



2-D thermal analysis of the model dipole for SIS300

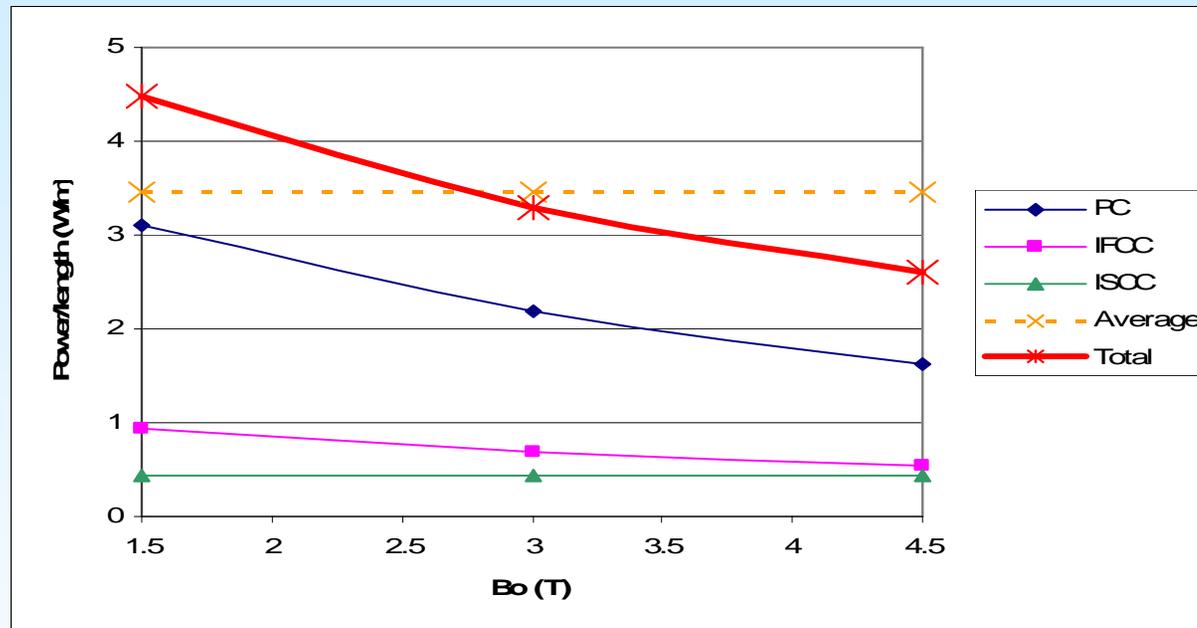
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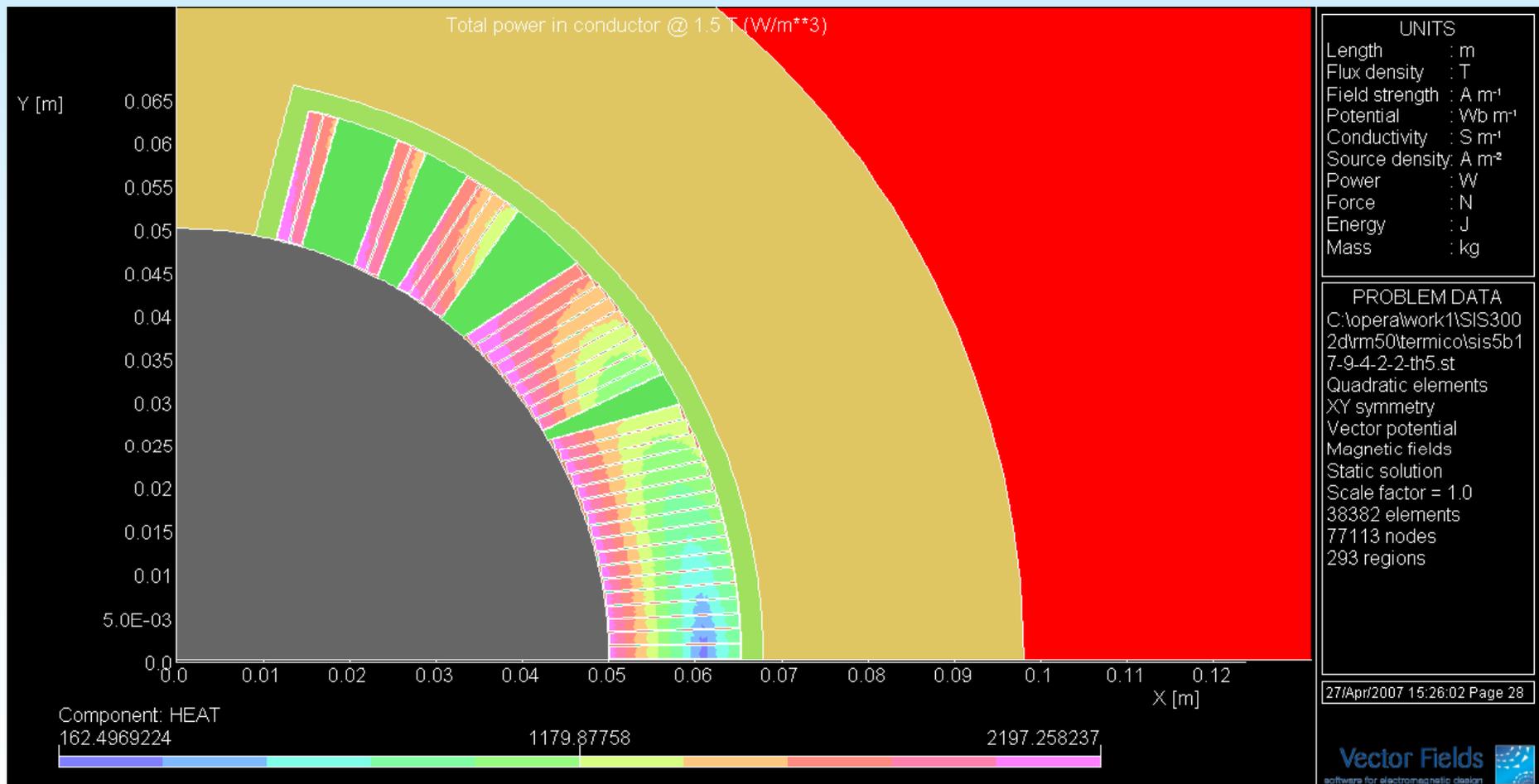
The study of the losses has allowed to calculate the losses in the conductors



- The losses are not constant during the ramp
- Losses are not constant also in the cross section

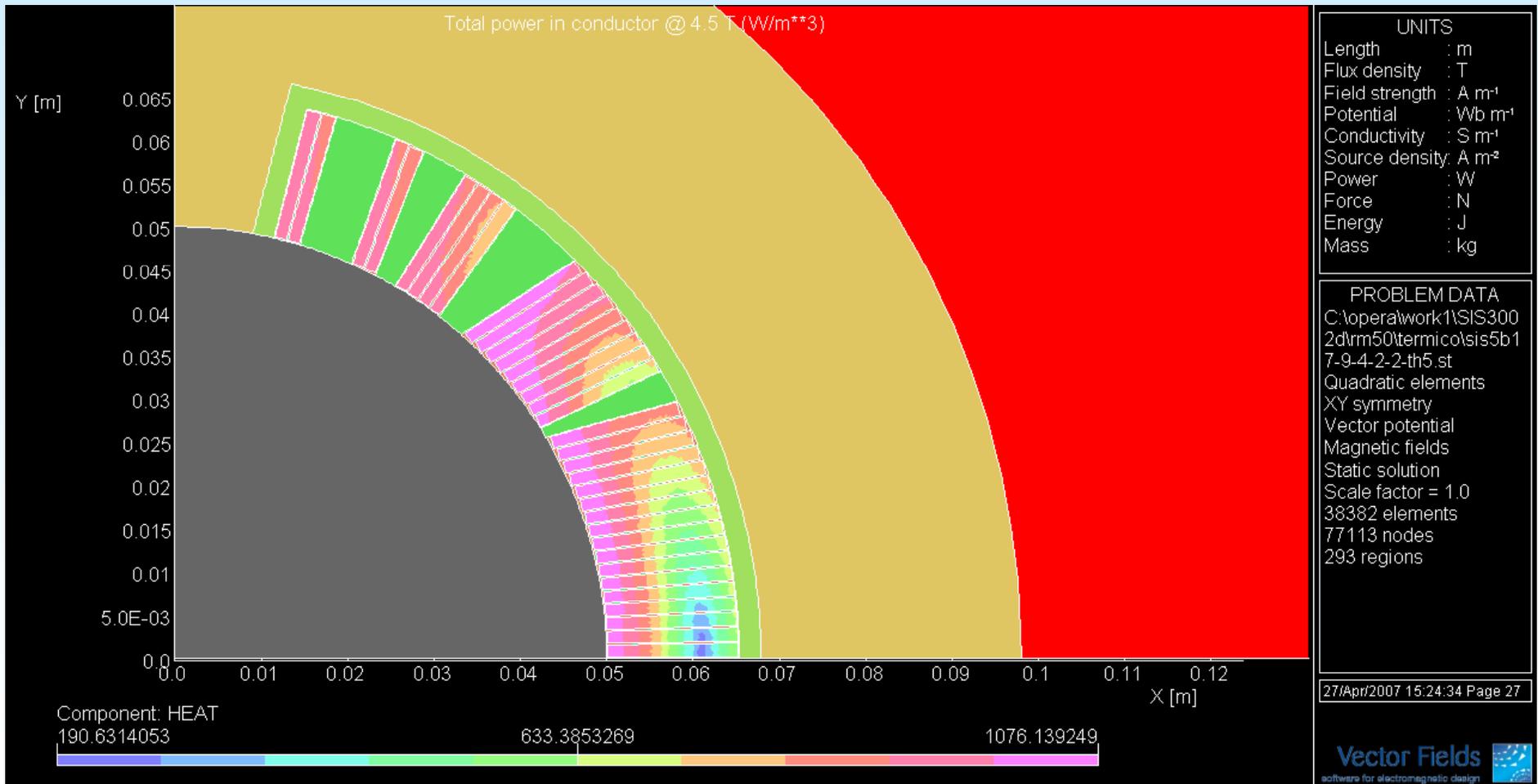
Power distribution in conductor @ $B_0=1.5$ T

[Peak power 2200 W/m^3]



Power distribution in conductor @ $B_0=4.5$ T

[Peak power 1080 W/m^3]



Assumptions in the study

The study of the temperature distribution on the conductors has been carried out assuming:

1. 2-D only. In the coil-end region the losses in conductor are lower and the magnetic field is lower
2. The coolant temperature is constant in time and in the whole magnet: 4.7 K
3. Only the narrow side of conductor is cooled by the coolant
4. Losses in collar, yoke and beam tube are neglected (losses in collar and yoke in the 2D section are very low)

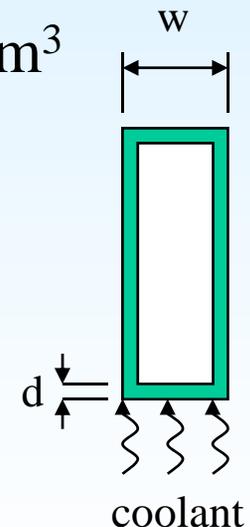
Zero order calculation of thermal gradient in the insulation:

Cooling of conductor only from inner short side.

- | | | |
|--|-----------------------|------------------|
| • Kapton thermal conductivity | $k = 1.1 \text{ E-5}$ | W/(K*mm) |
| • Insulation thickness | $d = 0.125$ | mm |
| • Conductor width | $w = 15.1$ | mm |
| • Average power in the 34 th turn | 1500 | W/m ³ |

$$\delta T = \frac{d \cdot w}{k} p = 0.26 \text{ K}$$

Consequently there is a strong motivation to perform a more accurate study about the real gradient



Temperature gradient in conductors

The study of the temperature distribution on the conductors has been carried out for the following cases:

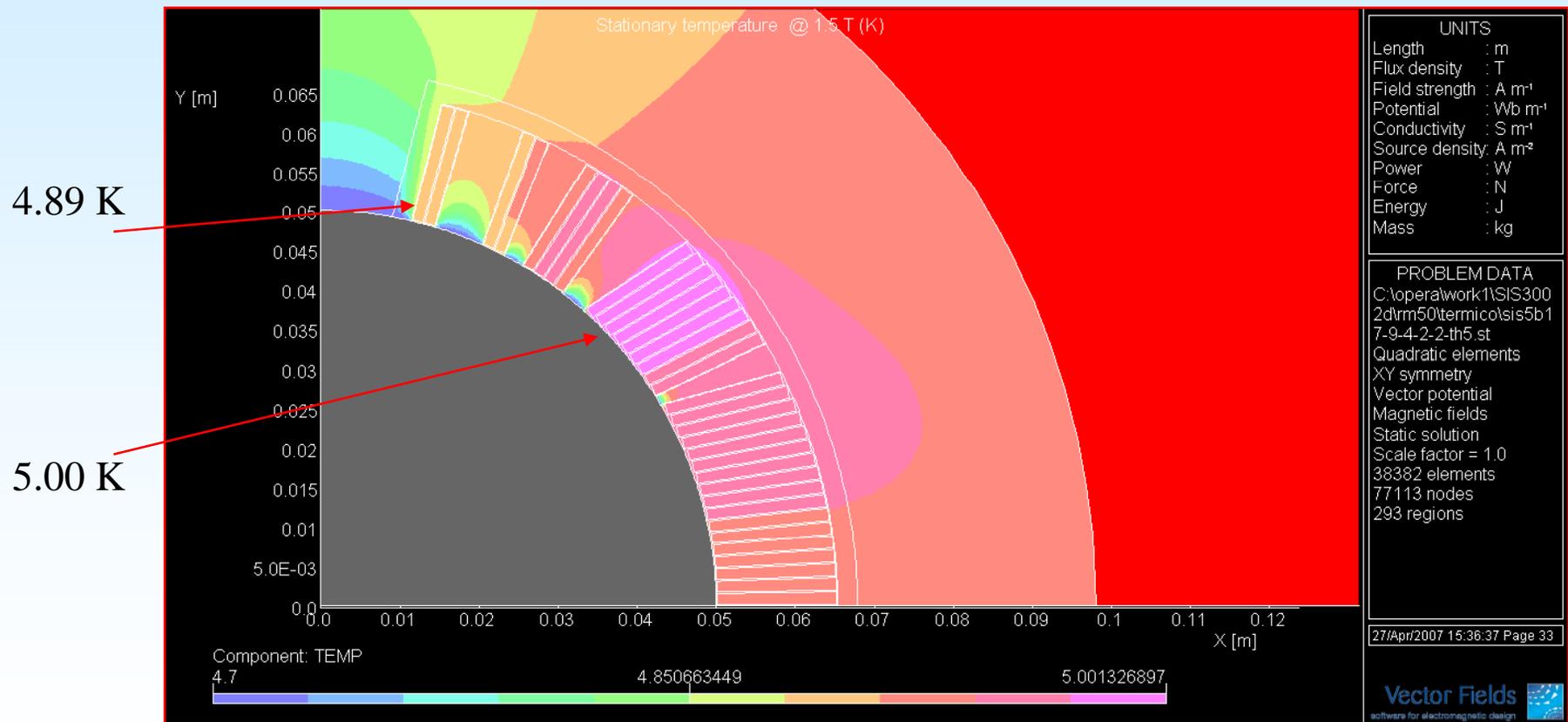
1. Steady state analysis with constant power at $B_0=1.5$ T
2. Steady state analysis with constant power at $B_0=4.5$ T
3. Transient analysis with initial temperature 4.7 K
4. Transient analysis with initial temperature from case 2
5. Transient analysis with initial temperature from case 1

Material properties for the thermal analysis

	Thermal conductivity [W/(m·K)]	Specific heat [J/(kg·K)]	Mass density [kg/m ³]
Collar	0.290	2.60	7800
Spacer (G11)	0.066	2.47	1900
Layer coil-collar	0.030	2.47	1900
Conductor	42.19	0.13	8512
Cond. insulation	0.010	2.47	1900

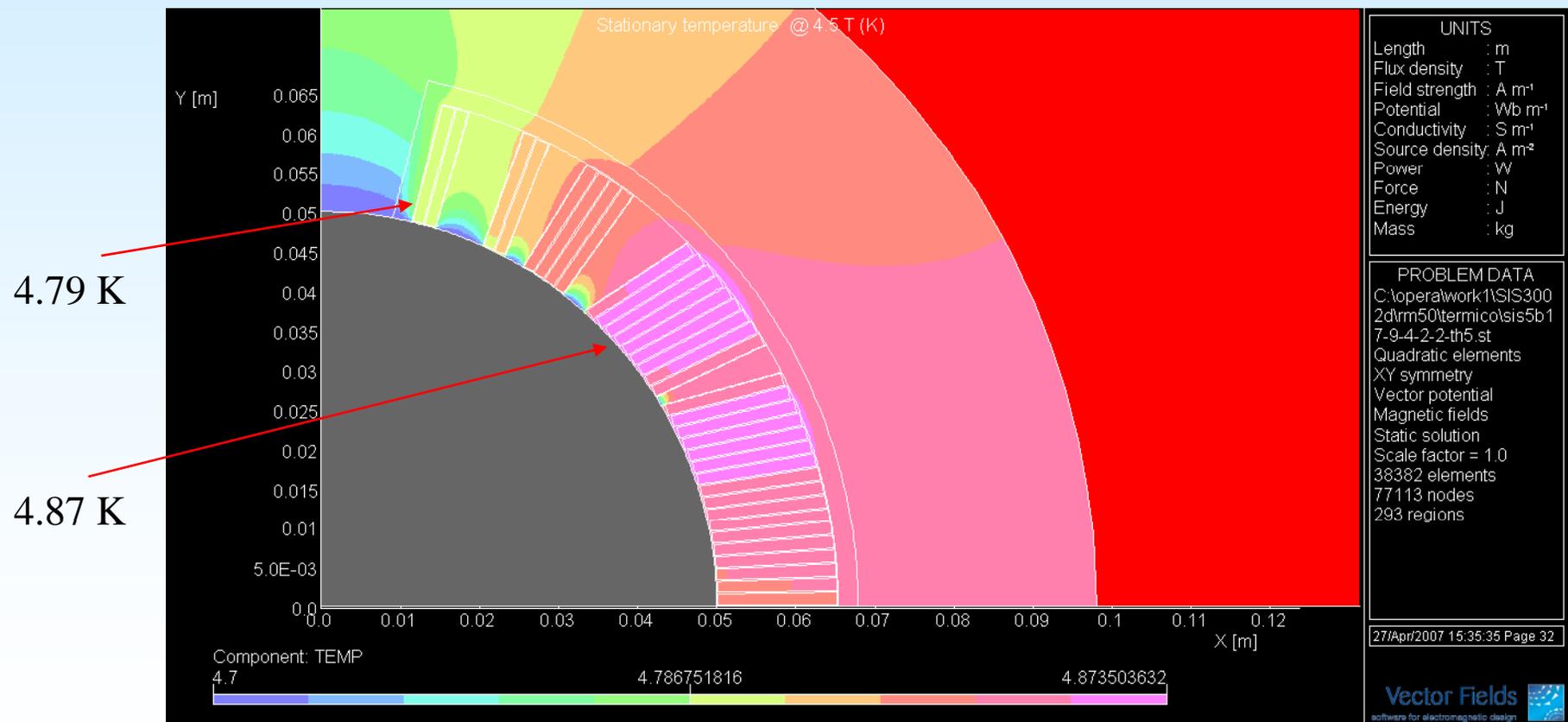
Steady state case:

Temperature distribution with power @ $B_0=1.5$ T



Steady state case:

Temperature distribution with power @ $B_0=4.5$ T



The current sharing temperature $T_g(\mathbf{J}, \mathbf{B})$ in principle can be calculated reverting the relation:

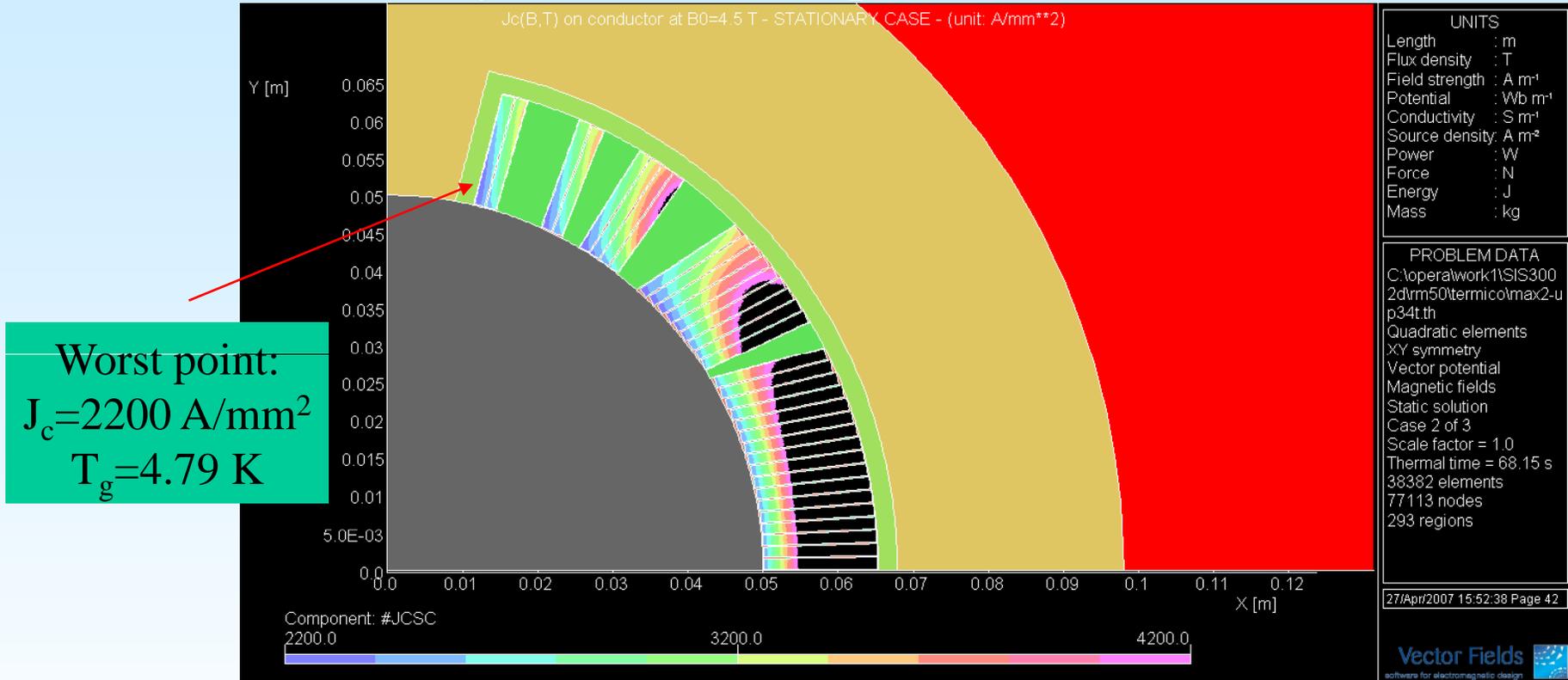
$$J_c(B, T) = J_c(@ 5T \ \& \ 4.2K) \cdot \frac{C_{NbTi}}{B} \left[\frac{B}{B_{C2}(T)} \right]^{\alpha_{NbTi}} \cdot \left[1 - \frac{B}{B_{C2}(T)} \right]^{\beta_{NbTi}} \cdot \left[1 - \left(\frac{T}{T_{C0}} \right)^{1.7} \right]^{\gamma_{NbTi}}$$

$$B_{c2}(T) = B_{C20} \left[1 - \left(\frac{T}{T_{C0}} \right)^{1.7} \right]$$

However this formula can not be easily reverted for the temperature.

For this reason it is easier to plot the critical current in conductor, and search the **minimum** value

Critical current density (A/mm^2) in superconductor in steady state case with power @ $B_0=4.5$ T

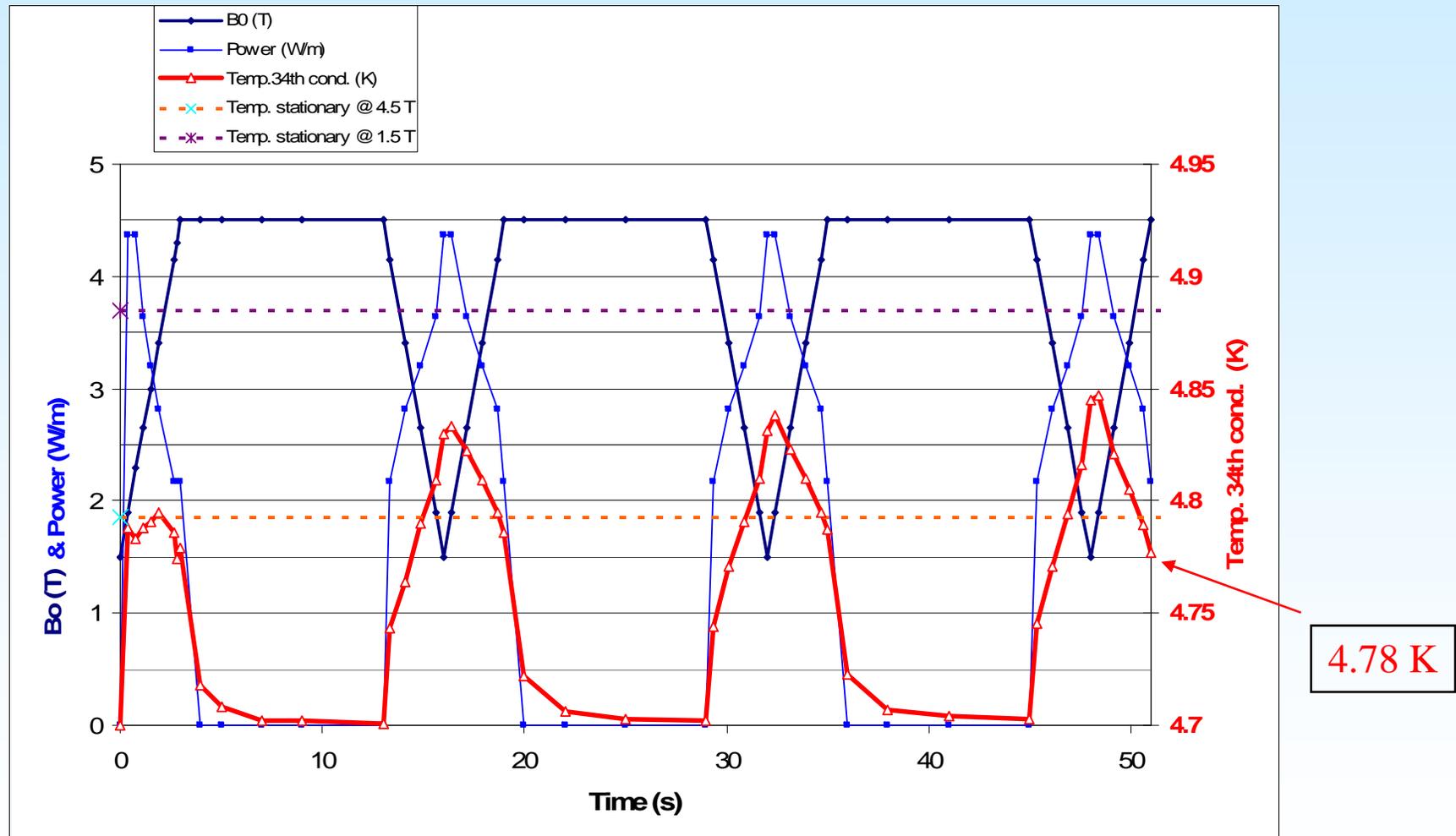


$(J_{op}=1300$ A/mm²)

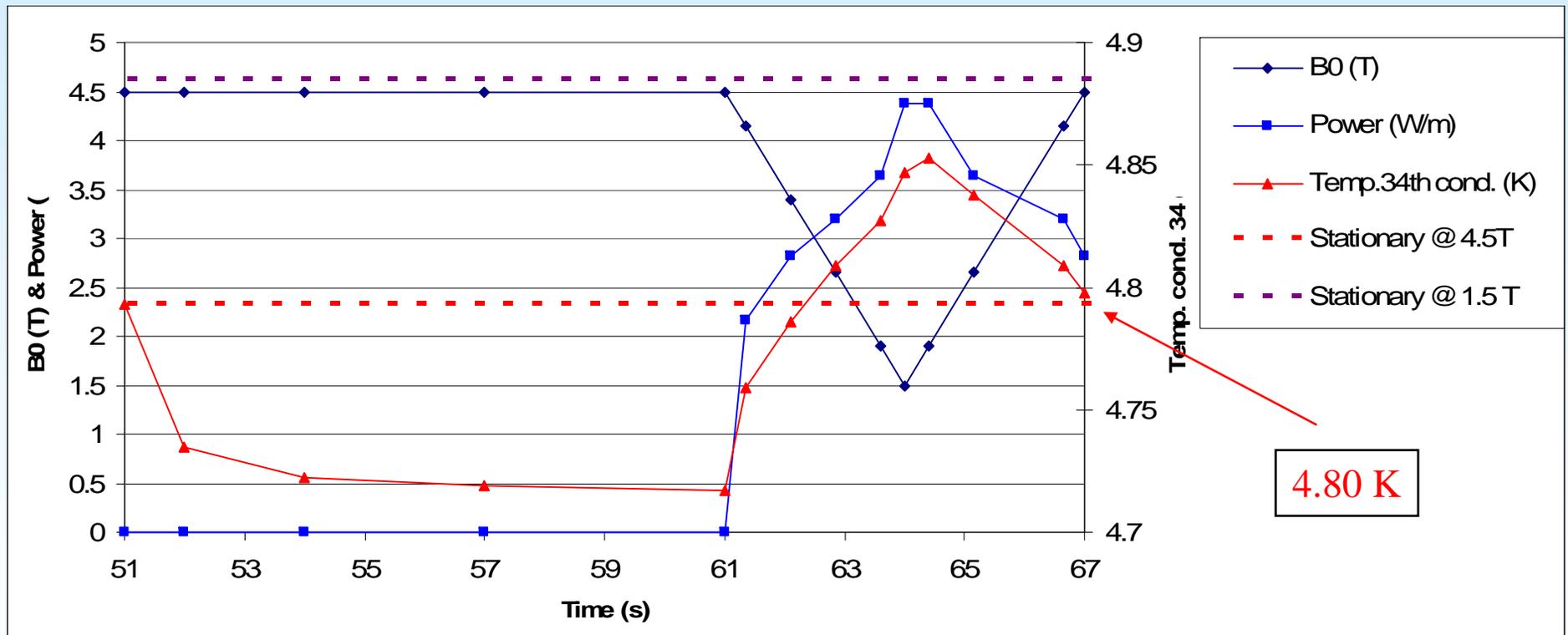
Conclusion: the minimum value of T_g (current sharing temp.)
occurs at $B_0=4.5$ T and in the conductor with peak field.

TRANSIENT ANALYSIS:

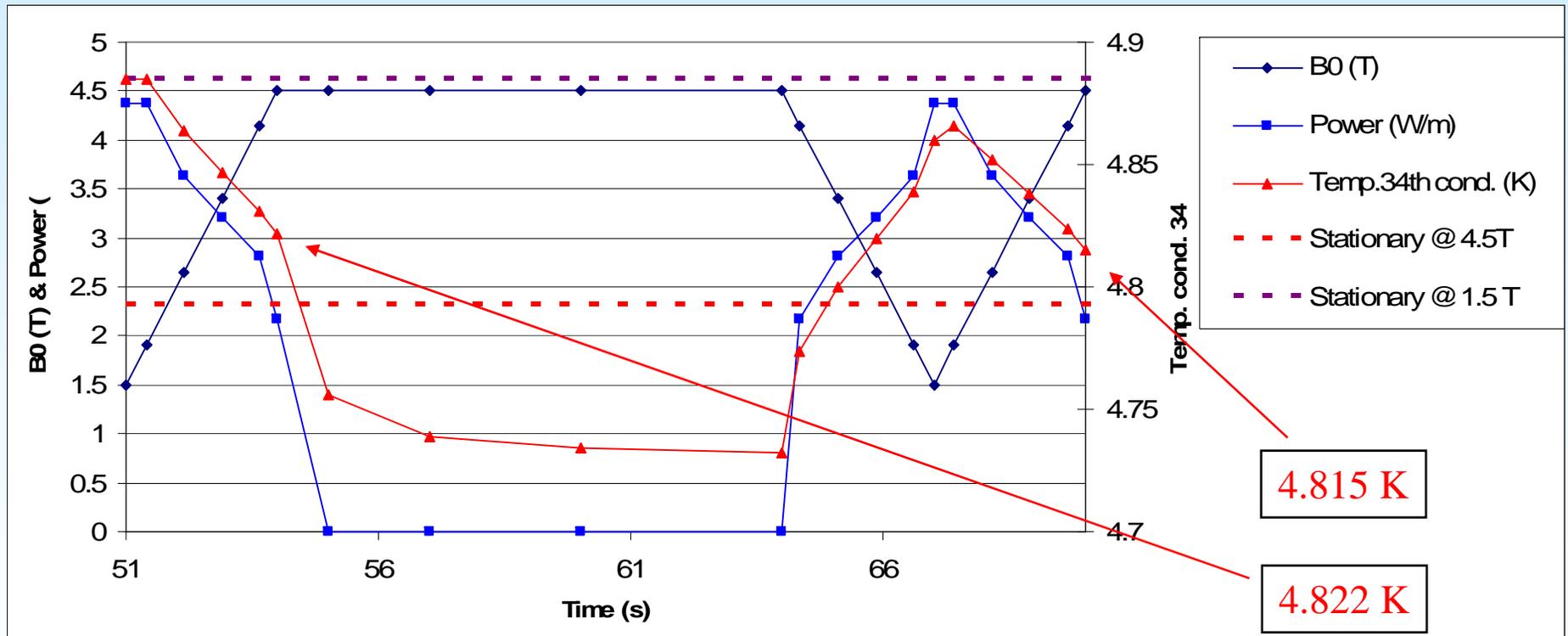
Temperature evolution starting from $T=4.7$ K



Temperature evolution starting from temperature distribution in steady state case with power @ $B_0=4.5$ T



Temperature evolution starting from temperature distribution in steady state case with power @ $B_0=1.5$ T



In conclusion, the transient thermal analysis, gives the following temperatures for the 34th conductor at the end of ramp-up:

- With initial temperature 4.7 K T=4.78 K
- With initial temperature from steady state @ 4.5 T T=4.80 K
- With initial temperature from steady state @ 1.5 T T=4.82 K

These values are reasonable close each others, and the differences are at the limit of the calculation errors.

We can conclude that **T=4.80 K +/- 0.02 K**

In the analysis it has been neglected:

1. The very large thermal capacity of supercrit. He inside the conductor. It could modify the temperature evolution in transient analysis
2. The surface thermal resistance between supercrit. He and kapton. This resistance can be estimated around $600 \text{ W}/(\text{m}^2\text{K})$: the additional increase in temperature in the 34th cond. could be between **0.03 K** and **0.05 K**
3. The surface thermal resistance between kapton and copper
4. The additional cooling of collar through the yoke (it should be a small effect).

As consequence, in collaboration with CERN, an experiment has been settled, in order to measure the actual thermal exchange between the **conductors**, insulated with **kapton**, and the **supercritical helium**.



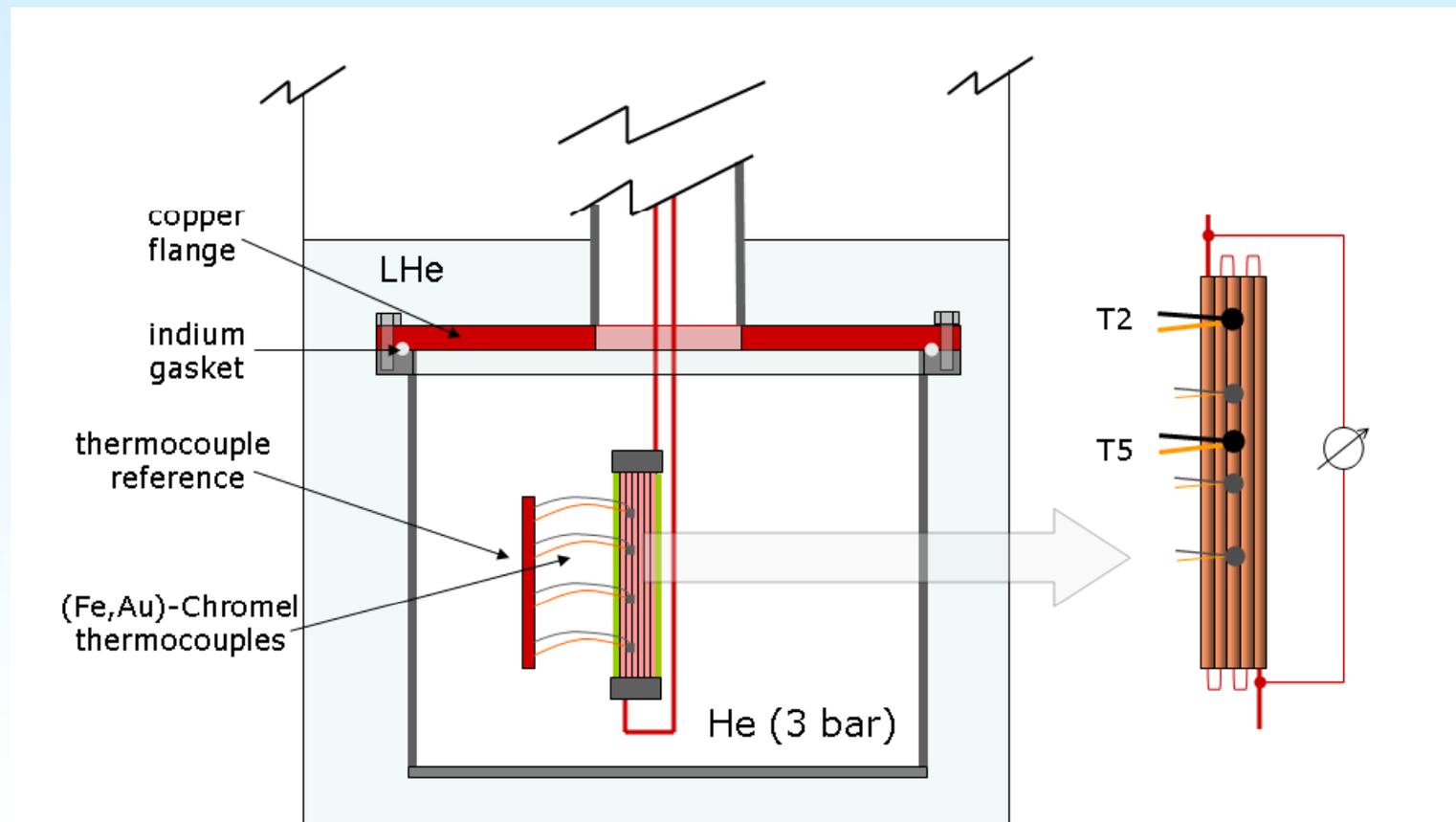
Courtesy of D. Richter, CERN

A stack of 6 cables (insulated with kapton, LHC lay-out) has been instrumented inside with thermo-couples in order to measure the temperature

The conductor can exchange heat only through the narrow side, as in the magnet

The sample was prepared and measured at CERN with **He-II**

We measured it in *static supercritical* helium

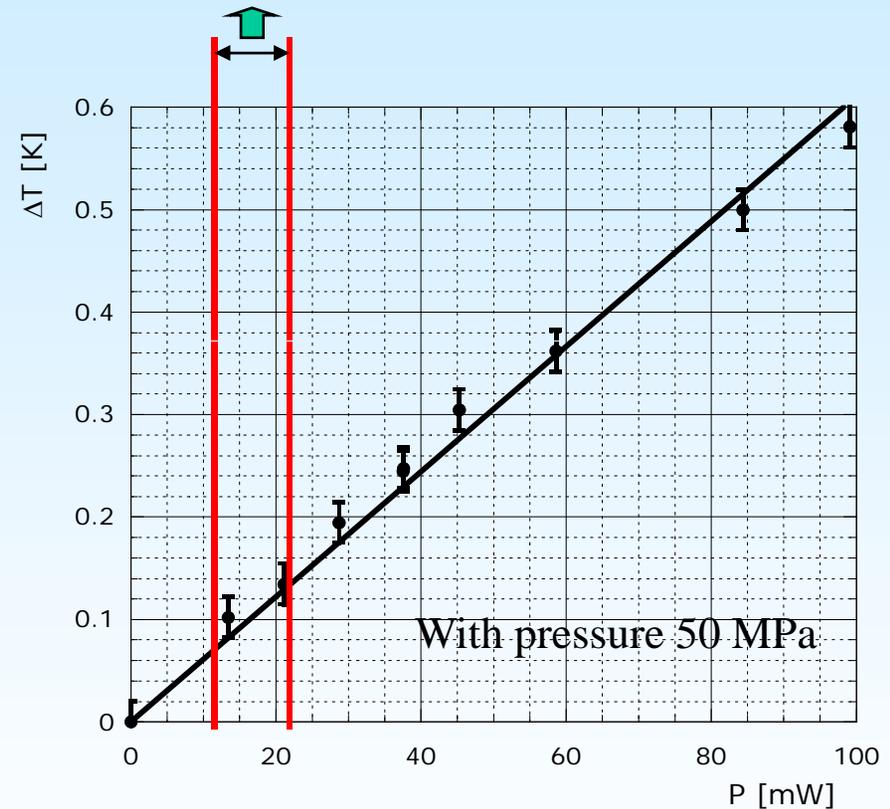
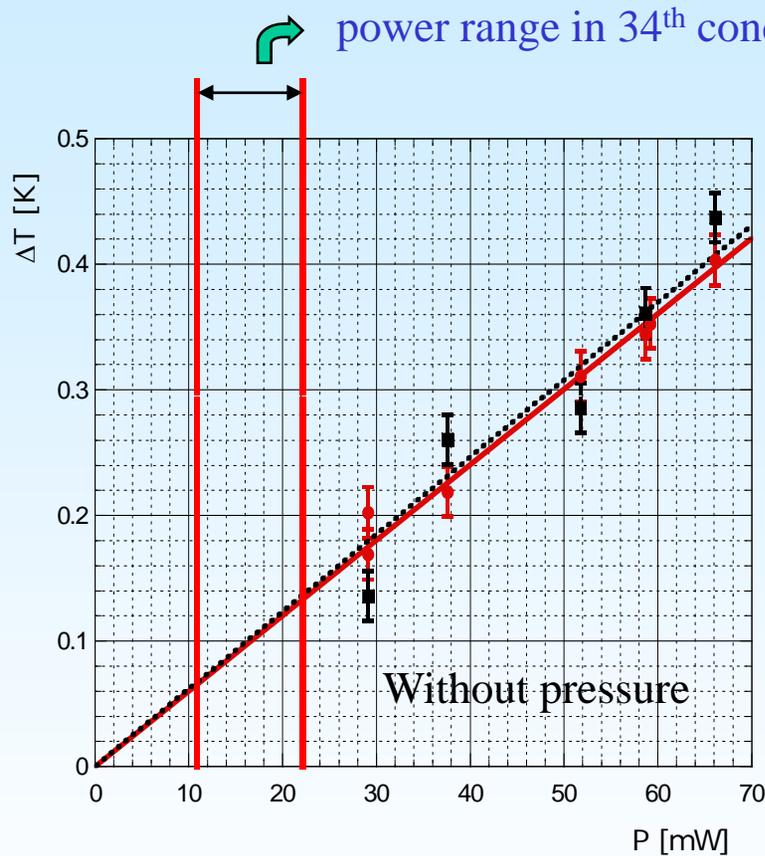


The sample was measured in the following condition:

1. Without “external” compression of the stack
2. With compression of 50 MPa by means of a tool, in order to reproduce the same situation in the magnet

The first measurement without compression was decided because there was some doubts about damaging thermo-couples at 50 MPa

Temperature drop between conductor and supercritical helium @ 4.2 K vs. the heat power generated in the conductors (the power density range corresponds to 1300-7000 W/m³)



Both the measurements give an *integral insulation conductivity* :

$$k = 0.019 \text{ W}/(\text{m} \cdot \text{K})$$

- The drop temperature is linear respect to the power, giving a constant *thermal conductivity*
- This measurement in *static* supercritical He gives a conservative value for the conductivity of kapton respect to a *flowing* supercritical He
- The measured conductivity includes the thermal resistance between kapton-He and kapton-cable
- The measured conductivity of kapton is a factor 1.9 larger than the value used in the calculation
- The thermal analysis can be considered quite **safe** for the most important parameter: **conductivity through kapton insulation.**

Conclusions:

From the thermal analysis:

- The *minimum* temperature margin occurs on the **34th conductor** of the magnet, at the **end of the ramp-up**
- At the end of the ramp-up, the 34th conductor temperature is **T-4.80 K +/-0.02 K** i.e. **0.10 K** above the coolant temp.
- Because the current sharing temp. is $T_g=5.69$ K (non-linear iron) the actual temperature margin in **0.89 K +/-0.02 K**
- Thermal conductivity measurements through the kapton confirm the validity of the analysis.