Thermal-hydraulic models for HTS power-transmission cables: status and needs

S. Viarengo, D. Placido, L. Savoldi

MAHTEP Group, Department of Energy "Galileo Ferraris", Politecnico di Torino, Italy

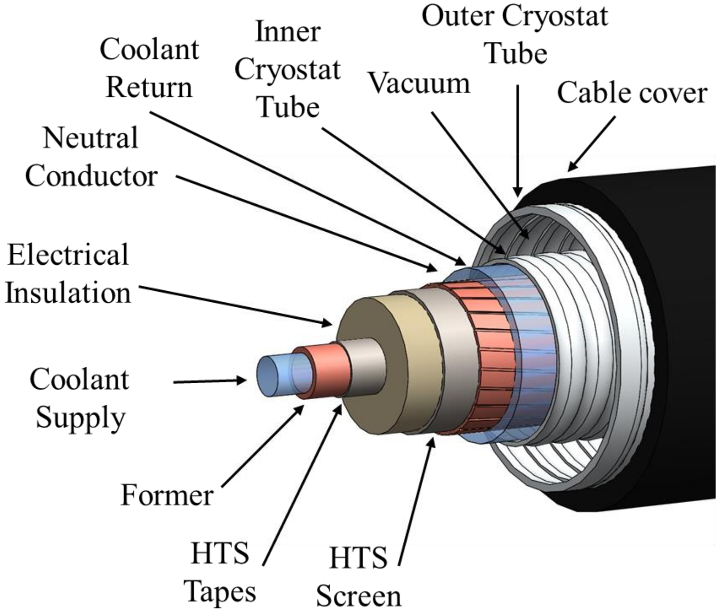
Outline

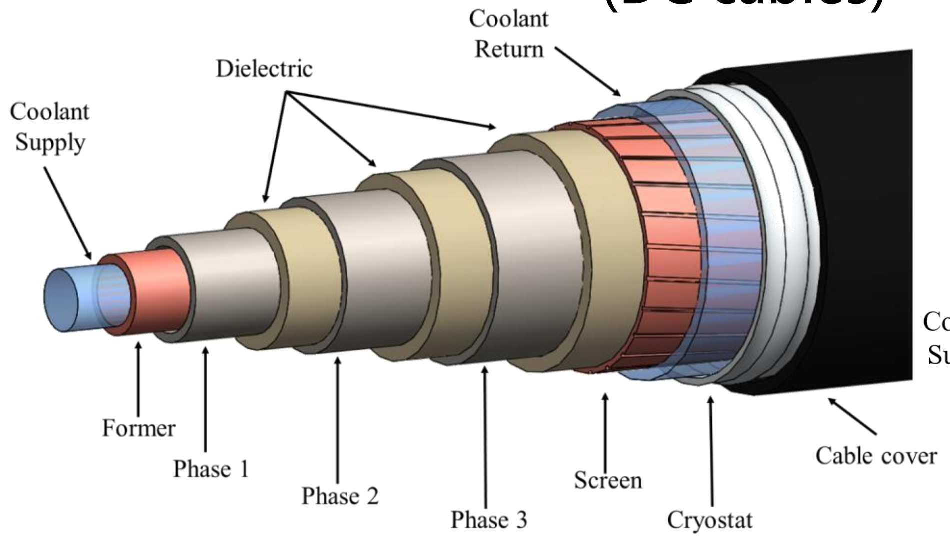
- HTS cables for power transmissions:
  - Use and design
  - Materials
- Models:
  - 1D (+1D)
  - 2D
  - 3D
- Model needs
- Conclusions

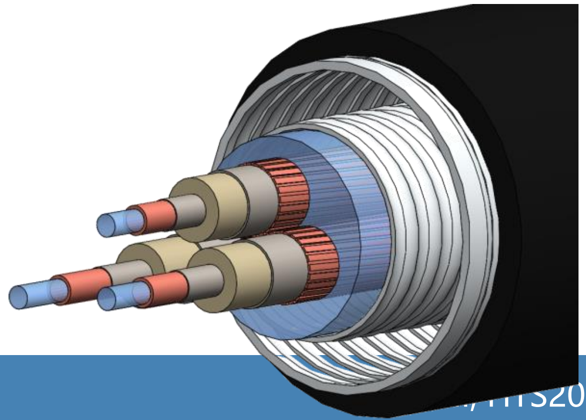
HTS cables for power transmission

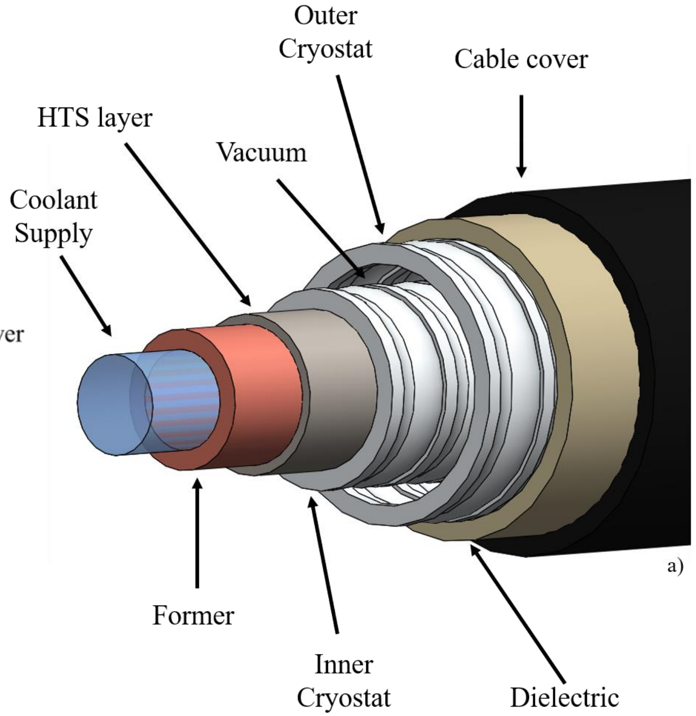
- SC transmission lines (SCTL):
  - High power AC transmission or distribution lines: TRL = 7 (*)
  - DC lines: TRL = 5 (*)

- SC transmission cables (SCTC):
  - Shipboard and aircraft applications (DC cables)









(*) *H. Thomas, Renew. Sust. Energ. Rev., 2016*

Aim of this work

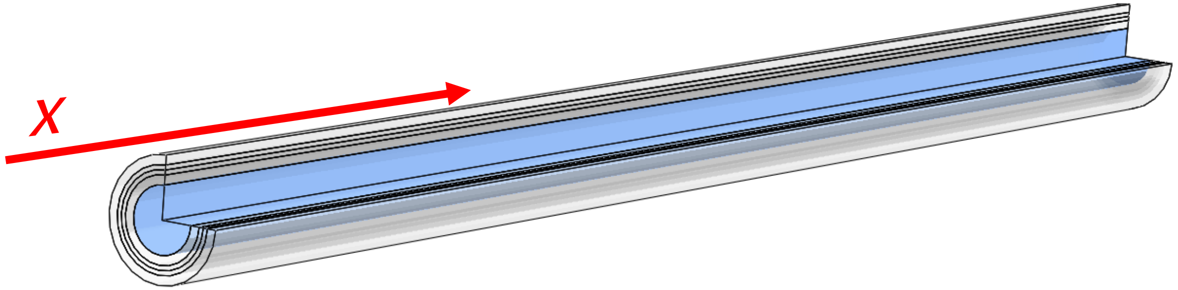
- Technical feasibility already demonstrated, but no long SCTL are currently in operation

- Substantial cost reduction + improvement of the system safety and reliability needed to reach TRL 9

→ Availability of reliable numerical models for the design, optimization and performance assessment in normal and off-normal conditions?

Models: 1D (axial) - I

- Only for the coolant:



$$\dot{m} c_p \frac{dT_{sup/rf}}{dx} = \pm \dot{q}(x) + \frac{\dot{q}_{el}}{2} + \dot{q}_0$$

[S. Fuchino et al., IEEE TAS 2002]

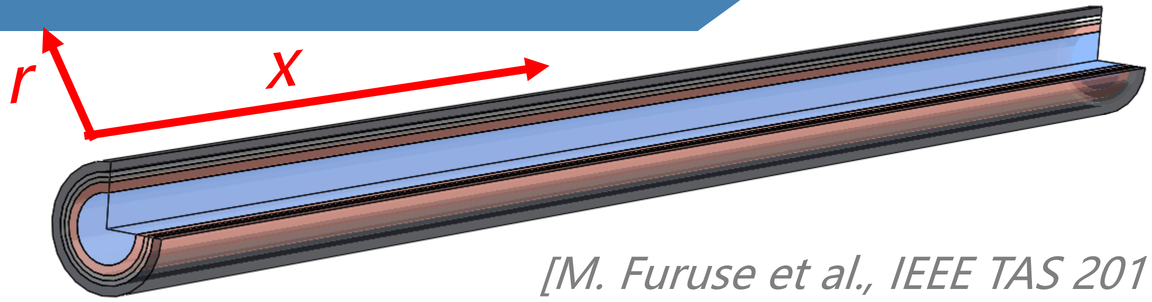
$$\begin{cases} \frac{\dot{m}_s}{\rho} \cdot \left(\frac{\partial p}{\partial T} - \rho \frac{\partial w}{\partial T} \right) \cdot \boldsymbol{\frac{dT}{dx}} + \frac{\dot{m}_s}{\rho} \cdot \left(\frac{\partial p}{\partial \rho} - \rho \frac{\partial w}{\partial \rho} \right) \cdot \boldsymbol{\frac{d\rho}{dx}} + \dot{Q}_{GEN_{int}} + \dot{Q}_{HS_{ext}} = 0 \\ -\frac{\dot{m}_s}{\rho} \cdot \frac{\partial p}{\partial T} \cdot \boldsymbol{\frac{dT}{dx}} + \frac{\dot{m}_s}{\rho} \cdot \left(\frac{\dot{m}_s^2}{\rho^2} - \frac{\partial p}{\partial \rho} \right) \cdot \boldsymbol{\frac{d\rho}{dx}} - \dot{m}_s \cdot g \cdot \sin\vartheta - \frac{\dot{m}_s}{\rho} \cdot \frac{P_{fl}}{A_{fl}} \boldsymbol{\tau_{fl}} = 0 \end{cases}$$

$$\dot{m}_s = \rho \cdot v$$

[G. Angeli et al., IEEE TAS 2017]

Models: 1D (axial) - II

For the coolant and the solids:



[M. Furuse et al., IEEE TAS 2011]

$$\begin{cases} \frac{\partial w}{\partial t} + v\frac{\partial w}{\partial x} = \frac{1}{V_{fld}\rho_{fld}}\dot{Q} \\ \rho c \frac{\partial T_i}{\partial t} = k\frac{\partial^2 T_i}{\partial x^2} + \dot{Q}_{in} - \dot{Q}_{out} \\ \frac{dp}{dx} = -\frac{2f\rho_{fld}v^2}{d_e} \end{cases}$$

[Y. Sato et al., IEEE TAS 2015]

[T. Yasui et al., IEEE TAS 2017]

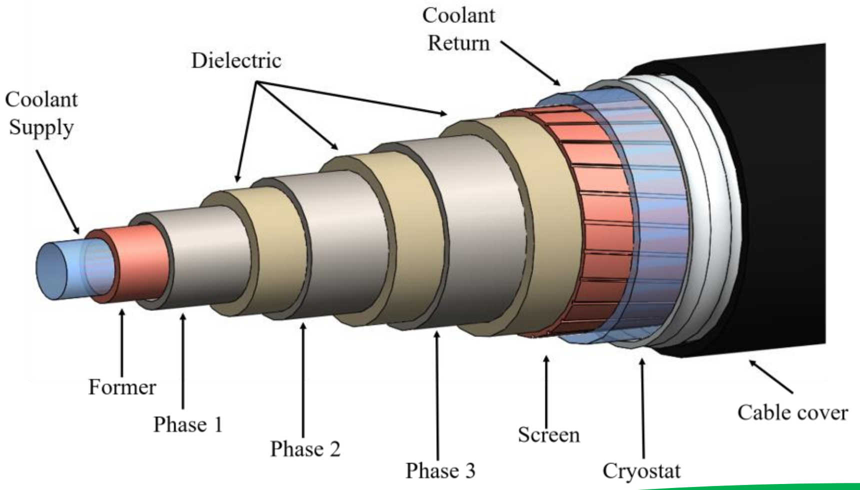
- Sinda/fluint network model [W. Choi et al., Energies 2020]

- Simulink model, including transient coupled conduction equations for solids, and conservation laws for fluids along each pipe segment, including 2-phase and compressibility effects:

$$\left(\frac{\partial \rho_i}{\partial p_i}\right)_{u_i}\frac{dp_i}{dt} + \left(\frac{\partial \rho_i}{\partial e_i}\right)_{p_i}\frac{du_i}{dt} + \rho_f\frac{d\chi_f}{dt} + \rho_{fg}\frac{d\chi_{fg}}{dt} + \rho_g\frac{d\chi_g}{dt} = \frac{\dot{m}_{i,in} - \dot{m}_{i,out}}{V_i}$$

[S. Yang et al., IEEE TAS 2021]

Models: 1D (radial) and 1D + 1D (radial + axial)



$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\dot{Q}}{k}$$

[Z. Zhou et al., IEEE TAS 2013]
[G. Del-Rosario-Calaf et al., IEEE TAS 2013]

$$\frac{d^2 T_\eta}{dr_\eta^2} + \frac{1}{r_\eta}\frac{dT_\eta}{dr_\eta} + \frac{\dot{Q}_\eta}{k_\eta} = 0$$

[WTB De Sousa et al., IEEE TAS 2018]

ALSO COUPLED TO

$$\frac{dT_{sl/rl}}{dx} = \pm \frac{h_{sl/rl} \cdot \pi \cdot \tilde{d} \cdot \left(T_{w_{sl/rl},z} - T_{sl/rl}\right)}{\dot{m} \cdot \bar{c_p}} - \frac{\dot{q}_{ext}}{\dot{m} \cdot \bar{c_p}}$$

\+ supply line
– return line

return line only

[E. Shabagin et al., Cryogenics, 2017]
[D. Kottonau et al., IEEE TAS 2019]
[WTB De Sousa et al., IEEE TAS 2019]

OR TO
Single phase, compressible 1D
Mass // momentum // energy conservation laws along the axis

[N. Hu et al., Physica C, 2011]

Models: 2D (Discrete)

- Volume Element Model (VEM):
  - Dimensional:

[J.A. Souza et al., IEEE TAS 2011]
[J.C. Ordonez et al., IEEE TAS 2013]
[N.G. Suttel et al., IEEE TAS 2017]
[D. I. Doukas et al., IEEE TAS 2017]

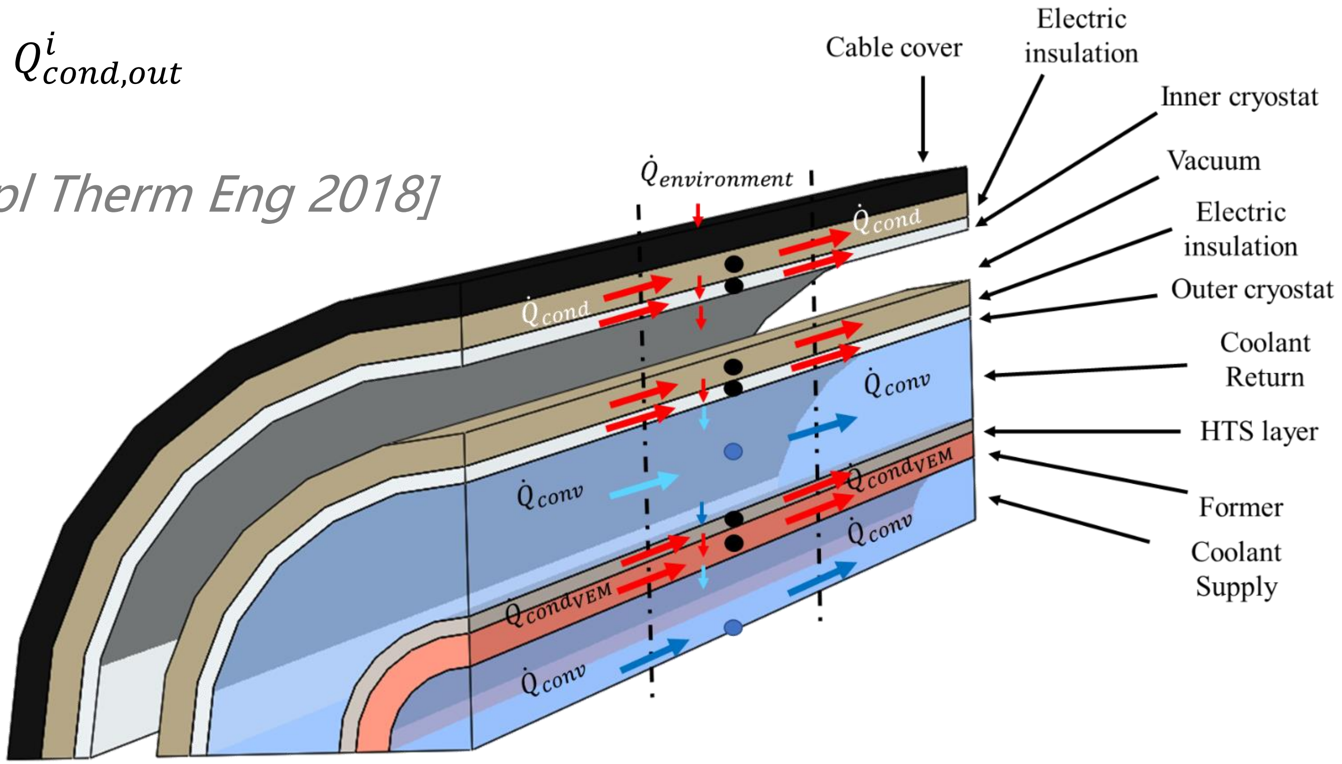
$$
\begin{cases}
M_{He} c_{v,He} \dfrac{dT_j^i}{dt} = Q^i{}_{j-k} + \dot{m}_{He} c_{p,He} \left(T_j^{i-1} - T_j^i\right) \\
M_{solid} c_{v,solid} \dfrac{dT_k^i}{dt} = Q^i{}_{j-k} + Q_{GEN,SC} + Q_{cond,in}^i - Q_{cond,out}^i
\end{cases}
$$

  - Dimensionless: *[N.G. Suttel et al., Appl Therm Eng 2018]*

$$
\begin{cases}
\dfrac{d\tau_j^i}{d\tilde{t}} = \left[-\tilde{Q}_{j-k}^i + \psi_j\left(\tau_j^{i-1} - \tau_j^i\right) - \widetilde{W}_{fr,j}^i\right] \dfrac{1}{\widetilde{M}_j^i \widetilde{c_v}_j} \\
\dfrac{d\tau_k^i}{d\tilde{t}} = \left[\tilde{Q}_{j-k}^i + \tilde{Q}_{GEN,SC}^i + \tilde{Q}_{cond,in}^i - \tilde{Q}_{cond,out}^i\right] \dfrac{1}{\widetilde{M}_k^i \tilde{c}_k}
\end{cases}
$$

  - Coupled to FDTD electric analysis

[D. I. Doukas et al., IEEE TAS 2017]



Models: 2D (Continuum)

- 2D FEM models of the SC lines

[N.G. Suttel et al., IEEE TAS 2017]
[S.J. Lee et al., Energies 2019]

- 2D FD

Fully 2D model for solid components

$$\frac{\rho c}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial T^2}{\partial x^2} + \frac{1}{k}\dot{Q}$$

[W.T.B. De Sousa et al., IEEE TAS 2019]

$former\ or\ Copper$

$$\rho c \frac{\partial T_{sl/rl}}{\partial t} \pm \rho c v_{sl/rl} \frac{\partial T_{sl/rl}}{\partial x} = \frac{h_{sl/rl} P_{sl/rl} \left(T_{frm/Cu} - T_{sl/rl}\right)}{A_{frm/Cu}} + \frac{\dot{q}_{rad}}{A_{frm/Cu}}$$

Return line only

+ supply line
− return line

Transient 1D advection in fluids

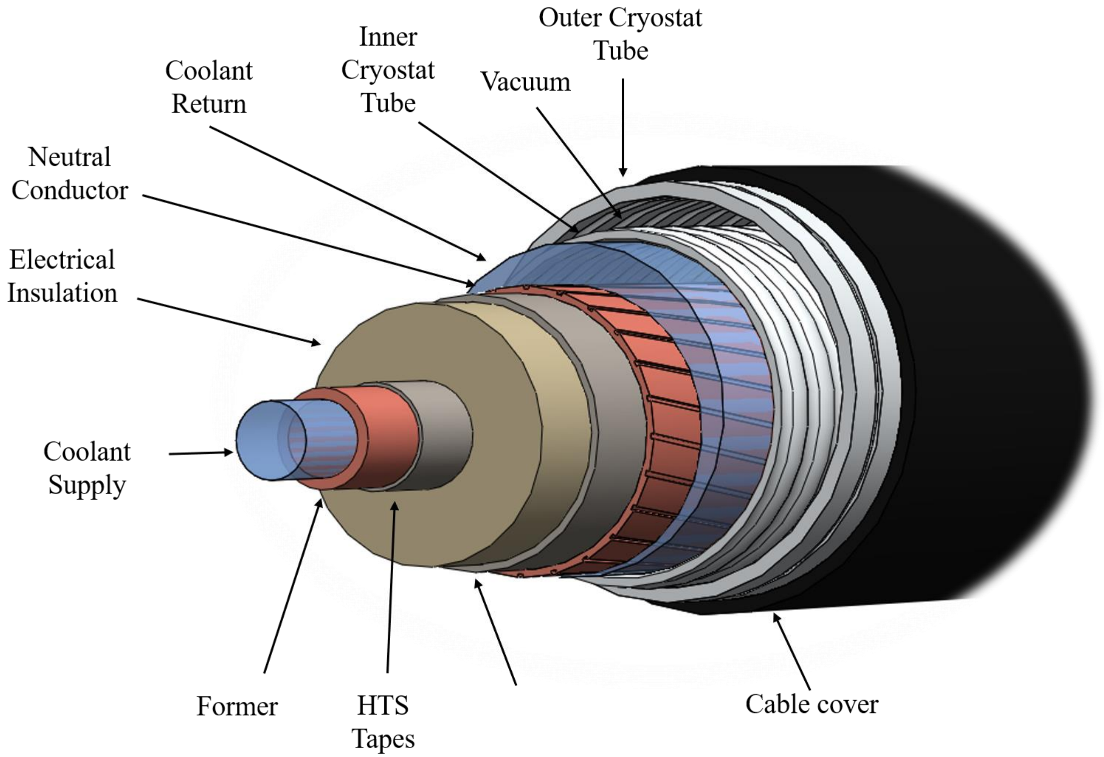
- Coupled to global pressure drop in an open-source code

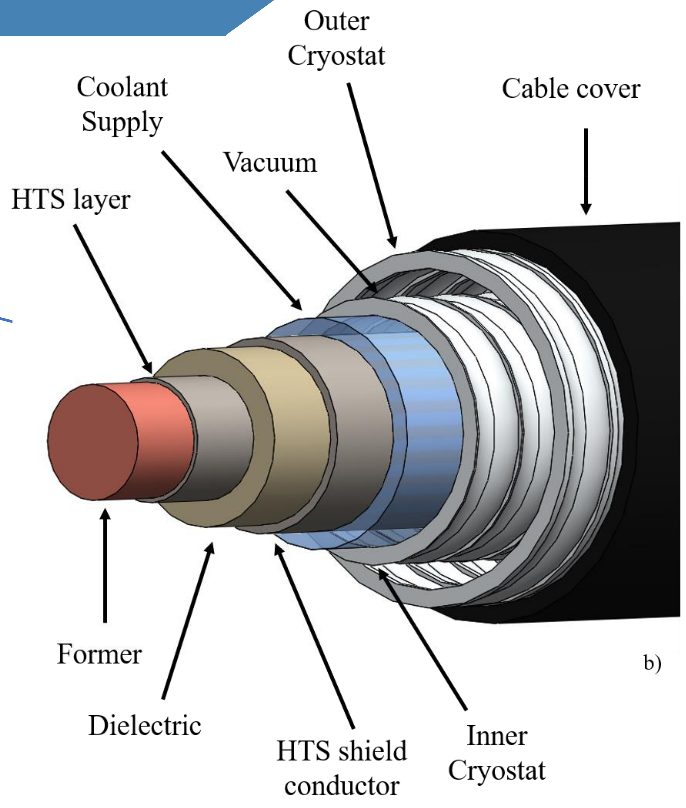
[W.T.B. De Sousa et al., Supercond. Sci. Technol. 2021]

Models: 3D

- 3D finite element method (FEM) thermal analysis for solid core for 50 cm-long cable

[J. He et al., IEEE TAS 2013]





- 3D FEM thermal-hydraulic analysis on eccentric cable

[O. Maruyama et al., IEEE TAS 2015]

Needs of a general Thermal-Hydraulic model

- Model features:
  - Transient, 1D (axial) + 1D (lumped?) radial (different layers)
  - Include V-I curve for SC materials + AC losses
  - Include parasitic heat from environment (radiation)
  - Flexibility to include different topological configuration
  - Flexibility for different coolants (→ compressible fluids, phase change)
  - (include auxiliaries)

- Numerics:
  - Low computational cost to simulate long lengths
  - Adaptive grids to capture local quenches
  - Adaptive time stepping to capture different time-scales

- Open-science!

Conclusions

- Comprehensive review of the different models currently available for thermal-hydraulic analysis of HTS SCTL / SCTC has been presented

- Based on the experience gained in fusion SC cables/magnets modelling, the needs of a general thermal-hydraulic model have been highlighted

- Open-source should become the standard!