STUDIES ON THE THERMO-MECHANICAL BEHAVIOR OF THE CLIC TWO-BEAM MODULE

R. Nousiainen*, Helsinki Institute of Physics and Department of Physics, University of Helsinki, Helsinki, Finland and VTT Technical Research Centre of Finland, Oulu, Finland
G. Riddone, CERN, Geneva, Switzerland
K. Österberg, Department of Physics, University of Helsinki and Helsinki Institute of Physics, Helsinki, Finland

Abstract

To fulfil the mechanical requirements set by the luminosity goals of the CLIC collider, currently under study, the 2-m two-beam modules, the shortest repetitive elements in the main linac, have to be controlled at micrometer level. At the same time these modules are exposed to variable high power dissipation while the accelerator is ramped up to nominal power as well as when the mode of CLIC operation is varied. This will result into inevitable temperature excursions driving mechanical distortions in and between different module components. A FEM model is essential to estimate and simulate the fundamental thermo-mechanical behaviour of the CLIC two-beam module to facilitate its design and development. In this paper, the fundamental thermal environments for the RF-components of the module are described. Also the thermal and structural results for the studied module configuration are presented showing the fundamental thermo-mechanical behaviour under the main CLIC collider operation conditions.

INTRODUCTION

CLIC is a multi-TeV normal conducting electron-positron collider with power supplied by a secondary electron Drive Beam (DB). The main beam (MB) passes through Accelerating Structures (AS), where the beam is accelerated by the RF power that is created in Power Extraction and Transfer Structures (PETS) from the low energy, high-intensity DB and transferred through waveguides. The 21 km long linacs are equipped with complex modular 2-m units. The so-called CLIC two-beam modules contain the needed linac RF components and all technical systems, such as alignment and beam instrumentation. The CLIC module is a precision assembly exposed to varying thermal fields in the accelerator caused by the ramp up and operation [1, 2]

This paper presents the thermo-mechanical modelling (TMM) of the CLIC module developed with ANSYS Finite Element (FE) software ANSYS Workbench 12.1. The estimated average thermal dissipation into the RF structures and magnets of a CLIC standard module is ~6.9 kW (3.45 kW/m). Therefore a dedicated cooling system is planned to extract heat and minimize temperature variations. The model discussed here focuses on thermo-mechanical effects caused only by RF-structure (PETS and AS) operation and thus not all the thermal load sources have been taken into account. In addition, gravity and vacuum loads were also included in the FE-model.

MODEL DESCRIPTION

The TMM was built according to the baseline module design [3] aiming at studying its thermo-mechanical behaviour. The geometry was created in CAD and implemented into ANSYS Design Modeler geometry incrementally enabling controlled extensions of the model. Steady-state static thermal and structural simulation environments were considered.

The overall optimised model consists of about 200 parts. The main components included in the model are shown in Fig. 1.

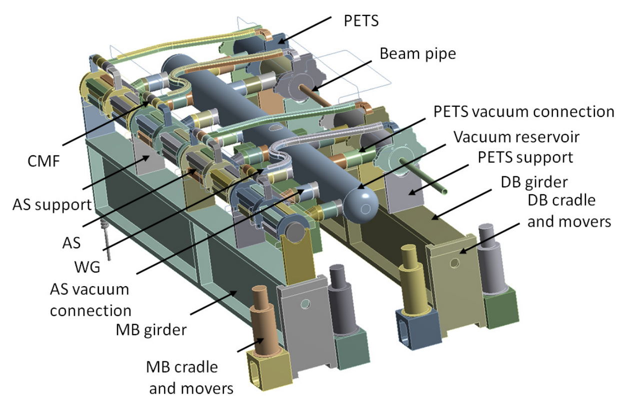

Figure 1: Thermo-mechanical model configuration based on a typical CLIC module type.

Inputs and Assumptions

To obtain thermal and mechanical responses for the CLIC module the following fixed inputs were given from the CLIC module working group:

- Ambient temperature in the tunnel 30°C,
- Thermal loads of the RF structures for unloaded (no beam) and loaded (beam) operation conditions,
- Current configuration of the CLIC module including girders and their supports,
- All eight accelerating structures brazed together as one solid object and longitudinally fixed at the centre of a module, and free to move at the extremities,
- Vacuum reservoir fixed to ground,
- MB and DB girder supports fixed to ground,
- Vacuum reservoir directly connected to the RF structures of the beams with flexible bellows,
- Only fixed contacts between components,
- Natural convection of heat to tunnel air.

*risto.nousiainen@vtt.fi

Geometry

From the TMM modelling point of view, the given CLIC module geometry consists of three main subsystems: MB, DB and vacuum system assemblies. This separation is done to ensure flexible vacuum connections between the subsystems to enable an independent beam alignment. In addition, the geometry consists of beam pipes, waveguides, and supports. The main component materials used in the model are copper OFE (RF structures), silicon carbide (girders), aluminium 7075-T6 (RF structure supports) and stainless steel (vacuum components, girder supports).

Contact Modelling and Connections

Contact and joint modelling focused on two main aspects: inclusion of flexible joints to decouple the mentioned subsystems as well as standard ANSYS component contacts. Flexible joints, analytically defined as stiffness matrices, were put into ANSYS workbench as bellow-conditions, and standard joints as bonded contacts. Perfect thermal contacts were assumed for the contacts. Adjacent surfaces of stiffness matrices were thermally coupled.

All contact modelling aimed at the lightest possible computation because the overall numbers of contacts and joints were 228 and 54, respectively. Frictionless contact modelling was tested for the MB AS V-shaped supports, but it increased the solution time up to unacceptable level.

The DB quadrupoles are mechanically connected to the DB girder. Since the beam pipe when passing through a DB quadrupole is not fully in contact, the DB quadrupole was omitted in the TMM. This has an effect on the gravity load condition but regarding thermo-mechanical responses the effect was considered negligible.

Load Conditions

The induced thermal dissipations are an essential part of the operation of the CLIC RF structures [2, 3]. The current estimations for the TMM thermal dissipations for loaded and unloaded are shown in Table 1. The dissipations are not uniformly distributed and thus input command lines for position dependent heat flux were used for the boundary conditions. The total input powers are 3.49 kW and 2.89 kW per module for unloaded and loaded TMM models respectively [4].

Table 1: Thermal Loads Into TMM

Structure	Thermal load	Total/module
AS unloaded	411 W	3.3 kW
AS loaded	336 W	2.7 kW
PETS	39 W	156 W
Waveguides	11 W	45 W

The TMM cooling system consists of distributed water channels (Figure 2), which correspond to the CLIC cooling design. For the TMM, the water cooling was implemented via the ANSYS FLUID 116 element.

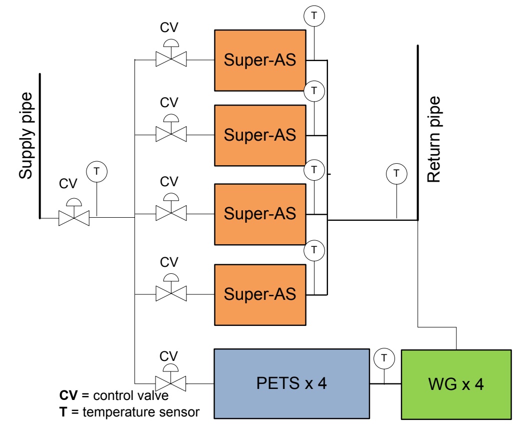

Figure 2: The TMM cooling water distribution; Super-AS: two consecutive accelerating structures; WG: waveguide.

Convection to tunnel air was included via a convection boundary condition. Regarding the water cooling and free convection to air, the thermal boundary conditions were analytically calculated as shown in Table 2.

Table 2: Cooling Boundary Conditions; HTC: Heat Transfer Coefficient

Item	Description	Value
Input flow MB	mass flow	68.6 kg/h
Input flow DB	mass flow	37.4 kg/h
Water input	Temperature	25°C
HTC MB	convection to water	3737 W/(m^2·K)
HTC DB	convection to water	1407 W/(m^2·K)
HTC Air	convection air	4 W/(m^2·K)

The vacuum modelling aimed at showing subsystem level results including inter-beam flexibility. Vacuum was applied as a negative atmospheric pressure on the internal vacuum surfaces.

The structural analysis was done in three steps. In the first step only gravity load was taken into account. The second step included also the vacuum conditions and the third combined gravity, vacuum and RF conditions. The unloaded and loaded operation conditions were simulated separately.

Supports

The CLIC RF structures are currently supported on precision V-shaped supports mounted on the MB and DB girders. The girders are attached to so-called cradles, which serve as articulation points for adjacent girders. The cradles are supported on kinematic stands constructed of adjustable, high precision linear actuators. The girder end supports are divided into master and slave cradles enabling a coupled support of adjacent girders.

The ANSYS modelling was done to the level of the mounting surface of the actuator lower ends. As a result, the estimated stiffness of the actuator support was taken into account. The actuator support containing six d.o.f. constraints was reduced to equally stiff linear and torsion springs to ease the computation. Both the master and slave cradle end designs were introduced into the model.

RESULTS

Based on the module input, a set of results was obtained for unloaded and loaded operation conditions. Table 3 summarizes the main thermal results.

Table 3: Thermal results of the TMM

Item	Unloaded	Loaded
Max temp. of medium	41.7˚C	40.0˚C
Water output temp MB	35.0˚C	34.9˚C
Water output temp DB	29.8˚C	29.8˚C
Heat to water / air	3390 / 98.2 W	2800 / 94.0 W

Temperature and deformation contours for unloaded condition are shown in Fig. 3. Table 4 summarizes the structural results.

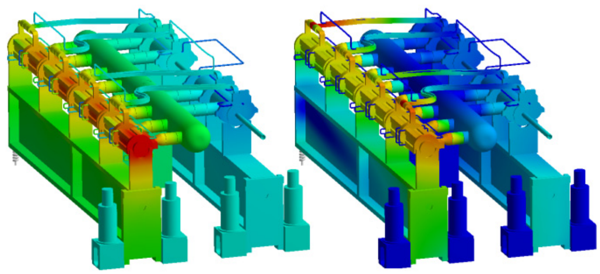

Figure 3: Temperature (left) and deformation (right) contours for unloaded condition including vacuum and gravity load conditions; Red: large variation, Blue: small variation.

Table 4: Structural Results of TMM; G: Gravity, V: Vacuum, RF: Thermal Load

Item	Unloaded	Loaded
Max. def. at MB line, G	33 μm	33 μm
Max. def. at DB line G	26 μm	26 μm
Max. def. at MB line, G, V	354 μm	354 μm
Max def. at DB line G, V	144 μm	144 μm
Max. def. at MB line, G, V, RF	553 μm	549 μm
Max. def. at DB line G, V, RF	128 μm	128 μm

DISCUSSION

The thermal results were cross-checked by comparing the model output power to input power. The corresponding error obtained was 0.5% (absolute ± 16 W). Thus the accuracy of the results can be considered sufficient and the overall temperature increase of 15 K in the RF structures is justified. Thermal dissipation to air was 49.1 W/m (2.8%) of a total of 1.7 kW/m. The input for natural convection of 4 W/(m^2·K) is the driving parameter to the result. For comparison, the total limit for dissipation to air is currently set at 150 W/m, mainly governed by the size of the tunnel ventilation system.

According to the results, vacuum and thermal load conditions cause the most significant distortions; vacuum mainly transversally and thermal longitudinally. Vacuum force driven deformations become extensive due to flexible bellows, which on the other hand enable active alignment. It has to be noted that the vacuum force might affect the alignment capability if not compensated.

Because the DB quadrupole has not been completely included in the model, the DB deformation is smaller than expected under gravity. The total deformation under gravity is at the level of equivalent supporting systems and thus the results can be considered reliable.

CONCLUSIONS

A finite element model was successfully built to enable an overall assessment of the thermo-mechanical response of the CLIC module. The results are in compliance with the inputs given proving the accuracy of the model.

According to the given design input, vacuum driven transverse deformations are few hundred micrometers. To reduce this, the design of the inter-beam vacuum connections needs to be improved and further developed, e.g. by changing the orientation of the flexible joints.

In the RF ramp up to unloaded condition, the thermally induced mainly longitudinal dilatation is of the order of 500 μm over the 2-m long bonded super accelerating structures. Nevertheless, if needed, the thermal expansion could be shared between more parts by splitting the bonded MB AS assembly into two or four pieces. Between different operation modes, the temperature difference and corresponding dilation is much smaller (Table 4) and can be adjusted by the coolant mass flow.

This partition could reduce relative displacements and thus ease the support design. In all cases, the effects caused by temperature changes in ramp up of the accelerator have to be carefully assessed in the technical design of CLIC.

ACKNOWLEDGEMENTS

This work has been supported by a collaboration between the CLIC group at CERN, Helsinki Institute of Physics and VTT Technical Research Centre of Finland.

The research leading to these results has received funding from the Academy of Finland.

REFERENCES

[1] G. Riddone et al.: “Technical Specification for the CLIC Two-Beam Module”, 11th European Particle Accelerator Conference, Genoa, Italy, 2008.

[2] H. Braun et al., "CLIC 2008 Parameters", CERN-OPEN-2008-021; CLIC-Note-764.

[3] J.-P. Delahaye: “Towards CLIC Feasibility”, IPAC’10, FRXCMH01, Kyoto, Japan, 23-28 May 2010.

[4] A. Samoshkin et al.: "CLIC Two-Beam Module design and integration", LINAC'10, Tsukuba, Japan, 12-18 Sep 2010.