



2-D thermal analysis of the 7.8 m long dipole for SIS300

Massimo Sorbi, Giovanni Bellomo
Milan University and INFN Sez. di Milano

Contents:

1. Review of power losses in cold mass
2. Steady state thermal analysis
3. Transient thermal analysis
4. Conclusions

The main sources of losses in the cold mass of the dipole are:

1. Magnetic hysteresis in the s.c.
2. Eddy current in conductor (inter-filaments and inter-strands)
3. Eddy current in the collar
4. Eddy current in the beam pipe
5. Eddy current in the yoke
6. Magnetic hysteresis in the yoke

The last two are not relevant for the temperature in conductor, and will be discussed by P.Fabbricatore.

Losses in conductor

The hysteresis losses and inter-filament losses are calculated with:

- Roxie
- Opera, Ansys and Fortran code from the conductor magnetization

$$P = M_w \dot{B}$$

- M.N.Wilson's Excel Worksheet (actual magnetic field on each conductor)

The interstrand coupling losses have been calculated with:

- Roxie
- Excel code (only eddy current through Ra for transverse field)
- M.N.Wilson's Excel Worksheet

All the methods converge to similar results!

Losses in conductor: comparison between different codes

	P.C. (W/m)	I.F.C.C.(W/m)	I.S.C.C.(W/m)	TOTAL (W/m)
Roxie	2.40	0.77	0.54 / 0.38 ??	3.71 / 3.55
Opera	2.27	0.71	-	-
Fortran code	2.27	0.71	-	-
Excel code	-	-	0.25 + Rc	-
Ansys	2.28	0.74	-	-
Wilson excel	2.41	0.69	0.23 + 0.11	3.45

Average losses, in the linear ramp between 1.5 T and 4.5 T

SUMMARY OF CABLE LOSSES (averaged 1.5 T – 4.5 T @ 1 T/s)

(from M.N.Wilson Excel Worksheet)

	ramp'g power W/m	loss/ cycle J/m	fraction of total %
transv'se cros'r	0.11	0.7	3.3%
transv'se adj'nt	0.23	1.4	6.8%
parallel adjacent	0.00	0.0	0.1%
fil'nt coupling	0.69	4.1	20.0%
total hysteresis	2.41	14.4	69.8%
total magnet	3.45	20.7	100.0%

cable twist pitch	p	0.1	m
crossover resistance	R _c	2.00E-02	ohm
adjacent resistance	R _a	2.00E-04	ohm
number of strands	N	36	
radius of fil't boundary	a _{fb}	0.3690	mm
matrix ratio	mat	1.800	
filament filling factor	λ _f	0.357	
wire trans res'y intercept	C _{pet}	4.00E-10	ohm.m
wire trans res'y gradient	m _{pet}	2.00E-10	ohm.m/T
wire twist pitch	p _w	5.00E-03	m
filament diameter	d _f	3.50E-06	m
cooking factors		1.00	

The power is averaged on the ramp up

The loss/cycle is averaged on the full cycle (up and down)

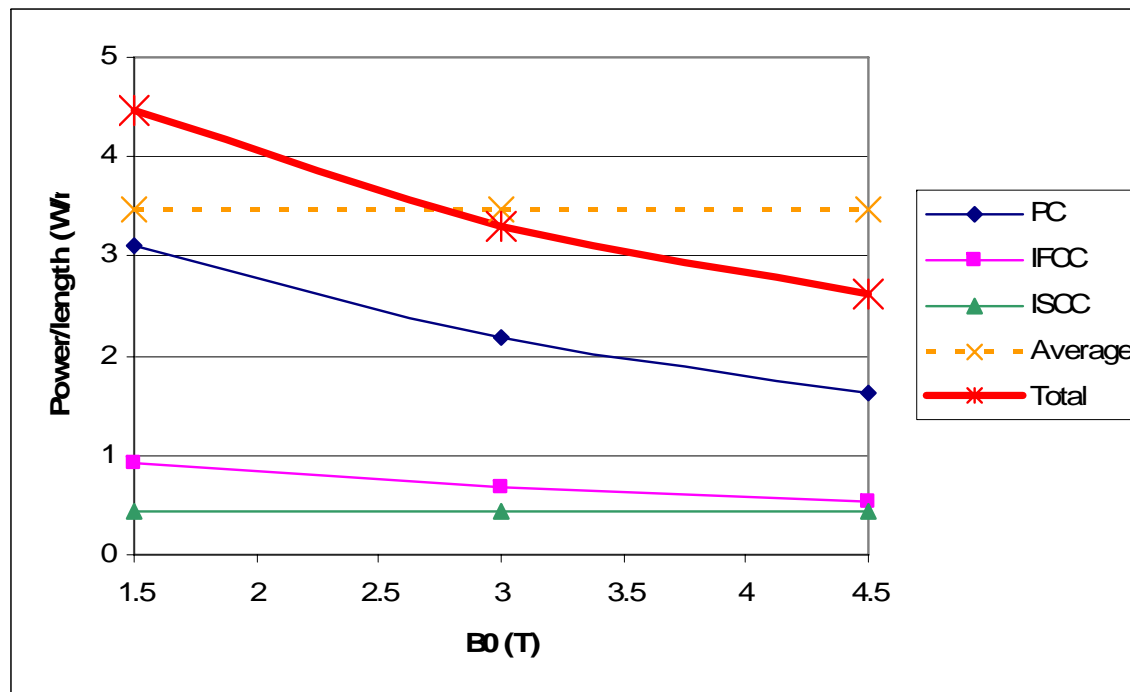
Losses during the ramp are not constant:

@ $B_0 = 1.5$ T $P = 4.5$ W/m

@ $B_0 = 4.5$ T $P = 2.6$ W/m

Average $P = 3.5$ W/m

Does it help for
temperature margins ??



Eddy current in the collar

- From a simplified 1-D analysis, the power/length P_{1-D} can be calculated with the analytical formula:

$$P_{1-D} = \int_{\text{Collar area}} \frac{1}{12\rho} \dot{B}^2 \Delta s^2 d\Sigma$$

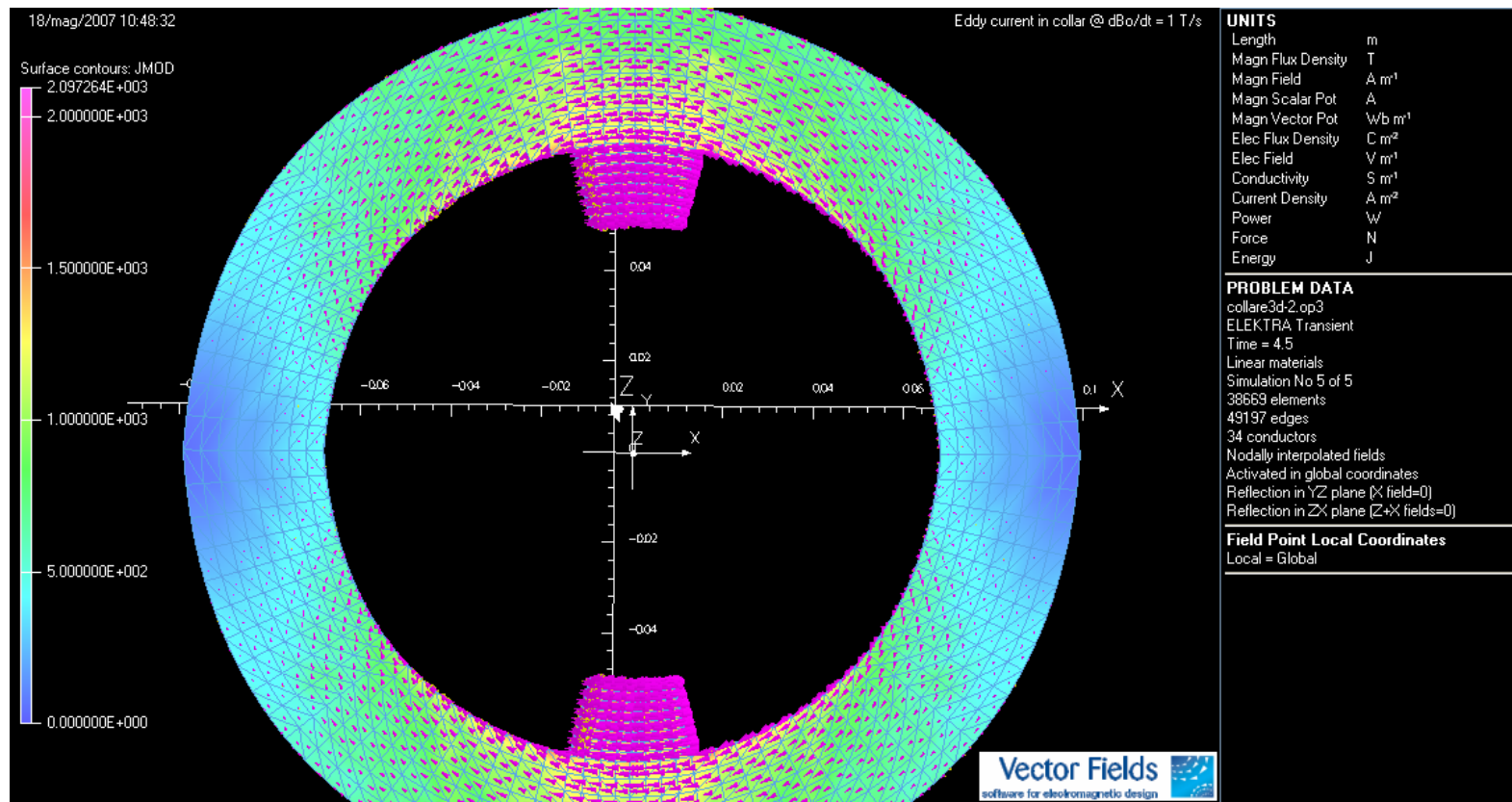
where Δs is the thickness of collar sheet and $\rho = 5.3\text{E-}7$ ohm*m the stainless steel resistivity.

- Assuming $\Delta s = 2$ mm, the integration gives the following value:

$$P_{1-D} = 2.4 \text{ mW/m}$$

This (apparently) rough estimation is totally confirmed by more refined 3-D calculations:

$$P_{3-D} = 2.5 \text{ mW/m}$$



Eddy current in beam pipe

- In this case the eddy currents are directed in z direction, and the power/length P can be analytical calculated:

$$P = \int_{r_{inner}}^{r_{outer}} \int_0^{2\pi} \rho \cdot J_z^2 \cdot r \cdot d\theta dr \approx \frac{\pi}{\rho} \dot{B}_0^2 \cdot r_{av}^3 \cdot \Delta r$$

where $r_{av} = 44 \text{ mm}$ is the average radius of the beam pipe and $\Delta r = 2 \text{ mm}$ is the pipe thickness

$$P = 1.0 \text{ W/m}$$

(not negligible as thermal load for the cooling gas)

Temperature gradient in conductors

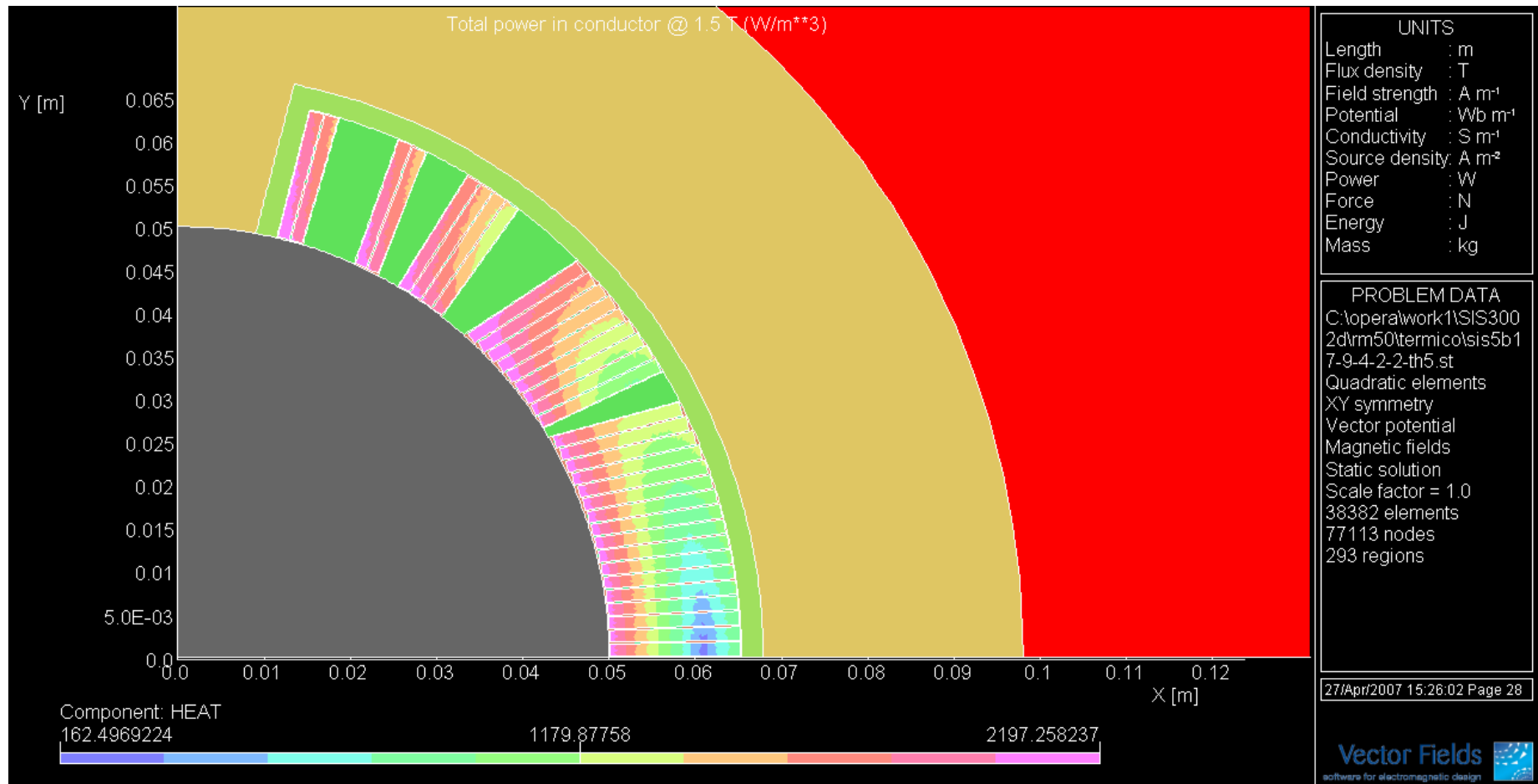
The study of the temperature distribution on the conductors has been carried out for the following cases:

1. Steady state analysis with constant power at $Bo=1.5$ T
2. Steady state analysis with constant power at $Bo=4.5$ 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

In all cases it has been assumed that the considered cold mass (conductors and collar) is cooled through the inner surface. The coolant temperature is 4.7 K (constant).

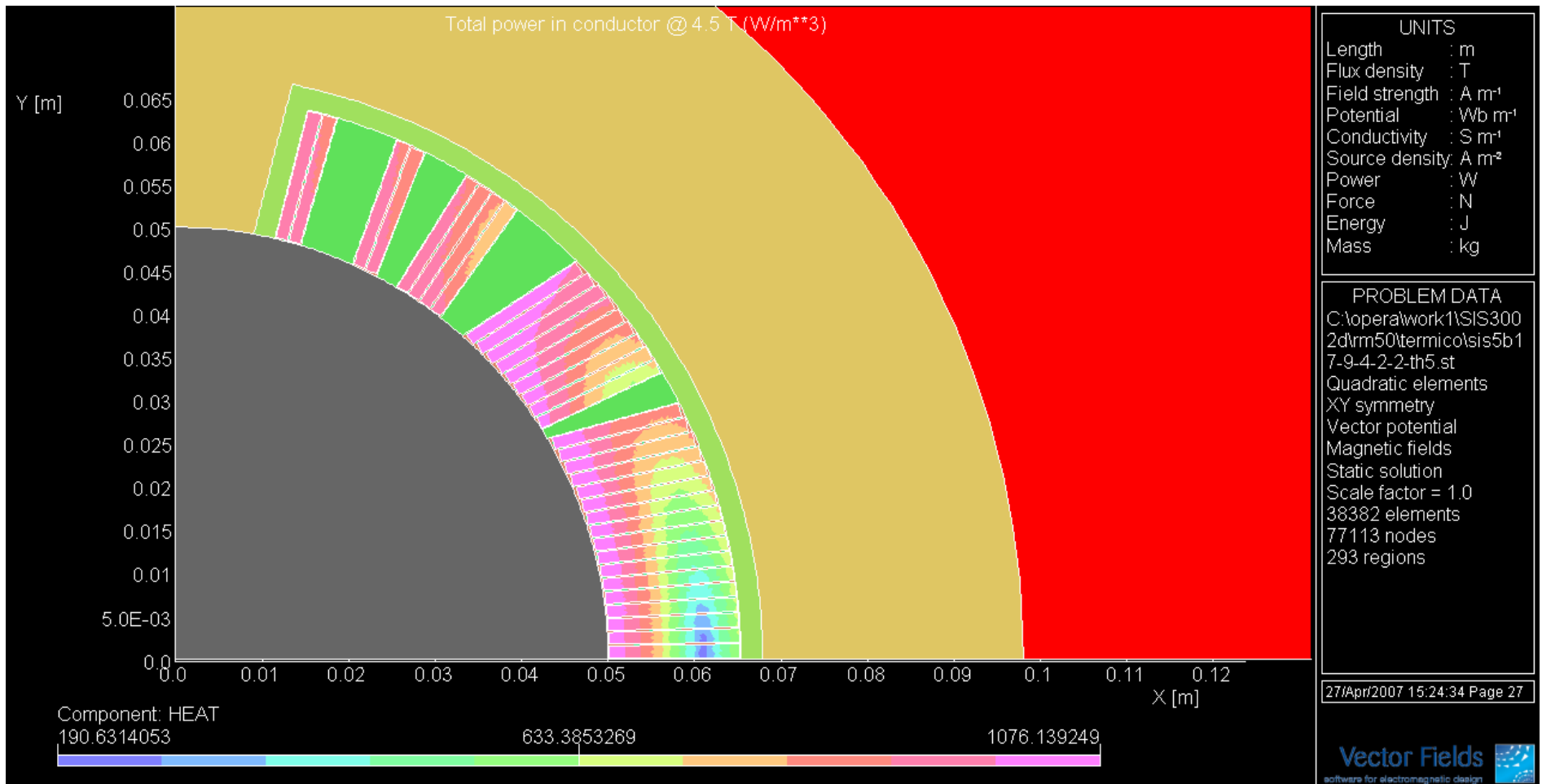
Power distribution in conductor @ $B_0=1.5$ T

[Peak power 2200 W/m^3]



Power distribution in conductor @ $B_0=4.5$ T

[Peak power 1080 W/m^3]



Zero order calculation of thermal gradient in the insulation:

Cooling of conductor only from inner short side.

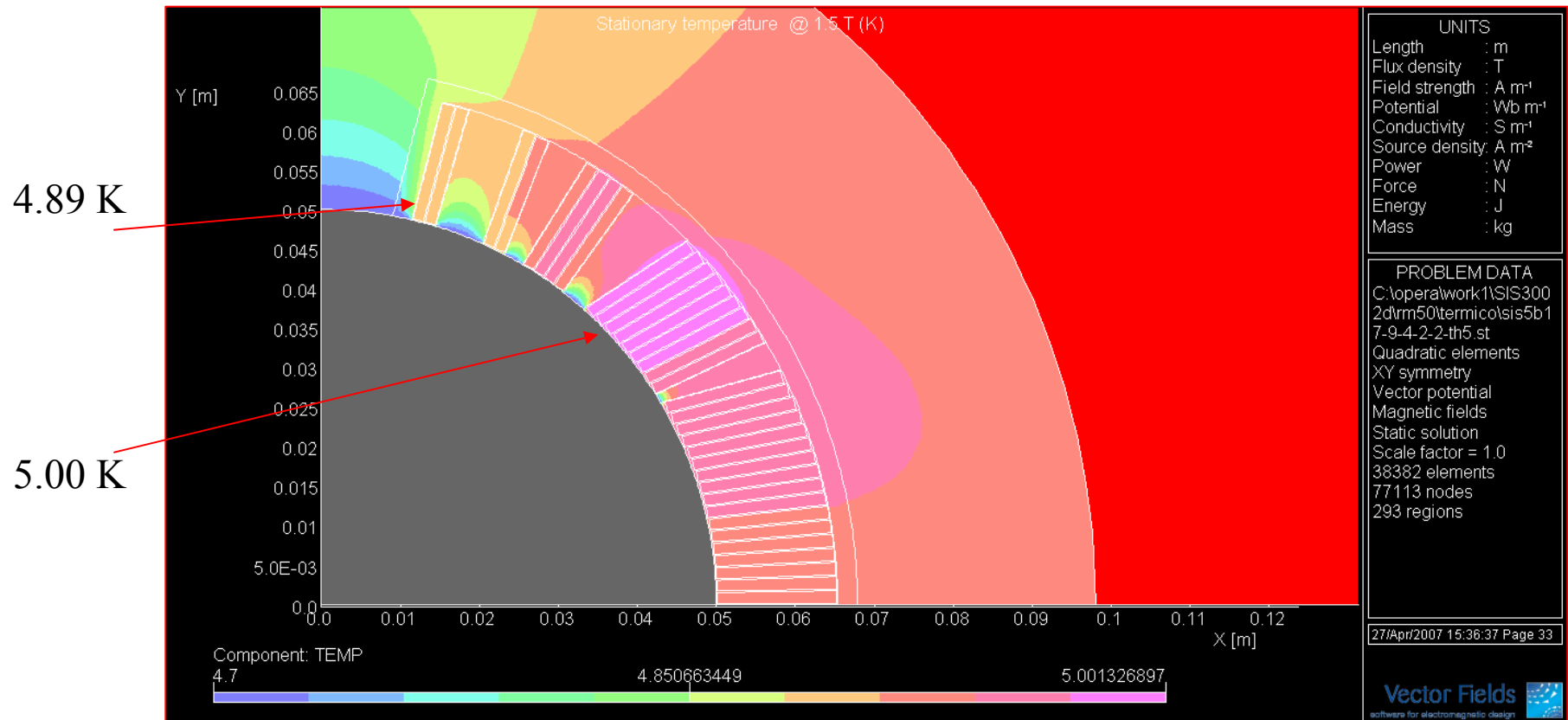
- Kapton thermal conductivity $k = 1.1 \text{ E-5}$ W/(K*mm)
- Insulation thickness $d = 0.125$ mm
- Conductor width $w = 15.1$ mm
- Average power in the 34th turn 1500 W/m³

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

(Thermal gradient in conductor \sim mK)

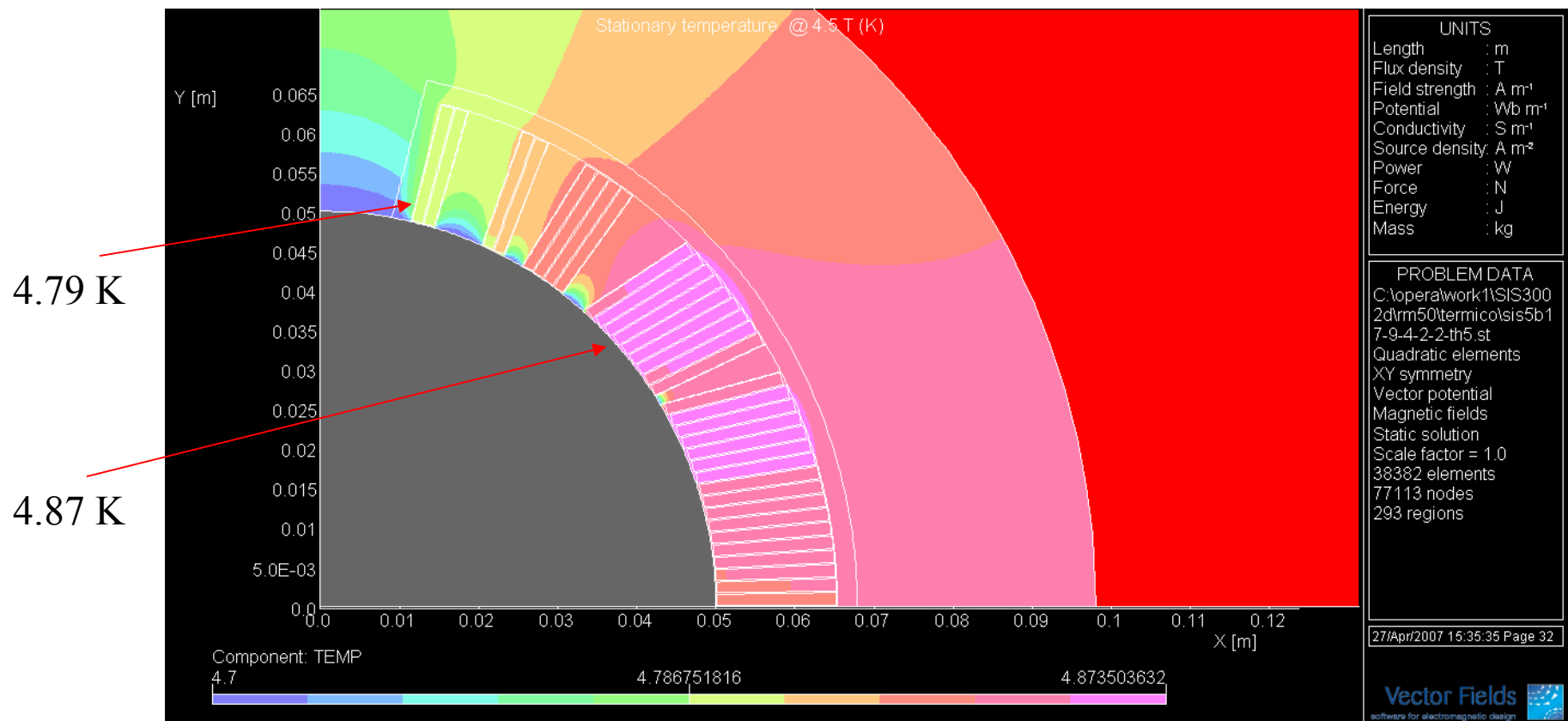
Steady state case:

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 from “Bottura fit”.

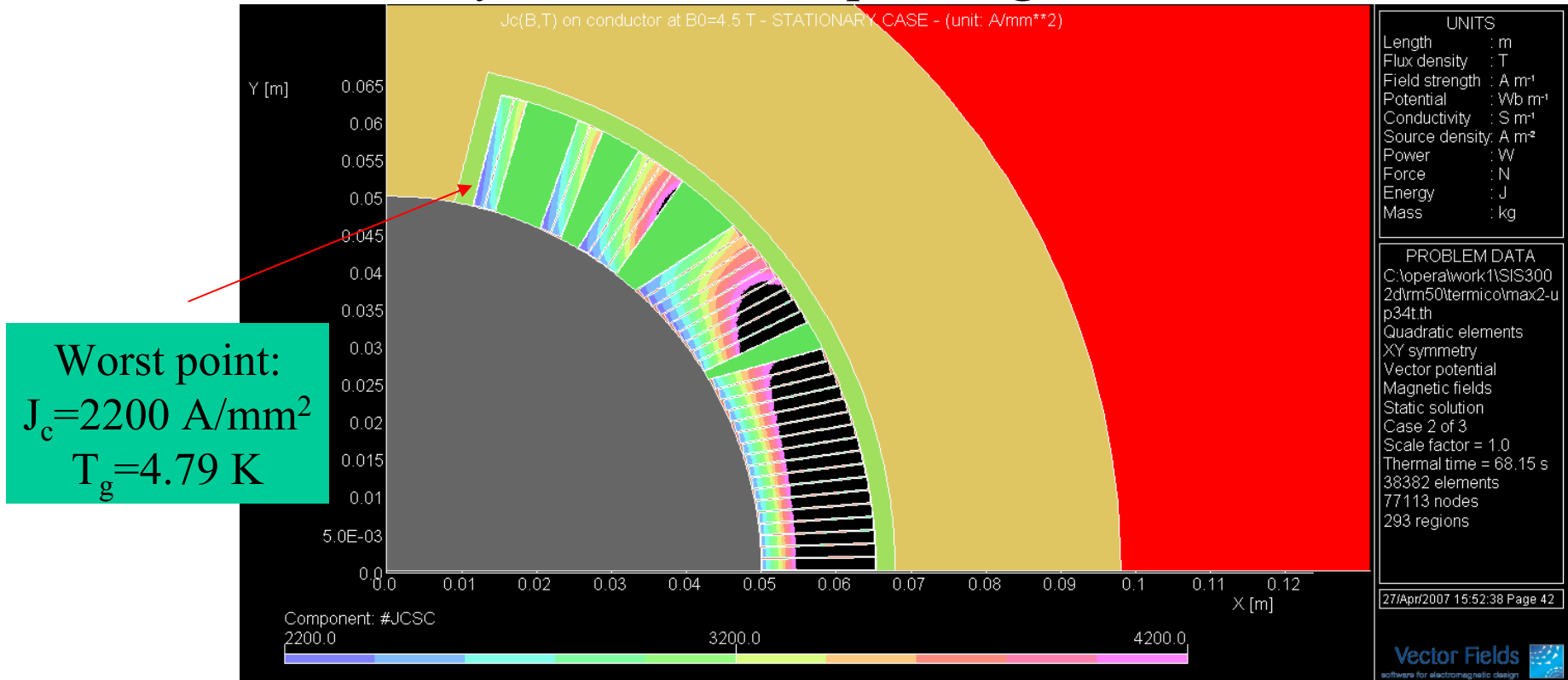
However this formula can not be easily reverted for the temperature.

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

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

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



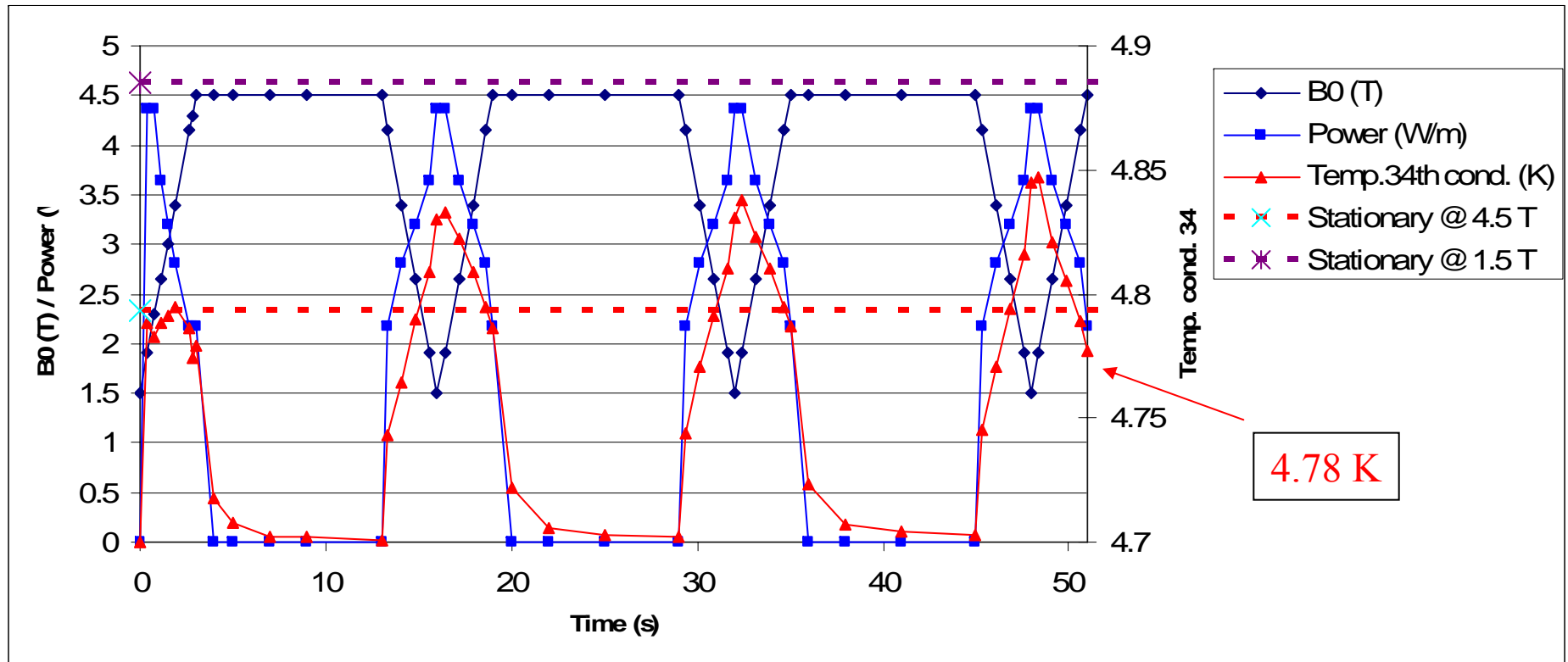
Worst point:
 $J_c=2200$ A/mm²
 $T_g=4.79$ K

$(J_{op}=1300$ A/mm²)

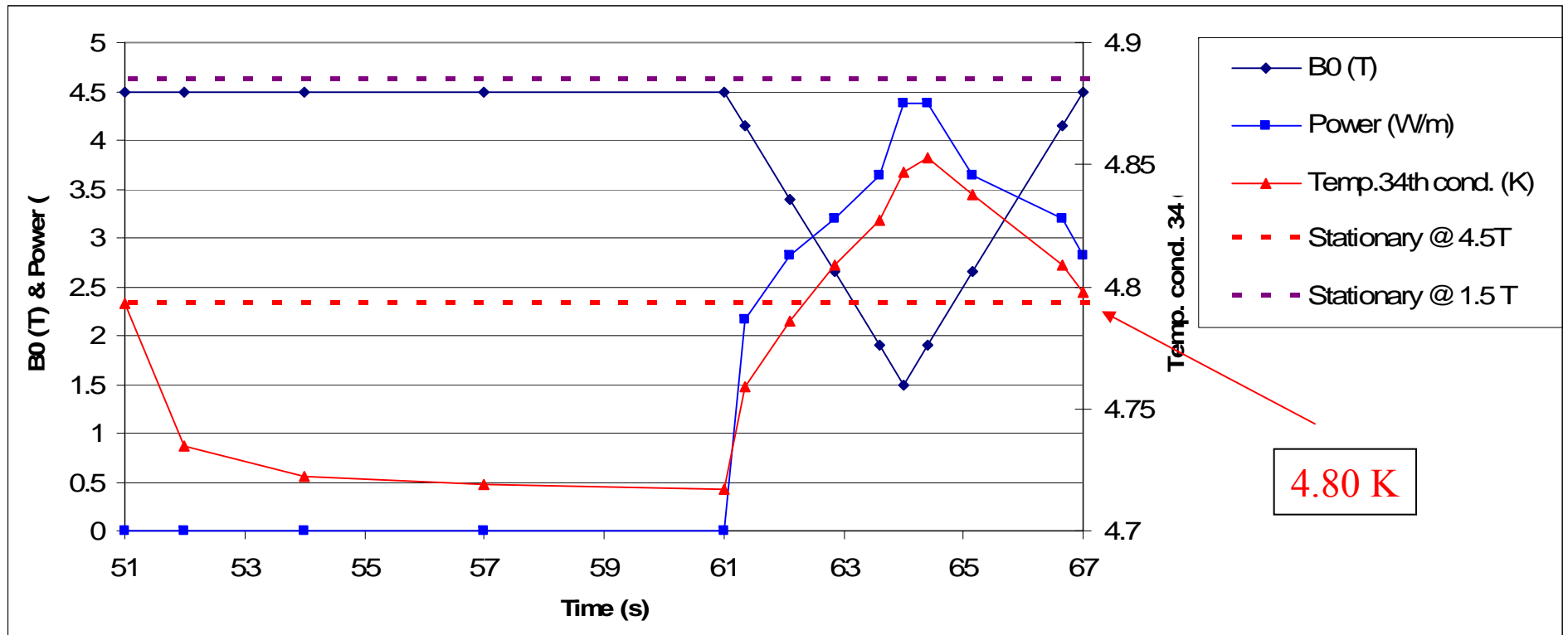
Conclusion: the minimum value of T_g (current sharing temp.) occurs at $B_0=4.5$ T and in the conductor with peak field.

TRANSIENT ANALYSIS:

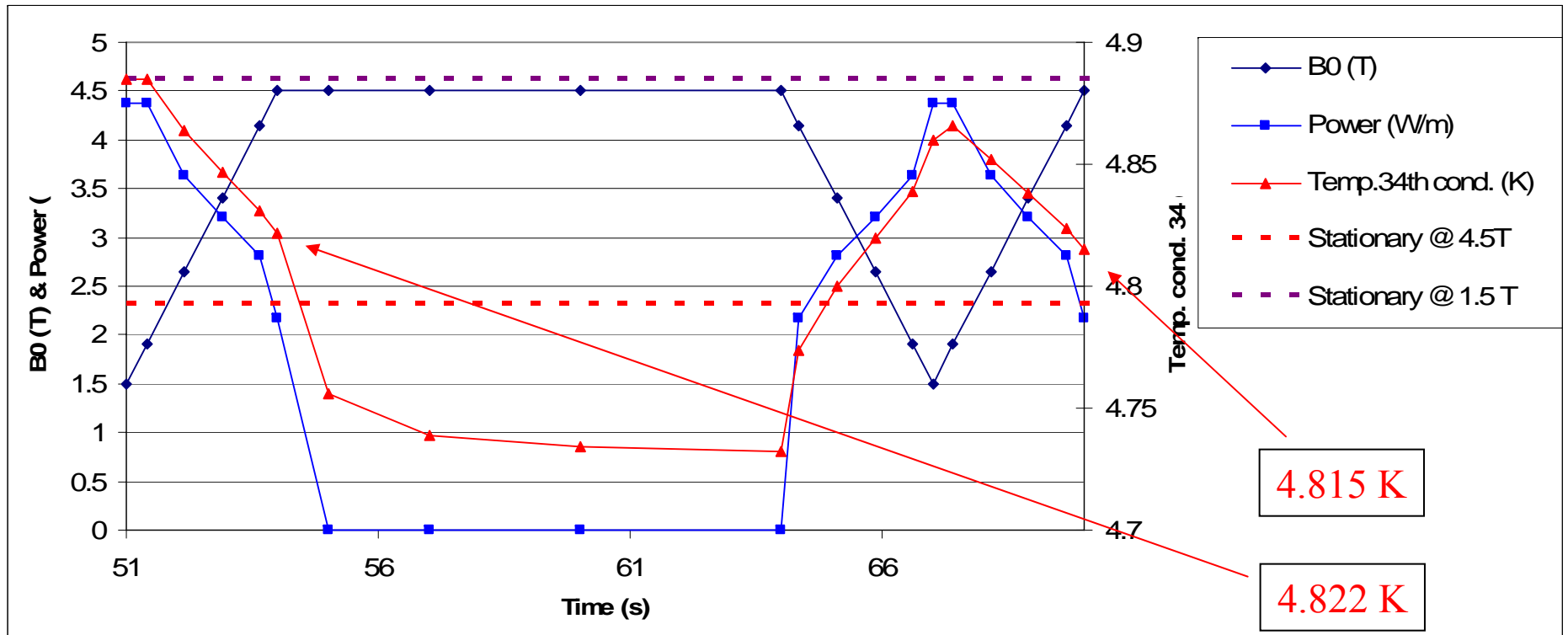
Temperature evolution starting from T=4.7 K



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 the analysis it has been neglected:

1. The very large thermal capacity of GHe inside the conductor. It could modify the temperature evolution in transient analysis
2. The surface thermal resistance between GHe 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. is 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).

Conclusions:

From the thermal analysis:

- The reduction of temperature margin ΔT_g in the worst hypothesis (stationary case @ 1.5 T) is **0.25 K**.
- In a more realistic scenario (transient analysis) $\Delta T_g = \sim \mathbf{0.15 K}$ (but thermal capacity of GHe??)

	Temperature margin reduction
Initial temperature margin @ $\mu_r = \infty$	$\Delta T_g = \mathbf{0.99 K}$
Iron yoke saturation	$\Delta T = -0.02 K$
Thermal analysis in conductor	$\Delta T = -0.12 K$
Contact resistance GHe-Kapton	$\Delta T = -0.04 K$
Actual temperature margin	$\Delta T_g = 0.81 K$

Conclusions (continued):

- This analysis, even if detailed, is meant to give only some *reference values* for power losses and temperature in conductors.
- Indeed all the codes converge to similar results on power losses, **but** there are some uncertainty on:
 - Actual values of conductor electrical parameters (contact resistances, effective filament diameters, etc.)
 - Accuracy of the used models for losses evaluation
 - Actual values of thermal material properties (thermal conductivity, specific heat, etc.)