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Mechanical analysis of MBHDP301b assembly and test

Carmen Abad on behalf 11Tesla team

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1. Introduction

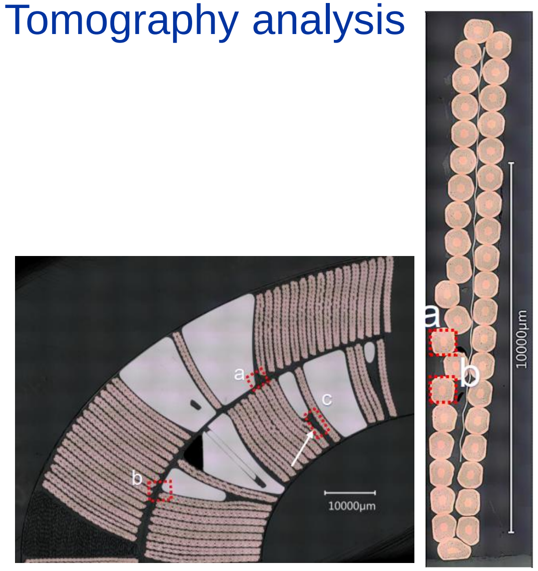
Context

After the test of four 11T series magnets (S1, S2, S3, S4), three of them showed performance degradation and the quenches were localized primarily in the coil heads. These results led to the decision not to install the 11T magnets during Long Shutdown 2 (LS2) and to reassess the next steps. Subsequent research metallographic analysis and comparison with a 3D FEA analysis [1] revealed high stress areas in the coil ends, that correspond to the quench localizations in S2 and S4. Tomography analysis showed strand pop outs.

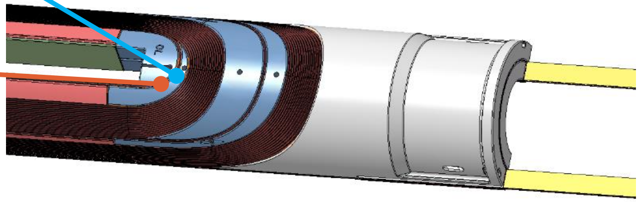
Two types of issues were identified, internal to the coils and external to the coils. The internal are outside of the scope of this study because they can't be addressed without manufacturing new coils. The external identified are:

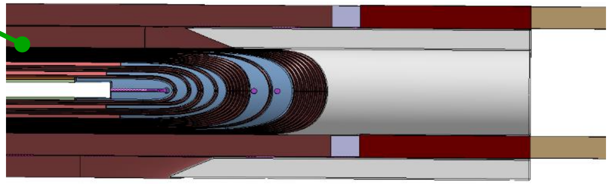
1. High stressed areas and stress singularities **after collaring** in the coil outer layer's first turn.
2. High stressed areas and stress singularities **after cool-down** in the coil outer layer's first turn.
3. High peak stresses **during powering** in the coil inner layer turns.
4. **Non-optimal coil end support** for the electromagnetic axial force difference in between the blocks.
5. **Non-optimal axial loading**. S2 & S3 cold masses had a loosened and deformed axial loading screw (bullet).

Tomography analysis



C-MAC - Review of the 11 T magnet programme - Rehearsal (February 25, 2021) · Indico (cern.ch)





Magnet new mechanical features

To assess the high stressed areas, new mechanical features are installed in a double aperture hybrid prototype.

Mitigation measures 1 (Aperture 1, **SP301**)

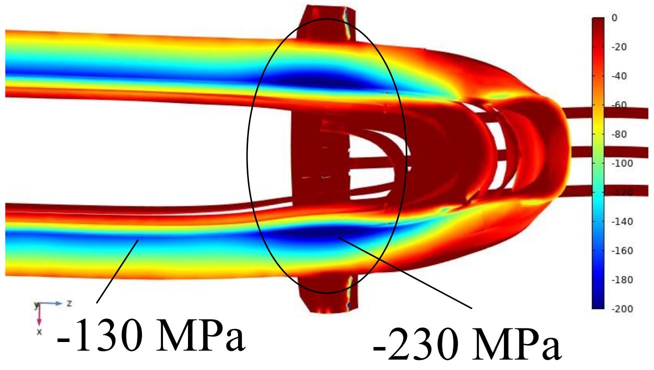
- New shimming plan with excess reduction in the ends.
- Pole material change from Titanium to austenitic Stainless Steel.
- With these two new features a reduction of the high peak stresses during powering is observed in the 3D FEA [1].

Mitigation measures 2 (Aperture 2, **SP302**)

Mitigation measures 1 + end cage system

Objective: compact the head coil blocks during powering and improve the axial loading.

Drawback: azimuthal stress in coil inner layer increase at the position of the end cage



Courtesy of M. Morrone C. Garion

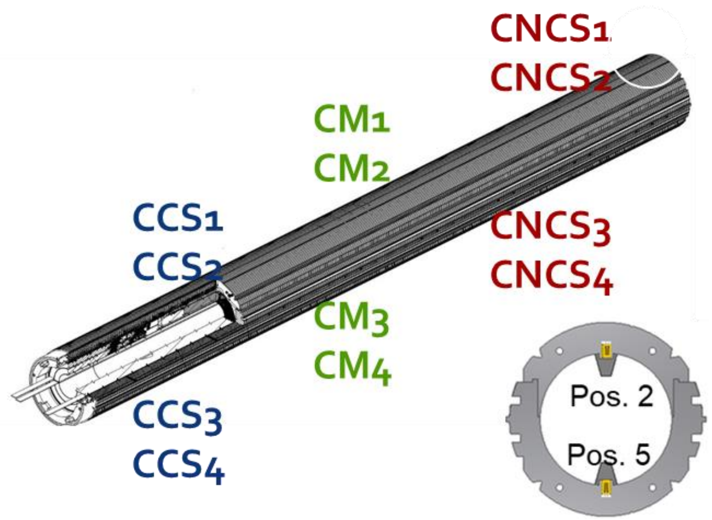
In previous models, the peak stresses on the mid plane has been found as one of the limitation for the coil performance [2].

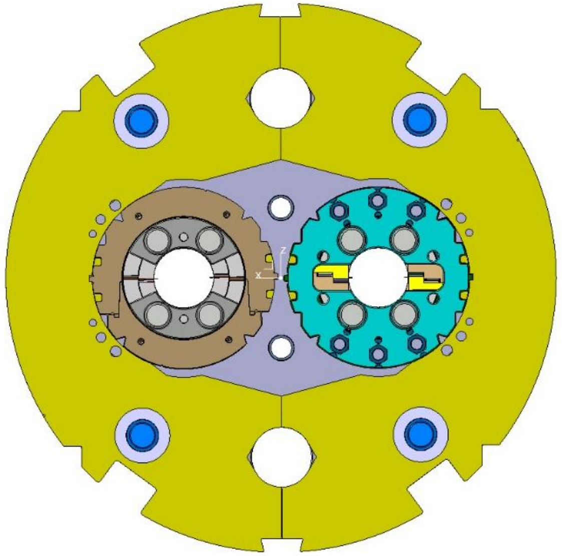
2. Magnet fabrication

Mechanical instrumentation

SP301

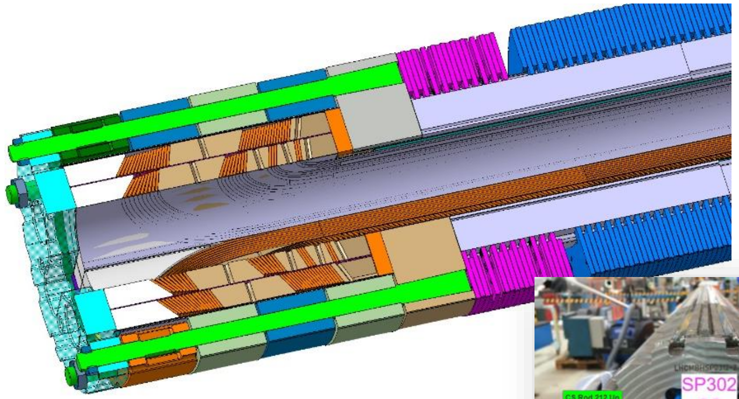
- 12 instrumented collars
  - 8 Bullet gauges

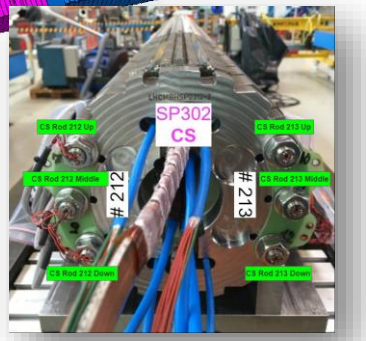




SP302

- 12 instrumented collars
  - 8 Bullet gauges
- 12 Tie rods (End cage)





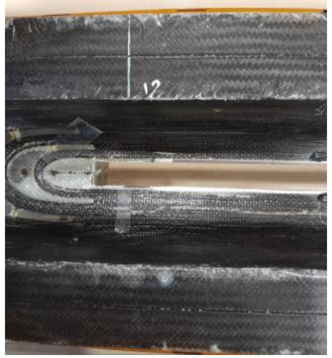
Courtesy of S. Mugnier EDMS #2711698

Coils

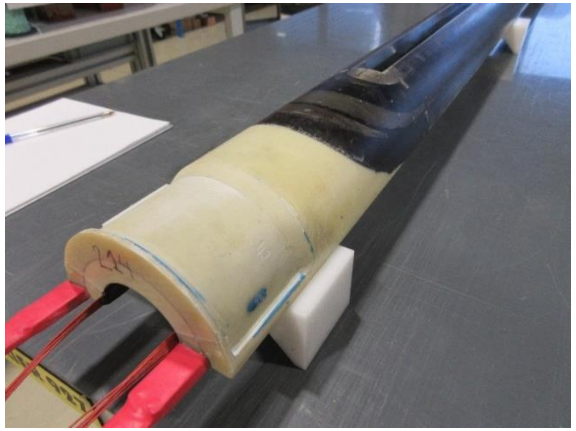
Discussed in https://indico.cern.ch/event/1326626/

SP301

Coil 108 - reused
1st generation, RRP cable



Coil 214 – new
2nd generation, PIT cable

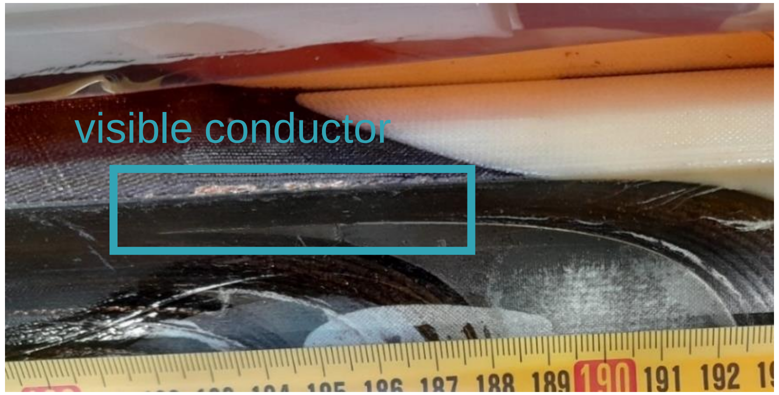


SP302

Coil 212 - reused
2nd generation, PIT cable

212 Mid plane left

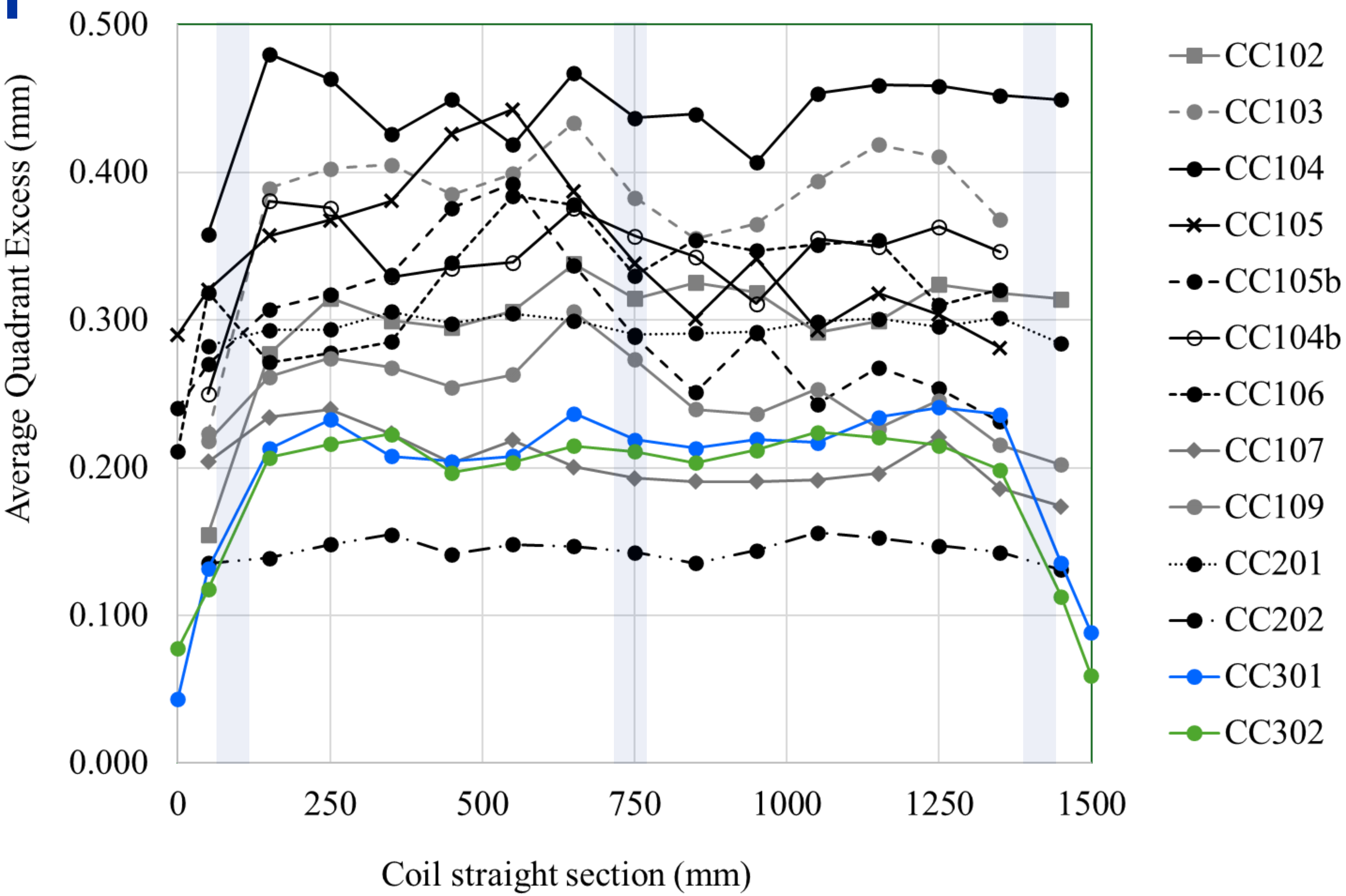
Coil 213 - reused
2nd generation, PIT cable



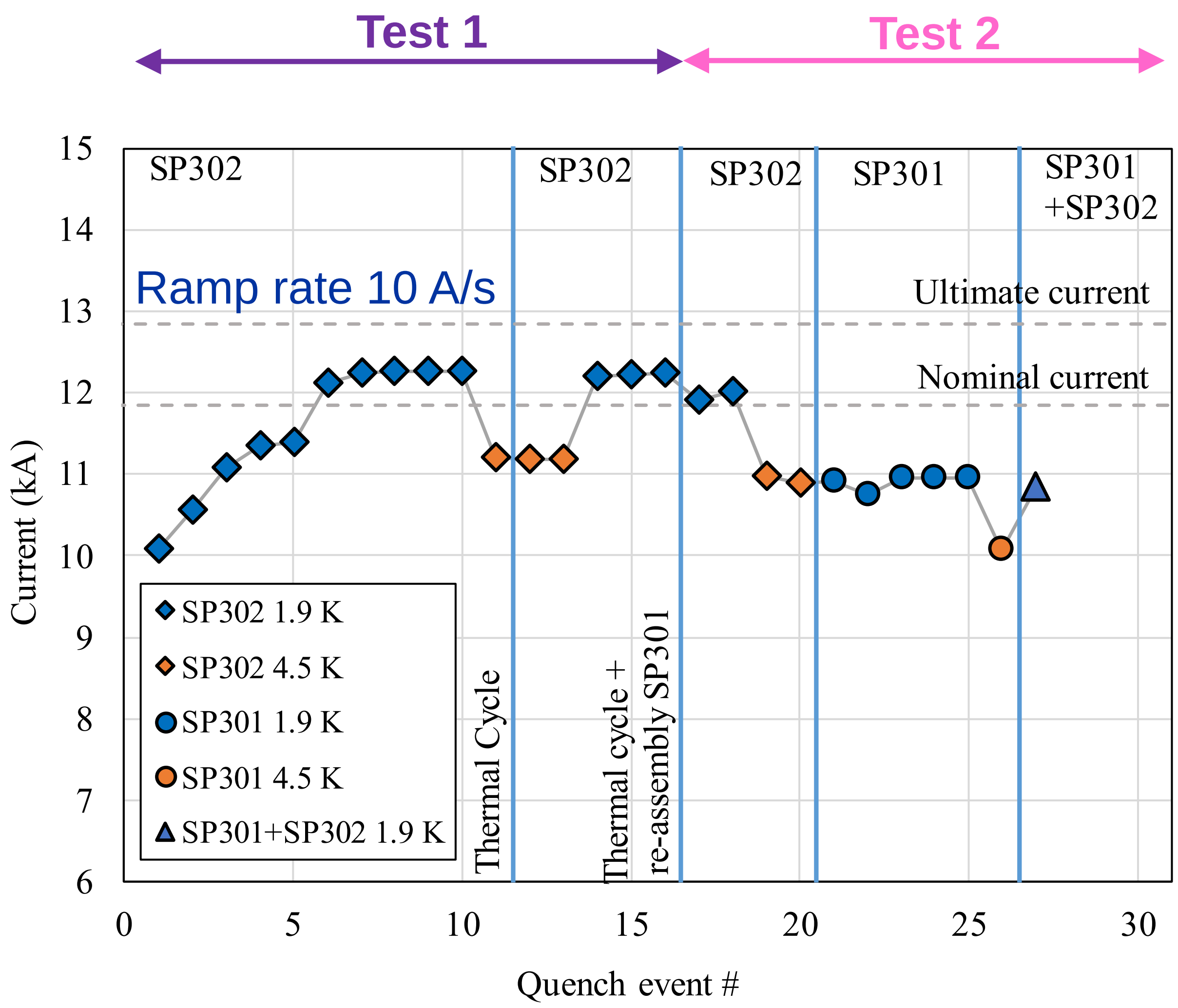
213 Mid plane right

Shimming plan

- **Excess reduction** in the last 150 mm until 75 um approximately.
- Measurements of the **virgin coil** used because the equivalent stiffness of the coil depends on the maximum stress previously seen by the coil mid-plane [3].
- Measurements reports: 108, 212, 213, 214.

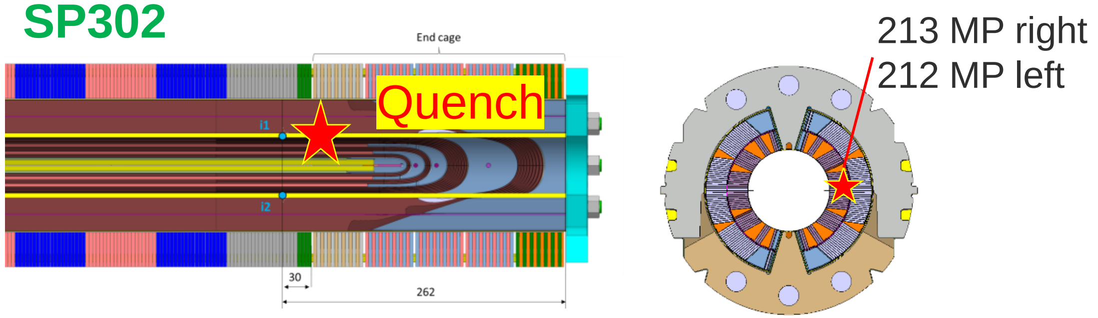


3. Cold test results



Test 1:

- Powering of **SP302**: limit 12.2 kA at 1.9k, 500 A less than these coils in DP201 magnet [4]; location coil 213 NCS mid plane inner layer, close to the end cage location.
- No powering of SP301, HL-LHC NCR.



From https://indico.cern.ch/event/1417760/ *G. Willering*

Test 2:

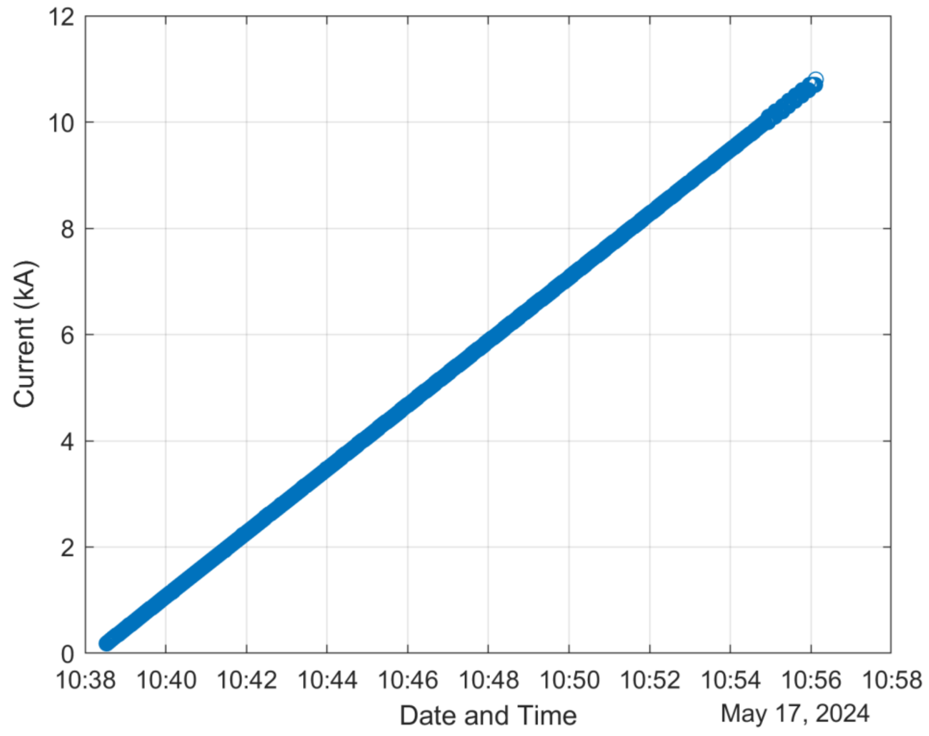
- Powering of **SP302**: limit 12 kA at 1.9k, 200A less than in test 1; location coil 213 NCS mid plane inner layer, close to the end cage location.
- Powering of **SP301**: limit 10.9 kA at 1.9 K, coil 108 NCS inner layer first turn mid plane + head. Coil 108 reached 13.2 kA at 1.9 K on its previous test in magnet DP101 [2].

4. Mechanical measurements

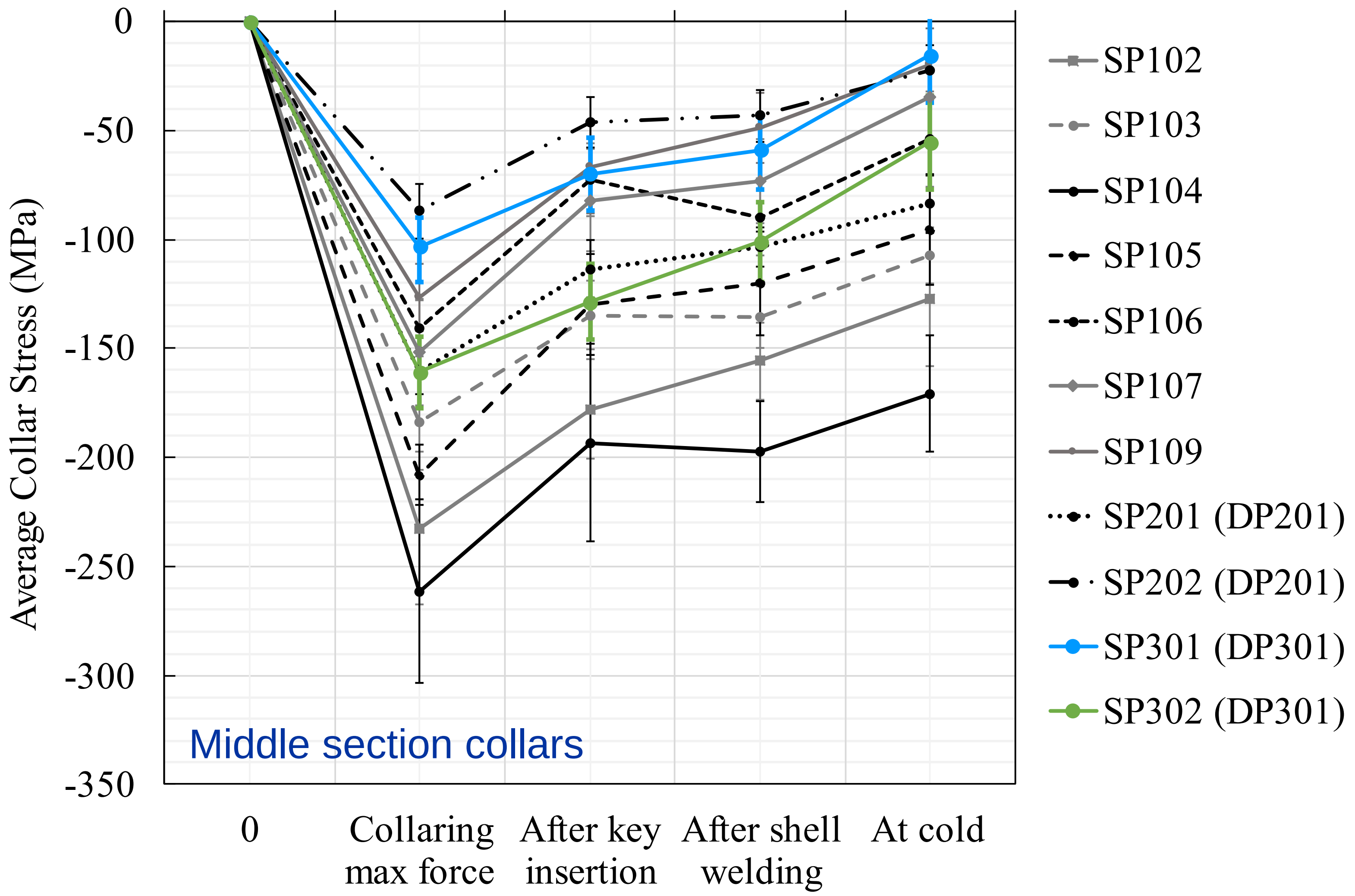
Some words

The 3D model [1]:
- Long magnet
- Symmetry
- Connection side
- Friction between coil and collars
- Collars and yoke are bulk but with modified properties to consider the longitudinal behaviour
- Collaring is not modelled. It directly applies a displacement to the coils.
- Powering at nominal current 11.85 kA
- Roxie axial electromagnetic forces: Fz=477kN/collared coil + Volumetric forces calculated in Comsol.

Ramp to quench used for the mechanical measurements analysis. It is the last ramp of the test that reached 10.8 kA.

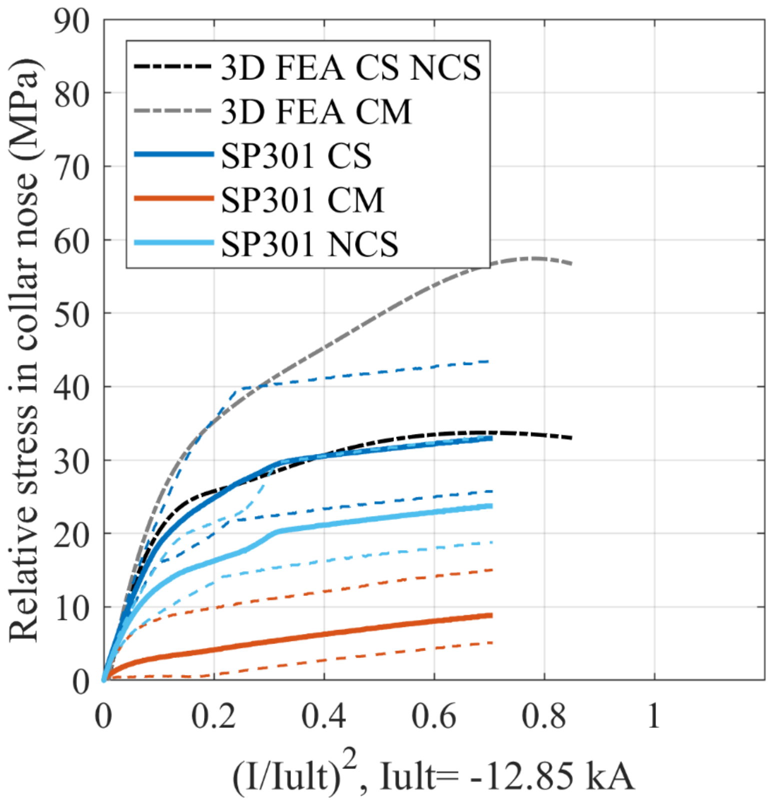


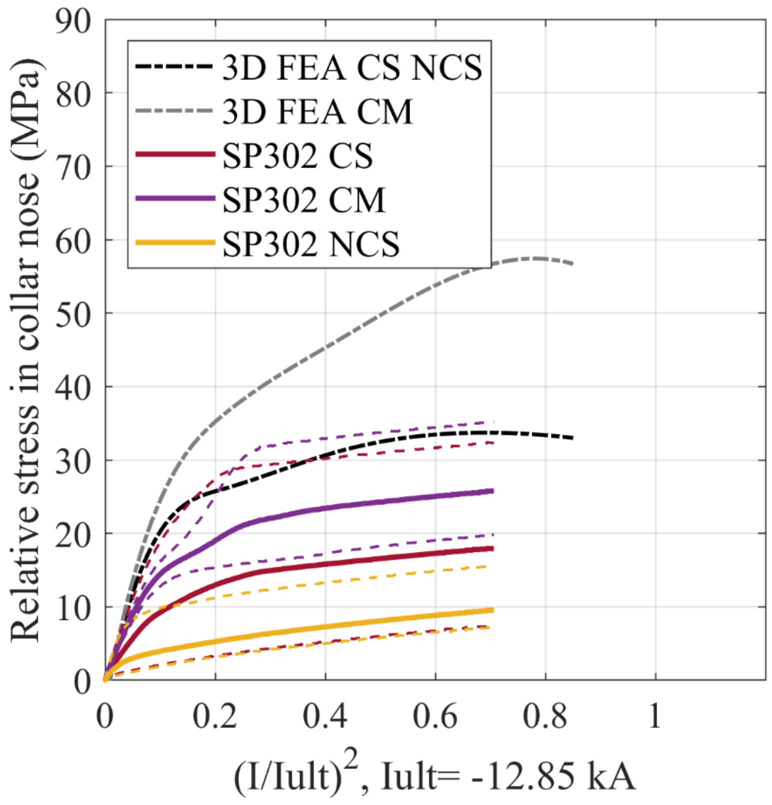
Collar nose stress (1)



- The **delta cool down** in SP301 and SP302 (44 MPa) is bigger than the average observed in previous models (27 MPa) due to the larger thermal contraction of the stainless-steel pole (2.95 mm/m) compared to titanium (1.7 mm/m). In the graph, only the middle section collars are represented, but the connection side and non-connection side show the same results for delta cool down.
- This difference has been verified using a 2D model of a 1-in-1 magnet, which showed that the delta cool down for 200 um excess is 35 MPa for stainless steel pole, compared to 22 MPa in the titanium pole.

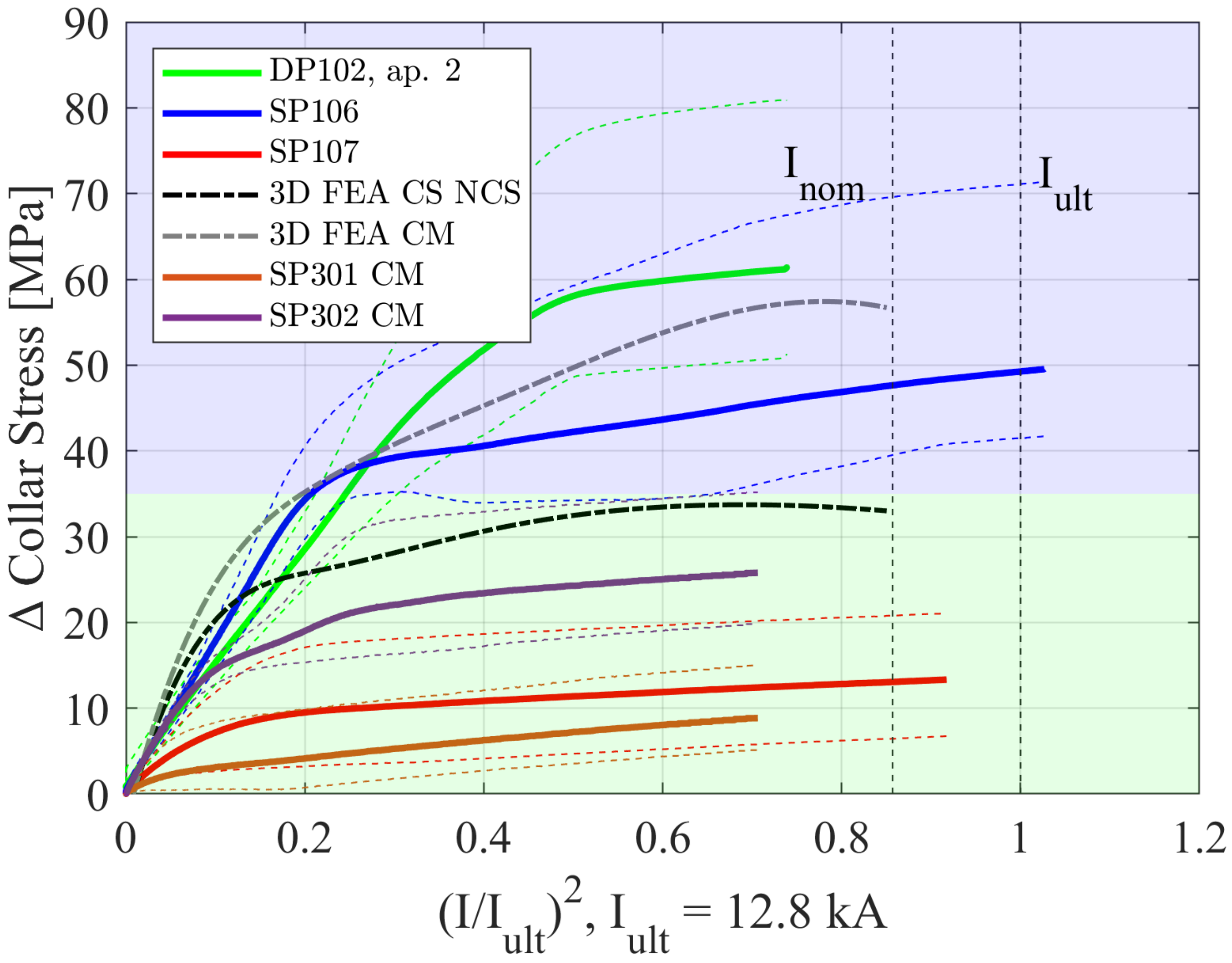
Collar nose stress (2)





- The continuous lines represent the average of the collars section, average of four collars.
- The dotted lines represent the maximum and minimum measured in the collars section.
- FEA lines in different longitudinal positions: FEA CS NCS (quadrant excess 225 um), FEA CM (quadrant excess 275 um)

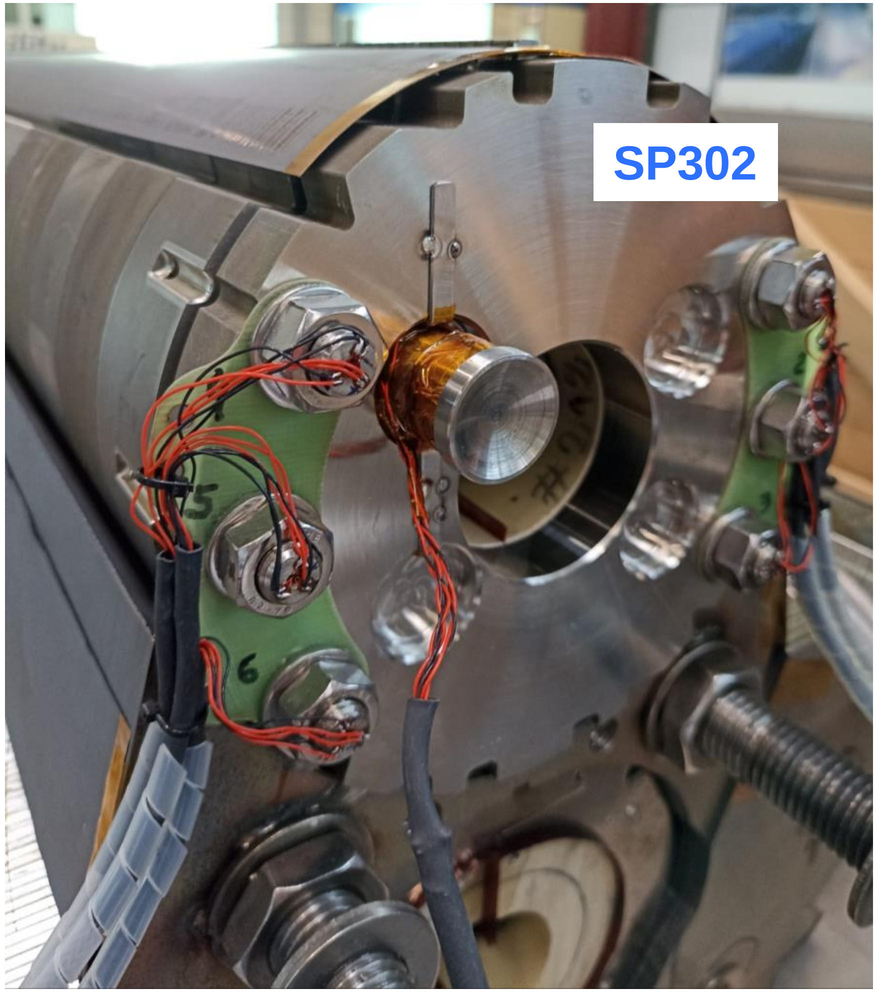
Collar nose stress (3)



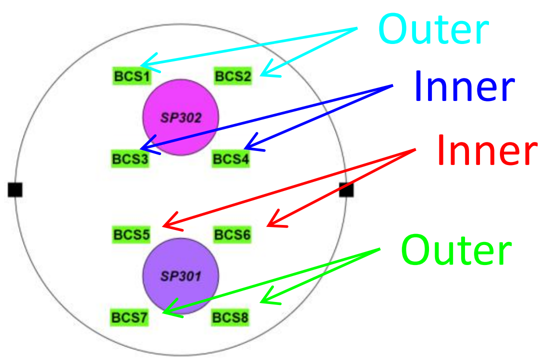
Zone excess
0.3 mm/quadrant

Zone excess
0.2 mm/quadrant

Magnet end plate bullets (1)

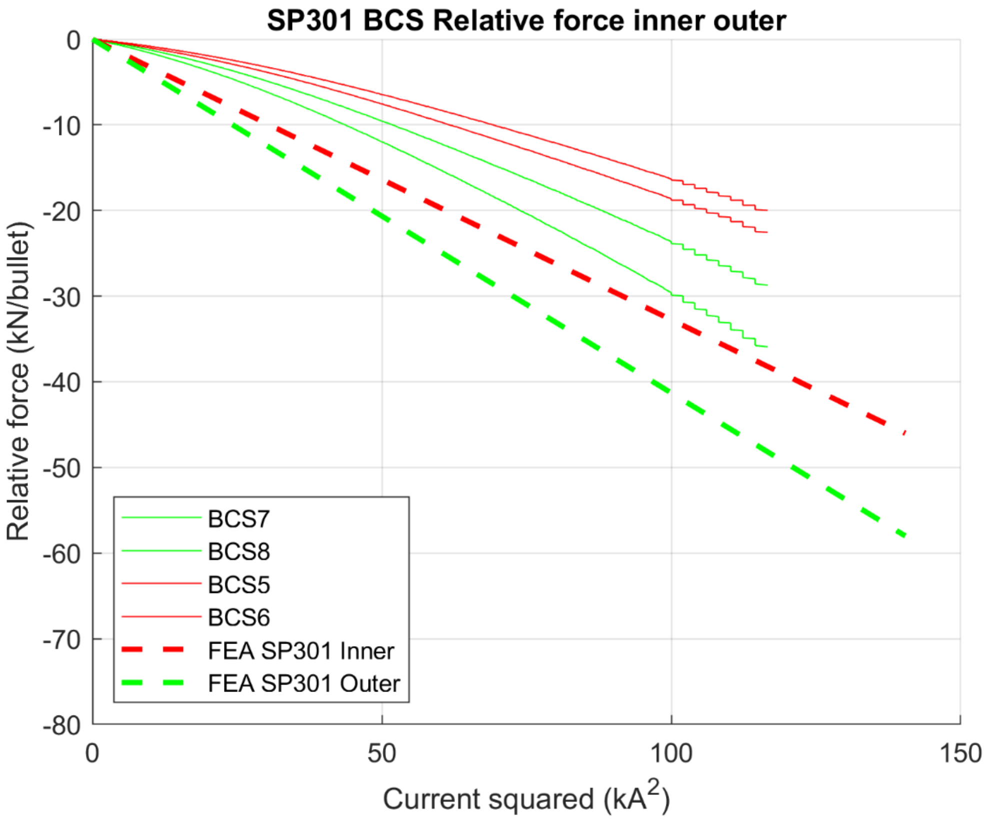


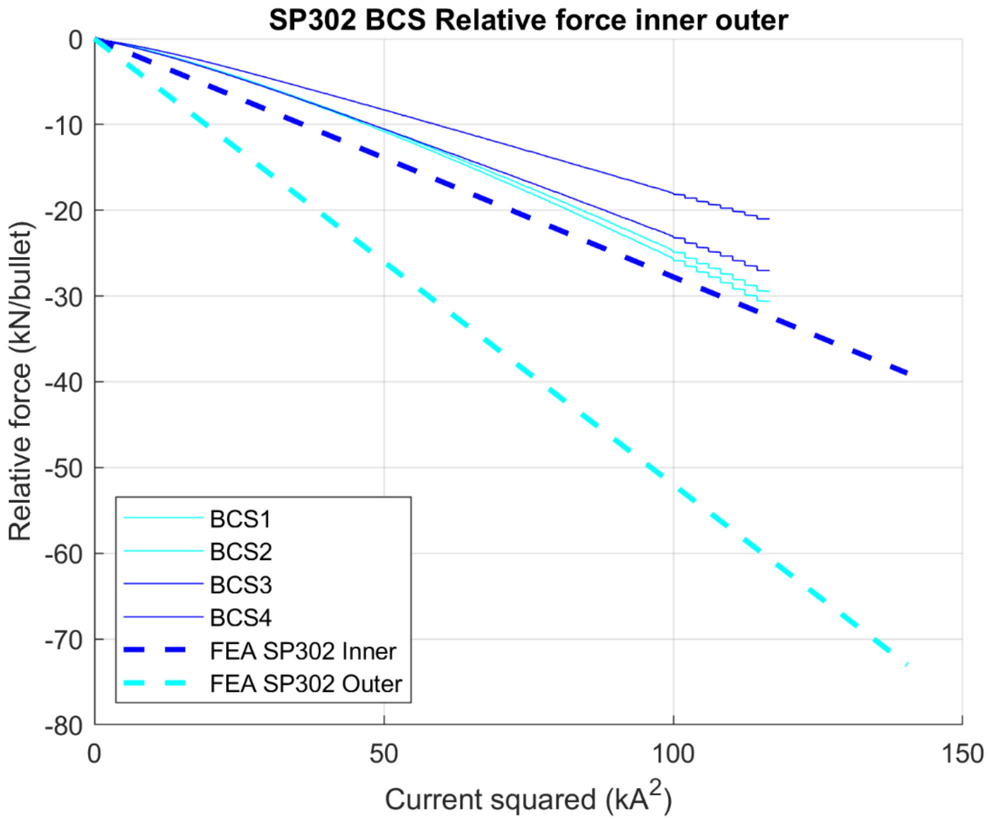
Magnet end plate bullets (2)



During powering

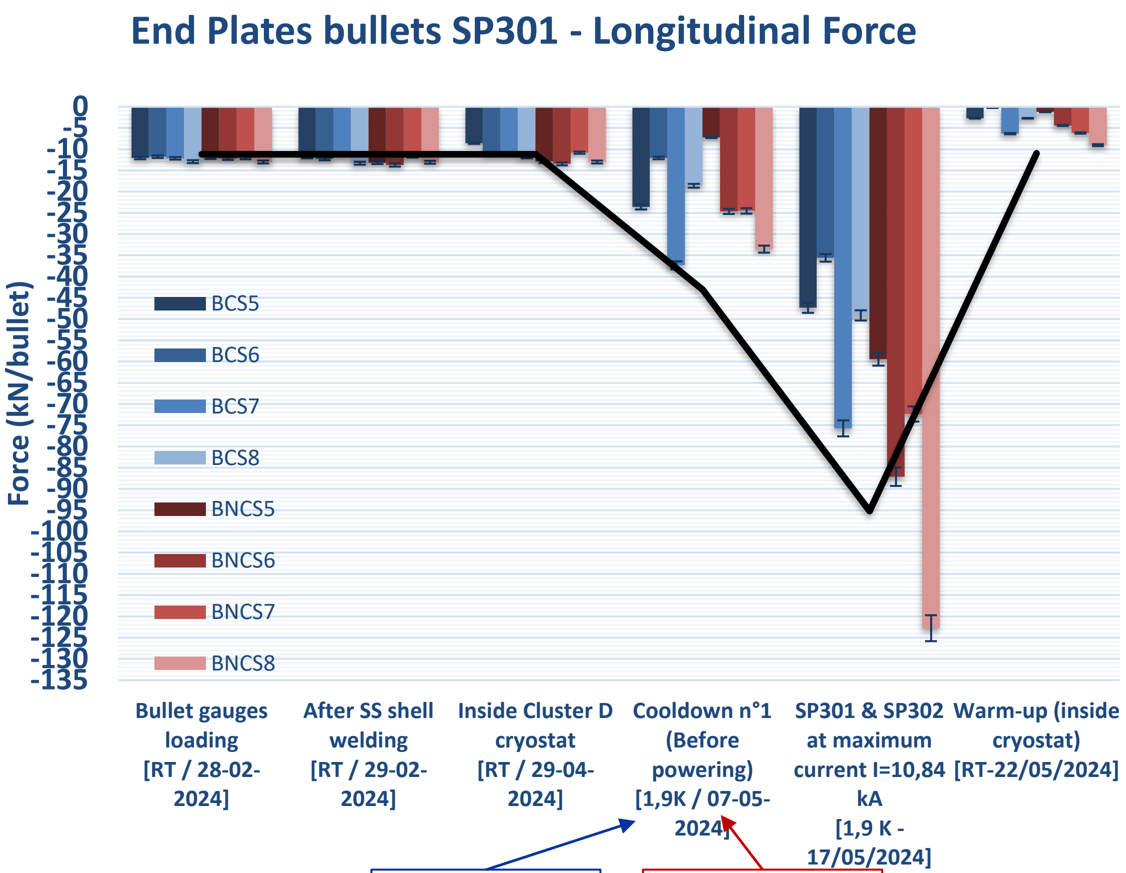
- Only **connection side** represented.
- Values sifted to 0 kN at 0 kA.
- More forces transferred to the outer bullets.





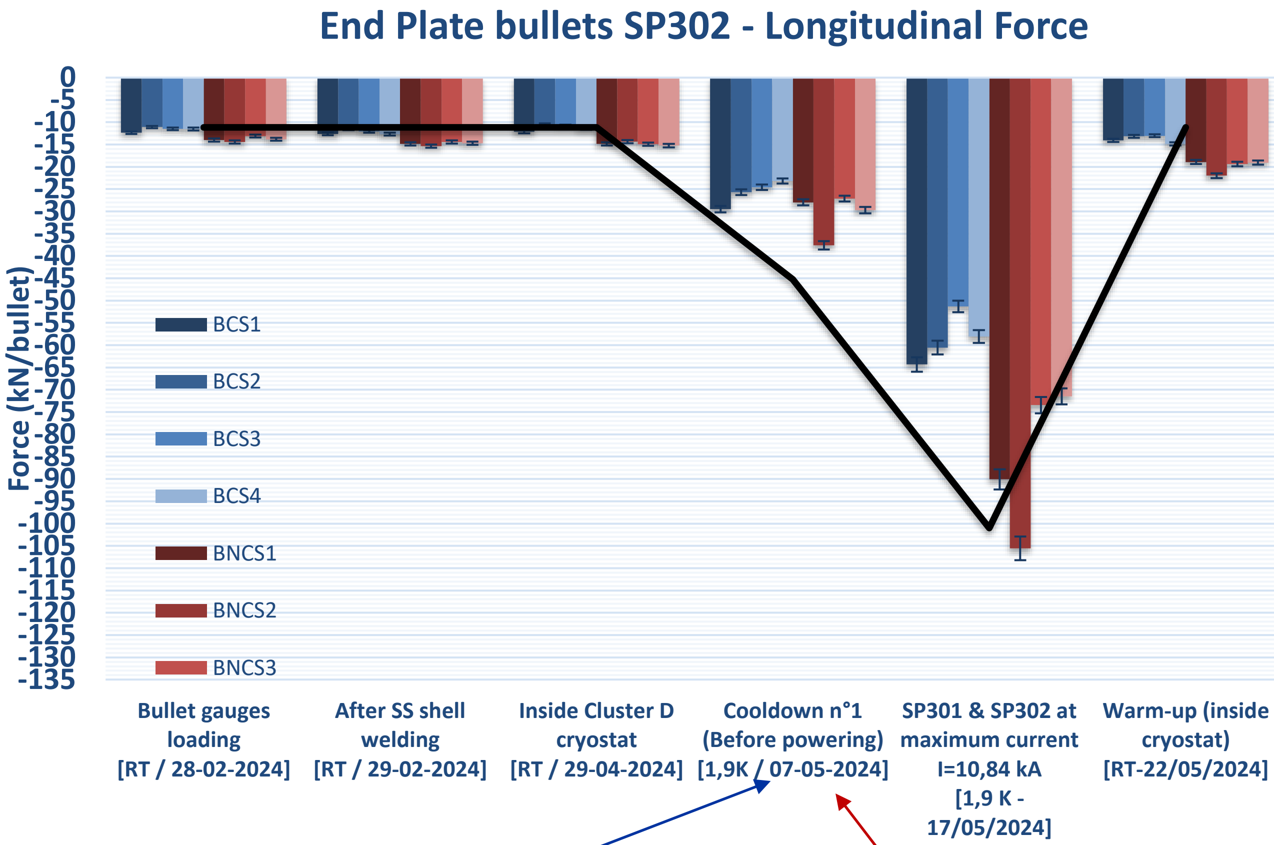
Magnet end plate bullets (3)

Extra information after meeting:
Bullets in the 11Tesla model DP101
Bullets delta cooldown comparison all the models
Recovered of values before and after quench



CS
Min=12kA
Max=37 kA
Range=25 kA

NCS
Min=7kA
Max=34 kA
Range=27 kA

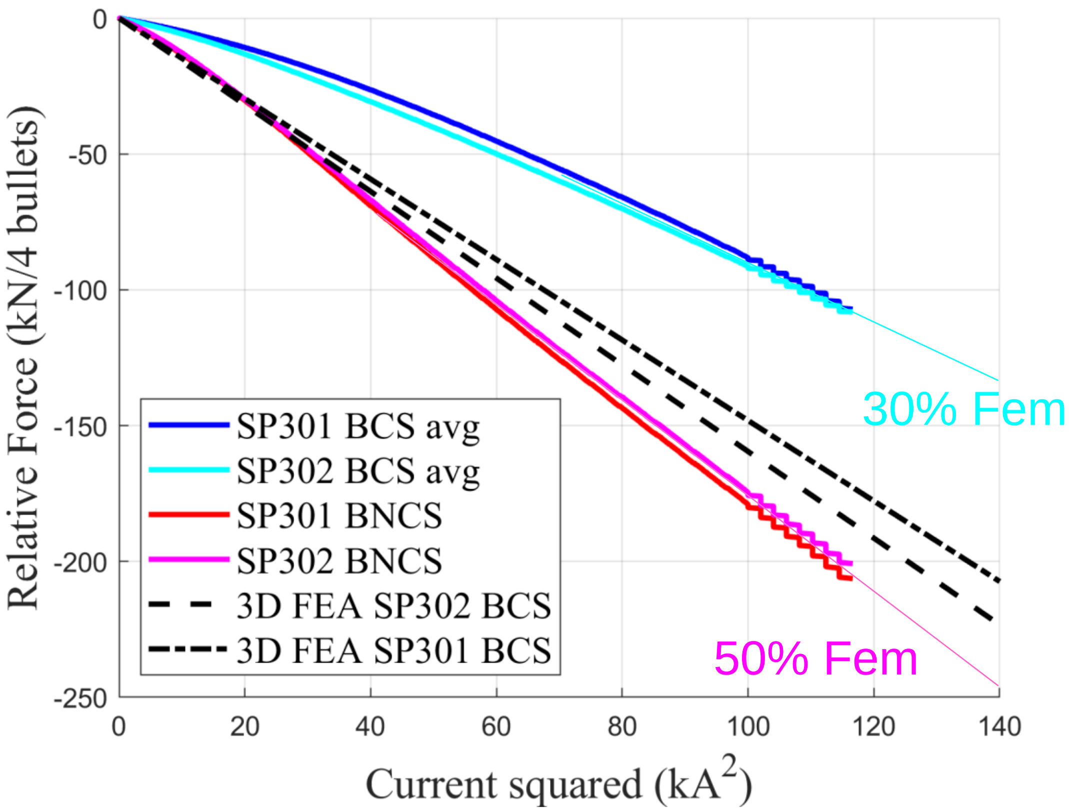


CS
Min=23 kA
Max=29 kA
Range= 6 kA

NCS
Min=23 kA
Max=38 kA
Range=15 kA

From EDMS #2711698 S. Mugnier

Magnet end plate bullets (4)



- Higher slope in non connection side, consistent with previous double aperture models [2].
- This phenomenon is attributed to the length difference of both sides, resulting in increased frictional force dissipation on the connection side. These measurements are valuable for calibrating numerical models.
- The forces transmitted to the bullets are inversely proportional to the length of the side:

$$\frac{l_{headCS}}{l_{headNCS}} = 1.7 \qquad \frac{F_{em\_bulletsNCS}}{F_{em\_bulletsCS}} = 1.7$$

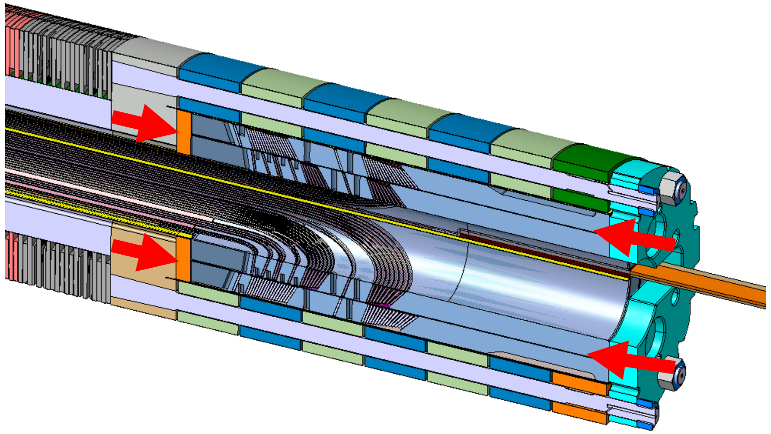
- The sum of the transferred forces to the bullets per aperture is the same but the spread is slightly larger in the aperture without end cage.

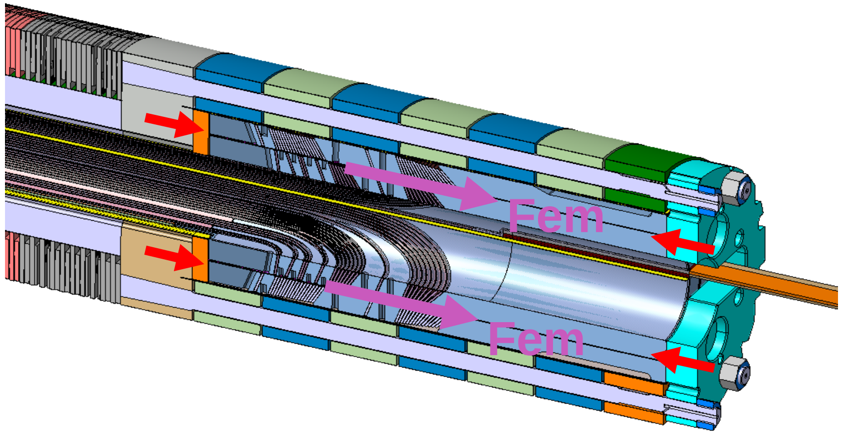
End cage rods (1)

<u>End cage activation</u> – room temperature
Preload with 12% of the electromagnetic forces, 29 kN/coil. Loading report. The rods compress the coil head.

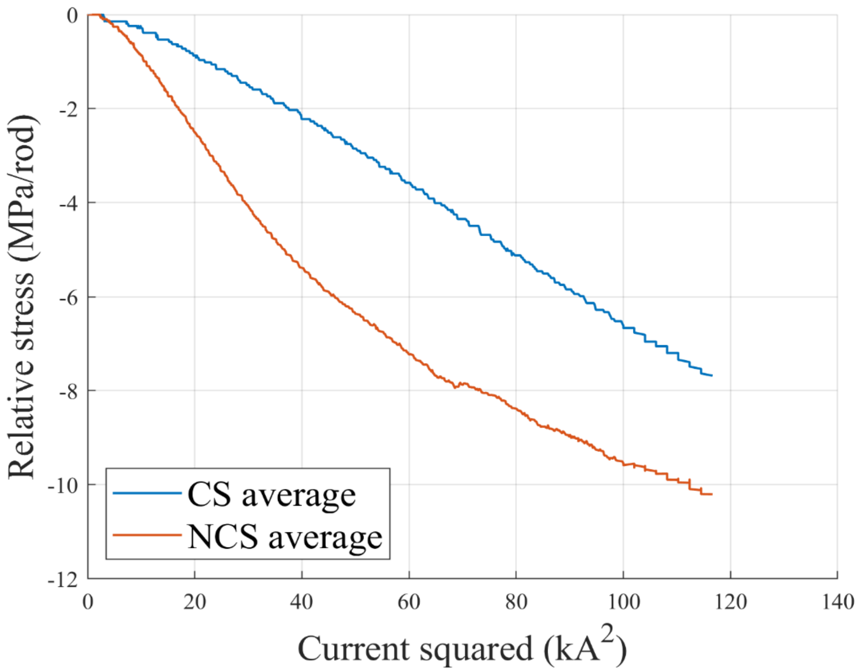
<u>Cool down</u> – 1.9k
During cooldown, some compression is lost, but the heads are still held by the rods.

<u>Energization</u> – 1.9k
During magnet energization, the end cage follows the coil head as it moves with the electromagnetic forces towards the outside of the magnet, compacting the coil head blocks together and preventing detachment between them due to the differential electromagnetic forces across the different blocks.





End cage rods (2)



- Good agreement in the delta cool-down between the 3D model and the strain gauges reading.
- No agreement in powering phase; the model shows an average delta powering of 52 MPa, almost 5 times larger.
- No linear behaviour of the non-connection side rods during powering.
- Big unbalance in the rods stresses in after cool down and powering.
- Lost the data of two rods in CS: one during assembly and another in the cluster D insertion.
- The rods are always under tension, ensuring constant compaction of the coil head.

	SP302 Rods train gauges (MPa)			**3D FEA (MPa)**		
	Loading	Cold	Powering	Loading	Cold	Powering
CS	**90** (92,116,99,75,68)	**81** (136,78,56,55)	**71** (128,63,49,44)	115	100	48 (33,48,64)
NCS	**68** (76,98,48,57,64,62)	**52** (32,78,37,73,58,35)	**38** (7,62,30,52,41,33)	-	-	-

5. Conclusions

The model magnet was tested under cold conditions for mechanical measurements, with no specific expectations regarding the current level achievable during powering due to the reuse of coils.

MECHANICAL MEASUREMENTS

- The effect of the material pole change is visible in the cool down reading of the **collar nose stresses**. The 3D model correctly represents collar behaviour during powering.
- The factor of the electromagnetic forces transferred to the **bullets in both CS (30%) and NCS (50%)** configurations is inversely proportional to the length of the head. The aperture with the end cage, SP302, shows a smaller spread of the transfer forces during cool down and powering due to the **homogenization of axial loading** by the end cage end plate. This configuration also shows **more reproducible values** than SP301 after warm-up in the test bench.
- The **end cage rods** remain under tension, ensuring coil head compaction. However, performance limitations of the coils prevent definitive conclusions regarding axial support improvement.

QUENCH PERFORMANCE

- Despite no alterations in the aperture SP302 between tests, the local damage increased (loss of 200 A in quench current) after thermal cycle and magnet re-assembly.
- In **SP302**, the quench appears near the end cage; however, it cannot be confirmed that this is due to the end cage, as the coils were damaged and repaired (increasing the mid-plane thickness) in this area.
- In **SP301**, the quench occurs at a very low current. Coil 108 seems to have significant damage in the mid plane and head coil head inner layer segment. This damage was likely not generated during the assembly of the presented magnet, as coil 214 does not exhibit similar limitations.

6. References

[1] C. Garion, M. Morrone, "Mitigation solutions on the 11 T magnet," CERN Internal technical note, Geneva, 2022.

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

[3] J. L. Rudeiros Fernandez“Characterization of the Mechanical Properties of Nb3Sn Coils” IEEE Transactions on applied superconductivity, vol. 29, no. 5, AUGUST 2019, Art. no. 8401205.

[4] **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“**

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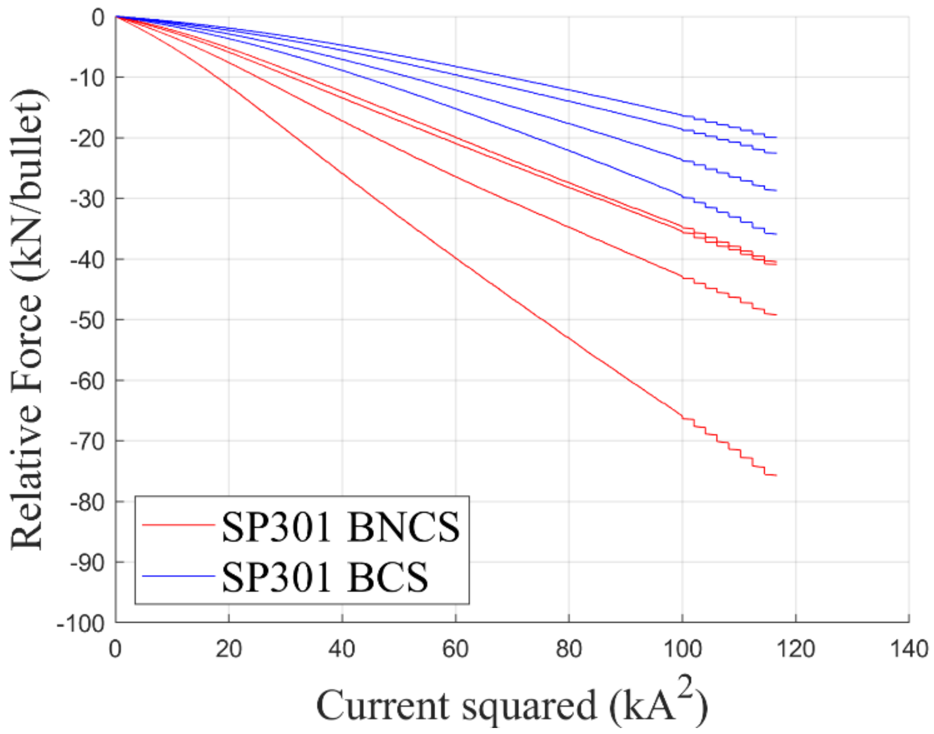
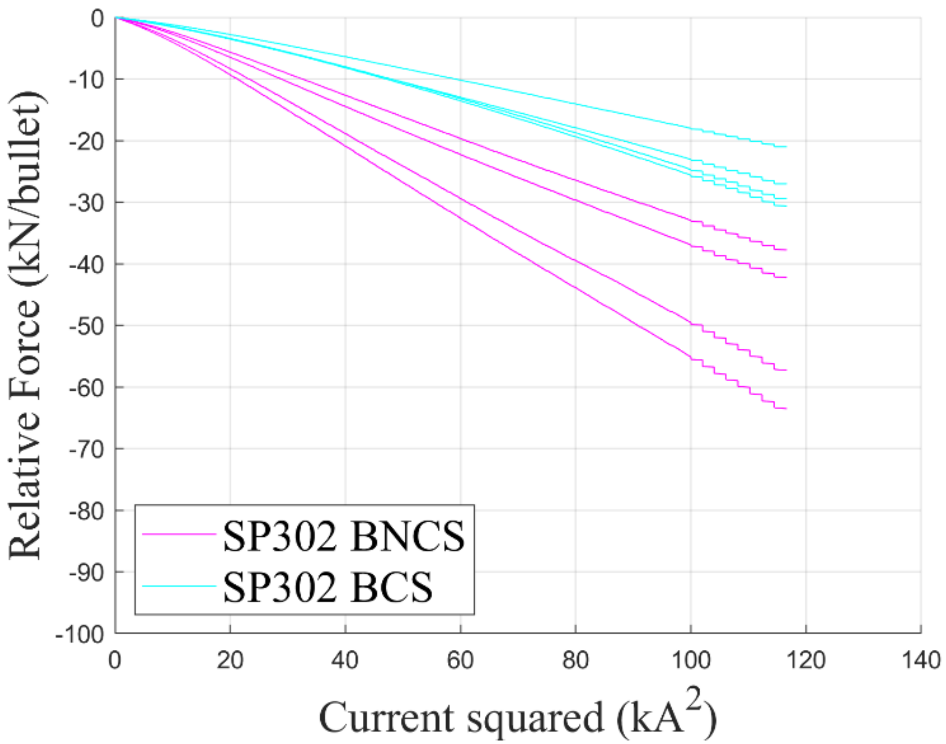
Collaring parameters of the reused coils for the magnet MBHDP301b

Parameter	Unit	Collared coil				
		CC102	CC999	CC202	CC301	CC302
		106 108	106 108	212 213	108 214	212 213
Collaring						
Nominal collaring cavity	mm	70	70	70	70	70
Stoppers height, including shims	mm	70.1	69.85	69.85	69.85	69.85
Key clearance	um	-100	150	150	150	150
Collaring force	MN	34.0	8.5	6.0	5.4	6.6
Collar nose stress at max collaring force	MPa	-227	-	-86	-103	-161
Collar nose stress after key insertion	MPa	-186	-	-46	-65	-130

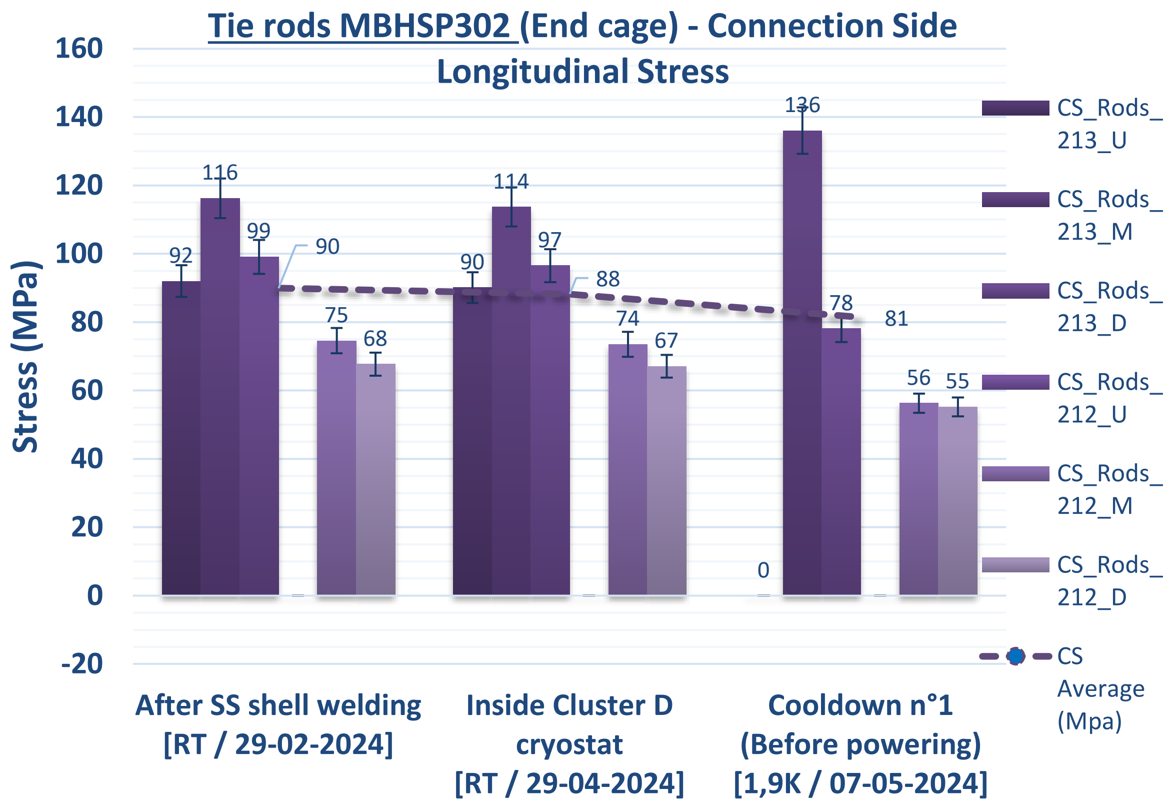
Bullets range of values during powering

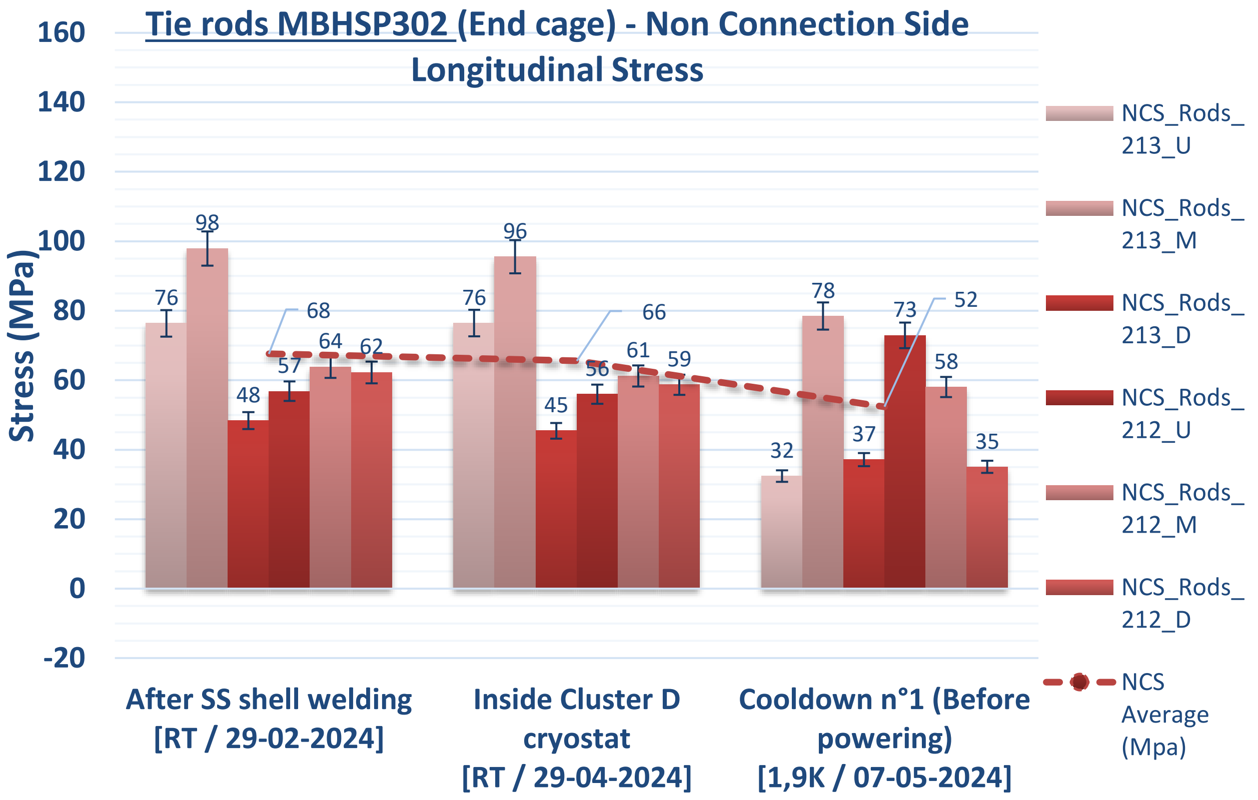




Bigger spread of the bullets during powering in the aperture without end cage SP301

End cage rods from loading to cool down





Courtesy of S. Mugnier EDMS #2711698

Analytical calculation of coil head elongation

$$\Delta L = \frac{F_{EM}}{K_{coil}}$$

$$\Delta L = \frac{F_{EM}}{K_{rods} + K_{coils}}$$

Parameter	Unit	CS	NCS
e.m Force, Nominal Current	MN	0.478	
Coil stiffness	MN/mm	3.7	6.3
Rod stiffness	MN/mm	0.5	0.1
Coil elongation without rods, no friction	um	65	38
Coil elongation with rods, no friction	um	46	35

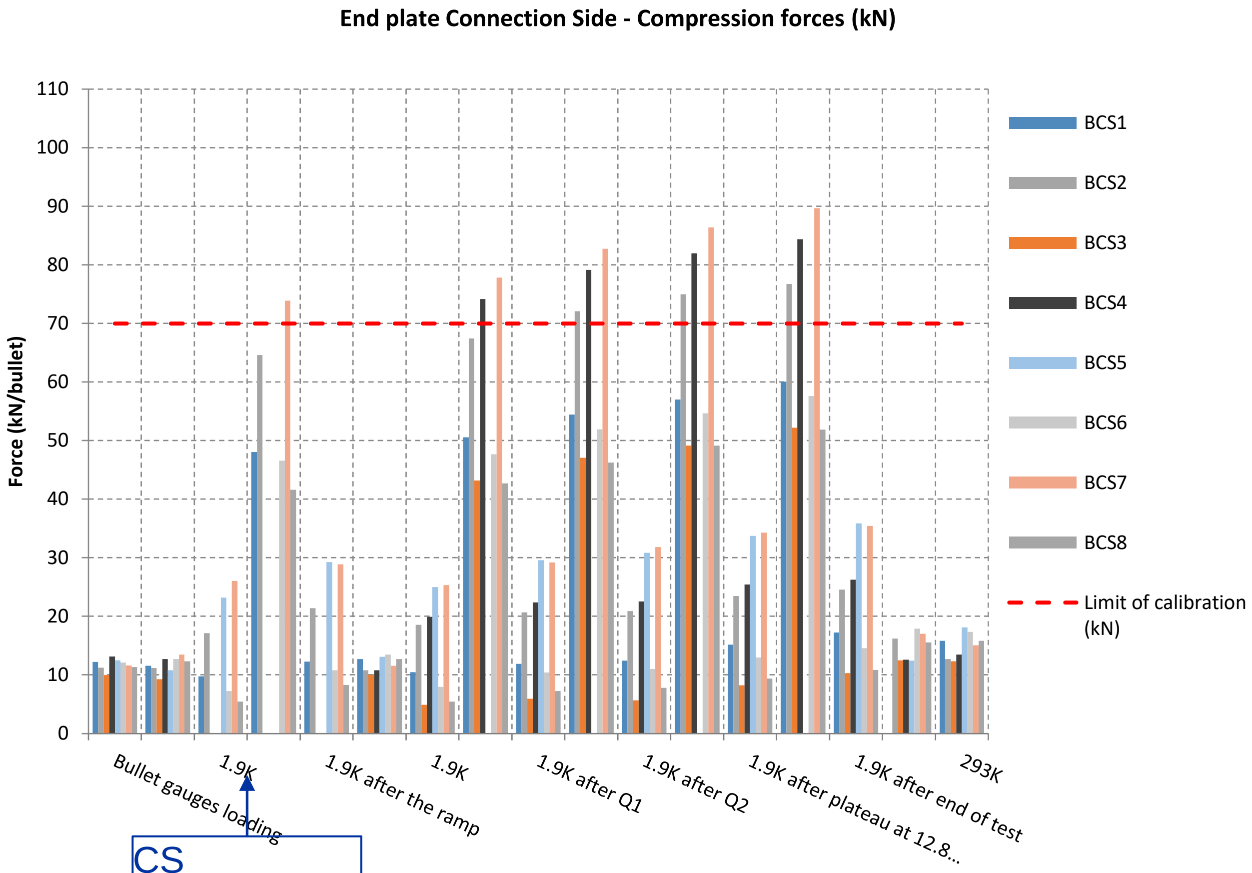
$$K_{coil} = \sum \frac{E_i A_i}{l_i} = \frac{E_{coil} A_{coil}}{l_{coil}} + \frac{E_{G11} A_{G11}}{l_{G11}} = A\left[\frac{E_{coil}}{l_{coil}} + \frac{E_{G11}}{l_{G11}}\right]$$

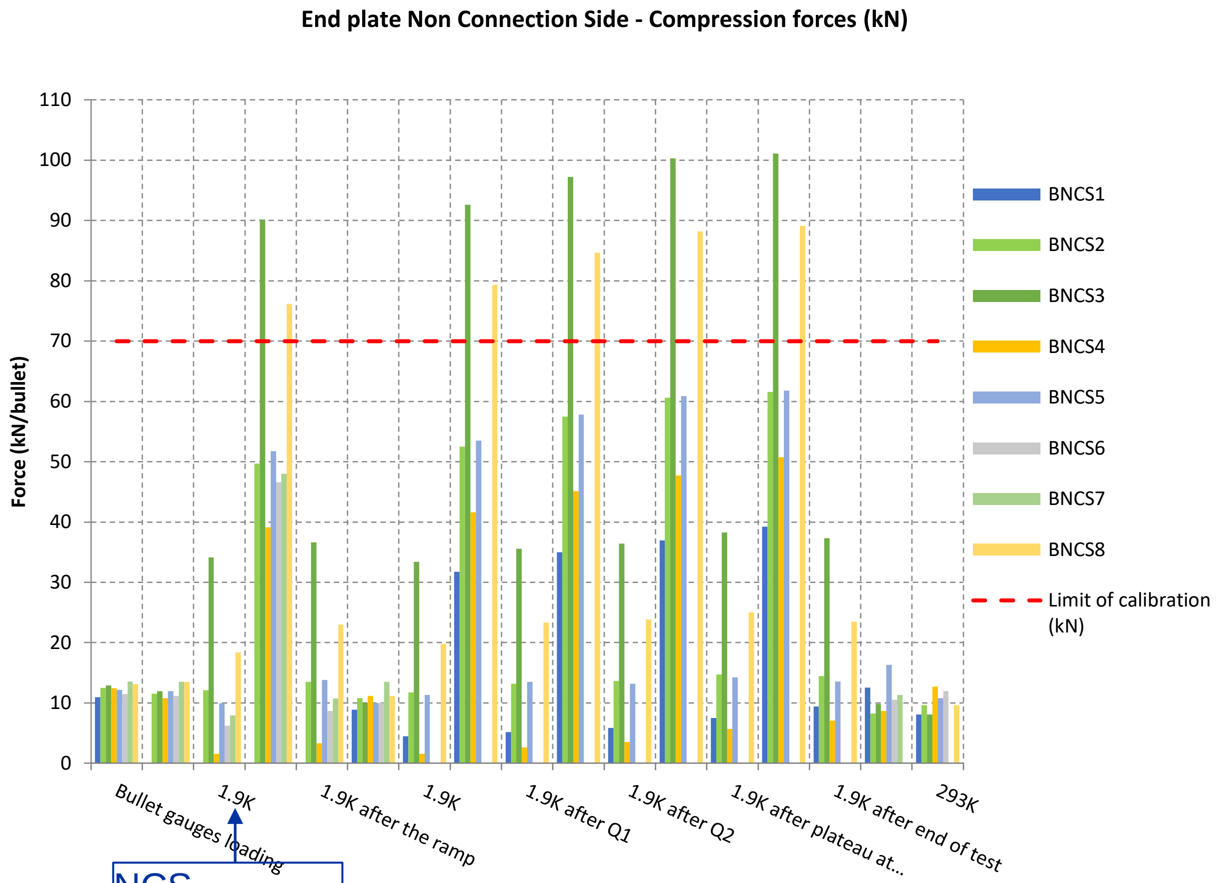
$$K_{rods} = \frac{EA}{l}$$

Slides added after the meeting

C. Abad Cabrera

Bullets - magnet DP101



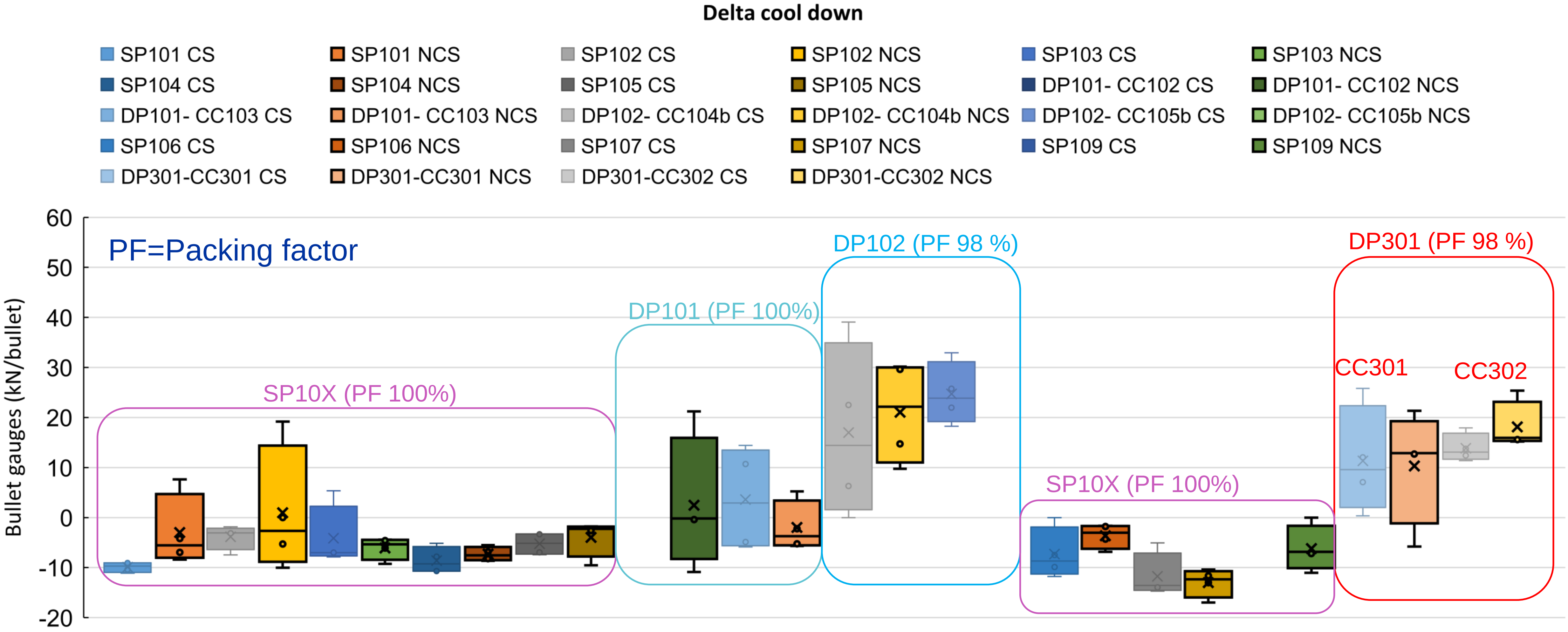


CS
Min=5kA
Max=26 kA
Range=21 kA

NCS
Min=2kA
Max=34 kA
Range=32 kA

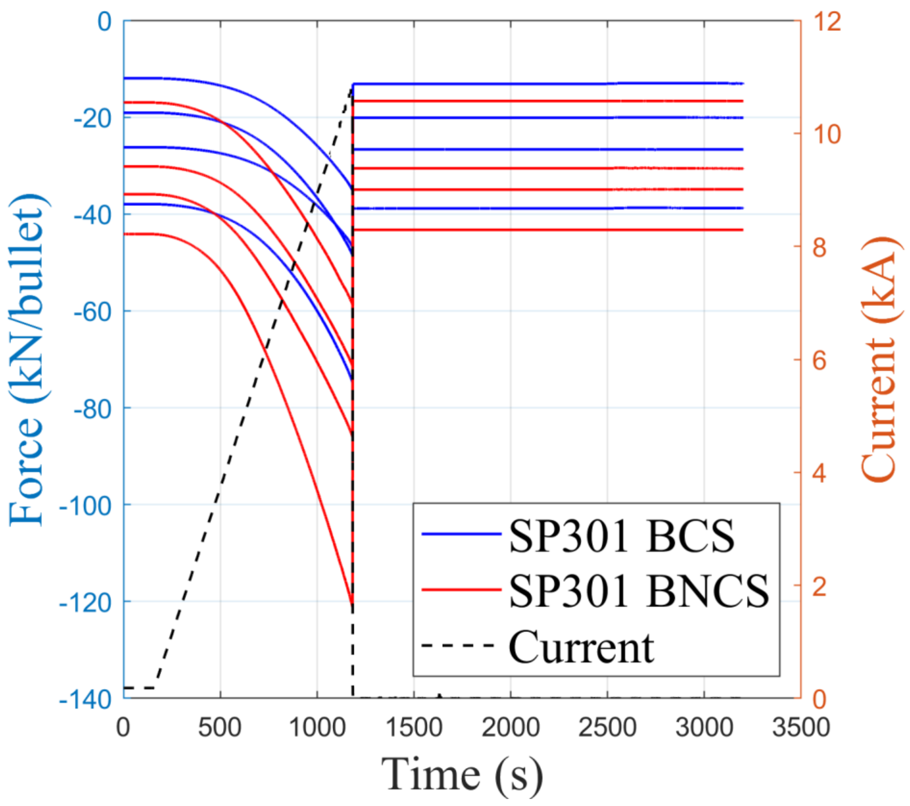
There is a big spread in values after cool down in the model DP101, bigger range in NCS.

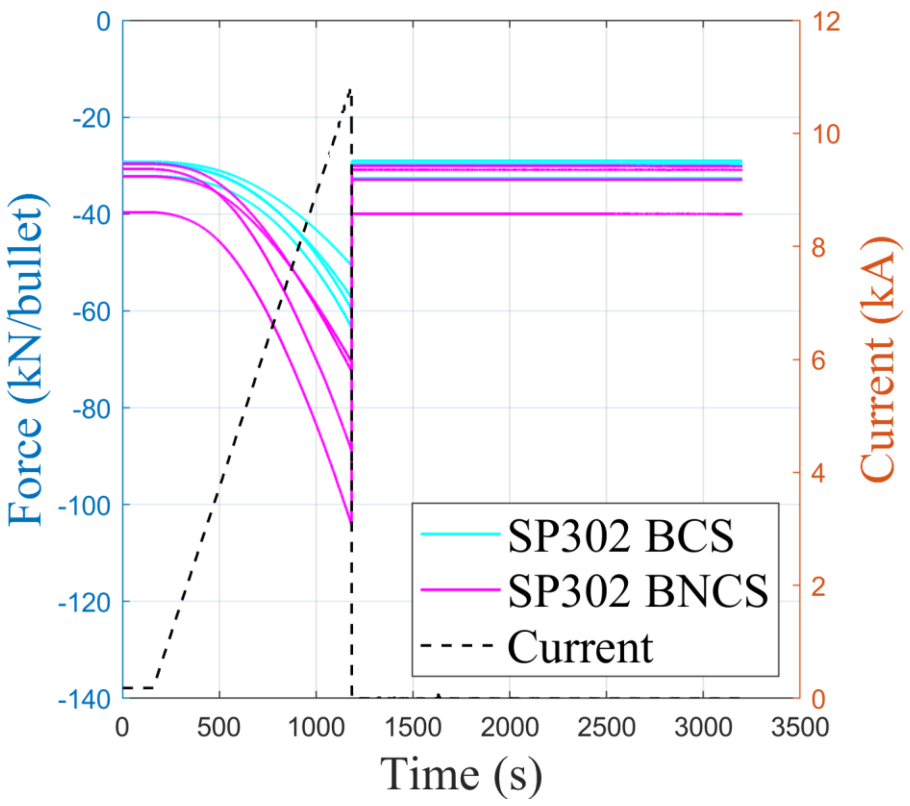
Bullets in all models – Delta cool down



Aperture SP302 (DP301) has the smallest range of bullet values after cooldown among the double-aperture magnets.

Bullets value before and after quench





The compression in the bullets is fully recovered after quenching.