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 analysing the heating dynamics of the Cornell high current injector module a computational tool has been set-up allowing time resolved analysis and optimization. We 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 us in pushing the operational limitations.

1. Introduction
In preparation for Energy Recovery Linac (ERL) at Cornell University [1], an injector cryomodule was designed and built to demonstrate high current generation and achieving low emittances. The construction of the Cornell injector shown in figure 1 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. The fundamental power couplers are designed for 60 kW

![Figure 1. Rendered 3-D cad model of the Cornell Injector Cryomodule (ICM), housing five 2-cell cavities, each fed by two 60 kW power couplers. Between the cavities and on ether end higher order mode (HOM) absorbers are located. Each HOM absorber has two cooling channels. The total length is 5m.](image)

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RF power, but during operation we observe a significant heating at the 80 K thermal intercept. At levels of around 40-50 kW RF power temperatures at these intercepts were rising to around 140 K.

The heating itself is not a hazard to the coupler, however, excessive release of absorbed gases from the cold surfaces were observed resulting in the increase in vacuum pressure. As a result, higher rates of RF breakdowns occur, eventually limiting increasing the beam current. In an attempt to diagnose the behaviour, we found an adequate sizing of the thermal intercept itself with a sufficiently high heat transfer to the cooling helium gas. Consequently, the heating might also be explained with insufficient mass flow through the intercept, which happened to be a parallel flow with the second branch providing the cooling of the higher order mode absorbers. This cryogenic flow diagram for the 80 K cooling circuit is symbolized in figure 2.

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 when designing another cryo-module[3]. In this paper, we describe the iterative numerical method we used to investigate and understand the transient heating issue and find a solution 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 2. The 80 K cryogenic cooling piping: The thermal intercept of the ten coupler and the 12 channels to cool the higher order mode absorbers are fed in parallel.](image1)

![Figure 3. Simplified model used for calculations.](image2)

2. Method

2.1. 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 and their impact in diverting mass 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 fact, the script we have set up and the connection to the helium database [4] easily allows calculating the dynamics of parallel circuits with different geometries and at other temperatures.

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 is represented in figure 2 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 figure 3.
Accommodating this simplification, the total mass flow has to be calculated as 

\[ m_{\text{tot}} = 10 m_{\text{coupler}} + 12 m_{\text{HOM}} \].

To conduct the calculation, the following geometrical data describing the cooling piping was used: In the ICM, 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.

2.2. Computational set-up

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:

\[ \Delta p = \frac{fLv^2\rho}{2D} \]  

Where \( L \) is the length of the pipe, \( v \) is the mean fluid velocity, \( \rho \) is the fluid density, \( D \) is the inner diameter of the pipe, and \( f \) is the Darcy friction factor, defined according to the Reynolds number. The Reynolds number characterizes the turbulence of the flow of cryogen, and is calculated like

\[ \text{Re} = \frac{Dv\rho}{\mu} \]  

Where \( \mu \) is the dynamic viscosity of the helium. In most of the circumstances we investigated in this paper, the Reynolds number was greater than \( 2 \times 10^4 \) in which case the Darcy friction factor can be approximated for a smooth tube) by

\[ f = 0.184 \text{Re}^{-0.2} \].

The heat exchange is given by

\[ \dot{Q} = h_c A_\gamma (T_p - T_f) \]  

Where \( A_\gamma \) 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 convection heat transfer coefficient, which is defined in terms of the Nusselt number like

\[ h_c = \frac{kNu}{D} \]  

The parameter \( k \) is the thermal conductivity of the fluid, taken from HEPAK, and \( Nu \) is the Nusselt number, defined by the Dittus-Boelter correlation:
\[ Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \]  

(6)

Here, \( Pr \) is the Prandtl number, as defined by

\[ Pr = \frac{c_p \mu}{k} \]  

(7)

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:

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

(8)

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 \( \Delta t \) 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 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 given on figure 4.

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.

Figure 4. Visualization of calculation procedure as described in the text.
3. Results

3.1. 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 figure 5 on the left, results of our simulation in figure 5 on the right.

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. We also observed that the flow rate through the coupler decreased with time while the HOM flow increased, a commonly known phenomena.

One of the reasons for this extreme unbalance is that the heat load on the HOM absorber is significantly smaller than initially expected. Furthermore, it turned out that after an initial fluid dynamics estimation, the two components were designed independently and sizing of the pipes and intercepts were changed based on availability.

![Figure 5](image)

**Figure 5.** Measured heating of the ICM during a high current run (left) and the simulation results (right). Upper curve(s) are coupler temperatures, lower curve(s) are at the HOM Absorbers.

3.1. 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 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 figure 6. 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, temperatures do not exceed 135 K which was found to be a tolerable temperature under beam running conditions.
Figure 6. Simulated conditions with the proposed high impedance inlet pipe. Upper curve is the coupler, lower curve the HOM temperature.

4. 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.

5. References
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