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HEAT LOADS MEASUREMENT METHODS FOR THE ESS ELLIPTICAL CRYOMODULES SAT AT LUND TEST STAND

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Abstract

The Site Acceptance Testing, SAT of all ESS elliptical cryomodules is done at the Lund Test Stand. Determining cryogenic heat loads (static and dynamic) is an essential part of the acceptance criteria. We present complementary measurement methods for evaluating the cryogenic heat loads and discuss a qualitative comparison between them. We also present a summary of the results of these methods for one of the cryomodules.

INTRODUCTION

The ESS accelerator is currently under construction in Lund, Sweden [1]. Thirty elliptical cryomodules (CM) distributed in 2 families: 9 Medium-Beta and 21 High-Beta, will go through SAT at the Lund test Stand, TS2 [2, 3]. Each CM integrates four superconducting radio-frequency cavities made of niobium immersed in a superfluid helium bath at 2 K. An important portion of the acceptance tests consists of verifying the proper working behaviour of the superconducting cavities and other cryomodule components at nominal working conditions [4].

Another important part of the cryomodule acceptance tests is the measurement of cryogenic static heat loads and RF-induced dynamic heat loads. This paper describes a set of methods used to evaluate these parameters.

THE CM CRYOGENICS AT TS2

The cold test takes place inside the radio-protection bunker where the CM is connected to various auxiliary systems, such as: radiofrequency distribution, beam vacuum, isolation vacuum, water cooling and cryogenic distribution.

The TS2 cryomodule cryogenics system is designed and constructed such that the nominal operating conditions for the accelerating cavities can be achieved. It also allows to safely go through a series of operating modes [5] necessary for example for the cool down, warm up or response to accidental states.

Simplified Cryogenics Layout

At the TS2 a dedicated cryogenic plant, TICP [6] and distribution system, CDS [7] supplies refrigeration to the cryomodule at conditions similar to those present in the accelerator tunnel where each single cryomodule operates together with a dedicated valve box (VBox) and can be operated independently from other CM.

At the interface between the CM and the VBox there are four cold process lines. Two of these lines are for the thermal shield cooling, TS (supply and return), whilst the other two lines are for the cold mass helium supply and vapour return. Figure 1 below shows a very simplified scheme of the cryogenic system at TS2 with selected relevant equipment.

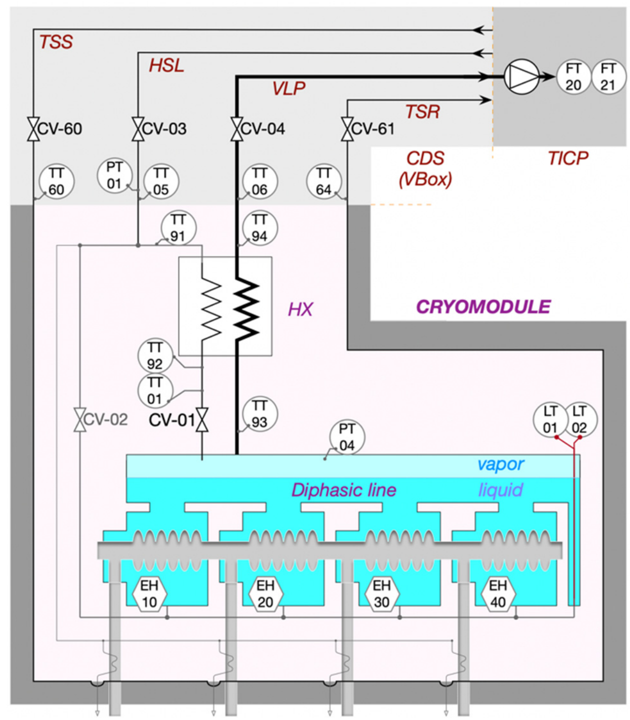

Figure 1: Simplified scheme of the cryogenic system.

The high-pressure (HP) supercritical helium is supplied at 3 bar and 5.3 K. It first passes through a heat exchanger (HX), where it is pre-cooled by heat exchange with the low-pressure (LP) evaporated vapours from the 2 K bath.

The pre-cooling of the HP line allows to recover the available frigories from the LP line and significantly enhance the efficiency of the "Joule-Thomson" (JT) expansion valve feeding the 2 K bath.

The typical thermodynamic conditions at the TS2 interface between Vbox and CM are shown Table 1.

Table 1: Conditions at the CM interface with VBox

Circuit name	Pressure, Temperature
Thermal shield supply, TSS	13.8 bar, 33 K
Thermal shield return, TSR	13.3 bar, 36 K
Helium supply line, HSL	3 bar, 5.3 K
Vapour return line, VLP	31 mbar, -

Under nominal conditions, the superconducting cavities operate fully immersed in the superfluid liquid helium bath, with the helium level stabilized inside the diphasic line which interconnects the four helium tanks at the top.

The level of the helium bath is measured by two redundant level gauges, LT-01 and LT-02, and it is controlled by

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regulating the JT valve (CV-01). The typical operating level is 90 %±5 % with liquid on the diphasic line.

The pressure of the saturated helium bath is measured by PT-04 sensor and maintained stable by controlling the VLP return valve (CV-04) placed downstream of the HX.

The flow returned to the TICP is measured after the 2 K pumps by the flowmeters FT-20 and FT-21.

A fraction of the HP helium supply is used to cool the power couplers double wall (23 mg/s per coupler), limiting heat loads by conduction from the external vessel parts through the power coupler structure into the cavities.

MEASUREMENT OF STATIC HEAT LOADS TO THE 2 K BATH

The cryomodule is equipped with a variety of instrumentation for process control and diagnostics, these are complemented with additional instrumentation located in the Vbox and TICP. Taking advantage from this variety, we developed complementary methods for determining the static heat loads.

The following methods can determine total heat loads (static plus dynamic) to the helium bath, however they are typically used for static heat load evaluation.

The measurements can be performed with the cavity heaters (EH) turned off or on. In the scenario where the heaters are turned on, the final result of static heat loads needs to be corrected by taking into consideration the power dissipated by the heaters.

Flowmeter Method

The static heat load $\dot{Q}_s$ to the 2 K helium circuit is calculated by the direct measurement of the evaporated liquid mass flow rate with flowmeters FT-20 or FT-21. During this measurement the helium supply to the bath is stopped by closing the valve CV-01. The helium level inside the diphasic starts at nominal height and decreases during the measurement as liquid evaporates. The bath pressure is kept stable at 31mbar (regulated by CV-04), with a stability <0.2 mbar, for improved measurement accuracy (Fig. 2).

The static heat loads are calculated by multiplying the measured mass flow rate $\dot{m}$, by the latent heat of evaporation L (23.06 J/g, for 31 mbar saturated bath pressure).

$$\dot{Q}_s = L \cdot \dot{m} \qquad (1)$$

This method provides a direct measurement of the heat loads; however, its accuracy is directly affected by the flow measurement accuracy.

Level Meter Method

Similar to the flowmeter method, in this method the helium supply to the bath is stopped. The heat loads to the 2 K helium circuit are derived via the direct measurement of the helium level decrease using the level gauges, LT-01 and LT-02.

Thanks to computer-aided-design (CAD) and the CM mechanical model we can compute the volume of liquid for a given helium level measurement. The mass of liquid is calculated by applying the corresponding helium density ρ, and then we calculate the evaporated mass flow by simply subtracting the initial m_i, and final m_f, helium mass over the test period $dt = t_f - t_i$, and:

$$\dot{m} = (m_i - m_f)/dt$$

The static heat loads are then calculated using Eq. (1).

Similar to the flowmeter method, as no helium is supplied to the bath, the level inside the diphasic line decreases for the duration the measurement as liquid evaporates. The accuracy of the measurement depends on a stable bath pressure and proper manufacturing according to design.

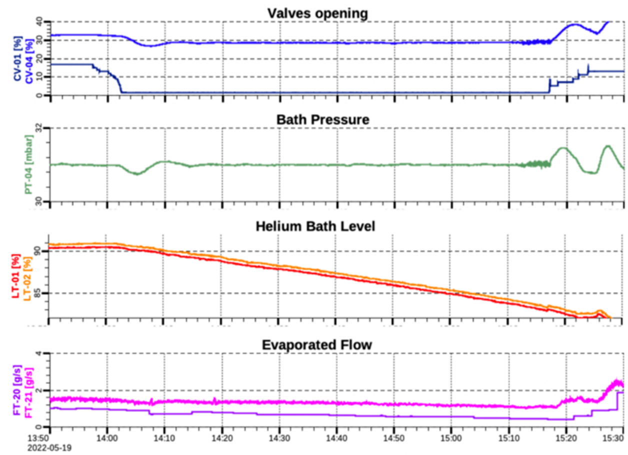

Figure 2: Selected process variables during static heat load measurement (flowmeter and level meter method).

Pressure Increase Method

During this measurement both the helium supply to the bath and vapour return from the bath are stopped. This is done by closing CV-01 and CV-04 keeping the system sealed, thus no flow to TICP.

The heat loads to the 2 K helium circuit (or energy gain over time) are calculated by measuring, with PT-04, the resulting increase of pressure in the system (Fig. 3).

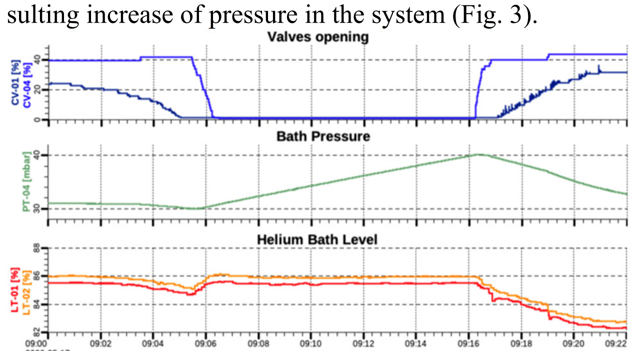

Figure 3: Selected process variables during static heat load measurement (pressure increase method).

The static heat loads (Eq. 2) are calculated from the change in energy, dE of the system 'liquid + vapour' over the test period, dt.

$$\dot{Q}_s = dE/dt \qquad (2)$$

The energy of the system is computed by adding the liquid enthalpy (H_l) and vapour enthalpy (H_v), considering the measured thermodynamic properties for a given measured pressure of the saturated bath and vapour.

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The mass of the liquid (m_l) and the mass of the vapour (m_v) are computed from the helium level measurement and considering the CM CAD model information. The static heat loads equation takes the following form:

$$\dot{Q}_s = \frac{(m_l \cdot H_l + m_v \cdot H_v)_f - (m_l \cdot H_l + m_v \cdot H_v)_i}{dt}$$

The contribution of the static heat load on the surrounding materials (niobium cavities, titanium helium tanks and titanium bi-phasic line) can also be included by taking in consideration the mass of each component, specific heat and sensible temperature increase.

MEASUREMENT OF DYNAMIC HEAT LOADS FROM CAVITY OPERATION

The dynamic heat loads from SRF cavity operation are calculated by measuring how much power due to RF origin is dissipated into the helium bath.

Heater Compensation Method

Before (or after) RF power is sent into the cavities the cryogenic system is stabilized and referenced. A steady helium flow is supplied to the bath by fixing the opening of CV-01. Heaters placed on the cavity tanks are powered and precisely adjusted to maintain the helium level constant, the power supplied to the heaters is noted, (EH_{No_RF}). The bath pressure PT-04 is maintained constant at 31 mbar by regulation of CV-04.

The cavities are then supplied with RF power and the additional dissipated power from this source is compensated by means of decreasing the total power supplied to the cavity heaters (EH_{With_RF}), while precisely maintaining the same thermodynamic conditions on the helium bath as for the reference (level, pressure). The dynamic heat load is given by the expression:

$$\dot{Q}_{RF\ dynamic} = EH_{No\_RF} - EH_{with\_RF}$$

Two-run Variance Method

This method consists in taking two measurement runs (one with RF and one without) using the methods described for static heat loads to the 2 K bath, and calculating the variance of the results. We tend to exclude this approach as the heater compensation method is fast and more accurate.

MEASUREMENT OF GLOBAL HEAT LOADS TO THE CM COLD MASS

Flow-Enthalpy method

The global heat loads to the CM cold mass are calculated by the direct measurement of the evaporated liquid mass flow with FT-20 or FT-21 and enthalpy difference between helium supply (H_{supply}) and helium return (H_{return}), where the enthalpy is derived from the temperature and pressure measurements.

$$\dot{Q}_{global} = \dot{m} \cdot (H_{return} - H_{supply}) \quad (2)$$

During the measurement, the helium supply to the bath is kept constant through CV-01, while maintaining a steady helium bath level in the diphasic line.

Throughout the measurement period the accepted level fluctuations are kept to a minimum. The helium bath pressure is maintained stable at 31 mbar ± 0.04 mbar.

A variation of Eq. (2) can be used for analysis of heat loads on segments of the system, becoming a useful tool to identify the approximate location of heat sources or to evaluate systematic errors in the temperature measurement.

MEASUREMENT OF STATIC HEAT LOADS TO THE CM THERMAL SHIELD

Enthalpic Difference Method

A calibration campaign of the TICP was done to evaluate the enthalpy difference between the TS supply and TS return to changes in dissipated power. A correlation between the temperature difference (within the TICP terminals) and the dissipated heat loads to the thermal shield was created.

When operating the TICP together with the CDS and the CM, the temperature difference within the terminals of the TICP is established for steady working conditions. Using the correlation taken during the TICP calibration campaign the global heat loads are calculated, $\dot{Q}_{TS\_tot}$.

During SAT, we calculate the total enthalpy difference on the thermal shield circuit at the TICP terminals (dH_{Tot}) and at the CM thermal shield terminals (dH_{CM}) by measuring the pressure and temperature at these points. The CM TS heat load ($\dot{Q}_{TS\_CM}$) is then calculated by scaling the total heat load with the enthalpy difference:

$$\dot{Q}_{TS\_CM} = (dH_{CM}/dH_{Tot}) \cdot \dot{Q}_{TS\_tot}$$

CONCLUDING REMARKS

We presented the various methods used at TS2 for determining cryogenic heat loads during elliptical CM SAT.

So far, 4 series and 1 prototype CM have completed SAT. The typical measured heat loads for these CM is about: 79 W for TS circuit static heat loads, 17 W for 2 K bath static heat loads and 6 W dynamic heat loads.

For the measurement for static heat loads to the 2 K bath we have created a set of complementary methods based on data from different instrumentation (Fig. 4).

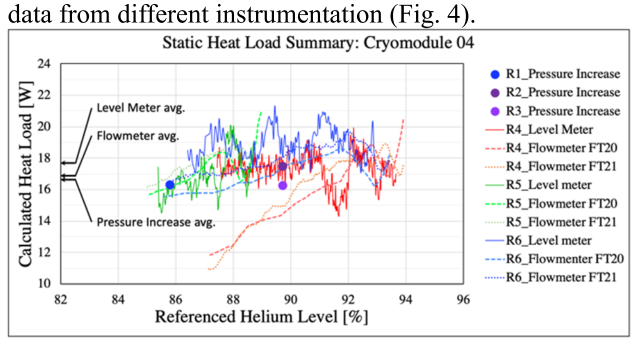

Figure 4: Static heat load measurement runs for CM04 with comparison between methods and average result.

We find that having the possibility of cross-checking these methods is a major advantage for understanding the measurement accuracy and confirming our understanding of the physical phenomena.

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