Analysis of mechanical stress during quench

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GENOVA
MILANO

SACLAY

Previous work

[1] J. Zhao et al. “Mechanical stress analysis during a quench in CLIQ protected 16 T dipole magnets designed for the Future Circular Collider” submitted to *Physica C: superconductivity and its applications*, 2018.

- COMSOL electro-thermal (STEAM) → COMSOL mechanical (TUT)
- Single aperture

[2] M. Maciejewski et al., "Coupling of Magnetothermal and Mechanical Superconducting Magnet Models by Means of Mesh-Based Interpolation," in *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 3, pp. 1-5, April 2018.

- COMSOL electro-thermal (STEAM) → ANSYS mechanical (INFN, CEA)
- Automated coupling with existing ANSYS mechanical models
- ➢ Double aperture

- FCC cos-theta magnet

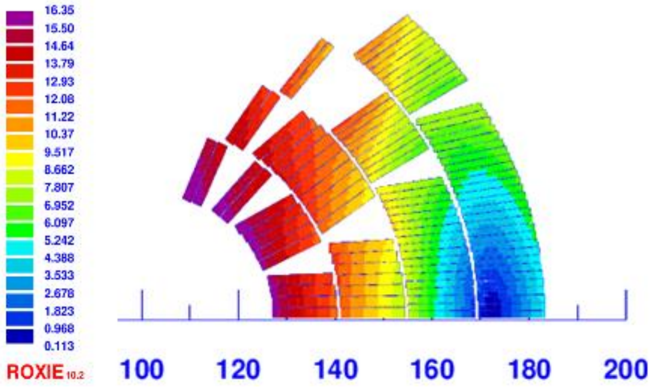
- FCC block-coil magnet

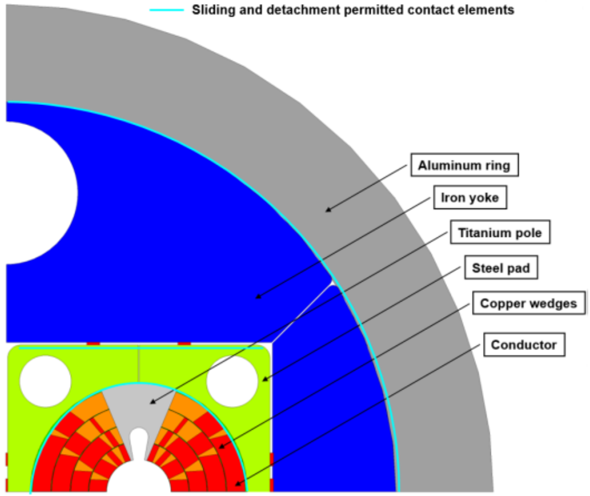
Inputs

Magnet

- 16 T cos-ϑ dipole
- Version 22b_38_v1

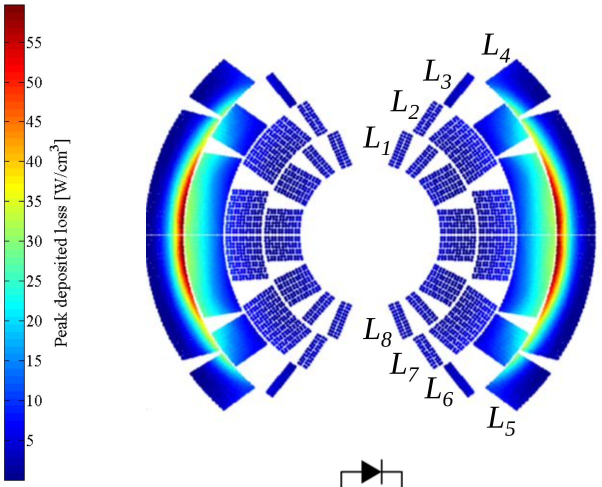
	HF Cable (inner)	LF Cable (outer)
Strand number	22	38
Strand diameter	1.1 mm	0.7 mm
Bare width	13.2 mm	14 mm
Bare inner thickness	1.892 mm	1.204 mm
Bare outer thickness	2.007 mm	1.3261 mm
Insulation	0.15 mm	0.15 mm
Keystone angle	0.5°	0.5°
Cu/NCu	0.82	2.08
Operating current	11390 A	11390 A
Operating point on LL (1.9 K)	86 %	86 %

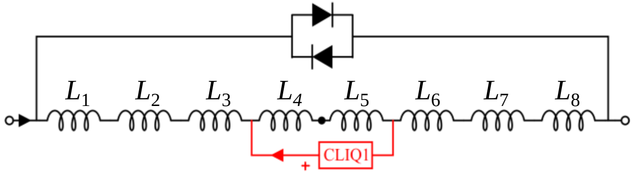




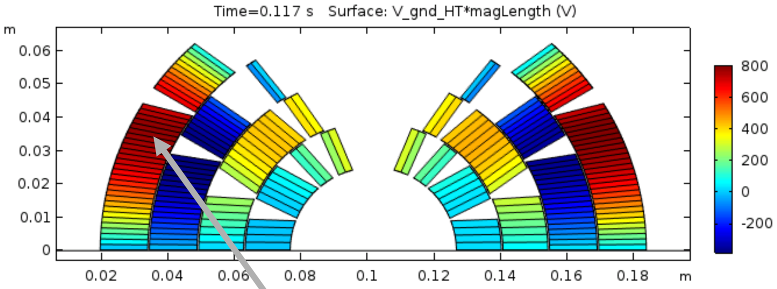
Quench protection

- COMSOL
- 2 apertures
- 100% of nominal current





V_0=1.25 kV, C=50 mF

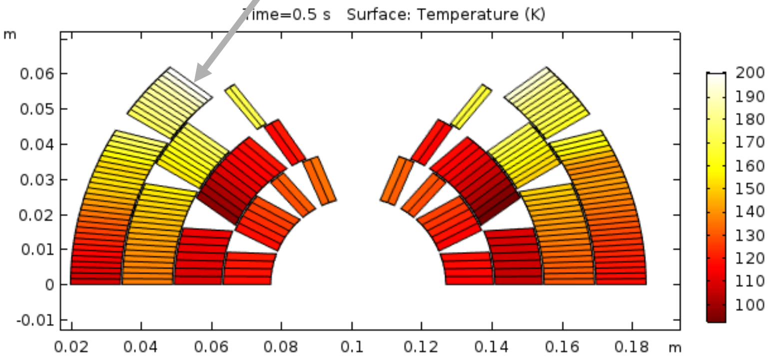


Max. voltage to ground 800 V

(Compares to LEDET 900 V)

Hot-spot temperature 286 K

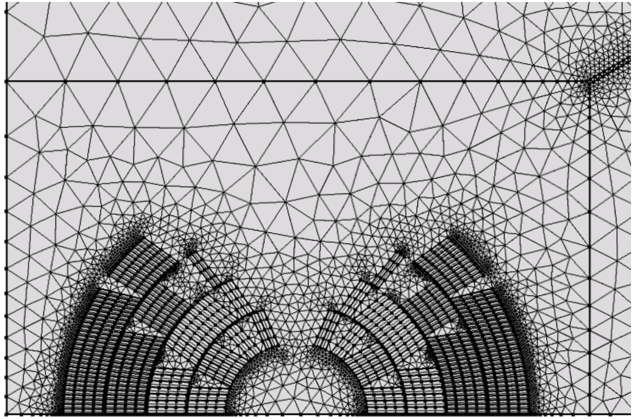
(Compares to LEDET 284 K)



Coupling strategy

Magneto-Thermal Model

COMSOL



Coupling Environment

MpCCI

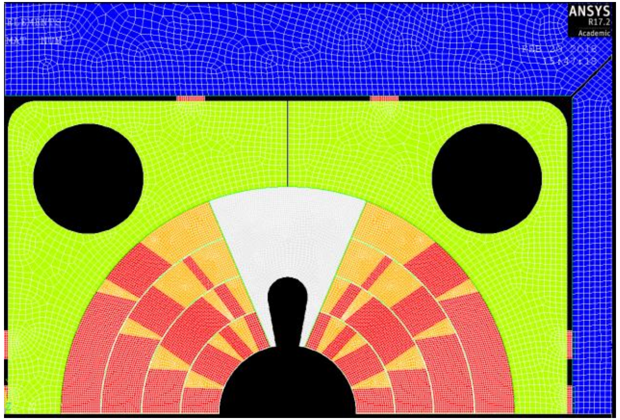
T → $\hat{T}$

$\vec{F}_L$ → $\widehat{\vec{F}_L}$

Mesh-based interpolation

Mechanical Model

ANSYS



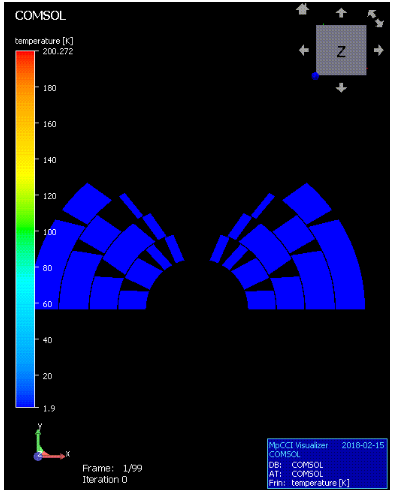
CERN

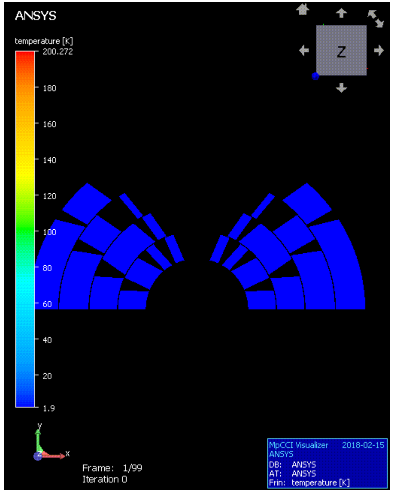
Fraunhofer SCAI

INFN

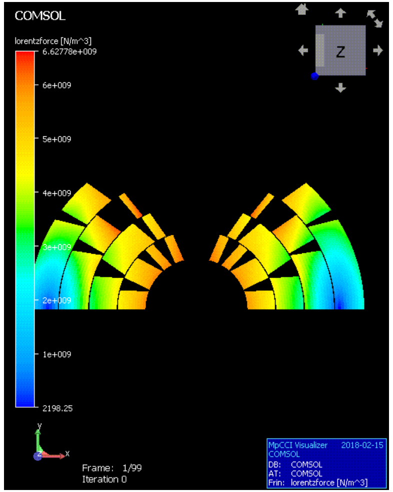
Data transfer preview in MpCCI GUI

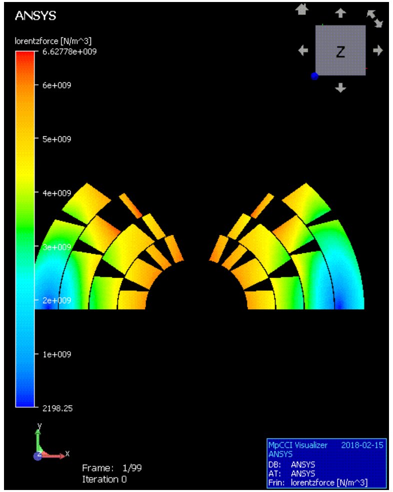
Temperature [K]
animated





Lorentz force [Pa]
animated





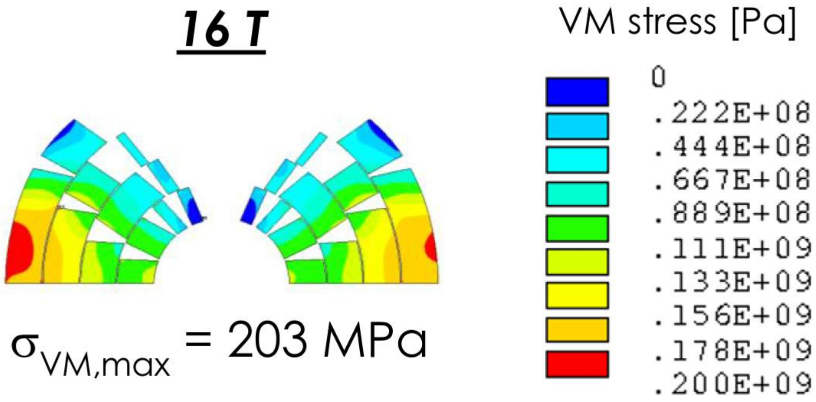
Temperature differences are increasing while Lorentz force is decreasing during discharge

→ Non trivial prediction of the moment of peak mechanical stress

Crosscheck at nominal current (t = 0)

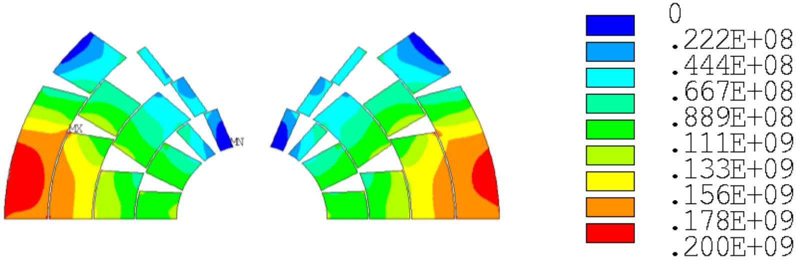
Reference simulation from Barbara:

Lorentz force from ROXIE → Mechanics in ANSYS



Simulation to be validated:

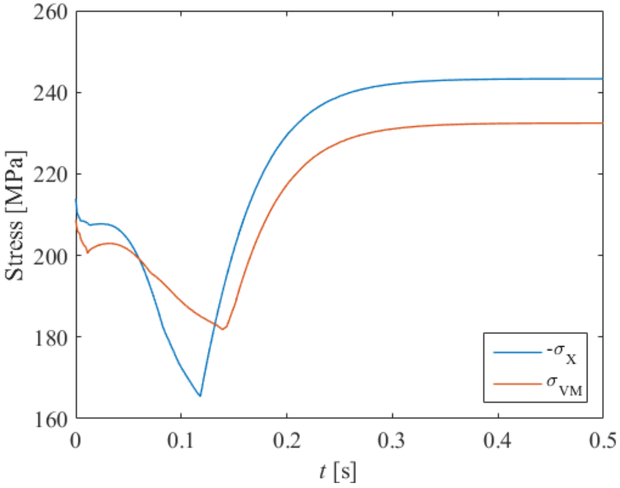
Lorentz force from COMSOL → Mechanics in ANSYS

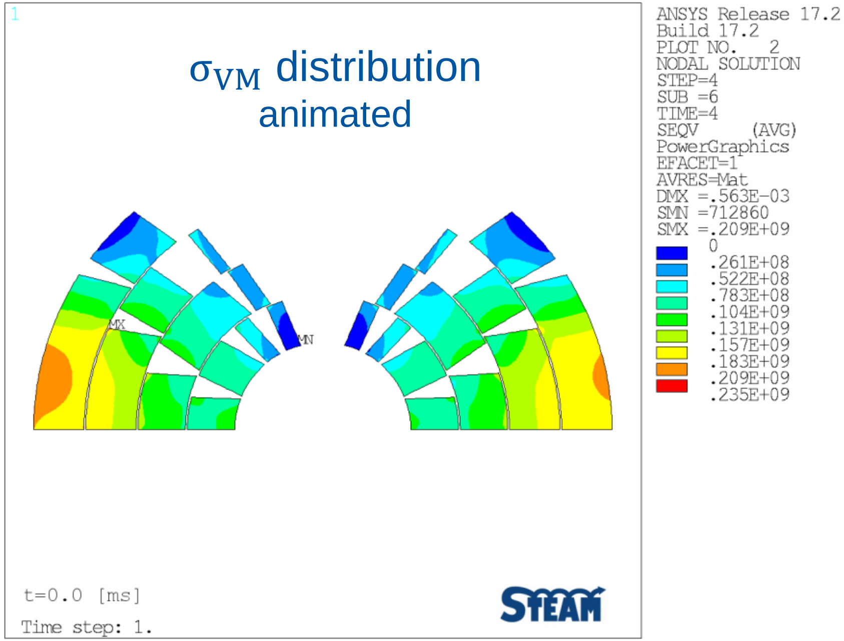


$\sigma_{VM,max} = 208$ Mpa

✓ Very similar stress distribution for the two approaches!

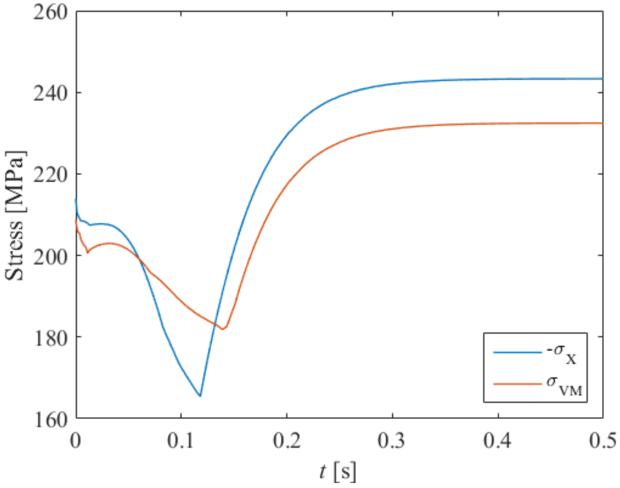
Case 1: no hot-spot

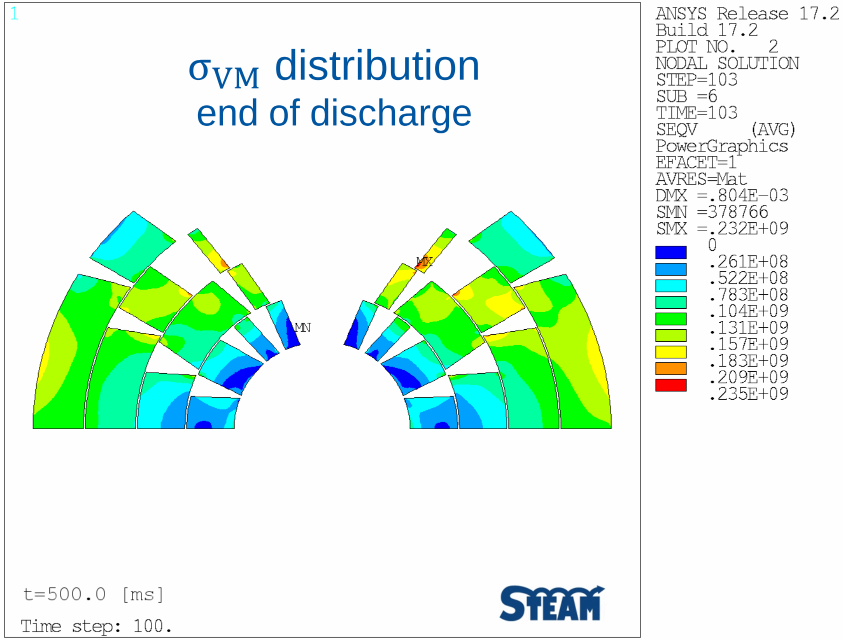




$\sigma_{VM,max} = 232$ Mpa at the end of the discharge

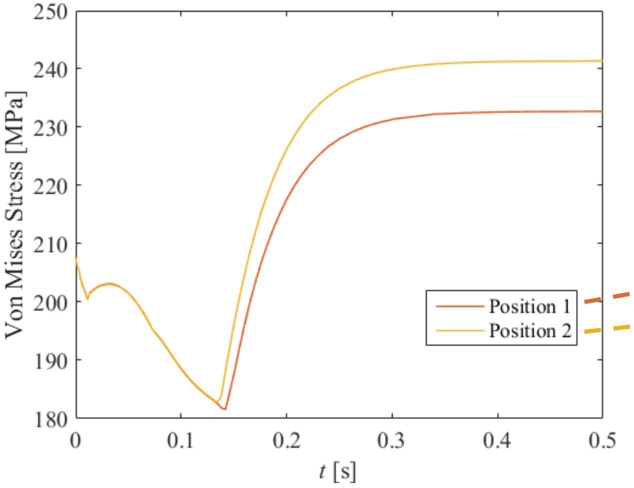
Case 1: no hot-spot

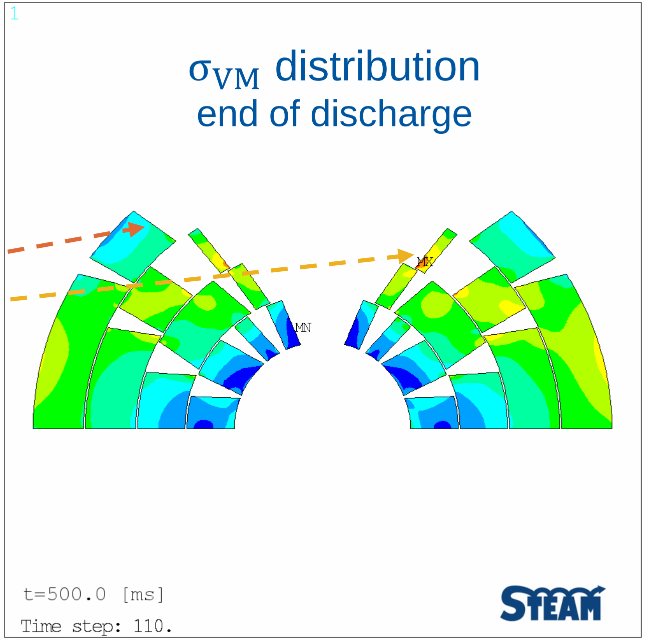




$\sigma_{VM,max} = 232$ Mpa at the end of the discharge

Case 2: with adiabatic hot-spot





$\sigma_{VM,max} = 241$ Mpa at the end of the discharge

Comments, cos-theta

- Peak stress is at the end of current discharge
  - Max. temperature differences
  - 208 MPa @ energization → 232 MPa after a quench

- The worse adiabatic hot-spot location is in the half-turn with maximum stress

  → 241 MPa after a quench in the peak stress location

- Similar results as in Junjie analysis for single aperture design
  - Same evolution but higher stress: 241 MPa instead of 222 MPa

➢ The location of peak stress at the end of discharge is the same as for the cool-down (Barbara's presentation, link)
  - Localised peak
  - A structure with lower peak stress at cool-down should also show lower stress at the end of discharge

- FCC cos-theta magnet

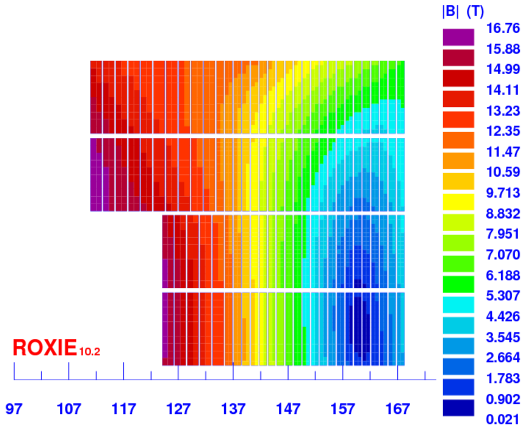
- FCC block-coil magnet

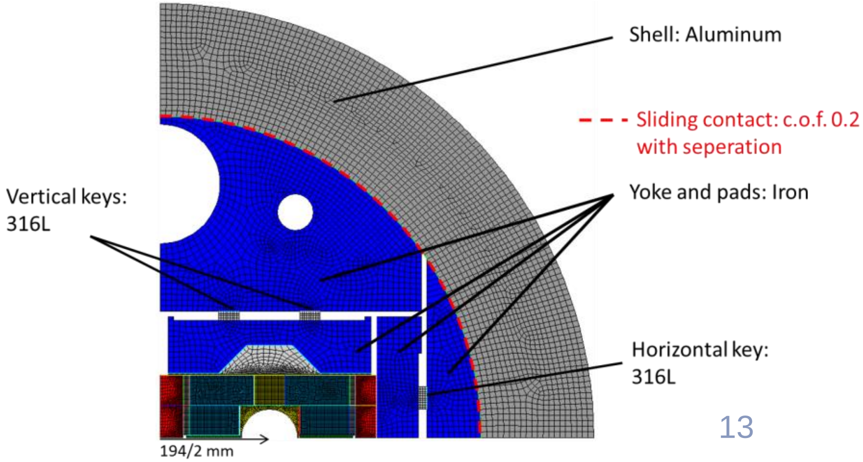
Inputs

Magnet

- 16 T block coil dipole
- Version v2ari194

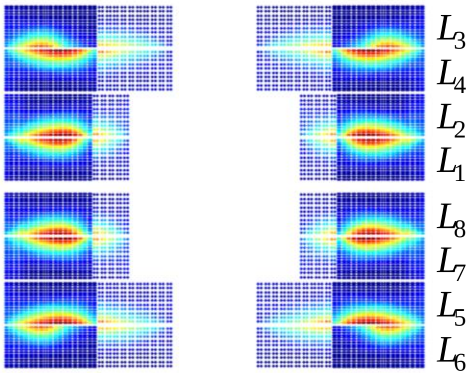
Quantity	v2ari194	Unit
strand diameter	1.1 – 0.7	mm
nb of strands	21 – 34	N/A
AF – Cable width	12.6	mm
AF – Cable thickness	2.0 – 1.27	mm
Cu/nonCu	0.8 – 2.0 (1.7)	N/A
I_{nom}	10000	A
B_{peak}	16.76	T
LL margin (1.9 K)	13.86	%
Inductance diff. (2 ap)	50.2	mH/m
Stored energy (2 ap)	2647	kJ/m
Nb of turns	116 = 5+5+10+10+21+21+22+22	–
Out yoke diameter	570	mm
Conductor area (2 ap)	**138**	cm²
4578 x 14.3 x 8.7 weight	**7860**	tons

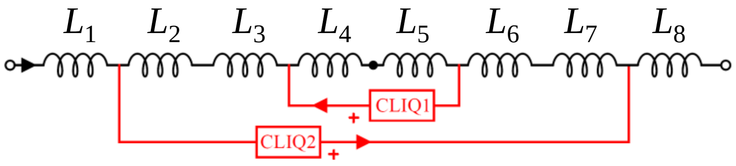




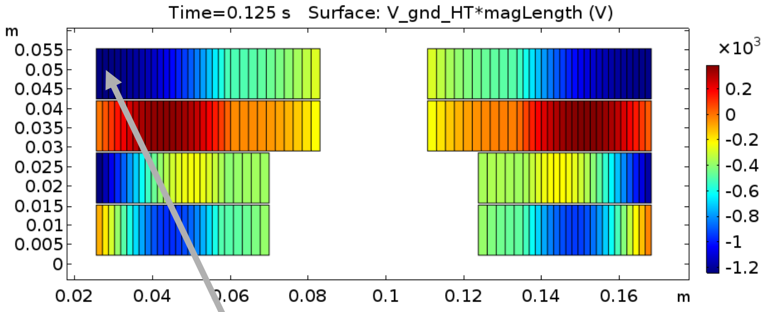
Quench protection (1)

- COMSOL
- 2 apertures
- 100% of nominal current



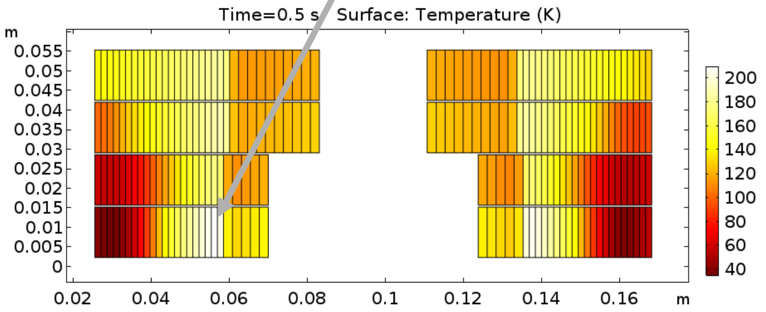


CLIQ1: V_0=0.8 kV, C=40 mF
CLIQ2: V_0=0.8 kV, C=40 mF



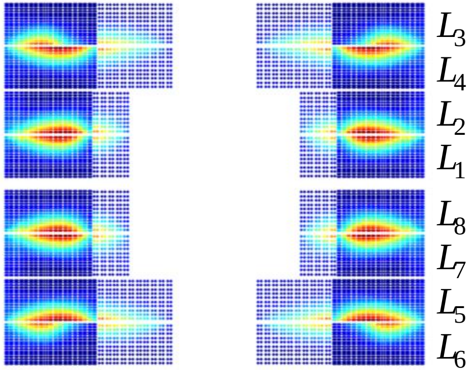
Max. voltage to ground 1.2 kV
Max. Layer-to-layer voltage 1.5 kV

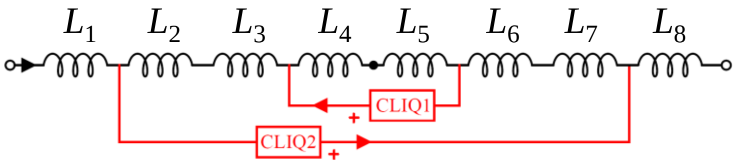
Hot-spot temperature 296 K



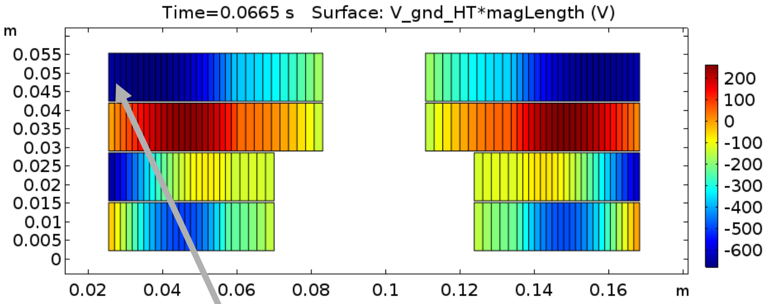
Quench protection (2)

- COMSOL
- 2 apertures
- 100% of nominal current



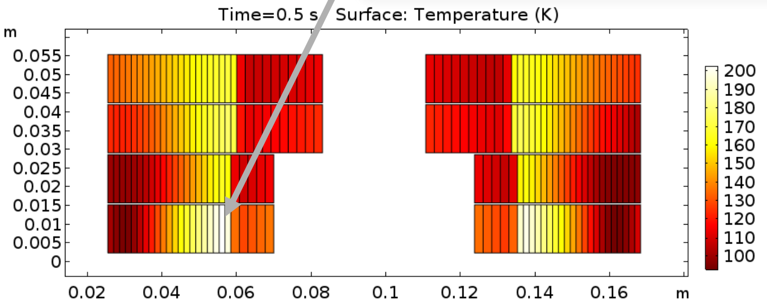


CLIQ1: V_0=0.6 kV, C=50 mF
CLIQ2: V_0=1.2 kV, C=50 mF



Max. voltage to ground 0.7 kV
Max. Layer-to-layer voltage 0.9 kV

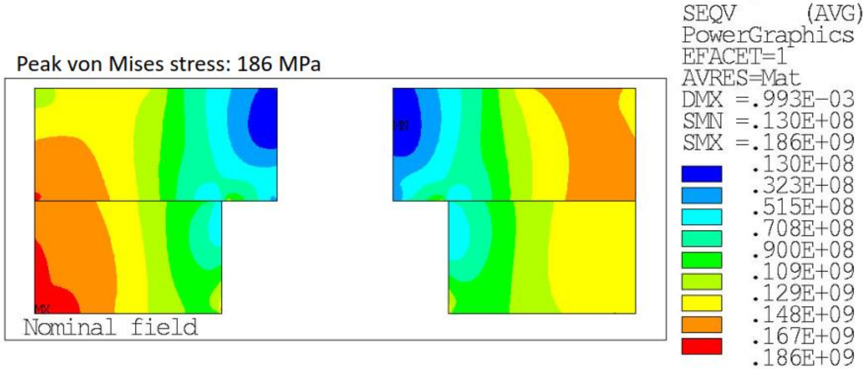
Hot-spot temperature 286 K



Crosscheck at nominal current ($t = 0$)

Reference simulation from Clement:

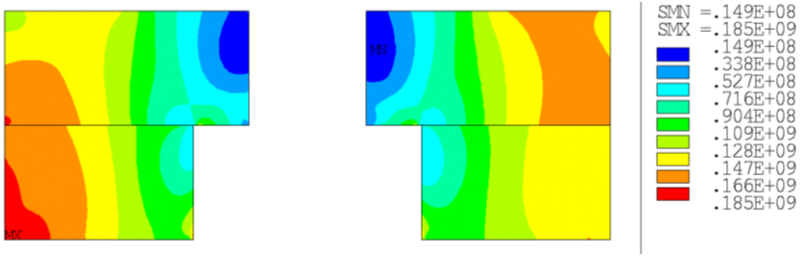
Lorentz force in ANSYS → Mechanics in ANSYS



Simulation to be validated:

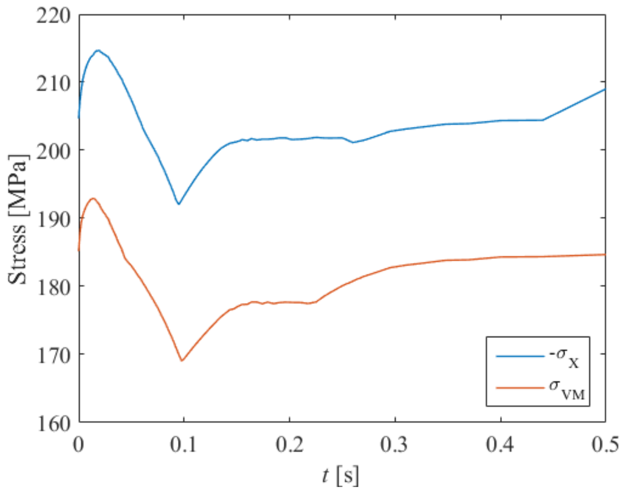
Lorentz force from COMSOL → Mechanics in ANSYS

Peak Von Mises stress: 185 MPa

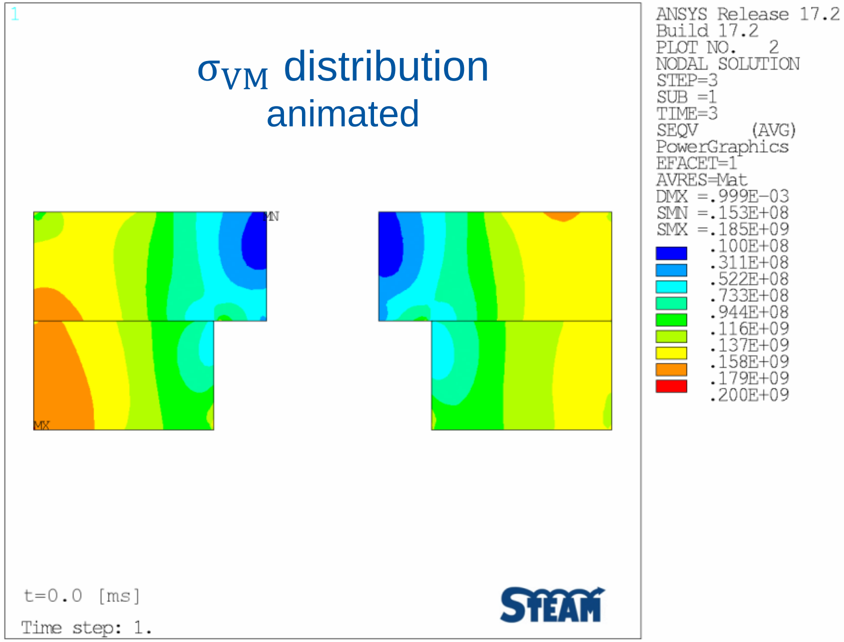


✓ Very similar stress distribution for the two approaches!

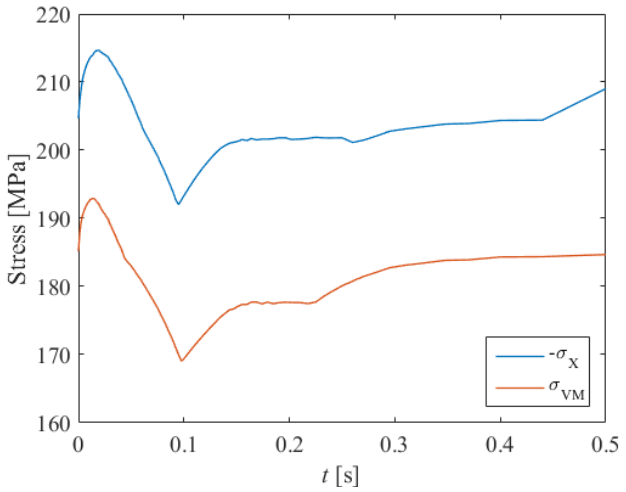
Case 1: no hot-spot

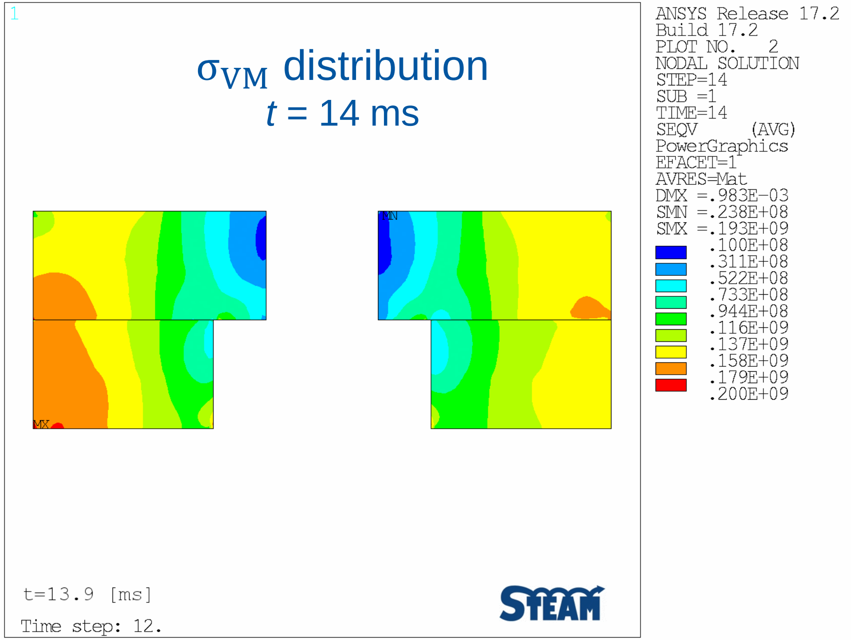


$\sigma_{VM,max}$ = 193 Mpa at *t* = 14 ms



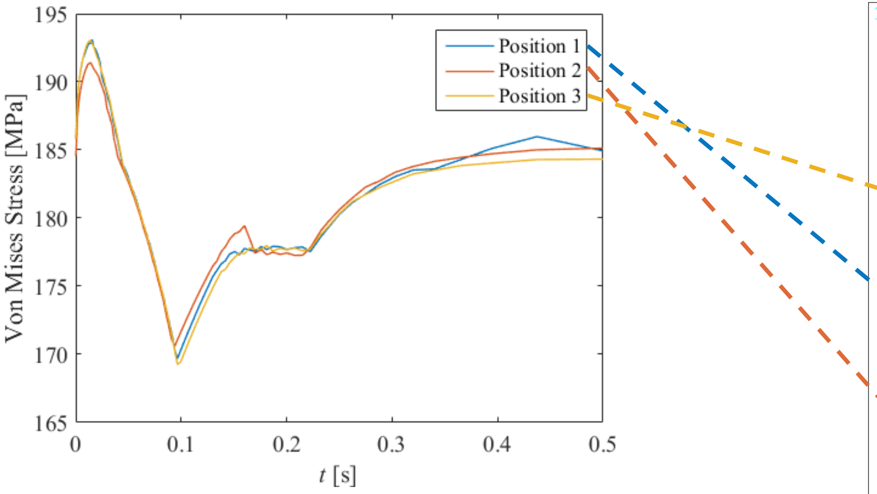
Case 1: no hot-spot



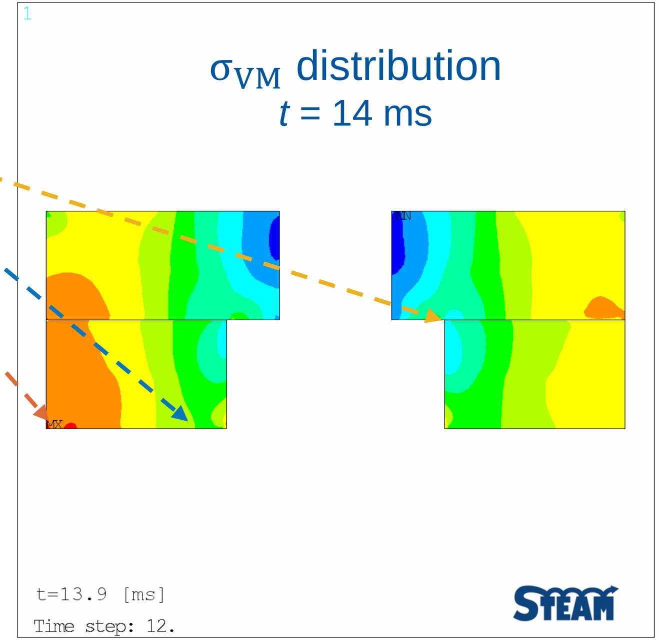


$\sigma_{VM,max}$ = 193 Mpa at t = 14 ms

Case 2: with adiabatic hot-spot



$\sigma_{VM,max}$ = 193 Mpa at t = 14 ms



Comments, block-coil

- Peak stress at $t = 14$ ms
  - Combination of Lorentz force introduced by CLIQ and temperature differences
  - 185 MPa @ energization → 193 MPa after a quench

- The adiabatic hot-spot location is not influencing the maximum stress

- Different results than in Junjie analysis for single aperture design
  - Different evolution and lower peak stress
  - The magnet version and the CLIQ configuration have changed!

➢ The effect of quench on the peak stress is limited

Conclusions

The effect of the quench on the mechanical stress is different for cos-theta and block-coil magnets

- The peak stress during quench for <u>cos-theta</u>
  - Is significantly higher than at energization
  - Occurs at the end of the discharge (t > 500 ms)
- The peak stress during quench for <u>block-coil</u>
  - Is slightly higher than at energization
  - Occurs during the CLIQ discharge (t = 14 ms)

➢ For both magnets, quench increases the stress above the peak values foreseen during the mechanical design

➢ Not possible to predict the moment of peak stress

- The evolution of Lorenz force and temperature during the full current discharge has to be considered
- Mesh based interpolation is a useful tool to automate this analysis