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TIME RESOLVED CRYOGENIC COOLING ANALYSIS OF THE CORNELL INJECTOR CRYOMODULE

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Abstract

Managing parallel cryogenic flows has become a key challenge in designing efficient and smart cryo-modules for particle accelerators. In analyzing the heating dynamics of the Cornell high current injector module a power-full computational tool has been set-up allowing time resolved analysis and optimization. We will describe the computational methods and data sets we have used, report the results and compare them to measured data from the module being in good agreement. Mitigation strategies developed on basis of this model have helped pushing the operational limitations..

INTRODUCTION

In preparation for full ERL at Cornell [1], an injector cryomodule was designed and built to demonstrate high current generation and achieving low emittances. The construction of the Cornell injector was completed in the summer of 2007 when initial beam commissioning experiments revealed an issue with charging up of one set of ferrites in the higher-order mode (HOM) absorbers. After a rebuilt taking out the troublesome material, commissioning resumed leading to a world record performance in achieving 75 mA beam current [2]. However, the goal set for the ERL was 100 mA and in pushing for that we realized that heating of the 80 K thermal intercept of the power couplers is the limitation. As beam power ramps up, RF power transmitted by the coupler increases. Even though the couplers are designed for 60 kW we observe a significant heating which at the level of around 40-50 kW leads to temperatures around 140 K at an intercept which should be hold cold at 80 K.

Even though the heating itself is not an issue, the increase in vacuum pressure in the coupler leads to breakdowns- eventually limiting us in increasing the beam current. A careful analysis of the insufficient cooling of the 80 K intercept of the coupler revealed an adequate sizing of the heat exchanger but a deficient mass flow through the cooling channel, which happened to be a parallel flow to the cooling of the higher order mode absorbers. This cryogenic flow diagram is symbolized in fig.1.

Having parallel cooling flows is one of the key concepts to be used in designing highly cryogenically efficient accelerator modules, and we have investigated the stability of parallel flows under variations of operating parameters in the past [3]. In this paper, we describe the iterative numerical method we used to investigate and understand the transient heating issue and find a solutions which finally helped us to resolve the problem: We found that by adding a high impedance inlet pipe to each of the HOMs, we can reduce the flow rate of the whole system by 50%, while both improving the stability of the flow and reducing the operating equilibrium temperature of the couplers.

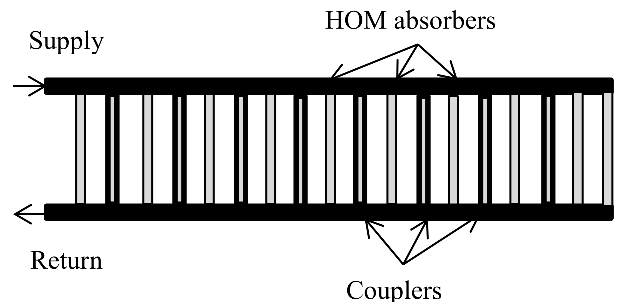

Figure 1: The 80 K cryogenic cooling piping: The thermal intercept of the ten coupler and the 12 channels to cool the higher order mode absorbers a fed in parallel.

METHOD

ICM Setup and Model Specifications

The focus of this paper is to outline the setup and results to a computational simulation intended to understand time dependent heating an their impact in diverting mas flows in parallel cooling channels. This paper focuses specifically on the HOM and coupler 80 K parallel flow channels of the injector cryo module (ICM) but our method is more general and can be applied to other scenarios, too.

In the ICM, the cooling helium is supplied at 80K. The fluid undergoes heat transfer as well as pressure drop as it flows across the couplers or the HOMs from the supply to the return pipe. Each of the HOM absorbers are represented in fig. 1 by thinly outlined channels, while the couplers are represented with thicker outlines. Because each coupler and HOM is geometrically identical, and as there is negligible head loss in the supply and return manifolds we can model this cryogenic system as a two pipe parallel system, shown in fig 2.

Accommodating this simplification, the total mass flow has to be calculated as $\dot{m}_{tot} = 10\, \dot{m}_{coupler} + 12\, \dot{m}_{HOM}$. To conduct the calculation, the following geometrical data describing the cooling piping was used: In the ICM,

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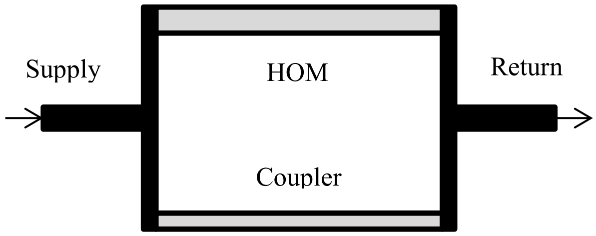

Figure 2: Simplified model used for calculations.

the coupler intercept channel is 84 cm long, with 48 cm being available for heat exchange. The pipe has an inner diameter of 3.9 mm. We found that applying the heating over the entire length of the pipe changed the results of the simulation by less than one part in a thousand compared with having only 48 cm of thermal contact. For simplicity of calculation, the rest of the simulations distributed the heat load uniformly along the length of the pipe.

The HOM cooling consists of four, 15.25 cm long channels with sharp bends connecting them. There is a total of 68.5 cm of pipe in the HOM. We modelled the HOM channel as a single 68.5 cm long straight pipe with a 5.9 mm inner diameter.

Computational Setup

In order to perform our calculations, we used the HEPAK [4] database as an add-on to an excel spreadsheet, as we have done before [3]. The simulation begins by representing a single pipe as a hundred smaller pipes connected in series. The input parameters for this pipe are set manually, including initial pressure, temperature and mass flow. HEPAK is used to calculate helium fluid properties. For each segment of the pipe, the simulation computes a pressure drop and the heat exchange between the helium and the pipe surface. The pressure drop is calculated according to the Darcy-Weisbach equation:

$$\Delta p = \frac{f\,L\,v^2 \rho}{2\,D}$$

Where L is the length of the pipe, v is the mean fluid velocity, ρ is the fluid density, D is the inner diameter of the pipe, and f is the Darcy friction factor, defined according to the Reynold's number. The Reynold's number characterizes the turbulence of the flow of cryogen, and is calculated like

$$Re = \frac{D\,v\,\rho}{\mu}$$

Where μ is the dynamic viscosity of the helium. In most of the circumstances we investigated in this paper, the Reynold's number was greater than 2×10^4 in which case the Darcy friction factor is found to be

$$f = 0.184\,Re^{-0.20}$$

The heat exchange is given by

$$\dot{Q} = h_c\,A_S\,(T_p - T_f),$$

where A_S is the contact surface area between the pipe and the fluid, T_p is the temperature of the pipe, T_f is the temperature of the fluid and h_c is the heat transfer coefficient, which is defined in terms of the Nusselt number like

$$h_c = \frac{k\,Nu}{D}.$$

The Parameter k is the thermal conductivity of the fluid, taken from HEPAK, and Nu is the Nusselt number:

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.4}$$

Here, Pr is the Prandtl number, as defined by

$$Pr = \frac{c_p \mu}{k}$$

Where c_p is the specific heat capacity of helium under constant pressure. We calculate these parameters for each segment of the pipe, then update the fluid properties according to change in pressure and the heat applied and perform the same calculation for the next cell. In this way we get a model for how the fluid behaves as it flows through this channel.

In order to accommodate a parallel flowing system, we have to equate the pressure drops. This is done by numerically optimizing the relative mass flow through the HOM and the coupler such that their final pressure is the same. We keep the total mass flow fixed, according to the operation mode of the ICMs cryogenic system. The last step of the algorithm sums the heat exchanged between the pipe and the fluid and adjust the pipe's temperature according to:

$$\Delta T_p = \left(\frac{P}{C_p} - \frac{\dot{Q}}{C_p}\right)\Delta t$$

Here, the pipe is modelled to be in thermal contact with a copper block of a certain mass. P is the heat load on the block, $\dot{Q}$ is the heat transfer rate between the pipe and the fluid, C_p is the heat capacity of the block and Δt is the time step. We approximate the pipe specific heat to be that of copper based on NIST data [5] with a mass of 0.2 kg. We then iterate by a time step and do the

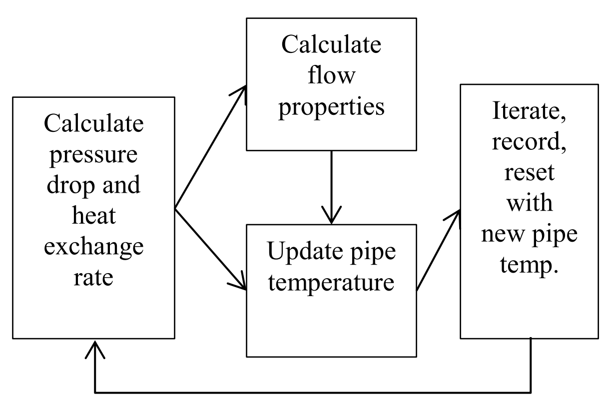

Figure 3: Calculation procedure

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calculation again. A Visual Basic macro within the Excel program was used to do so. We found that a time step of 2 min is a good balance between performance and accuracy. A simplified flow chart of the calculation process is shown on fig. 3.

In our simulations, the supply pressure and temperature of the helium are set to be at 80 K and 3 bar. Under normal operating conditions with a 9 g/s mass flow (considered a high flow regime in the ICM), we calculated a typical pressure drop of about 5 mbar.

RESULTS

Simulating Empirical Conditions

To validate our simulation's setup, we tested its predictions against experimental data from an ICM run. In that run, beam was accelerated for 4.8 hours and then turned off. Our simulation ran with a time step of 2 min, with a 50 W heat load on the couplers and 5 W heat load on the HOMs corresponding to the actually observed values. The flow rate chosen matched the high flow regime at 9 g/s. The experimental data is shown in fig. 4(a), results of our simulation in fig. 4(b).

The couplers rise to a temperature of ~140 K in 4.8 hours not reaching equilibrium, yet. Our simulation showed that 1.2 g/s went through the couplers, while the remaining 7.8 g/s is diverted through the HOMs by the end of the run.

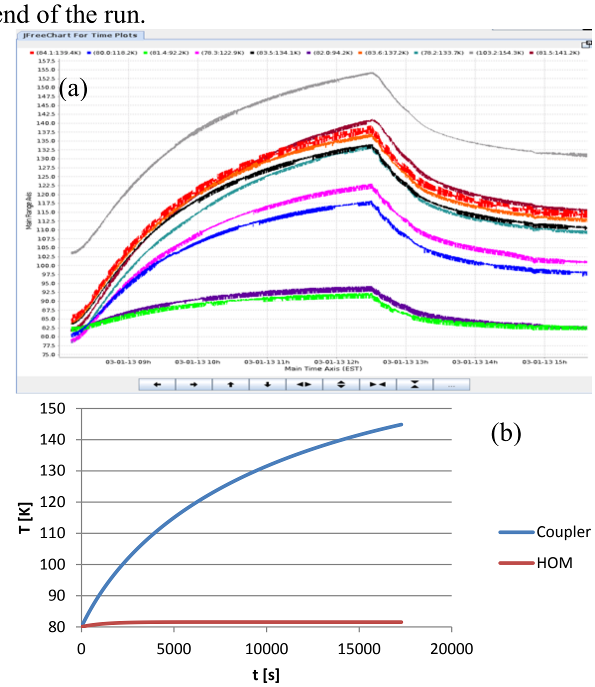

Figure 4: Measured heating of the ICM during a high current run (a) and the simulation results (b).

Amended System Calculation

As the couplers heat excessively when operating, even under the highest possible flow regime, we investigated mitigation strategies. To divert the flow of cryogen into the coupler instead of the HOM, we added a high impedance inlet pipe to the HOMs. The inlet pipe added is 50 cm long, with an inner diameter of 2 mm. The

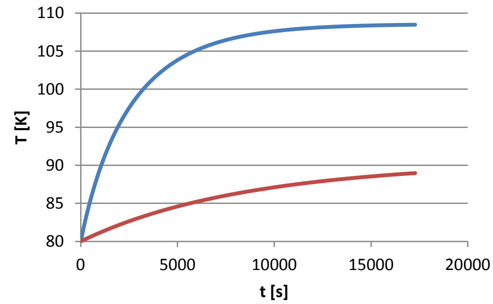

Figure 5: Simulated conditions with the proposed high impedance inlet pipe.

simulations used the same heating conditions, but the nominal mass flow of only 4.5 g/s, for which the system originally was designed. Adding the inlet pipe, the mass flow ratio improved dramatically. The simulation found 3.4 g/s going through the couplers, with the remaining 1.1 g/s diverted through the HOMs. The calculated temperature profiles are shown in fig. 5. The couplers keep substantially cooler, reaching a plateau by the end of the simulation below 110 K. Compared to the initial heating of up to 150 K, the modified cooling should allow high current running without coupler vacuum actions.

To understand the operation margin of the modified arrangement, we ran worst ever case scenarios: We increased the coupler heat load to 70 W which increased temperatures seen, but by raising the mass flow to 6 g/s temperatures could be brought down again below 110 K. Even with 120 W heating, temperature do not exceed 135 K which was found to be a tolerable temperature under beam running conditions.

CONCLUSION

We found that our simulation adequately models the operation of the cryogenic system of the Cornell Injector Cryomodule. Using this software, we calculated the operation of the cryogenic system with the proposed changes, and found that it improved its operation efficiency substantially. Plans are currently underway to add the proposed impedance pipe to the HOM channels which will allow us to accelerate beam above the current 75 mA limitation.

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