

# THERMO-MECHANIC OF A DTL VESSEL FOR THE IPHI PROJECT

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## Abstract

The mechanical design of a short model of a DTL (Drift Tube Linac) vessel for the IPHI project is presented. This model has thermal, mechanical and technological properties of a full 6 meters long DTL.

We first compare the mechanical properties, welding behaviour and ultra-vacuum compatibility of various materials. In the end, stainless steel is chosen.

Analytical calculations help to various configurations and to identify the variation of the most important parameters. Several 3D computations confirm these values and strengthen the dimensions of strongly 3D geometry like the pumping ports or the opening for the drift tubes' supporting girder.

An additional copper layer appreciably improves the cooling and minimises stresses in the vessel. This layer is obtained by an electroplating process.

Future tests made in CERN with the nominal RF power will confirm the options used for this design.

## 1 OBJECTIVES

The DTL of the IPHI project [1] is working at 352 MHz. It will accelerate a 100 mA cw proton beam from 5 to 10 MeV. It is equipped with electromagnets.

The short model requires all functions of the final DTL but with only three drift tubes. So the transverse dimensions are the final ones but the length is reduce to about 400 mm. The fabrication means have to be extrapolated for a 6 m long device.

The vessel is composed of the cylinder shell, the support of the drift tubes, the pumping ports, the RF input, one flange at each end, the diagnostics ports and the cooling channels. The vacuum intended is  $5 \cdot 10^{-6}$  Pa under working conditions.

## 2 FIRST OPTIONS

The geometry, tolerances and constraints of the ultra-vacuum technology impose some characteristics:

- thin thickness for the welded shell,
- thick rectangular support for the drift tubes to avoid deformations and to keep high tolerances in the position of them.
- metallic seals,
- copper for the internal surface,
- welded openings.

### 2.1 The shell material

The different materials intended for the vessel shell are compared from the welding, operation and vacuum abilities as shown in table 1.

In operation conditions, copper and aluminium are the best choice but they are hard to weld. Computations are

reliable for operational use. So, if stresses obtained by computation are below the yield point, stainless steel can be chosen.

Table 1: Compared properties of materials

	Copper	Aluminium	Steel	Stainl. steel	Stainless steel+thick copper layer
<b>Welding</b>					
Thermal conduction (W/m)	400	180	54	15	17
Ratio to stainless steel	27	12	3,5	1	1
	Pre-heating	Pre-heating	Often used	Often used	Good
<b>Operational use</b>					
Ratio $\lambda/\alpha$ (longitudinal)	20	10	6	1	5
Ratio $\lambda/\alpha$ (radial)	20	10	6	1	1
<b>Ultra-vacuum compatibility</b>	Good	Good	*	Good	Good

\* depends strongly of manufacturing process.

### 2.2 Cooling

We prefer to solder regularly spaced external channels rather than to put another shell around the first one, because the former is a well known technology that does not induce more pressure on the internal shell.

## 3 ANALYTICAL THERMO-MECHANICAL CALCULATIONS

### 3.1 Buckling

Rules of the CODAP give a minimum thickness of 4 mm for the 6 m long shell. The various openings will enhance stiffness on the final shell.

### 3.2 Thermal behaviour of a periodic structure

The cooling system is modelled by discrete, pure convective areas (the cooling channels) over a pure conductive area (the shell), as shown on figure 1.

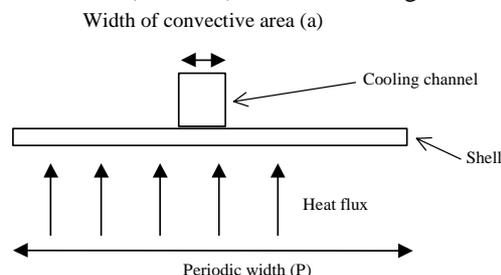


Figure 1: Geometry of the cooling scheme. One tries to approximate this 2-D scheme to identify the variation of the most important parameters.

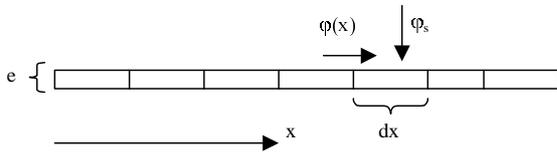


Figure 2: Longitudinal conduction.

When integrated, the conservation of the flux gives (see figure 2):

$$\Delta T = \frac{\varphi_s}{2ke} b^2 \quad (1)$$

with:

$$b = \frac{P-a}{2} \quad (2)$$

For the convective exchange, one gets:

$$h\Delta T_2 = \frac{S_1}{S_2} \varphi_s \quad (3)$$

where  $S_1/S_2$  is the ratio of the convective area over the whole surface.

We add the conduction through the thickness:

$$\Delta T_3 = \frac{e}{k\varphi_s} \quad (4)$$

The total gradient is the sum of the three  $\Delta T$  terms.

This system of equations is more complicated with a copper layer on the steel shell. All equations have the same form:

$$\Delta T = R\varphi_s \quad (5)$$

If  $R1$  is the conduction of the first material and  $R2$  is conduction of the layer, one can use the electrical equivalence (figure 3).

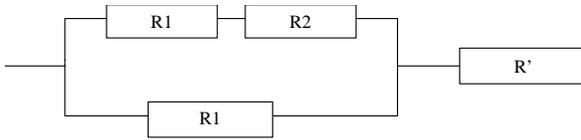


Figure 3: Electrical equivalence of the 2-layers conduction scheme.

Two hypotheses are considered. The hypothesis 1 supposes that the heat flux is travelling through the whole thickness of both materials in the end while the hypothesis 2 neglects the copper thickness.

The results of these analytical calculations are given on figure 4 and 5.

The copper layer improves the thermal conductivity of the shell: one can double the cooling period with a 1,5 mm thick copper layer. Stainless steel alone is convenient with a step of 40 mm.

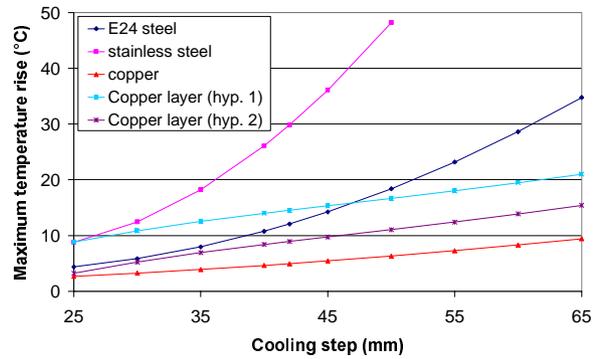


Figure 4: maximum temperature increase of the system with respect to the cooling period for different materials.

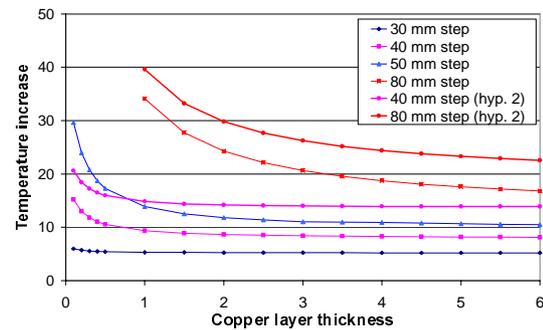


Figure 5: maximum temperature increase with respect to the copper layer thickness for different cooling periods.

### 3.3 3D calculations

In addition to the periodic structure, the vessel has strongly 3D openings like the pumping ports and the RF input. This geometry needs additional numerical computations using the analytical ones as a basis. Three separated hypothesis are taken into account:

- (a) no flanges at the vessel ends which are let free;
- (b) no flanges at the vessel ends which are fixed;
- (c) flanges with a perfect thermal contact.

None of these hypothesis is absolutely correct. The first one can be compared directly with the analytical computations, the second one is conservative. The third one should be closer to reality.

We consider two options for each opening: a massive block or a thin plate to link the opening flange to the shell. The block is better for cooling while the plate is more flexible.

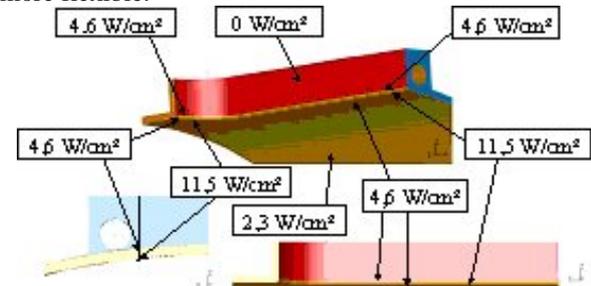


Figure 6: heat flux extrapolated from MAFIA.

The RF heat flux is given by *MAFIA*. The surface is divided in areas of similar power densities (figure 6).

Computations are first made considering a stainless steel shell alone (not taking into account the copper layer) with the chosen 40 mm cooling period. The *I-DEAS* code is used. Thermal results for the block configuration are shown on figure 7.

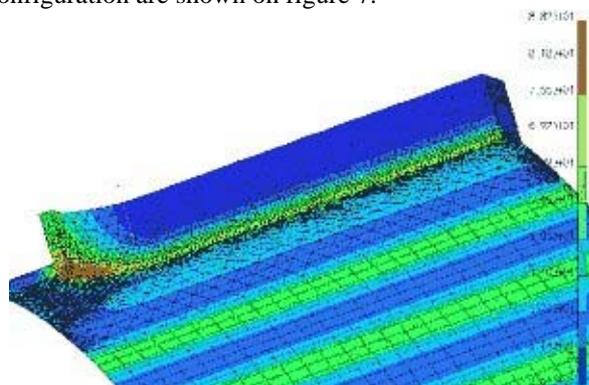


Figure 7: temperature map for the pumping block. The maximum temperature (in red) is 88°C.

These temperature lead to stresses as shown on figure 8, considering the hypothesis (b) conditions.

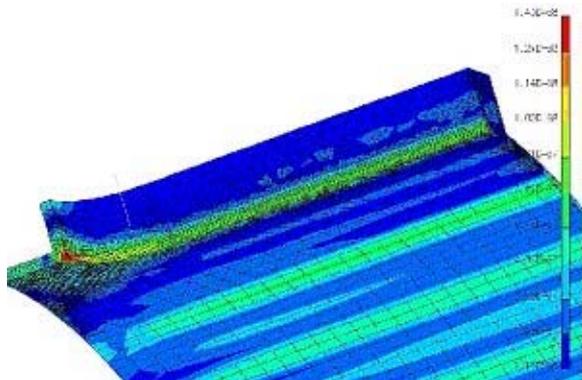


Figure 8: thermal stress on the pumping block in hyp. (b) case. Maximum stress (in red) is 143 MPa.

The thermal and mechanical results of these computations for the pumping block are recapitulated on table 2.

Table 2: Pumping port's thermo-mechanical behaviour.

		"Block"	"Plate"
Maximum $\Delta T$		63,2°C	81°C
Hyp 1	Von Mises stress	143 MPa	150 MPa
	Radial thermal expansion at pumping port	151 $\mu m$	389 $\mu m$
	Radial thermal expansion at 90° from pumping port	100 $\mu m$	~90 $\mu m$
	Dilatation longitudinale	65 $\mu m$	78 $\mu m$
Hyp. 2	Contraintes Von Mises	172 MPa	161 MPa

The block solution is preferred because of the best cooling. The difference of stress is not significant. The

small dimensions of the block as compared to the length's shell keep the system flexible.

For the opening of the drift tubes' supporting girder, the same type of calculations are made and lead to choose the plate solution, as the dimensions of this support are closer to the shell's ends.

### 3.4 Around the cooling channel

Cooling channels are flatten pipes. The temperature map around these channels with an external 2-mm copper layer are shown on figure 9.

The maximum temperature rise is twice without the copper layer. If the layer is internal, the temperature increase is 5°C more than if it is external.

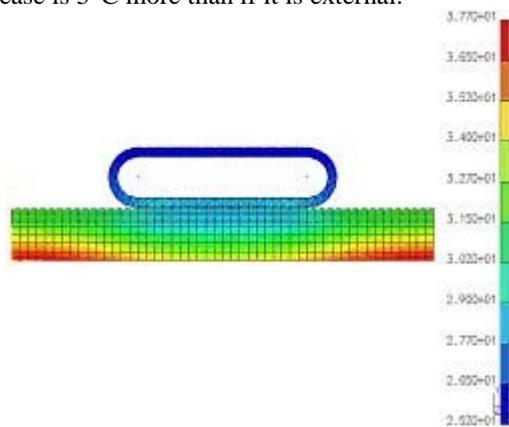


Figure 9: external copper layer on stainless steel, 50 mm period. Maximum temperature rise (in red) is 12°C

Computations are made for different materials (steel, stainless steel, copper, copper plated steel, thermally sprayed copper on various steels, etc.) and periods. The difference between analytical and computer 2D calculations are within 15%. An external copper layer of 1 mm on the stainless steel shell is a good choice.

## 4 CONCLUSION

This study leads to the design of a DTL short model whose technology is usable for the 6 meters long machine. Stainless steel is the best material because stresses under operation conditions are acceptable and manufacturing is easy. An external layer of copper improves the cooling, reducing by a factor of 2 the number of cooling channels needed.

Next step will be to test the device with full RF power. Displacements of the drift tubes will be measured. These tests will be made soon in CERN.

## 5 ACKNOWLEDGEMENT

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## 6 REFERENCES

[1] "Design of the IPHI DTL", P.-E. Bernaudin & al., Proceedings of the 2001 Particle Accelerator Conference.