16T Cosθ Dipole Mechanical Analysis

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on behalf of INFN team:

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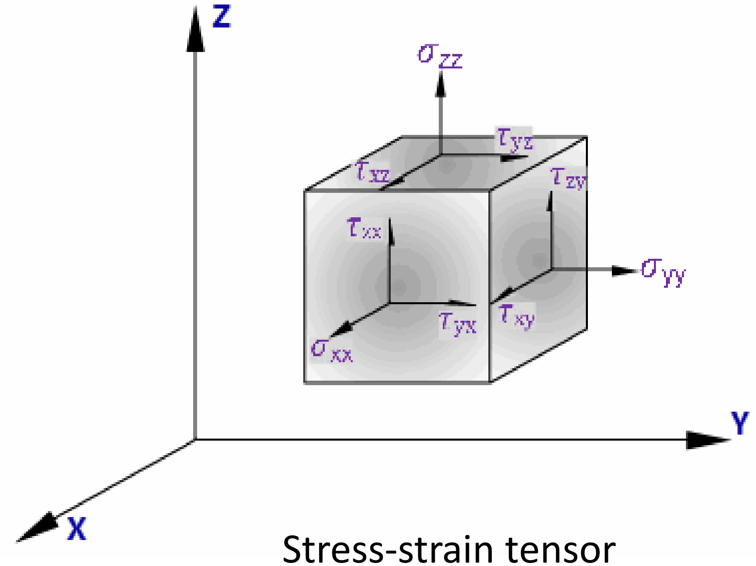
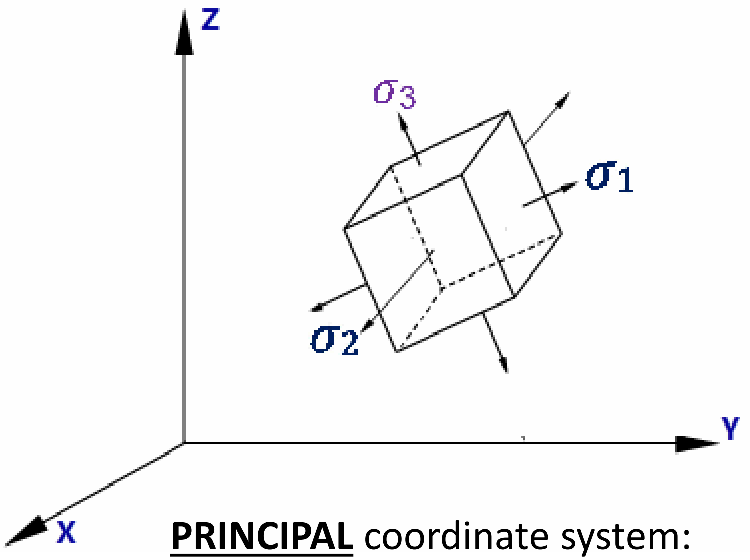
Overview

- Principal stresses and failure criteria
- 2D calculation: plain strain vs plain stress
- 2D mechanical optimization
- Cosθ 2D models
- Conclusions

Principal Stresses



Stress-strain tensor
In cartesian coordinate system



PRINCIPAL coordinate system: system in which the SS tensor is **DIAGONAL**

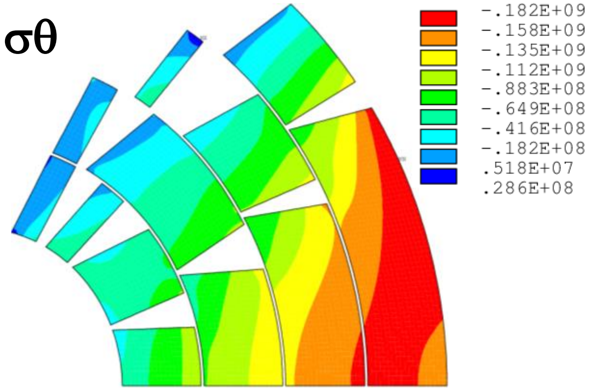
$$\sigma = \begin{Bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{Bmatrix} = \begin{Bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{Bmatrix}$$

- The principal stress $\sigma 1$, $\sigma 2$ and $\sigma 3$, defined for each single element, are those in which the stress-strain tensor is diagonal ($\sigma 3 < \sigma 2 < \sigma 1$).
- $\sigma 3 \sim \sigma x$ in block coil geometry
- $\sigma 3 \sim \sigma\theta$ in $\cos\theta$ geometry
- Von Mises stress is defined as:

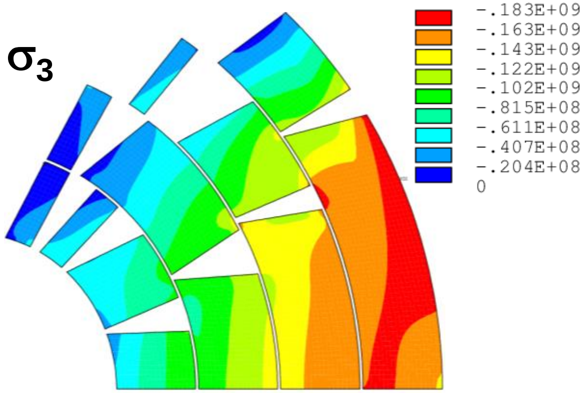
$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Principal Stresses

σθ

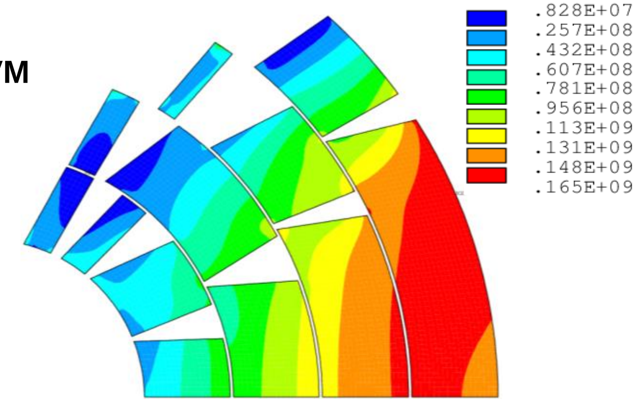


σ_3

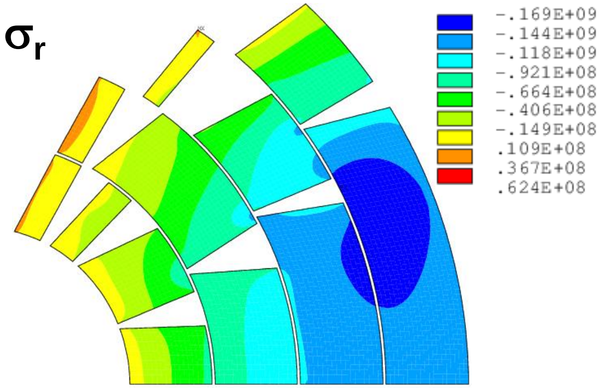


- Principal stresses σ_1, σ_3 are shown together with σ_r, σ_θ σ_{VM} for comparison.
- In cosθ design, the symmetry is almost azimuthal: σ3 ≈ σθ. σθ can be compared with σy of block coil configuration.
- σ_r is negligible.
- σ_{VM} is a sort of average between σ_1 and σ_3.

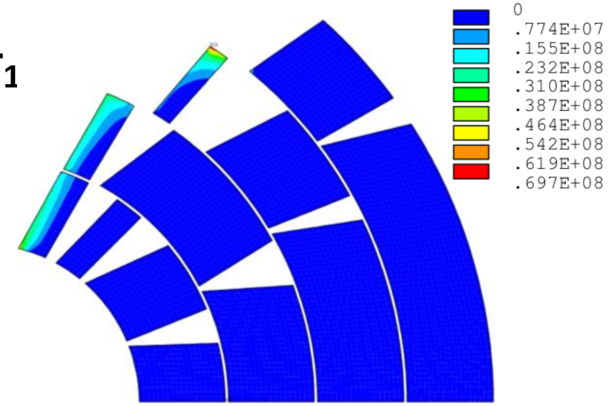
σ_{VM}



σ_r



σ_1



2D Mechanical Optimization

Cables undergo degradation if:

- stress on conductors >150 MPa @room temperature;
- stress on conductors > 200 MPa @cold;
- stress on conductors > 150 MPa @cold after energization in the high field region → attention must be given in particular to first layers.
- Tensile stress on the iron yoke at 4 K < 200 MPa.
- Contact pressure Ti pole-conductors > 2 MPa after energization at 16T.

Critical Current Measurements of High-J_c Nb_3Sn Rutherford Cables under Transverse Compression

B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli

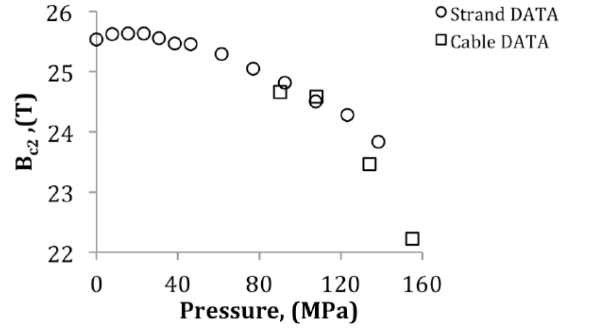
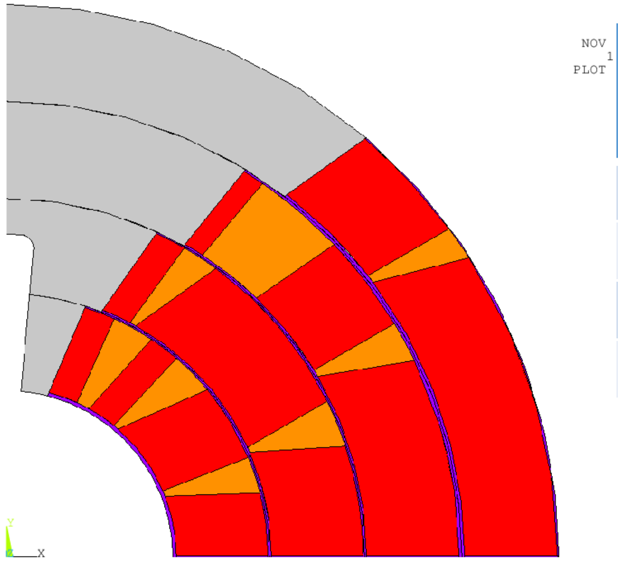
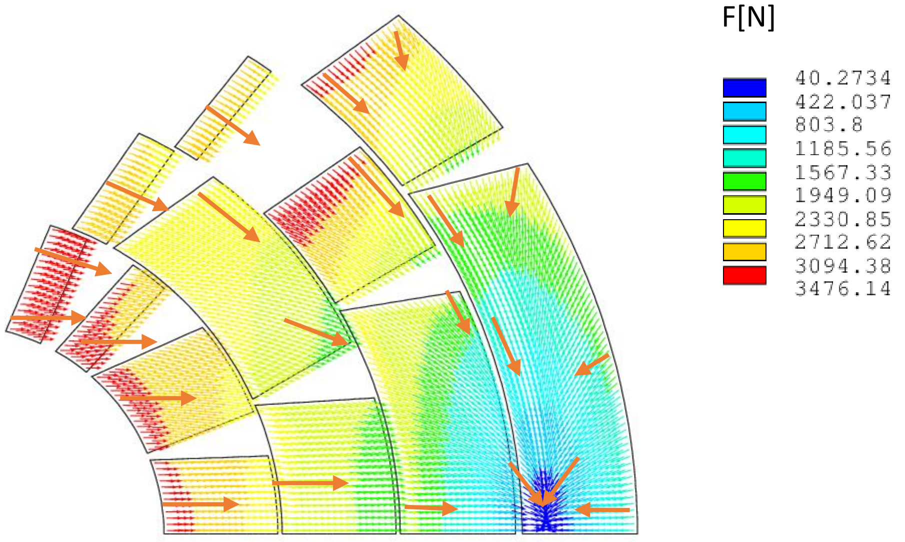


Fig. 6. Upper critical field at 4.2 K estimated from the critical current measurements under transversal pressure.



	Nº turns	σ_θ – layer (MPa)	σ_θ – winding (MPa)
layer 1	13	86	121
layer 2	20	123	
layer 3	29	126	
layer 4	39	148	



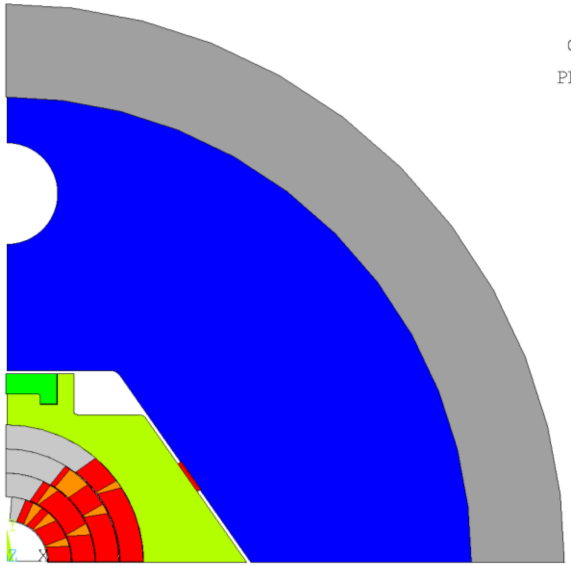
Material Properties

	E modulus [GPa] (T=4K)	E modulus [GPa] (T=300K)	α (K^{-1})	ν_{xy}
Conductor	E_x=33 E_y=27.5	E_x=30 E_y=25	α_x=3.08E-3/296 α_y=3.36E-3/296	0.3
Steel	210	191	2.8e-3/296	0.28
Iron	224	204	2.0e-3/296	0.28
Aluminum	79	72	4.2e-3/296	0.3
Copper	110	100	3.4e-3/296	0.3
Resin	27.5	25	2.5e-3/296	0.2
Titanium	126.5	115	1.7e-3/296	0.3

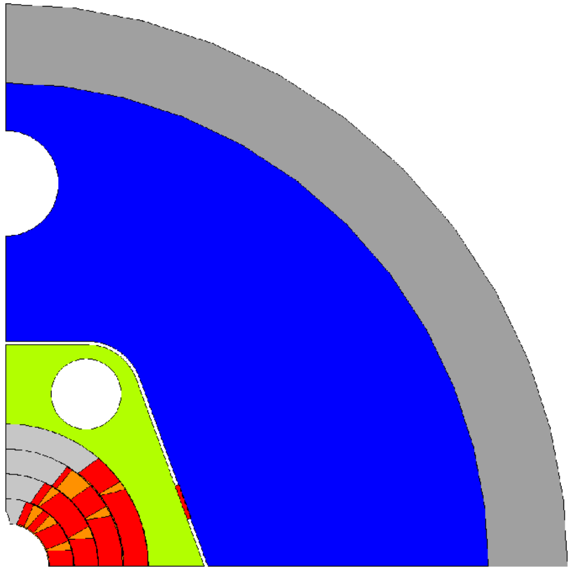
+10%

2D Mechanical Model

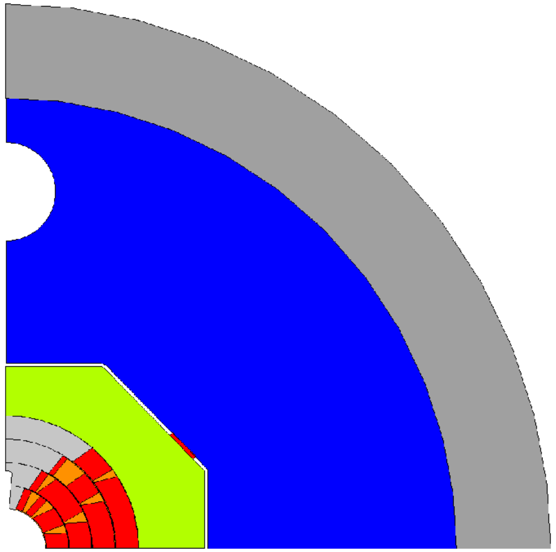
- Configurations studied:



- Vertical cut in iron yoke and steel pad
- Bladder&key
- C-clamp



- Horizontal cut in iron yoke and steel pad
- Bladder&key

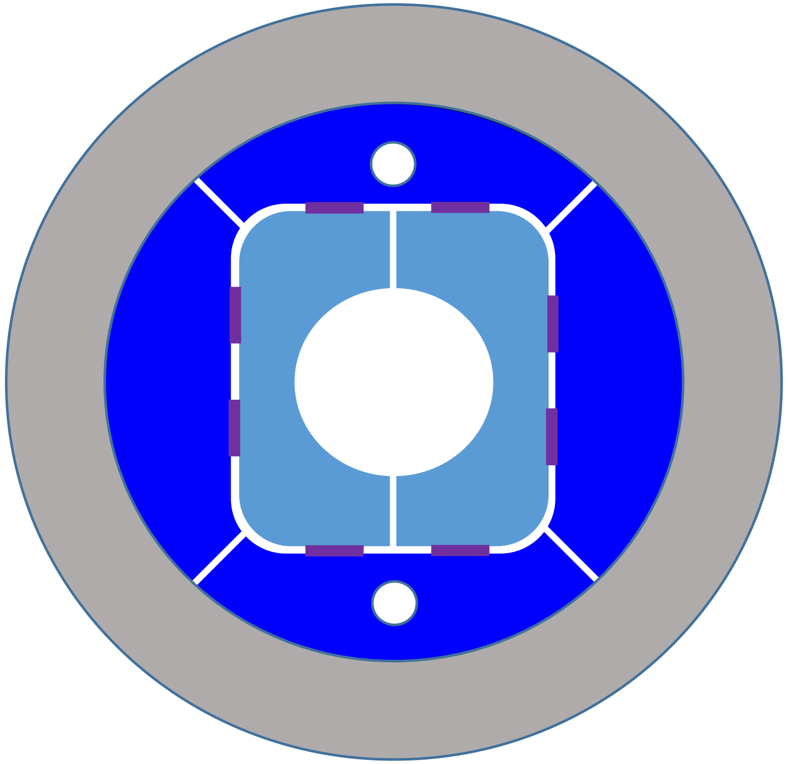


- Vertical cut in the steel pad
- Horizontal cut in the iron yoke
- Bladder&key

- There is not a best mechanical solution, each E.M. design must be optimized with ad hoc configurations!

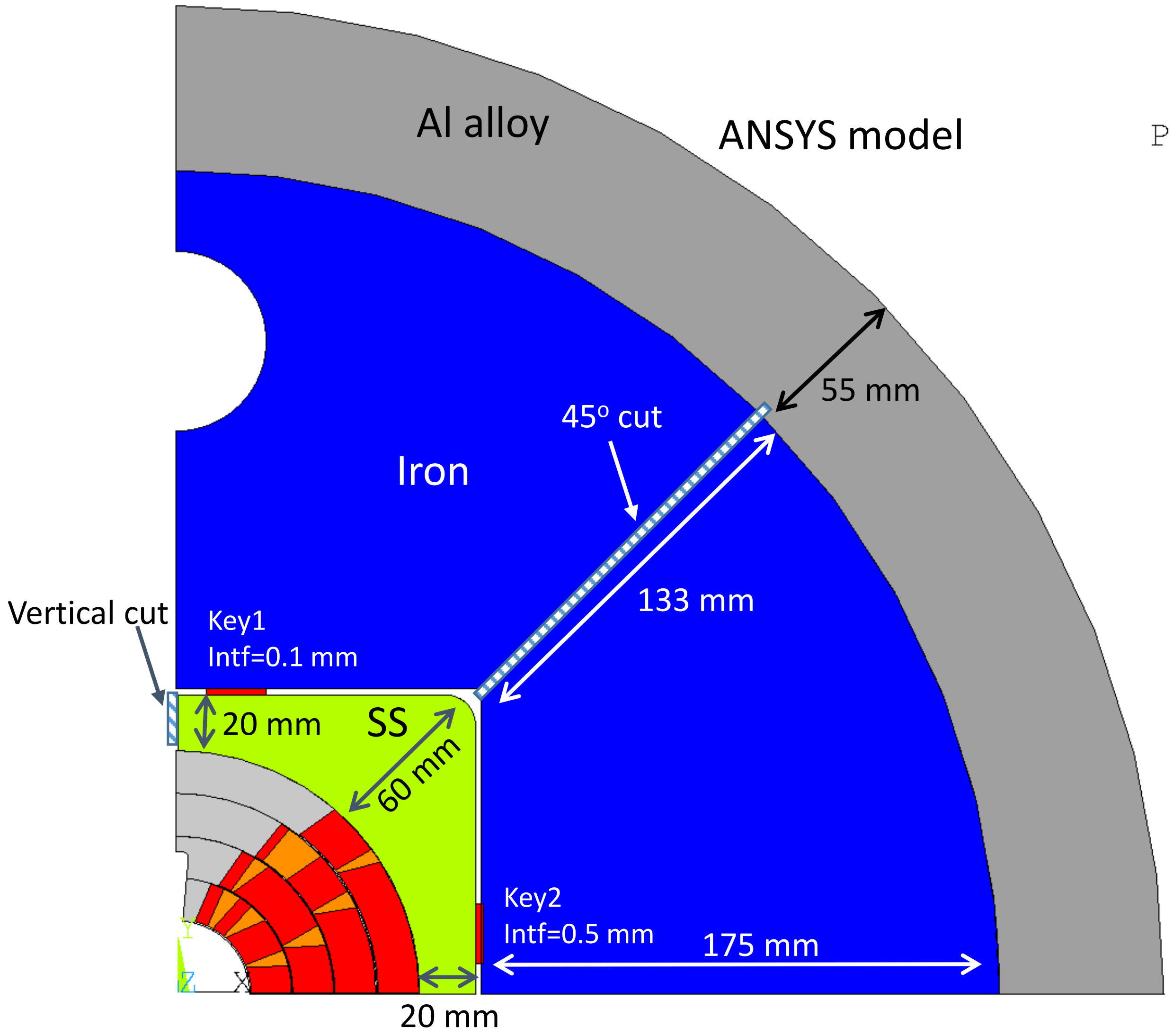
2D Mechanical Model

- New E.M. design and new material properties (EM modulus for conductors, etc.) requires new mechanical solutions and optimizations.



- Aluminum alloy shell;
- Iron yoke cut at 45^{o};
- Rectangular steel pad cut vertically;
- Bladder&key, used to give pre-stress, 4 keys place horizontally and 4 keys placed vertically

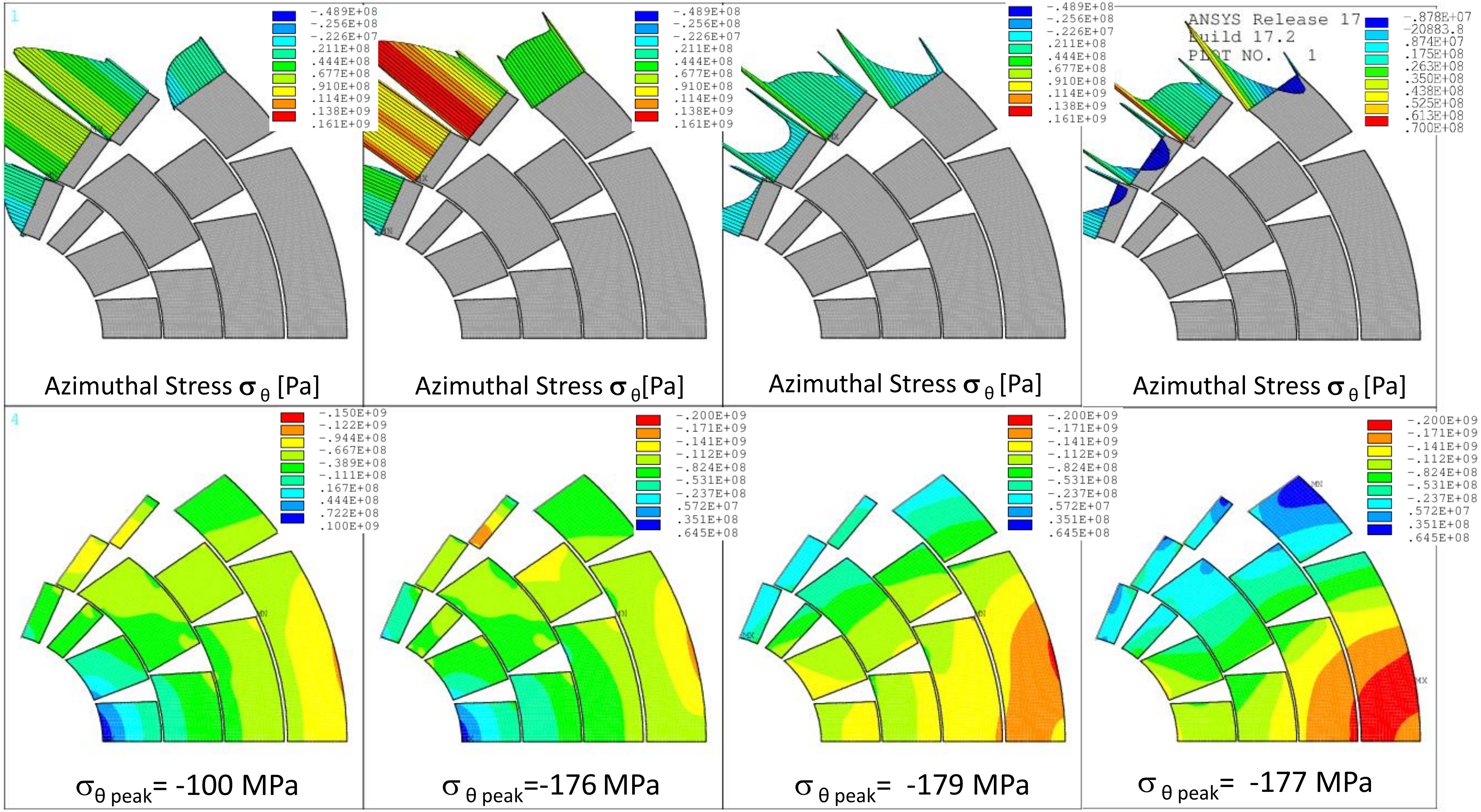
2D Ansys Model



- <u>Bladder & key configuration</u>
  Keys length= 20 mm, x_{key1}=10 mm, y_{key1}=10 mm, interference key1= 0.1 mm, interference key2= 0.5 mm.
- Rectangular steel pad, cut vertically, 20-60 mm thick.
- Circular iron yoke, cut at 45°, 133-175 mm thick.
- Rectangular shaped steel pad and horizontal and vertical keys allow to decouple x and y component of pre-stress.

Contact Pressure and Azimuthal Stress

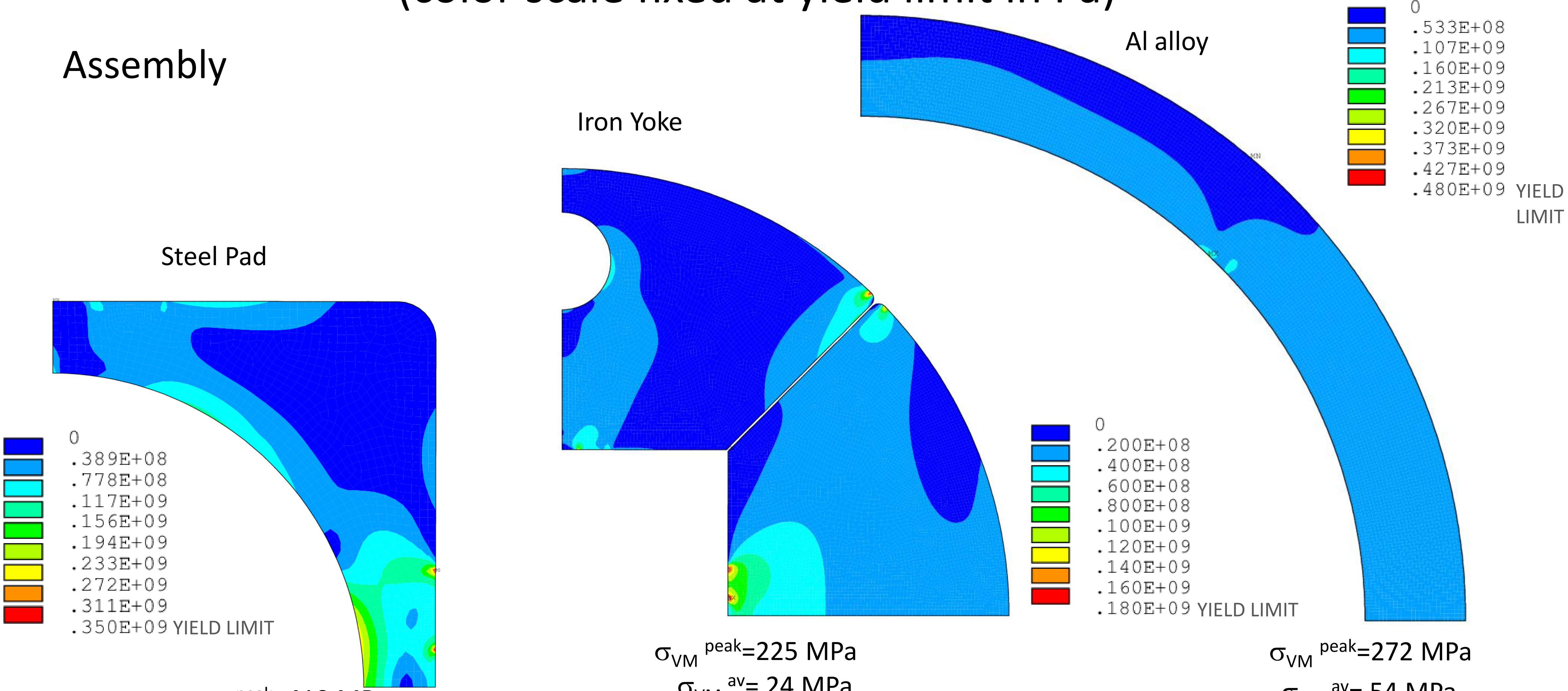
Assembly	Cool Down	Energization	Energization @ 105%I
Contact Pressure [Pa]	Contact Pressure [Pa]	Contact Pressure [Pa]	Contact Pressure [Pa]



Assembly	Cool Down	Energization	Energization @ 105%I
$\sigma_{\theta\ peak}$= -100 MPa	$\sigma_{\theta\ peak}$=-176 MPa	$\sigma_{\theta\ peak}$= -179 MPa	$\sigma_{\theta\ peak}$= -177 MPa

Von Mises Stress in Mechanical Structures
(color scale fixed at yield limit in Pa)

Assembly



Steel Pad: $\sigma_{VM}^{\ peak}$=410 MPa, $\sigma_{VM}^{\ av}$=52 MPa

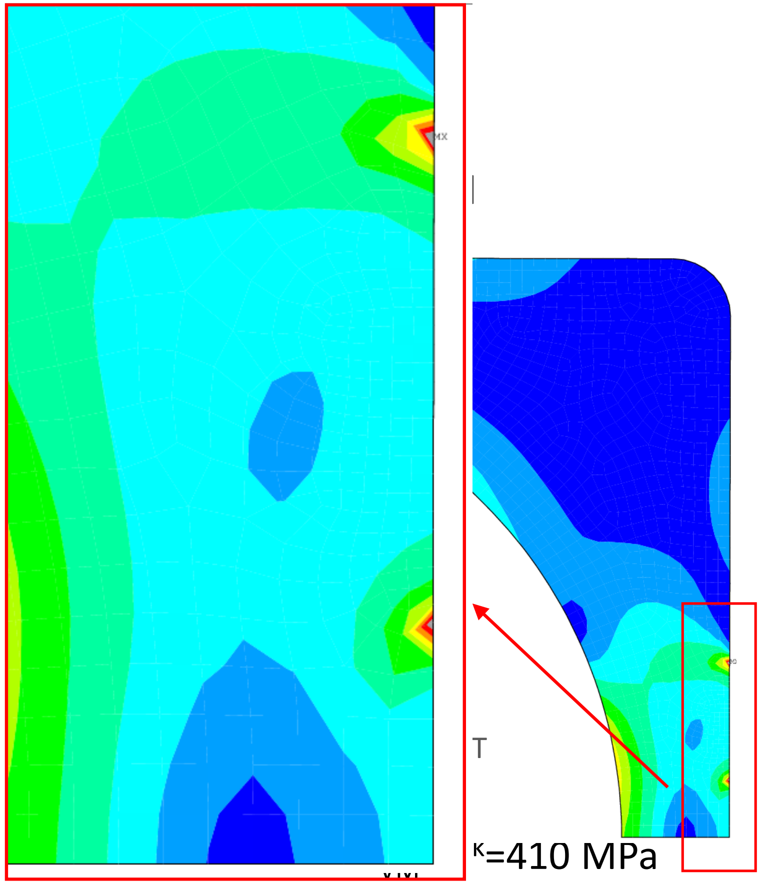
Iron Yoke: $\sigma_{VM}^{\ peak}$=225 MPa, $\sigma_{VM}^{\ av}$= 24 MPa

Al alloy: $\sigma_{VM}^{\ peak}$=272 MPa, $\sigma_{VM}^{\ av}$= 54 MPa

Von Mises Stress in Mechanical Structures

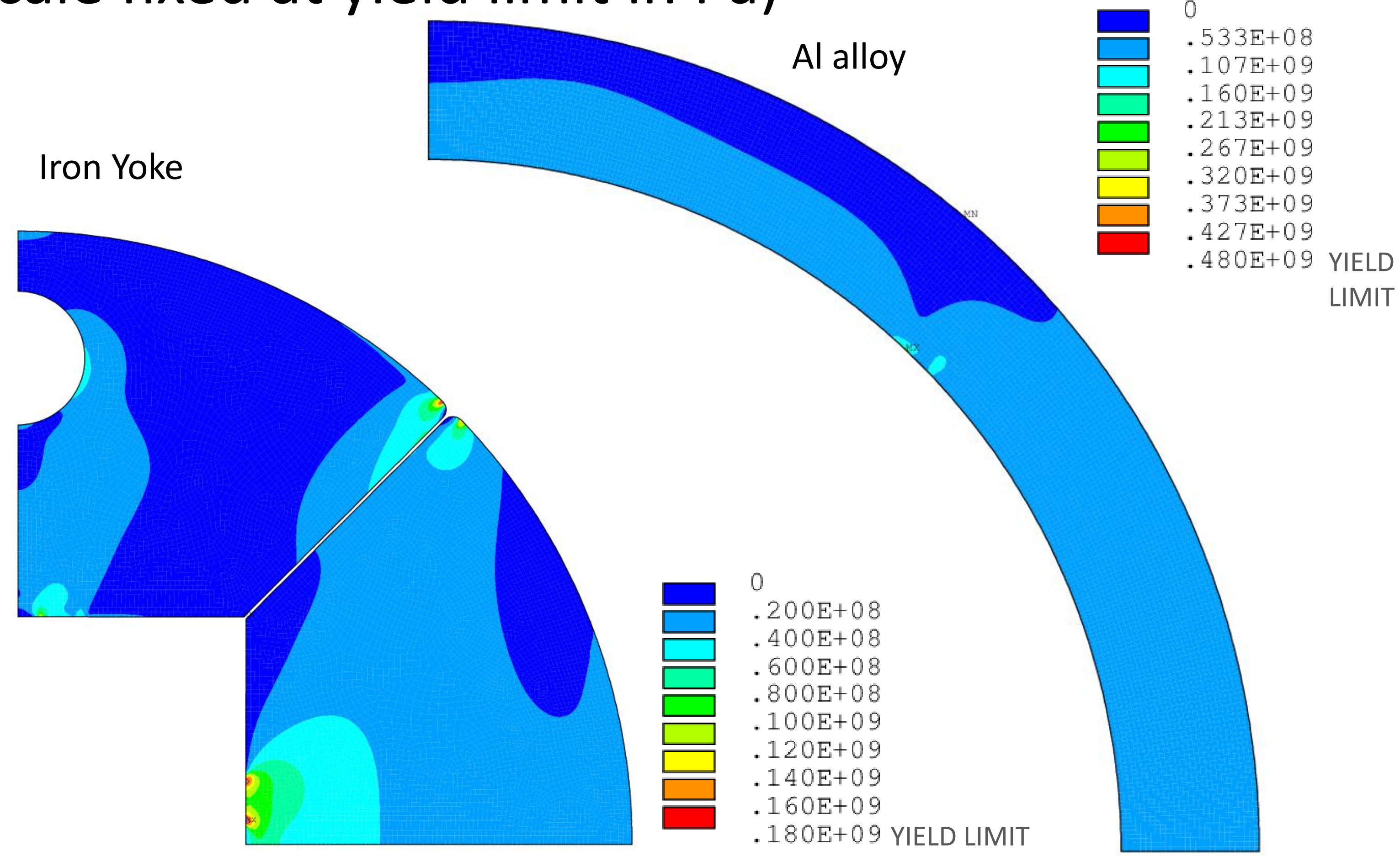
(color scale fixed at yield limit in Pa)

Assembly



…=410 MPa

$\sigma_{VM}{}^{av}$=52 MPa



$\sigma_{VM}{}^{peak}$=225 MPa

$\sigma_{VM}{}^{av}$= 24 MPa

$\sigma_{VM}{}^{peak}$=272 MPa

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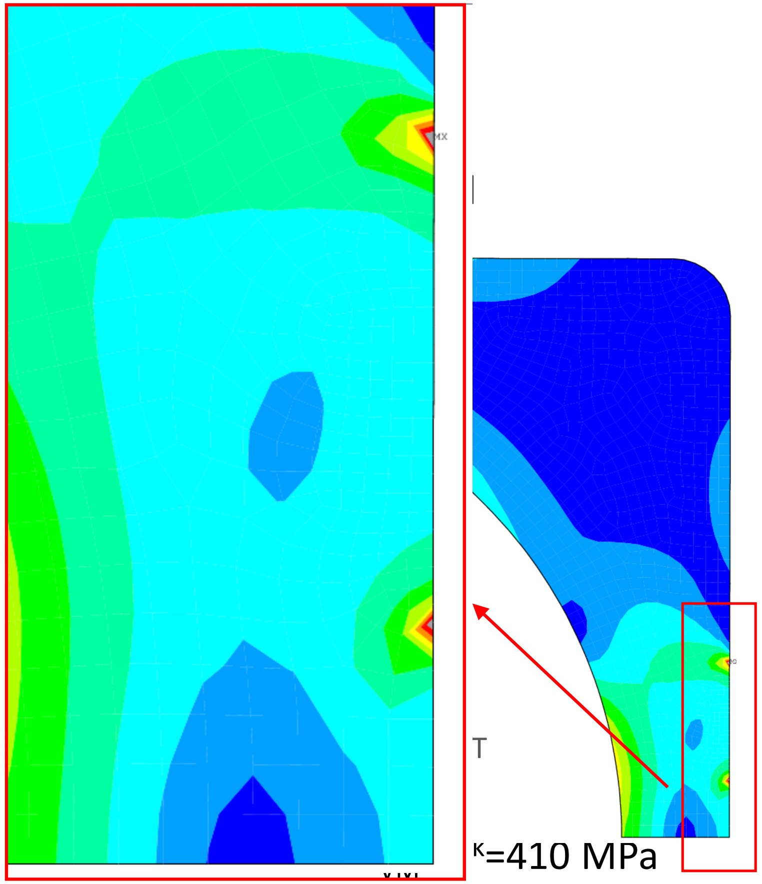
Von Mises Stress in Mechanical Structures

(color scale fixed at yield limit in Pa)

Assembly

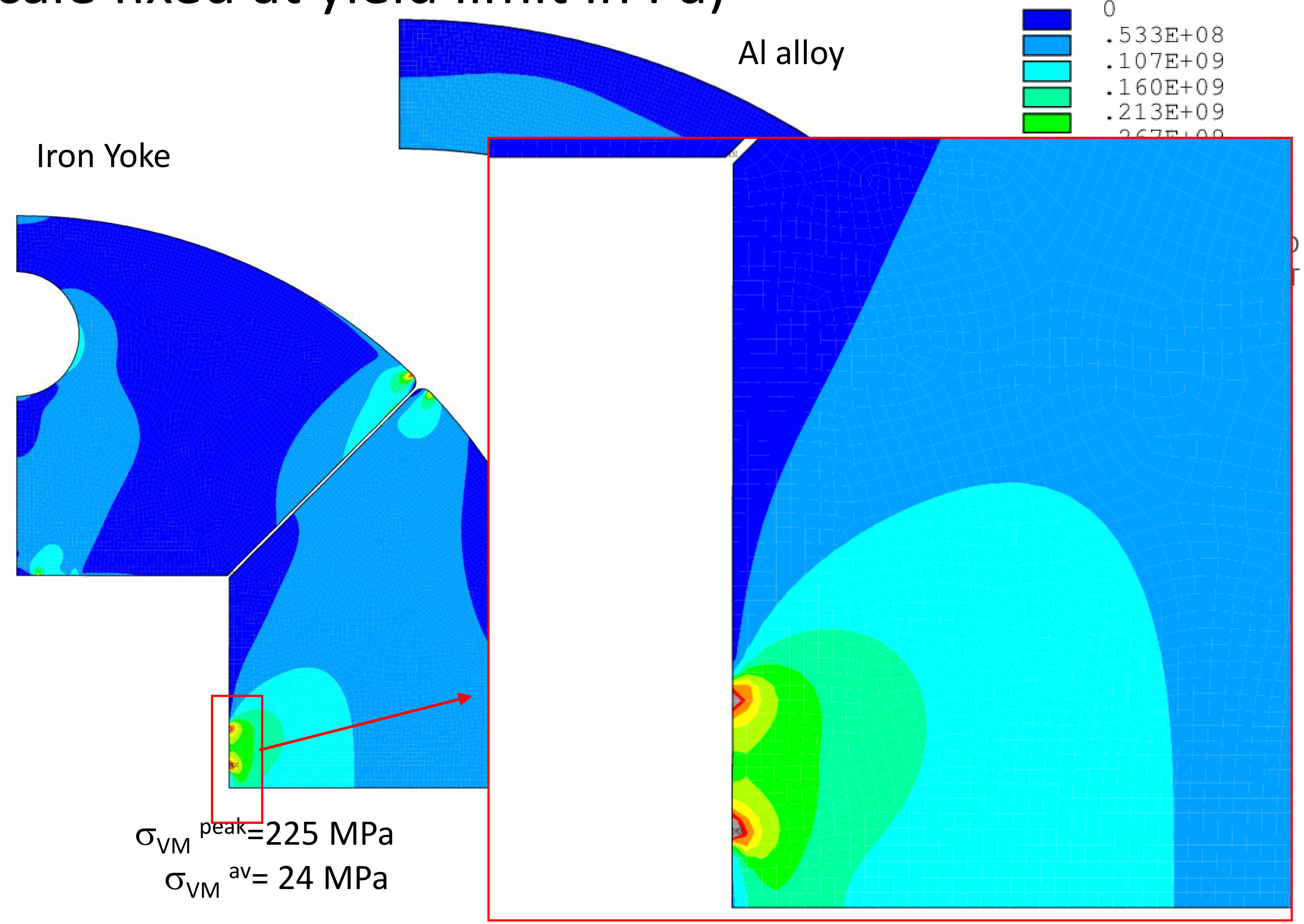


K=410 MPa

σ_{VM} ^{av}=52 MPa

Iron Yoke

Al alloy



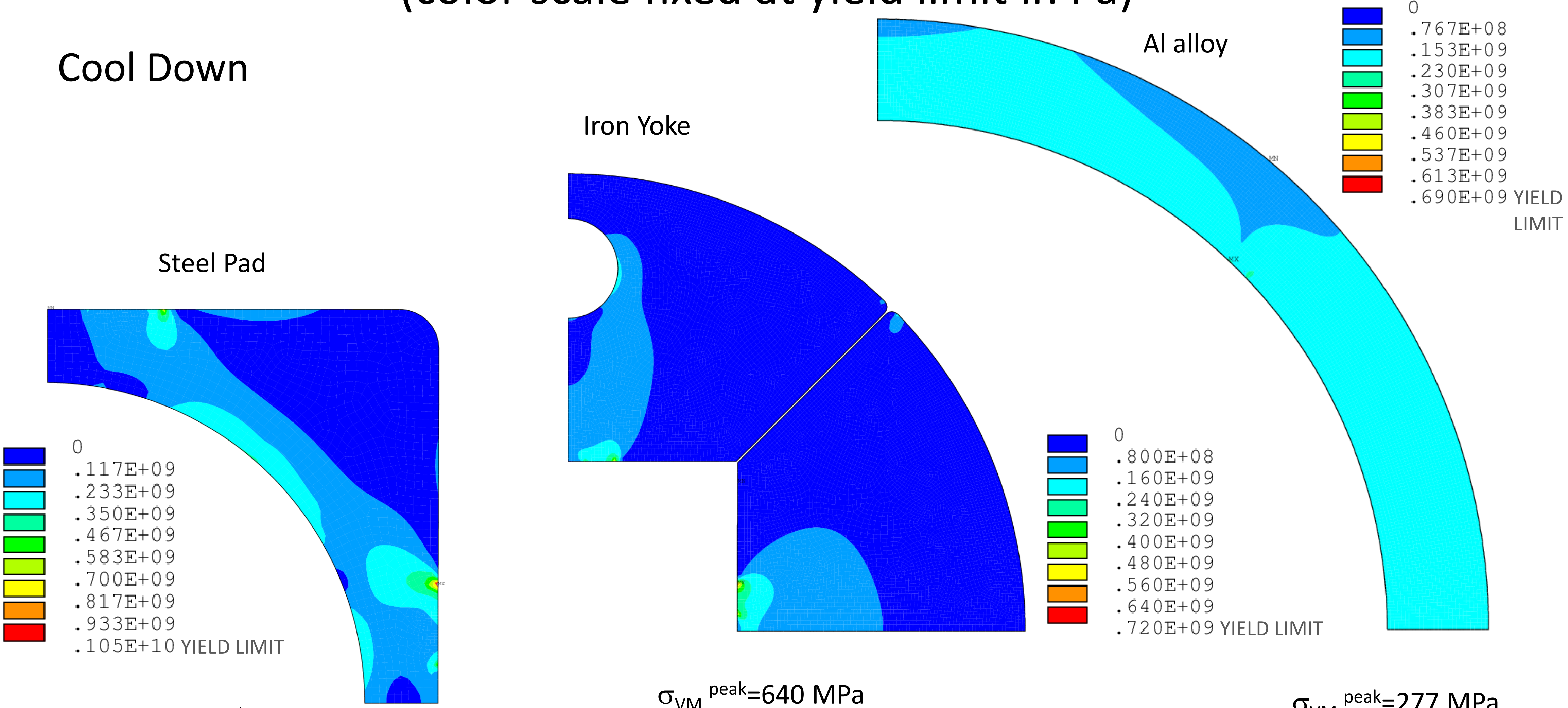
σ_{VM} ^{peak}=225 MPa

σ_{VM} ^{av}= 24 MPa

Von Mises Stress in Mechanical Structures

(color scale fixed at yield limit in Pa)

Cool Down



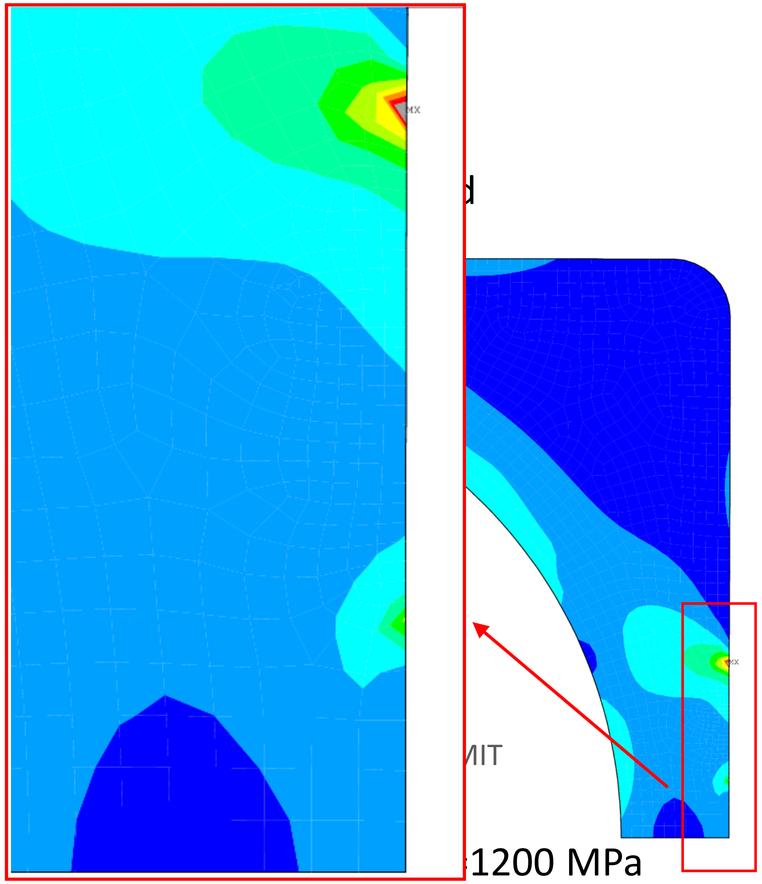
Steel Pad: $\sigma_{VM}{}^{peak}$=1200 MPa, $\sigma_{VM}{}^{av}$=131 MPa

Iron Yoke: $\sigma_{VM}{}^{peak}$=640 MPa, $\sigma_{VM}{}^{av}$=56 MPa

Al alloy: $\sigma_{VM}{}^{peak}$=277 MPa, $\sigma_{VM}{}^{av}$=170 MPa

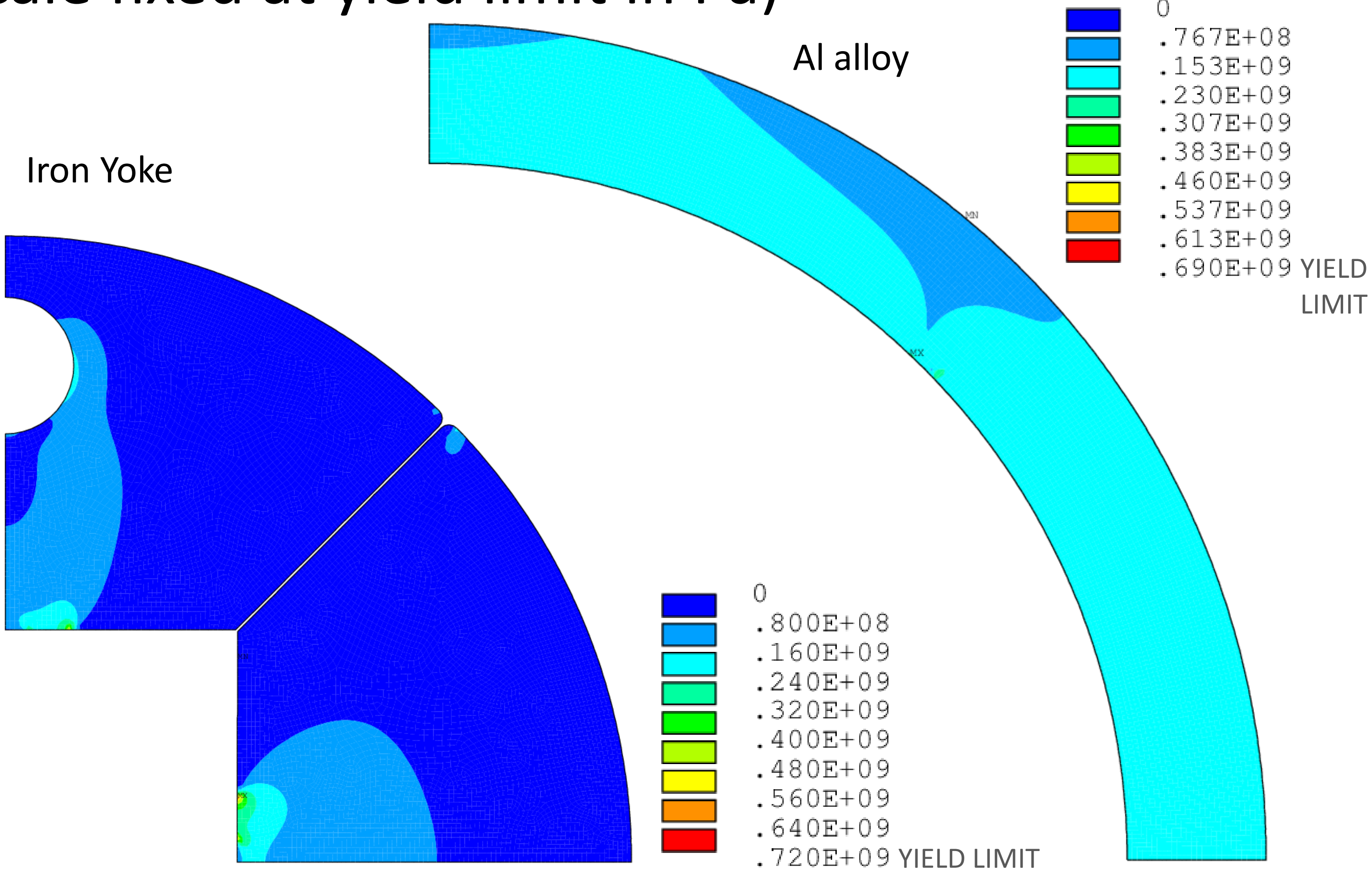
Von Mises Stress in Mechanical Structures
(color scale fixed at yield limit in Pa)

Cool Down



1200 MPa

σ_{VM}^{av}=131 MPa



σ_{VM}^{peak}=640 MPa

σ_{VM}^{av}=56 MPa

σ_{VM}^{peak}=277 MPa

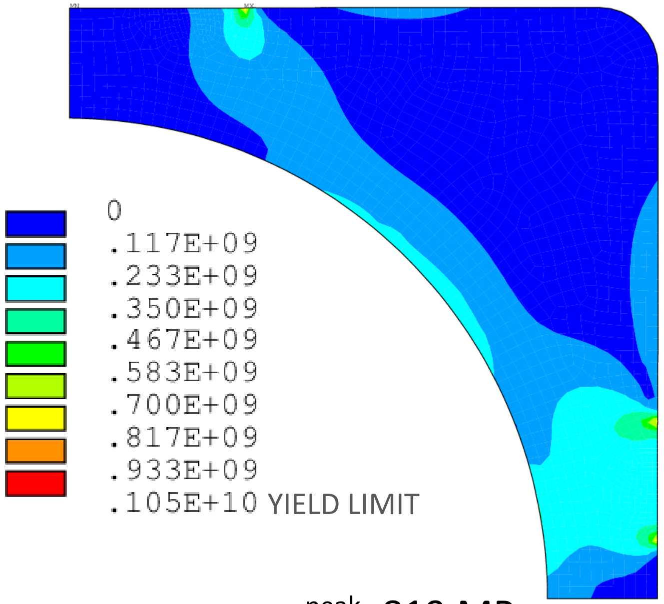
σ_{VM}^{av}=170 MPa

Von Mises Stress in Mechanical Structures

(color scale fixed at yield limit in Pa)

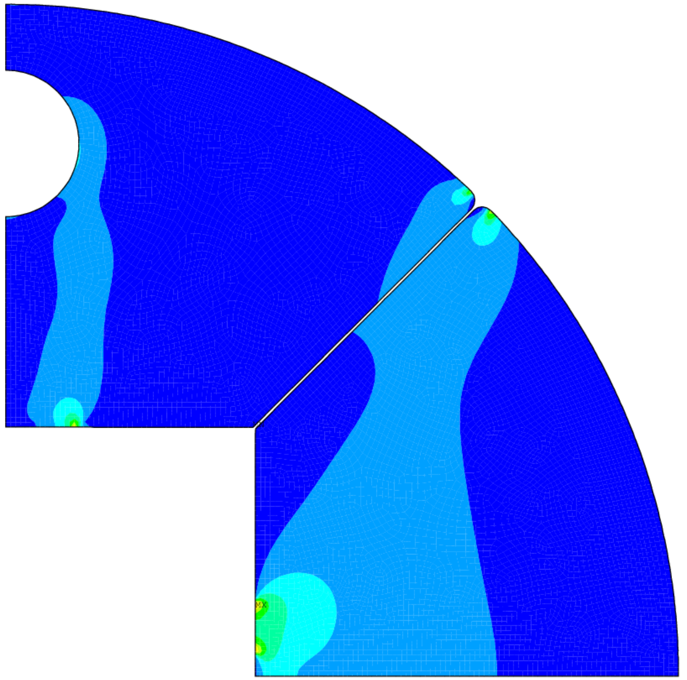
Energization

Steel Pad



$\sigma_{VM}{}^{peak}$=819 MPa

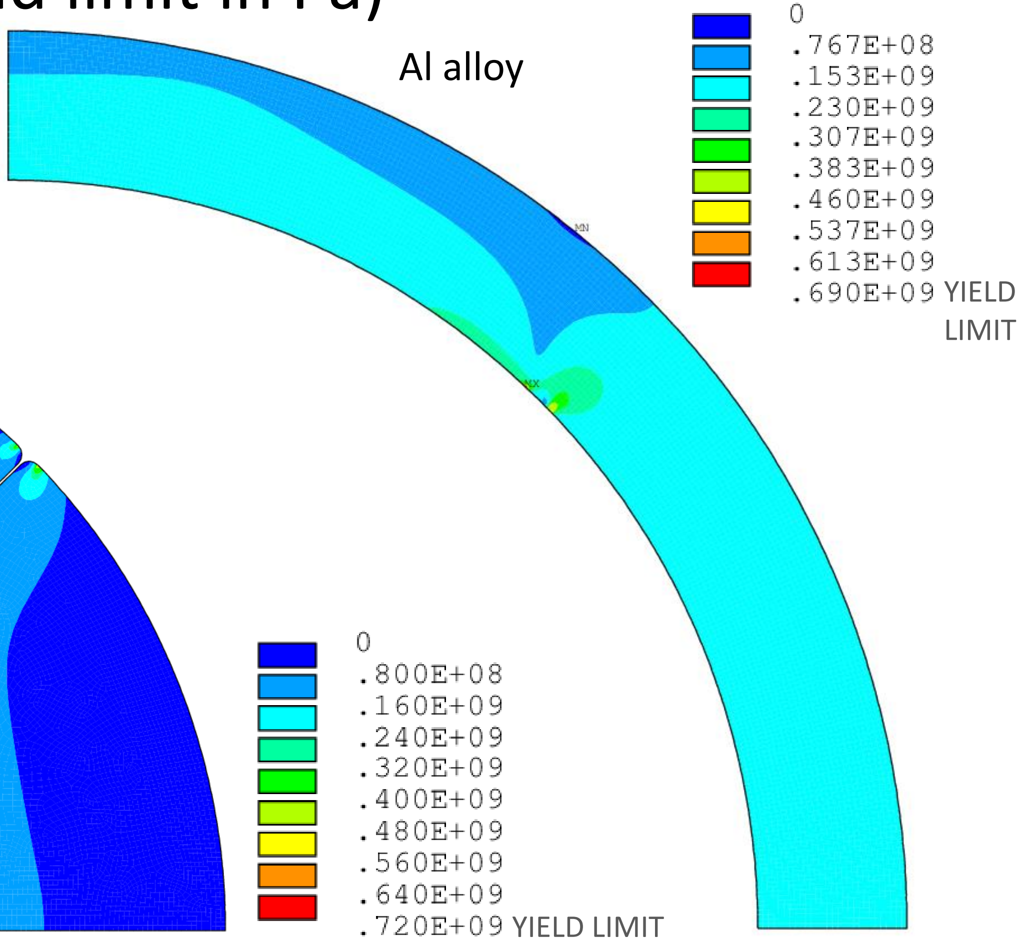
$\sigma_{VM}{}^{av}$=122 MPa



$\sigma_{VM}{}^{peak}$=589 MPa

$\sigma_{VM}{}^{av}$=70 MPa

Al alloy



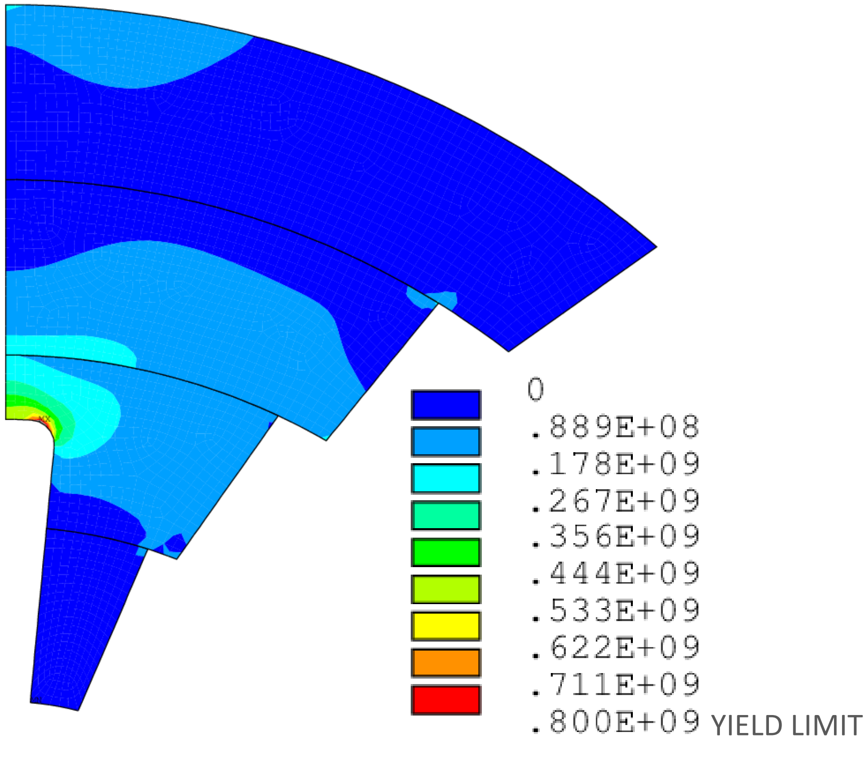
$\sigma_{VM}{}^{peak}$=521 MPa

$\sigma_{VM}{}^{av}$=175 MPa

Von Mises Stress in Titanium Poles

(color scale fixed at yield limit in Pa)

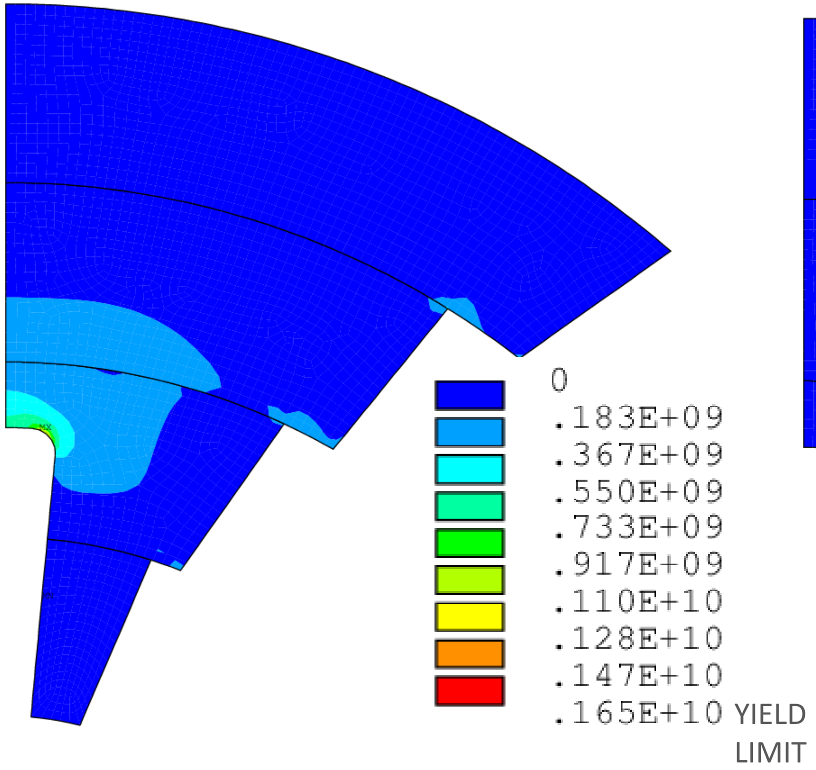
Assembly



σ_{VM}^{peak}=850 MPa

σ_{VM}^{av}=84 MPa

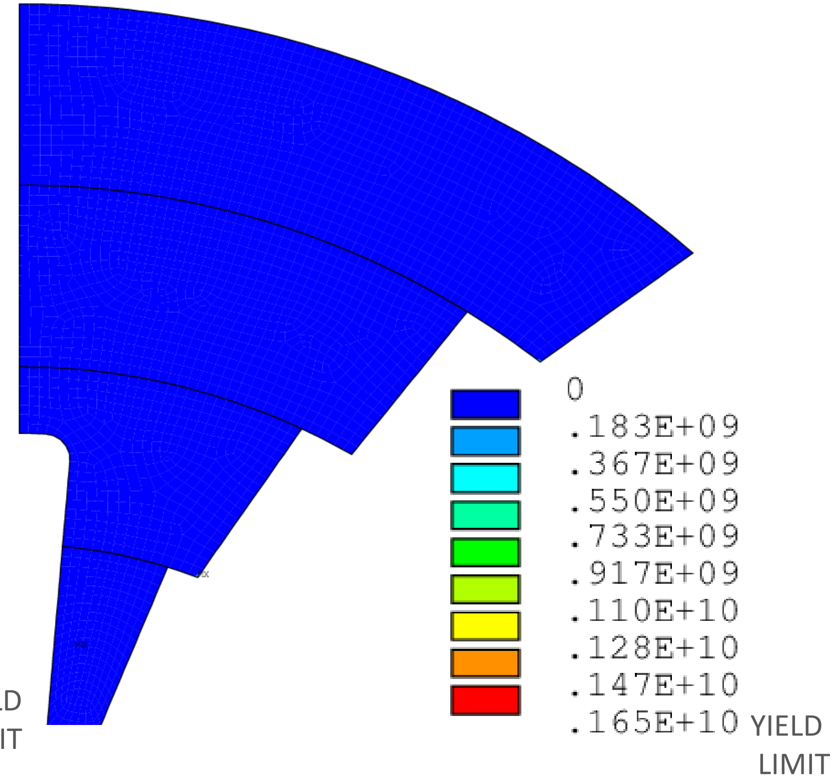
Cool Down



σ_{VM}^{peak}=1120 MPa

σ_{VM}^{av}= 124 MPa

Energization

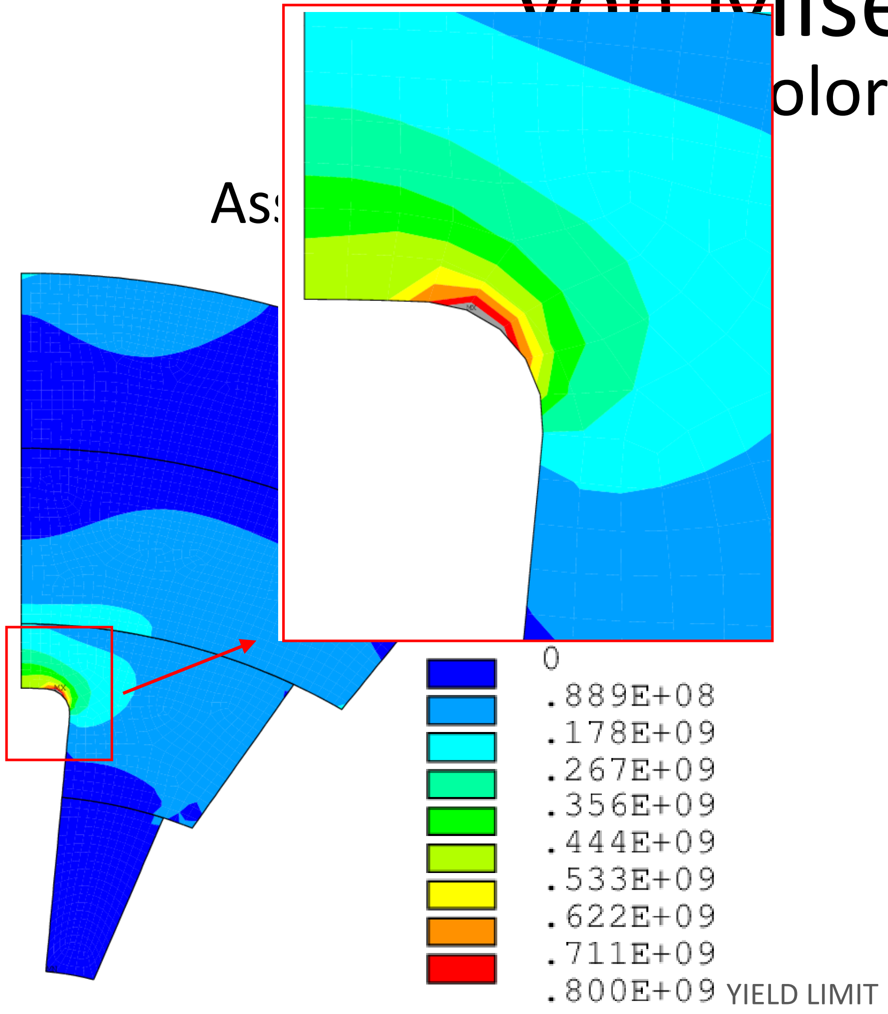


σ_{VM}^{peak}=255 MPa

σ_{VM}^{av}=50 MPa

Von Mises Stress in Titanium Poles
olor scale fixed at yield limit in Pa)

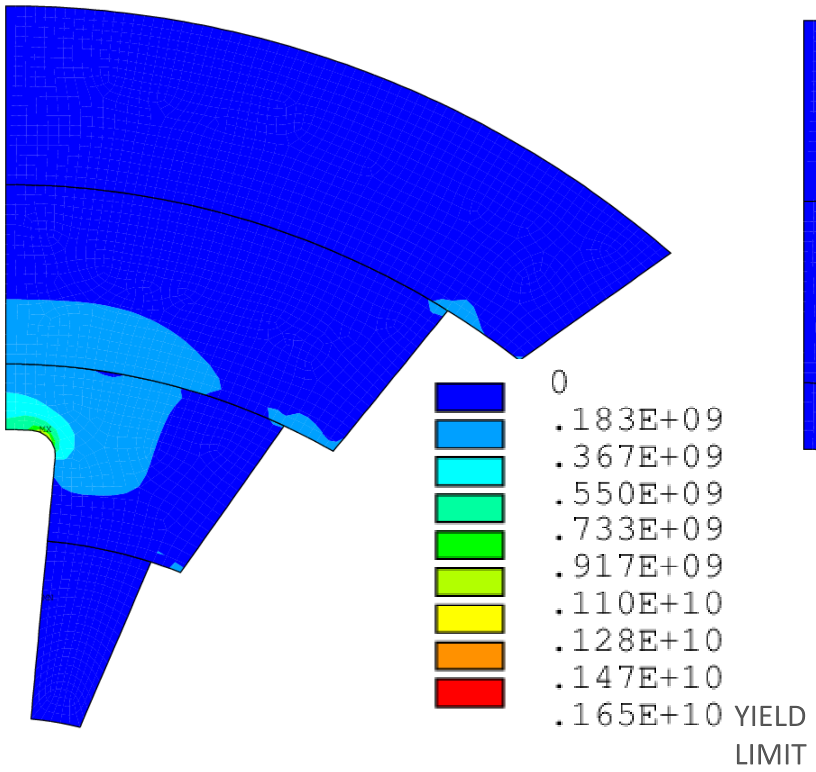
Ass



$\sigma_{VM}{}^{peak}$=850 MPa

$\sigma_{VM}{}^{av}$=84 MPa

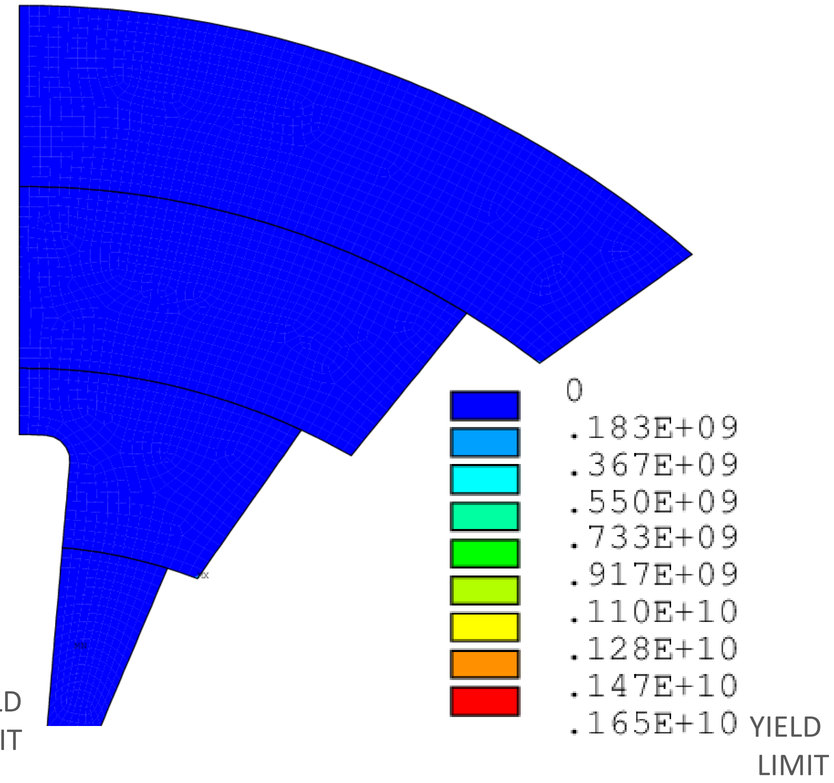
Cool Down



$\sigma_{VM}{}^{peak}$=1120 MPa

$\sigma_{VM}{}^{av}$= 124 MPa

Energization



$\sigma_{VM}{}^{peak}$=255 MPa

$\sigma_{VM}{}^{av}$=50 MPa

Conclusions

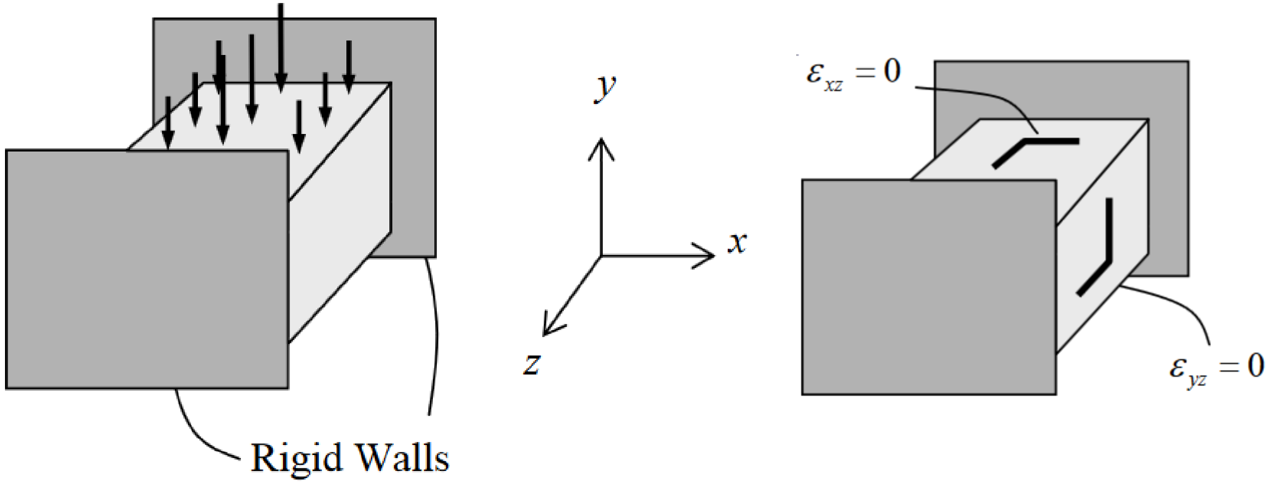
- The mechanics of the 16T cosθ dipole has been investigated, giving particular importance to the fulfillment of the following requirements: stress on conductors (<150 MPa @room temperature, < 200 MPa @cold, <150 MPa after energization in the high field zone), contact pressure Ti pole-conductors > 2 MPa after energization.
- Taking into account that:
  - recommended material properties list was finalized during last EuroCircol collaboration meeting;
  - a new E.M. for cos-theta model was considered after US-EuroCirCol meeting;

  a completely new mechanical model was developed, in order to fulfil these new conditions.
- The new configuration has:
  - rectangular steel collar, cut vertically;
  - circular your yoke, cut at 45°;
  - 4 key placed horizontally and 4 key placed vertically, in order to give x and y pre-stress separately
- ANSYS calculations show that the new configuration:
  - fulfills stress limits on the conductor;
  - has good contact pressure at the pole for all the layers;
  - almost fulfills stress limit on stress on structure materials .

Back-up slides

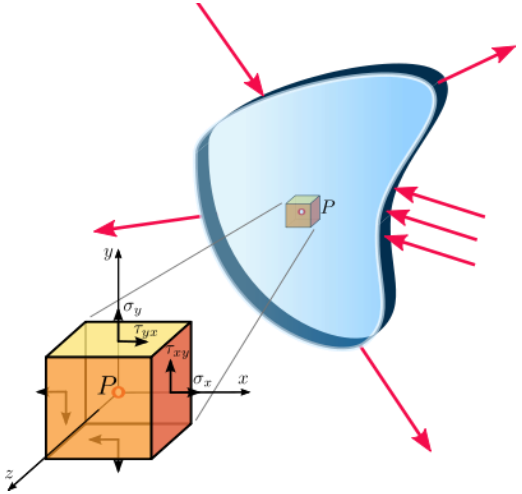
Plain Strain vs Plain Stress

Plane strain



Plane strain is a stress state that varies only in the X and Y directions. The strain in the Z direction is always zero, as are the XZ and YZ shear strains, since the boundaries are fixed.

Plane stress



Plane stress is a stress state that varies only in the X and Y directions. The stress in the Z direction is always zero, as are the XZ and YZ shear stresses.
Plane stress is generally used on flat, thin structures, where the deformation is assumed to be solely in the plane of the structure.

<u>**Plain stress**</u> approximation is less conservative but more compatible with 3D simulation results.