Modelling quench in a 50 kA REBCO conductor with twisted-soldered-stacked strands

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Szczecin

1. Why quench behavior of HTS is important?

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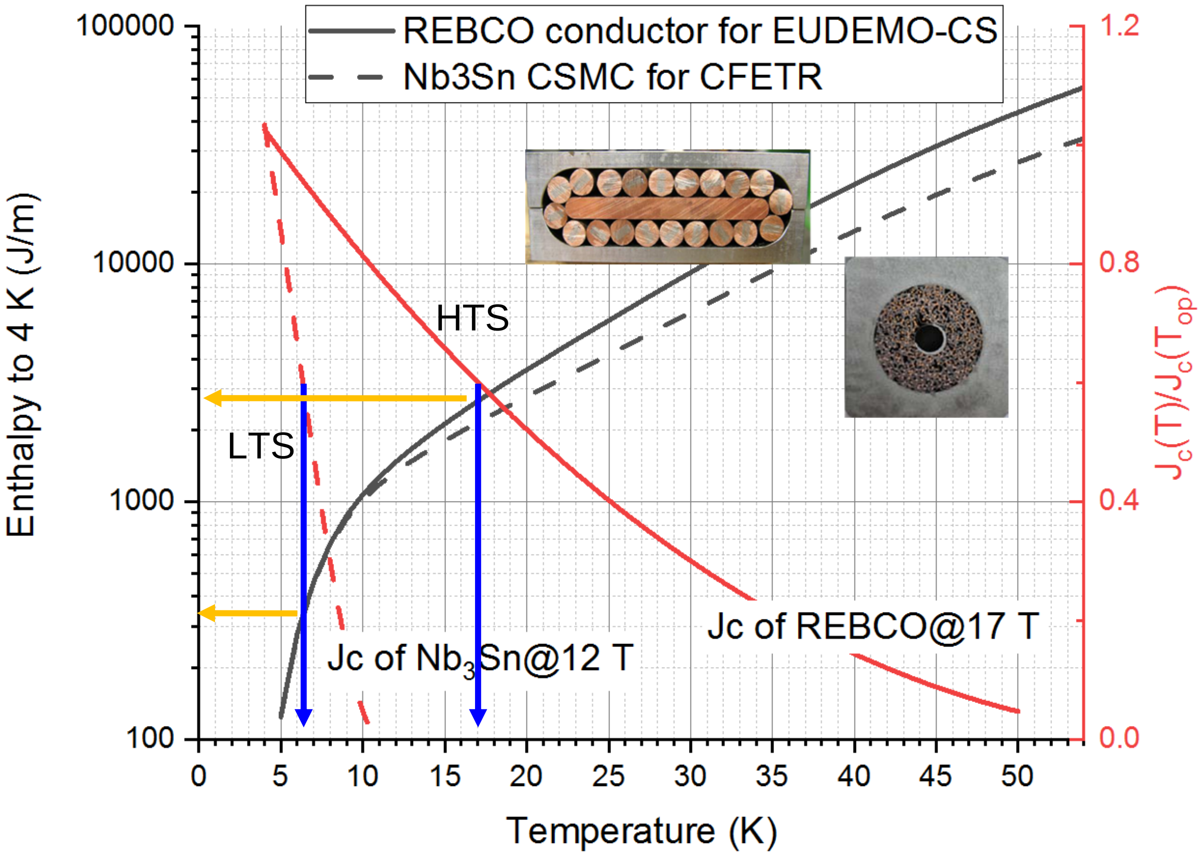

High T_{cs} is easily accessible with HTS:

HTS conductor can be designed much more stable than LTS.

→ Difficult to quench

Quench protection is still needed considering the enormous cost once the magnet damages by unrecoverable quench.

Quench propagation of HTS is significantly slower than LTS: cm/s V.S. m/s.

→ Difficult to detect quench

→ May get high hot spot temperature

Understand quench behavior of HTS conductor is important.

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2. What do we need to study for HTS conductor?

From the perspective of (fusion) conductor design:

- How long it takes from a local quench initiation to detection (NZPV)
- How high the hot spot temperature will be (T_{max})

with the given parameters:

1) detection voltage
2) delay time for quench validation and protection system activation;
3) discharge time constant

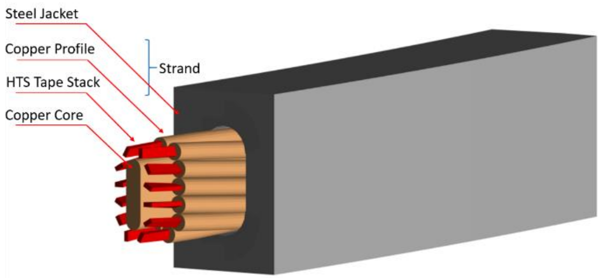
An accurate quantitative study is needed to give some convincing values.

=> Simulation is the cheap and easy way.

3. What kind of simulation model works?

- The 1-D numerical model (e.g. THEA) was well verified for LTS CICCs.
- The physical principles for HTS are the same (to solve thermal, electrical and hydraulic equations).

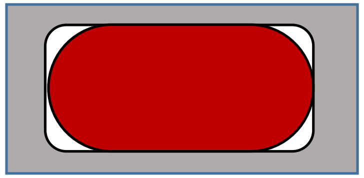
However, what could be different is: **The proper simplification for an 1-D model**



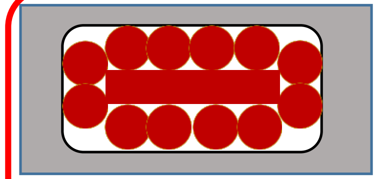
Features:

- **Multi-stage coupling:**
  - **Tape to tape**
  - **Tape to copper profile**
  - **Strand to strand**
  - **Strand to core**
  - **Strand to jacket**

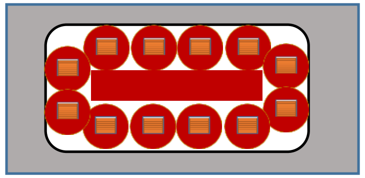
- **Anisotropic J_c**



Single cable model:
Assume perfect coupling in cable (porosity).
validated for LTS CICC.



Multi-monolithic strand model:
Assume perfect coupling inside strand. Inter-strand coupling (heat transfer and current sharing) is calculated.
Achieved with THEA. To be benchmarked.



(Quasi-)3D model:
Each tape is modeled. Coupling of tape to tape and tape to copper profile are calculated. Could be achieved with commercial FEM software.

4. How to benchmark the model

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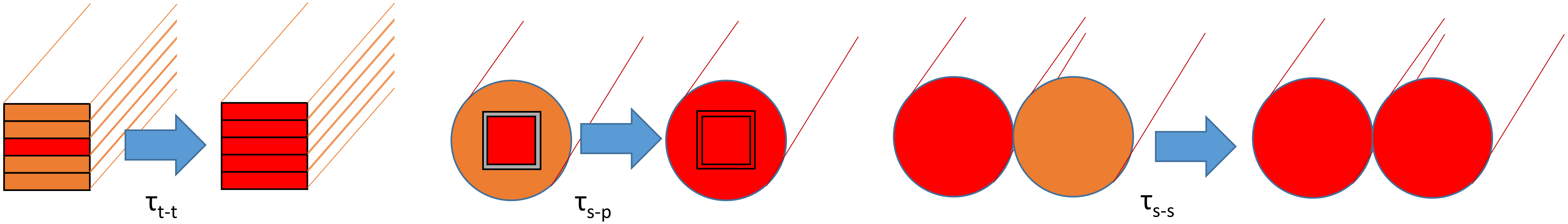
Two approaches:

- ➤ Compare the predication of simulation with experimental results
    - *Quench experiment on 15 kA level HTS conductors will be implemented at SULTAN around these two years.*
- ➤ Figure out at which condition the monolithic strand assumption is valid with simulation
    - *The time scale for current redistribution and heat transfer:*



$$\tau_{s\text{-}s} > \begin{matrix}\tau_{s\text{-}p}\\ \tau_{t\text{-}t}\end{matrix} \;?$$

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5. Critical current

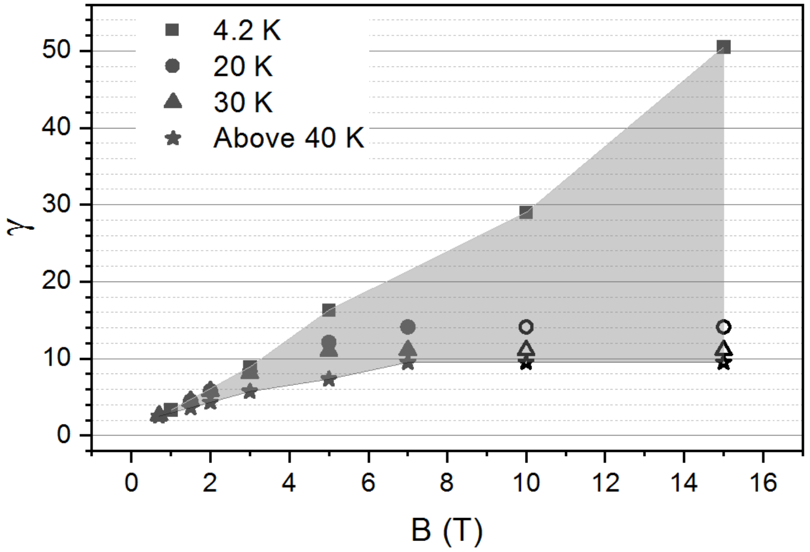
$$J_c(B_\perp, T, \theta) = J_{c\perp}(B_\perp f(\theta), T)$$

$$f(\theta) = \sqrt{\cos^2\theta + \gamma^{-2}\sin^2\theta}$$

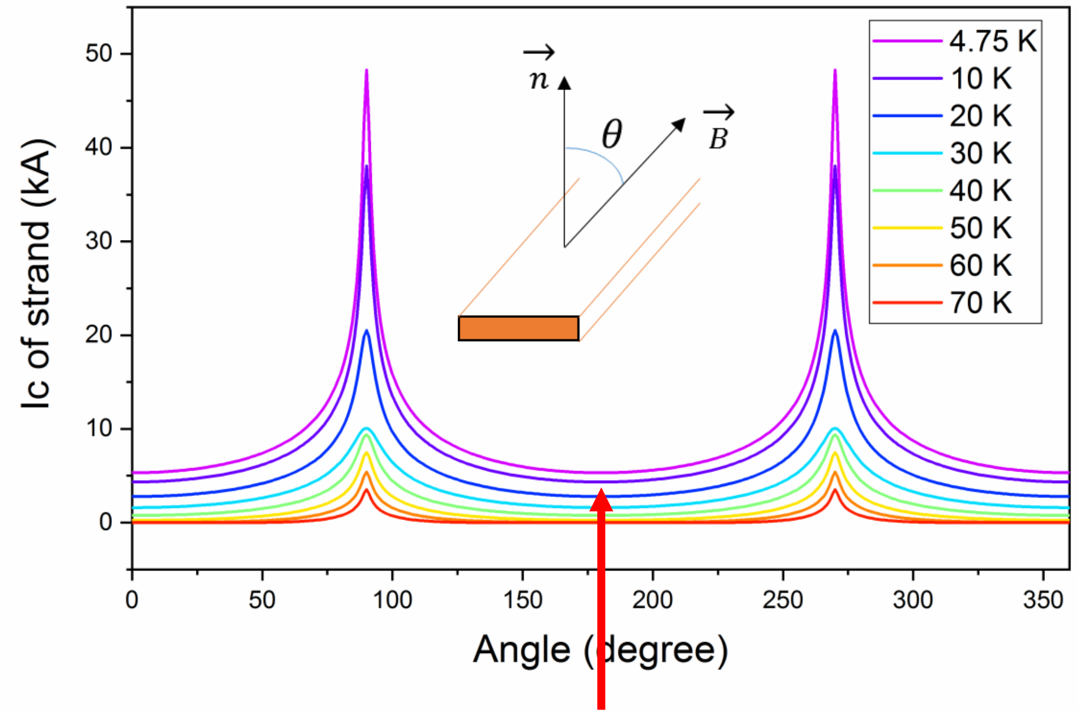
$$J_{c\perp}(B_\perp, T) = A\left(\left(\frac{B_0(T)^\beta}{B}\right)\right)\left(\frac{B}{B_0(T)}\right)^p\left(1 - \frac{B}{B_0(T)}\right)^q$$

$$B_0(T) = B_0(0)\left(1 - \frac{T}{T_0}\right)^\alpha$$

B_0 (0) [T]	T_0 [K]	A [MA·$T^{1-\beta}$/m^2]	α	β	p	q
170.78	138.91	836	3.48	1.61	0.54	2.82



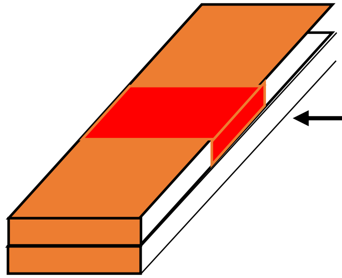
Critical current of one strand at 17.5 T



Quench will be initiated here

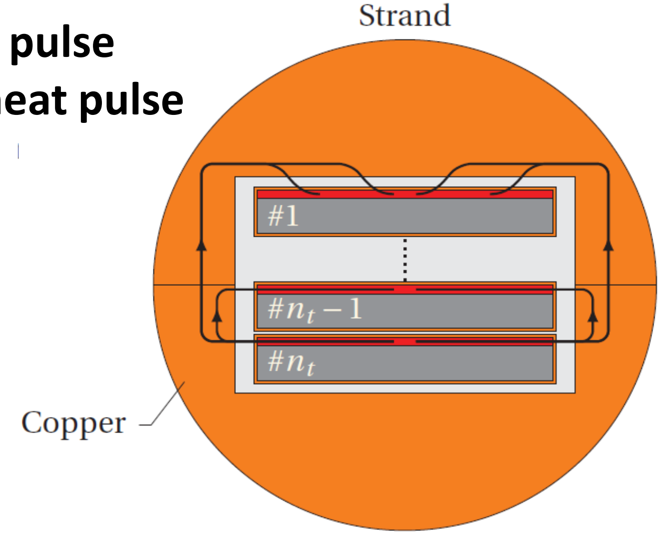
* R. Kang et al "Quench Simulation of REBCO Cable-In-Conduit Conductor with Twisted Stacked-Tape Cable," *IEEE Transactions on Applied Superconductivity,* 2019.

6. Inter-tape coupling

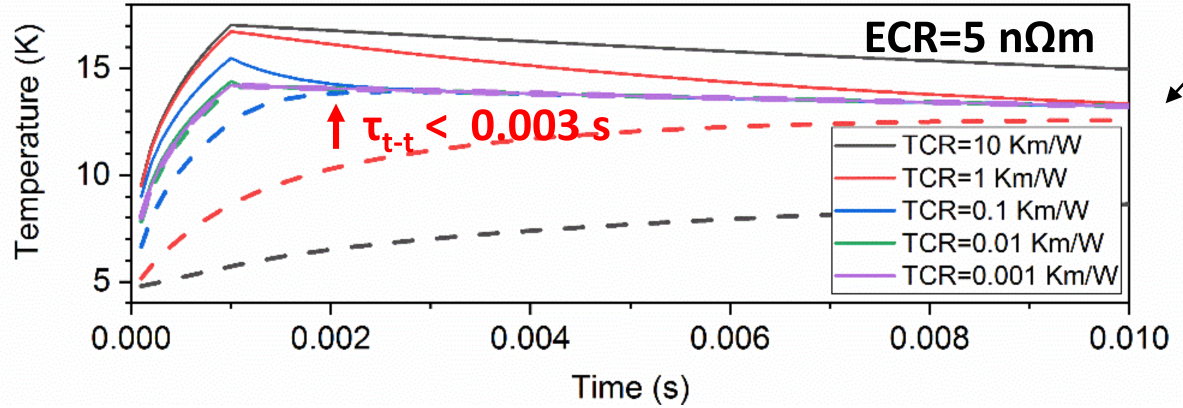


Heat pulse at one tape
1 cm & 1 ms, 100 W/m
(adiabatic)

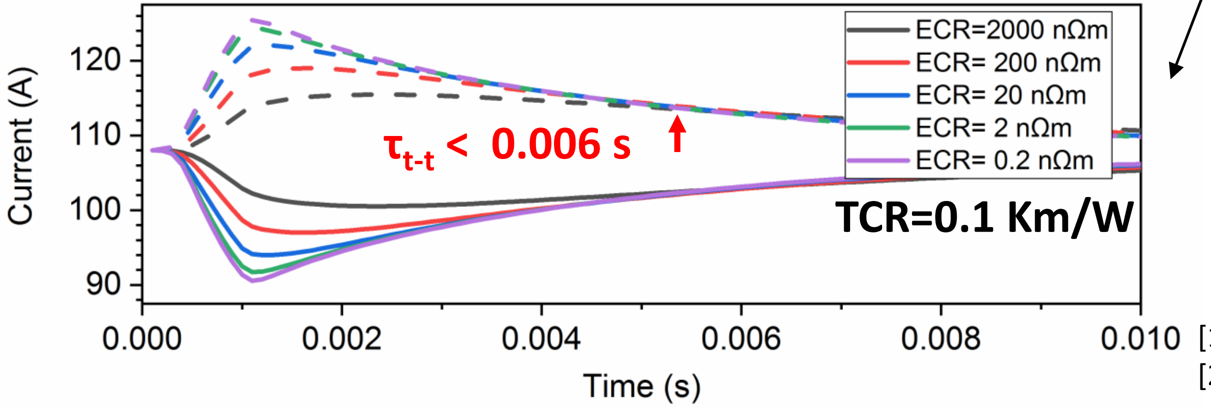
Solid lines: tape with heat pulse
Dash lines: tape without heat pulse



Temperature at tape center V.S. thermal contact resistance (TCR)



Current at tape center V.S. electrical contact resistance (ECR)



ECR~ 5 nΩm at 5 K for any two tapes (measured and deduced [1])

TCR~ 0.1 Wm/W for adjacent two tapes (measured [2])
Heat will also transfer to solder and copper profile

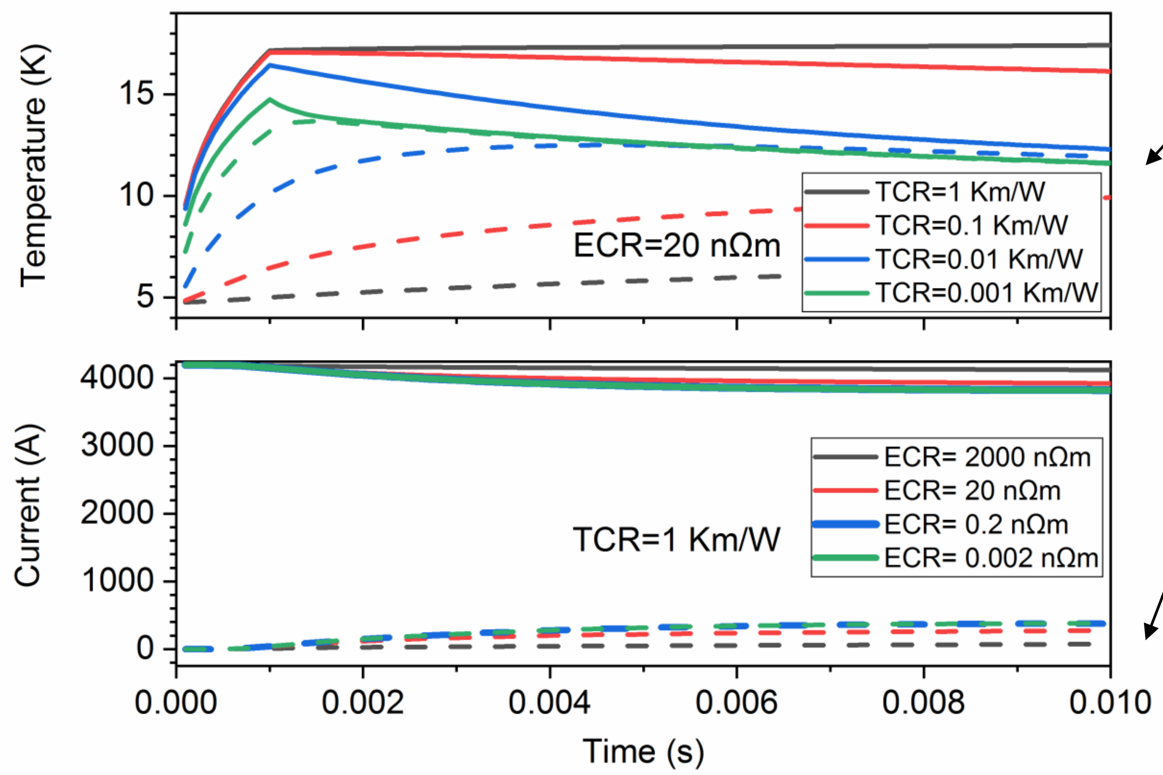
- **For electrical coupling, $\tau_{t\text{-}t}$ is in the magnitude of ms in a soldered strand for any two tapes.**
- **For thermal, it is in the magnitude of ms for adjacent tapes.**
- **For other two tapes?**

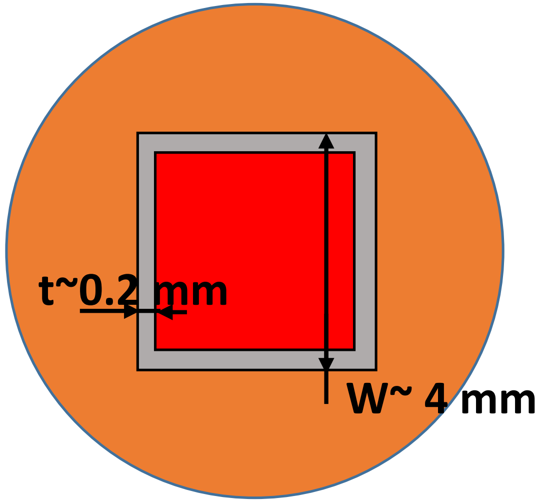
[1] N. Bykovsky, "HTS high current cable for fusion application," PhD, EPFL, 2017.
[2] Bonura, M. and C. Senatore (2015). "Transverse Thermal Conductivity of REBCO Coated Conductors

7. Stack-profile coupling

Solid lines: tape stack
Dash lines: copper profile

Temperature and current at strand center V.S. TCR and ECR



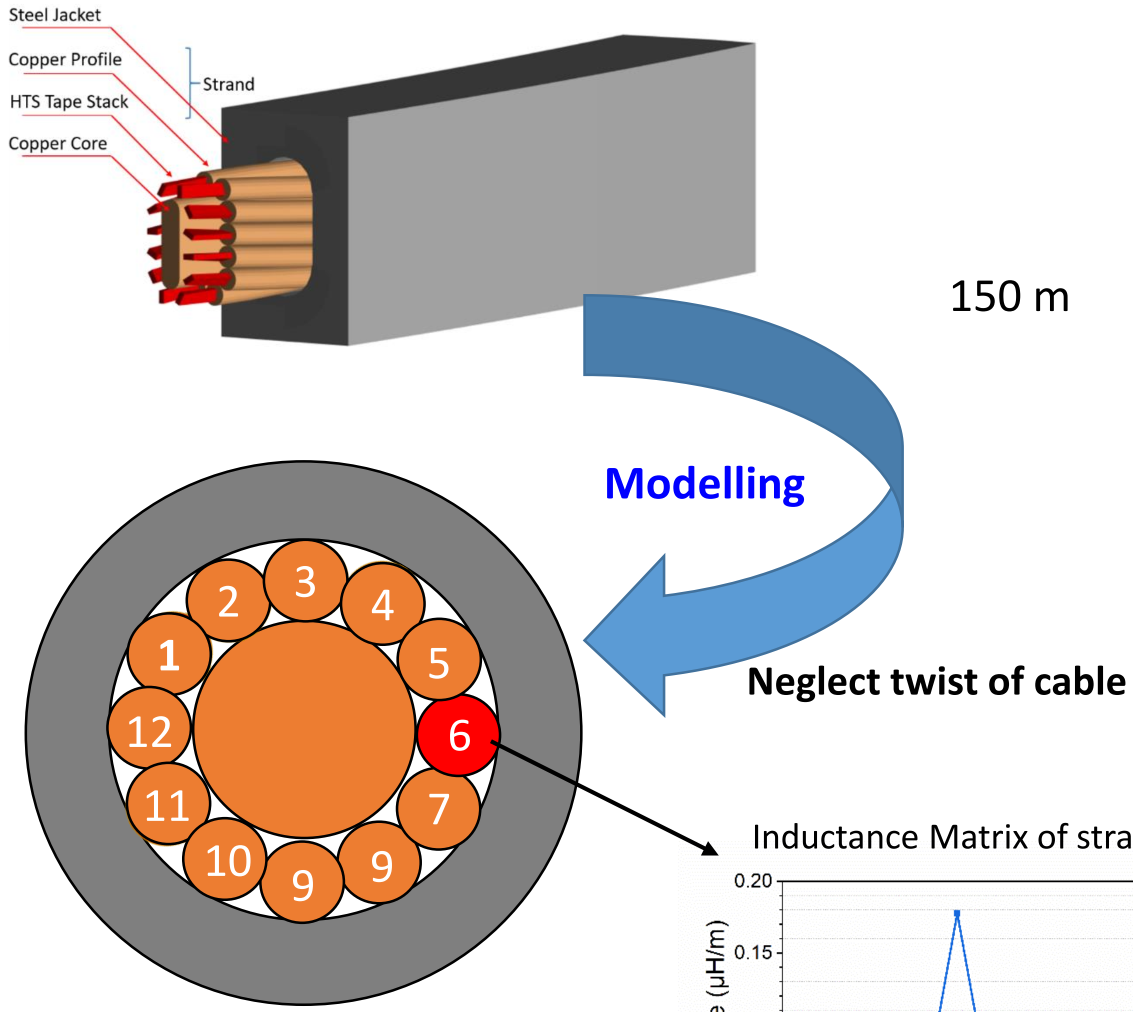


Assume the resistance between REBCO stack and cooper profile is mainly contributed by the soldered

- **ECR~ $\rho_{sd}\cdot t/(4\cdot w)$ ~ 0.04 nΩm**
- **TCR~ $t/(4\cdot w\cdot k_{sd})$ ~ 0.0008 Km/W**

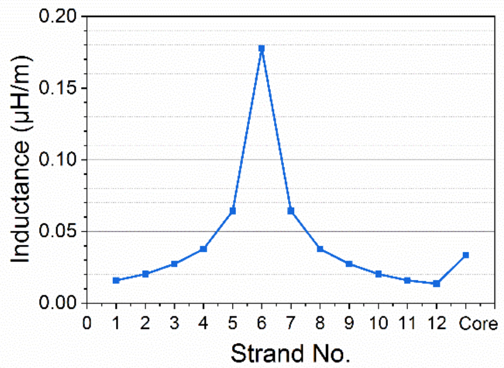
➡ **$\tau_{s\text{-}p}$ is in the magnitude of ms in a soldered strand**

8. Conductor model



Topological in round shape

Inductance Matrix of strand 6



Parameter	Full-size Conductor
Operating temperature (K)	4.75
Operating current (kA)	50.9
Maximum magnetic field (T)	17.5
Current sharing temperature (K)	~10.5
Number of strands	12
Strand diameter (mm)	7.5
Number of REBCO tapes in each strand	42
Tape width (mm)	4
Tape thickness (mm)	0.095
Fraction of tape composition: REBCO: Cu: Hastelloy: Ag	1:40:50:4
Copper (RRR=30) area in each strand (mm^2)	32
Copper area in core (mm^2)	189
Steel area (mm^2)	2588
Helium area (mm^2)	151
Hydraulic diameter (mm)	1.52
Helium inlet pressure (bar)	6
Twist pitch of tape stack (m)	0.4
Orientation of stacks between two neighbor strands (°)	30

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9. Quench by transient local disturbance

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Disturbance spectrum at superconducting magnet *

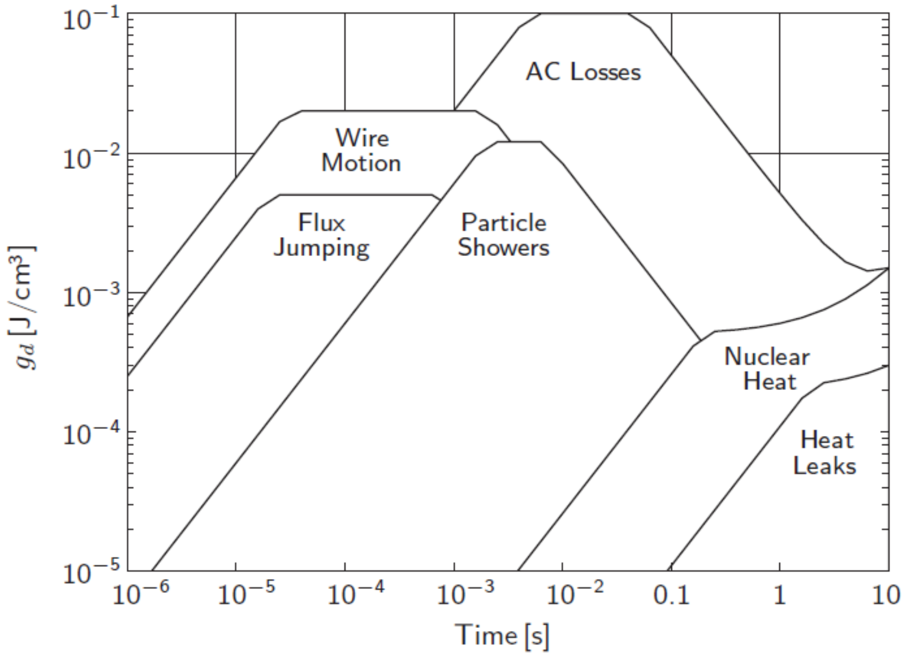


Fig. 6.1 Spectra of $g_d(t)$ compiled for LTS magnets [6.14].

Possible transient local disturbance: strand movement.

- Might be easier to happen than in LTS since cable is less rigid with longer twist pitch.

The disturbance energy (density) can be estimated as:

$$q = \frac{c \cdot I \cdot B \cdot l \cdot \Delta x}{l \cdot A}$$

For one strand

- Operating current (I)=4250 A
- Peak magnetic field (B)= 17.5 T
- Cross section (A)= 44 mm^2

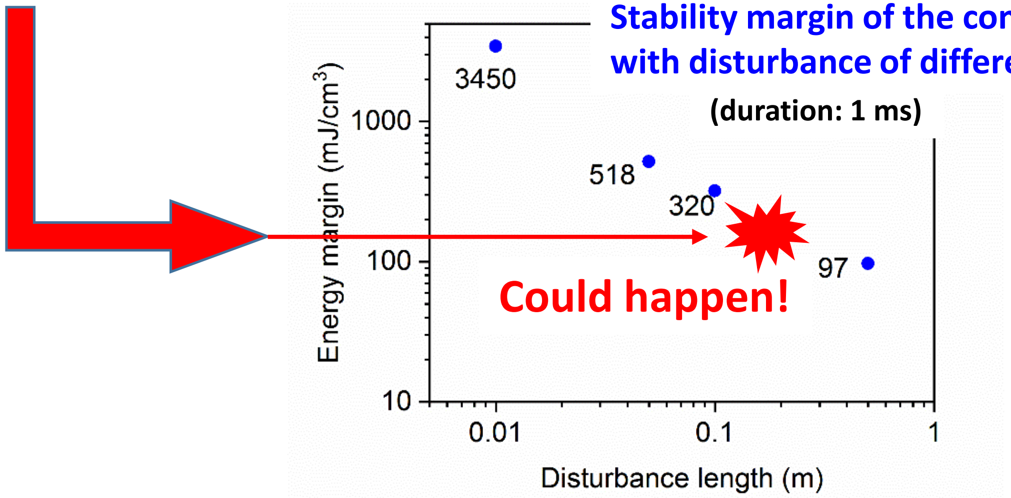
Assume

- Displacement (Δx)=1 mm
- Proportion of heat deposition and work (c)=10%

➔ q = 169 mJ/cm^3

Stability margin of the conductor with disturbance of different length

(duration: 1 ms)



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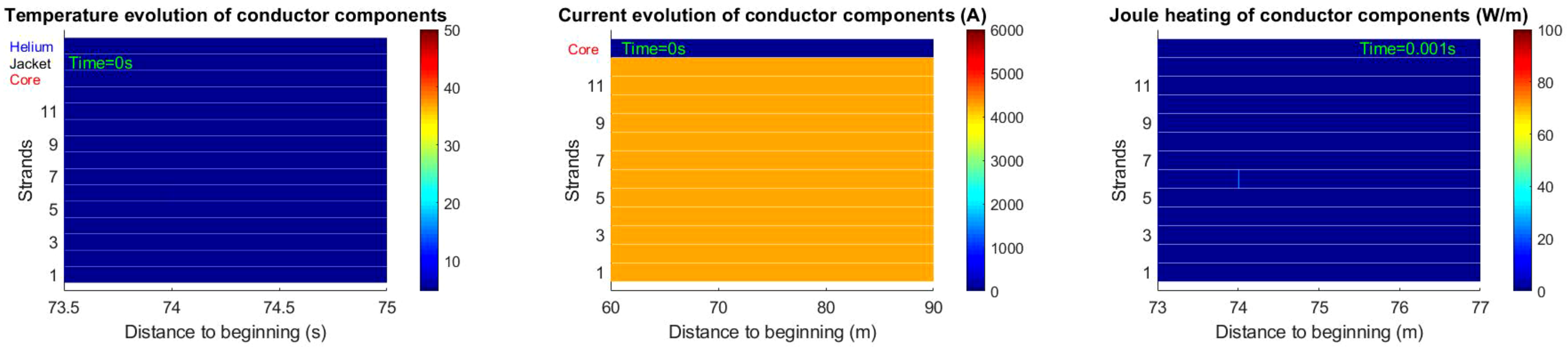
* Y. Iwasa, *Case Study in Superconducting Magnets*. Springer US, 2009.

10. Quench Propagation



Significant change happens in 10 ms, > $\tau_{t\text{-}t}$ and $\tau_{s\text{-}p}$

ECR=2 μΩm TCR=1 Km/W

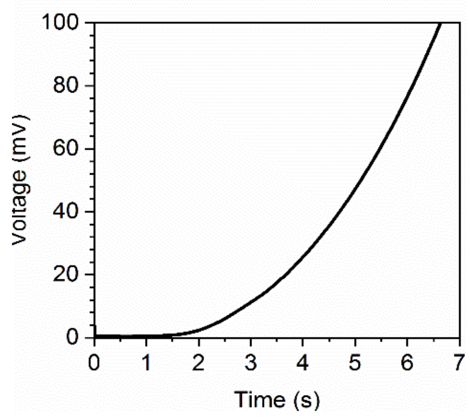
Influenced by helium flow, quench mainly propagates along downstream direction, with average velocity of 140 mm/s.

Fast or slow?

➔ Assume 1.1 s for quench protection system validating and activating and 20 s as the time constant for dumping current exponentially, the hot spot temperature at strand will go to 120 K*.

Criteria for strands: 200 K

Voltage of the conductor



* R. Bonifetto *et al.*, "Common approach for thermal-hydraulic calculations,"

11. Influence of inter-strand resistance

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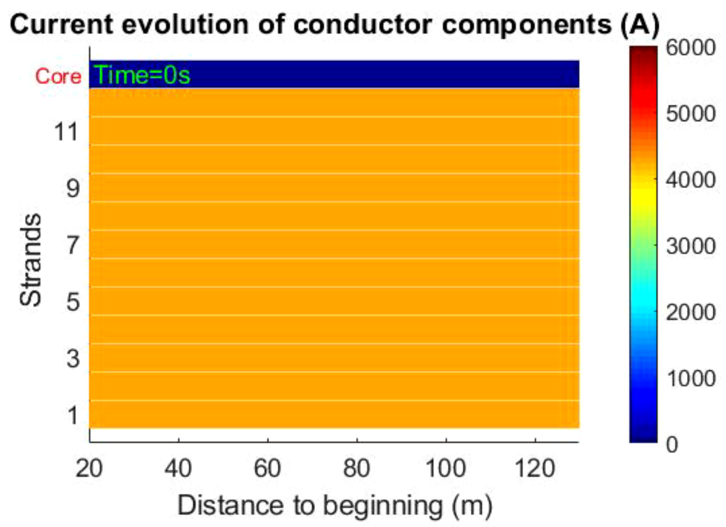
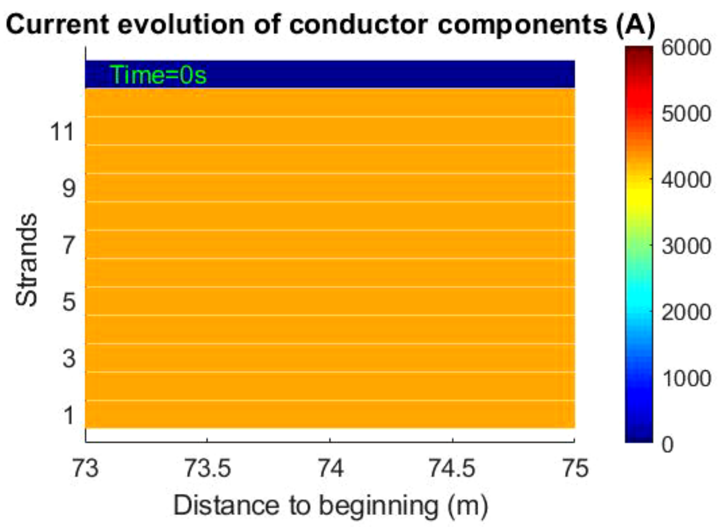
Two motivations:

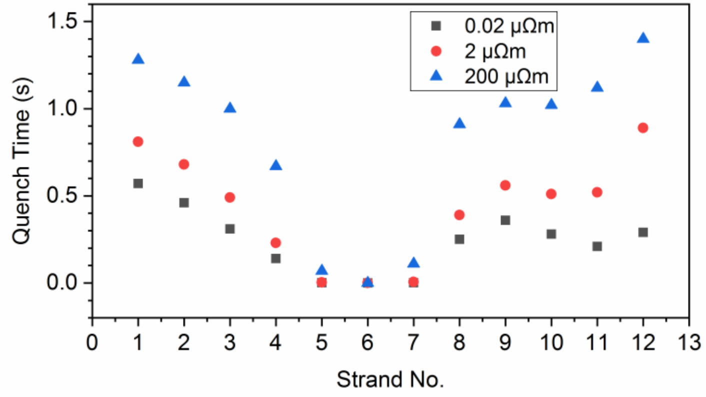
- In real conductor, it may vary in the manufacturing process.
- An important parameter for optimization of conductor: coupling loss.

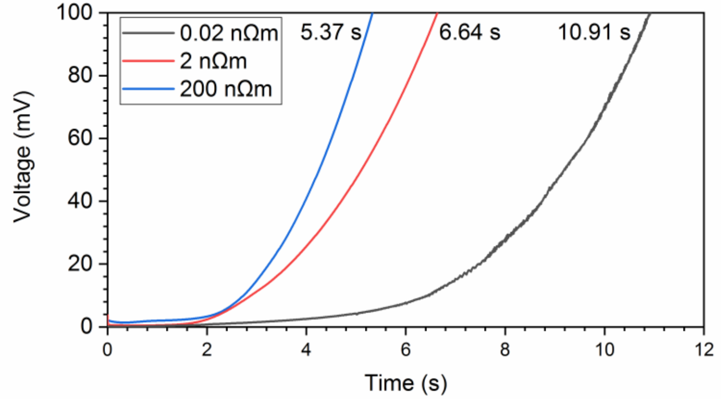


ECR=200 μΩm, MQE~1 J



ECR=0.02 μΩm, MQE~2.4 J





Both transverse and longitudinal quench propagation are influenced.

Hot spot temperature at strand: ~200 K for ECR=200 μΩm and 120 K for ECR=0.02 μΩm

➔ Differs with what was observed on sub-scale conductor *.

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* R. Kang et al "Quench Simulation of REBCO Cable-In-Conduit Conductor with Twisted Stacked-Tape Cable," *IEEE Transactions on Applied Superconductivity,* 2019.

12. Summary and outlook

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Summary:

- The monolithic strand is a good assumption of the twisted-soldered-stacked REBCO strand for quench modelling.
- Strand movement might be one source of transient local quench, which can be perfectly simulated with the multi-monolithic strand model.

Outlook:

Parametric study to optimize the conductor in view of quench behavior:

- ➢ Strand (stack) orientation
- ➢ Twist pitch of stack (and cable)
- ➢ Inter-strand resistance
- ➢ T_{cs}
- ➢ RRR
- ➢ ……

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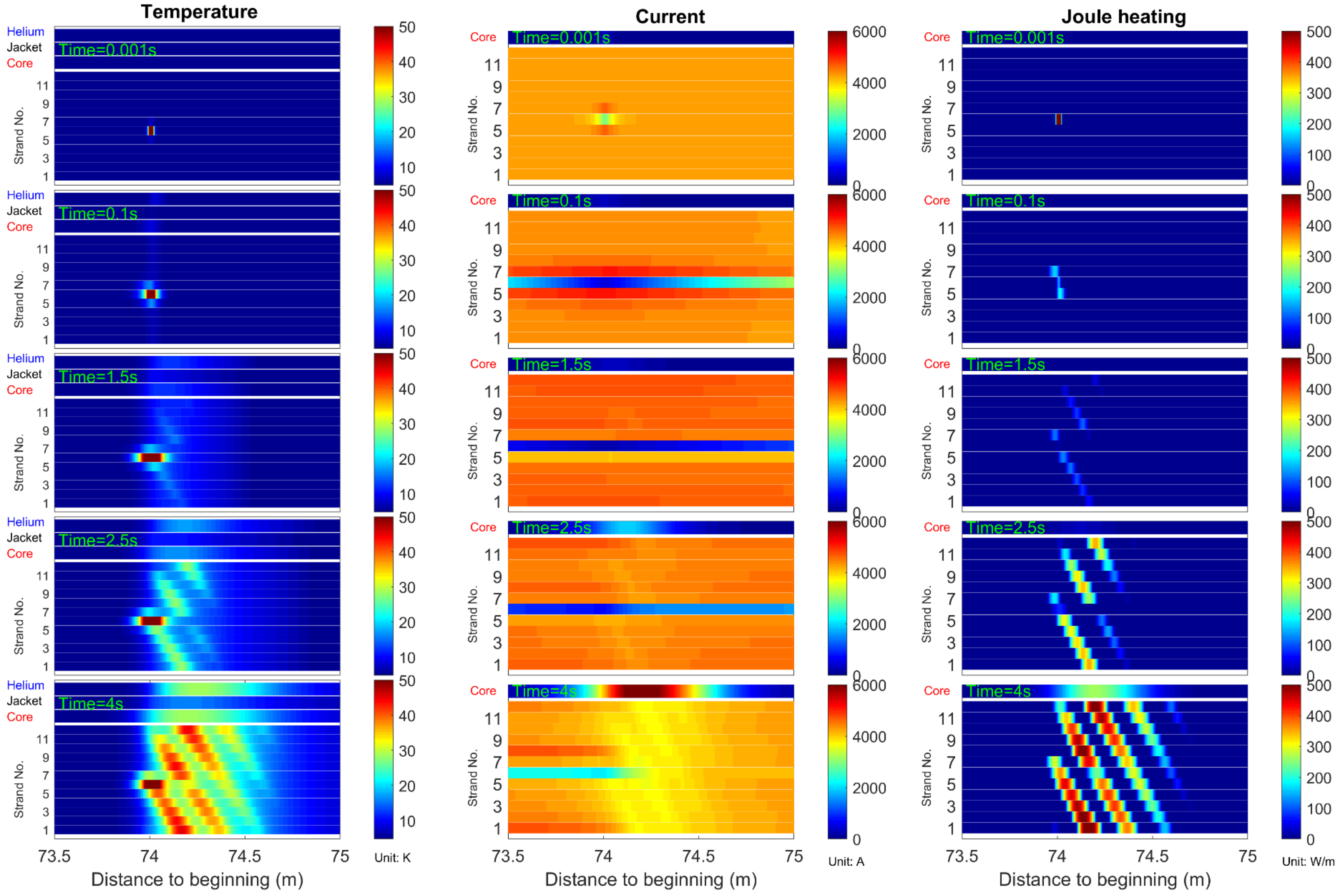
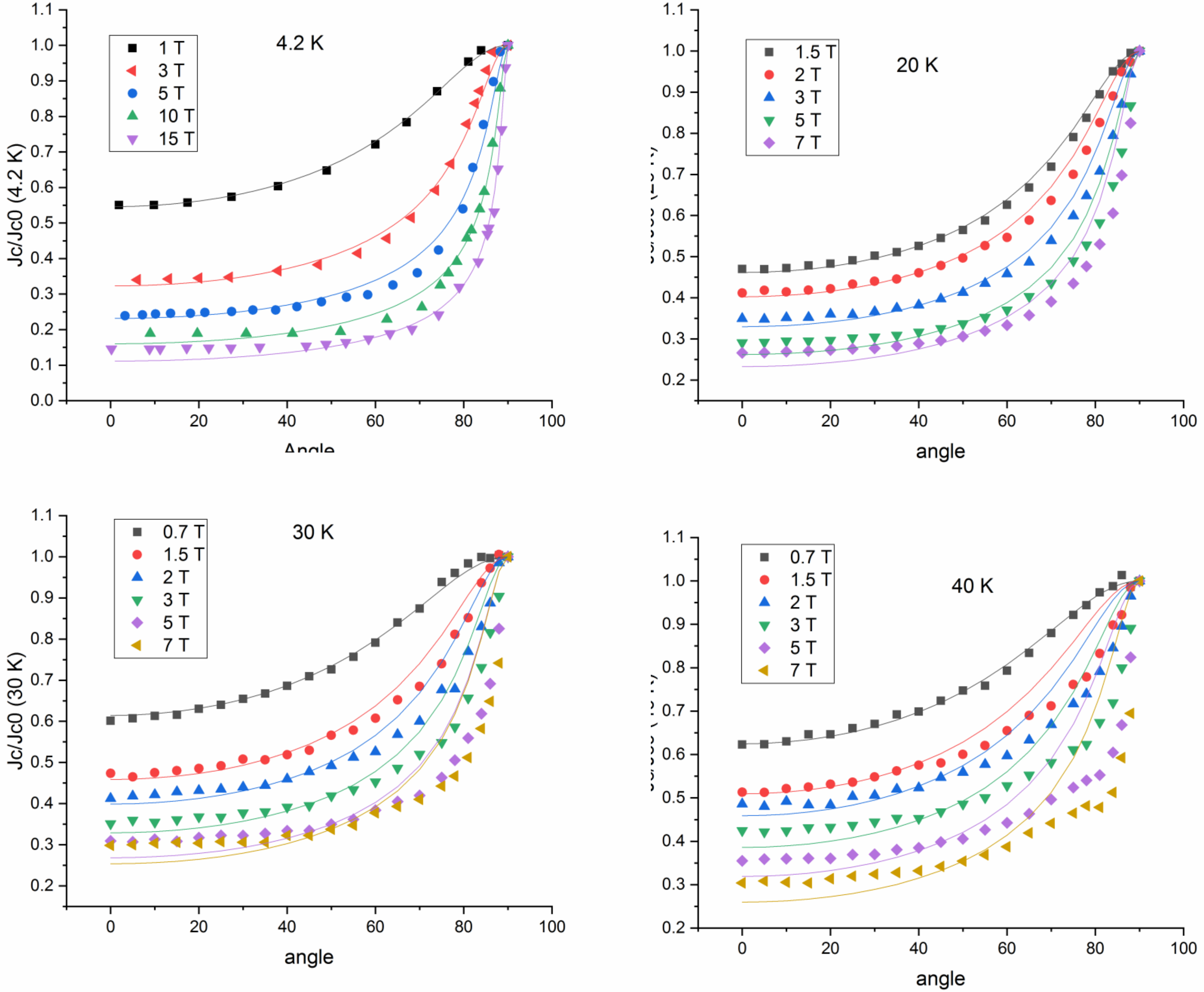
Thank you for your attention!

Backup pages

10. Quench Propagation



Fitting of Jc



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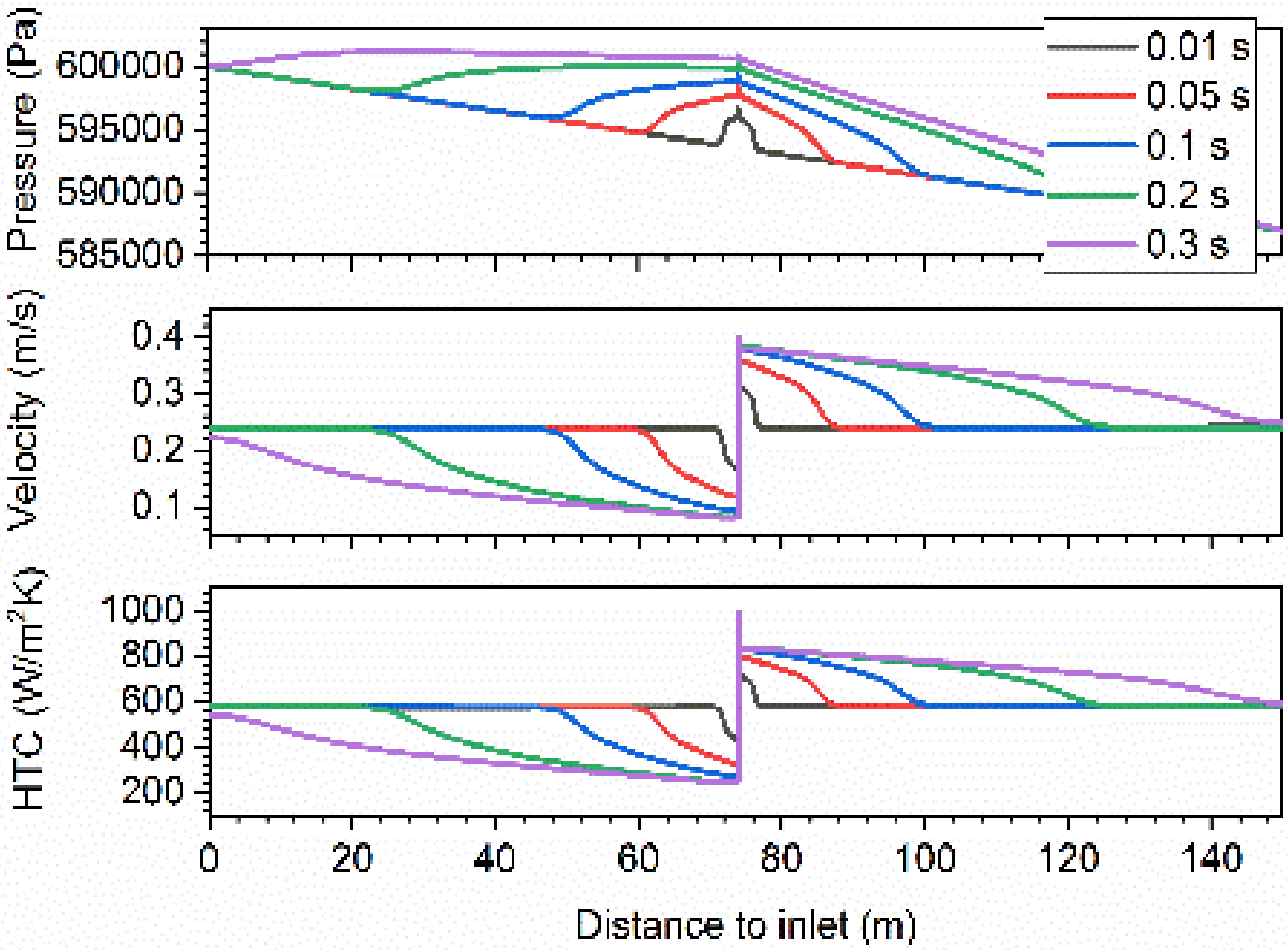
Hydraulic



Pressure (Pa)
600000
595000
590000
585000
0.01 s
0.05 s
0.1 s
0.2 s
0.3 s
Velocity (m/s)
0.4
0.3
0.2
0.1
HTC (W/m²K)
1000
800
600
400
200
0
20
40
60
80
100
120
140
Distance to inlet (m)