THERMAL AND STRUCTURAL MODELING OF THE TTF CRYOMODULE COOLDOWN AND COMPARISON WITH EXPERIMENTAL DATA

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Abstract

The study of thermal and structural behavior during cooldown/warmup of long SRF cryostats is important for both the XFEL and ILC, which base the design on the successful TTF design.

We present the finite elements analysis of the main internal components of the cryomodules during the transient cooldown and warmup, comparing the data obtained with data taken at DESY on the linac.

INTRODUCTION

We present here the work done at INFN Milano to set a finite element model of the TTF like cryomodule main components and perform thermal and thermo-structural analyses of these components during cooldown and warm up operations. We developed a simplified model of the FLASH cryomodule, simulated the cooldown/warmup procedures and verified the resulting data with experimental data measured at DESY Cryomodule Test Bench (CMTB), the facility used to test the cryomodules before the final installation in the FLASH machine.

The simulation is used to verify the cooldown procedure, in terms of the maximum temperature gradient developed along the thermal shields during the transients and the maximum relative displacements and deformations of the components.

The simulation has been initially validated performing a static analysis of the module components behaviour, at cryogenic operational temperature, and comparing the simulated results of heat loads with the data extracted from the Tesla Design Report.

SUMMARY OF THE MODEL

The design consists of a simplified model of the following components:

- High Temperature (HT: 40 – 70 K range) Al shield parts and cooling finned pipe;
- Low Temperature (LT: 4 – 8 K range) Al shield parts and cooling finned pipe;
- Stainless steel Helium Gas Return Pipe (HeGRP);
- Support Posts;
- Stainless steel cavity supports (shapes).

The input data required to perform the transient simulation are extracted either from the Tesla Design Report (radiation and conduction heat loads at the couplers) or are the nominal operational values of the CMTB cold operation (temperatures, pressures, mass flows and all the data required to calculate the convection coefficient for the cooling circuits).

SIMULATION CONSTRAINTS

Between January and April 2008 many cool down have been performed at the DESY Cryomodule Test Bench (CMTB), test facility for the FLASH modules. We choose one of these cool downs as our reference data to set the transient simulation and compare its results.

In the CMTB a set of sensors monitor the main cooldown parameters (temperatures, pressures and mass flows in the cryogenic system circuits) and the data are stored in the control system database, based on Doocs. We use these data as an input for the simulation: temperatures as function of time (i.e. total cool down duration), mass flow as function of time, convection coefficient as a function of pipe dimension, pressure, mass flows and temperatures (i. e. as a function of time) are the input data we need to fully constrain thermally our model.

Moreover, the CMTB has recently been equipped with a complete set of sensor to monitor the temperature on the HT and LT shields. These data (and their behaviour along the time of the cool down) are used as the verification data for our results.

Cooling Circuits Input Data

The data collected at the CMTB show an almost constant behaviour of the pressure in all the cooling lines, the following table resumes these values:

HT shield line	3 bar
LT shield line	2 bar
2K line (during cooldown)	2 bar

Figure 1 shows an example of the temperature and mass flow data collected at CMTB for the 2 K circuit (continuous lines) and the simplified data (dashed lines) we used as input data in the simulation.

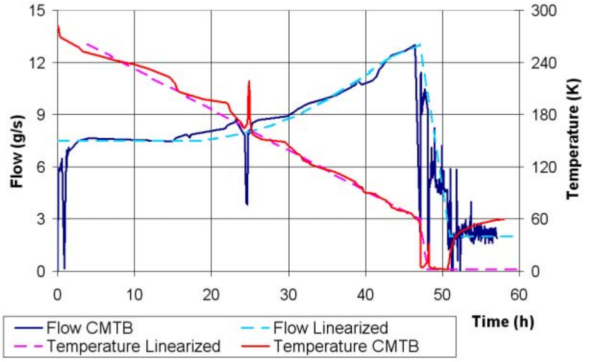


Figure 1: CMTB 2 K circuit CMTB data (continuous lines) and simplified data used in simulation (dashed lines).

Radiation Heat Loads Between Shields

For the radiative component of the heat load on the model, we scaled the transient behaviour from the CERN empirical data for the MLI radiation on the shields in static conditions (0.05 W/m^2 from RT to 5 K and 1 W/m^2 from RT to 70 K) [3].

We considered the radiation contribution between the two shields despite a low temperature gradient between them during cooldown, because, as it is easy to demonstrate, in the T^4 trend a high absolute value of the higher temperature affects the final result much more than the temperature gradient between the two objects.

Conduction Heat Load at Couplers

To estimate the conduction heat load at couplers during the cooldown (i.e. the dependency of these loads from the shield temperature), we considered the values reported in the Tesla Design Report [1] as the reference values at stationary cryogenic temperatures and we scaled these values with the temperature dependent conduction coefficient of Aluminium to obtain approximated data for intermediate temperatures.

SIMULATION RESULTS

Static Model Validation

We compared the data obtained performing a static simulation with reference data reported in the Tesla Design Report [1]. The two sets of data show a good agreement within reasonable approximation.

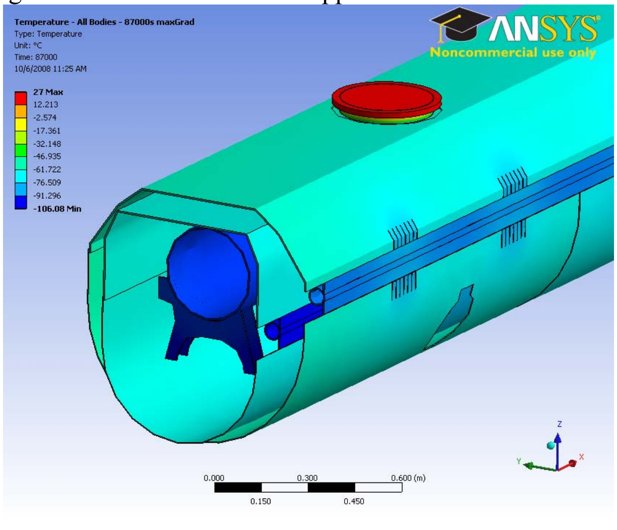


Figure 2: A detail of the temperature distribution obtained with the ANSYS simulation, at the time corresponding to the maximum gradient over the High Temperature Shield.

Temperature Gradient over the Shields

We use the simulation results to monitor the temperature distribution on the shields during the cooldown operation. The goal, to have a safe cooldown of the entire module, is to keep a low (less than 50 – 60 K) thermal gradient along the shields, to avoid excessive differential shrinkages between inner module parts with small cross-section clearances. We find in the simulation that a maximum gradient of about 35 K is reached in the High Temperature Shield after about 24 hours, while in the Low Temperature Shield we reach the maximum value of about 40 K after 14 hours. These values agree with previous simulation work performed on individual shields during the development of the module design [2].

Deformation Analysis at Maximum Gradient

The thermal condition at the maximum gradient on the High Temperature Shield has been used for a static structural analysis in order to evaluate the induced deformations on the system.

The maximum deformations in the structure are here resumed:

- Longitudinal deformation: 28 mm
- Horizontal deformation: 13 mm
- Vertical deformation: 10 mm

Deformation Analysis at End Time

We performed a further static structural analysis with the temperature condition at the end time of the simulation (i.e. stationary condition).

The deformations in the structure are here resumed:

- Longitudinal deformation: 51 mm
- Horizontal deformation: 10 mm
- Vertical deformation: 13 mm

These values agree with the nominal shrinkage values of aluminium available in literature (for example, data extracted from the CRYOCOMP library shows an Aluminium shrinkage between 300 K and 70 K of 0.435%, that for a 12 m long module brings to 52 mm of longitudinal shrinkage).

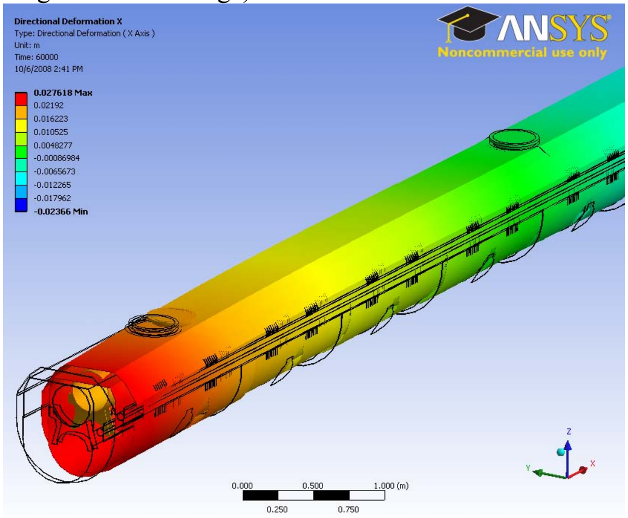


Figure 3: Longitudinal deformation of the model.

Agreement with Real CMTB Data

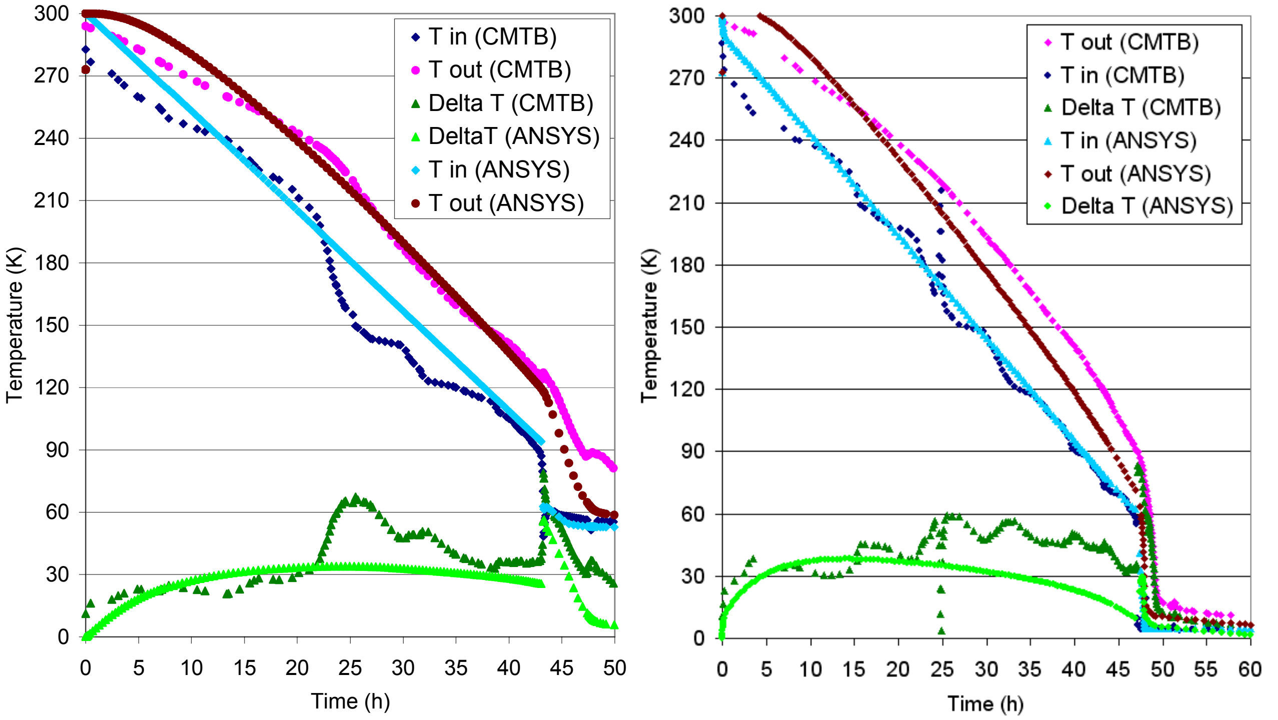
Thanks to the sensors positioned in the CMTB facility on the shields surfaces, we were able to compare the data evaluated in the simulation to the measured data in the CMTB for both the High Temperature and Low Temperature Shield.

In the CMTB we extracted for each shield the temperature of the cryogenic line entering the module ("T in (CMTB)" in the Fig. 4 and 5) and the maximum temperature measured along the shield ("T out (CMTB)") to evaluate the maximum gradient of temperature along the shield itself ("Delta T (CMTB)").

We compare these values with the maximum ("T out (ANSYS)") and minimum ("T in (ANSYS)") temperatures calculated from the simulation, and the temperature gradient calculated from these values ("Delta T (ANSYS)"). Figures 4 and 5 show the obtained trends.

For both shields, we notice immediately a good agreement of the simulated data with the effective thermal distribution measured along the shields during cooldown. The calculated data shows a smoother line, mainly due to the simplifications performed in the preparation of the data used in the simulation. In the High Temperature shield plots (Figure 4), we see a smoother calculated Delta T line corresponding to a smoother behaviour of the inlet temperature.

For the low Temperature Shield we notice a quicker thermalization of the shield in the simulated data: this could depend on many uncertainties of the model: the thermal properties of the material found in literature and used for the simulation (for example a higher thermal diffusivity with respect to real values), a better conduction path (shields fingers have been simplified in the model as a single contact region) or a higher radiation shielding (less heat load on the low temperature surfaces).



Figures 4: (left) – 5 (right): Comparison of the calculated (ANSYS) and real (CMTB) temperature data of the Low Temperature (right) and High Temperature (left) Shields.

CONCLUSIONS AND FUTURE WORK

We implemented a finite element model of the TTF like cryomodules main components and validated its static and transient behavior with real data measured at the Desy CMTB facility within reasonable approximations.

The model implemented can be easily used now to study different cooldown procedures: change of the refrigerating liquid (like for the Fermilab ILCTA, where Nitrogen instead of Helium is used for the High Temperature Shield) or monitoring the impact of changes in the cooldown procedures (duration, T profile).

Furthermore we can develop further the model to obtain a rough estimation of the heat load assessment of the proposed ILC module without Low Temperature shield.

Further improvements can be introduced by developing a simplified model for the cavity string and 2 K environment. In the present model the 2 K environment is represented as a time-dependent Temperature boundary at the HeGRP cavity supports, with unlimited thermal exchange capabilities during cooldown (this neglects the influence of the cavity string enthalpy in the cooldown).

REFERENCES

[1] TESLA Technical Design Report, (Deutsches Elektronen-Synchrotron DESY, Hamburg, 2001).

[2] D. Barni et al, Cooldown simulations for TESLA Test Facility Cryostats, Advanced in Cryogenic Engineering, 43, 315, (Plenum Press, NY, 1998).

[3] F. Barron, Cryogenic Heat Transfer, (Taylor & Francis, Philadelphia, 1999).