6th International Workshop on Numerical Modelling of HTS

Thermal stability and mechanical behaviors in the no-insulation coil

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Outline

- Motivation
- Multiphysics coupling model
- Stress and strain in NI coils
- Conclusions

Mechanical stress in coil

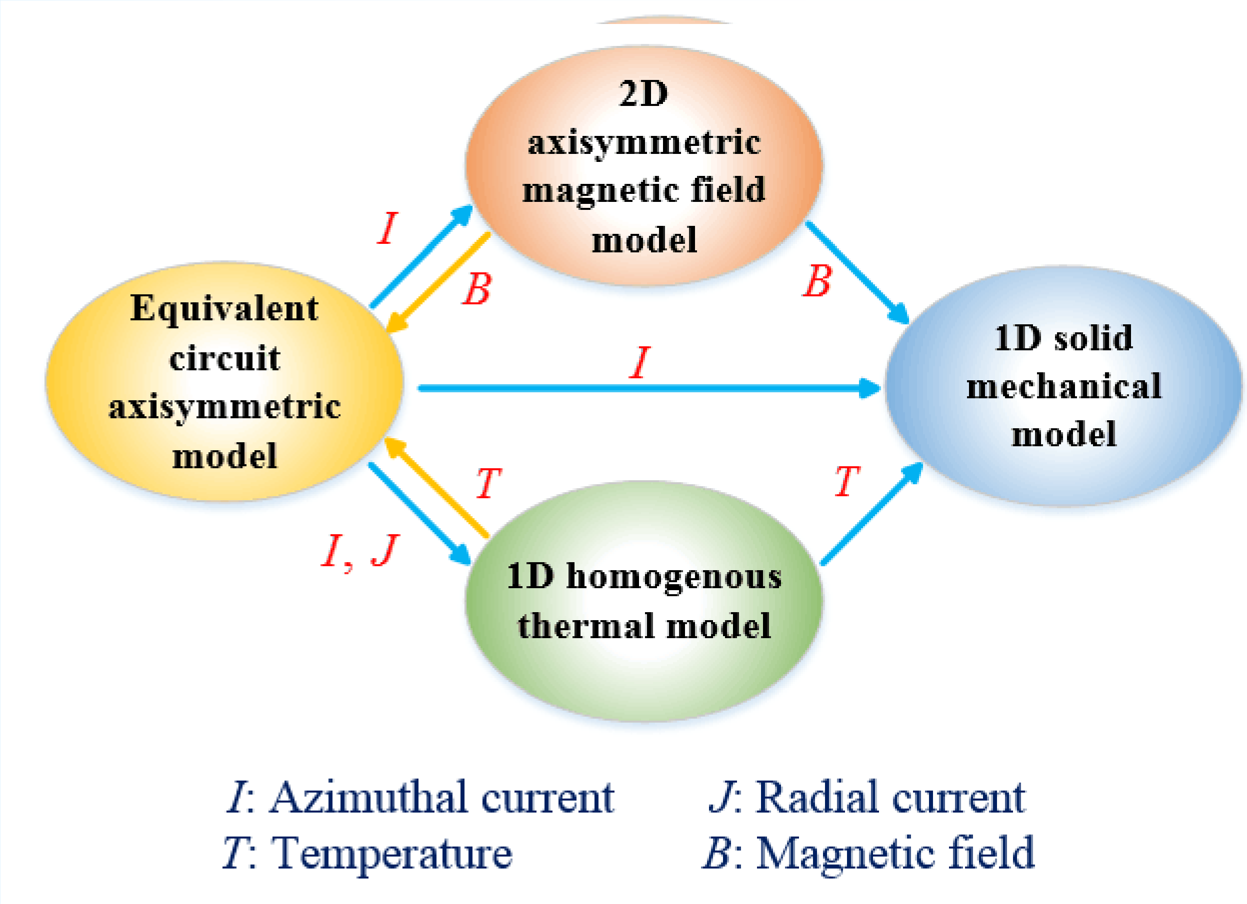
□ Electromagnetic force: The coil will undergo a large electromagnetic force generated by the current and magnetic field.

□ Thermal stress: During the quench, the change of temperature and difference of thermal expansion coefficients can lead to significant thermal stress and strain.

□ Winding stress: For the winding process, the coil experiences the prestress or prestrain.

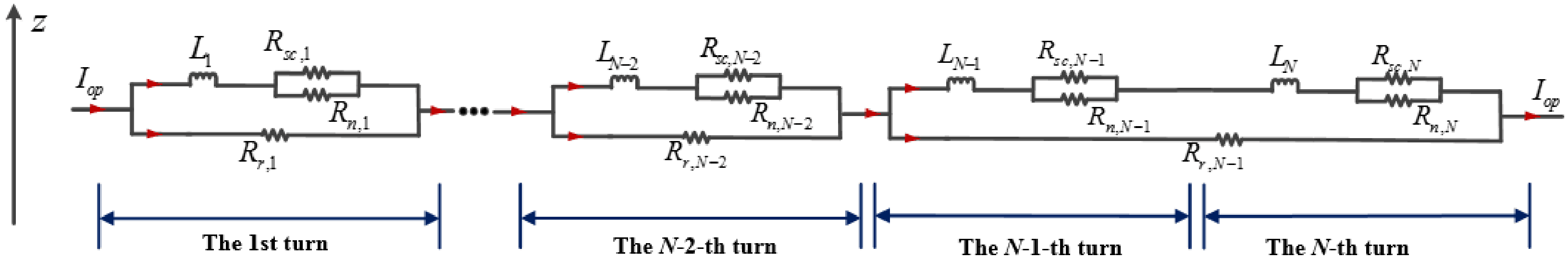
With the increasing of critical current, the application of superconductor may be limited by their mechanical strength!

Multiphysics coupling model



Numerical model

Axisymmetric equivalent circuit model:



L_m : self and mutual inductances of m-th turn

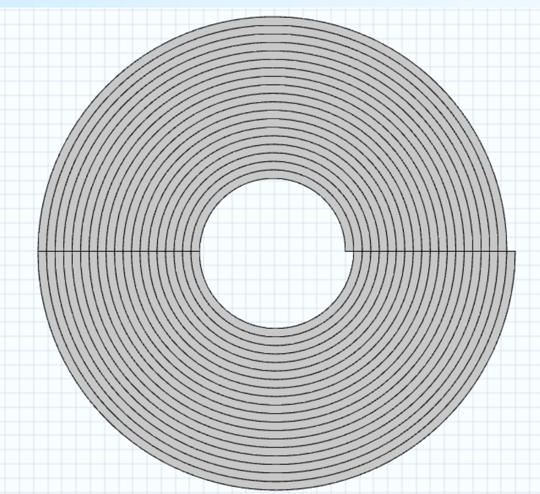
$R_{sc,m}$: resistance of superconducting layer of m-th turn

$R_{r,m}$: equivalent turn-to-turn resistance of m-th turn

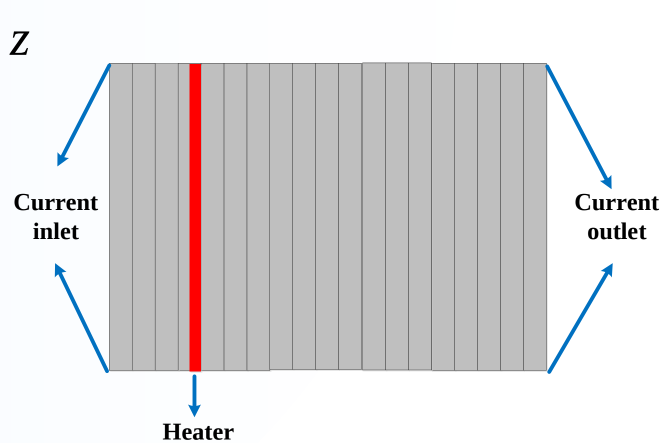
$R_{n,m}$: resistance of normal layers of m-th turn

I_{op} : power supply current

NI single-pancake coil:



Axisymmetric homogenous thermal and mechanical models:



Liu, Zhang, Yong and Zhou, Supercond. Sci. Technol. 31 (2018) 085010

Numerical model

The governing equations of circuit model:

$$\begin{cases} I_{op} = i_m + j_m \\ u_m - j_m R_{r,m} = 0 & m < N\text{-}1 \\ u_m + u_{m+1} - j_m R_{r,m} = 0 & m = N\text{-}1 \end{cases}$$

Contact resistance and voltage in m-th turn:

$$R_{r,\mathrm{m}} = \frac{\rho_r}{S_m}$$

$$u_m = \sum_{l=1}^{N} M_{\mathrm{m},l} \frac{di_l}{dt} + V_{sc,m}(i_m, I_{c,m})$$

The calculation of magnetic field:

$$B_r = -\frac{\mu_0}{2\pi}\left(\frac{i_m}{w}\right)\int_0^w \int_0^\pi \frac{R(z-z_1)\cos\theta d\theta dz_1}{\left[r^2+(z-z_1)^2+R^2+2rR\cos\theta\right]^{3/2}}$$

$$B_z = \frac{\mu_0}{2\pi}\left(\frac{i_m}{w}\right)\int_0^w \int_0^\pi \frac{R(R+r\cos\theta)d\theta dz_1}{\left[r^2+(z-z_1)^2+R^2+2rR\cos\theta\right]^{3/2}}$$

Coupling equations:

$$\begin{cases} E_c l_m \left(\frac{i_{sc,m}}{I_{c,m}}\right)^n - (i_m - i_{sc,m}) R_{n,m} = 0 \\ V_{sc,m} = E_c l_m \left(\frac{i_{sc,m}}{I_{c,m}}\right)^n \\ R_{n,m} = \rho_n \frac{l_m}{S} \\ I_{c,m} = I_c(T_\mathrm{m}) I_c(B_{\|,m}, B_{\perp,m}) \end{cases}$$

Field-dependent critical current:

$$I_{c,m}(\mathbf{B}) = \frac{1}{\left[1+\sqrt{(kB_\|)^2+B_\perp^2}\Big/B_c\right]^b}$$

Temperature-dependent critical current:

$$I_c(T) = \begin{cases} I_{c0}\frac{T_c - T}{T_c - T_0} & \text{if } T < T_c \\ 0 & \text{if } T \ge T_c \end{cases}$$

(Wang *et al*. SUST 2016, Chan *et al*. SUST 2017 and Liu *et al*. AIP ADV 2017)

Numerical model

The governing equations of thermal model:

$$\begin{cases} dC\dfrac{\partial T}{\partial t}+\nabla\bullet(-k\nabla T)=\rho_n(T)\left(\dfrac{i_m-i_{sc,m}}{S_c}\right)^2+\rho_r\delta(r-r_j)\left(\dfrac{j_m}{S_k}\right)^2+Q_{\text{heat}} & \text{in } \Omega \\ \mathbf{n}\bullet(-k\nabla T)=h(T-T_0) & \text{on } \partial\Omega \end{cases}$$

For finite difference method, the delta function can be discretized:

$$d_{\Delta r}^{(1)}(r-r_j)=\begin{cases} \left(\Delta r-|r-r_j|\right)/\Delta r^2, & |r-r_j|\le\Delta r \\ 0, & \text{otherwise} \end{cases}$$

The governing equations of mechanical model:

$$d\frac{\partial^2 u}{\partial t^2}=\frac{\partial\sigma_r}{\partial r}+\frac{\sigma_r-\sigma_\varphi}{r}+J_\varphi B_z$$

$$u|_{t=0}=0,\qquad \left.\frac{du}{dt}\right|_{t=0}=0,\qquad \sigma_r|_{r=r_2}=0$$

Two different inner boundaries:

$u|_{r=r_1}=0$	**Fixed boundary**
$\sigma_r|_{r=r_1}=0$	**Free boundary**

Numerical model

■ **The relationship of stress and strain:**

$$\varepsilon_r = \frac{\partial u}{\partial r}, \qquad \varepsilon_\varphi = \frac{u}{r}$$

$$\sigma_r = \frac{Y_m}{1-\mu^2}\left(\varepsilon_r + \mu\varepsilon_\varphi\right) - \frac{Y_m \alpha \Delta T}{1-\mu}$$

$$\sigma_\varphi = \frac{Y_m}{1-\mu^2}\left(\varepsilon_\varphi + \mu\varepsilon_r\right) - \frac{Y_m \alpha \Delta T}{1-\mu}$$

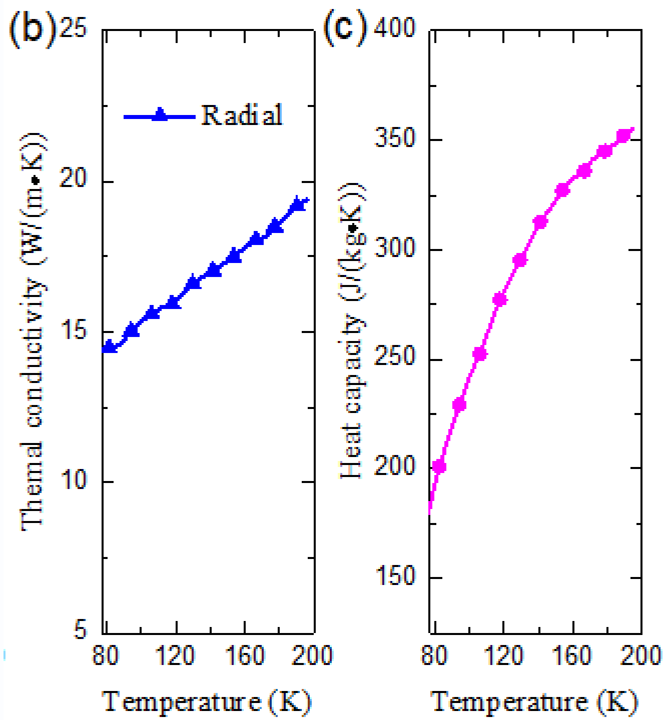
Young's modulus: 172 GPa

Poisson's ratio: 0.33

Thermal expansion coefficient: $13.2\times10^{-6}\ \mathrm{K}^{-1}$

Shin *et al*. SUST 2012; Wang *et al*. IEEE Trans Appl Surpercond 2014

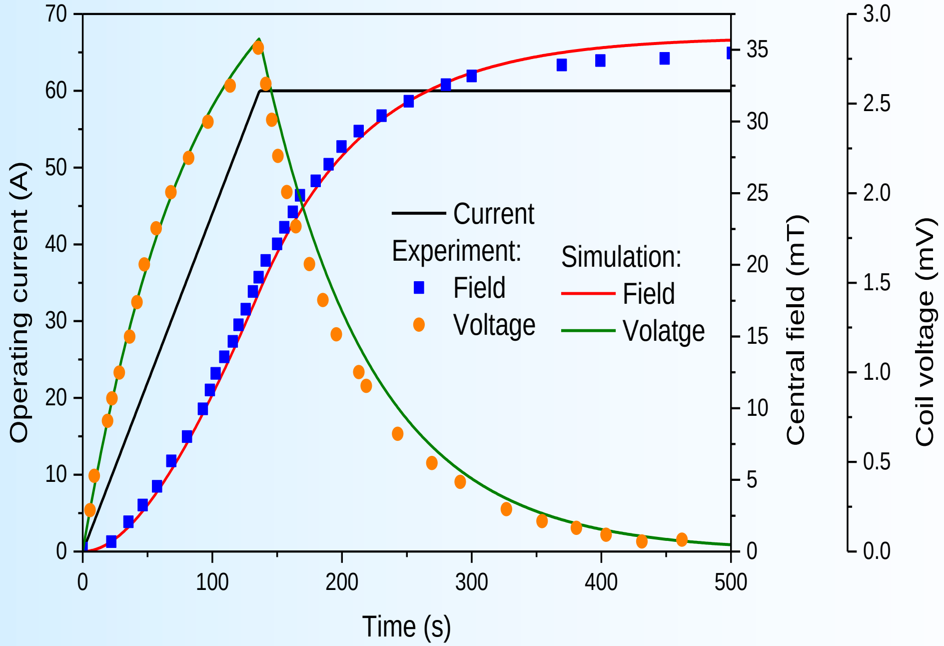
Equivalent thermal parameters



Wang *et al*. SUST 2016

Results

Verification of numerical model



Comparisons between experiment and simulation:

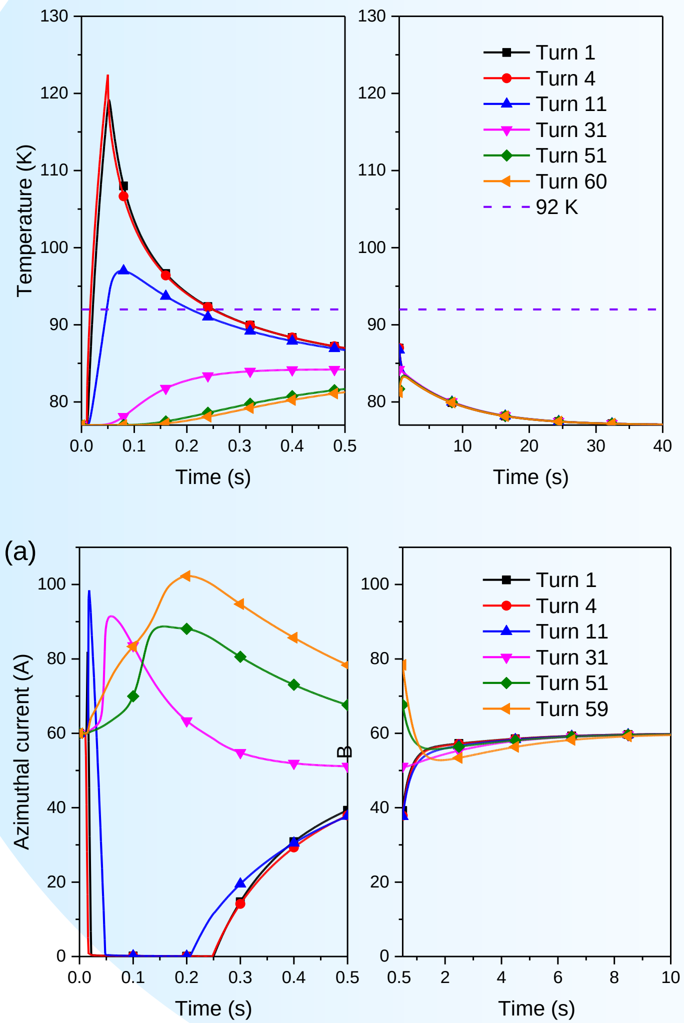
Table I. Specification of the single-pancake (SP) NI coil

Parameters	coil
Turn Number	60
Inner and outer diameters (mm)	100, 112
Height (mm)	4
Thickness of tape (mm)	0.1
Total length of wire (m)	19.9
Inductance, L_{coil} (mH)	0.78
B_z per amp at centre (mT)	0.71
Critical temperature T_c (K)	92
I_c coil, @ 77 K (A)	89
I_c tape, @ 77 K (A)	220
Operating current I_{op} (A)	60

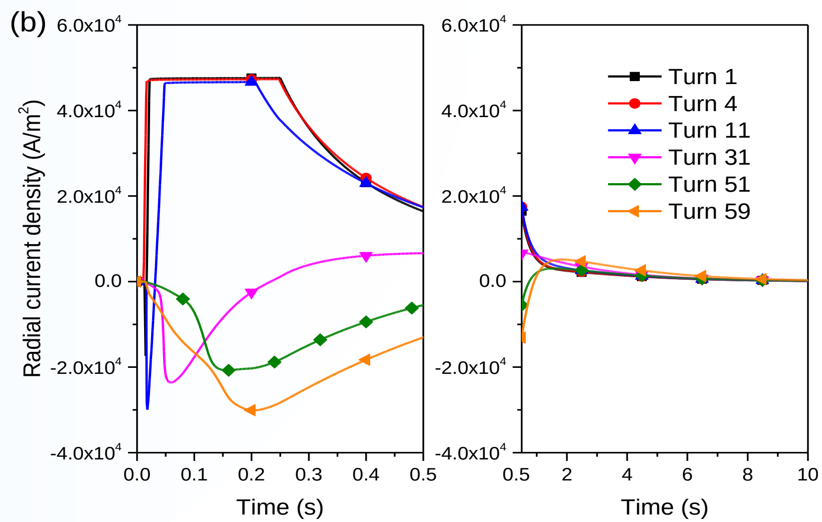
Wang *et al*. SUST 2015

Results

The distributions of temperature and current in 60-turn coil:



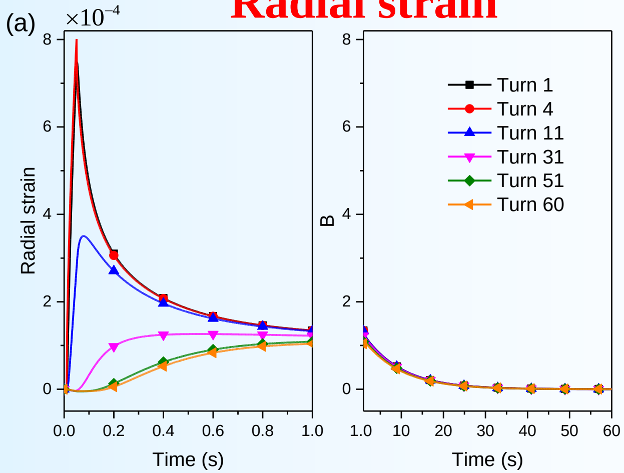
- **The largest temperature rise happens at the location of the heater.**
- **The temperature of the outer turns is always lower than the critical temperature.**
- **The current of the inner turns only flows in the radial direction.**



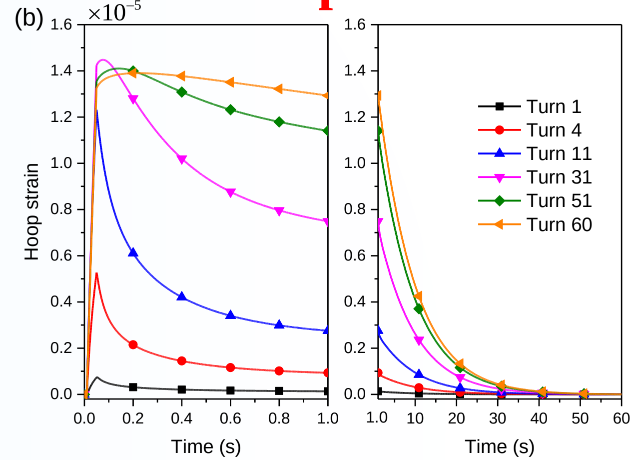
Results

Fixed inner boundary:

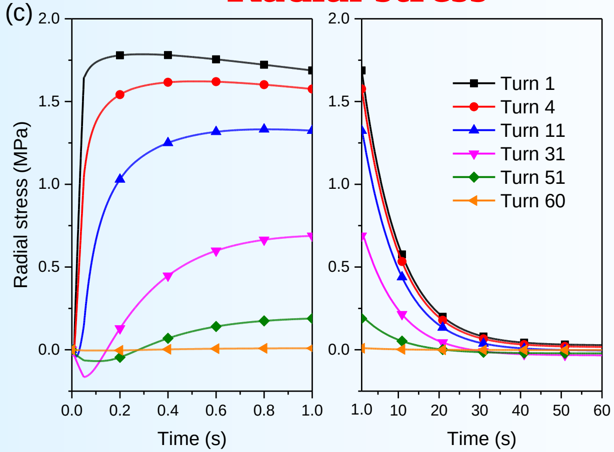
Radial strain



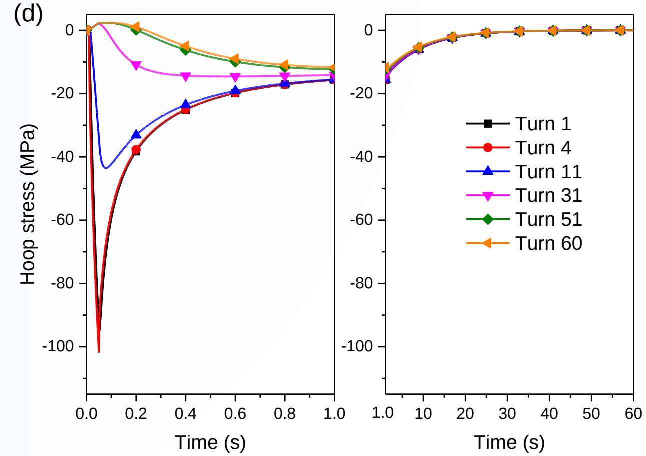
Hoop strain



Radial stress



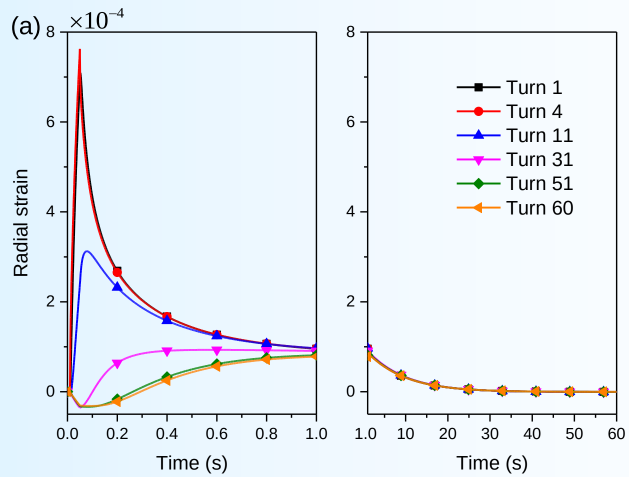
Hoop stress



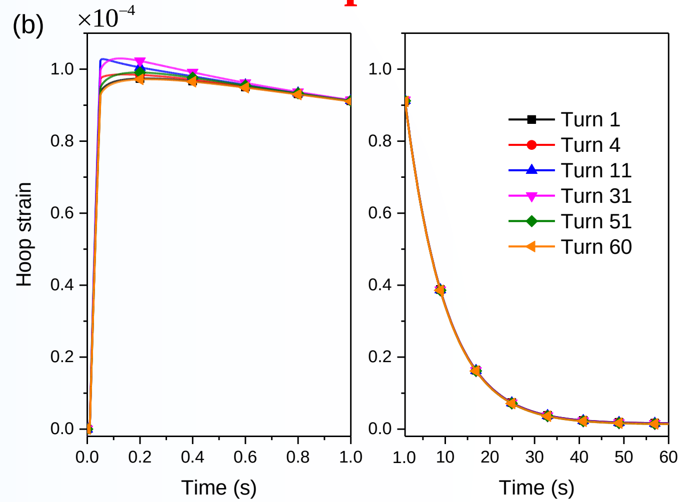
Results

Free inner boundary:

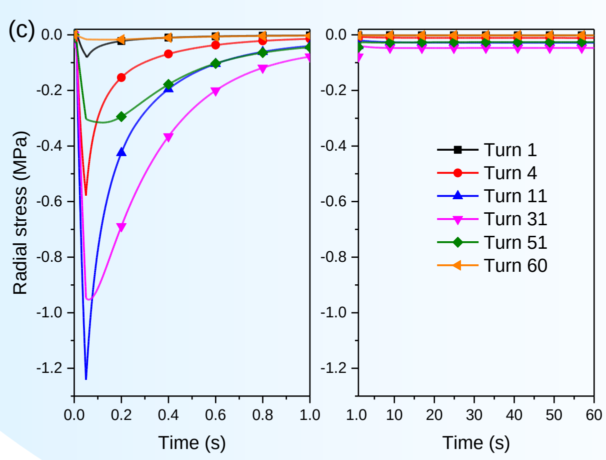
Radial strain



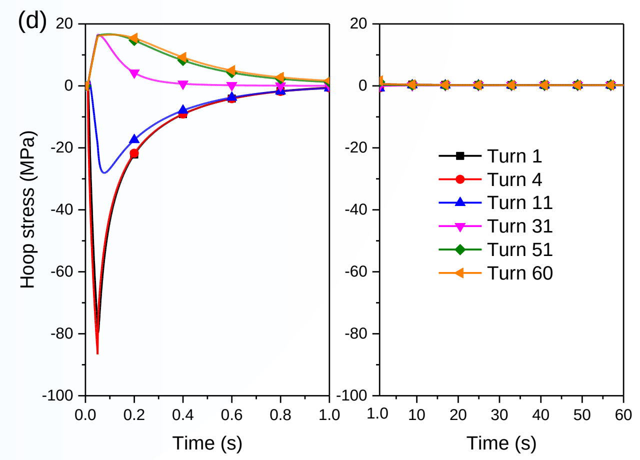
Hoop strain



Radial stress

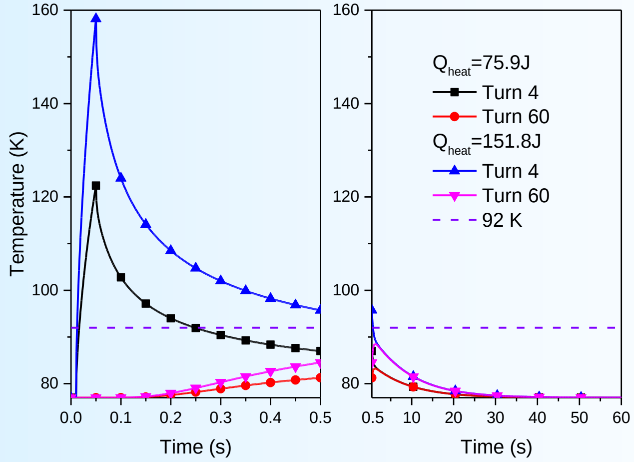


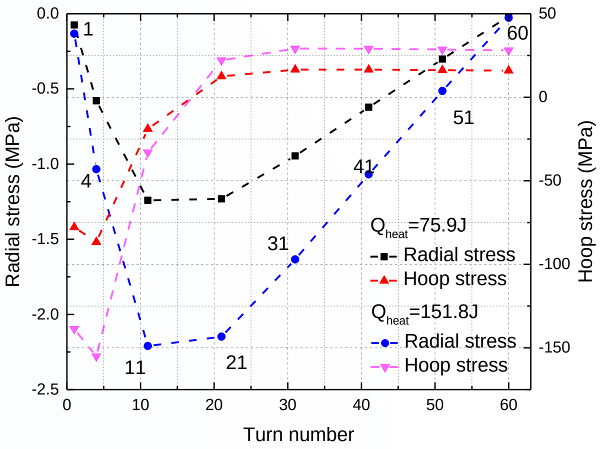
Hoop stress



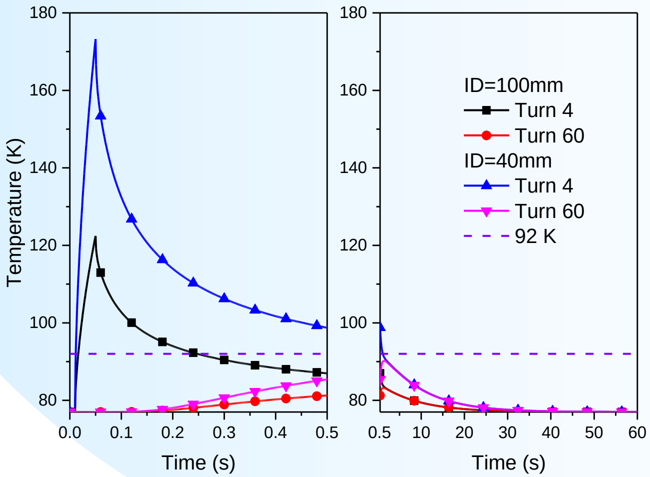
Results

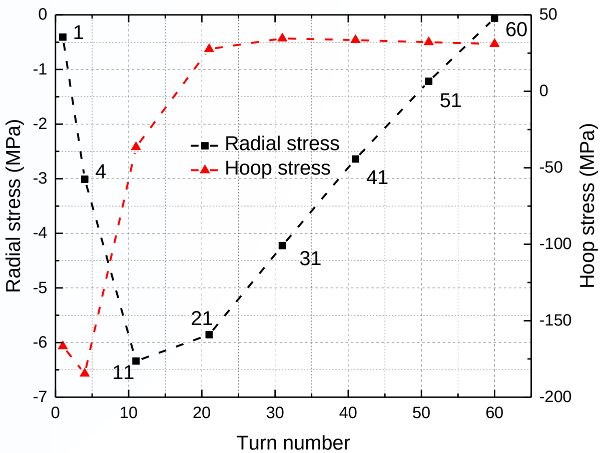
The effect of the different pulsed energies:





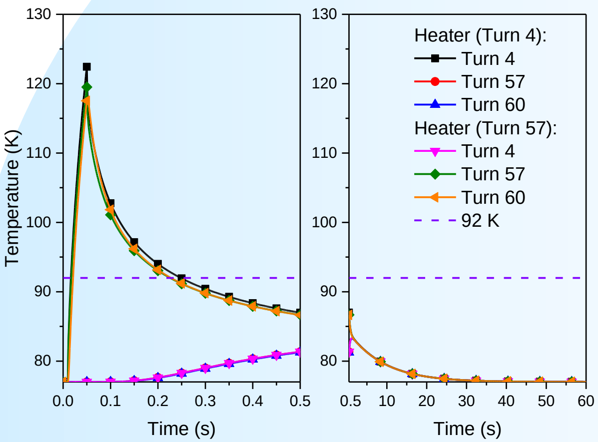
The effect of the different inner diameters:

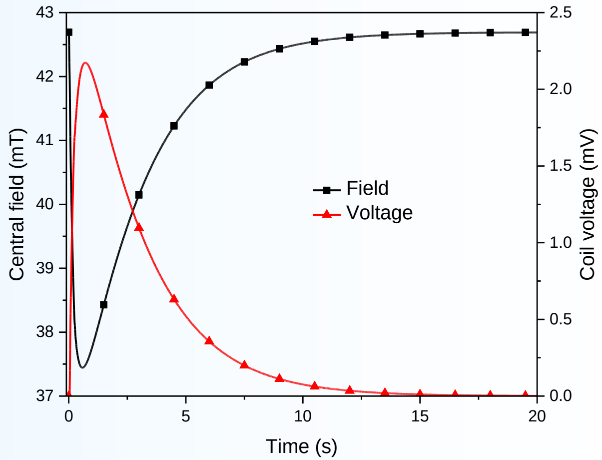


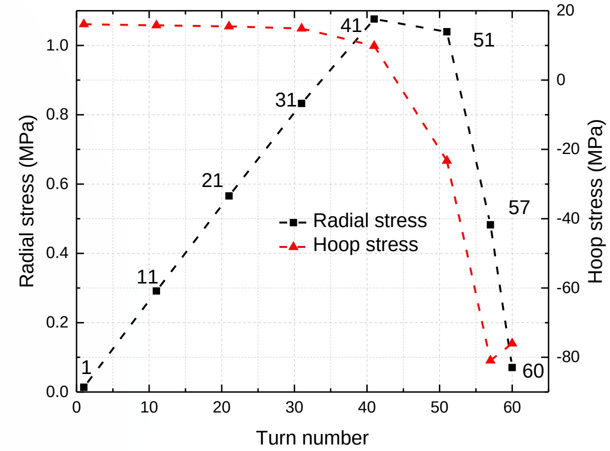


Results

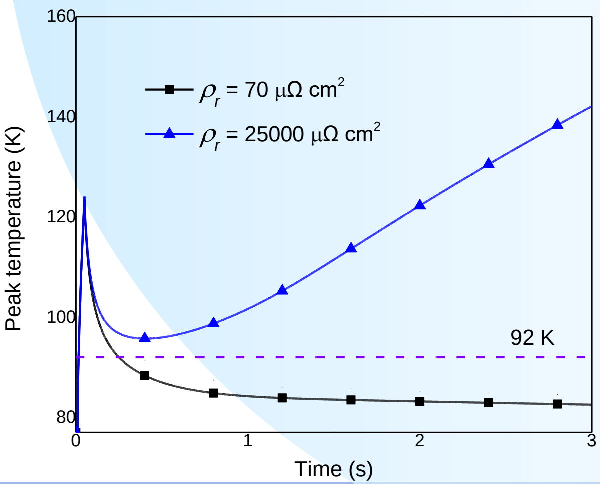
The effect of the location of the heater:

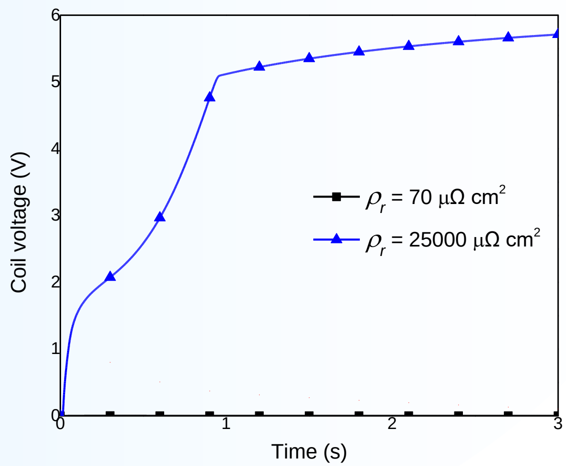


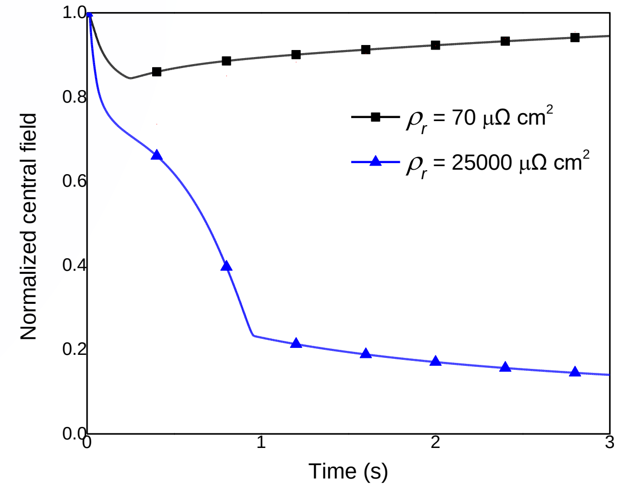




The effect of the different contact resistivities:

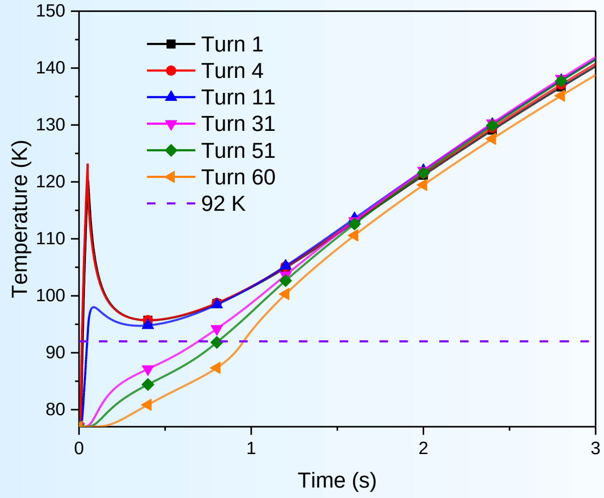


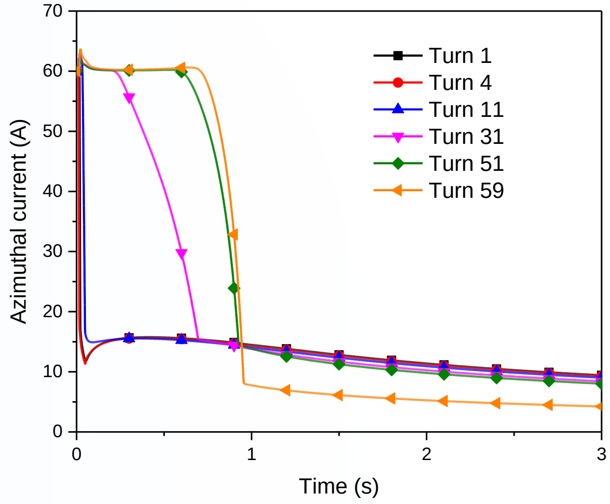


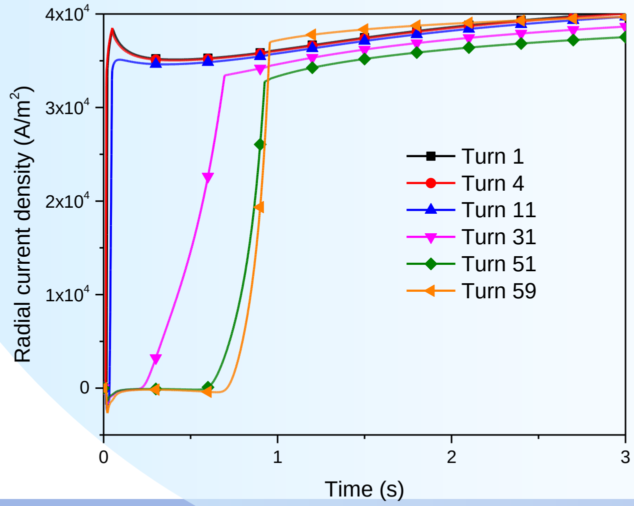


Results

Large contact resistivity ($\rho_r = 25000\ \mu\Omega\ \mathrm{cm}^2$):





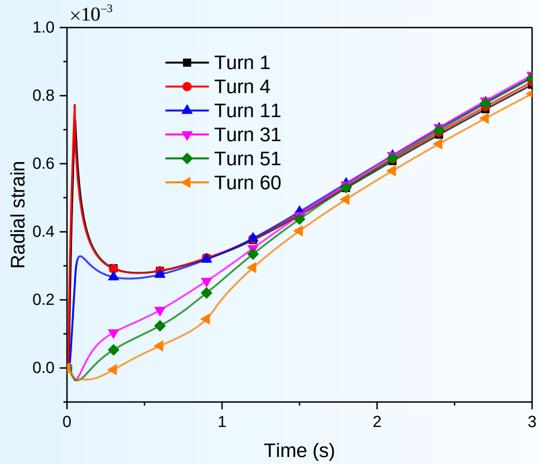


- **The large contact resistivities can lead to increase of total contact resistances.**
- **The normal layers can shunt the current, and both the circumferential and radial currents exist.**

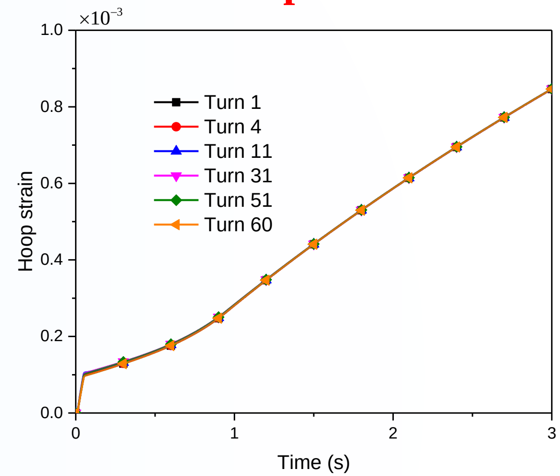
Results

Large contact resistivity ($\rho_r = 25000\ \mu\Omega\ \mathrm{cm}^2$) and free inner boundary:

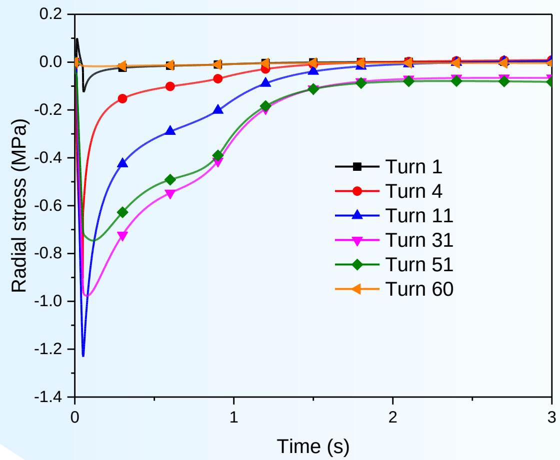
Radial strain



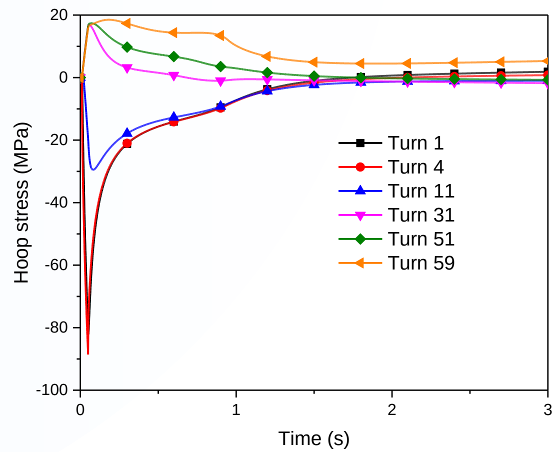
Hoop strain



Radial stress



Hoop stress



Summary

- ✓ **The temperature rise is mainly determined by the heater.**
- ✓ **The hoop stress dominates the mechanical stability during the heat disturbance.**
- ✓ **The pulsed energy, inner diameter of the coil and the location of the heater have obvious effects on the thermal stability and mechanical behaviors.**
- ✓ **The large contact resistivity can induce quench of the entire coil, while the distributions of stress and strain are different.**

Thank you for your attention!