THERMAL CONTROL OF THE FERMI@ELETTRA ACCELERATING SECTIONS *

C. Serpico, G. D'Auria, P. Delgiusto, SINCROTRONE TRIESTE, Trieste, Italy.

Abstract

FERMI@Elettra is a single pass FEL user facility under construction at Sincrotrone Trieste, Italy. It will use the existing normal conducting S-band Linac and seven accelerating sections received from CERN after the LIL decommissioning.

In the past, the existing accelerating sections had been operated at 10 Hz. During the first stage, the FERMI operating frequency will be kept at 10 Hz, but later it will be ramped up from 10 Hz to 50 Hz.

The higher RF power will also increase the temperature distribution on the accelerating structures, implying a larger thermal deformation of the cavities, both in the transversal and in the longitudinal direction. This has to be kept under control due to the stringent requirements asked by FERMI@Elettra project in terms of phase and amplitude stability.

In this paper the thermo-mechanic behaviour of the accelerating sections is investigated and the results of the simulations are presented. Furthermore an algorithm has been developed to control thermal deformation of the sections.

INTRODUCTION

Fermi will use three different S-band RF structures. Table 1 summarizes the structure types and their main operating parameters.

Table 1: S-band RF structures

Name	Nr.	Length (m)	Type	Max. RF power dissipated (kW)
S0A S0B	2	3	Forward TW; Const. Imp.; Iris Loaded	3.75
C1-C7	7	4.5	Forward TW; Const. Grad.; Iris Loaded	4.3
S1-S7	7	6	Backward TW; Const. Grad.; Nose Cone	6.5

The seven sections equipped with SLED cavities (S1-S7) are powered by a single klystron (Thales TH2132A). The remaining sections are powered in pairs by a common klystron.

Figure 1 shows the typical arrangement of the structure cooling system: it consists in 10 cylindrical copper pipes, with an internal diameter of 12 mm, brazed on the cavities. Based on our past experience, to reduce vibrations as well as corrosion effects of the copper pipes, we have fixed at 3m/s the maximum water flow velocity in each pipe.

* Work supported by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3

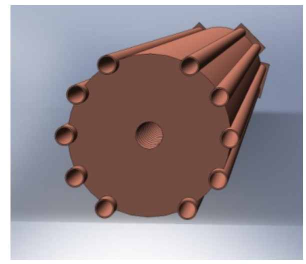

Figure 1: Accelerating section cooling pipes

Considering the maximum power dissipation we will have and the maximum flow rate we can allow (i.e. 6 m^3/hour), the ΔT between the output water and the input one is 0.9 °C.

This value has been assumed as the maximum $\Delta T_{out\text{-}in}$ we should have on all the sections when the dissipated power is at the highest level.

In the following thermo-mechanic simulations of a FTW (Forward Travelling Wave), 3m long accelerating structure are presented. Furthermore an algorithm has been developed to control the temperature and the longitudinal deformation of the sections.

THERMAL ANALYSIS

The thermal analysis has been performed on the section S0A. The structure is made by 93 accelerating cells, and it has a total length of 3 m. The average input power is 5.25 kW, and the dissipated power is 3.75 kW.

Starting from an electromagnetic analysis the field distributions of the accelerating mode have been evaluated. Since the structure is a FTW, the power exponentially decays along the z-direction (the beam direction). The total power dissipated into the Nth cavity has the following expression:

$$P_N = P_{in} \cdot \left(1 - 10^{-\frac{\alpha_{cell}}{10}}\right) \cdot 10^{-\frac{(N-1)\alpha_{cell}}{10}} \qquad (1)$$

where P_N is the dissipated power into the Nth cavity; P_{in} is the input power into the sections; α_{cell} is the attenuation of the single cell.

As said the average dissipated power into the section P_d is 3.75 kW. We know that:

$$P_d = \dot{m} \cdot c_p \cdot \Delta T_{out-in} \qquad (2)$$

Considering a $\Delta T_{out\text{-}in}$ of 0.9°C, a flow rate of 3.6 m^3/hour will be sufficient. This will sensibly reduce the velocity of the fluid in each pipe. If we maintain the maximum condition in terms of fluid velocity, we can reduce the $\Delta T_{out\text{-}in}$ up to 0.54°C.

In order to complete the setup for the thermal analysis we need to model the convection phenomena. Let us calculate the film coefficient h and the bulk temperature T_∞ of the cooling water.

Starting from the data we have we can evaluate the film coefficient h:

$$h = (Nu \cdot \lambda)/L \qquad (3)$$

where Nu is the Nusselt Number, λ is the thermal conductivity and L is the characteristic length of the pipes. In our case Nu has the following expression:

$$Nu = 0.23 \cdot \mathrm{Re}^{08} \cdot \mathrm{Pr}^{0.4} \qquad (4)$$

The Reynolds Number is given by:

$$\mathrm{Re} = \rho \cdot v \cdot D/\mu \qquad (5)$$

where ρ is the fluid density, v is the fluid velocity, D is the pipes' diameter and μ is the dynamic fluid viscosity. In this case we obtain:

$$h = 8490 \quad [W/(m^2 \cdot °C)] \qquad (6)$$

Let us now calculate the bulk temperature T_∞ of the cooling water. In the following figure it is shown the scheme of the cooling system.

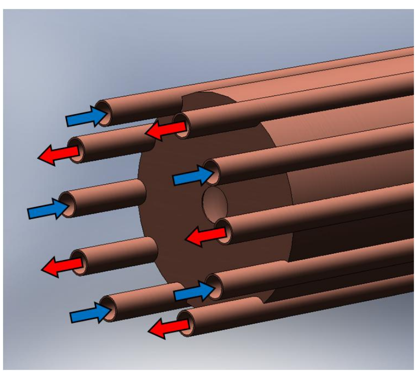

Figure 2: Cooling system scheme

When the input power is zero, the operation temperature T_{set} of the section must be set to an assigned value, T_{S0A}, we have optimized in the past, maximizing its energy gain. In our case T_{S0A} = 35 °C.

At full power, in the worst case the output temperature will be T_{out}=35.9 °C. Obviously the temperature of the fluid along the accelerating structure will not be constant. We can assume that there is a constant thermal gradient of the bulk temperature along the z-direction.

By means of Ansys Multiphysics we can carry out a thermal analysis of the full structure. In order to reduce the model complexity (i.e. the number of meshing elements).

To setup the thermal analysis, the RF dissipated power is applied as an Heat Flux load on the copper surfaces of the accelerating cavities. Furthermore, cooling system parameters are applied to the model as thermal loads.

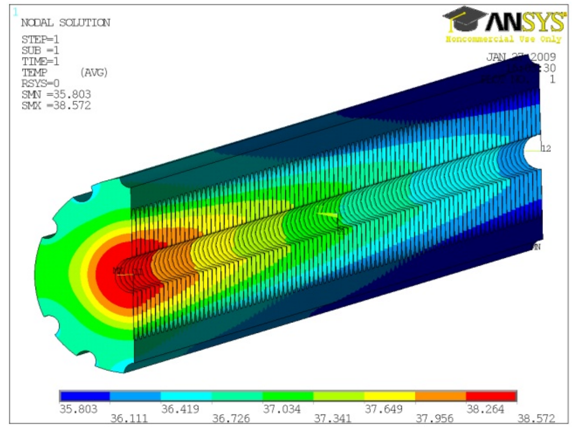

Figure 3: Temperature distribution evaluated for P_d=3.75kW, Flow Rate=60l/m, T_{in}=35°C

As it is shown in the figure, the maximum temperature will be reached in the first cells of the structure. In this case the maximum temperature is 38.6° C.

After evaluating the temperature distribution along the accelerating structure next step is to analyze the thermal deformation of the structure.

STRUCTURAL ANALYSIS

Starting from the thermal analysis, we are able to evaluate the deformations of the section due to RF heating.

As said, the accelerating section is a 3 m long structure, made by 93 cavities. Due to the tiny deformations induced on the structure, the simulations will ask for a very accurate mesh size of the copper structure, and this will require too large computing resources.

A solution to the problem could be achieved by limiting the computing domain in the z-direction. Unfortunately, the model has no symmetries along the z-direction, however, as the RF dissipated power decays along the beam direction, the temperature distribution and the structural deformations will have the same behaviour. Smaller and smaller deformations will occur as we proceed along the z-direction, with an exponential behaviour.

This will allow us to limit our structural analysis to few cavities. Then, starting from these results we can evaluate the total longitudinal deformation of the section.

Figure 4 shows the structural deformations of the first three cells. Those have been computed with respect to a reference temperature T_{set}.

This figure shows how the volume of each cell increases, the original profile of the cavities and the deformed one.

In particular we can evaluate that the variation of the first cell length ΔL_1 is 0.6 μm, while the total variation of the whole section is $\Delta L_{section}$ = 49.5 μm.

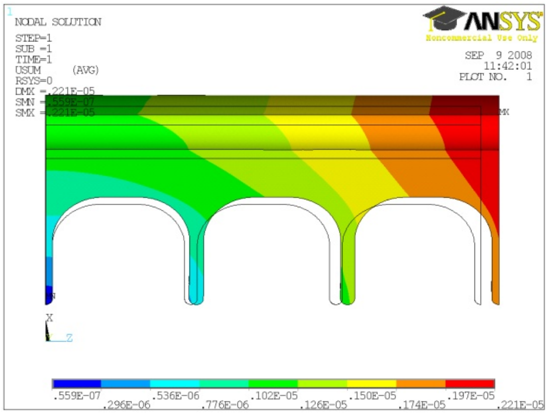

Figure 4: Structural deformations of the first three cells

THERMAL CONTROL STRATEGY

The operating temperature Tset of each section need to be fixed in order to get the electromagnetic performances we want to achieve. So, when the RF input power is zero, the input water temperature must be set to its nominal value for the operating frequency. For S0A, as said:

$$T_{in} = T_{set} = 35°C \qquad (7)$$

As the input power level increases, the accelerating section will experience RF heating, temperature changes and thermal deformations, that influence its RF characteristics in term of phase velocity. This could not be allowed for the stringent requirements imposed by the FERMI project and a thermal control strategy to keep the section temperature as constant as possible will be implemented.

Maintaining "constant" the water flow rate during the machine operation, we will keep constant the temperature of the section, in the range P_d=[0;Max], modifying the input water temperature. The optimal solution could be decreasing the input water temperature linearly when the dissipated power increases, according to:

$$T_{in} = T_{set} - k \cdot \Delta T_{out-in} \qquad (8)$$

where the slope *k* is evaluated on the basis of the previous thermo-mechanical simulations.

For the S0A, when the dissipated power reach its maximum value, we have evaluated that its input temperature has to be set to T_{in} = 33.8 °C.

Figure 5 shows a typical output of the algorithm we have developed for optimizing the structure thermal parameters at different power levels.

As it is proved, the proposed thermal control offers us the chance to stabilize the thermal deformation of the structure. It is based only on the measurement of the input and output water temperature, the knowledge of the flow rate is needed only during the start-up phase for the calibration of the control system.

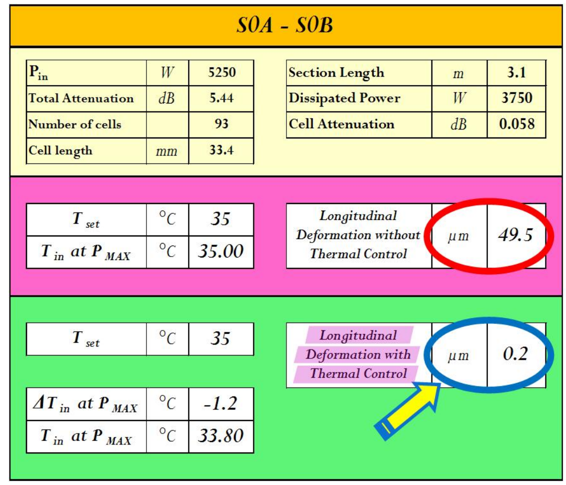

Figure 5: Thermal control strategy

However, during the operation it is important to maintain as constant as possible the water flow. This will also give the possibility to have a measure of the RF power dissipated on the structure.

CONCLUSION

The thermal behaviour of the FERMI@Elettra accelerating sections has been analysed. A structural analysis of one of them at full RF power has been carried out and a thermal control strategy to stabilize the operating temperature has been presented.

The control algorithm seems very promising and gives the chance to limit the thermal deformation of the section to few microns.

Even if detailed simulations have been showed only for one structure, S0A, similar studies has been carried out on all the different types of accelerating sections that will be used for the FERMI project.

REFERENCES

[1] FERMI@Elettra Conceptual Design Report, Trieste, January 2007.
[2] G. D'Auria, C. Rossi, "RF Measurements on the First Backward TW of the Trieste 2 Linac", Sincrotrone Trieste, 1991.
[3] G. D'Auria, "RF Measurements on the 100 MeV Linac Accelerating Section", Sincrotrone Trieste, 1991.