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Auteurs :	Pierre-Emmanuel Bernaudin (DSM/DAPNIA/SACM)	
Objet :	Dimensionnement RF d'un coupleur 1 MW pour un DTL	
Réf :	DAPNIA-05-25	

RF design of a DTL power coupler

Commissariat à l'énergie atomique
Centre de Saclay
CEA/Saclay 91191 GIF sur YVETTE Cedex
Tel : (+33) 1 69 08 00 00 – FAX : (+33) 1 69 08 00 00

1 Introduction

The purpose of this study is the design of a RF power coupler for the first tank of the CERN Linac 4 Drift Tube Linac (DTL) project.

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2 Computing principles and methods

This study uses the 3D RF simulation code Ansoft's *HFSS* (version 8.5). All computations are lossless simulations. With such a 3D code it is absolutely impossible to simulate a full multicell DTL and in the same time achieve a reasonable degree of precision. Therefore the problem is simplified as much as possible to enhance both precision and computing time.

To do so, the problem is reduced to a single cell with the RF power coupler. The chosen cell is the one which will be (or at least is the more likely to be) used for the RF input: the central, 18th one.

A coupling factor is determined by the ratio of the fields in the coupler and in the cavity at the coupling port. Thus, when one simulates only a fraction 1/N of a periodic, resonant structure like a DTL, the external Q factor which must be achieved for a single cell must be 1/N times the external Q factor of the whole tank:

$$Q_{ext}^{1cell} = \frac{1}{N} Q_{ext}^{Ncells}$$

To further simplify the problem, only half a cell (and half a coupler) is modelled. By working this way, one neglects the fact that the cell is not exactly symmetrical (the centre is offset). Therefore the cell geometry is slightly modified to be symmetric to keep the proper accelerating gap.

The external Q factor is computed using the fast frequency sweep, single port method: the driven model is scanned in frequency around the resonance, only one port being used, and the Q factor is then given by the ratio:

$$Q_{ext} = \frac{f}{\Delta f}$$

where Δf is computed using the phase of the S_{11} parameter (frequencies at ±90° around the zero phase[1]). The validity of this method has been checked using the two-ports, S_{12} technique. The external Qs computed with both methods are closer than 1%. The single port method is preferred because it is independent of the coupling factor of the pickup port, and because the required mesh is smaller (no pickup port to mesh).

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[1] More precisely, ±90° around the inflexion point of the phase versus frequency curve.

3 Basic data

The basis of the practical study is the data provided by V. Pershin from ITEP, in charge of the RF design of the CERN Linac 4 DTL. The cell geometry is described in Figure 1, while the DTL and coupling cell RF data are shown in Table 1 and Table 2 respectively.

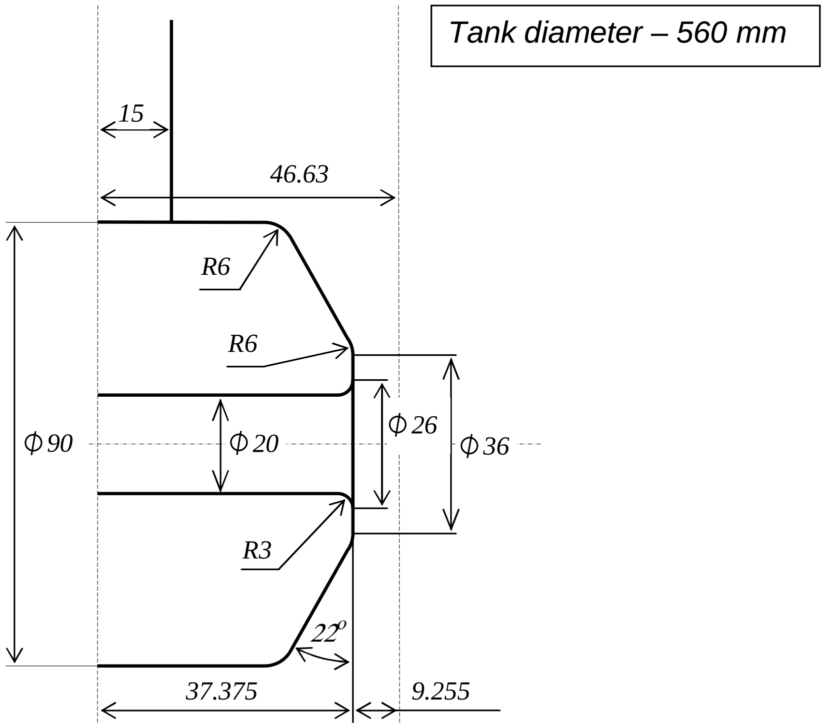

Figure 1 – 18th cell geometry and dimensions (courtesy V. Pershin).

Resonant frequency	MHz	352.2
Input / output energy	MeV	3.0 / 10.0
Tank diameter	mm	560
Tank length	mm	3 403
Cell number		36
Average electric field	MV/m	3.0
Electric field at the gap centers	MV/m	10.0…..12.2
Quality factor		52 900
Stored energy	J	9.93
RF power dissipation	kW	416

Table 1 – Linac 4 first tank properties (courtesy V. Pershin).

Cell length (between stem axes)	mm	93.26
Drift tube diameter	mm	90
Face angle	deg	22.0
Half-tube lengths	mm	37.07 & 37.68
Gap length	mm	18.51
Stem diameter	mm	30
Stored energy	J	0.2728
RF power dissipation	kW	11.18

Table 2 – Linac 4 first tank 18th cell properties (courtesy V. Pershin).

The coupling factor to be achieved is calculated as follows.

For the whole tank:

$$Q_{ext}^{\tan k} = \frac{2\pi . f . W_{cav}}{P_{losses} + P_{beam}}$$

where:

f	is the resonance frequency,
W_{cav}	is the energy stored in the cavity,
P_{losses}	is the power lost in the copper walls,
P_{beam}	is the RF power going to the beam (30 mA, 7 MeV energy gain)

It follows that, for the lone cell:

$$Q_{ext}^{1cell} = \frac{1}{N} \frac{2\pi . f . W_{cav}}{P_{losses} + P_{beam}}$$

A 20% safety margin factor is taken for the RF losses in the copper walls (500 kW instead of 416). It comes that the loaded Q for the DTL is 31 000, and for our one-cell simulations 861.

The coupler basic scheme is presented on Figure 2. The WR2300 standard waveguide is connected to the DTL cell via a “connecting guide”. The coupling is therefore performed by evanescent wave. The main advantage of this scheme is the easy tuneability of the coupling factor which can be adjusted by shifting the short-circuit position.

The parameters used to optimize the coupler and get the proper coupling factor are:

the length of the connecting guide,

the width and height of the connecting guide.

Finally the tuneability of the design is checked by moving the short-circuit position (the coupling factor shall be raised or lowered).

Note: the connection between the DTL and the connecting guide is *not* rounded in this simulation because it is very difficult to model using HFSS. Nevertheless, this should be performed in the actual coupler. A small radius of up to 5 mm would lead to little difference as far as the coupling factor is concerned.

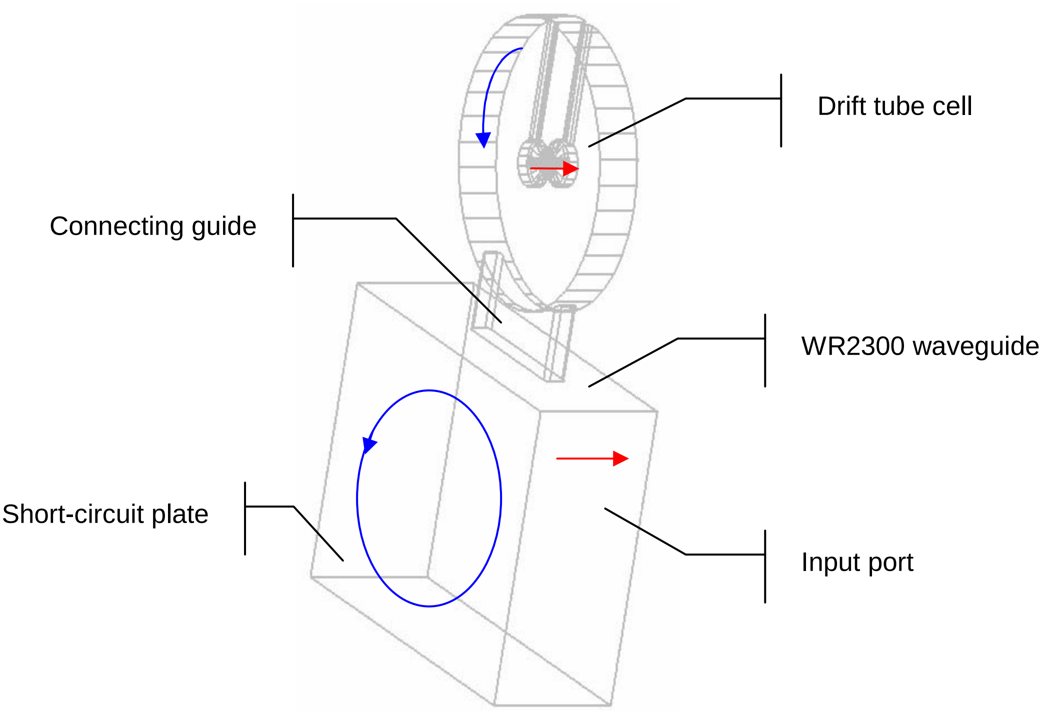

Figure 2 – Coupler basic scheme.

General direction of the electric field is shown in red, of the magnetic field in blue.

4 Coupler dimensions and properties

The resulting design's dimensions are described in Figure 4. The coupling factor tuneability is presented in Figure 3.

The coupler is responsible of an important frequency shift which is varying along with the coupling factor. Frequency shifts are shown in Table 3. Frequency shift versus coupling factor variation is shown in Figure 1.

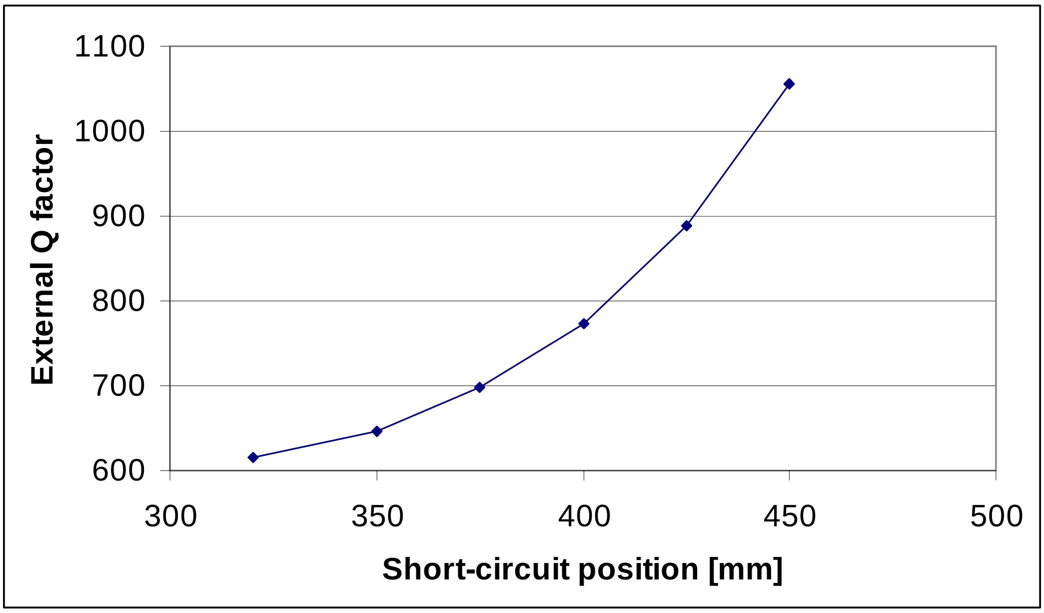

Figure 3 – Coupling factor tuneability.

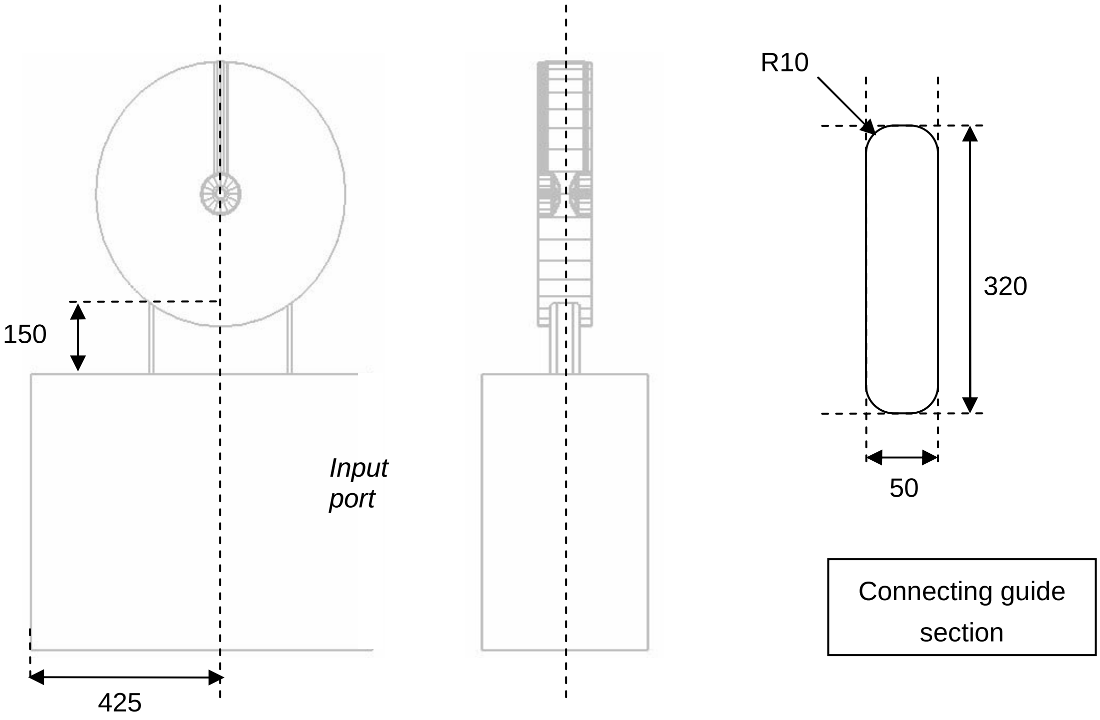

Figure 4 – Coupler dimensions.

	Frequency [MHz]	Frequency shift [kHz]
DTL cell alone	356.169	
DTL cell with coupler (eigenmode computation)	348.234	-7 935
DTL cell with coupler @Q_{ext}=888	348.035	-8 134

Table 3 – Frequency shift caused by the coupler.

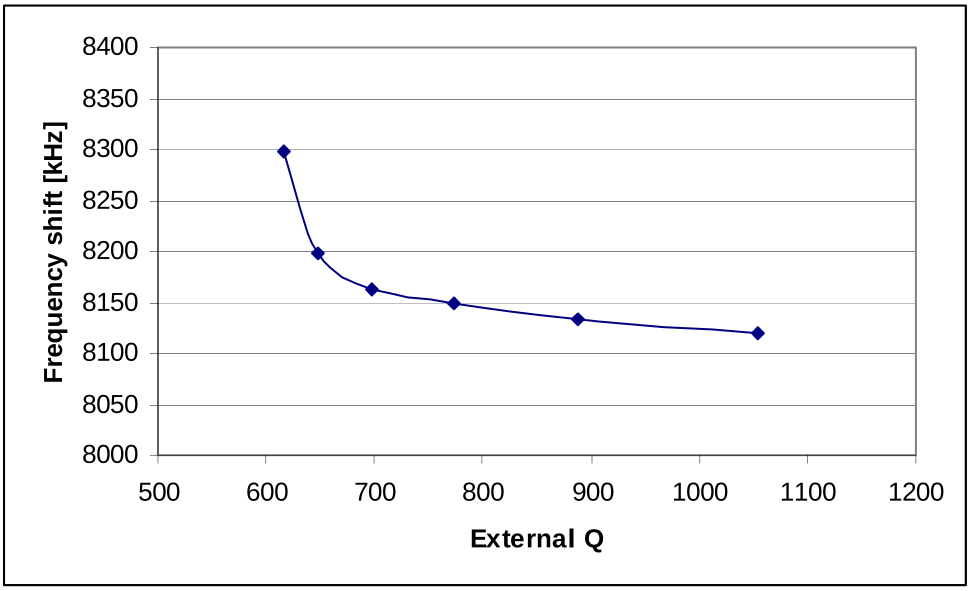

Figure 5 – Frequency shift versus Q_{ext}.

5 RF losses

RF losses in the copper walls are computed using the following parameters:

normalization of the fields using the DTL cell nominal voltage (280 kV),
copper surface resistance *Rs* at 352 MHz: value of 4,90 m□,
cw regime (therefore all powers must be moderated by the RF duty cycle),
short-circuit position and geometry giving an external Q factor value of 888,
resonance frequency of the system (348.035 Hz).

Two computations are performed. The first uses the same scheme as described previously (one port only). In this case, all the energy is reflected as there are no losses in the cavity and no other port, which leads to a standing wave in the coupler area. Nevertheless, in the ideal case, all the energy goes in the copper walls and to the beam, with no reflected wave at all and therefore no standing wave. To simulate this case, a symmetrical and identical second port is put in front of the first one, on the opposite wall of the DTL cell (the stem is rotated by 90°).

In actual operation of the accelerator, one will stand somewhere between these two extreme cases, depending on the coupling factor tuning, on the beam loading, etc. Therefore, for all thermal and mechanical purposes, it would be reasonable to consider the higher value.

In both cases, RF losses are strongly inhomogeneous. Except on the short-circuit area, all losses are higher in the standing wave (all reflected power) case.

Figure 6 describes the geometry mapping used to study the RF losses spatial distribution. Table 4 and Table 5 are summing up the RF losses with respect to the spatial distribution described in Figure 6. Finally, Table 6 sums up the total RF losses of the system.

Caution: all values in *Table 4* and *Table 5* (only) are relative to *half* a model. The cut plane is the plane of symmetry, parallel to the one shown in Figure 6. Values in Table 6 are relative to the full geometry.

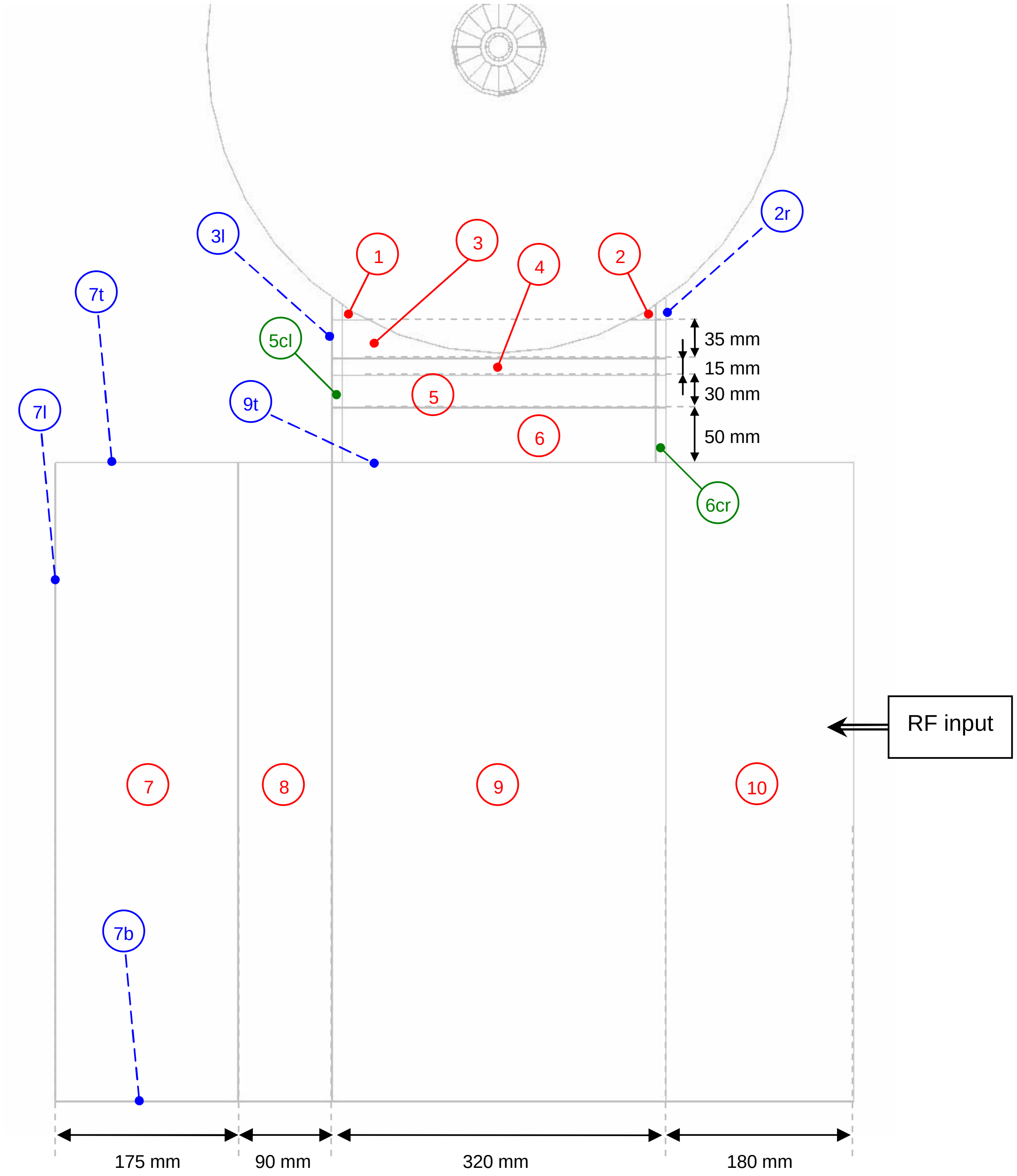

Figure 6 – Surfaces definitions for the RF losses repartition.

Indexes are as follow: “t” stands for top, “b” for bottom, “l” for left, “r” for right and “c” for chamfer. All directions are relative to this picture orientation.

		All power reflected		All power transmitted	
Surface#	**Surface [cm^2]**	**Absolute RF power (cw) [W]**	**Power per surface unit [W/cm^2]**	**Absolute RF power (cw) [W]**	**Power per surface unit [W/cm^2]**
1	1.7	48	28.0	21	12.2
2	1.7	49	28.9	20	11.6
3	56	617	11.0	278	5.0
4	45	275	6.1	126	2.8
5	90	425	4.7	193	2.1
6	150	525	3.5	234	1.6
1cl	3	80	26.5	35	11.5
3cl	5.5	81	14.7	37	6.8
4cl	2.4	25	10.5	11	4.7
5cl	4.7	40	8.5	18	3.9
6cl	8	59	7.4	26	3.3
2cr	3	80	26.5	35	11.5
3cr	5.5	81	14.7	37	6.7
4cr	2.4	25	10.5	11	4.7
5cr	4.7	40	8.5	18	3.8
6cr	8	58	7.3	26	3.2
1l	3	57	19.0	26	8.7
3l	5.2	77	14.7	35	6.8
4l	2.2	24	10.9	11	5.0
5l	4.5	39	8.6	18	3.9
6l	7.5	54	7.2	25	3.3
2r	3	57	19.0	26	8.6
3r	5.2	77	14.8	35	6.7
4r	2.2	24	10.9	11	4.9
5r	4.5	39	8.6	17	3.8
6r	7.5	54	7.2	24	3.1

Table 4 – RF losses in the connecting guide *(half model)*.

		All power reflected		All power transmitted	
Surface#	**Surface [cm^2]**	**Absolute RF power (cw) [W]**	**Power per surface unit [mW/cm^2]**	**Absolute RF power (cw) [W]**	**Power per surface unit [mW/cm^2]**
7	1022	4.9	4.8	5.1	5.0
8	526	4.5	8.6	3.5	6.7
9	1870	45.0	24.1	25.6	13.7
10	1052	12.0	11.4	10.3	9.8
7b	256	0.9	3.7	0.7	2.7
8b	131	1.9	14.3	1.4	10.7
9b	467	14.3	30.5	8.0	17.1
10b	263	5.6	21.4	3.2	12.2
7t	256	0.2	0.7	0.5	2.0
8t	131	10.1	77.3	7.6	58.0
9t	387	123.4	318.8	56.2	145.2
10t	263	9.8	37.1	4.5	17.1
7l	853	3.8	4.4	3.9	4.6

Table 5 – RF losses in the waveguide *(half model)*.

	All power reflected		All power transmitted	
	Total RF power	**Mean RF losses**	**Total RF power**	**Mean RF losses**
Connecting guide	6 020 W	8.2 W/cm^2	2 708 W	3.1 W/cm^2
Waveguide (up to short-circuit plate)	572 W	0.03 W/cm^2	261 W	0.02 W/cm^2
Total	6 592 W	0.4 W/cm^2	2 969 W	0.2 W/cm^2

Table 6 – *Total* RF losses in the system.

6 Conclusion and perspectives

The power coupler being designed from the RF point of view, only the mechanical aspects remain to be performed.

Thermal load is reasonably low. Cooling to admissible thermal stress levels is an important task which should be relatively challenging at high RF duty cycle only, but the somewhat cramped geometry may be a disturbance.

The mechanical management of the coupling factor tuning procedure is the other major remaining task. It should be decided at the earliest moment whereas one prefers a cheap design, with a crude method for tuning (like machining the waveguide to the proper length), or a more subtle but also more expensive approach involving a mechanical flexibility (like using bellows) somewhere in the system. Usually, only the first method is used.

The mechanical design of the coupler will be performed by the Laboratoire de Physique Subatomique et de Cosmologie (LPSC) in Grenoble, in collaboration with CEA Saclay.