Electrothermal modeling of HTS coils using homogenization and different formulations

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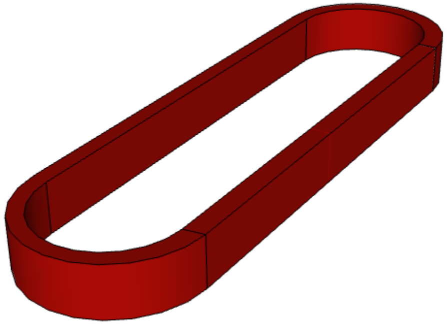
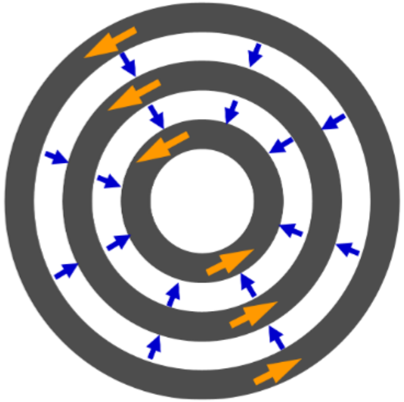
c Université de Lorraine, GREEN, Nancy, FRANCE
d Instituto de Ingeniería, UNAM, Mexico City, MEXICO
e Paul Scherrer Institut PSI, Villigen, SWITZERLAND
f Tampere University, Tampere, FINLAND
g Rio de Janeiro State University, Rio de Janeiro, BRAZIL
h Universidade Federal Fluminense, Rio de Janeiro, BRAZIL
i Atled Engineering, Oxford, UK

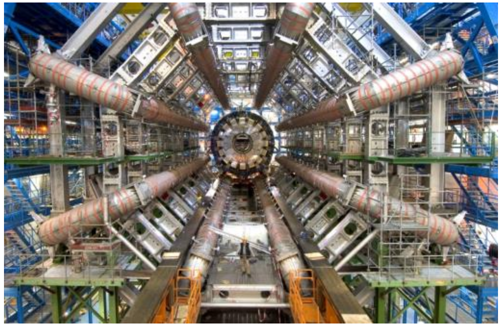




Current applications

MRI machines

High field magnets



Particle accelerators

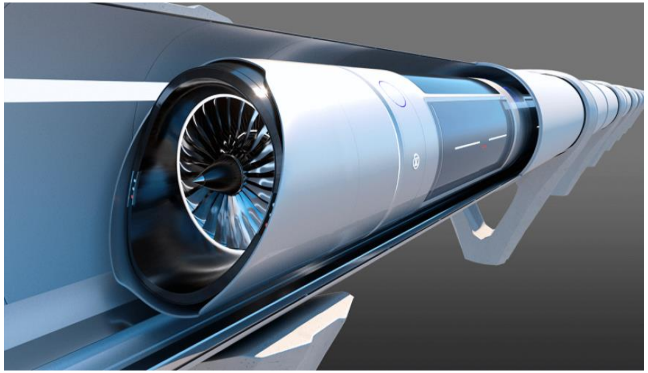
Ship Propulsion

Wind generator

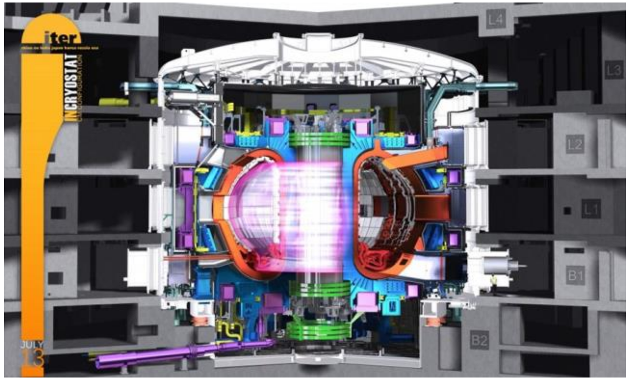
Electric aircraft

Future applications

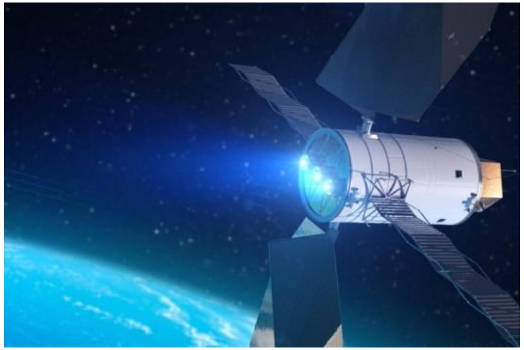
Maglev trains



Hyperloop

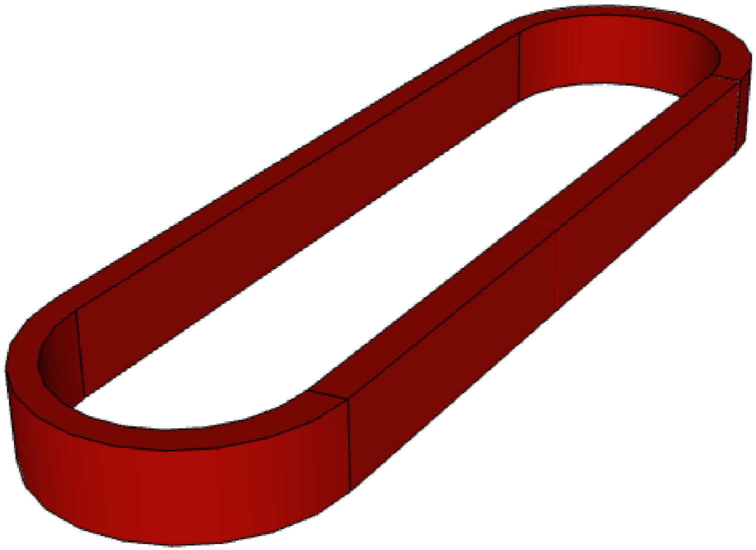


Fusion



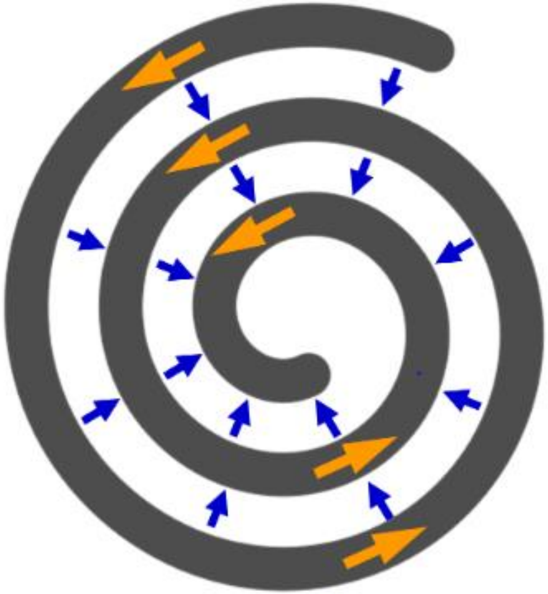
Space propulsion

Racetrack coil



Application: Rotating machines, high field magnets

Pancake coil



Motivation

Modeling superconductors is tough and time consuming

- Complicated non-linear multiphysics (specially for quench analysis)
- Need for a fast and efficient method
- **Developed a novel and fast homogenization method!**

Development and benchmark of various numerical models

- **14 models or combinations for different cases!**

Collaboration between research teams within superconductor community

- **8 countries, 9 institutes!**

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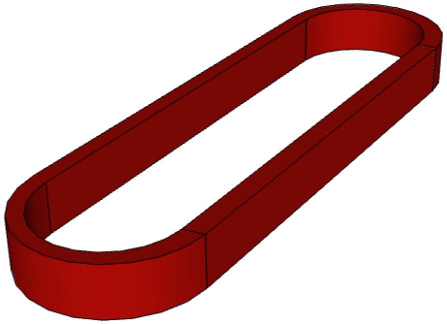

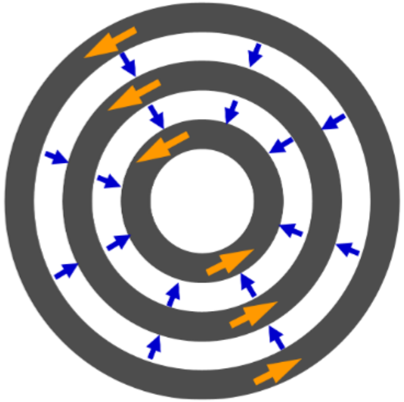

Institute of Electrical Engineering,
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Problem statements

Material properties

Numerical models

Benchmark results

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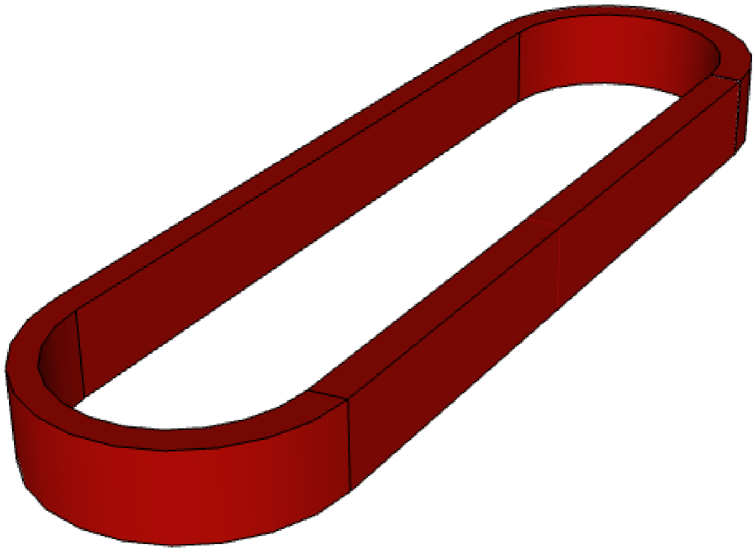
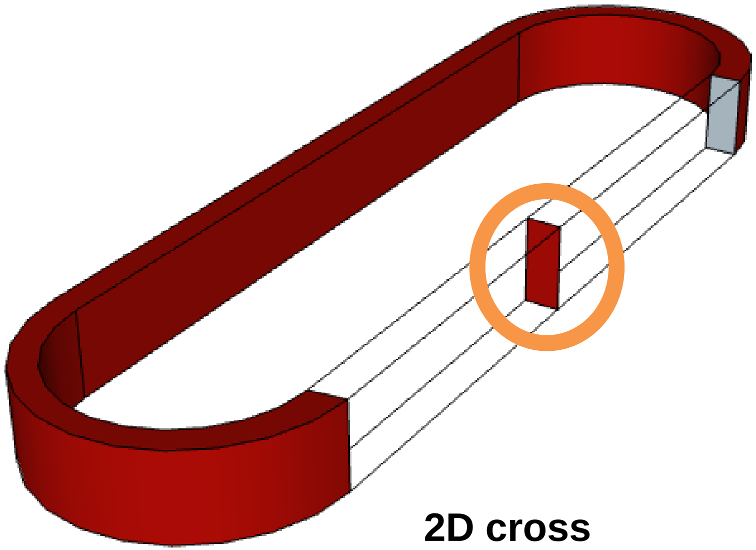
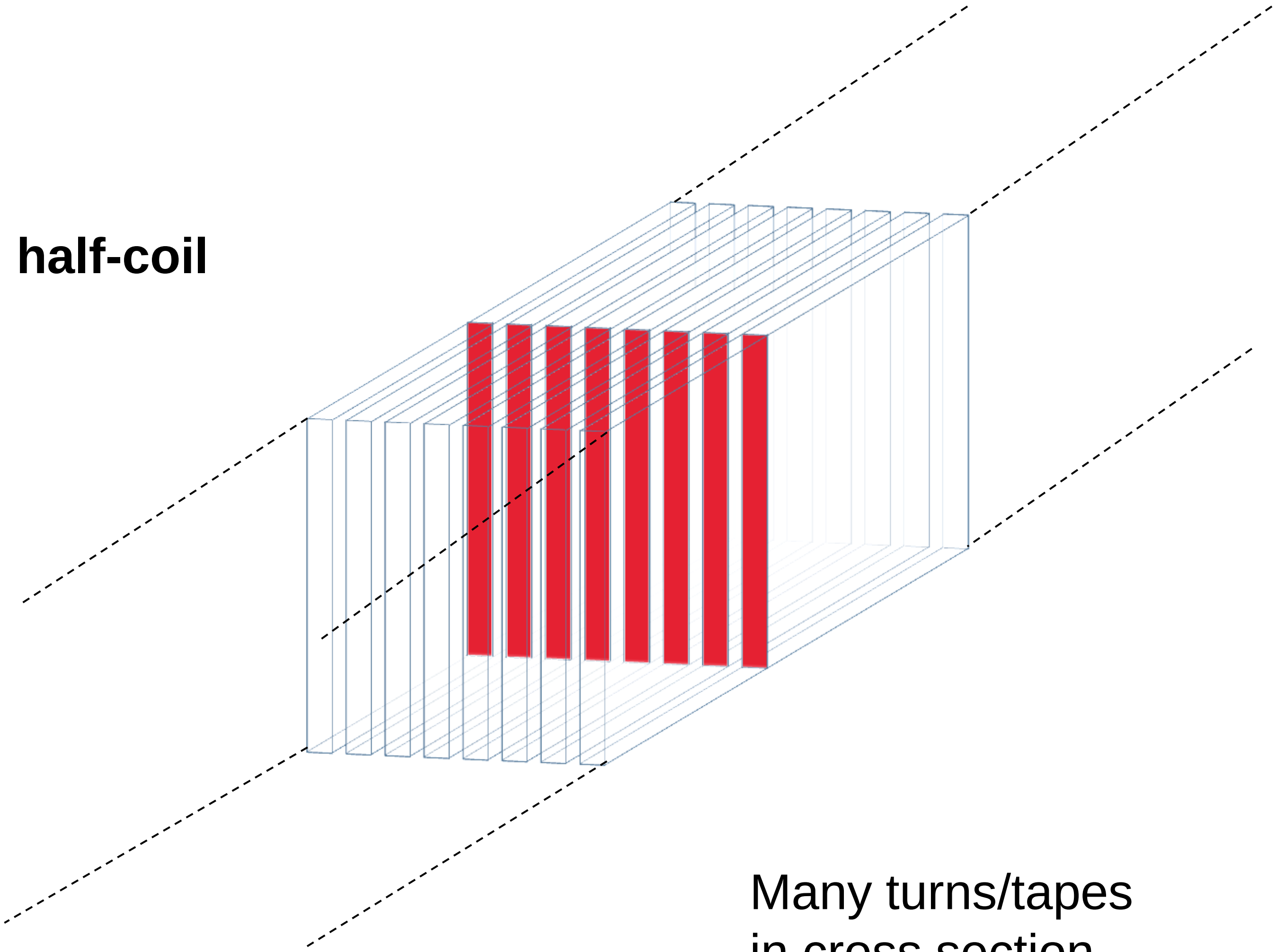
Racetrack coil





Application: Rotating machines

We consider **infinitely long half-coil** for benchmark



Many turns/tapes
in cross section

Tape geometry

5 tapes

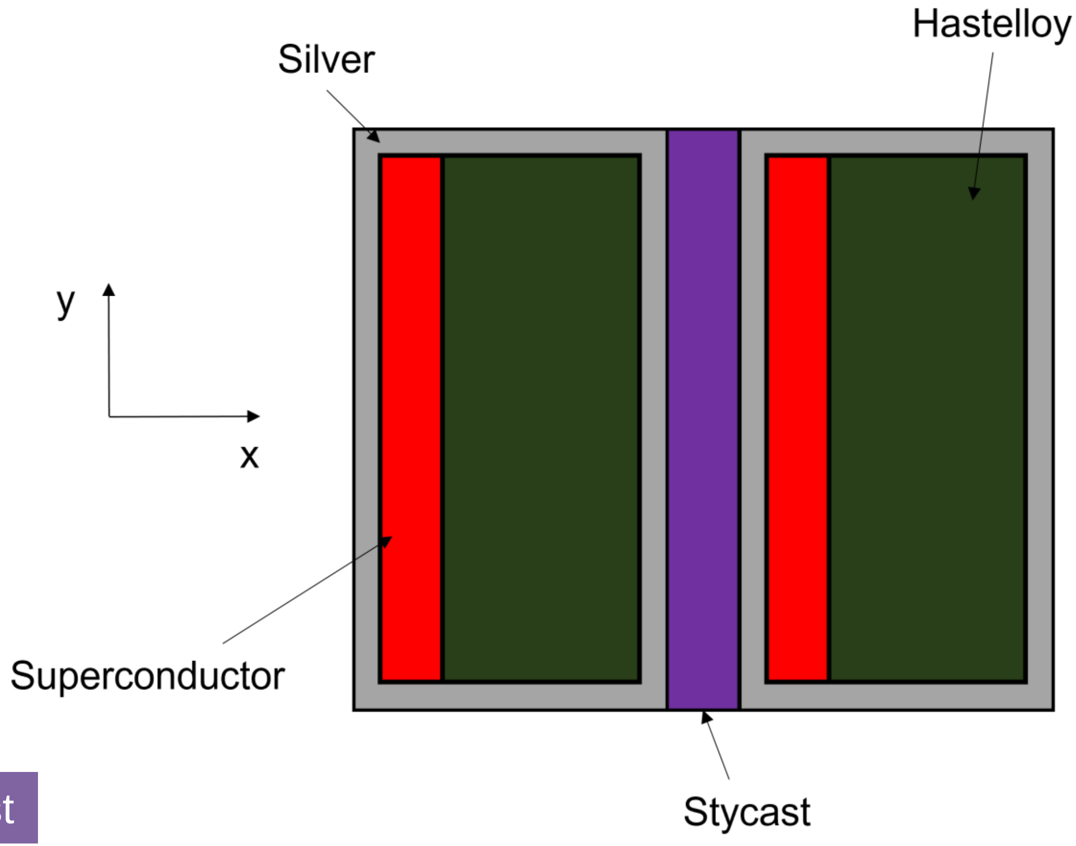
Width= 4 mm

Initial temperature = 77 K

Critical temperature = 92 K

Initial $J_c = 1.875 \times 10^{10}$ A/m^2

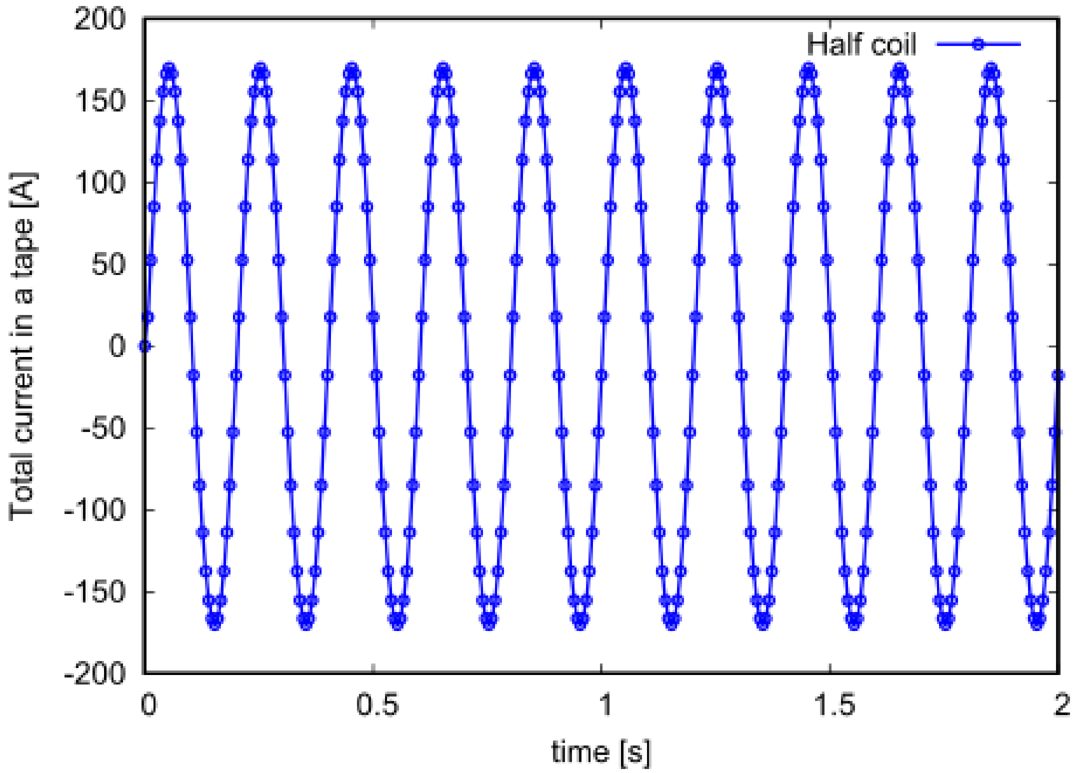
Homogenized C_v, k, and ρ



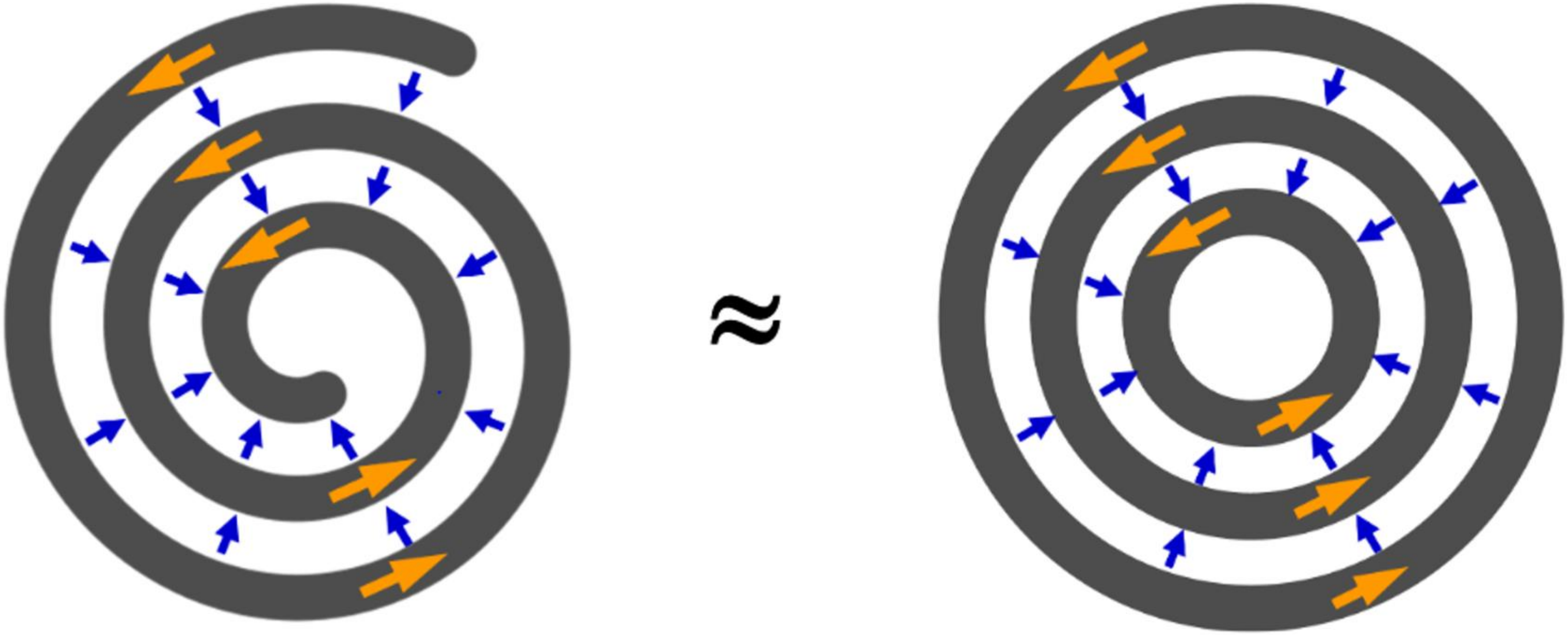
Electrical insulation between turns via Stycast

I_c = 150 A

Input : AC current (170 A and more, 5 Hz)



Pancake coil
(axisymmetric assumption)



Application: High field magnets

Tape geometry

5 tapes

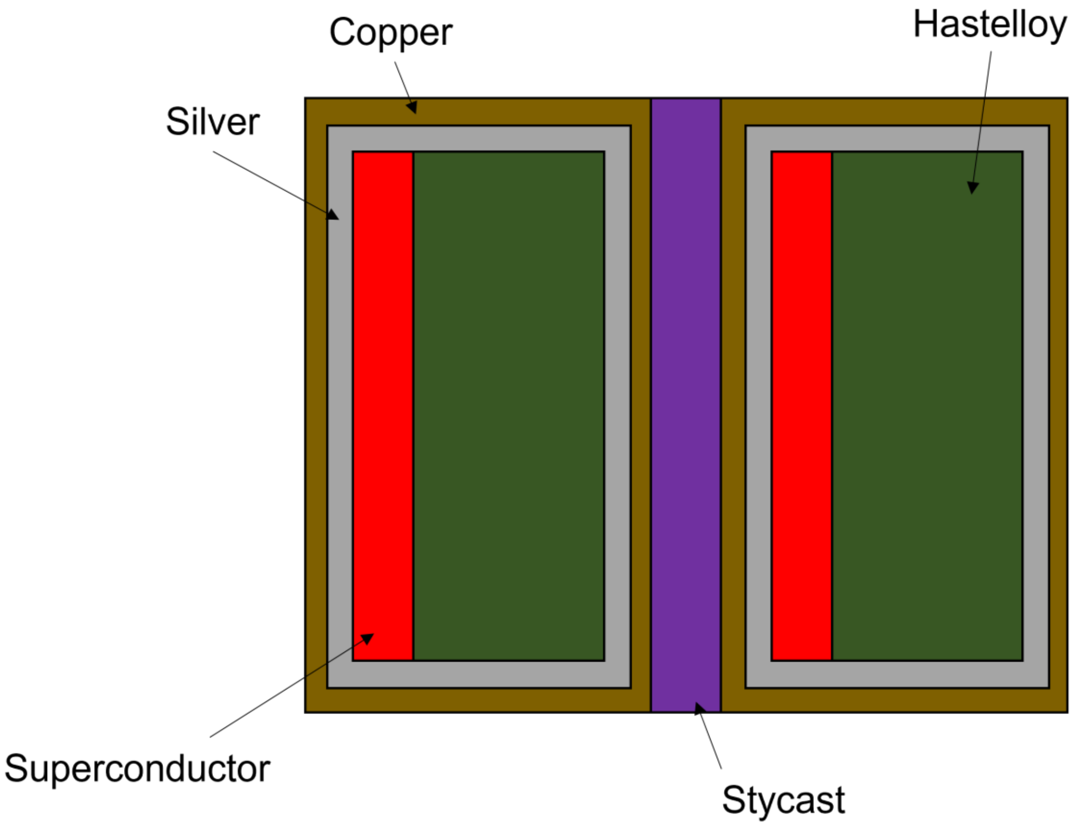
Width= 4 mm

Initial temperature = 77 K

Critical temperature = 92 K

Initial J_c = 1.875 x 10^{10} A/m^2

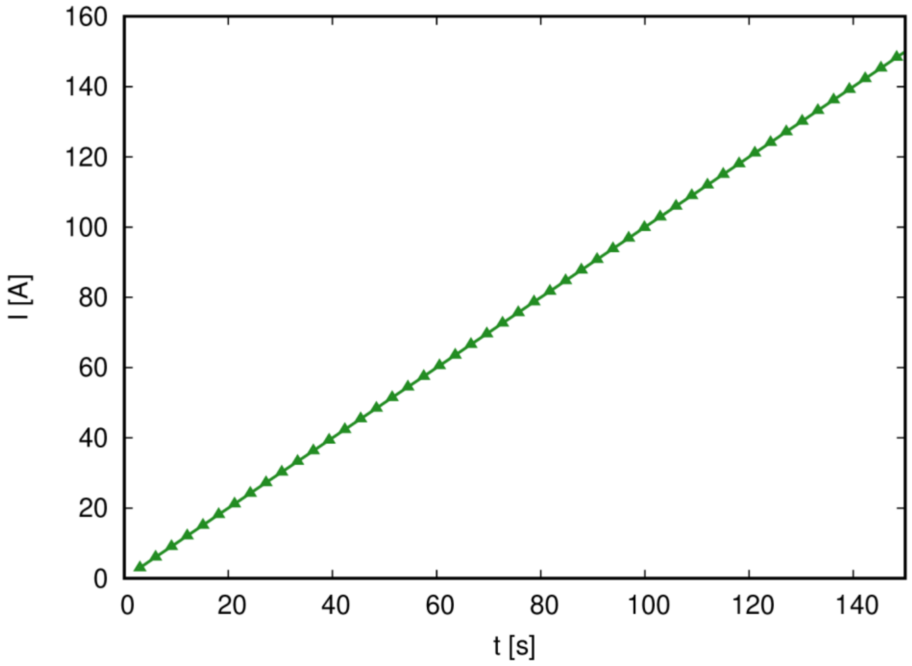
Homogenized C_v, k, and ρ



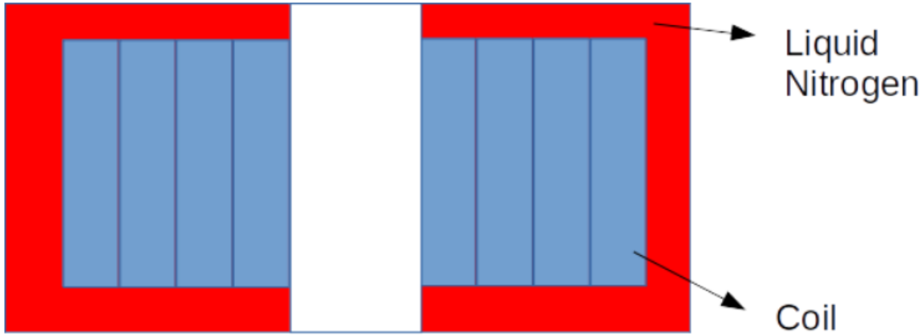
Electrical insulation between turns via Stycast

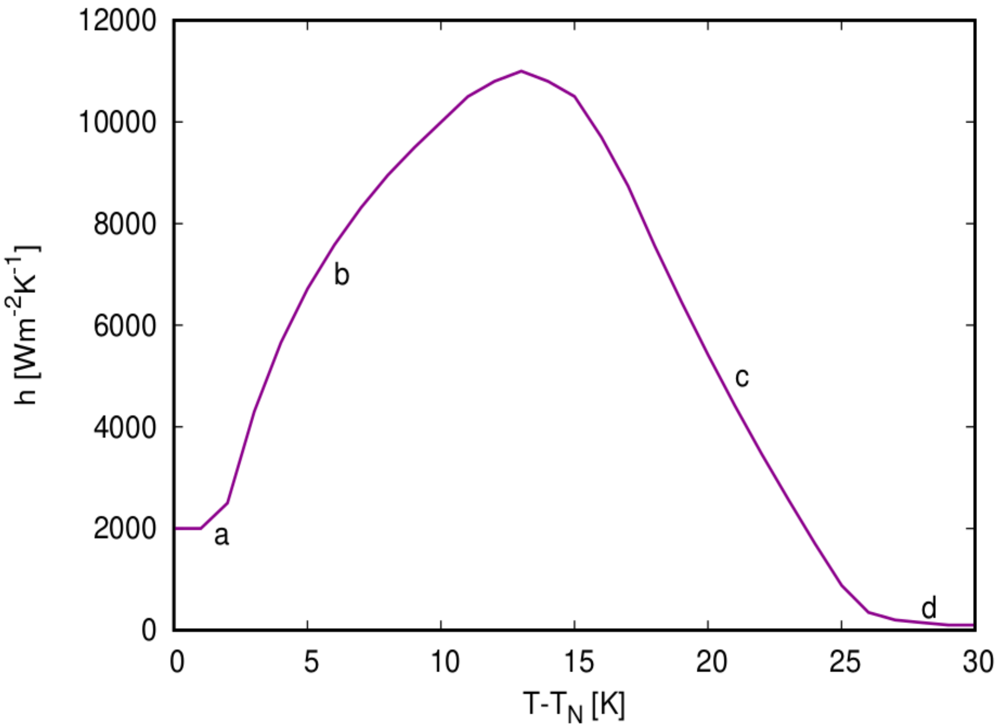
I_c = 150 A

Input : Current ramp (1 A/s) up to 160 A and more



Cooling





By Dr. Frederic Sirois
Polytechnique Montreal

Problem statements

Material properties

Homogenization

Numerical models

Benchmark results

Electrical and thermal properties

Material	Thickness [µm]	k [$\mathrm{W\,m^{-1}\,K^{-1}}$]	C_p [$\mathrm{J\,kg^{-1}\,K^{-1}}$]	ρ [$\Omega\,\mathrm{m}$]	ρ_m [$\mathrm{kg\,m^{-3}}$]
HTS	2	9	156.65	3×10^{-7}	6390
Ag	4	400	235	1×10^{-8}	10500
Hastelloy	100	7	425	1.2×10^{-6}	8940
Stycast	50	0.8	138.6	1×10^{13}	2290
Copper	20	489.56	195.98	2.288×10^{-9}	8960

Considered constant for simplification

Problem statements

Material properties

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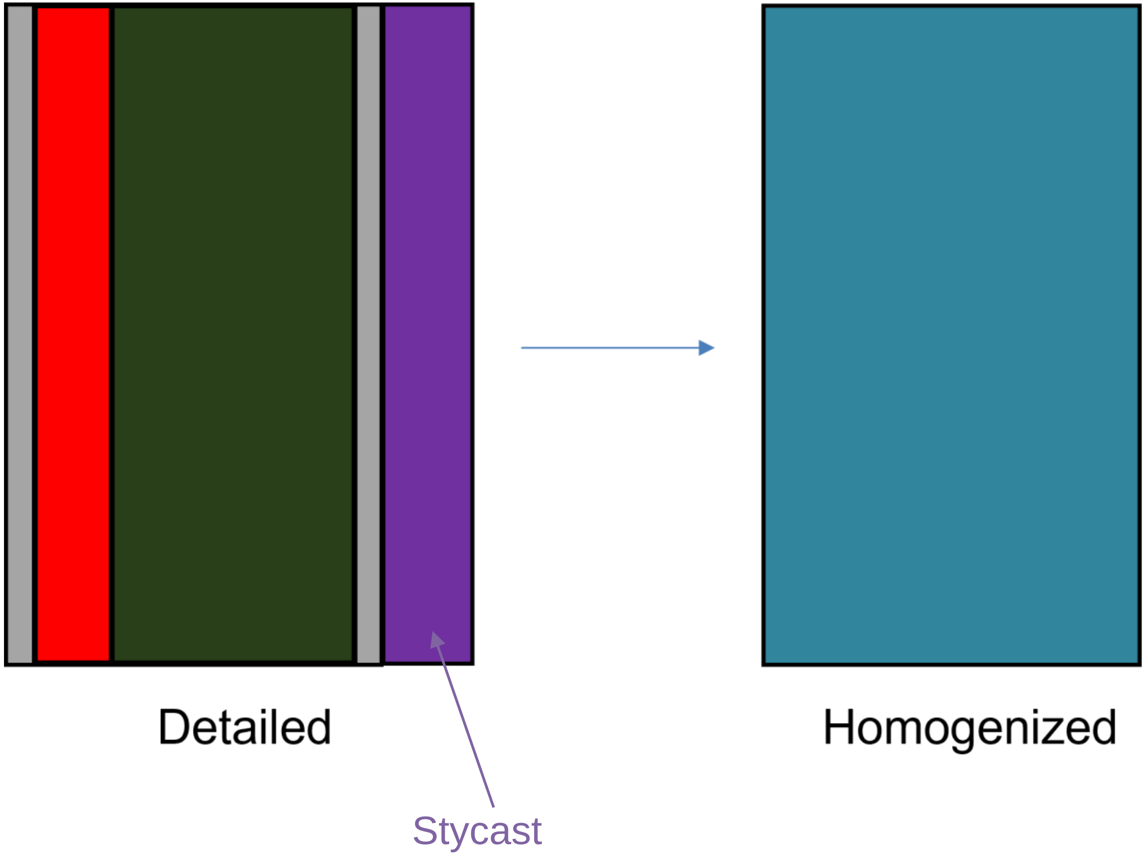
Homogenization of layers



Include Stycast or not?

Homogenized electrical properties

Total thickness

Normal conductivity

$$\sigma_{hom} = \frac{1}{d_T}\left[\frac{1}{\rho_{HTS}}d_{HTS} + \frac{1}{\rho_{Ag}}d_{Ag} + \frac{1}{\rho_{Hast}}d_{Hast} + \frac{1}{\rho_{Sty}}d_{Sty}\right]$$

Parallel resistivity

$$\rho_f(\mathbf{J}) = \begin{cases} \frac{1}{\sigma_{sc}(\mathbf{J})+\sigma_{hom}} & \text{if } T < T_c, and \\ \frac{1}{\sigma_{hom}} & \text{if } T \geq T_c\ . \end{cases}$$

Comes from power law

$$\mathbf{E} = \rho_f(\mathbf{J})\mathbf{J}$$

(Electric field)

Homogenized thermal properties

Thermal capacity

$$C_{v,hom} = \frac{d_{HTS}C_{v,HTS} + d_{Ag}C_{v,Ag} + d_{hast}C_{v,hast} + d_{sty}C_{v,sty}}{d_T}$$

Mass density

$$\rho_{m,hom} = \frac{d_{HTS}\rho_{m,HTS} + d_{Ag}\rho_{m,Ag} + d_{hast}\rho_{m,hast} + d_{sty}\rho_{m,sty}}{d_T}$$

$C_p = C_v/\rho_m$

Anisotropic conductivity

$$k_x = \frac{d_T}{\left(\frac{d_{HTS}}{k_{HTS}} + \frac{d_{Ag}}{k_{Ag}} + \frac{d_{hast}}{k_{hast}} + \frac{d_{sty}}{k_{sty}}\right)}$$

$$k_y = \frac{d_{HTS} \cdot k_{HTS} + d_{Ag} \cdot k_{Ag} + d_{hast} \cdot k_{hast} + d_{sty} \cdot k_{sty}}{d_T}$$

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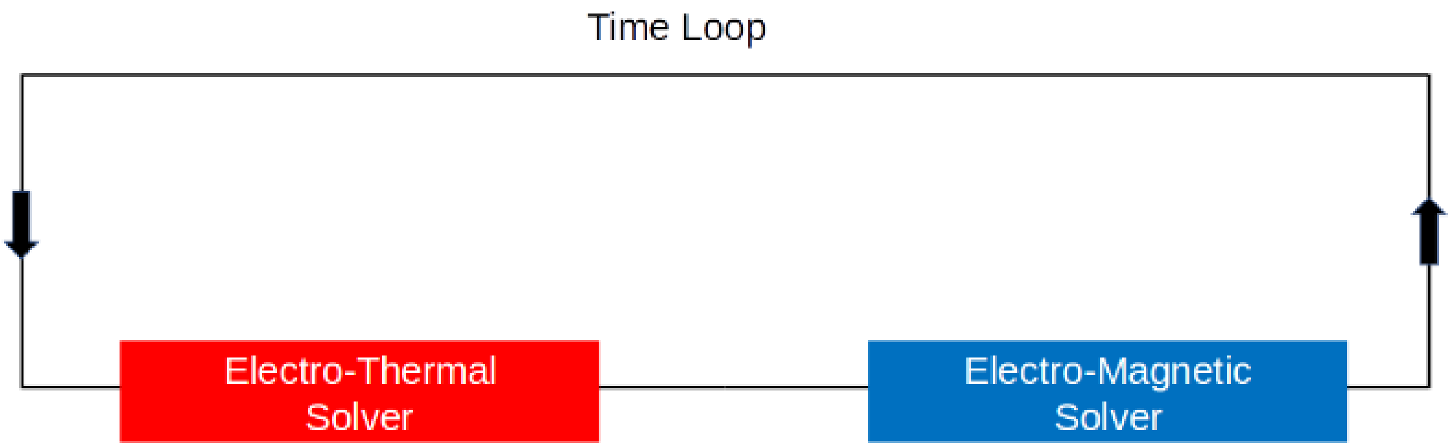
Different formulations and combinations

- **H** + FEM : For racetrack and pancake coils (Homogenized method).
- **H-A**, + FEM : For racetrack coil (Detailed and Homogenized methods).
- **H**-ϕ + FEM : For racetrack and pancake coils (Detailed and Homogenized methods). The racetrack coil results use GetDP and the pancake coil results uses COMSOL for this combination.
- **J-A**, + FEM : For racetrack coil (Homogenized method).
- MEMEP + FD : For racetrack and pancake coils (Homogenized method).
- MEMEP + METEP : For racetrack coil (Homogenized method).
- **T-A** + Equivalent lumped circuit : For racetrack coil (Homogenized method).

Coupling



Calculates T
Modifies $J_c(T)$

Calculates J
Modifies q(J)

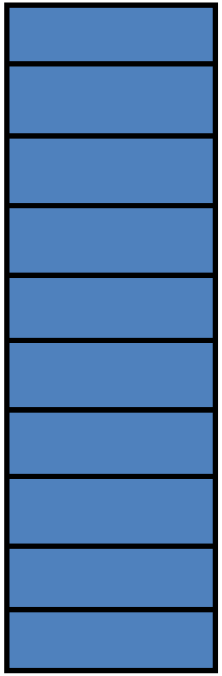
$$J_c(T) = J_c(T_N)\frac{T_c - T}{T_c - T_N}$$

q(J) = **E(J)**.J(T)

Standard mesh and inputs

Mesh elements in tape thickness: 1
Mesh elements in tape width: 50

Time step per cycle: 200 (racetrack)
Time step per second: 20 (pancake)



Problem statements

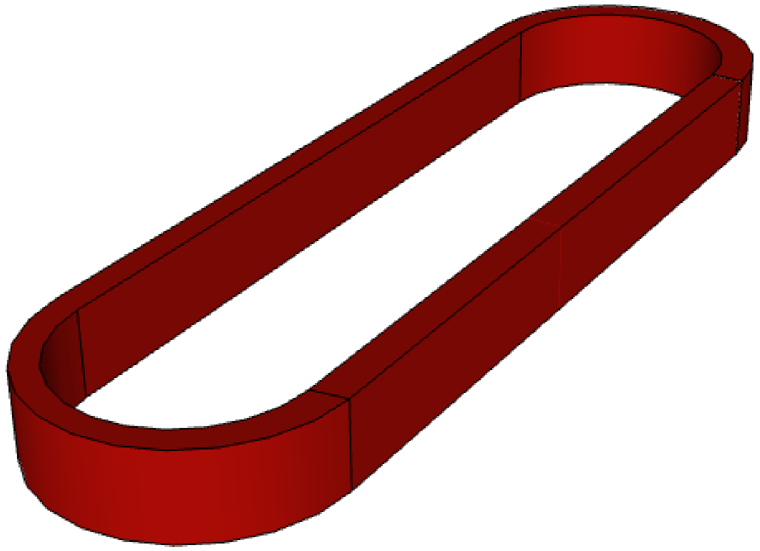
Material properties

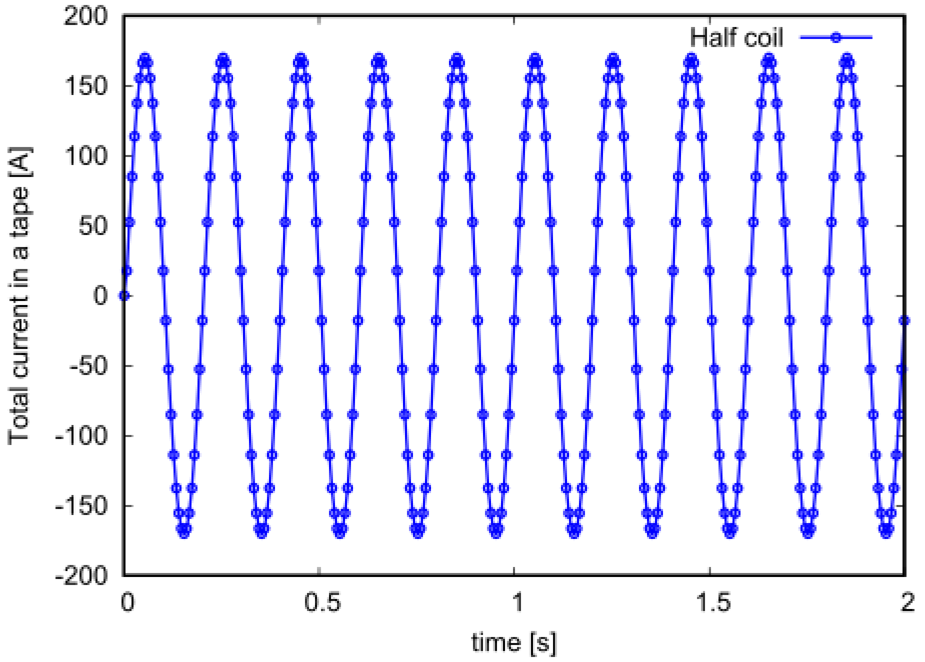
Numerical models

Benchmark results

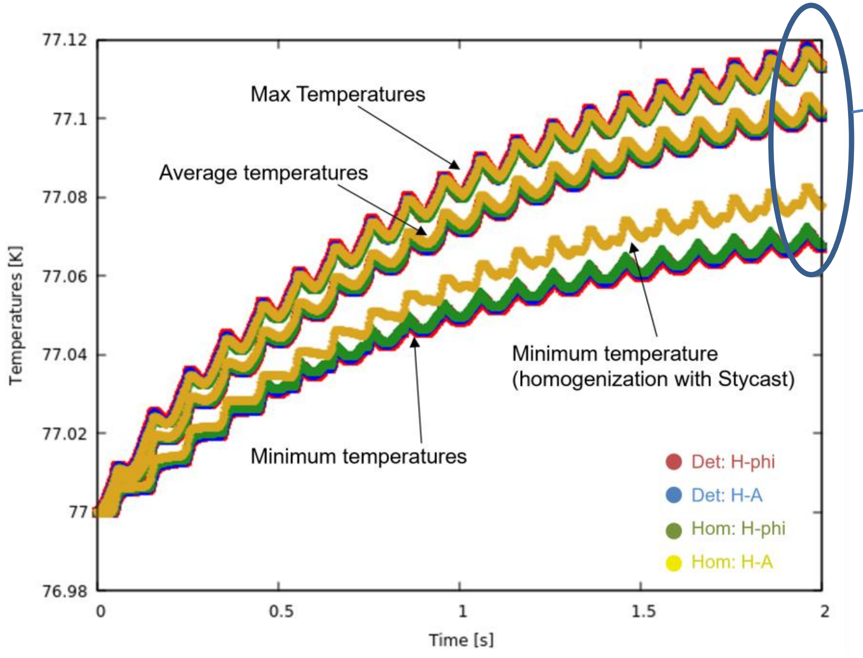
- Racetrack coil (Detailed vs Homogenized models)
- Racetrack coil (Homogenized models)
- Pancake coil (Detailed vs Homogenized models)

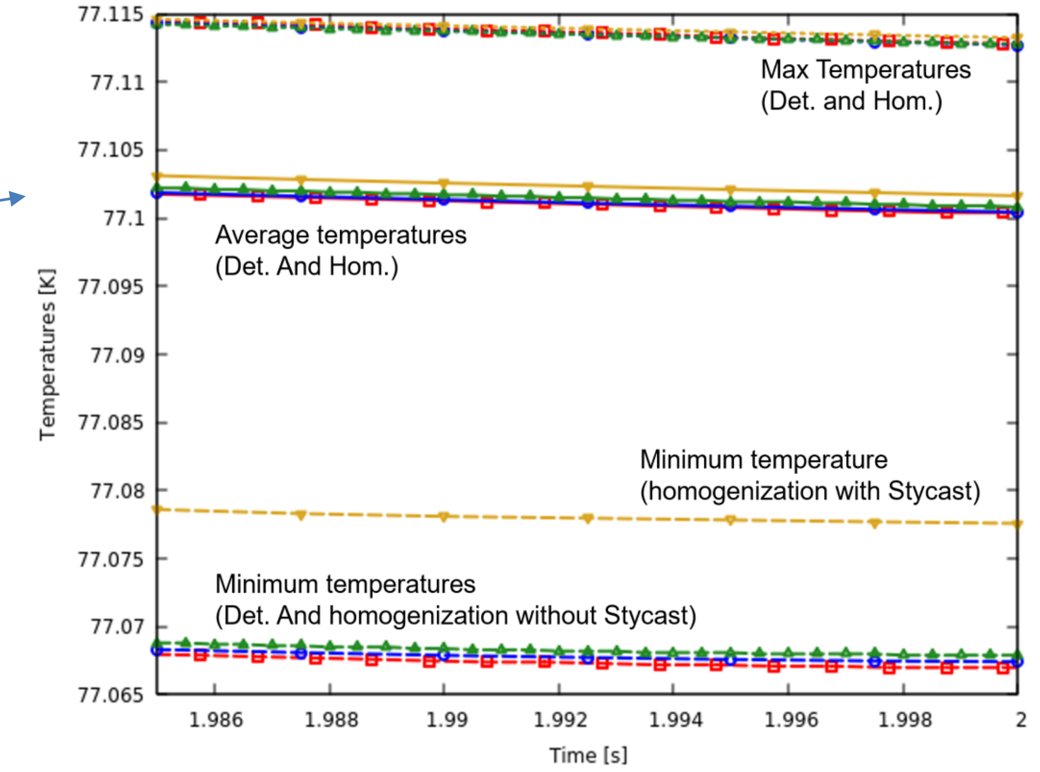
Racetrack coil





Only minimum temperature is affected with Stycast in homogenization

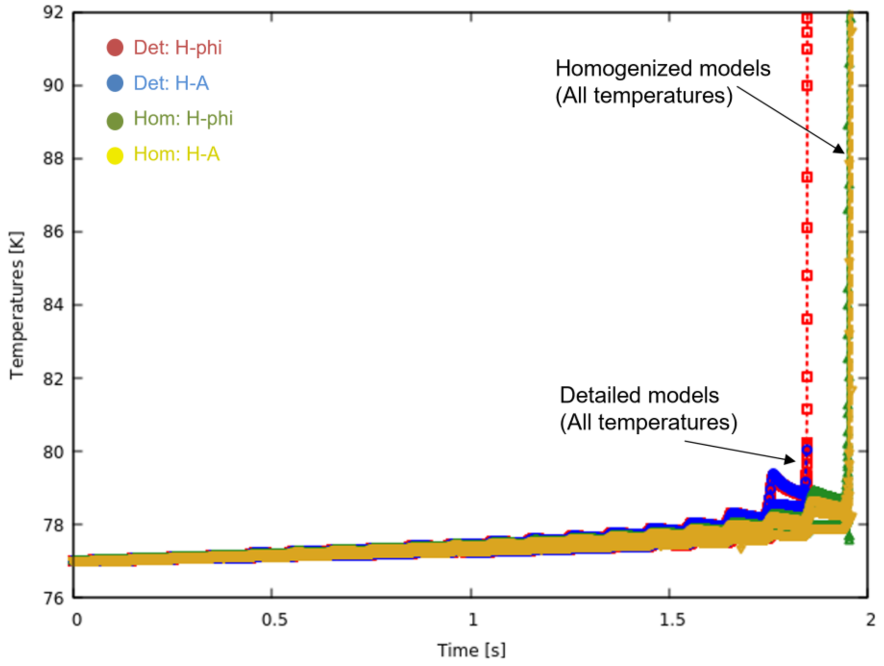


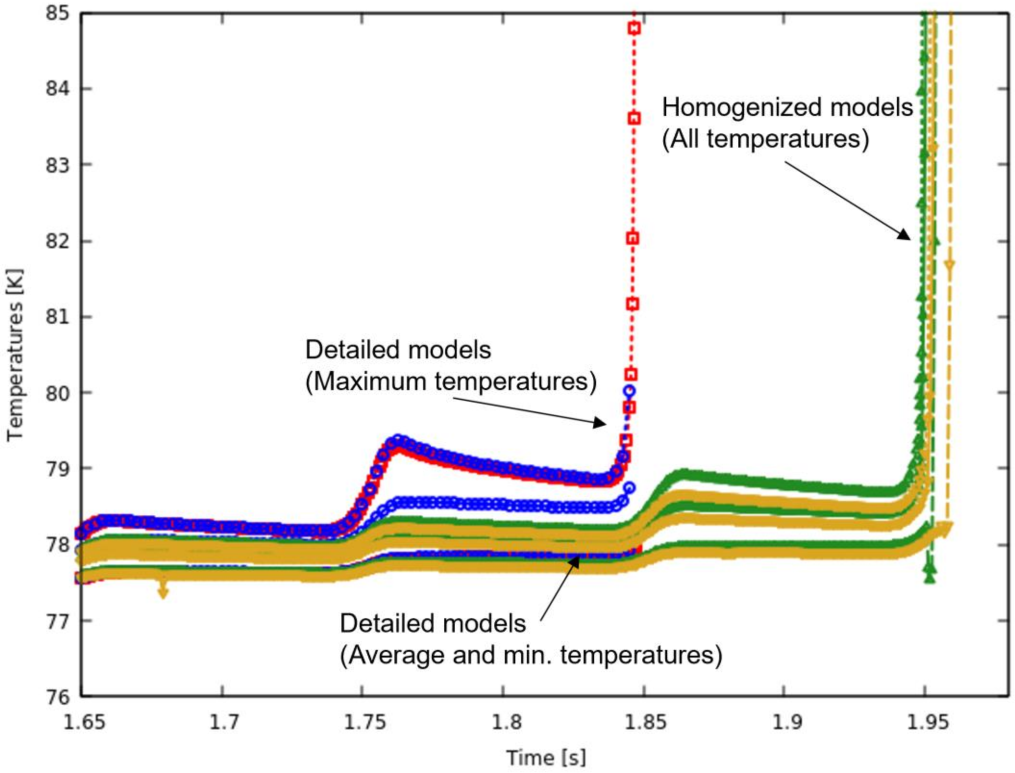


Very good agreement in maximum and average temperatures

180 A

Maximum temperature matters for studies like quench





Detailed model predicts quench slightly earlier?

Problem statements

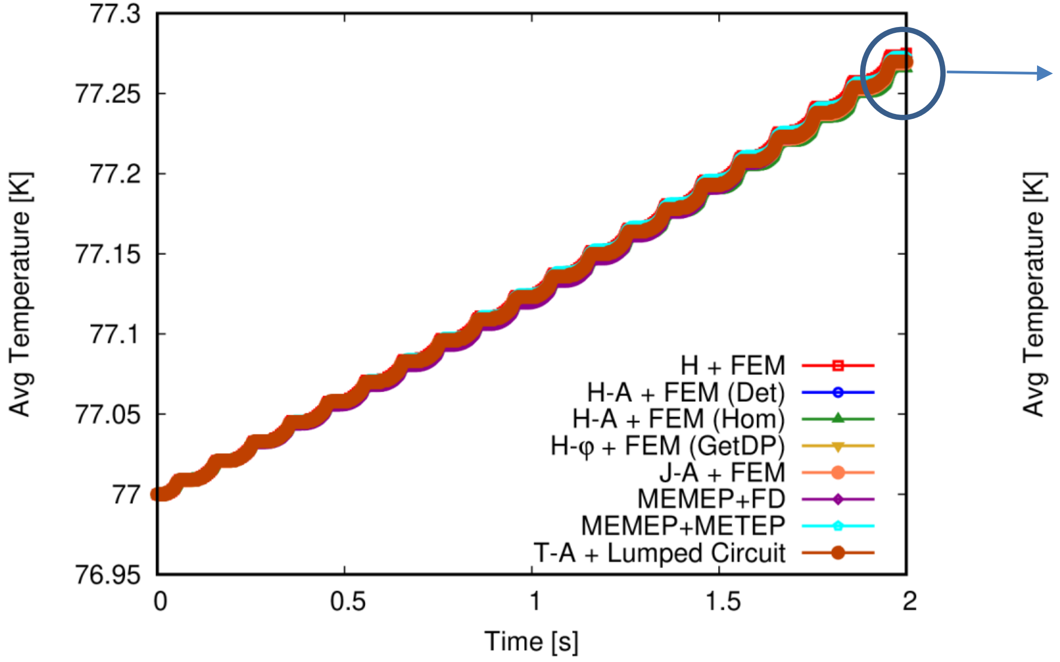
Material properties

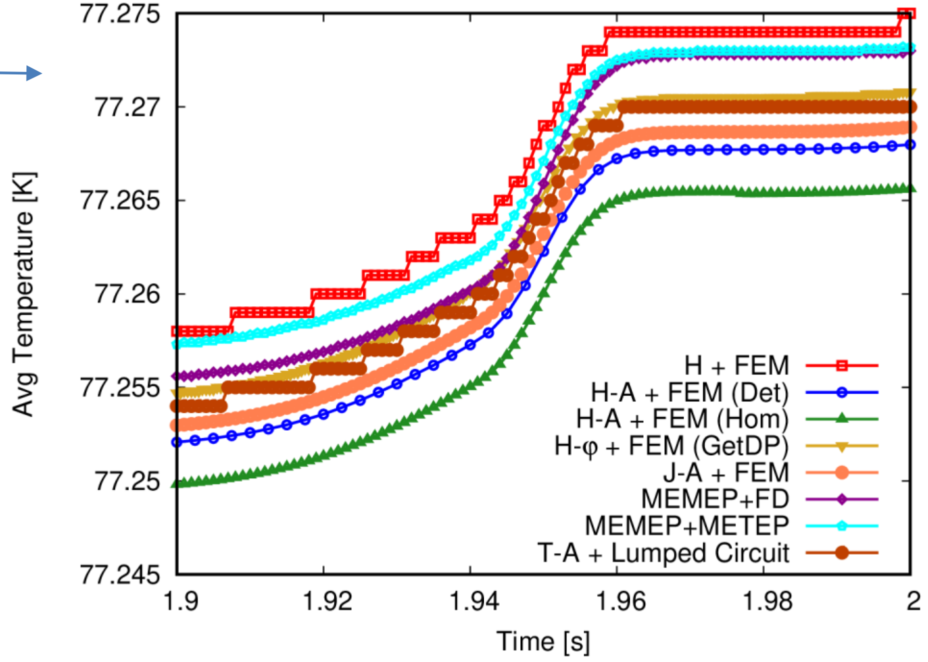
Numerical models

Benchmark results

- Racetrack coil (Detailed vs Homogenized models)
- Racetrack coil (Homogenized models)
- **Pancake coil (Detailed vs Homogenized models)**

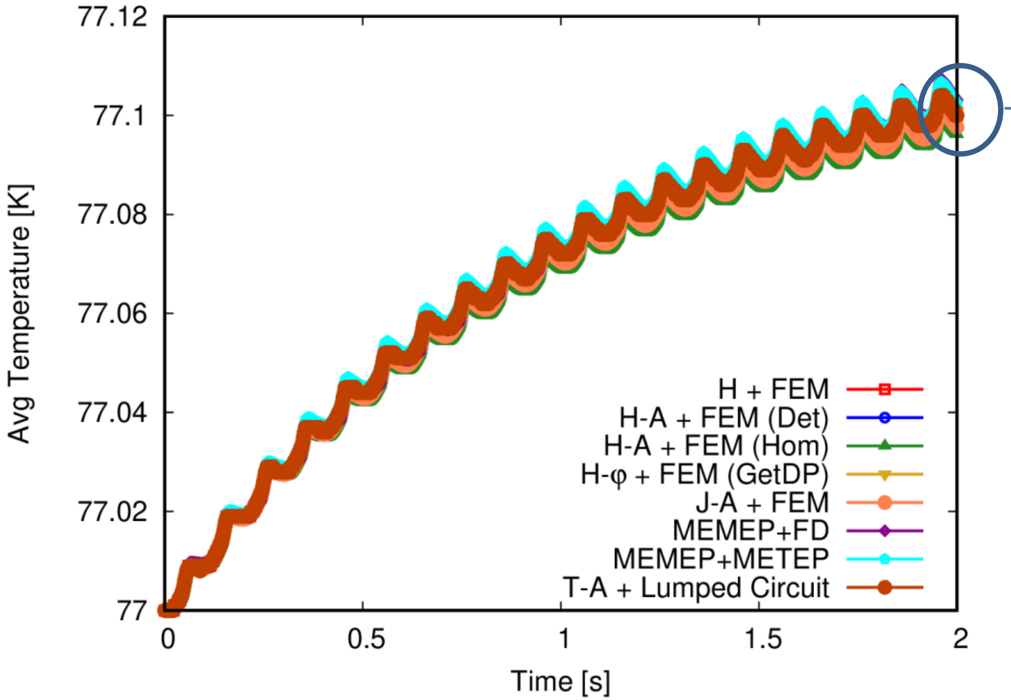
170 A (adiabatic)

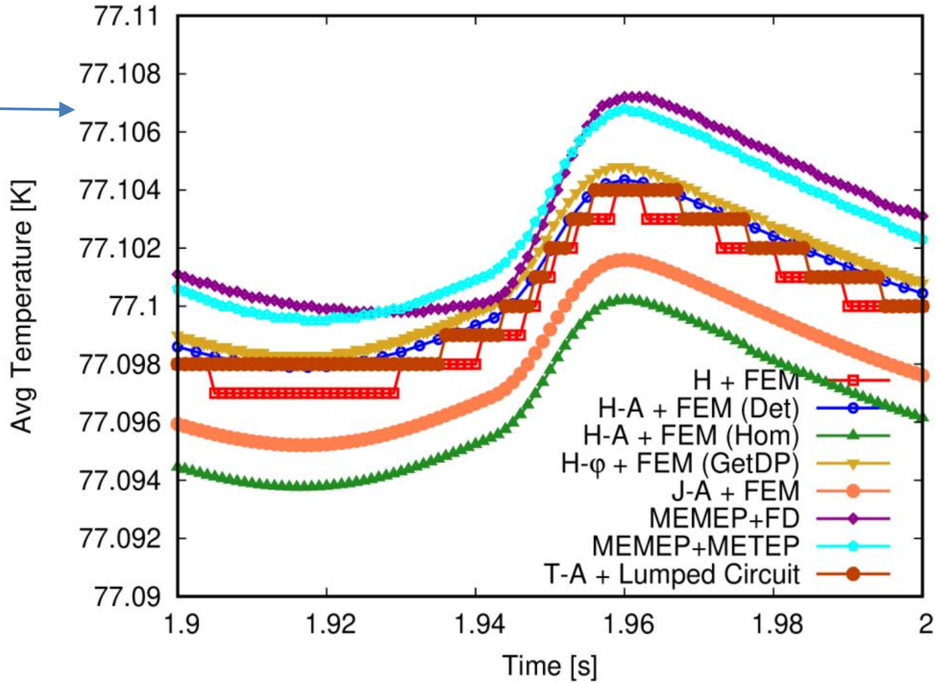




Very good agreement!

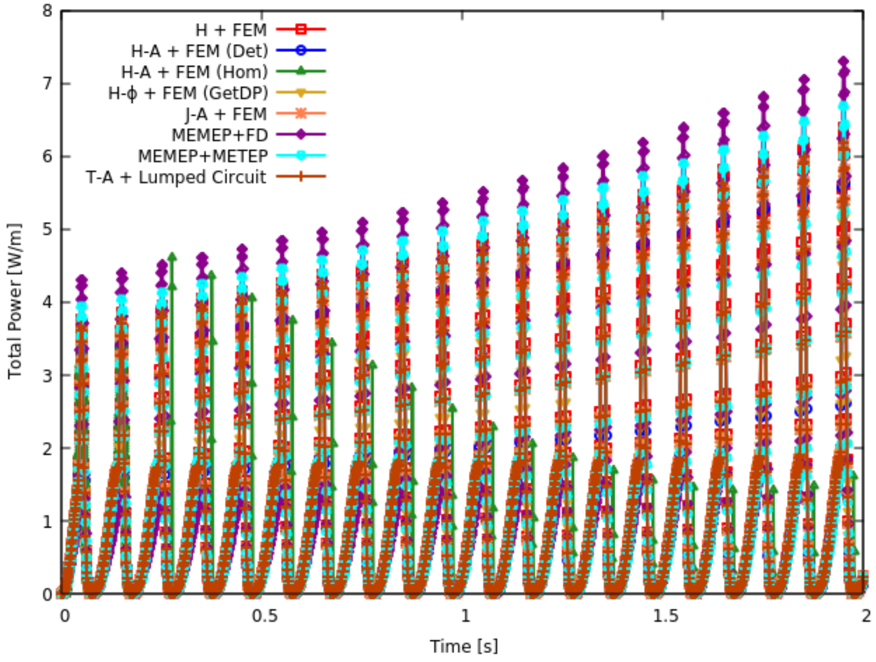
170 A (cooling)



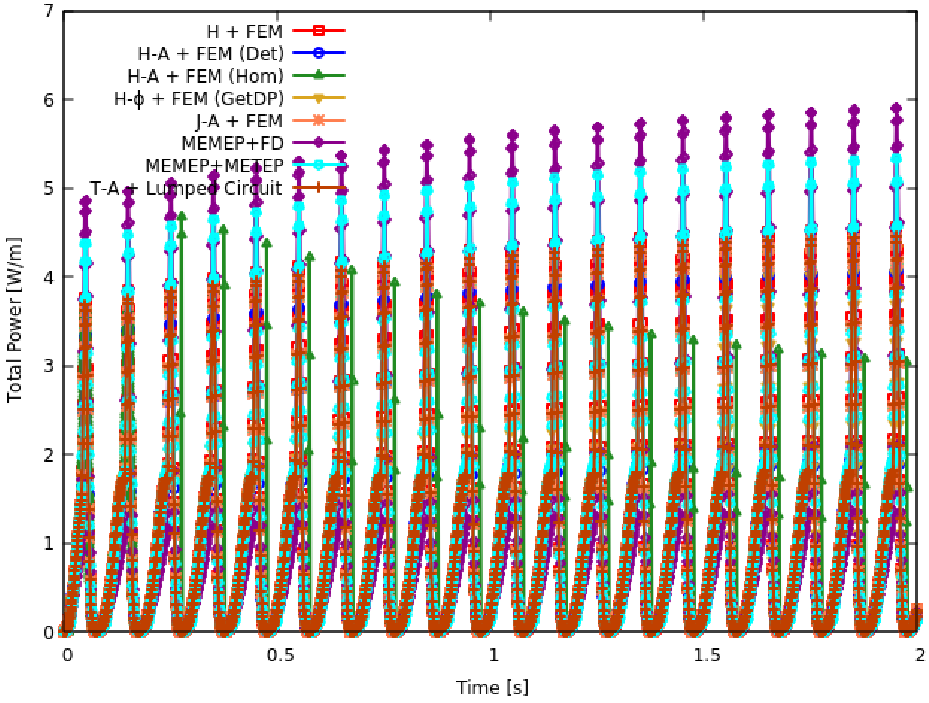


Very good agreement!

Total Power

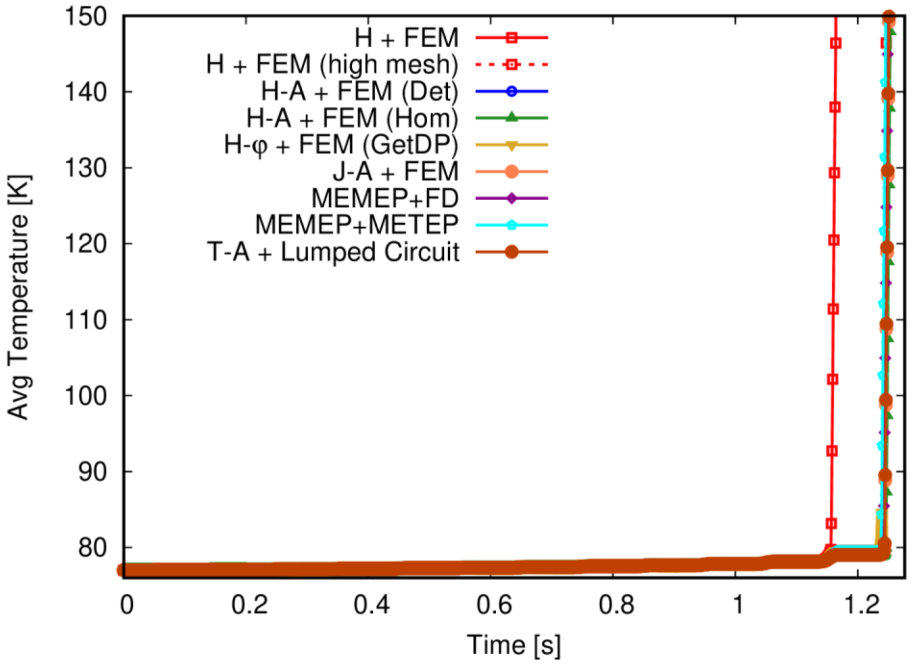


170 A (adiabatic)

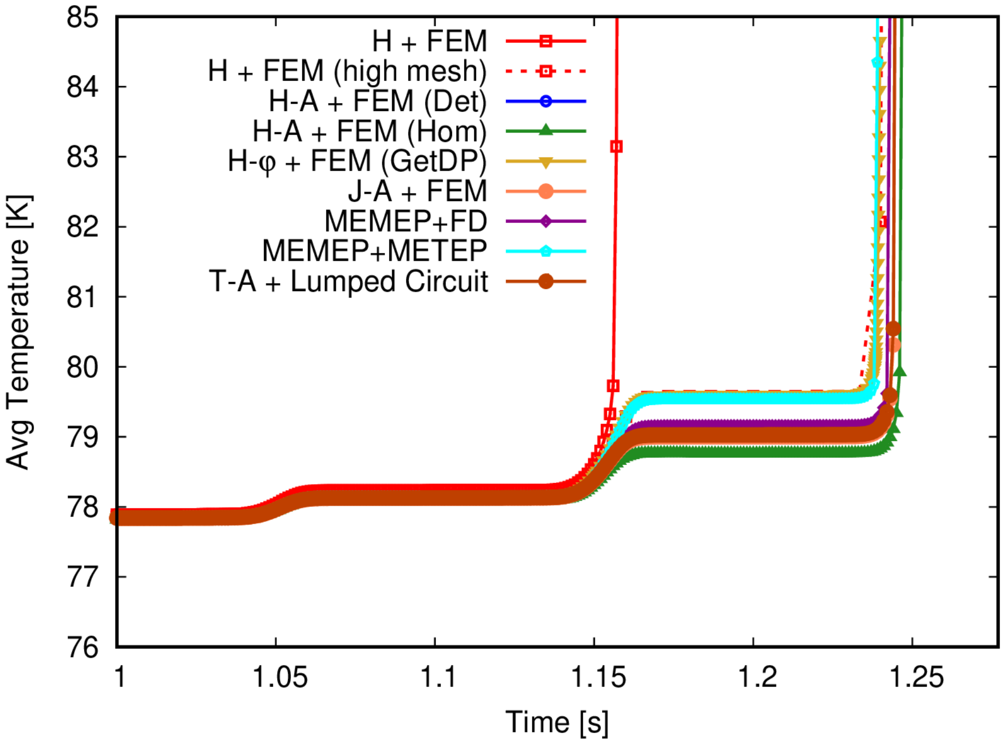


170 A (cooling)

180 A (adiabatic)



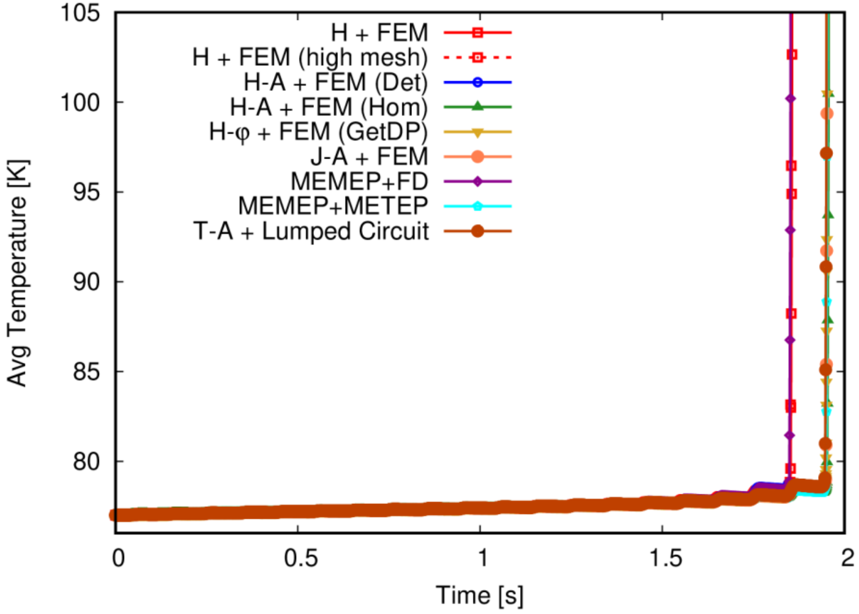
Minor difference due to mesh

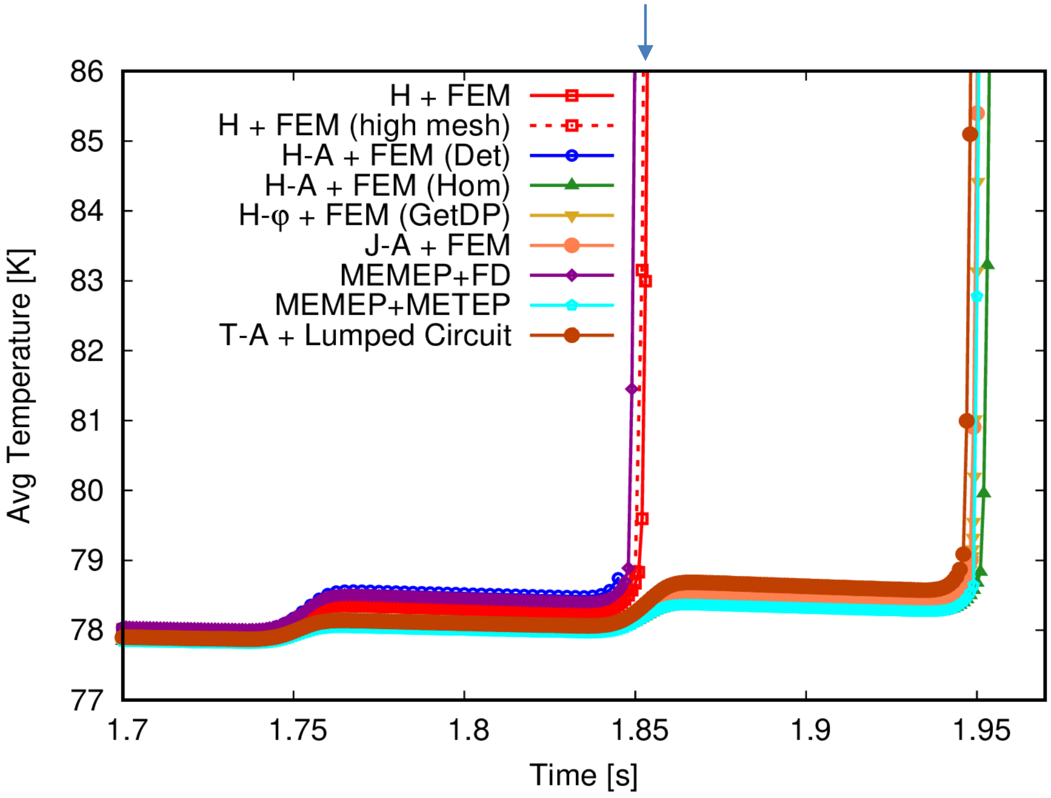


Good agreement!

180 A (cooling)

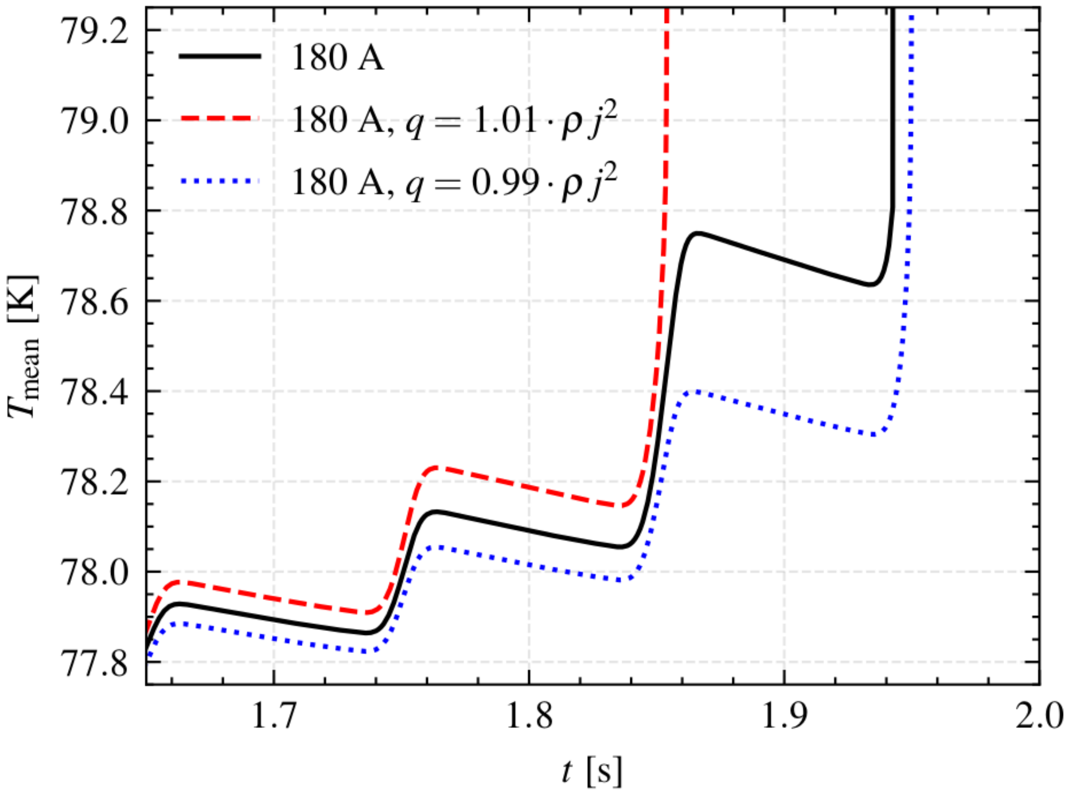
Some homogenized models also predict quench at 1.85 s, like detailed models!





Differences arise between models
But why?

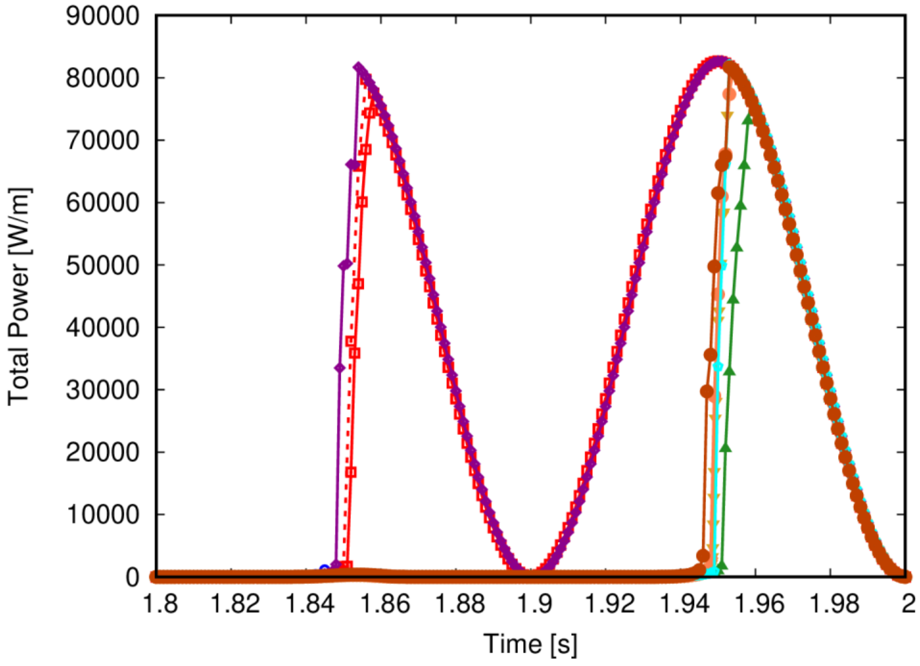
1 % difference in power accuracy initiates quench differently

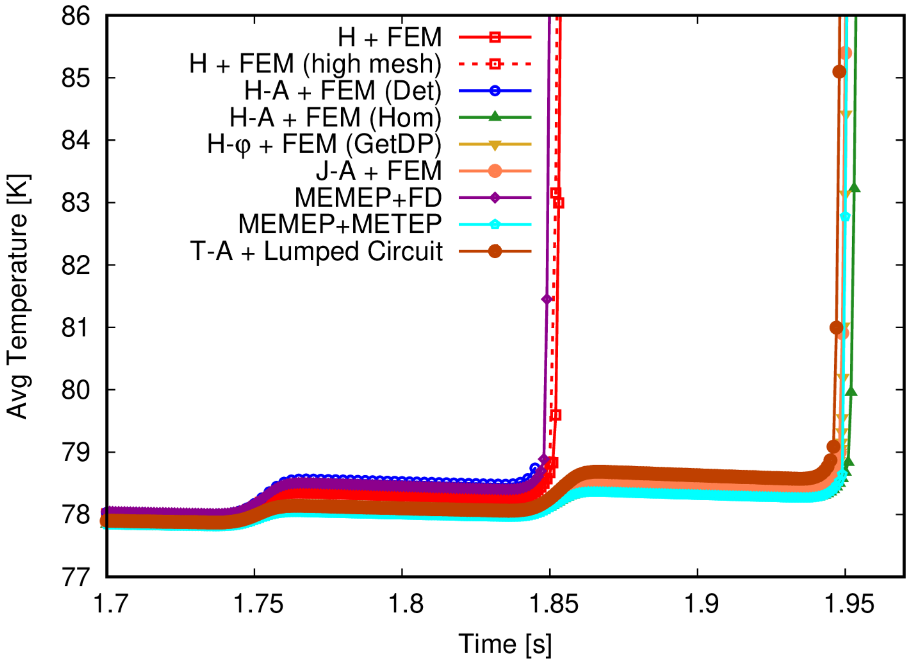


By H-phi + FEM

1 % difference in power accuracy initiates quench differently

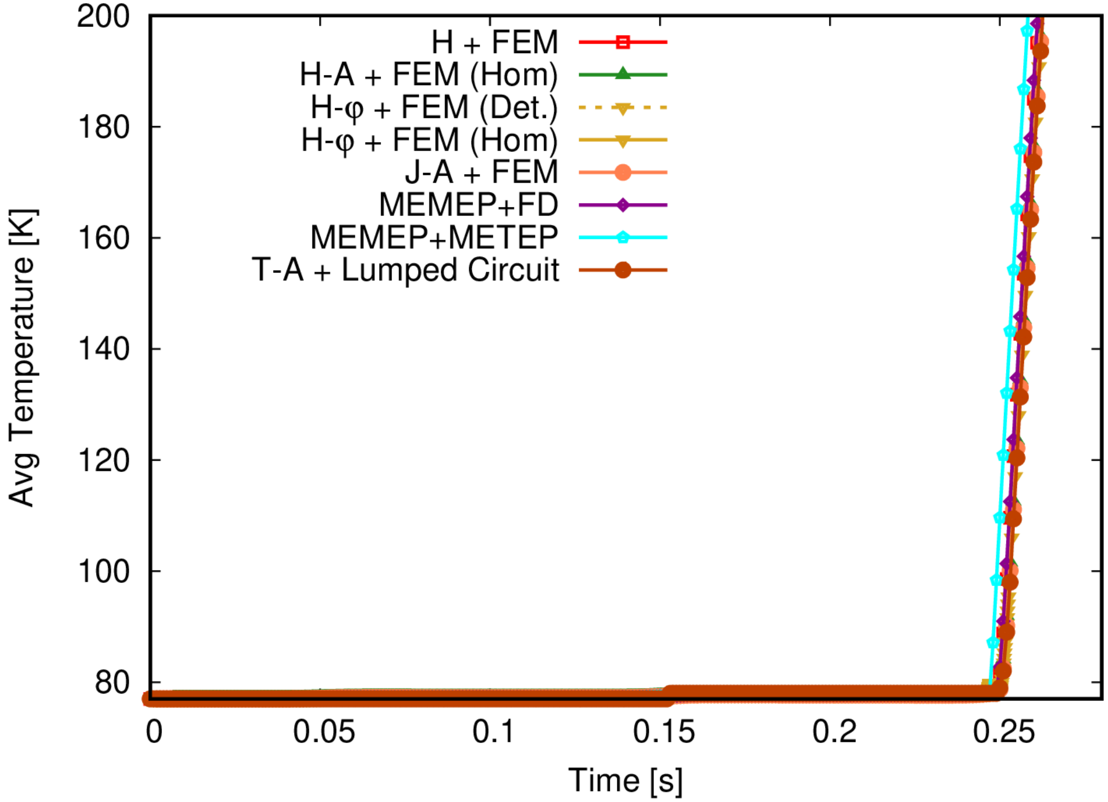
Even a very small difference in models can be important for some cases!





Total power **Average temperature**

190 A (cooling)



Very good agreement!

Problem statements

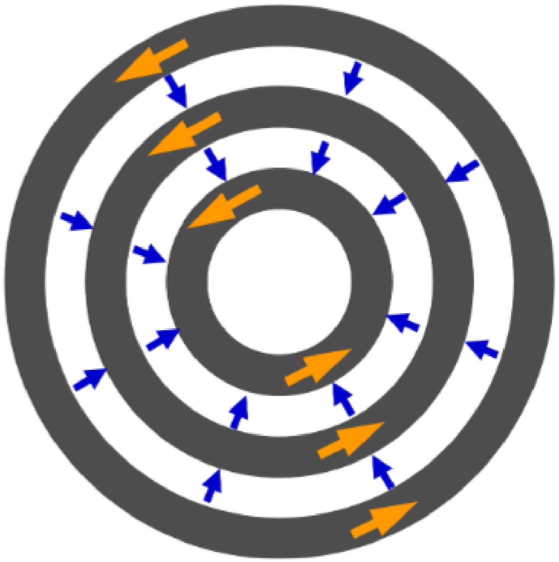
Material properties

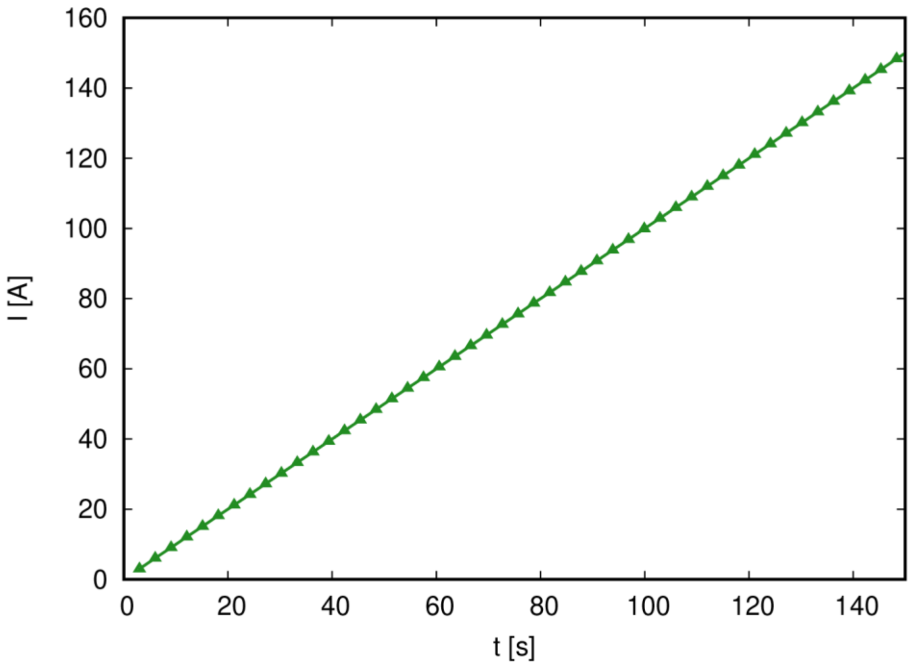
Numerical models

Benchmark results

- Racetrack coil (Detailed vs Homogenized models)
- Racetrack coil (Homogenized models)
- Pancake coil (Detailed vs Homogenized models)

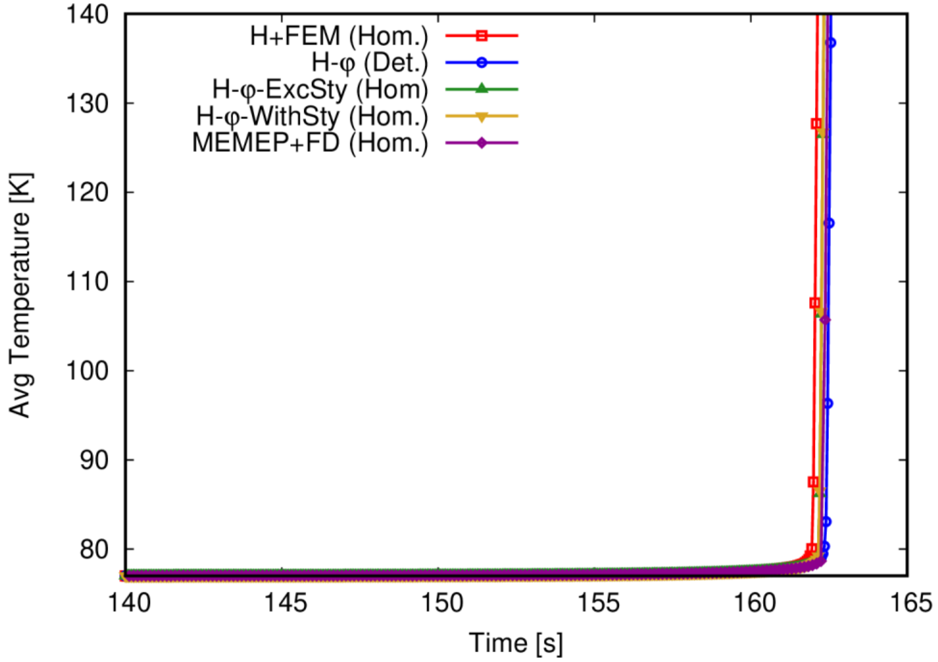
Pancake coil





Adiabatic case

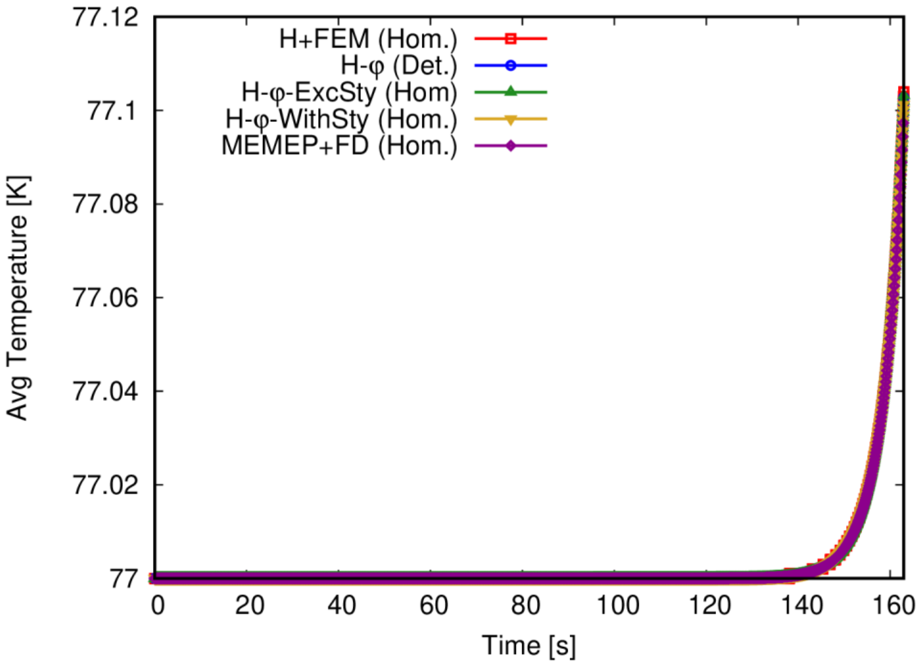
Quench is initiated faster due to tougher conditions
(even after including copper!)

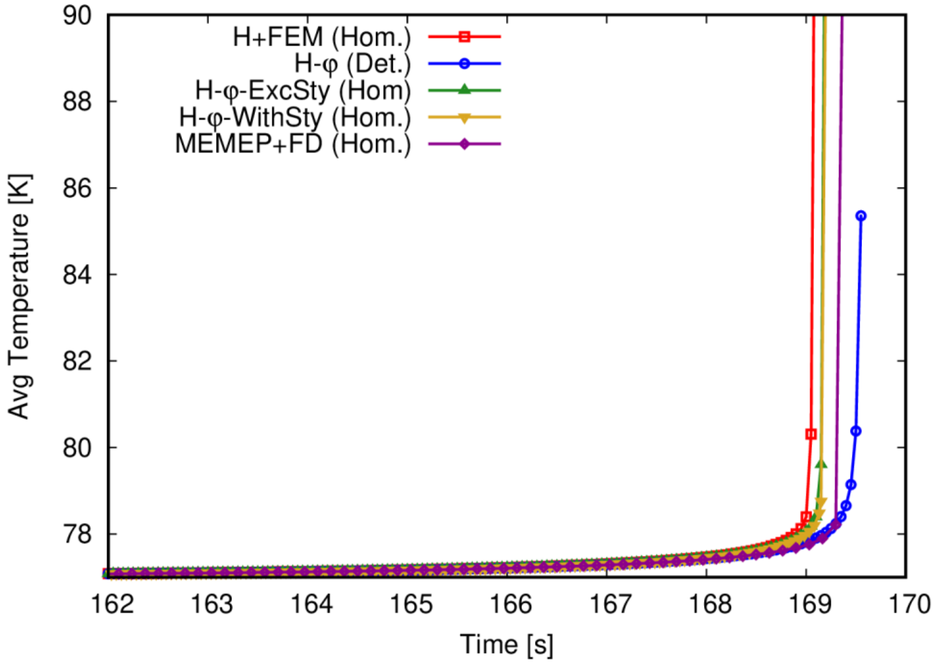


Very good agreement!

Cooling case

Quench is predicted slightly earlier than detailed model





Very good agreement!

Conclusion

Various models are benchmarked for homogenized method

- Very good agreement with detailed method
- Very good agreement between each other

Including Stycast in homogenization only affects minimum temperature

Even 1-2% difference between models can affect quench prediction

Future work

More development of models and comparison with experiments
Publication of paper (stay tuned!)

Join our collaboration or questions? Contact: ☺

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Thank you!

Questions?

Extras

180 adia total power