TIME RESOLVED CRYOGENIC COOLING ANALYSIS OF THE CORNELL INJECTOR CRYOMODULE

R. Eichhorn#, A. Bartnik, B. Dunham, M. Ge, G. Hoffstaetter, H. Lee, M. Liepe, S. Markham, T. O'Connell, P. Quigley, D. Sabol, J. Sears, E. Smith, V. Veshcherevich
Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University
Ithaca, NY 14853-5001, USA

Abstract

To demonstrate key parameters of an energy recovery linac (ERL) at Cornell, an injector based on a photo gun and an SRF cryomodule was designed and built. The goal was to demonstrate high current generation while achieving low emittances. While the emittance goal has been reached, the current achieved so far is 75 mA. Even though this is a world record, it is still below the targeted 100 mA. While ramping up the current we observed excessive heating in the fundamental power coupler which we were able to track down to insufficient cooling of the 80 K intercepts. These intercepts are cooled by a stream of parallel cryogenic flows which we found to be unbalanced. In this paper we will review the finding, describe the analysis we did, modeling of the parallel flow and the modifications made to the module to overcome the heating.

INTRODUCTION

In preparation for full ERL at Cornel [1], an injector cryomodule (ICM) was designed and built to demonstrate high current generation and achieving low emittances. A 3-D rendered model of that injector is shown in Fig. 1, describing the features of the module.

The construction of the Cornell injector was completed in the summer of 2007 and commissioning started. In pushing for currents it was realized that some components in the Higher Order Mode (HOM) absorbers were charging up. As a result, the module was rebuilt for the first time, removing one type of absorbing ceramics. After that rebuilt, commissioning resumed leading to a world record performance in accelerating a 75 mA electron beam[2]. In pushing for high power operation, excessive heating was observed at the fundamental power couplers, two of which feed 60 kW of RF each to a single (2-cell) cavity.

At power levels of 40 kW and above, temperatures at the thermal intercept of the coupler, nominally at 80 K, reached 130 – 140 K. As a result, desorption of gasses in the coupler was observed, eventually leading to vacuum induced break-downs in the RF.

A careful analysis of the insufficient cooling of the 80 K intercept of the coupler revealed an adequate sizing of the heat exchanger: by increasing the overall mass flow we were able to lower the incept temperatures. As a conclusion we started investigating the mass-flow through the coupler channel, which happened to be a parallel flow to the cooling of the higher order mode absorbers. By adding a heat load to the HOM absorbers, holding the overall mass-flow constant, we were also able to lower the coupler temperatures. This indicated that a higher than required flow is passing through the HOM absorber, starving the higher temperature line through the coupler.

Having parallel cooling flows is one of the key concepts to be used in designing highly cryogenically efficient accelerator modules, and with the heat loads giving in the injector cryo-module cooling by conduction was not an option. However, as we experienced, keeping parallel flow well balanced is a demanding design issue and we have refined our methods doing this several times. Starting with a steady state analysis [3] we added capabilities to calculate the time defendant variations based on an iterative numerical method [4]. This 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 %,

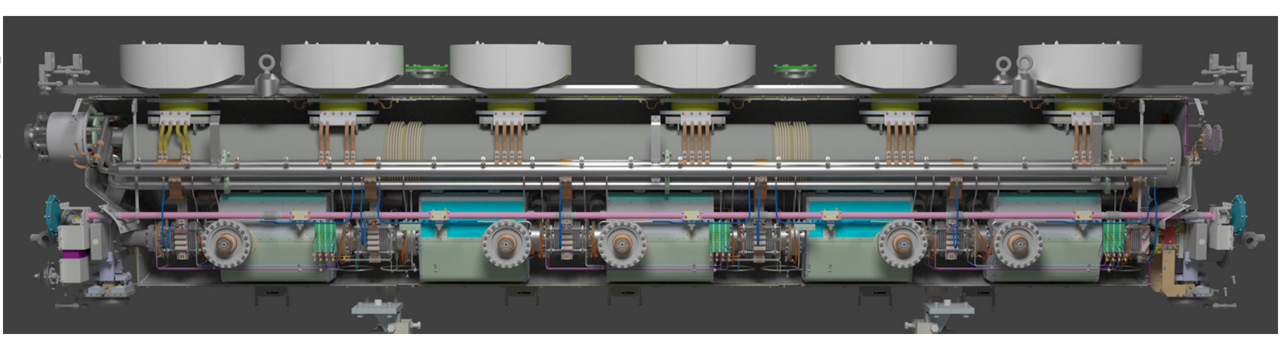

Figure 1. Rendered 3-D cad model of the Cornell Injector Cryomodule (ICM), housing five 2-cell cavities, each fed by two 60 kW power couplers. Between the cavities and on ether end higher order mode (HOM) absorbers are located. Each HOM absorber has two cooling channels. The total length is 5m.

#r.eichhorn@cornell.edu

while improving the stability of the flow and meanwhile reducing the operating equilibrium temperature of the couplers. In this paper we review the background and describe the modifications we made to the cryogenic piping of the injector cryo module.

FLOW CALCULATION OF THE 80 K COOLING CHANNELS

In the ICM, the thermal intercept cooling is provided by a stream of gaseous helium, entering the module at 80K. The flow 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 by thinly outlined channels, while the couplers are represented with thicker outlines. There are 6 HOM absorbers in that module, each having two independent cooling channels. In addition, there are 10 couplers with only one channel. 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 parameters of the piping are given in table 1. 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 we distributed the heat load uniformly along the entire length of the pipe.

The HOM cooling consists of four long channels with sharp bends connecting the for which we accommodated by a scaled length that we used in our calculation.

In order to perform our calculations, we used the HEPAK [5] database as an add-on to an excel spreadsheet, as we have done before [3]. Within the calculation we represent 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.

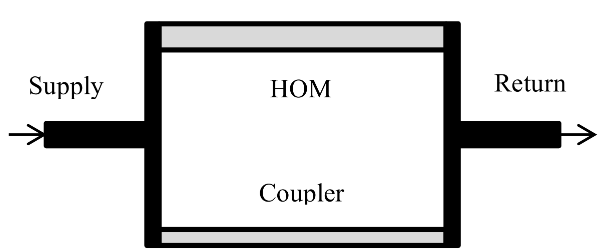

Figure 2: Simplified model used for calculations.

Table 1: Parameters of the Cryogenic Piping

Pipe	Inner Diameter	Length	Mass
HOM	5.94 mm	686 mm	0.2 kg
Coupler	3.88 mm	838 mm	0.2 kg
Inlet flow restrictor	2.0 mm	500 mm	N/A

We calculate all parameters for each segment of the pipe, 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 equated 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. Here, the pipe is modelled to be in thermal contact with a copper block of a certain mass, representing the coupler and the HOM absorber. A more detailed description of the procedure used including all formulae can be found in [6]. 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. Table 2 summarizes the assumptions about the scenarios we were investigating.

Table 2: Input Pressure is 3 bar, 80 K Inlet Temperature

Scenario	HOM heat load	Coupler heat load	Mass-flow
No inlet	5 W	50 W	9 g/s
Inlet, low heating	5 W	50 W	4.5 g/s
Inlet, high heating	5 W	120 W	6 g/s

RESULTS

To validate our simulation's setup, we tested its predictions against experimental data from an ICM run. We calculated that the couplers rise to a temperature of ~140 K in 4.8 hours not reaching equilibrium, yet which perfectly matches the experimental findings [4]. Our calculation also showed that only 1.2 g/s of helium went through the couplers, while the remaining 7.8 g/s is diverted through the HOMs by the end of the run. These mass flow rates could not be measured or controlled separately and revealed the reason for the heating in the couplers: too little flow made it through that cooling channel. This situation is show in Fig. 3.

ISBN 978-3-95450-147-2

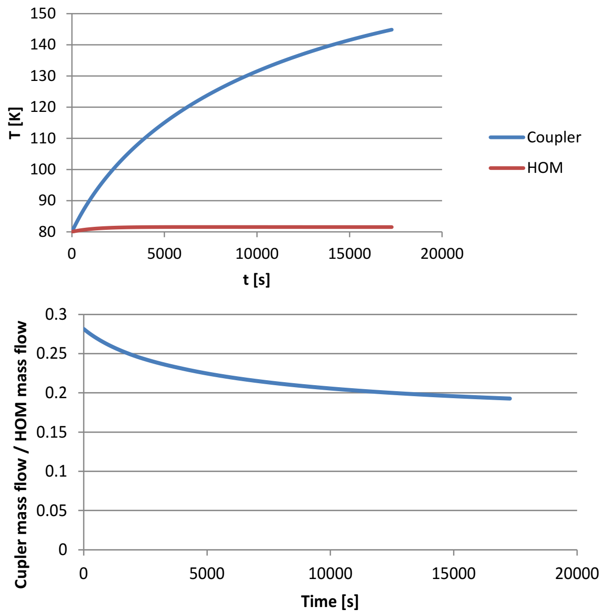

Figure 3: Calculated heating of the ICM (upper plot) during a high current run. This data matches the observed heating [4]. The lower plot shows the calculated mass-flow ratio indicating an imbalanced flow, getting worse with time.

To mitigate this flow deficiency, we added a high impedance inlet pipe to the HOMs in our calculation. The inlet pipe added was 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 Fig. 4. 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.

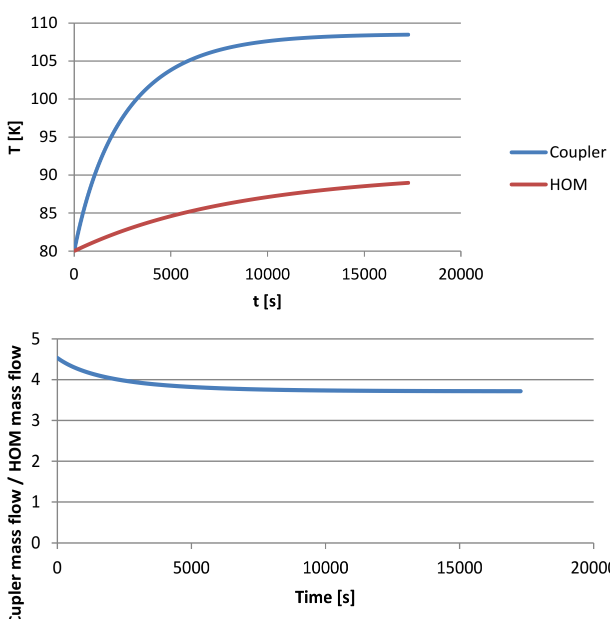

Figure 4: Predicted heating on the coupler and the HOM absorber after adding the flow restrictor (upper plot). It should be noted that the mass-flow through the system is smaller compared to the scenario described in Fig. 3. The mass- flow ratio is shown in the lower plot.

MODIFYING THE CRYOMODULE

In preparation for building an FFAG based ERL, the injector cryomodule had to be moved, giving us the chance to modify the piping as described. While the actual modification of the piping was only two days of work, disassembling and reassembling the module required 6 month of labor as we almost had to strip down the cold-mass. Figure 5 shows the location of the added flow restrictor.

Besides this, we experienced some practical issues: the piping is usually specified by its pressure rating and the outer diameter of the pipe. The ID in contrast is only specified within a 20 % band, which we calculated is enough to change results by a factor of two. Accordingly, we adjusted the length of the pipe to 87 cm, making up for the ID being between 2.3 and 2.4 mm. We also learned that the ID can fluctuate within one batch. Eventually we bubble tested all pipes to be assured the all have the same flow impedance.

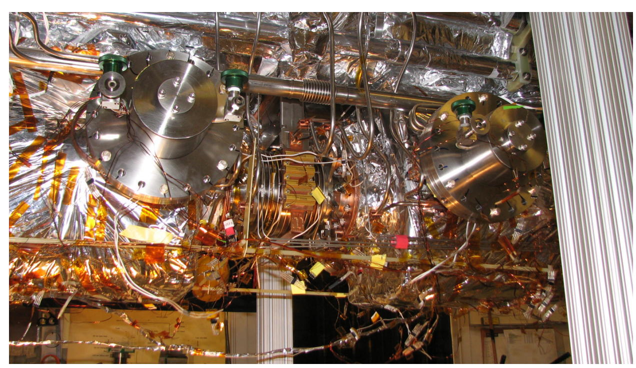

Figure 5: Photo taking of the ICM cooling piping to be modified.

CONCLUSION

We found that our simulation adequately models the operation of the cryogenic system of the Cornell injector cryo module. Using our software, we calculated the operation of the cryogenic system with the proposed changes, and found that it improved its operation efficiency substantially. Based on our findings, we rebuilt the module, adding the proposed impedance pipe to the HOM channels. By now, the module has been reassembled and installed in the accelerator fault. Cool-down is scheduled to happen within the next 4 weeks. We expect that after this modification, temperatures at the coupler thermal intercept will be much lower, preventing the coupler from RF breakdowns. We expect to be able to accelerate beam beyond the current 75 mA limitation.

REFERENCES

[1] M. Tigner et. al. “Cornell Energy Recovery Linac: Project Definition Design Report”, www.classe.cornell.edu/ERL/PDDR Our old paper

[2] B. Dunham et al., “Record high-average current from a high-brightness photoinjector,” App. Phys. Lett. 102 034105 (2013).

[3] R. Eichhorn, A. Holmes, S. Markham, D. Sabol, E. Smith, “Managing Parallel Cryogenic Flows to the Thermal Intercepts in the Cornell ERL”, Advances in Cryogenic Engineering 59B (2013) 1078.

[4] R. Eichhorn, S. Markham, E. Smith, P. Quigley, “Time Resolved Cryogenic Cooling Analysis of the Cornell Injector Cryomodule”, Proc. of the 2015 Intern. Part. Acc. Conf., Richmond, VA, USA (2015)

[5] HePak Version 3.40, Horizon Technologies, 7555 S. Webster St., Littleton, CO 0128, USA.

[6] R. Eichhorn, E. Smith, S. Markham, P. Quigley, “Time resolved cryogenic cooling analysis of the Cornell Injector Cryomodule”, IOP Conf. Series: Materials Science and Engineering 101 (2015) 012039.

ISBN 978-3-95450-147-2