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Mechanical Structure for the PSI Canted-Cosine-Theta (CCT) Magnet Program

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ABSTRACT

The Canted-Cosine-Theta (CCT) technology promises, by its intrinsic stress-management, to lower coil stresses in high-field accelerator magnets. This is especially relevant for Nb_3Sn magnets, which may be subject to irreversible degradation if the coil stresses exceed critical values. The internal structure of CCT coils, however, dilutes the engineering current density. For an efficient design, the internal structure, therefore, needs to be reduced to the limit given by the computer-numerical-control (CNC) machining capabilities. In that case, however, additional mechanical stiffness must be provided by an external mechanical structure. The mechanical structure for the PSI CCT program, which is described in this paper, is based on the bladder and key concept. The CCT-specific deviations from the prevalent bladder and key implementations are discussed. In addition, a 2-D and 3-D analysis in all stages of loading, cooling, and powering of the first PSI magnet prototype, as well as a tolerance analysis, are reported.

Context

Future Circular Collider study
- Development of a 16-T bending magnet;
- Nb_3Sn as technical superconductor;
- *Required*: keep mechanical stress on the coils below 150 MPa @ 300 K and 200 MPa @ 1.9 K

Canted-Cosine-Theta
- Intrinsic stress management through coil former;
- Lower J_e compared to classical designs;
- Challenge: optimize both formers and mechanical structure for cost-efficient design.
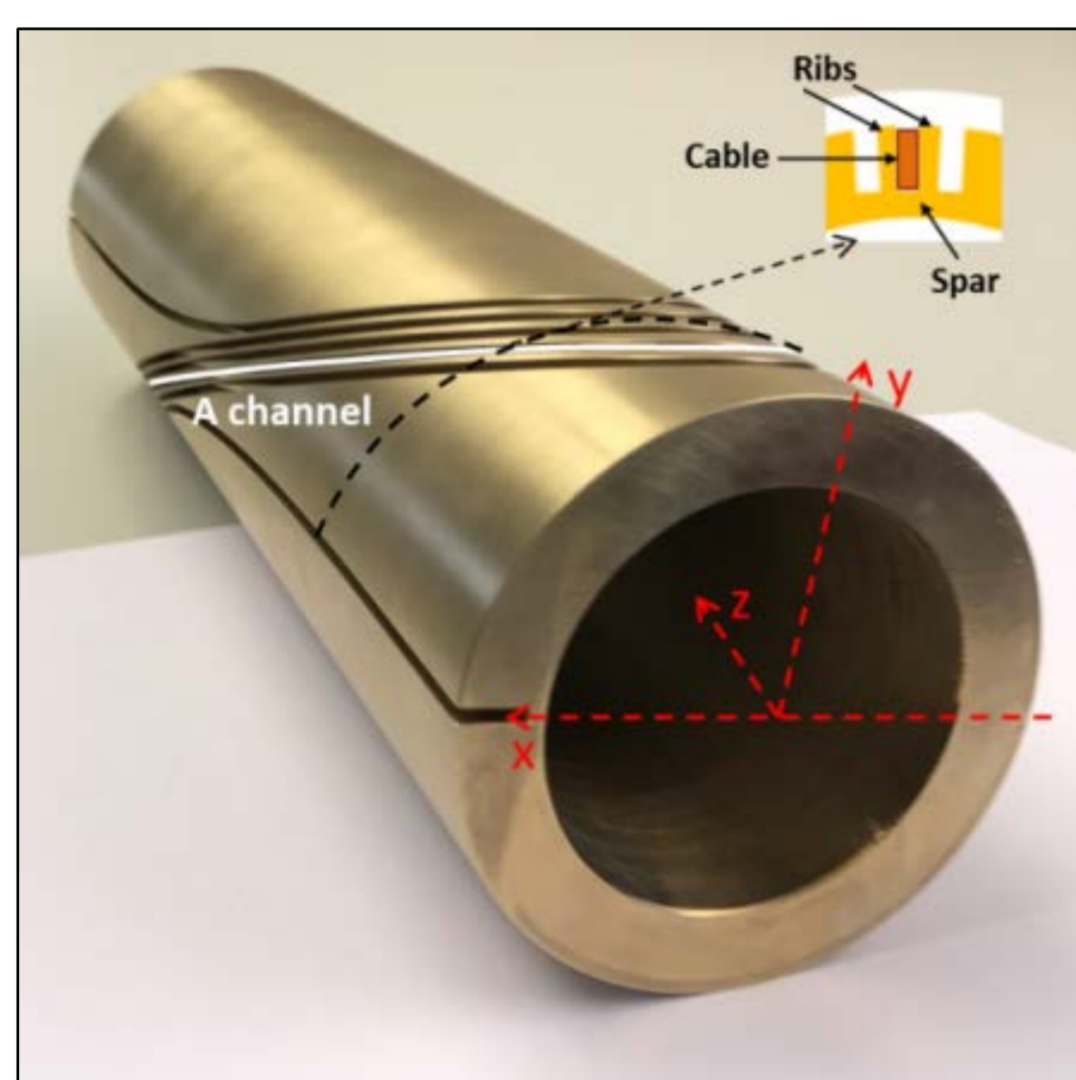
PSI CCT Development Program

16-T CCT dipole accelerator magnet

Efficient Canted-Cosine-Theta design
- Minimal formers' spar thickness and ribs;
- wide (15 mm) Nb_3Sn cables with large (1 mm) diameter strands;

PSI CCT Program road map
- 2 x 1-m-long, 2-layers CCT single-aperture dipole model with same bladder and keys mech. structure:
  - **CD1**: Formers with 3-mm-thick spars; 10.6-mm-deep channels; Minimum rib thickness of 0.35 mm; cable: 21 x 0.85 mm ϕ strands (RRP 108/127);
  - **CD2**: Formers with 2-mm-thick spars; 16-mm-deep channels with geometry optimization for cable windability [1]; Minimum rib thickness of 0.25 mm; cable: 28 x 1.00 mm ϕ strands (RRP 150/169);
- Manufacturability improvement and cost reduction of formers for long magnets.

Mechanical Structure

Bladders and Keys structure
- Increasing of the rigidity of the impregnated coil-former assembly;
- Minimizing the coils' movement during energization to avoid epoxy cracking or delamination from the channel walls;
- CCT specific feature: gap between pads closed during all the loading steps.
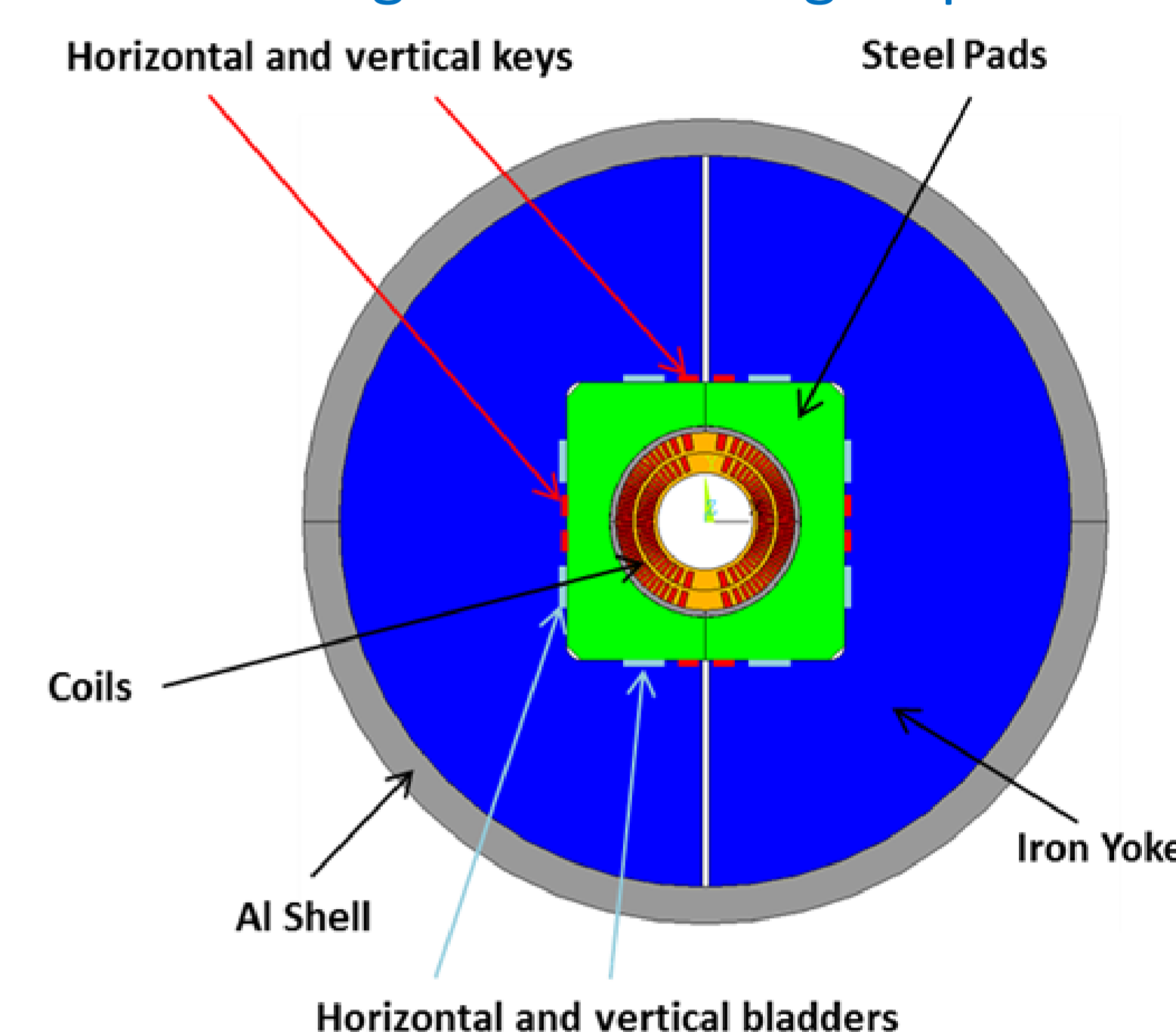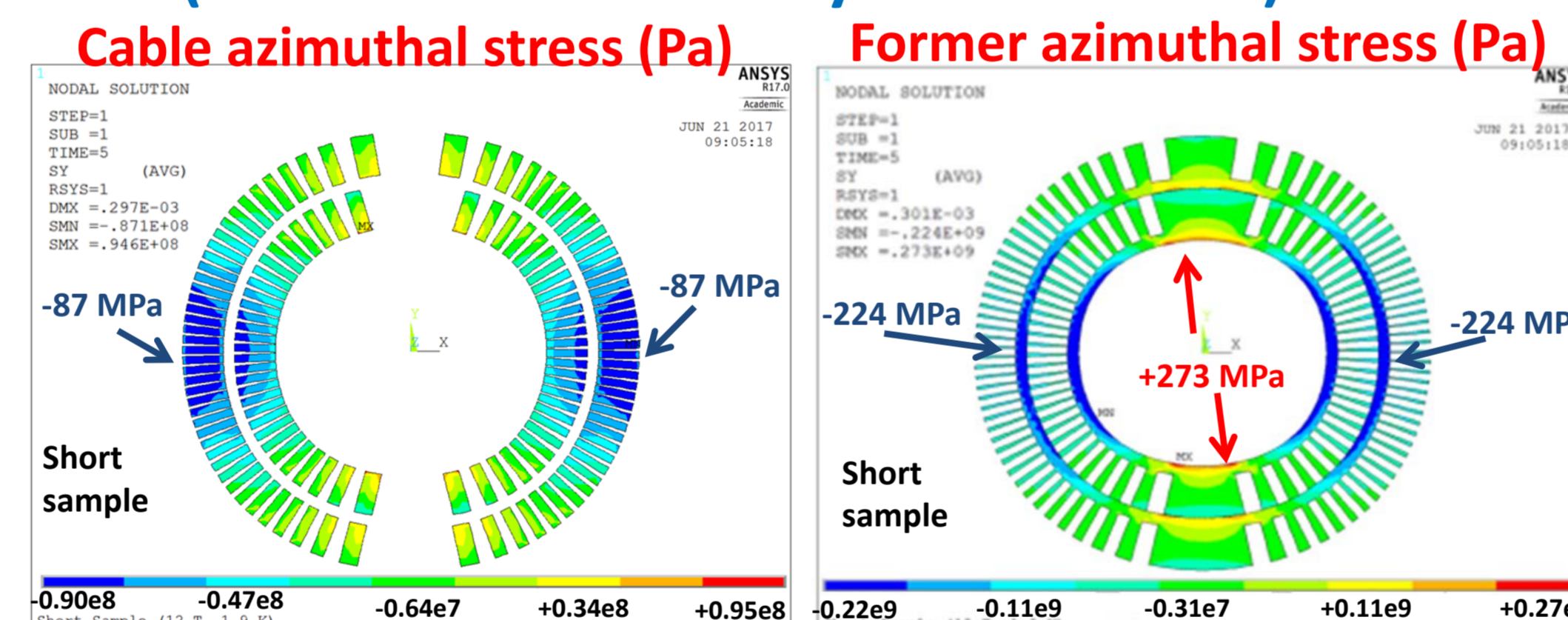

Mechanical Analysis of CD1

- 2-D analysis using plane stress condition
- 3-D analysis using generalized plane stress boundary condition (periodic slice model [2]);
- Five load steps simulation: from bladder and keys operation to cool down and subsequently energization according to short sample limit (12 T in the magnet bore at 20 kA)
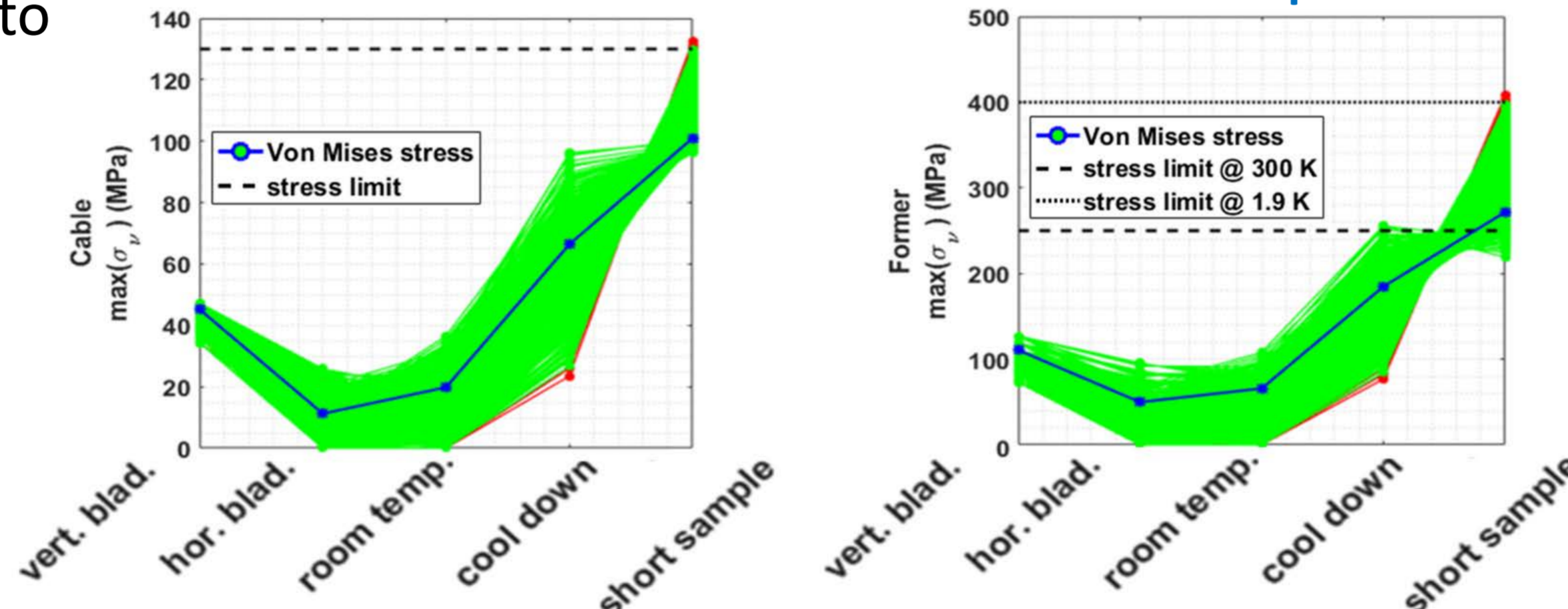- Material properties according to EuroCircleCol guide lines

Material	Stress Limit (MPa) 300 K/ 4.2 K	E (GPa) 300 K/ 4.2 K	ν	α (10⁻³)
Coil	130(2-D); 150/200 (3-D)	E_x=30/33 E_y=25/27.5 G_{xy}=21/21	0.3	$α_x$=3.1 $α_y$=3.4
Steel	350/1050	193/210	0.28	2.8
Al	480/680	70/70	0.3	4.2
Iron	180/720	213/224	0.28	2.0
Al Bronze	150/400	120/110	0.3	3.12

2-D Simulations Results

Baseline design (0.3 mm horizontal keys interference)

Cable azimuthal stress (Pa)   -87 MPa   Short sample

Former azimuthal stress (Pa)   -224 MPa   +273 MPa   -224 MPa   Short sample

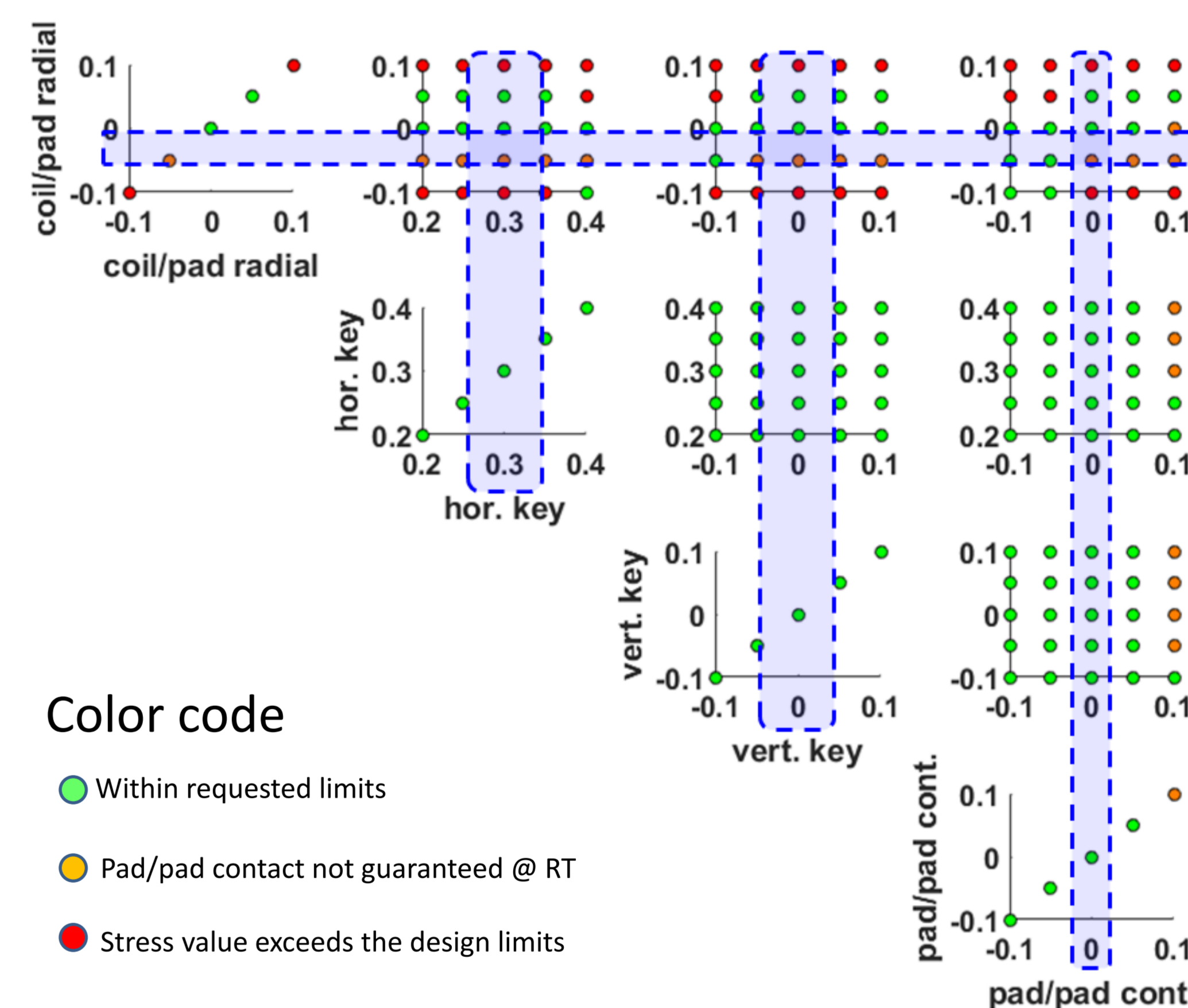### Maximum Von Mises stress on the five load steps

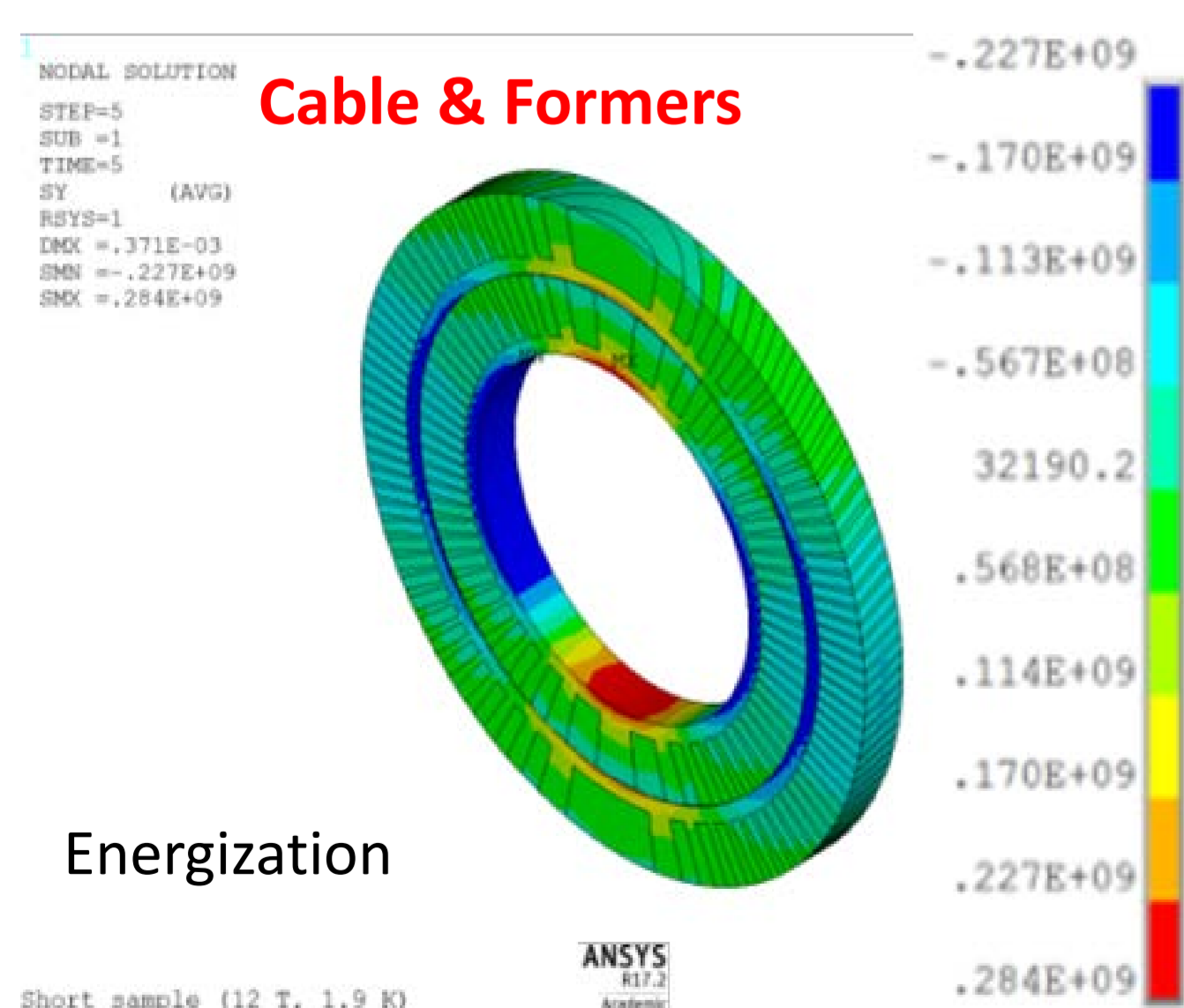### Parametric study for tolerances definition

Color code
- Within requested limits
- Pad/pad contact not guaranteed @ RT
- Stress value exceeds the design limits

- Stress requirements met, only four cases (out of 625 simulations) exceed limits by an amount of not more than 7 MPa

3-D Simulations Results

Baseline design (0.3 mm horizontal keys interference)

Cable & Formers   Energization   Short sample (12 T, 1.9 K)

Strain distribution on coil turns (at short sample limit)

$ε_t$

- **Azimuthal stress distribution**
  - Cable compressive stress, $σ_{θ,3-D}$ = -120 MPa vs. , $σ_{θ,2-D}$ = -87.1 MPa;
  - Formers tensile stress, $σ_{θ,3-D}$ = 284 MPa→ 9 MPa higher than 2-D analysis;
- Maximum Von Mises stress of 156 MPa
- Need to run full 3-D analysis to check if differences due to periodic model
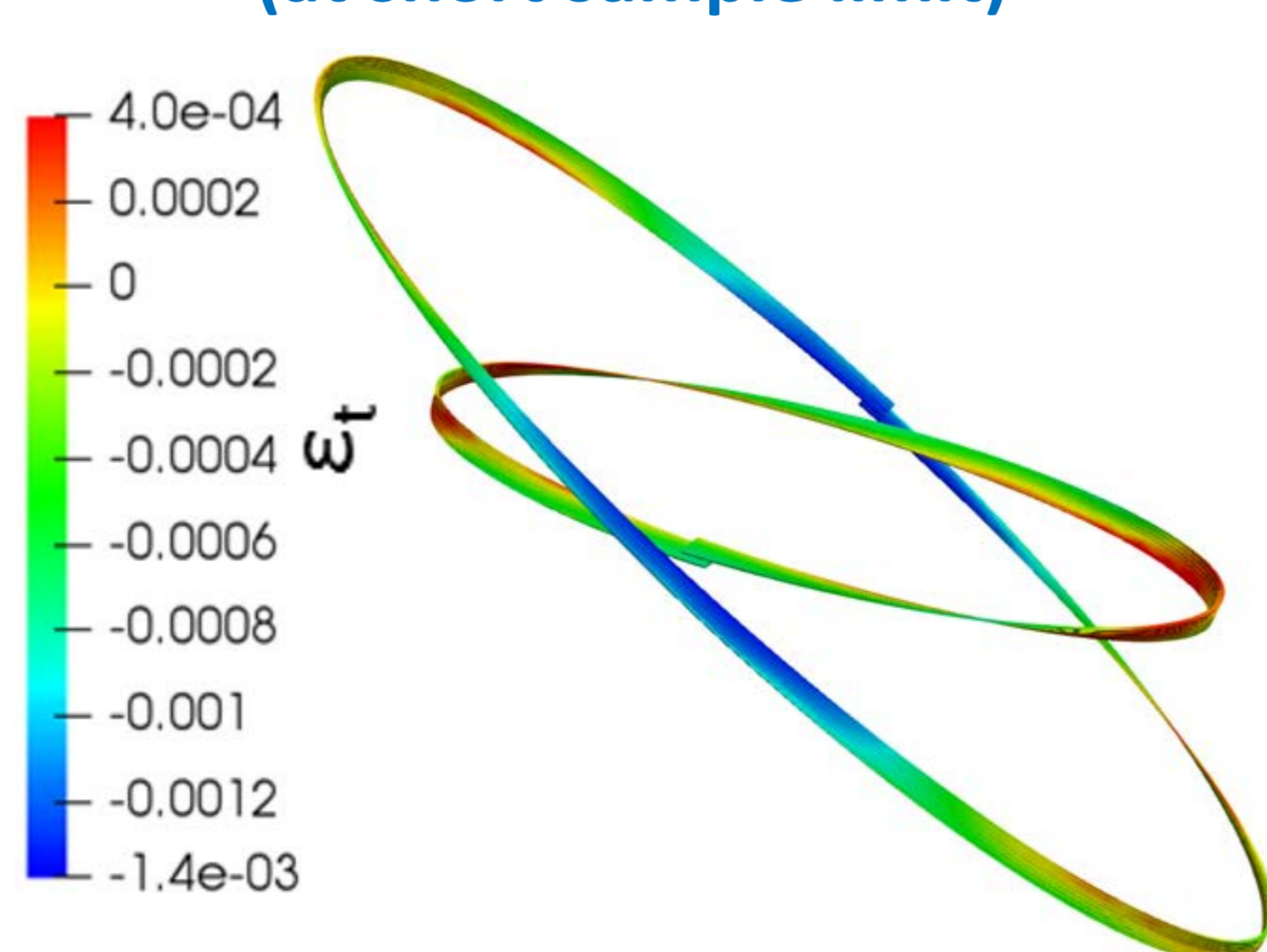
- **Strain distribution** on the tangential direction
  - peak strain 0.04 %;
- Further investigation to estimate corresponding critical current degradation [3]

Conclusions

- PSI CCT Program is outlined.
- 2-D and 3-D (periodic slice model) structural analysis of the first CCT model magnet is presented.
- Full 3-D analysis will be performed
- Results show the soundness of the design→ peak stress below limits. Using a bladders and keys structure
- The first, 310-mm-long, short mechanical structure is being produced.
- CD1 manufacturing planned for November 2017.

References

[1] B. Auchmann et al., "Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC", this conference, 2017.

[2] L. Brouwer, "Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy," Ph.D. Thesis, UC Berkeley Electronic Theses and Dissertations, 2015.

[3] E. Barzi, D. Turrioni, and A. V. Zlobin, "Progress in Nb_3Sn RRP Strand Studies and Rutherford Cable Development at FNAL," IEEE Trans. Appl. Supercond., vol. 24, no. 3, June 2014, Art. no. 6000808.