Current and temperature distributions in HTS coils with and without insulation in a layer-wound configuration

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- Experimental set-up
- 1-D Thermal model
- Comparison of NI coil and insulated coil
  - Dependence of the coil electrical parameters on the heater current and temperature
  - Temperature distribution in the layers of the two coils
- Conclusions

Introduction

- Two layer-wound High Temperature Superconducting (HTS) coils are realized, **with and without electrical insulation** [1].
- Both coils are wound from the **same laminated BSCCO tape**, and have a very **similar geometry**.
- **Charging tests** are performed in **LN_2 bath**, until the tape critical current is exceeded.
- A constant heat input is applied on both coils. Tests are repeated at **different heat loads**.
- The signals acquired at the ends of each layer are used to compare the **electro-thermal behavior** of the two coils, at the same testing conditions.
- The **temperature distribution** of the coils is estimated by means of a **1-D thermal model**.

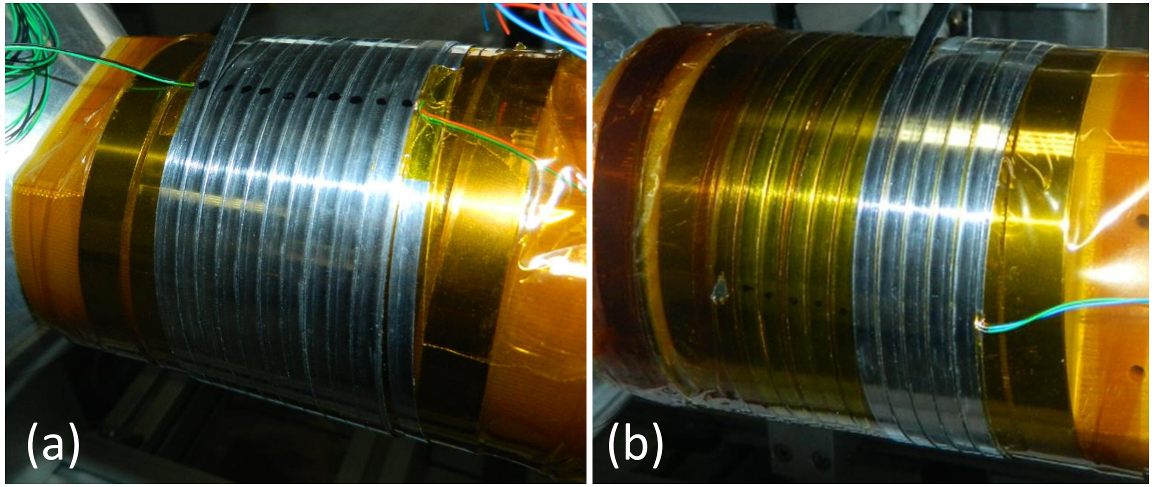
[1] A. Musso *et al., IEEE Trans. on Appl. Supercond.*, vol. 31, no. 5 Feb. 2020.

Experimental set-up

- An AISI 301 stainless steel tape is wound around each mandrel, forming a homogeneous **heater** layer on top of which the BSCCO tape turns are wound.
- The coils are instrumented with **voltage taps at the ends of each layer** and at the ends of the heater winding ➡ preliminary tests are carried out to obtain the *ρ(T)* function of the heater material, then used to indirectly estimate the heater temperature (T_h).

TAPE AND WINDINGS PARAMETERS

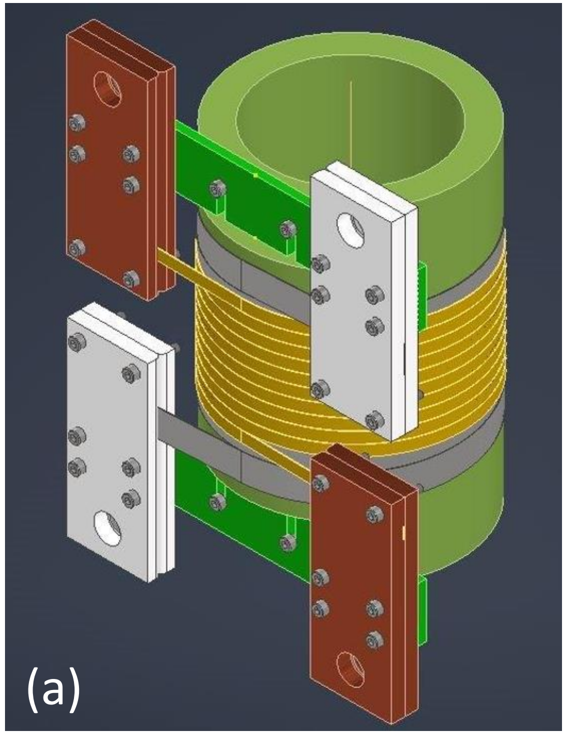
Tape name (BSCCO)	*High Strength Plus by AMSC*
HTS tape thickness [μm]	300.0
HTS tape width [mm]	4.1
Inner radius of each HTS winding [mm]	41.0
Number of HTS layers (N_L)	3
Number of HTS turns per layer (N_T)	10
Length of each layer of the NI coil [cm]	258.8 ; 260.6 ; 262.5
Length of each layer of the insulated coil [cm]	259.1 ; 261.4 ; 263.6
I_c *and n-value of each layer with heater off* (77 K)	109.5 A; 13.5

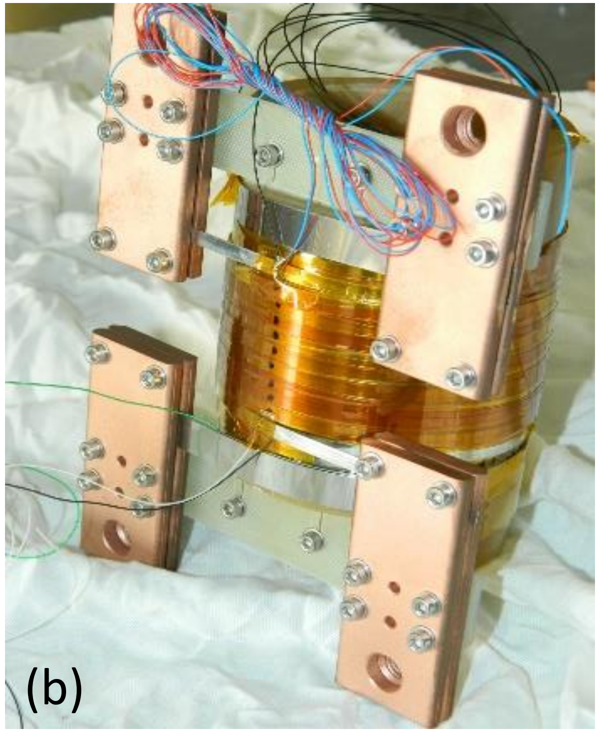


Winding phase for the (a) insulated and (b) NI coils.

Experimental set-up

- The charging tests are performed in **LN2 bath**, exceeding the **critical current of each layer**.
- The heater is supplied with a constant current during tests (I_h). The tests are repeated for both coils **varying I_h and thus the applied heat load**.
- A **special design of the coil termination system** is developed, which ensures a separate power supply for the heater layer and the HTS winding.



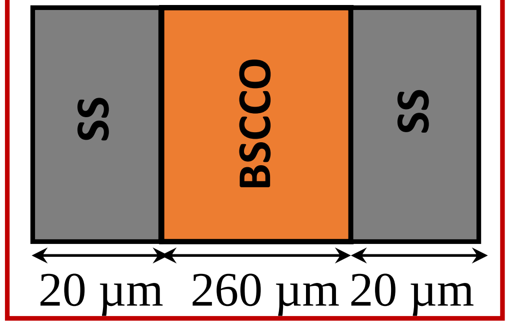


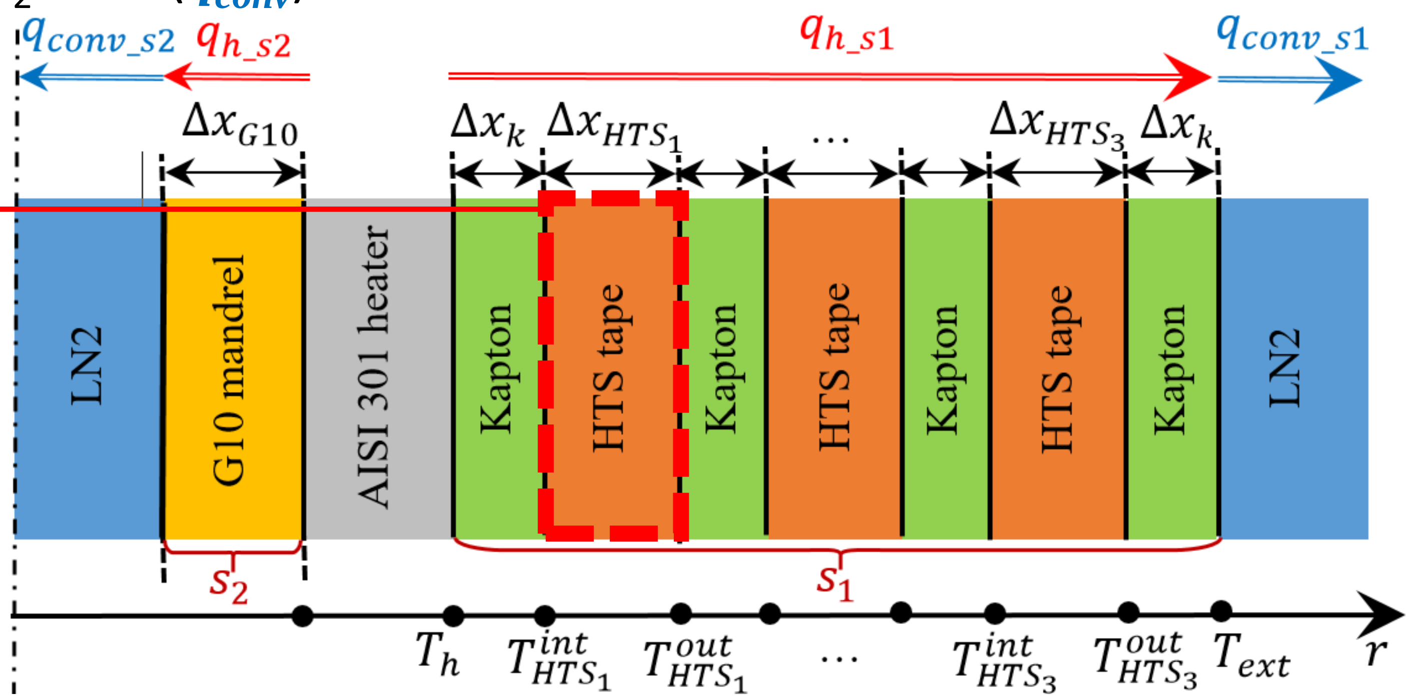
Current supply connection system for the heater and the HTS coil, in (a) the CAD design phase and (b) at the end of the winding phase.

1-D Thermal model

- **1-D approximation**: heat transfer and temperature variations only occur in the radial direction.
- The heat load propagates in 2 opposite radial directions: HTS winding (structure 1, s1) and G10 mandrel (structure 2, s2).
- The thermal power generation is given by the heater.
- **Stationary thermal conditions**: the heat conducted through the structure (**q_h**) is set equal to the heat transferred to the LN_2 bath (**q_{conv}**).

The stainless steel laminated HTS tape is represented in the model with 3 sub-layers:

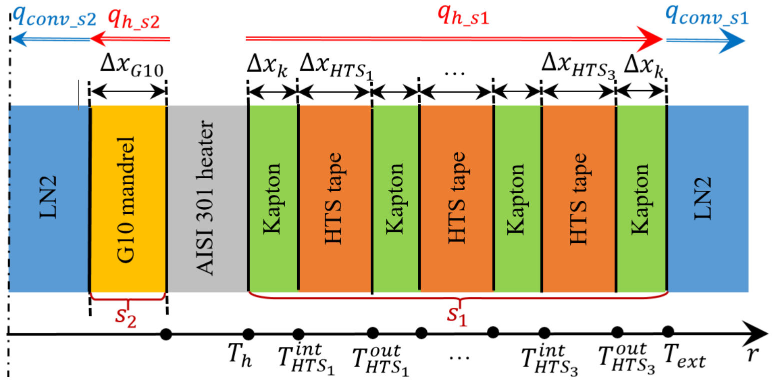




Geometry and heat flows of the insulated coil, as represented in the model. The radial thickness of the whole winding is much smaller than the mandrel radius:

Cartesian coordinates are used.

1-D Thermal model



- The **heat balance equation** is applied at the heater:

$$\rho(T_h)\, a_h\, j_h^2 = \sum_{i=1}^{N_{st}} f_i\, p_h \left(\frac{T_h - T_{ext_i}(T_h)}{\sum_j \frac{\Delta x_j}{k_j}} \right)$$

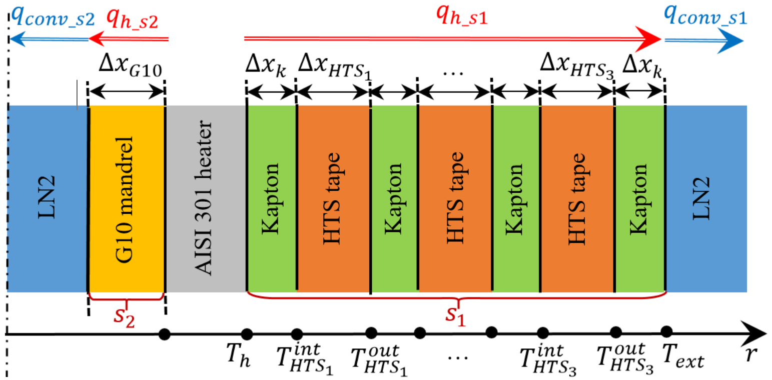
Implicit function of the variable T_h:

$$\underbrace{\left(\frac{T_h - T_{ext_i}}{\sum_j \frac{\Delta x_j}{k_j}} \right)}_{q_{h\_i}} = \underbrace{h_{conv}^{LN2}\left(T_{ext_i} - T_{LN2}\right)}_{q_{conv\_i}}$$

- $\rho(T_h)$= resistivity-temperature function for AISI 301.
- a_h = cross-section of the AISI 301 heating tape.
- j_h = current density supplied to the heater.
- N_{st} = n° of heated structures (=2, the HTS winding and the G10).
- p_h = perimeter of heater cross-section.
- f_i = fraction of p_h in contact with the i^{th} structure (= 0.5).
- T_h= heater temperature.
- T_{ext_i}= temperature of the external surface of the i^{th} structure.
- T_{LN2} = LN2 temperature.
- x_j = thickness of the j^{th} layer of the i^{th} structure.
- k_j = thermal conductivity of the j^{th} layer of the i^{th} structure.
- h_{conv}^{LN2} = heat transfer coefficient with LN2 (function of T_{ext} - T_{LN2}).

- **Non-linear temperature-dependent** thermo-physical properties of the materials are included in the model: the problem is **solved numerically**.

1-D Thermal model

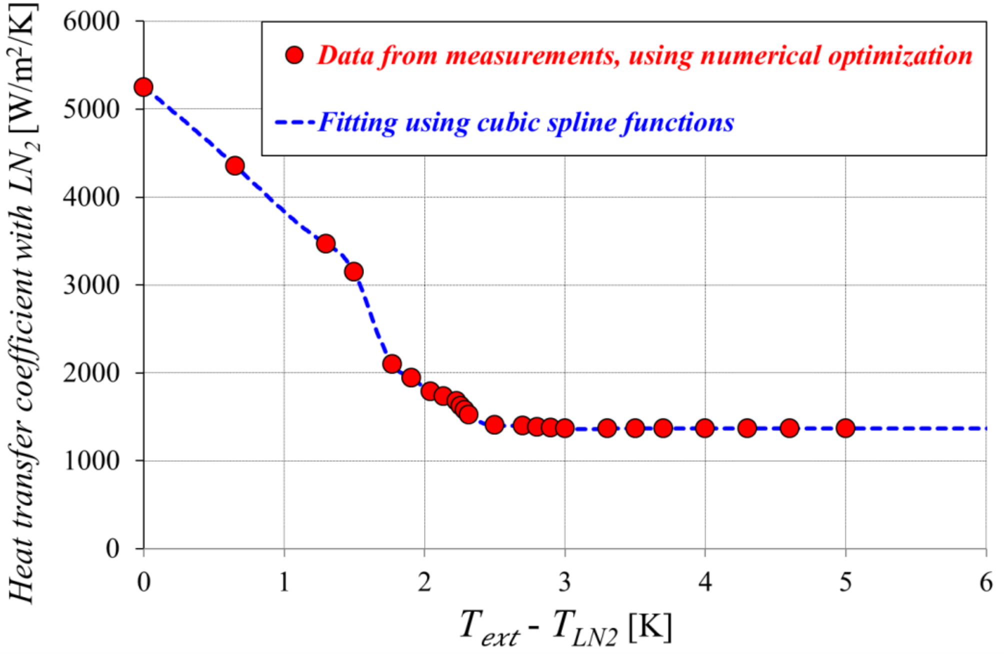


- The **heat balance equation** is applied at the heater:

$$\rho(T_h)\, a_h\, j_h^2 = \sum_{i=1}^{N_{st}} f_i\, p_h \left(\frac{T_h - T_{ext\,i}(T_h)}{\sum_j \frac{\Delta x_j}{k_j}} \right)$$

Implicit function of the only variable T_h:

$$\underbrace{\left(\frac{T_h - T_{ext\,i}}{\sum_j \frac{\Delta x_j}{k_j}} \right)}_{q_{h\_i}} = \underbrace{h^{LN2}_{conv} \left(T_{ext\,i} - T_{LN2} \right)}_{q_{conv\_i}}$$

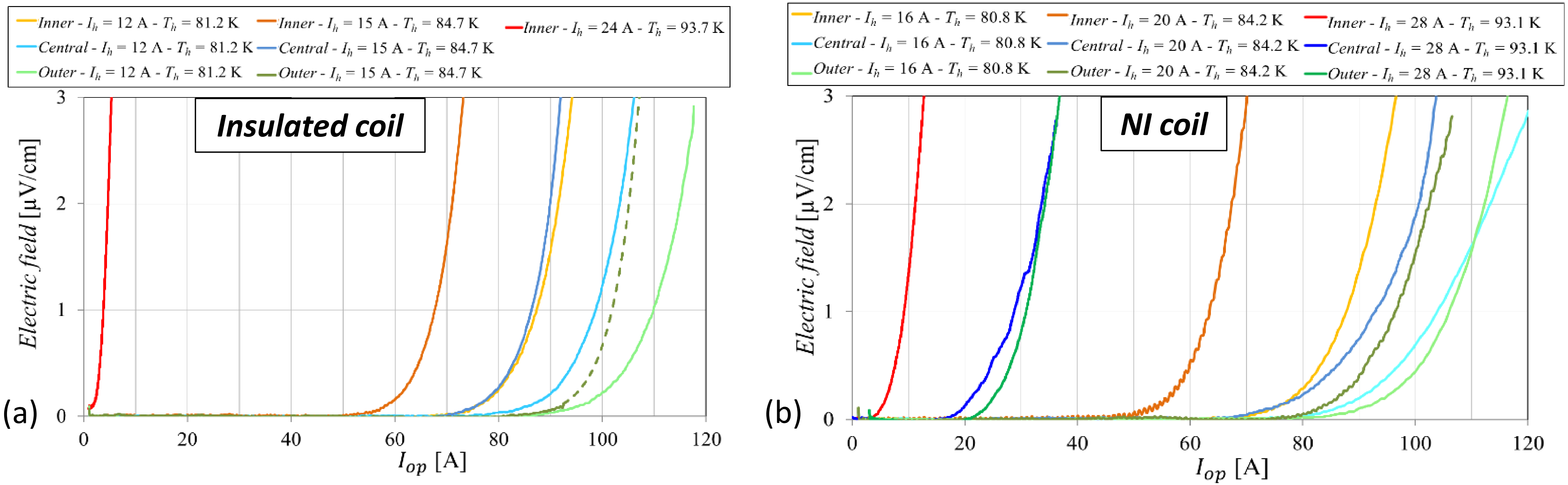


- The heat transfer through the layers of each structure (HTS winding and G10 mandrel) is constant. **The temperatures of all separation surfaces** can be computed in cascade, starting from the innermost layer of each structure.

Comparison of NI coil and insulated coil

Dependence of the coil electrical parameters on the heater current and temperature

- For both coils, the innermost layer adjacent to the heater reaches the critical field (*i.e.* 1 μV/cm) **at lower operating current** (I_{op}) than the outermost layers, at the same T_h.
- The electric field in the central layer of the NI coil increases more slowly with I_{op}, compared to the other layers, due to **inhomogeneous current distribution** between the turns of this layer [1].



Electric field profiles during charging tests carried out at different I_h, for the 3 layers of the (a) insulated and (b) NI coils.

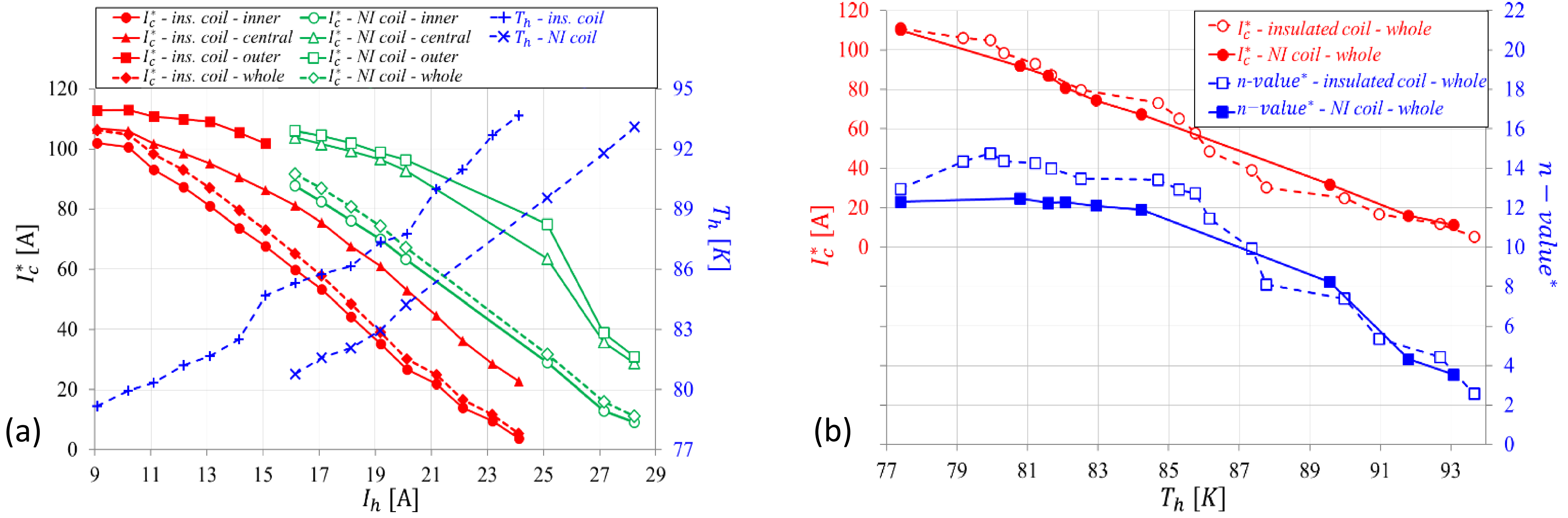
[1] A. Musso *et al., IEEE Trans. on Appl. Supercond.*, vol. 31, no. 5 Feb. 2020.

Comparison of NI coil and insulated coil

Dependence of the coil electrical parameters on the heater current and temperature

- The critical current of each layer is obtained as the value of I_{op} corresponding to the critical field, **regardless of the actual value of the current flowing in each turn**.

The I_c and the *n-value* shown are **"effective" values**, indicated as I_c^* and $n\text{-}value^*$.



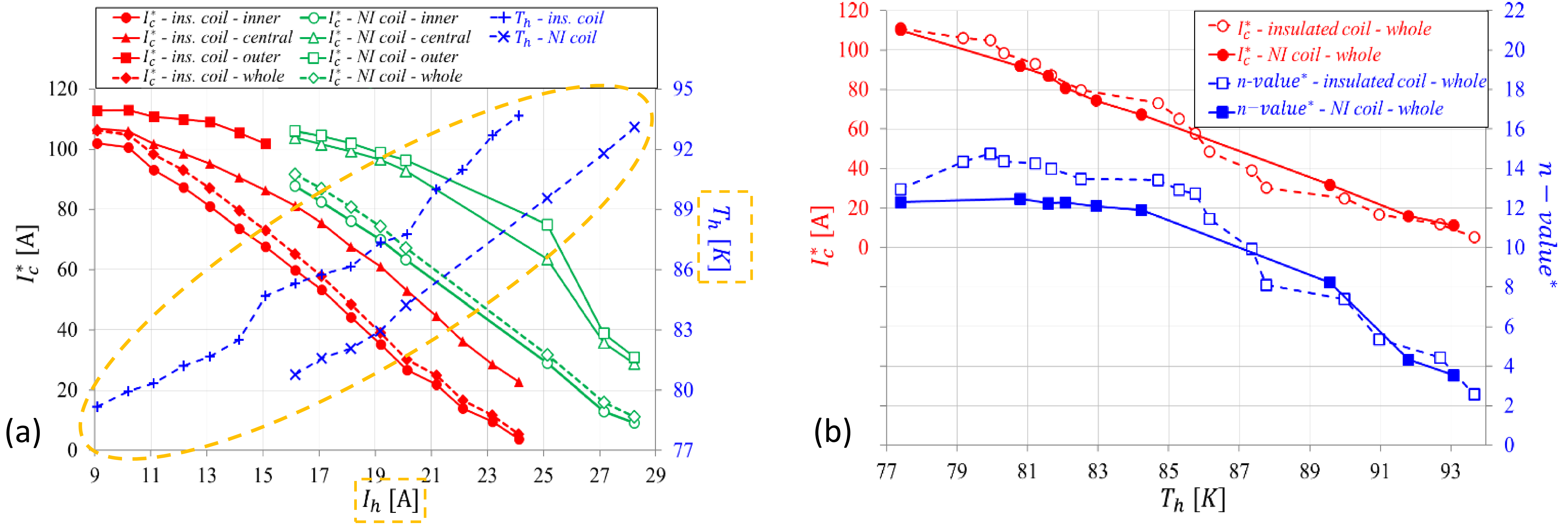
(a) I_c^* measured in each layer of the two windings and (b), I_c^* and $n\text{-}value^*$ measured in both coils, for different I_h and T_h.

Comparison of NI coil and insulated coil

Dependence of the coil electrical parameters on the heater current and temperature

- At similar T_h values, the current supplied to the heaters (I_h) differs substantially for the two coils:

  with the same heat load, the insulated coil heats up more than the NI coil.

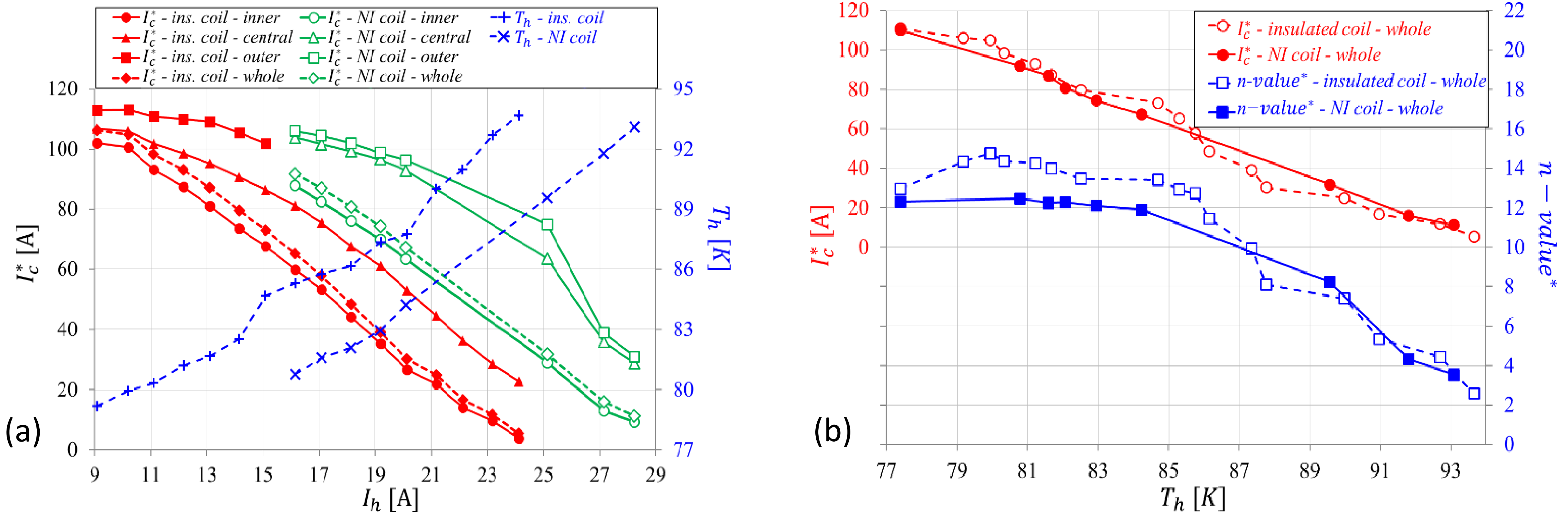


(a) I_c^* measured in each layer of the two windings and (b), I_c^* and n-value* measured in both coils, for different I_h and T_h.

Comparison of NI coil and insulated coil

Dependence of the coil electrical parameters on the heater current and temperature

- For the insulated coil, the I_c^* of each layer appears to **decrease with decreasing the distance between the layer and the heater**.
- For the NI coil, **the I_c^* reduction appears less gradual**: the central and outermost layers exhibit a similar behavior. This agrees with the results shown in [1], where no heat input was applied.

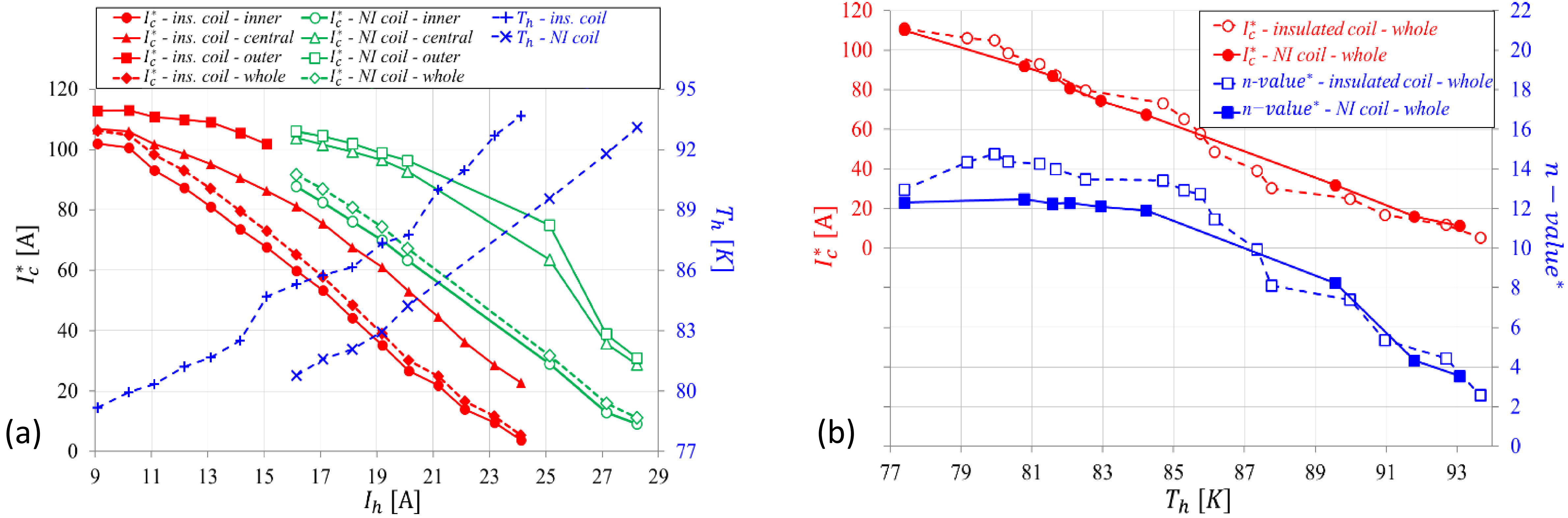


(a) I_c^* measured in each layer of the two windings and (b), I_c^* and n-value* measured in both coils, for different I_h and T_h.

Comparison of NI coil and insulated coil

Dependence of the coil electrical parameters on the heater current and temperature

- The I_c^* and $n\text{-}value^*$ obtained across the whole coil length are close to those measured on their inner layers.
- At the same T_h, the overall **electrical characteristics of the two coils are similar**.



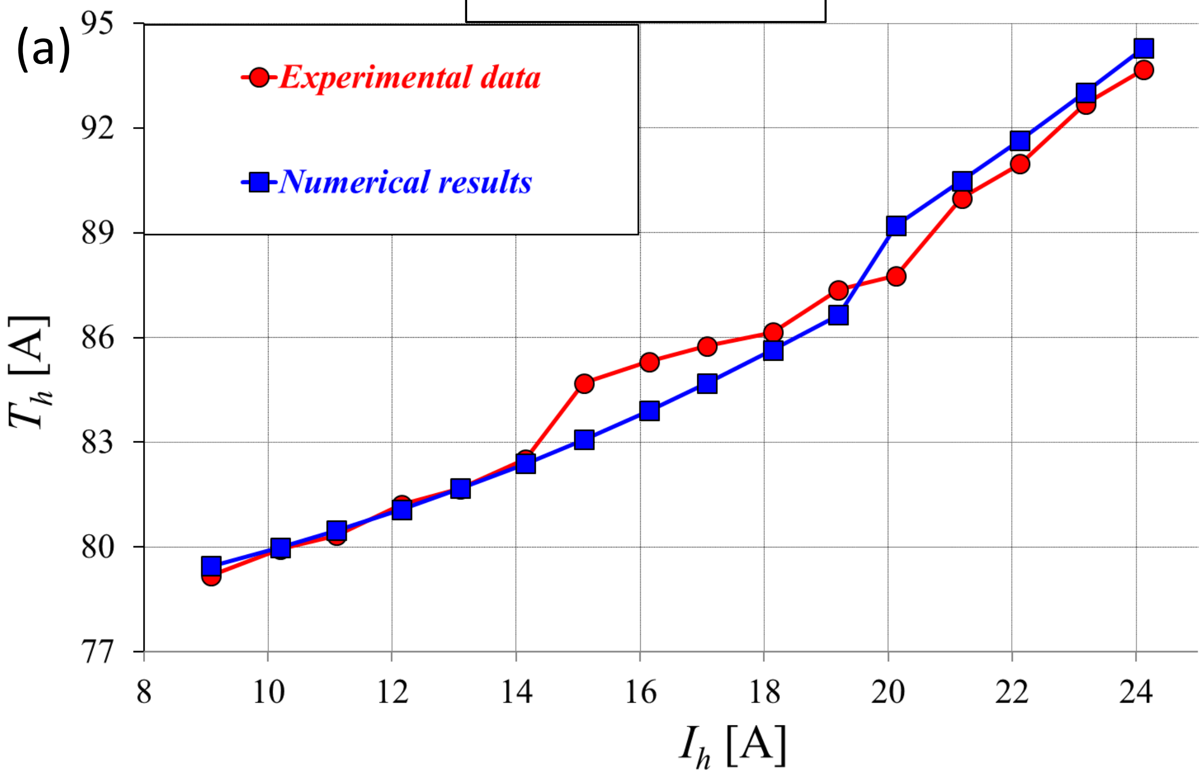
(a) I_c^* measured in each layer of the two windings and (b), I_c^* and $n\text{-}value^*$ measured in both coils, for different I_h and T_h.

Comparison of NI coil and insulated coil

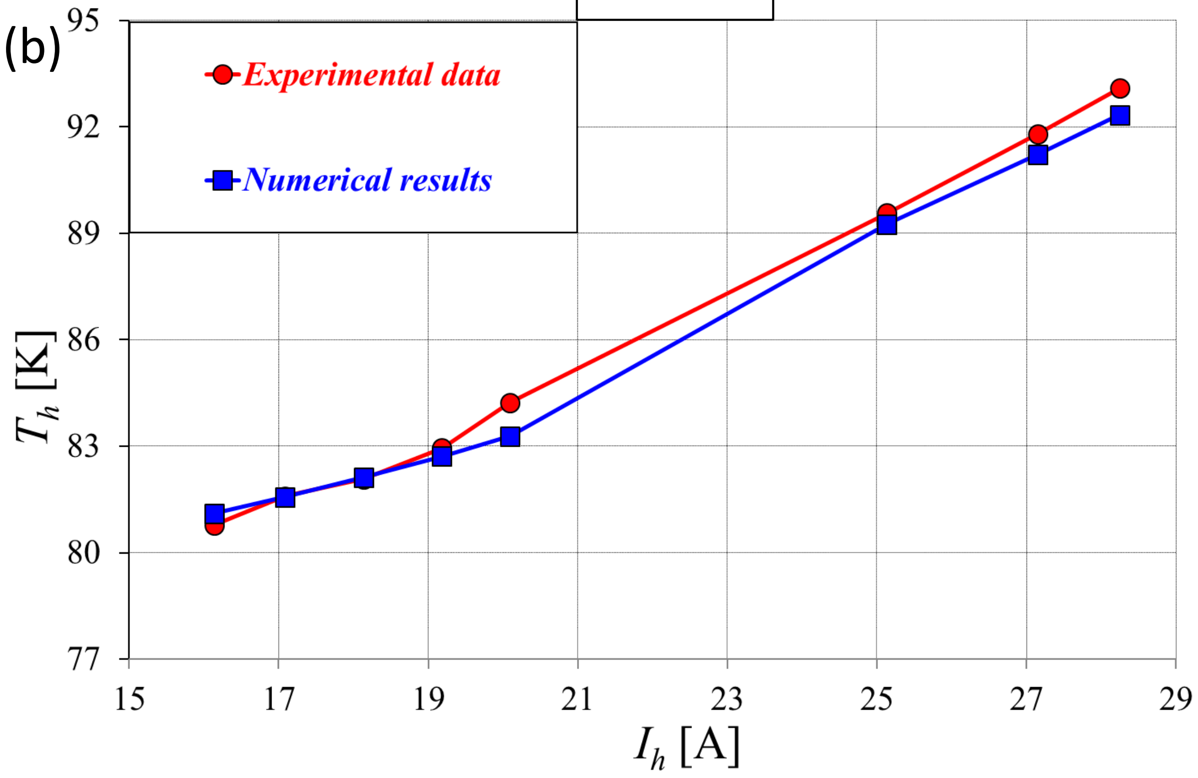
Temperature distribution in the layers of the two coils

- A **good agreement** between the measured and computed values of T_h is found.
- The thermal model allows one to compute the temperature distribution for both coil configurations.

Insulated coil



NI coil

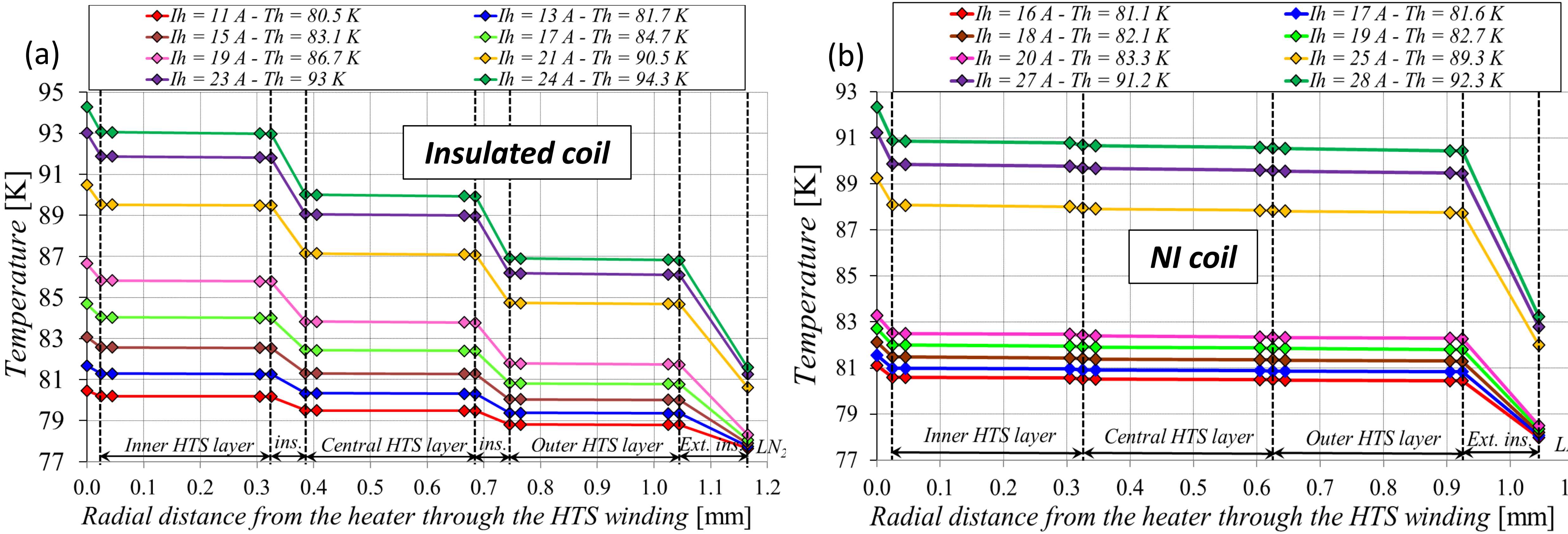


T_h as a function of I_h determined experimentally and with the numerical model for (a) the insulated and (b) the NI coils.

Comparison of NI coil and insulated coil

Temperature distribution in the layers of the two coils

- In the **insulated coil**, the presence of insulation differentiates the temperatures of the HTS layers, which leads to a gradual reduction of I_c^* approaching the heater.
- In the **NI coil**, the 3 layers have a similar temperature ➡ the difference in their I_c^* depends on the current distribution.



Computed temperature distribution into (a) the insulated and (b) the NI windings at different testing conditions

Conclusions

- The electro-thermal behavior of 2 **layer-wound BSCCO coils**, **with and without electrical insulation** was compared.
  - With the same heat load, the insulated coil reaches higher temperatures than the NI coil.
  - The **1-D thermal model** developed shows that, for the **insulated coil**, the gradual I_c^* reduction approaching the heater is a consequence of the **different temperature** of the HTS layers due to the electrical insulation.
  - For the **NI coil**, the I_c^* reduction is due to **current distribution phenomena**, rather than temperature gradients in the coil.
  - The insulation does not significantly affect the electrical characteristics of the coil when the heater temperature is the same.