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AN APPROACH FOR COMPONENT-LEVEL ANALYSIS OF CRYOGENIC PROCESS IN SUPERCONDUCTING LINAC CRYOMODULES*

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Abstract

Powerful superconducting linear accelerators feature accelerating sections consisting in a series of cryomodules (CM), each hosting superconducting radiofrequency (SRF) cavities cooled by a cryogenic process. Despite the extensive instrumentation used for the tests and validation of the prototype cryomodules, it is usually very complex to link the measured global thermodynamic efficiency to the individual component performance. Previous works showed methods for assessing the global efficiency and even for allocating performances to sets of components, but few went down to a component level. For that purpose, we developed a set of techniques based on customized instrumentation, on dedicated test protocols, and on model-based analysis tools. In practice, we exposed the components to various operating conditions and we compared the measured data to the results from a detailed dynamic component model at the same conditions. This method was applied to the cryogenic debugging phase of the tests of the MINERVA prototype cryomodule, which, despite the liquid helium shortage, led to an extensively detailed characterisation, for its validation towards the serial construction.

INTRODUCTION

One advantage of superconducting cavities over normal conducting ones is the power savings, which are directly linked to the amount of heat captured by the cryogenic process. Thus, precise estimate and break-down of the heat loads of a CM during the prototyping phases are crucial to further optimize its efficiency for the series operation.

Along its path, a cryogenic loop collects heat from different components. In the cryomodule field, heat load measuring method based on the knowledge of the mass flowrate and of the specific enthalpy difference can be as accurate as +/- 5%, with properly calibrated sensors and perfect steady-state conditions. One problem is that the conditions are never steady, as cryogenic operation may feature long transients, spanning over several days. Another problem is that those methods only provide the total heat load received by a given heat sink. Without careful measurements and expensive instrumentation, it is hard to break them down.

What we propose, instead, is to rely on a model-based diagnostic tool associated to a specific comparison method. In the following, we first describe the cryomodule cryogenic process, then we present our diagnostic tool, and finally we give two use cases of our method.

CRYOMODULE CRYOGENIC PROCESS

In the superconducting accelerating section of most modern linear accelerators, like GANIL or FRIB, a modular architecture based on a series of up to tens of cryomodules, is chosen [1-2].

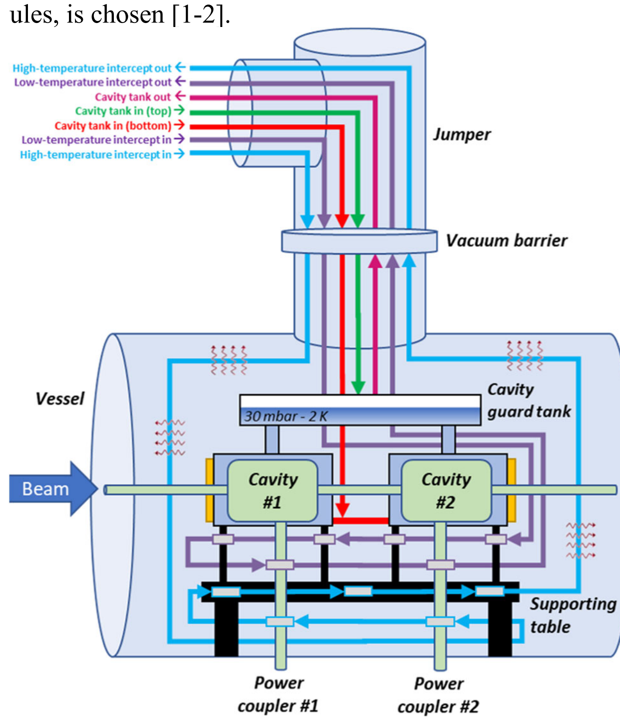

Figure 1: The simplified flow schematics of the MINERVA prototype SPOKE cryomodule.

Over this paper, we consider the MINERVA prototype cryomodule [3-4] – currently being tested at IJClab in Orsay, France – to illustrate our approach.

This cryomodule contains a pair of SRF cavities which are maintained at 2 K by a pool of saturated helium at about 30 mbar. To optimize the global thermal efficiency, two cryogenic lines intercept the incoming heat from the parts in contact with the 2 K tanks:

- A high-temperature line circulating saturated nitrogen at about 80 K (in prototype test mode).
- A low-temperature line circulating saturated helium between 5 and 10 K (in prototype test mode).

All the lines are supplied by a test valve box; the flow schemes and the cryomodule main components are displayed in Fig. 1.

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CRYOMODULE TEST DIAGNOSTIC TOOL PRESENTATION

1D Simulation Tool with MATLAB/Simulink

When it comes to analyse heat transfer tests, using Excel as a model-based tool is possible, but one will certainly stumble on the lack of flexibility. Instead, we developed a cryomodule model in the MATLAB/Simulink environment, using tailored Simscape building-blocks which solves for fluid dynamics and heat transfer equations. Similar modelling platforms do exist in the accelerator cryogenic field, like in [5-6], yet, used for other purposes.

By connecting those blocks, standing for pipes, rods, or valves for instance, one builds a model of a component, like a coupler, a heat exchanger or a supporting system. Generally, some tens of blocks associated to only 1-dimension (1D) discretization are enough to reach the desired accuracy. By connecting the individual components, one builds-up the global cryomodule model, that physically behaves like the real one. By introducing thermal masses and fluid reservoirs, one can even simulate transient states. As the model is kept simple, the run time is about 50 time faster than the simulated time.

Analysis Method

The method consists in running the model in the same conditions as the test, then trimming the model "free" parameters so that its outputs match the measured ones.

The cryomodule model contains physical parameters (conductive lengths, volumes, material …) that match the real devices and that are not to be trimmed. They are based on thorough investigations of the real component. By contrast, some parameters involved in complex physics like 3D radiation or thermal contacts can be considered as "free" and can be trimmed, although reasonably.

The key is finding the set of "free" parameters that minimizes the output error over a large range of operating points, rather than being 100% accurate on one specific point. This approach is well-suited to a prototype test phase, where many preparation tests can feed this procedure: other cryogenic fluids, room temperature tests or transients due to aborted test. We are now going to look at two applications of the method.

EXAMPLE #1: HEAT LOAD DISTRIBUTION TO THE 2K TANK

During the first prototype cryomodule test phase, the cavities were not installed. Instead, a tube (called the 2K bottom tank in Fig. 2) closed the main process loop between the cavity lower and upper ports. A frame (called cavity mock-up in Fig. 2), was installed to mimic the cavity packaging, and was supported by the same system as foreseen for the cavities: 4 arms each, linked to a table. The table itself is supported by two feet connected to the vessel at 300 K. The table is cooled by conduction with the thermal shield. Finally, the cavities are maintained in the longitudinal direction by invar rods. For further details on the MINERVA prototype cryomodule layout, refer to [4].

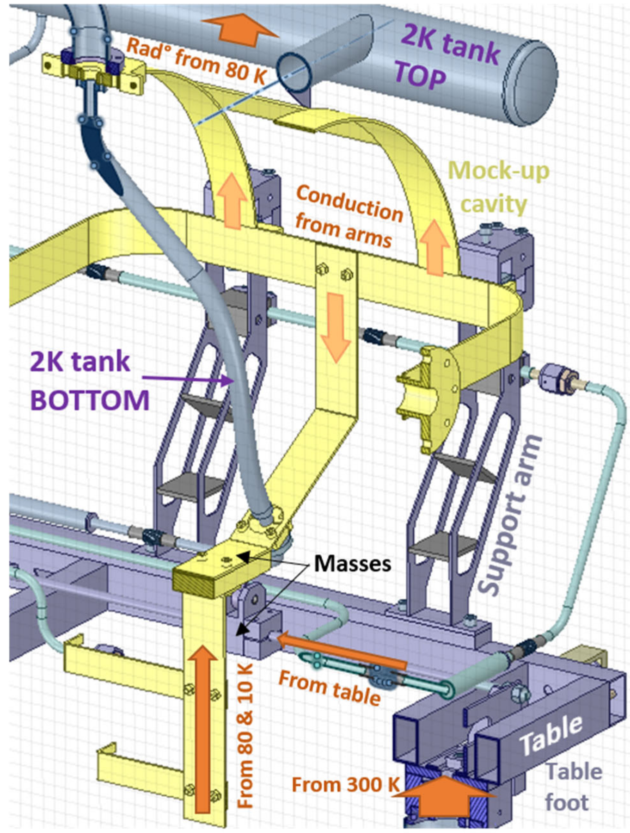

Figure 2: Cross-section of the MINERVA prototype cavity string supporting system, and main heat fluxes.

The 2K tanks (bottom and top), containing the liquid helium, receive heat from all the parts of the supporting system. Furthermore, radiative transfer adds heat to the 2K top tank. The total load to the 2K tanks was indeed measured, but the lack of time and helium did not allow to achieve steady-state: a part of the measured heat is transient, due to parts still being cooling-down.

The challenge is to break-down the heat loads from this global measurement. By using the Simscape model of the prototype cryomodule, which accounts for all the previously described effects, including the transient state, we ended-up with a consistent heat load distribution (Fig. 3). This diagram shows the instantaneous heat distribution in the same conditions as the test. The bar to the far right shows the transient heat load, obtained from the difference between the model in the same unsteady state as the test, and the model in steady-state.

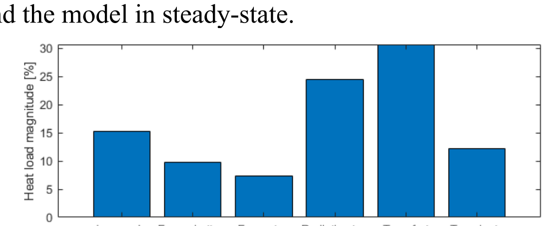

Figure 3: Instantaneous heat load distribution on the 2K tanks, at the same condition as the measurement.

This heat load distribution indeed proved to be consistent, as the model could faithfully reproduce all the

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different test conditions that were carried out along the test phase: helium at 4 K, helium at 2 K and nitrogen at 80 K, at different levels and different flow rates.

There was one degree of freedom that needed to be trimmed: the radiative heat transfer coefficient between the 2K top tank and its surrounding, which is complex because of a mix of 80 K and 300 K surfaces and non-intuitive view factors. This contribution was initially estimated to be almost negligible. The method thus enabled to pinpoint this unexpected effect for further investigation.

This example shows how this kind of simple model can help setting up a scenario of a complex problem and be a guideline for prototype investigations. By extension, it can be used as a continuous reference to follow-up the heat load evolution along the project, when hardware updates are performed.

EXAMPLE #2: COUPLER MULTIPACTING HEAT LOAD

The power coupler delivers the power to the cavity, and consists in an internal conductor (the antenna) and an external conductor. The external conductor is physically connected at one end to the cavity at 2 K, at the other end to a flange at about 300 K. Two intercept lines reduce the heat transfer to the cavity, as shown in Fig. 1. The details of the MINERVA prototype coupler design can be found in [4-7].

On top of those conductive heat loads, the coupler outer conductor may itself heat-up because of:

- Joule effects from the radiofrequency (RF) waves.
- Electron multipacting events.

While the former usually provides some tens of Watt of heating and is proportional to the power of the waves that travel in the coupler [8], the latter can reach several hundreds of Watt and be localised at one specific RF wave power. During the conditioning of the MINERVA couplers, in view of their integration in the cryomodule, such events did occur. We used a Simscape coupler model to investigate on it. Figure 4 displays the model, which is a 1D axisymmetric representation along the coupler axis. As illustrated in the picture, three sensors (TT207, TT208, TT209) are placed along the coupler outer conductor outside surface.

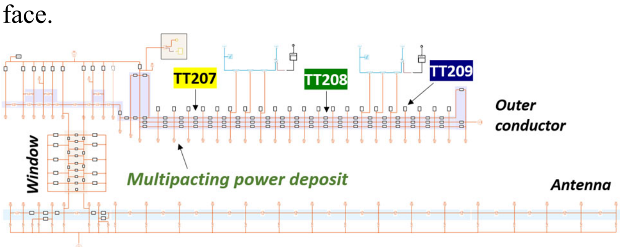

Figure 4: Simscape model of the MINERVA coupler.

When a multipacting event occurs, all three temperatures consecutively rise and fall abruptly, within some minutes. Three questions were investigated:

- How much power is released?
- Where, along the coupler, does it occur?
- Does it move or stay static over time?

We first roughly estimated the released power from indirect RF measurements. We then applied it in the simulation at the location where the first sensor temperature rose. Finally, we compared the measured and simulated time evolution (Fig. 5).

We could confirm the amount of released heat, and the initial location, as TT207 was correctly reproduced. On the other hand, the mismatch on TT208 and TT209 points toward a migration of the multipacting over time, rather than a fixed spot, which was confirmed by other indicators. This example shows how this tool can contribute to address complex multi-physic phenomena, that would be time-consuming to analyse by just looking at the test results.

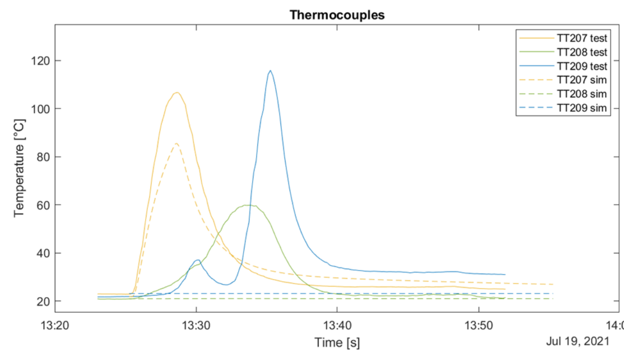

Figure 5: Measured (solid) and Simulated (dotted) temperature evolution after a multipacting event occurred.

This example also shows the versatility of these simulations: although the modelling environment is adapted to simulate cryogenics, it does also work at room temperature, like in these conditioning tests.

CONCLUSION

To analyse heat load distributions, we created a method that consists in a 1D digital representation of the cryomodule, in the form of a MATLAB/Simulink model, that we compare to the tests. The strength of this model-based approach is not the accuracy of the models on one specific output, but the global consistency over many different outputs and test conditions. This approach is reinforced by the fact that the models have multi-physic capabilities. One advantage of the method, is that it can seamlessly handle whatever transients and very poor tests, thus limiting the experimental time.

Beyond the heat transfer distribution, the method can be used for other physical analysis that require a global system approach and 1D discretization, like the pressure drops in the lines, in order, for instance, to precisely size control valves in whatever conditions. Finally, the models built for analysis during the prototype tests can be further used as references along the project cycle, to assist the design.

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