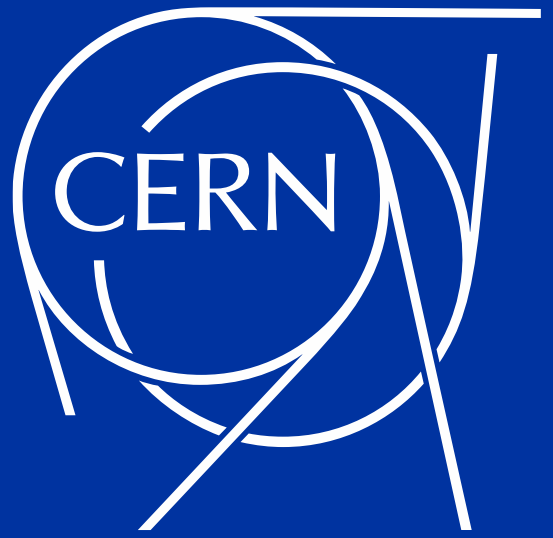
CERN

Mechanical analysis of MBHDP301 assembly and test

Carmen Abad on behalf 11Tesla team

Diego Perini, Ruth Diaz Vez, Emma Gautheron, Cedric Garion, Marco Morrone, Francois-Olivier Pincot, Frederic Savary, Attilio Milanese, Susana Izquierdo Bermudez, Nicolas Bourcey, Nicholas Lusa, Sebastien Luzieux, Michael Guinchard, Sylvain Mugnier, Franco Julio Mangiarotti, Gerard Willering, Jerome Freuvrier, Filip Kosowski, Jean-Luc Guyon, Patrick Viret

Meeting category:
https://indico.cern.ch/category/5095/

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5. **Longitudinal forces**
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   - Rods of end cage analysis
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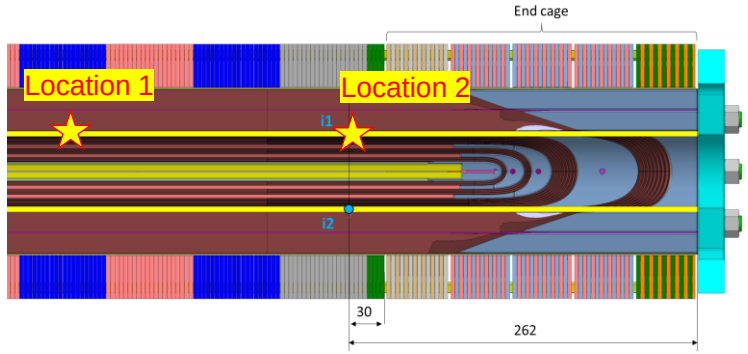
1. Previous conclusions https://indico.cern.ch/event/1309024

Test:

- Aperture SP302 all the training quenches are happening in one region in coil 213. Ramp rate studies show that the highest local damage is likely in location 2. No degradation after thermal cycle.
- Aperture SP301 could not be tested. During the first quench heater discharge without current in the magnet, a quench heater failed and damaged the quench heater to coil insulation.



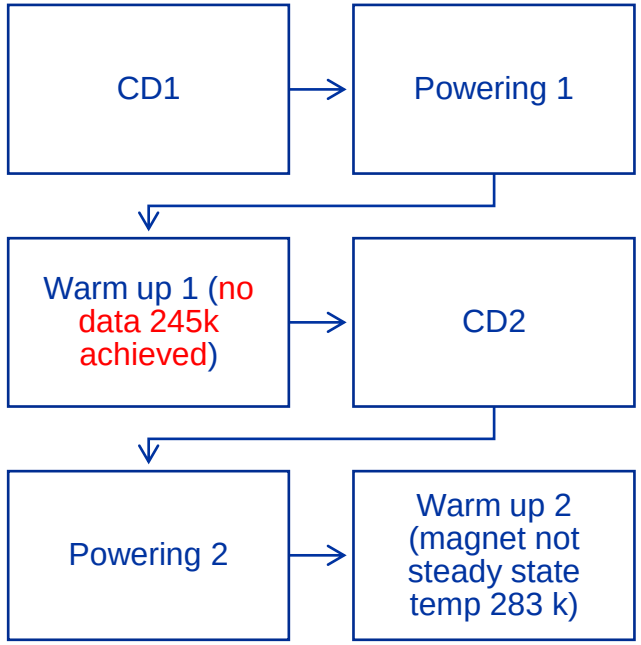
Images courtesy Carmen Abad Cabrera, Diego Perini and Gerard Willering

Assembly analysis:

- The second aperture (SP302) has been collared with less excess than the first (SP301) due to the high stresses in the collar nose at maximum collaring force (200 MPa in a collar with a target of 170 MPa).
- Further analysis in the location of the quenches is necessary.

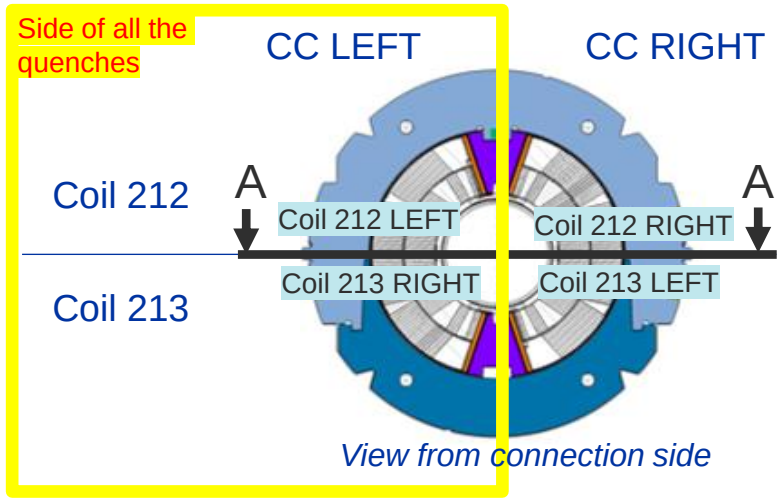
Mechanical measurements:

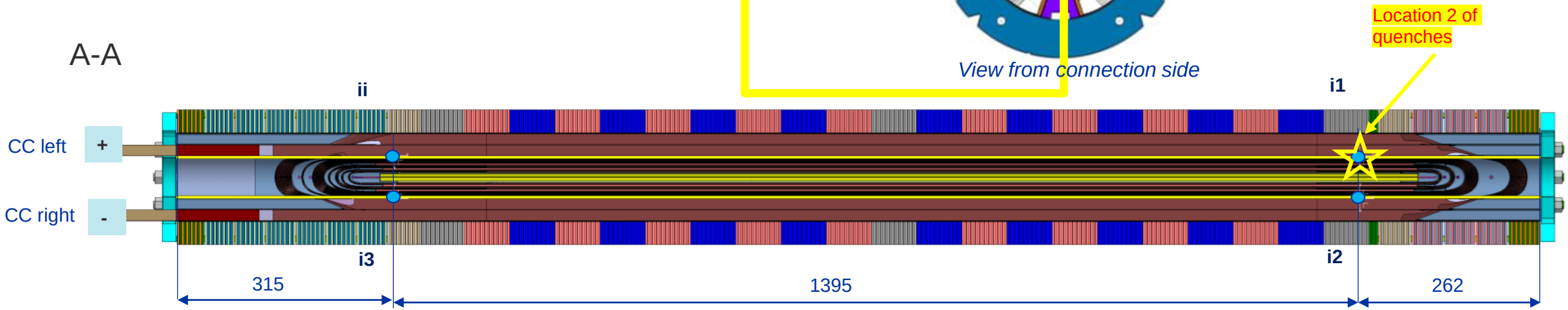
- SP301 was overloaded during the assembly (compared to the target).
- SP302 The aperture MBHSP302 was loaded at the same level than MBHSP301 in the middle section and half in the extremities.
- Bullet gauges and end cage rods are unbalance at cold and show different longitudinal stiffness between connection and non-connection side.



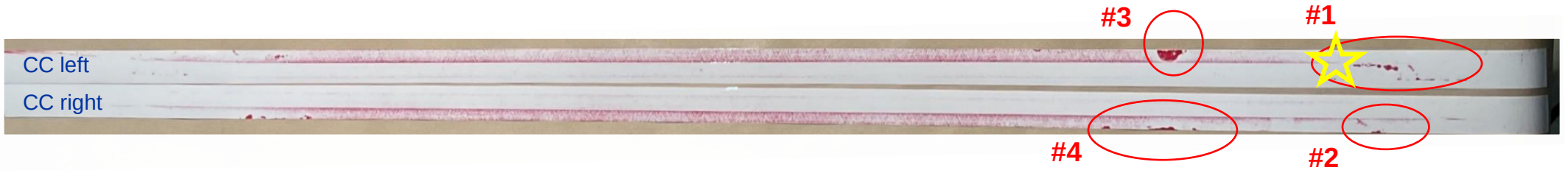
2. Focus on collared coil SP302

- Marks on the mid plane Fuji



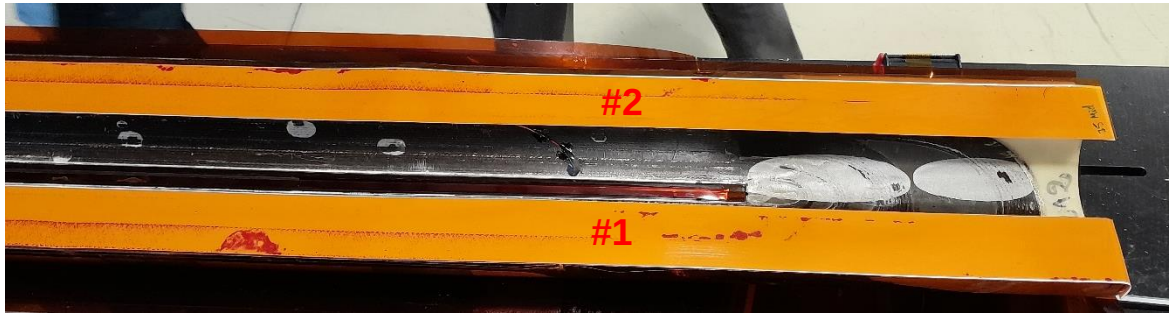


Marks in the fuji paper during Fuji 2 (MS 10-50 MPa)



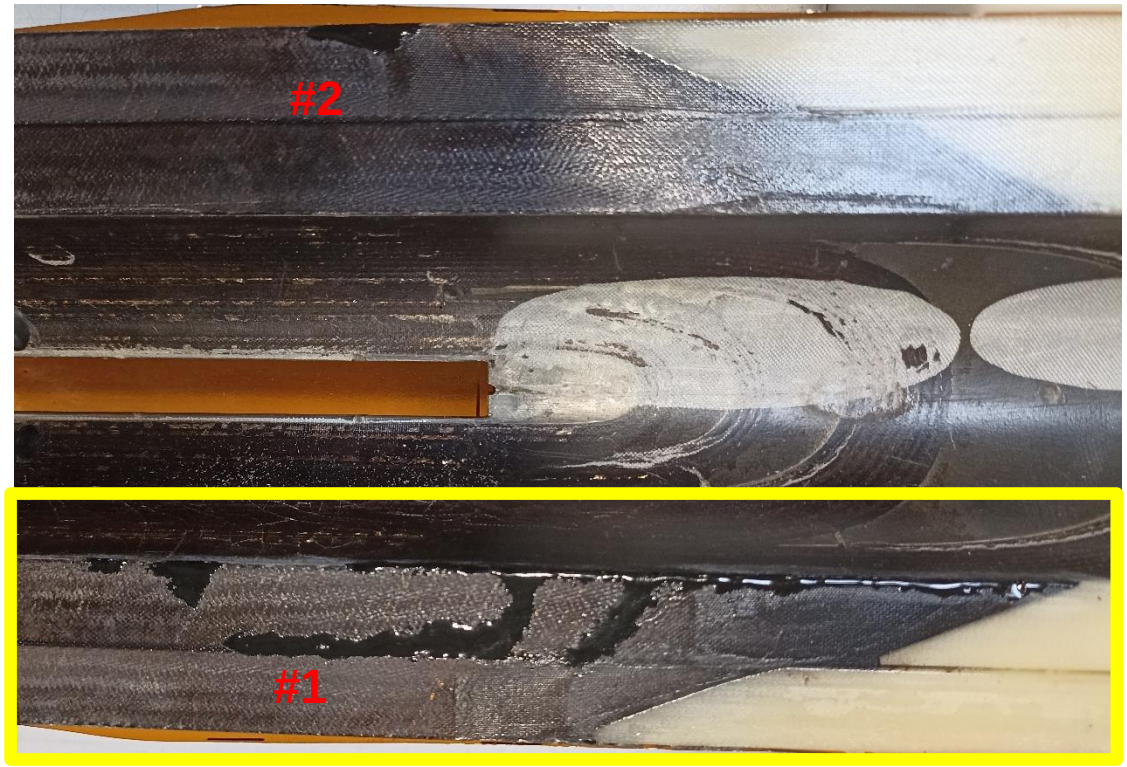
- Coils visual inspection

Marks



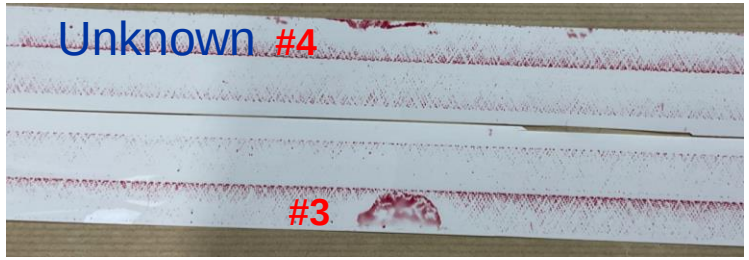
Coil 212: before surface defect correction

Coil 212: after correction with epoxy resin adhesive (stycast)

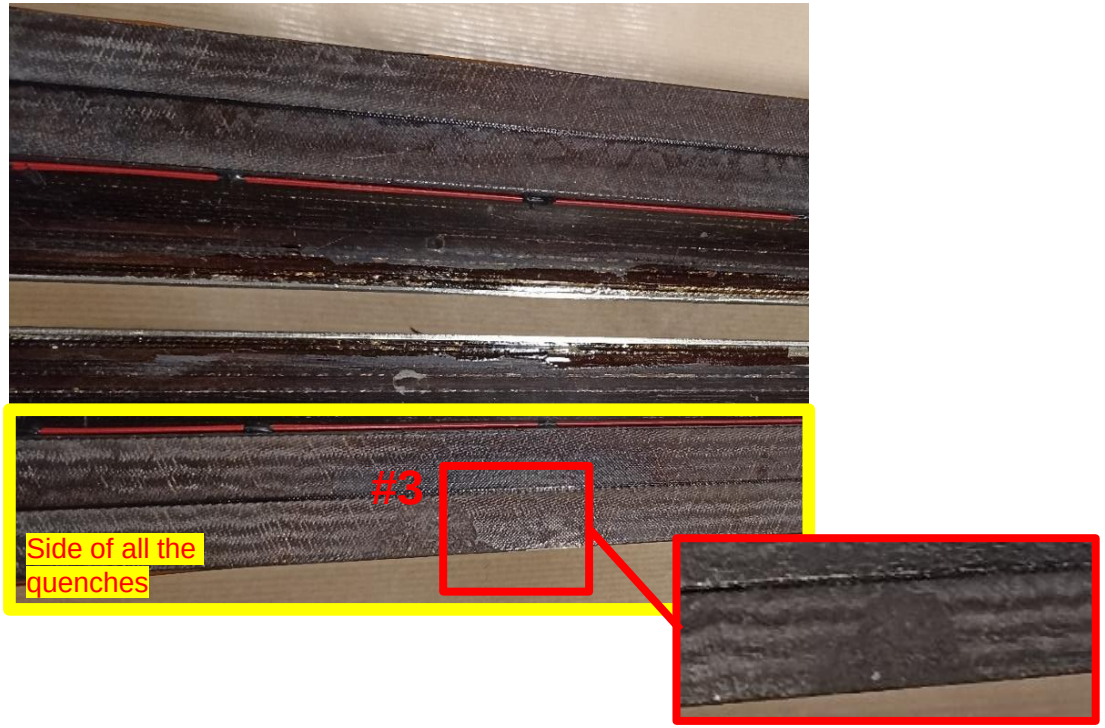


- Coils visual inspection

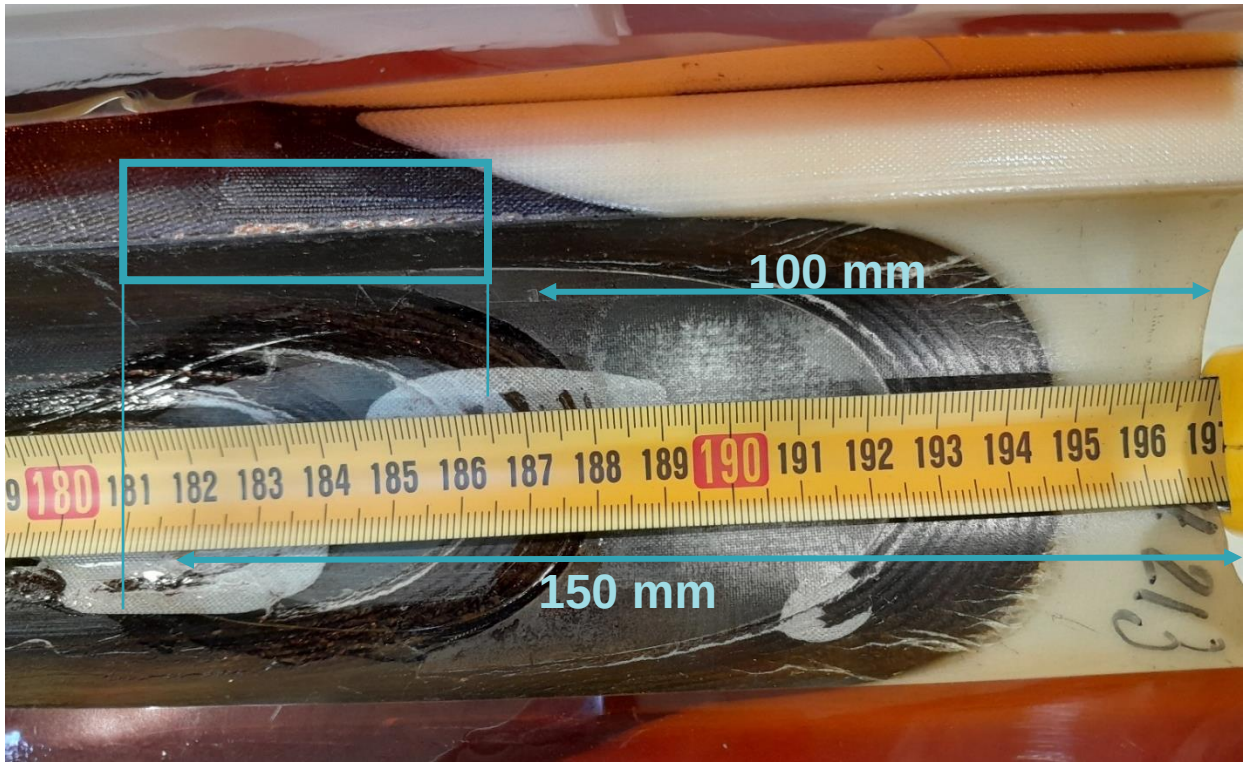
Marks



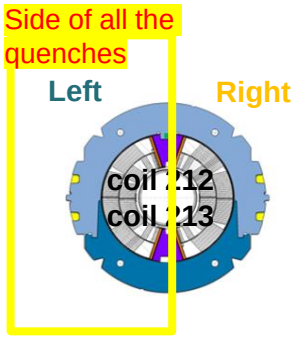
Coil 213: surface defect (unknown origin)

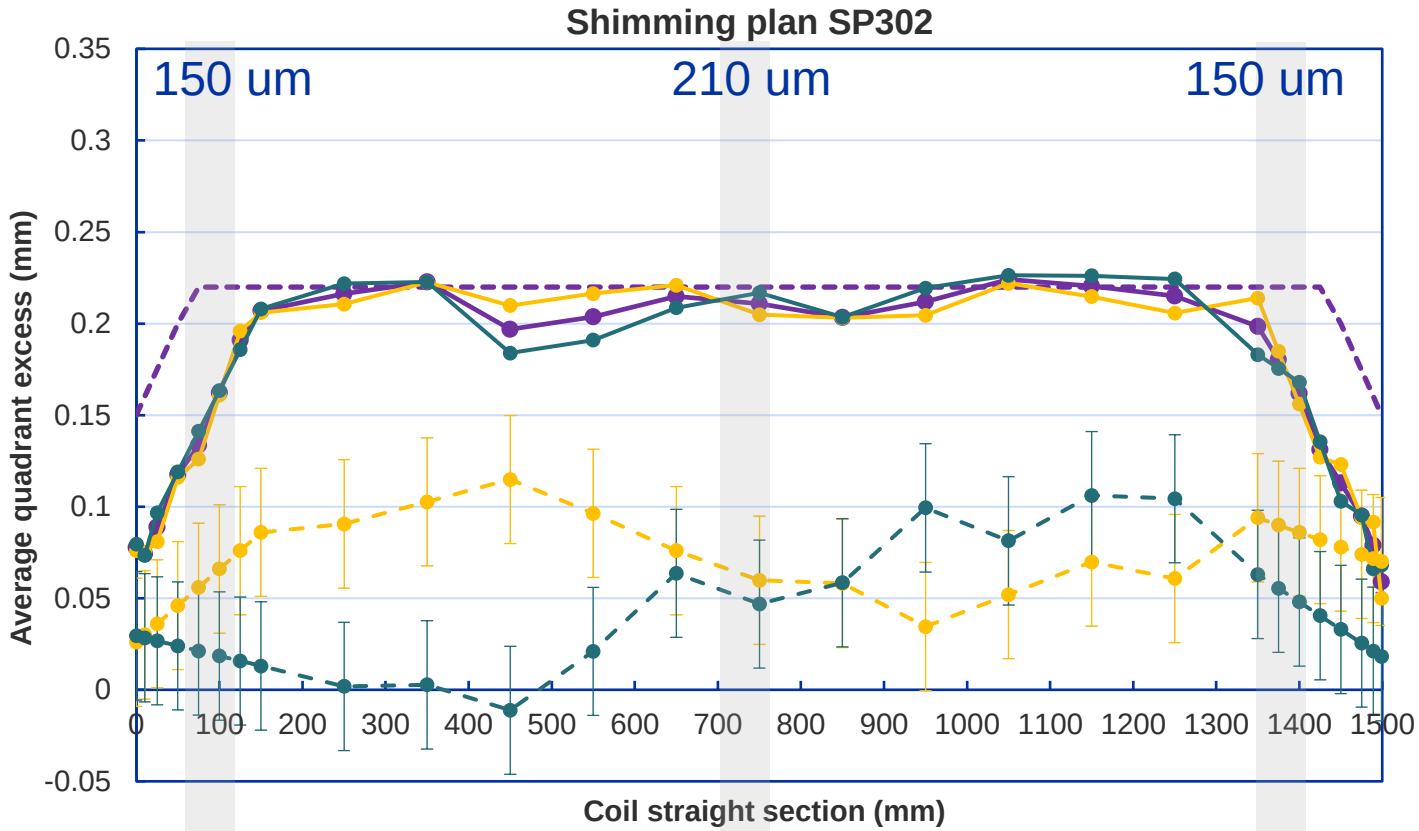


Coil second visual inspection: visible cable that has not been fixed/repaired during assembly.

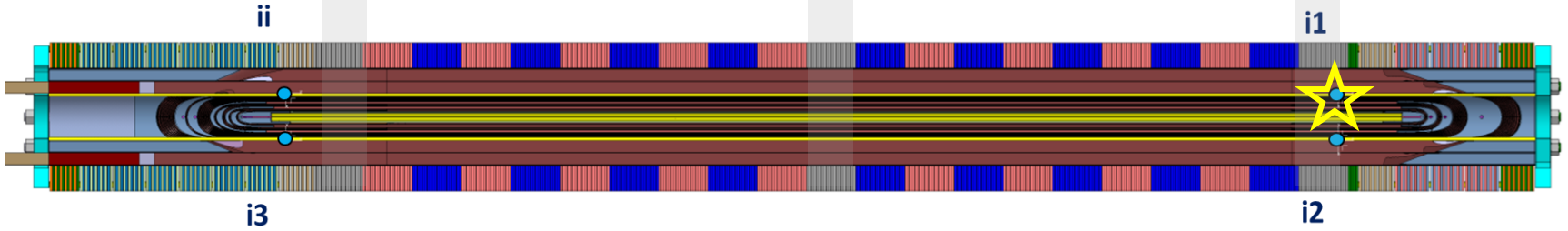


- Shimming plan and stresses during final collaring SP302

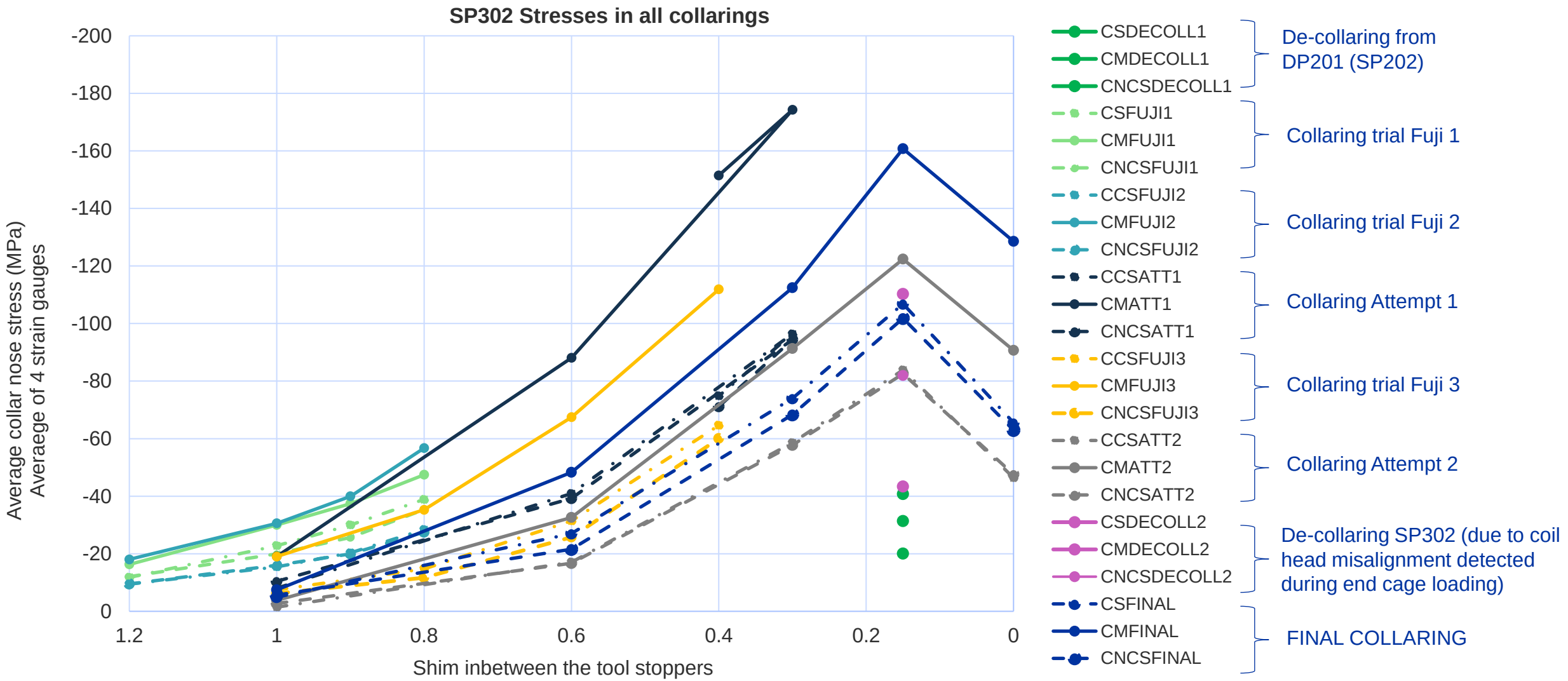




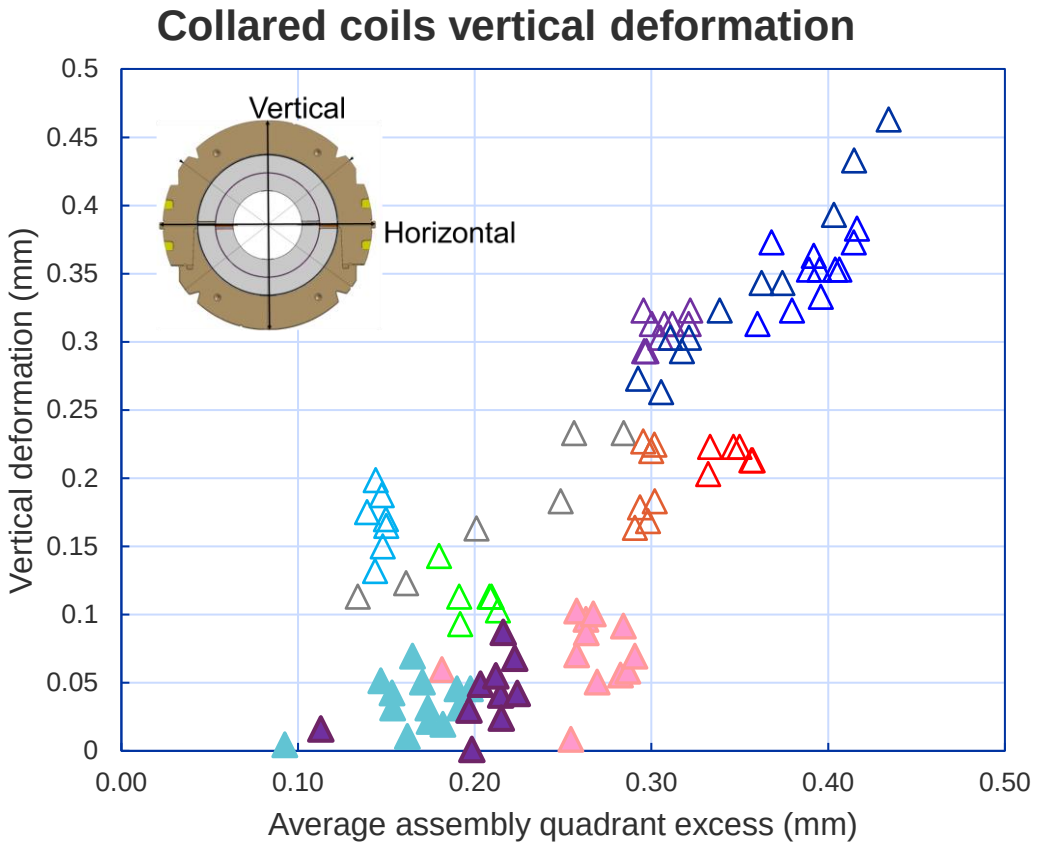
Collaring force: 4.5 kN (center) 4 kN (CS and NCS)
Metrology error 70 um. Reference [3]

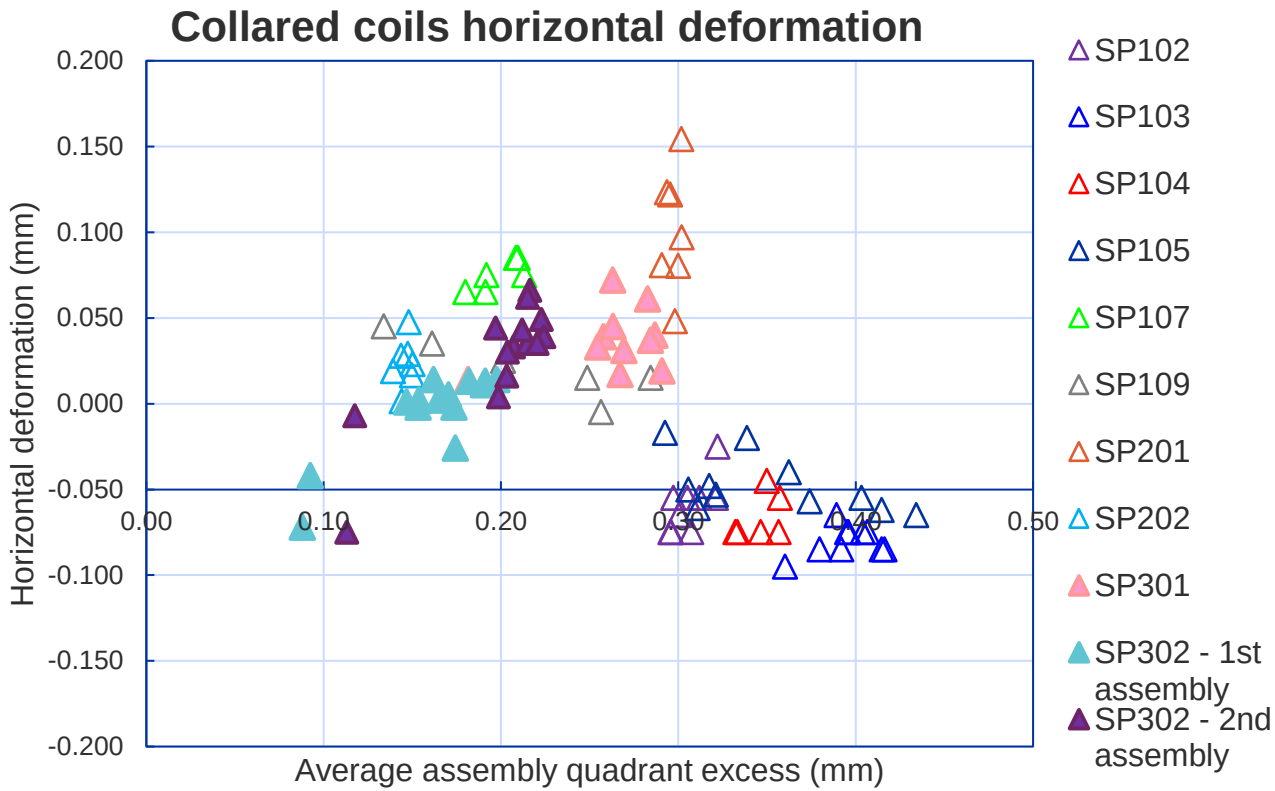


- Stresses during all the collarings done in SP302



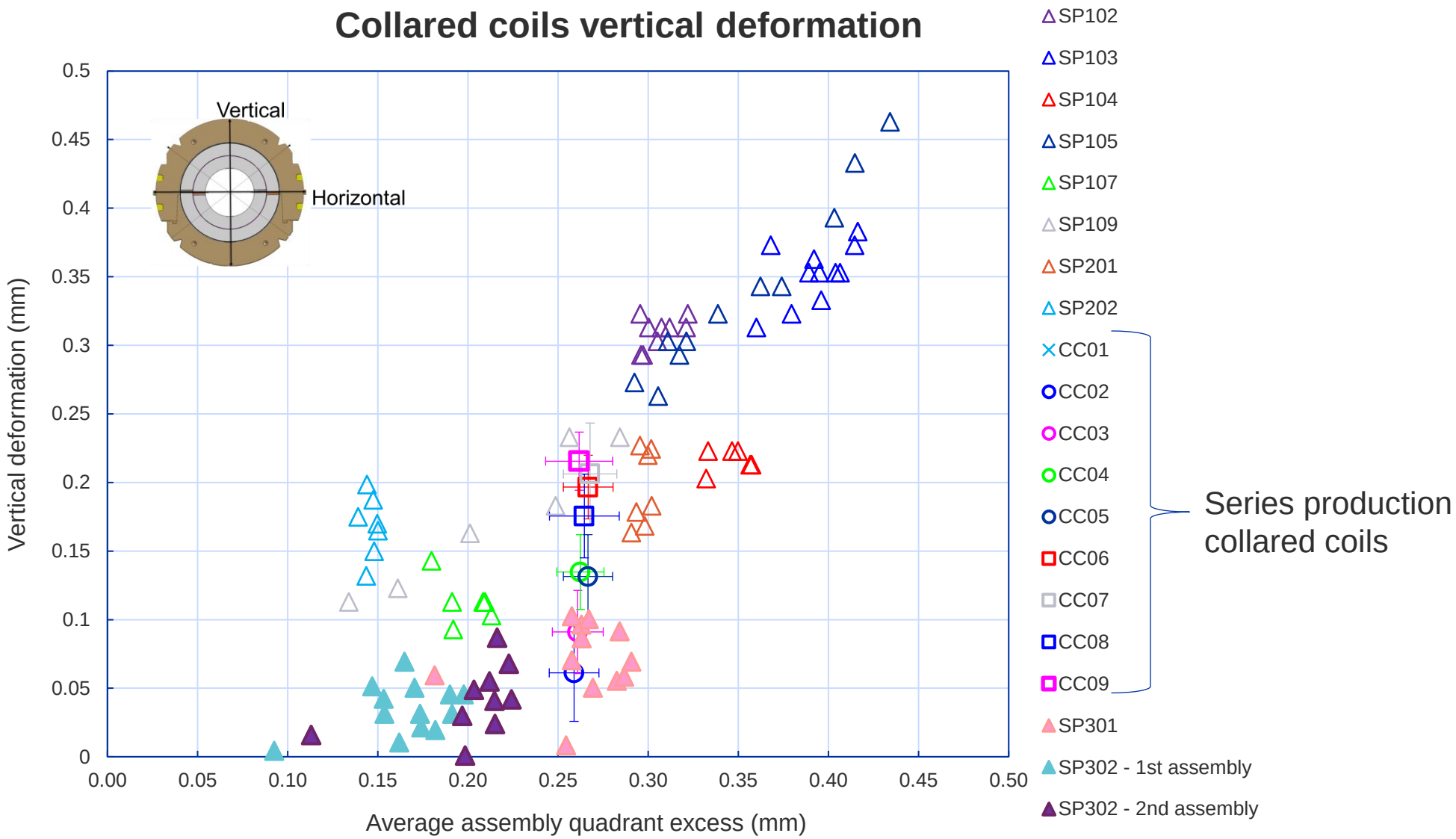
3. Collared coil oversize





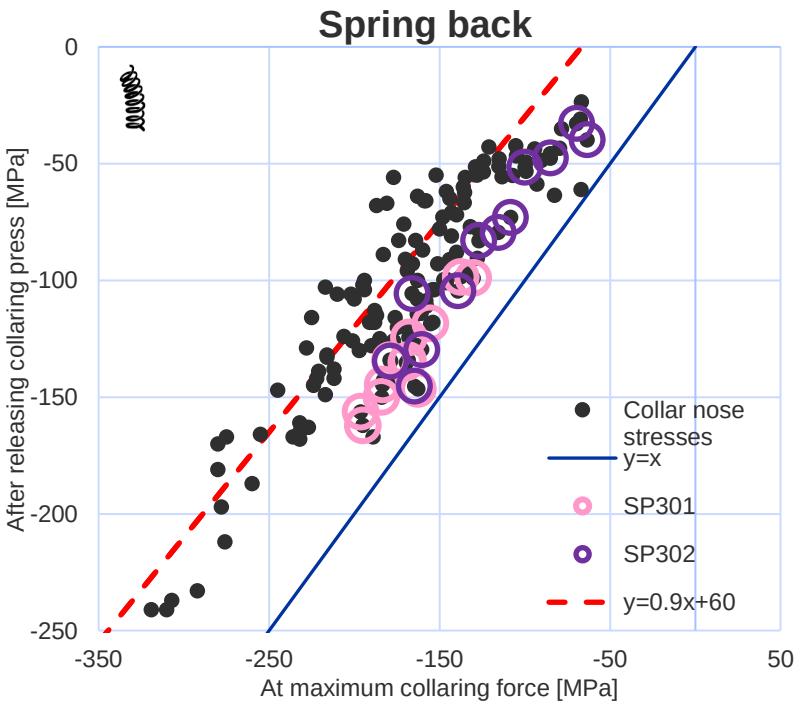
- MBHDP301 was measured with the LMF tool with LVDTs. The rest of the models were measured with vertical tower.
- A comparison of collared coil measurement methods (Dariusz Pulikowski) was done in the 11T Dipole Technical Meeting #21. It was found a deviation of 20-40 um in vertical and 50-70um in horizontal, the bigger values were obtained with the vertical tower.

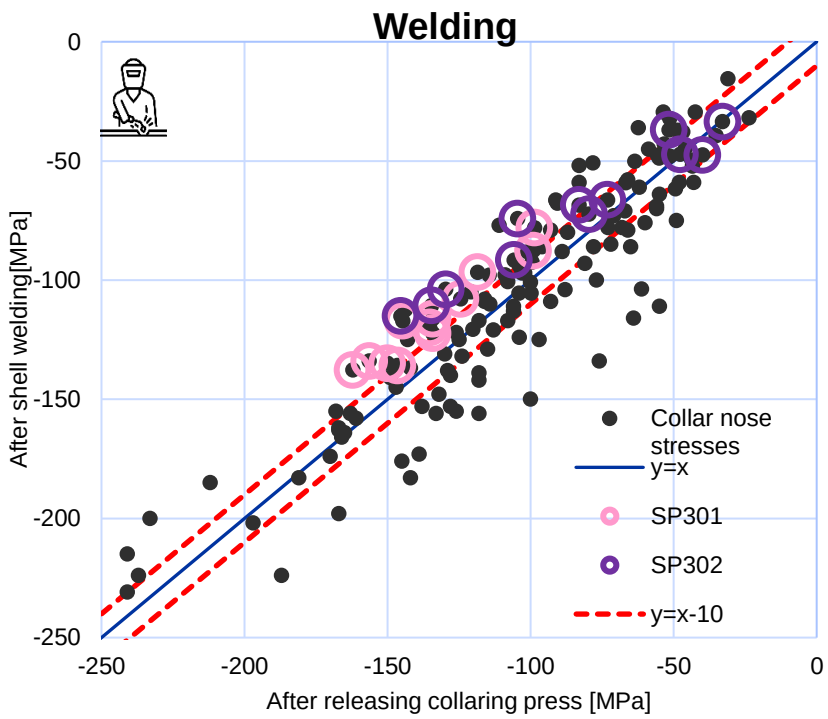
3. Collared coil oversize

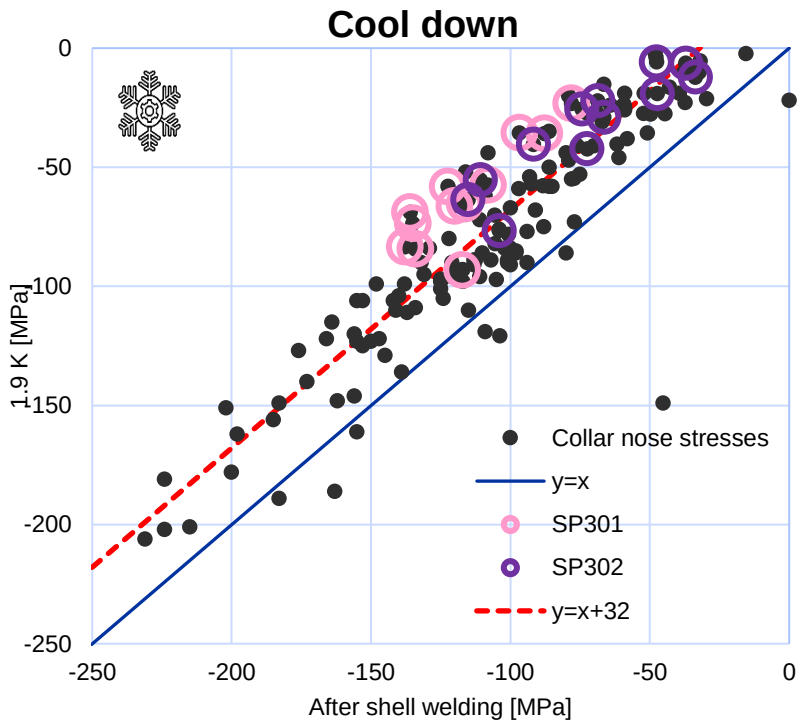


4. Azimuthal stresses

- Stress release at spring back, welding and cool down compared with the previous 11Tesla models



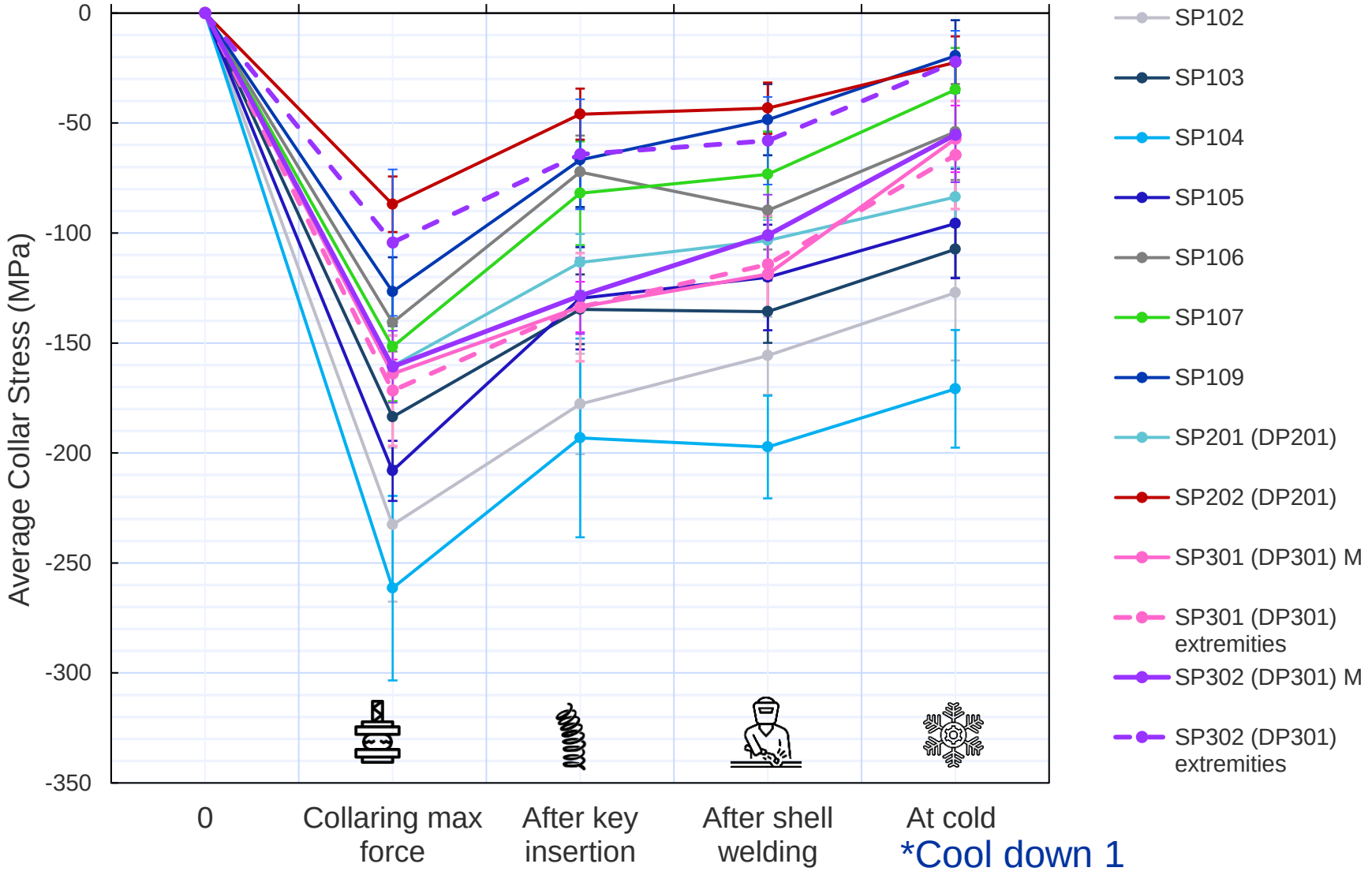




Plot from reference [1]

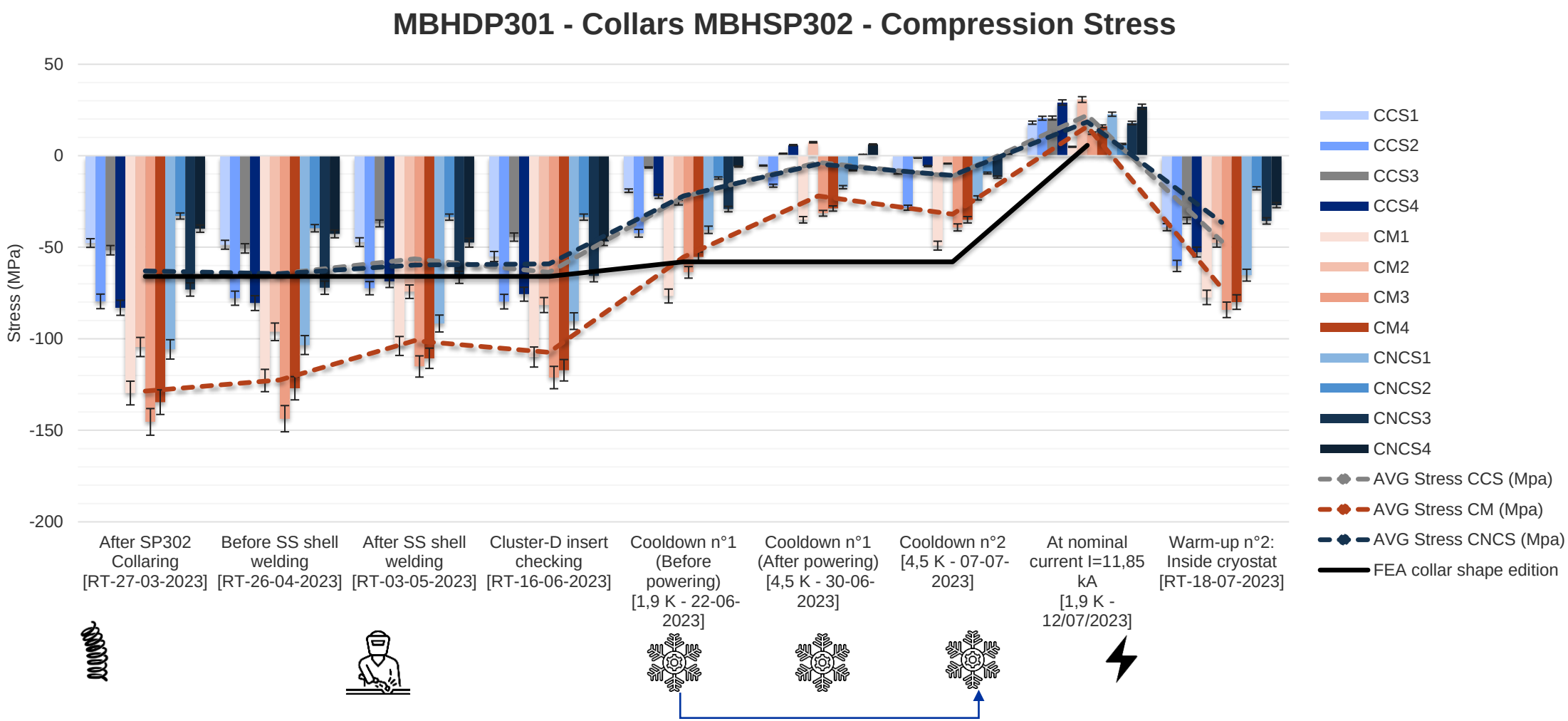
- Stresses at spring back, welding and cool down

Visible effect of the stainless steel pole (delta cool down higher than in the previous models)

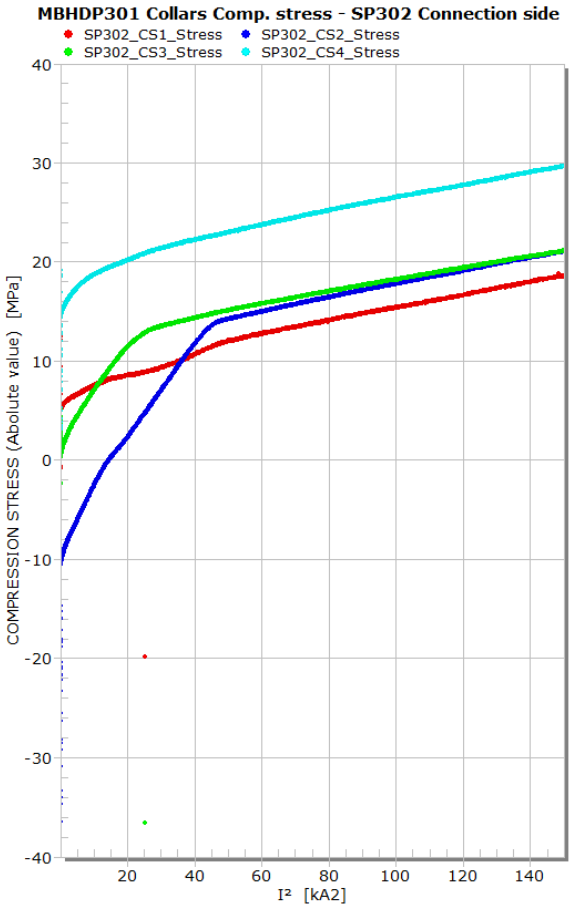


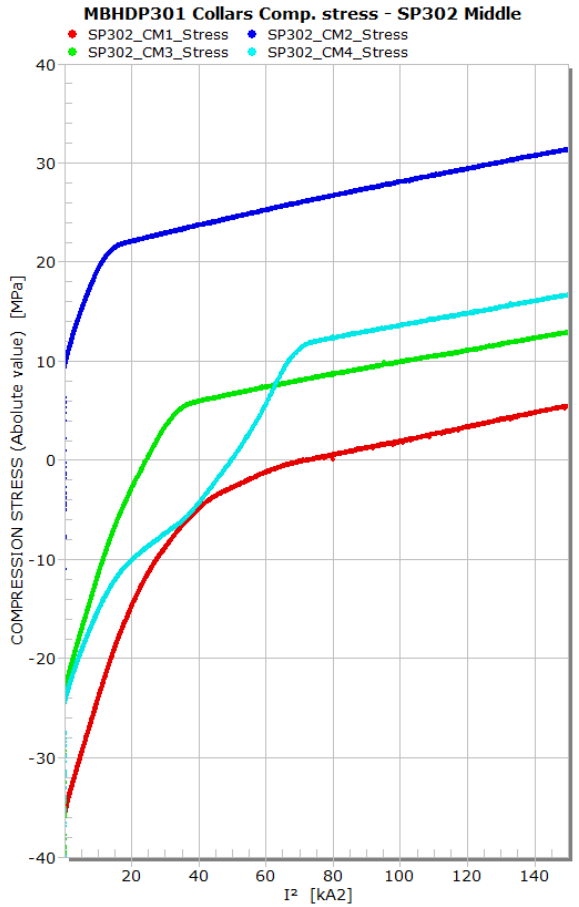
Plot from reference [1]

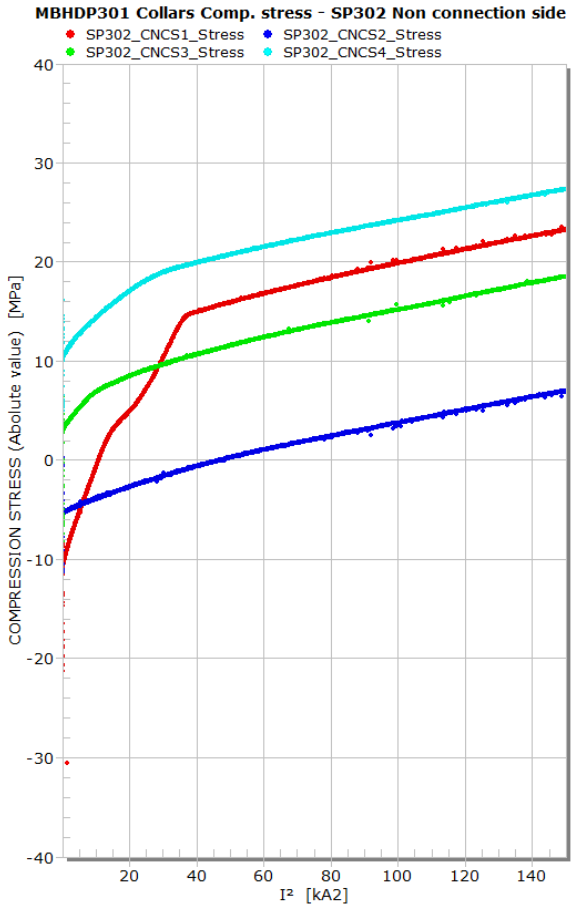
- Stresses in all steps in SP302 with the FEA values updated with the change of shape in the collar nose.
  Important: in the 3D FEA the excess is 300 um and in SP302 is 220 um (middle section, CM) and 150 um in the extremities (CS and NCS).



- Collar nose stresses at powering of SP302





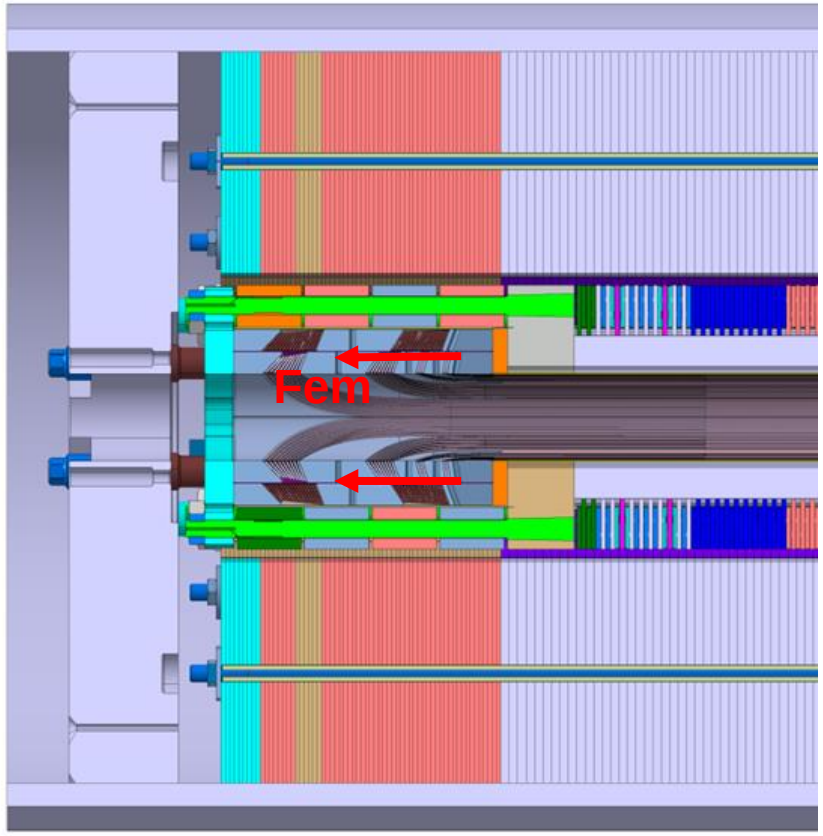


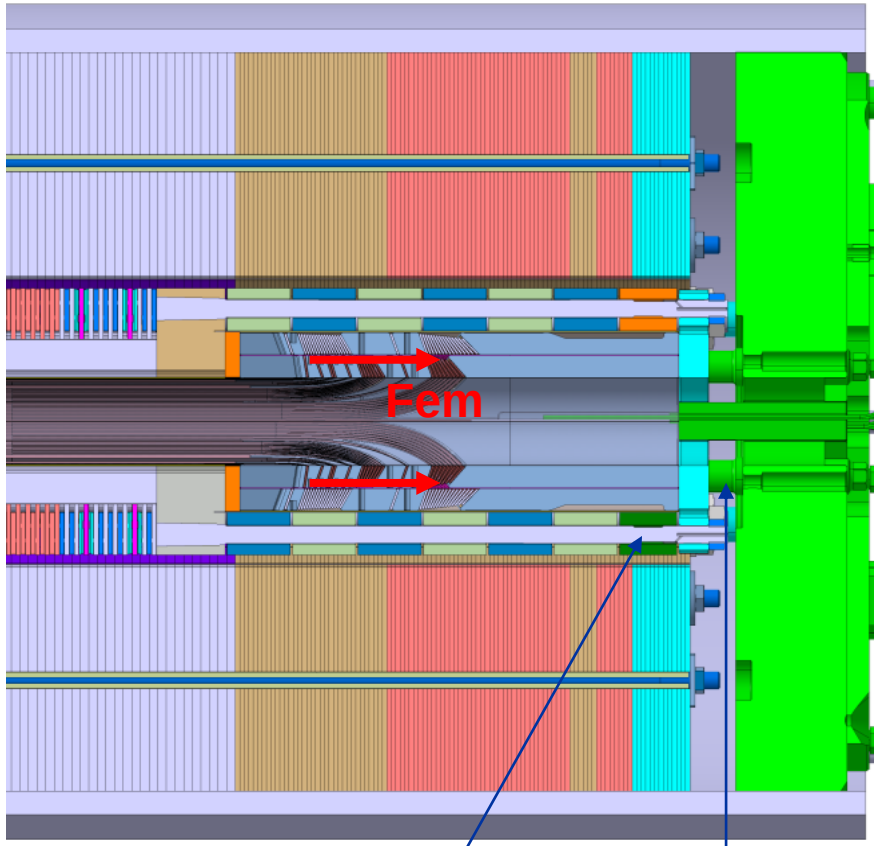
- All the collars are in traction during powering.
- Stable system, same slope in the three sections.
- Change in slope function of the stress before powering and the delta stress.

ΔStress~30 MPa
ΔStress~15 MPa
ΔStress~20 MPa
ΔStress~15 MPa

ΔStress~20 MPa
ΔStress~40 MPa
ΔStress~35 MPa
ΔStress~40 MPa

ΔStress~8 MPa
ΔStress~15 MPa
ΔStress~15 MPa
ΔStress~35 MPa





3. Longitudinal forces

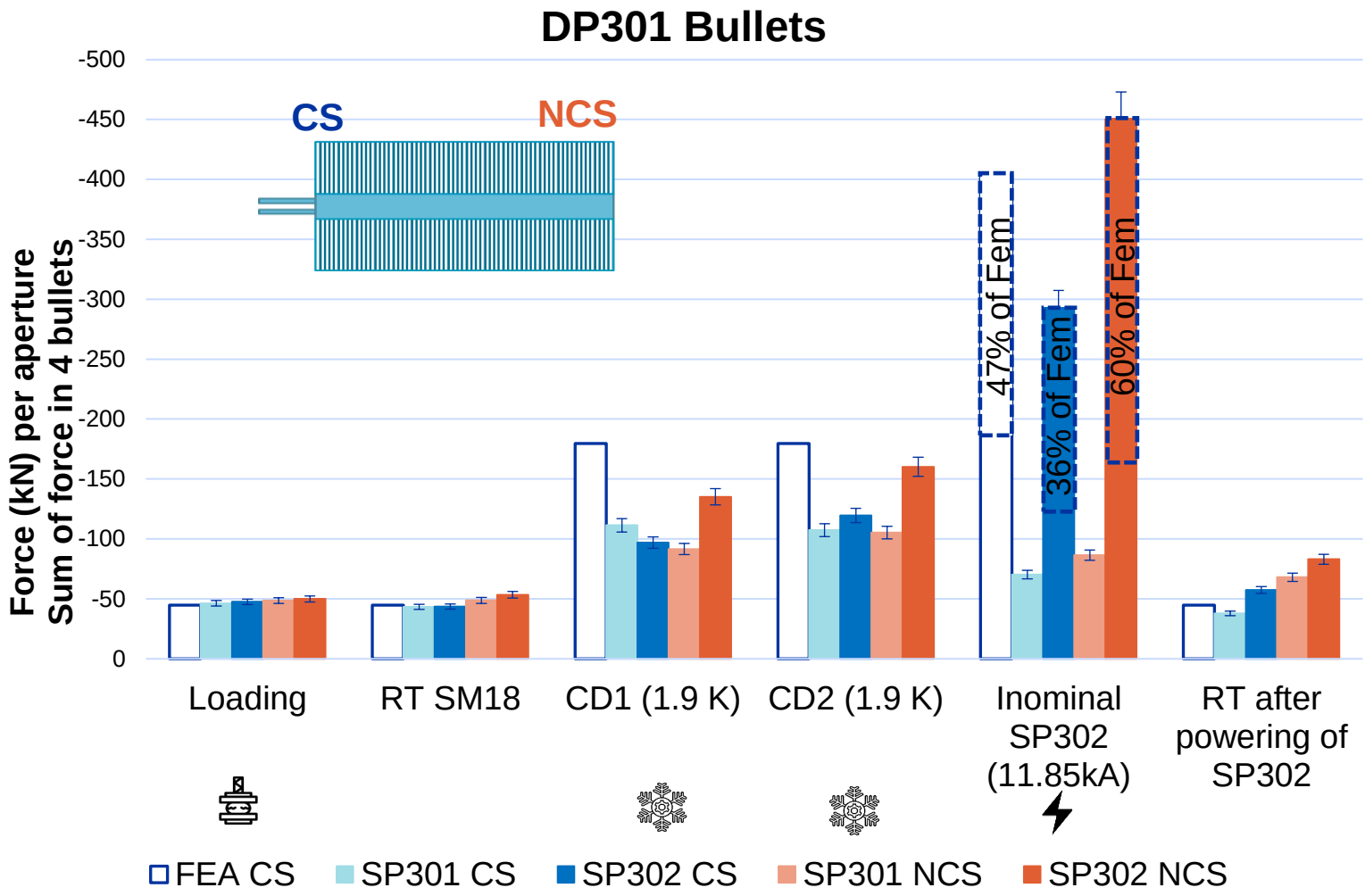
Bullet gauges analysis

- **Longitudinal electromagnetic force** from Roxie in connection side and at nominal current are **477.6 kN per collared coil** (page 15 in Mitigation solutions report).

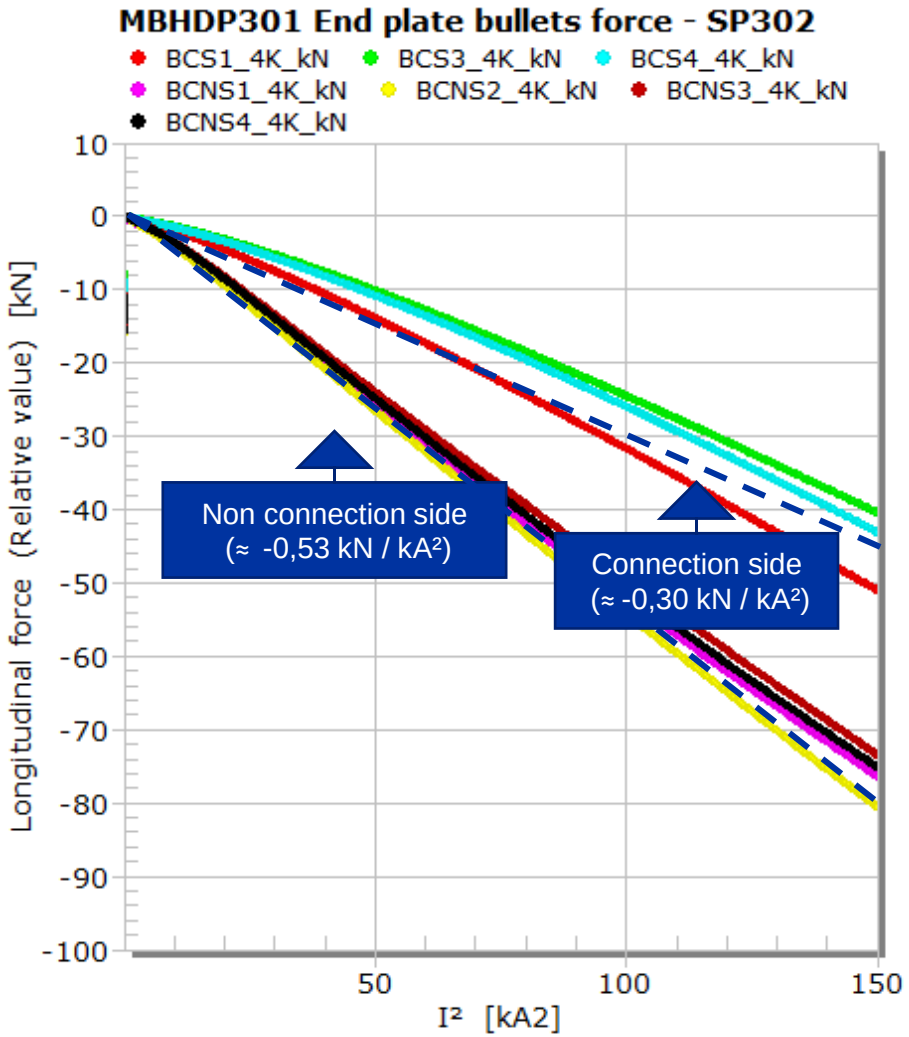
- **Buller preload with 48KN/collared coil** which is 10% of longitudinal electromagnetic force at nominal current.

- **Cool down**. Increase of 50-80 kN per aperture.

- **Powering at Inominal of SP302:**
  - Average of 50% of electromagnetic forces transferred to SP302 bullets. The rest is hold by friction and coil longitudinal stiffness. Similar values with respect to the double aperture magnets without end cage [2].
  - Lost of compression in the non-powered aperture.

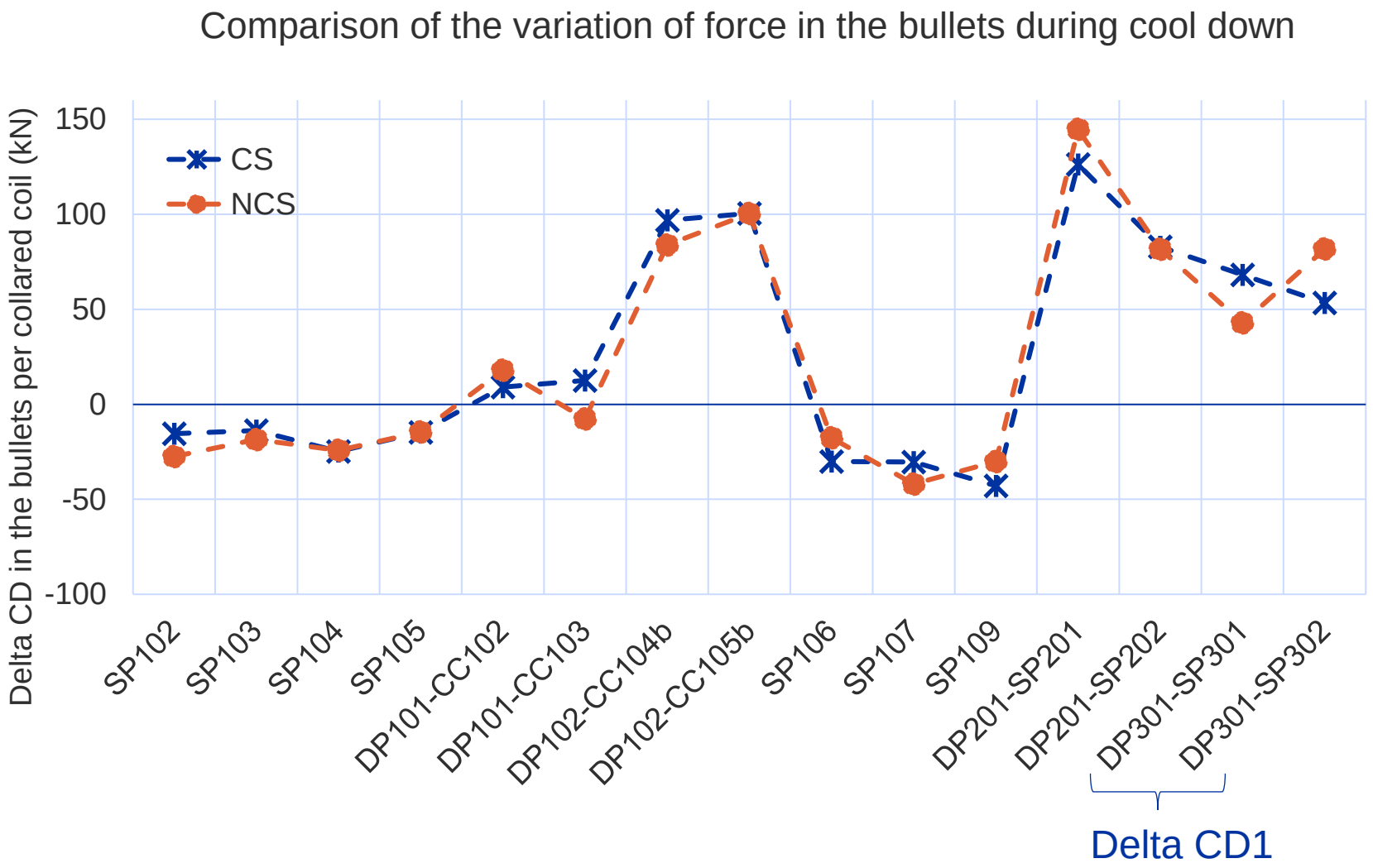


- Bullet gauges analysis at Imax (relative values)



- Higher slope in non connection side, consistent with previous double aperture models [1].
- This phenomenon could be attributed to the longer length of the connection side, leading to a higher amount of force being dissipated due to friction.

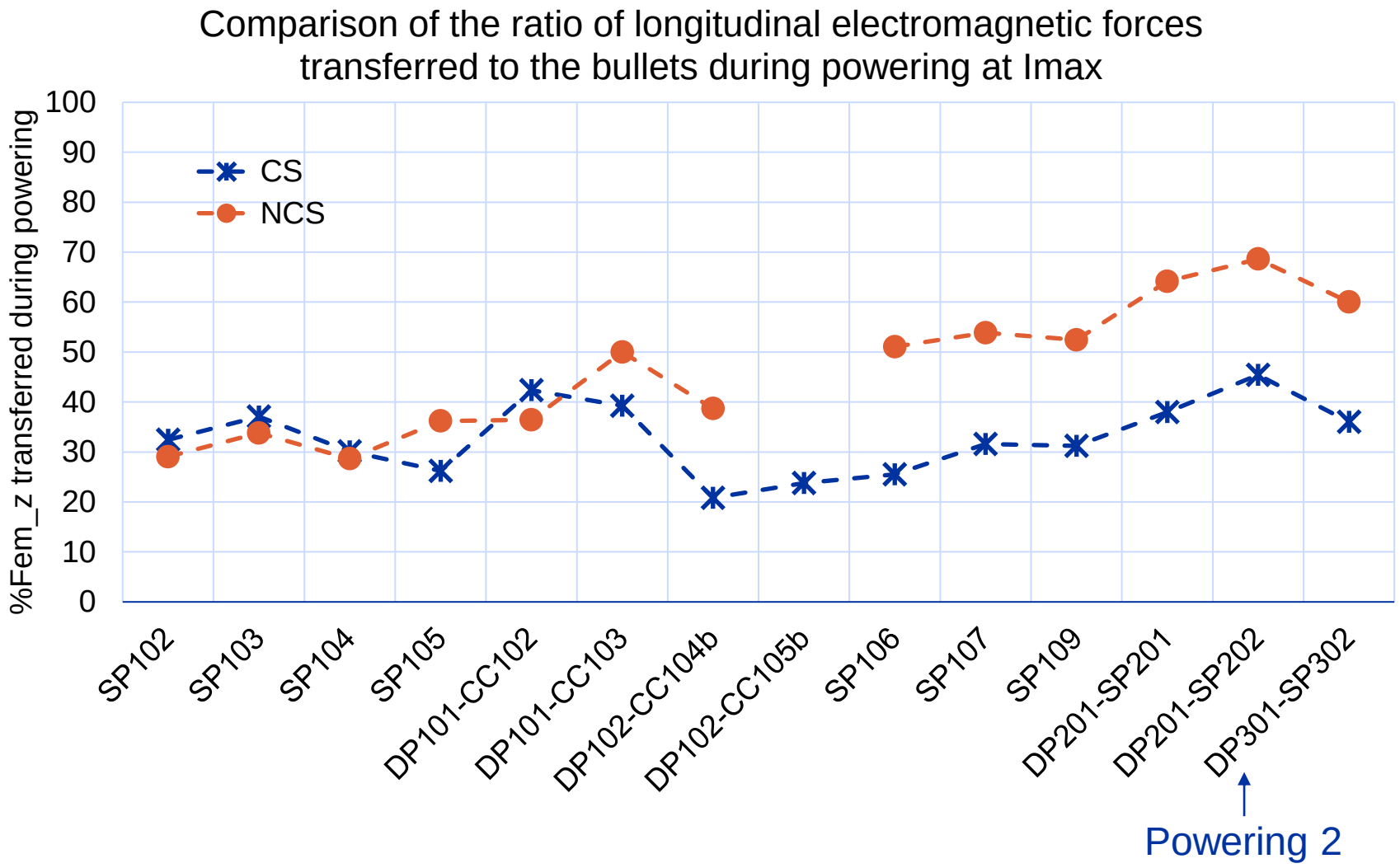
- Bullet gauges cool down – comparison with other models



No clear tendency for the delta cool down:

- SP301 bigger delta in connection side.
- SP302 bigger delta in non connection side.

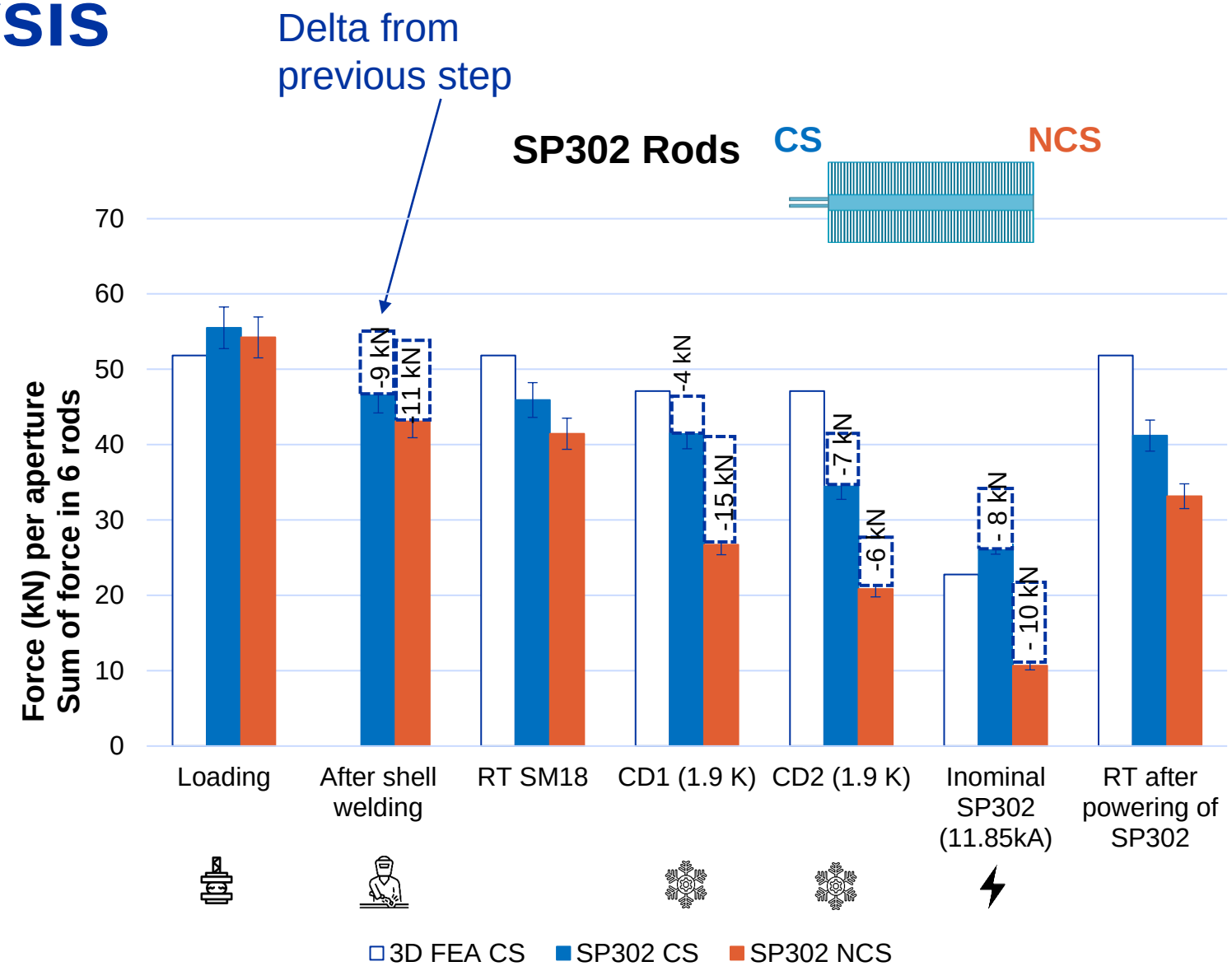
- Bullet gauges powering – comparison with other models



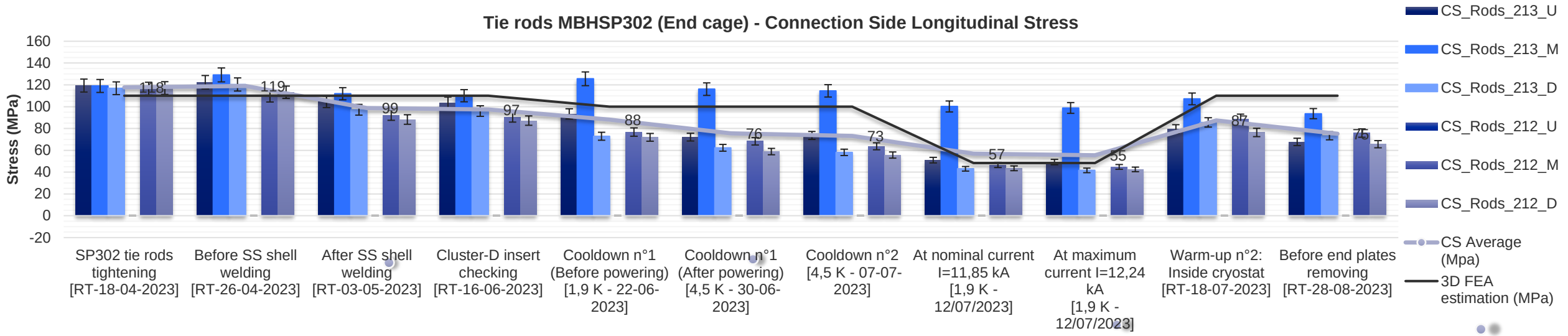
From DP102 average difference in electromagnetic forces transferred to the bullets CS and NCS of 25%

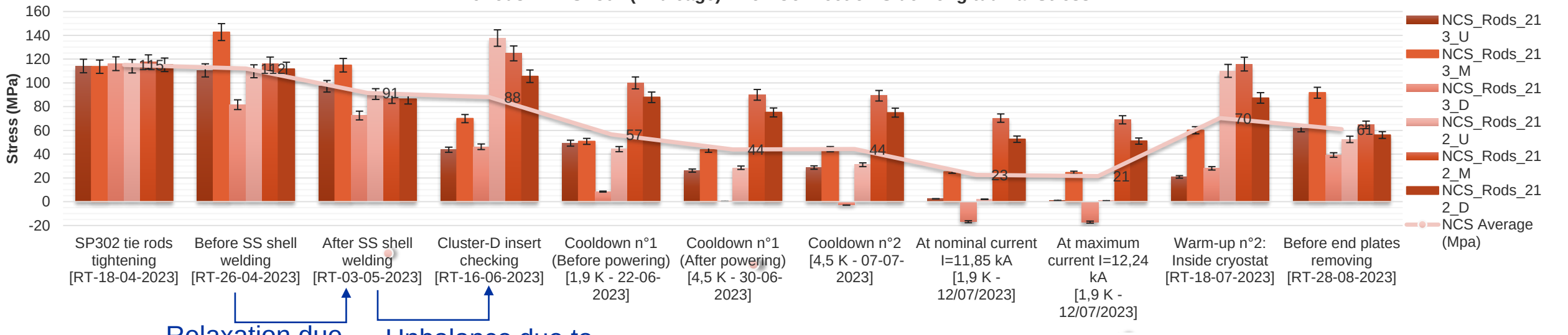
End cage rods analysis

- **Preload the collared coils with 55kN** (12% of longitudinal electromagnetic force at nominal current).
- Loss of tension after shell welding.
- **Cool down.** Higher relaxation in non connection side (-15kN) compared to the connection side (-4kN), that may be attributed to differences in length of the rods and coil head.
- **During powering at Inominal**. Slightly higher relaxation in non connection side.
- **Final warm up**. The system doesn't fully recover the initial tension applied. By the end of the process, it retains approximately 60-70% of the initial tension.



- Stresses in all steps rods

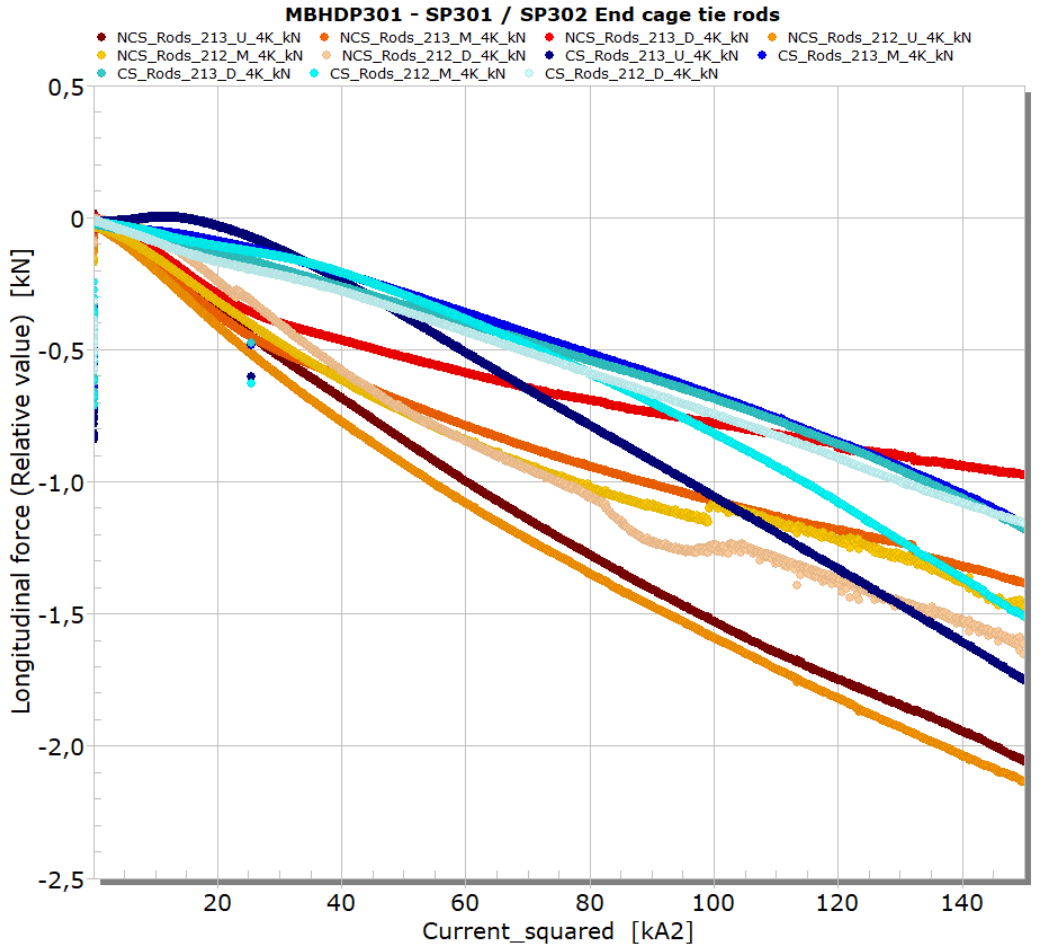




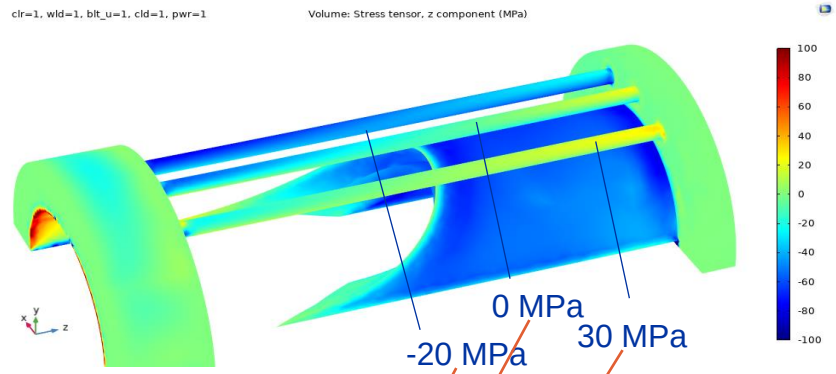
Relaxation due to welding

Unbalance due to transport

- End cage rods during powering (relative values)

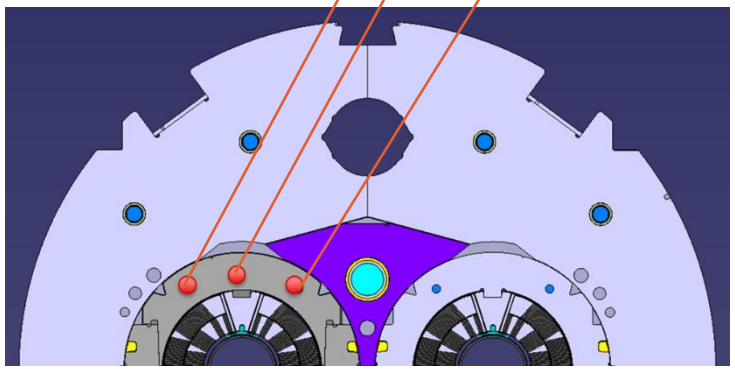


High unbalance in stresses during powering, in between the rods and along the length of one rod



Images courtesy Marco Morrone and Cedric Garion

Not uniform stress
Local values



- Similar slope in both sides (CS and NCS)

Conclusion

Assembly SP302

- The cover of visible conductor in the mid-plane may not be the optimal solution, as it adds extra thickness to this area.

Azimuthal stresses in SP302

- Notable impact of the stainless steel pole is observed after the cooling phase in comparison with the titanium pole in previous models.
- Stress loss occurs between the first and second cooling.
- All the collars are in traction during powering.

Longitudinal forces

- The gain in compression in the bullets and the lost in tension in the rods is, in both cases, higher in the non-connection side compared to connection side. Same pattern during the powering phase.

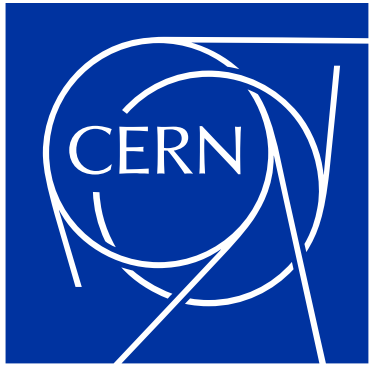
References

[1] S. Izquierdo et al., "Mechanical analysis of the Nb3Sn 11 T dipole short models for the High Luminosity Large Hadron Collider"

[2] E. Gautheron *et al*., "Pre-Load Studies on a 2-m Long Nb3Sn 11 T Model Magnet for the High Luminosity Upgrade of the LHC“

[3] J. Ferradas Troitino *et al*., "Applied Metrology in the Production of Superconducting Model Magnets for Particle Accelerators"

Thank you



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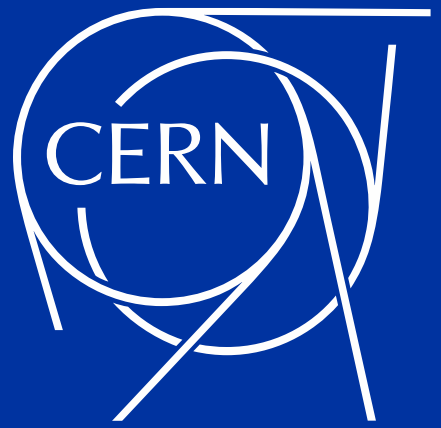
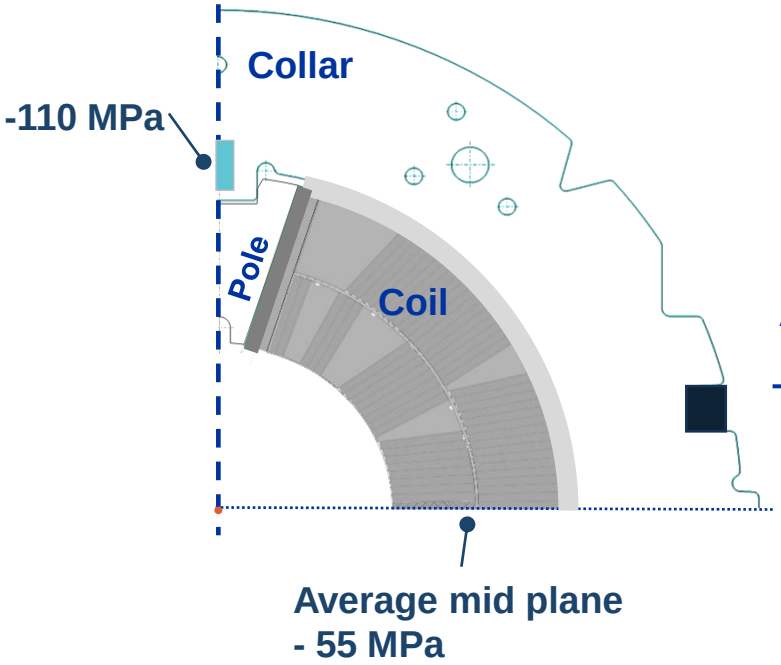


Back up slides

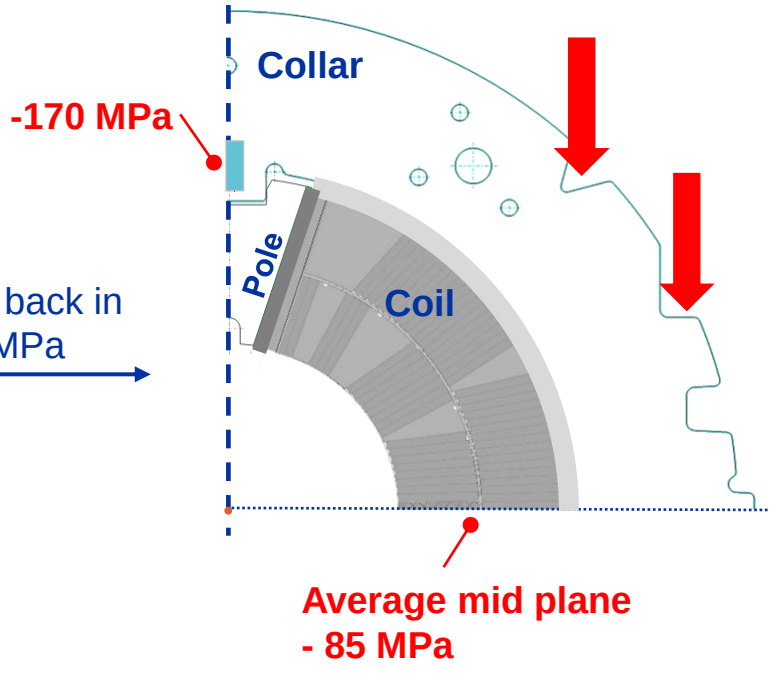
- Collaring target values with 300 um of excess:

With the keys inserted



AVG spring back in models 60 MPa

At maximum collaring force (key clearance of -0.15 mm)



To have the mid plane peak stresses under 150 MPa

IEEE Xplore Full-Text PDF:

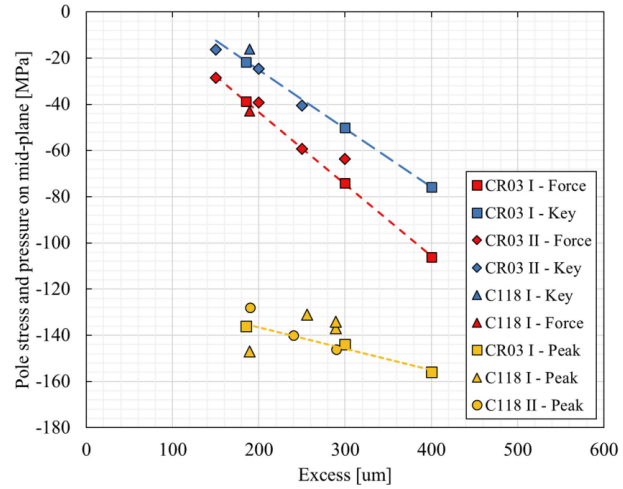
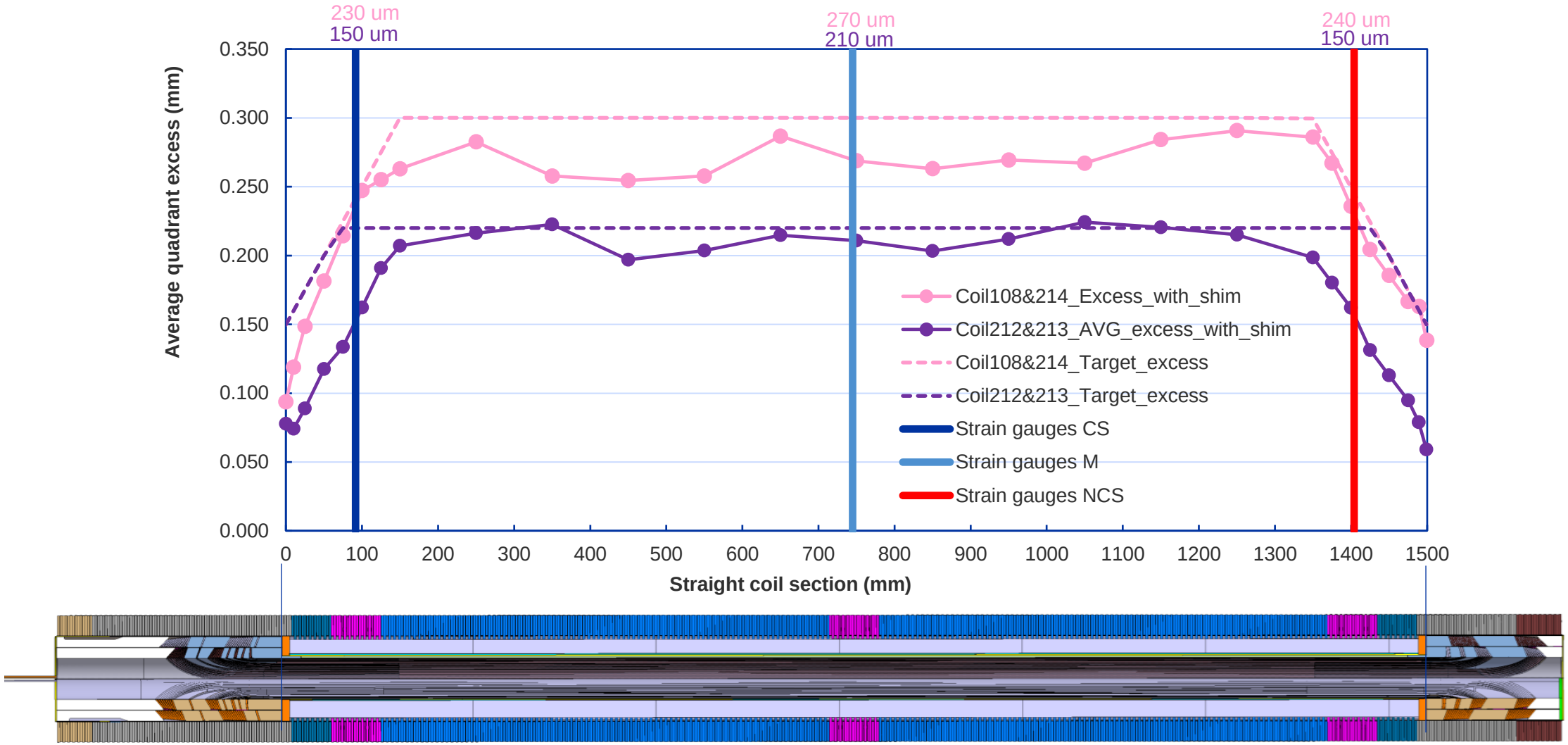


Fig. 6. Azimuthal stress in the removable pole vs vertical (or radial) stress in the collars: measurements and liner fit.

- Shimming plan and stresses during final collaring SP301



- Collaring

- We did 3 collaring test and 3 collaring trials per aperture.

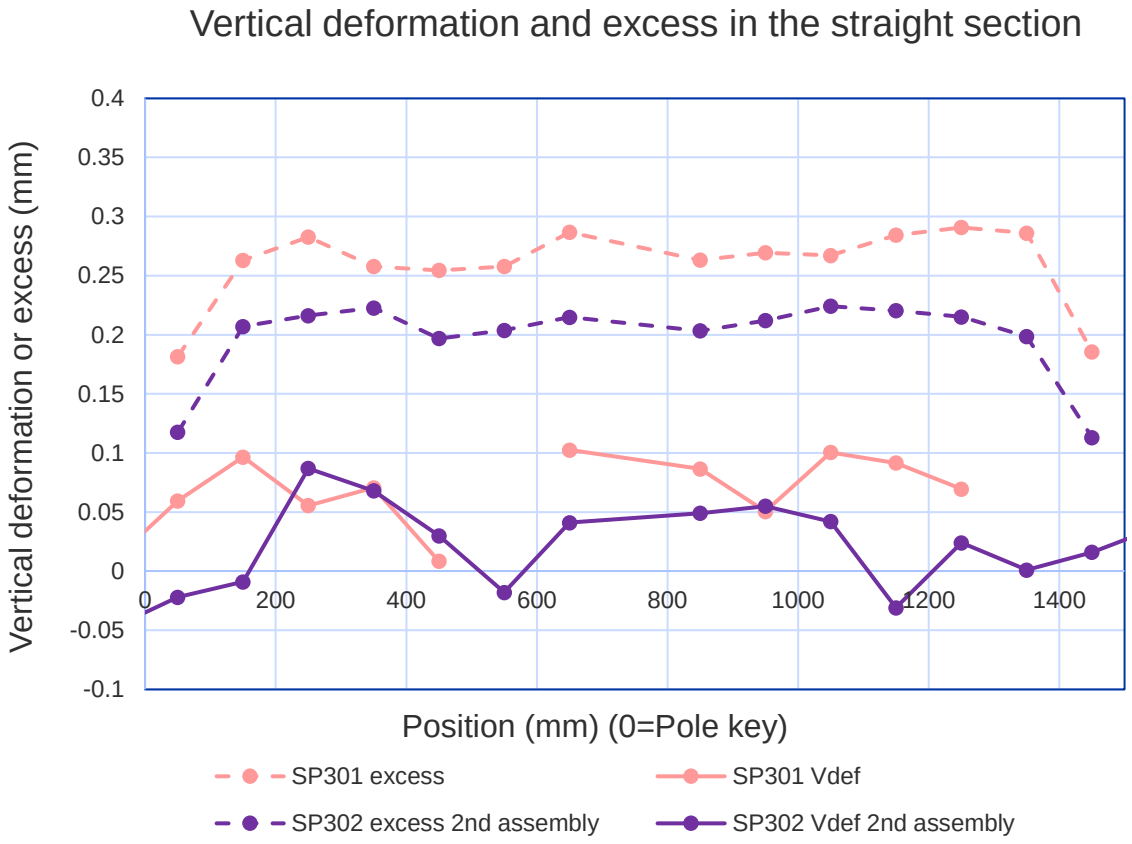
- The **maximum stress** reached during all the collarings is:
  - SP301: -196 MPa in CS during final collaring
  - SP302: -189 MPa in CM during attempt 1

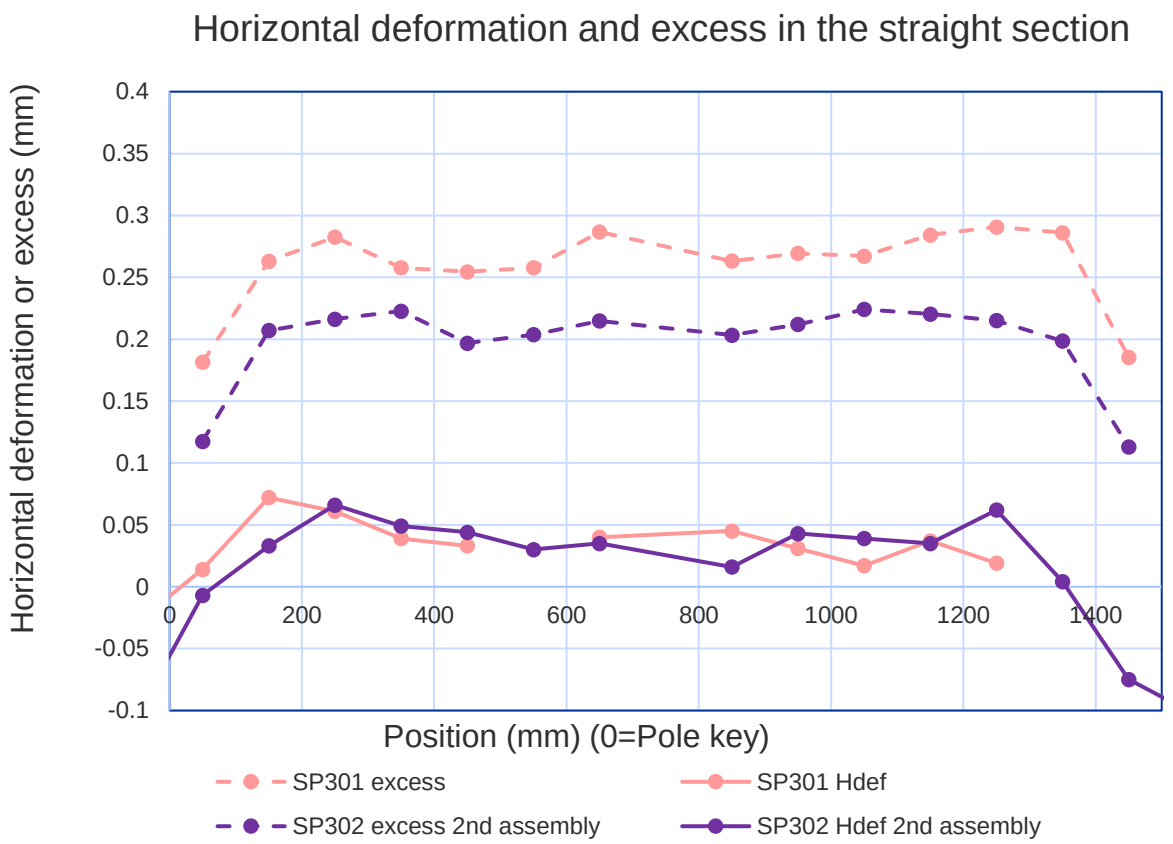
- The **spring back** is 30 MPa in average.

- **The final pre-stress after collaring is:**

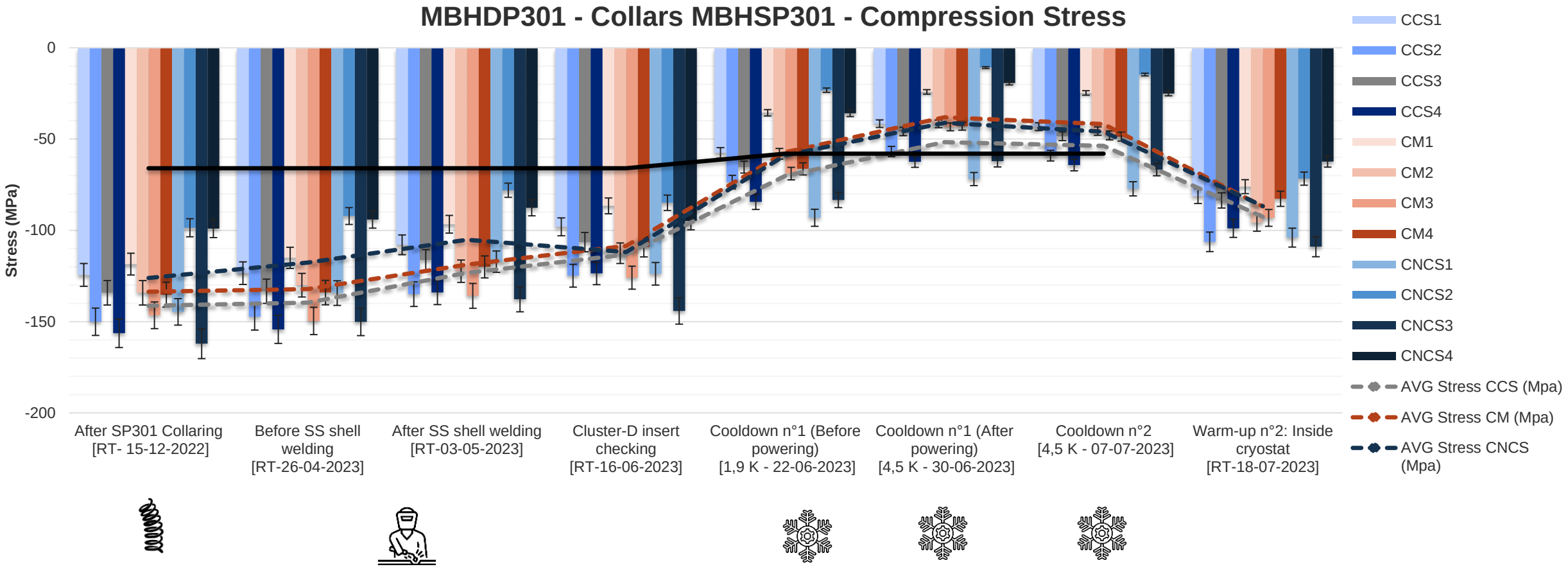
Excess and pre-stress			
Aperture	Connection side	Middle (MPa)	Non connection side (MPa)
SP301	-140 MPa	-130 MPa	-125 MPa
	230 um	270 um	240 um
SP302	-65	-130	-65
	150 um	210 um	150 um

- Collared coil deflection along the CC legnth





- Stresses in all steps SP301. With the FEA values updated with the change of shape in the collar nose.
  Important: in the 3D FEA the excess is 300 um and in SP301 is 270 um (middle section, CM) and 230 um in the extremities (CS and NCS).



- Stresses in all steps bullet gauges