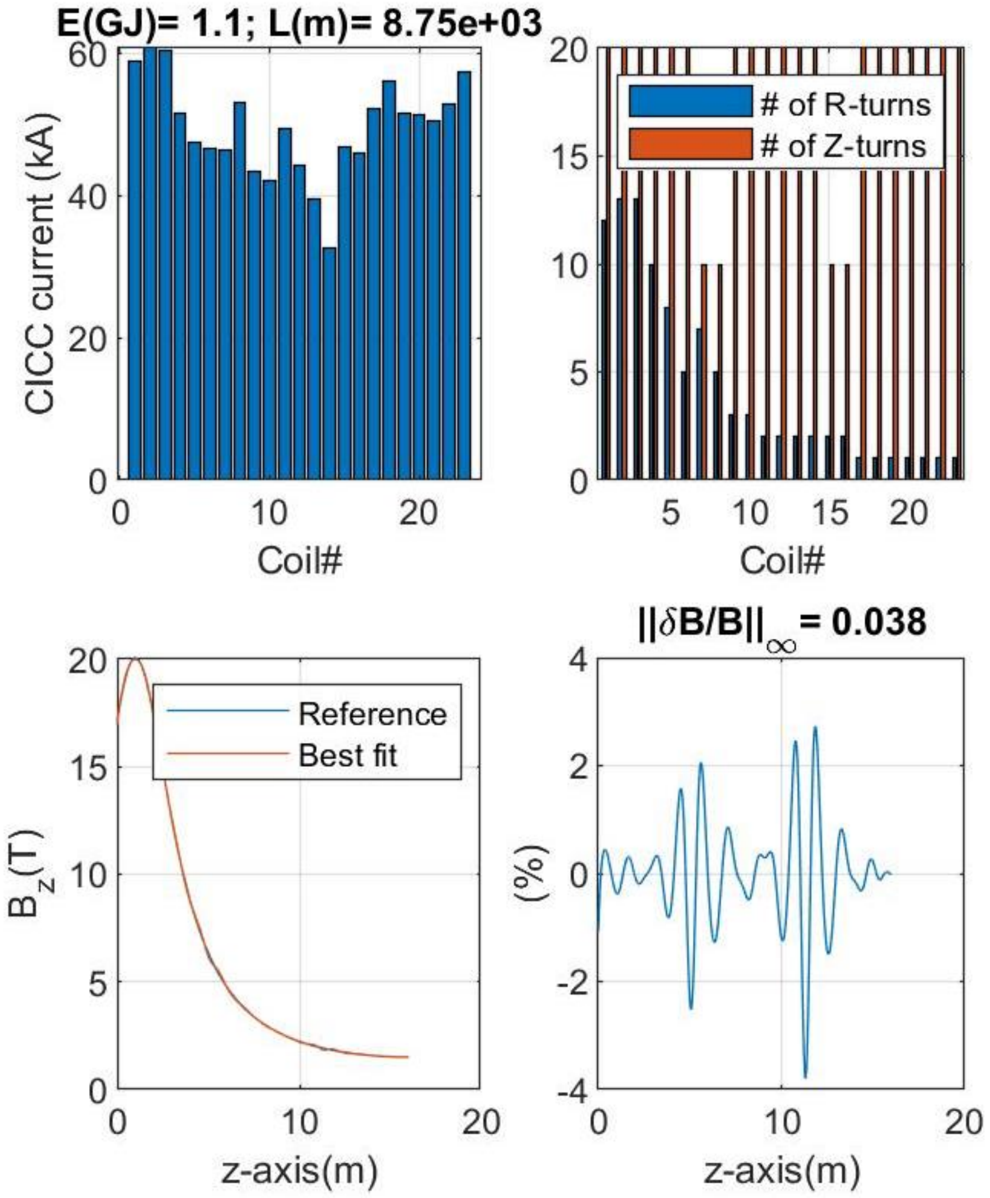
(H. K. Sayed and J. S. Berg, 2014)

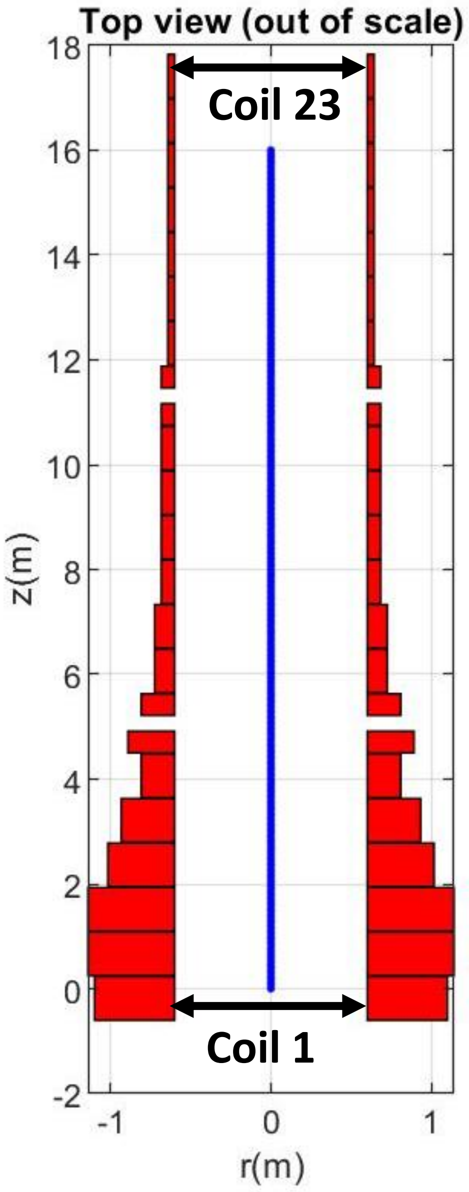
$$B_z = \frac{B_i B_f L_t^3}{B_i z^2 (3L_t - 2z) + B_f (L_t - z)^2 (2z + L_t)}$$



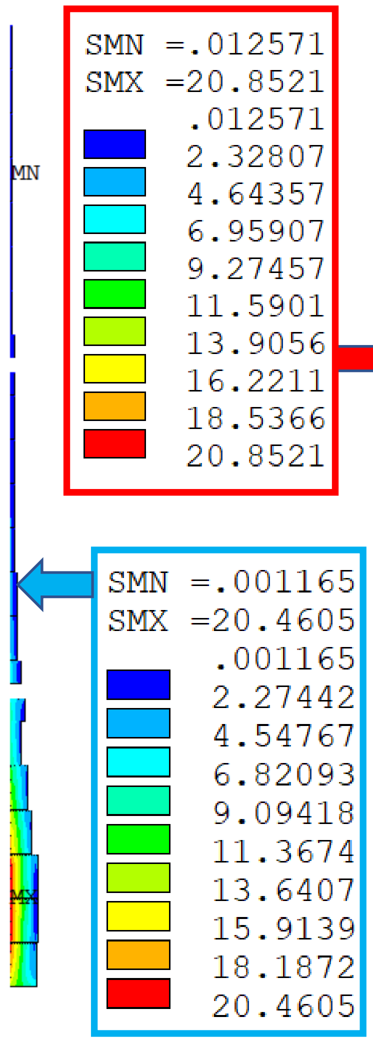
Coil	R_c [m]	Z_c [m]	DR [m]	DZ [m]	Layers	Pancakes	I [kA]	It [MAt]
1	0.849	-0.185	0.498	0.830	12	20	58.90	14.137
2	0.870	0.665	0.540	0.830	13	20	60.71	15.785
3	0.870	1.515	0.540	0.830	13	20	60.39	15.702
4	0.808	2.365	0.415	0.830	10	20	51.65	10.331
5	0.766	3.215	0.332	0.830	8	20	47.47	7.595
6	0.704	4.065	0.208	0.830	5	20	46.50	4.650
7	0.745	4.708	0.291	0.415	7	10	46.29	3.240
8	0.704	5.423	0.208	0.415	5	10	53.17	2.658
9	0.662	6.065	0.125	0.830	3	20	43.28	2.597
10	0.662	6.915	0.125	0.830	3	20	42.15	2.529
11	0.642	7.765	0.083	0.830	2	20	49.45	1.978
12	0.642	8.615	0.083	0.830	2	20	44.18	1.767
13	0.642	9.465	0.083	0.830	2	20	39.57	1.583
14	0.642	10.315	0.083	0.830	2	20	32.71	1.309
15	0.642	10.958	0.083	0.415	2	10	46.72	0.934
16	0.642	11.673	0.083	0.415	2	10	45.90	0.918
17	0.621	12.315	0.042	0.830	1	20	52.31	1.046
18	0.621	13.165	0.042	0.830	1	20	56.06	1.121
19	0.621	14.015	0.042	0.830	1	20	51.60	1.032
20	0.621	14.865	0.042	0.830	1	20	51.38	1.028
21	0.621	15.715	0.042	0.830	1	20	50.47	1.009
22	0.621	16.565	0.042	0.830	1	20	52.86	1.057
23	0.621	17.415	0.042	0.830	1	20	57.44	1.149

HTS-Based Target Solenoids: Coils Current and Field

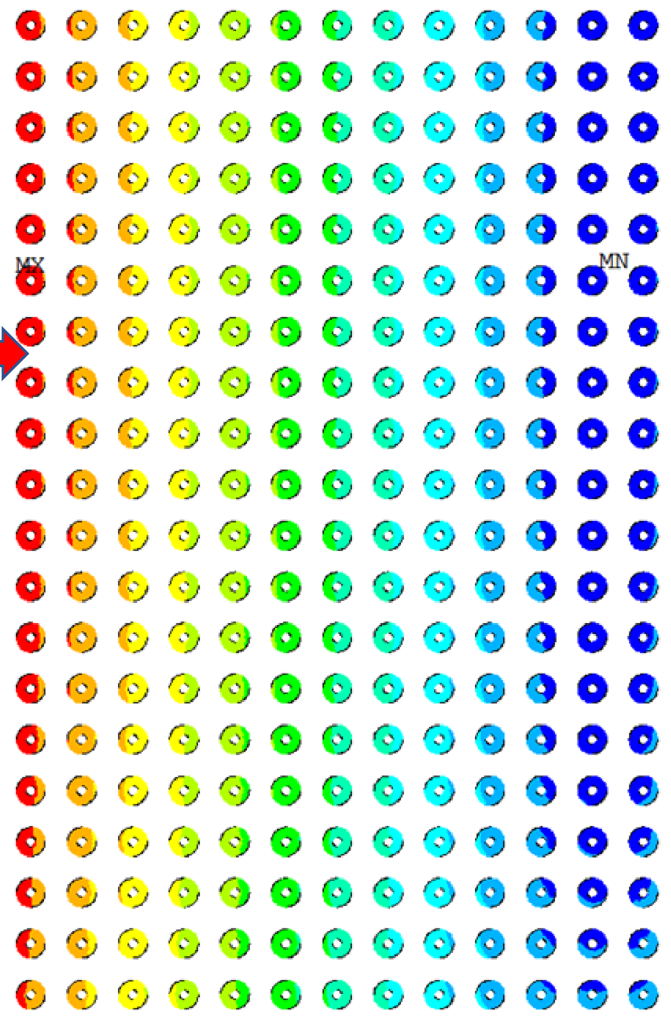




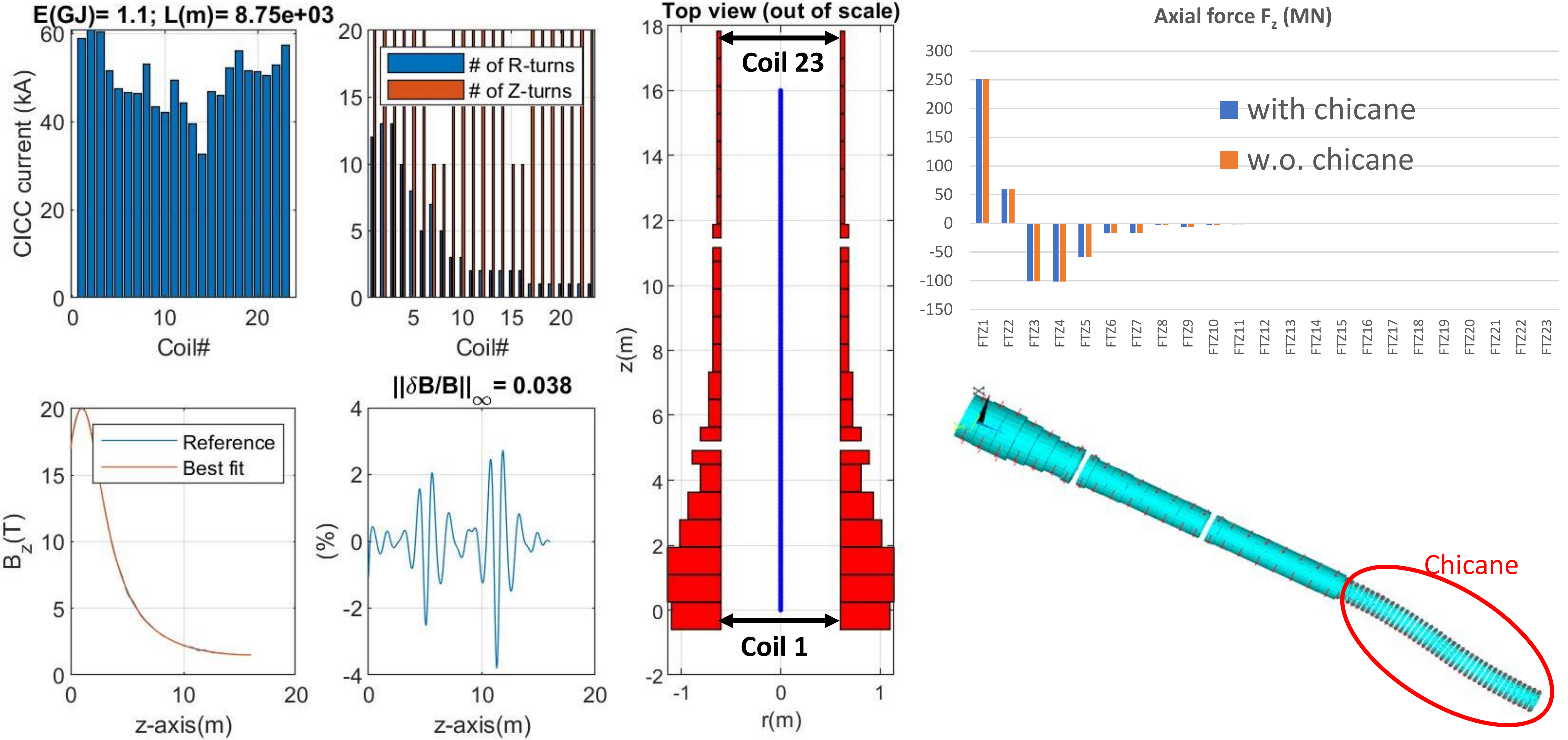
Magnetic Field [T]



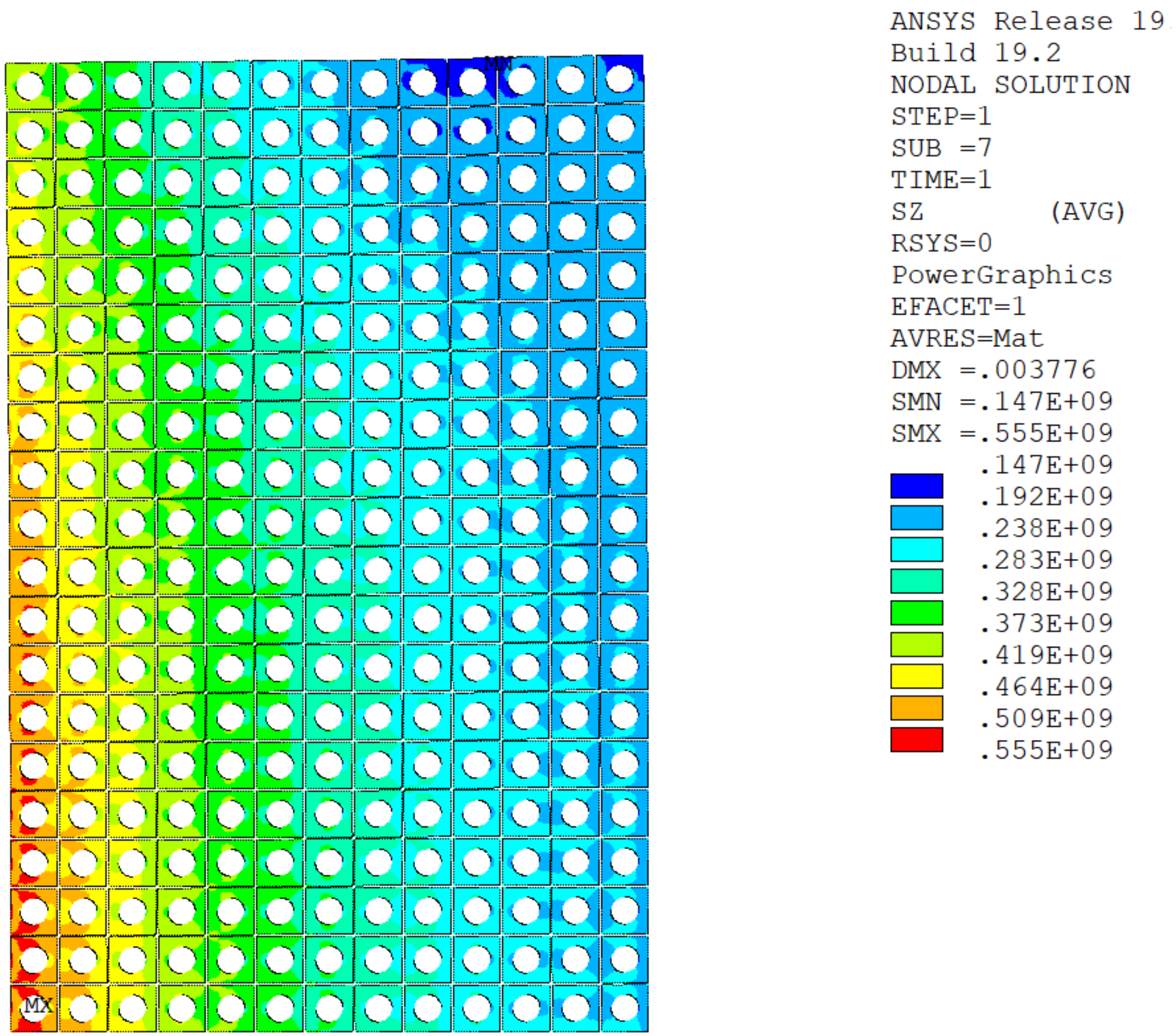
Peak field in coil 2



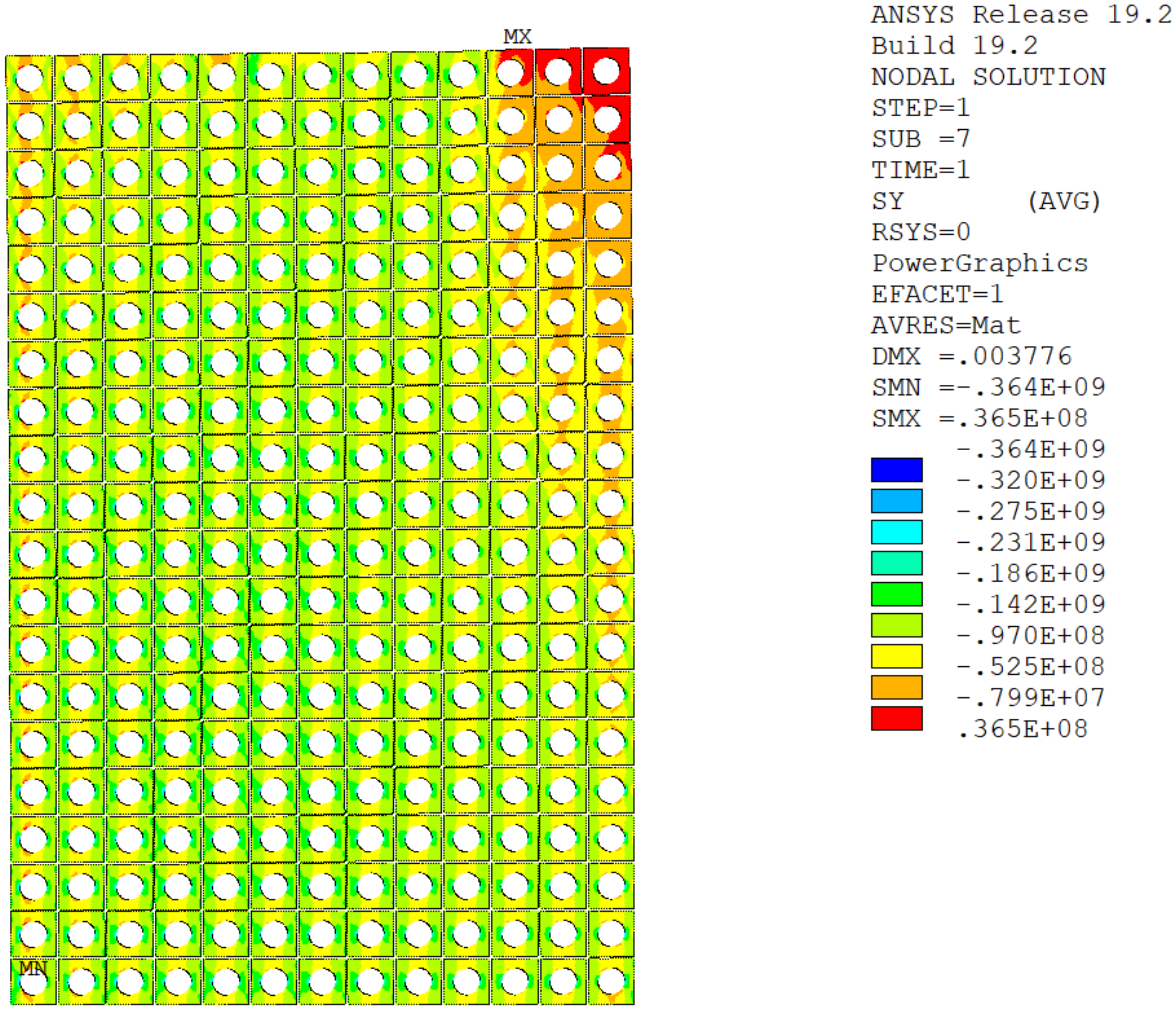
HTS-Based Target Solenoids: Axial Forces



HTS-Based Target Solenoids: Jacket Stresses



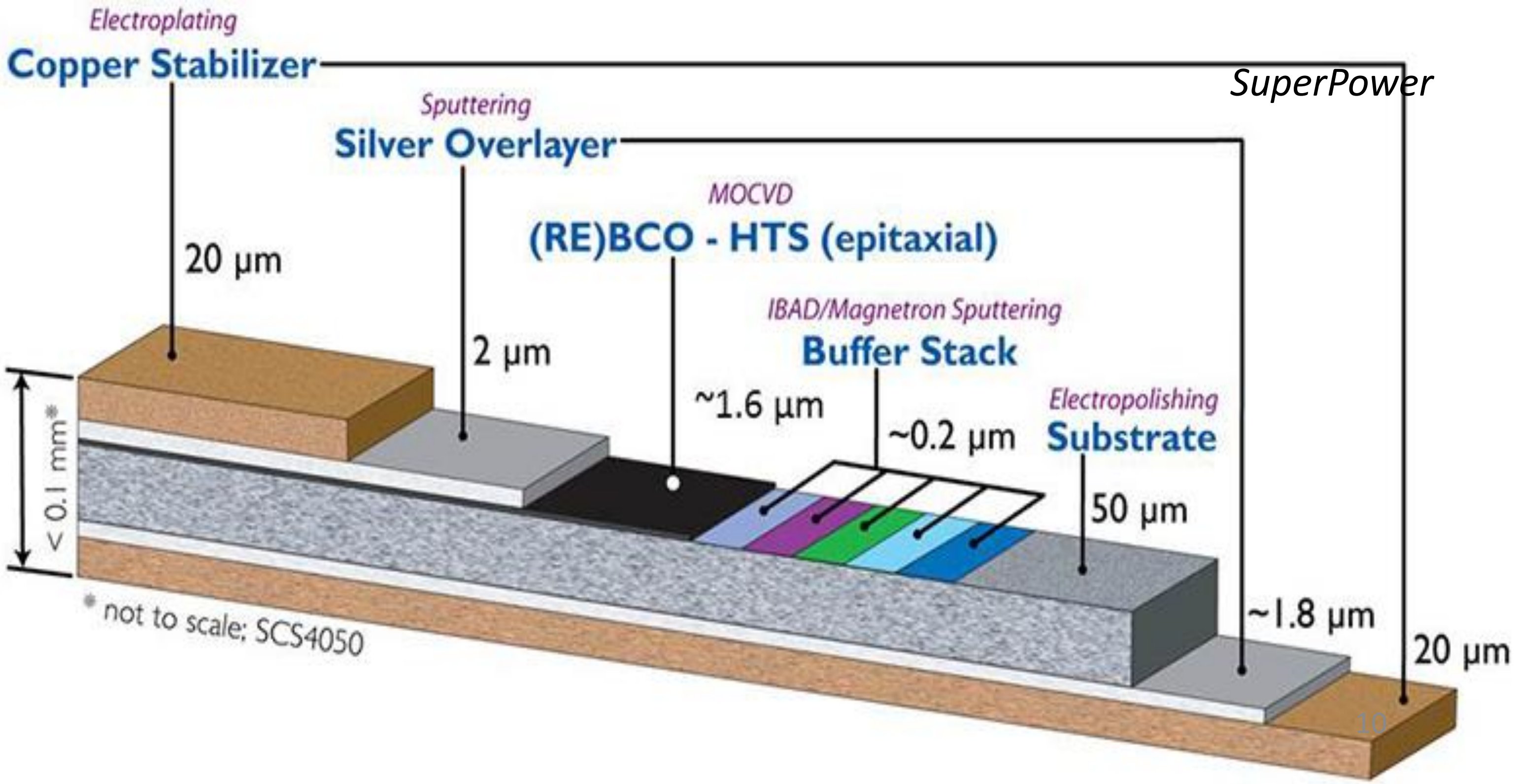
a) Hoop Stress



b) Axial Stress [Pa]

HTS-Based Target Solenoids: Tapes Stresses

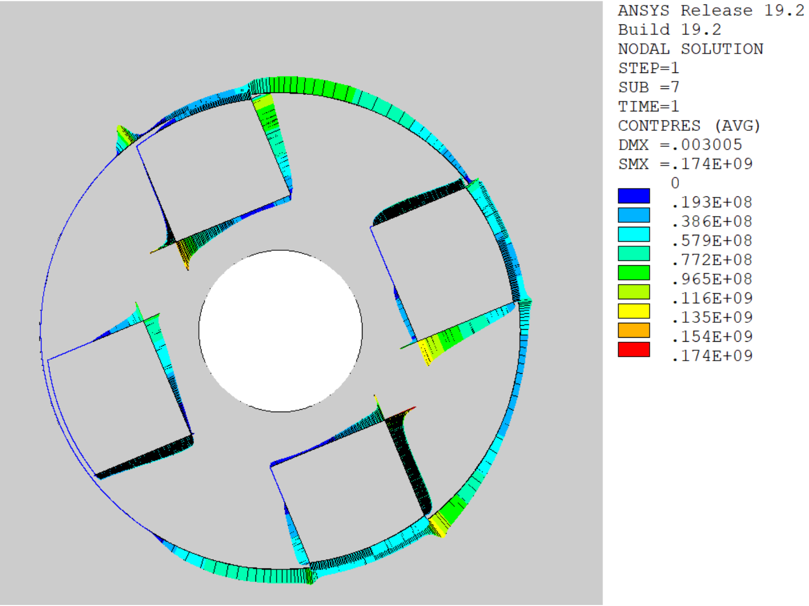
1. Stress components of interest in the HTS tapes (de-bonding, degradation):
   - Tensile stress across HTS tapes.
   - Shear stress in HTS tapes.
2. The tapes are modelled as relatively stiff components (~100 GPa) due to the large amount of Hastelloy and copper.
3. The surrounding solder is modelled as a rather soft material (~10 GPa) due to the mix of Sn and Pb.
4. Parametric Analyses:
   - Bonded/frictional stack.
   - Number of stacks (3, 4, 6, 8).
   - Width of stacks (3 mm, 4 mm, 6 mm).



HTS-Based Target Solenoids: Tapes Stresses

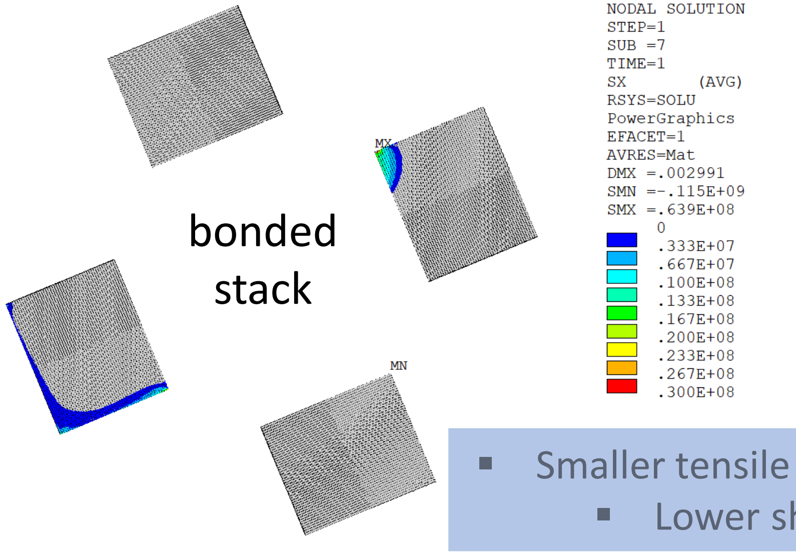
1. Stack bonded to copper former.
2. Stack allowed to separate and slide in the copper former (μ = 0.2).

Contact Pressure [Pa]



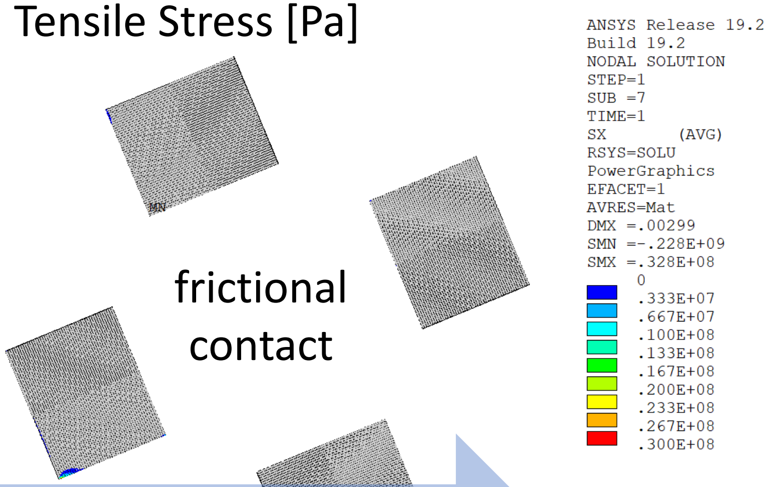
Tensile Stress [Pa]

bonded stack



Tensile Stress [Pa]

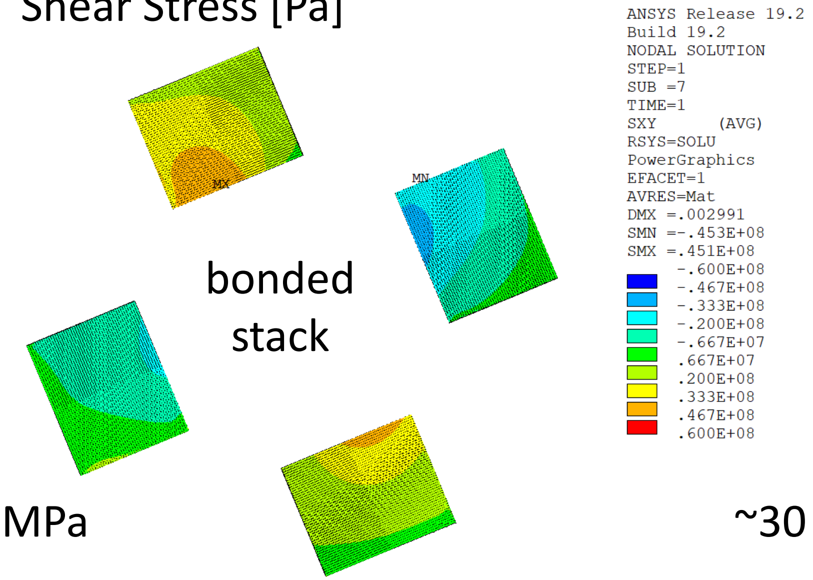
frictional contact



- Smaller tensile stress area with lower peak.
  - Lower shear stress in general.

Shear Stress [Pa]

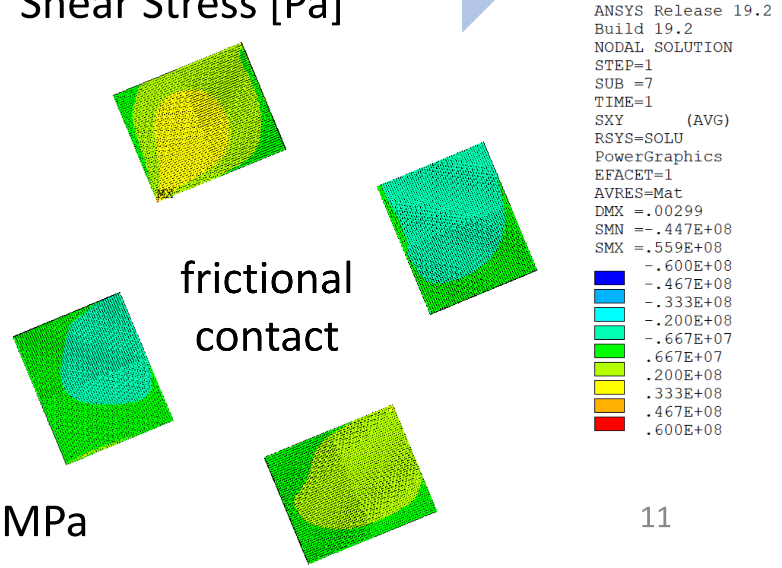
bonded stack



~40 MPa

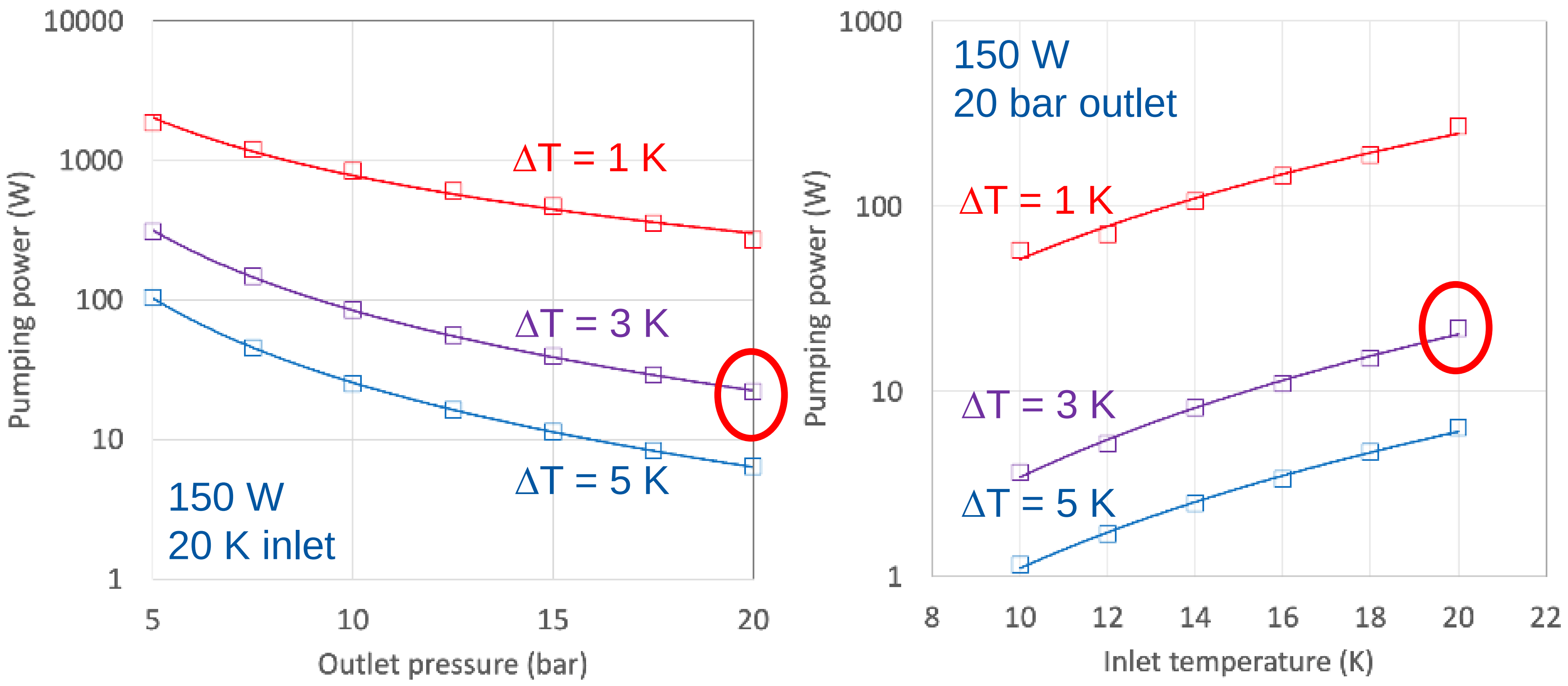
Shear Stress [Pa]

frictional contact



~30 MPa

HTS-Based Target Solenoids: Optimal Cooling



Compared to typical conditions at 4.5 K, operation at 20 K implies

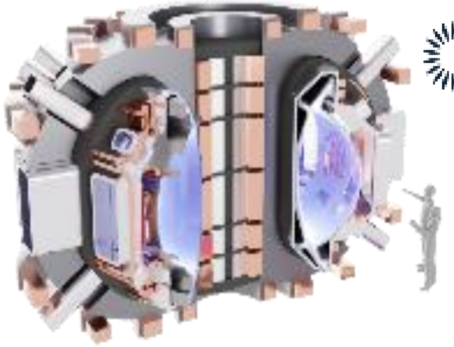
- High pressure, o(20) bar
- Large temperature increase, o(3) K

Conclusions and Outlook

- We are looking for a solution to the design of the target and capture channel of the Muon Collider, which needs a **peak field of 20 T on axis, based on an HTS force-flow cooled cable operating at 20 K**
  - Lower footprint, mass, stored energy and cost than a LTS/NC hybrid
  - Better energy efficiency than a 4.5 K system

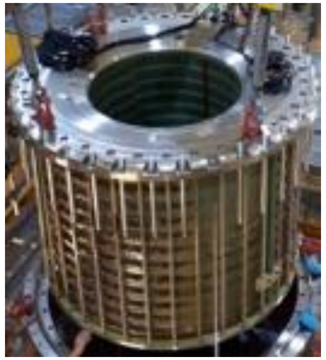
- Though there is much work to do, ***the design selected seems not too far from being feasible !***

- This is also interesting because of implications for
  - **Compact fusion machines**
  - **Hybrid UHF magnets for science**



Commonwealth Fusion Systems

LNCMI



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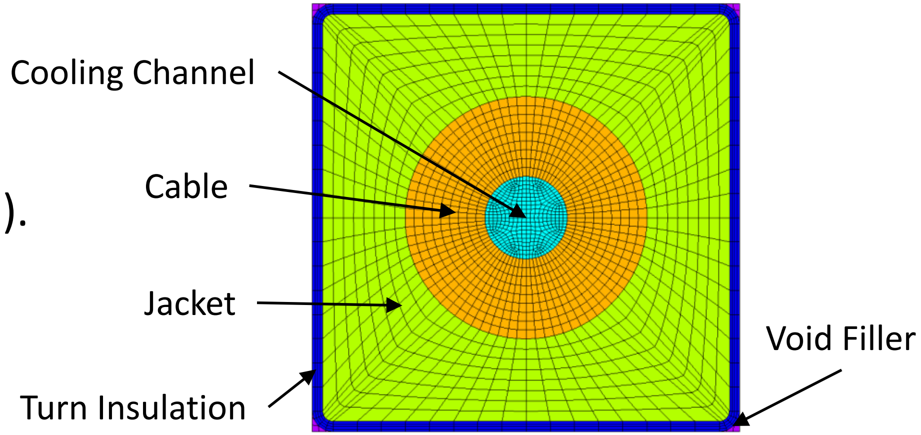
1. R.J. Weggel, N. Souchlas, H.G. Kirk, V.B. Graves, K.T. McDonald, A TARGET MAGNET SYSTEM FOR A MUON COLLIDER AND NEUTRINO FACTORY, TUPS053 Proceedings of IPAC2011, San Sebastián, Spain
2. R.J. Weggel, N. Souchlas, H.K. Sayed, J.S. Berg, H.G. Kirk, X. Ding, V.B. Graves, K.T. McDonald, DESIGN OF MAGNETS 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)

THANK YOU

Introduction: Conductor

Conductor features

- Diameter of central cooling channel = 8 mm.
- Cable diameter = 23.5 mm.
- Square steel jacket 39.5 mm x 39.5 mm (minimum thickness of 8 mm).
- 1 mm thick turn insulation.

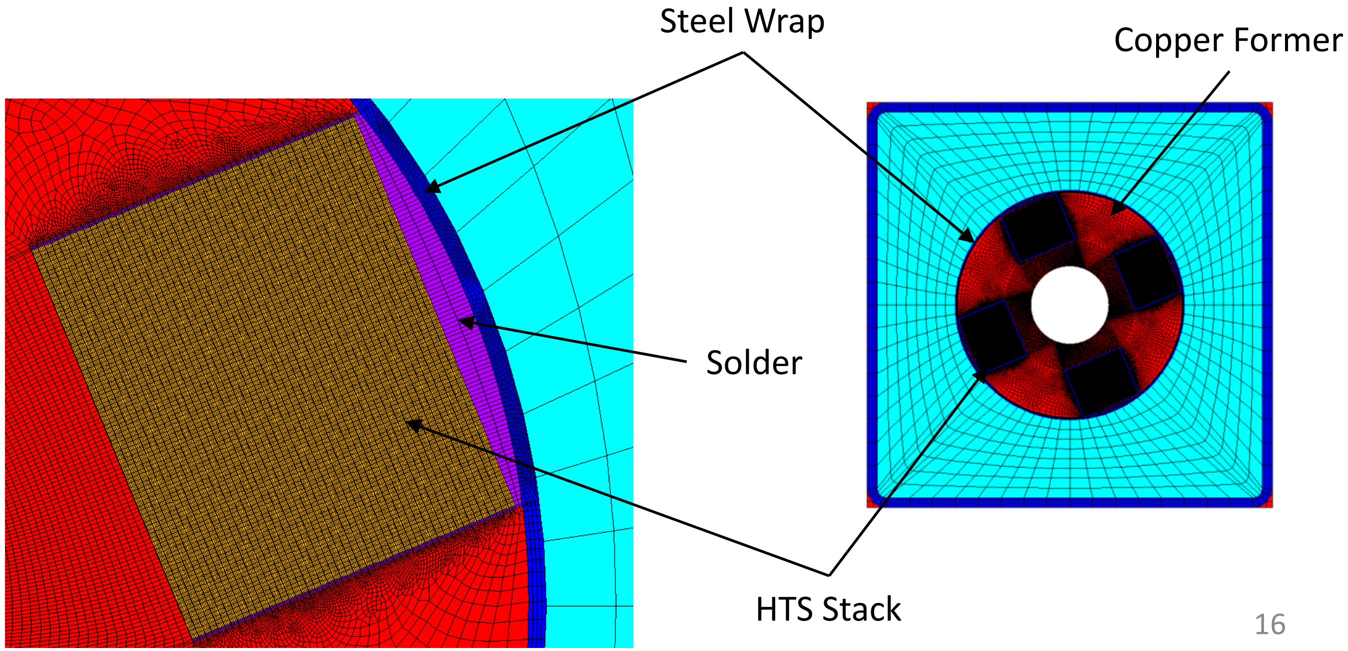


Cable features (parametric studies, 50 tapes/stack)

- Bonded/frictional stack-former contact.
- 3/4/6/8 stacks of HTS tapes.
- 3/4/6 mm wide HTS tapes.

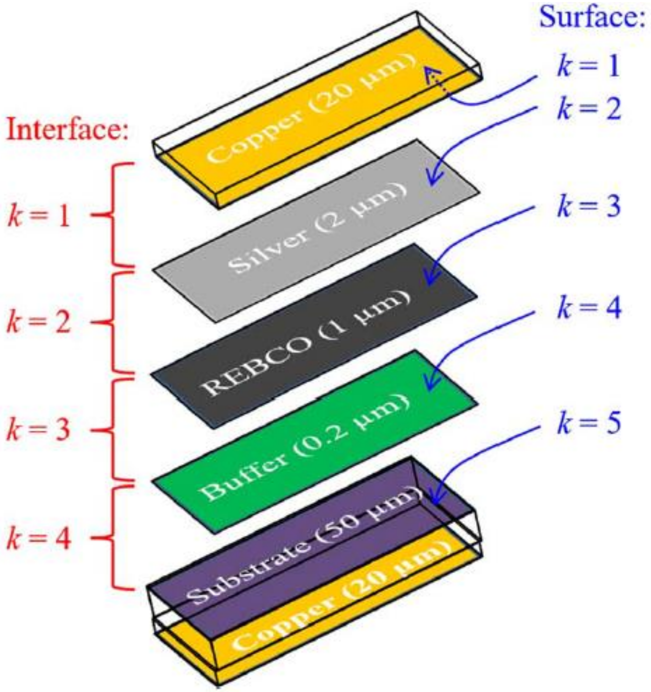
HTS tape features (90 um thickness)

- 44 um thick Hastelloy.
- 20 um thick copper layers (x2).
- 2 um thick silver layers (x2).
- 1.6 um REBCO layer.
- 0.4 um buffer layer.



Introduction: Material Properties

	Steel	Copper	Insulation	Filler	WP (smeared)	Solder	HTS Tape (smeared)
E_x [GPa]	205	110	12	7	112	10	100
E_y [GPa]	205	110	20	7	112	10	121
E_z [GPa]	205	110	20	7	160	10	132
ν_{xy} []	0.29	0.33	0.33	0.3	0.25	0.33	0.25
ν_{xz} []	0.29	0.33	0.33	0.3	0.21	0.33	0.24
ν_{yz} []	0.29	0.33	0.17	0.3	0.21	0.33	0.30
G_{xy} [GPa]	79	41	6	3	31	4	37
G_{xz} [GPa]	79	41	6	3	42	4	46
G_{yz} [GPa]	79	41	6	3	42	4	43



Properties of HTS tape obtained from smearing of isotropic properties of individual components at 77 K.

P. GAO, et al. *Superconductor Science and Technology*, 2020, vol. 33, no 4, p. 044015.

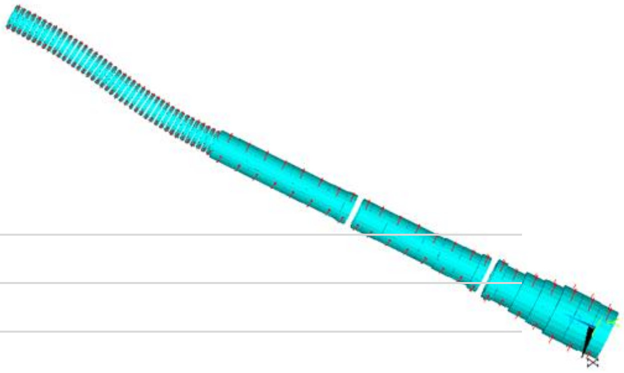
Supercond. Sci. Technol. 33 (2020) 044015 P Gao *et al*

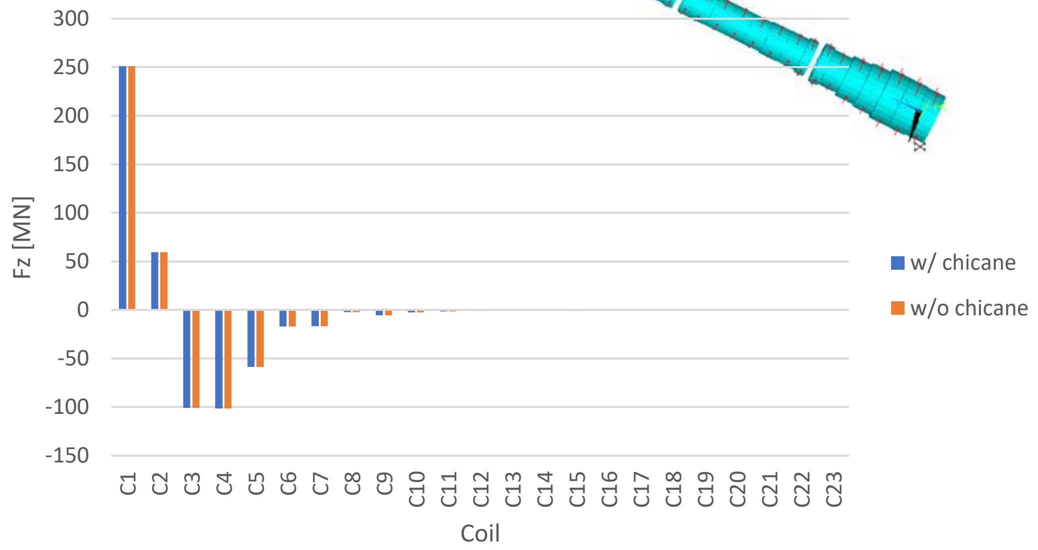
Table 1. Material properties of all the constituent materials of the REBCO conductor [8, 10, 11, 17, 25, 36–38].

	Young's modulus E (GPa)		Poisson's ratio υ	Yield strength σ_y (MPa)		Tangent modulus E_t (GPa)	CTE α ($\times10^{-6}$ K^{-1})
Temperature (K)	77	300		77	300		
Copper	85 [17]	70 [17]	0.34 [11]	330 [17]	190 [17]	5 [17]	17.7 [8, 10, 11]
Silver	76 [36, 37]		0.37 [36]	14 [36, 37]		1 [36]	17.1 [10, 36]
REBCO	157 [8, 10, 11, 25, 38]		0.3 [10, 11]	1030 [8]		1	11 [8, 10, 11]
Buffer	170 [25]		0.226 [25]	1030		1	9.5 [25]
Hastelloy	178 [17]	170 [17]	0.307 [11]	1200 [17]	980 [17]	6 [17]	14 [8, 10, 11, 25, 38]

Introduction: Loads

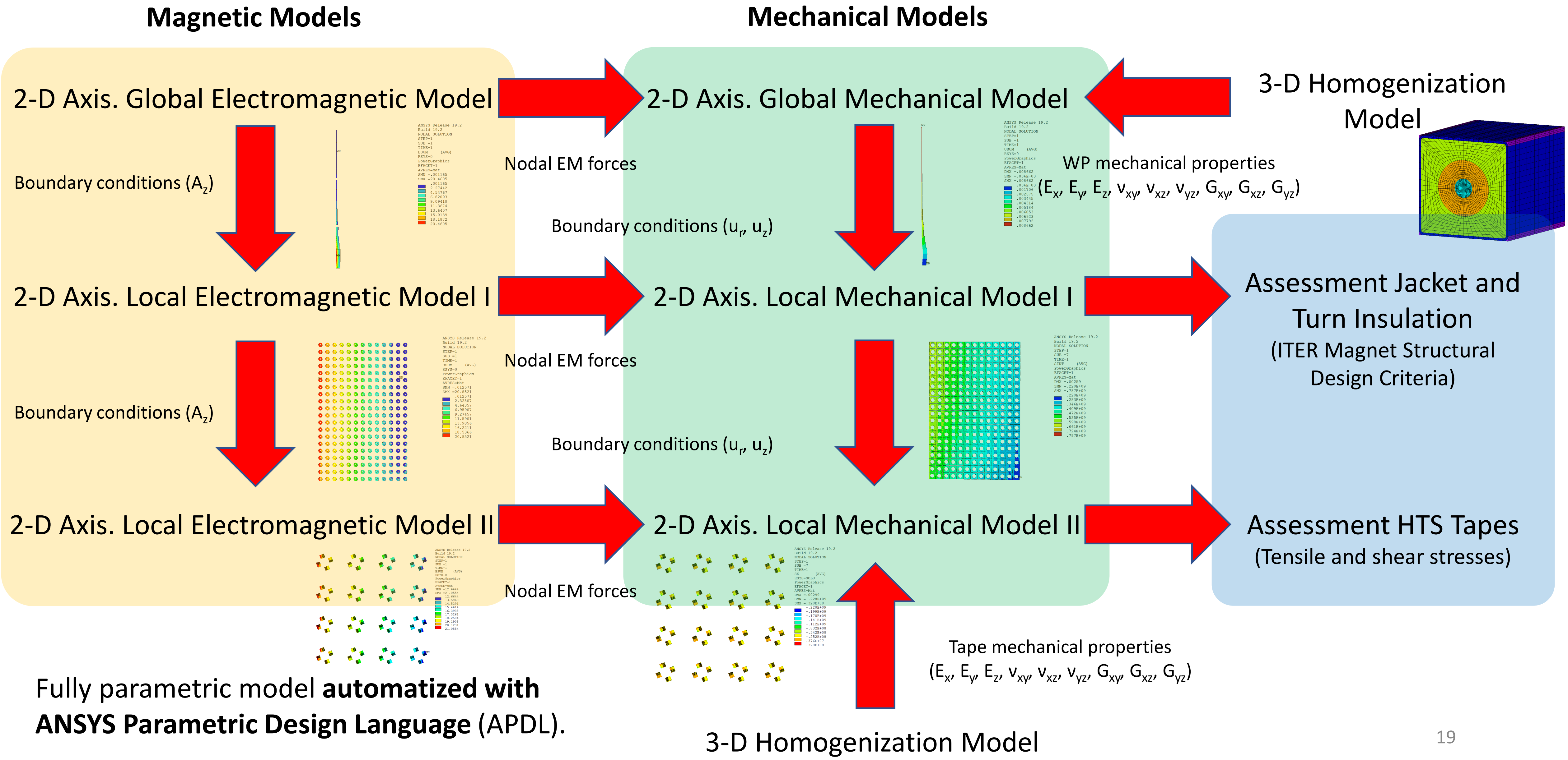
Coil	Rc [m]	Zc [m]	DR [m]	DZ [m]	NR	NZ	I [A]	It [MAt]	Fz [MN] Net Vertical Forces (without chicane coils)	Fz [MN] Net Vertical Forces (with chicane coils)
1	0.849	-0.185	0.498	0.830	12	20	58905	14.137	251.2	251.2
2	0.870	0.665	0.540	0.830	13	20	60710	15.785	59.50	59.51
3	0.870	1.515	0.540	0.830	13	20	60392	15.702	-101.0	-101.0
4	0.808	2.365	0.415	0.830	10	20	51654	10.331	-101.4	-101.4
5	0.766	3.215	0.332	0.830	8	20	47469	7.595	-58.48	-58.48
6	0.704	4.065	0.208	0.830	5	20	46504	4.650	-17.10	-17.10
7	0.745	4.708	0.291	0.415	7	10	46293	3.240	-16.60	-16.60
8	0.704	5.423	0.208	0.415	5	10	53168	2.658	-2.179	-2.177
9	0.662	6.065	0.125	0.830	3	20	43280	2.597	-5.691	-5.69
10	0.662	6.915	0.125	0.830	3	20	42146	2.529	-2.609	-2.608
11	0.642	7.765	0.083	0.830	2	20	49452	1.978	-1.687	-1.686
12	0.642	8.615	0.083	0.830	2	20	44183	1.767	-0.9150	-0.9147
13	0.642	9.465	0.083	0.830	2	20	39567	1.583	-0.7432	-0.7428
14	0.642	10.315	0.083	0.830	2	20	32713	1.309	-0.1610	-0.1603
15	0.642	10.958	0.083	0.415	2	10	46717	0.934	-0.8960	-0.8958
16	0.642	11.673	0.083	0.415	2	10	45905	0.918	0.3742	0.3754
17	0.621	12.315	0.042	0.830	1	20	52310	1.046	-0.3951	-0.3941
18	0.621	13.165	0.042	0.830	1	20	56056	1.121	-0.0839	-0.08169
19	0.621	14.015	0.042	0.830	1	20	51602	1.032	-0.0973	-0.09354
20	0.621	14.865	0.042	0.830	1	20	51376	1.028	-0.0427	-0.03481
21	0.621	15.715	0.042	0.830	1	20	50471	1.009	-0.0091	0.01137
22	0.621	16.565	0.042	0.830	1	20	52861	1.057	-0.0188	0.06418
23	0.621	17.415	0.042	0.830	1	20	57438	1.149	-0.9872	-0.3138





- No pre-compression needed to keep the coils together.
- Gravity load is not considered.
- Cool-down is not considered.
- Only Lorentz forces applied.
- No cyclic loading considered (fatigue).

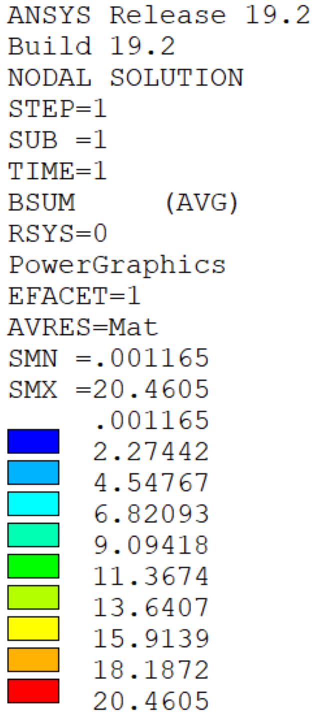
Analysis Strategy: Overview



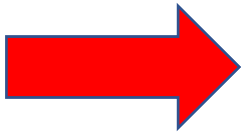
Fully parametric model **automated with ANSYS Parametric Design Language** (APDL).

Analysis Strategy: Global Models

Magnetic Field [T]



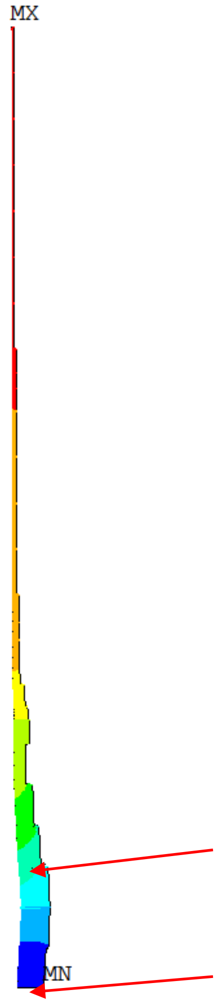
- Peak field in coils 2/3.

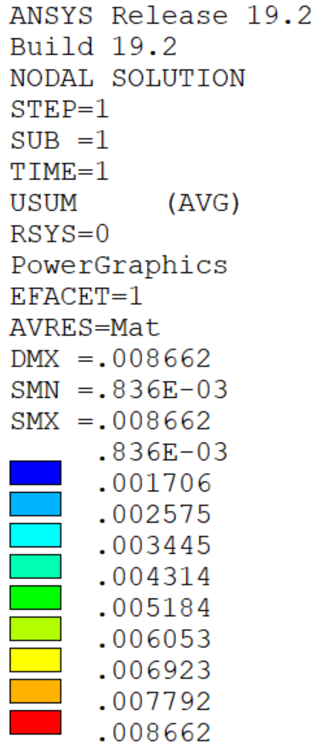


Nodal EM forces

Most loaded coil for detailed analysis

Displacement [m]

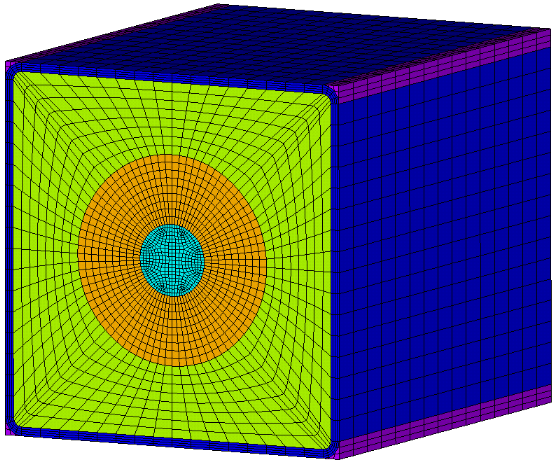




- Homogenized WP.
- Frictional contact between coils.
- No pre-compression force applied.
- Boundary Condition: $u_y = 0$

Global displacements

Smeared Properties

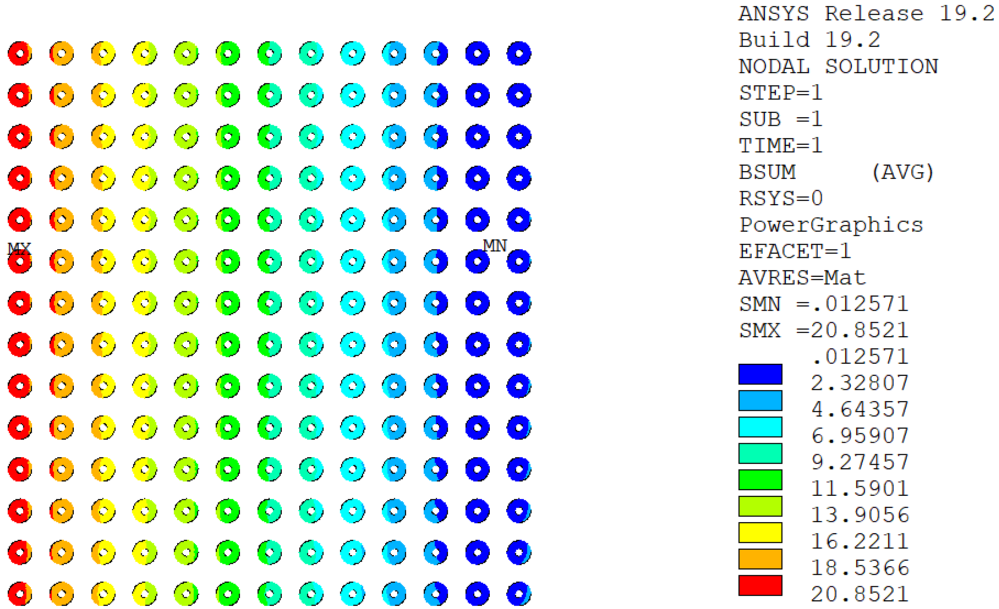


The global stiffness of the WP is modelled by means of a homogenized orthotropic material.

Ex	=	1.11857E+02	[GPa]
Ey	=	1.11857E+02	[GPa]
Ez	=	1.60381E+02	[GPa]
Gyz	=	4.15534E+01	[GPa]
Gxz	=	4.15534E+01	[GPa]
Gxy	=	3.14987E+01	[GPa]
Nuyz	=	2.09159E-01	[]
Nuxz	=	2.09159E-01	[]
Nuxy	=	2.49296E-01	[]

Analysis Strategy: Local Models I

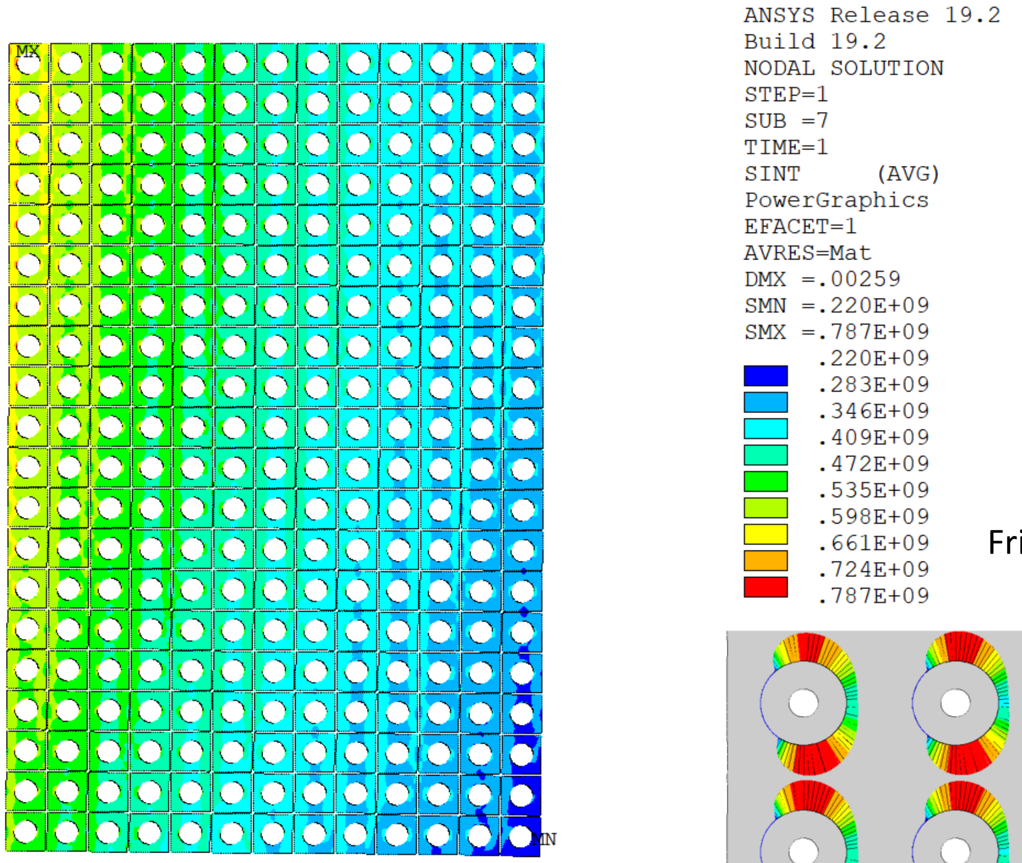
Magnetic Field [T] in Coil 2 cables



Fine distribution of magnetic field

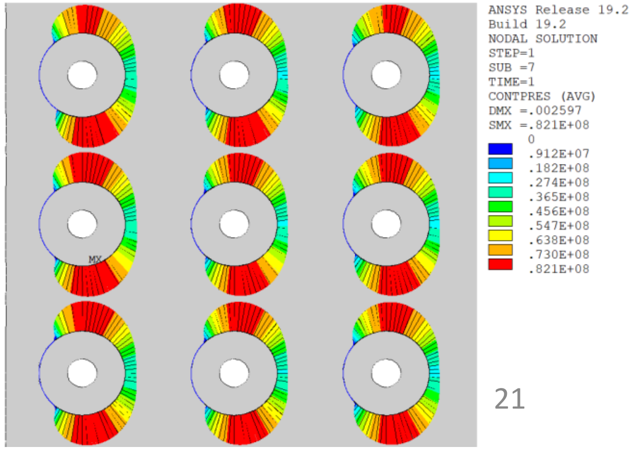
Nodal EM forces

Tresca Stress [Pa] in Coil 2 jackets

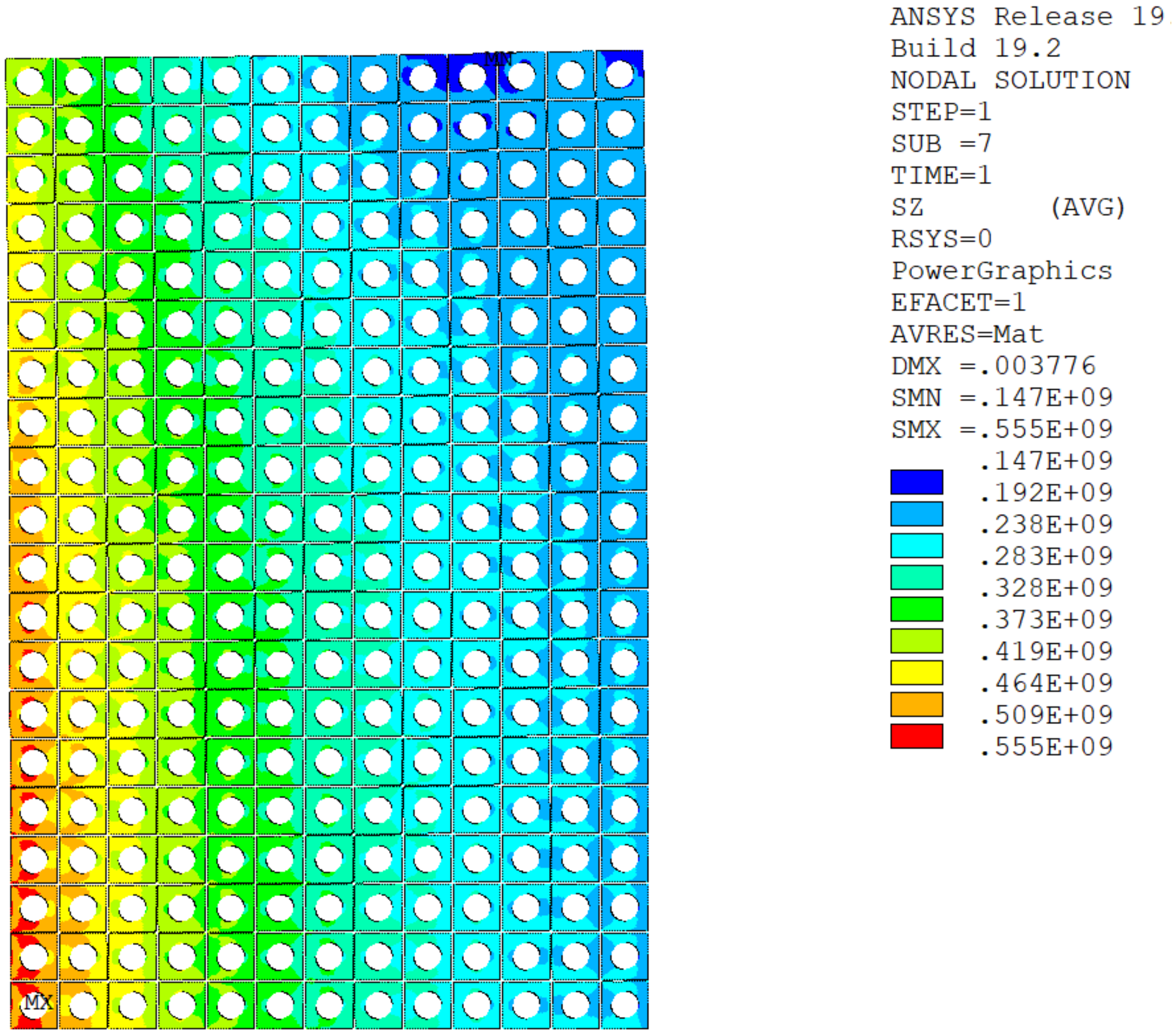


Stresses in jackets and insulation

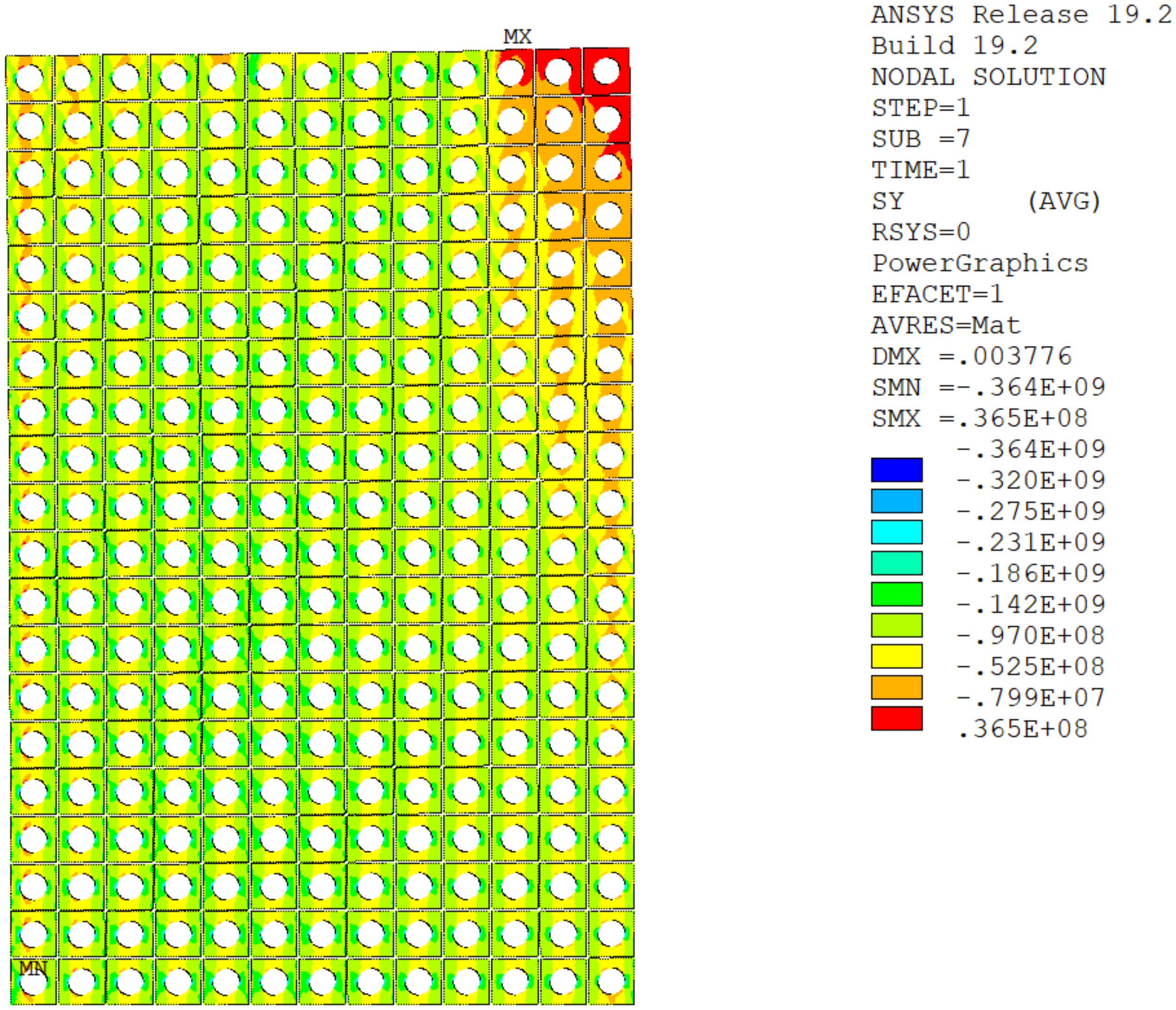
Frictional contact between cable and jacket



Analysis Strategy: Local Models I



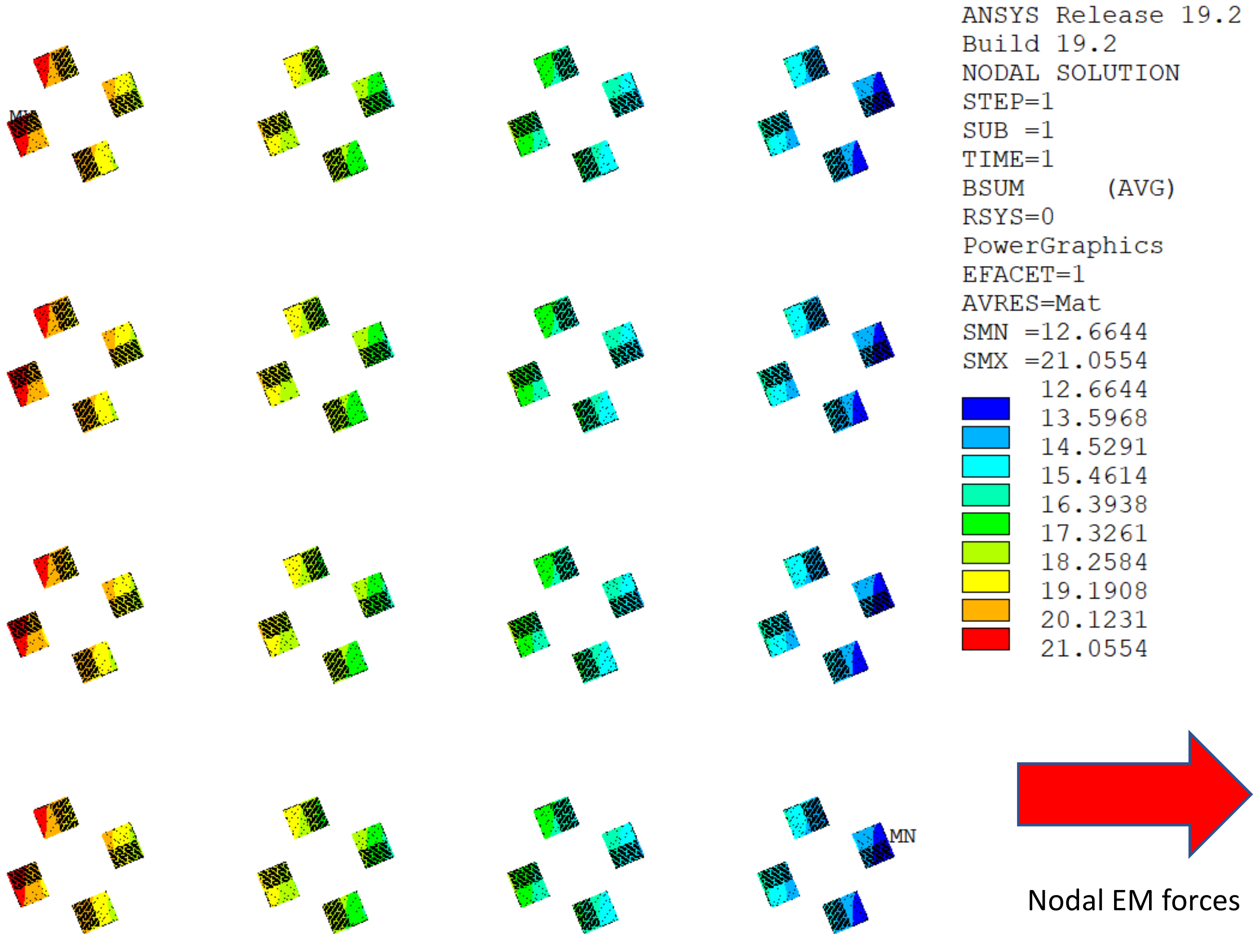
a) Hoop Stress



b) Axial Stress [Pa]

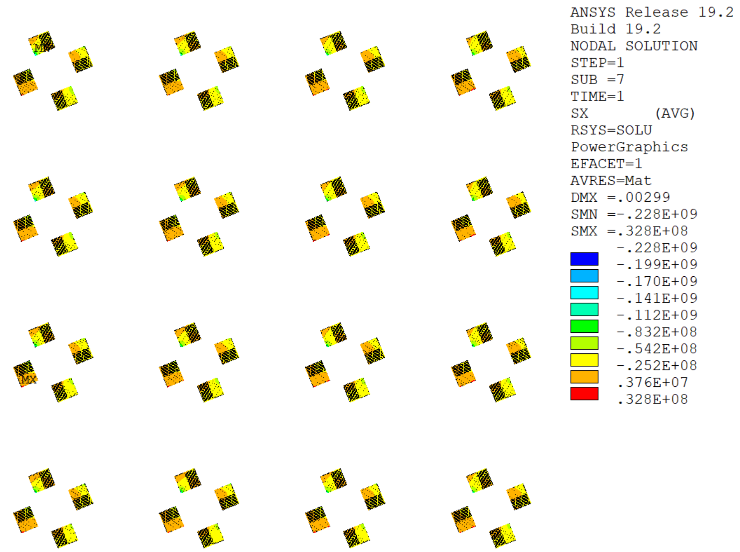
Analysis Strategy: Local Models II

Magnetic Field [T] in tapes

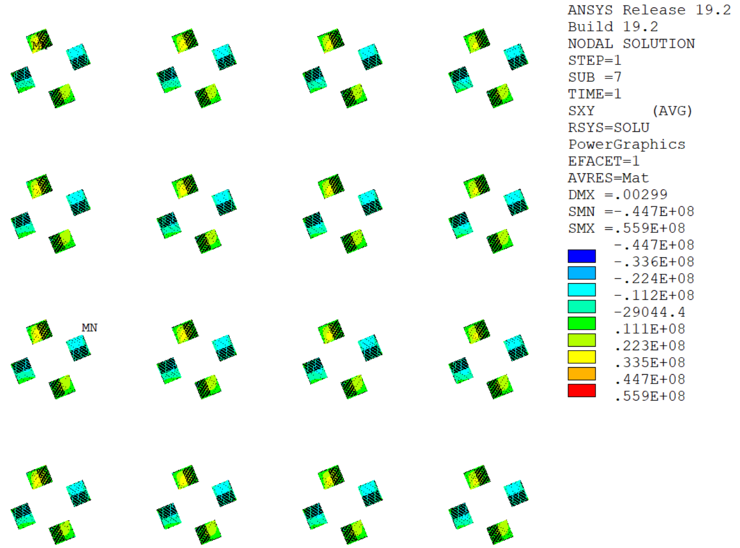


Nodal EM forces

Compressive/Tensile Stress [Pa] in tapes



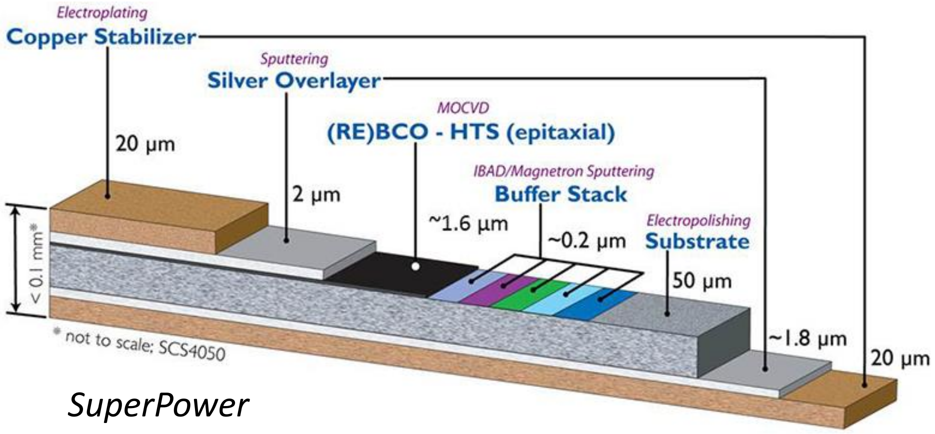
Shear Stress [Pa] in tapes



Stresses in HTS Tapes

Stress components of interest in the HTS tapes (de-bonding, degradation):

- Tensile stress across HTS tapes.
- Shear stress in HTS tapes.



SuperPower

The tapes are modelled as relatively stiff components (~100 GPa) due to the large amount of hastelloy and copper.

The surrounding solder is modelled as a rather soft material (~10 GPa) due to the mix of Sn and Pb.

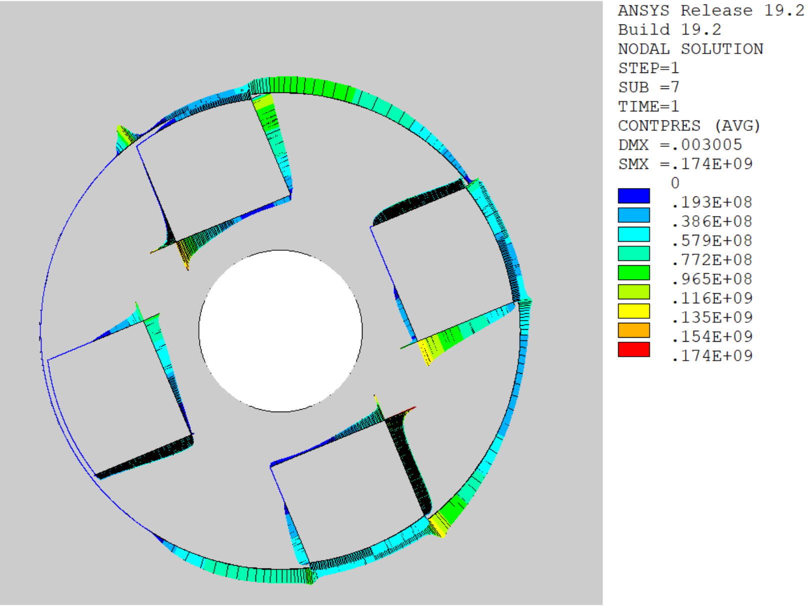
Parametric Analyses:

- Bonded/frictional stack.
- Number of stacks (3, 4, 6, 8).
- Width of stacks (3 mm, 4 mm, 6 mm).

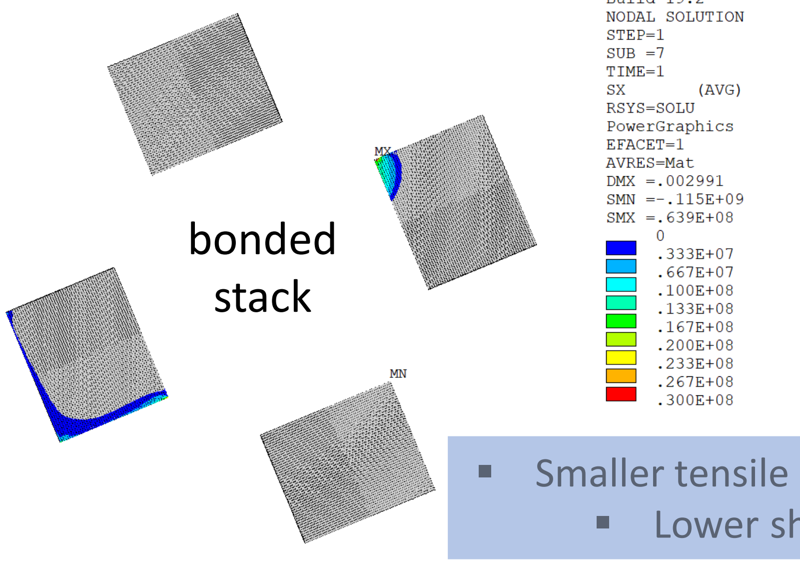
Bonded/Frictional Stack

1. Stack bonded to copper former.
2. Stack allowed to separate and slide in the copper former (μ = 0.2).

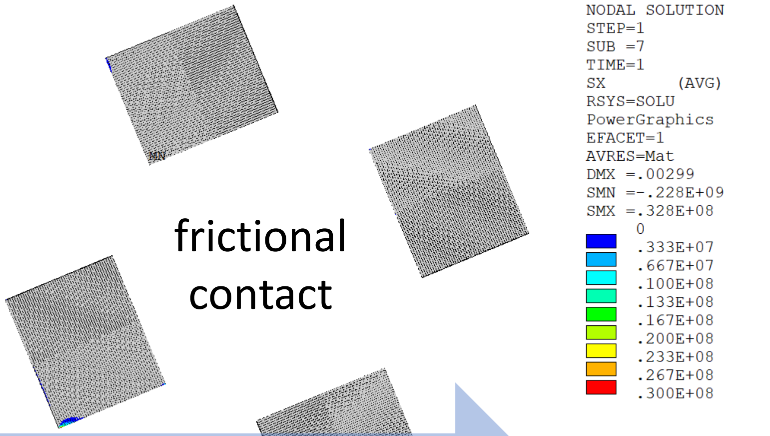
Contact Pressure [Pa]



Tensile Stress [Pa]

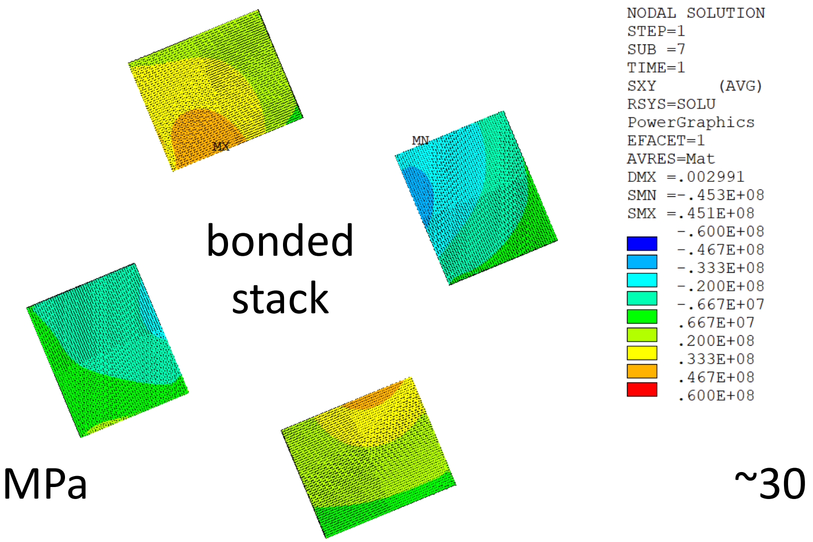


Tensile Stress [Pa]

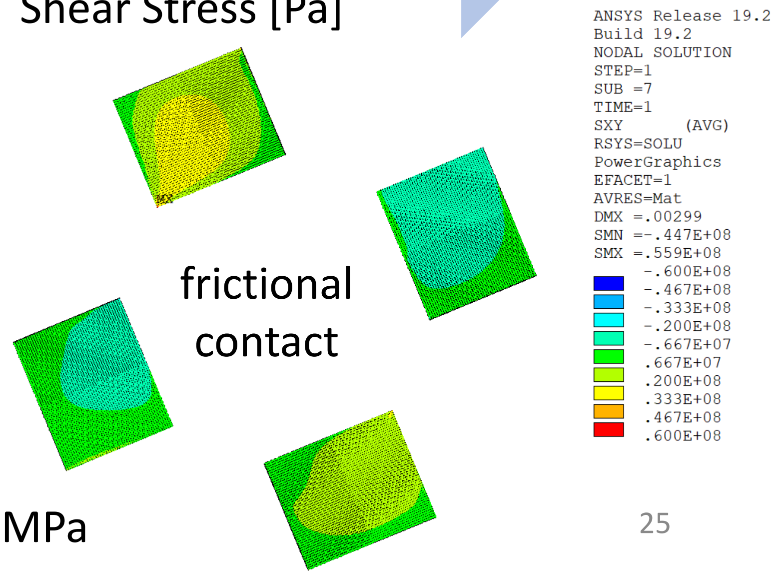


- Smaller tensile stress area with lower peak.
  - Lower shear stress in general.

Shear Stress [Pa]



Shear Stress [Pa]

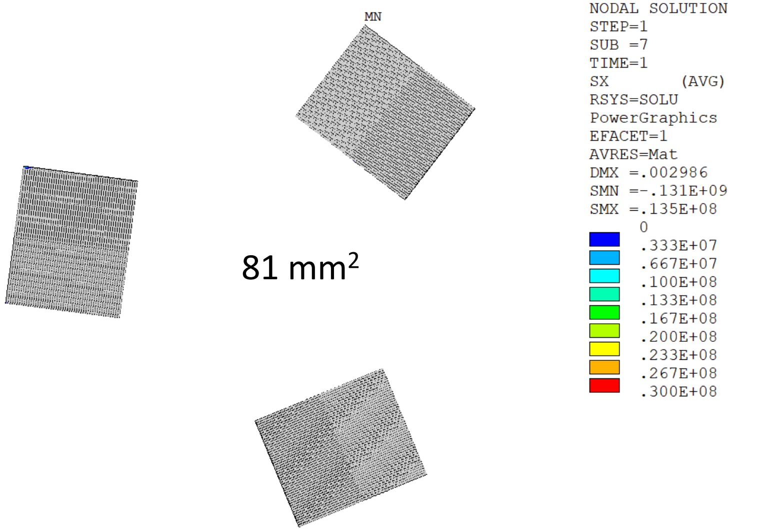


~40 MPa

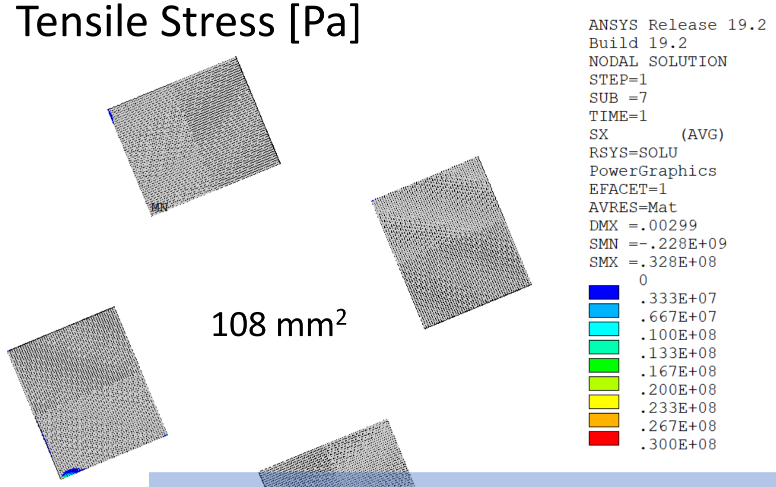
~30 MPa

Stack Number (6 mm wide tape, frictional contact)

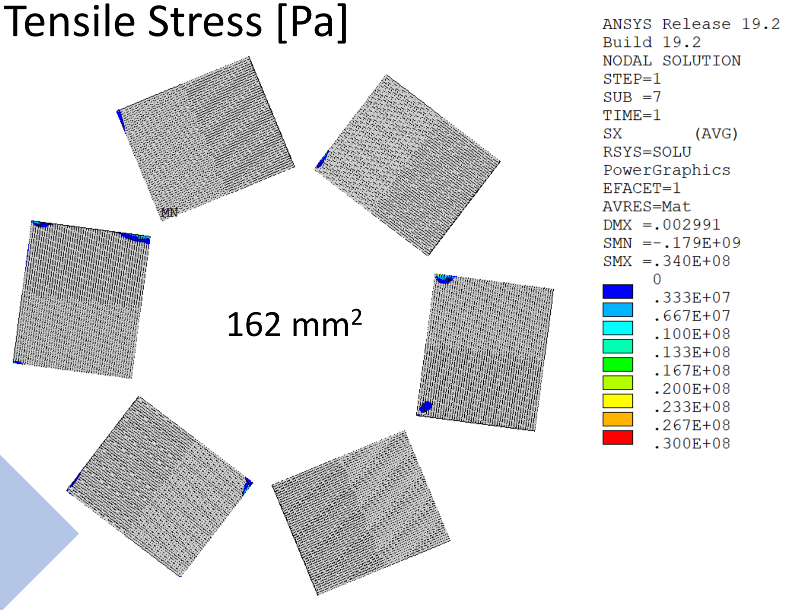
Tensile Stress [Pa]



Tensile Stress [Pa]

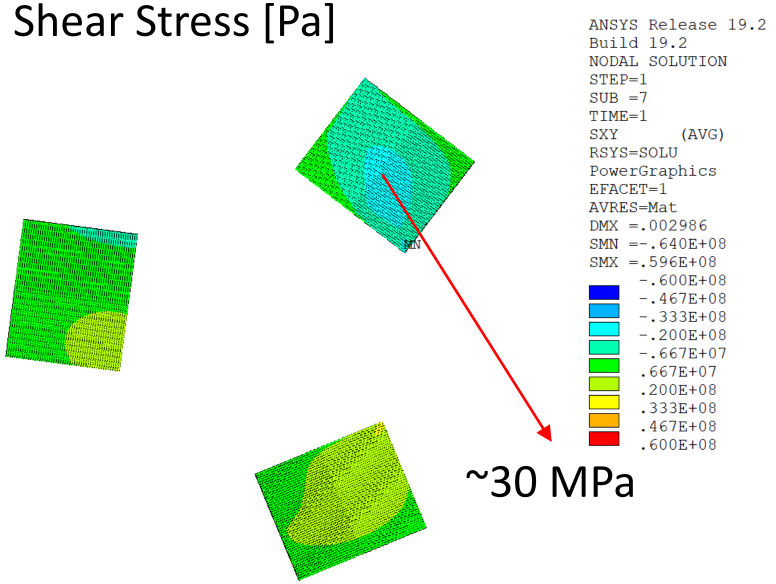


Tensile Stress [Pa]

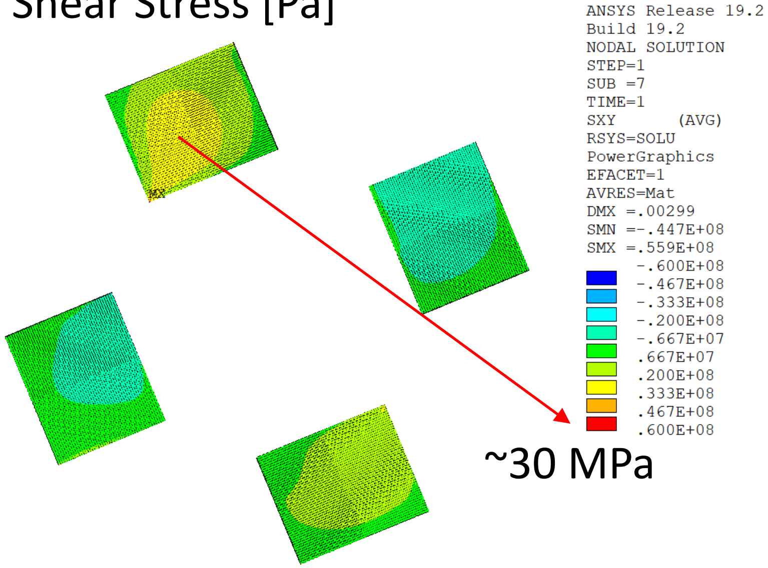


- Larger tensile stress area.

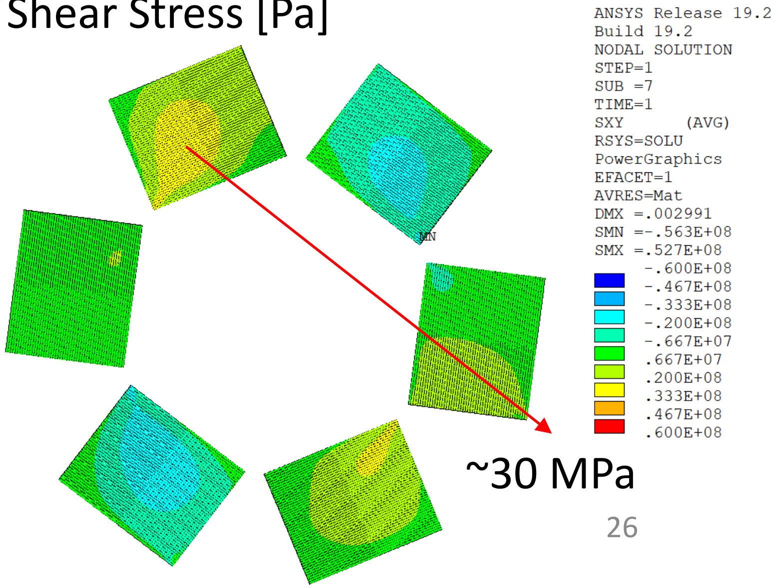
Shear Stress [Pa]



Shear Stress [Pa]

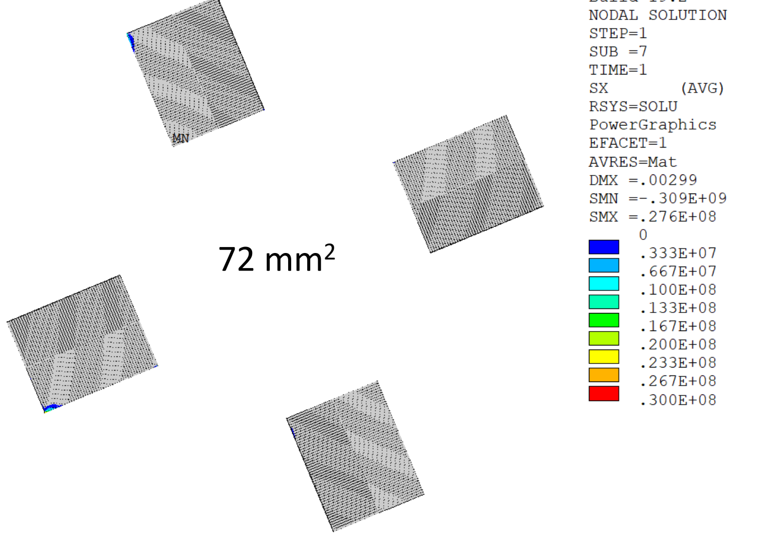


Shear Stress [Pa]

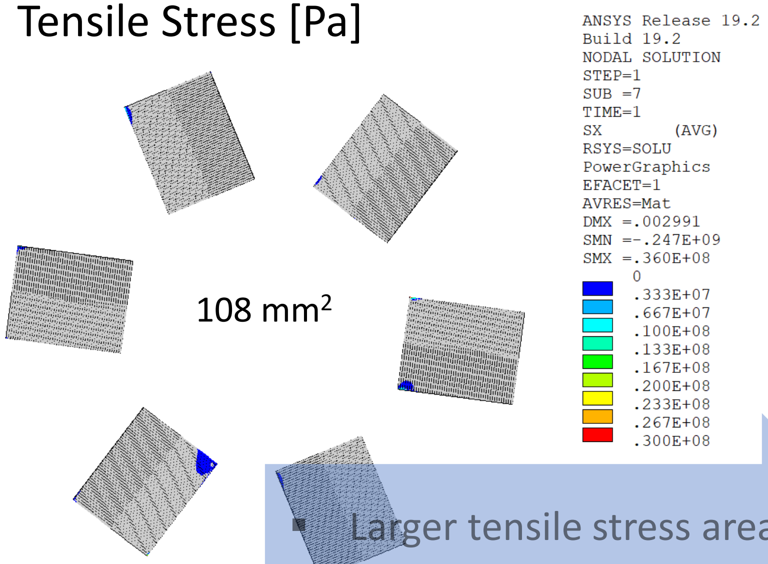


Stack Number (4 mm wide tape, frictional contact)

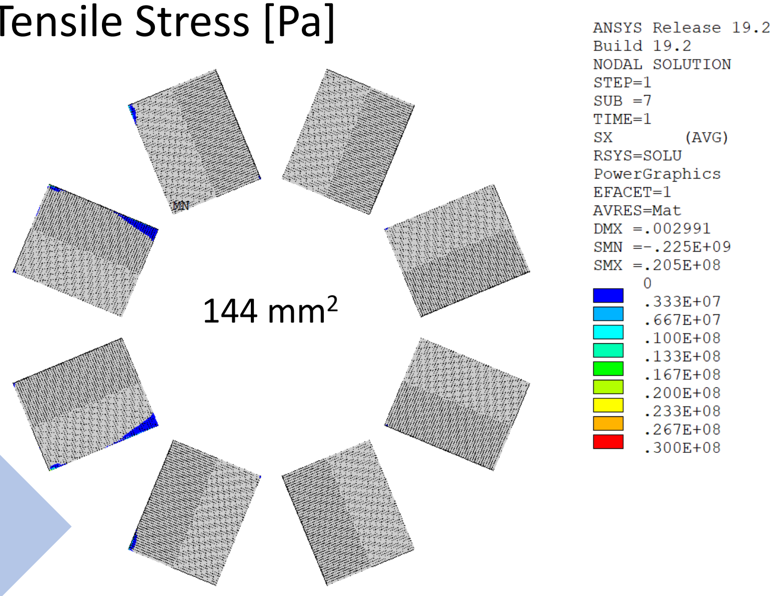
Tensile Stress [Pa]



Tensile Stress [Pa]

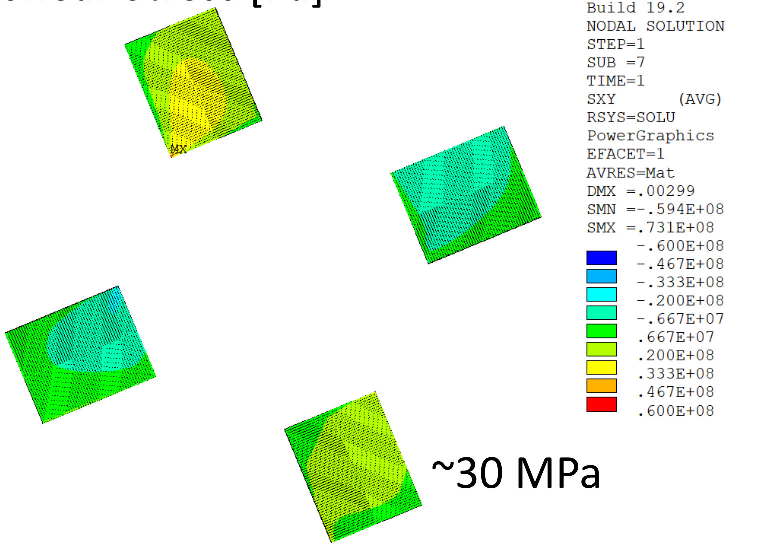


Tensile Stress [Pa]

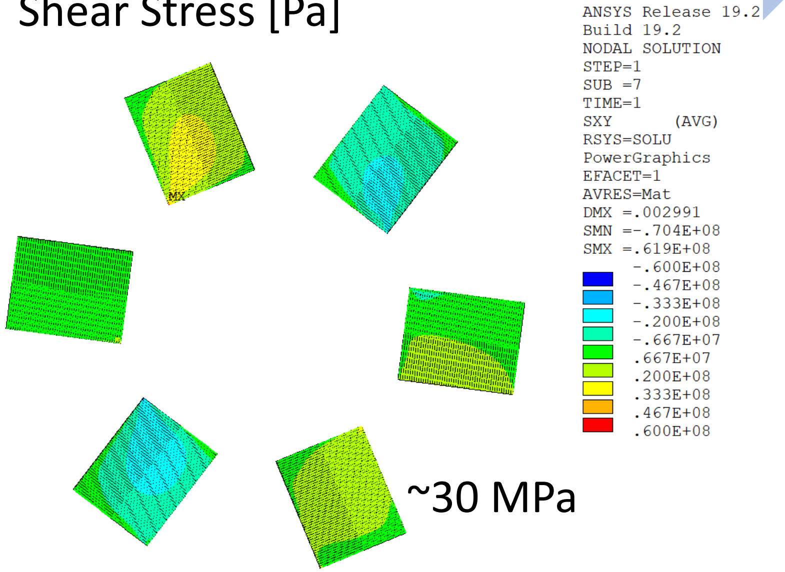


- Larger tensile stress area.

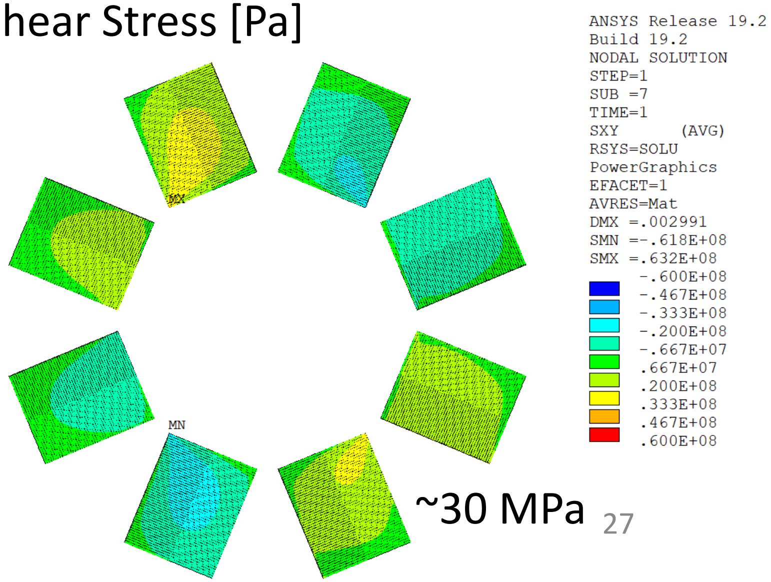
Shear Stress [Pa]



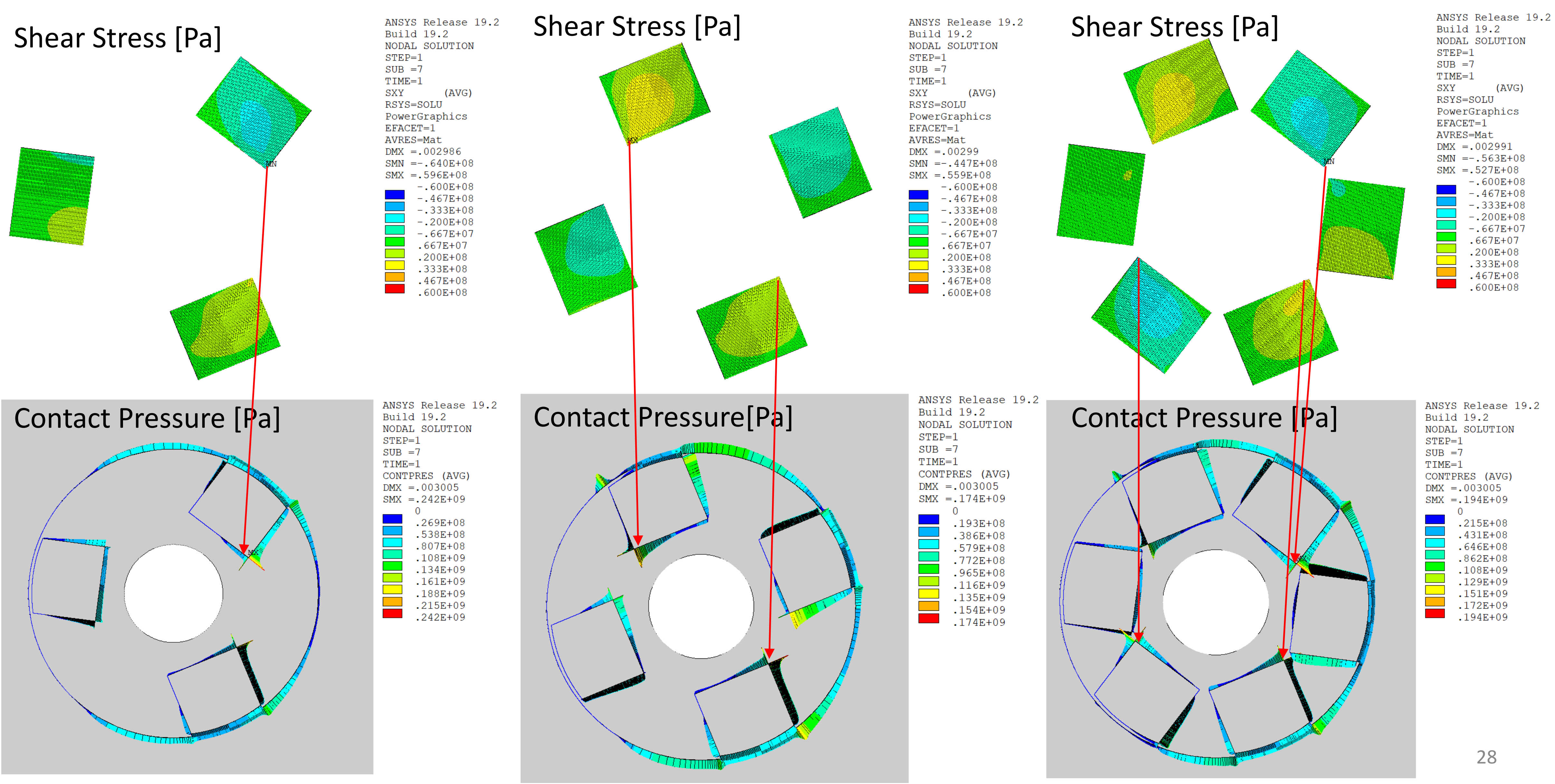
Shear Stress [Pa]



Shear Stress [Pa]

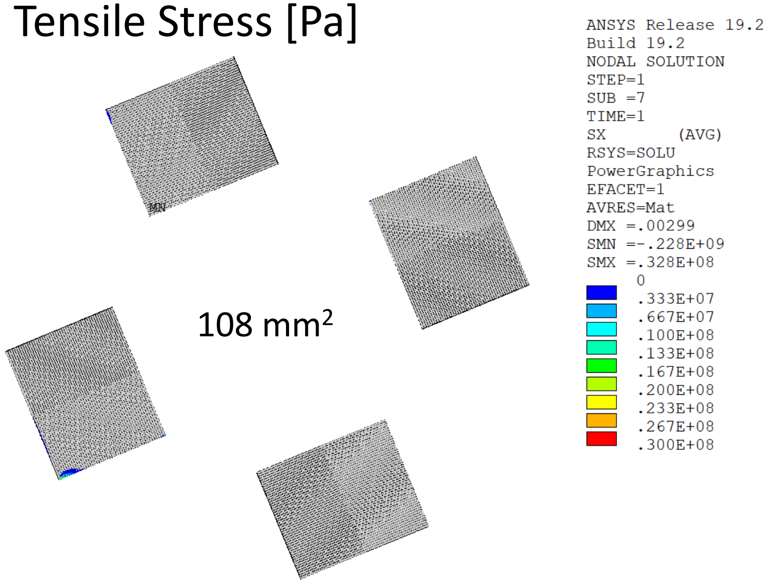


Stack Number (6 mm wide tape, frictional contact)

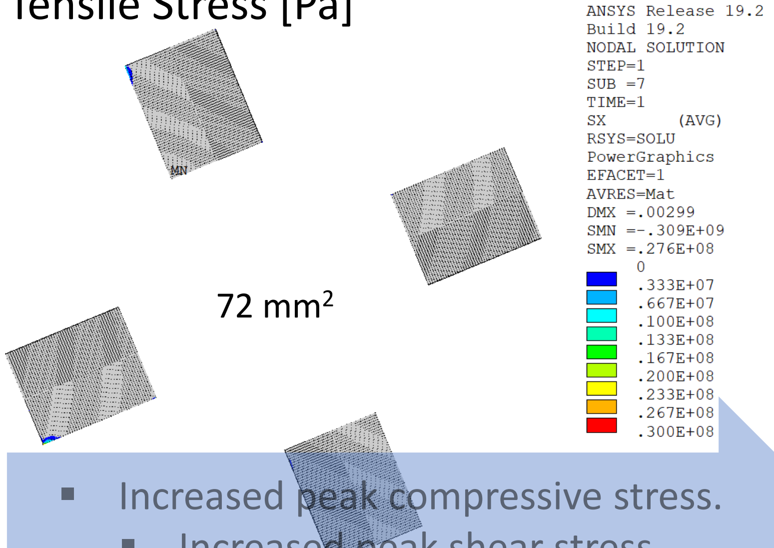


Stack Width (4 stacks, frictional contact)

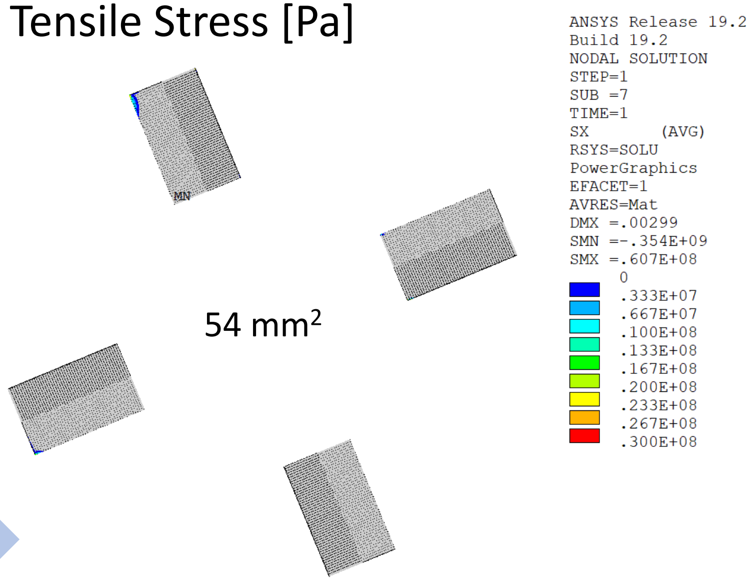
Tensile Stress [Pa]



Tensile Stress [Pa]

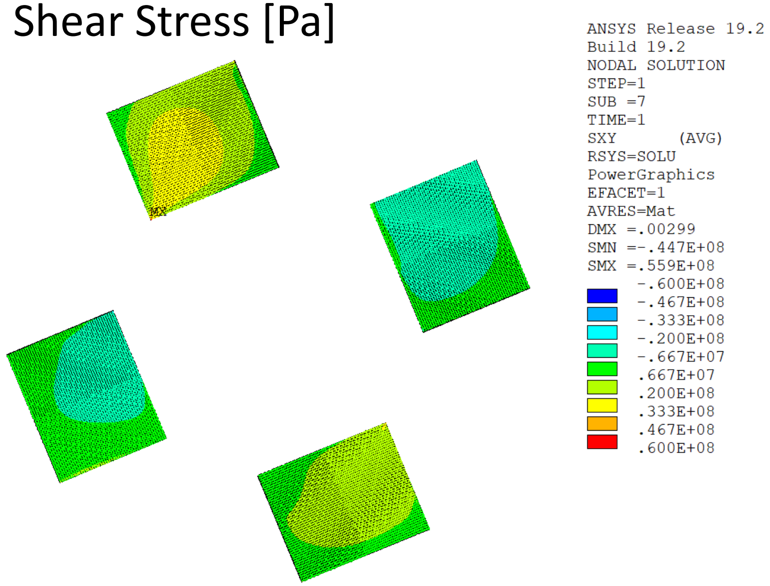


Tensile Stress [Pa]

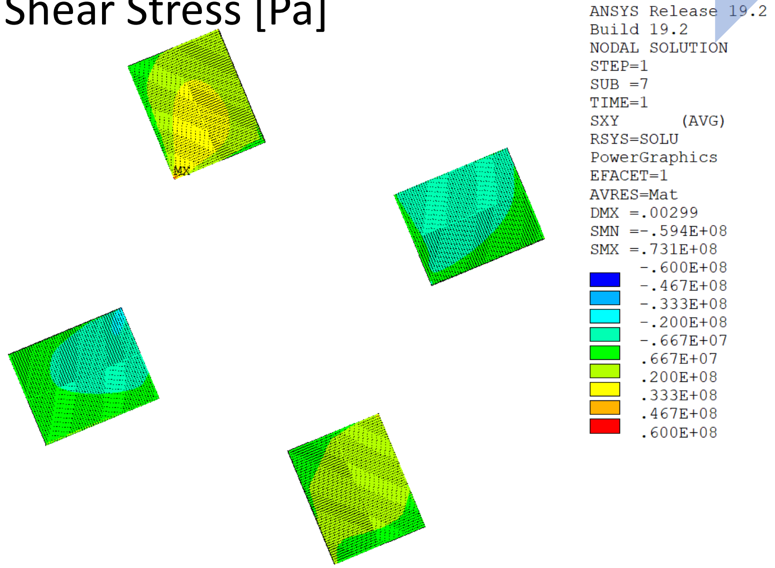


- Increased peak compressive stress.
  - Increased peak shear stress.

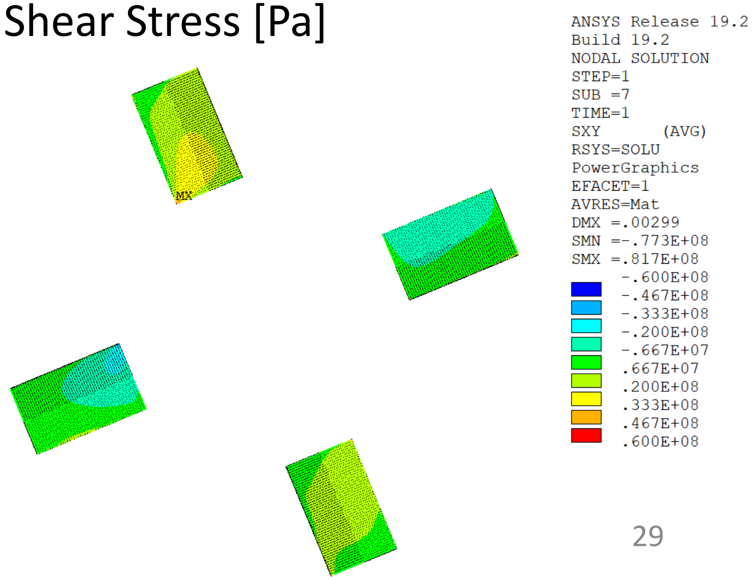
Shear Stress [Pa]



Shear Stress [Pa]

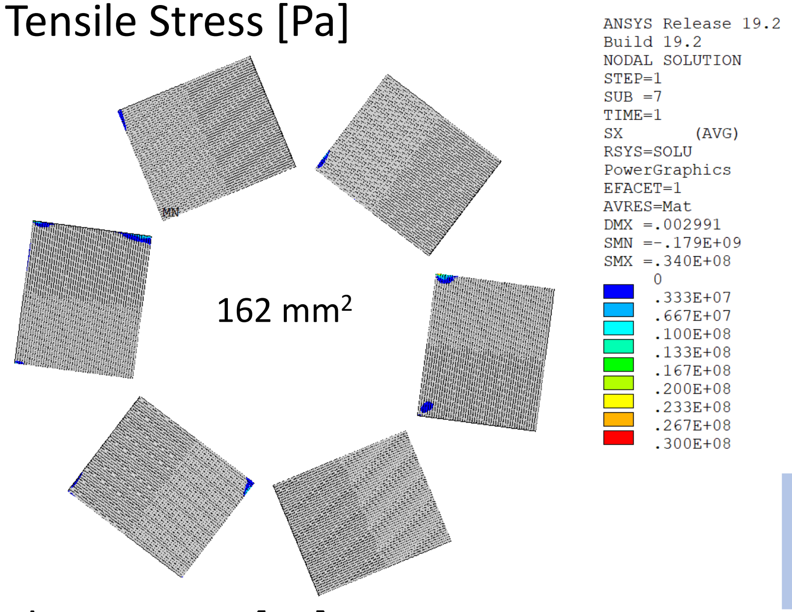


Shear Stress [Pa]

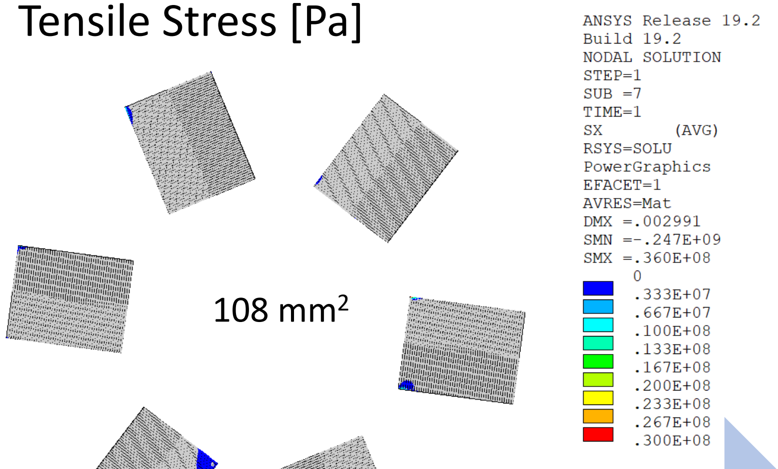


Stack Width (6 stacks, frictional contact)

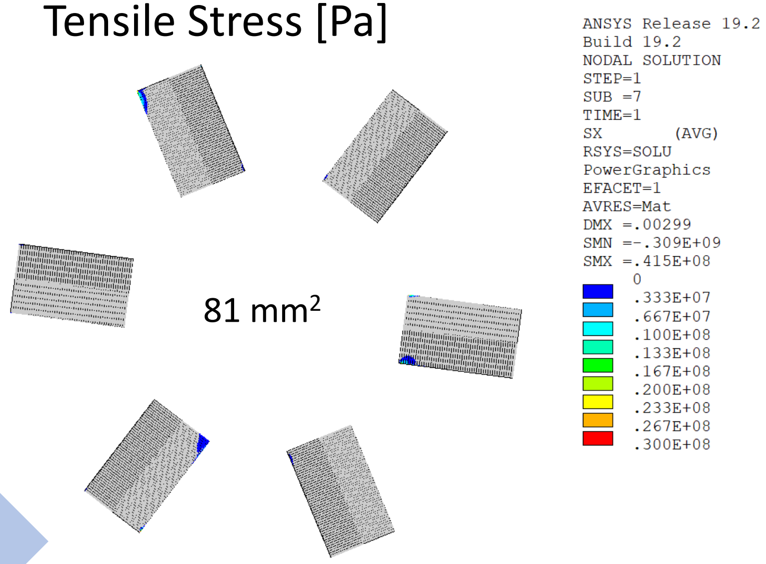
Tensile Stress [Pa]



Tensile Stress [Pa]

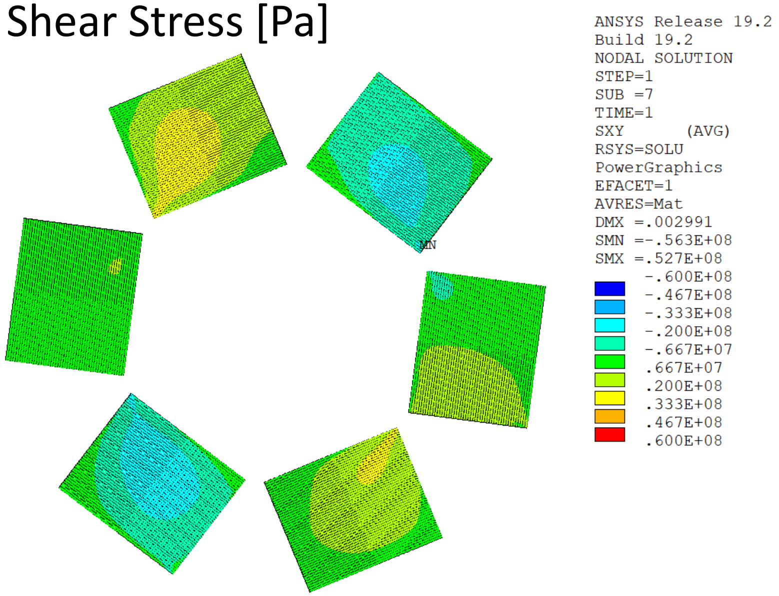


Tensile Stress [Pa]

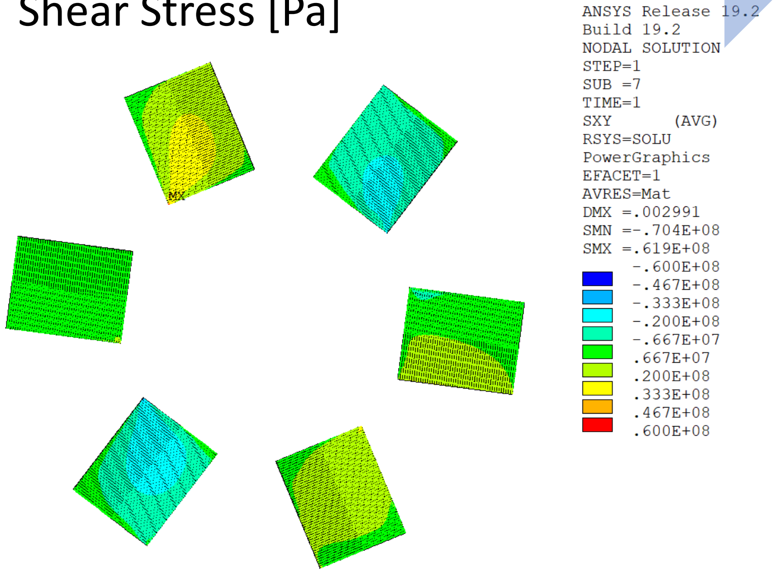


- Increased peak compressive stress.
  - Increased peak shear stress.

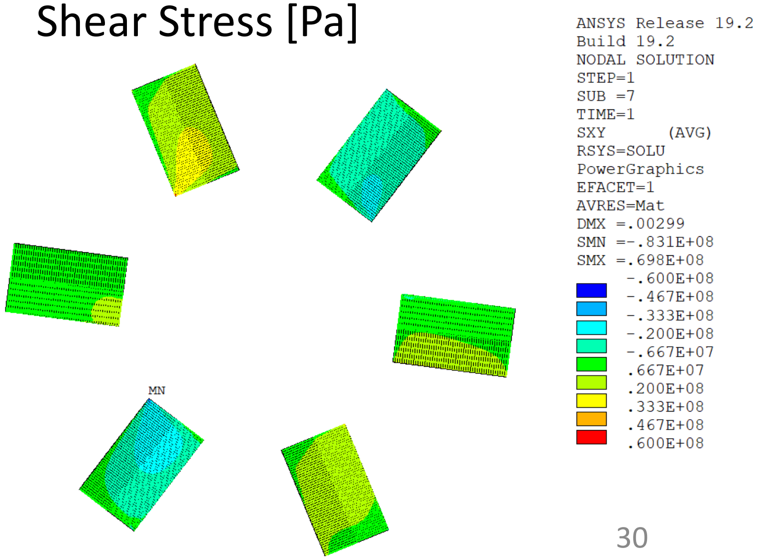
Shear Stress [Pa]



Shear Stress [Pa]



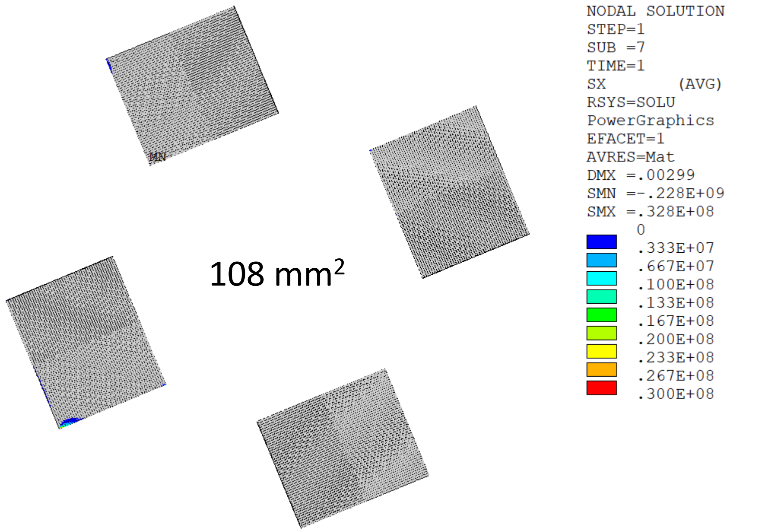
Shear Stress [Pa]



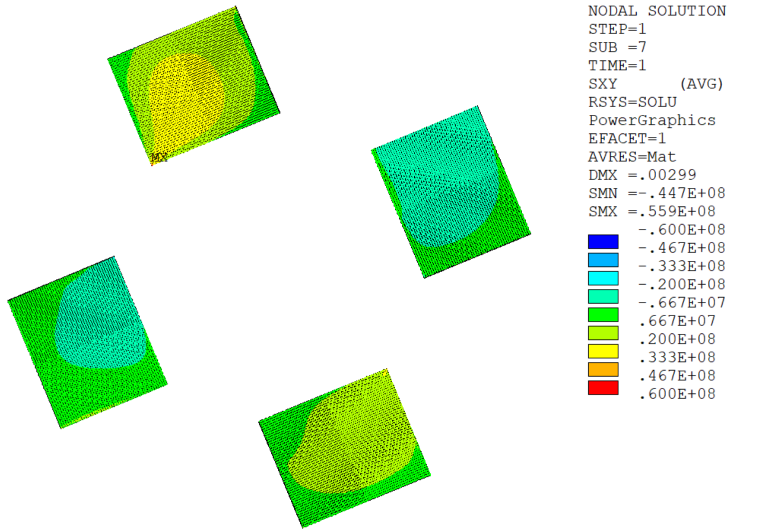
Tape Thickness (4 stacks, frictional contact)

- 50 tapes
- thickness = 90 um

Tensile Stress [Pa]

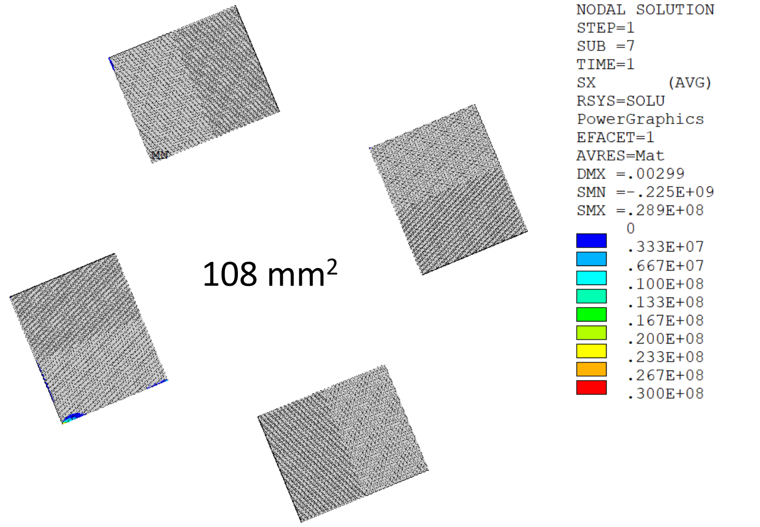


Shear Stress [Pa]

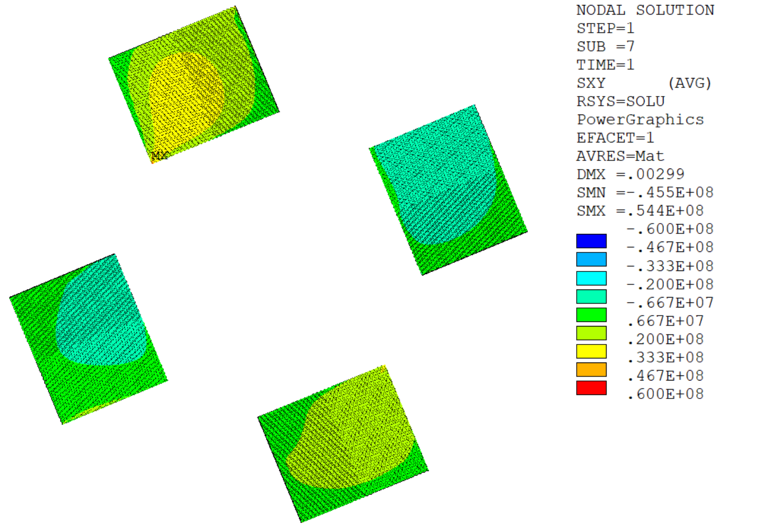


- 75 tapes
- thickness = 60 um

Tensile Stress [Pa]



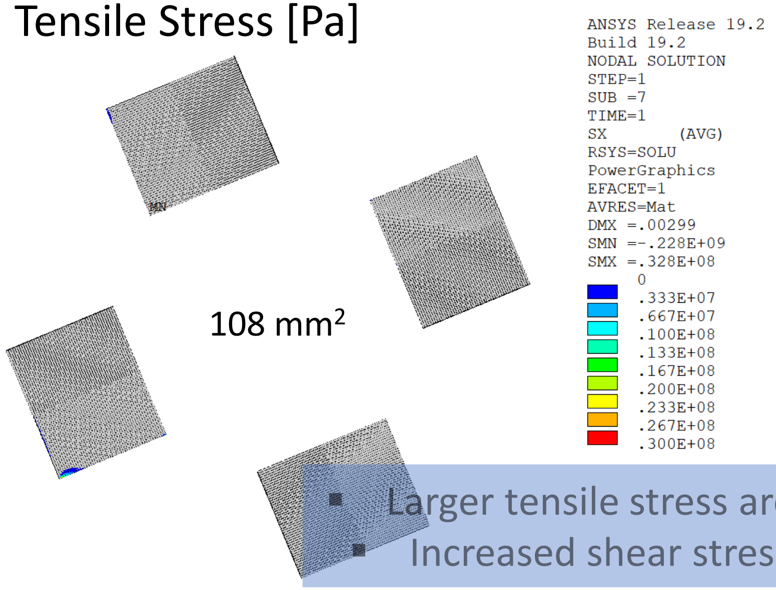
Shear Stress [Pa]



Solder Stiffness (4 stacks, frictional contact)

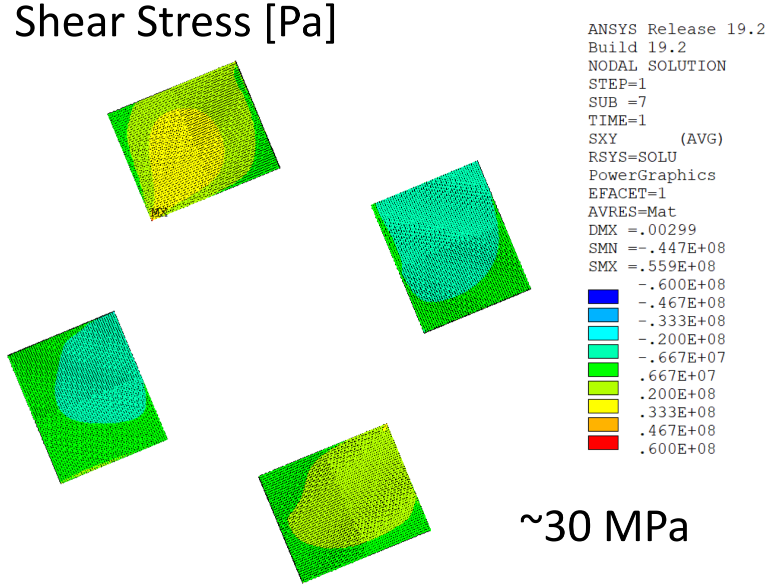
- E_{solder} = 10 GPa

Tensile Stress [Pa]



108 mm²

Shear Stress [Pa]

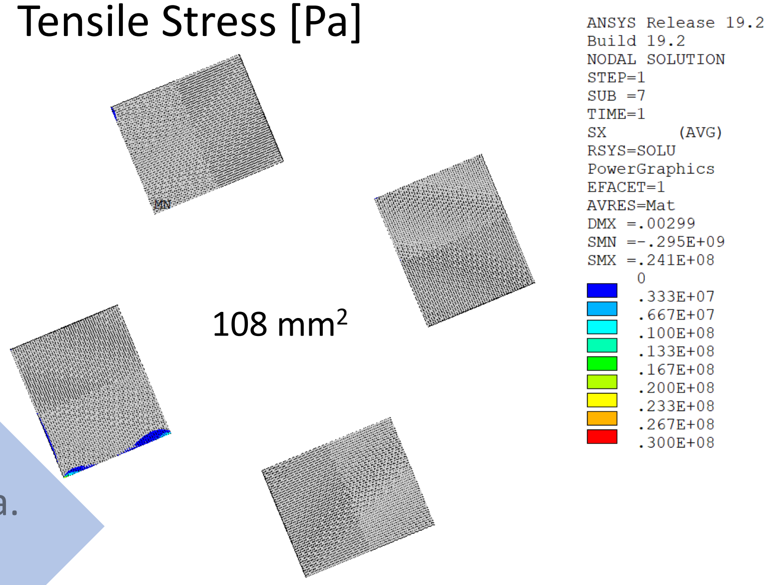


~30 MPa

- Larger tensile stress area.
- Increased shear stress.

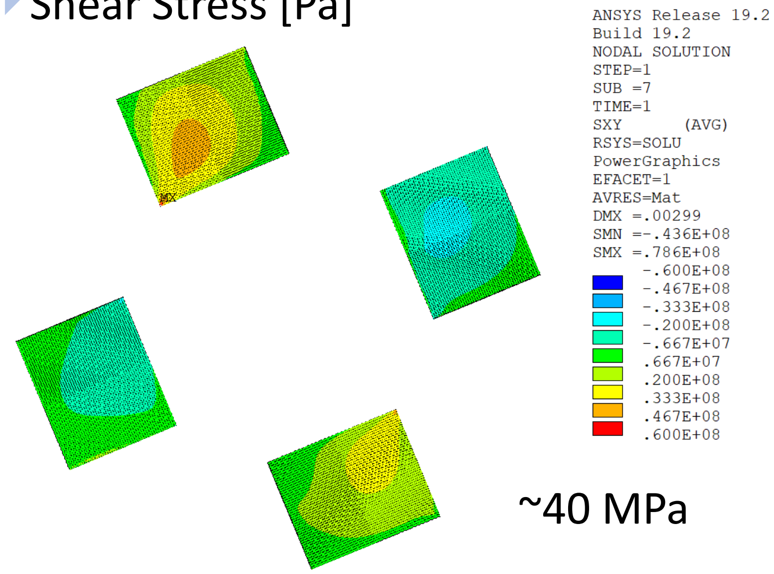
- E_{solder} = 20 GPa

Tensile Stress [Pa]



108 mm²

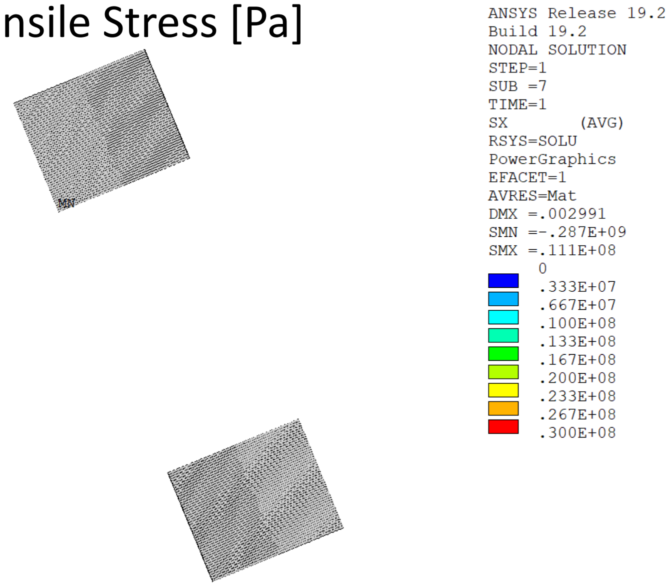
Shear Stress [Pa]



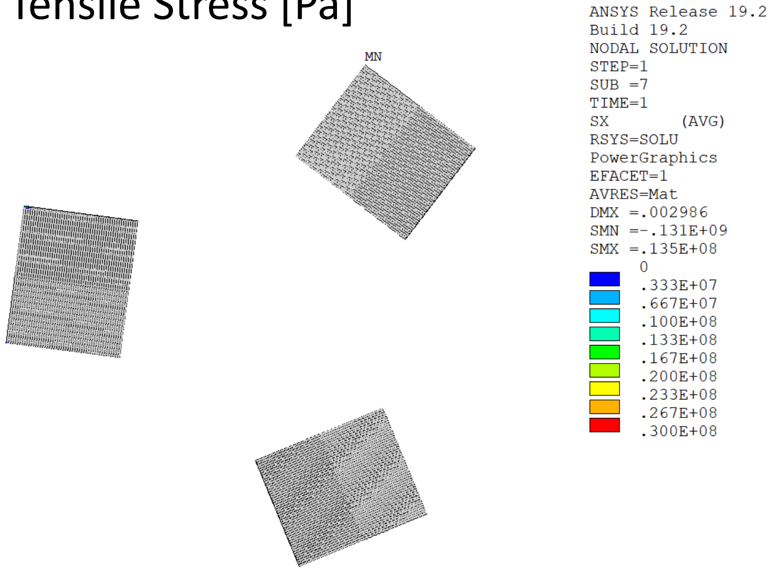
~40 MPa

Stack Number (6 mm wide tape, frictional contact)

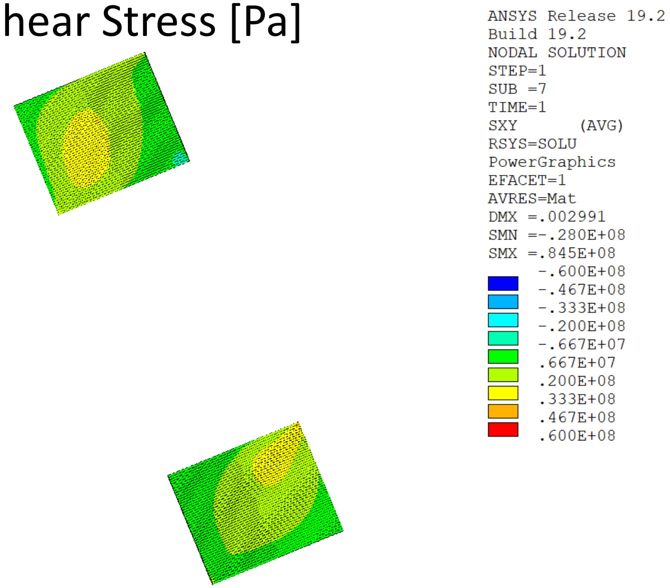
Tensile Stress [Pa]



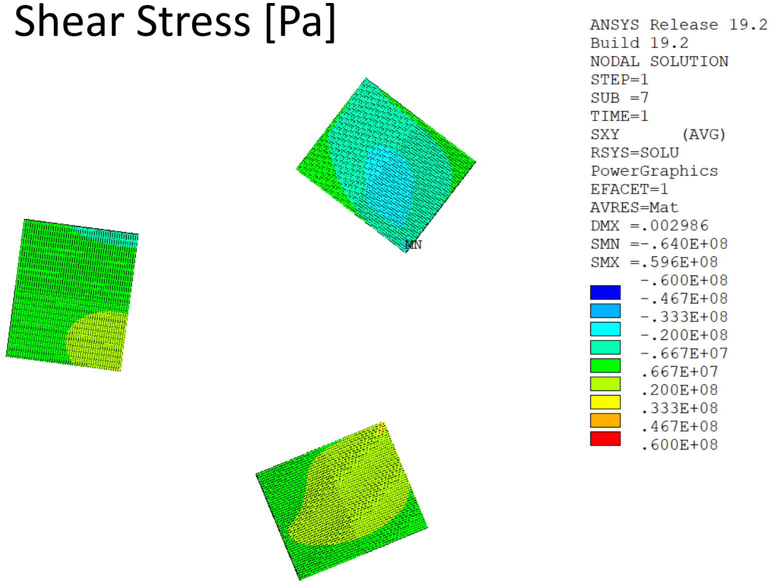
Tensile Stress [Pa]



Shear Stress [Pa]



Shear Stress [Pa]



Structural Design Criteria & Assessment

ITER Magnet Structural Design Criteria:

- Part 1: Main Structural Components and Welds.
- **Part 2: Magnet Windings (Radial Plates and Conductors) with High and Low Voltage Insulation and Epoxy Filler.**
- Part 3: Bolts, Keys, Supports and Special Components.
- Part 4: Cryogenic Piping.

Jackets

- Only static stress limits are considered.
- Relevance of fatigue stress to be discussed (cyclic loading?).

Turn insulation

Structural Design Criteria & Assessment: Stress Linearization

$$\sigma_{ij}(x) \approx \sigma_{m,ij} + \sigma_{b,ij}\frac{2x}{t}, \qquad -\frac{t}{2} \le x \le \frac{t}{2}$$

- $\sigma_{m,ij}$ = membrane stress tensor (constant part).
- $\sigma_{b,ij}$ = bending stress tensor (linear part).

$$\min_{\sigma_{m,ij},\sigma_{b,ij}} \frac{1}{t}\int_{-\frac{t}{2}}^{\frac{t}{2}} \left[\sigma_{ij}(x) - \sigma_{m,ij} - \sigma_{b,ij}\frac{2x}{t}\right]^2 dx$$

$$\sigma_{m,ij} = \frac{1}{t}\int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma_{ij}(x)\,dx \qquad \sigma_{b,ij} = -\frac{6}{t^2}\int_{-\frac{t}{2}}^{\frac{t}{2}} x\sigma_{ij}(x)\,dx$$

Figure 17.4: Coordinates of Cross Section

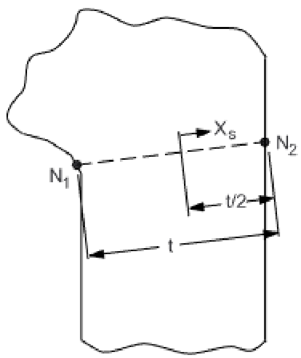
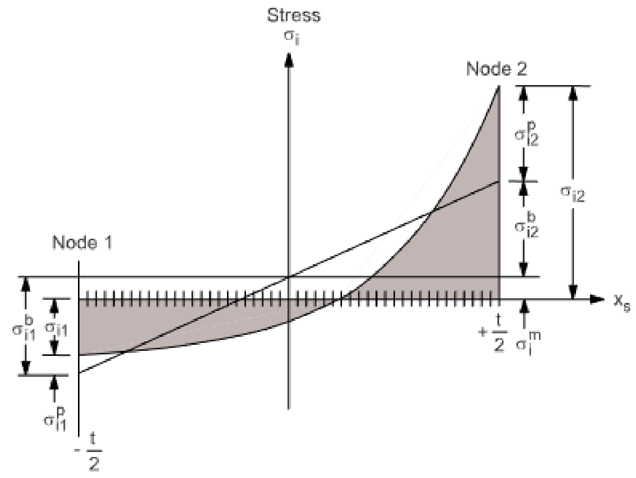


Figure 17.5: Typical Stress Distribution



Source: ANSYS Theory Reference

- Once membrane and bending stress tensors are known, von Mises/Tresca stresses can be computed as usual.
- Von Mises/Tresca stresses do not vary linearly along the defined paths.

Structural Design Criteria & Assessment: Stress Classification

Primary Stress, P

- Stress developed by imposed loading.
- Necessary to satisfy laws of equilibrium.
- Not self-limiting.
- Result in failure/gross distortion if considerably exceeds yield strength.
- Thermal stress is not primary.

$$\begin{gathered} \varepsilon_{ij} = C_{ijkl}(\sigma_{kl}) \\ \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ \sigma_{ij,j} + X_i = 0 \\ u_i = 0 \quad \text{on } \partial\Omega_D \\ \sigma_{ij} n_j = 0 \quad \text{on } \partial\Omega_N \end{gathered}$$

$+$

$$\begin{gathered} \varepsilon_{ij} = C_{ijkl}(\sigma_{kl}) \\ \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ \sigma_{ij,j} = 0 \\ u_i = 0 \quad \text{on } \partial\Omega_D \\ \sigma_{ij} n_j = \bar{t}_i \quad \text{on } \partial\Omega_N \end{gathered}$$

$+$

Secondary Stress, Q

- Stress developed by constrain of adjacent material or by self-constraint of the structure.
- Self-limiting.
- Thermal stress.

$$\begin{gathered} \varepsilon_{ij} = C_{ijkl}(\sigma_{kl} - \alpha_{kl}\Delta T) \\ \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ \sigma_{ij,j} = 0 \\ u_i = 0 \quad \text{on } \partial\Omega_D \\ \sigma_{ij} n_j = 0 \quad \text{on } \partial\Omega_N \end{gathered}$$

$+$

$$\begin{gathered} \varepsilon_{ij} = C_{ijkl}(\sigma_{kl}) \\ \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ \sigma_{ij,j} = 0 \\ u_i = \bar{u}_i \quad \text{on } \partial\Omega_D \\ \sigma_{ij} n_j = 0 \quad \text{on } \partial\Omega_N \end{gathered}$$

Rule of thumb:

- Thermal stresses are classified as secondary.
- Stresses induced by EM loads, inertial/gravity loads, pressure loads, etc., are classified as primary.

Structural Design Criteria & Assessment: Metallic Components

ITER MSDC Part 2 for Metallic Components:

- Allowable stress: $S_m = \frac{2}{3} S_y$
- Primary membrane stress: $P_m \leq 1.0\ K_m\ S_m$
- Primary membrane + bending stress: $P_m + P_b \leq 1.3\ K_m\ S_m$
- Primary + secondary stress $P + Q \leq 1.5\ K_m\ S_m$

K_m depends on type of service conditions:

Table 3-1 Km factor values for base metal and weld joints

Service Level	Base metal	Welds
A	1.0	1.0
B	1.1	1.1
C *	1.2	1.2
D *	1.5	1.5

* Evaluation of secondary stress is not required.

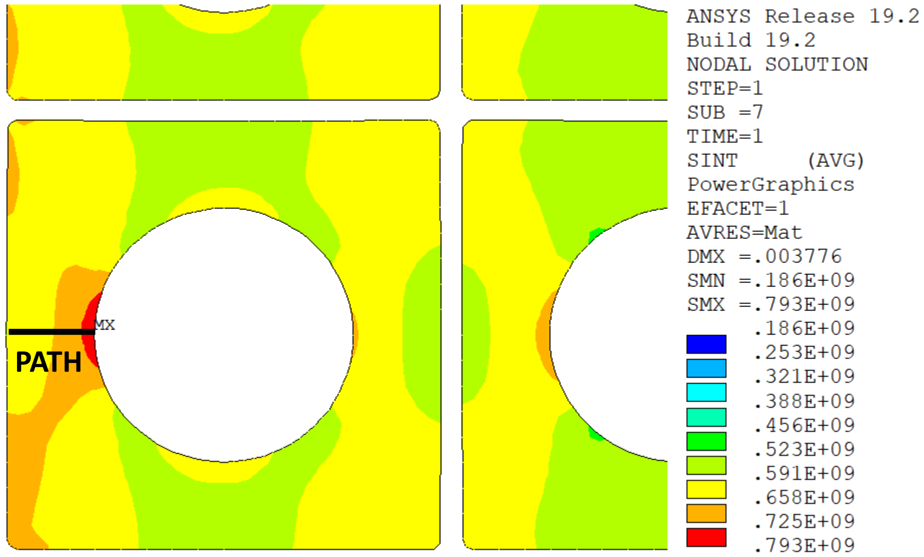
Structural Design Criteria & Assessment: Metallic Components

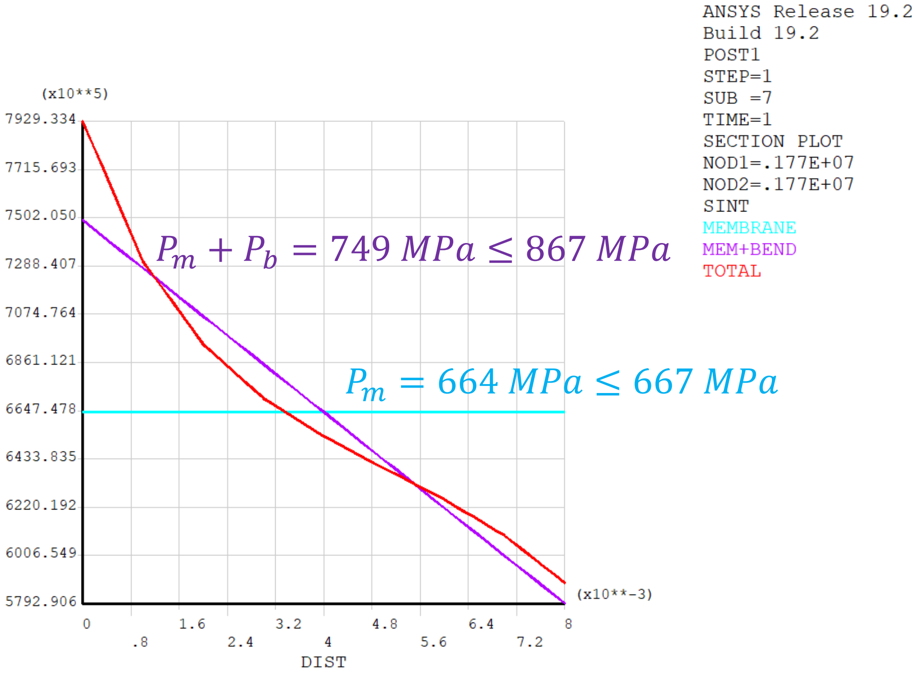
ITER MSDC Part 2:

- $K_m = 1.0$
- $S_y = 1000\ MPa$

TF conductor jacket, CS conductor jacket	Modified and aged 316 LN for Nb3Sn, as extruded circular tube or square sections	205GPa σ_y=1000MPa σ_u=1600MPa	K_{IC}= 150MPam$^{1/2}$	C=3.86E-11m/cycle m=2.394

- Allowable stress: $S_m = \frac{2}{3} S_y = 667\ MPa$
- Primary membrane stress: $P_m \leq 1.0\ K_m\ S_m = 667\ MPa$
- Primary membrane + bending stress: $P_m + P_b \leq 1.3\ K_m\ S_m = 867\ MPa$
- Primary + secondary stress (not considered, no thermal load applied).





Structural Design Criteria & Assessment: Metallic Components

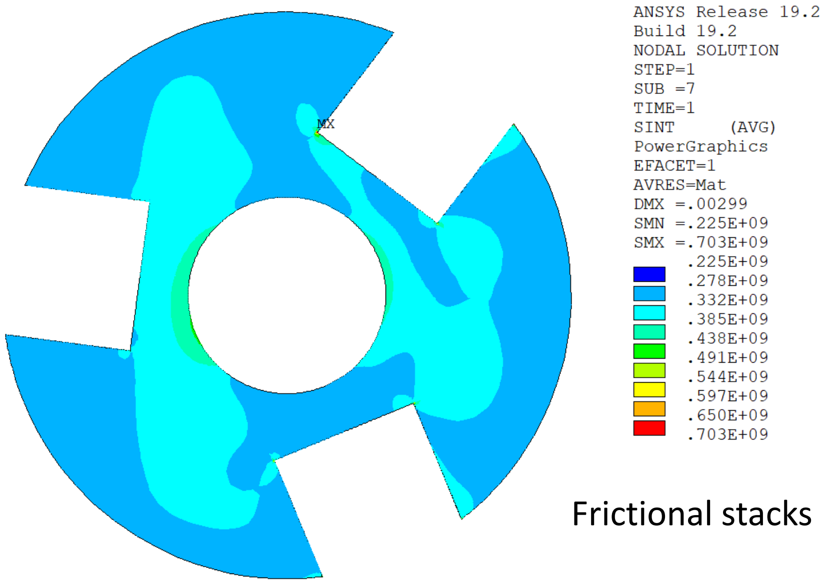
- Copper former is not intended to be a structural component in the cable but it reacts the magnetic load due to its relatively high stiffness (110 GPa vs. 205 GPa of steel).
- The yield strength of copper is rather low compared to that of steel (factor ~3)), at least at room temperature (strength at cryogenic temperature needs to be investigated).

Table A.S30.3.2-1: Minimum yield strength for plates, tubes and rod products from pure copper

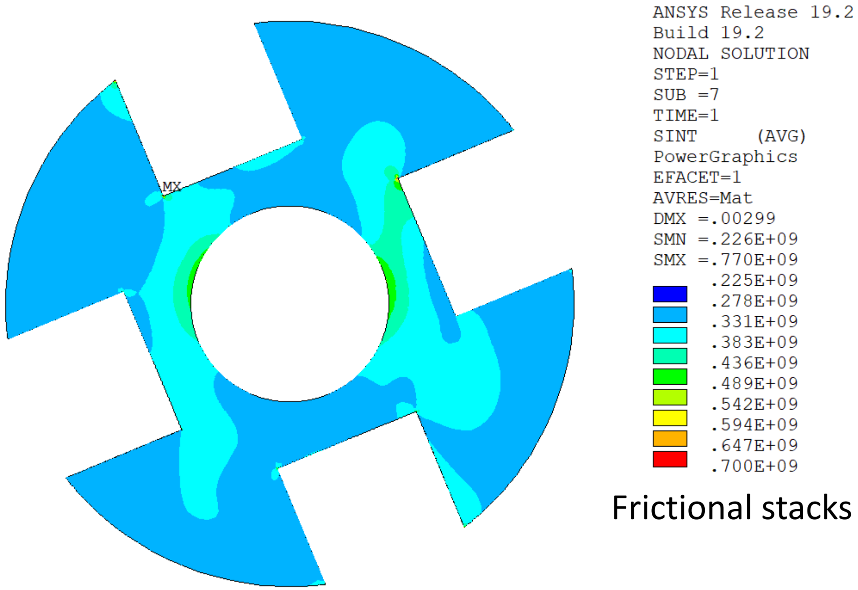
T, °C	20	50	100	150	200	250	300	350	400	450	500
$S_{y\ min}$, plates, MPa	69	62	56	54	51	45	43	40	37	34	32
$S_{y\ min}$, tubes, MPa	62	55	50	48	46	40	37	35	33	30	28
$S_{y\ min}$, rods, MPa	55	49	45	43	41	37	35	32	30	28	26

Table A.S30.3.3-1: Minimum tensile strength of pure copper

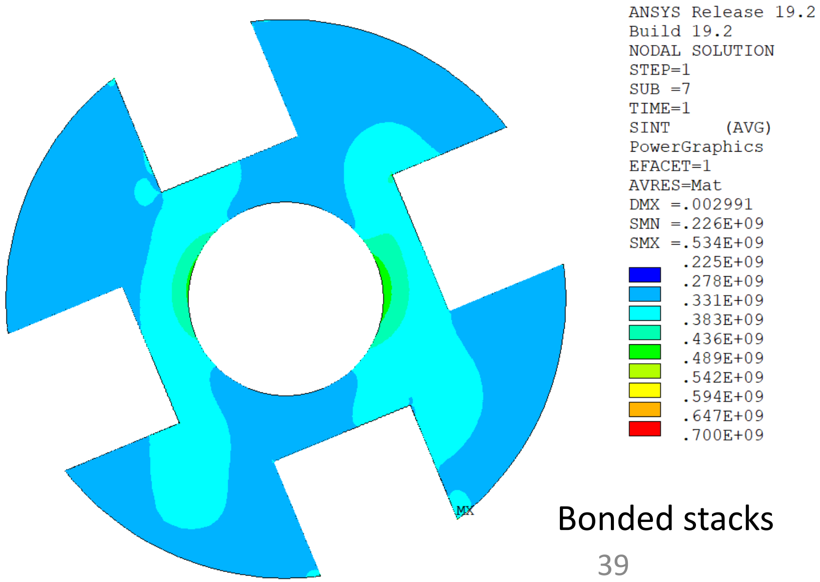
T, °C	20	50	100	150	200	250	300	350	400	450	500
$S_{u,\ min}$, MPa	200	192	178	165	152	139	127	116	104	93	83



Frictional stacks



Frictional stacks



Bonded stacks

Structural Design Criteria & Assessment: Non-Metallic Components

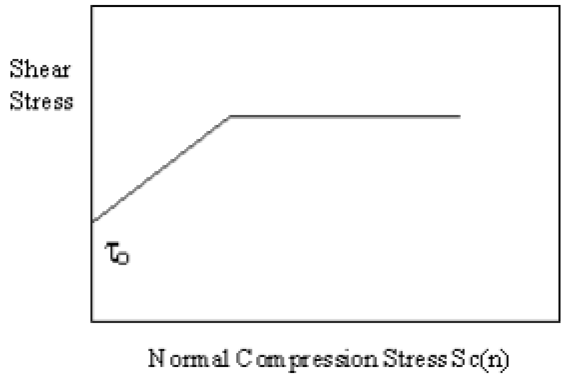
ITER MSDC Part 2 for High-Voltage Insulation:

1. Allowable compressive stress normal to the reinforcing plane. The compressive static stress in the through-thickness direction of the insulating material is limited to 50% of the minimum ultimate compressive strength:

$$S_c = 0.5\sigma_{cs}$$

2. Allowable tensile strain normal to reinforcing plane. No primary tensile strain is allowed in the direction normal to the adhesive bonds between metal and composite.
3. Allowable shear stress. The allowable shear strength of an insulator depends on the applied compressive stress.
4. Allowable strain in plane of reinforcing. The allowed tensile or compressive strain in the plane of the insulation material is in the range [-0.5%, 0.5%].

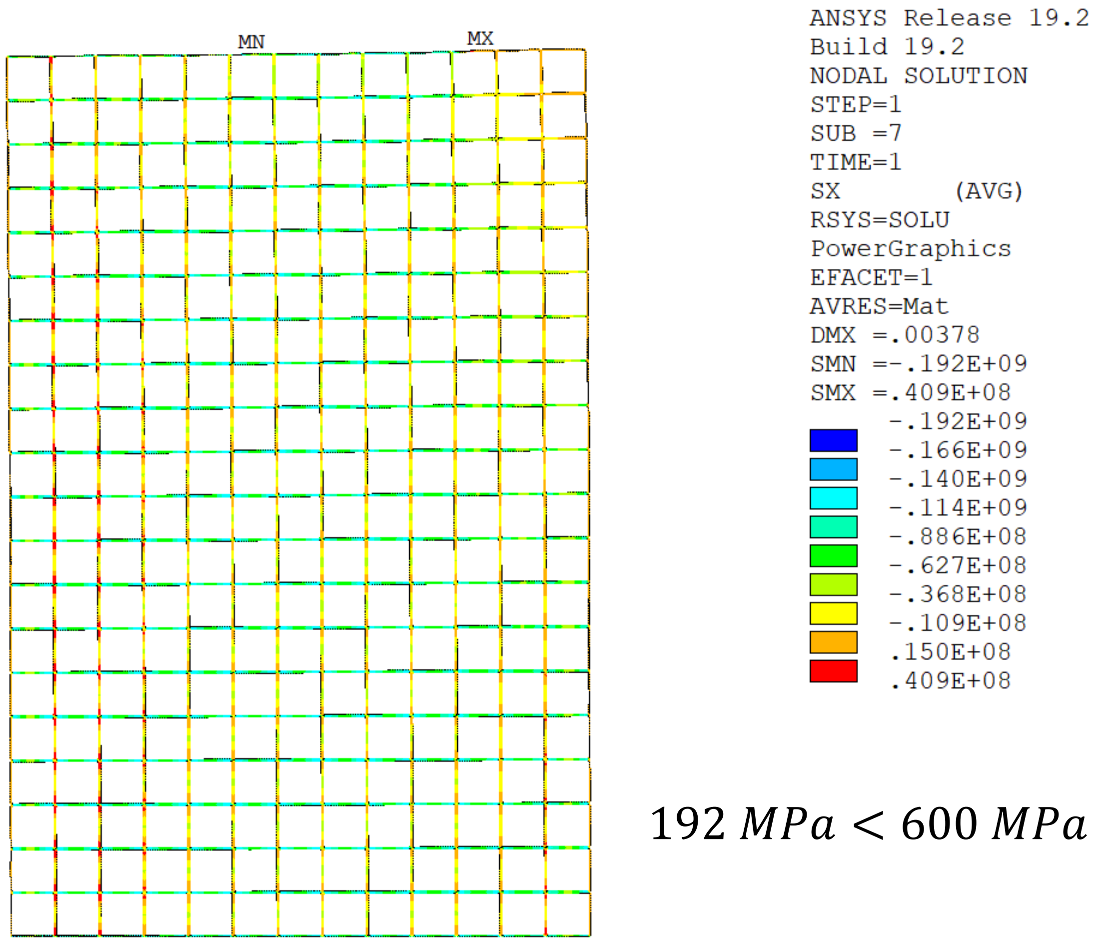
Components	Material and Form	Minimum specified properties at 4K		
		Young's Modulus, Yield and Ultimate Strength	Static Stress Limits	Fatigue Stress Limits
TF, CS, PF Turn Insulation	VPI epoxy glass with kapton barrier	$E_1=E_2=20GPa$ $E_3=12GPa$ G(all)=6GPa $\nu_{12}=0.17$ $\nu_{13}=\nu_{23}=0.33$ $\sigma_{cs}=1200MPa$	$\tau_o=85MPa$ $C_2=0.45$ for $S_{c(n)}<58MPa$ Sss=68.6MPa for $58<S_{c(n)}$	$\tau_o=50MPa$ $C_2=0.45$ for $S_{c(n)}<55MPa$ Ssf=50MPa for $50<S_{c(n)}$



Structural Design Criteria & Assessment: Non-Metallic Components

1. Allowable compressive stress normal to the reinforcing plane.

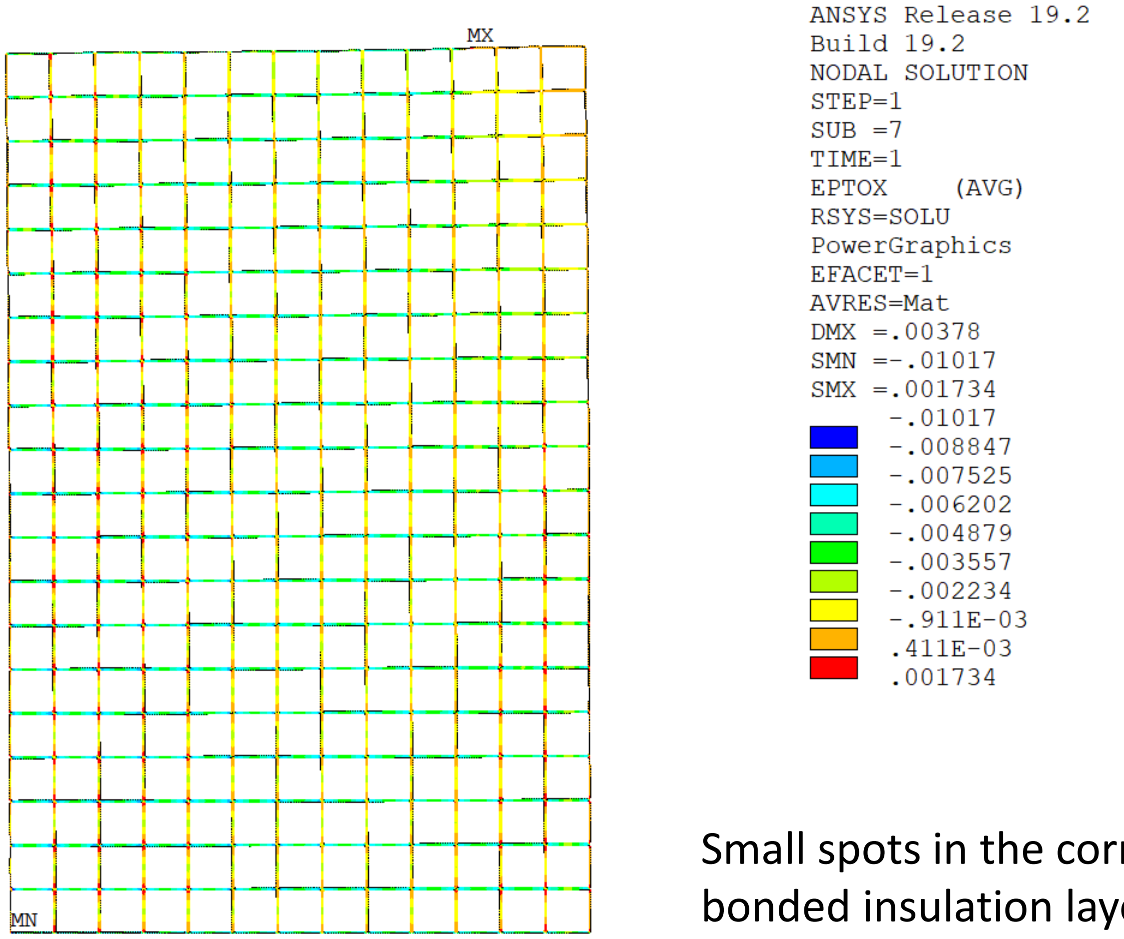
$$S_c = 0.5\sigma_{cs} = 600\ MPa$$

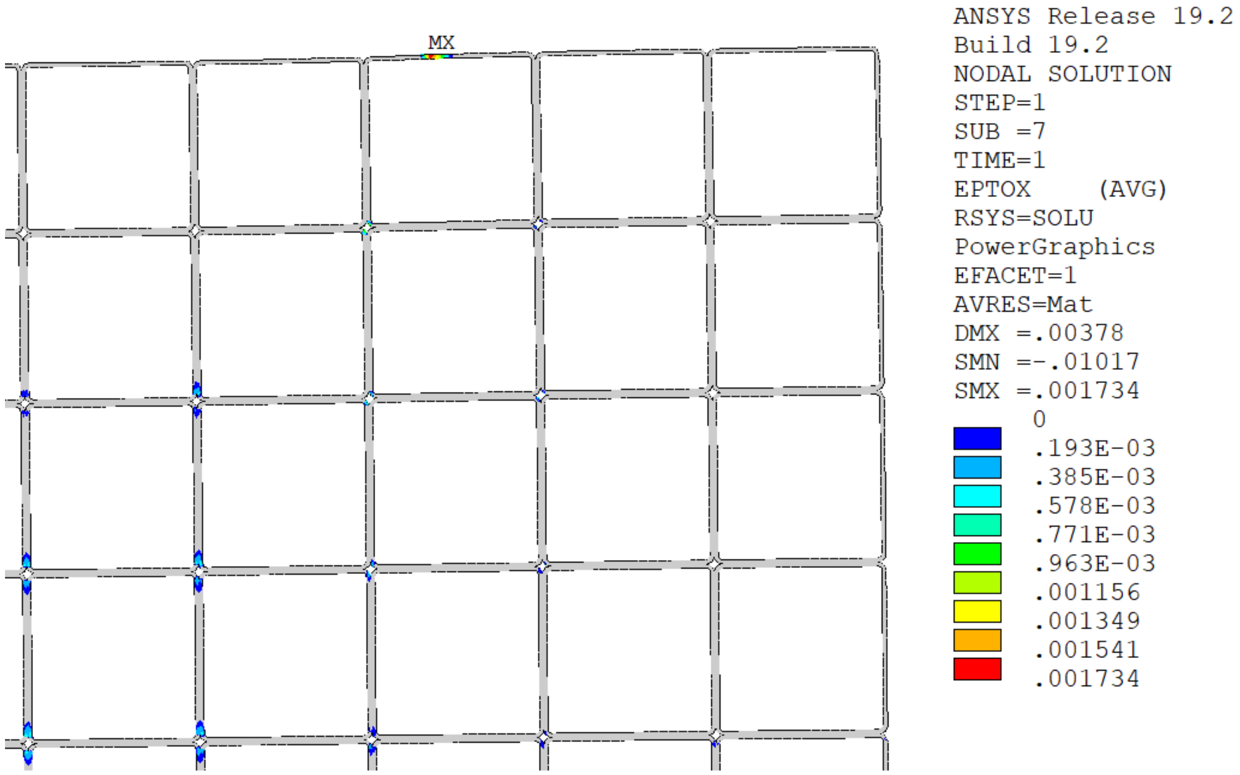


$$192\ MPa < 600\ MPa$$

Structural Design Criteria & Assessment: Non-Metallic Components

2. Allowable tensile strain normal to reinforcing plane.

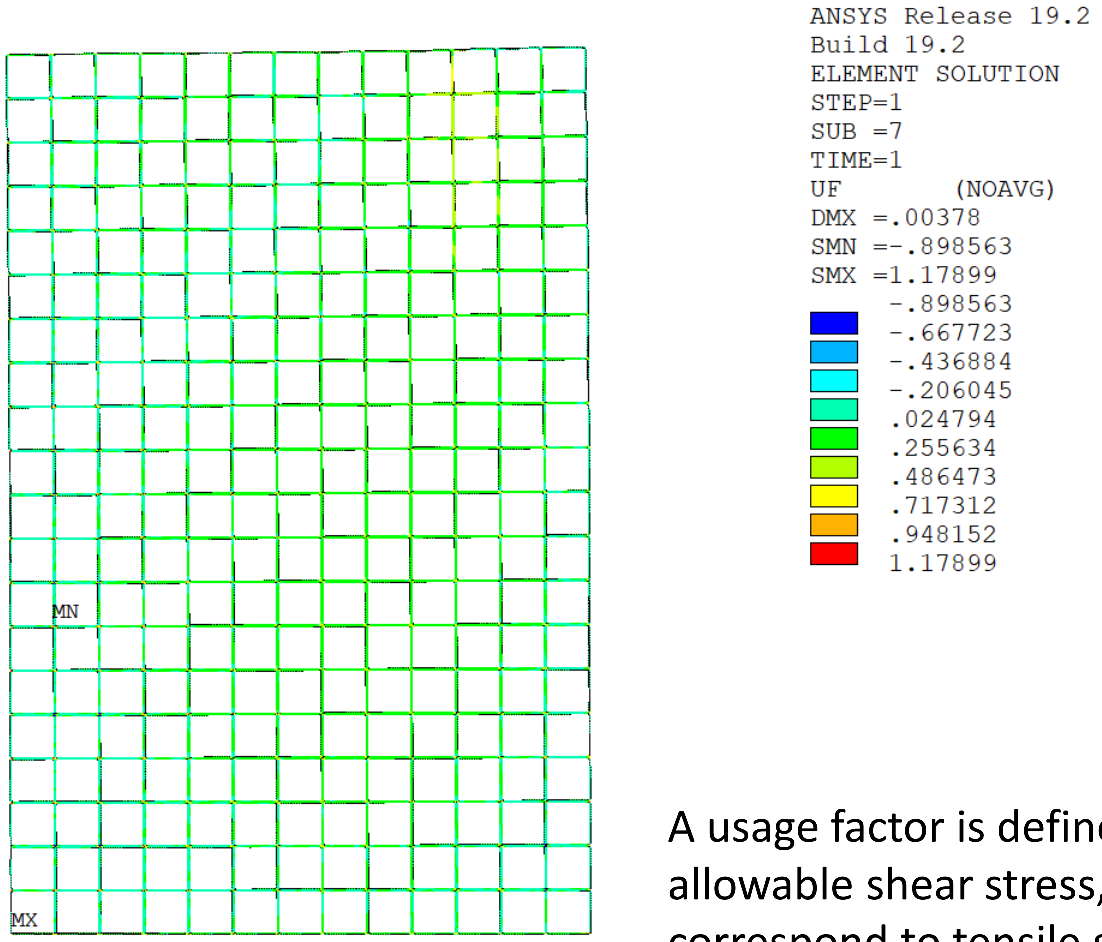


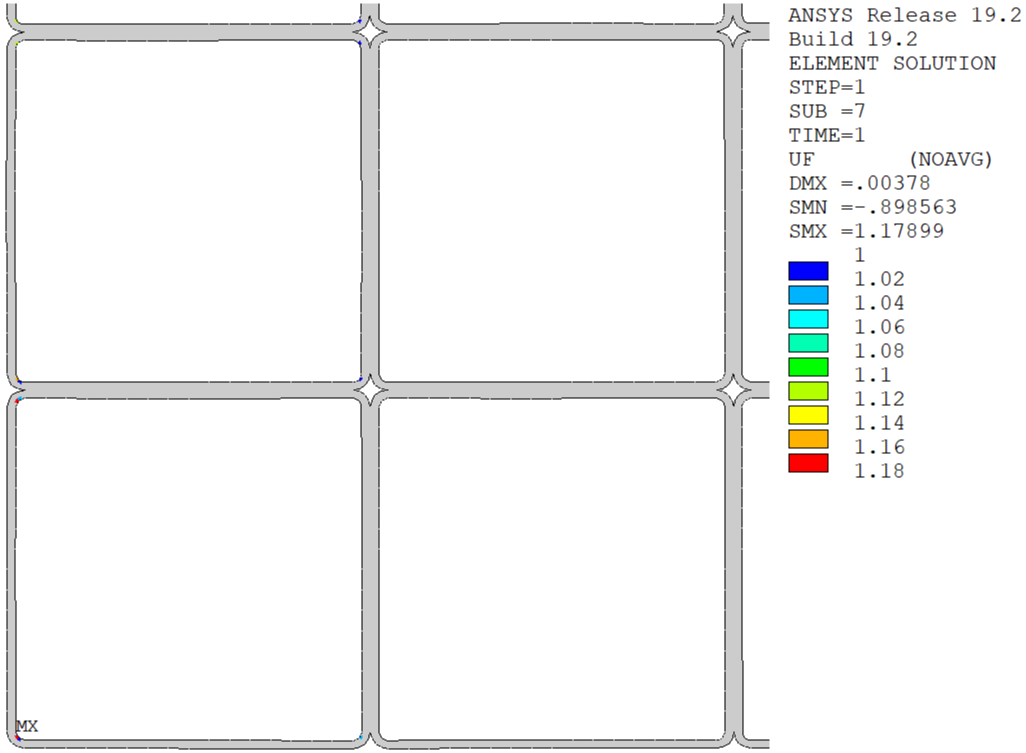


Small spots in the corner regions show normal tensile strain likely due to the fact that bonded insulation layers are assumed, and no separation is allowed.

Structural Design Criteria & Assessment: Non-Metallic Components

3. Allowable shear stress.

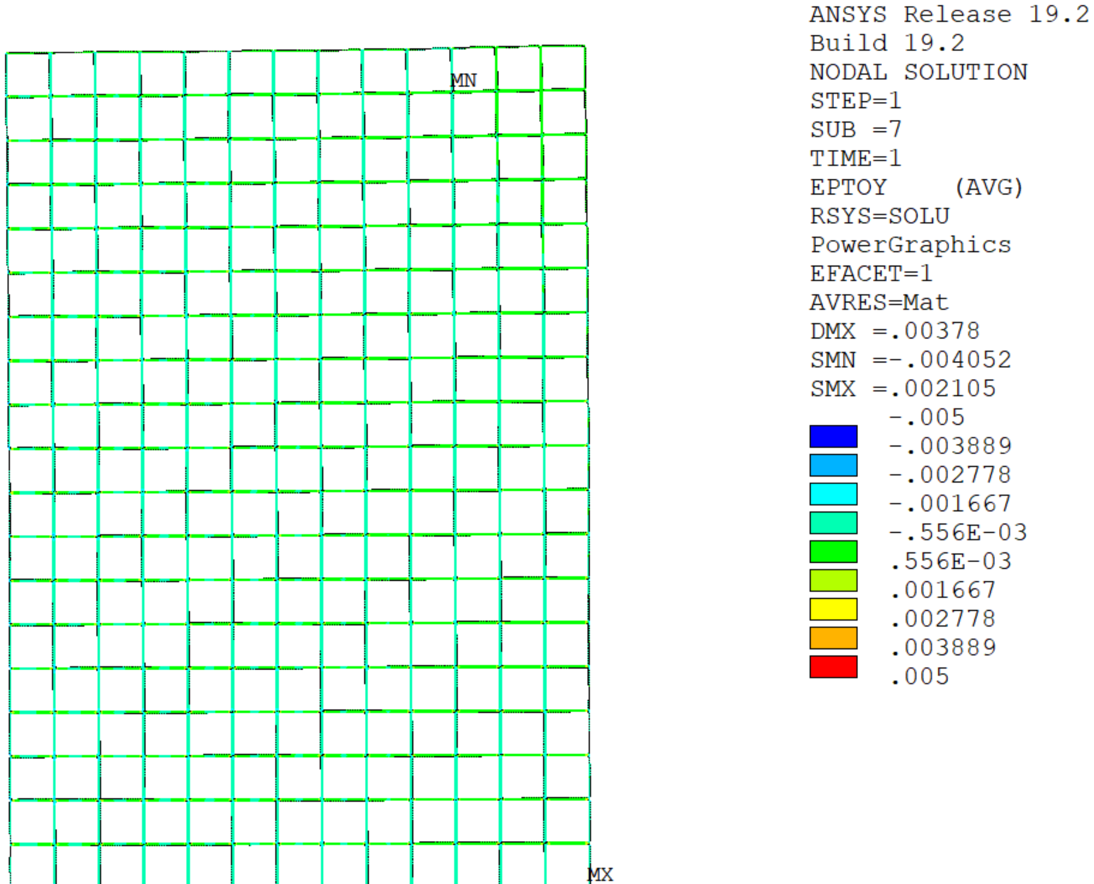




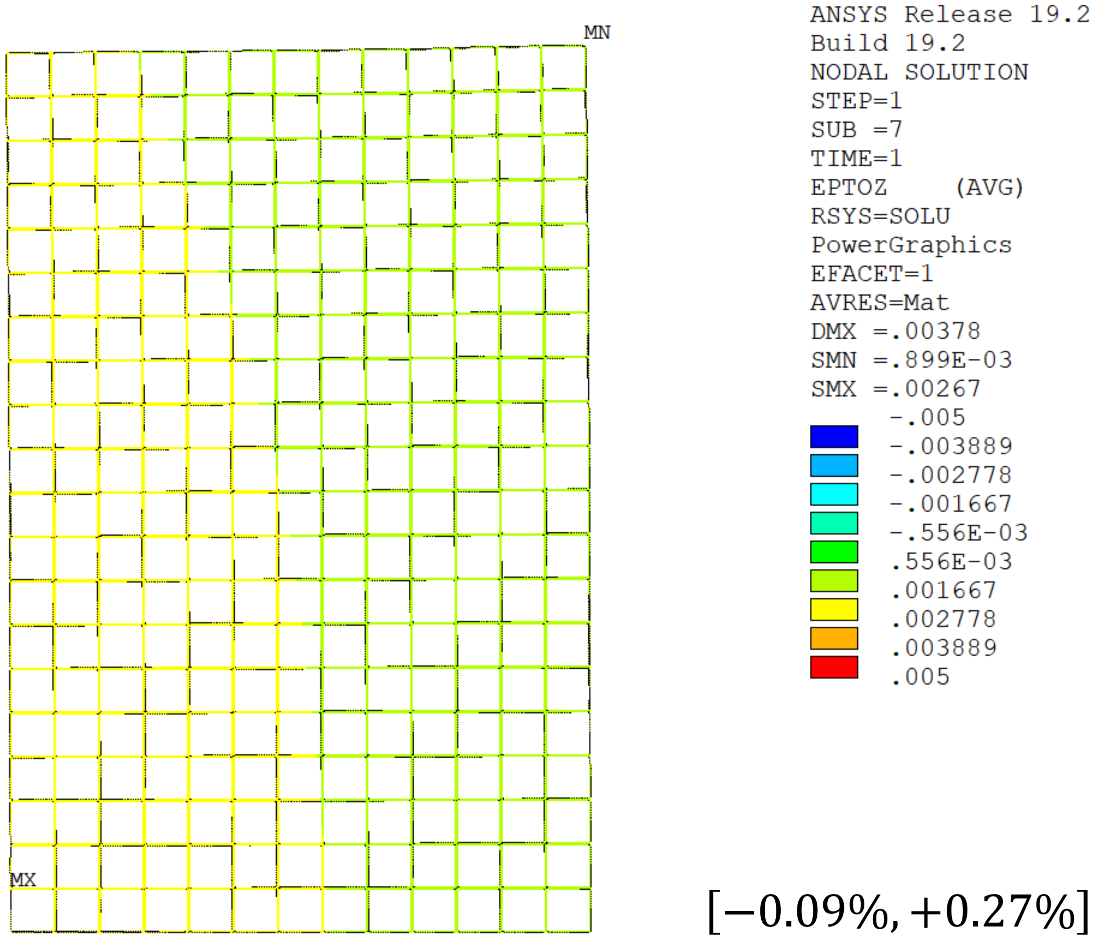
A usage factor is defined as the ratio between element shear stress and allowable shear stress, which must be less than 1. Negative values correspond to tensile stresses that should be avoided, but these are likely due to the modelling of contact between adjacent insulating layers.

Structural Design Criteria & Assessment: Non-Metallic Components

4. Allowable strain in plane of reinforcing.

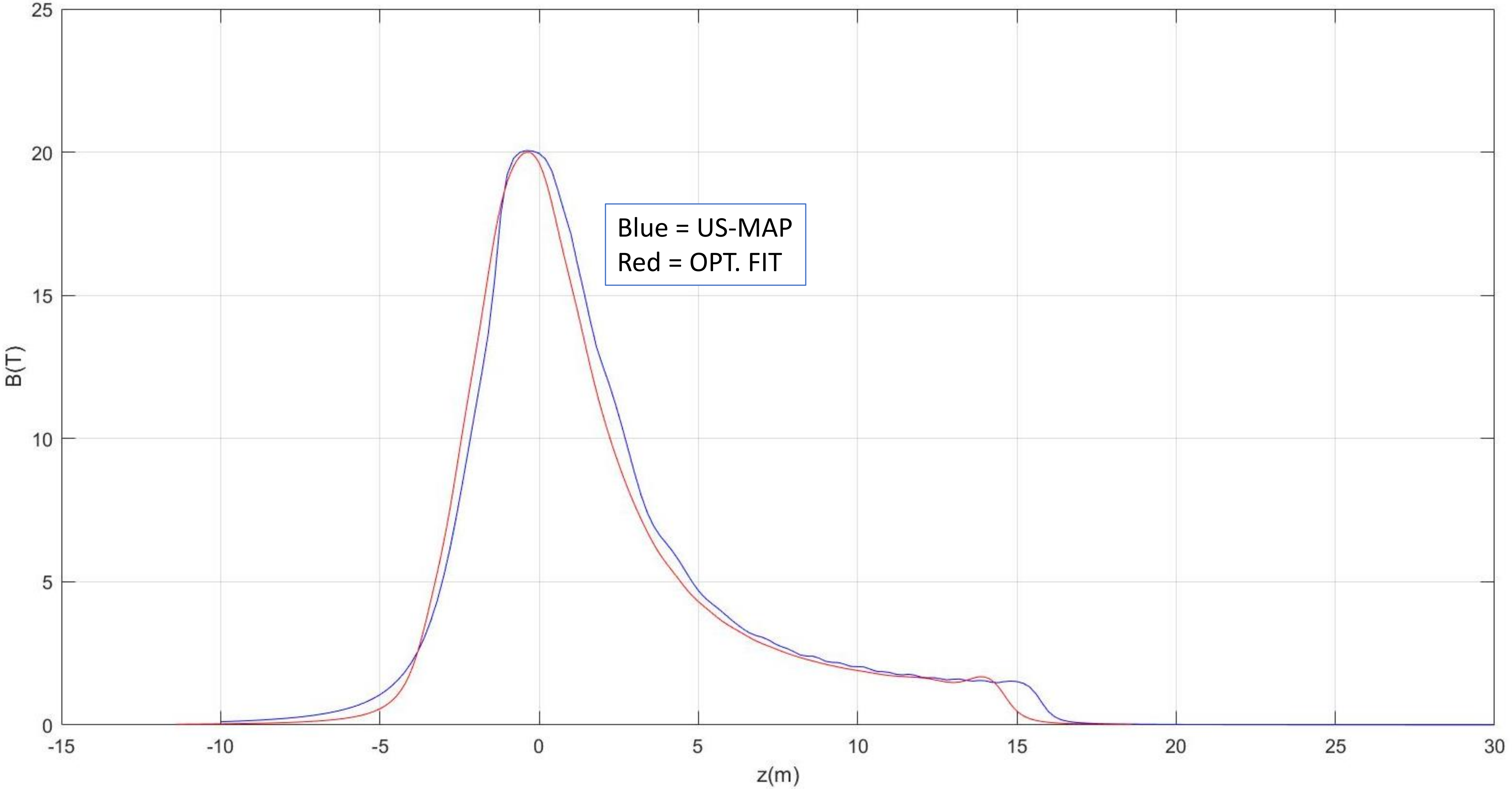


$[-0.41\%, +0.21\%]$



$[-0.09\%, +0.27\%]$

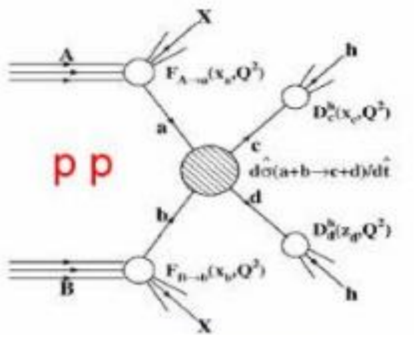
COMPARE FIELD ON AXIS



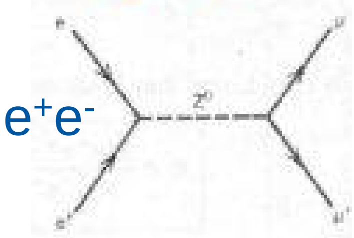
Collider Choices

- Hadron collisions: compound particles
  - LHC collides 13.6 TeV protons
  - Protons are mix of quarks, anti-quarks and gluons
  - **Very complex to extract physics**
  - **But can reach high energies**

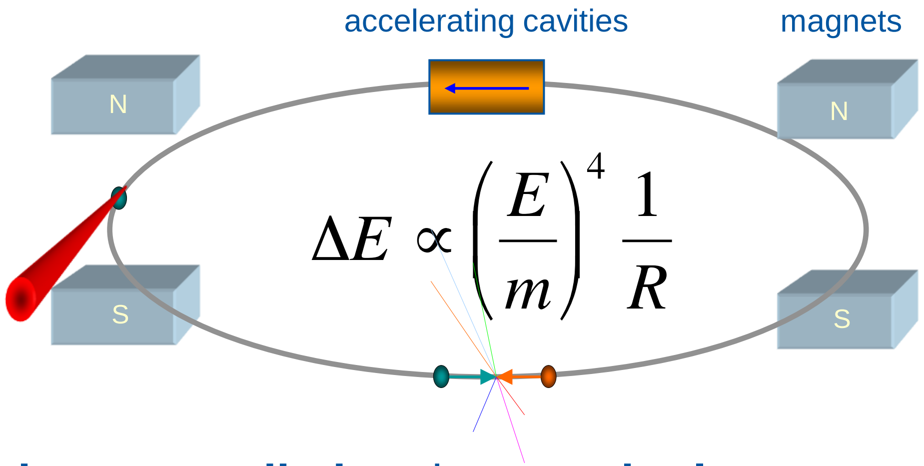
- Lepton collisions: elementary particles
  - LEP reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - **Lepton collisions $\Rightarrow$ precision measurements**
  - **Hard to reach high energies**



e^+e^-



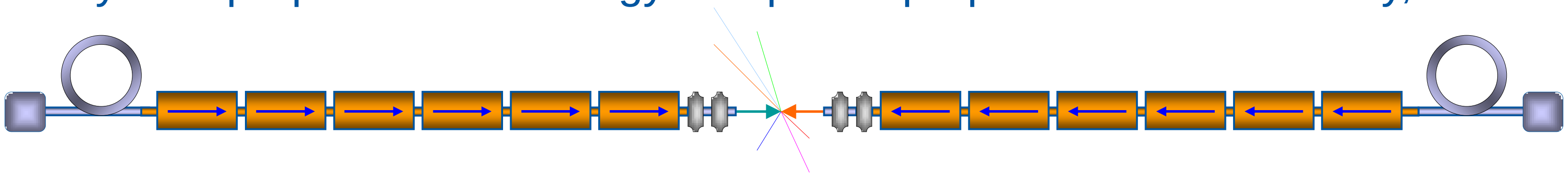
Energy Limit



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron rings (*multi-pass colliders*) are **limited by synchrotron radiation**

Electron-positron linear colliders **avoid synchrotron radiation**, but are **single pass**
Typically cost proportional to energy and power proportional to luminosity,



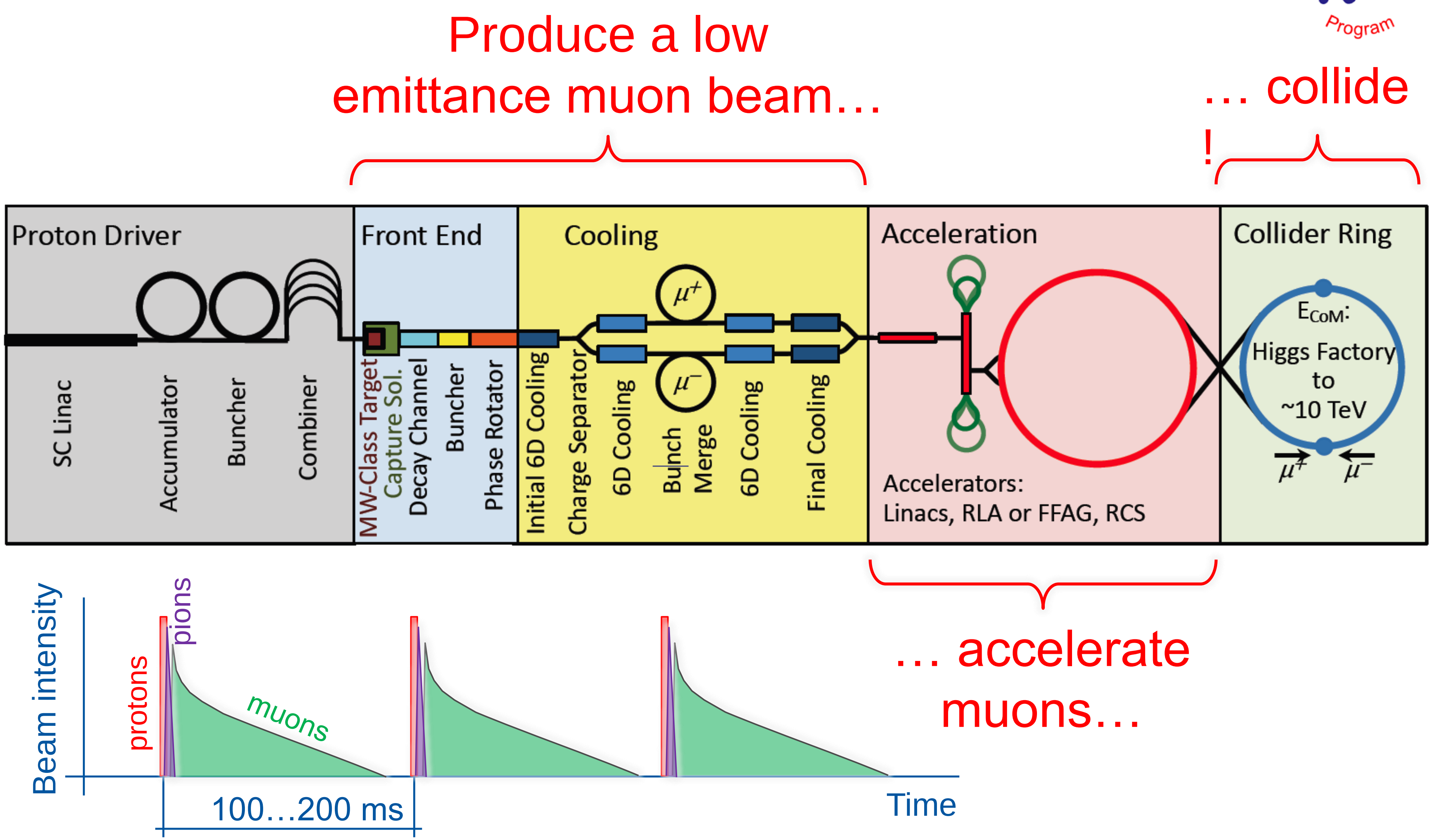
Hence present energy frontier is probed by proton rings

Novel approach: the **muon collider**
Large mass suppresses synchrotron radiation => circular collider, **multi-pass**
Fundamental particle yields clean collisions => **less beam energy** than protons
But lifetime at rest only 2.2 μs (increases with energy)

The muon collider is part of the European Accelerator R&D Roadmap

e^-: 0.511 MeV
μ: 106 MeV
p^+: 938 MeV

Proton-driven Muon Collider Concept

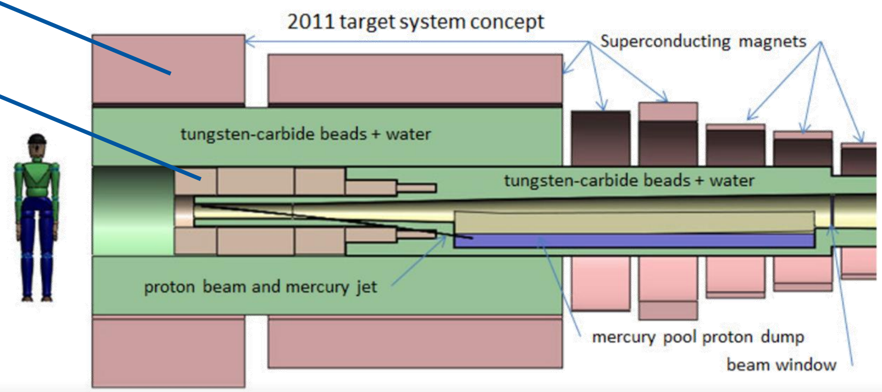


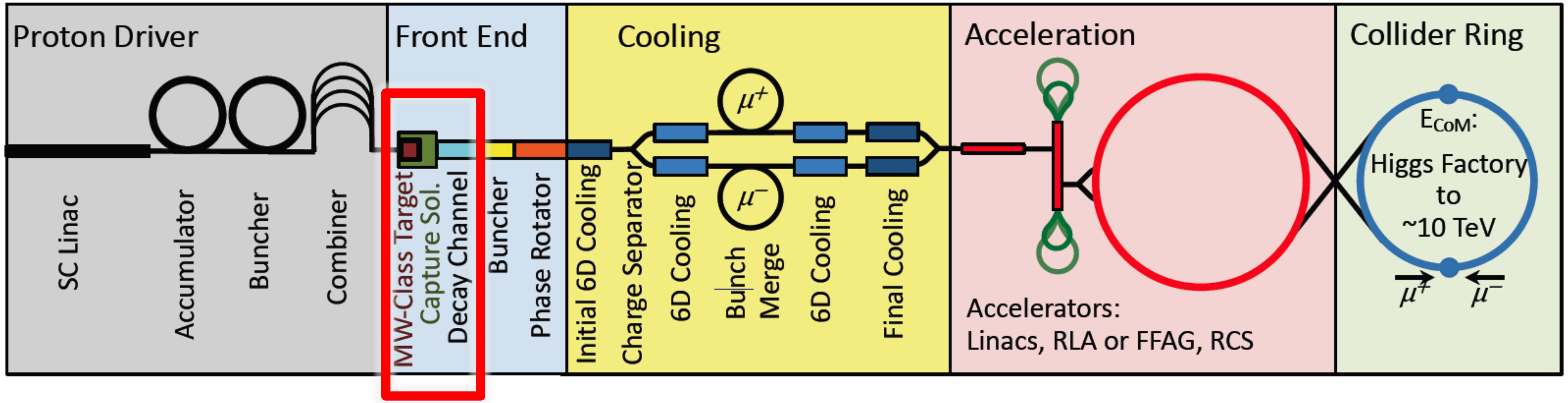
Target and capture solenoid – 1/4

Superconducting (LTS) outsert

Rad-hard resistive insert

Field on target 20 T, 150 mm
Beam power on target: 1…2 MW



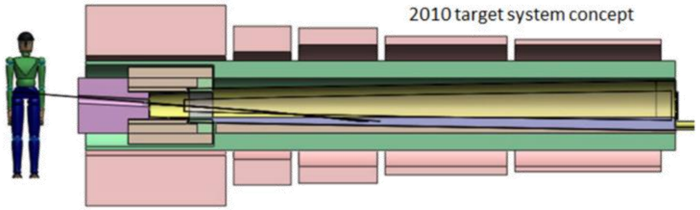


Large stored energy o(2) GJ, mass o(300) tons, cost o(100) M

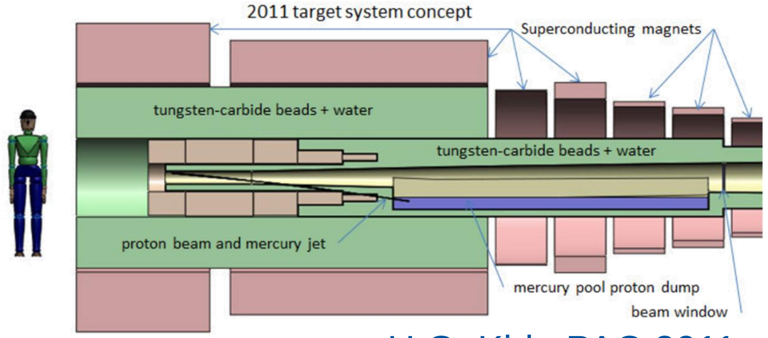
Target and capture – 2/4

- Reduce the mass (CAPEX) of the system, and increase operating temperature to improve cryogenic CoP (OPEX)

US-MAP **2010** design
LTS (14 T) + NC (6 T)

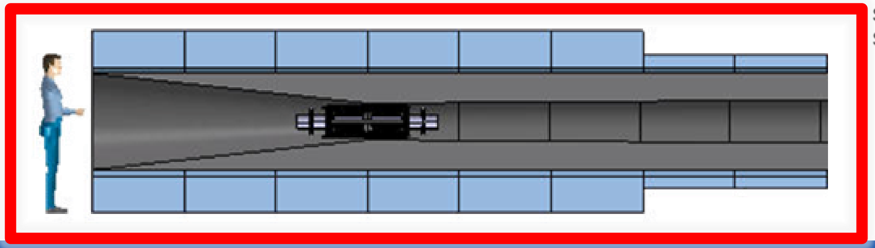


US-MAP **2011** design
LTS (14 T) + NC (6 T)



H.G. Kirk, PAC 2011

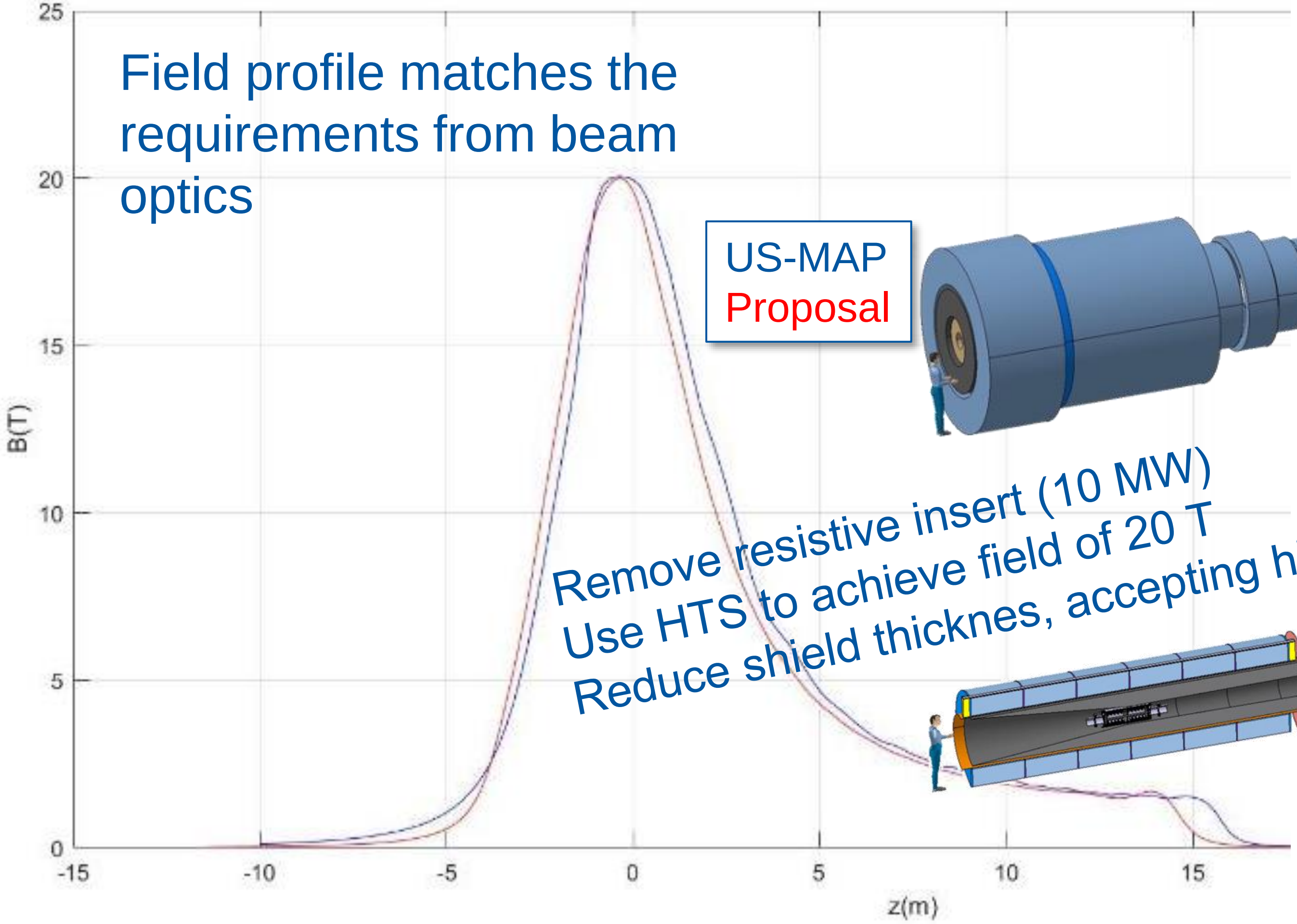
MuCol **2022** design
HTS (20 T, 20 K)



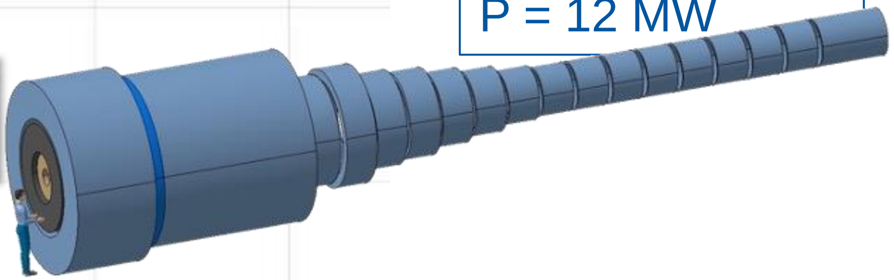
Magnet	z_{min} (cm)	Δz (cm)	r_{min} (cm)	Δr (cm)	I (A/mm^2)
RC1	-131.3	47.3	17.8	30.24	16.56
RC2	-84	86.2	17.8	30.88	16.56
RC3	2.1	56.2	17.8	30.25	16.56
RC4	58.3	57	17.8	16.6	16.56
RC5	115.3	43.5	21.88	7.96	16.56
SC1	-222.6	169.4	120	75.85	23.22
SC2	-53.1	26.1	120	54	0
SC3	-27.1	327.1	120	54.07	23.1
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

Target and capture – 3/4

Field profile matches the requirements from beam optics

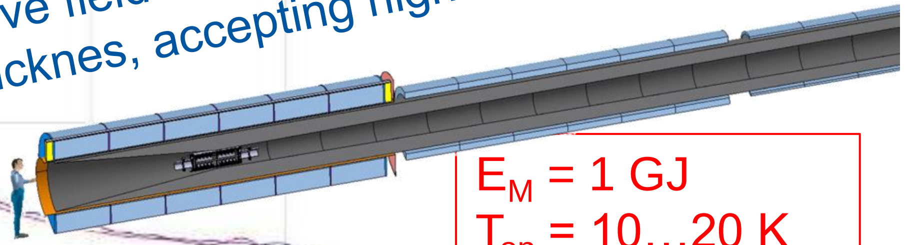


US-MAP Proposal



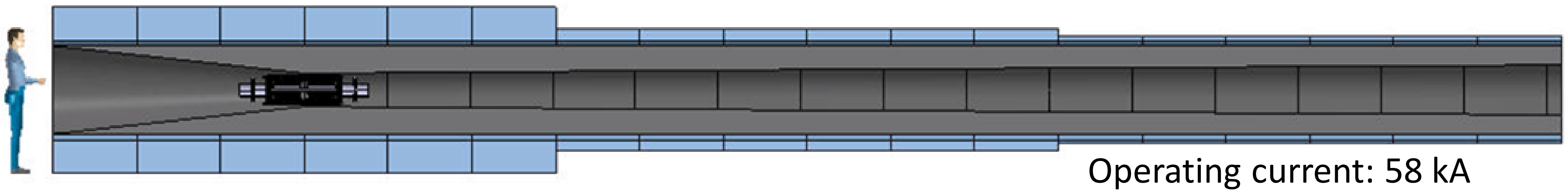
E_M = 2.9 GJ
T_{op} = 4.2 K
M_{coils} = 200 tons
M_{shield} = 300 tons
P = 12 MW

Remove resistive insert (10 MW)
Use HTS to achieve field of 20 T
Reduce shield thicknes, accepting higher heat load at 20 K



E_M = 1 GJ
T_{op} = 10…20 K
M_{coils} = 110 tons
M_{shield} = 196 tons
P = 1MW

Target and capture – 4/4

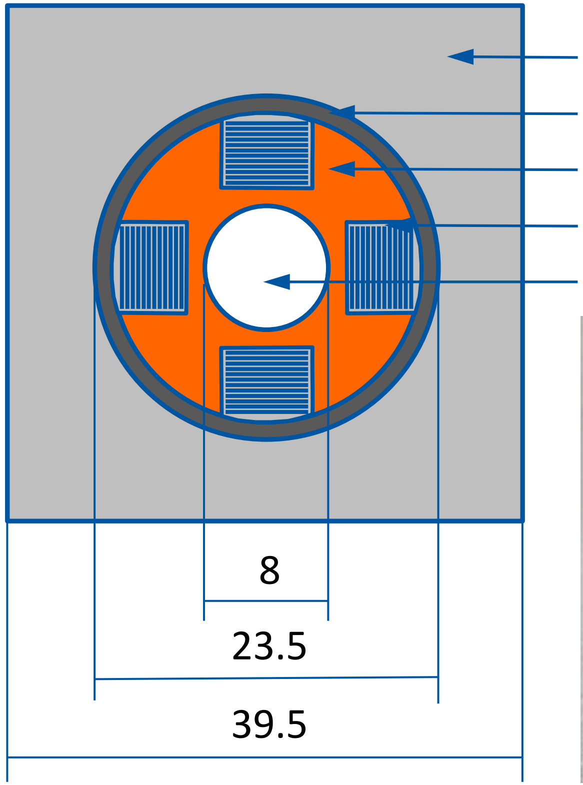


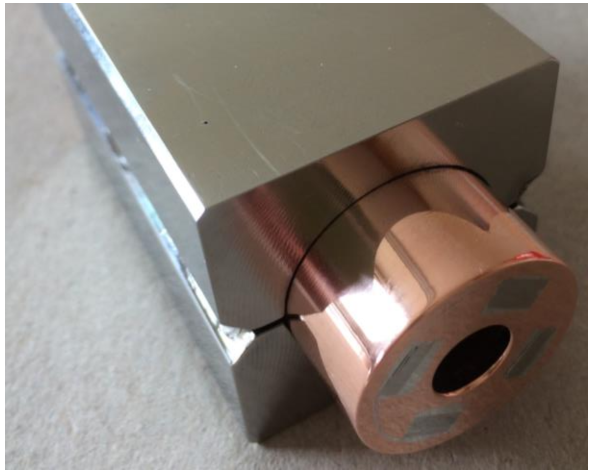
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

MIT "VIPER" conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

HTS conductor design

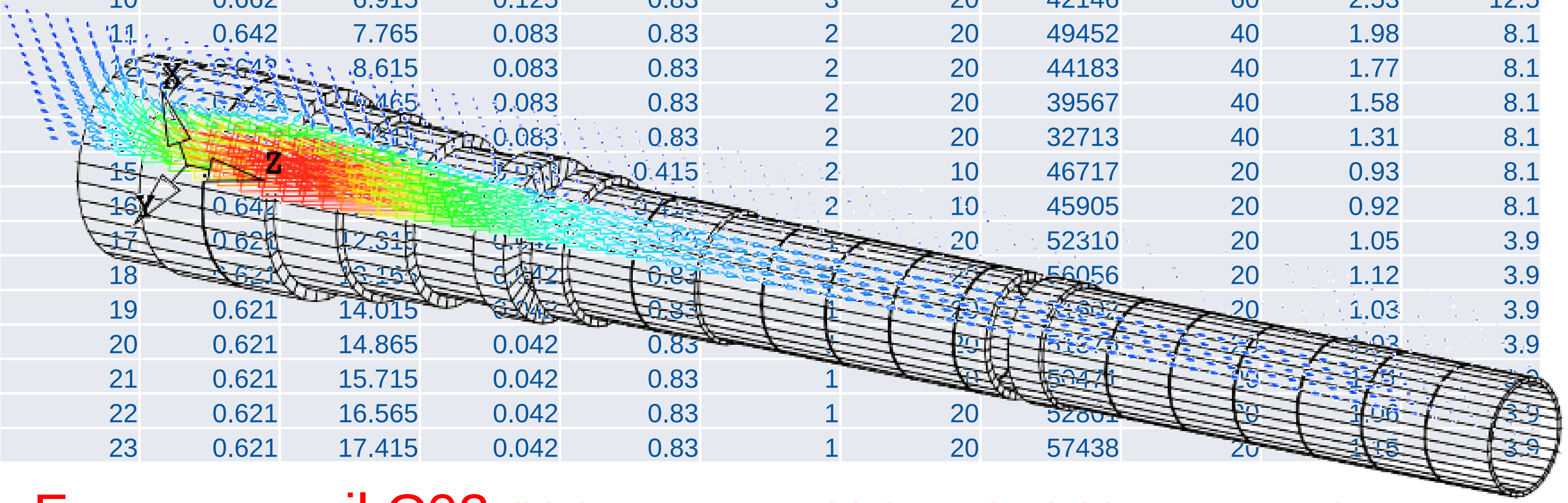




Looks much like an HTS magnet for fusion !!!

Coil geometry

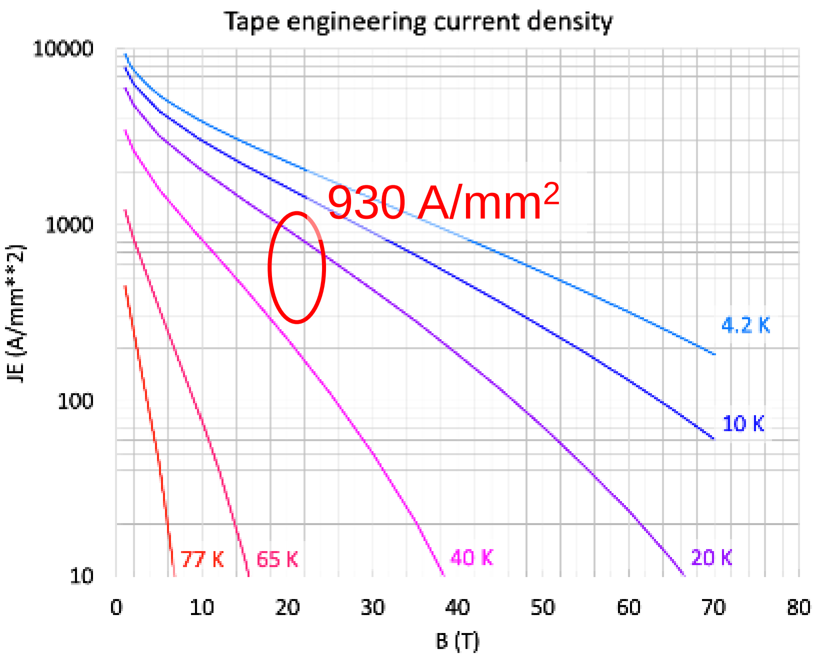
Coil	Rc (m)	Zc (m)	dR (m)	dZ (m)	Layers (-)	Pancakes (-)	Iconductor (A)	Turns (-)	Icoil (MA-turn)	Lpancake (m)
1	0.849	-0.185	0.498	0.83	12	20	58905	240	14.14	64.0
2	0.87	0.665	0.54	0.83	13	20	60710	260	15.78	71.1
3	0.87	1.515	0.54	0.83	13	20	60392	260	15.70	71.1
4	0.808	2.365	0.415	0.83	10	20	51654	200	10.33	50.8
5	0.766	3.215	0.332	0.83	8	20	47469	160	7.60	38.5
6	0.704	4.065	0.208	0.83	5	20	46504	100	4.65	22.1
7	0.745	4.708	0.291	0.415	7	10	46293	70	3.24	32.8
8	0.704	5.423	0.208	0.415	5	10	53168	50	2.66	22.1
9	0.662	6.065	0.125	0.83	3	20	43280	60	2.60	12.5
10	0.662	6.915	0.125	0.83	3	20	42146	60	2.53	12.5
11	0.642	7.765	0.083	0.83	2	20	49452	40	1.98	8.1
[illegible]	[illegible]	8.615	0.083	0.83	2	20	44183	40	1.77	8.1
[illegible]	[illegible]	[illegible]	0.083	0.83	2	20	39567	40	1.58	8.1
[illegible]	[illegible]	[illegible]	0.083	0.83	2	20	32713	40	1.31	8.1
15	[illegible]	[illegible]	[illegible]	0.415	2	10	46717	20	0.93	8.1
16	[illegible]	[illegible]	[illegible]	[illegible]	2	10	45905	20	0.92	8.1
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	52310	20	1.05	3.9
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	56056	20	1.12	3.9
19	0.621	14.015	[illegible]	[illegible]	1	[illegible]	[illegible]	20	1.03	3.9
20	0.621	14.865	0.042	0.83	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.9
21	0.621	15.715	0.042	0.83	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	0.621	16.565	0.042	0.83	1	20	[illegible]	[illegible]	[illegible]	[illegible]
23	0.621	17.415	0.042	0.83	1	20	57438	[illegible]	[illegible]	[illegible]



Focus on coil C02 (highest current, highest field, higest energy)

Conductor design

HTS tape thickness	(mm)	62
HTS tapes	(-)	80
HTS stack width	(mm)	6
HTS stack thickness	(mm)	5
HTS stack width	(mm)	6
HTS tapes	(-)	80
Number of HTS stacks	(-)	4
Copper diameter	(mm)	23
Hole diameter	(mm)	8
Wetted perimeter	(mm)	25
Wrap thickness	(mm)	0.25
Jacket outer dimension	(mm)	39.5
A_{SC}	(mm^2)	4.2
$A_{Substrate}$	(mm^2)	77
A_{Cu}	(mm^2)	361
A_{Helium}	(mm^2)	50
A_{Wrap}	(mm^2)	18
A_{Jacket}	(mm^2)	1127
$A_{Cable\ Space}$	(mm^2)	511
$A_{Conductor}$	(mm^2)	1560



$$J_C = \frac{C_0}{B} h(t) f_p(b)$$

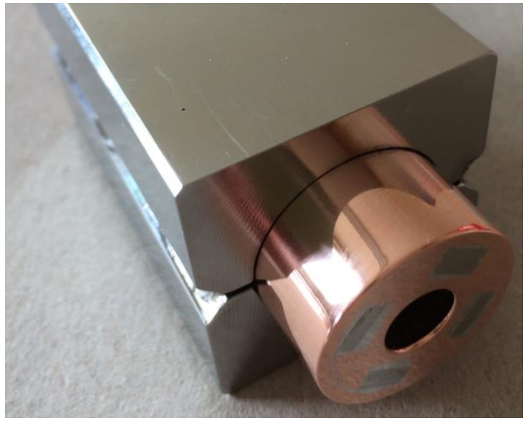
$$B_{irr}(T) = B_{irr0}\left(1 - \frac{T}{T_{irr0}}\right)^{\nu}$$

$$T_{irr}(B) = T_{irr0}\left(1 - \frac{B}{B_{irr0}}\right)^{\frac{1}{\nu}}$$

$$h(t) = (1 - t^{\nu})(1 - t^{m})$$

$$f_p(b) = b^p (1 - b)^q$$

$$t = \frac{T}{T_{irr0}} \qquad b = \frac{B}{B_{irr}(T)}$$



I_{op} = 61 kA
B_{op} = 20 T
T_{op} = 20 K
T_{cs} = 29.7 K

Heat load from recirculation

State equation

$$\frac{p}{\rho} = RT$$

Heat removed

$$\dot{m}\Delta h = \dot{q} \rightarrow \dot{m} \approx \frac{\dot{q}}{c_p \Delta T}$$

Pressure drop

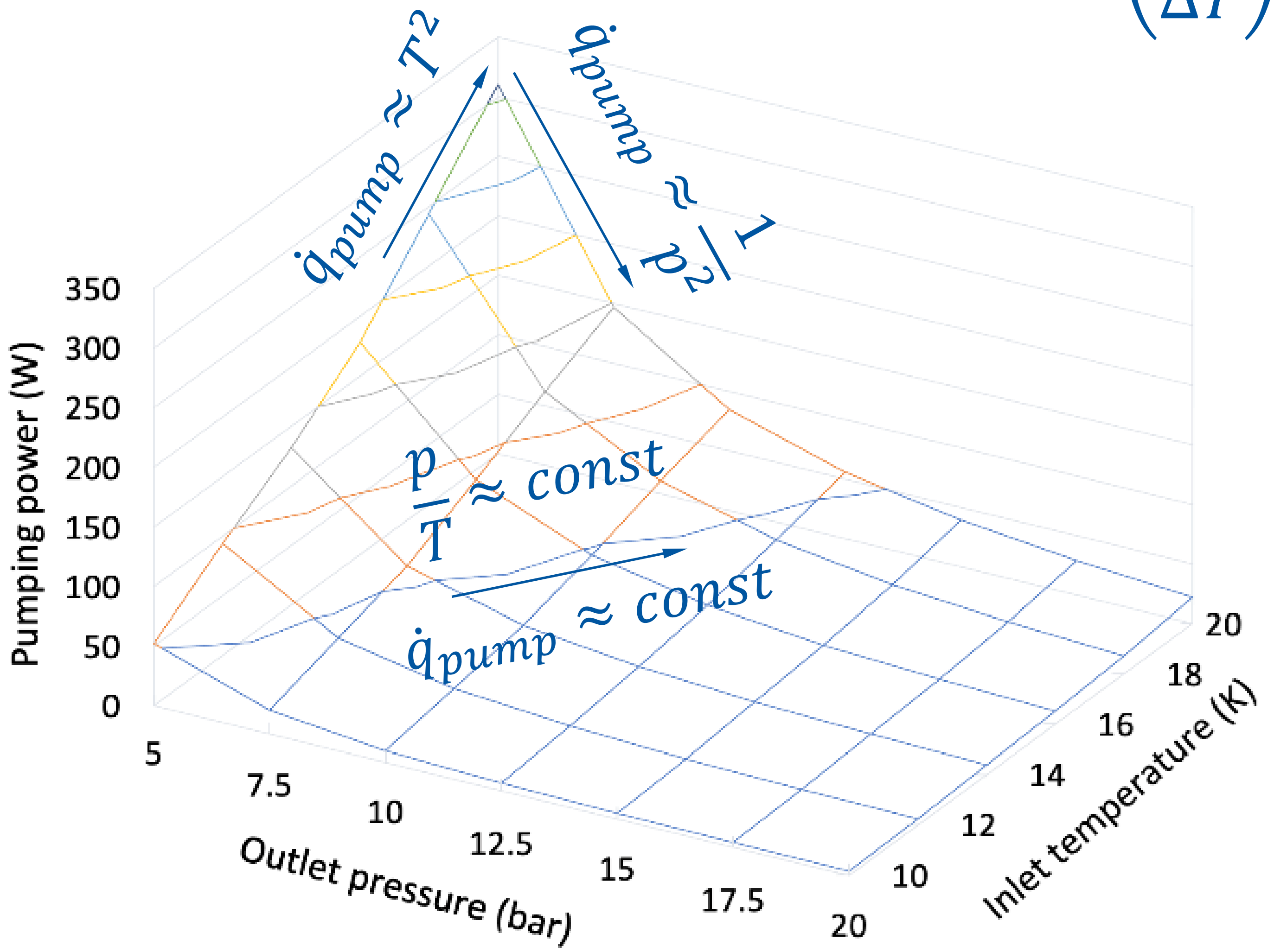
$$\frac{dp}{dx} \approx \frac{2f}{D_h}\frac{\dot{m}^2}{\rho} \rightarrow \Delta p \approx \frac{\dot{m}^2}{\langle\rho\rangle}$$

$$\dot{q}_{pump} \approx \frac{\dot{m}}{\langle\rho\rangle}\Delta p \rightarrow \dot{q}_{pump} \approx \frac{\dot{m}^3}{\langle\rho\rangle^2} \rightarrow \dot{q}_{pump} \approx \left(\frac{\dot{q}}{\Delta T}\right)^3 \left\langle\frac{T}{p}\right\rangle^2$$

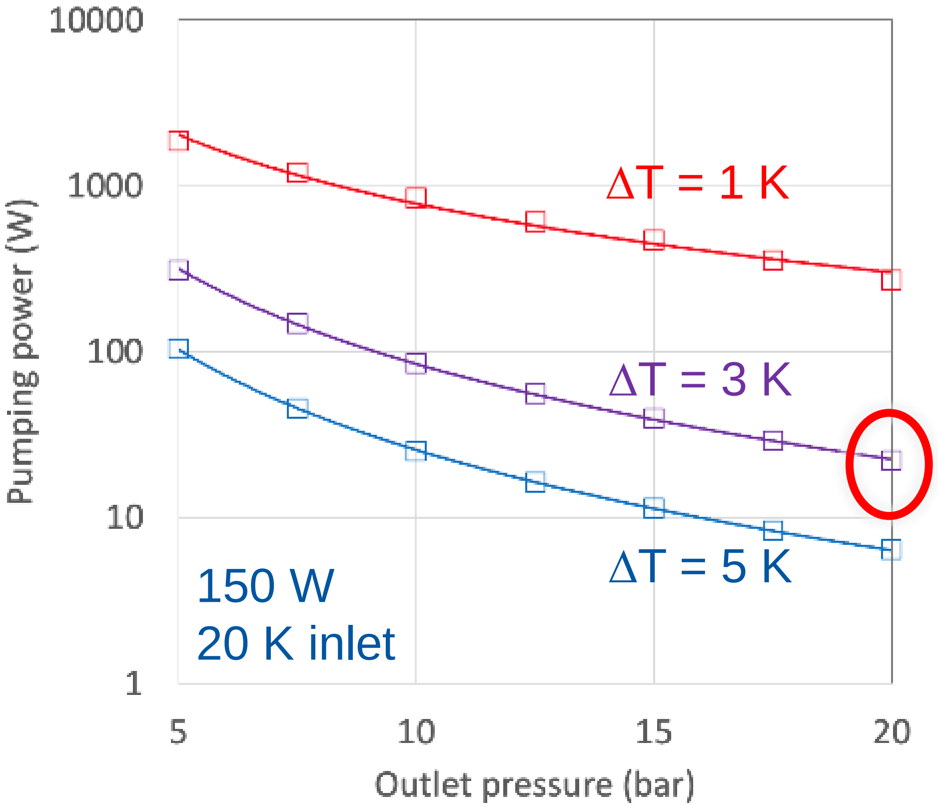
Parametric study

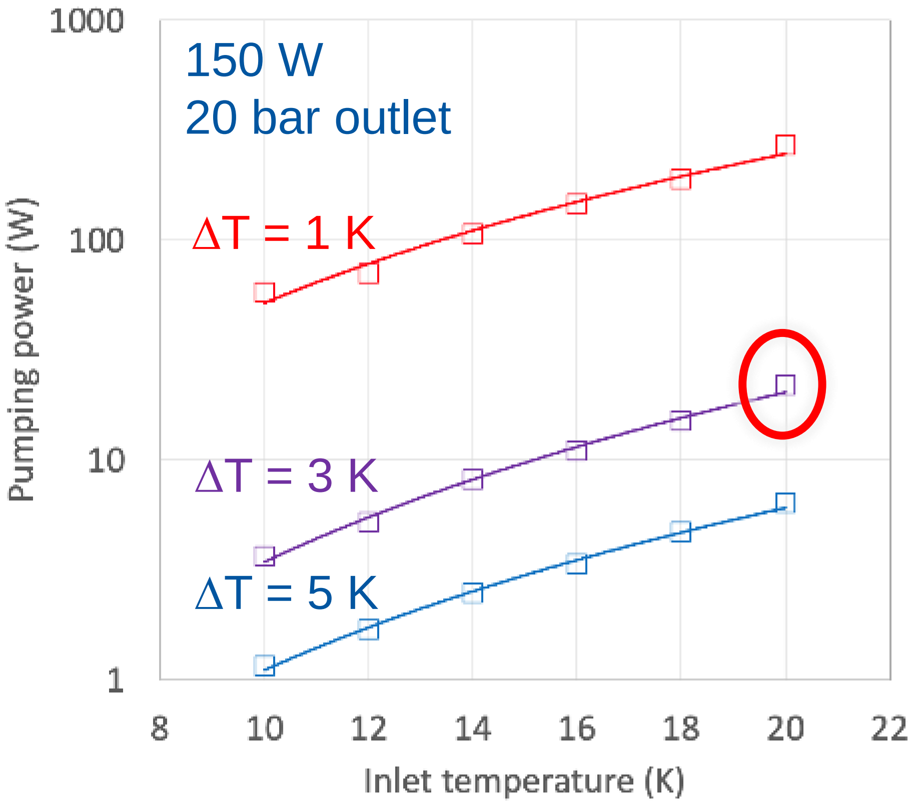
$$\dot{q}_{pump} \approx \left(\frac{\dot{q}}{\Delta T}\right)^3 \left\langle\frac{T}{p}\right\rangle^2$$

A = 5 mm²
D_h = 8 mm
L = 150 m
$\dot{q}$ = 150 W
ΔT = 3K
η_{Pump} = 80%



Optimal cooling conditions

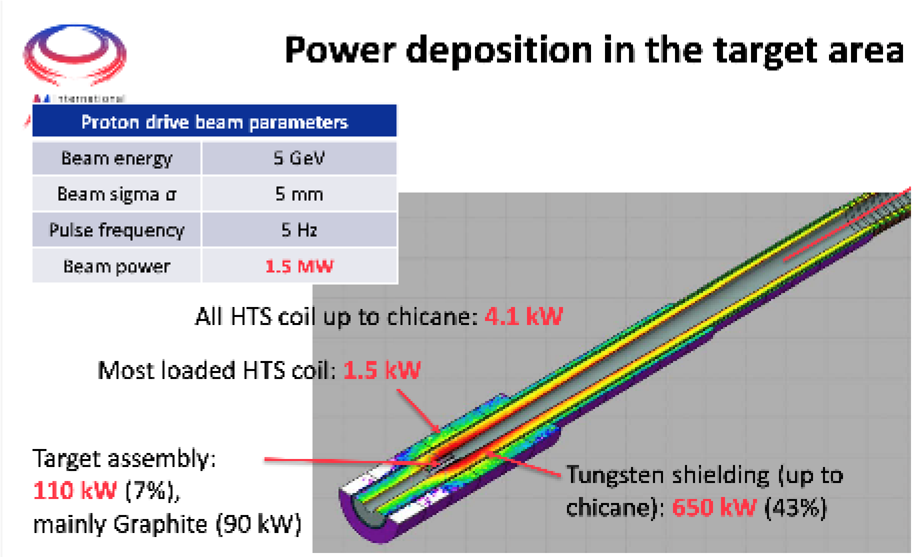




- Compared to typical conditions at 4.5 K, operation at 20 K implies
  - High pressure, o(20) bar
  - Large temperature increase, o(3) K

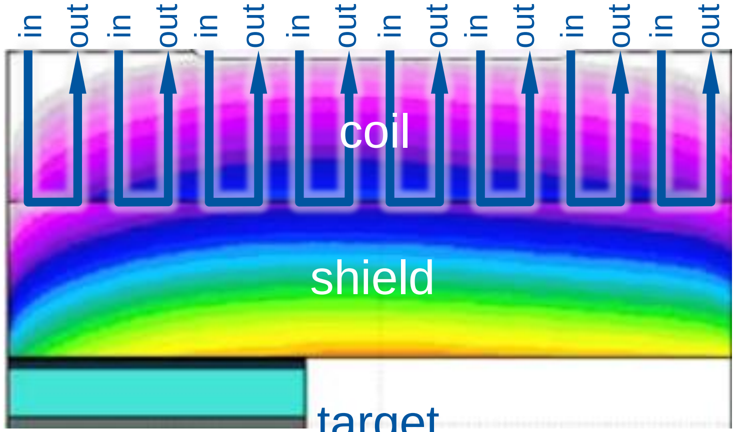
Cooling

NOTE: time stucture ignored



Proton drive beam parameters	
Beam energy	5 GeV
Beam sigma σ	5 mm
Pulse frequency	5 Hz
Beam power	1.5 MW

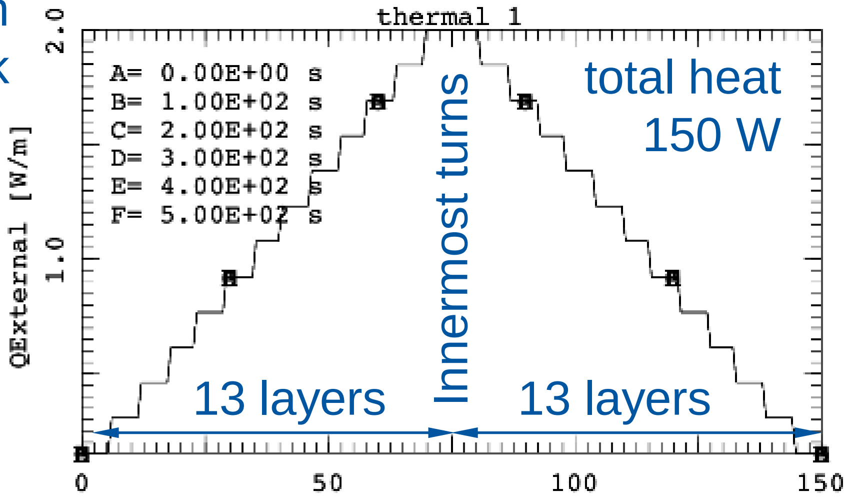
Total heat in the coil 4.1 kW



Proton beam

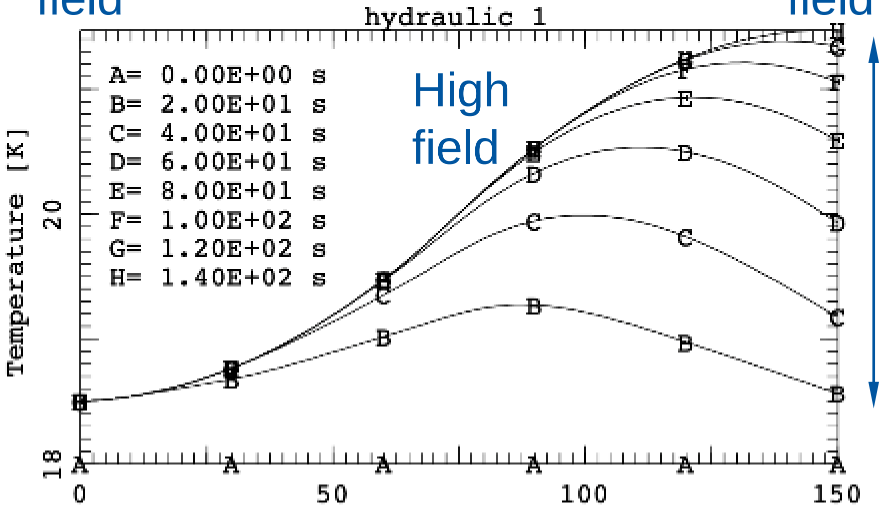
D. Calzolari and A. Lechner, CERN

2 W/m peak



Low field

Low field



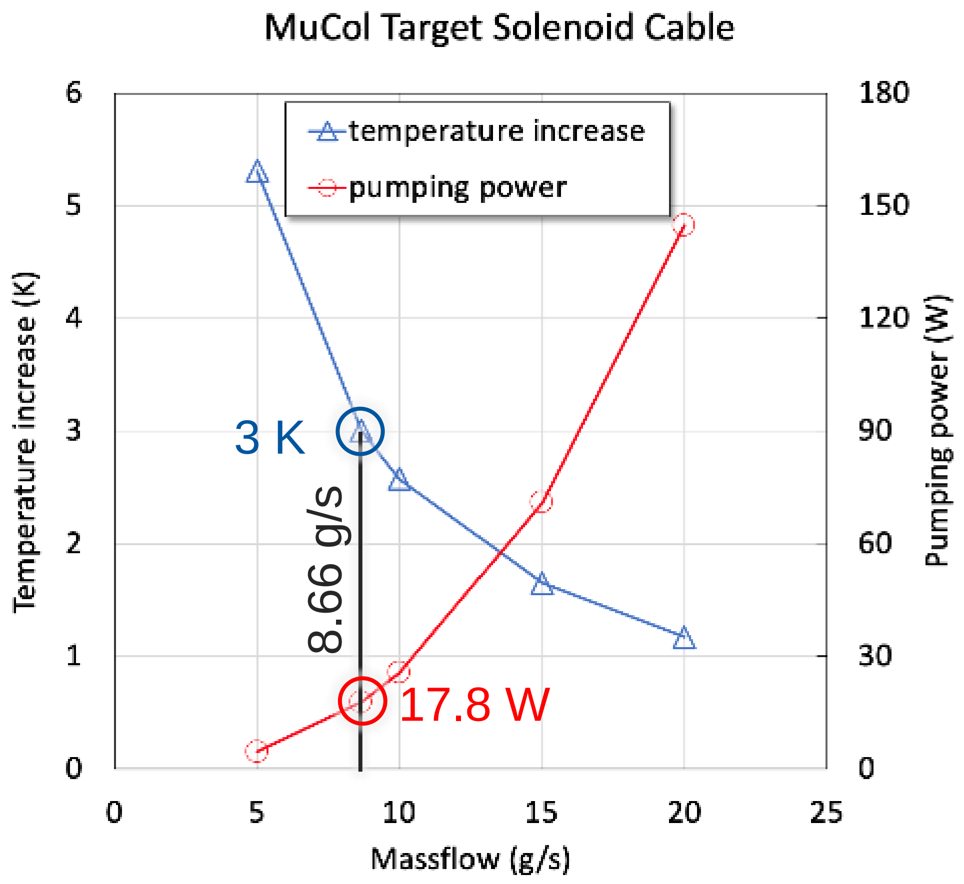
Nominal cooling condition

- A flow dm/dt of approximately 8 g/s is required to remove a nuclear heat load of 150 W with a temperature increase ΔT of 3 K

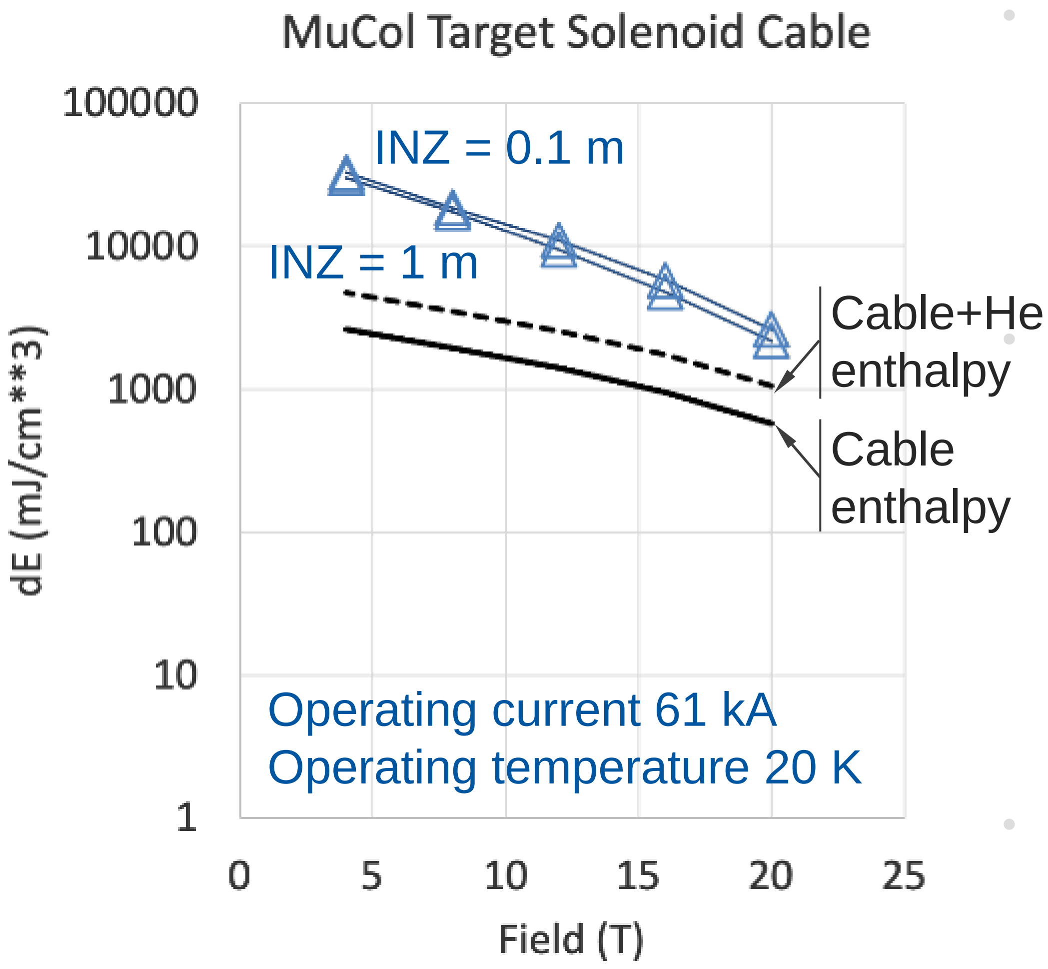
- With this flow the pumping loss is about 20 W (considering an adiabatic efficiency η_{pump} of 80 %)

- This is about 13 % of the nuclear heat load, and is an acceptable overhead

- It would be possible to remove higher heat loads under the same temperature increase, but the pumping loss grows rapidly, approximately like $(dm/dt)^3$



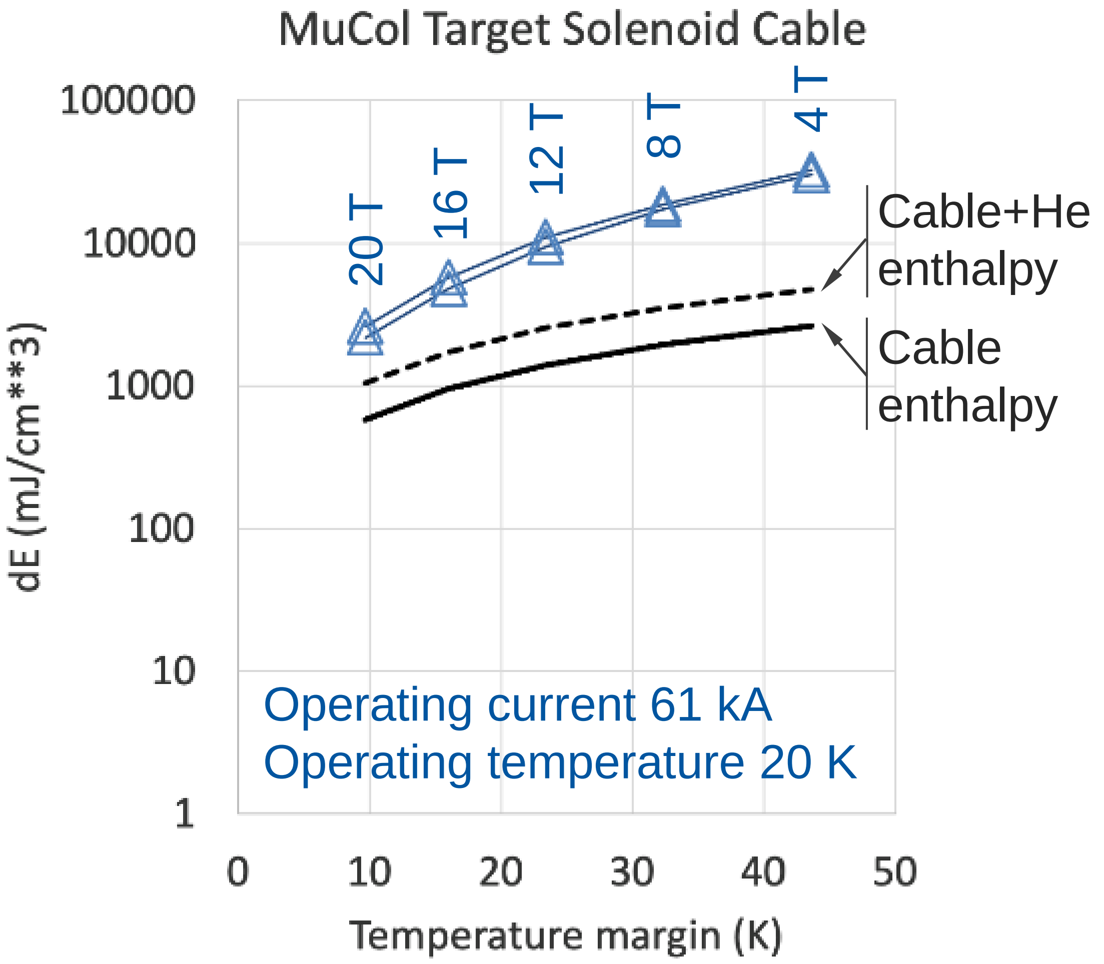
Margin and stability – 1/3



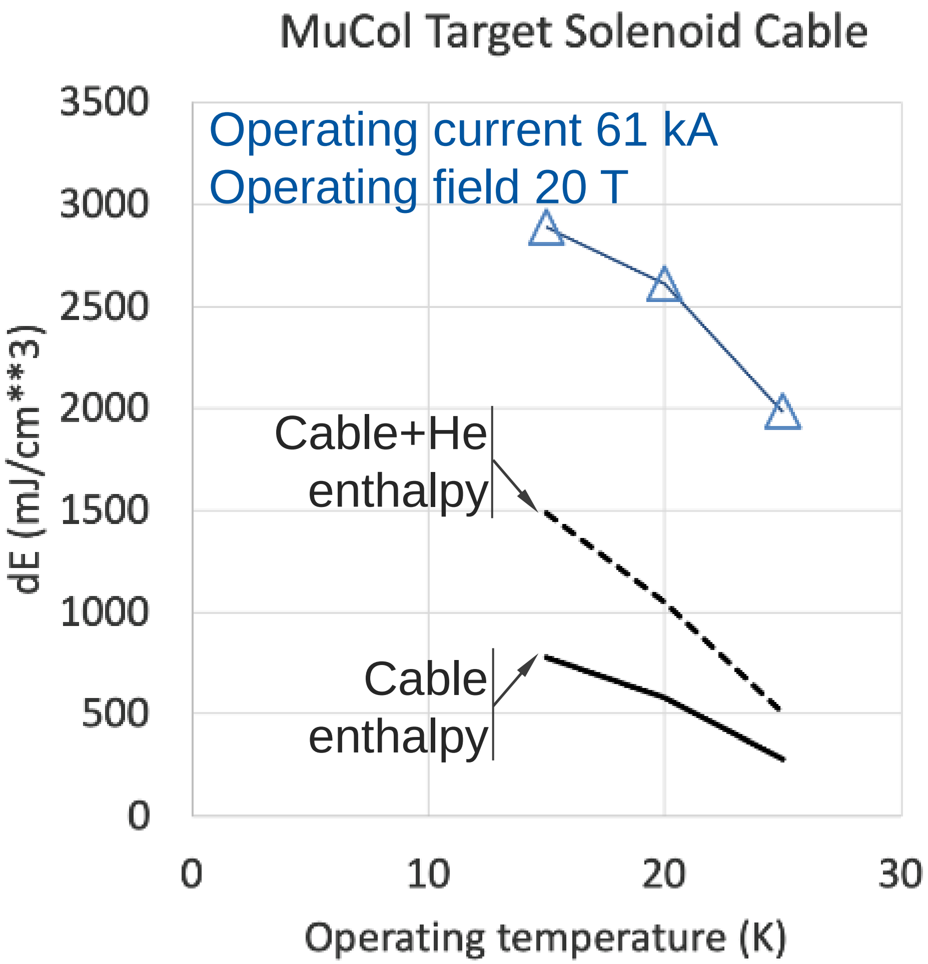
- Values of stability margin are (as expected) very high ! It is very unlikely that the cable will quench because of transient heat inputs
- The stability margin is well above the enthalpy reserve of the cable, also including helium. The reason is that the transient is slow, and there is time to *conduct* and *convect* heat away even for very large INZ lengths
- This effect is even more marked at low field (high temperature margin)

Margin and stability – 2/3

- The temperature margin ΔT **is about 10 K** at nominal conditions of current, field and temperature
  - I_{op} = 61 kA
  - B_{op} = 20 T
  - T_{op} = 20 K
- In the low field regions of the coil (e.g. 4 T) **the temperature margin is above 40 K**
- The large stability in the low field region may make protection difficult ?



Margin and stability – 3/3



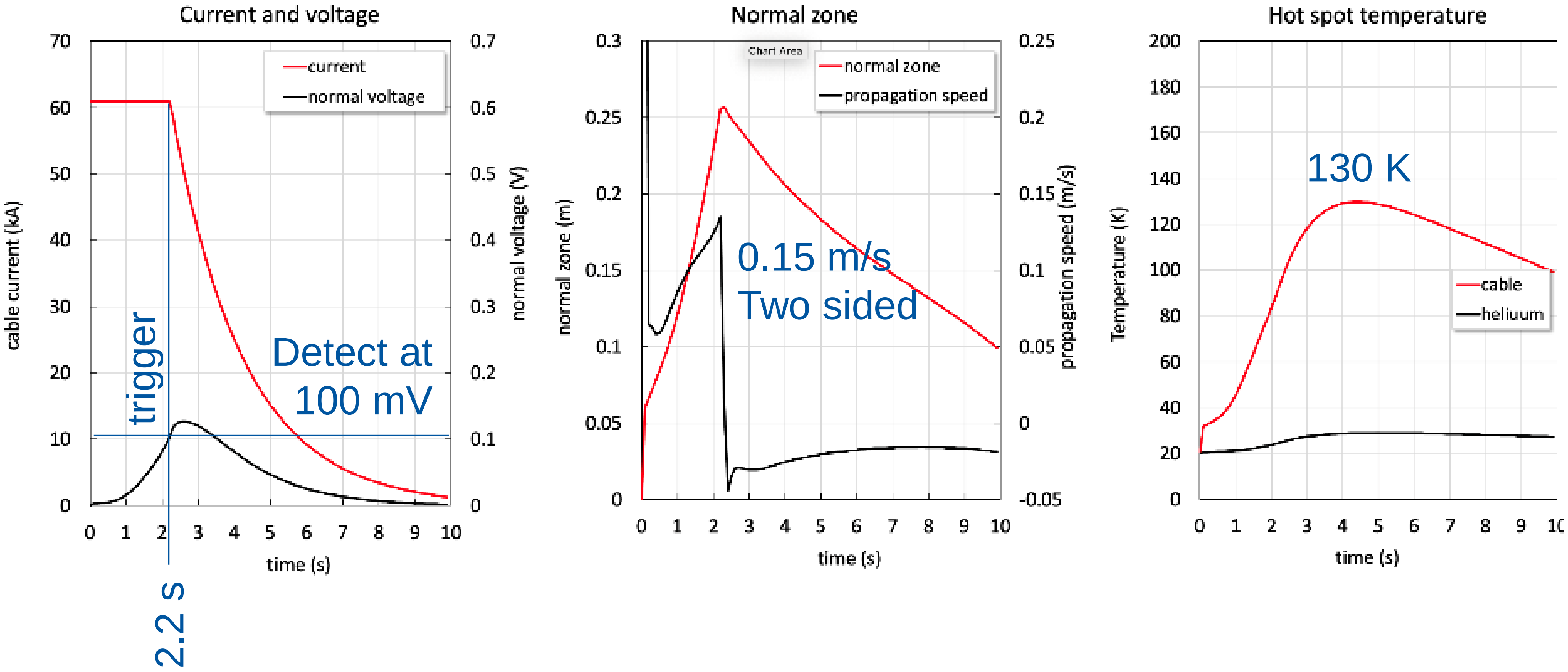
- Operating at higher temperature than 20 K (e.g. 25 K) **may still be an option**, the energy margin is substantial
- Operating at lower temperature than 20 K (e.g. 15 K) does not bring a substantial benefit in energy margin
  - **Recall that the heat capacity drops dramatically at low temperature**

Detection and protection – 1/3

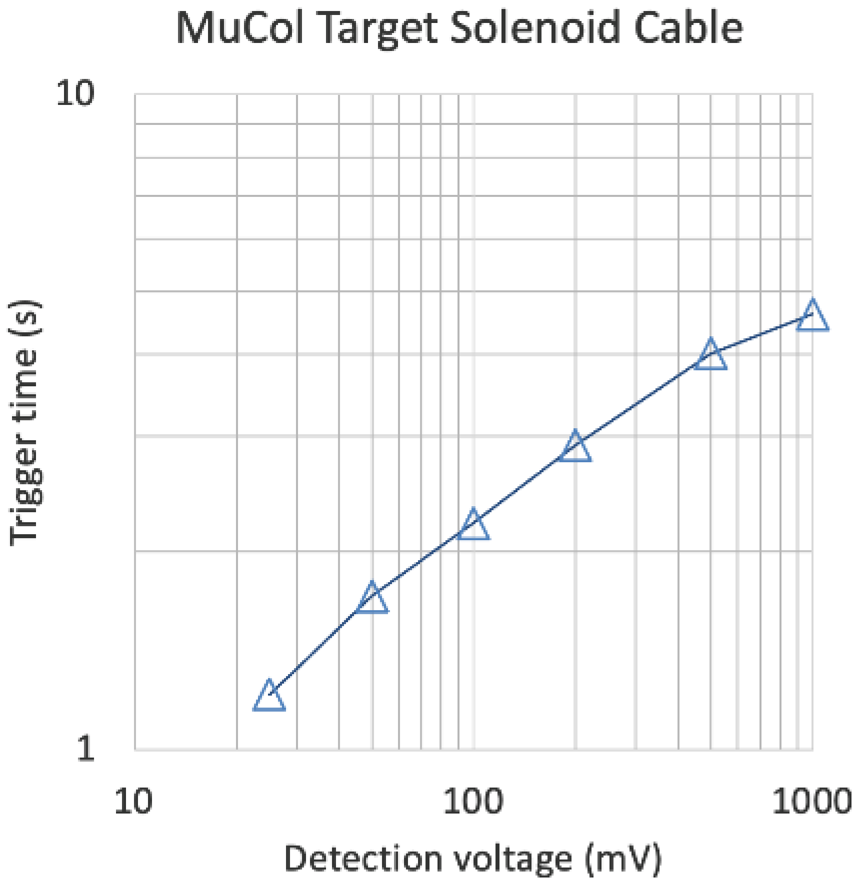
Coil Module 2 (high field and current)

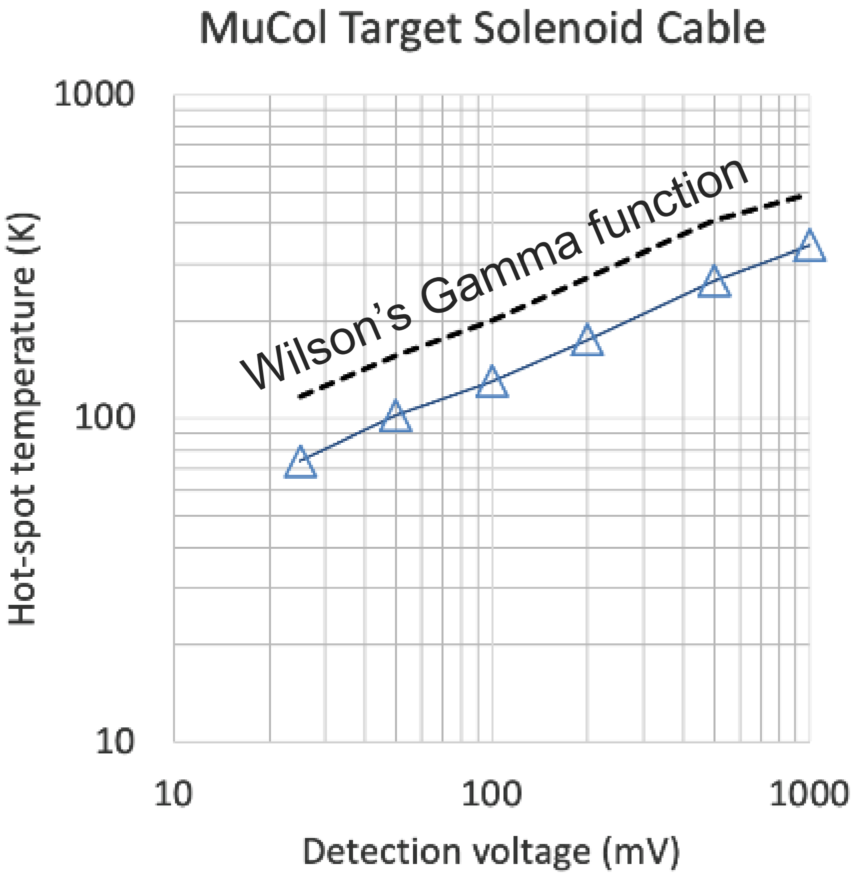
- Single coil stored energy: 165 MJ
- Coulped stored energy: 299.7 MJ
- Dump voltage: 5 kV

INZ in the center of the double pancake
10 cm length quenched
Exponential dump following trigger



Detection and protection – 2/3





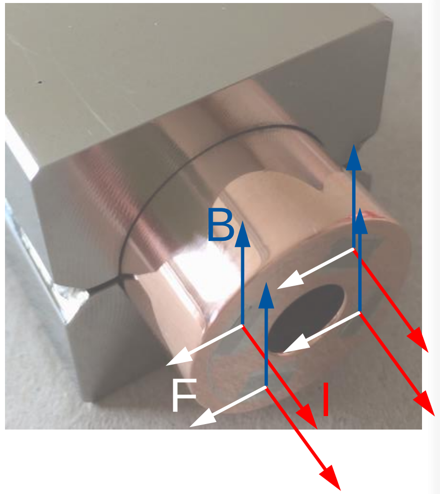
Detection with "reasonable" voltage values appears to work !

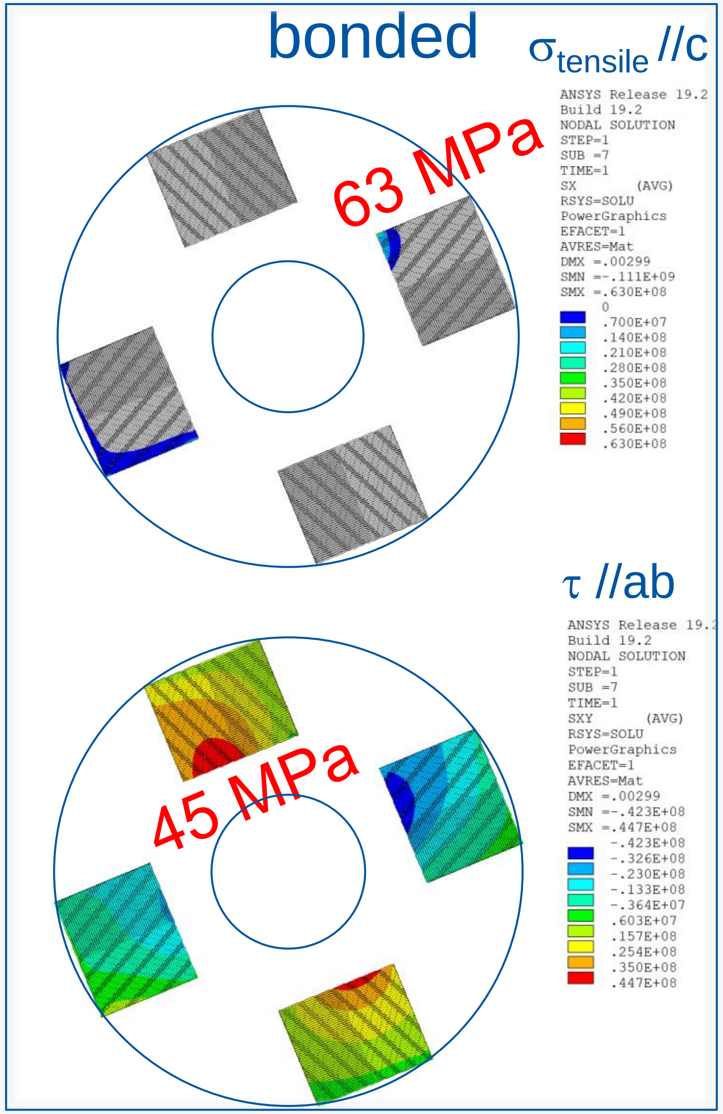
Detection and protection – 3/3

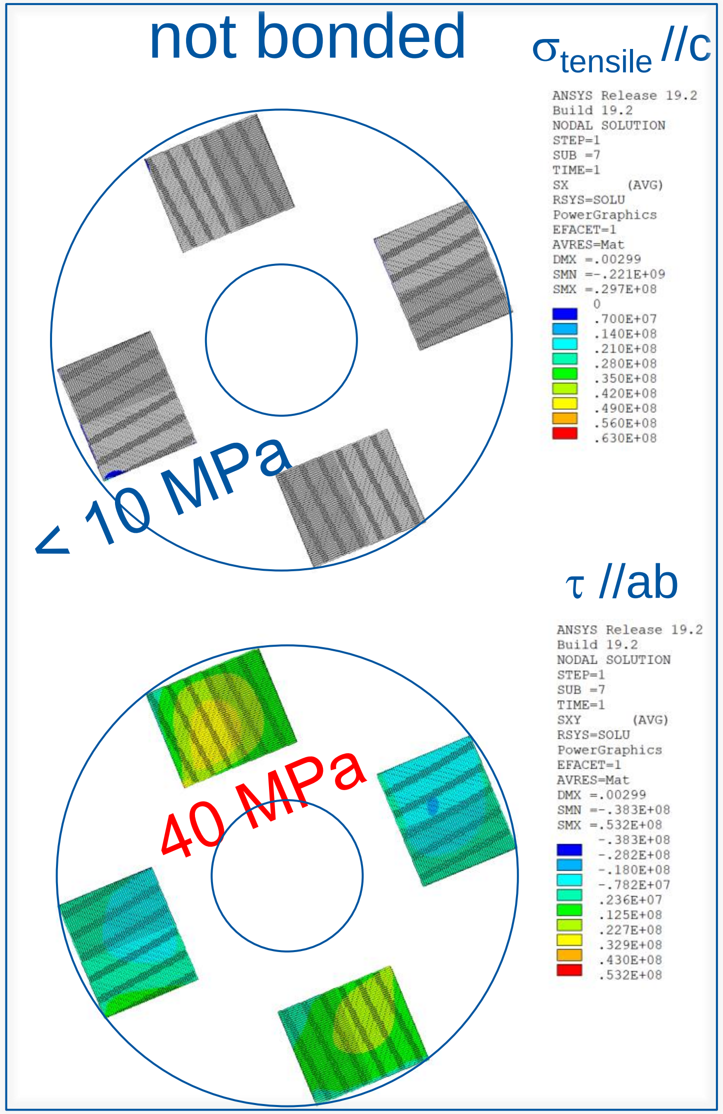
- Study the detection and dump for quenches in the low field region or at low current/field
  - The low field region at nomnal current seems to be most dangerous
  - Low current/low field (e.g. during ramp) implies long detection times, but this appears compatible with modest hot-spot limits

I_{op} (kA)	B_{op} (T)	$t_{Detection}$ (s)	T_{max} (K)
61	20	2.2	130
61	4	2.8	172
30	9.84	14.8	140

HTS cable mechanics







May this be the reason why soldered and twisted high field and high current cables are also subject to degradation ?

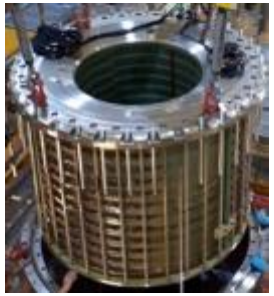
Opportunities and perspective

- We are looking for a solution to the design of the target and capture channel of the Muon Collider, which needs a **peak field of 20 T on axis, based on an HTS force-flow cooled cable operating at 20 K**
  - Lower footprint, mass, stored energy and cost than a LTS/NC hybrid
  - Better energy efficiency than a 4.5 K system
- Though there is much work to do, **the design selected seems not too far from being feasible !**
- This is also interesting because of implications for

Commonwealth Fusion Systems

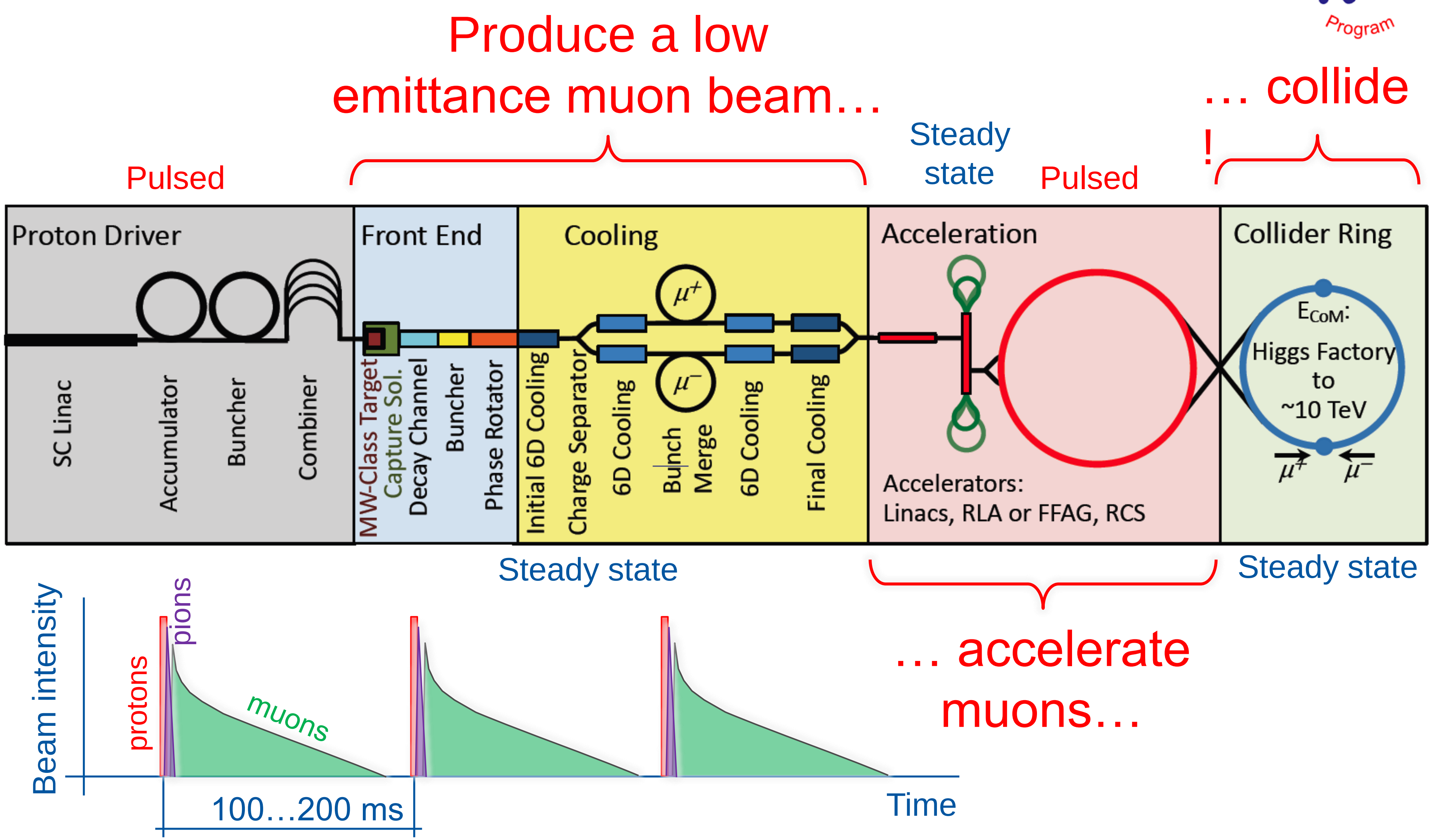
- **Compact fusion machines**
- **Hybrid UHF magnets for science**

LNCMI



CERN

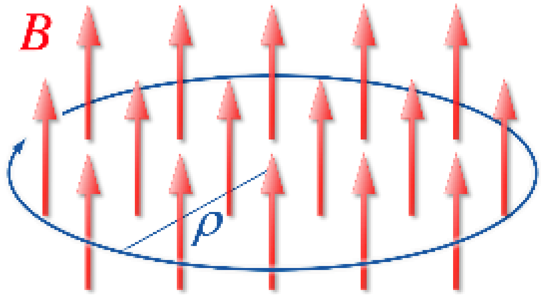
Proton-driven Muon Collider Concept



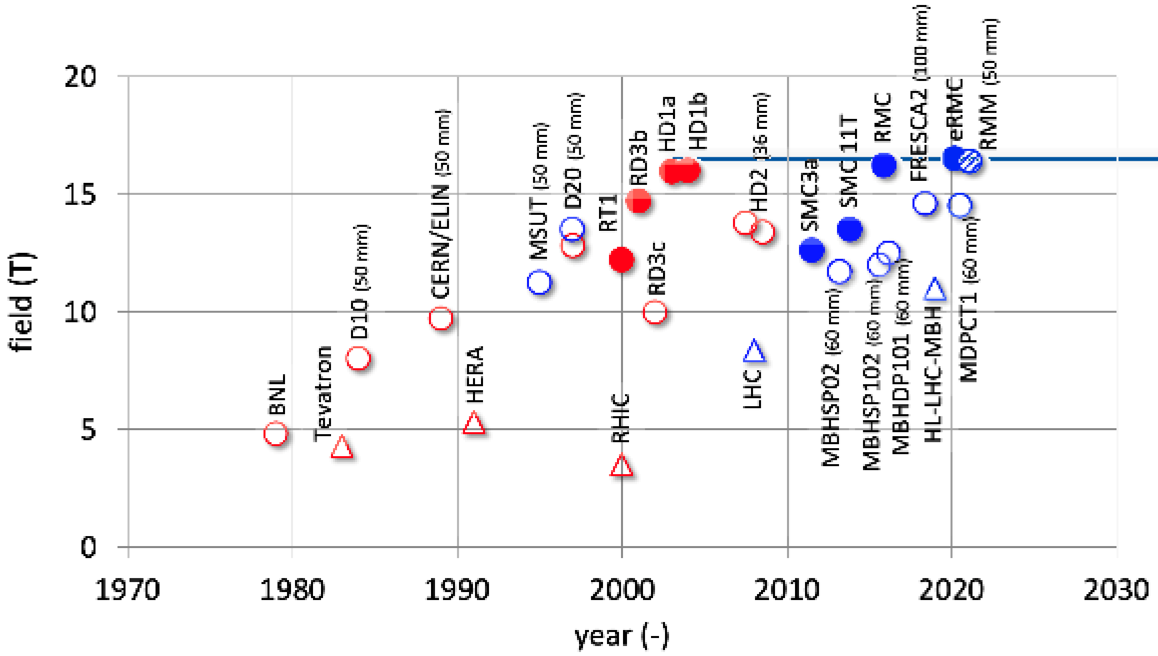
The need for high field

Beam energy — Bending radius — Dipole field

$$E[GeV]=0.3\,B[T]\,r[m]$$



This is the reason for the steady call for **higher fields** in accelerator magnets

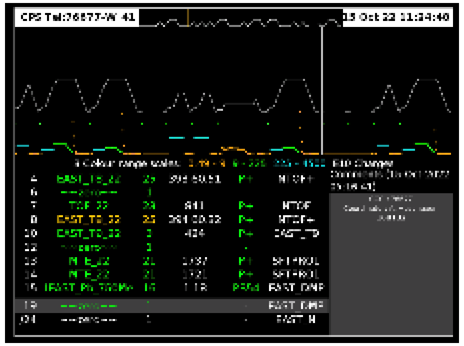


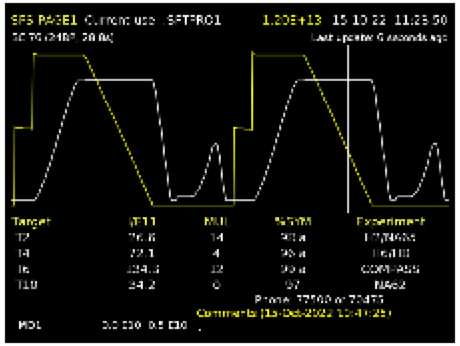
Upper limit of LTS (Nb_3Sn)

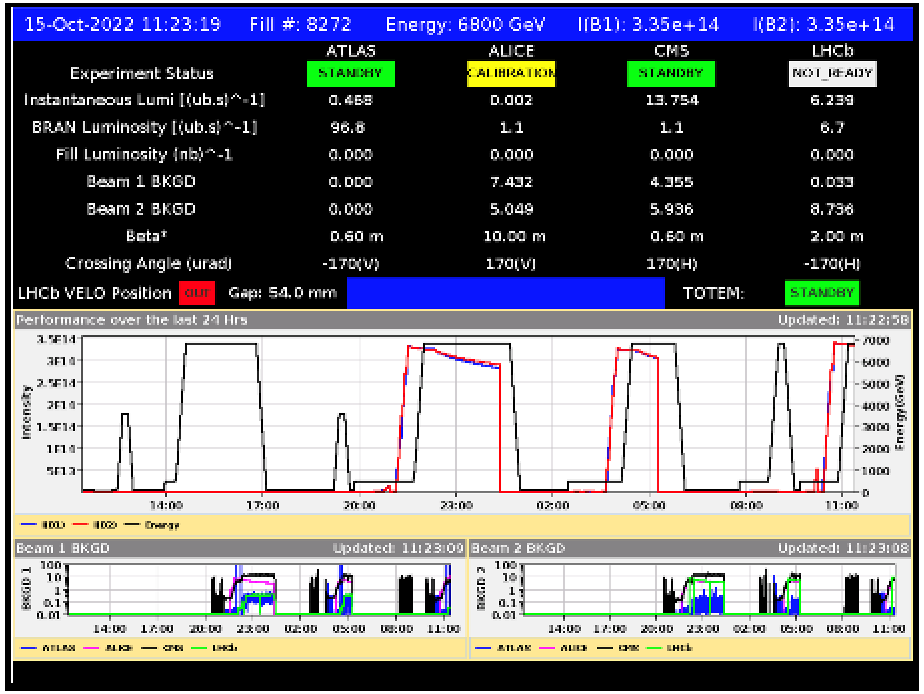
HTS is the only path beyond 16 T

The need for energy

- CERN uses today **1.3 TWh** per year of operation, with peak power consumption of **200 MW** (running accelerators and experiments), dropping to **80 MW** in winter (technical stop period)
- Electric power is drawn directly from the French 400 kV distribution, and presently supplied under agreed conditions and cost
- **Supply cost, chain and risk** are obvious concerns for the present and future of the laboratory

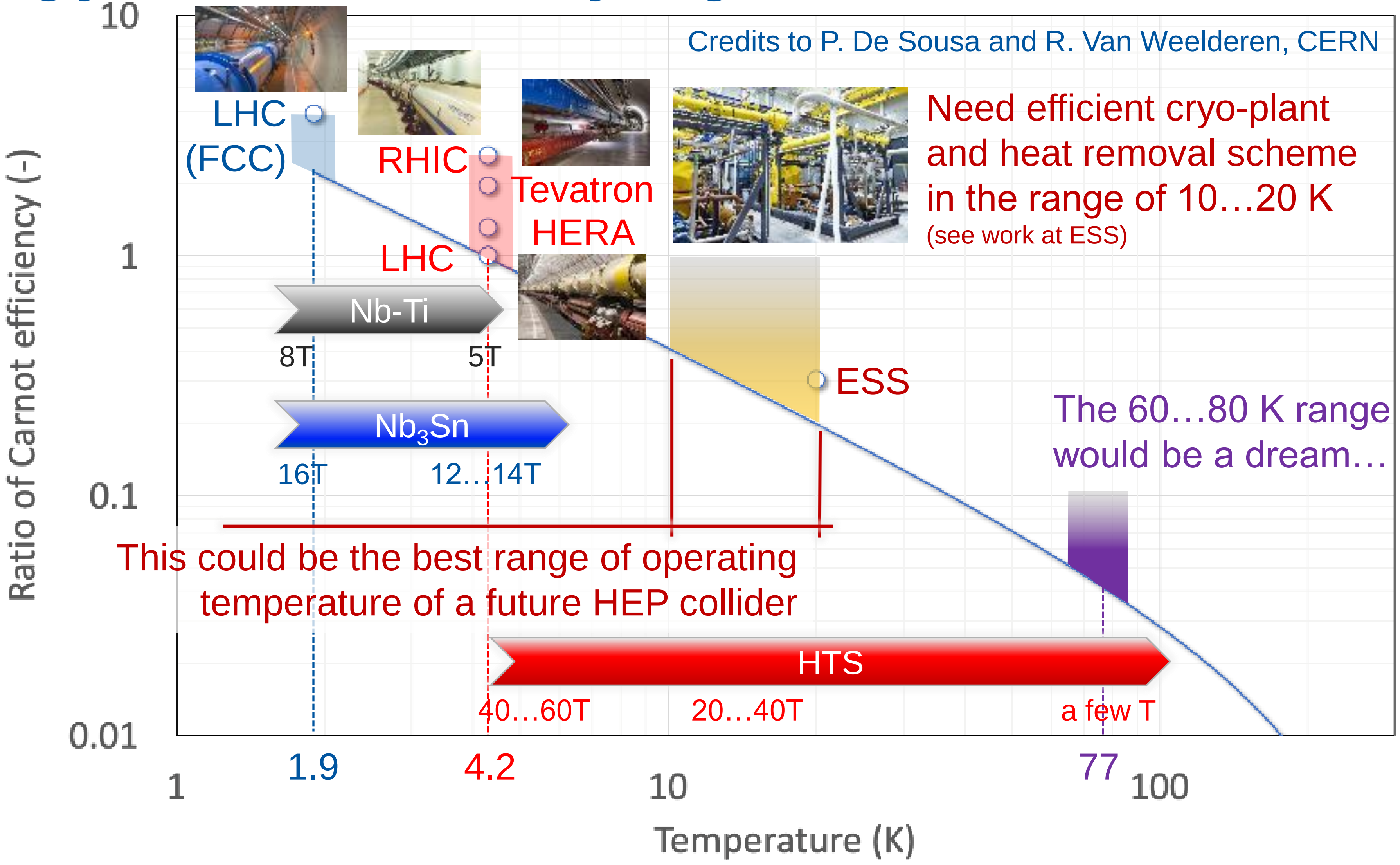




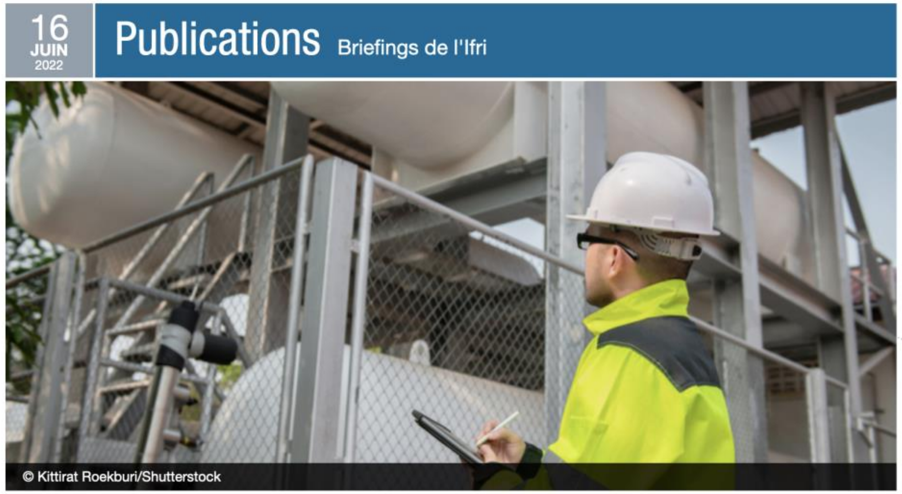


Energy efficient cryogenics

$W/Q = (T_h - T_c)/T_c$



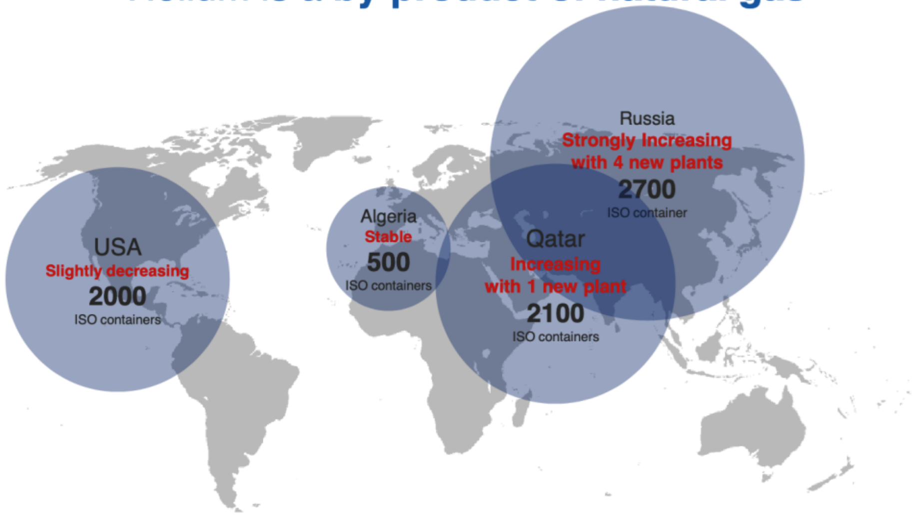
HTS may be the only path towards a future collider



Aurélien REYS, Vincent BOS

Hélium : les nouvelles géographies d'une ressource critique
Briefings de l'Ifri, 16 juin 2022

Helium is a **by-product of natural gas**



Tentative forecast in 2026 based on public announcements of new capacities available in quantity of Iso container of 4.5 tonnes

TE CRG

Future helium **supply is limited** and entails a substantial economical and availability **risk**

Consequences

Current situation

- Market shortage is affecting industrial and scientific customers
- Manufacturing industry contracts are impacted with volume limitations
- Large scientific instrument cannot do so & rely on established industrial partnership

Helium market still at risk in 2023 and for the coming years

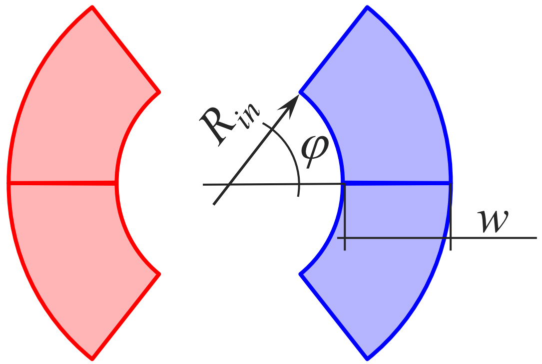
- Uncertainty on the effective Russian production capacity and market access
- Algerian gas production transferred using pipeline instead of LNG
- No more back-up from the US federal authorities, Cliffside for sale ! (C&en News)

The need for economics

- A large component in the magnet cost is the **amount of superconductor** (coil cross section)
- High-field superconductors are (significantly) more expensive than *good-old* Nb-Ti
- Need to work in two directions:
  - **Reduce the coil cross section** (**increase *J* !**)

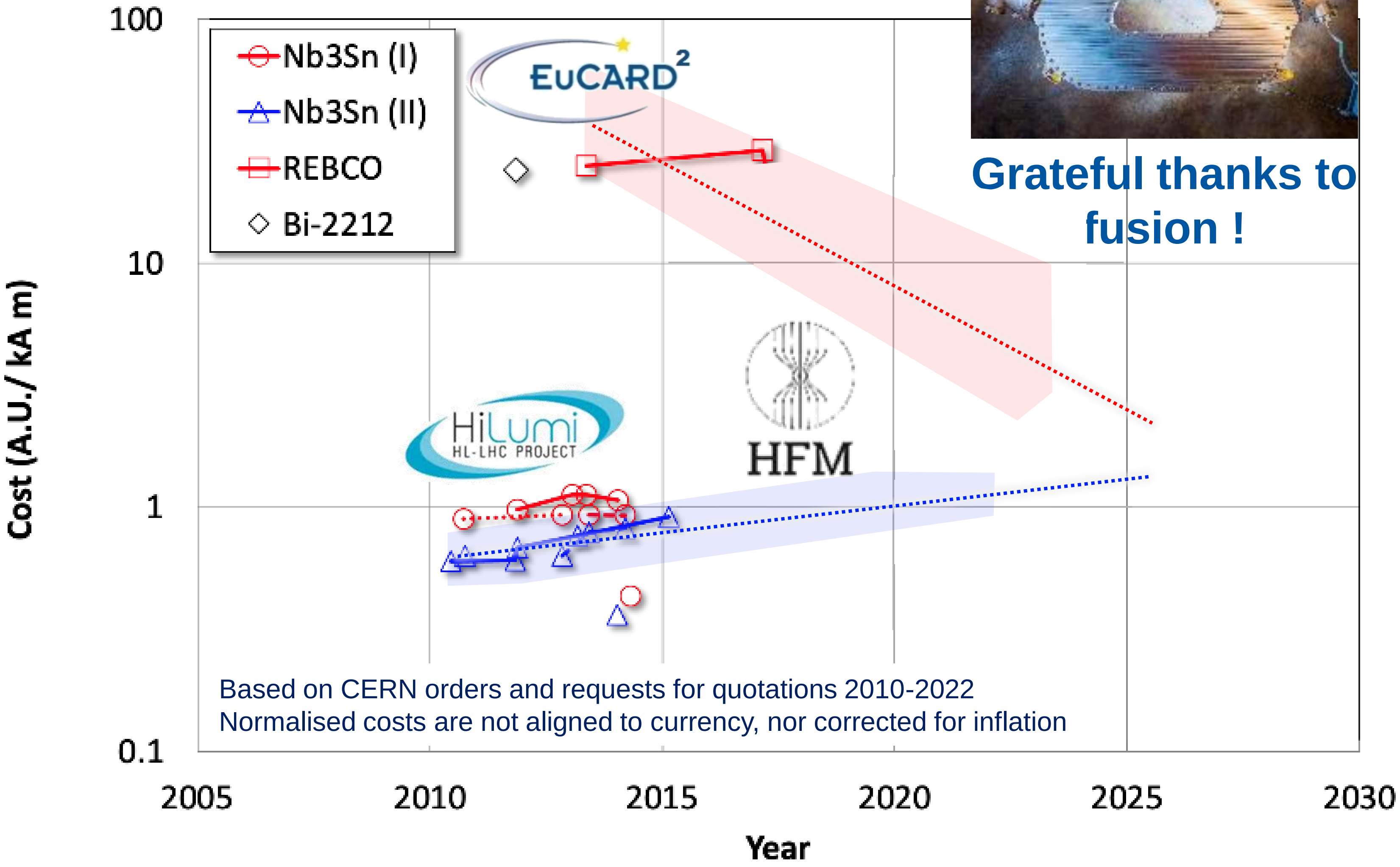
$$B = \frac{2\mu_0}{\pi} Jw \sin(\varphi)$$

$$A_{coil} = 2\varphi(w^2 + 2R_{in}w) \sim \frac{1}{J^{1.5}}$$



  - **Reduce unit conductor cost**

Conductor cost



Grateful thanks to fusion !

Impressive cost reduction in HTS !