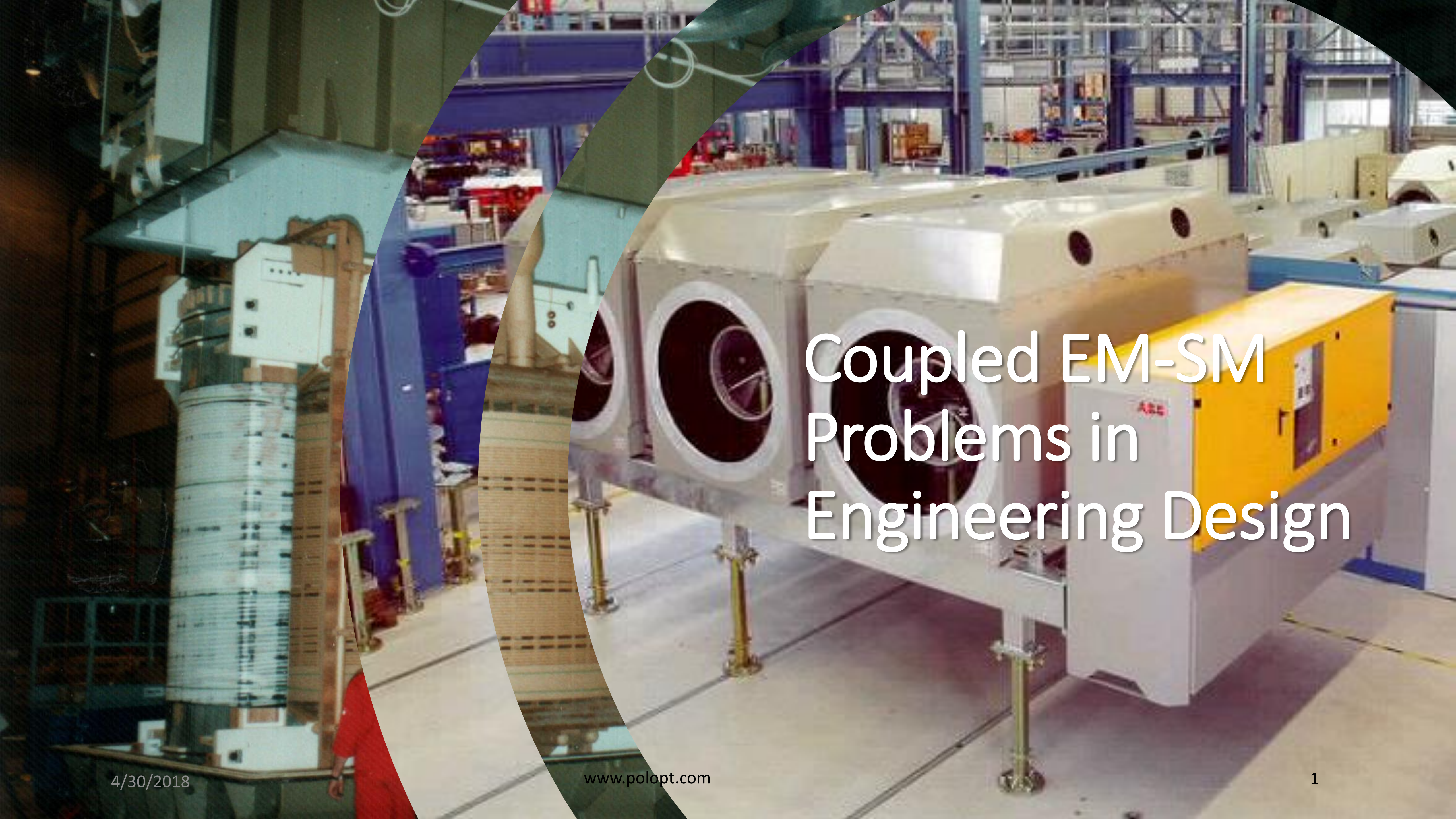
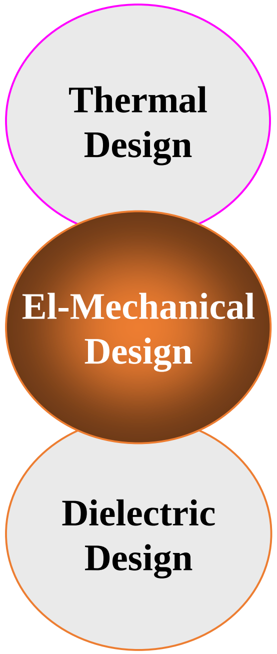
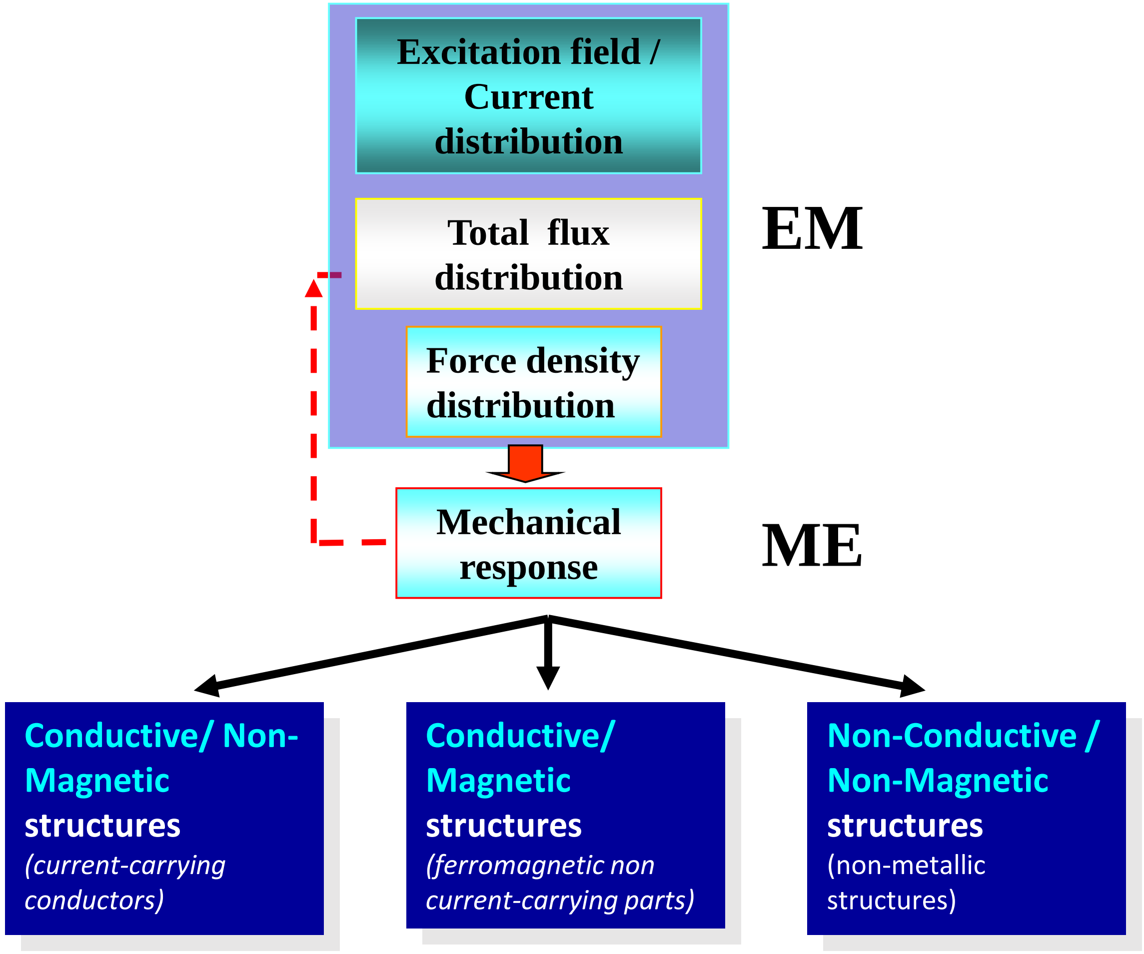


Coupled EM-SM Problems in Engineering Design

Couple EM-SM Design Problems

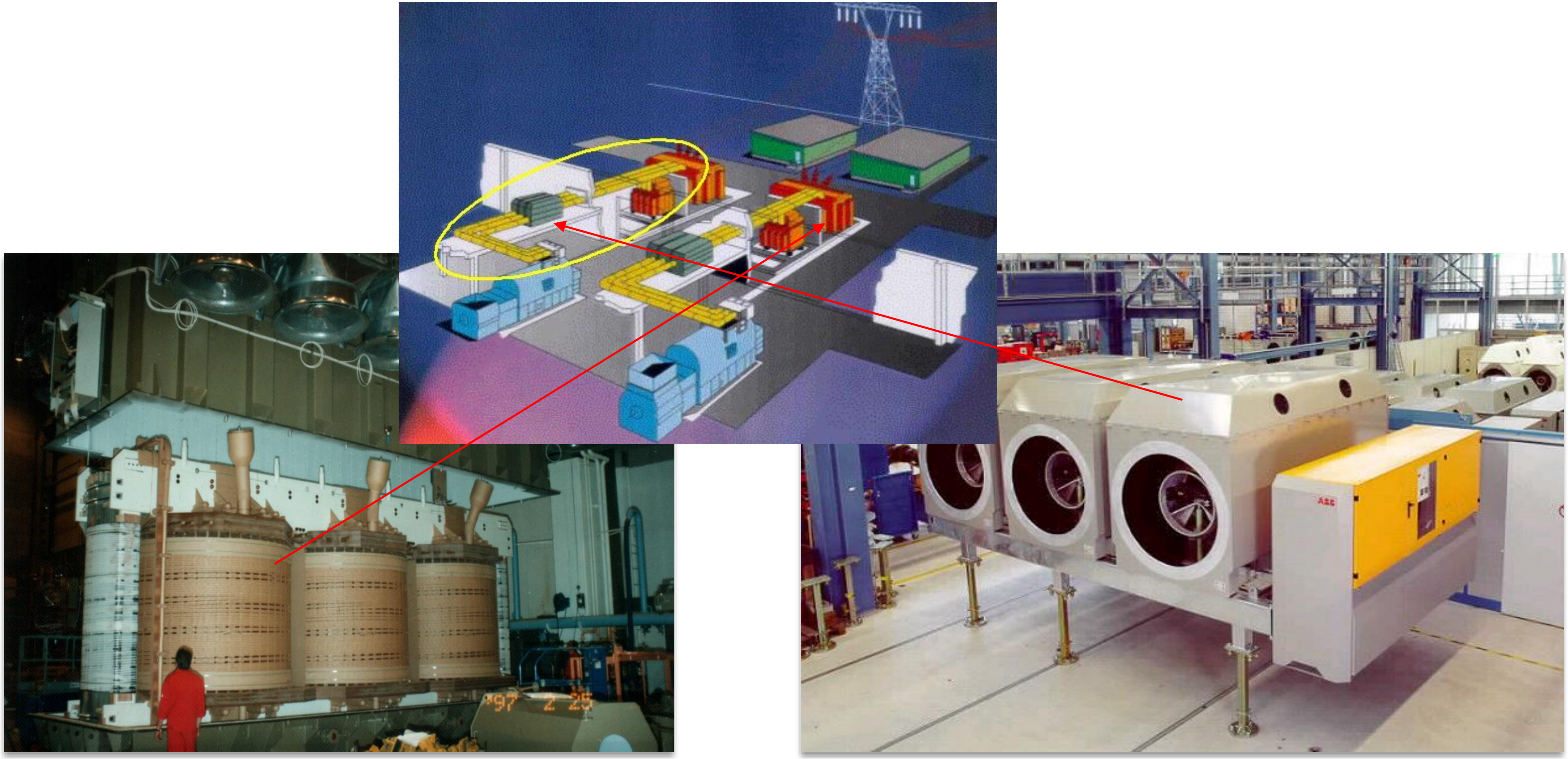




Transformers **Actuators** **Sensors**

Switchgears

Couple EM-SM Problems in Engineering Design



Simulation

Tools

Geometry modeling: **Pro/Engineer**
http://www.ptc.com/

Pre/Post Processing: **CADfix**
http://www.transcendata.com/products/cadfix/

Electro-Magnetic solver: **POLOPT**
http://www.polopt.com

Structural-Mechanic solver: **Abaqus**
https://www.3ds.com/products-services/simulia/

Couple EM-SM Problems in Engineering Design

Key design challenge:

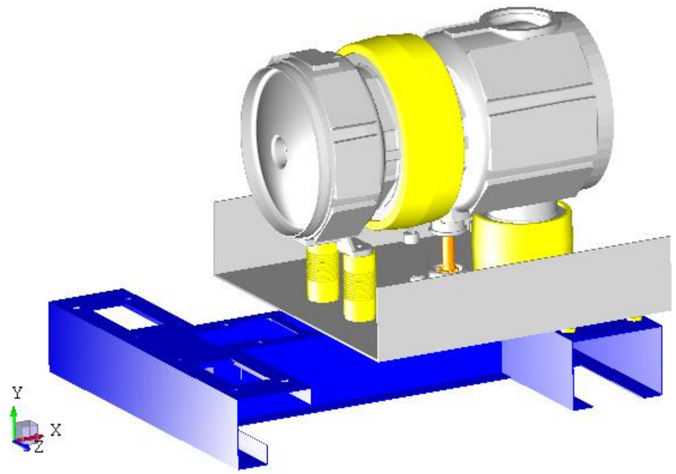
Achieve the most compact design that will:

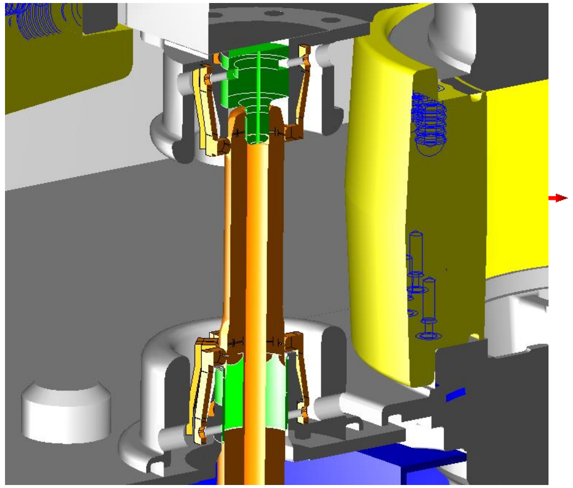
1. Withstand the electrical / mechanical damages caused by:
   1. EM/EM stresses caused by the Short-Circuit appearance,
   2. EM/EM stresses caused by the ON/OFF operations.

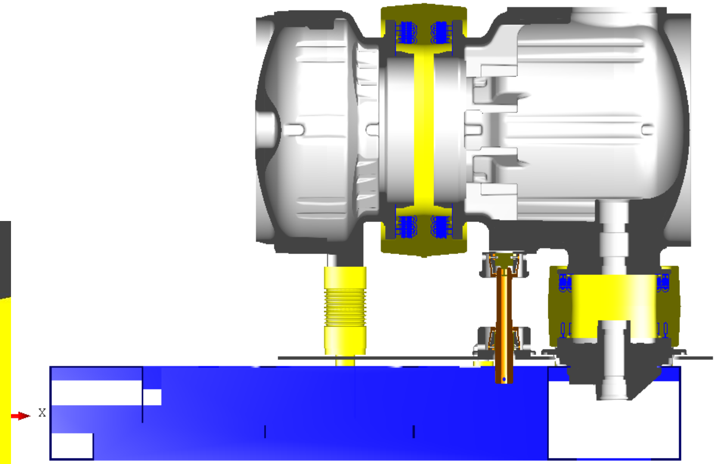
2. Enable the most cost-effective design

Couple EM-SM Problems in SWITCHGEAR DESIGN

The analysis task was to conduct the coupled Electromagnetic / Structural mechanics modelling of the new HEC 170 breaker in order to locate eventual week points in the analyzed design.







Couple EM-SM Problems in SWITCHGEAR DESIGN

Workflow for coupled Electrodynamics - Structural Mechanic Analysis

Electromagnetic

Current density distribution

Flux density distribution

↓

Force density distribution

↓

Structural Mechanics

Mechanical displacements

Von Misses Stresses

↓

Yield Tensile Stress Analysis

Tools used for the analysis

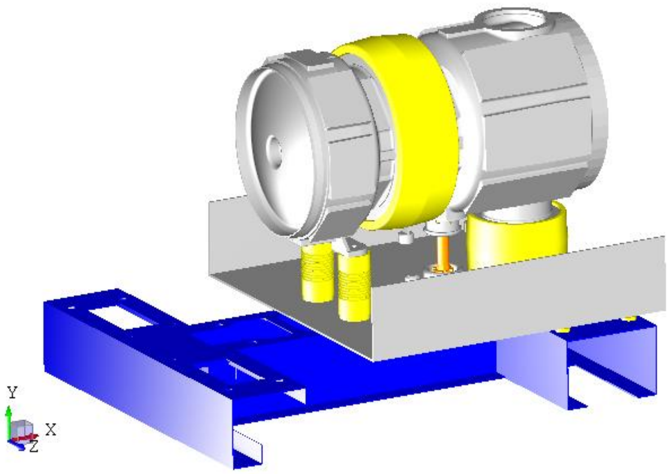
CAD Modelling	Pro/Engineer	www.ptc.com
EM pre-post processing	CADfix	www.transcendata.com
EM analysis	POLOPT	www.polopt.com
ME pre-post processing	CADfix	www.transcendata.com
ME analysis	Abaqus	www.3ds.com

Couple EM-SM Problems in SWITCHGEAR DESIGN

CAD Model

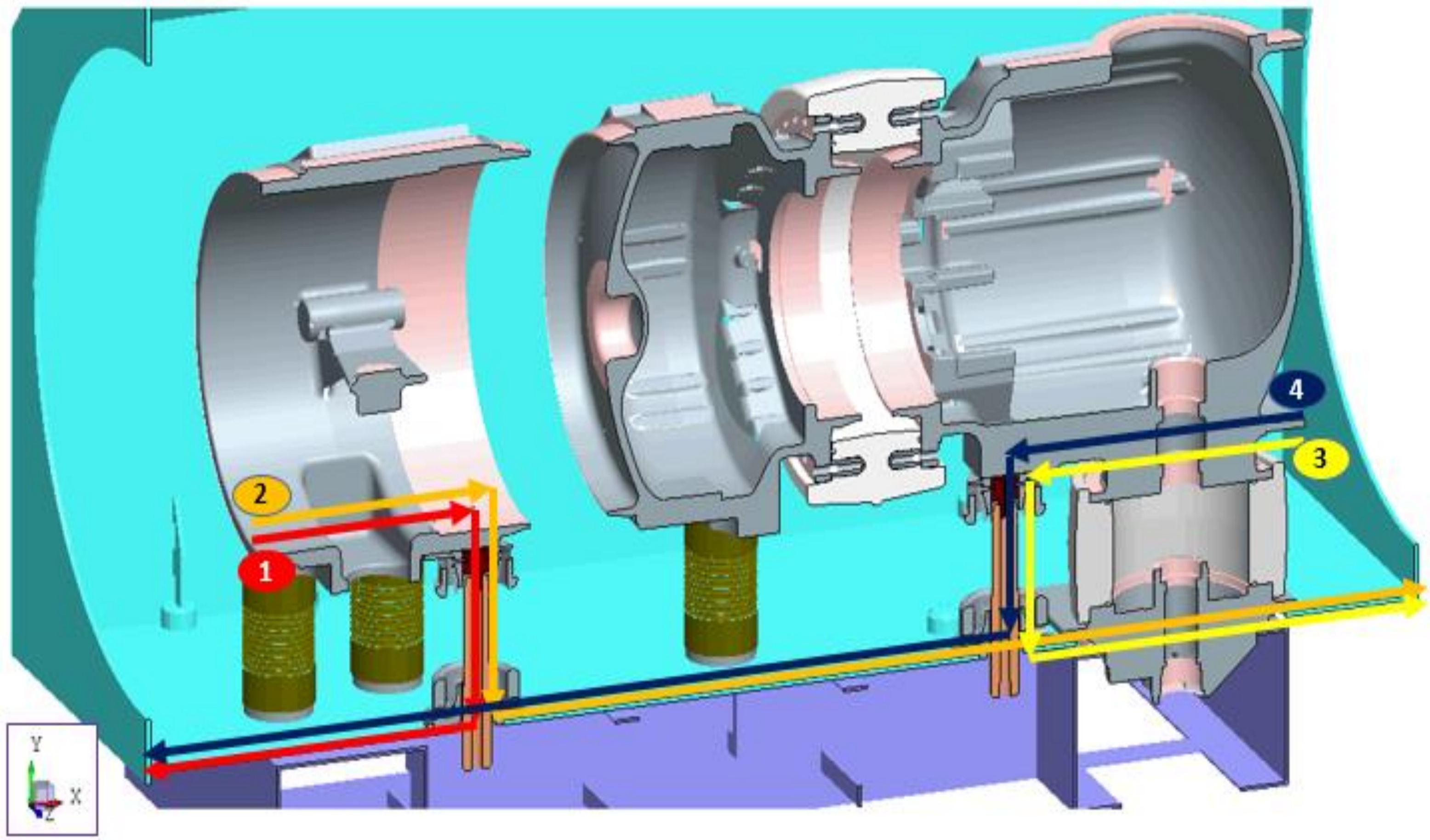
- **Two separated models had to be estabilished**
- **Main differences between the models:**

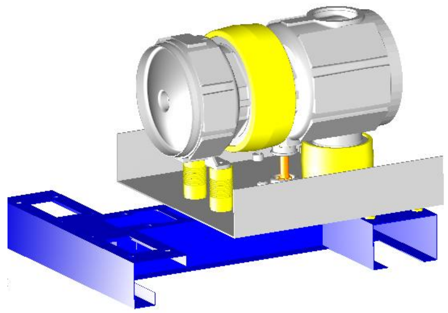
1. Way of defining the contacts between the separate parts / components in the entire model (for example in EM part these must be "conducting" contacts between the metal components providing the current path; in ME modelling these are either "tie" or "moving contacts")
2. Defining the loads
3. Meshing
4. Materials



Loading current	kA
Short-term withstand current	170
Peak withstand current	470

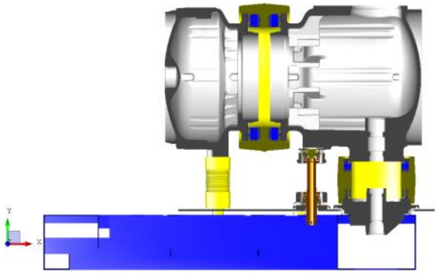
Couple EM-SM Problems in SWITCHGEAR DESIGN



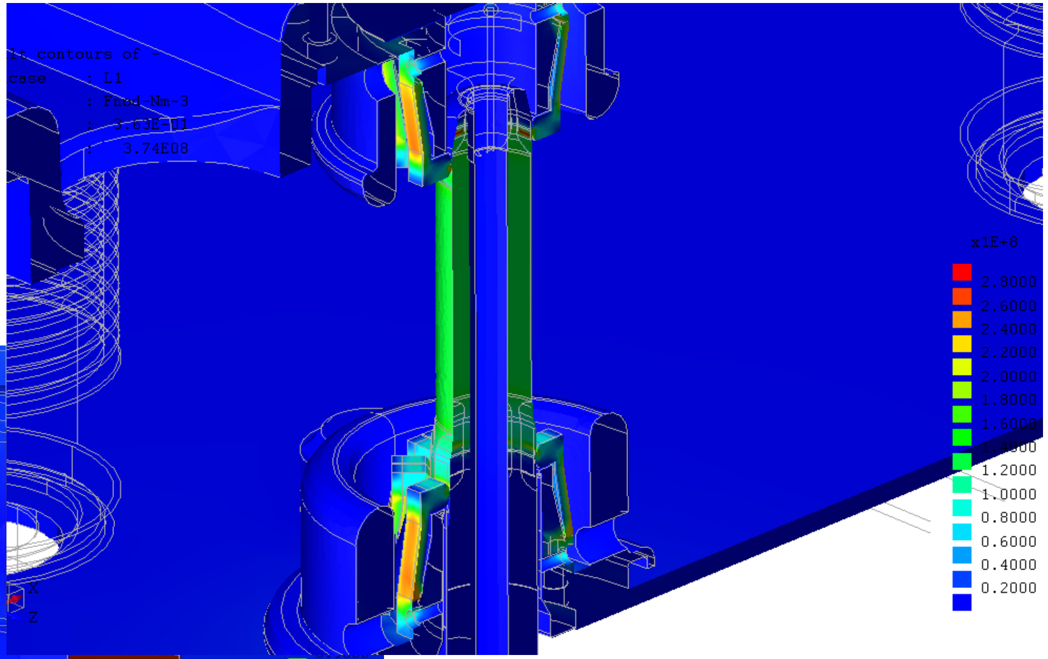


Pro/E model with the analyzed current paths 1, 2, 3 and 4.

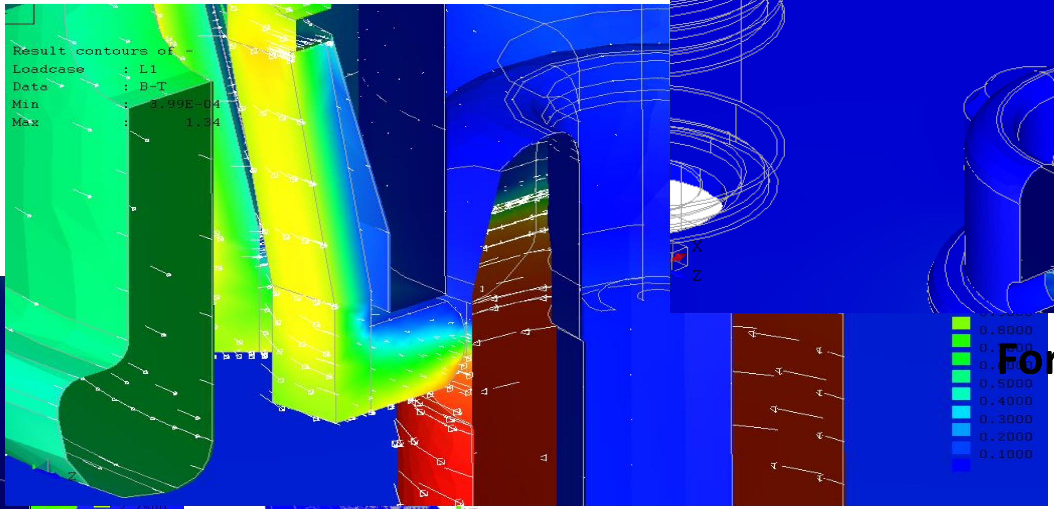
Couple EM-SM Problems in SWITCHGEAR DESIGN

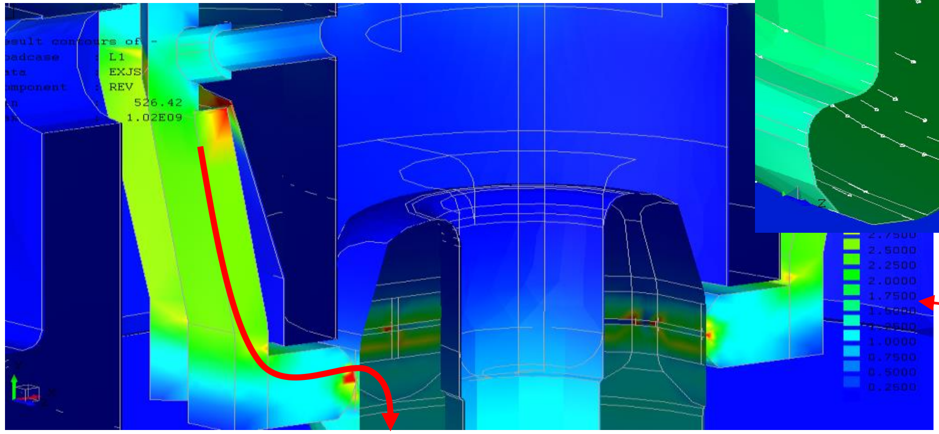


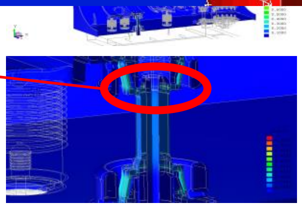
Loading current	kA
Short-term withstand current	170
Peak withstand current	470



Force density distribution F [N/m³]



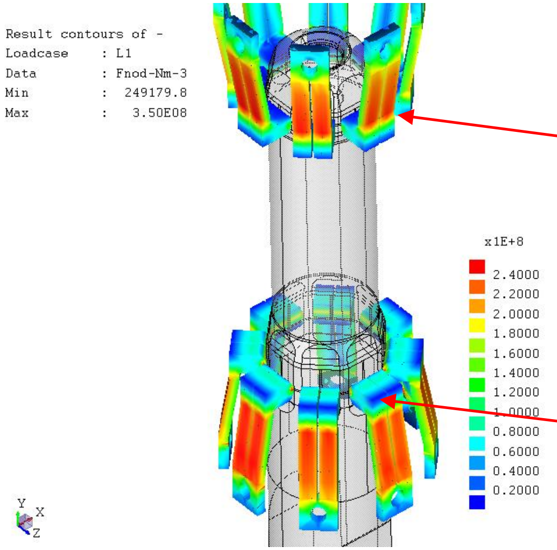


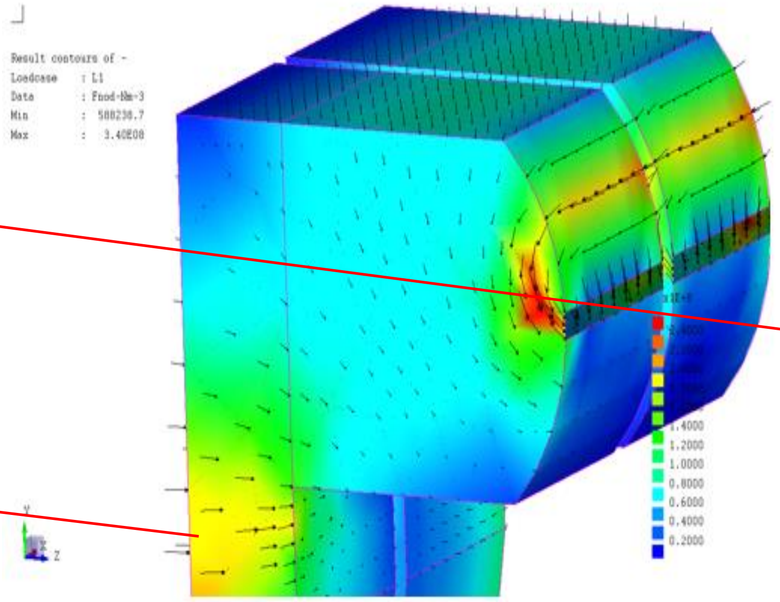


Current distribution J[A/m²]

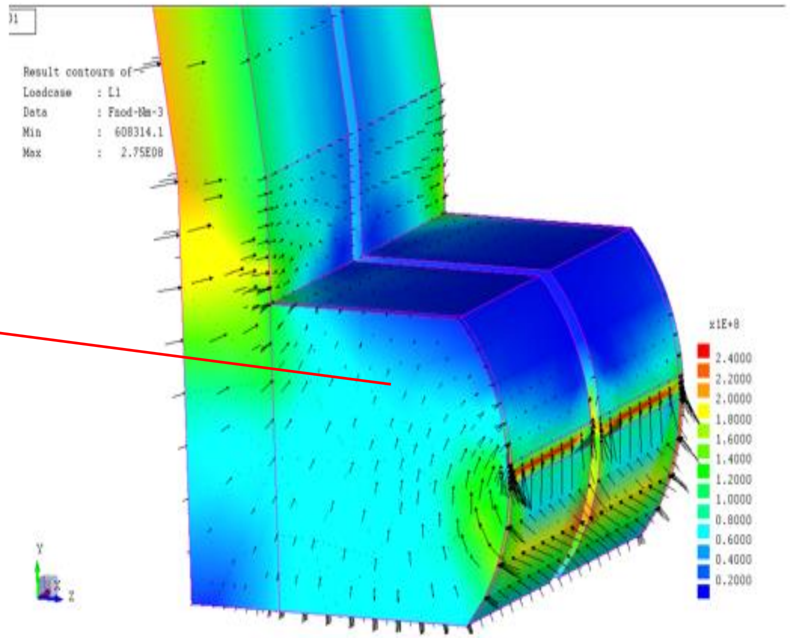
Flux density distribution B[T]. Maximal flux density B_{max} = 1.34 [T]

Couple EM-SM Problems in SWITCHGEAR DESIGN





Force vectors flow on the lower set of fingers



Force vectors flow on the upper set of fingers

Couple EM-SM Problems in SWITCHGEAR DESIGN

Additional Test 1: Model without Tank

With tank

Short-term withstand current 170kA

	Fx	Fy	Fz	F[N]
CP1	2.50E+02	-2.15E+02	3.95E+02	5.15E+02
CP2	3.02E+02	1.37E+03	1.57E+03	2.11E+03
CP3	-1.61E+03	2.35E+03	-1.52E+02	2.85E+03
CP4	-1.44E+03	3.12E+03	-6.24E+02	3.49E+03

Peak withstand current 470kA

	Fx	Fy	Fz	F[N]
CP1	1.92E+03	-1.65E+03	3.03E+03	3.95E+03
CP2	2.31E+03	1.05E+04	1.21E+04	1.62E+04
CP3	-1.24E+04	1.80E+04	-1.17E+03	2.19E+04
CP4	-1.10E+04	2.40E+04	-4.79E+03	2.68E+04

Without tank

	F[N]
CP1	
CP2	*4.04E+03*
CP3	
CP4	5.01E+03

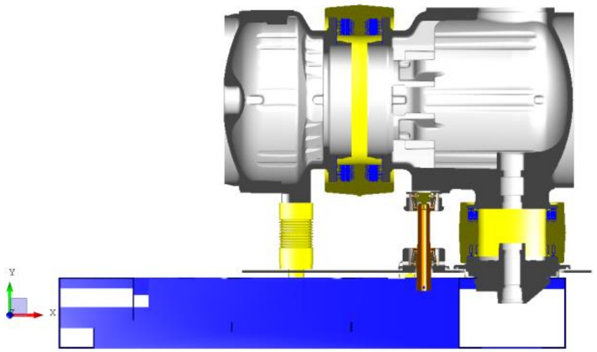
	F[N]
CP1	
CP2	3.10E+04
CP3	
CP4	3.84E+04

The cumulative forces in the case without tank are for around 43% higher than in the case with the tank; i.e. the tank contributes to a kind of force reduction for 43%.

Couple EM-SM Problems in SWITCHGEAR DESIGN

Couple EM-SM Problems in SWITCHGEAR DESIGN

Mechanical Model



Contact definitions

As the first approximation, we have used in the mechanical model the following assumptions:

1. All components connected with the screws are simulated as the "**tie**" contact. In such type of contacts, the contact surfaces do not move from each other.

1. The real "**moving contacts**" are simulated at all other positions where the different components (geometrical parts) come into the contacts. These are the following contacts:
   a) Contacts between the upper and lower contact fingers and the moving bolt (32 contact positions),
   b) Contact between the moving bolt and centering components, (ceramic parts)
   c) Contact surfaces between the breaking chamber and earthing structure. These two components are kept fix via the eight screws. Forces acting on those screws are discussed in Forces between the breaking chamber and earthing knife.

In computational mechanics, the treatment of the **contact problems** can be considered as the **nonlinear minimization problem**, requiring special care in the contact definitions and typically resulting in a long computation time.

Couple EM-SM Problems in SWITCHGEAR DESIGN

Mechanical Model

Materials

The material data used for the mechanical run are given in Table 6.

Material	E-module [N/mm2] or [MPa]	n	Density r [kg/mm3]	Yield stress [MPa]
Al	73000	0.3	8.85E-09	200-400
Cu (99.9% Cu)	117000	0.3	7.85E-09	70
Steel (mild 1090)	200000	0.3	7.86E-09	248
Epoxy Resin	8600	0.3	1.85E-09	40

Loading

The load for the mechanical run are the electromagnetic force densities calculated in the previous step. As the meshes in the EM and ME model must not be compatible, a special procedures is used for **the interpolation of the EM forces on the ME mesh.**

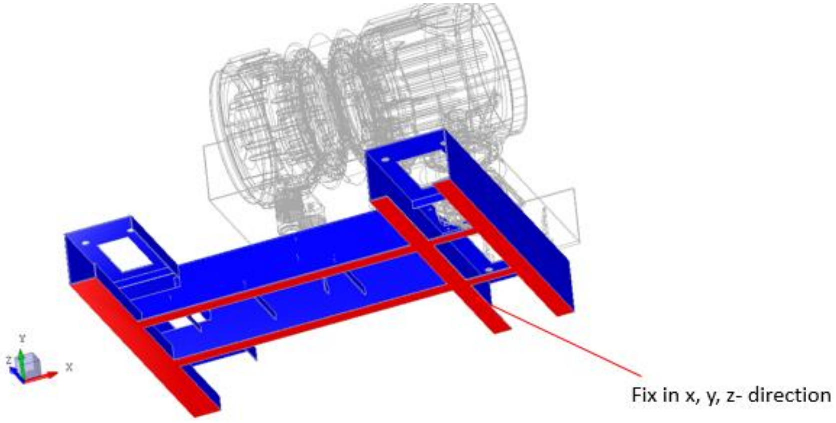
Friction

The friction between different materials is taken into account. The following friction parameters have been used:

- For Cu-Cu: f=1.0
- For Al-Al: f=1.04 (http://de.wikipedia.org/wiki/Reibungskoeffizient)
- For Cu-PTFE f=0.04 (http://de.wikipedia.org/wiki/Reibungskoeffizient)

Couple EM-SM Problems in SWITCHGEAR DESIGN

Mechanical Model



Constraints

Two constraints are employed in the model:

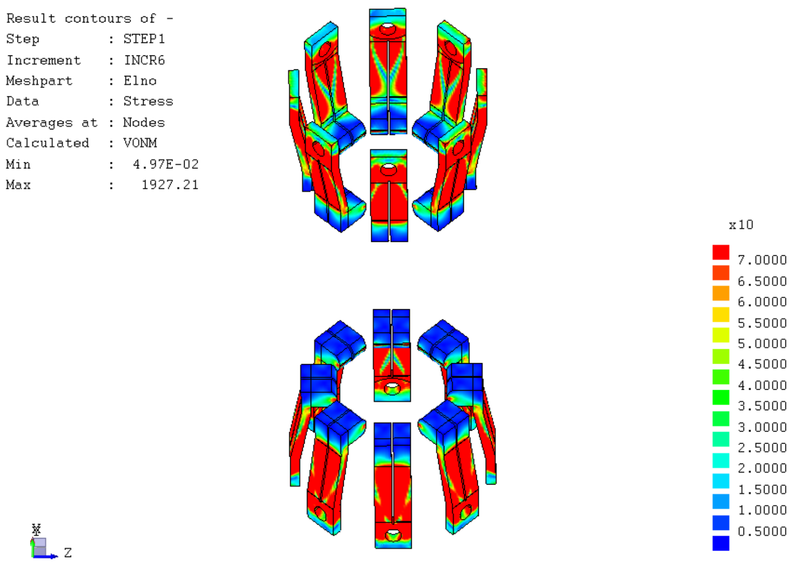
1. Firstly, the model is constraint in all three directions at the bottom of steel basement (shown in red in Figure 43).

1. Additionally, one more constraint is added at the end of the moving bolt. The bolt can move around the rotational axis going through the center of the fixing hole at the bottom of the bolt

Couple EM-SM Problems in SWITCHGEAR DESIGN

Some results:

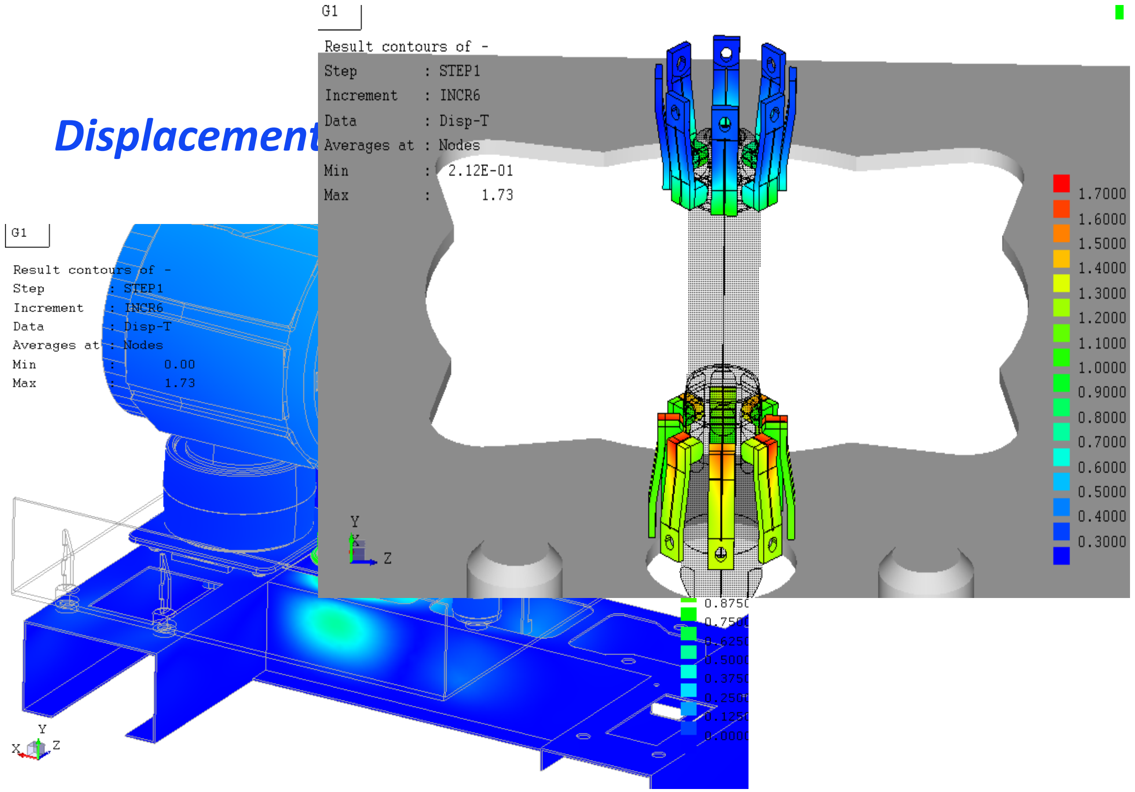
Von Misses Stress Analysis



Von Misses stress [MPa]on Cu parts.

Maximal calculated stress on Cu components is **1927 MPa**

Displacement



Displacement of the overall model

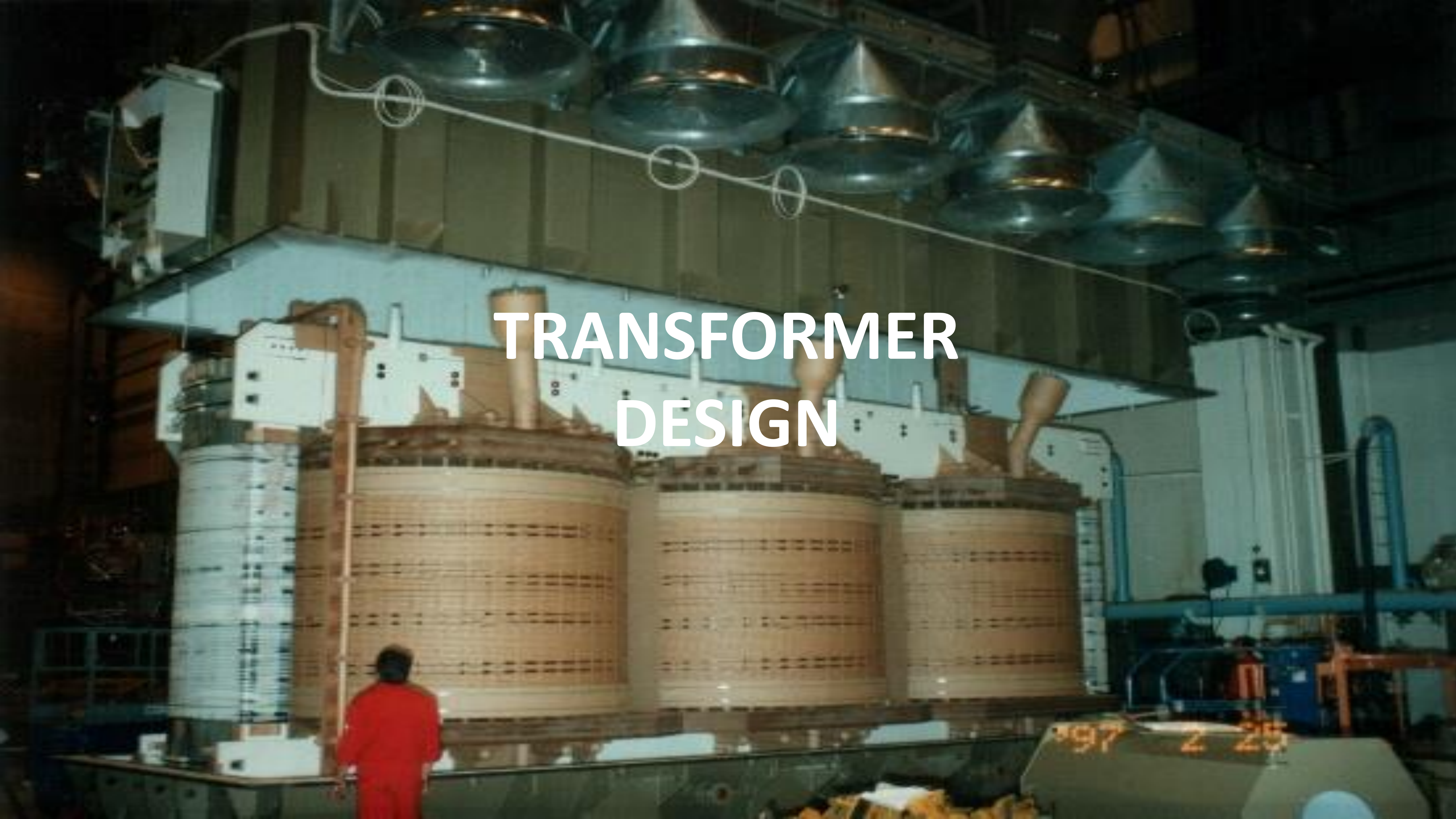
Maximal displacement is **9.7**mm

Couple EM-SM Problems in SWITCHGEAR DESIGN

Concluding remarks:

1. **The above analysis has shown that the currently realized design of HEC 170 would sustain the possible stresses caused by the peak withstand current of 470kA as:**
   - Calculated **stresses** are in the acceptable range for all Al-made components (tank, breaking chamber, earthing heads), Fe-made components (basement), see discussion in Stress on Al-made components.
   - The only exception are the stresses appearing on the contact fingers (see discussion in Stress on Cu-made parts).
   - Same yields for the calculated **displacement**, whereby the displacement is also for Cu-made parts (contact fingers, moving bolt) in the acceptable range (see more in Fingers displacement).
   - Calculated **forces** acting on the screws between the breaking chamber and the earthing structure are in the range of **100-300[N]**.
2. **The generally good "behavior" of the structure is mostly achieve through the overall "symmetry" of the model.** The design is almost symmetrical with respect to the z=0 plane. Thanks to this "symmetricity" the EM forces compensate each other what leads to much lower stresses and displacements of the whole structure.
3. **Some small improvements could be possibly achieved by:**
   - **Additional re-enforcement of the steel basement**
   - **Choice of more stiff material for the centering components**. According to Stress on PET-made Centering Components, maximal stress on both lower and upper centering part is above the yield value (55MPa).

TRANSFORMER DESIGN



TRANSFORMER DESIGN

EM/EM stresses caused by the Short-Circuit (SC) appearance

- We should distinguish between the
  - **Short-circuit current**
  - **Inrush current** (encountered during the switching process of the transformer)

- During the SC conditions, high currents flow in both primary and secondary winging

- During the ON/OFF switching, the secondary winding might be open circuited, and thus, totally unloaded!

TRANSFORMER DESIGN

EM/EM stresses caused by the Short-Circuit (SC) appearance

- When a fault occurs on the load side of a transformer, the **fault current** will pass through the transformer.
- As components on these systems, transformers need to be **able to withstand** these fault currents.
- Fault currents flowing through transformers are **significantly higher** than the **rated currents** of the transformers.
- **In the worst case**, the current would be as high as the current that would flow if system voltage was applied to the primary terminals **while the secondary terminals are shorted** – limited by the transformer impedance only.
- These currents produce both **mechanical** and **thermal** stresses in the transformers.

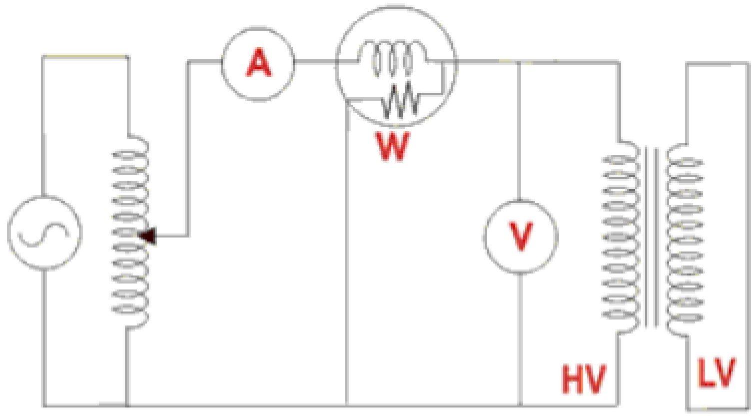
TRANSFORMER DESIGN

EM/EM stresses caused by the Short-Circuit (SC) appearance

Each new transformer type has to be tested against the SC!

Short Circuit Test on Transformer

Applied voltage is slowly increased until the ammeter gives reading equal to the rated current of the HV side

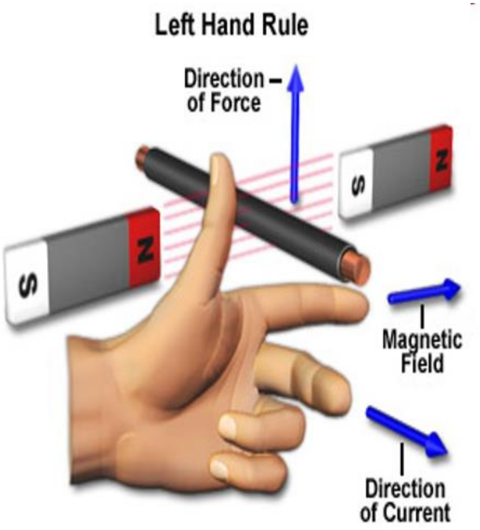


TRANSFORMER DESIGN

EM/EM stresses caused by the Short-Circuit (SC) appearance

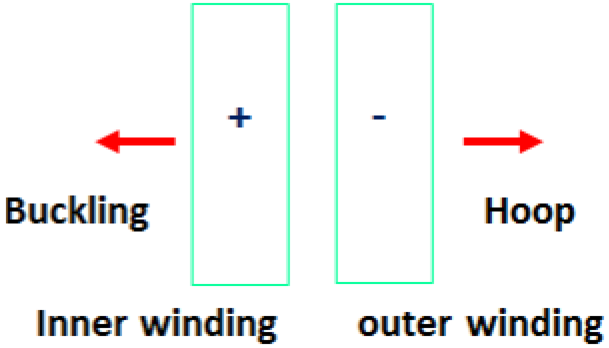
Short-circuit Design

Current carrying conductors in a magnetic field experience force in accordance with Fleming's left hand rule.



- **Axial flux produces radial force** and **radial flux produces axial force**
- Conductors are **attracted** to each other when **currents are in same direction**
- Conductors are **pushed away** from each other when currents are **in opposite direction**
- **Force is proportional to square of current**

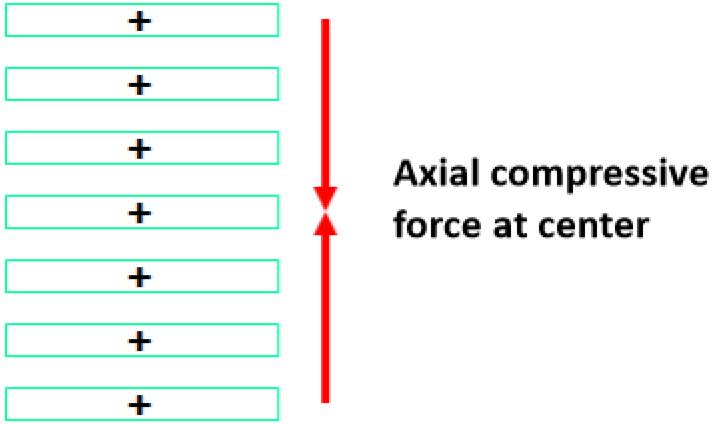
TRANSFORMER DESIGN



Stresses due to radial forces

- Hoop stress in outer winding
- Buckling stress in inner winding

Supported buckling and free buckling



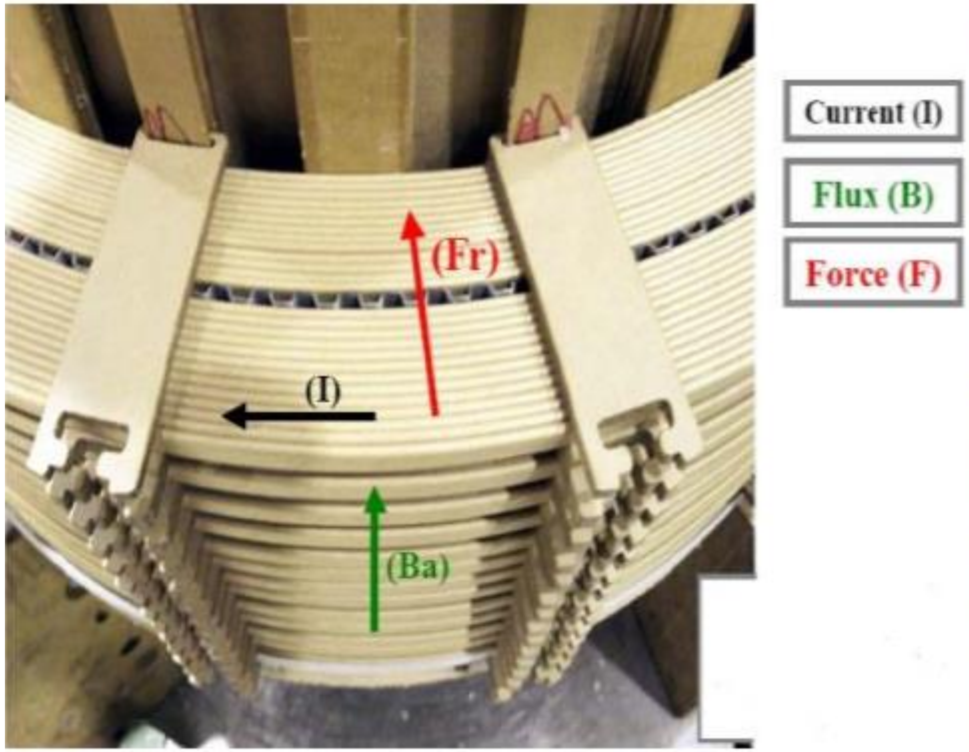
Stresses due to axial forces

- Compressive stress on key spacers
- Tilting of conductors
- Axial bending between key spacers

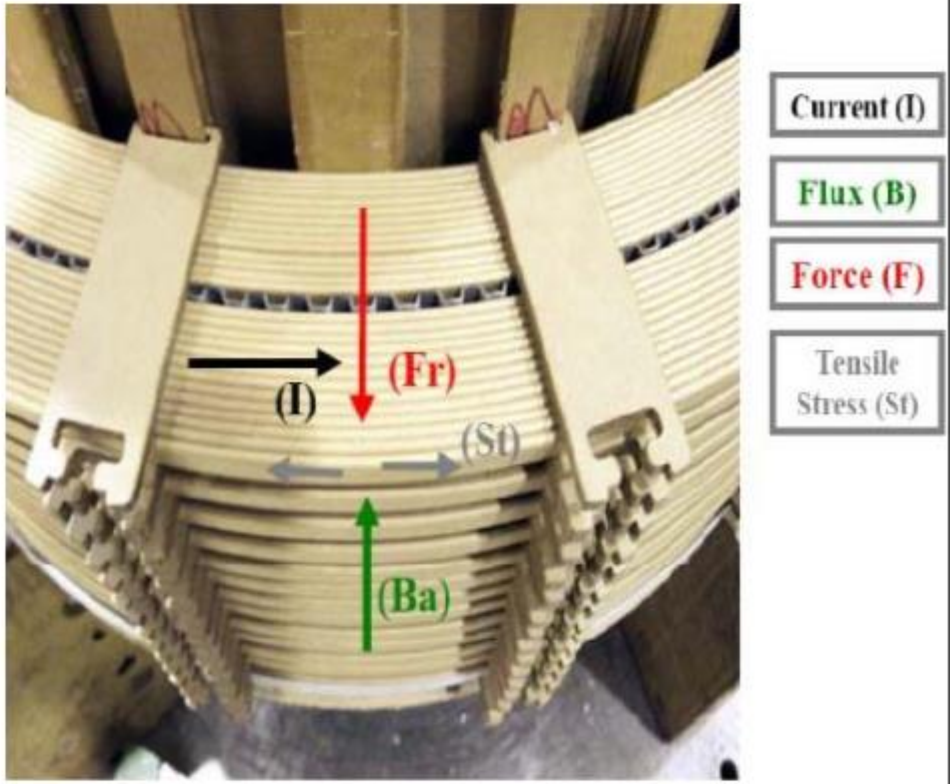
TRANSFORMER DESIGN

Radial Forces

Buckling



Hoop



TRANSFORMER DESIGN

Buckling

Hoop

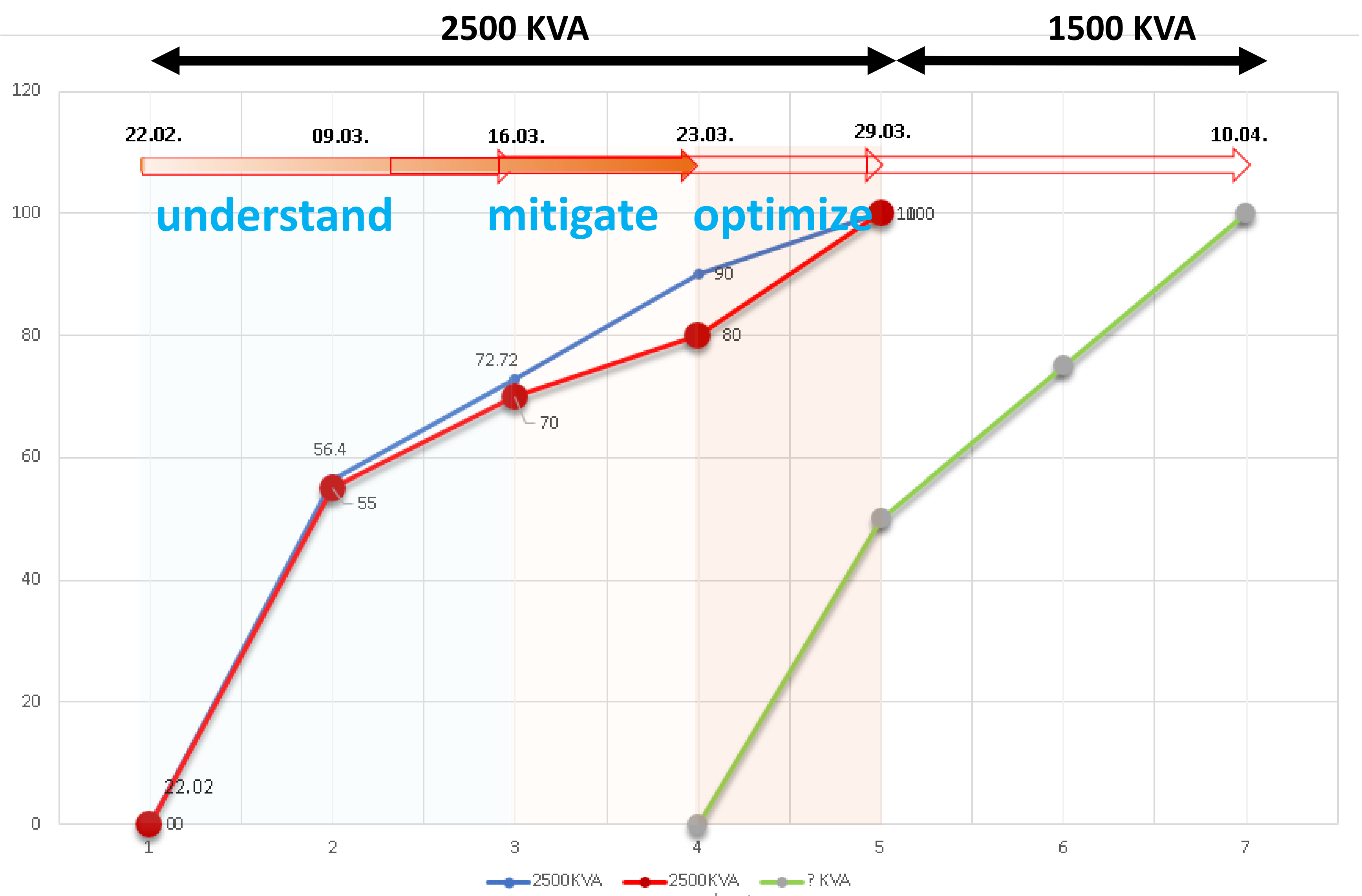
2500 kVA
Distribution Transformer

2500 kVA Distribution Transformer

Project task:

- Find out why the transformer tank is cracking
- Propose the solution that resolves the observed problems

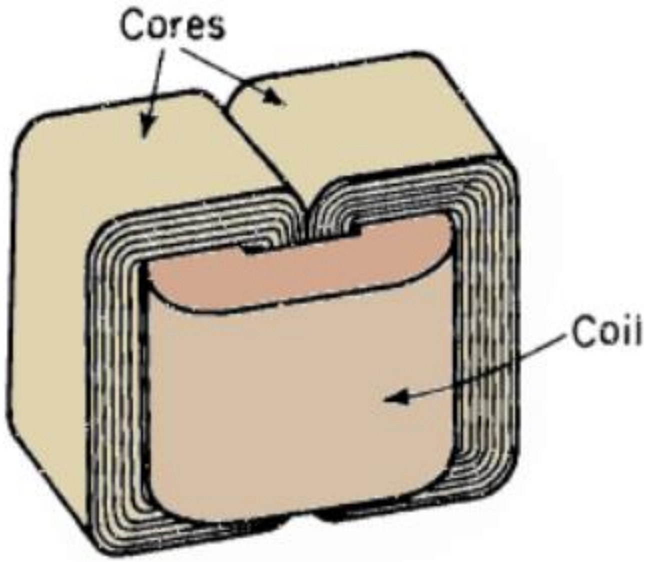
Project Roadmap



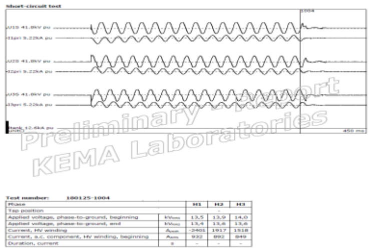
Some design specificums

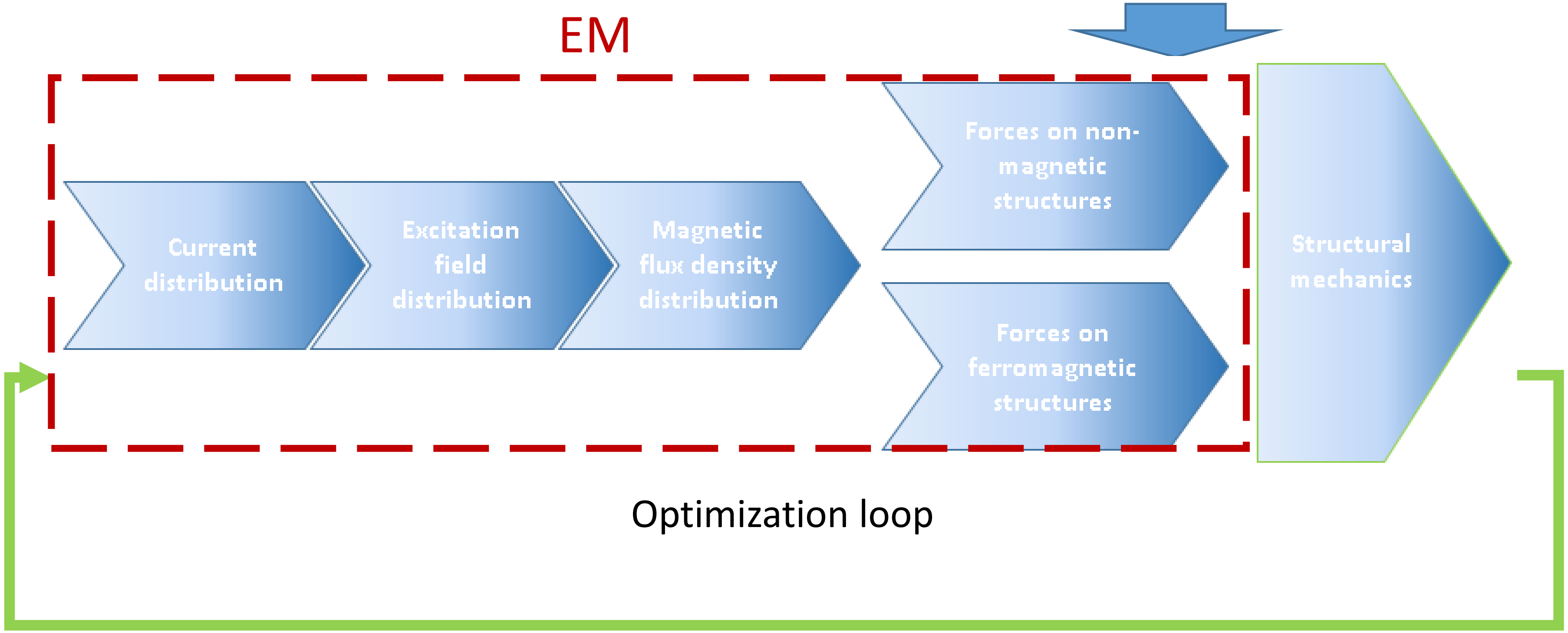
Stacked-type core

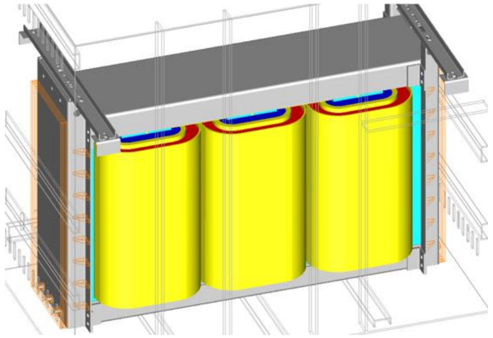
Wounded-type core



Workflow of the EM-SM Analysis







Input data:

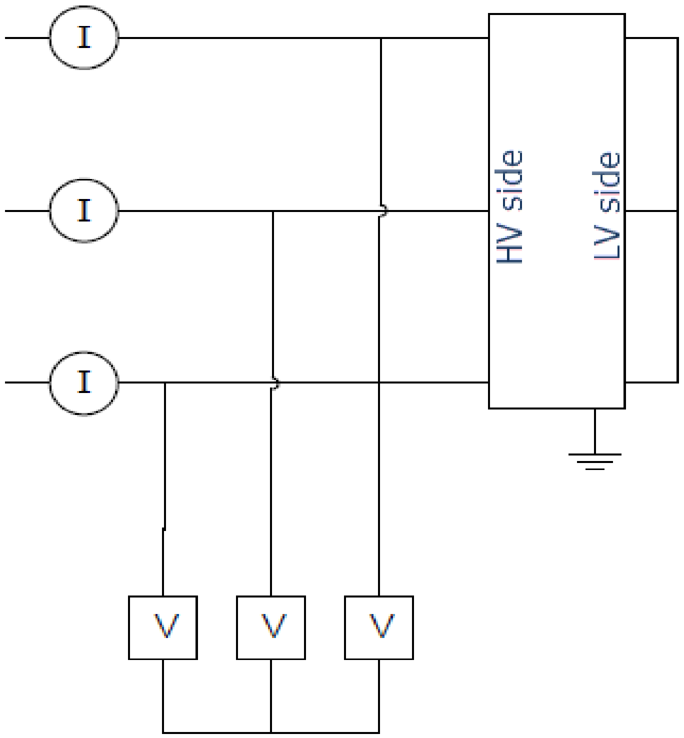
Tested transformer parameters

Transformer power (kVA)	2500
Frequency (Hz)	60
Number of phases	3

	HV	LV
Coil voltage (kV)	14.4	0.48
Connection	Y	Y
Tap position	N/A	N/A

Short circuit test parameters

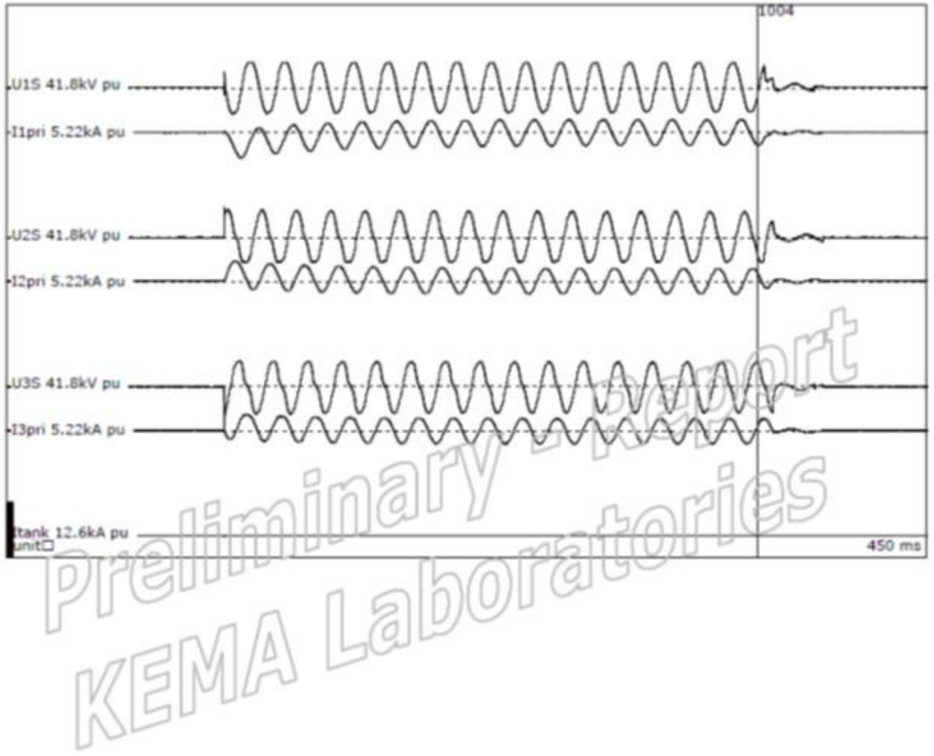
Short circuit test transformer category	II
Rated current (A)	57.87
Impedance (%)	6.16
Resistance (Ω)	15.35
Reactance (Ω)	1.27
HV short circuit current Isc (A)	939.45
K	1.414
Asymmetrical current Ipeak (A)	1328.59



Input data:

- Oscillographs for each of 6 shoots

Short-circuit test

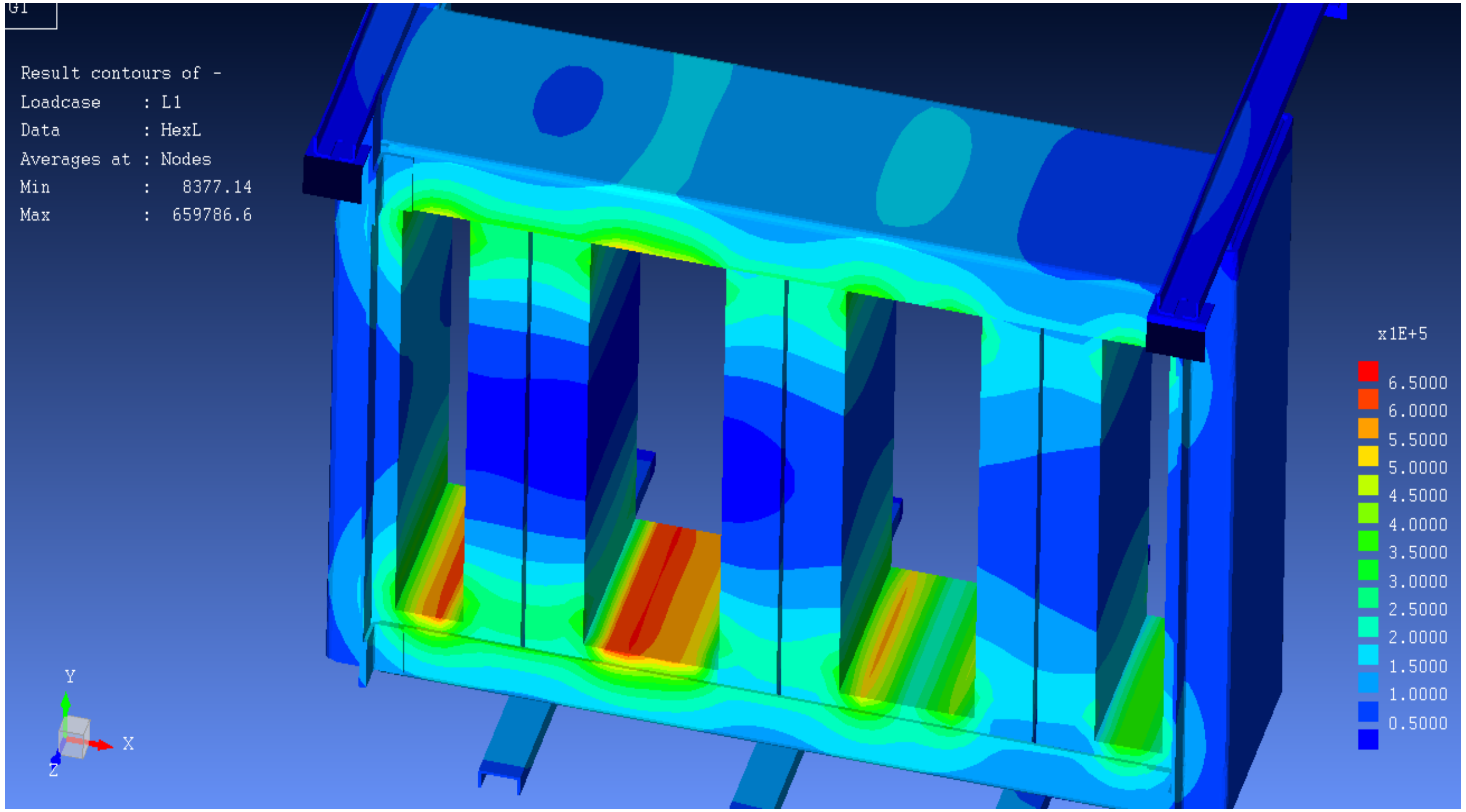


Test number: 180125-1004

Phase		H1	H2	H3
Tap position			-	
Applied voltage, phase-to-ground, beginning	kV_{RMS}	13,5	13,9	14,0
Applied voltage, phase-to-ground, end	kV_{RMS}	13,4	13,6	13,6
Current, HV winding	A_{peak}	-2401	1917	1518
Current, a.c. component, HV winding, beginning	A_{RMS}	932	892	849
Duration, current	s	-	-	-

Some results

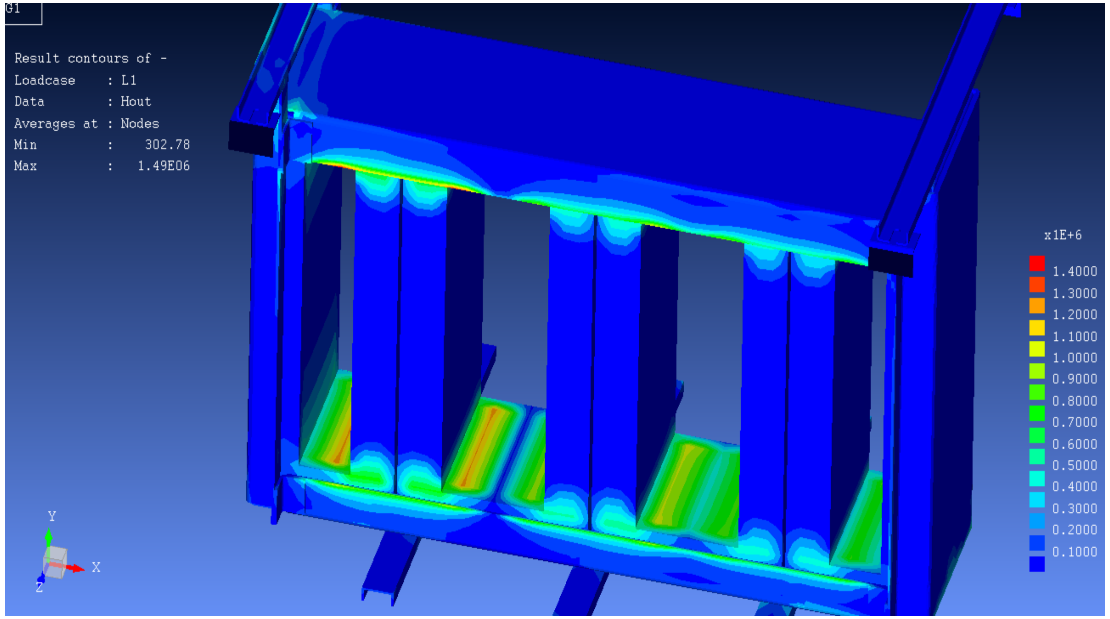
Fig. a) shows the distribution of the excitation field over the ferromagnetic structures (tank notshown).



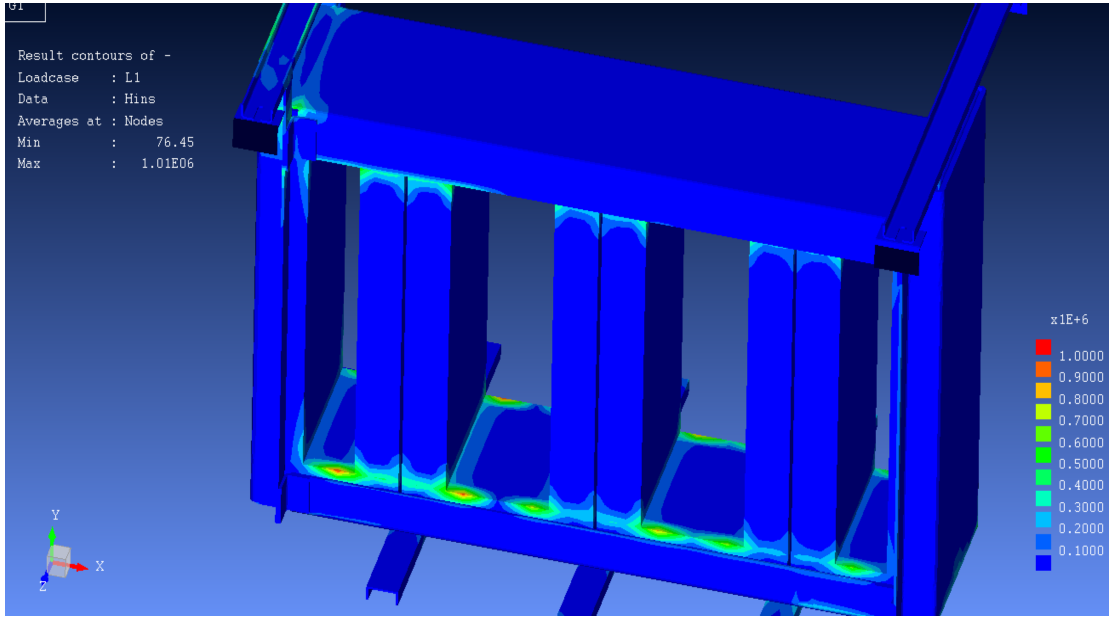
a.) Excitation magnetic field H[A/m]; SC on R-phase

Some results

Fig. b.) and c.) distribution of the magnetic field H outside and inside of the core
(all figures for the case when SC happens on the R-phase (USA A-phase);

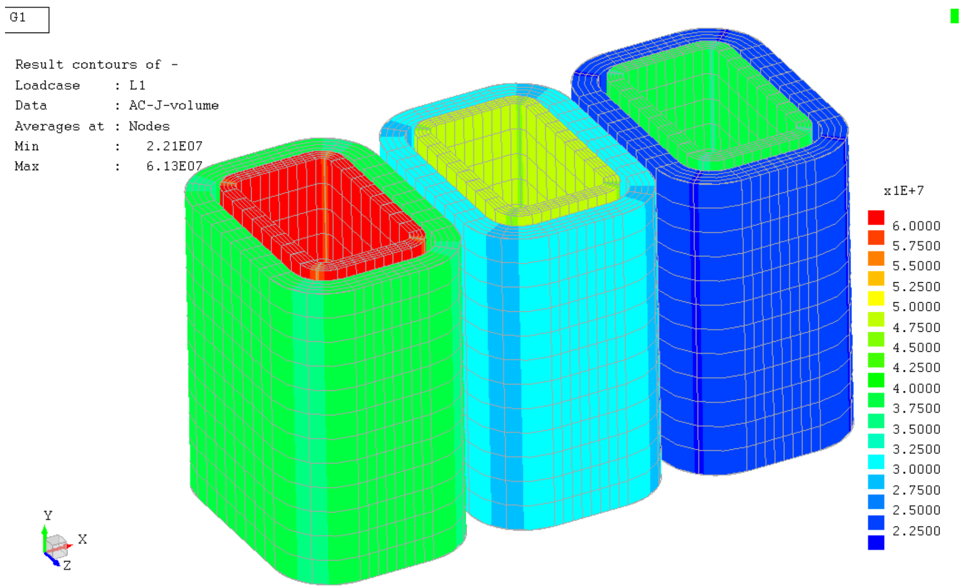


b.) Magnetic field H[A/m] (outside)



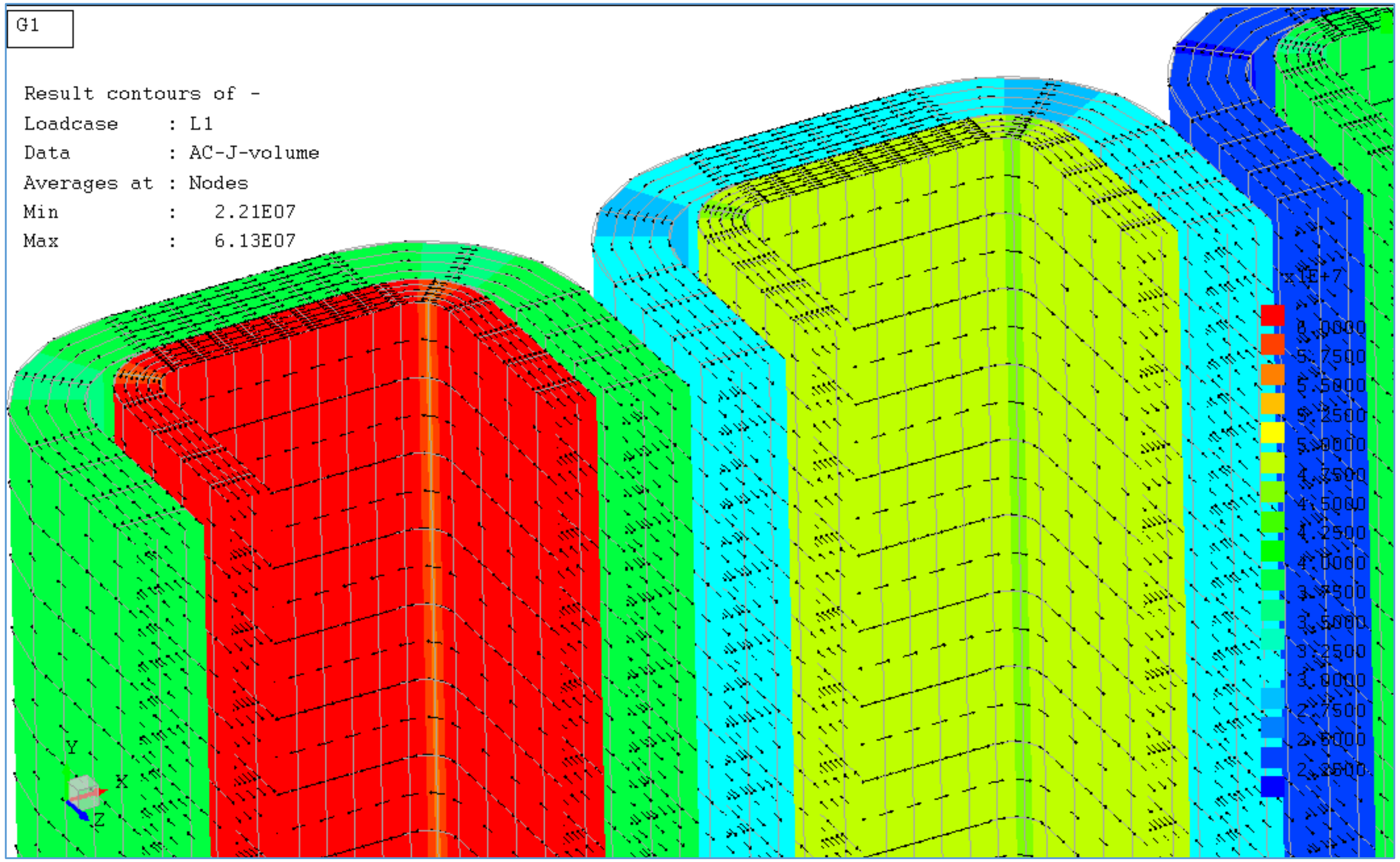
c.) Magnetic field H[A/m] (inside)

WINDINGS: Current density distribution in the windings (SC on R-phase)

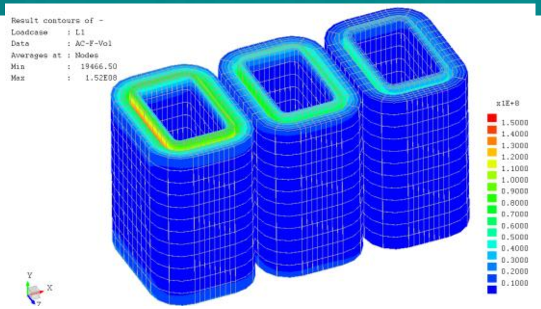


Current density distribution J[A/m3]

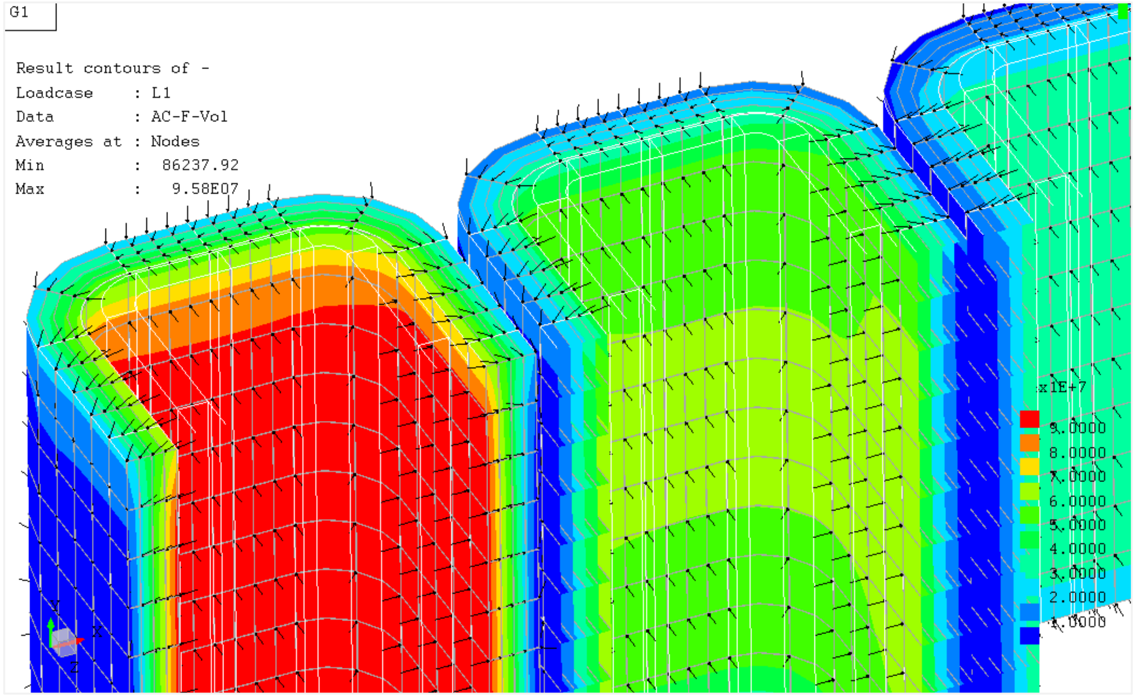
$I_1N_1=I_2N_2$ - is it preserved?



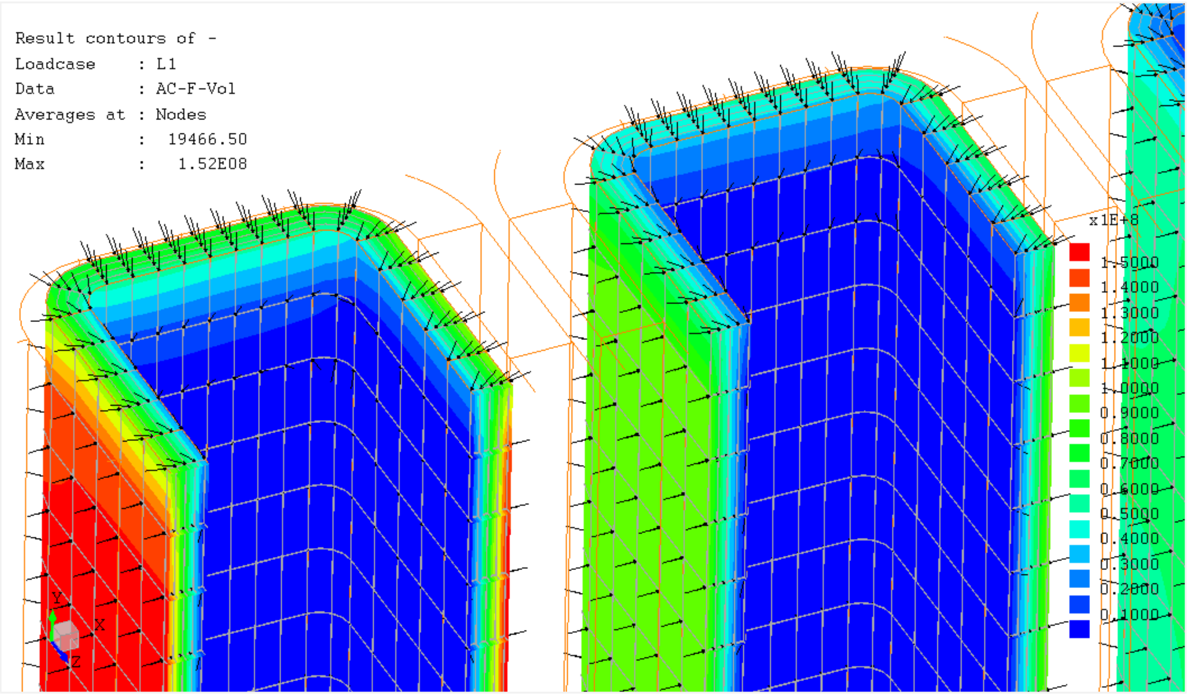
Current density distribution J[A/m3]
Cut view, with the current vector flow



WINDINGS: Force density distribution in the windings (SC on R-phase)



Force density distribution F[N/m3] on the **HV winding**, (averaged in nodes)
Cut view, with the force vector flow



Force density distribution F[N/m3] on the **LV winding**, (averaged in nodes)
Cut view, with the force vector flow

- Current and force graph during the SC test (the shown case corresponds to the test case No. 1004 given in the document “Short Circuit test data”

- Forces oscillate with double frequency to current!

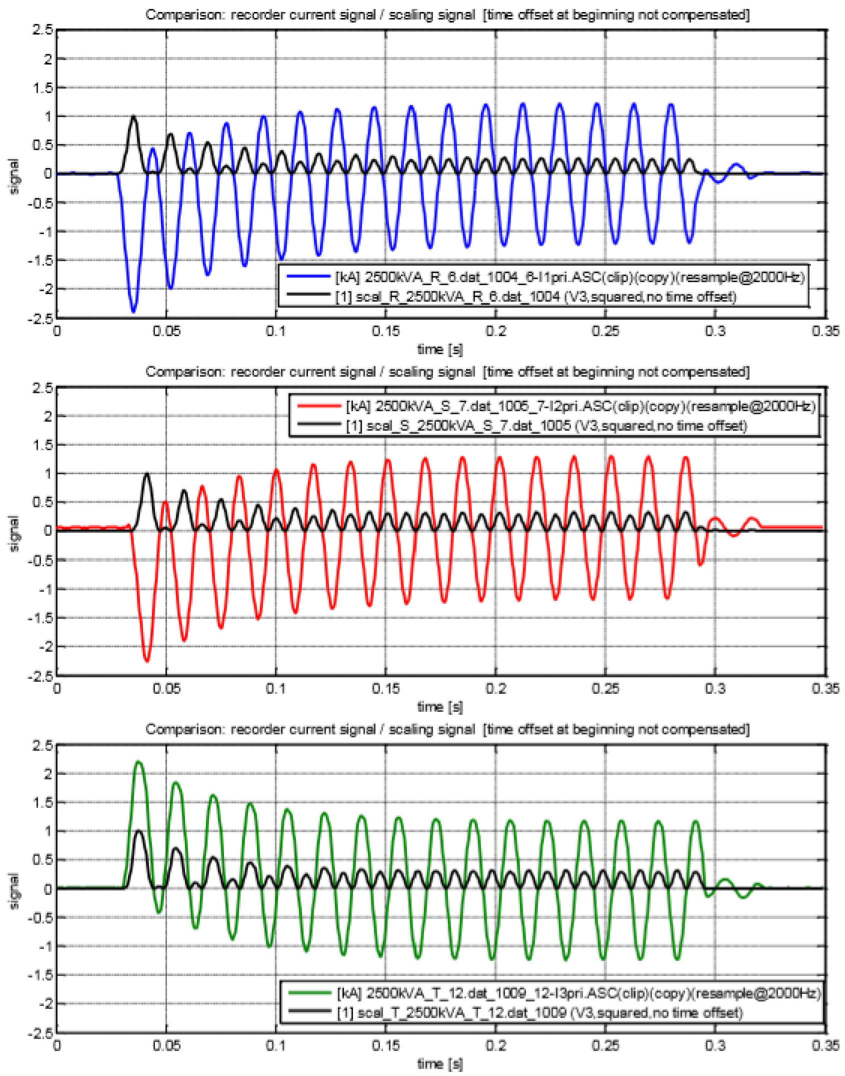
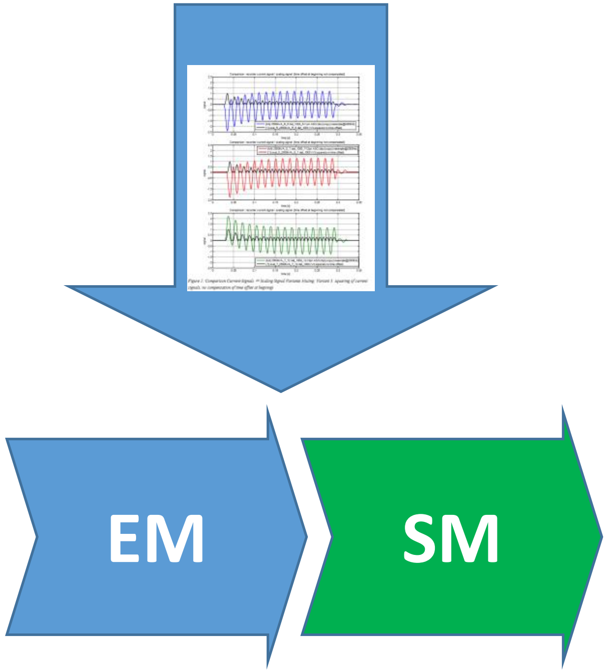
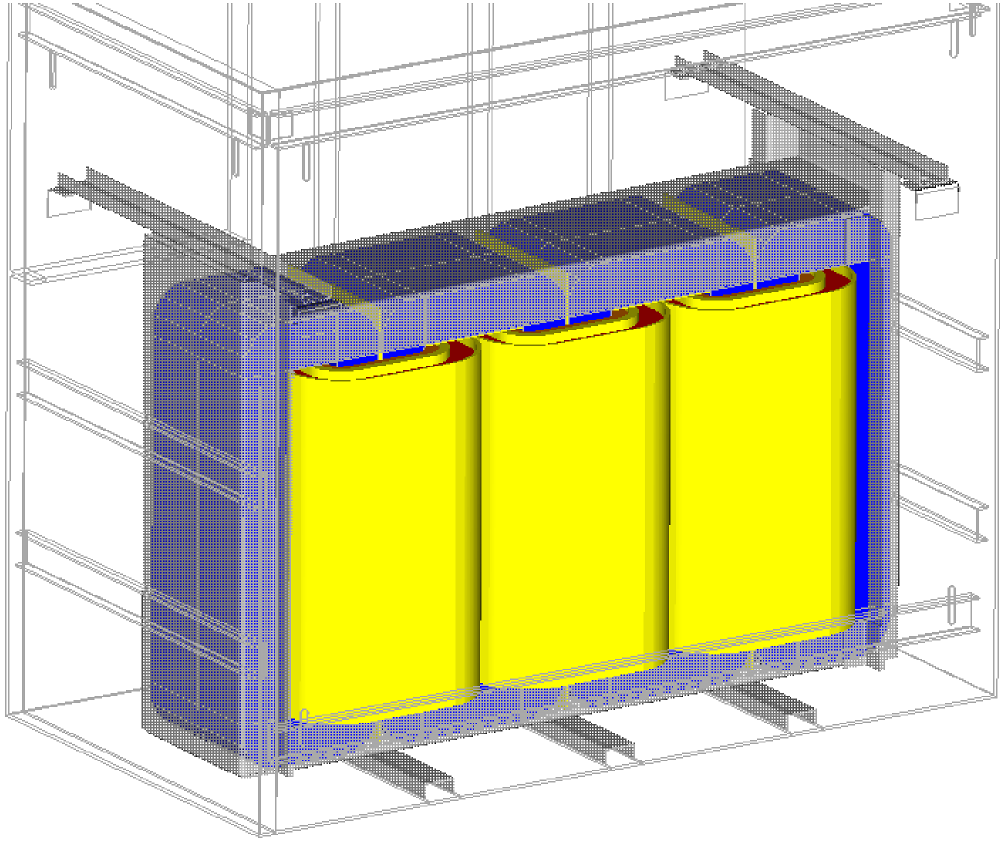
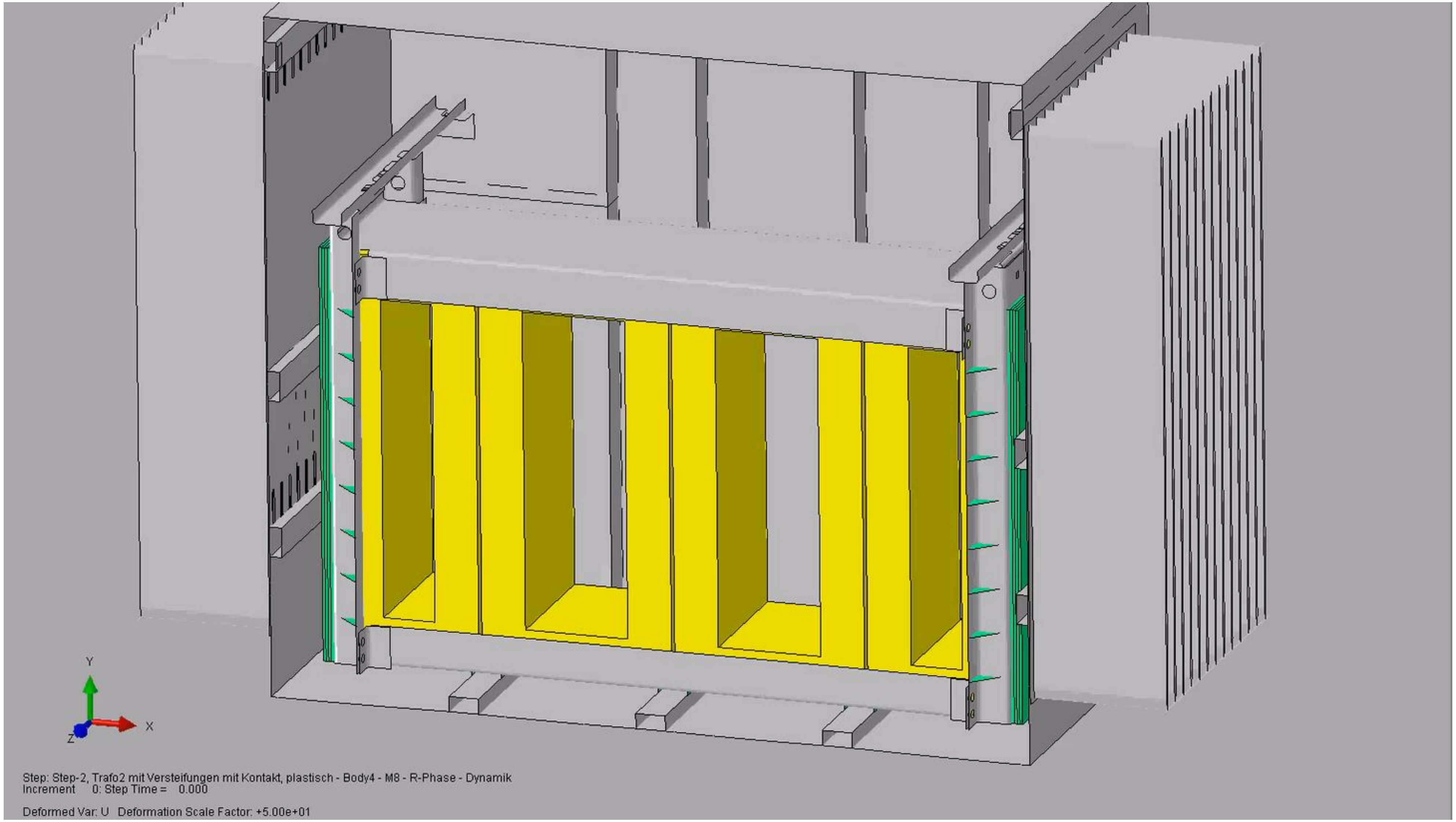


Figure 1: Comparison Current-Signals ⇔ Scaling Signal Variante 3(using: Variant 3: squaring of current signals, no compensation of time offset at beginng)

Full coupled dynamic EM-SM run

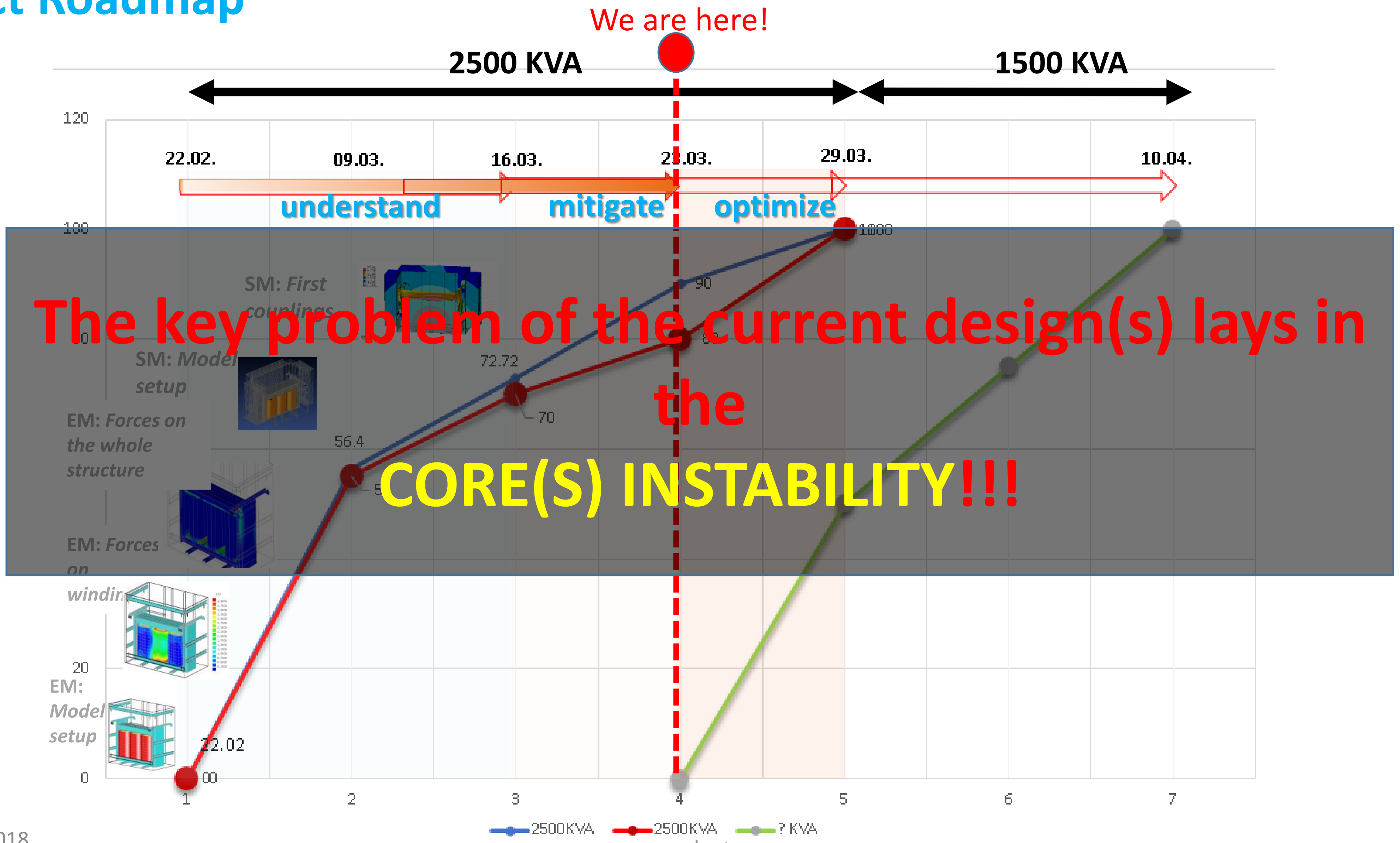






Full dynamic run of the SC appearing on **R / S / T-phase**

Project Roadmap



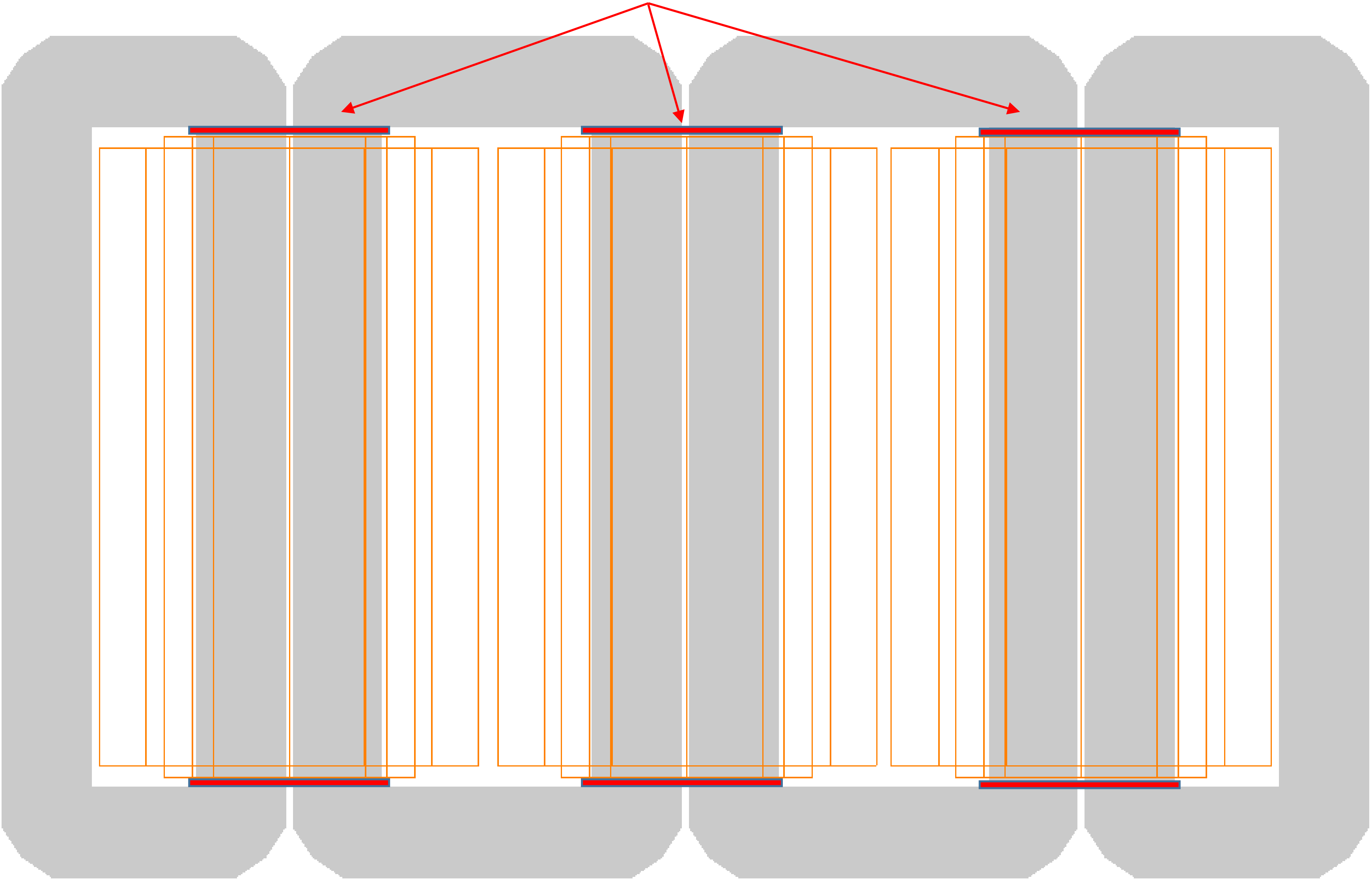
The key problem of the current design(s) lays in the

the

CORE(S) INSTABILITY!!!

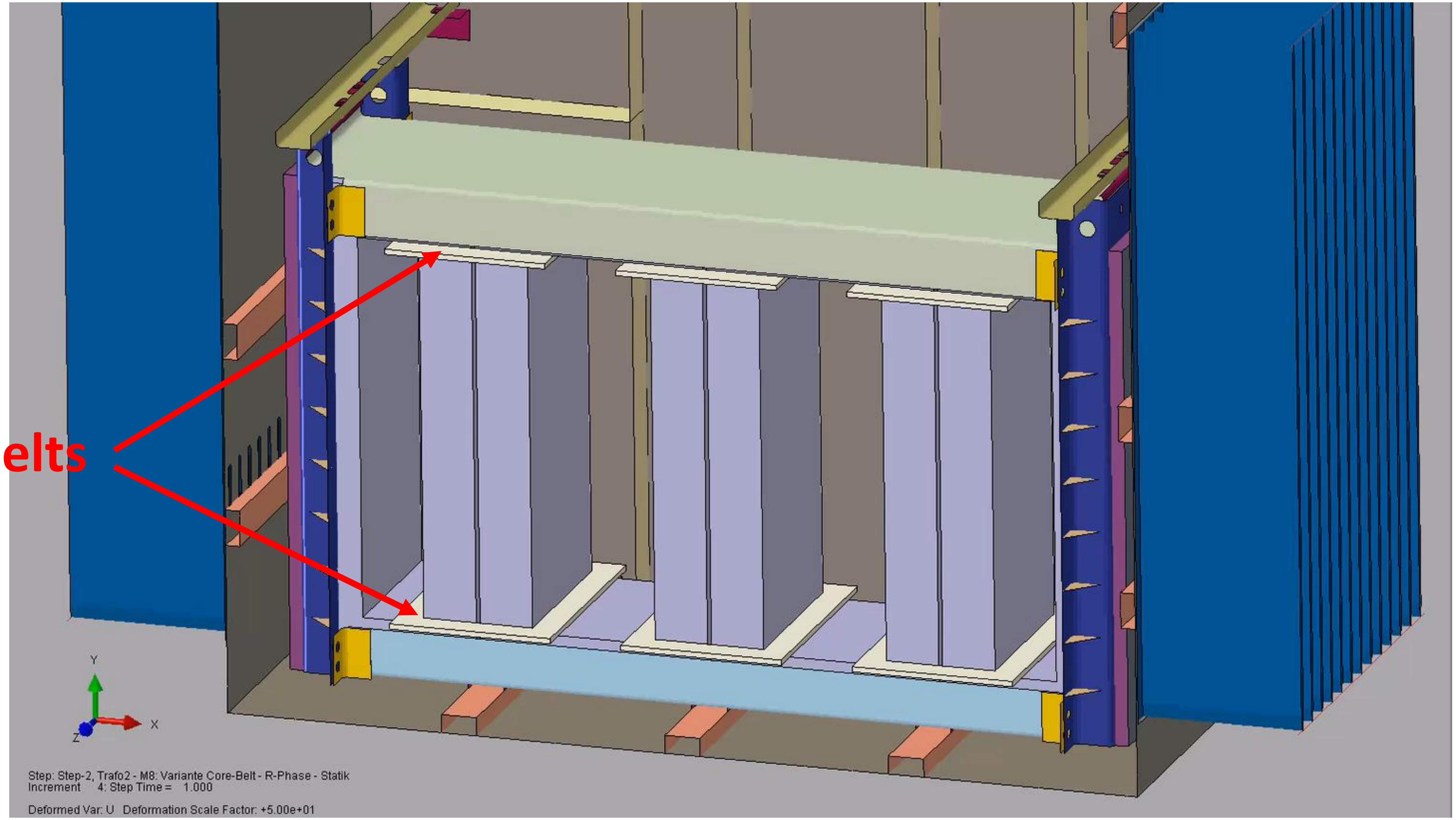
Proposed Solution:

Additional core-belts keeping the core components together



Current design- stabilized

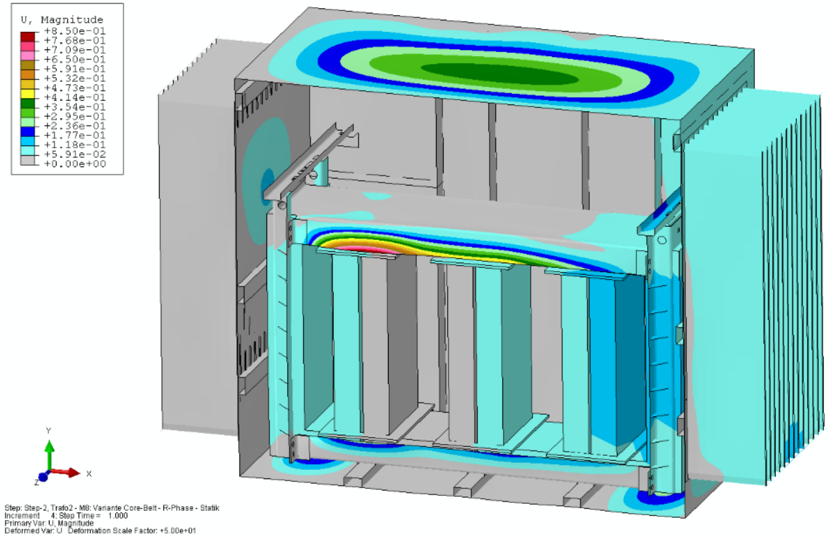
Core-belts



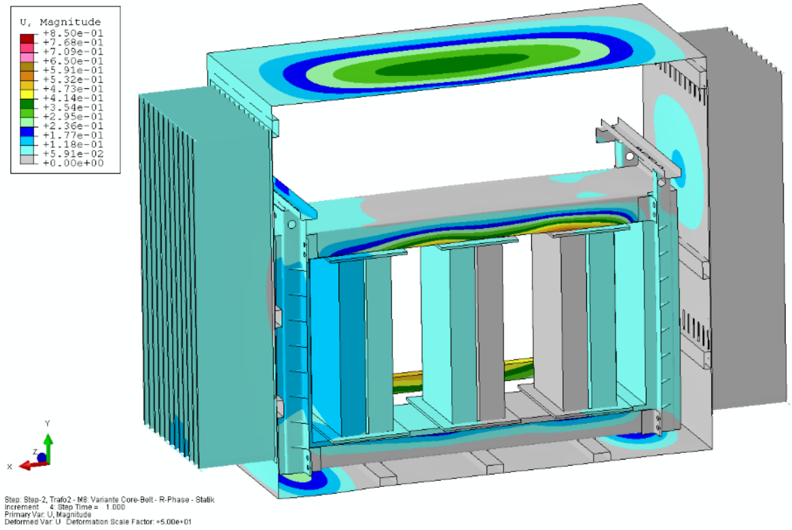
SC only on R-phase

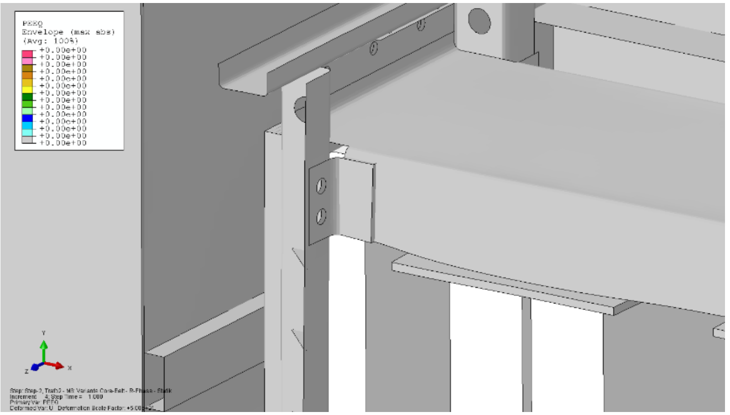
Current design with stabilization; SC on R-phase

Front view



Back view

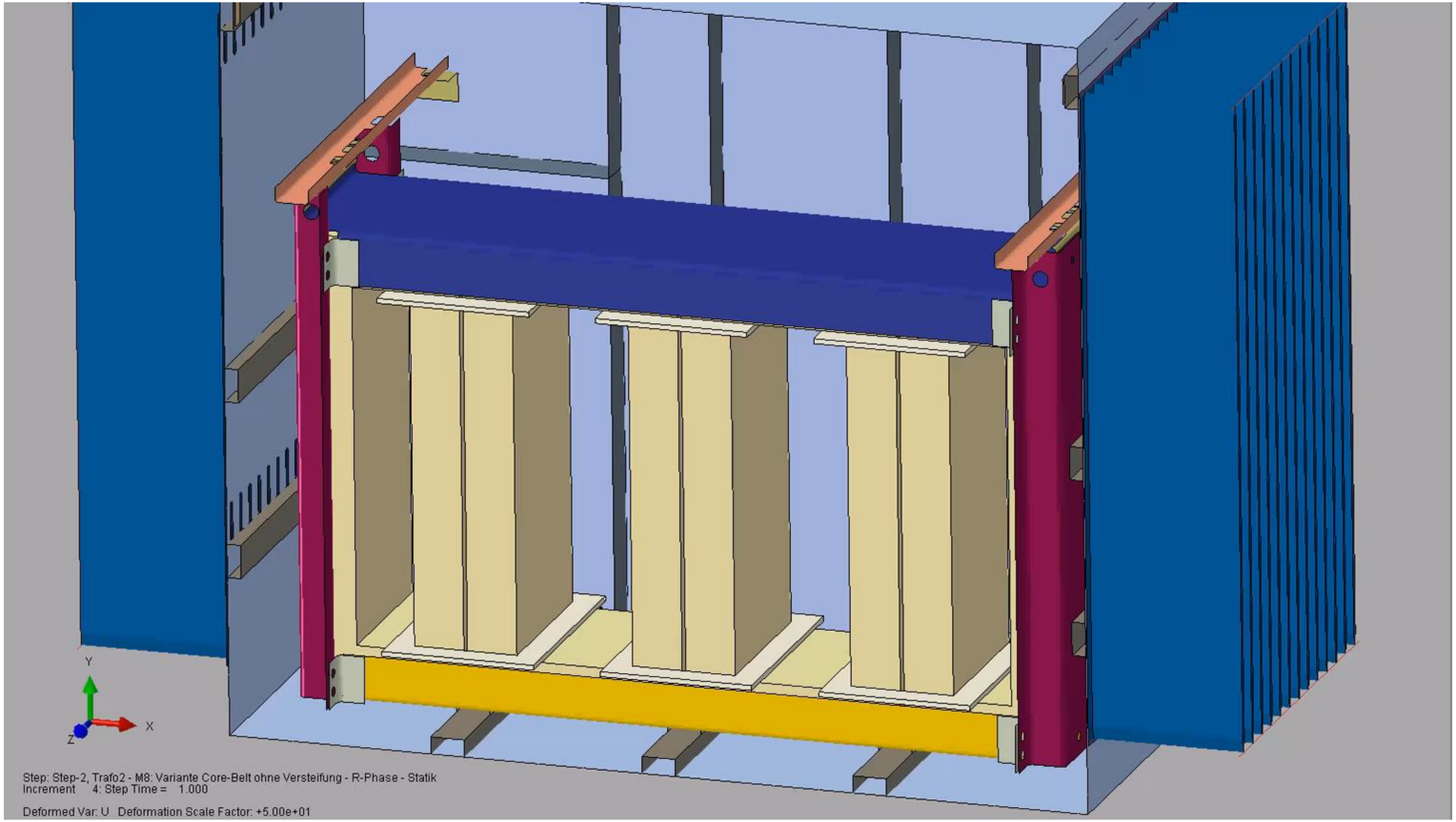




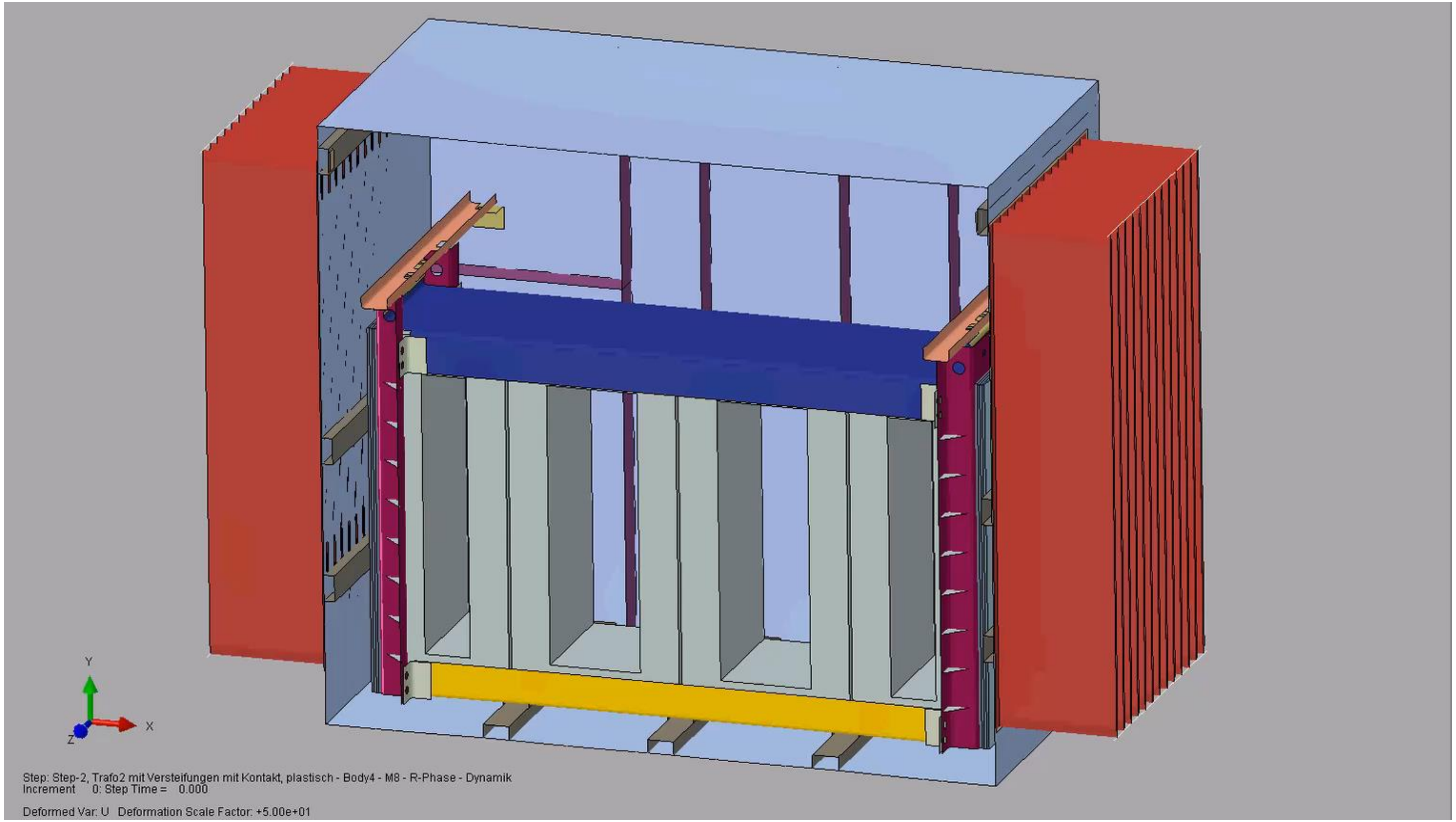
80% reduction of the displacement in x-direction!

No plastification!

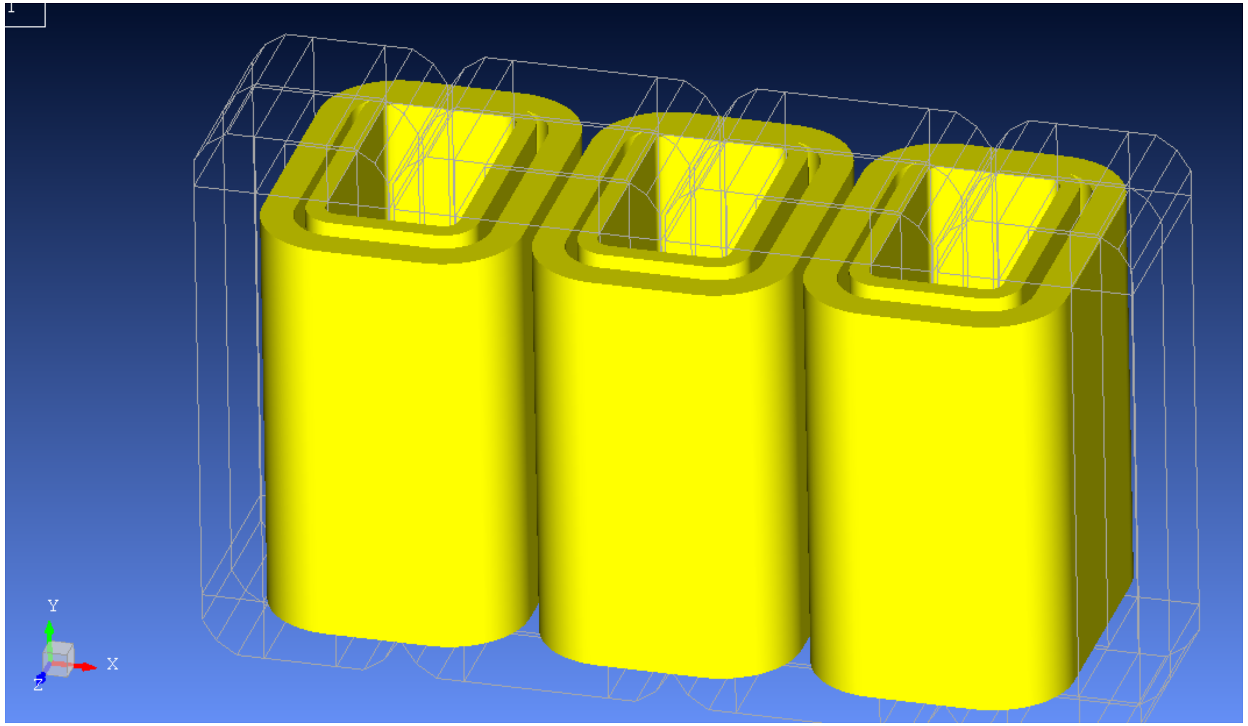
Stabilized trafo without any additional stiffeners



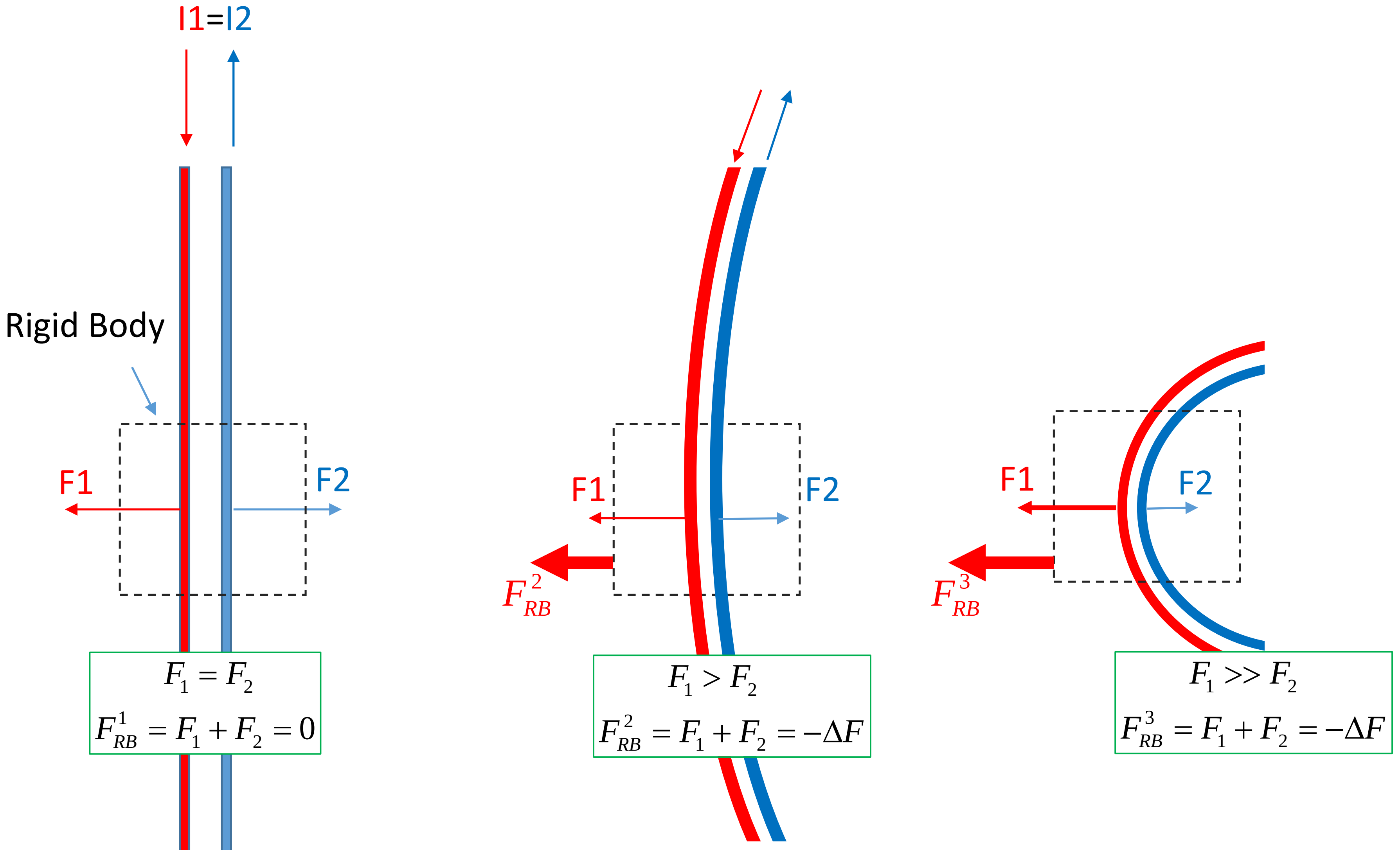
Dynamic simulation of the SC on the R-phase without stabilisation (trafo with stiffeners)



But, what causes the splitting of the core segments?

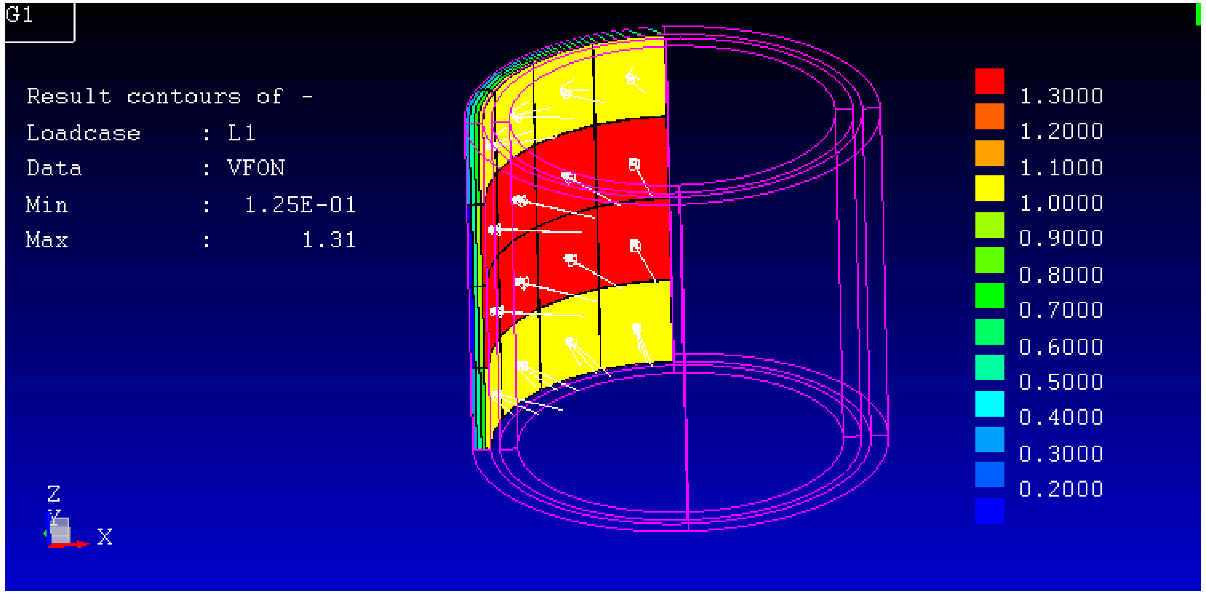


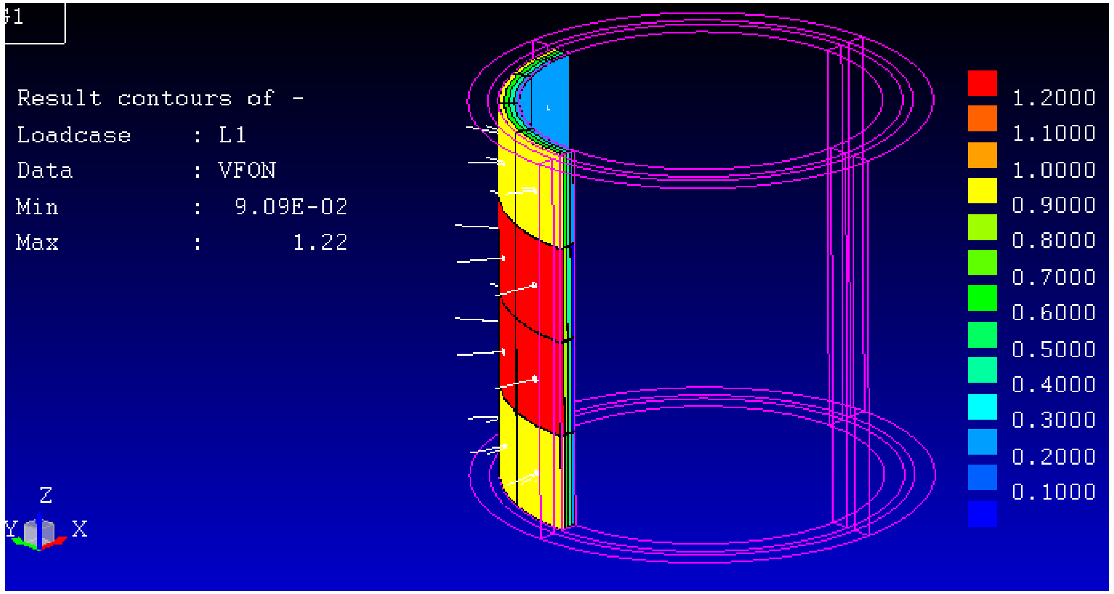
Exercise



$$F_{RB}^1 < F_{RB}^2 < F_{RB}^3$$

ACE vs. POLOPT





SC on S-phase

- Test model consist only of core sets and the windings
- All coils are positioned symmetric with respect to the core
- SC is on the S-phase

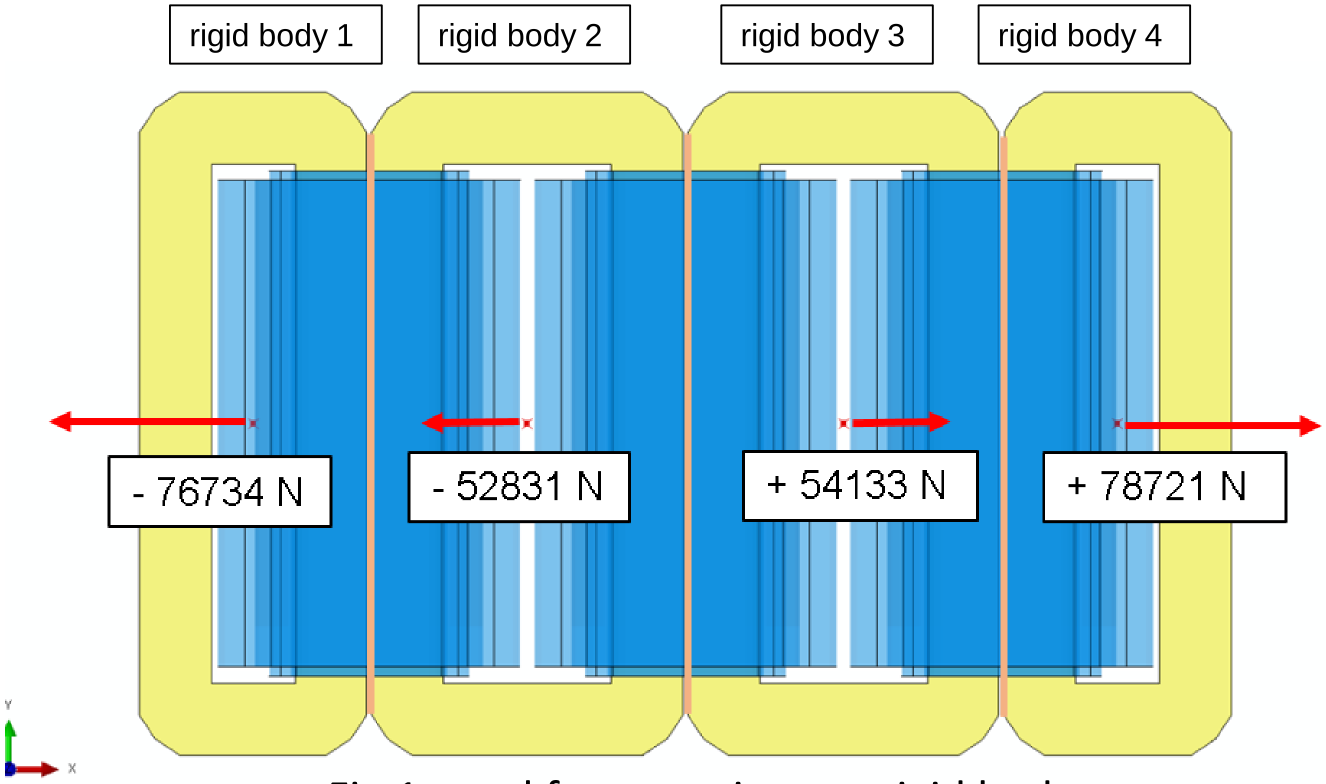
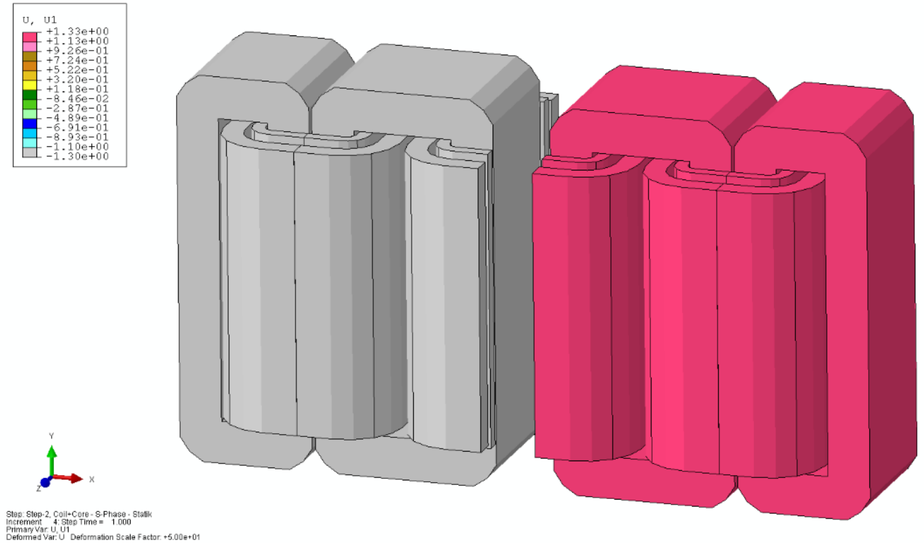
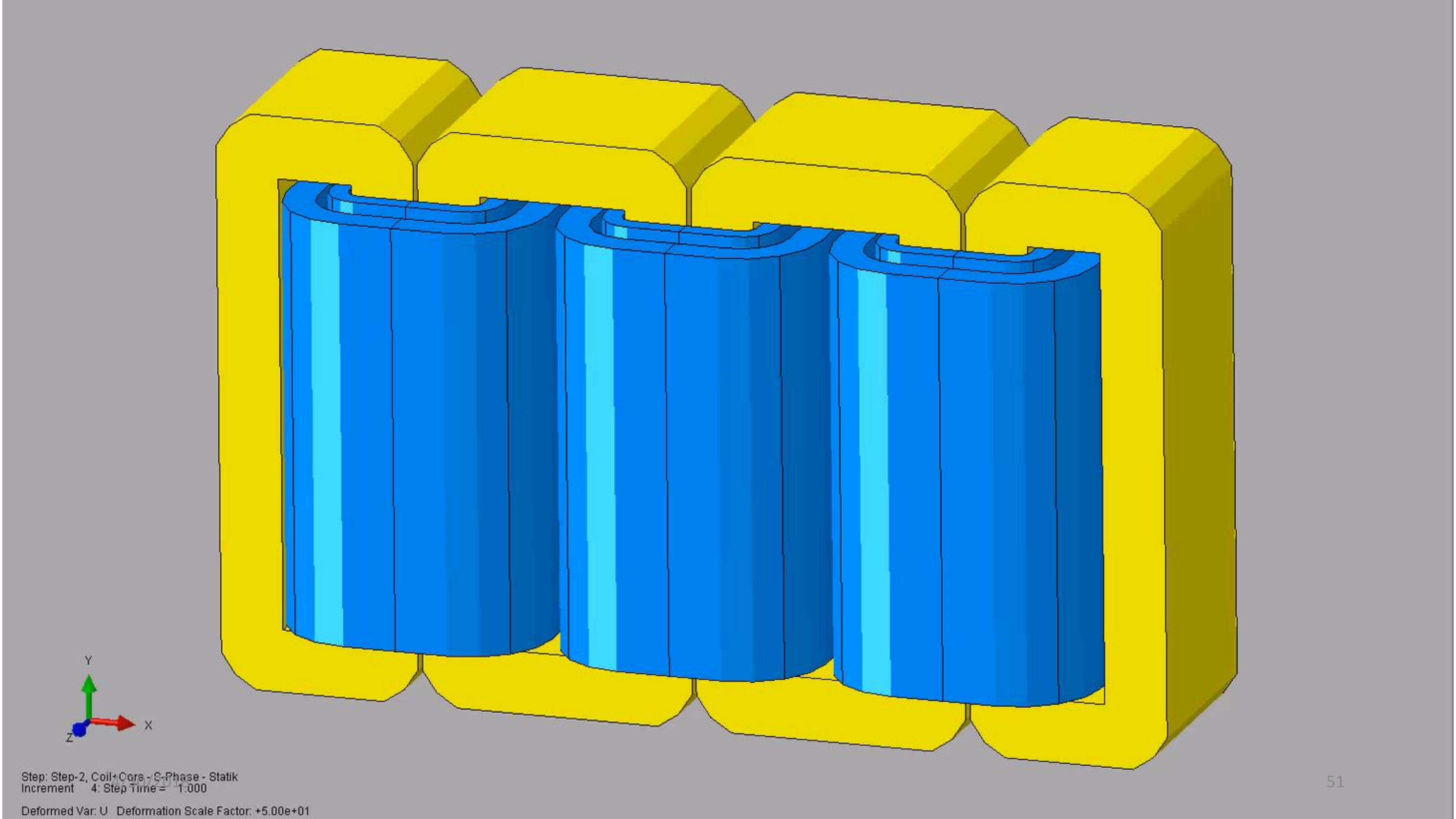


Fig.1: total forces acting per rigid body



Maximal displacement 1.3mm


Y
X
Z
Step: Step-2, Coil+Core - 3-Phase - Statik
Increment 4: Step Time = 1.000
Deformed Var: U Deformation Scale Factor: +5.00e+01

SC on R-phase

- Test model consist only of core sets and the windings
- All coils are positioned symmetric with respect to the core
- SC is on the R-phase

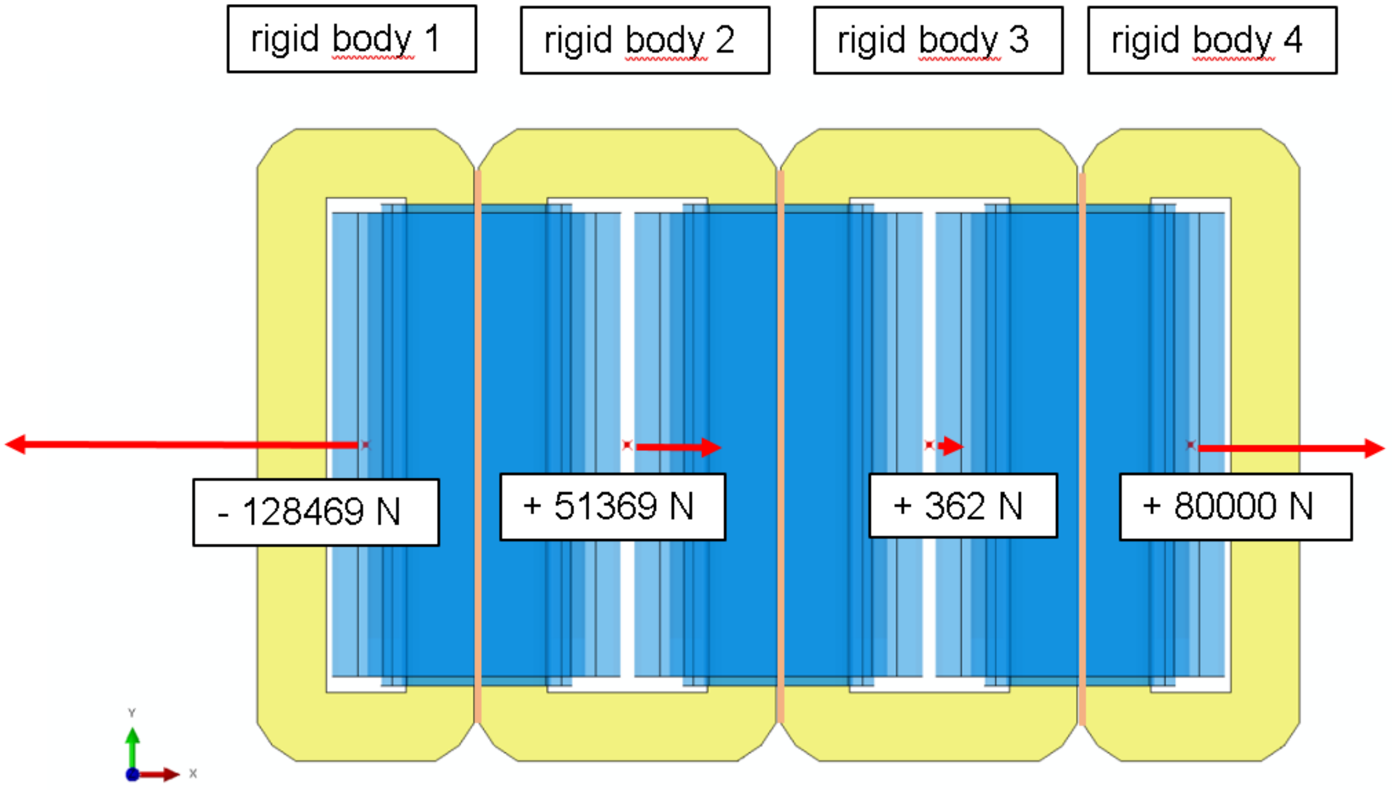
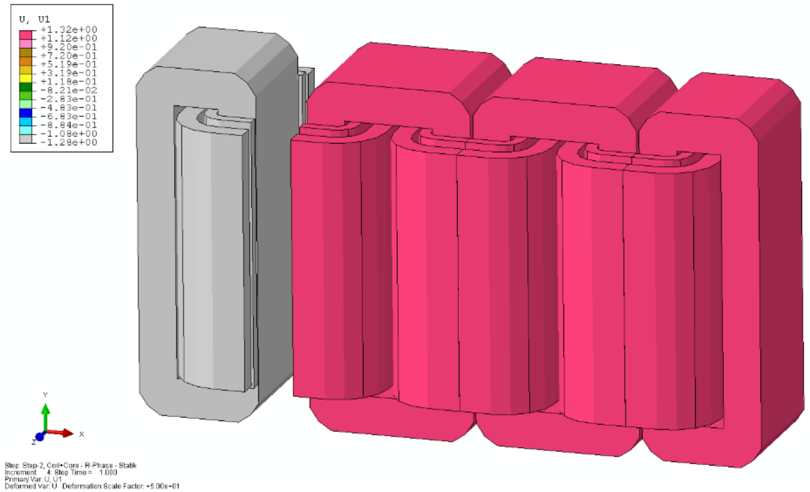
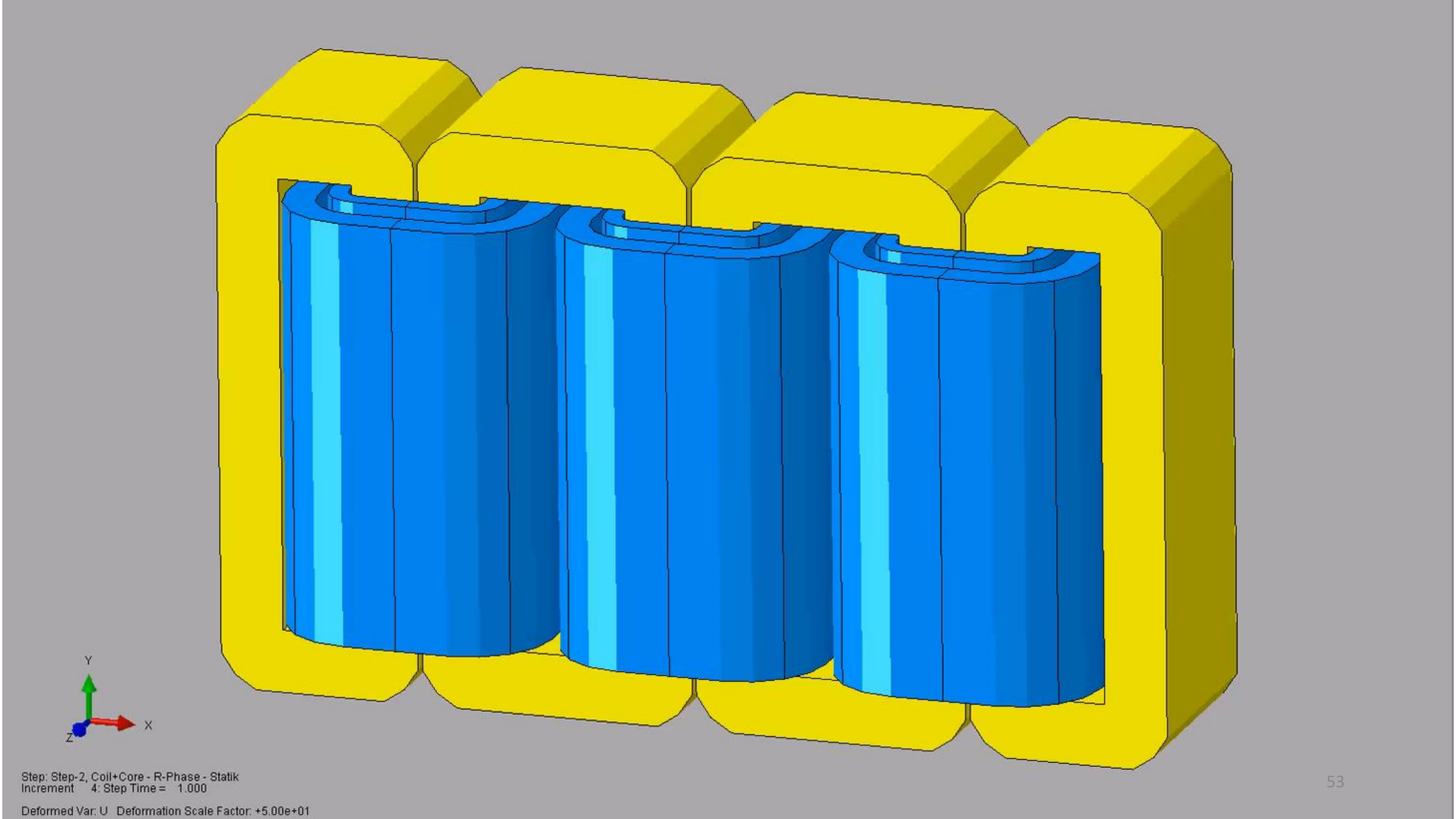


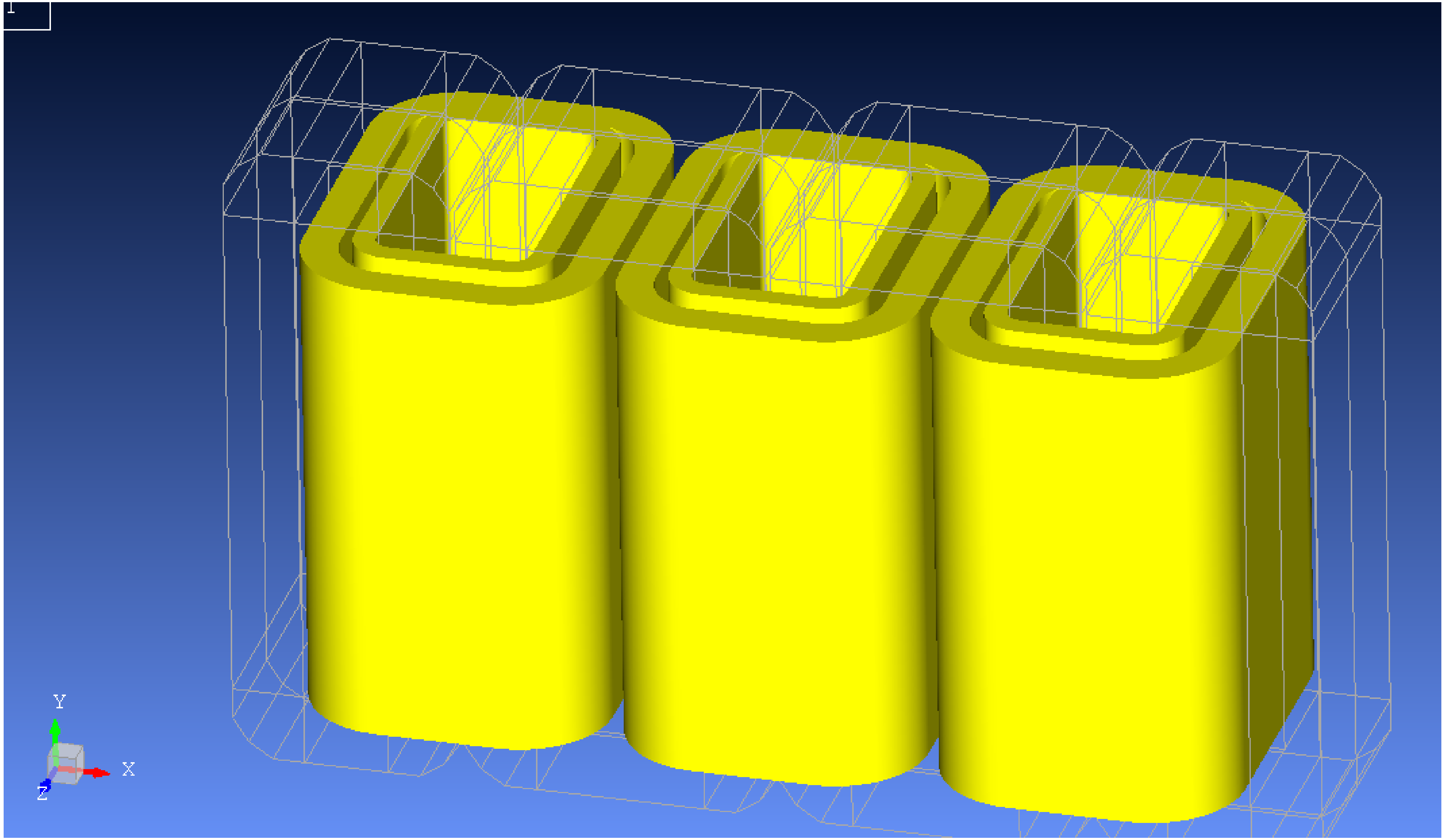
Fig.1: Total forces acting per rigid body

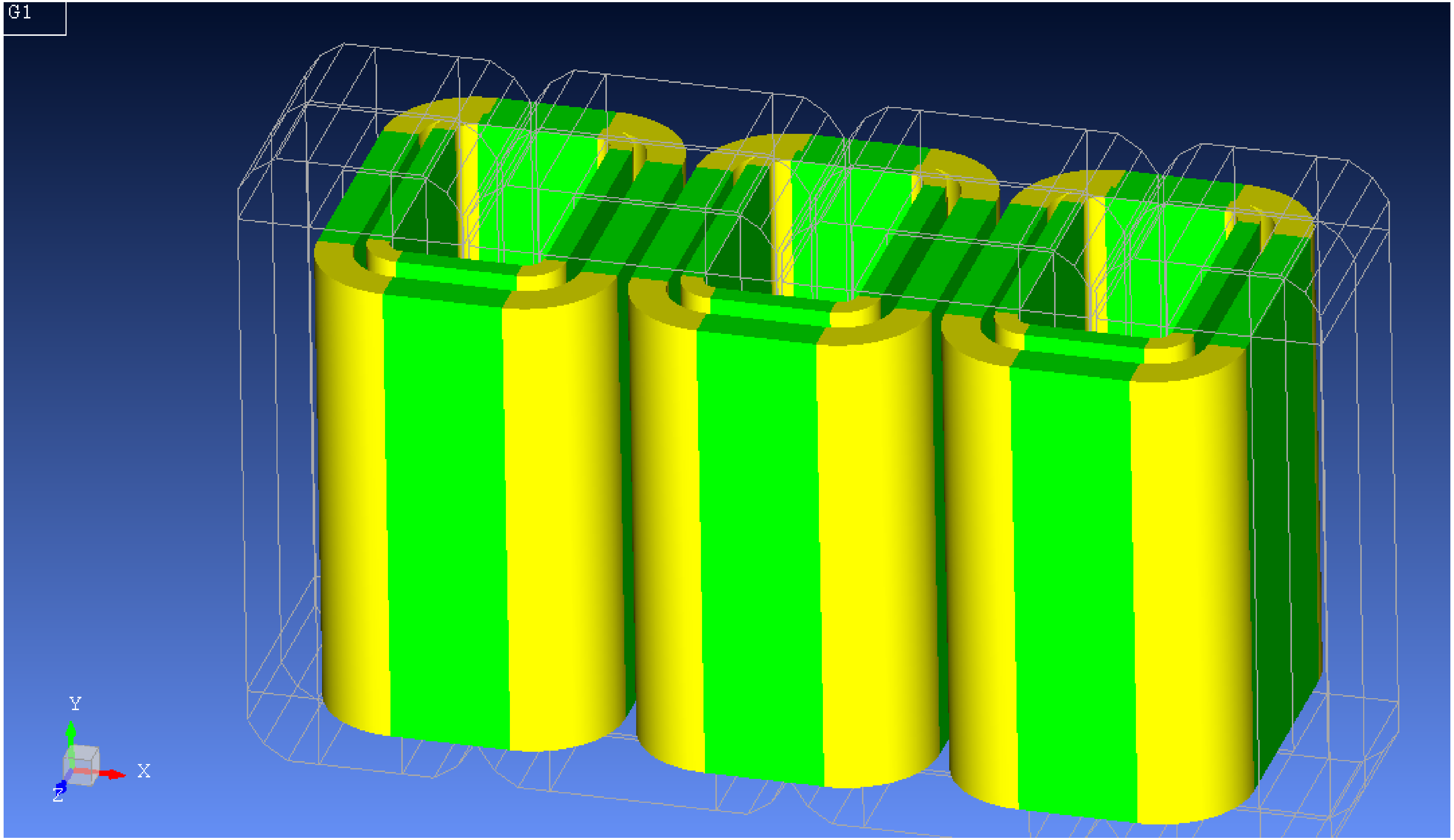


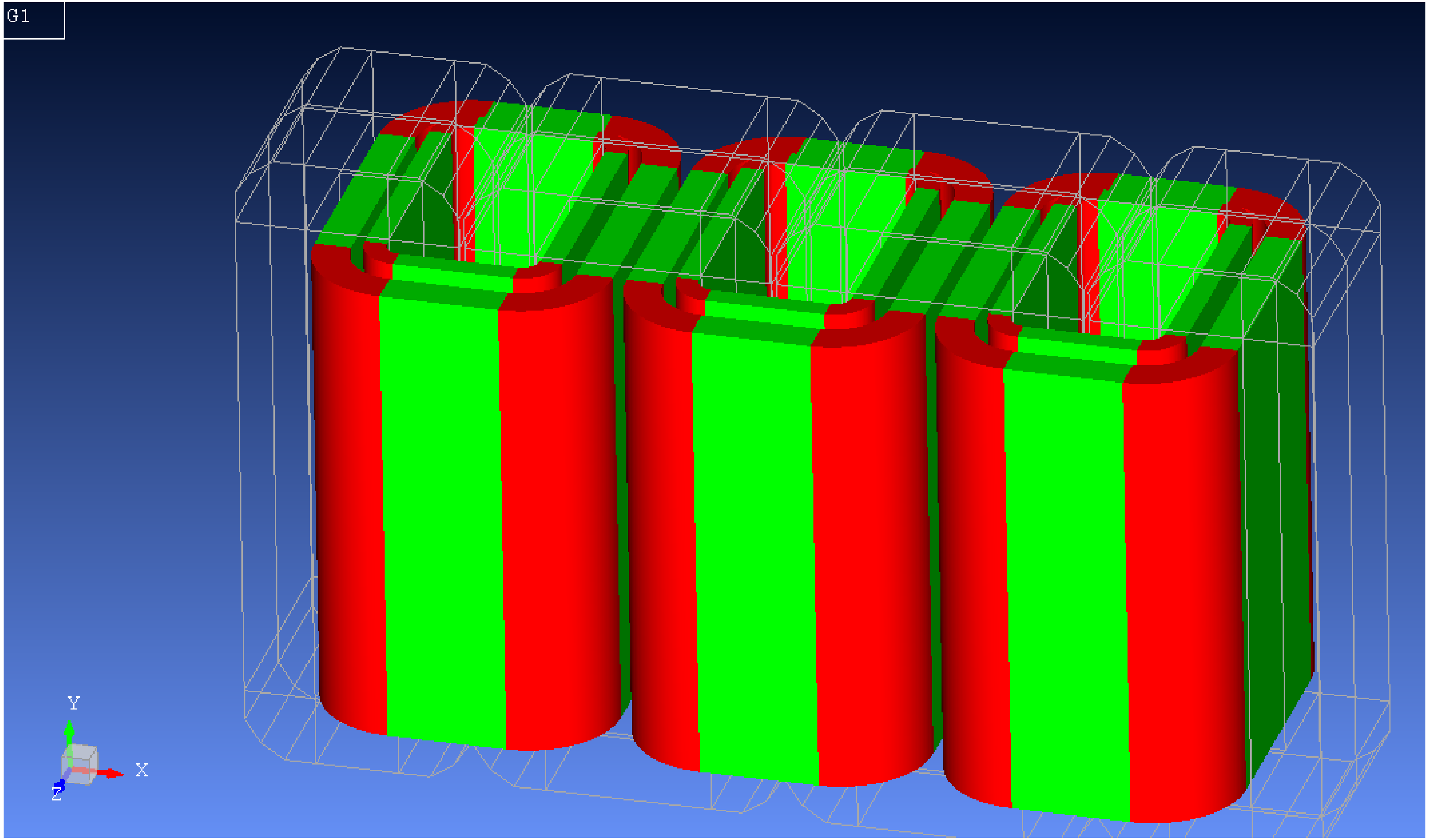
Maximal displacement 1.32mm

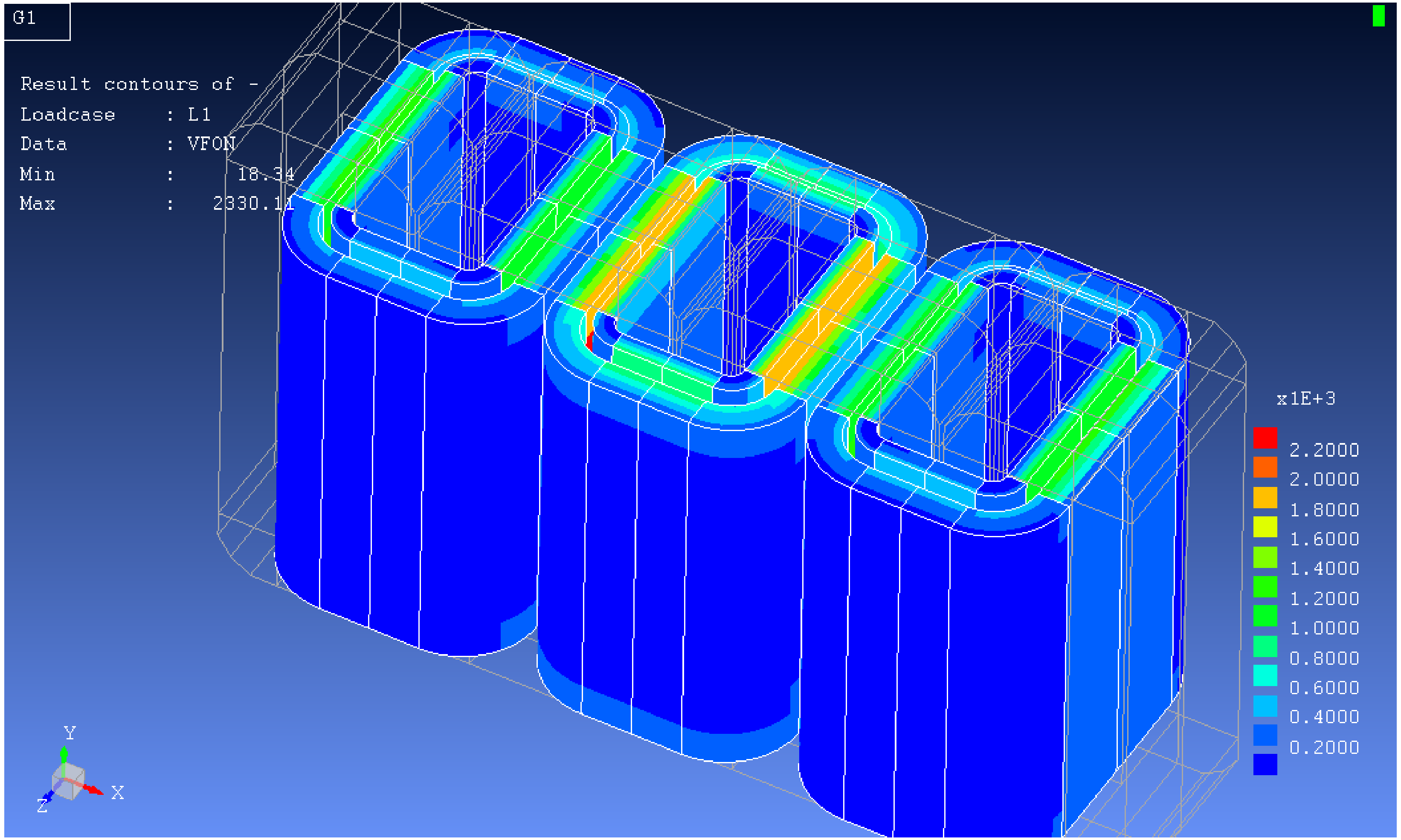
ANIMATION


Y
X
Z
Step: Step-2, Coil+Core - R-Phase - Statik
Increment 4: Step Time = 1.000
Deformed Var: U Deformation Scale Factor: +5.00e+01

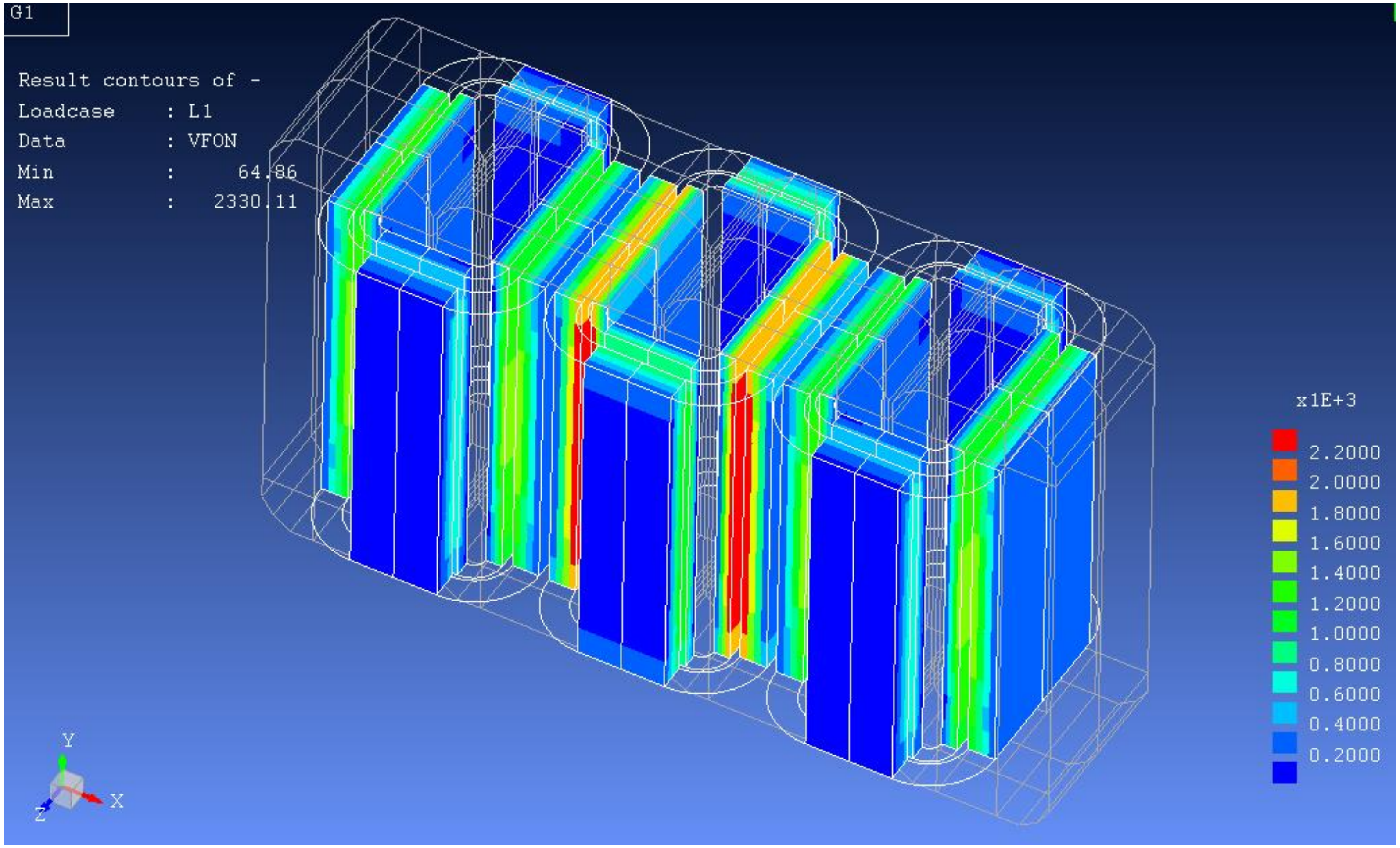

Y
X
Z


G1
Y
X
Z

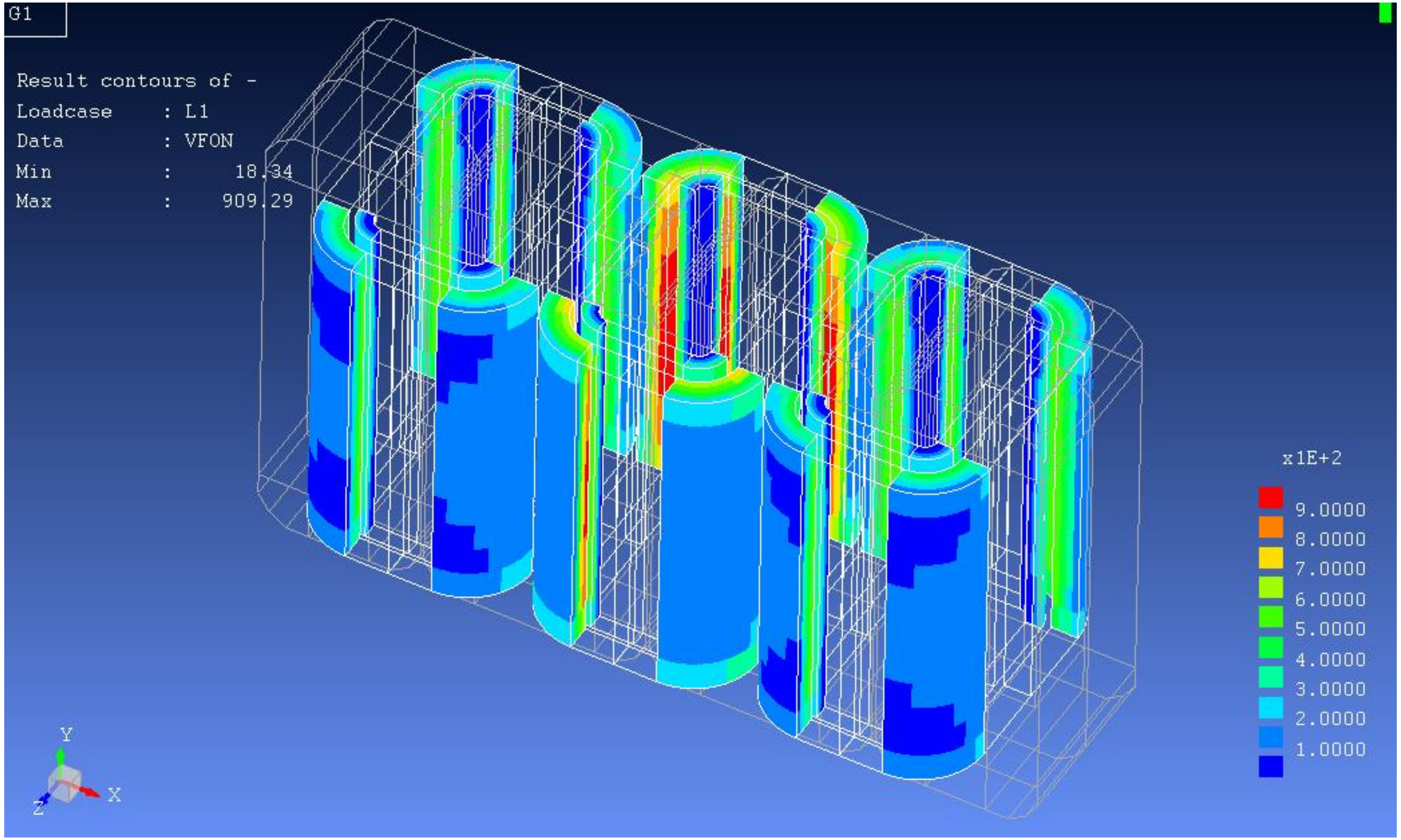

G1
Y
X
Z



Forces in [N] acting on the windings

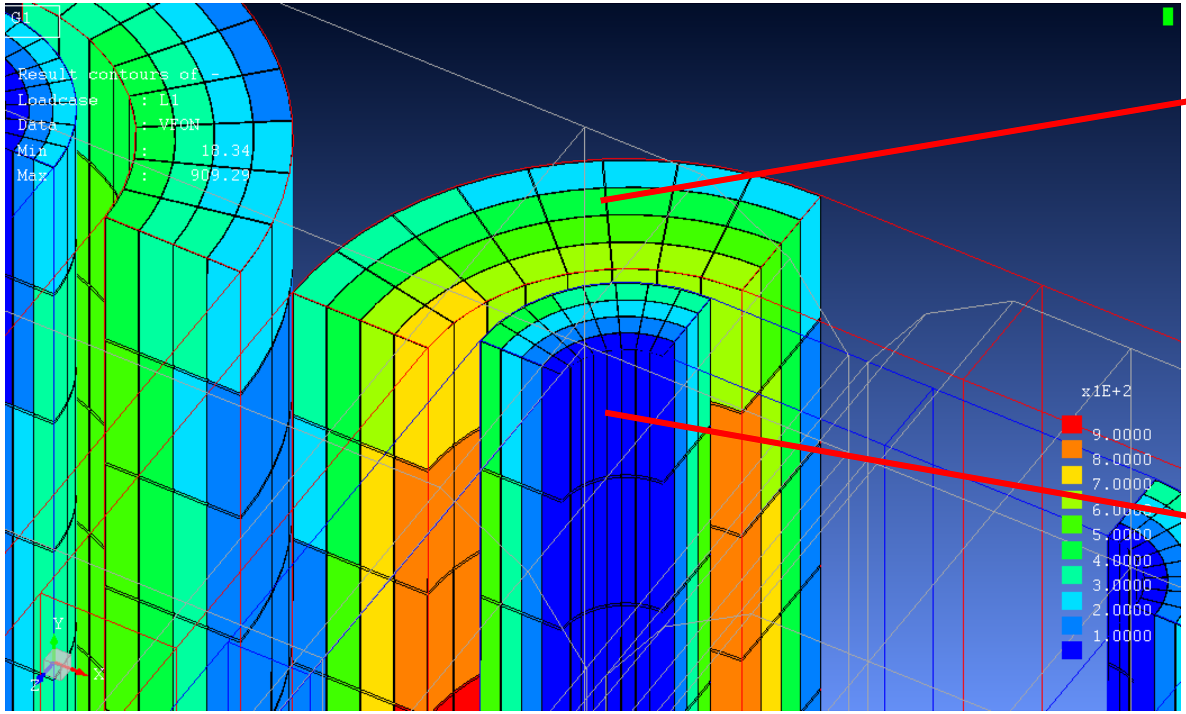


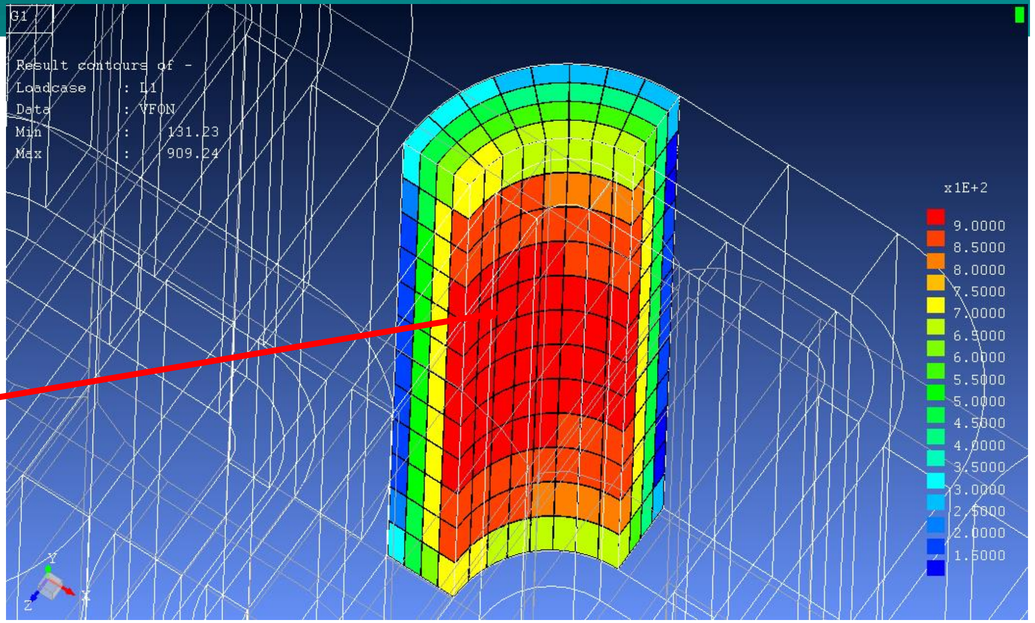
Forces are almost 100% compensated between the parallel laying HV and LV windings' segments

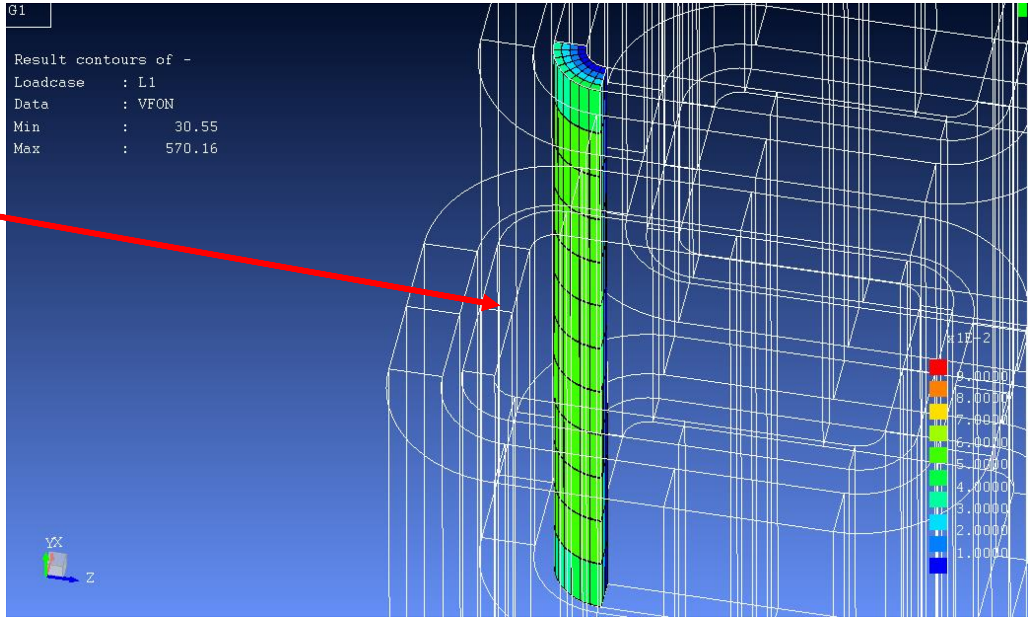


Forces on the belted part of the windings are not compensated!

FORCES ON THE LV CORNERS ARE SMALLER (30%) THEN THE FORCES ON THE HV CORNERS!







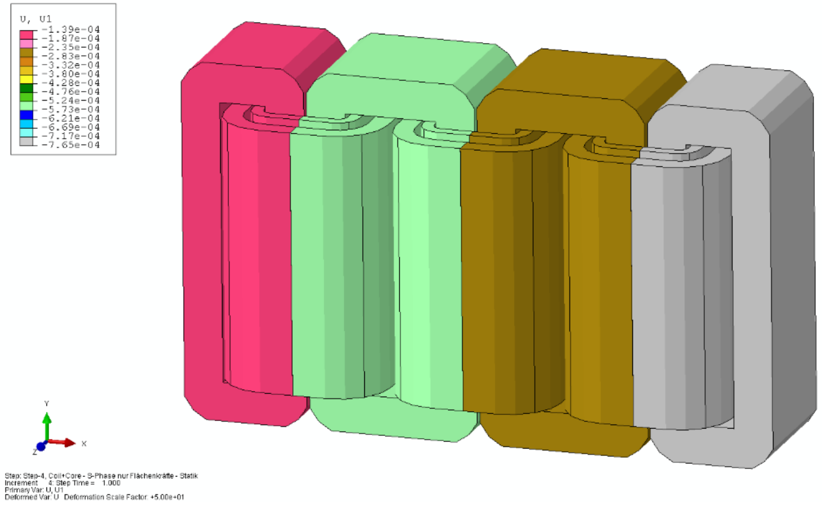
One more test:

Which forces are dominating?

Volumetric forces (F=JxB)

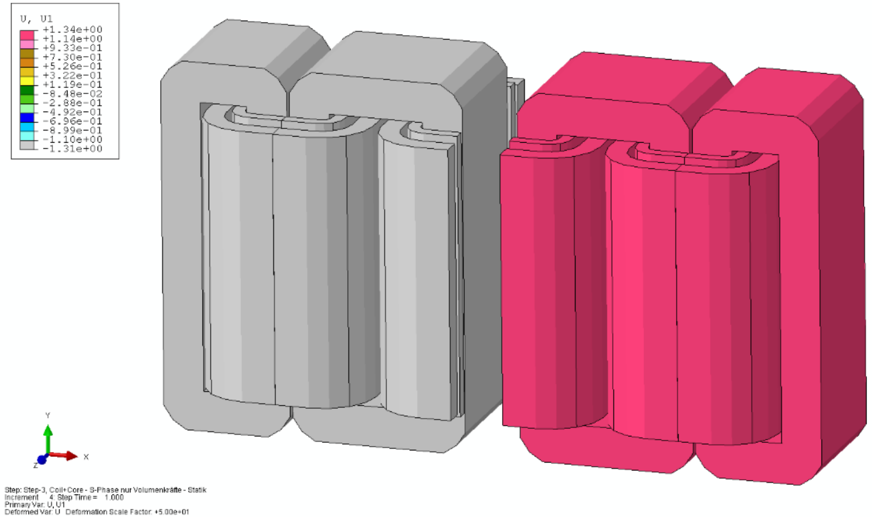
Body forces $F = \int_S \left[\varepsilon (\boldsymbol{E} \cdot \boldsymbol{n}) \boldsymbol{E} + \mu (\boldsymbol{H} \cdot \boldsymbol{n}) \boldsymbol{H} - \frac{1}{2} (\varepsilon E^2 + \mu H^2) \boldsymbol{n} \right] dS - \frac{1}{c^2} \frac{d}{dt} \int_V \boldsymbol{E} \times \boldsymbol{H} dV$

Only body forces



Displacement = 1.29e-4mm

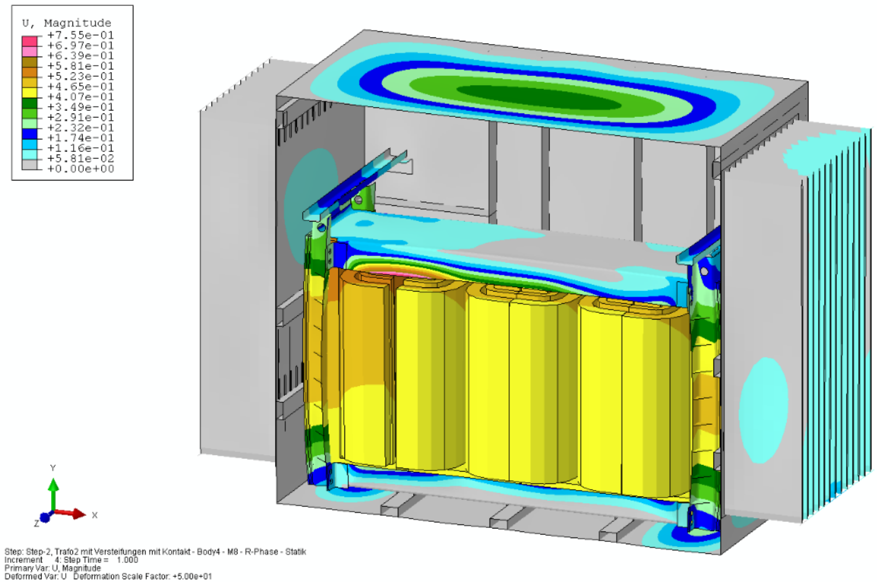
Only volumetric (winding) forces



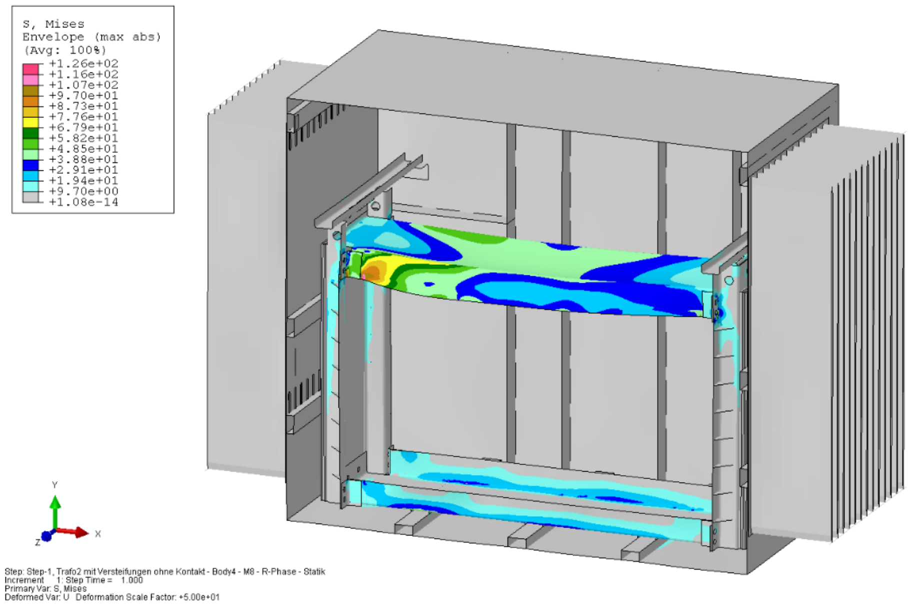
Displacement = 1.34mm

Some more tests…

The displacement / deformation of the clamping structure is significantly influenced by the contact between the pressboard plates and the adjacent metal structures!



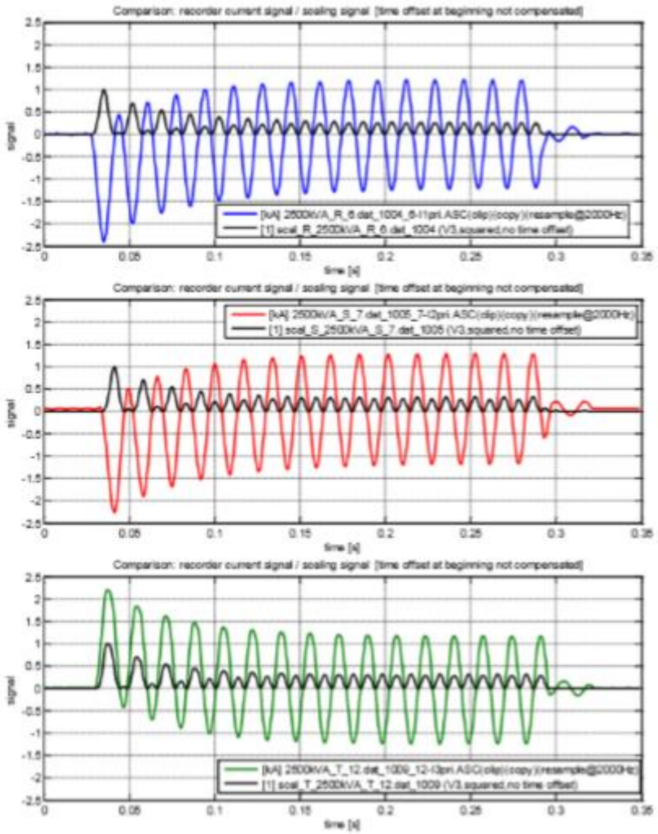
With contact



Without contact

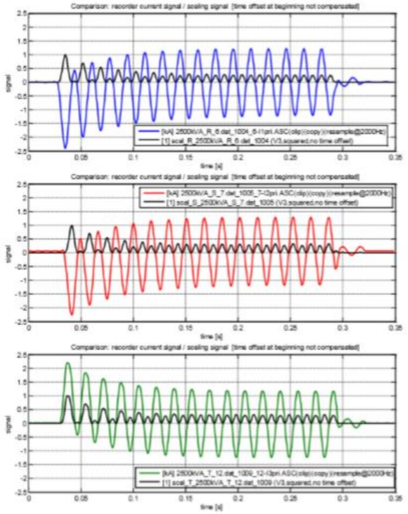
Final Results of the full dynamic simulation of the successive SC test on R, S and T phase

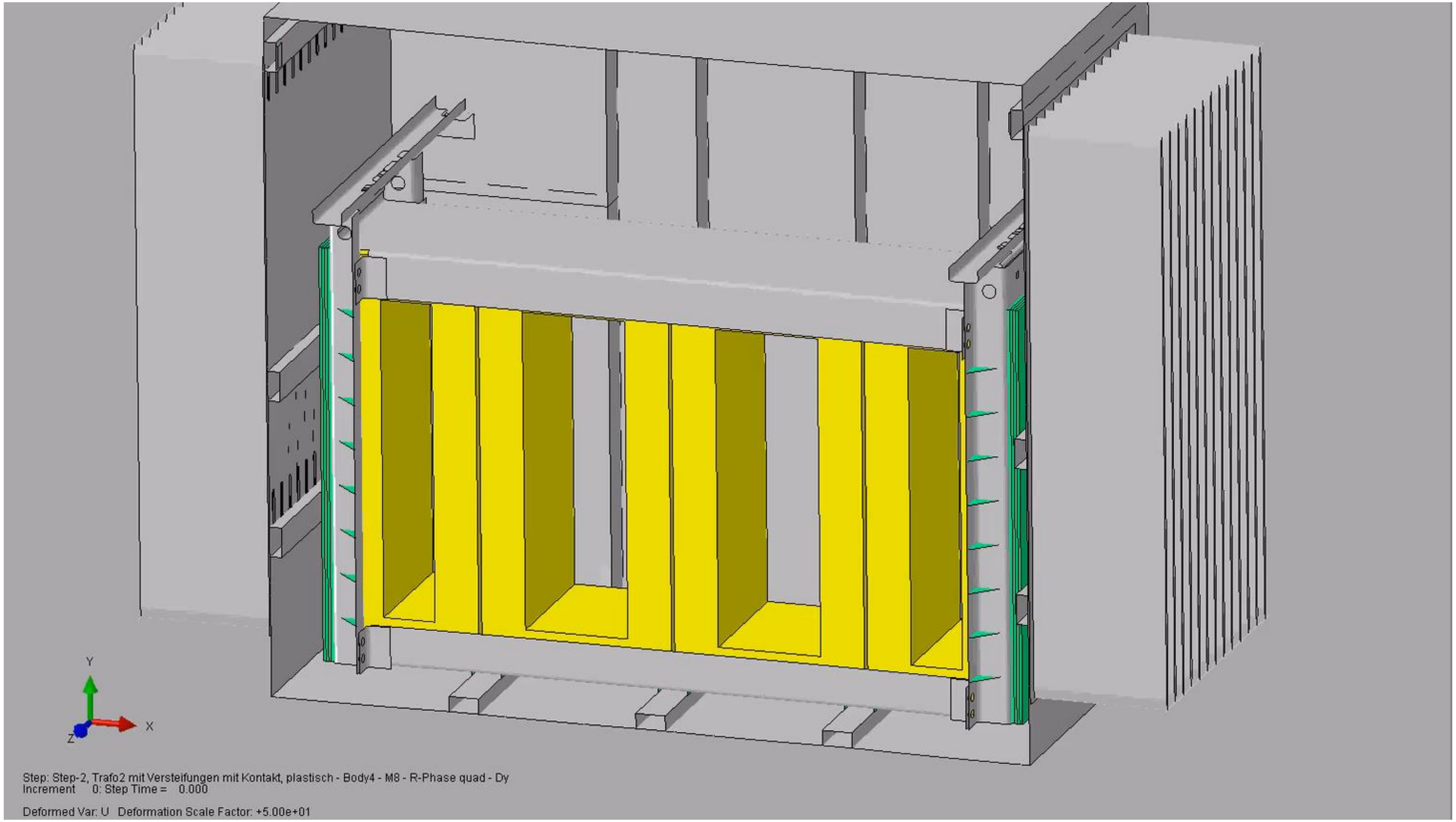
- Current design with stiffeners
- SC on R / S / T phase
- Forces applied during the full dynamic simulation following the dynamic oscillations from the input oscillographs



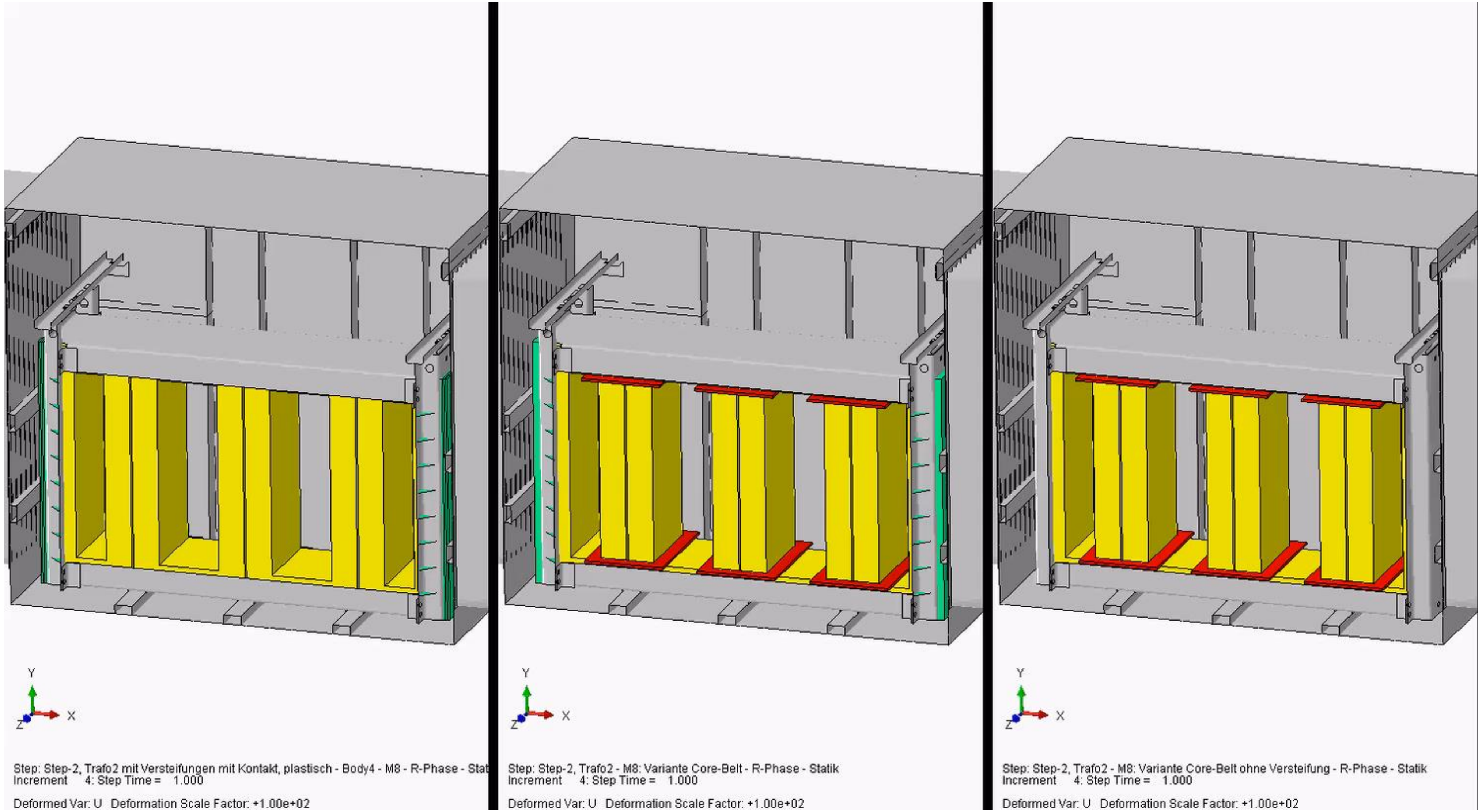
Final results of the full dynamic simulation of the successive SC test on R, S and T phase

- Current design with stiffeners
- SC on R / S / T phase
- Forces applied during the full dynamic simulation:



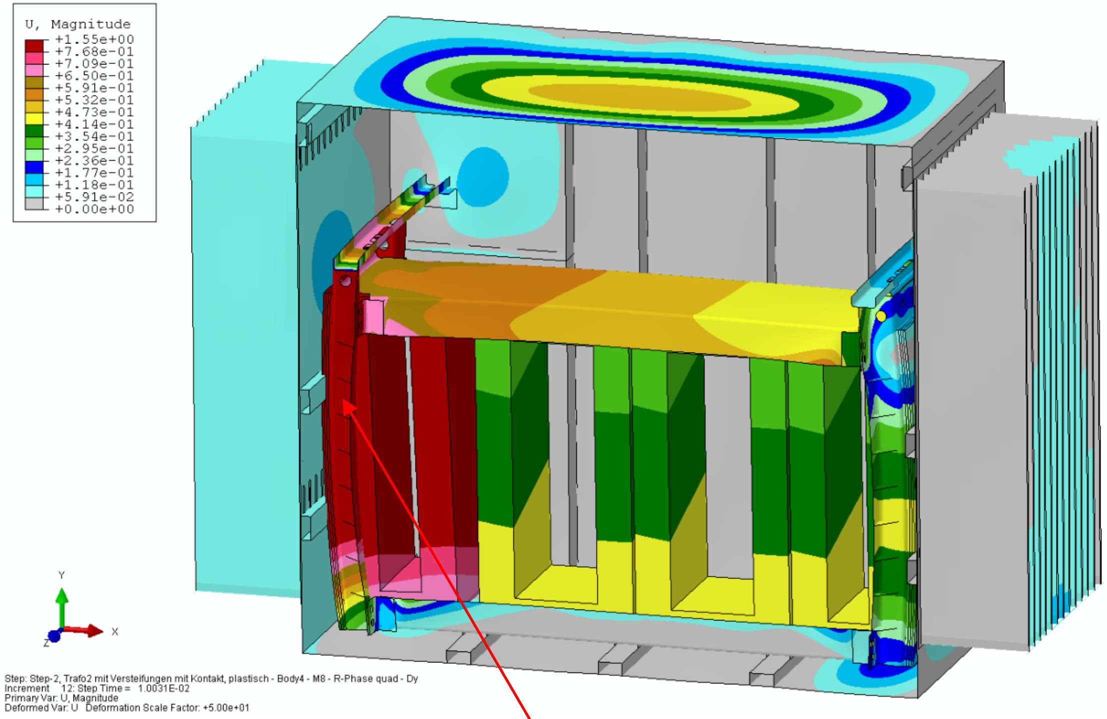


Solution 1: Core belts

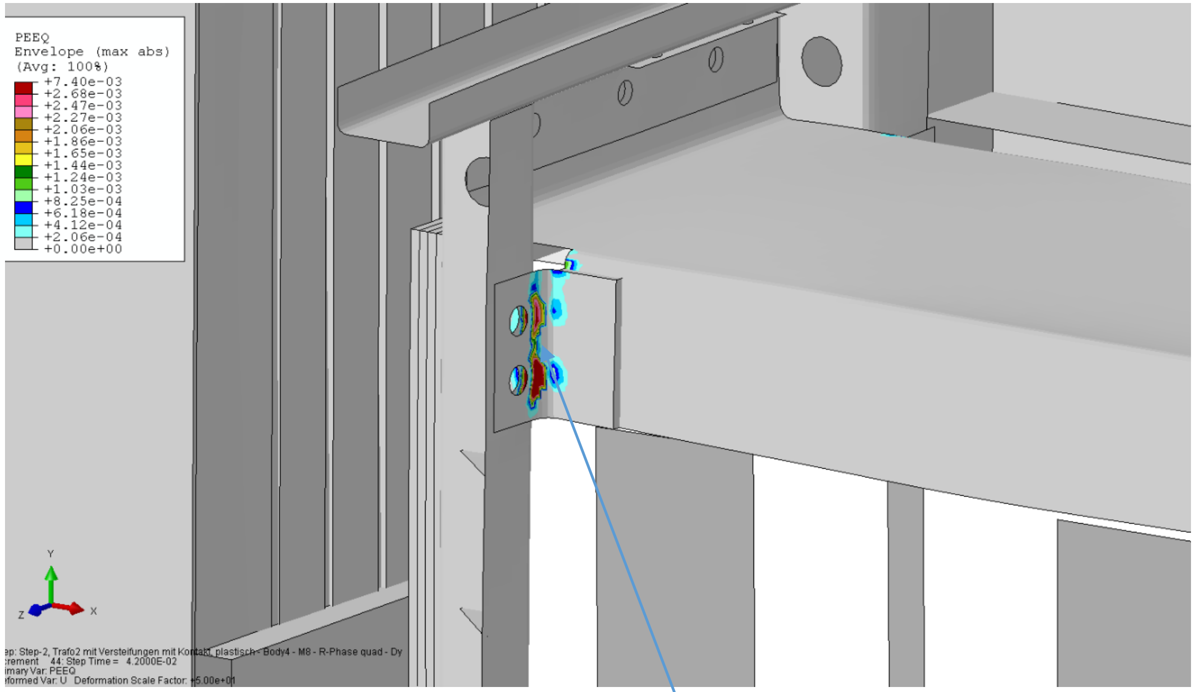


CURRENT DESIGN WITH THE STIFFENERS

Final Results of the full dynamic simulation of the successive SC test on R, S and T phase



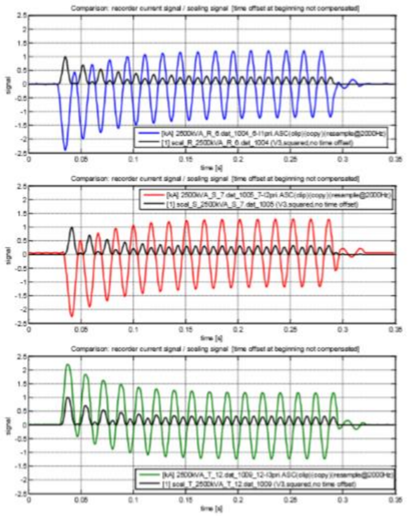
Maximal deformation on the left clamping plate = 1.55mm

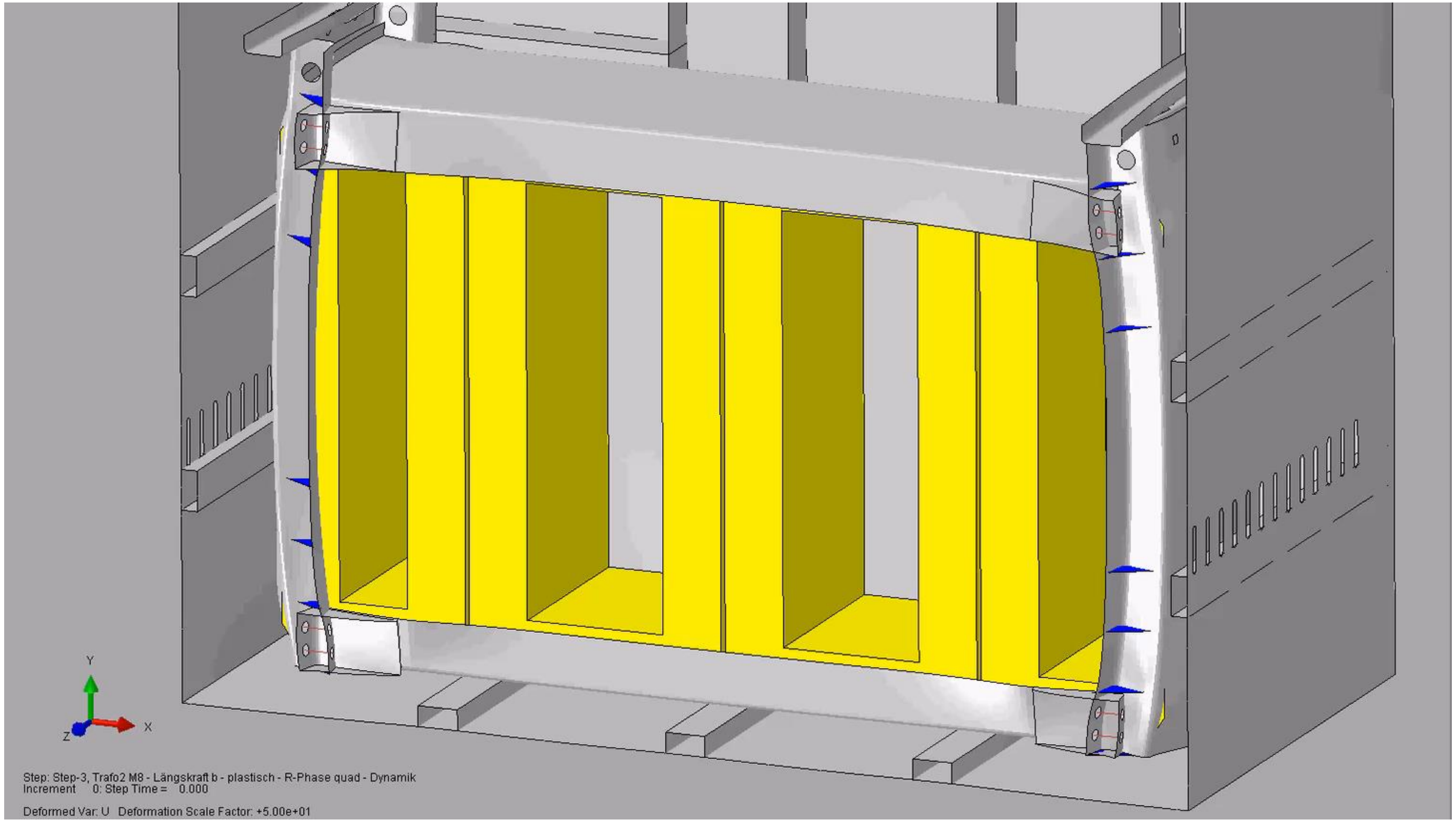


Maximal permanent plastification is on the belted connections

Solution 2: Pre-stressed structures

- Current design with stiffeners
- SC on R / S / T phase
- Forces applied during the full dynamic simulation:





Final results of the full dynamic simulation of the successive SC test on R, S and T phase

Project Roadmap