Viscoelastic explanation of the loss of pre-stress in impregnated superconducting magnets

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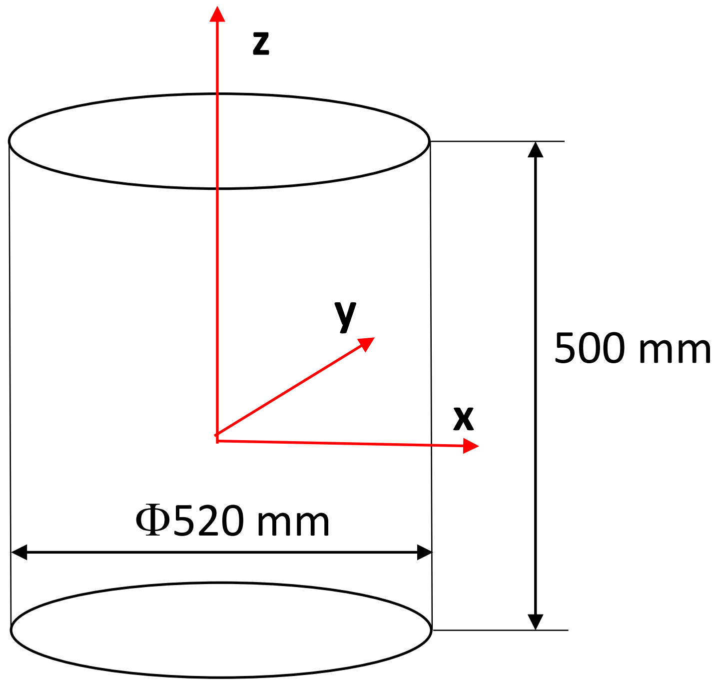
Outline:

1. **Motivation**
2. **The principle of bladders & keys**
3. **SMC magnet instrumentation**
4. **General load cycle**
5. **Strain measurements**
6. Viscoelastic materials
7. Viscoelastic materials – constitutive models
8. FEM model of the SMC magnet
9. Elastic solution vs the experimental results
10. Viscoelastic solution
11. Impact of friction coefficient
12. **Conclusions/ideas**

1. Motivation

SMC – Short Model Coil

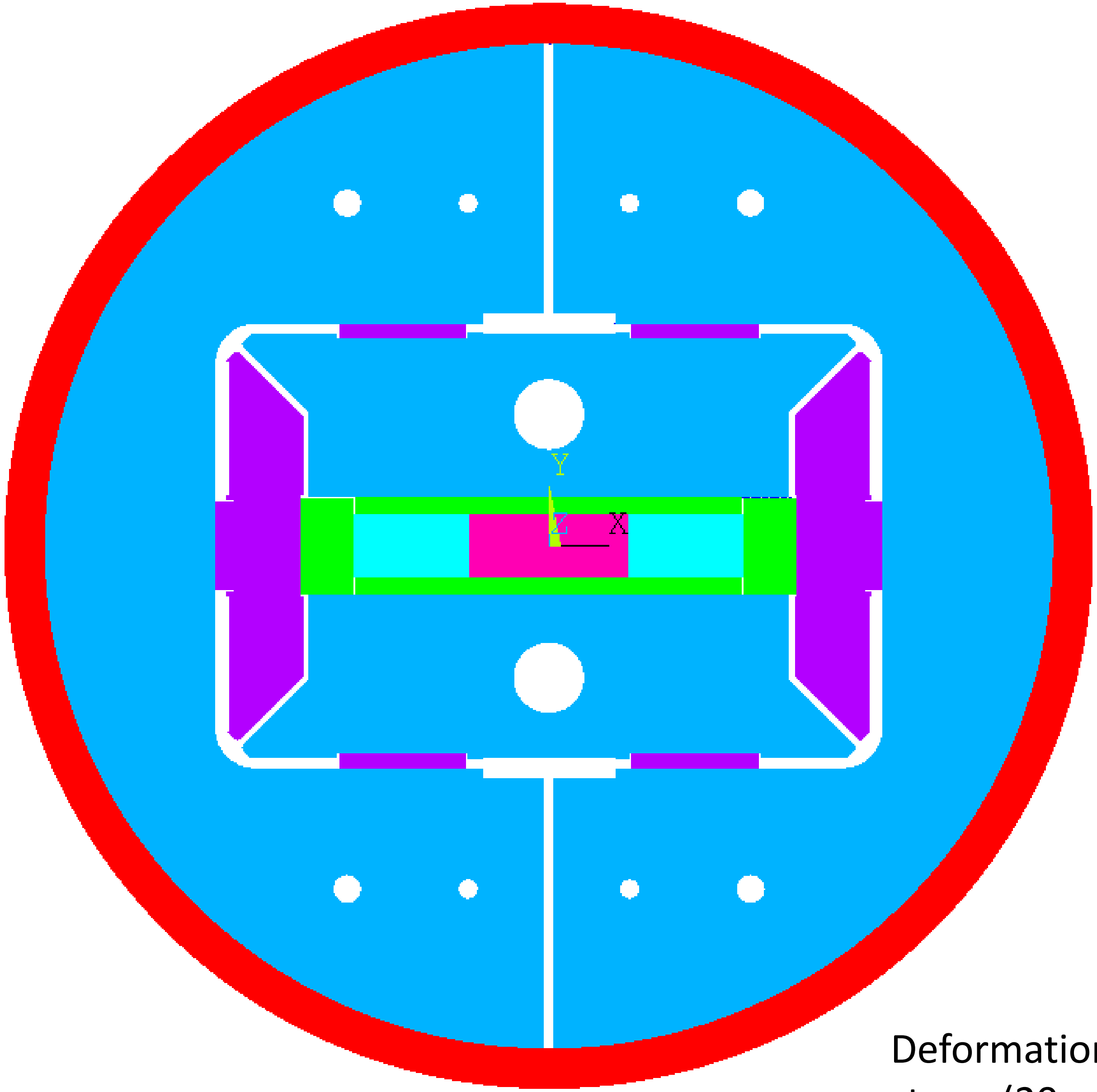
Number	Name	Number of DP	Conductor type	Resin type
1	SMC#1	2	IT	Mix71A
2	SMC#2	2	PIT	Not impregnated
3	SMC#3a	2	PIT	Mix71A
4	SMC#3b	2	PIT	Mix71A
5	SMC#4	2	PIT	CTD-101K
6	SMC#5	2	RRP	CTD-101K
7	SMC11T#1	1	RRP	Mix71A
8	SMC11T#2	1	RRP	CTD-101K
9	SMC11T#3	1	RRP	CTD-101K
10	SMC11T#4_1	1	PIT	CTD-101K
11	SMC11T#4_2	1	PIT	CTD-101K

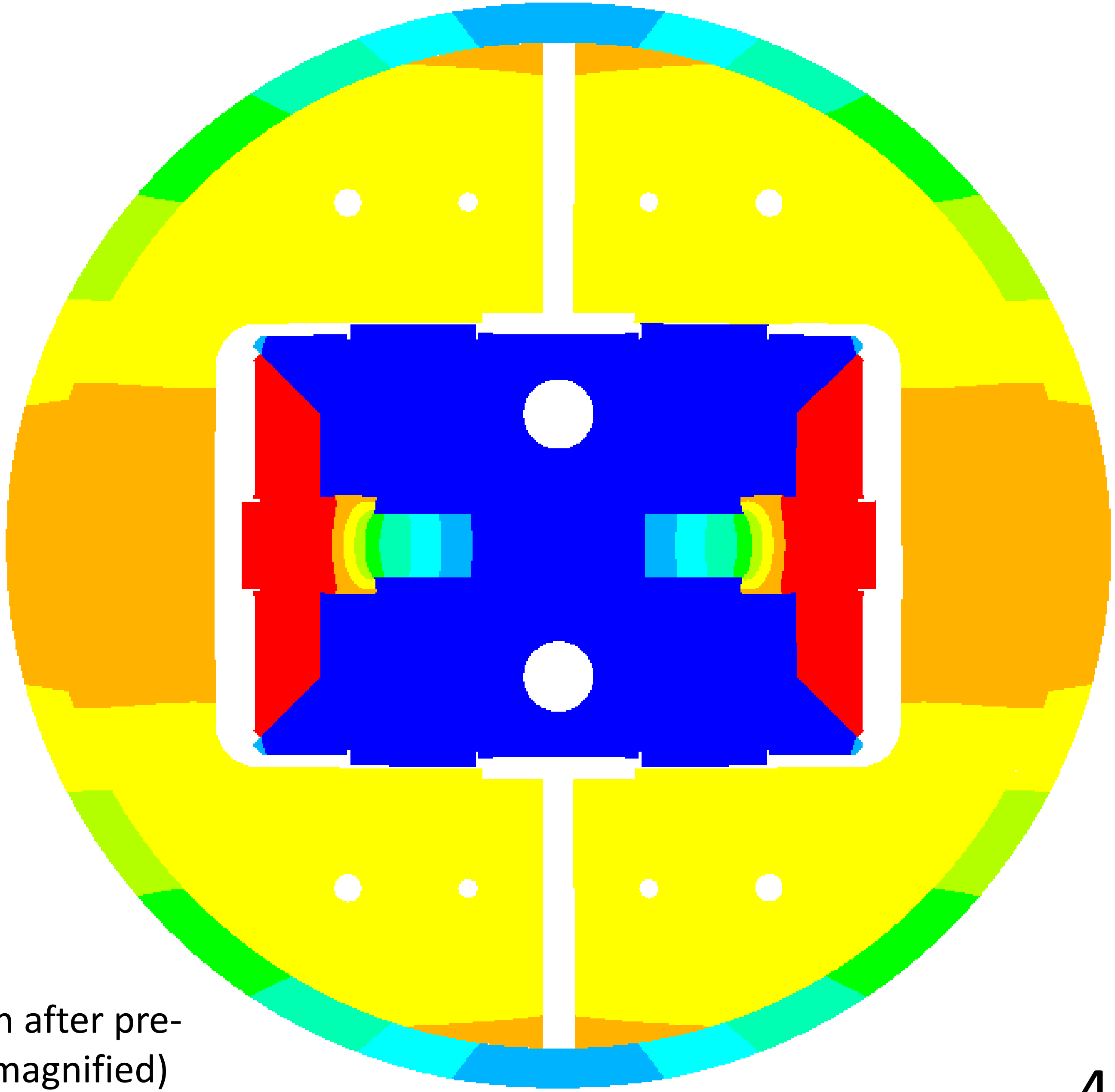


Summary of the work done during the years 2008-2017

[1] R. Ortwein. Review of the state of the art, SMC (Short Model Coil). CERN EDMS 1836763 v.1 http://edms.cern.ch/ui/file/1836763/1/Review_SMC_Final_OrtweinR.pdf

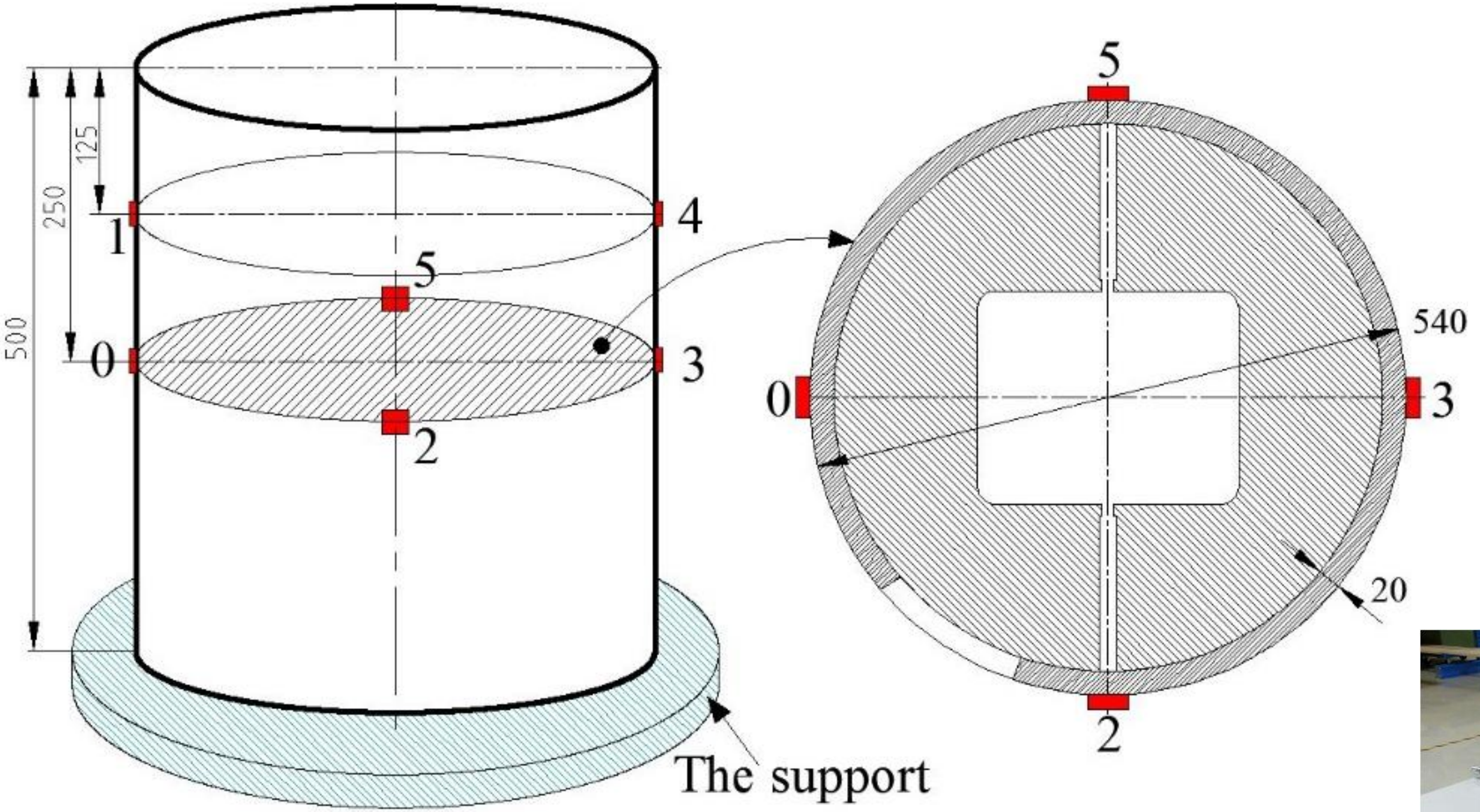
2. The principle of bladders & keys





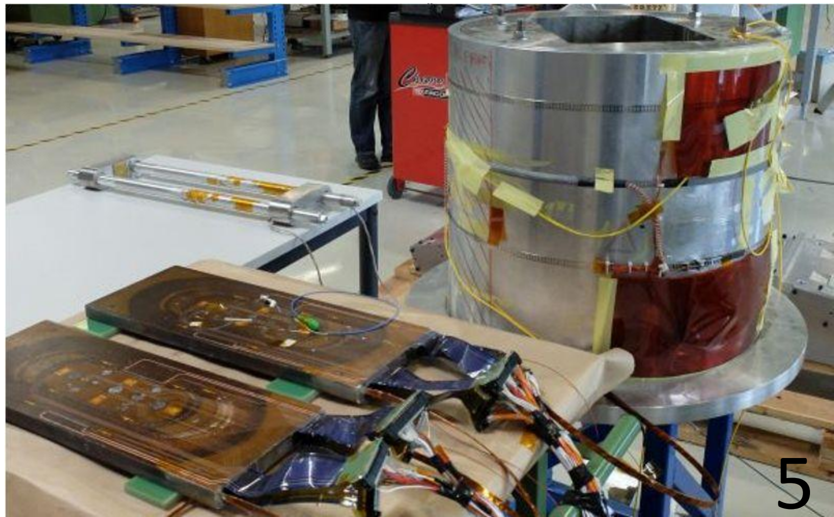
Deformation after pre-stress (20x magnified)

3. SMC magnet instrumentation

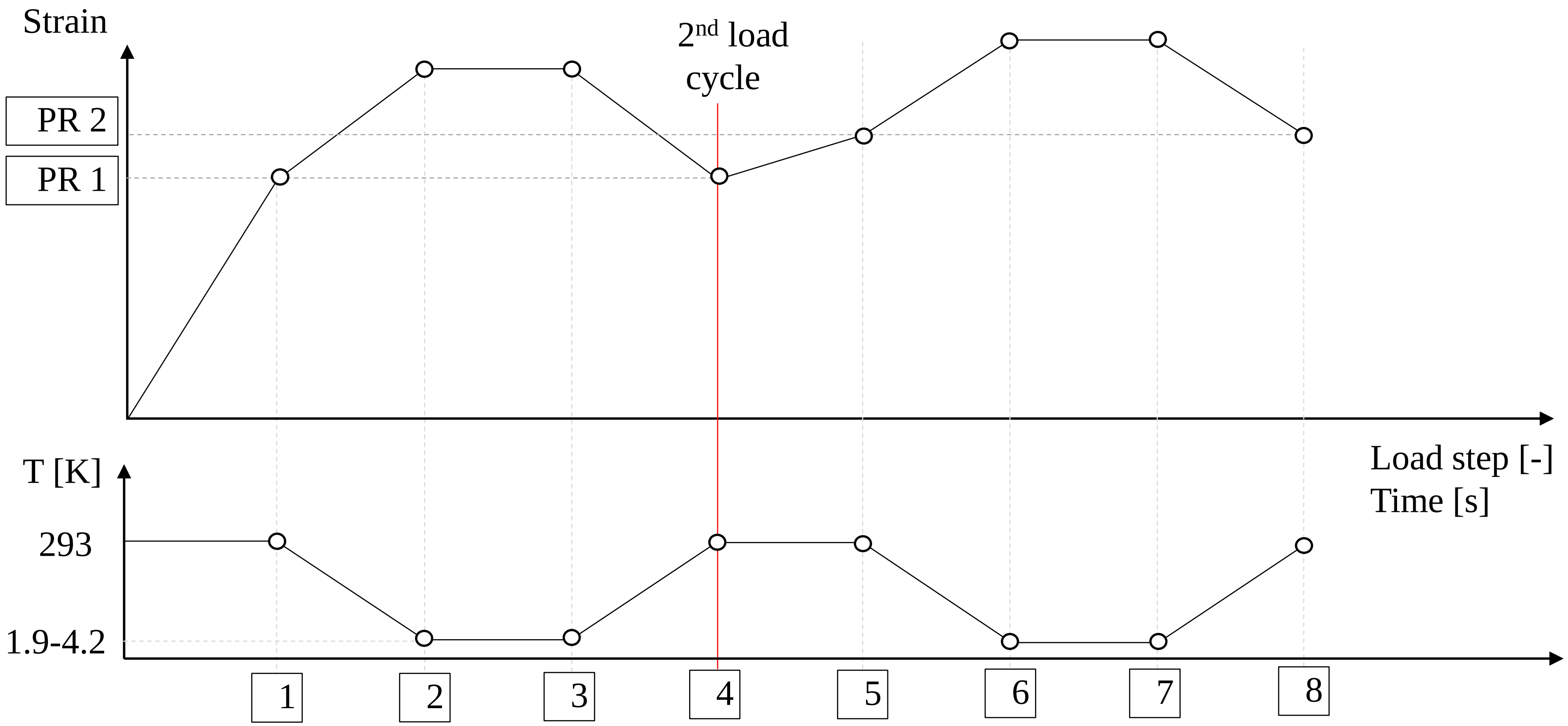


T – circumferential (azimuthal) direction

[1]

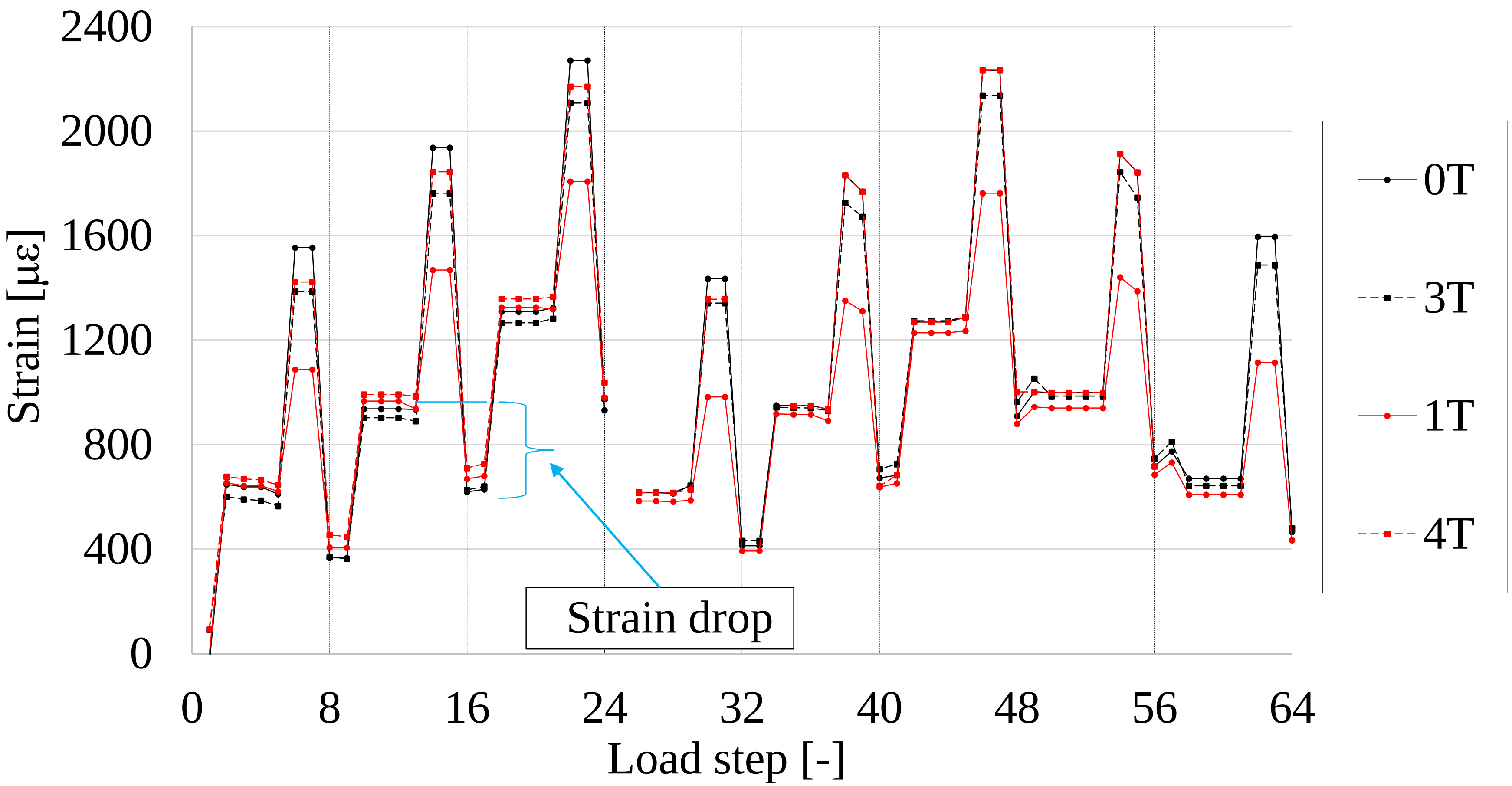


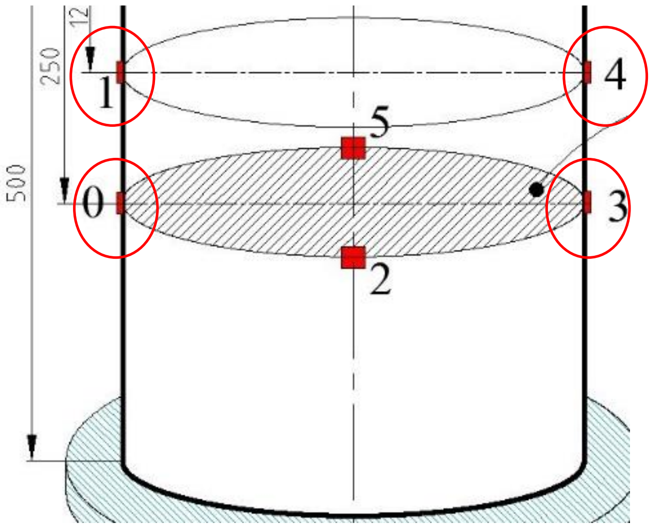
4. General load cycle



1: pre-load
2: cool-down
3: powering
4: warm-up

5. Strain measurements (1/9)





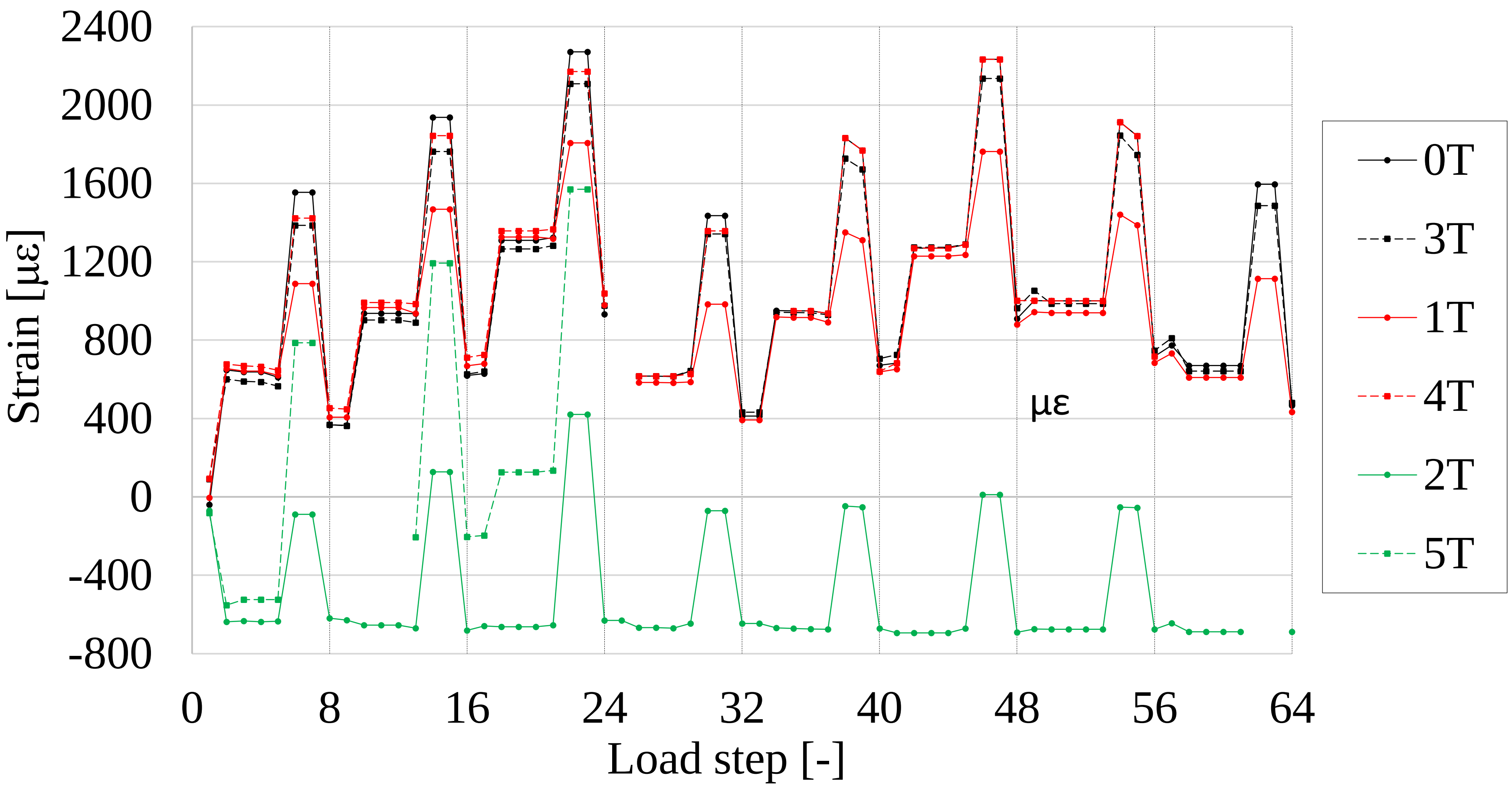
Each load cycle divided into 8 steps:
1 – start of the horizontal pre-load,
2 – end of the horizontal pre-load,
3 – start of the longitudinal pre-load,
4 – end of the longitudinal pre-load,
5 – cooldown start,
6 – cooldown end,
7 – warm-up start (end of powering),
8 – warm-up end

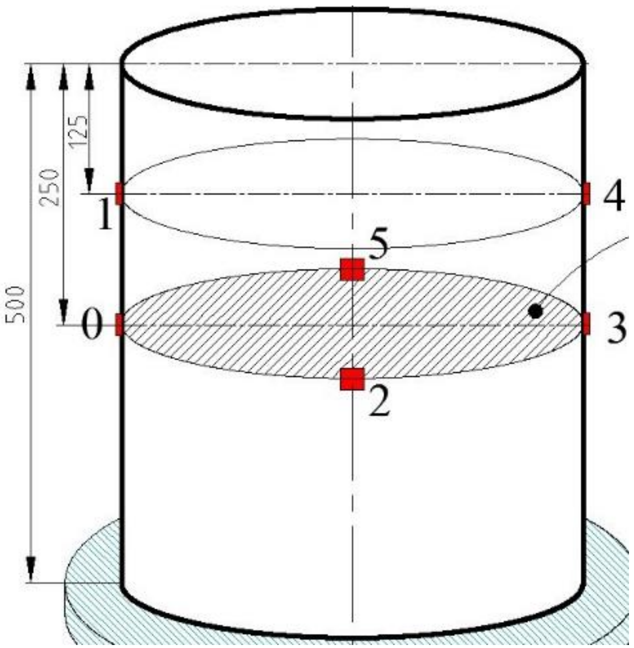
1με=1e-6 [-] = 0.0001 %

2000με=2e-3 [-] = 0.2 %

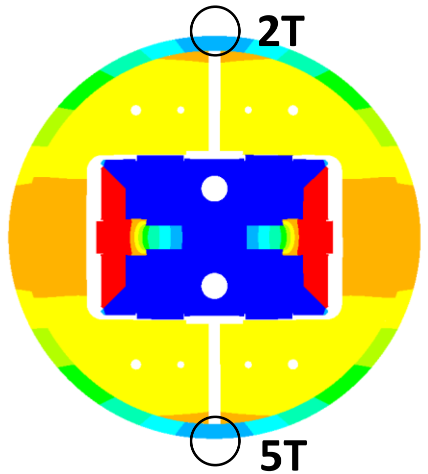
SMC11T#3

5. Strain measurements (2/9)





Asymmetry in the gauges 2 and 5 very large!

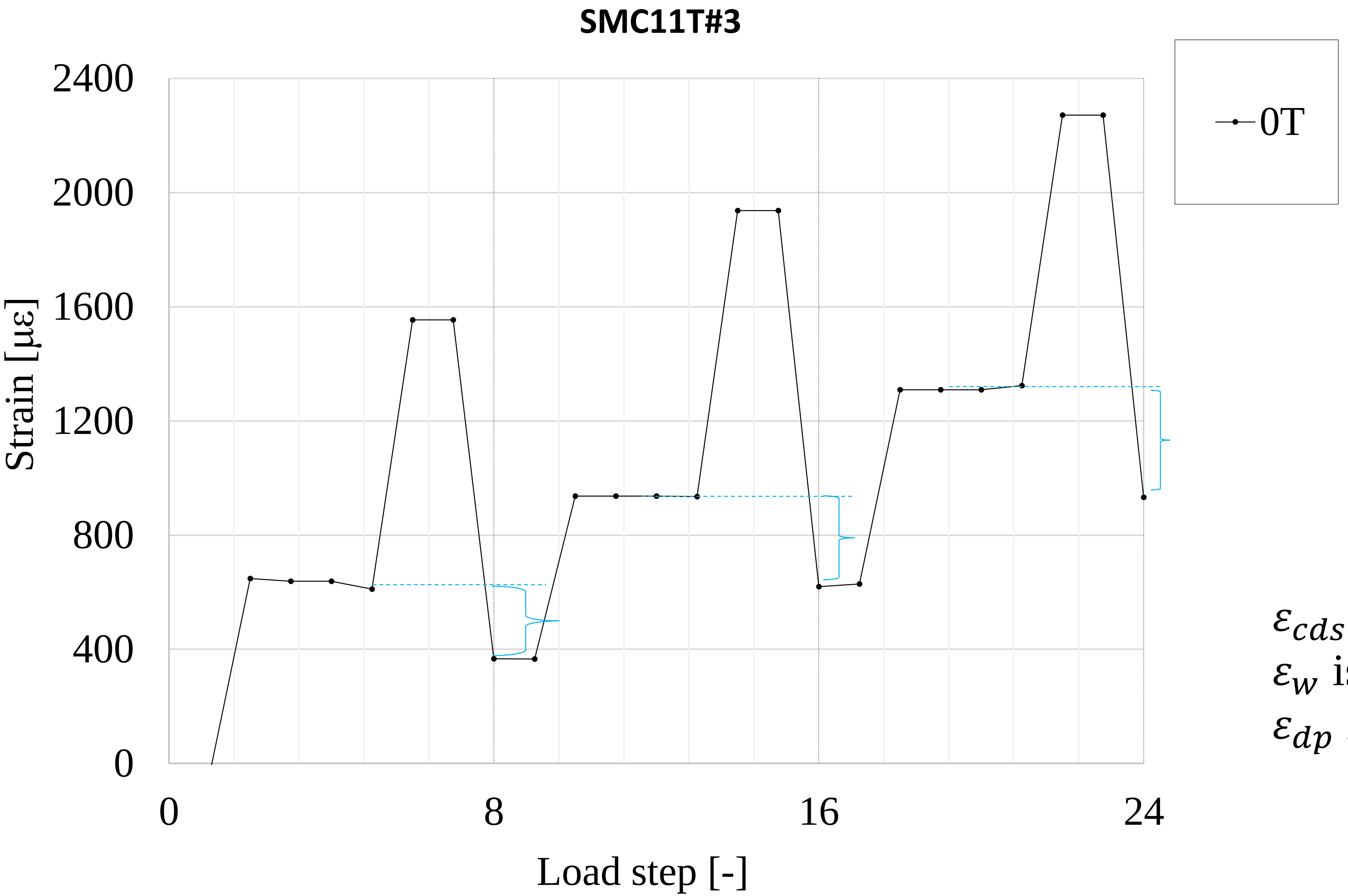


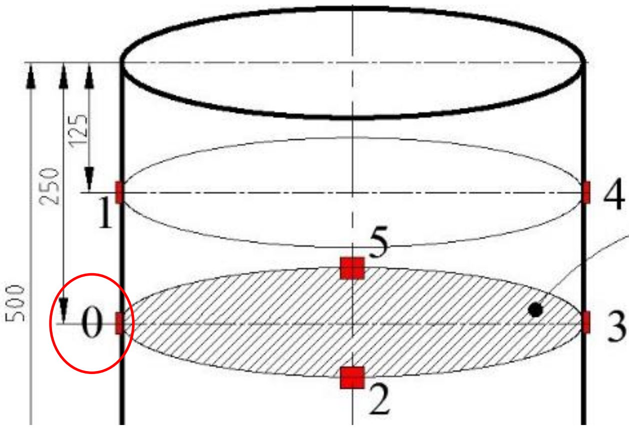
1με=1e-6 [-] = 0.0001 %

2000με=2e-3 [-] = 0.2 %

SMC11T#3

5. Strain measurements (3/9)



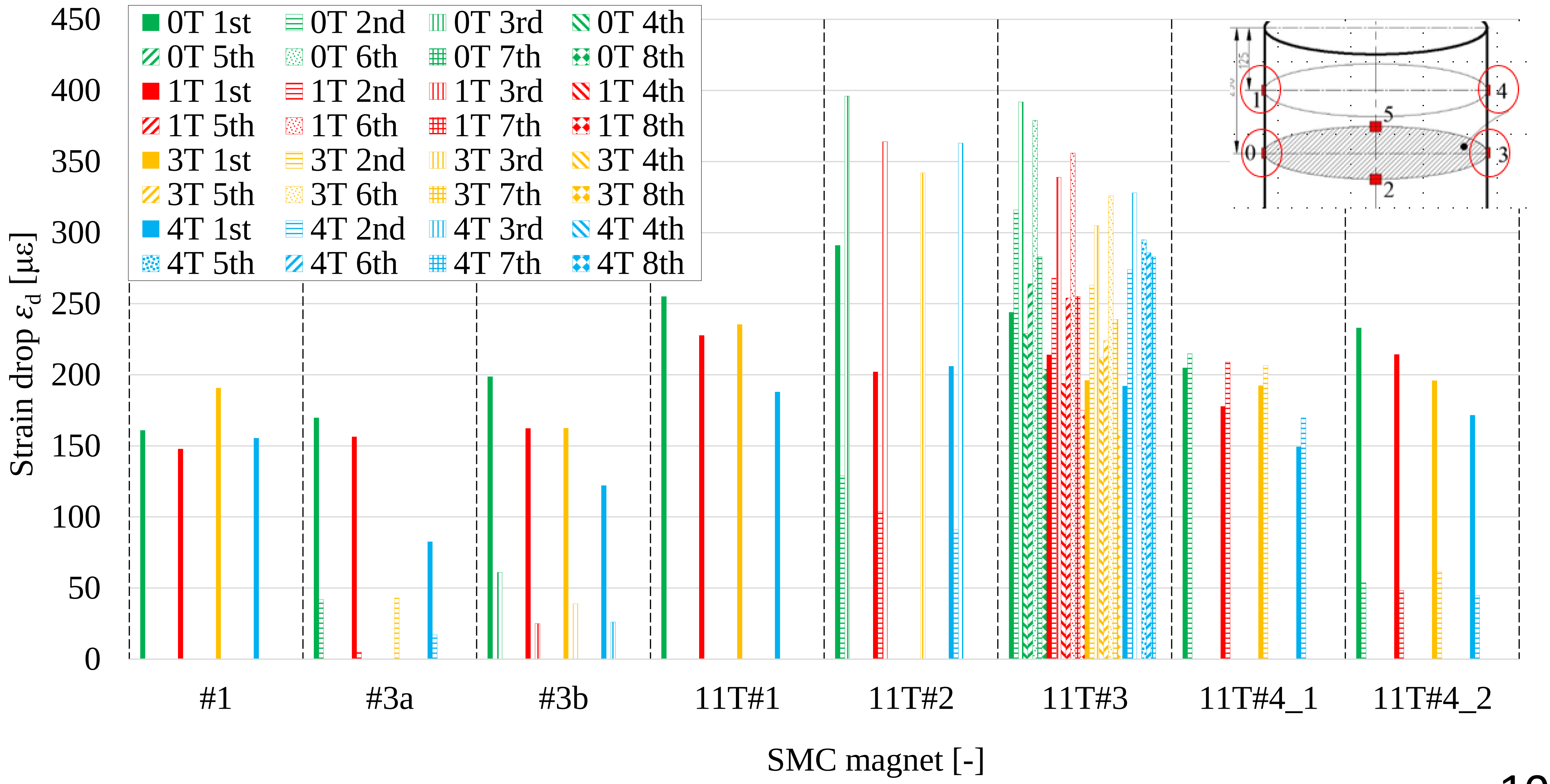


$$\varepsilon_d = \varepsilon_{cds} - \varepsilon_w$$

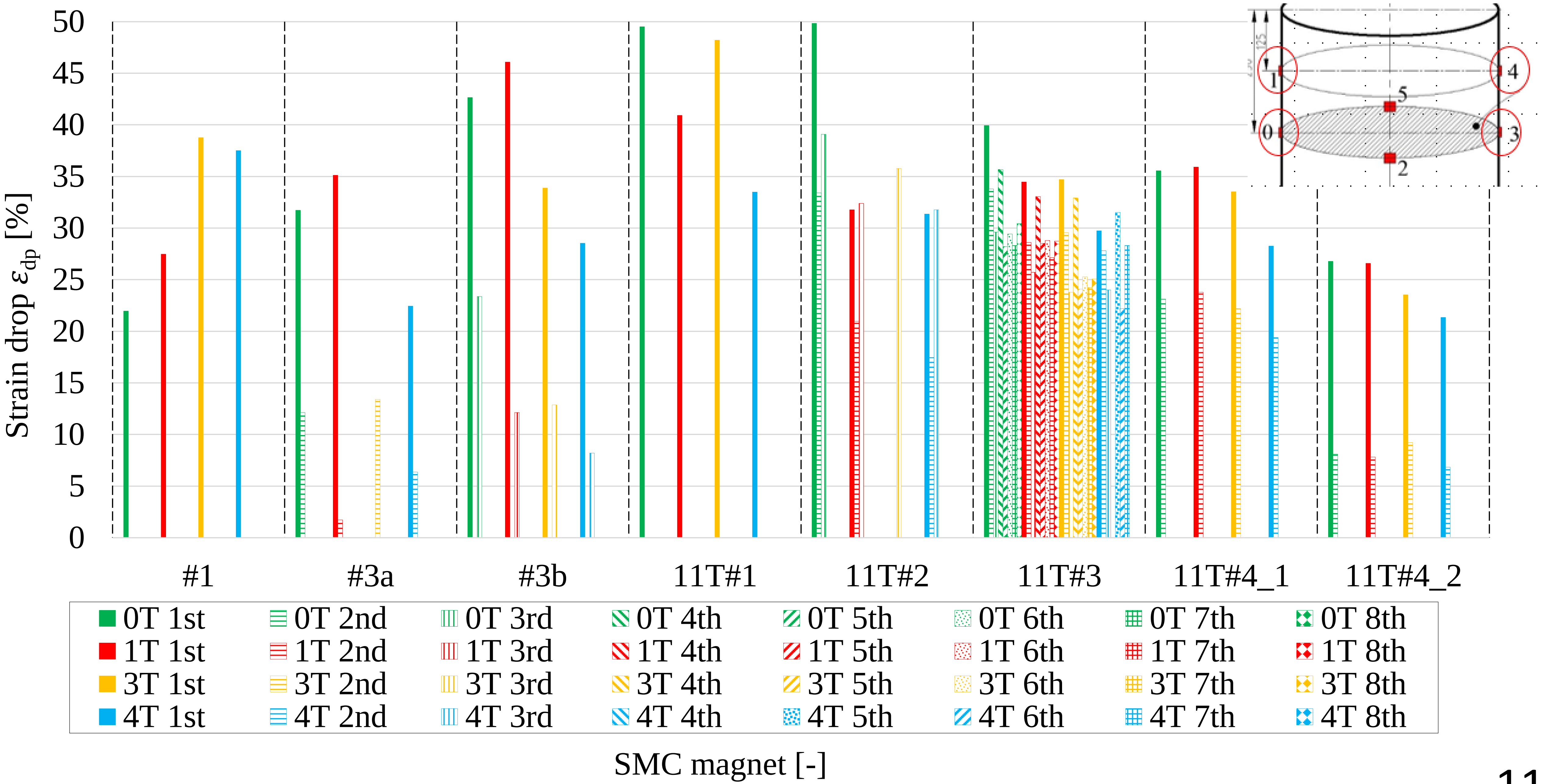
$$\varepsilon_{dp} = \frac{\varepsilon_d}{\varepsilon_{cds}} 100\%$$

ε_{cds} is the strain before cool-down
ε_w is the strain after warm-up
ε_{dp} is the percent strain drop

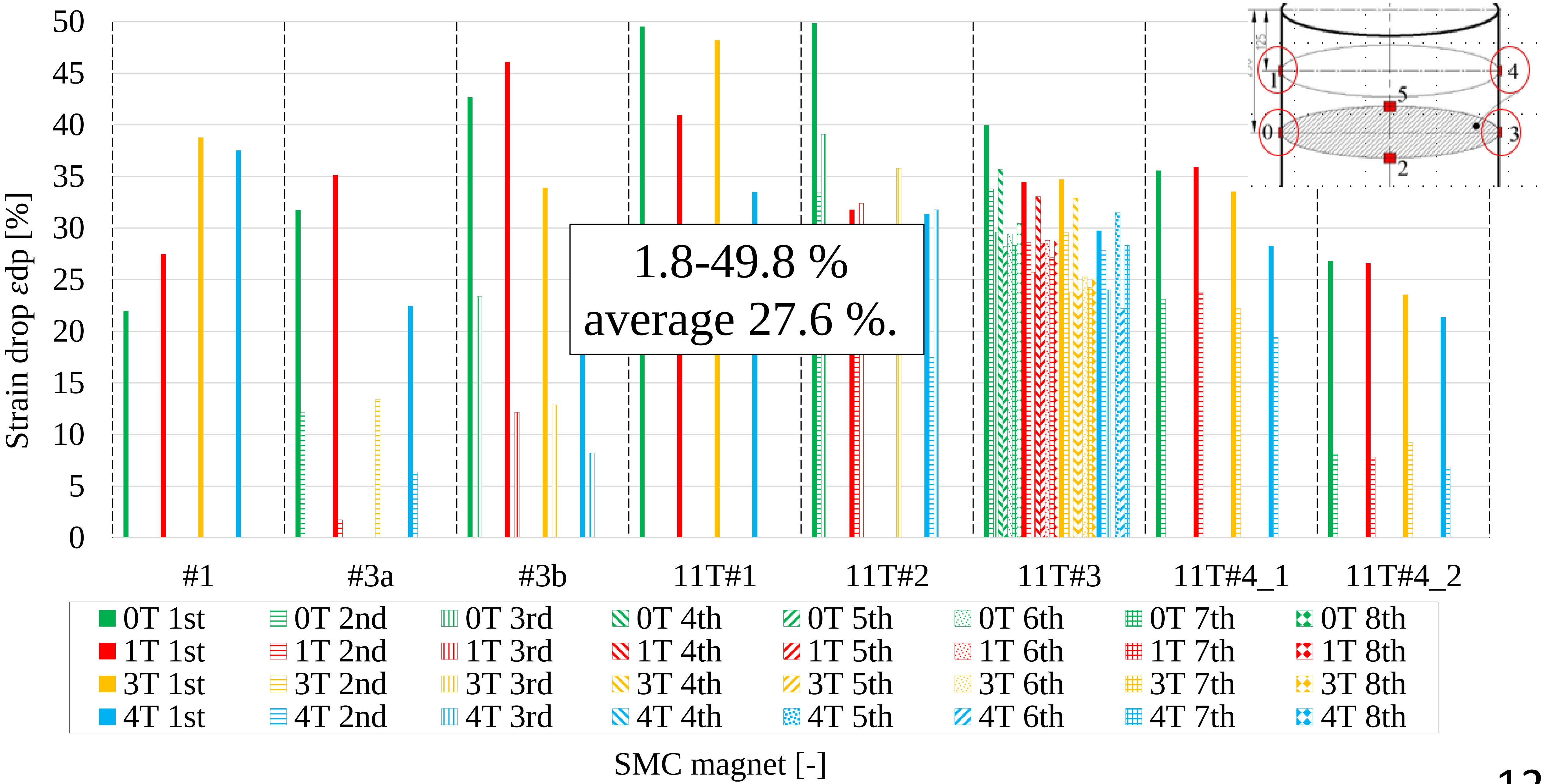
5. Strain measurements (4/9)



5. Strain measurements (5/9)



5. Strain measurements (6/9)



1.8-49.8 %
average 27.6 %.

5. Strain measurements (7/9)

From the data in the page

A. Chiuchiolo et al. Strain Measurements With Fiber Bragg Grating Sensors in the Short Models of the HiLumi LHC Low-Beta Quadrupole Magnet MQXF, *IEEE Trans. Appl. Supercond.* 28:4 (2018) 4007805

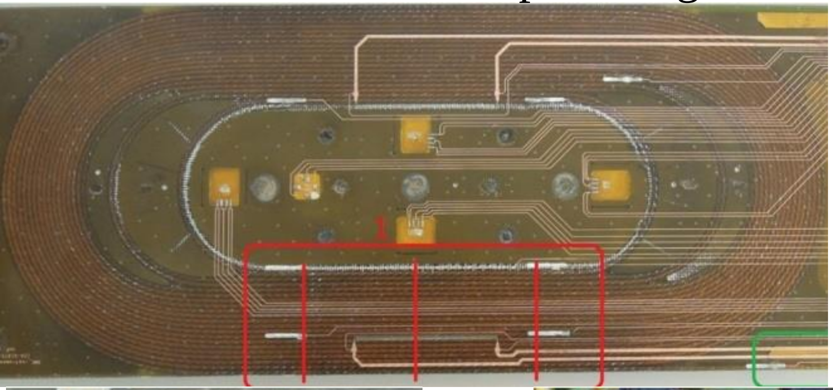
strain drop of 9-18 %

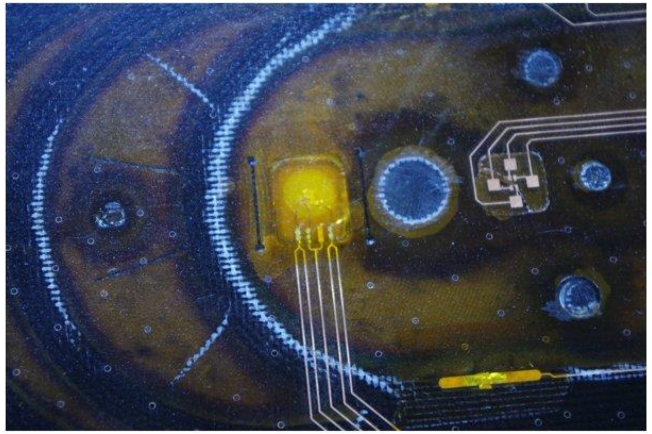
J.C. Perez et al. Construction and Test of the Enhanced Racetrack Model Coil, First CERN R&D Magnet for the FCC, *IEEE Trans. Appl. Supercond.* 32:6 (2022) 4005105

34-56 % (midplane strain gauges)
52-61 % (the rest of the gauges)

5. Strain measurements (8/9)

SMC#3b after powering

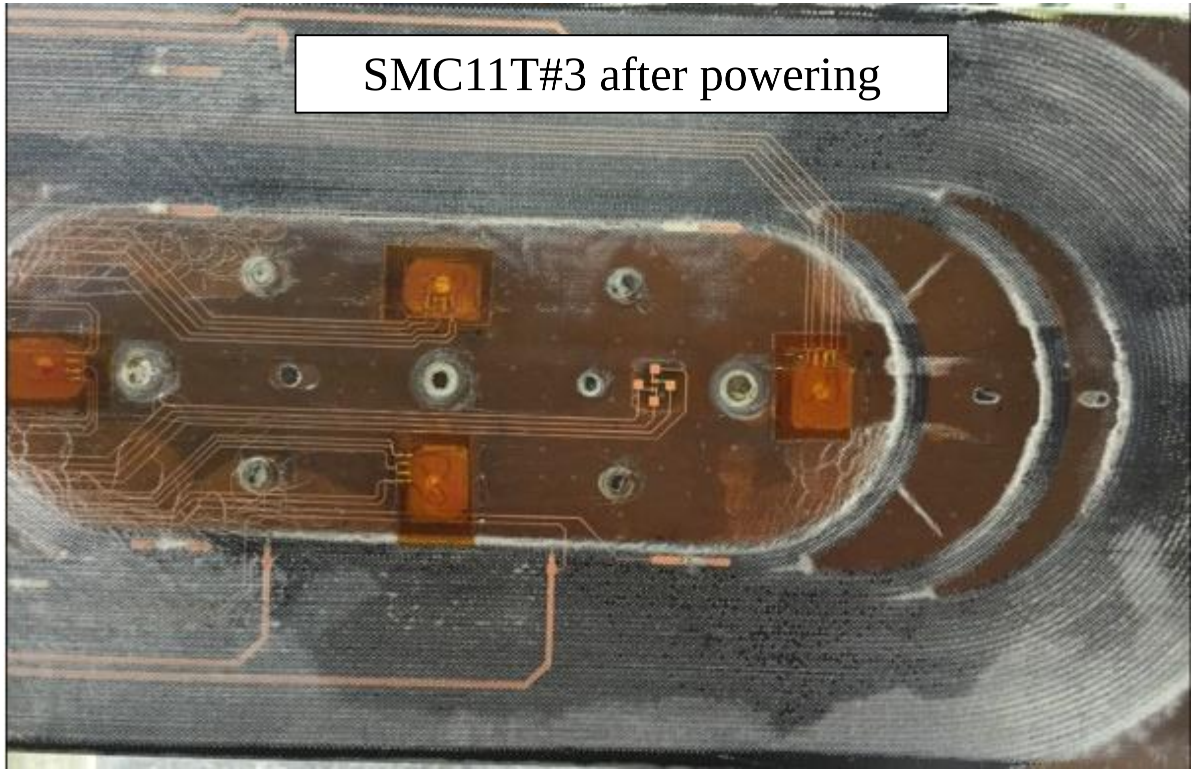




SMC11T#1 after powering

SMC11T#2
after impregnation

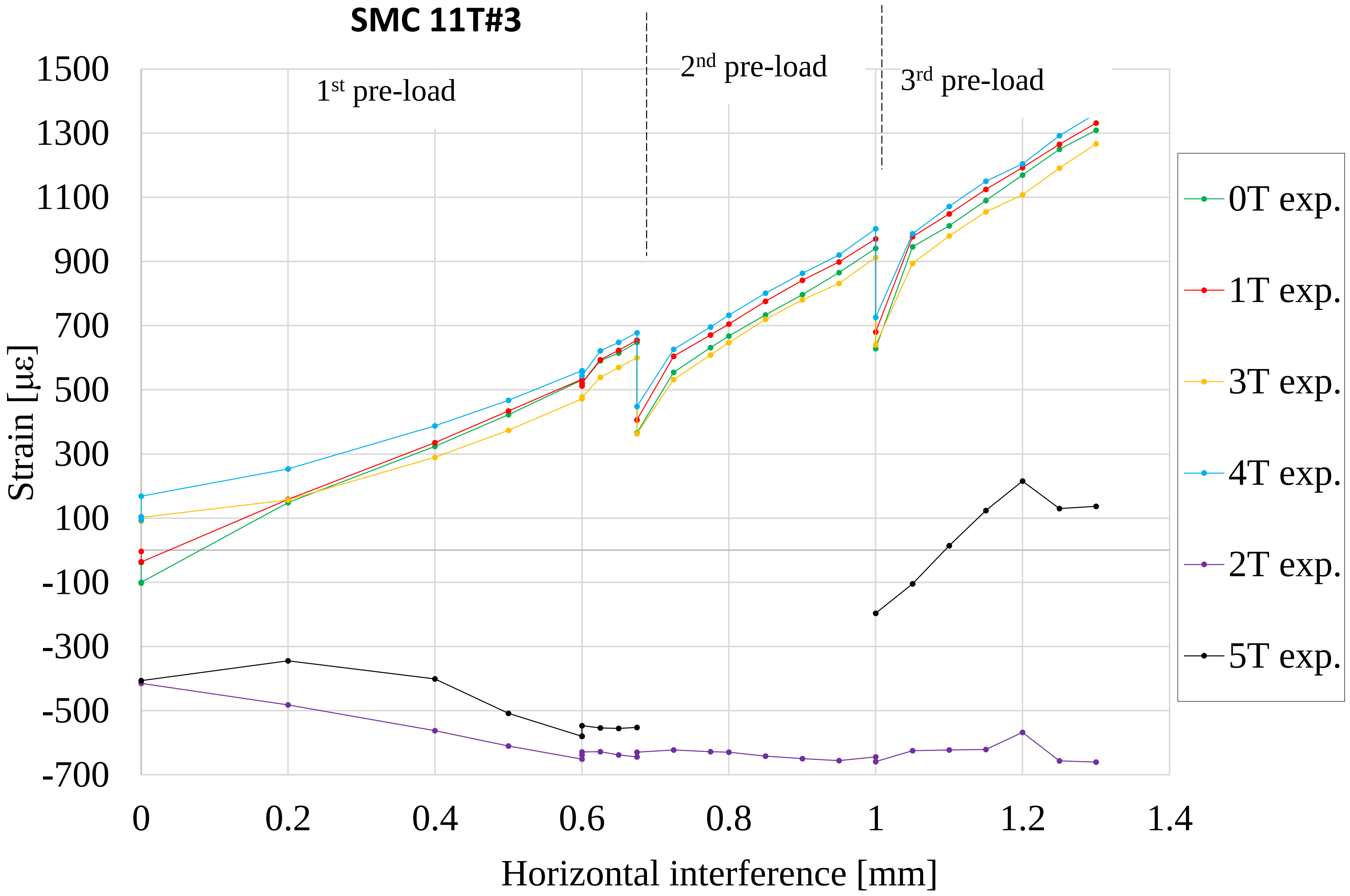
SMC11T#2
after powering

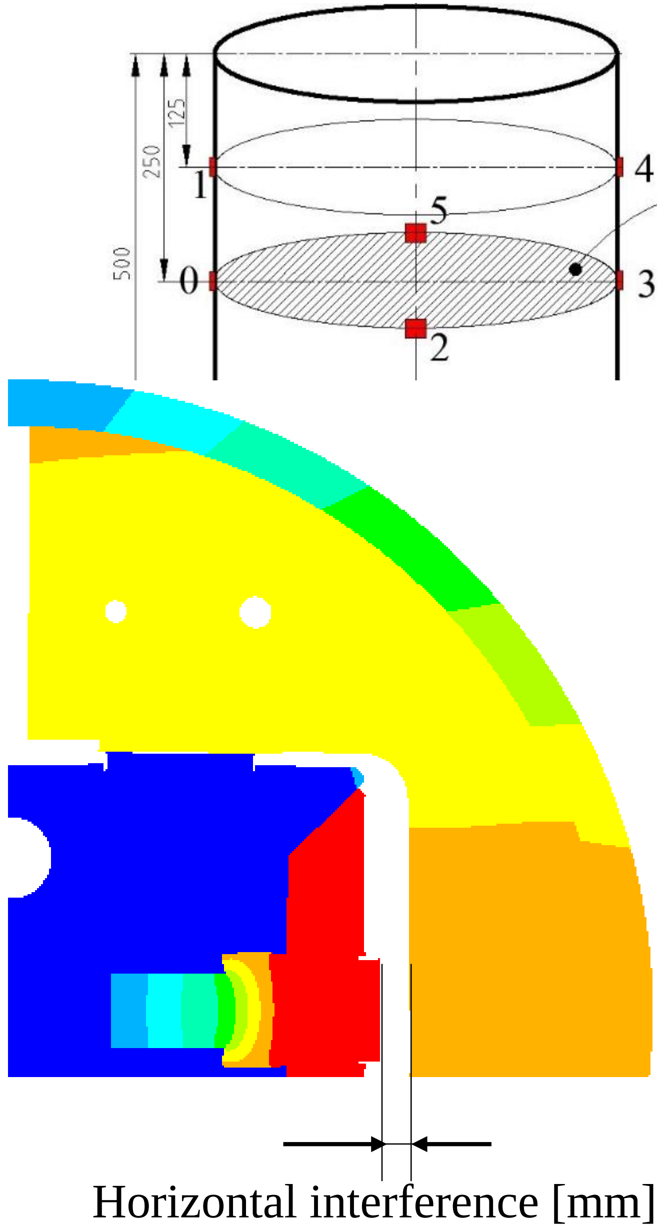


SMC11T#3 after powering

[1] R. Ortwein. Review of the state of the art, SMC (Short Model Coil). CERN EDMS 1836763 v.1 http://edms.cern.ch/ui/file/1836763/1/Review_SMC_Final_OrtweinR.pdf

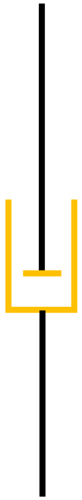
5. Strain measurements (9/9)

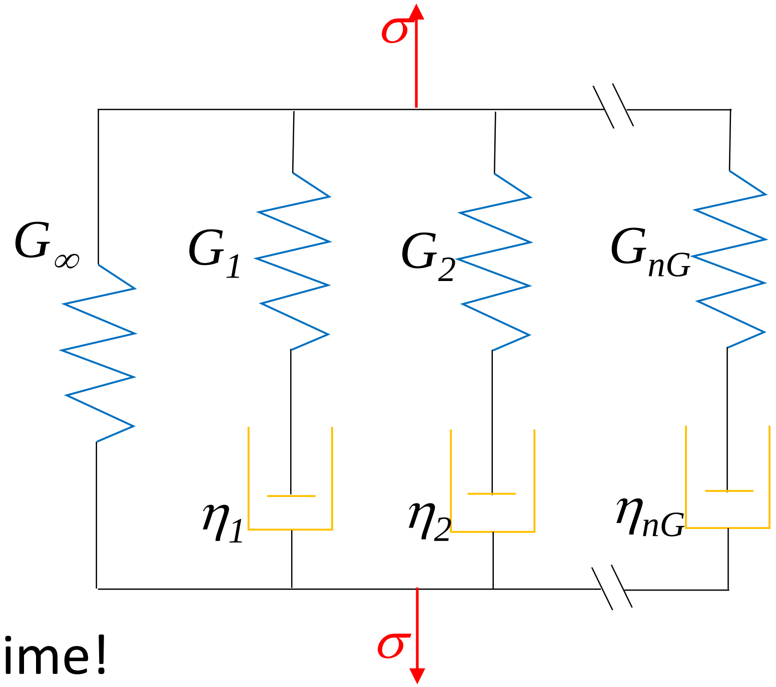




6. Viscoelastic materials (1/4)

SOLID (elasticity) + FLUID (viscosity) = VISCOELASTIC MATERIAL

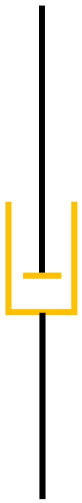


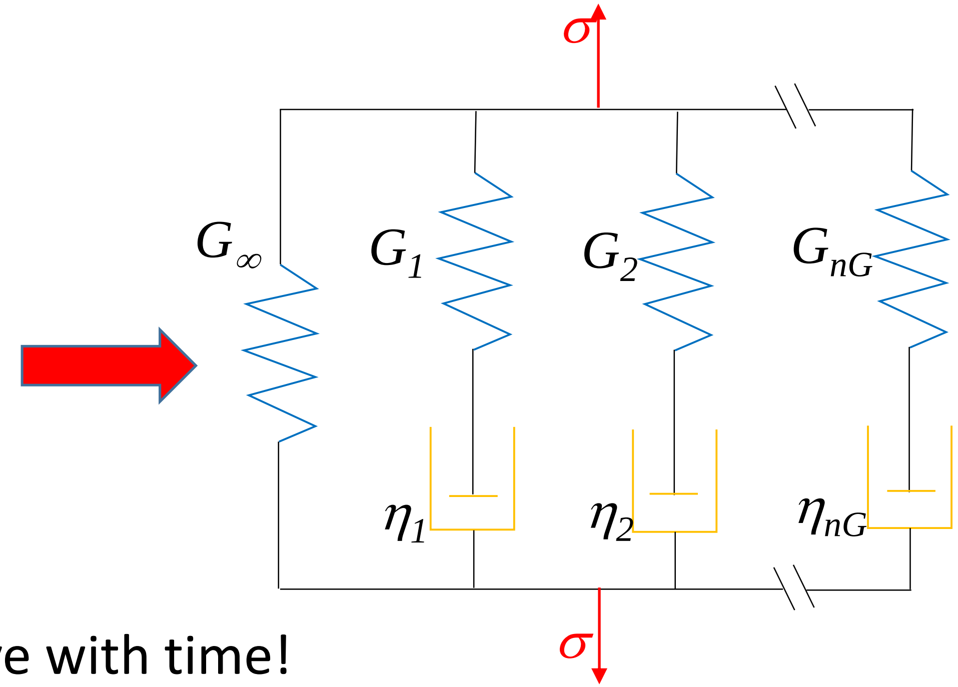


Mechanical properties of viscoelastic materials evolve with time!

6. Viscoelastic materials (1/4)

SOLID (elasticity) + FLUID (viscosity) = VISCOELASTIC MATERIAL

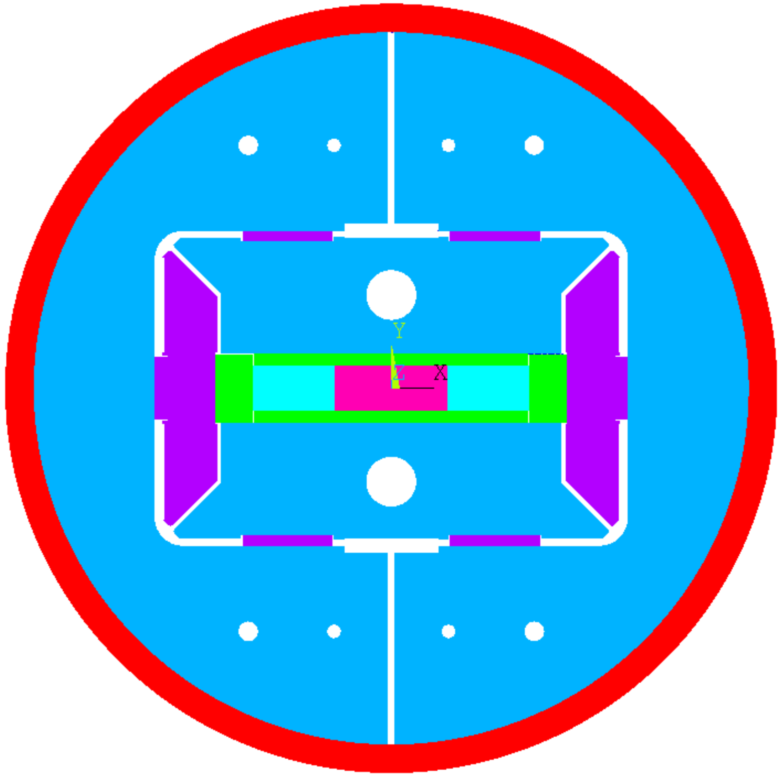




Mechanical properties of viscoelastic materials evolve with time!

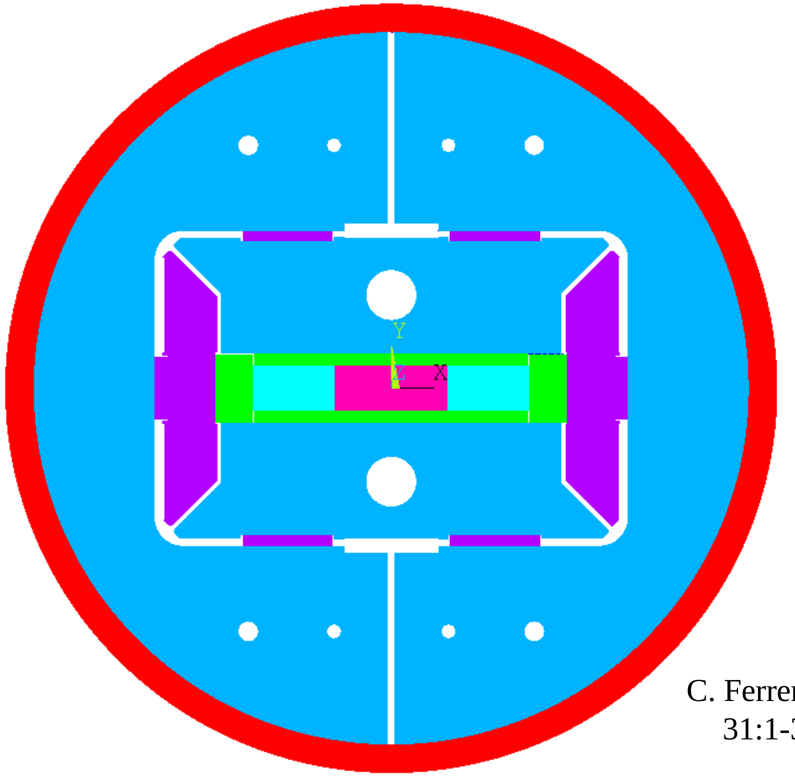
6. Viscoelastic materials (3/4)

Are there viscoelastic materials inside the SMC magnet?



6. Viscoelastic materials (3/4)

Are there viscoelastic materials inside the SMC magnet? **YES**



G10/G11 – high-pressure fiberglass laminate

Z. Zhang, G. Hartwig. Low-temperature viscoelastic behavior of unidirectional carbon composites, *Cryogenics* 38:4 (1998) 401-405

J. V. Gauchel, J. L. Olinger, D. C. Lupton: Characterization of Glass-Reinforced Composites for Cryogenic Applications. In: Adv. Cryog. Eng., Vol. 28, pp. 211-222. New York, Plenum Press (1982).

S.S. Wang et al. Tensile and Torsional Fatigue of Fiber-Reinforced Composites at Cryogenic Temperatures, *J. Eng. Mater. Technol.* 104:2 (1982) 121-127

S.S. Wang, E.SM. Chim. Degradation of fiber-reinforced composite materials at cryogenic temperatures, part I - uniaxial tensile and pure torsional fatigue. In: Reed, R.P., Clark, A.F. (eds) Advances in Cryogenic Engineering Materials . Advances in Cryogenic Engineering Materials , vol 28. Springer, Boston, MA

Epoxy resin

M. Wang et al. Rheological and mechanical properties of epoxy/clay nanocomposites with enhanced tensile and fracture toughnesses, *Polymer* 58 (2015) 43-52

Kapton

C. Ferrero, C. Marinari and E. Martino. Calibration systems for strain gauges to be used at cryogenic temperatures, *Sensors and Actuators A*, 31:1-3 (1992) 125-129

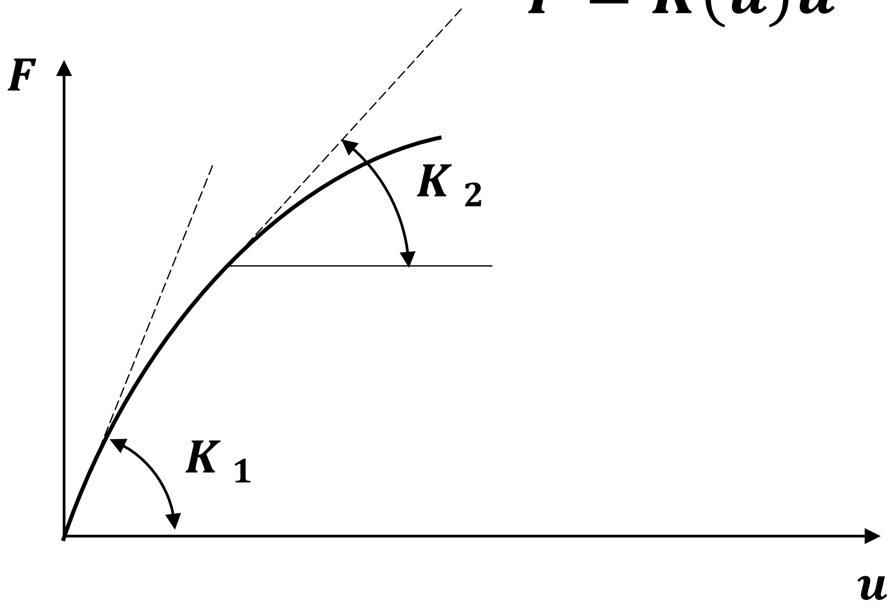
Copper

R.P. Reed, N.J. Simon, R.P. Waish. Creep of copper: 4-300 K. *Materials Science and Engineering, A* 147:1 (1991) 23- 32

6. Viscoelastic materials (4/4)

Continuum damage mechanics (CDM)

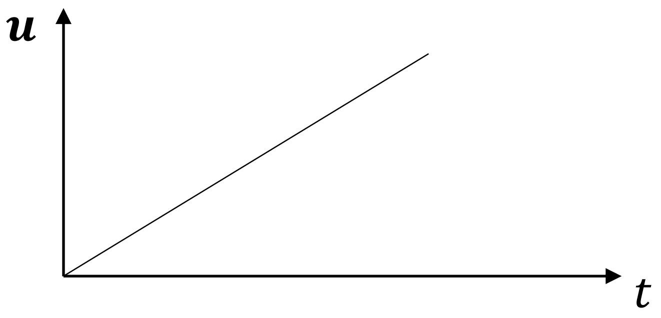
$$\boldsymbol{F} = \boldsymbol{K}(\boldsymbol{u})\boldsymbol{u}$$



- Stiffness evolves as function of the load
- Large number of iterations required
- Large computational cost

Viscoelasticity

$$\boldsymbol{F} = \boldsymbol{K}(t)\boldsymbol{u}$$



$$\boldsymbol{F} = \boldsymbol{K}(\boldsymbol{u})\boldsymbol{u}$$

- Stiffness is known function of time
- Much lower computational cost compared to CDM
- If loads is a function of time we can relate the stiffness evolution to the load evolution as in CDM

7. Viscoelastic materials – constitutive models (1/4)

$$\boldsymbol{\sigma} = \int_0^t 2G(t-\tau)\frac{d\boldsymbol{e}}{d\tau}d\tau + \boldsymbol{I}\int_0^t K(t-\tau)\frac{d\Delta}{d\tau}d\tau$$

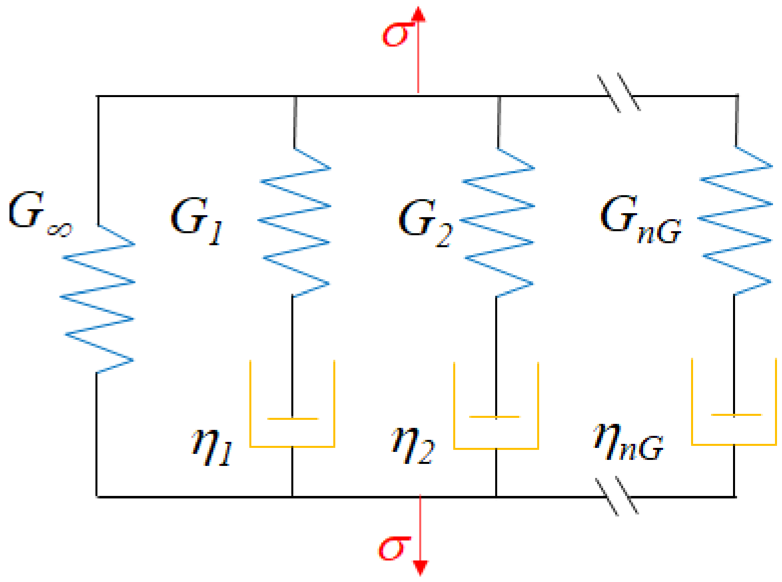
Isotropic viscoelaticity

$$\boldsymbol{\sigma} = 2G\boldsymbol{e} + \boldsymbol{I}K\Delta$$

Isotropic elasticity

σ – is the Cauchy stress tensor,
$\boldsymbol{e}$ – is the deviatoric strain tensor (strain deviator),
$\boldsymbol{I}$ – is a unit tensor,
Δ – is the volumetric strain,
G - shear modulus,
K – bulk modulus,
$G(t-\tau)$ – is the deviatoric stress kernel function,
$K(t-\tau)$ – is the volumetric stress kernel function,
t – is time
τ – is the past time

7. Viscoelastic materials – constitutive models (2/4)

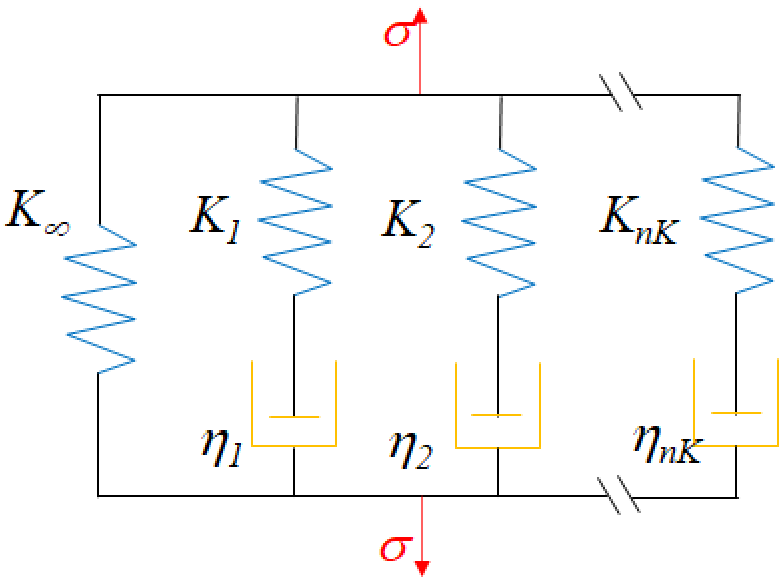


$$G(t) = G_\infty + \sum_{i=1}^{nG} G_i e^{-\left(\frac{t}{\tau_i^G}\right)}$$

$$\tau_i^G = \frac{\eta_i}{G_i} \qquad \alpha_i^G = \frac{G_i}{G_0}$$

$$G_0 = G_\infty + \sum_{i=1}^{nG} G_i$$

$$G(t) = G_0 \left[1 - \sum_{i=1}^{nG} \alpha_i^G \left(1 - e^{-\left(\frac{t}{\tau_i^G}\right)}\right)\right]$$



$$K(t) = K_\infty + \sum_{i=1}^{nK} K_i e^{-\left(\frac{t}{\tau_i^K}\right)}$$

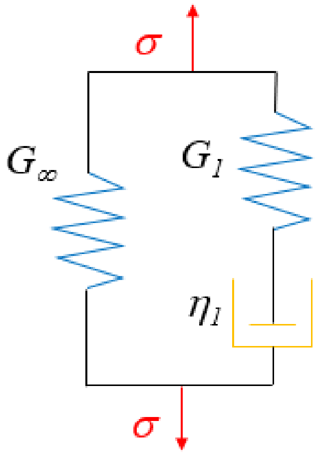
$$\tau_i^K = \frac{\eta_i}{K_i} \qquad \alpha_i^K = \frac{K_i}{K_0}$$

$$K_0 = K_\infty + \sum_{i=1}^{nK} K_i$$

$$K(t) = K_0 \left[1 - \sum_{i=1}^{nK} \alpha_i^K \left(1 - e^{-\left(\frac{t}{\tau_i^K}\right)}\right)\right]$$

7. Viscoelastic materials – constitutive models (3/4)

nG=1



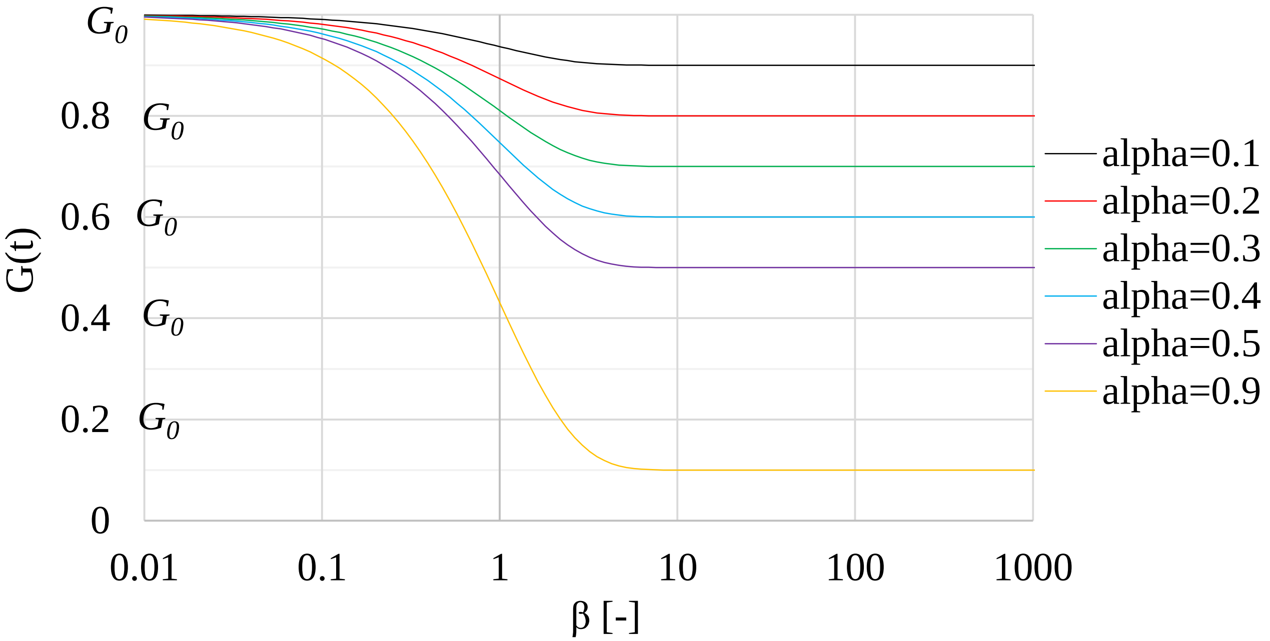
$$G(t) = G_0\left[1 - \alpha_1^G\left(1 - e^{-\left(\frac{t}{\tau_1^G}\right)}\right)\right]$$

$$\beta = \frac{t}{\tau_1^G}$$

$$G(t) = G_0\left[1 - \alpha_1^G\left(1 - e^{-\beta}\right)\right]$$

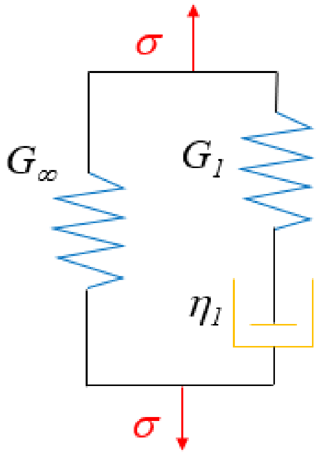
$$For\ t \to \infty \quad (\beta \to \infty)$$

$$G(t) = G_0\left(1 - \alpha_1^G\right)$$



7. Viscoelastic materials – constitutive models (3/4)

nG=1



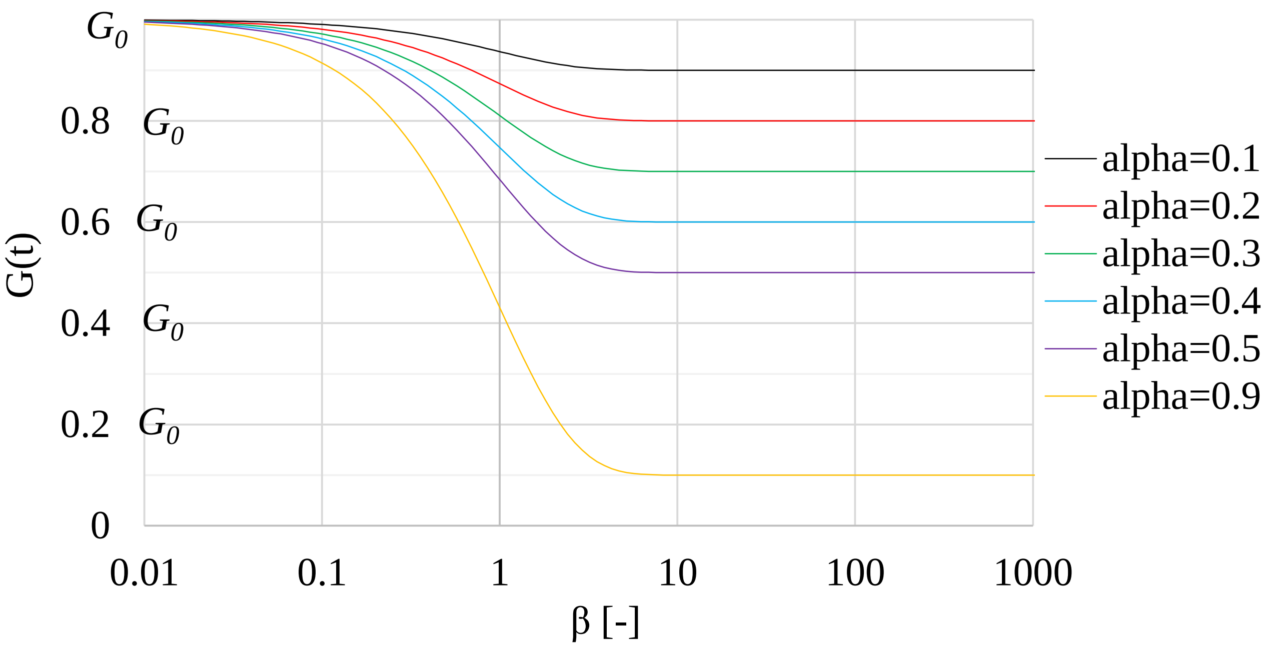
$$G(t) = G_0\left[1 - \alpha_1^G\left(1 - e^{-\left(\frac{t}{\tau_1^G}\right)}\right)\right]$$

$$\beta = \frac{t}{\tau_1^G}$$

$$G(t) = G_0\left[1 - \alpha_1^G\left(1 - e^{-\beta}\right)\right]$$

$$For\ t \to \infty \quad (\beta \to \infty)$$

$$G(t) = G_0\left(1 - \alpha_1^G\right)$$

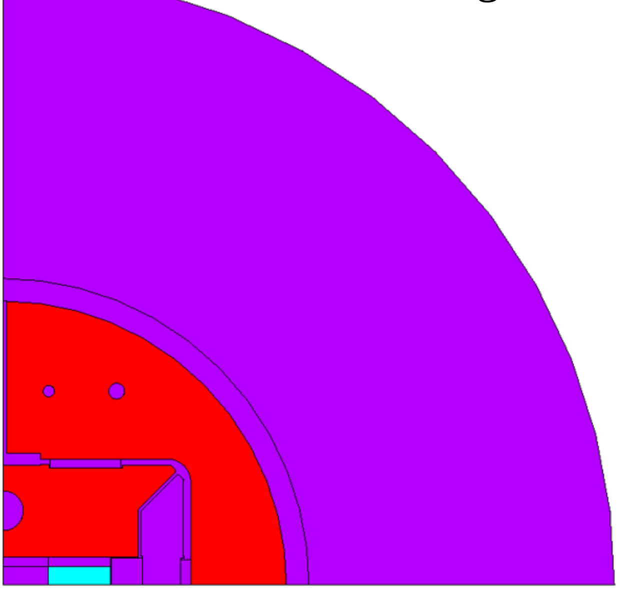


Direct analogy of α_1^G
of the scalar damage parameter D

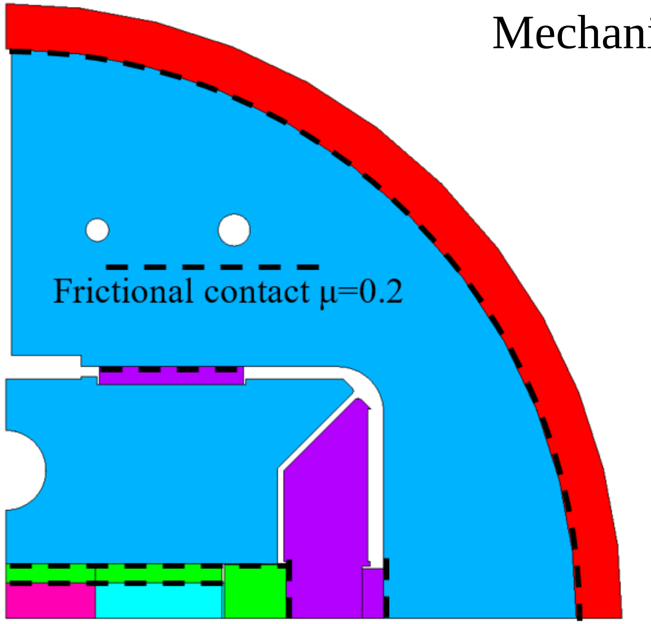
$$G(t) = G_0\left(1 - \alpha_1^G\right) \qquad E = E_0(1 - D)$$

8. FEM model of the SMC magnet (1/2)

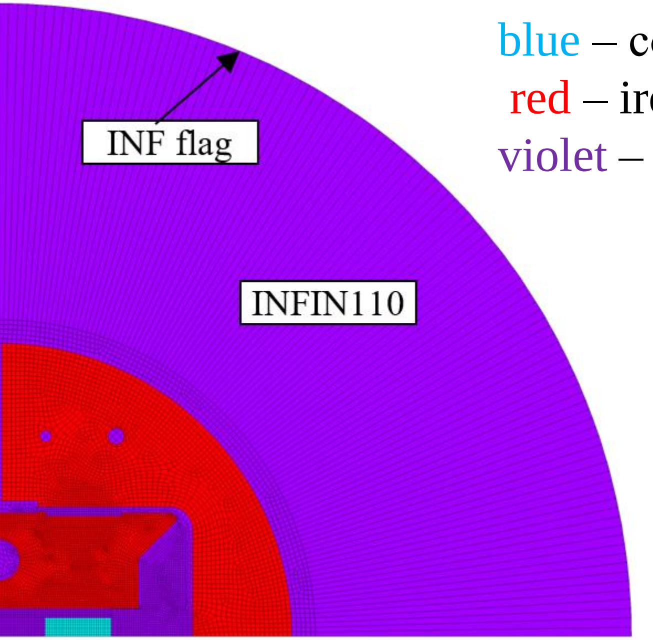
Electromagnetic model



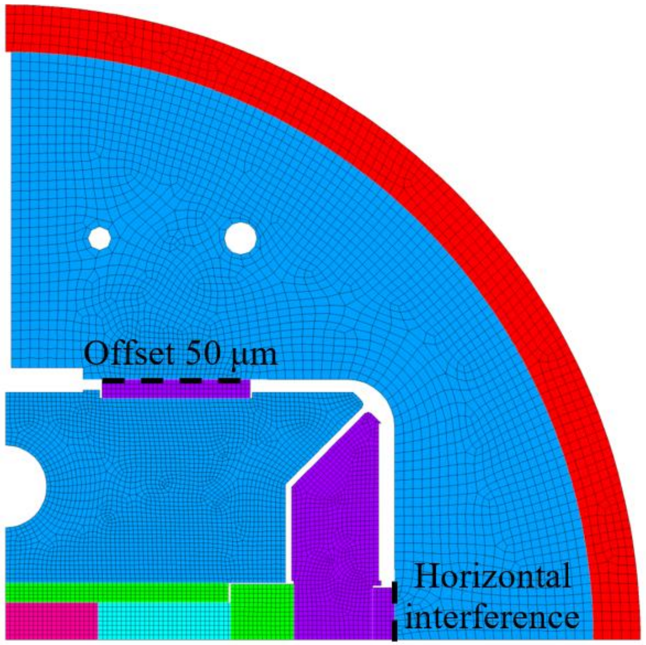
Mechanical model



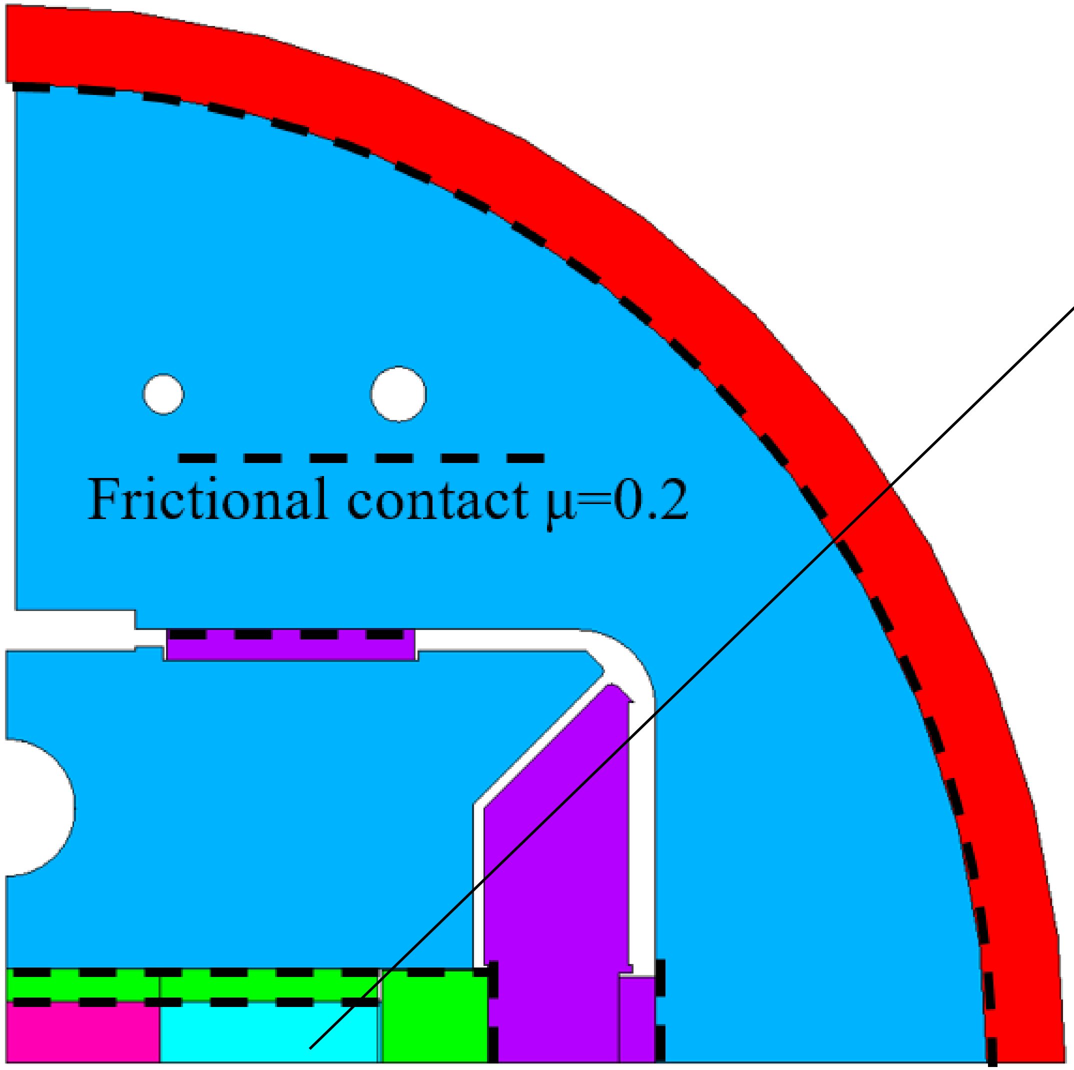
blue – coil
pink – titanium
dark blue – iron
violet – stainless steel
red – aluminum
green – G10/G11

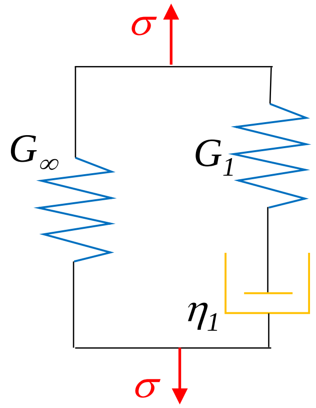


blue – coil (μ_R=1)
red – iron (B-H curve)
violet – air (μ_R=1)



8. FEM model of the SMC magnet (2/2)





$$G(t) = G_0 \left[1 - \boldsymbol{\alpha_1^G} \left(1 - e^{-\left(\frac{t}{\boldsymbol{\tau_1^G}}\right)}\right)\right]$$

$$K(t) = K_0 \left[1 - \boldsymbol{\alpha_1^K} \left(1 - e^{-\left(\frac{t}{\boldsymbol{\tau_1^K}}\right)}\right)\right]$$

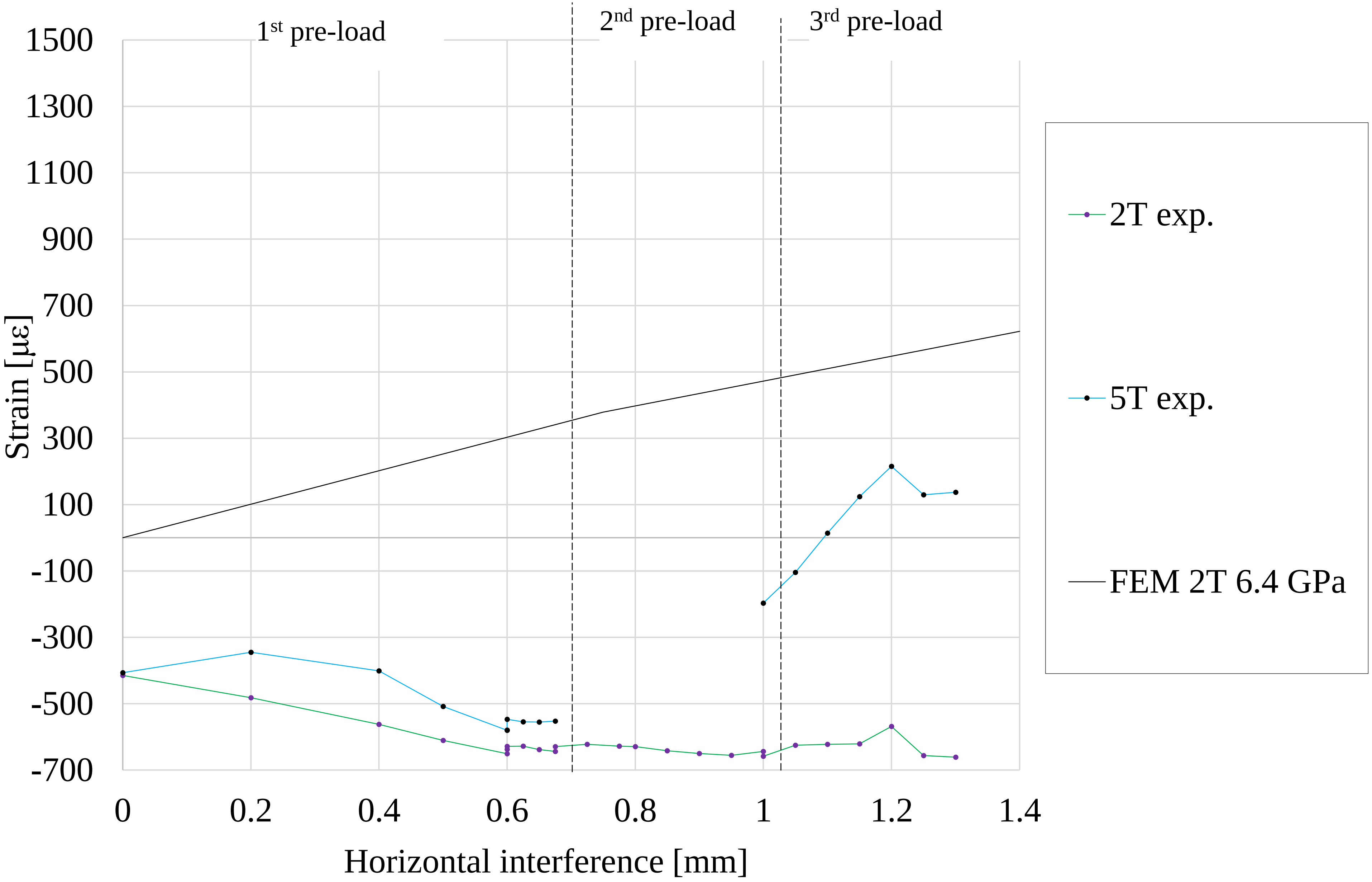
D. Przenny. Finite element modelling of viscoelastic effects in superconducting Nb3Sn magnets, Master thesis (2022)

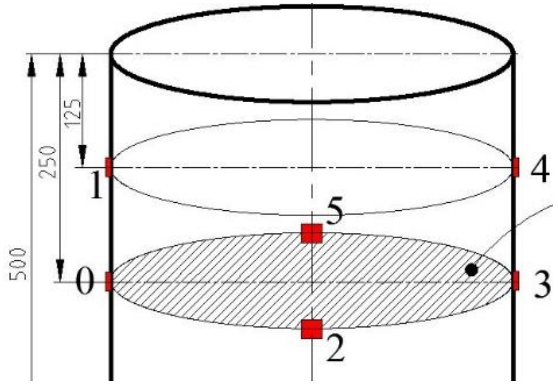
$$\boldsymbol{\alpha_1^G} = \boldsymbol{\alpha_1^K}$$

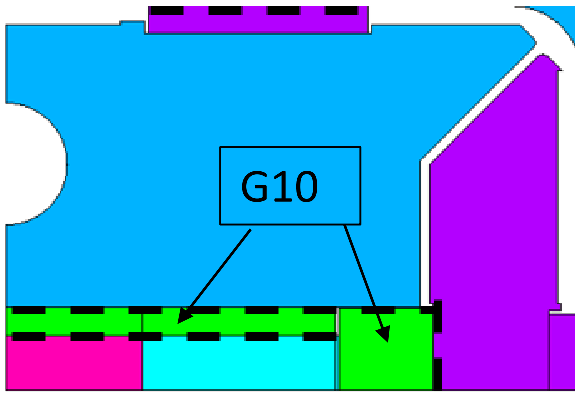
Only one parameter is needed to calibrate the viscoelastic model with one branch

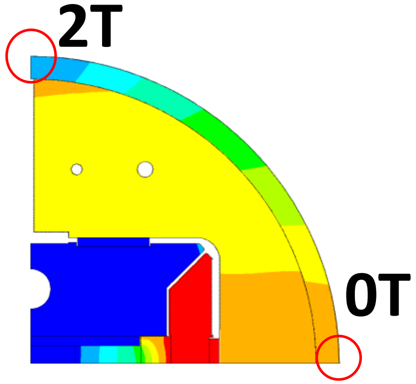
9. Elastic solution vs the experimental results (1/4)

SMC 11T#3



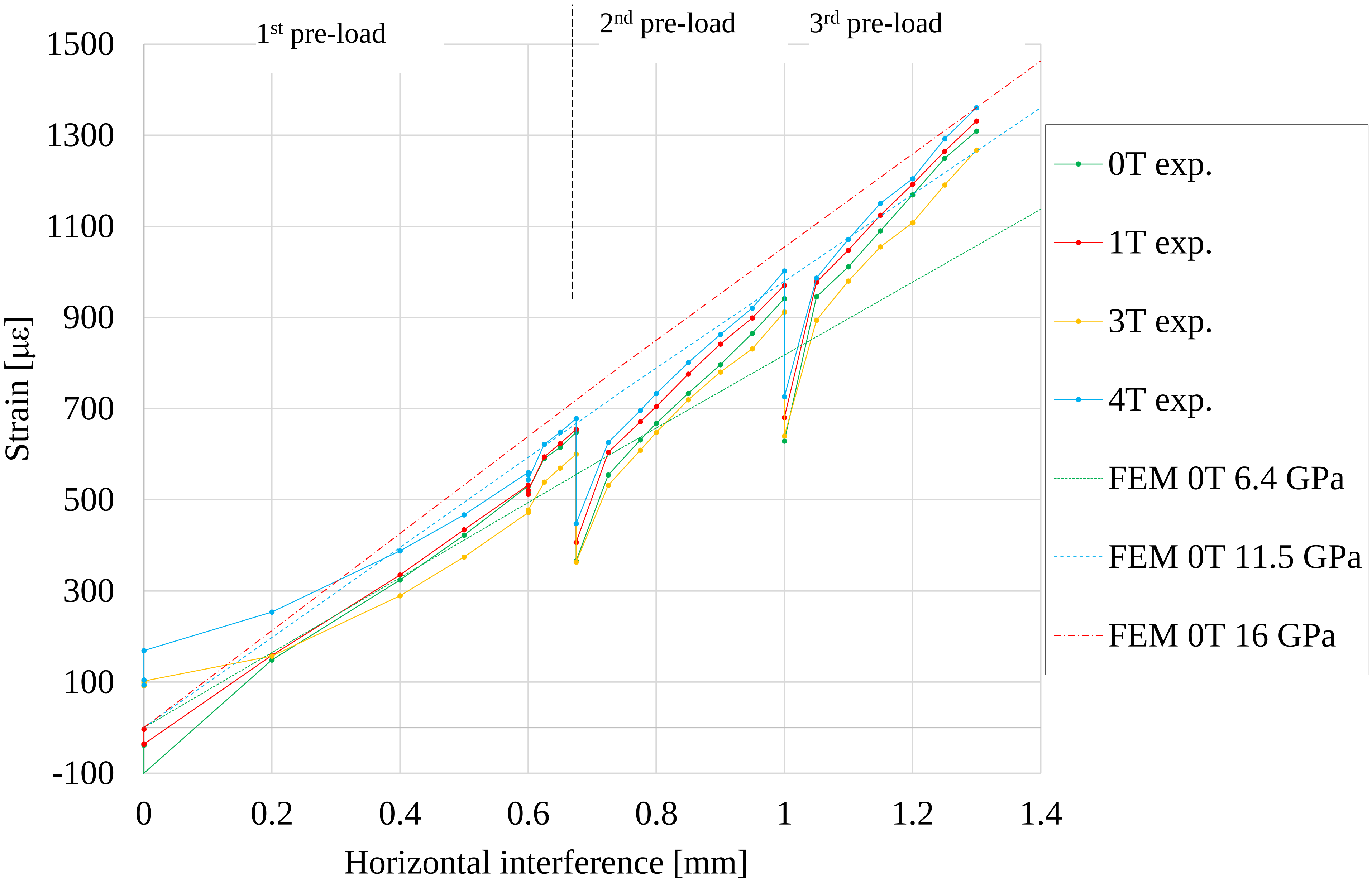


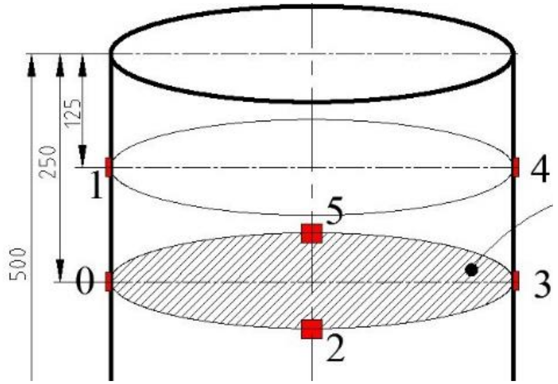


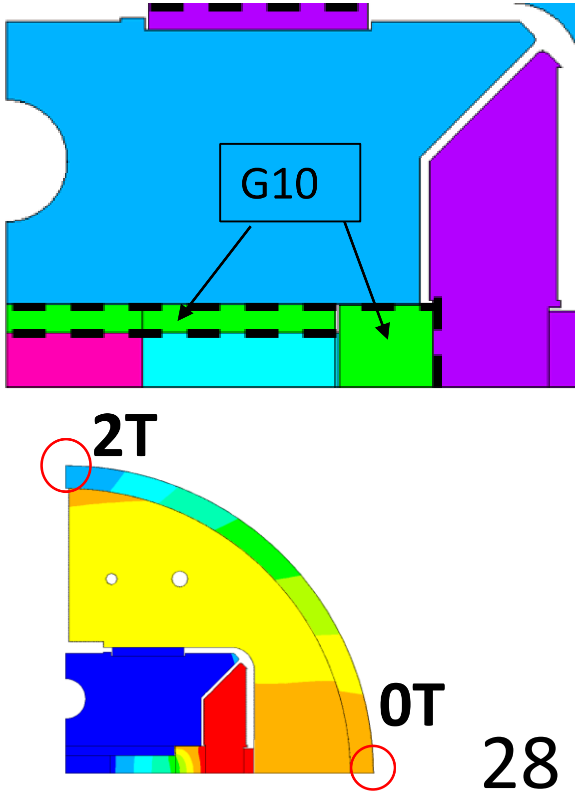


9. Elastic solution vs the experimental results (1/4)

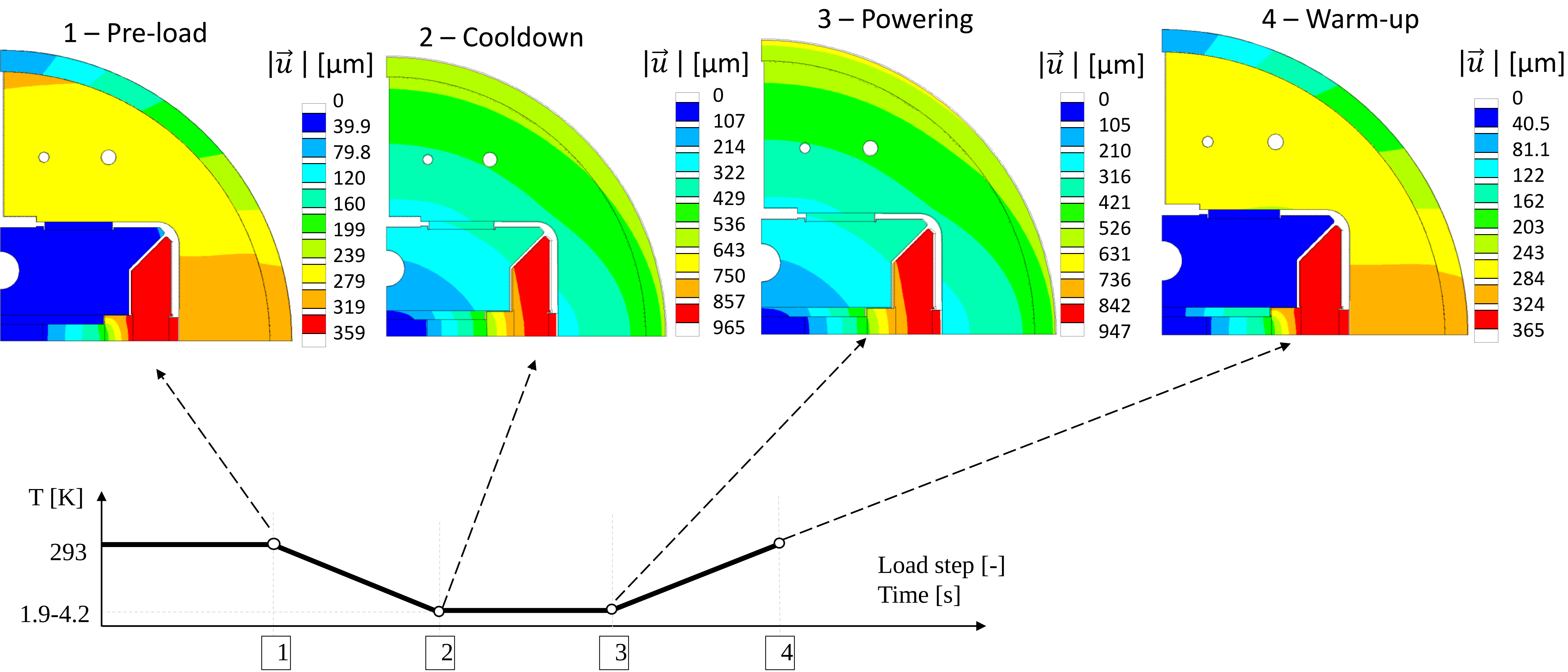
SMC 11T#3





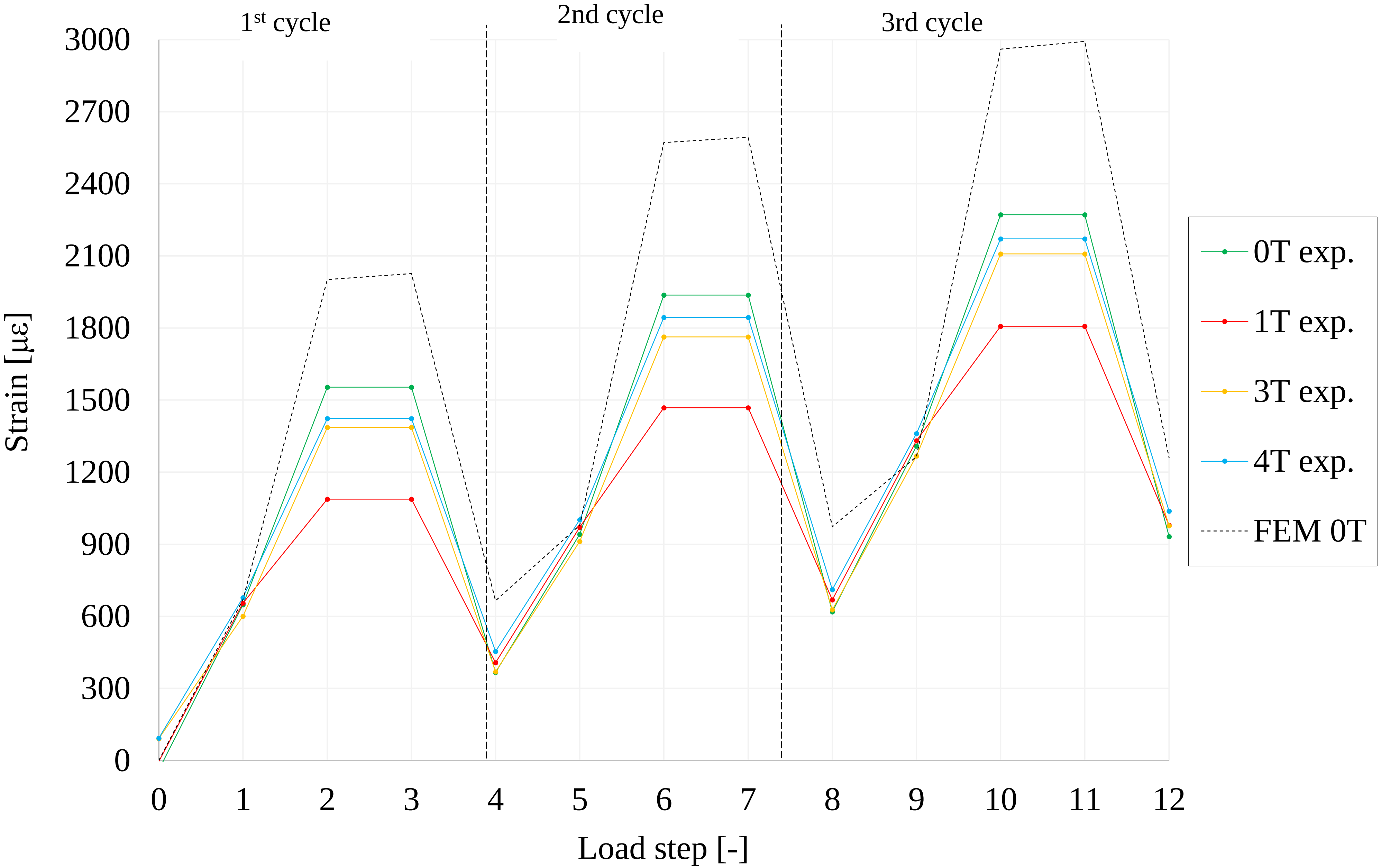


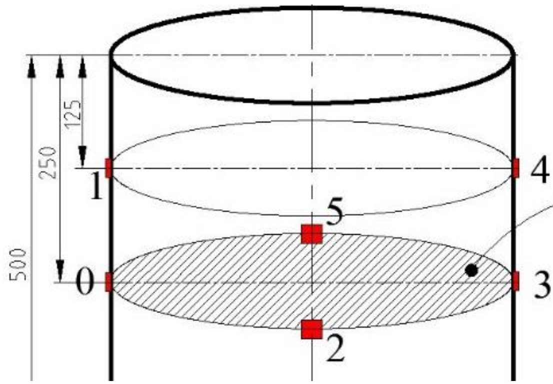
9. Elastic solution vs the experimental results (2/4)

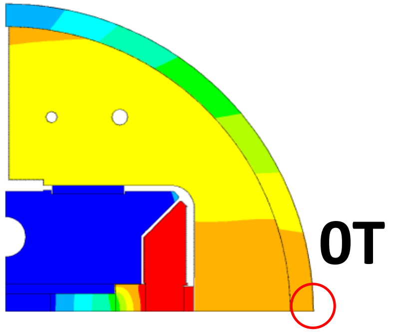


9. Elastic solution vs the experimental results (3/4)

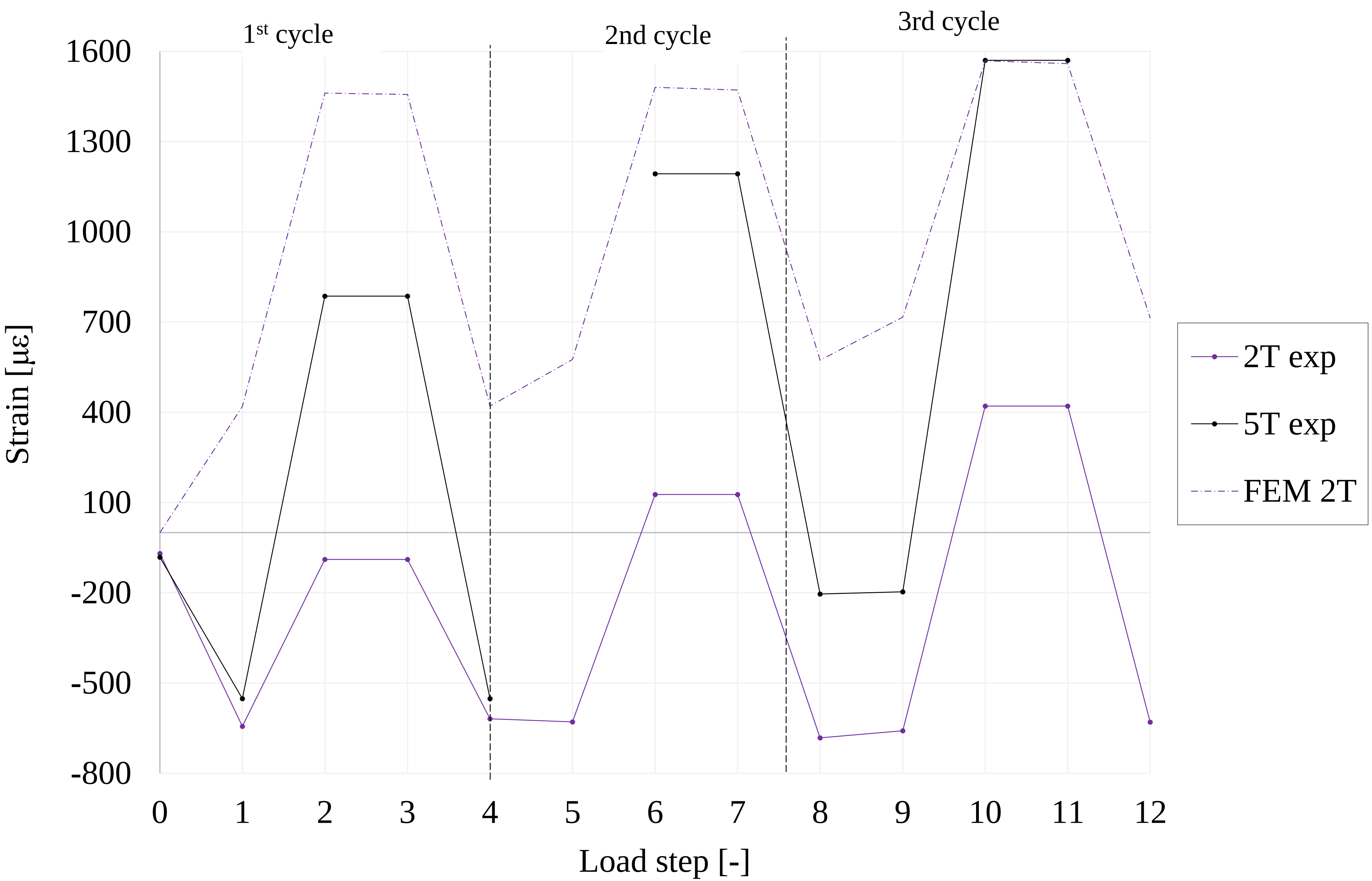
SMC 11T#3

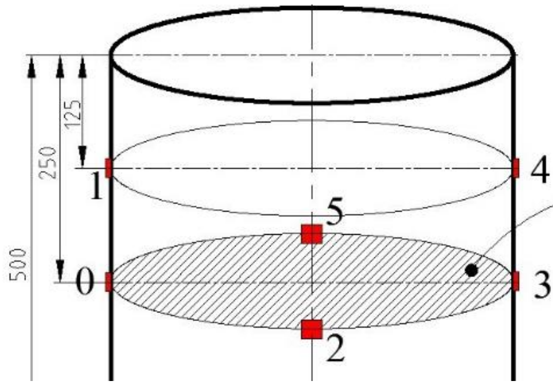


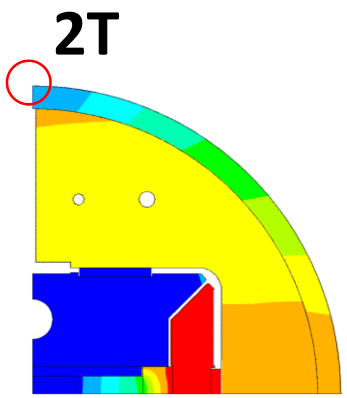




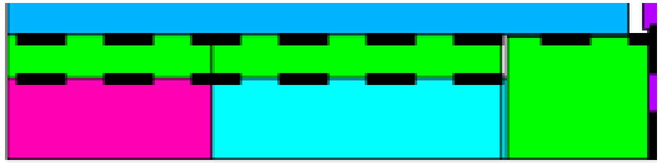
9. Elastic solution vs the experimental results (4/4)

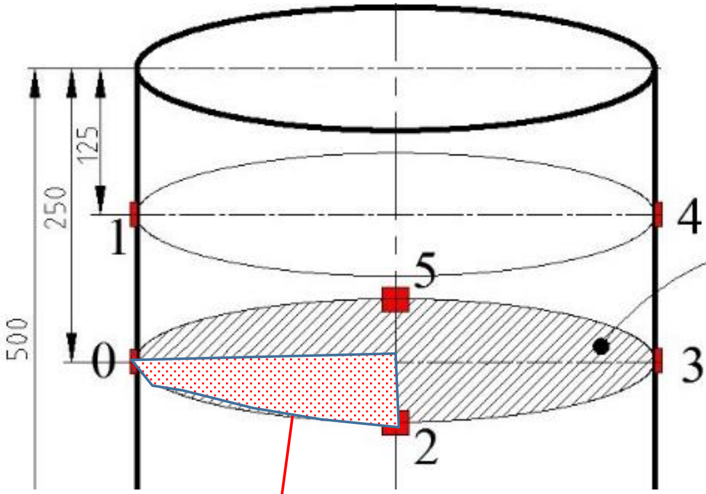




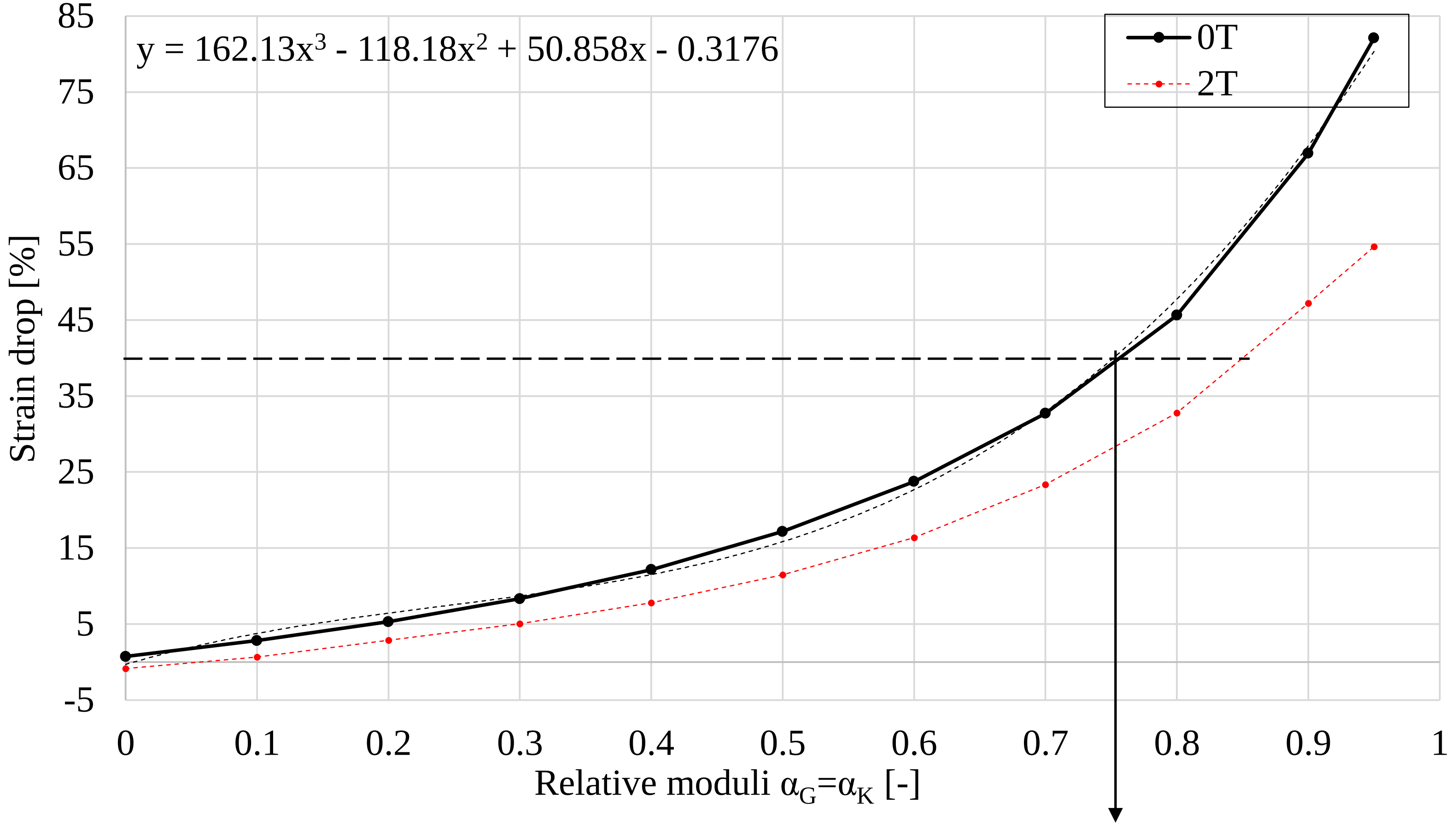


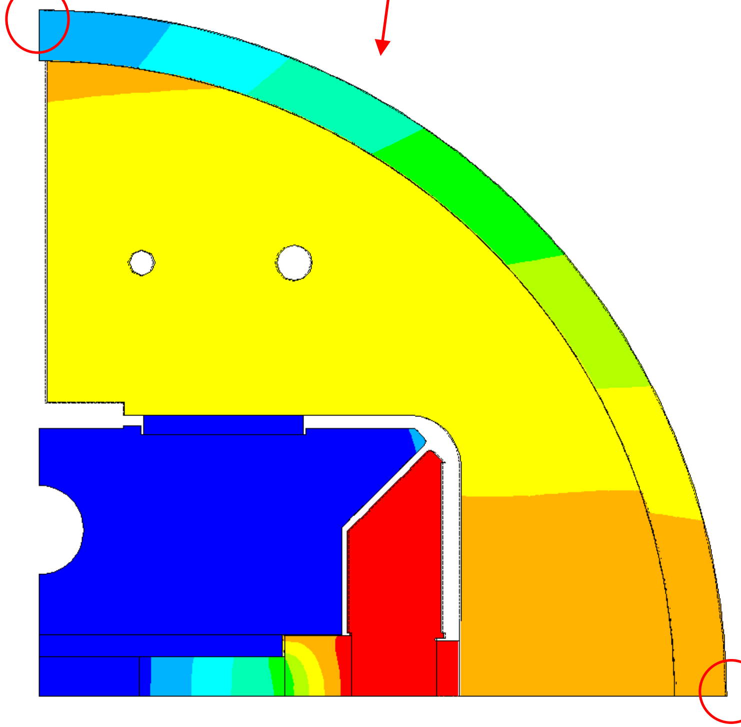
10. Viscolastic solution (1/5)





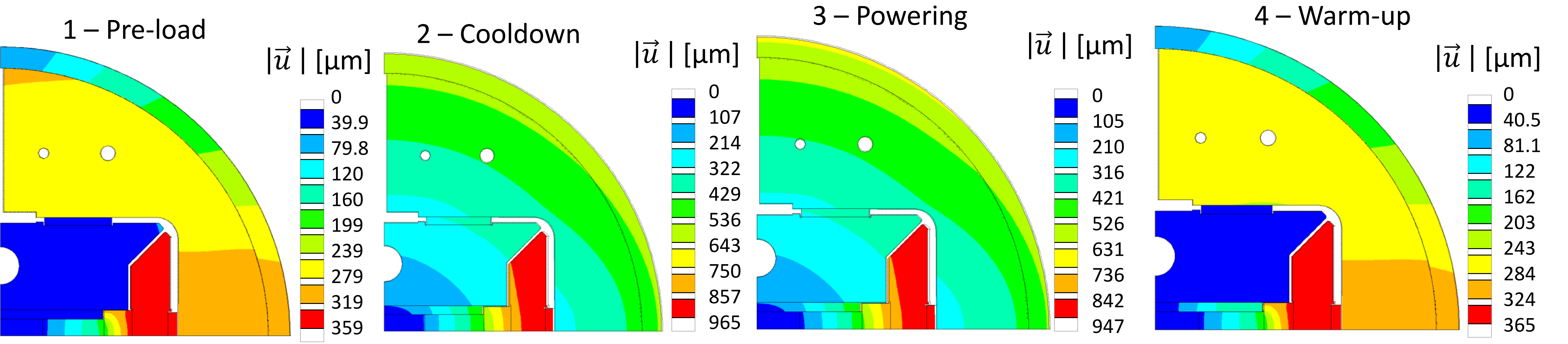
Calibration of the viscoelastic model



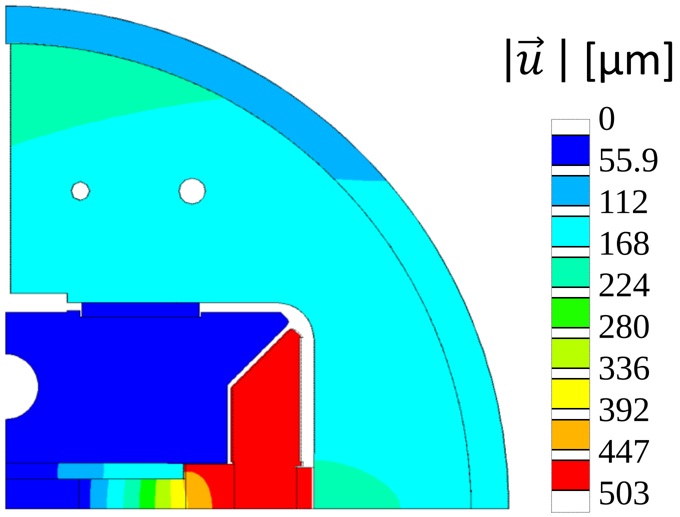


$\alpha_1^G = \alpha_1^K = 0.756$

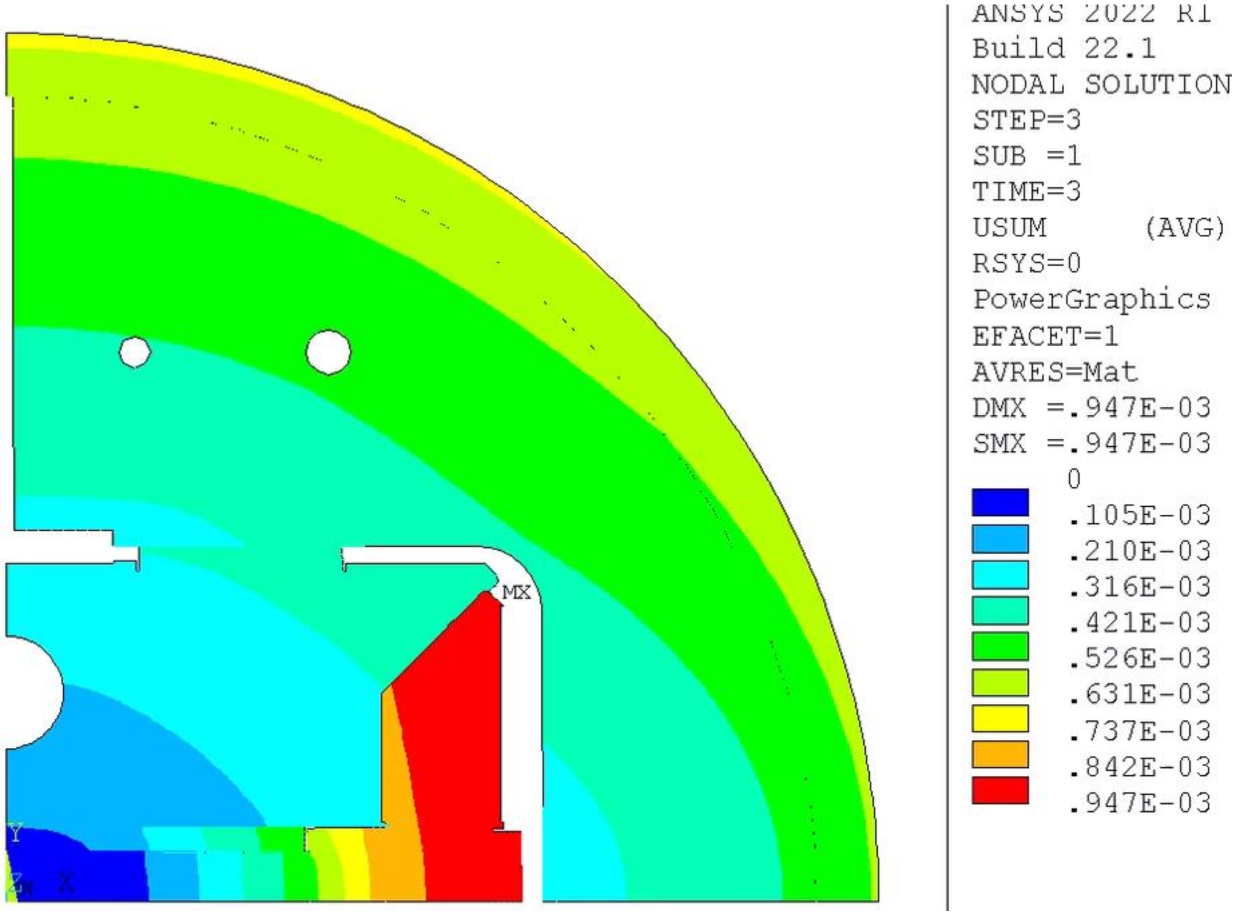
10. Viscolastic solution (2/5)

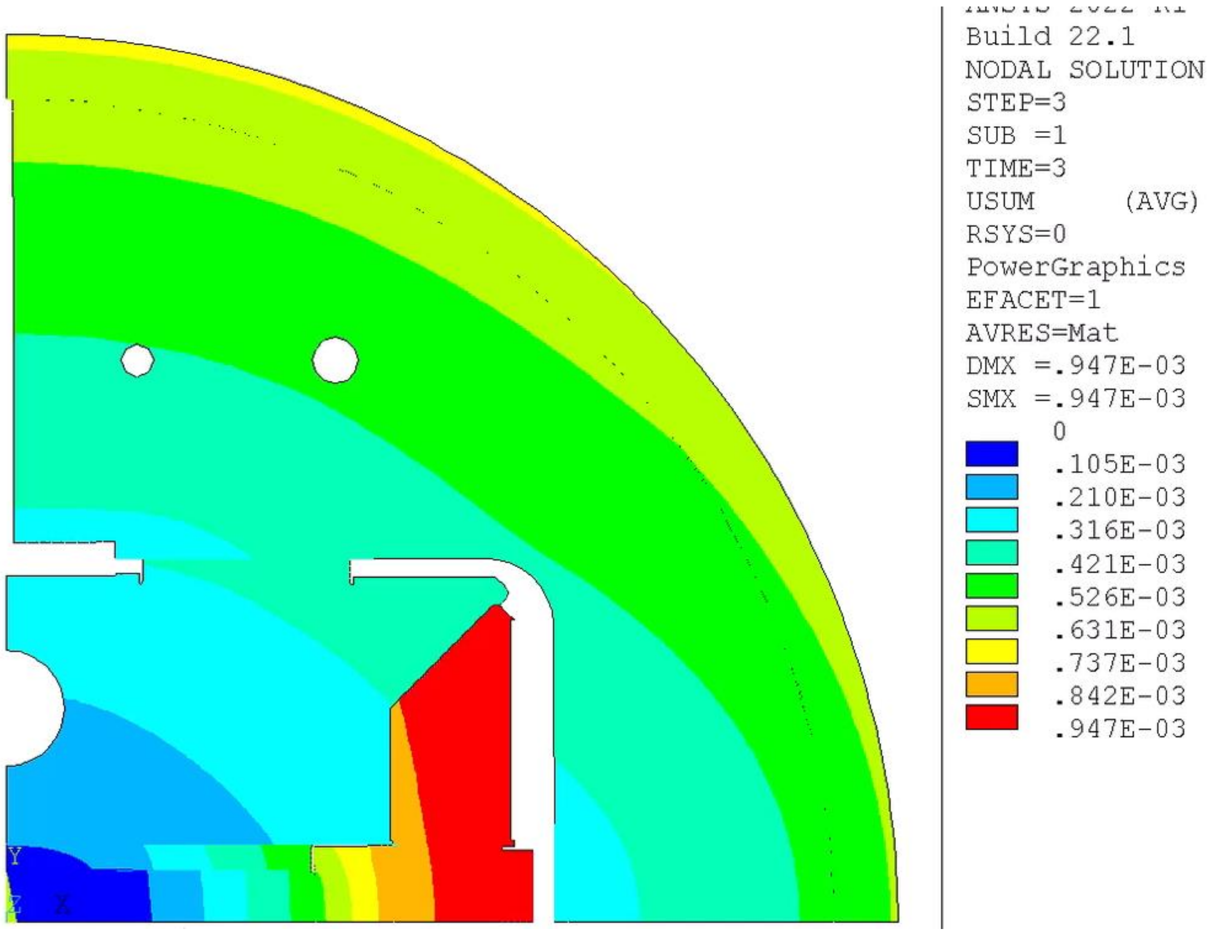


Viscoelastic solution



10. Viscolastic solution (3/5)





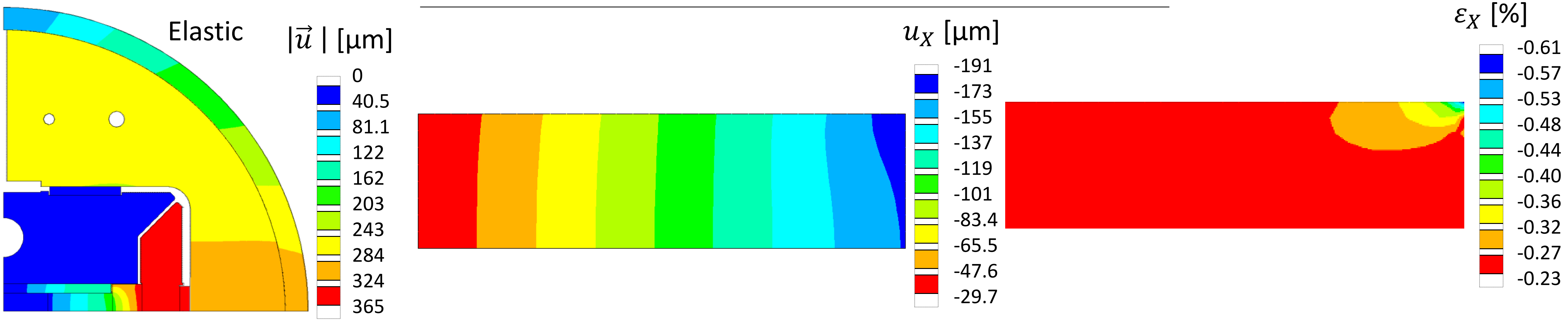
Elastic

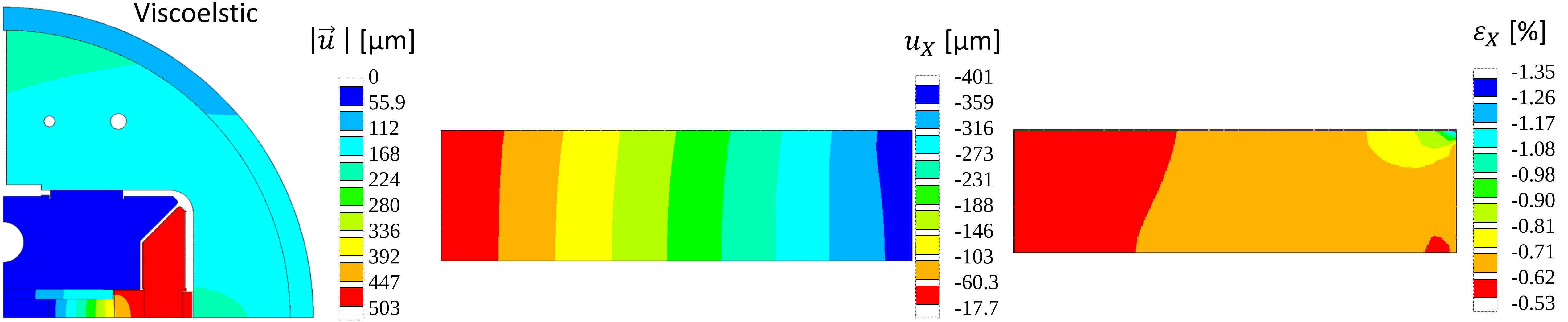
10x magnified

Viscoelastic

10. Viscolastic solution (4/5)

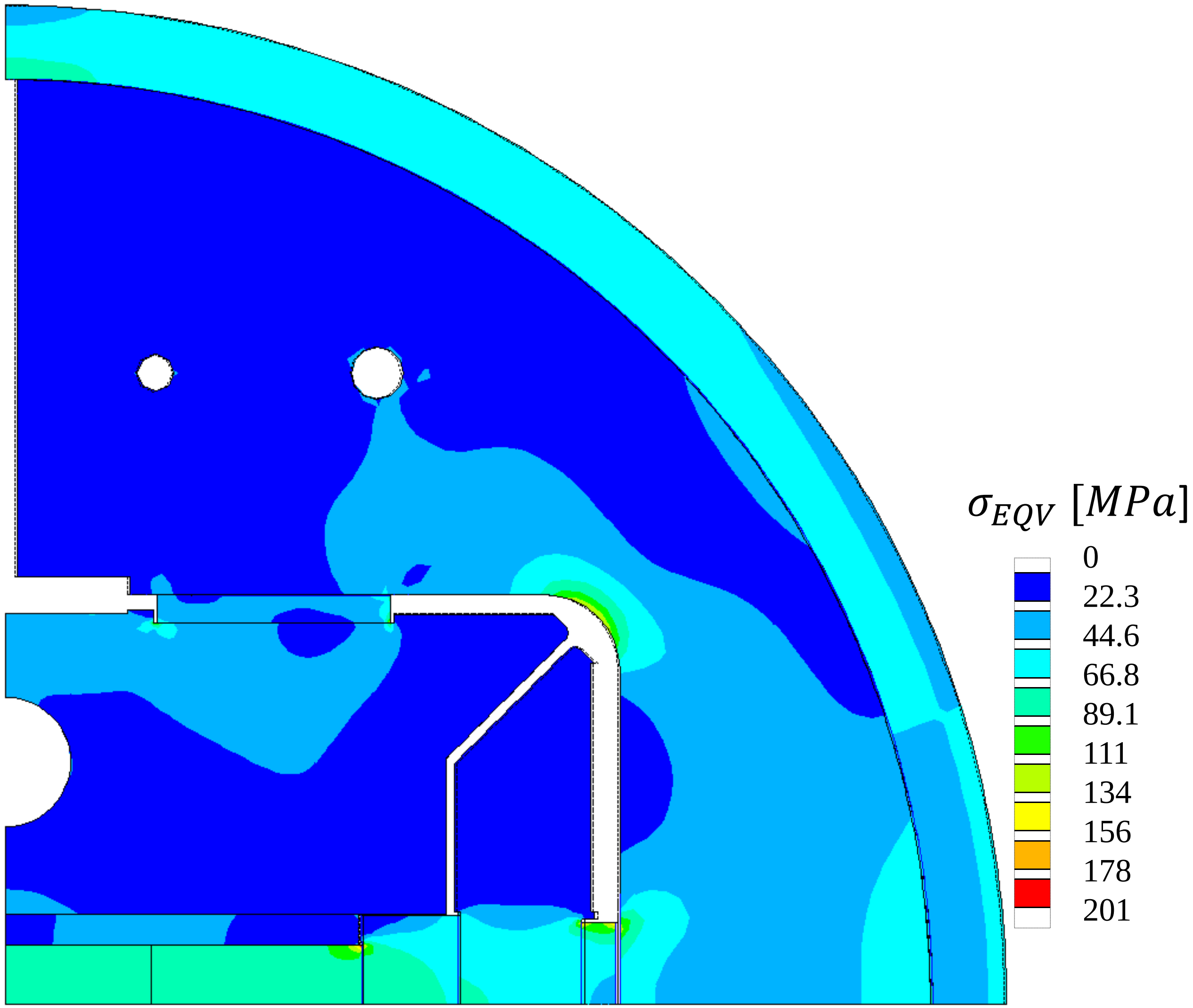
4 – Warm-up



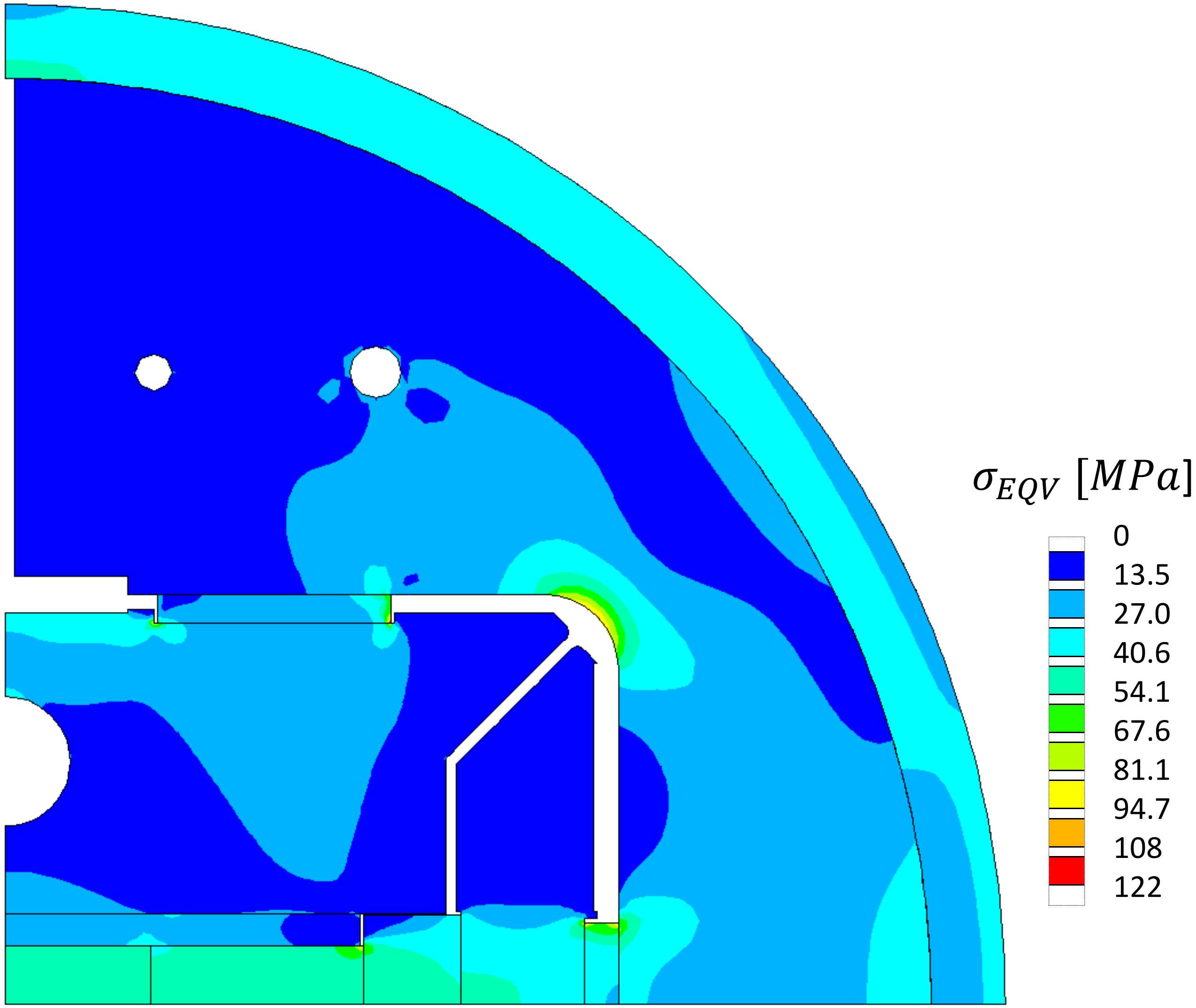


10. Viscolastic solution (5/5)

4 – Warm-up

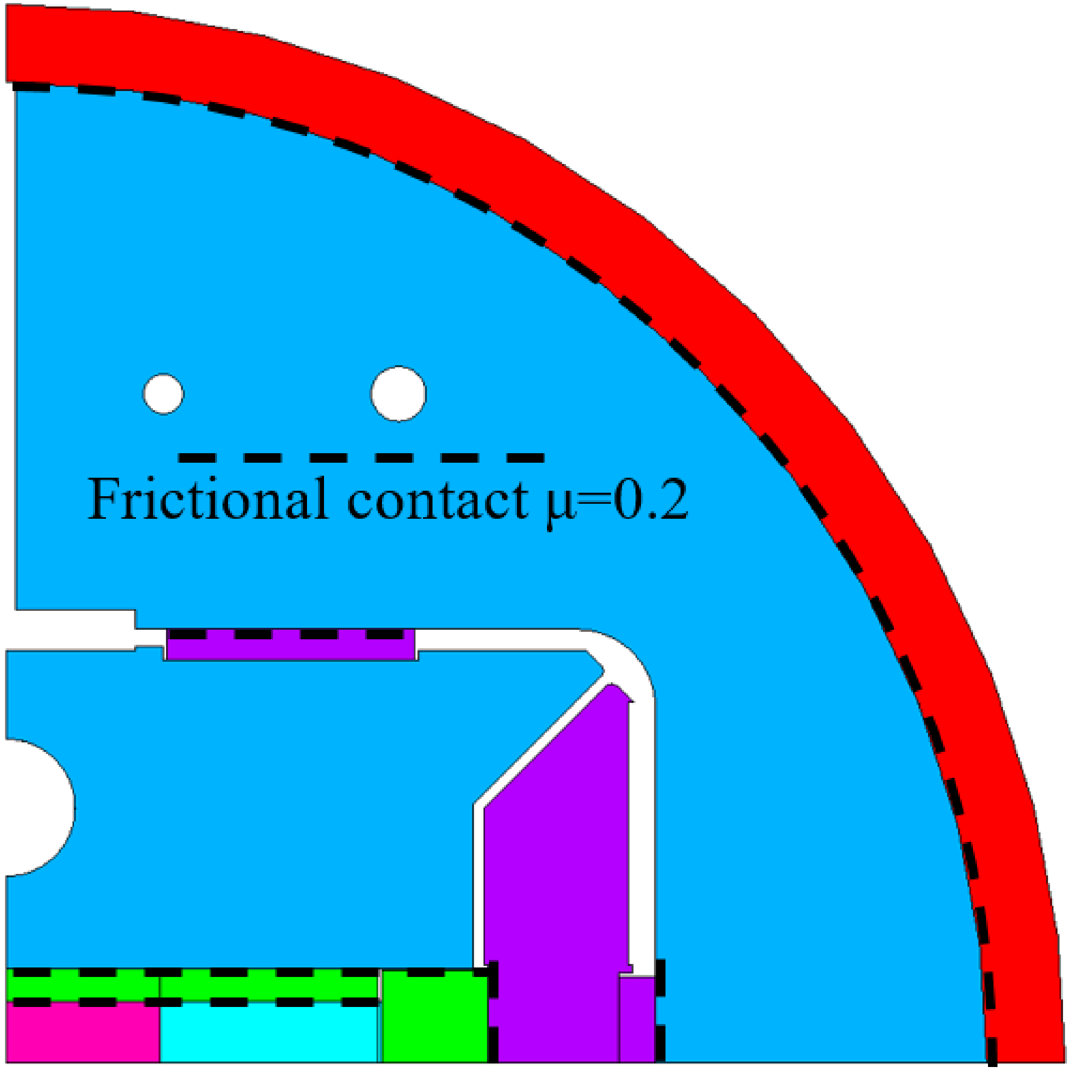


Elastic



Viscoelastic

11. Impact of the friction coefficient (1/4)



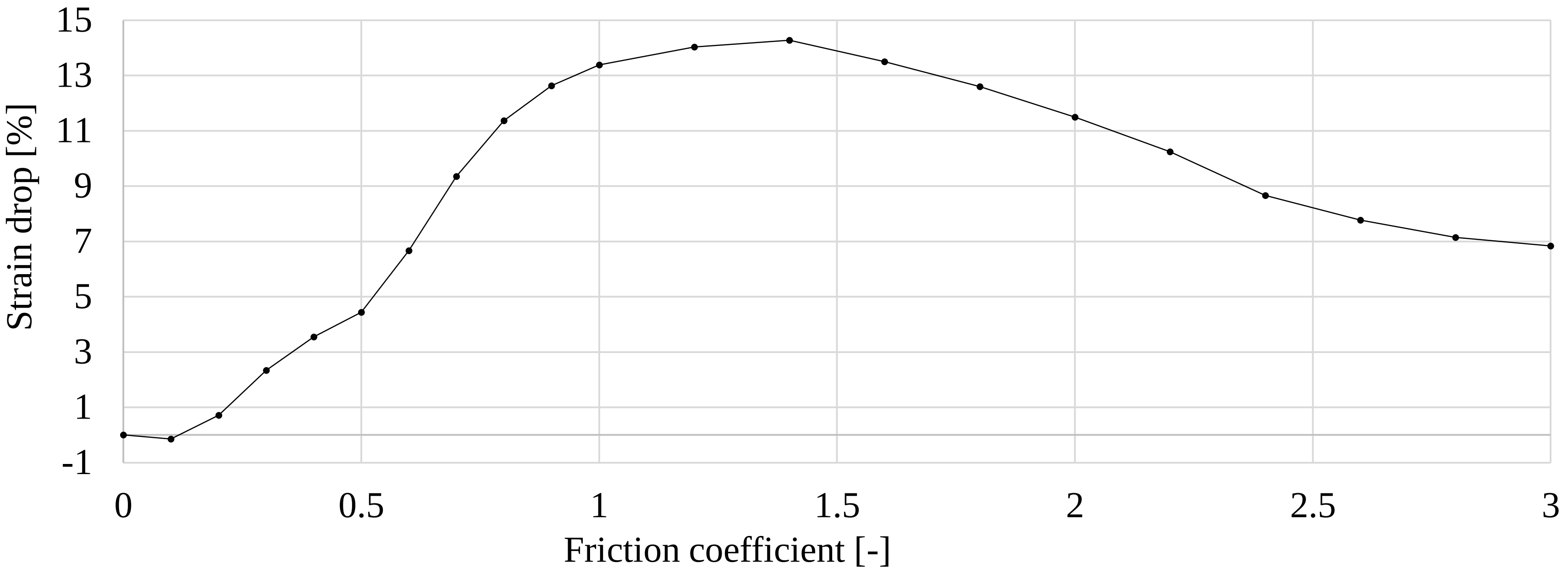
$$\mu \leq \frac{Tangent\ force}{Normal\ force}$$

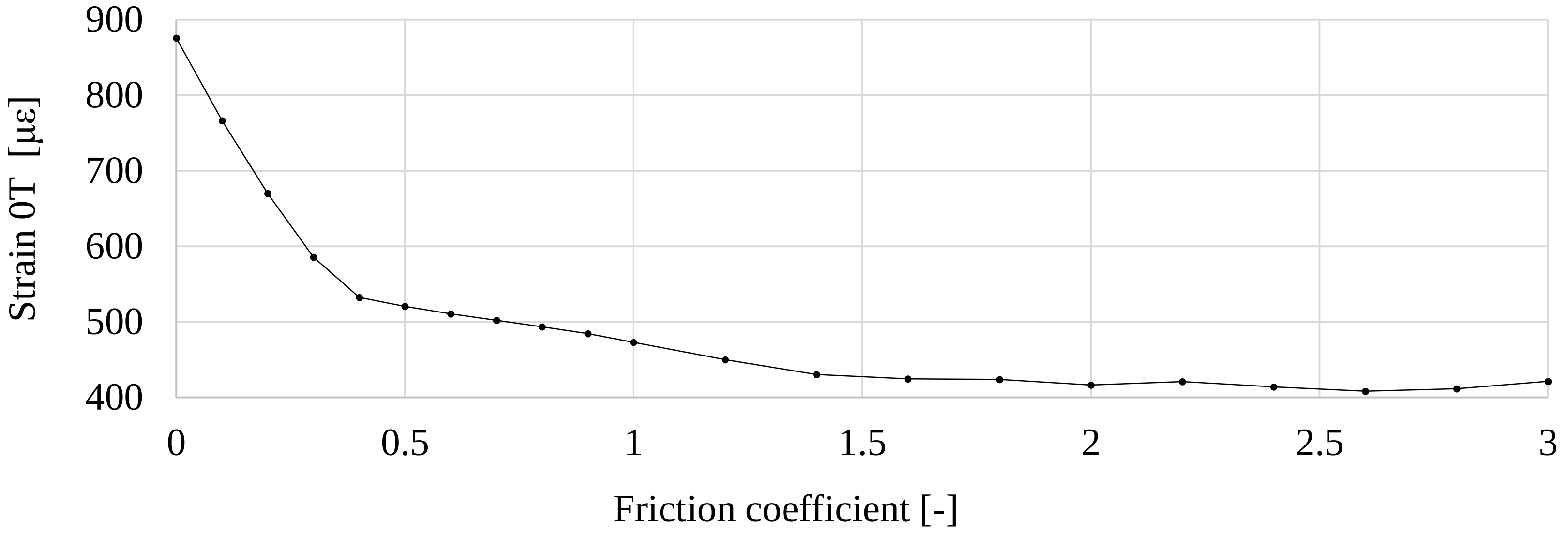
$\mu = 2.9$ Stainless steel on stainless steel under vacuum conditions

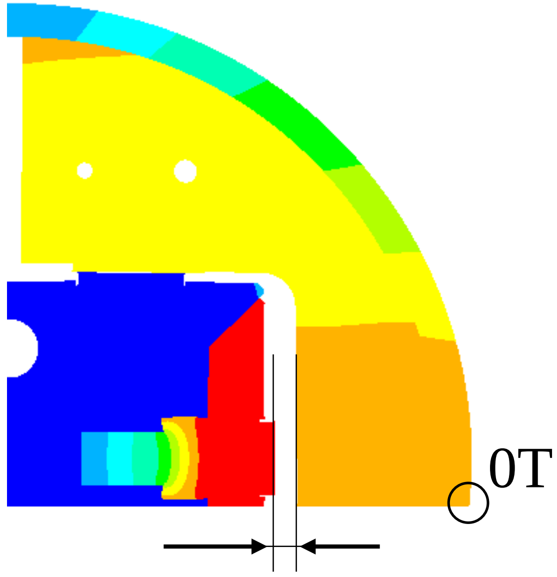
E.A. Deulin, V.P. Mikhailov, Y.V. Panfilov, R.A. Nevshupa. Mechanics and Physics of Precise Vacuum Mechanisms. Fluid Mechanics and Its Applications 91, Springer 2010

$\mu = [0,3]$ Large range of values was analyzed

11. Impact of the friction coefficient (2/4)

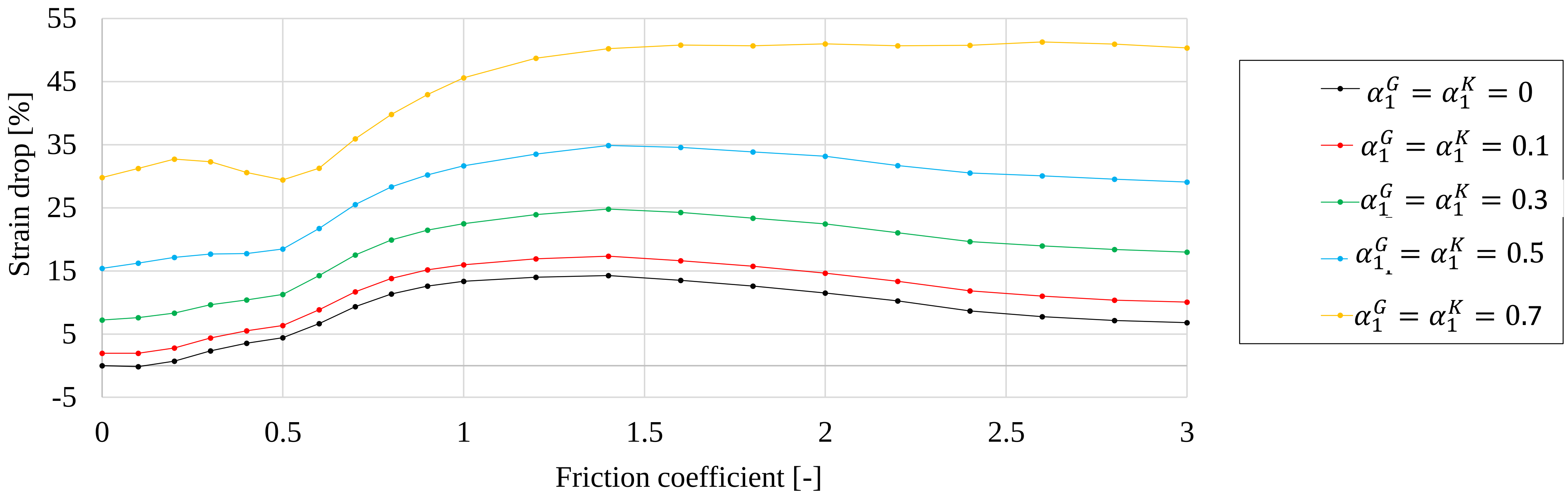


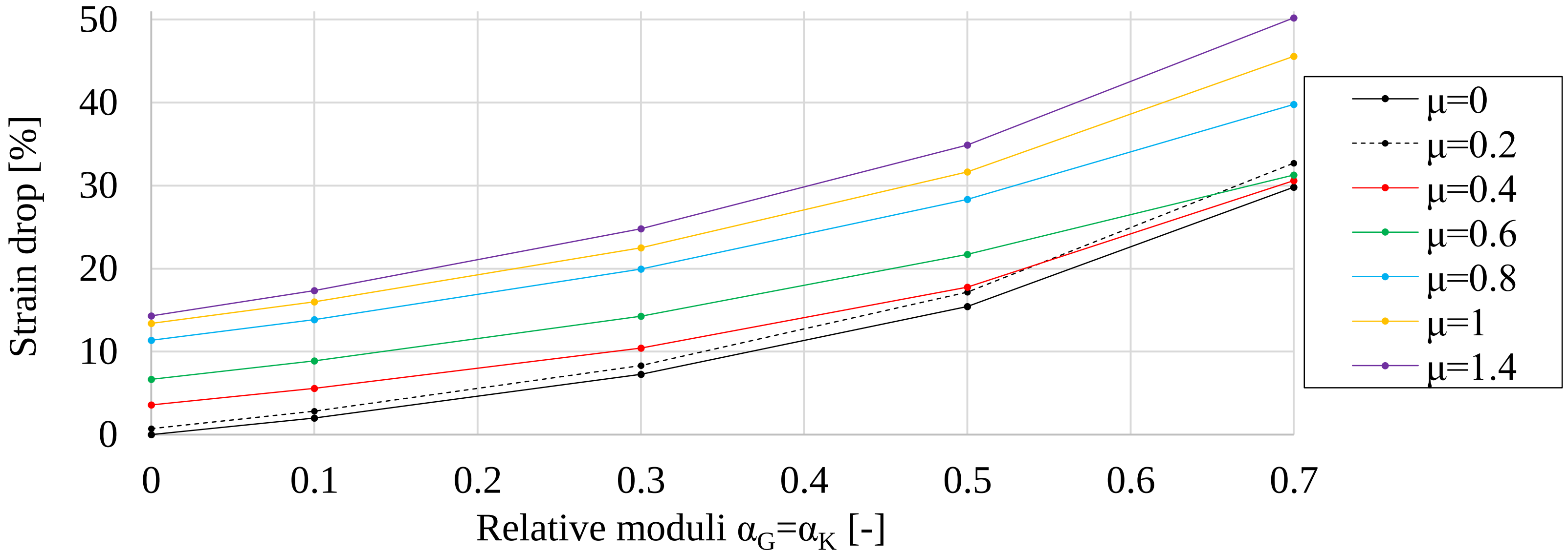




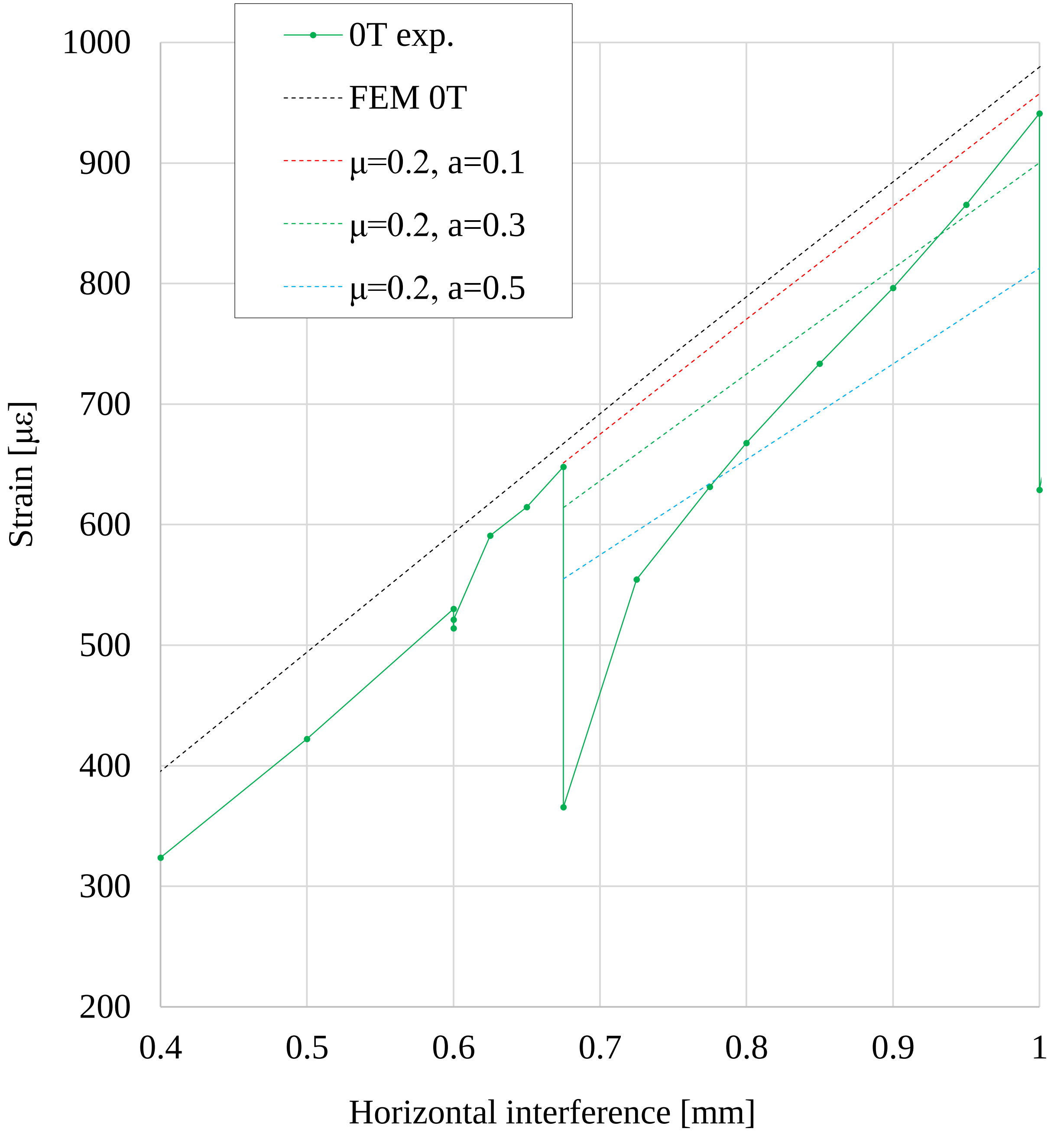
Horizontal interference=0.675 mm

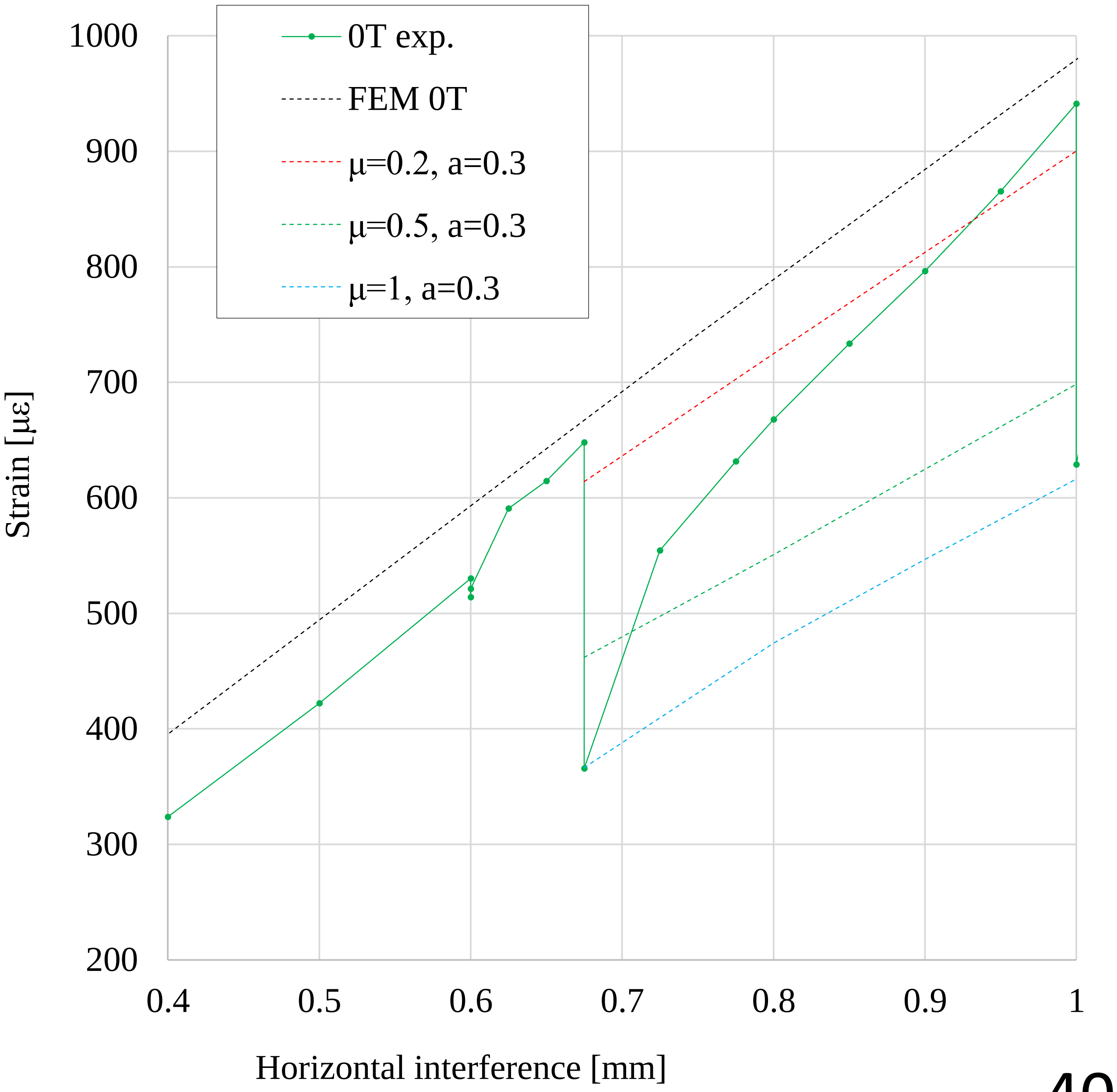
11. Impact of the friction coefficient (3/4)





11. Impact of the friction coefficient (4/4)

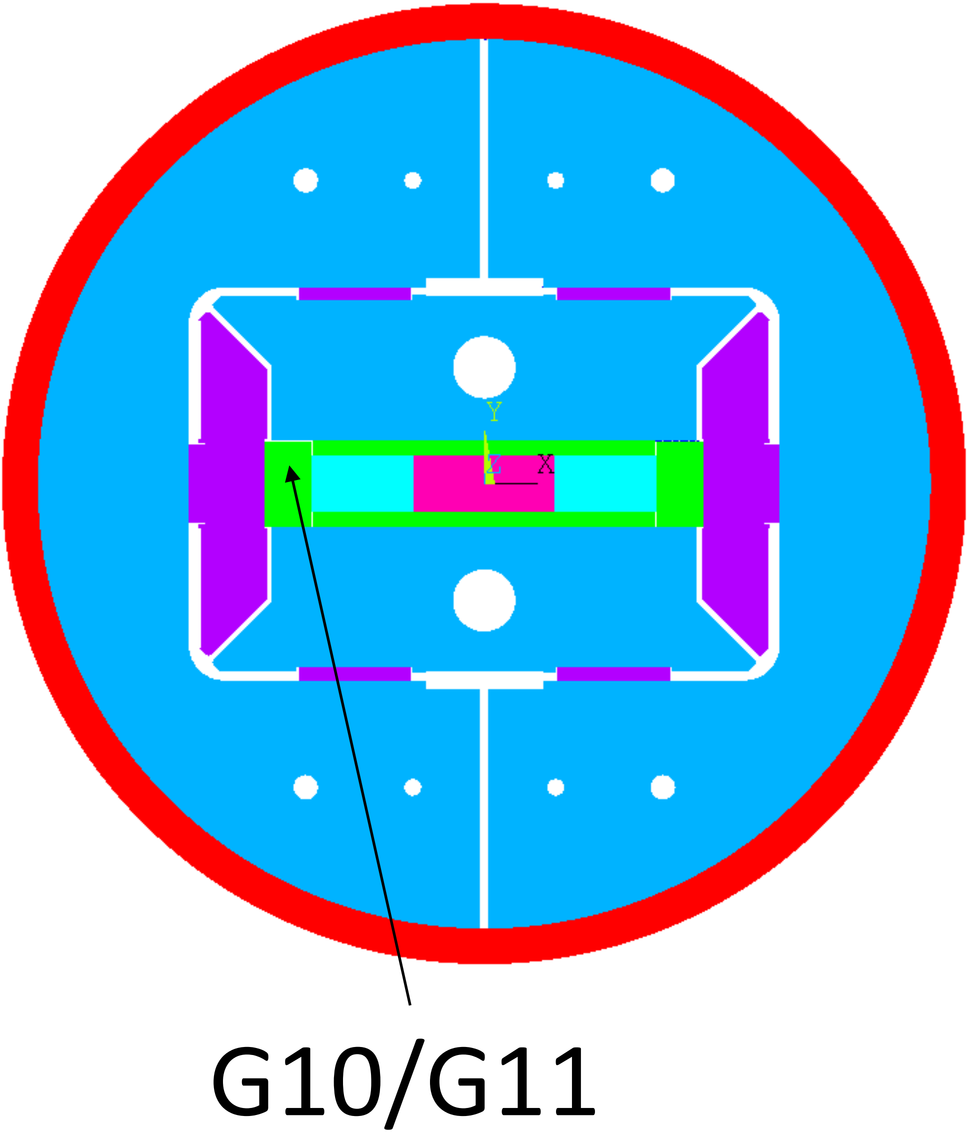




12. Conclusions/ideas

- The strains on the cylinder are not symmetric, especially for the gauges 2T and 5T -> the FEM model based on symmetry cannot explain such results, full 360° should be developed and the reasons for the asymmetry studied
- Strain drop observed experimentally can be explained by the viscoelastic model. The experimental data can be used to calibrate the single constant of the viscoelastic model
- Friction plays a role in the strain drop mechanism, and could explain even up to 15 % of the strain drop
- The loss of stiffness of the Nb3Sn coil of ~50% necessary to obtain the experimentally measured strain drop of ~40% (SMC11T#2) seems however too large and the data for the 2nd pre-load show clearly that with such decrease of stiffness the 2nd pre-load curve cannot be explained well
- The viscoelastic approach was shown to be easy to implement and solve as well as indicating the possibility of explaining the loss of pre-stress, further developments are needed

12. Conclusions/ideas



Module	RT					4 K				
	[105] G11CR	[81] G10	[80] G-10	[85] G-10	[85] G-11	[105] G11CR	[85] G-10	[85] G-11	[82] G-10CR	[106] G10
E_{11} [GPa]	30	18.8	24.63	28	32	37	35.9	39.4	35.6	35
E_{22} [GPa]	27	18.9	27.38	22.4	25.5	35	29.1	32.9	32.94	35
E_{33} [GPa]	16	7.83	11.49	n/a	n/a	24	n/a	n/a	25.19	20
G_{12} [GPa]	6.8	n/a	5.52	n/a	n/a	11.6	n/a	n/a	10.35	n/a
G_{23} [GPa]	4.8	n/a	12.18	n/a	n/a	8.2	n/a	n/a	10.16	n/a
G_{13} [GPa]	5.7	n/a	12.18	n/a	n/a	9.7	n/a	n/a	10.13	n/a
ν_{12} [-]	0.21	n/a	0.194	0.144[2]	0.146[2]	0.27	0.21[2]	0.215[2]	0.21	0.326
ν_{23} [-]	0.7	n/a	0.518	n/a	n/a	0.7[1]	n/a	n/a	0.36	0.298[3]
ν_{13} [-]	0.2	n/a	0.455	n/a	n/a	0.2[1]	n/a	n/a	0.24	0.326[3]

Estimates

experiment

Theoretical