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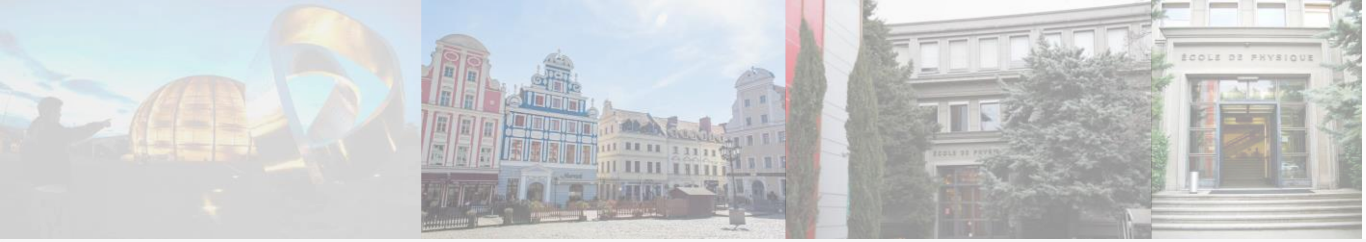
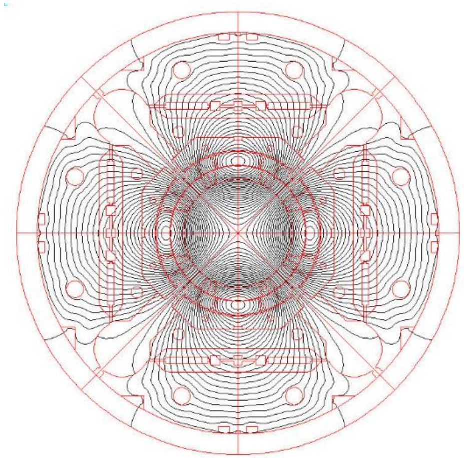


CHATS On Applied Superconductivity 2019

09/07/2019

On the magnet mechanics during a quench: Three-Dimensional Finite Element Analysis Of a Quench Heater Protected Magnet



Jose Ferradas — University of Geneva & CERN TE-MSC-MDT

Paolo Ferracin — CERN TE-MSC-MDT

Carmine Senatore — University of Geneva

On behalf of a group of amazing experts:

G. Ambrosio, H. Bajas, M. Bajko, L. Bottura, L. Brouwer, B. Castaldo, M. Guinchard, S. Izquierdo Bermudez, J.V. Lorenzo Gomez, F.J. Mangiarotti, J.C. Perez, E. Ravaioli, E. Tapani Taakala and G. Vallone

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OUTLINE

1.- Introduction – Quench processes and superconducting magnets

2.- MQXF – The low-β quadrupole for HL-LHC

3.- Finite element modelling for the analysis of the magnet mechanics during a quench

4.- 2D FE Analysis of a quench heater protected magnet

5.- 3D FE Analysis of a quench heater protected magnet

6.- Final conclusions

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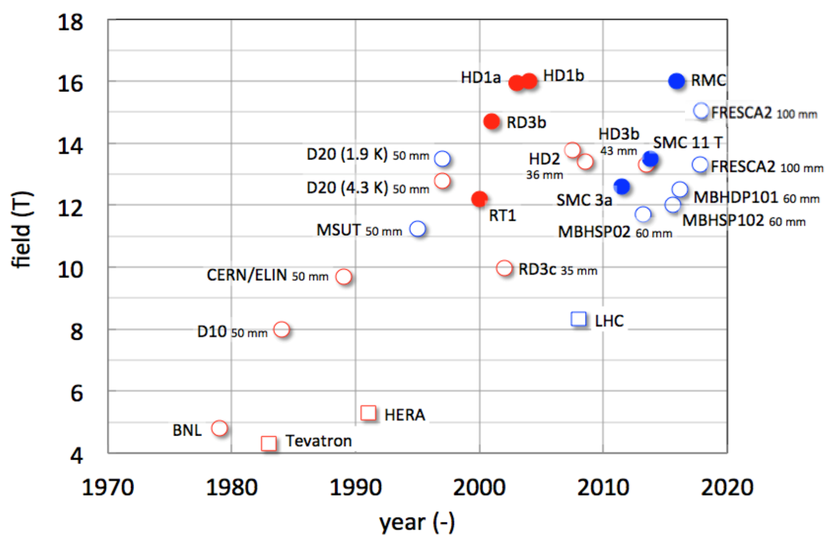
Quench processes and superconducting magnets

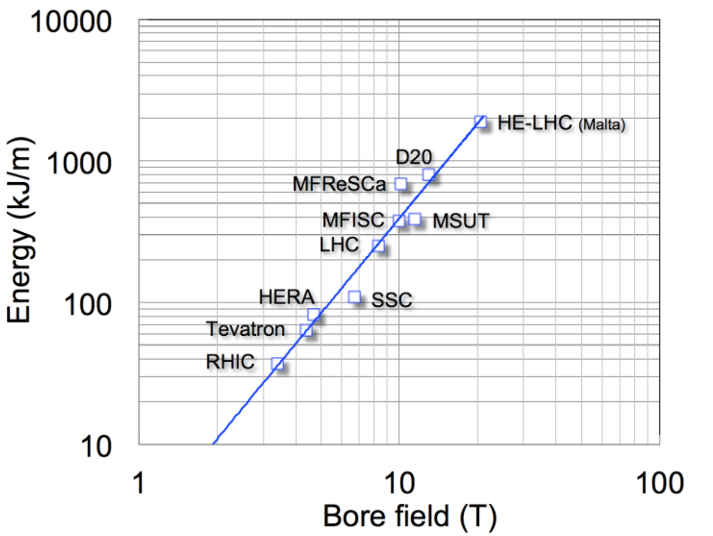
New **high-field Nb_3Sn** accelerator magnets are pushing the boundaries of magnet **design** and **quench protection** towards new **limits.**

Their large **stored energy** and **current densities** pose **new challenges** for the community…



Maximum magnetic field for state of the art superconducting accelerator magnets

Courtesy of L. Bottura

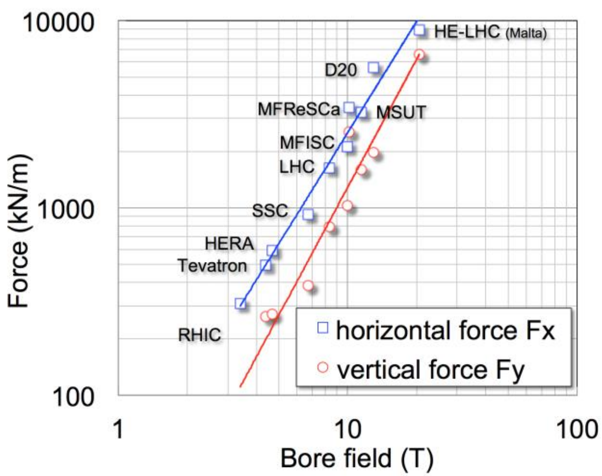


Scaling of the energy per unit length with the bore field

Courtesy of L. Bottura

Quench processes and superconducting magnets

… but also the **electro-mechanical** limits of the **conductor** become a parameter of **extreme importance**.



Courtesy of L. Bottura

Digression on thermal stresses: Thermal buckling in railway tracks
Source: [Business Insider]

Quench → Thermo-mechanical stresses → Risk of magnet damage / conductor degradation

The study of **quench** processes and their **intrinsic mechanics** becomes **essential!**

We need **tools** capable of **predicting** the **mechanical response** of the magnet during a **quench**

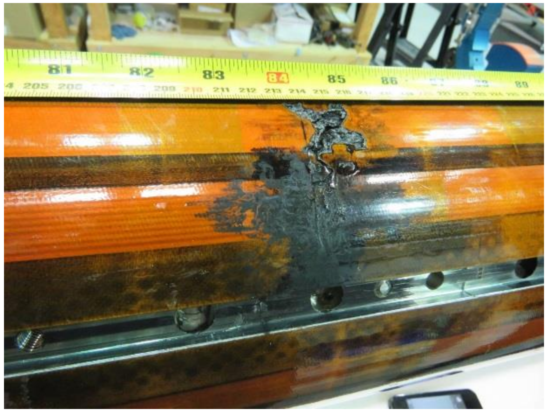
Quench processes and superconducting magnets

At the same time one cannot forget that the **accurate simulation** of **quench** transients is a real **multiphysics** effort:

- *Electromagnetic study ~ Safe voltage levels*
- *Thermal analysis ~ Safe temperature level*
- *Mechanical analysis ~ Safe stress levels*

This is the result of a chain of events triggered by a quench in an LHC bus-bar

Courtesy of Marta Bajko



Damage in HL-LHC coil as a result of an electrical fault

Courtesy of Paolo Ferracin

This is the result of a quench in the pre series magnet during its qualification test

Courtesy of Marta Bajko

Objective

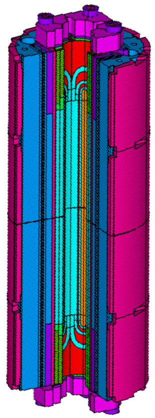
Perform the **2D** and **3D** analysis of the **magnet mechanics** during a **quench** in relevant **operation conditions** using **ANSYS APDL**.

The HL-LHC **MQXF** Low-β quadrupole **magnet**, our playground field.

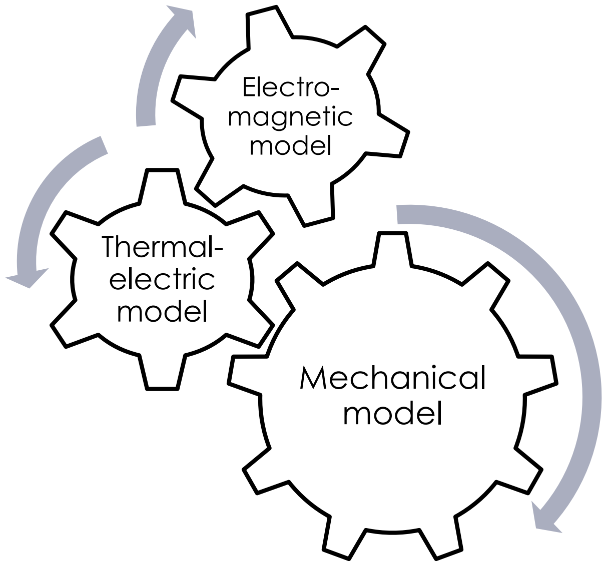
Magnet protected with **quench heaters** (placed in the outer layer of the coils), quench at **nominal current**. Characterize the magnet response.

The method should combine the necessary **multi-physics models**. They will **provide** the **input** for the **mechanical model**.

Main goal of today: **Show** that the **methodology works.**



3D MQXF magnet mechanical model (G. Vallone, 2017)



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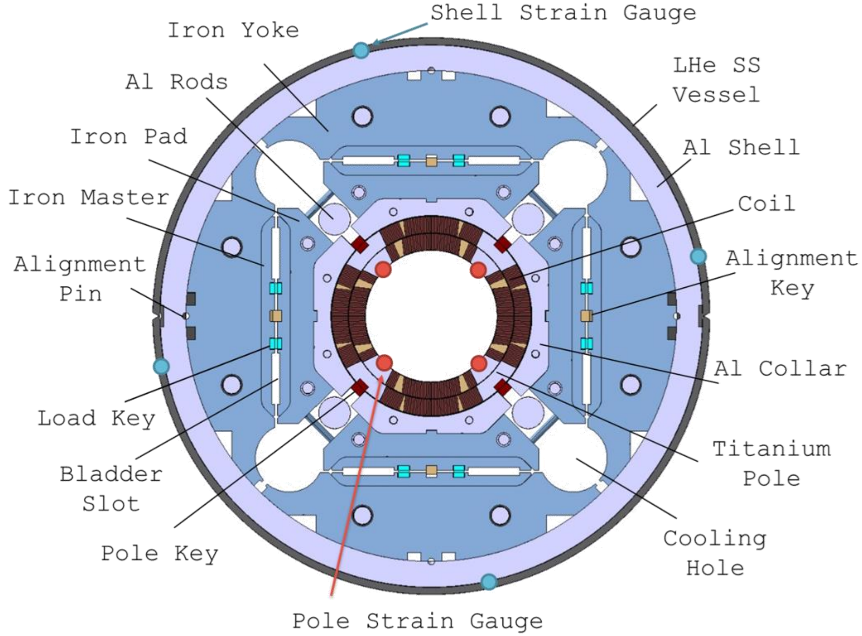
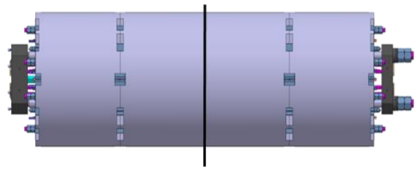
MQXF Low-β quadrupole magnet

- *Nominal gradient:* **132.6 T/m**
- *Nominal current:* **16470 A**
- *Peak field in the conductor* at I_{nom}: **11.4 T**
- *Aperture:* **150 mm**
- Magnet outer radius: **630 mm**
- Stored energy at I_{nom}: **1.17 MJ/m**
- F_x / F_y (per octant) at I_{nom} = **+2.47 / -3.48 MN/m**
- F_z (Whole magnet) at I_{nom} = **1.17 MN**

Mechanical concept: Aluminium shell pre-loaded with bladders.

First time for an accelerator magnet.





Courtesy of Giorgio Vallone

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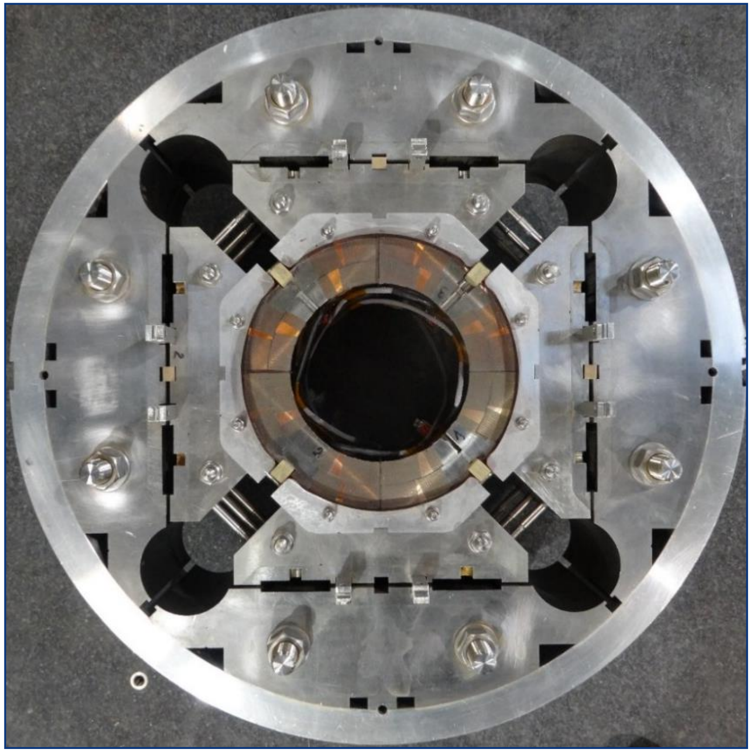

Courtesy of Paolo Ferracin

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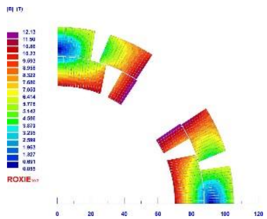
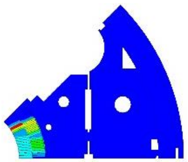
Modelling strategy

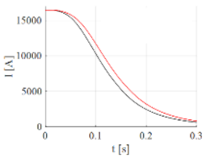


2D/3D ROXIE electromagnetic model

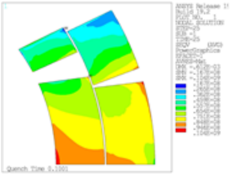
Magnetic field on each conductor

3D Thermal-Electric quench simulation

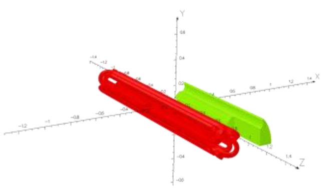




Mechanical model



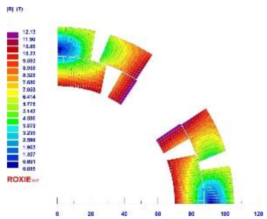
Opera Simulation Software



2D/3D Electromagnetic model

Modelling strategy

Main focus of today's talk



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Magnetic field on each conductor

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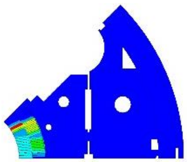
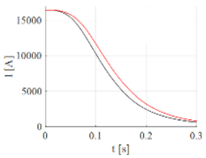
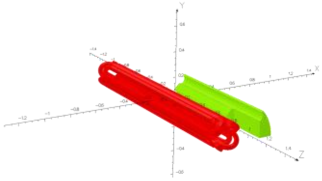
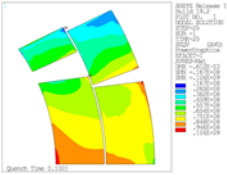




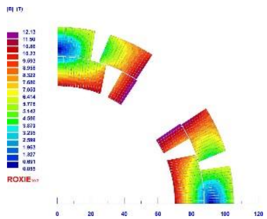


2D/3D Electromagnetic model

Mechanical model



Modelling strategy



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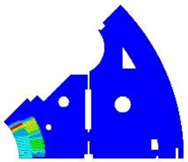
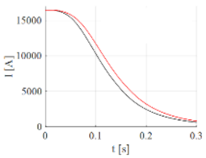
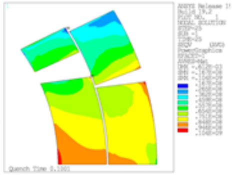
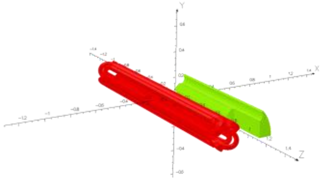




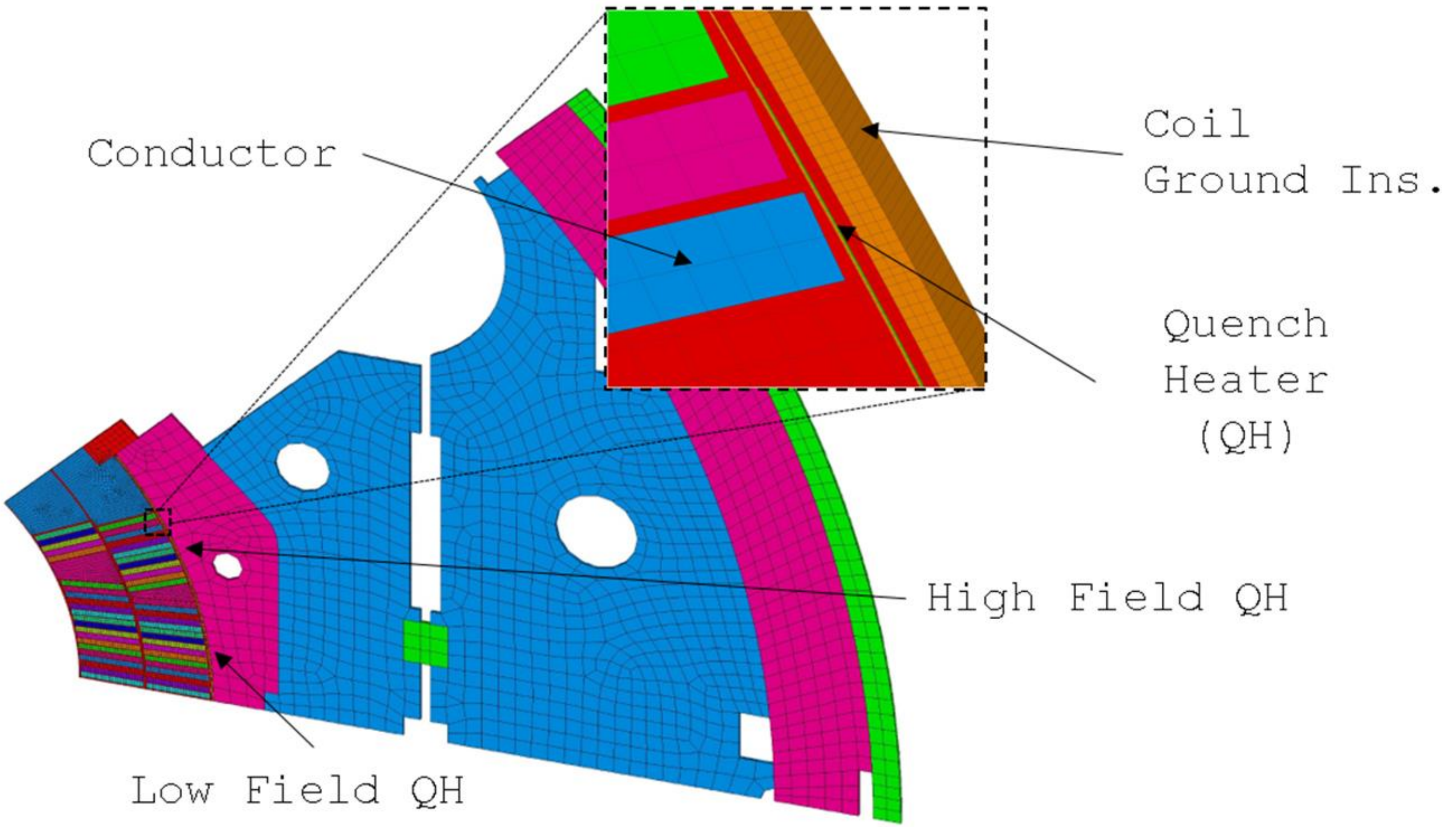
Mechanical model





2D/3D Electromagnetic model

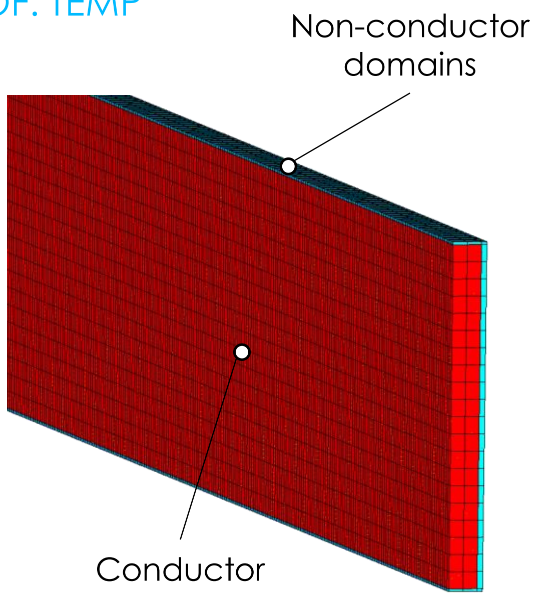
3D MQXF Thermal-Electric model



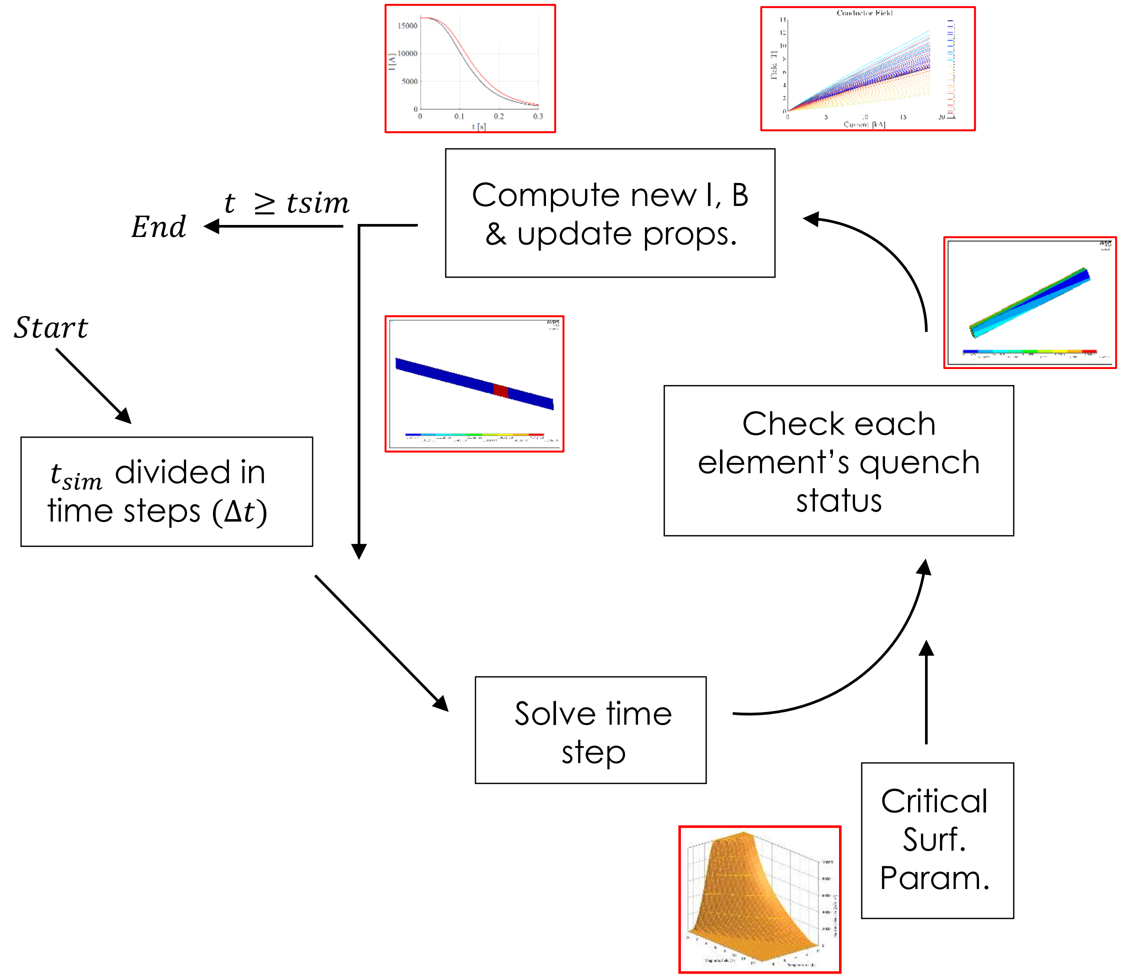
Adiabatic boundary conditions

From previous episodes (ASC 2018)…

ANSYS SOLID278
3-D 8-Node Thermal Solid
8 nodes 3-D space
DOF: TEMP



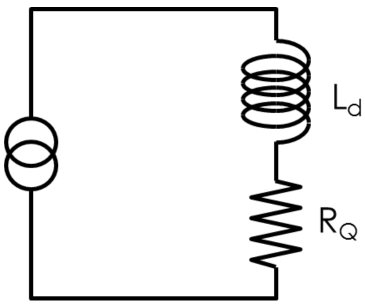
ANSYS SOLID226
3-D 8-Node Coupled-Field Solid
8 nodes 3-D space
DOF: TEMP, VOLT



Modelling the full current decay

- On the assumption of a **quench heater** protected magnet **without external dump**:

$$I_m R_Q + L_d \frac{dI_m}{dt} = 0$$



Equation **solved** by the code with a **step-by-step** method. It provides a **piecewise exponential decay** for the current.

The model **updates R_Q** and **L_d** at each **time step**.

*Magnetic **field** on each conductor **using** ROXIE **load lines.***

$$B = LL_B I_m$$

LL_B [T A^{-1}]

- **Inter filament Coupling Losses** (IFCL) are **included** in the formulation [1].

$$P_{IFCL(FEM)} = (\frac{A_s}{A_c}) P_{IFCL}$$

$$P_{IFCL} = (\frac{l_f}{2\pi})^2 \frac{1}{\rho_{eff}} (\frac{dB_s}{dt})^2 \qquad B_s = B_a - \tau_{if} \frac{dB_s}{dt} \qquad \tau_{if} = \frac{\mu_0}{2\rho_{eff}} (\frac{l_f}{2\pi})^2$$

B_s: Total field (under the effect of IFCC)

B_a: Applied magnetic

A_s: Total area of strands

A_c: Total area of the conductor

l_f: Filament twist-pitch

ρ_{eff}: Effective transv. resistivity

μ_0: Magnetic perm. of vaccum

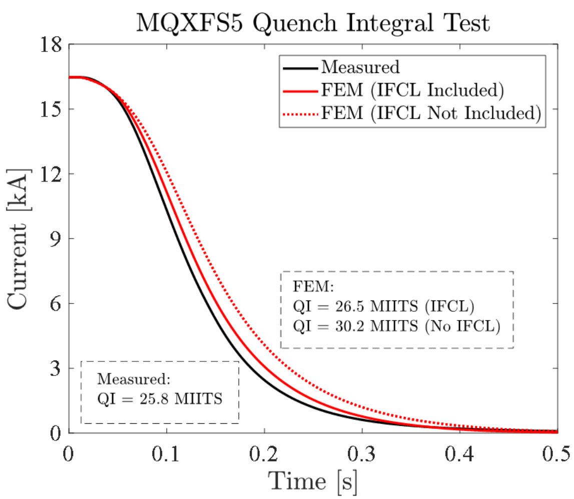
[1] j. Ferradas Troitino et al, "On the magnet mechanics during a quench: 2D Finite element analysis of a quench heater protected magnet" Submitted for publ.

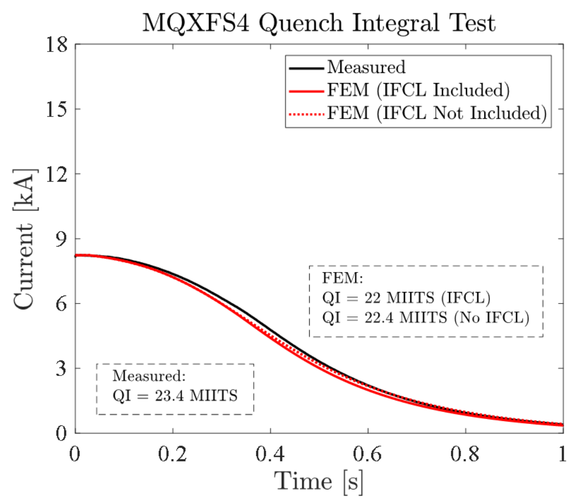
Simulation results obtained under the explained assumptions.
An "error bar" should be always considered!

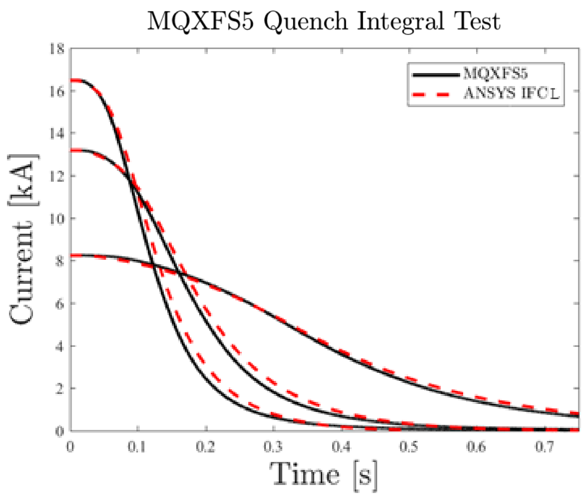
Model results and validation

The model could be validated using the extensive experimental campaign for MQXFS magnets:

Quench Integral (QI) tests







QI ~ Less than 10% difference w.r.t. experimental data in all tests

Simulation results obtained under the explained assumptions. An "error bar" should be always considered!

Model results and validation

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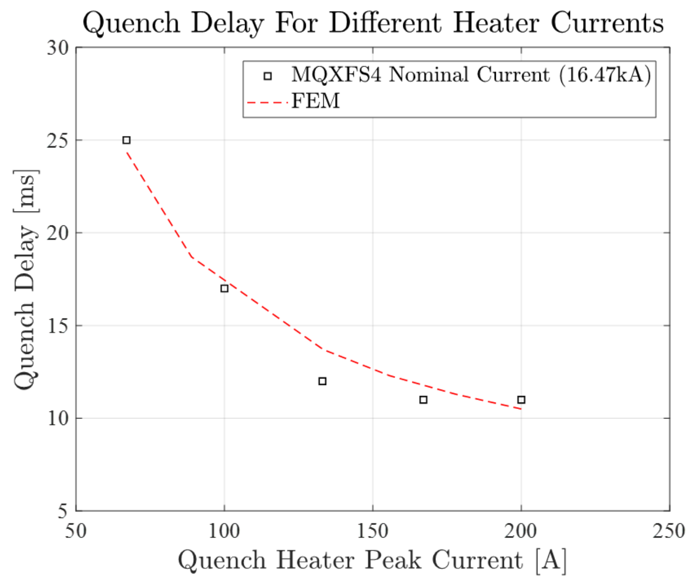
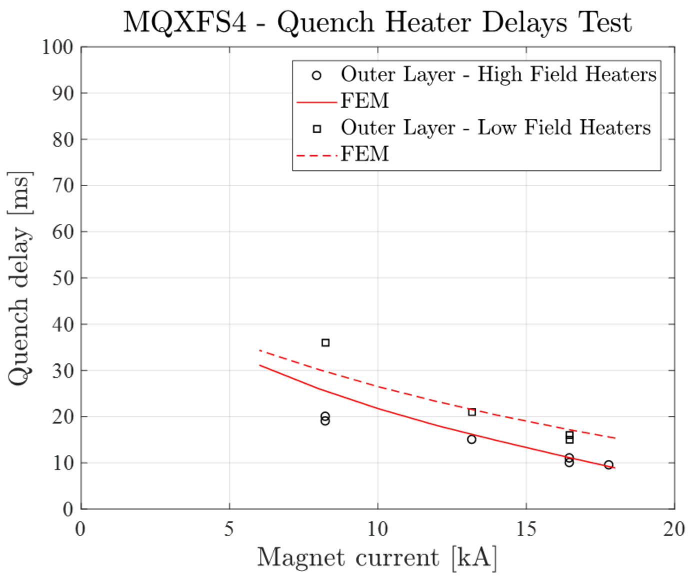
Quench Heaters (QH) tests

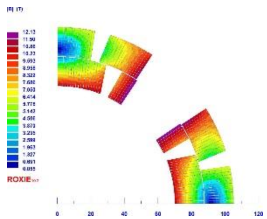




Max. discrepancy ~ 14%   Delay precision ~ Around 1 ms at I_{nom}

Thermal behaviour matched

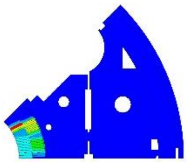
Modelling strategy

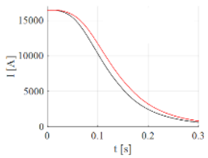


2D/3D ROXIE electromagnetic model

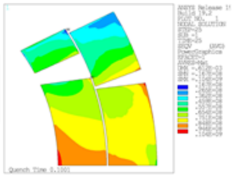
Magnetic field on each conductor

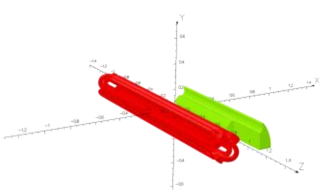
3D Thermal-Electric quench simulation





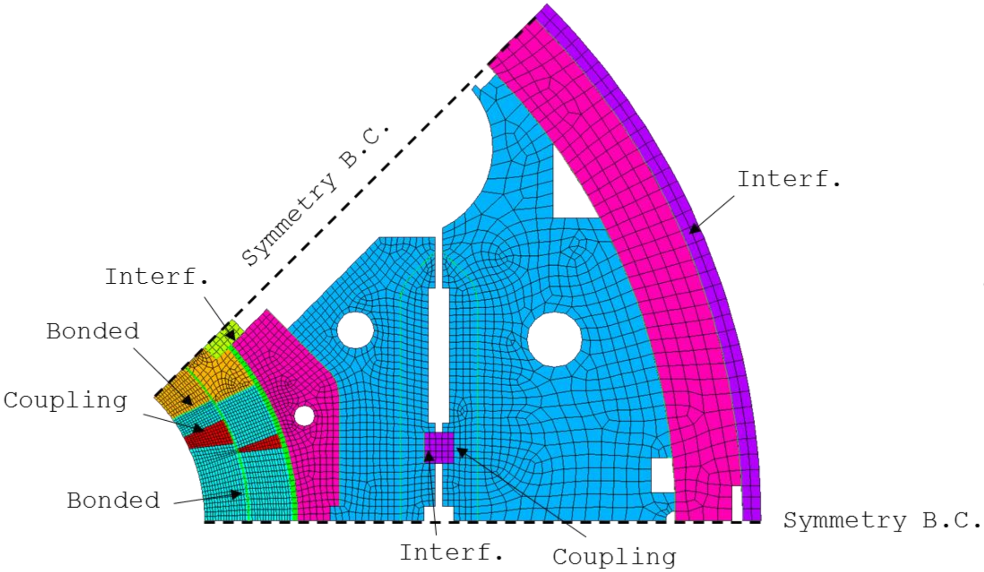
Mechanical model

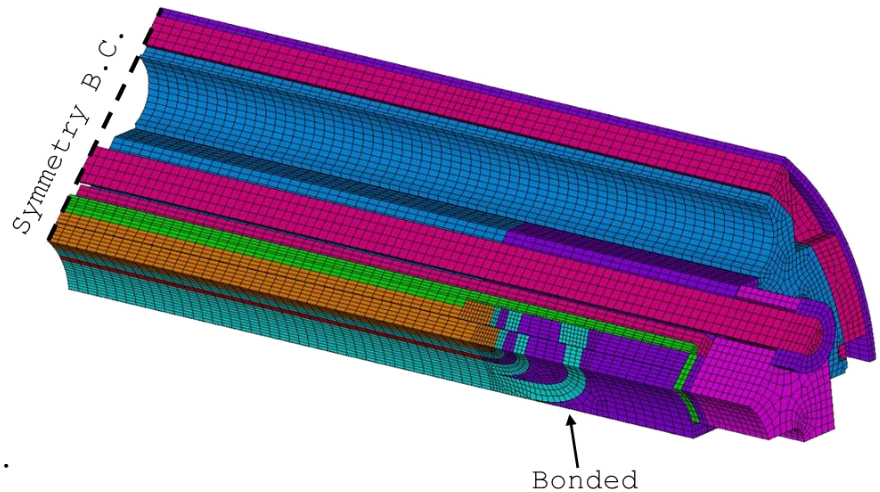




2D/3D Electromagnetic model

2D & 3D MQXF Mechanical model





PLANE82 – **structural** 2D **quadratic**
Surf./Surf. **contact** elements (CONTA172/TARGE169).

Plane stress assumption, verified against 3D models and measurements.

Exploit the quadrupole **symmetry.**

Linear elastic material properties.

Coil simulated as a **block** with smeared properties **(isotropic).**

Adds:

Half-magnet length, longitudinal symmetry B.C.

Longitudinal loading

*Validation results in the backup slides

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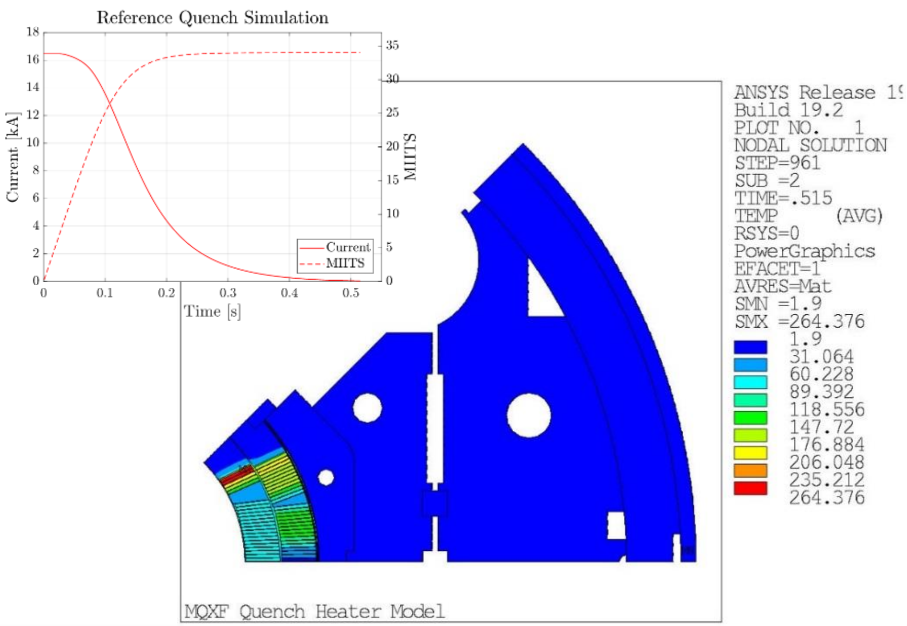
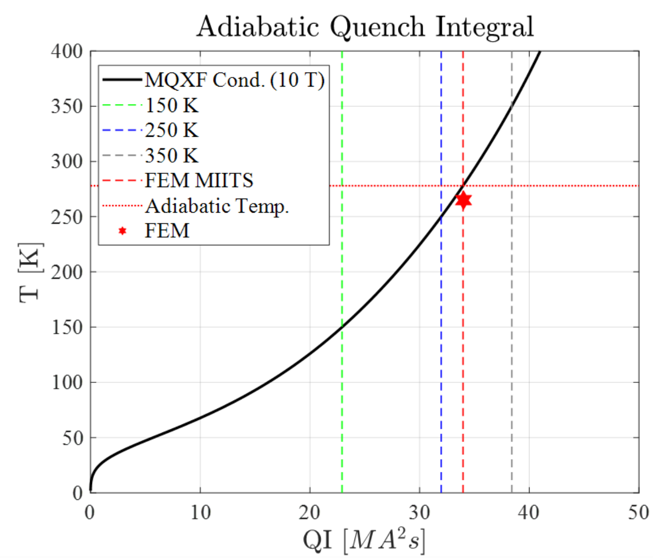
Case study: Nominal current training quench

- 15 ms Detection + Validation time example.
  - Inner layer pole turn quenched (**Highest peak field conductor**)
- Magnet protected with outer layer QH:
  - Reference MQXF conductor parameters.
  - Results: **34 MIITS** → **Peak T** at the end of disch. **= 264 K**

Adiabatic estimation of hot spot temp.

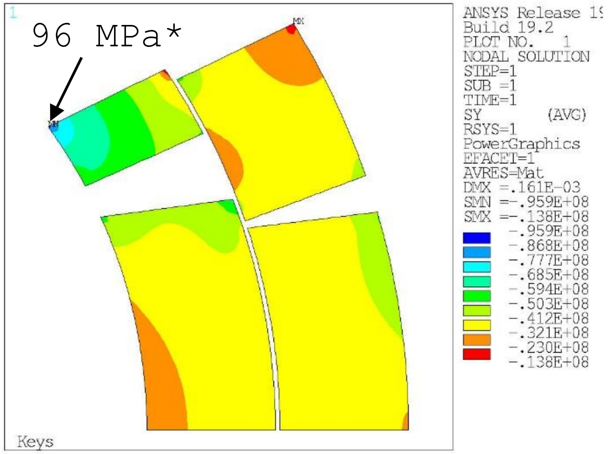
$$\int_0^{\infty} I(t)^2 dt = A_{cable} A_{Cu} \int_{T_0}^{T_\infty} \frac{C_p^{avg}(T)}{\rho_{Cu}(T,B)} dT$$



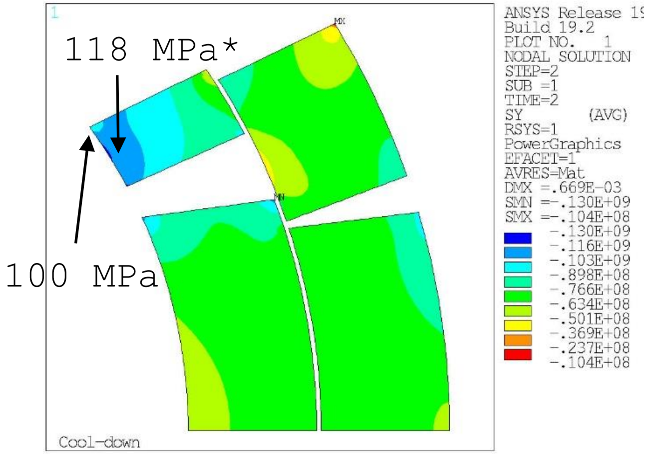


2D Mechanical results: Azimuthal stress

Assembly



Cool-down

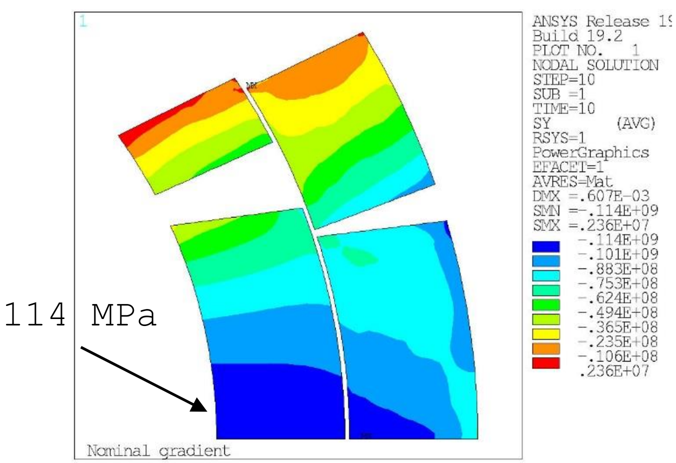


Careful interpretation needed!

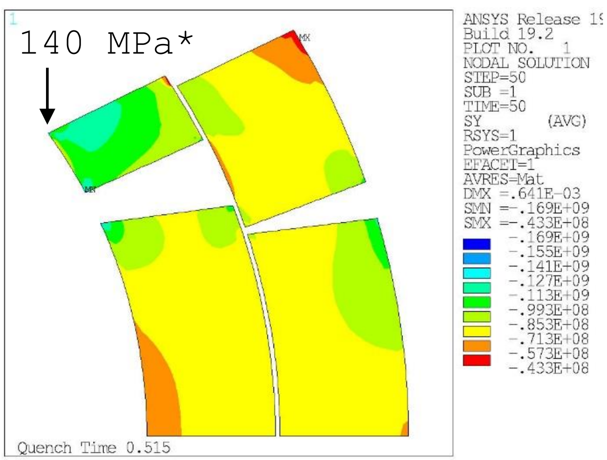
*Singular corner values

More information in the 3D part

Nominal Operation

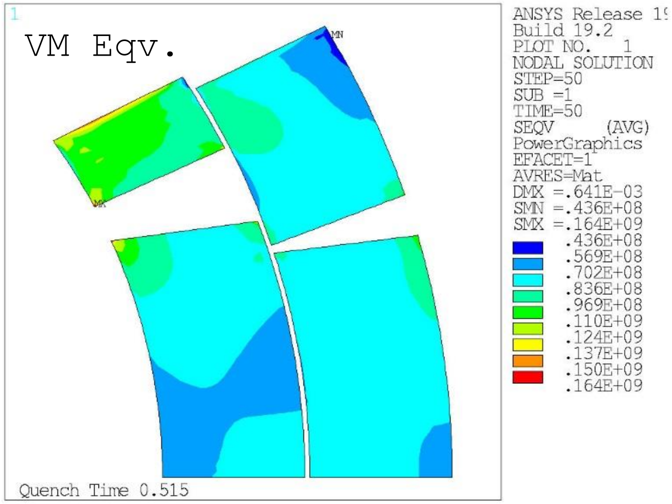


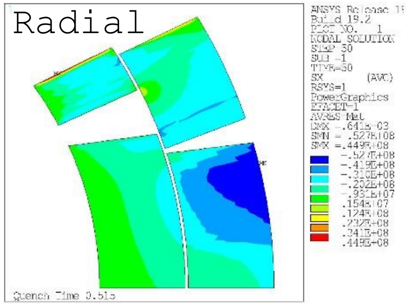
End of quench discharge

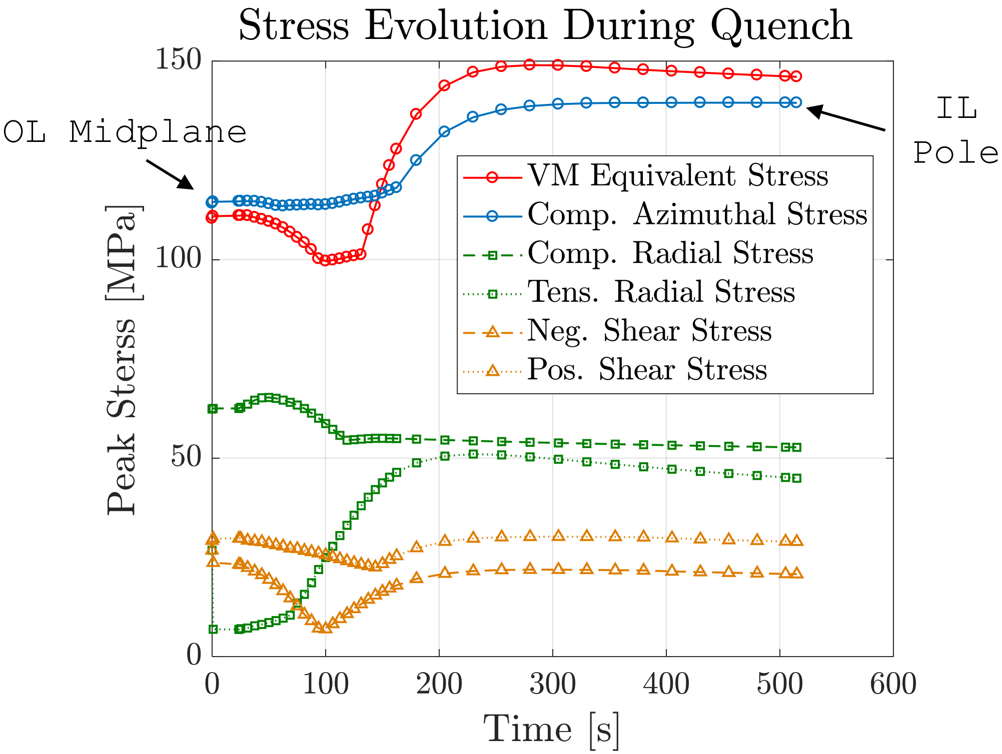


2D Mechanical results: Stress evolution

- **Peak** Von Misses **equivalent stress** at the end of the discharge ~ **146 MPa**
  - **Stress evolution** during quench is important.





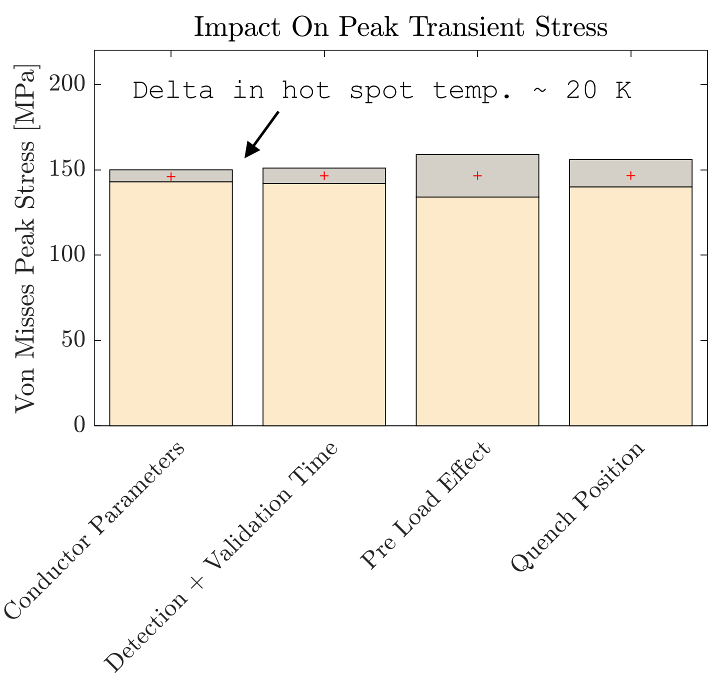


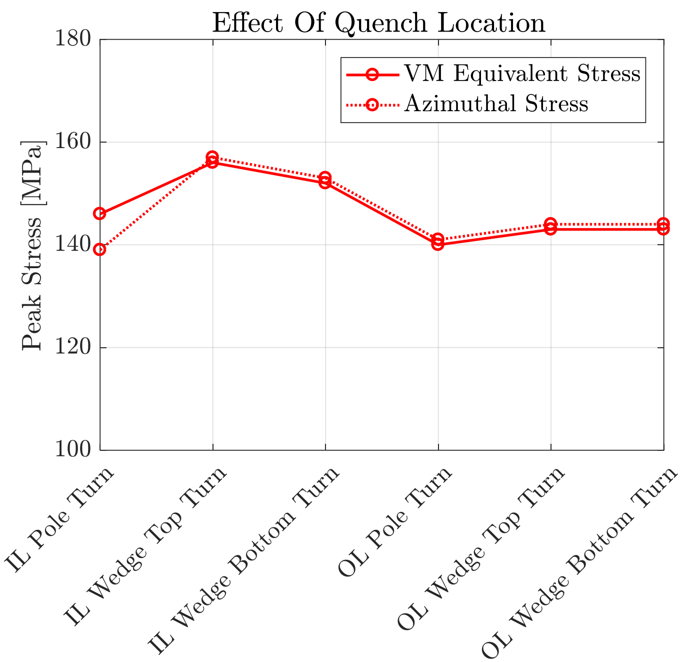
* Not necessary at the same place

2D Mechanical results: Full nominal characterization

Results under the coil block assumption

Analysis on the peak stress impact respecting project tolerances:





Conductor Parameters: 100< **RRR** <200
1.0 < **Cu2SC** < 1.4

Detection + Validation: 10 ms < **time** < 20 ms

Preload effect: Nom-20 MPa < Nominal **preload** < Nom+20 MPa

Corner nodes neglected

Three main conclusions

***For our** reference case and under the modelling **assumptions**:*

The **peak stress** during a quench **in** the **coil block** is not defined by the hot spot temperature. Rather than that, it is **governed by** an **average/global temperature** in the coil:

Dissipated energy

In global terms, **the** parametric **study shows** that the **mechanical response** for a quench at nominal current does **not change if** the **design parameters** are **kept** within the established **tolerances**.

The **quench** transient **adds** an additional **azimuthal compression** of **40 MPa** to the **pole turn** (Compared with the value after cool down).

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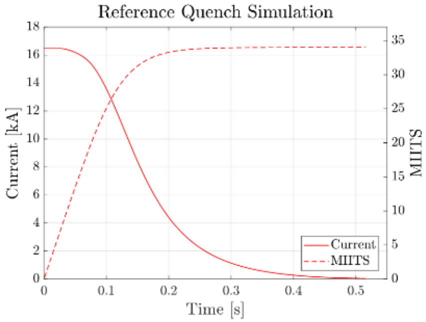
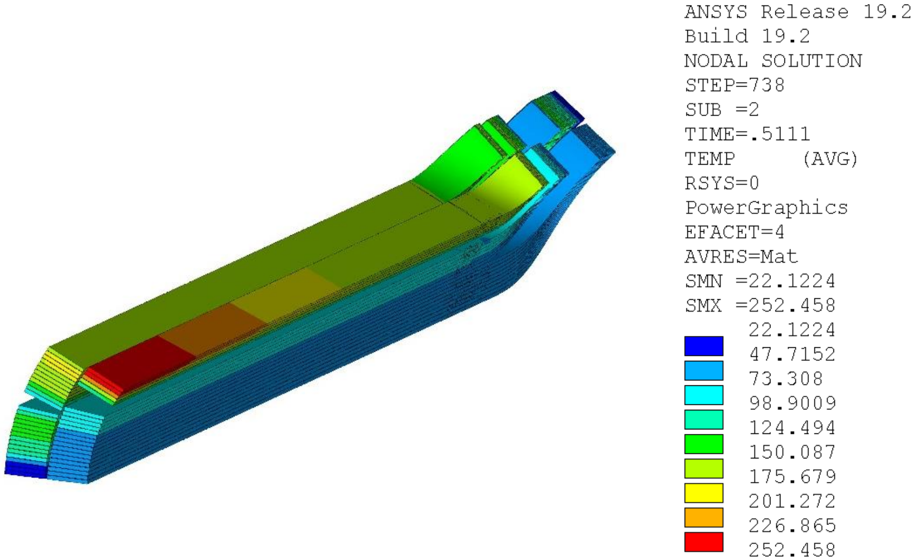
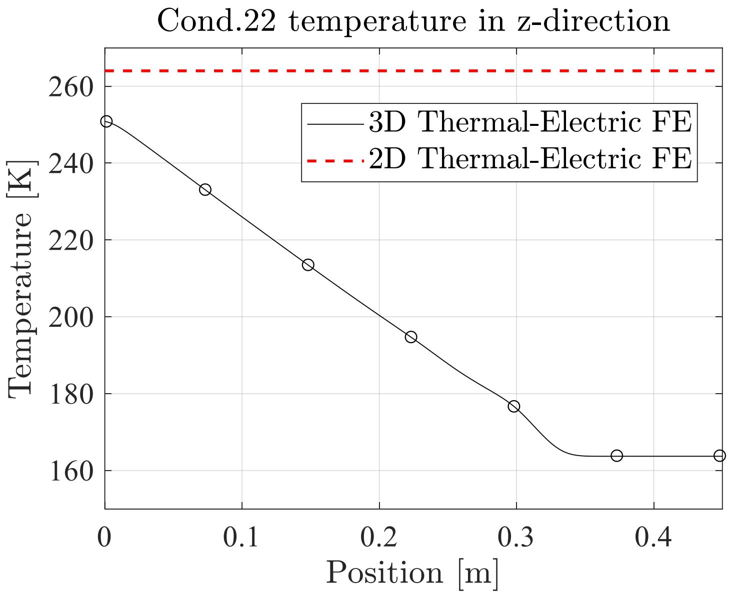
Case study: Nominal current training quench

- The **reference case** is simulated in **3D**
  - **~ 34 MIITS → Peak T** at the end of the discharge = **252.5 K** (Effect of longitudinal heat propagation)

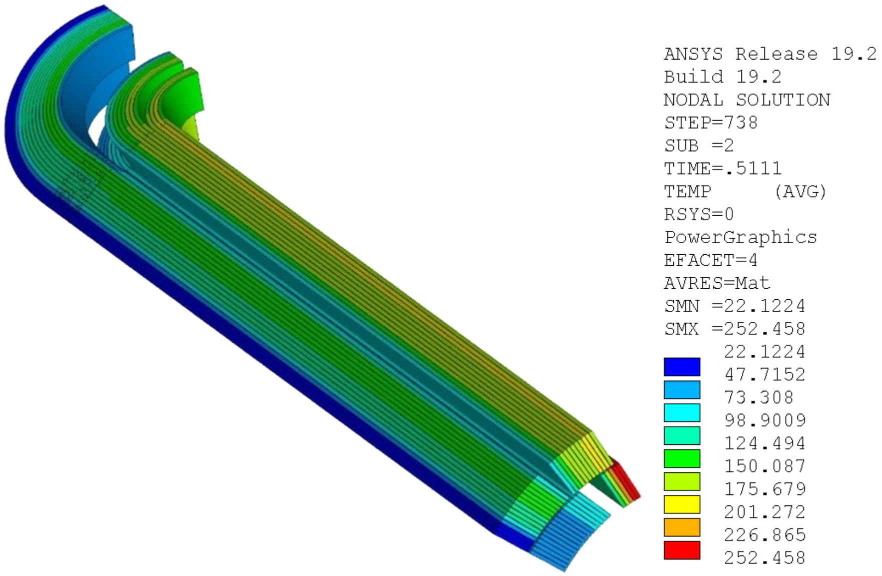


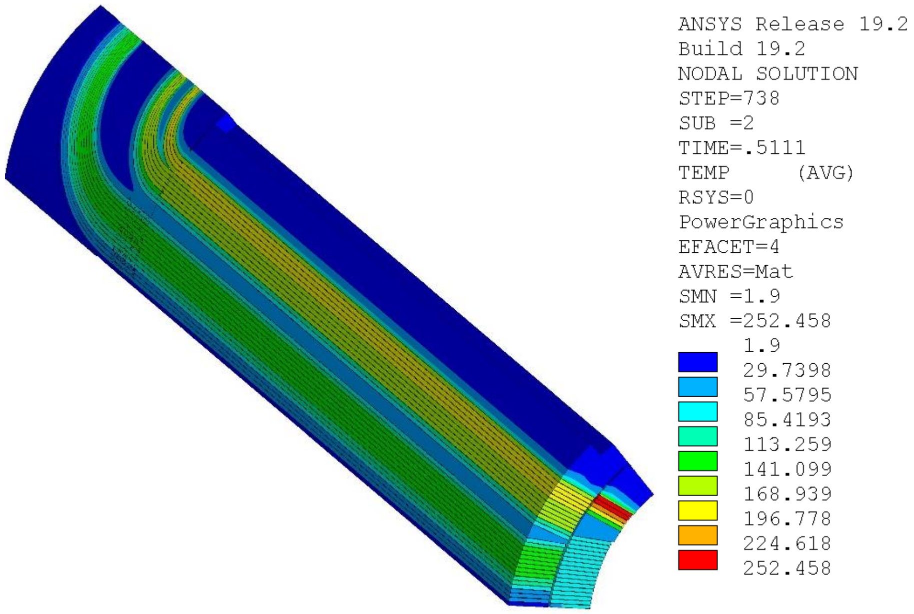




Case study: Nominal current training quench

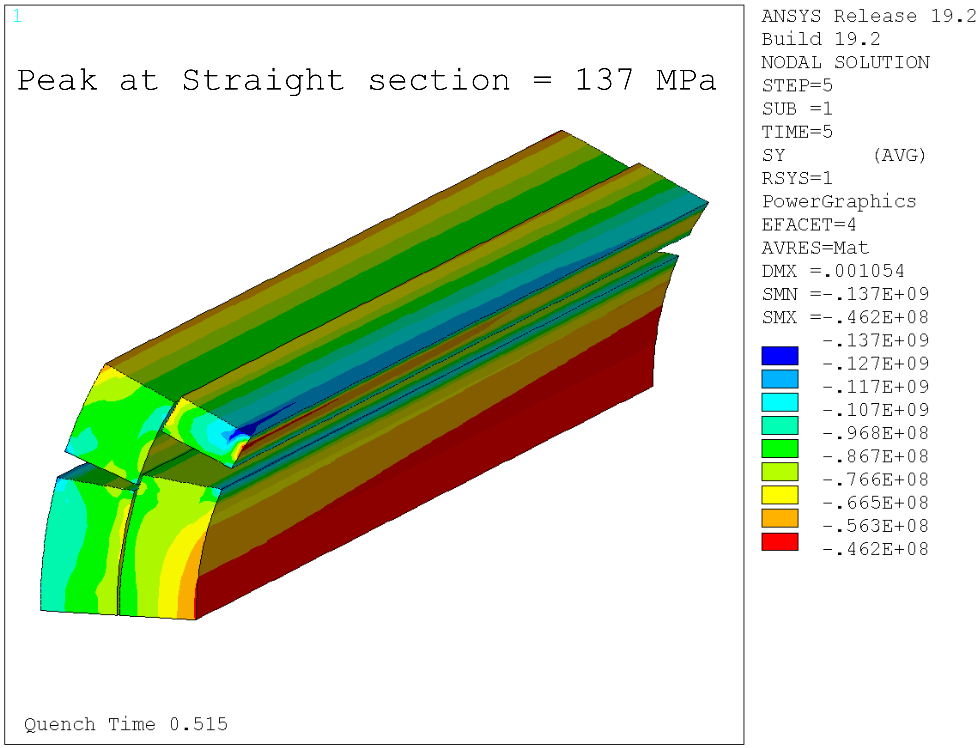
- A closer look to the 3D coil temperature (Insulation not shown)



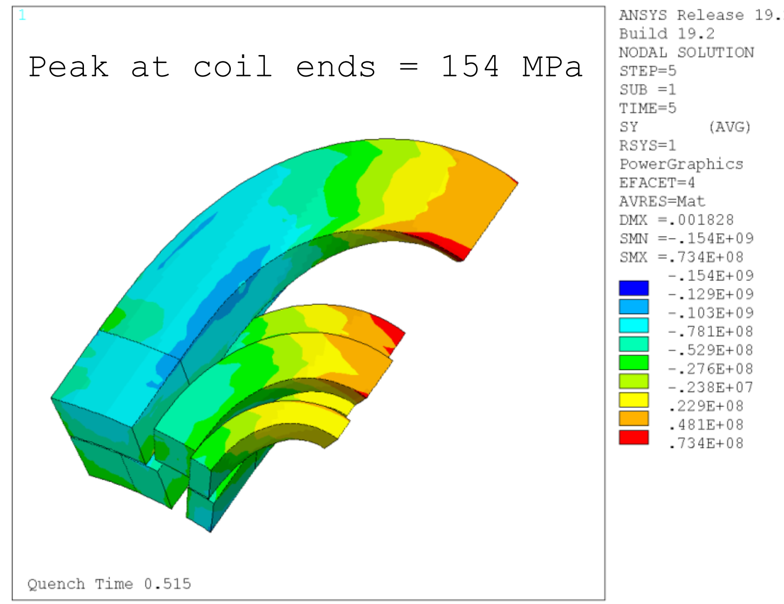


3D Mechanical results at the end of the discharge

AZIMUTHAL STRESS



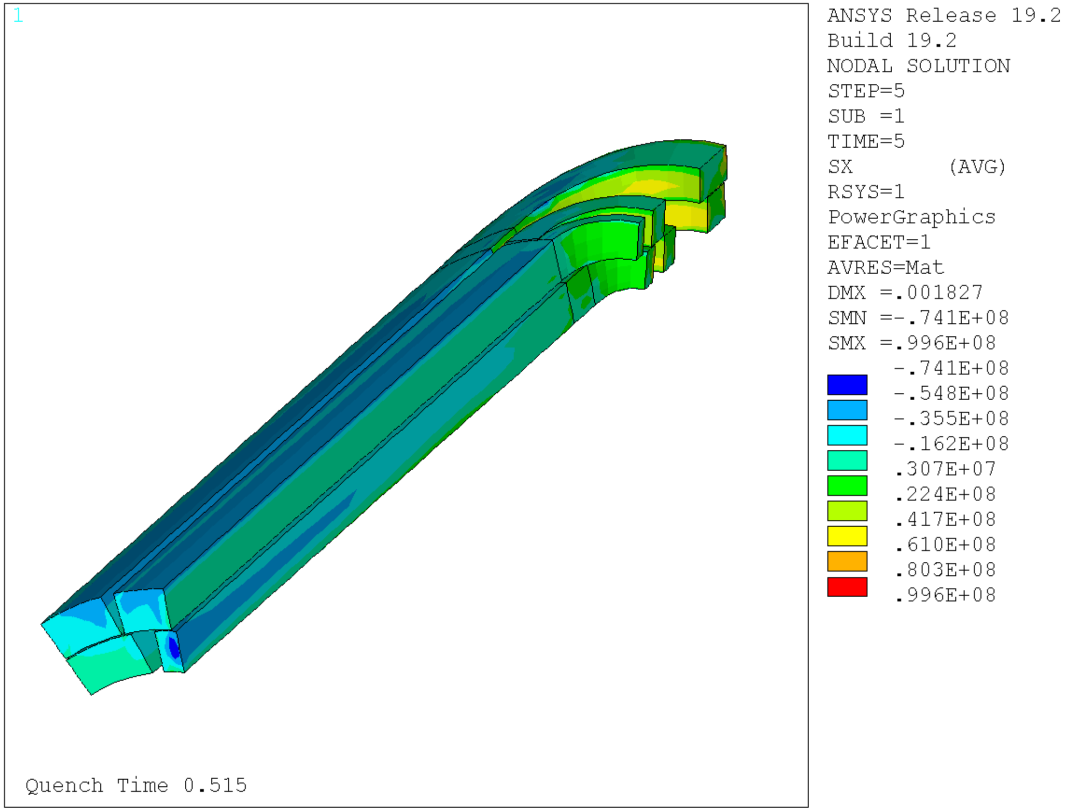
(Straight section results similar to 2D ~ 140 MPa)



Some areas in the coil ends see a higher stress. Some others see tension.

3D Mechanical results at the end of the discharge

RADIAL STRESS



Peak radial stress below 100 MPa

3D Mechanical results at the end of the discharge

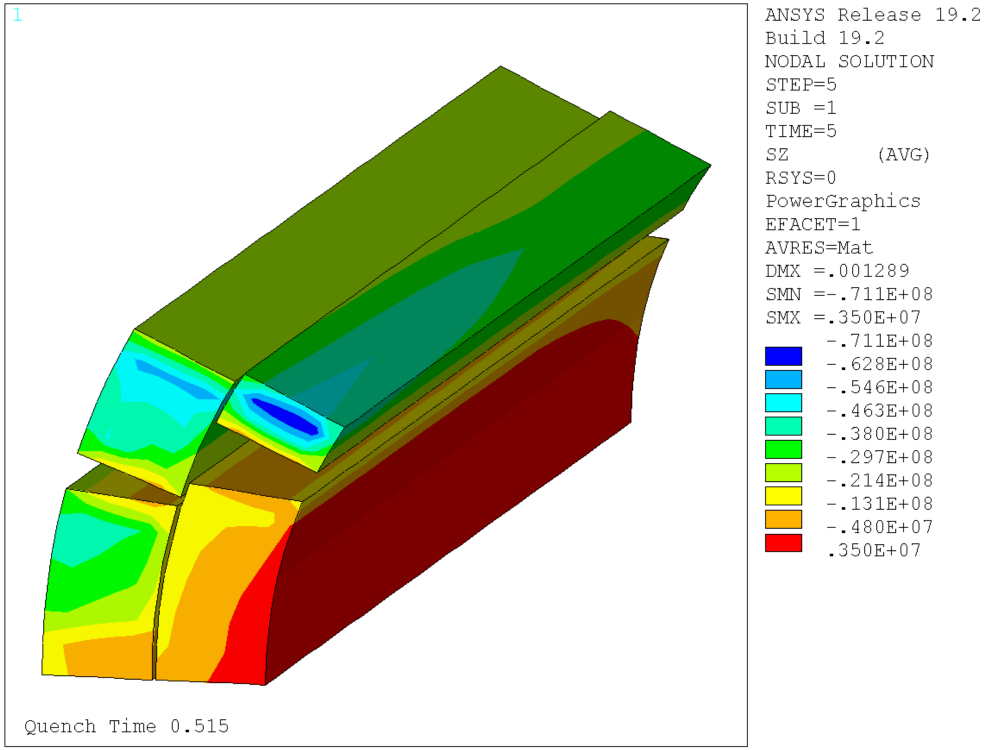
SPECIAL FOCUS ON HOT SPOT REGION

LONGITUDINAL STRESS

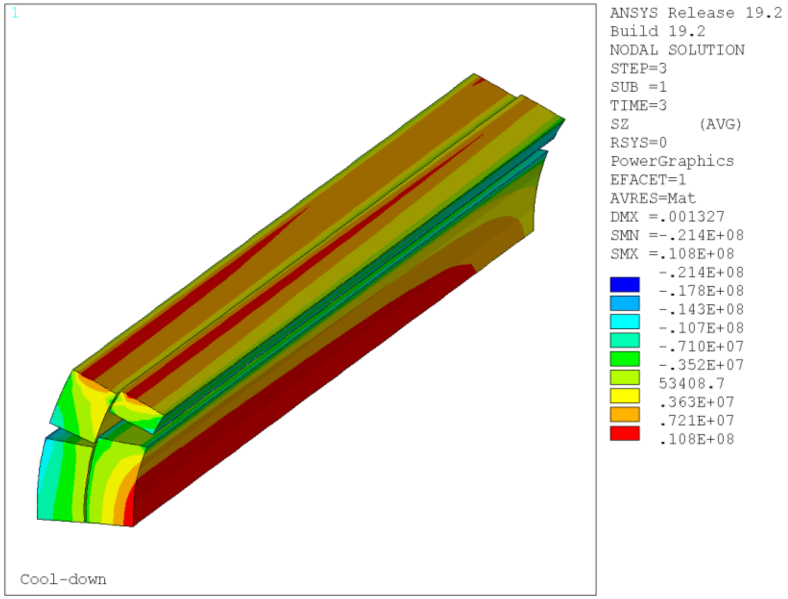
End of the discharge

Local peak at Straight section = -71 MPa

Needs further study.
Work on-going with mech. model.



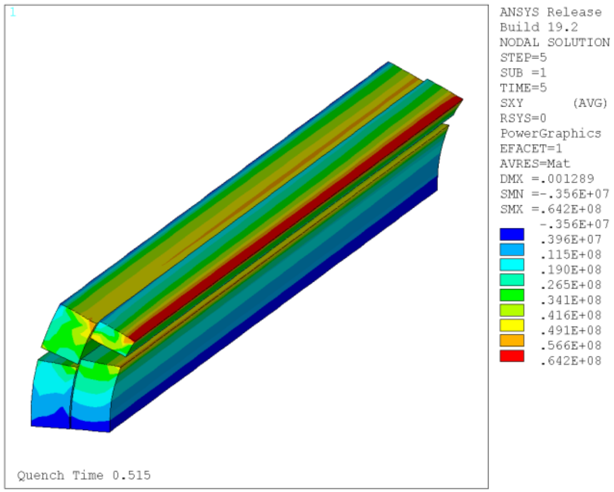
For reference, after Cool down = +20 MPa



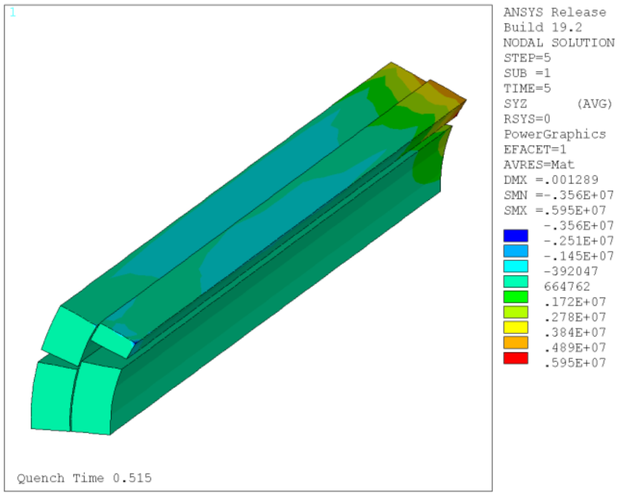
3D Mechanical results at the end of the discharge

SHEAR STRESSES

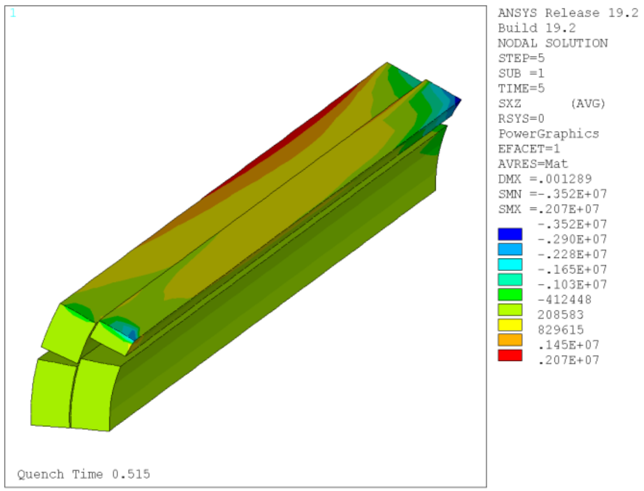
SXY (Cartesian)



SYZ (Cartesian)



SXZ (Cartesian)



Main conclusions and identified next steps

2D and **3D** analysis of the quench mechanics give **similar** values in the **straight section** when singularities are neglected.

A **peak azimuthal** stress of **140 MPa** appears close to the hot spot as a result of the thermal gradients. **All other** stresses remain well **below** that value.

Longitudinal stresses are **very important** close to the hot spot region. They need further study.

A **more detailed** analysis is **necessary**. Currently the **3D mechanical model** is **being re-checked** by CERN and LARP. A **new analysis** will come **soon**.

This can be seen as a proof-of-concept right now.

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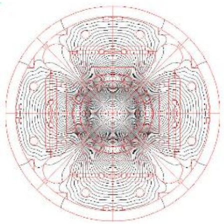
CONCLUSIONS



A methodology for the 2D and 3D study of the magnet mechanics during a quench has been presented.

It uses a combination of finite element models in ANSYS APDL with other usual tools used in the magnet community.

The different models have been validated with experimental measurements separately.

The method allows to extract essential information about the magnet behavior during a quench.

The 3D case needs to be further studied. The model is currently being re-checked.

More to come in the following months… stay tuned!

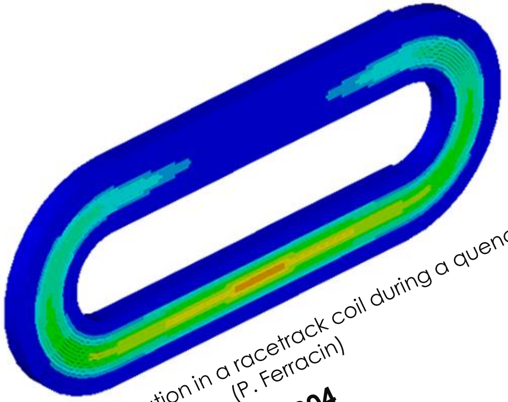
www.cern.ch

Quench simulation in superconducting magnets

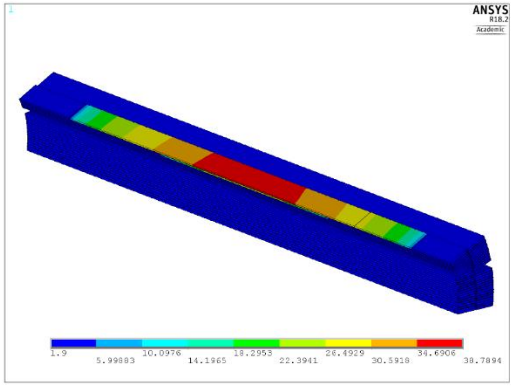
Many codes available in the community. **From lumped elements** formulations **to Finite Element** (FE) models.

Since **FE** models are our **main tool** for the **simulation** of the **magnet mechanics** during the assembly and operation…

Could we **integrate** the analysis of the magnet **mechanics during quench** in these models?



Temp. distribution in a racetrack coil during a quench
(P. Ferracin)
2004

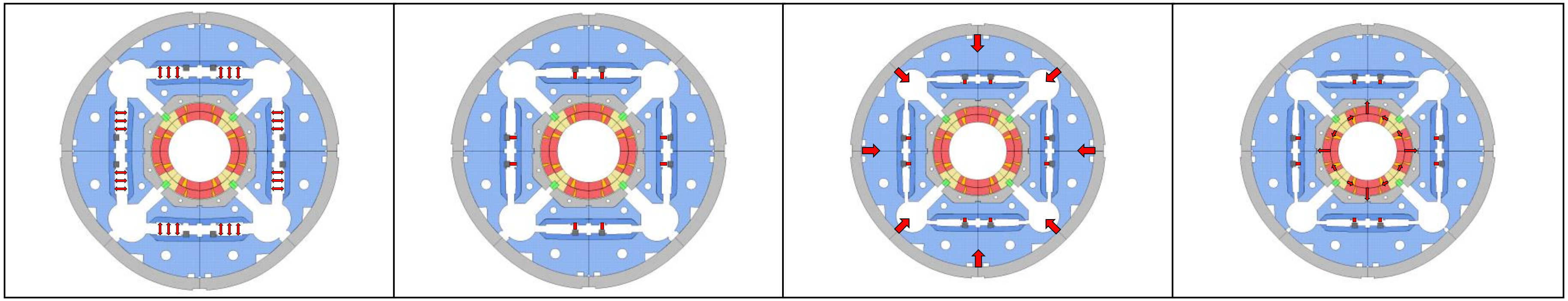


Temp. distribution in a MQXF coil during a quench
(J. Ferradas)
2018

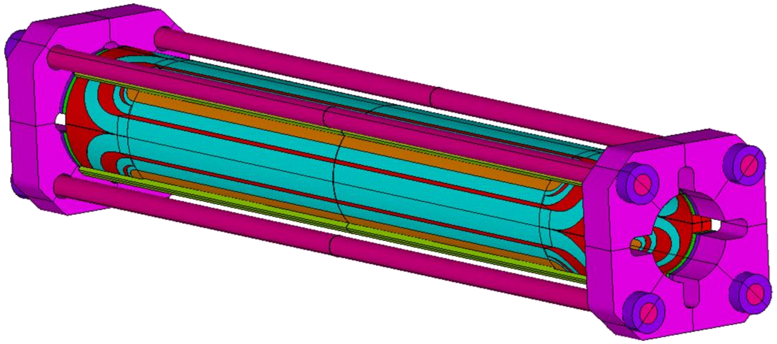
The efforts on using **ANSYS APDL** to model quench processes started **long time ago**, now **new** and more advance **techniques** are **available**[1]

[1]L. Brower, ANSYS User defined elements for quench simulation

MQXF Low-β quadrupole magnet: Mechanical concept



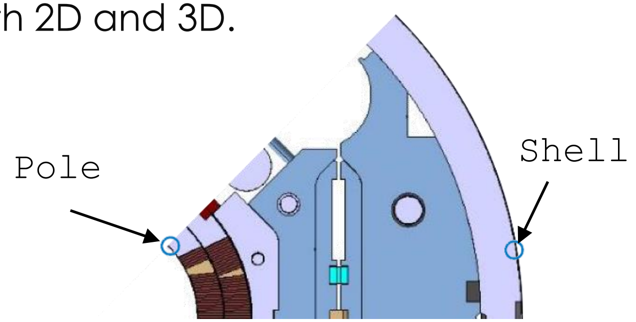
1. Bladder Operation / Key Insertion (Azimuthal Loading)
2. Longitudinal Loading
3. Pressure vessel welding
4. Cool-down
5. Powering

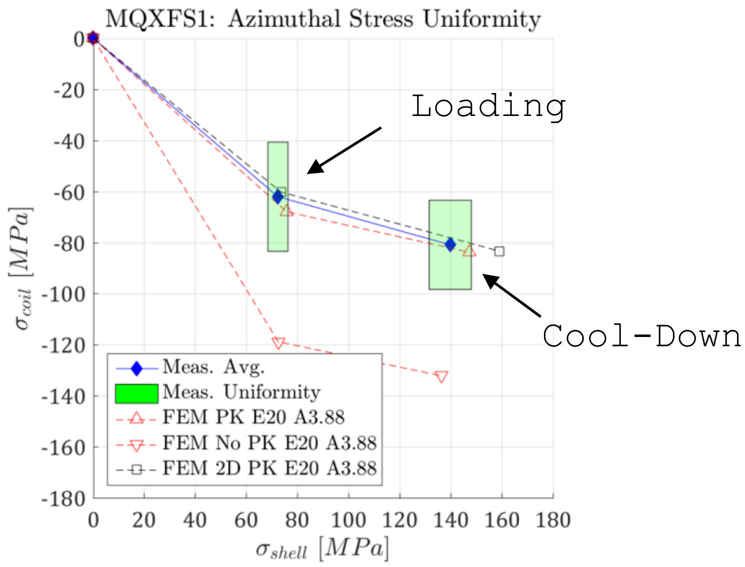


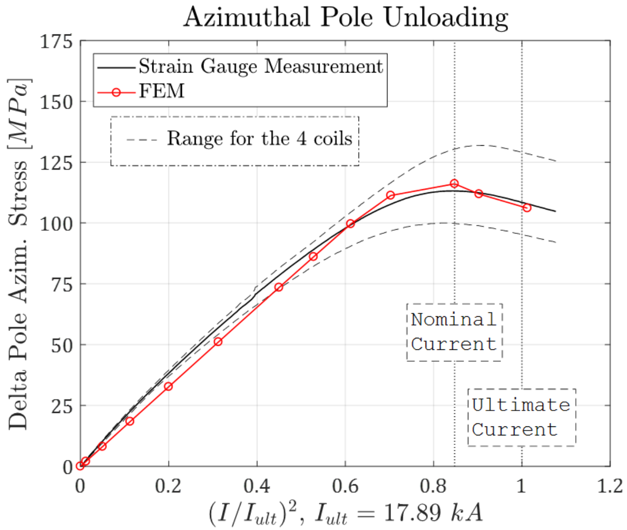
Model results and validation

Very good agreement along the experimental campaign, both 2D and 3D.

Assembly and magnet powering



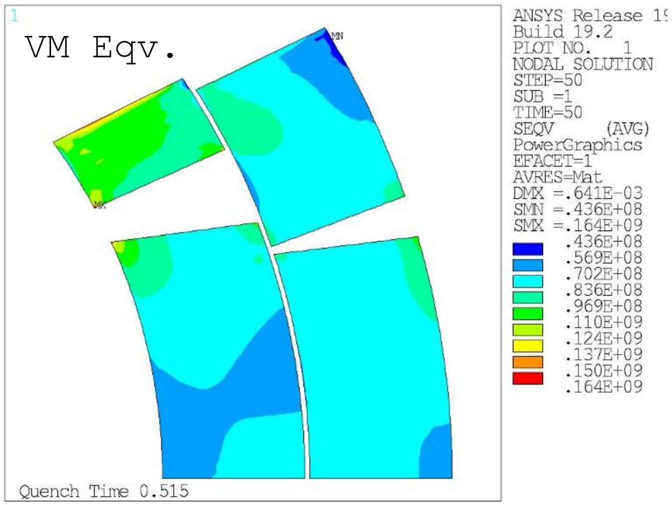


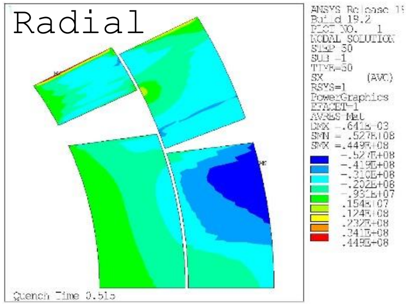


2D MECHANICS OF A QH PROTECTED MAGNET

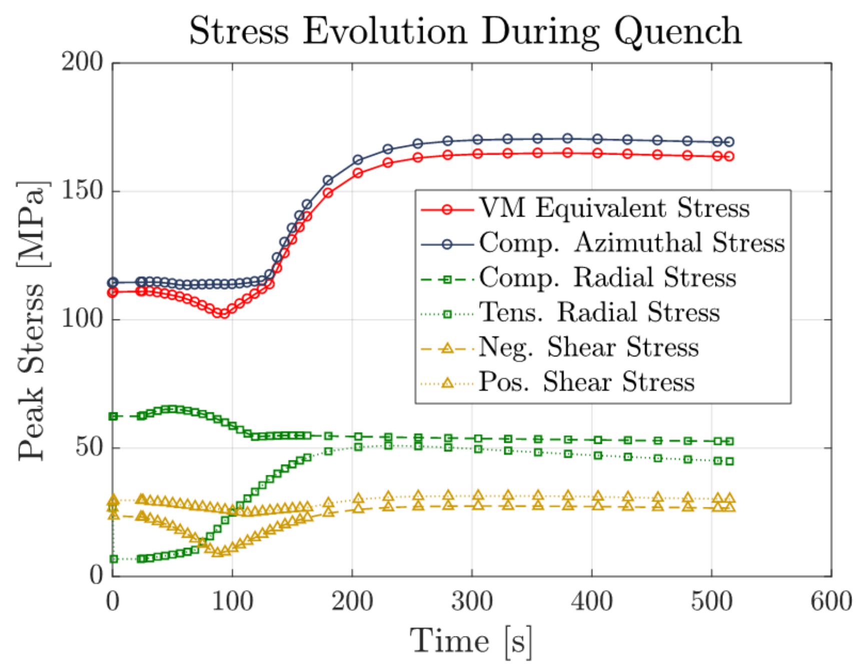
2D Mechanical results: Stress evolution

- **Peak** Von Misses **equivalent stress** at the end of the discharge ~ **164 MPa**
  - **Stress evolution** during quench is important





Most conservative, keeping corner nodes

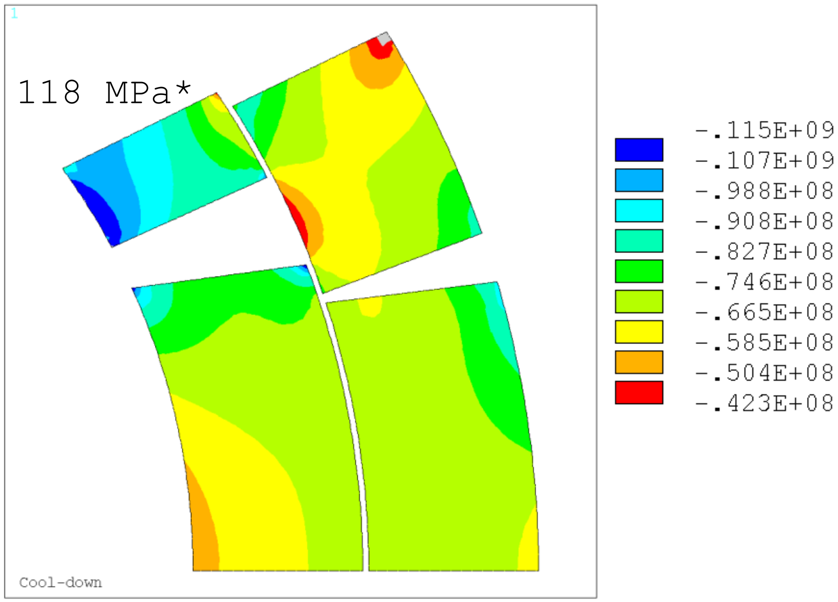


* Not necessary at the same place

3D Mechanical results before quench

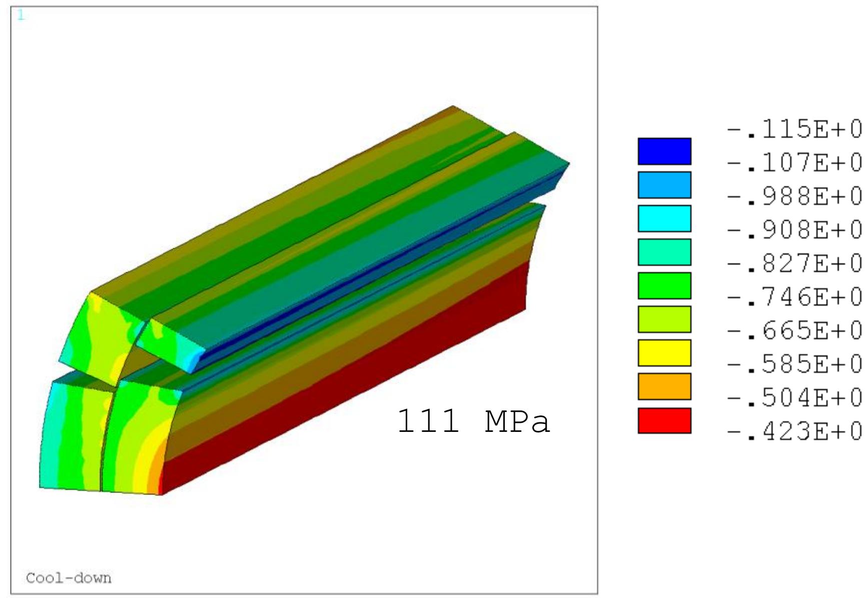
Before quench load step, very **similar** stress **results** when comparing **3D** to **2D**
Less problematic corner nodes

2D Azim. Stress after Cool Down



(With corner nodes active 130 MPa*)

3D Azim. Stress after Cool-down



Remember plane stress assumed.