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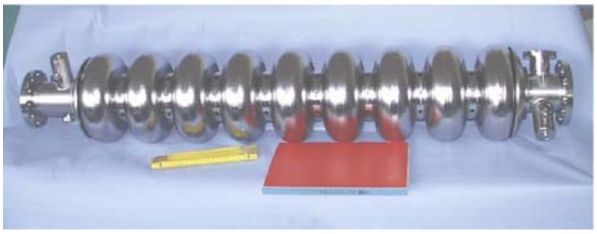

TESLA RF POWER COUPLER THERMAL CALCULATIONS

Dohlus M., Kostin D., Möller W.-D.**,** *DESY, D-22607 Hamburg, Germany*

Abstract

The main RF power coupler is one of the key elements of the accelerating module for the superconducting linac. It provides RF power to the cavity and interconnects different temperature layers in the module. Therefore statistical and dynamical thermal losses have to be optimised. Different operating modes as well as geometries were investigated. Coupler design optimisation studies are carried out for TESLA and for the XFEL case. Especially long pulse operation for the XFEL is being investigated.

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The main RF power coupler is one of the key elements of the accelerating module for the superconducting linac. It provides RF power to the cavity and interconnects different temperature layers in the module. Therefore statistical and dynamical thermal losses have to be optimised. Different operating modes as well as geometries were investigated. Coupler design optimisation studies are carried out for TESLA and for the XFEL case. Especially long pulse operation for the XFEL is being investigated.

THEORETICAL BACKGROUND

Heat Conduction Equations

The general heat conduction equation (see Eq. 1) for the steady state in one dimension becomes the Eq. 2, *P* is internal heating power source, *l* - thermal conductivity, ***n*** - material index.

$$rC_p \frac{\partial T}{\partial T} = \nabla(l \nabla T) + \frac{dP}{dV} \qquad (1)$$

$$\frac{dT}{dz} = R'(z,T(z)) \cdot p(z),\ R'(z,T) = \left(\sum_n A_n(z) l_n(T)\right)^{-1} \qquad (2)$$

The thermal resistance *R(z,T)* describes the thermal properties of the material, it can be calculated as:

$$R_i(T_a,T_b) = (T_b - T_a)\frac{l}{A} \Bigg/ \int_{T_a}^{T_b} l(T)dT \text{ , } l \text{ - length} \qquad (3)$$

The radiational thermal resistance is (k_{em} is the emissivity and *s* - Boltzmann constant *5.67´10⁻⁸*):

$$R_{rad}(T_1,T_2,A_{rad}) = \frac{T_1 - T_2}{A_{rad}(T_1^4 - T_2^4)k_{em}s} \qquad (4)$$

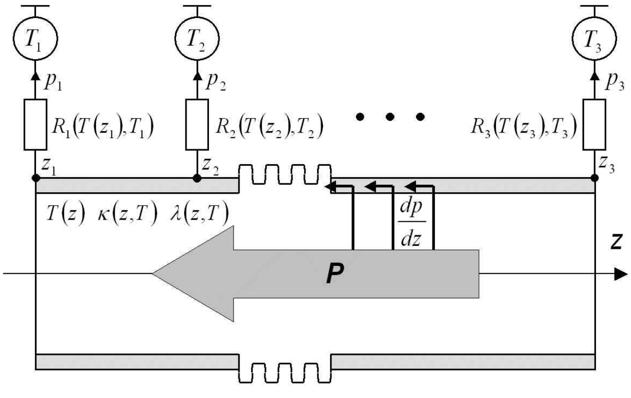

Figure 1: The Boundary Problem.

The problem to solve is a boundary problem with internal power sources introduced by RF power losses and fixed temperature points as boundary conditions (see Fig. 1). RF power losses was calculated using MAFIA and recalculated using Eq. 5, where *k* is the electrical conductivity. The coupler bellows are simulated by geometry coefficient *gb(z)>1* (ratio of the material length along the bellow surface to the bellow length, see Eq. 6).

$$\frac{dp}{dz} = \underbrace{\left(\frac{dp}{dz}\right)}_{\substack{k=k_0, \\ P=P_0 \\ \text{MAFIA}}} \cdot \frac{P}{P_0} \cdot \sqrt{\frac{k_0}{k(z,T)}} \qquad (5)$$

$$\frac{dT}{dz} = R'(z,T(z)) \cdot p(z) \cdot gb(z),\quad gb(z) = \frac{d\tilde{z}}{dz} \qquad (6)$$

Numerical Solution

The coupler was simulated by set of discrete elements (see Fig. 2) similar to the electrical circuits, in this case the resistive elements are the thermal resistances, currents are power flows and voltages are the temperature differences (see Eq. 7), for element ***n*** one can write Eq. 8. and for the whole system the matrix equation with tridiagonal matrix **G**(**t**) (see Eq. 9), solved using method of iterations in MathCAD (See Eq. 10).

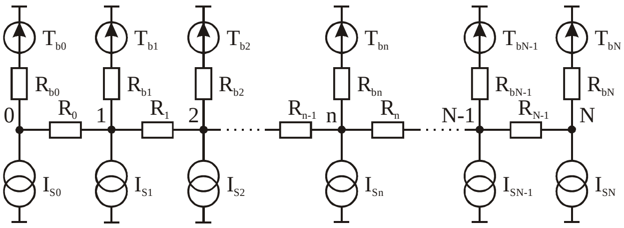

Figure 2: Equivalent Circuit Diagram.

$$G = 1/R,\ \mathbf{t} = (T_n),\ \mathbf{i} = (I_n) = \mathbf{i}(\mathbf{t}),\ I_n = \frac{dp}{dz}dz \qquad (7)$$

$$\begin{aligned}&(-1/R_{n-1})T_{n-1} + (1/R_{n-1} + 1/R_n + 1/R_{bn})T_n + \\ &+ (-1/R_n)T_{n+1} = (I_{sn} + T_{bn}/R_{bn})\end{aligned} \qquad (8)$$

$$\mathbf{i}(\mathbf{t}) = \mathbf{G}(\mathbf{t})\,\mathbf{t} + \mathbf{G}_b(\mathbf{t},\mathbf{T}_b)\mathbf{T}_b \qquad (9)$$

$$\begin{aligned}&\mathbf{i}(\mathbf{t}_n) = \mathbf{G}(\mathbf{t}_n)\mathbf{t}_{n+1} + \mathbf{G}_b(\mathbf{t}_n,\mathbf{T}_b)\mathbf{T}_b \\ &\mathbf{t}_0 \rightarrow \text{linear between } \mathrm{T}_1 \text{ and } \mathrm{T}_\mathrm{N}\end{aligned} \qquad (10)$$

TESLA RF POWER COUPLER

The RF power input coupler specifications are presented in the Table 1. The coupler is shown in Figure 3, it has 4 fixed temperature points: outside connection to 300 K, 70 K shield connection, 4 K shield connection and the cavity flange at 2K. Coupler inner and outer conductors are made from stainless steel coated by copper, coupler antenna is a whole copper made. Coupler has 2 ceramic windows (warm and cold) and 3 bellows.

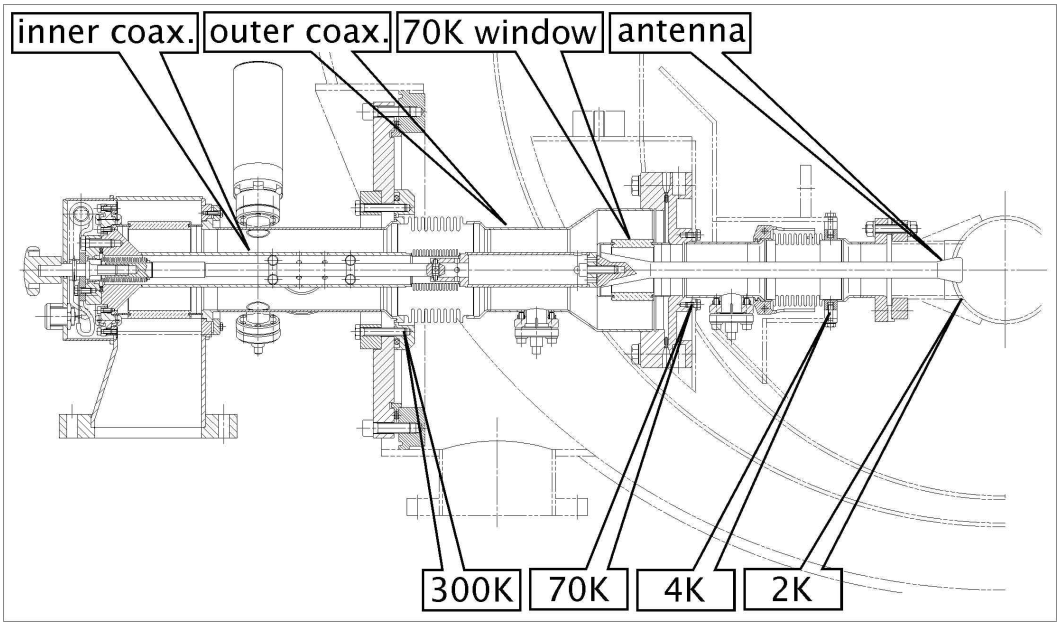

Figure 3: TTF III Coupler Design.

Table 1: RF Power Coupler Specifications.

	TTF	TESLA	XFEL
frequency [GHz]	1.3		
operation	pulsed: 500 µs rise time, 800 µs flat top with beam		
2 K heat load [W]	0.06		
4 K heat load [W]	0.5		
70 K heat load [W]	6		
peak power [kW]	250	250 – 500	150
rep. rate [Hz]	10	5	10
average power [kW]	3.2	3.2 – 6.4	1.9

CALCULATIONS RESULTS

RF Power Losses

Calculated RF power losses using MAFIA 4.0 are shown in Fig. 4. Travelling wave regime calculations done for the copper, $?_0=5.8\times10^{7}$ 1/(O×m) (300K), power losses in the 70K ceramic window (e=9, tgd=10^{-4}): $P_{loss.win}/P_{in} = 1.94\times10^{-4}$.

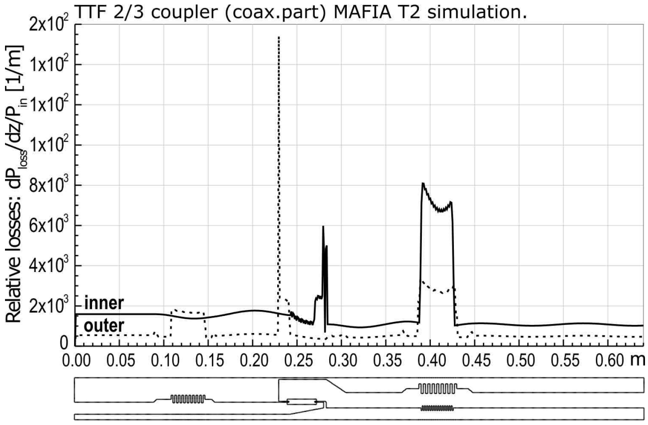

Figure 4: RF Power Losses.

Material Properties

The material properties of the materials used in the simulations are shown in Figures 5a and 5b. Calculations done for the copper with RRR 10 and 100.

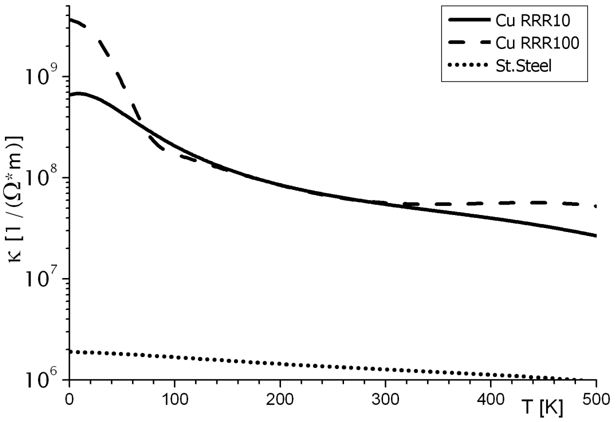

Figure 5a: Electrical Conductivities with Temperature.

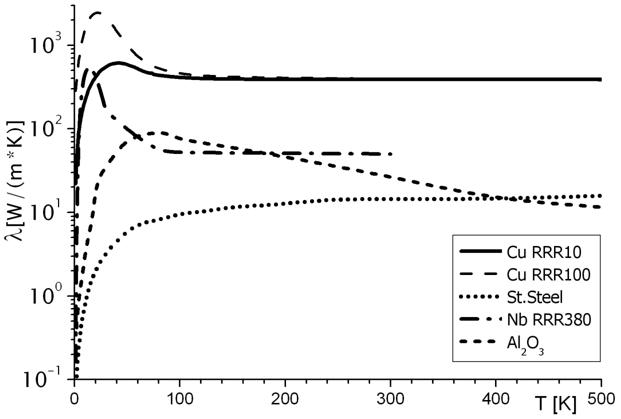

Figure 5b: Thermal Conductivities with Temperature.

Calculated Data

Temperature distributions along the TTF III coupler as well as the cryogenic power losses (statical and dynamical) were calculated for different sets of parameters. The copper coating thickness and RRR as well as average input power were varied. The obtained data are presented in the Table 2 and in the Figures 6a, 6b, 7 and 8.

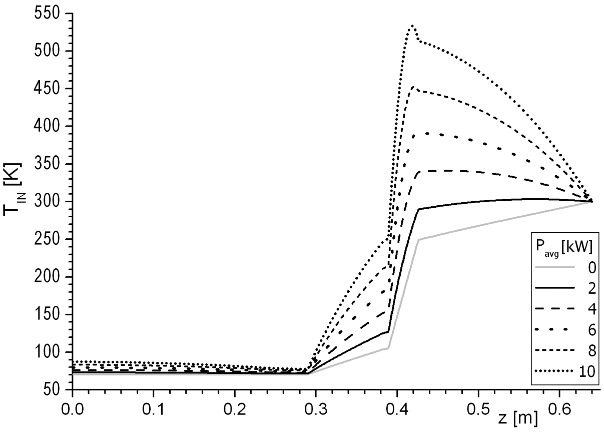

Figure 6a: Inner conductor temperature distribution.

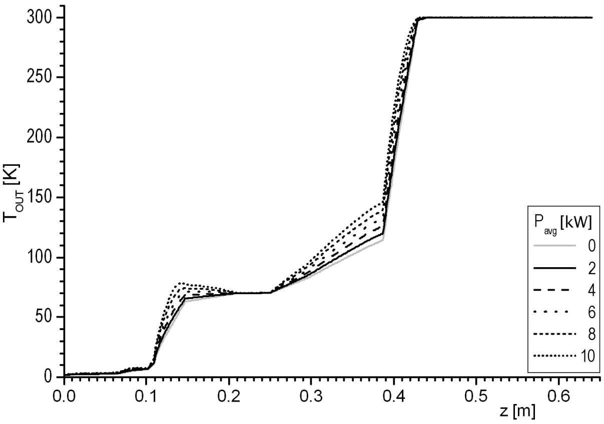

Figure 6b: Outer conductor temperature distribution.

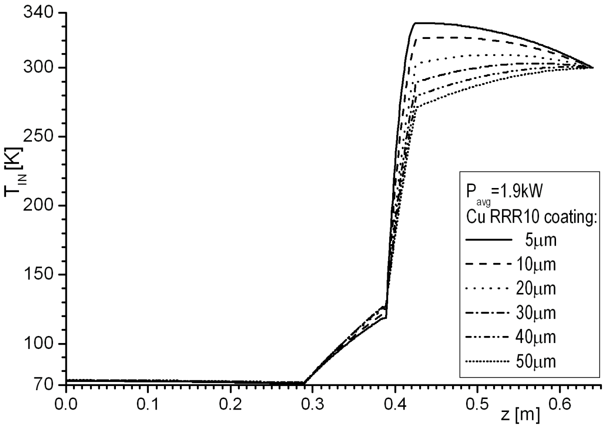

Figure 7: Cu coating of inner conductor.

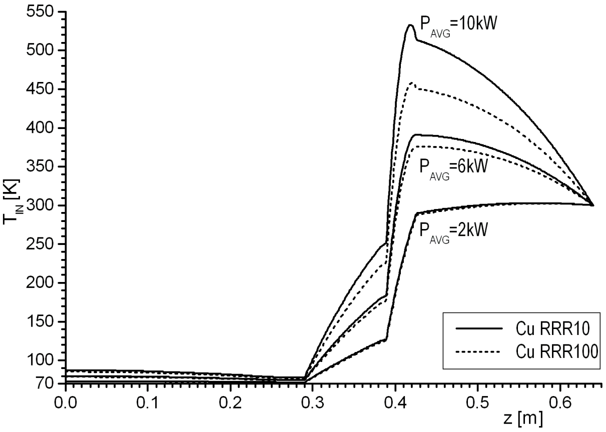

Figure 8: RRR of Cu coating of inner conductor.

Table 2: Cryogenic Power Losses.

Cu coating		P_{avg}	P Σ	P Σ	P in	P out	P win	P Σ
in	out		2K	4K	70K			
μm		kW	W					
Cu RRR = 10								
10	30	0.0	0.02	0.2	0.8	1.1	0.0	1.9
		1.9	0.04	0.3	2.3	1.5	0.4	4.1
		4.0	0.05	0.4	4.0	2.0	0.8	6.8
		6.0	0.07	0.5	5.8	2.5	1.2	9.6
		8.0	0.09	0.6	7.8	3.1	1.6	12.4
		10.0	0.11	0.7	10	3.6	1.9	15.6
10	5	1.9	0.04	0.3	1.7	1.5	0.4	3.6
	10				1.8			3.7
	20				2.1			3.9
	30				2.3			4.1
	40				2.5			4.3
	50				2.6			4.5
5	30	1.9	0.03	0.2	2.3	1.3	0.4	3.9
10			0.04	0.3		1.5		4.1
20			0.05	0.5		1.9		4.6
30			0.06	0.6		2.3		5.0
40			0.08	0.8		2.8		5.4
50			0.09	0.9		3.2		5.8
Cu RRR = 100								
10	30	1.9	0.10	0.5	2.3	1.2	0.4	3.8
		6.0	0.11	0.6	5.9	2.1	1.2	9.2
		10.0	0.13	0.7	9.7	3.1	1.9	14.8

CONCLUSIONS

TTF III coupler fulfils the cryogenic losses requirements for TESLA and XFEL. At higher average power levels the inner conductor bellow becomes overheated. Average power level limit is about 6 kW (without cooling of the inner conductor). The copper coating of the inner (30±10 μm) and outer (10±5 μm) is optimal. The RRR value for the copper (10..100) is not critical up to 6 kW of average power.