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1D Quench Propagation Analysis in HTS Tapes with the Spectral Element Method

Outline

- Reminder: Numerical Aspects of SEM
- Background: HTS vs. LTS
- HTS-Applications in NIC
- Simulated Model
- Simulation Results
- Conclusion

No description of the underlying numerical method here – see presentation from 22/08/2019, https://indico.cern.ch/event/796548/contributions/3532107/attachments/1895965/3128024/mid_term_presentation.pdf

➢ See presentation from 22/08/2019

Numerical Aspects of SEM

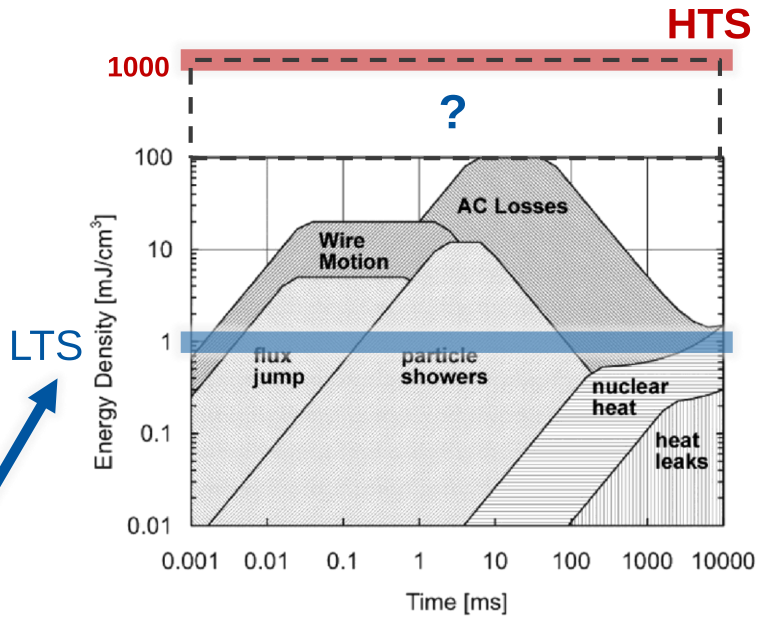
- 1D Cheby-SEM and necessary framework has been implemented in Matlab
- Implementation has been verified for an academic example against FEM

- Clear advantages of SEM compared to FEM for quench propagation have been shown:
  1. Simple refinement
     - ➢ Obtain desired accuracy
  2. Less memory consumption
     - ➢ Cheaper application to larger geometries
  3. Local resolution
     - ➢ Easy adaption to quench front

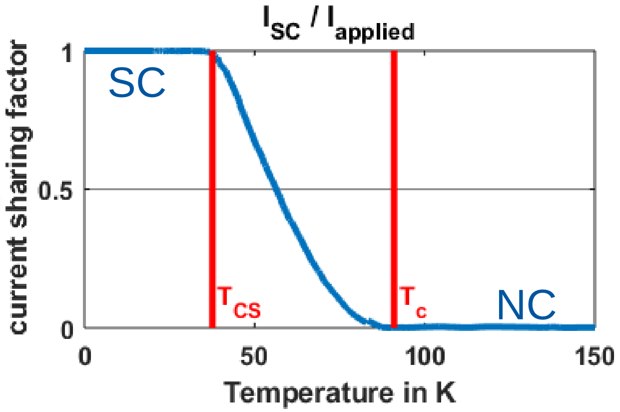
Background: HTS vs. LTS

	Rebco	NbTi
Tc [K]	93	9
Bc [T]	250	15
Jc [A/mm²]	~ 100 000	~ 2 000
Conductor construction	Tape	Multi-filament wire
MQE	~ 1 000 mJ/cm³	~ 1 mJ/cm³
Transition to NC state	Current sharing	Sharp transition
Vnzp	~ 0.1 m/s	~ 10 m/s

(Sources: v. Nugteren 2016, Uglietti 2019, for overview: Uglietti @WAMHTS 2019 or Marchevsky @WAMHTS 2015)

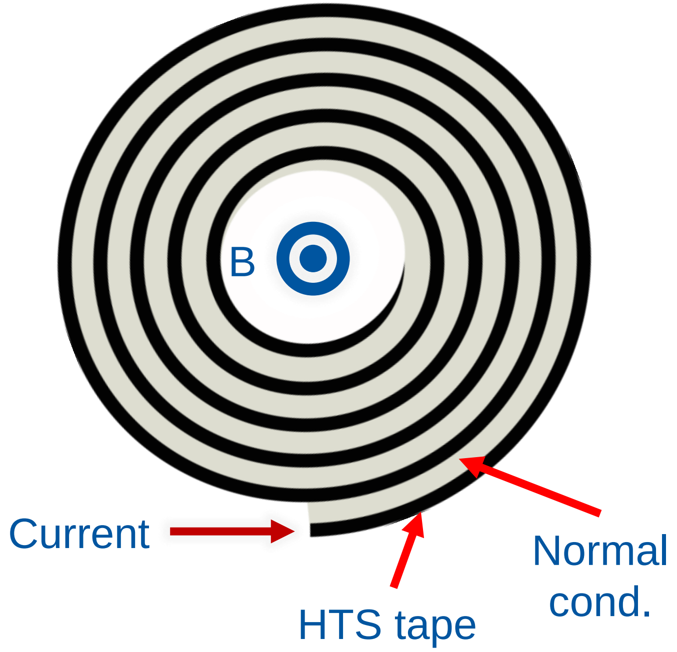


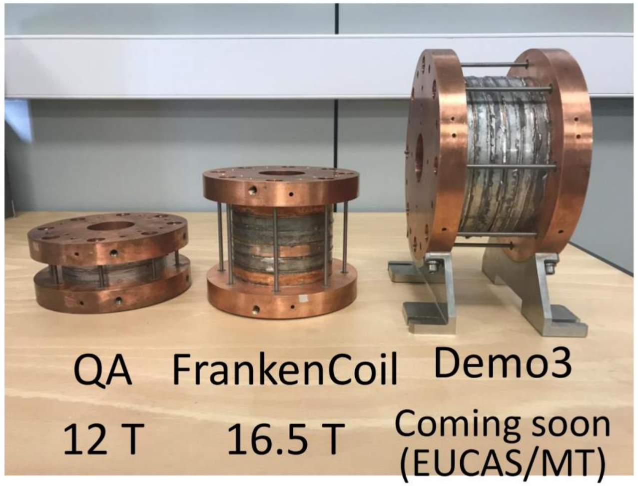
(Picture taken from Y Iwasa (and L Bottura), 2005, https://doi.org/10.1109/TASC.2005.849207)



HTS-Application in NIC

- Non-insulated HTS coils
  - Wounded tapes with normal conducting filling/tape in between
  - Solenoid
  - Quench through impurities, ind. coupling, (massive) radiation …

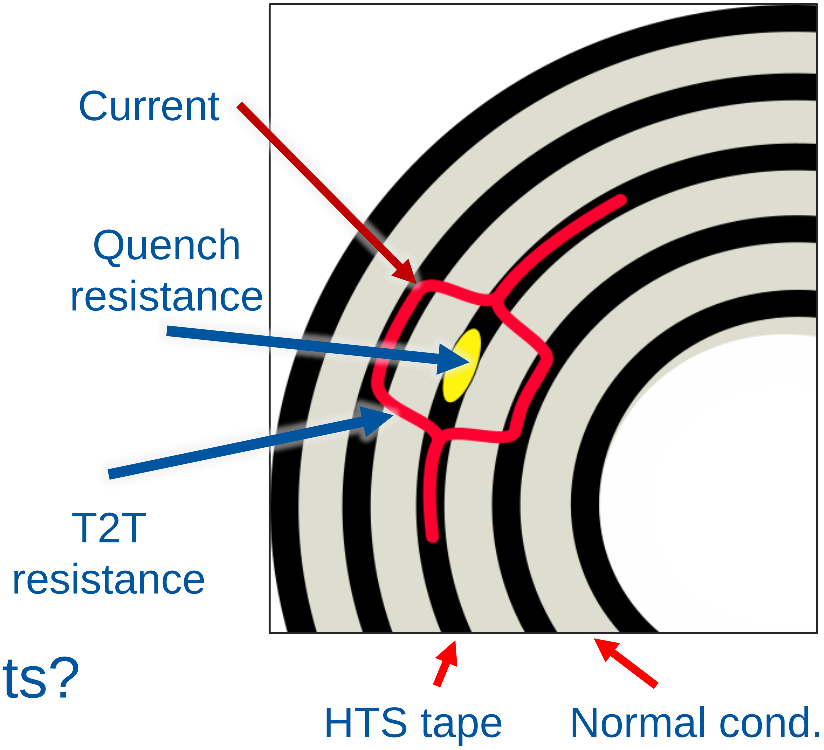




(Picture taken from tokamak energy, WAM-HTS presentation, 2019, https://indico.cern.ch/event/775529/contributions/3334053/attachments/1829923/3003215/20190412_GB_Stability_and_quench_dynamic_behaviour_of_Tokamak_Energy_REBCO_QA_coils_Indico.pdf)

HTS-Application in NIC

- Non-insulated HTS coils
  - Current can bypass quenching region in adjacent turns
  - Turn-to-turn (T2T) resistance?
  - External protection?
  - Upscaling for larger magnets?

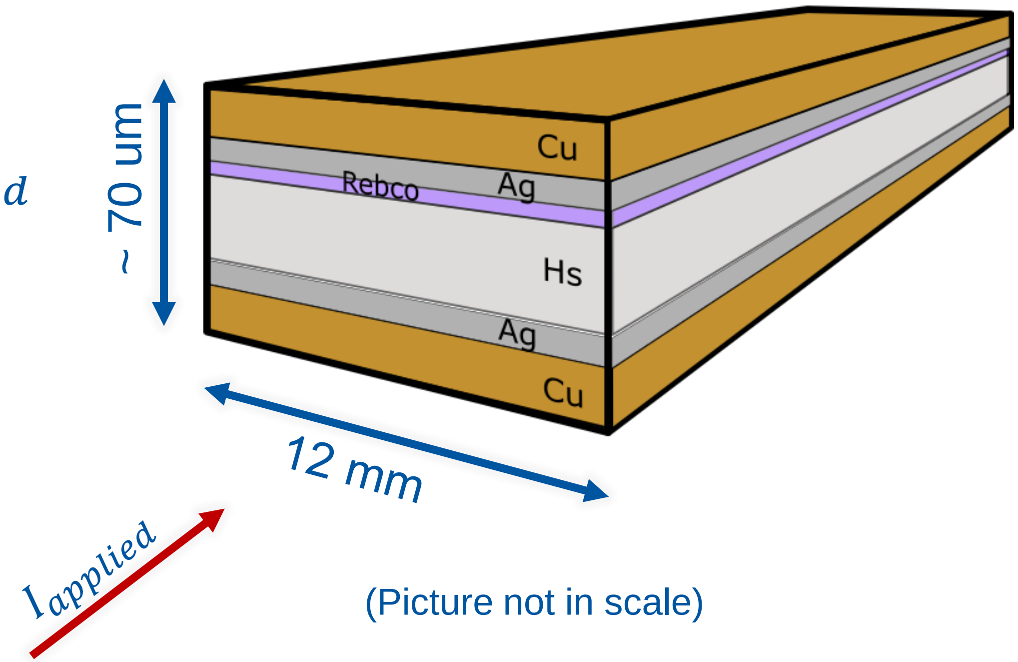


Understanding of single tape quench behavior required

- ➢ Normal zone development?
- ➢ Quench resistance?

Model – Single HTS Tape

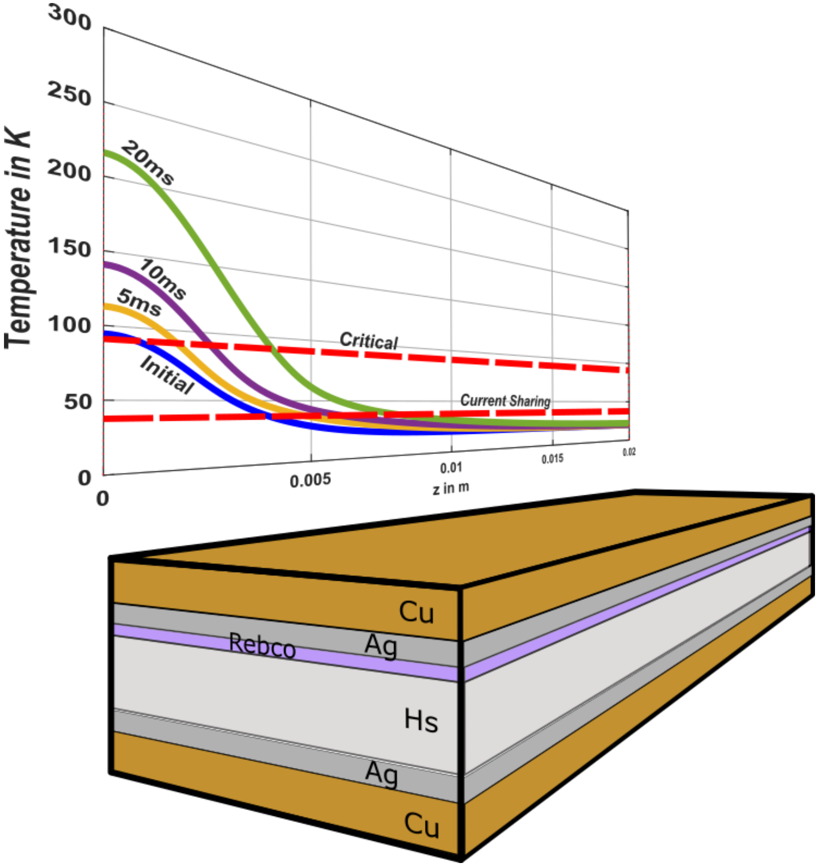
- Layers of Hastelloy, copper (x2), silver (x2) and Rebco
- External circuit:
    - Applied current $I_{applied}$ constant over time
    - No active protection schemes



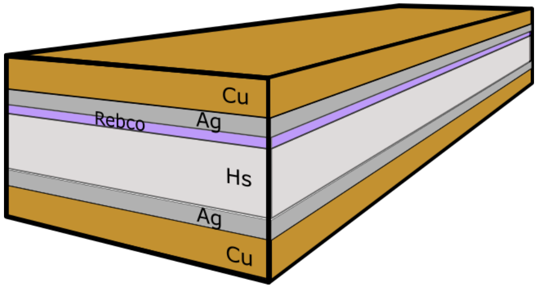
(Picture not in scale)

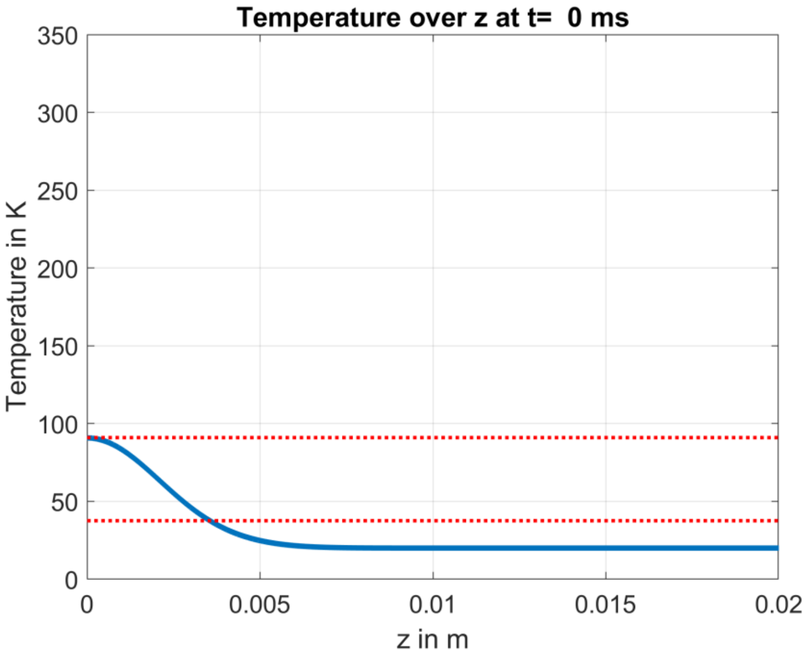
Model – Transient Simulation

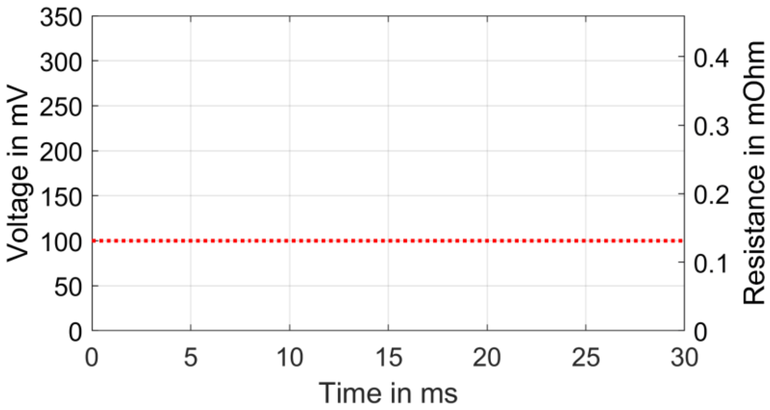
- 1D Thermal runaway in HTS tape:
  - Ohmic losses
  - Thermal conduction
  - Adiabatic boundary
- Initial deposition of energy in tiny region around hotspot
- Simulate up to hotspot temperature of 300 K

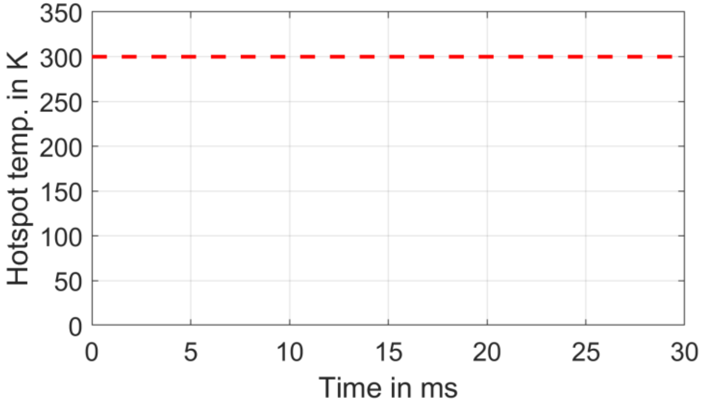


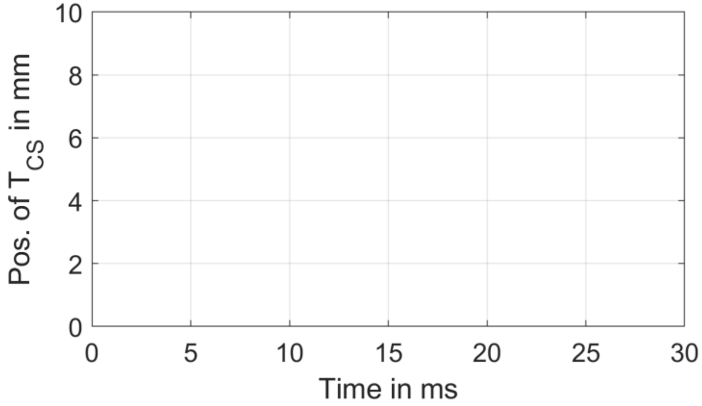
Model – Visualisation



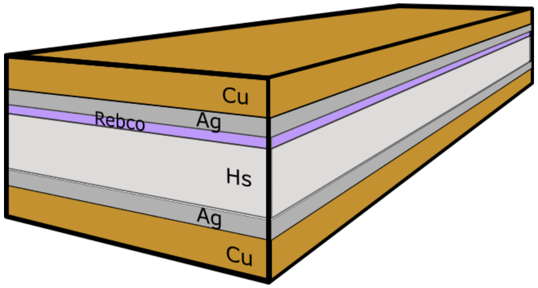


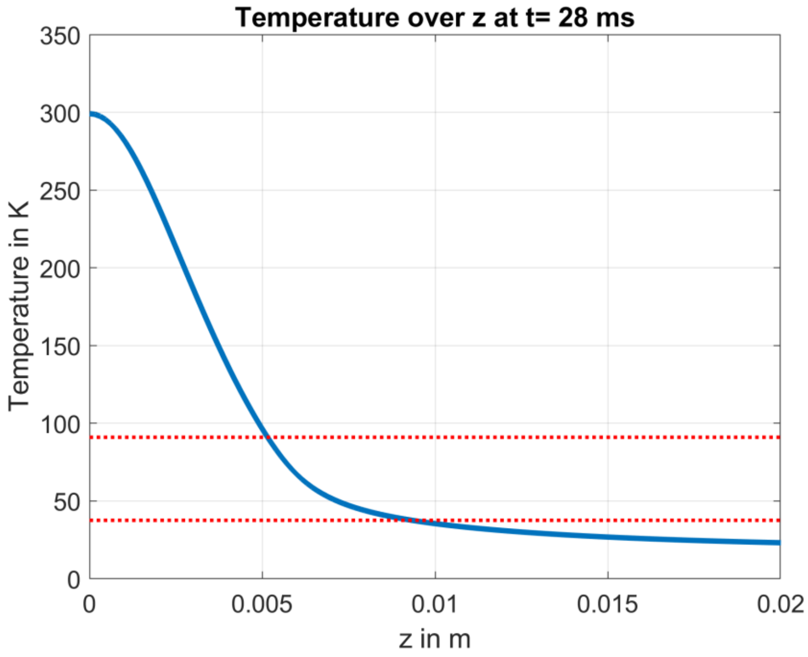


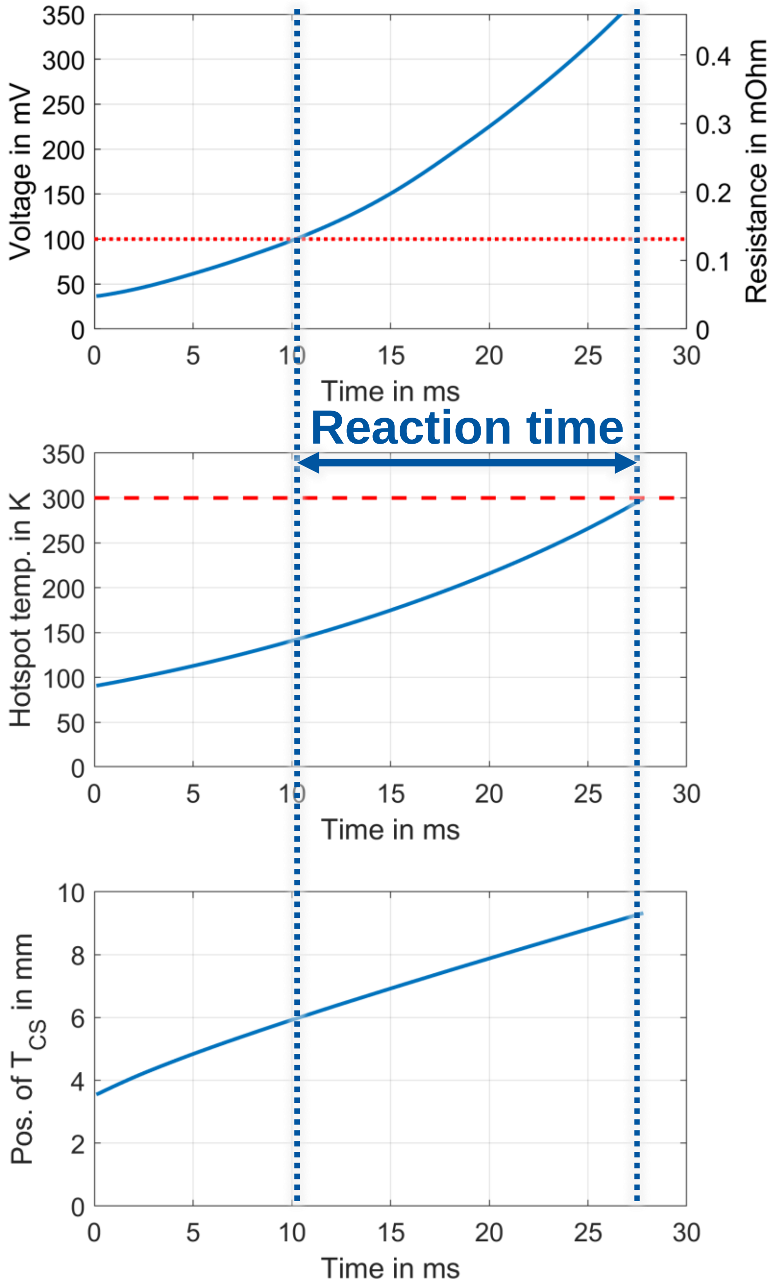




Model – Visualisation

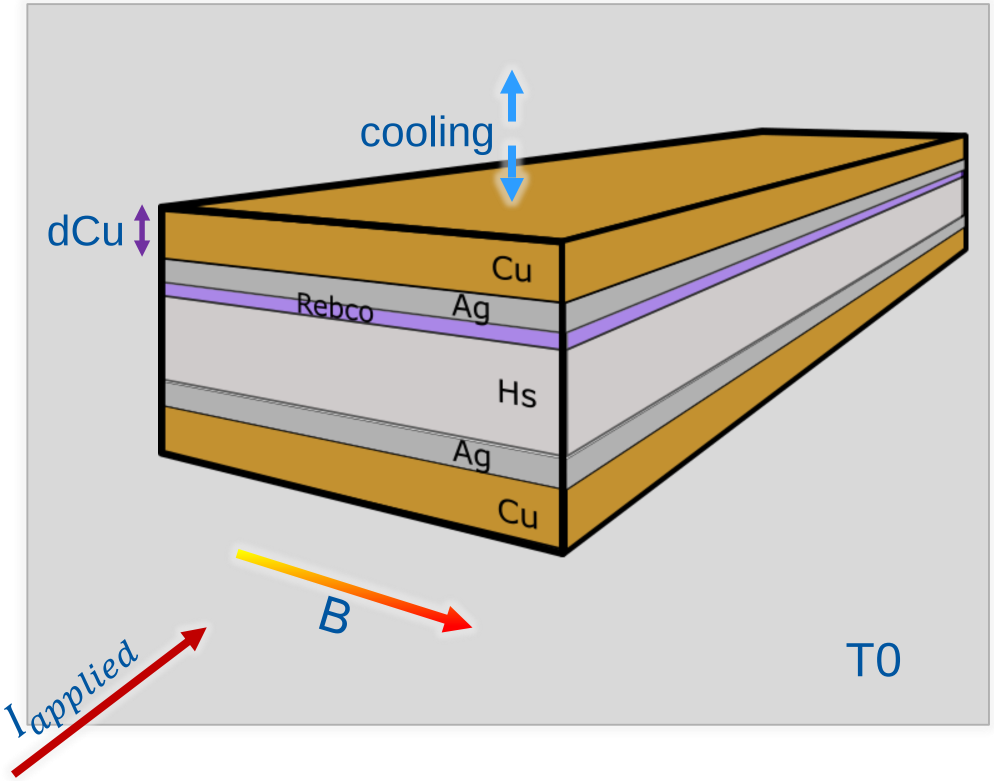



Temperature over z at t= 28 ms



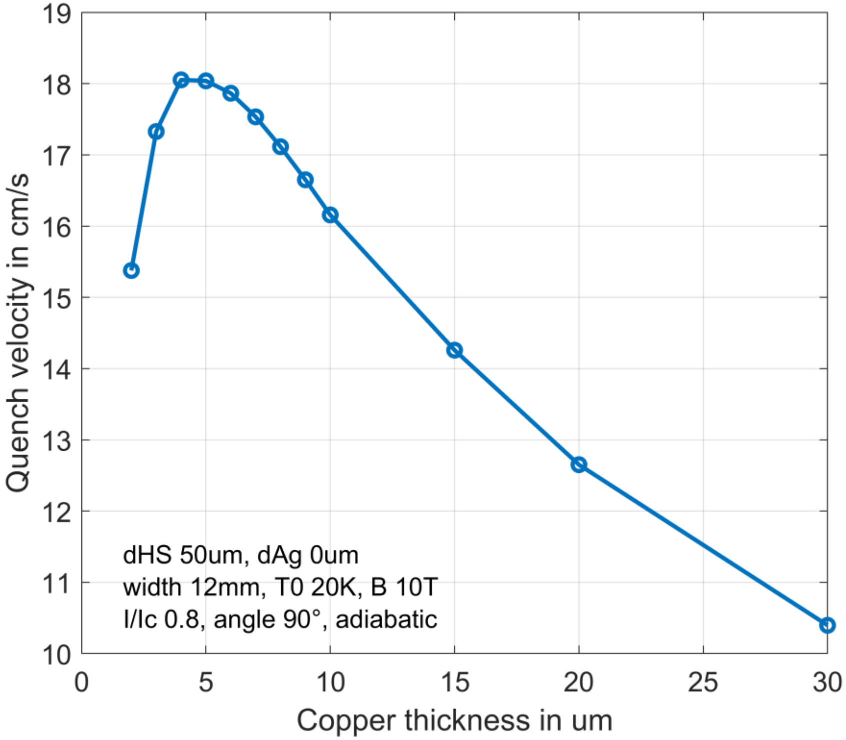
Model – Simulation Objectives

Results shown here for:	
Geometry	I. Influence of Cu layer
External	II. Influence of Cooling
Working point (T0, B, I) influence	III. On Vnzp
	IV. On Reaction time
	III. On Quench resistance



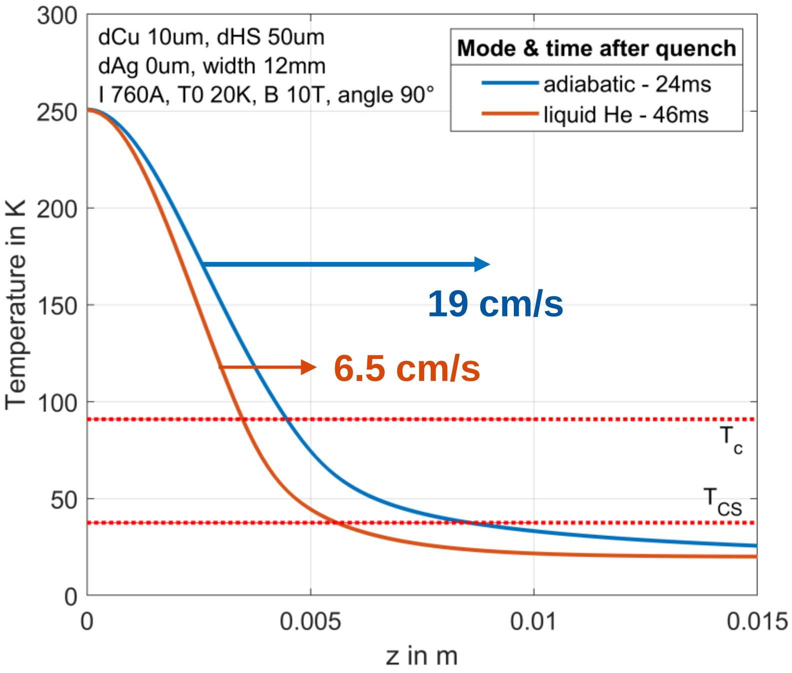
Results I – Copper Layer Thickness

- Less Cu: less thermal transport
  = lower Vnzp
- More Cu: more total mass and less resistance
  = less power in larger volume
  = lower Vnzp



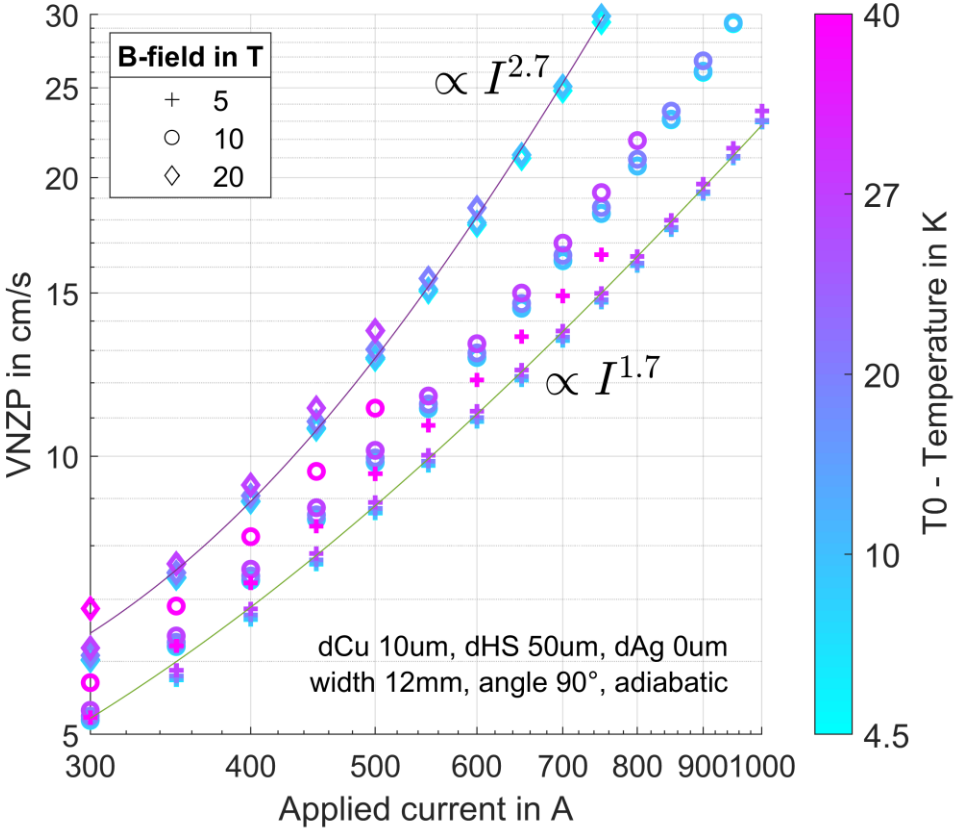
Results II – Cooling

- Cooling in liquid He ~2 kW/m² K on total surface (non-practical)
- Rapid increase in reaction time, massive decrease in Vnzp
- Does not prevent burnout -> high cooling not a good idea?
- Low cooling -> insignificant influence



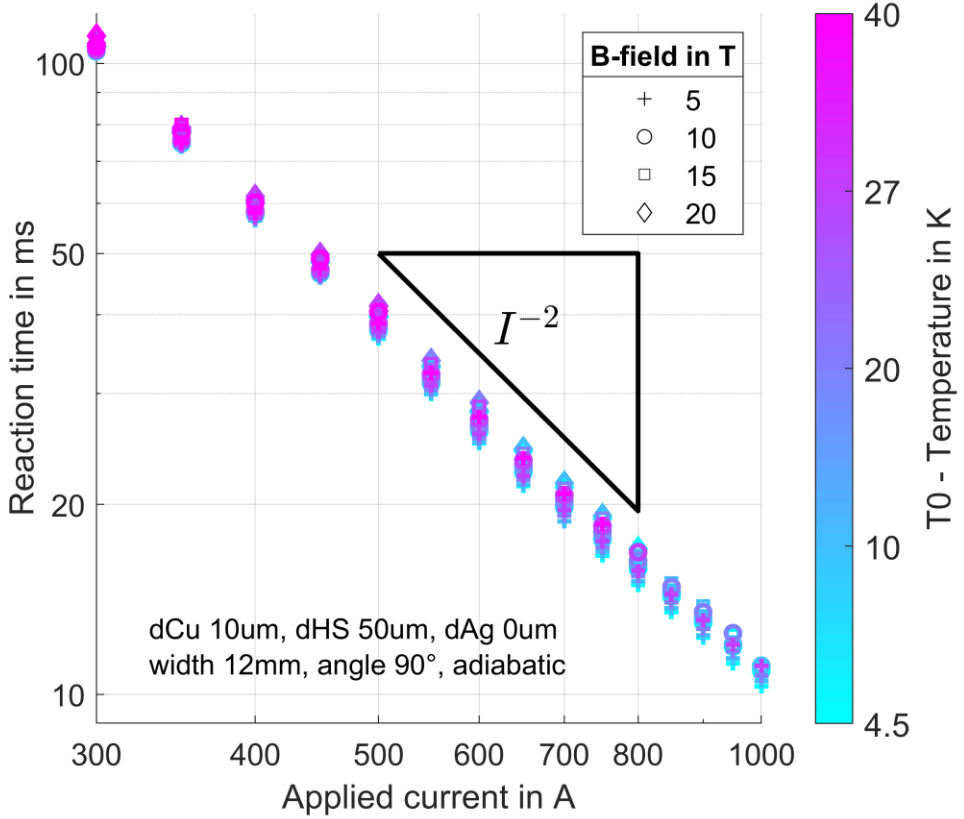
Results III – Normal Zone Propagation Velocity

- For low temperatures (i.e. ~constant el. resistivity), Vnzp is found to be mainly a function of I
- More precisely: $V_{nzp} \propto I^{x(B,T0)}$ with weak influence of T0



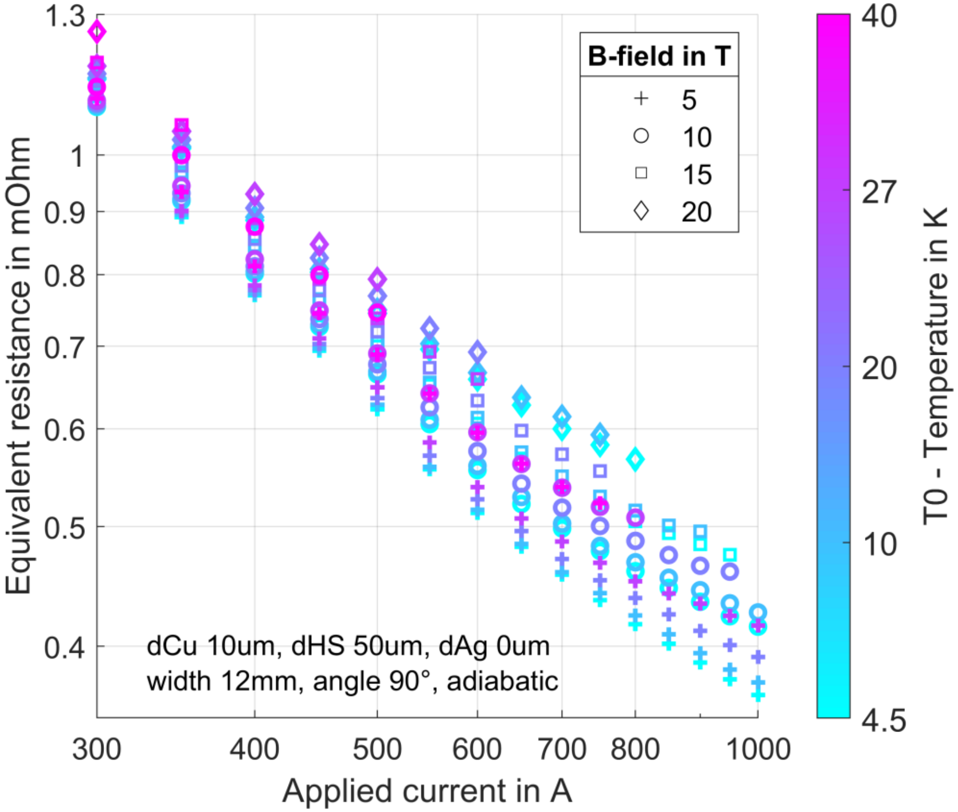
Results IV – Reaction Time

- Time between 100 mV external voltage and 300 K at hotspot
- Above all, reaction time depends on applied current
- Precisely: power measure, $t_{react} \propto I^{-2}$
- Is external reaction during a few ms feasible?



Results V – Quench Resistance

- Exemplary: Resistance at end of simulation 300 K hotspot
- Clear dependency on applied current
- Significant influence of working point conditions
- Tuning of T2T resistance possible



Summary

Single tape quench protection challenges:

- External:
  - Influence of applied current on reaction time ~ $1/I^2$
  - Very short reaction time
- In practical applications cooling without influence (if not even worsening the situation)

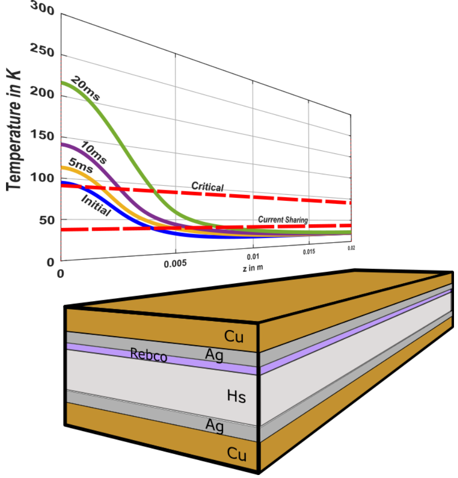
How (if at all) is an active (external) protection scheme feasible?

Construction of self protective NIC

- Tuning of T2T resistance requires knowledge of quench-resistance
- Self protection has to be very fast and effective
- Consideration of time-constants?

➢ Think outside the (LTS) box!

Conclusion for Cheby-SEM



Matlab tool dedicated for

  - Transient quench simulation
  - Parameter studies
- Manual
- Documentation
- plug&play routines
- ➢ no need to understand the numerics

Beta-Version on Gitlab:
https://gitlab.cern.ch/steam/steam-ChebySEM

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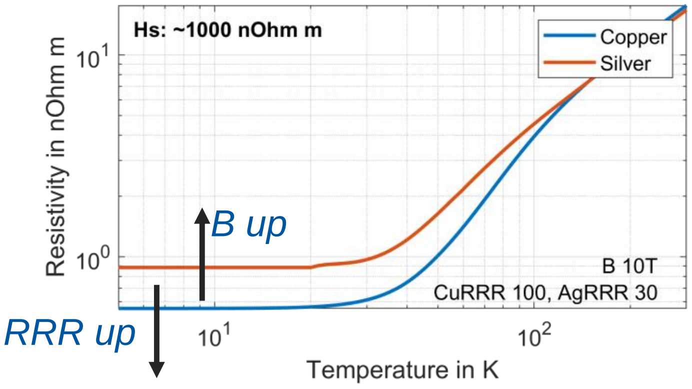
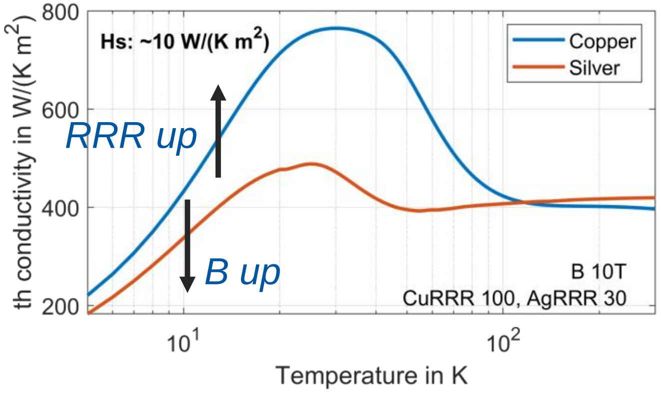
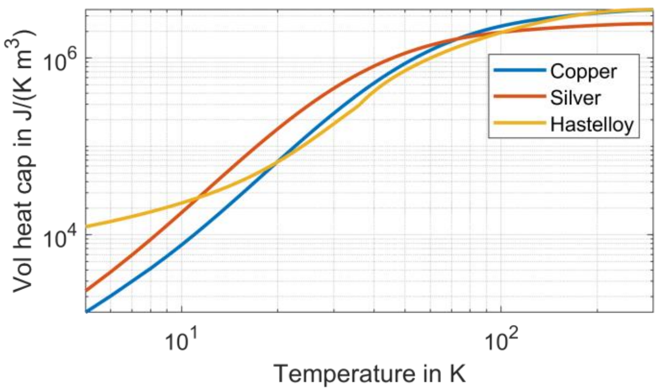
App 1.1 – Material Properties

- Influence of RRR and B relevant for low temperatures
- Less (parametrized) material data found for Ag, especially for high field or different RRR

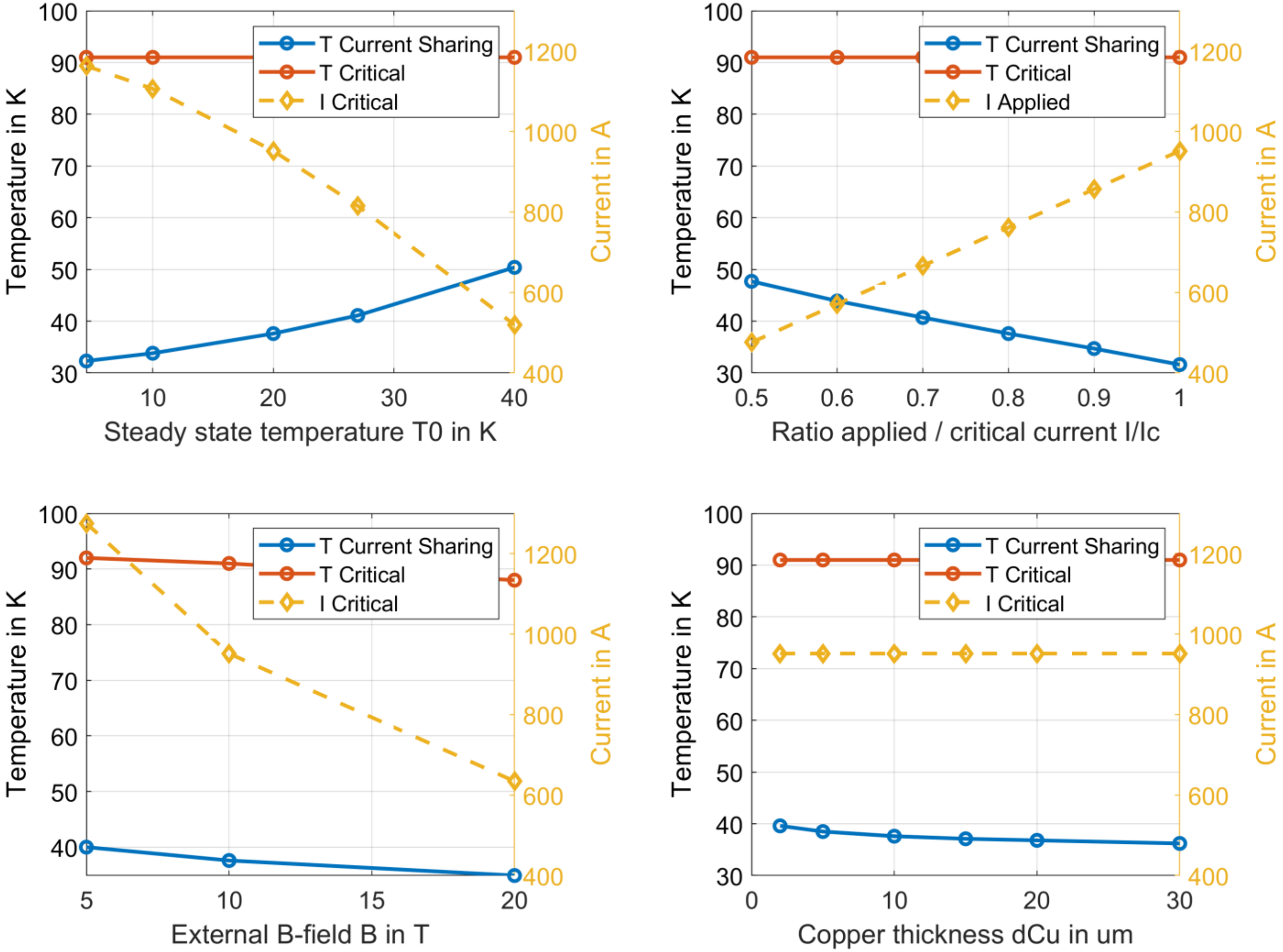






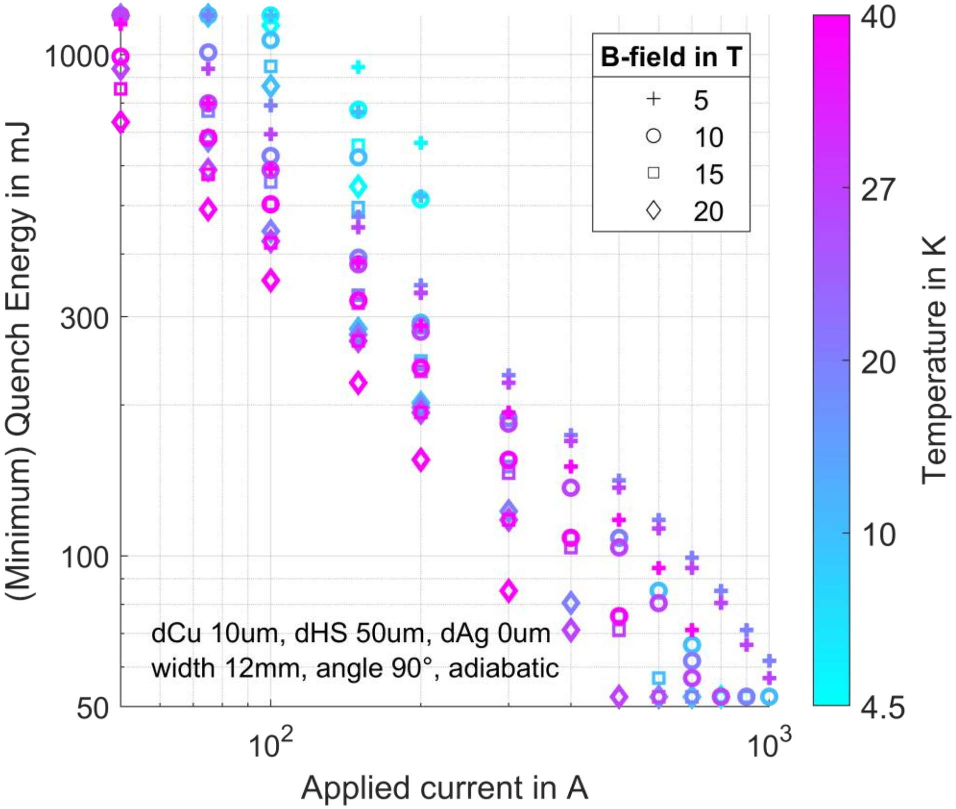
App 1.2 – Parameters on Critical Values

Default: dCu 10um, dHS 50um, dAg 0um, width 12mm, T0 20K, B 10T, I/Ic 0.8, angle 90°, adiabatic



App 1.3 – (M)QE as Function of Working Point (Iapp,B,T0)

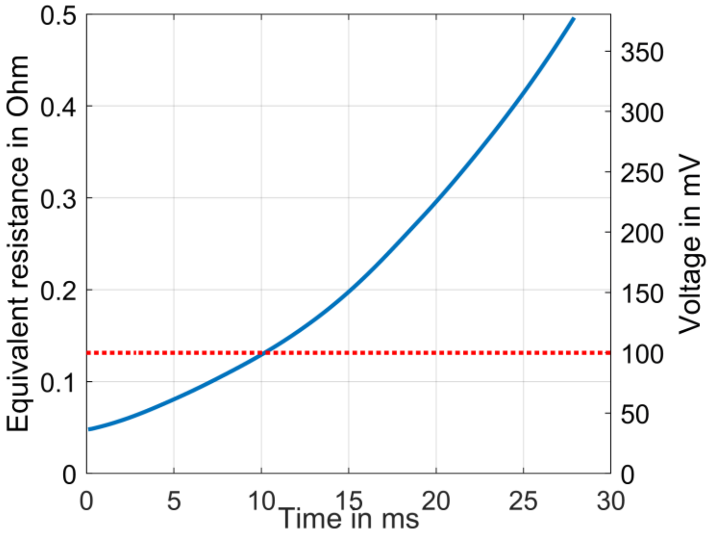
- Limits of calculation <u>here</u>: 50 – 1200 mJ, resolution 5 mJ (for runtime purposes)
- Minimum only for used initial temperature profile: Gaussian with fixed variance 3mm
  - ➢ (M)QE

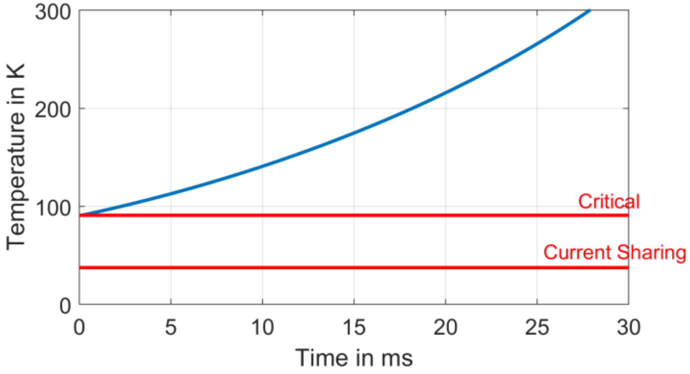


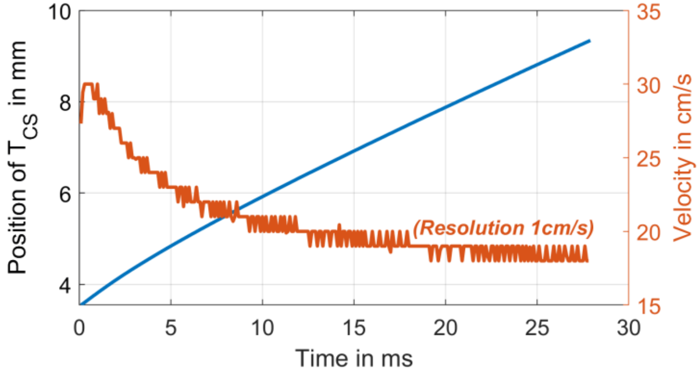
QE of 5mJ in initial quench volume ~(12mm x 0.1mm x 10mm)
➢ ~ 0.4 J/cm^3

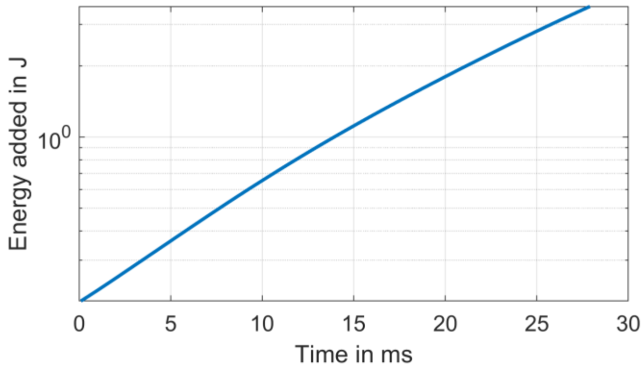
App 1.4 – Transient Behaviour

- (remember: default simulation settings)





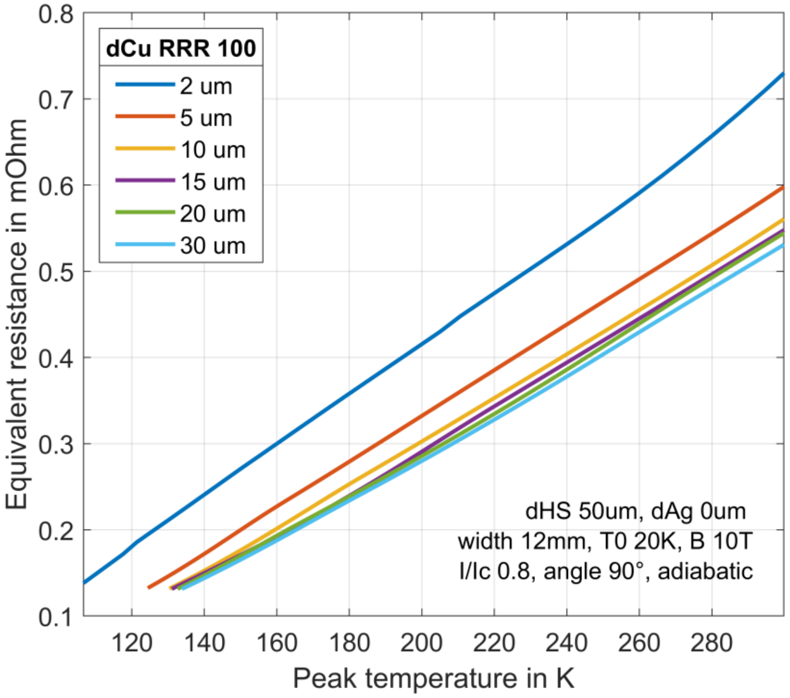




App 2.1 – Cu layer on Resistance

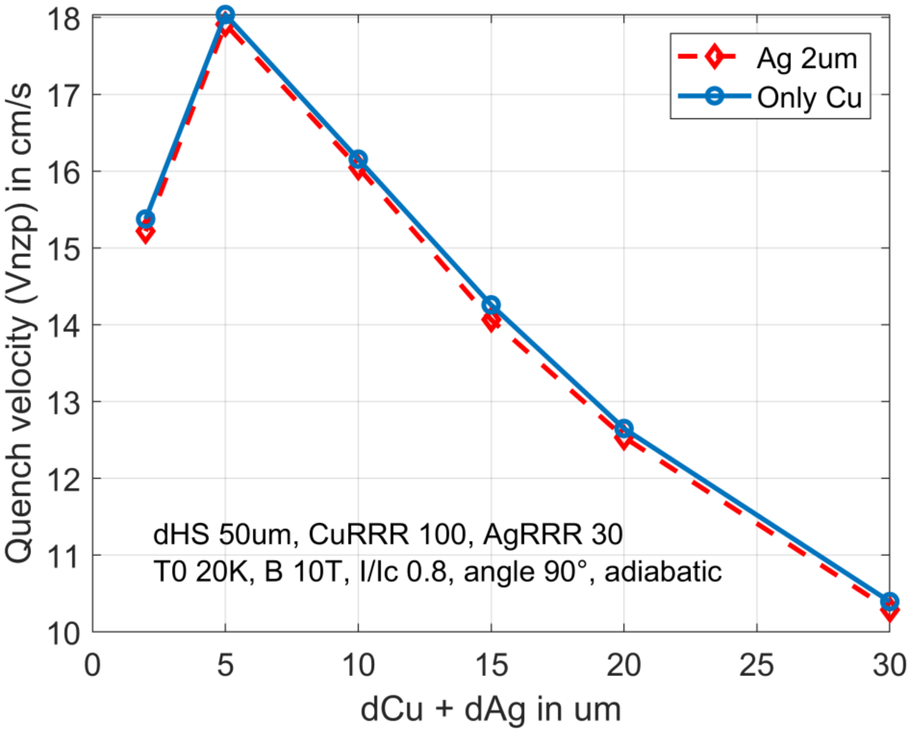
- Variation of layer thickness without significant influence for dCu > 10um

➢ constant factor $\frac{V_{nzp}\, t_{react}}{d_{Cu}}$ (Wiedemann-Franz law?)



App 2.2 – Including Ag Properties

- Same initial energy for same NC-thickness
- No significant influence
- Replacing with Cu for given simulation reasonable
- *Influence of RRR of Cu and Ag may change this statement for low thicknesses*



App. - Reminder: Excerpt of Standa Simulation Workflow

- Backup: presentation from 22/08/2019

PDE & model

↓

Discretization method

Discretizing PDE as algebraic (matrix) equation

↓

Solving

↓

Postprocessing: physical interpretation

Temperature $\theta(z)$

↓

build matrix system

$Au = b$

↓

find unknown u

↓

Comsol / Ansys

plot simulated $\theta(z)$

App. - Spectral Element Method (SE) I

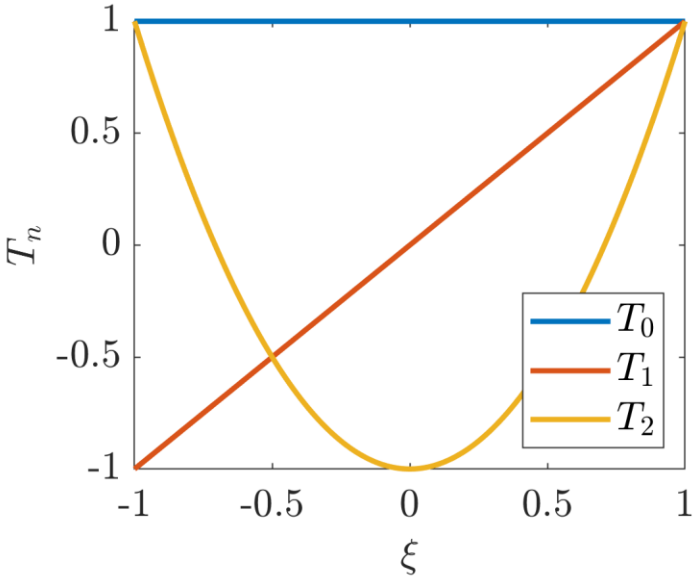
➢ Backup: presentation from 22/08/2019

- Polynomial approximation of function

$$f(\xi) \approx \sum_{n=0}^{N} \widetilde{f}_n \, \xi^n$$

- Chebyshev-polynomials T_n :

$$T_0 = 1, \qquad T_1 = \xi,$$
$$T_2 = 2\,\xi^2 - 1, \ldots$$



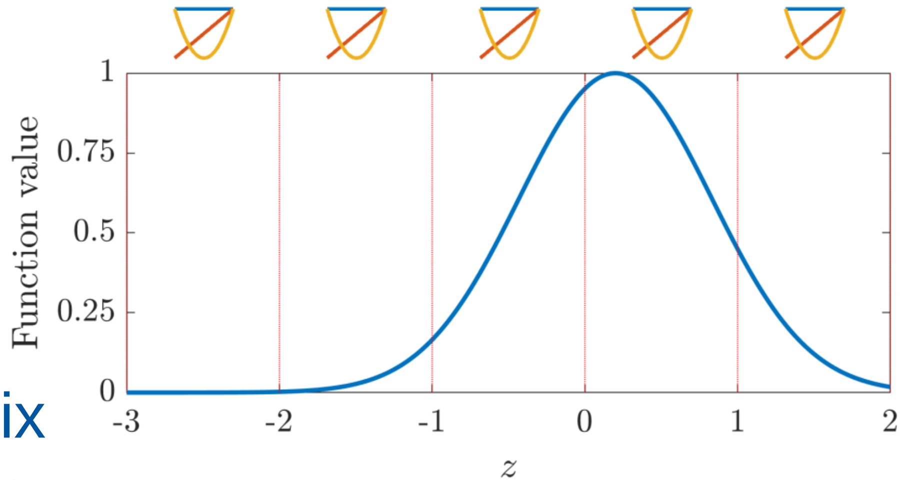
➢ Orthogonality

$$\int_{-1}^{1} T_n T_m \, \omega_T \, d\xi = c_n \delta_{n,m}$$

App. - Spectral Element Method (SE) II

➢ Backup: presentation from 22/08/2019

- Discretization of space with mesh and polynomials



- Discretized PDE as matrix equation for element wise representation

$$\theta^e \approx \sum_{n=0}^{N} u_n^e \, T_n$$

(heat conduction PDE)

$$-\nabla\,(\,\lambda\,\nabla\,\theta\,) + c_v\,\partial_t\theta = j^2\,\rho$$

$$\downarrow$$

$$K_\lambda\,u + M_{c_v}\,\partial_t\,u = q$$

$$\downarrow$$

$$A\,u = b$$

➢ Sparse mesh, high order polynomials

➢ Backup: presentation from 22/08/2019

App. - Benchmark: Proof of Concept

	Solver	Runtime	# DoF
Comsol	FEM, standard fine mesh	33 s	12.000
Comsol	FEM, adaptive mesh	15 s	400 – 500
Matlab	SEM, adaptive polynomial order	19 s	< 200

➢ More general:

Pro FEM

- Multi-purpose tool
- Steep changes
- Inhomogeneous materials

Pro SEM:

- Specialized tool
- Accuracy
- Less storage requirements
- Simple refinement

➢ Backup: presentation from 22/08/2019

App. - What’s next? – Background II

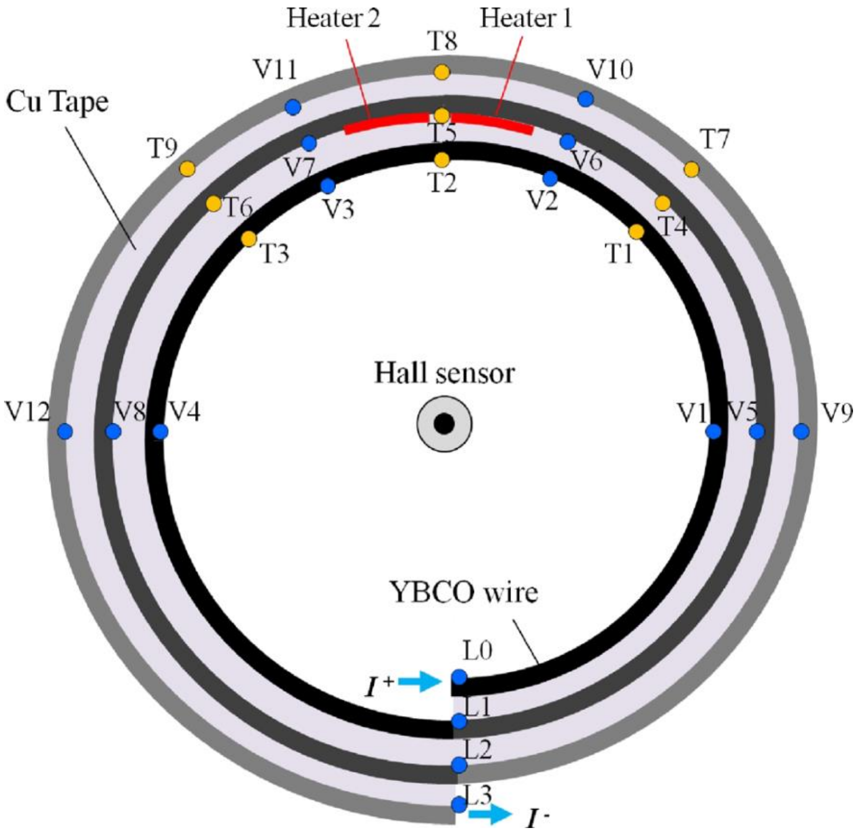
- Non-insulated (NI) HTS coils
  - Wounded tapes
  - Solenoid
  - Quench tolerant (Self protection)
- Planned application in fusion technology (cmp. e.g. tokamak energy)
- Application in accelerator technology?

(Picture taken from tokamak energy, WAM-HTS presentation, 2019, https://indico.cern.ch/event/775529/contributions/3334053/attachments/1829923/3003215/20190412_GB_Stability_and_quench_dynamic_behaviour_of_Tokamak_Energy_REBCO_QA_coils_Indico.pdf#search=van%20nugteren%20AND%20EventID%3A775529)

➢ Backup: presentation from 22/08/2019

App. - What’s next? - Task

- Simulation of HTS tape peak temperature during quench
  - 1D simplified model
  - Current sharing btw. super- and normal-conducting domains
  - Equivalent resistance
- Mid-term:
  - Coolant (1D + 1D)
  - Turn-to-turn propagation



(Picture taken from Seok Beom Kim, 2012, https://doi.org/10.1109/TASC.2011.2174559)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