STUDY OF THE DYNAMIC RESPONSE OF CLIC ACCELERATING STRUCTURES

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Abstract

CLIC is a linear electron-positron collider, 48 km long, consisting of more than 20000 repetitive modules. The target beam size of 1 nm dictates very tight alignment tolerances for the accelerating structures (AS). In order to assess the effect of short-term RF power interruptions (breakdowns or failure modes) on the alignment, the dynamic behaviour of the AS was investigated on the prototype two-beam module. On a dedicated experimental setup, the thermal and mechanical time constant (TC) was monitored as a function of ambient temperature, water flow and power. The experimental results showed that the thermal TC ranged between 4 and 11 minutes and presented strong correlation with the cooling water flow. These results were in very good agreement with the theoretical expectations. The displacement dynamics were found to be comparable with the thermal ones. The study indicates that temperature measurement, which is a fast and easy process, can be used as an indicator of the AS displacement. Moreover, it is shown than the transient response can be efficiently controlled through appropriate regulation of the cooling water flow.

INTRODUCTION

CLIC [1] is a multi-TeV normal conducting electron-positron collider foreseen to be constructed in two 21-km long linacs comprising more than 20000 repetitive modules. The principle of CLIC lies on the concept of two beams, a high-energy Main Beam (MB) and a low-energy, high-intensity Drive Beam (DB). The MB is accelerated in the Accelerating Structures (AS) by the RF power produced from the Power Extraction and Transfer Structures (PETS) of the DB. The alignment tolerances of CLIC are very tight due to the low target beam size of 1 nm. All components must be pre-aligned without beam with an accuracy of 10 μm. Alignment can be affected by the power dissipation on the components estimated to be 7 kW per module during normal operation.

A prototype two-beam module has been assembled in order to study the thermo-mechanical behavior of CLIC components [2]. In the module, the power is applied by electrical heaters, while ambient conditions and cooling can be regulated. Until now, temperature and alignment have been extensively studied during steady-state under different operating conditions [3]-[5]. However, in order to assess the effect of short-term power interruptions, e.g. during a failure mode, the study of transient response is important.

In this paper, the dynamic thermo-mechanical response of the CLIC AS is investigated as a function of the main operation conditions of CLIC, i.e. the water flow, ambient temperature and dissipated power. The correlation of the thermal and mechanical response is evaluated as well as the agreement of the experimental results to theoretical expectations.

THEORETICAL ANALYSIS

When the AS is powered-up, the power of the heater (P_h) is assumed to be distributed among the AS material (P_{cu}), the water (P_{water}) and the air (P_{air}):

$$P_h = P_{cu} + P_{water} + P_{air} \qquad (1)$$

The time response of each power component is described as follows [6]:

$$P_{cu}(t) = m_{cu} c_{p,cu} \frac{dT_{cu}(t)}{dt} \qquad (2)$$

$$P_{water}(t) = \dot{m}_w c_{p,w} \left[T_w(t) - T_w(0) \right] \qquad (3)$$

$$P_{air}(t) = hA_{cu} \left[T_{cu}(t) - T_\infty \right] \qquad (4)$$

where $c_{p,x}$ the heat capacity, m_{cu} the AS mass, A_{cu} the AS surface, $\dot{m}_w$ the water mass flow, h the heat transfer coefficient, and T_∞, T_{cu} and T_w the ambient, AS and outlet water temperatures respectively. Combining Eq. 1-4, the temperature response of the AS is described by a first order differential equation with the following analytic solution:

$$T_{cu}(t) = T_{ss} - ce^{-t/\tau} \qquad (5)$$

where T_{ss} is the steady-state AS temperature, c is a constant and τ is the time constant (TC) given by:

$$\tau = \frac{m_{cu} c_{p,cu}}{\dot{m}_w c_{p,w} + hA_{cu}} \qquad (6)$$

The TC describes the speed of a first-order system's response to a step input and equals the time to reach the 62.3% of its steady-state. A similar approach can be followed for the AS power-down.

Based on the theoretical analysis, the TC depends on the material and geometry (mass and surface) of AS and is inversely proportional to the water flow.

EXPERIMENTAL PROCEDURE

The experimental procedure involved two series of measurements referred here as Study-1 and Study-2. Study-1 was dedicated to the measurement of the dynamic thermal response, while in Study-2 the displacement dynamics were investigated.

Study-1

A total of 27 tests were conducted for three cases of power (290, 820, 910 W), water flow (0.04, 0.068, 0.09 m^3/h) and ambient temperature (20, 30, 40 ^{o}C) combined in all possible configurations. Prior to each test the module was stabilized with the respective cooling flow and ambient temperature. At time t=0, the AS was powered-up at full power. When temperature reached steady-state, power was switched-off. Temperature was monitored every one second from t=0 until temperature stabilization to initial conditions after power-off.

Study-2

One representative configuration of power (820 W), water flow (0.04 m^3/h) and ambient temperature (20 ^{o}C) was chosen for Study-2. The same power cycle was followed as in Study-1, this time monitoring, at the same time, the dynamic displacement of the AS axis. The AS axis was defined through the combination of the position of four chosen points on the AS as shown in Fig. 1 and described in detail in [7].
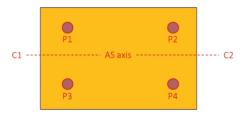

Figure 1: Comparison of experimental and theoretical temperature profile.

Two cases of measurements were investigated. In the first case only one point (P1) of the AS was followed in order to acquire more frequent measurements and study its dynamics with increased accuracy. As a second step, the position of all four points was measured and the AS axis was followed over time. In all cases the tracker AT401 was used. The precision of the measurement procedure was 5 μm.

RESULTS

In this section the results of the two studies are presented and discussed.

Study-1

As expected from the theoretical analysis, the temperature response should follow the dynamics of a first-order system and, thus, its transient behaviour can be described by its TC. In order to estimate the TC from the experimental data, Eq. 5 was least-squares fitted to the temperature measurements. Fig. 2 presents the calculated TC for all tests as a function of water flow. Each graph corresponds to one ambient temperature, while both temperature rise and fall are illustrated. From Fig. 2 an inverse dependence of the TC on the water flow can be observed as expected by theory. For the range of operating conditions analysed, the TC varied between 4 and 11 minutes.
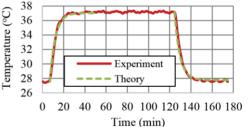

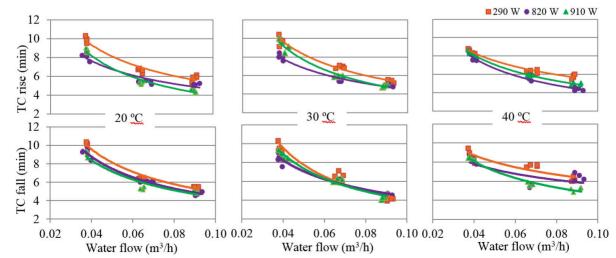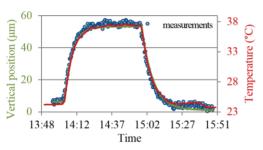Figure 3: Comparison of experimental and theoretical temperature profile.

Figure 2: Thermal TC of AS against water flow for all power cases during temperature rise and fall.

In order to verify our results, the rising and falling temperature profiles were reproduced, based on the calculated TC, and compared to the experimental ones. Such a result is illustrated in Fig. 3.

Study-2

Following the investigation of the temperature dynamics, the displacement of the AS was monitored during transient response. As previously stated, in a first experiment, the position of one point (P1) was followed over time and the results are presented in Fig. 4.

Figure 4: Position measurement of AS point P1 and best-fit line plotted against AS temperature.

On the same graph the respective temperature curve of the AS is plotted (red line). The results indicate that the transient displacement of P1 follows closely the temperature dynamics. The mechanical TC is estimated similarly to the temperature case by fitting the first-order system response (Eq. 5) to the position measurements (green line).

As a second step, the AS axis position was followed over time based on the previously discussed procedure. No radial axis movement was detected, thus the results refer to vertical displacement. The respective graphs for the beginning (C1) and the end (C2) of the axis are presented in Fig. 5 where a good correlation with the temperature dynamics can be again observed.
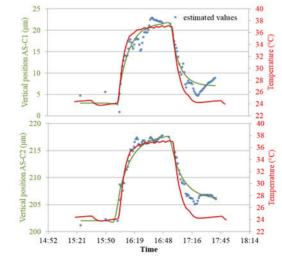

Figure 5: Position measurement of AS axis beginning (C1) and end (C2) plotted against AS temperature.

In this case the plotted points are estimates of the axis position based on the monitoring of four points. This process accumulates errors expressed by the observed deviations from the first-order dynamic response.

Finally, Table 1 summarizes the estimated TC values of the temperature (ΔT) and alignment response for one point (Δx-P1), and axis beginning (Δx-C1) and end (Δx-C2). In agreement with the previously discussed observations, the TC of P1 is very close to the temperature TC, while when the AS axis is considered the dynamics are matching, however presenting a slower response.

Table 1: Estimated TC (min) of Temperature (ΔT), Displacement of one Point (Δx-P1), Axis Beginning (Δx-C1) and End (Δx-C2)

	ΔT	Δx-P1	Δx-C1	Δx-C2
Power-up	7.35	7.52	11.00	13.28
Power-down	7.47	7.33	8.65	12.38

CONCLUSIONS

The present study investigates the thermo-mechanical dynamics of the CLIC AS. The transient temperature response is monitored and correlated to the operational parameters of power, water flow and ambient temperature. The temperature dynamics follow a first-order system behaviour and are determined by the estimation of the TC. Experimental results are in very good agreement to theoretical expectation. The displacement and thermal dynamics were found to be highly correlated with comparable TC.

An interesting outcome of this study is the correlation of the AS dynamic response to the cooling water flow. This observation opens the possibility to control CLIC dynamics during failure scenarios through appropriate regulation of water flow. Moreover, the correlation of thermal and mechanical response may lead to the use of temperature measurement, which is a fast and easy process, as an efficient indicator of AS displacement, which is complex and time-consuming.

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