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THERMAL-MECHANICAL ANALYSIS OF THE RF STRUCTURES FOR THE ELI-NP PROPOSAL

V. Pettinacci, INFN Roma, Rome, Italy
D. Alesini, L. Pellegrino, INFN-LNF, Frascati (RM), Italy
L. Palumbo, Sapienza University of Rome, Rome, Italy

Abstract

The room temperature RF structures in the ELI-NP LINAC will operate in multi-bunch with high repetition rate (100 Hz). For these reasons they are subject to some kW of power dissipated on the internal cavities surfaces. The resulting thermal deformation of the cavities shapes could imply variations in their electromagnetic fields. To limit these effects and optimize the cooling design, a fully coupled Electromagnetic-Thermal-Mechanical analysis has been performed on the S-Band Radiofrequency Gun and on the C-Band multi-cell structures. In this paper the study done in Ansys Workbench with HFSS and Ansys Mechanical is reviewed.

RF GUN

The RF gun of the ELI-NP LINAC is a 1.6 cell gun of the BNL/SLAC/UCLA type [1,2] with several modifications from the electromagnetic and mechanical point of view described in [3]. The two cells operate on the TM010-like accelerating mode and the field phase advance per cell is π. The electrons are emitted on the cathode through a laser that hit the surface and are then accelerated trough the electric field that has a longitudinal component on axis. The accelerating field on the cathode for the ELI-NP gun is 120 MV/m. The structure is fed by a waveguide coupled to the accelerating cells through a hole. The gun operates at 100 Hz and the average dissipated power is 1 kW. Details of the gun design and can be found in [3]. The main gun parameters are given in Table 1.

Table 1: RF Gun Parameters

Parameters	Value
Resonant frequency f_{res}	2.856 GHz
Unloaded quality factor Q_0	15000
Repetition rate	100 Hz
Coupling coefficient β	3
Shunt impedance (R)	1.78 MΩ
Filling time τ_F	420 ns
Frequency separation between the 0 and the π-mode	38 MHz
Average dissipated power	1 kW

Mechanical Design (Workbench and APDL)

The goal of the mechanical design is to define a cooling pipes system, able to get a uniform temperature distribution and a consequent homothetic deformation of Gun body, in order to maintain the nominal EM field configuration [5]. Two complementary approaches have been followed:

- Steady-State Thermal Analysis with Line Bodies to calculate the heating of the coolant and of the body ("*Straightforward model*");
- Totally coupled Steady-State Thermal and Static Structural Analysis, using the previous results as part of the boundary conditions for the temperature and deformation field calculation, and closing the loop in HFSS, to evaluate its effect on the internal EM field ("*Loop model*").

Straightforward model: HFSS and Steady-State Thermal analysis. In the first analysis the EM model geometry has been refined, designing the cooling channels inside the body and the toroidal slot for the cathode cooling; the EM field has been imported as Heat Flux (W/m^2) on the internal cavity surfaces (Fig.1).

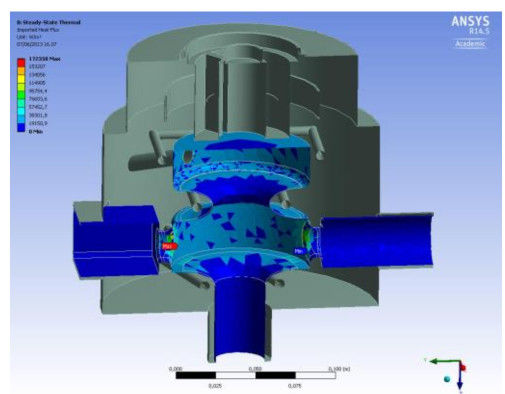

Figure 1: Heat Flux imported from HFSS.

The convective exchange coefficient derives from the *Gnielinski* correlation (for Nusselt number) [6]:

$$Nu_D = \frac{(f/8)\,(Re_D - 1000)\,Pr}{1 + 12.7\,(f/8)^{1/2}\,(Pr^{2/3} - 1)} \quad (1)$$

Valid for:

- $0{,}5 < Pr < 2000$
- $3000 < Re_D < 5\times10^6$

Water velocity inside tubes (diameter 6 mm) is set to 1 m/s; this value derived from considerations about channels pressure and corrosion problems. Higher values of fluid velocity, until 3 m/s, could be in case adopted. An APDL section has been added in the Steady-State Thermal module of ANSYS Workbench to implement the heat exchange across the channels walls.

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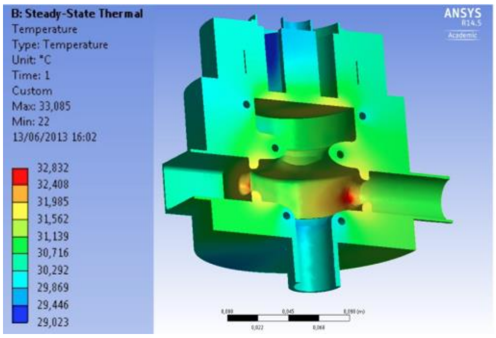

Figure 2: Gun Body Temperature Distribution.

The temperature distribution calculated in the Gun body is represented in Fig. 2 with $\Delta T_{Gun} \approx 3.8$ °C and $T_{max\ Gun} = 32.8$ °C.

The related cooling water temperature distribution inside tubes is depicted in Fig. 3.

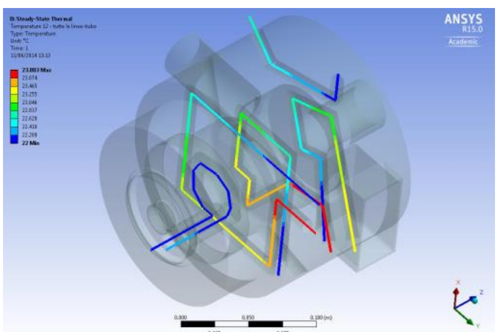

Figure 3: Coolant Temperature Distribution.

The maximum temperature rise is about 1,9°C. The tubes temperature distribution has been set as boundary condition for the next analysis.

Loop model: totally coupled analysis HFSS, Steady-State Thermal and Static-Structural. The goal of the model is to evaluate the deformation, due to thermal load acting on the body, and its effect on the EM field configuration, including their mutual influence. The total deformation calculated is depicted in Fig. 4.

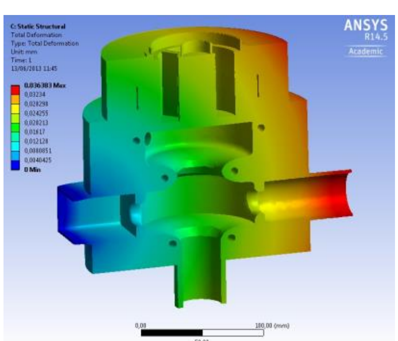

Figure 4: Total Deformation of Gun Body.

Closing the loop analysis on the HFSS module, this deformation entails a -400 kHz variation of the resonant frequency. Therefore in order to maintain the gun on resonance with respect to the nominal RF frequency, the water temperature has to be decreased of about 8 °C assuming a thermal expansion coefficient for copper α = 1.7e-05 °C^{-1} and considering that $\Delta f_{res}/f_{res} = \Delta L/L = \alpha\ \Delta T$.

C-BAND ACCELERATING STRUCTURE

The LINAC energy booster of the European ELI-NP proposal foresees the use of 12 travelling wave C-Band structures, 1.8 m long with a field phase advance per cell of $2\pi/3$ and a repetition rate of 100 Hz. Because of the multi-bunch operation, the structures have been designed with a damping of the HOM dipoles modes in order to avoid beam break-up (BBU). They are quasi-constant gradient structures with symmetric inputs couplers and a strong damping of the HOM in each cell. The main structure parameters are given in Table 2. The detail of the structure design can be found in [4].

Table 2: Main Parameters of the ELI-NP Structures

Structure type	**Quasi-Constant gradient**
Working frequency (f_{RF})	5.712 [GHz]
Number of cells	102
Structure length	1.8 m
Working mode	TM_{01}-like
Iris half aperture radius	6.8 mm-5.78 mm
Cell phase advance	$2\pi/3$
RF input power	40 MW
Average accelerating field	33 MV/m
Acc. field struct. in/out	37-27 MV/m
Average quality factor	8850
Shunt impedance	67-73 MΩ/m
Phase velocity	c
Group velocity (v_g/c)	0.025-0.014
Filling time	310 ns
Output power	0.3*Pin
Pulse duration for beam acceleration (τ_{BEAM})	<512 ns
Rep. Rate (f_{rep})	100 Hz
Average dissipated power	2.3 kW
Working temperature	30 deg

Mechanical Design (Workbench and APDL)

Straightforward model (102 cells): given the symmetry respect the XZ and YZ plane (Z beam axis), only ¼ of structure has been modelled, reducing computing requirements. In the first model the 2 cooling counter-flow circuits have been modelled through line bodies (ANSYS Workbench and APDL), with convection imposed on the channels surfaces and on the external surface. The Heat Flux is imported from the HFSS model. The fluid velocity is the same (1 m/s), but larger tubes has been chosen (ID=10mm); therefore the convection coefficient, from *Gnielinski* correlation [6], is different, as described by equation (1). Temperature distribution

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calculated for module body (copper cells) is represented in Fig. 5. The temperature distribution for the water running counter-flow in the 2 coolant channels is depicted in Fig. 6: the coolant temperature increase is less than 1°C.

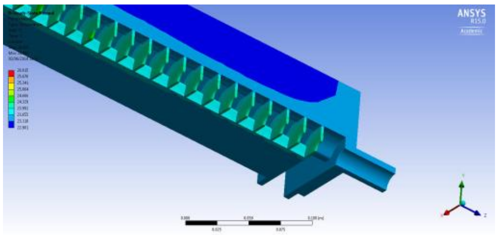

Figure 5: 102 cells Temperature distribution.

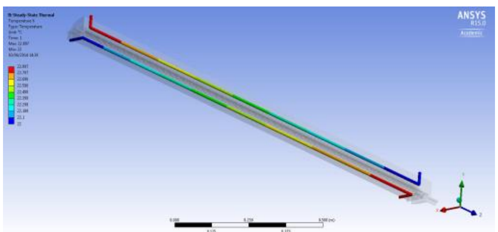

Figure 6: 102 cells structure coolant Temperature.

Loop model (102 cells): the temperature distribution in the line bodies (water flow lines) of the first model has been used to take in account thermal exchange towards the water and to calculate the body temperature distribution and the related deformation (Fig. 7, 8, 9).

Frictionless supports have been set at the symmetry planes and at one end of the structure, to simulate the free elongation along the Z-axis.

The deformation calculated presents the main component in the axial direction (Z-axis): the maximum is about 0,053 mm. It presented the main component in the Z-axis (main dimension of the overall structure), with negligible radial components. The maximum deformation calculated on the inner surfaces, in radial direction, is about 1.2 μm (in the cells near the input coupler, Fig.7,8). Consequently a negligible frequency shift has been calculated in the HFSS module.

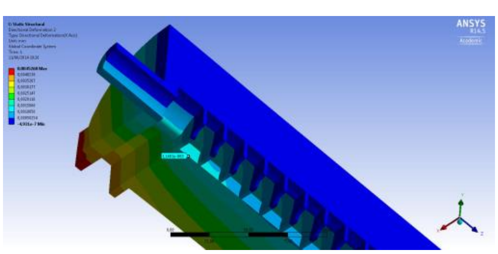

Figure 7: 102 cells X-axis deformation.

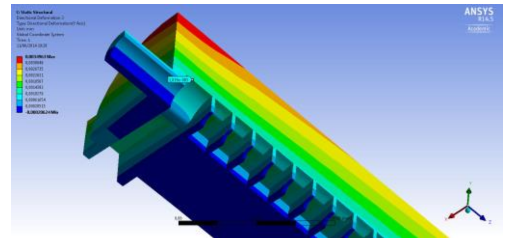

Figure 8: 102 cells Y-axis deformation.

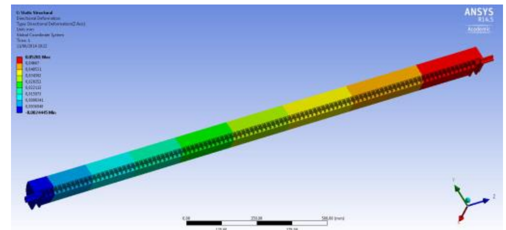

Figure 9: 102 cells Z-axis deformation.

CONCLUSIONS

The room temperature RF structures in the ELI-NP LINAC will are subject to some kW of power dissipated on the internal cavities surfaces due to the 100 Hz operation. The cooling systems have been designed to get homothetic deformations on the RF structures. For the S-Band Gun there will be the necessity to cool down the inlet water temperature by about 8°C (using a local chiller), in order to keep the structure on resonance. For the C-band structures the calculations results entails negligible deformations in the radial direction of the cells (about 1,2 μm in the worst case) while the deformation main component is along the longitudinal Z-axis and the overall maximum deformation integrated on the 102 cells is about 0,05 mm. As a consequence, a negligible frequency shift has been calculated.

ACKNOWLEDGEMENTS

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