Evaluating the Impact of Return Pressure Variation on C100 Cryomodule Performance

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Introduction

Performance of SRF cavities is dependent in part on the local surface resistance which is a function of the bulk niobium temperature. The surface temperature is maintained by convective heat transfer into the superfluid helium (SFHe) surrounding the cavity. The dissipated RF power is conducted through the SFHe to the liquid-vapor interface where helium gas evolves. The gas is pumped away through the cryomodule (CM) internal piping into the u-tubes and then into the return transfer line. The saturated pressure at the liquid vapor interface, determined by the local gas evolution rate and the piping sizes (internal piping, u-tubes, transfer lines, valves and plumbing, etc.) between the source and the pumping system, ultimately sets the local bath temperature and hence directly impacts the cavity performance. In the C100 CMs, there is pressure-dependent heat transfer limitation due to its particular internal piping configuration.

Comparison of C100 and Original CEBAF (OC) CM Helium Vessels

The internal piping in the original CEBAF CMs is different from the C100 CMs (Figure 1). For the original CEBAF CMs, a cavity pair is immersed in SFHe inside the 24” diameter helium vessel. Individual helium vessels and helium piping, as opposed to large HVs and minimal piping, were selected as part of the C100 design in order to eliminate seals between the cavity vacuum and the helium bath. This was an important design consideration since OC CMs suffered from some number of superfluid leaks. The helium enters the C100 HV through the fill line from the bottom directly below the center cell and exits through the riser directly above the center cell.

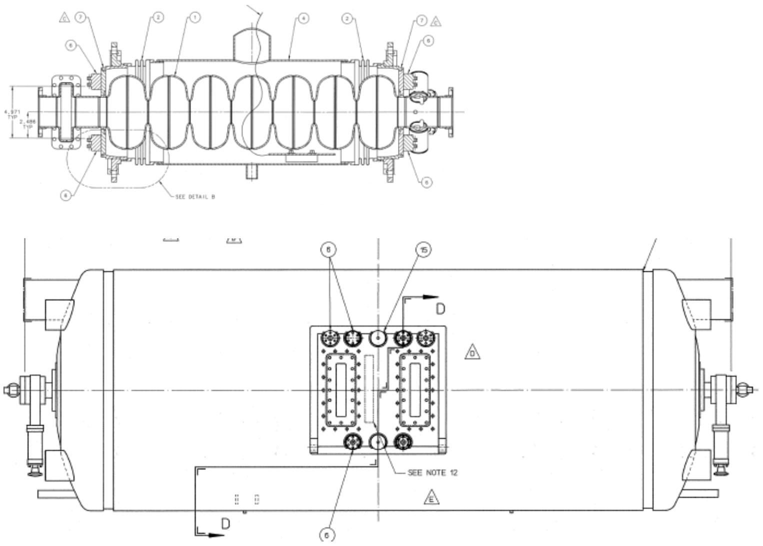

Figure 1: C100 Cavity with Helium Vessel in cross section (above) and Original CEBAF CM HVs with cavities not shown (below)

SFHe is an excellent conductor of heat up to a critical heat flux beyond which the properties change dramatically. Although not understood analytically, this interesting behavior has been observed in experiments in narrow channels and internal flow configurations. It was necessary when sizing the C100 internal piping to ensure that heat conduction in the SFHe did not exceed this critical heat flux [1]. This value is a function of local bath pressure and temperature. Observed below the lambda point, this heat flux is a relatively strong function of bath pressure and temperature.

The critical heat flux in saturated liquid at 2 K is two times larger than at 2.1 K (Figure 2). An internal pipe in the C100 CM, the helium vessel riser, is the limit for heat flow from a cavity to the return header. The diameter and length of this riser dictates the heat flow for a given bath pressure and temperature. Heat can flow through parallel paths in the helium bath. When testing individual cavities, the critical heat flow can be higher since there are at least seven other parallel heat flow paths via the fill lines and up through adjacent risers. In those cases, the fill line diameter and length determines the additional heat flow.

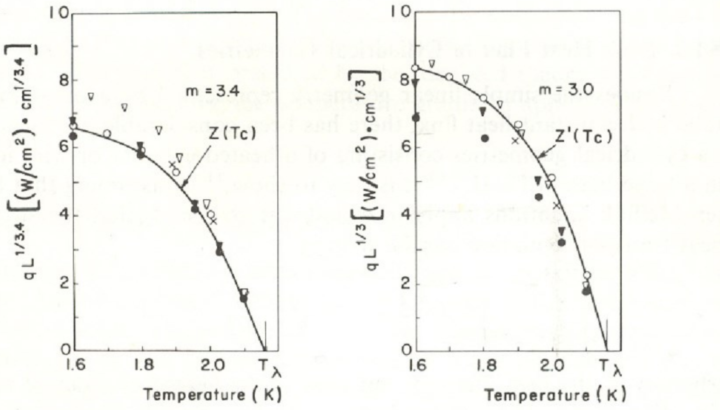

Fig. 5.4. Generalized steady-state limiting heat flux in He II (as compiled by Seyfert[60]).

Figure 2: Critical Limiting Heat Flux for SFHe

Specifications for Pressure and Temperature in Helium Bath

For the C100 cavities, the assumed Qo value is 8 x 10^9 at 19.2 MV/m which results in 27 W dissipated in each cavity. Adding in dynamic coupler heating, the total for each cavity is 30 W. The design value for power dissipation was doubled and the lines were sized to avoid any type of limitation in the heat flow due to the critical heat flux. The interface point for the CM pressure was defined as 0.0375 atm at the bottom of the return bayonet in the end can assuming a total design heat load of 300 W. This pressure corresponds to a temperature of 2.07 K. At these conditions the critical heat flow for a single riser is 65 W (Figure 3) or more than 500 W for the CM. As the bath pressure rises, the critical heat flow is reduced. If the bath pressure rises to 0.044 atm, or about 2.13 K, the critical heat flow is about 30 W. Neglecting increased surface resistance due to increase BCS losses, operating a C100 CM set at design gradient at this bath pressure would cause the critical heat flux to be exceeded in the riser. Operating cavities at higher bath pressure increases BCS losses which adversely impacts Qo values used by LEM for machine set-up. The actual dissipated power could be ~50% larger than computed by LEM.

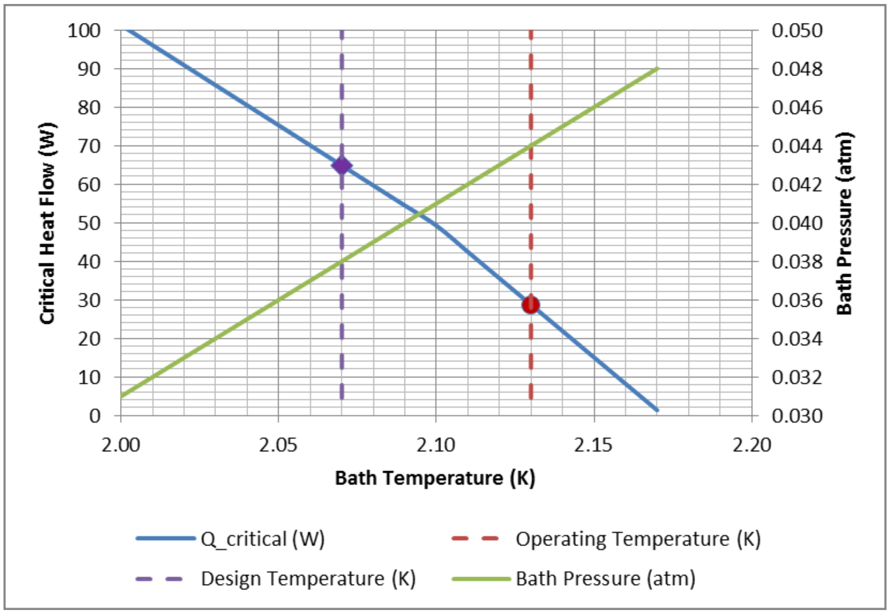

Figure 3: Critical Heat Flow in the C100 HV Riser as a Function of Pressure

When the critical heat flux is exceeded, SFHe transitions from liquid to gas. It should be noted that the lambda point has not been exceeded in the bath, but that a local phase transition is occurring where the heat flux exceeds the critical value. Curiously enough, the liquid level probe in the CM can sense this transition by showing some rapid variation in the read-out. It is possible that bubbles form in the riser, disturbing the free surface of the liquid causing waves to propagate. In any case, this feature can be used as an indicator to determine when the critical heat flux is exceeded in a riser. By calculating the critical heat flux, the local bath conditions can be inferred.

0L04 - Estimation of Pressure and Temperature in Helium Bath

A series of measurements were made on 0L04 using known heater power settings to determine when the transition was occurring by observing the change in liquid level (LL) readback, thereby estimating the local bath pressure [2 – 5]. No RF was applied during any of the measurements. At a measured pressure of 0.041 atm, a heater heat of 142 W was applied uniformly over the eight cavity heaters. The LL readback was stable. The heater heat was ramped until the LL readback began to fluctuate indicating a transition. The measured pressure was 0.0435 atm, and the heater heat was 240 W. Since there are eight cavities in this CM, the critical heat flow per riser is 1/8 of this total power, or 30 W per cavity. Using Figure 3, a value of 30 W corresponds to an inferred bath temperature and pressure of 2.13 K and 0.044 atm.

It should be noted that the bath pressure increases with mass flow rate and corresponding heat loads in the CM. The value of 2.07 K and 0.0375 atm specified corresponds to an expected total heat load of 300

W. The additional pressure drop due to mass flow is at maximum 0.003 atm. Even at 2.1 K in the bath, the critical heat flow is 50 W per cavity or 400 W per CM.

Using the cavity heaters and the LL as an indicator, the local bath pressure can be estimated.

An additional set of measurements was made to determine if resistive heat, RF heat or both causes any type of detuning instability that would affect RF performance.

First the heater heat was set to 200 W while monitoring the cavity detune angles (TCDETA). As the resistive heat was ramped down, the detune oscillations decreased. At a value of 50 W, the detune angles returned to expected amplitudes.

Then RF was turned on in the cavities while monitoring the liquid level and JT valve position. The cavity gradients were increased. At about 80 watts of dissipated power (87 MV), the detune instability began. This persisted and increased in magnitude with increasing gradients up to a heat load of about to 168 watts. The gradients were then ramped down and the detune oscillations abated.

It appears that regardless of the source, when heat in the module is increased the tuning becomes increasingly unstable. This is possibly due to bubbles created as the critical heat flow is exceeded in the risers. It is expected that at reduced pressures, this instability would be reduced or eliminated.

Proposal for Addition of Pressure Transducers

It was shown by measurements on 0L04 that the mass flow from each CM can affect local pressures and the overall pressure drop in the cryogenic distribution system. The absolute pressure is lowest at the inlet to the cold compressors and highest at the ends of the linacs.

The proposal is to place one sensor near the tee in each linac to monitor the exhaust pressure from each linac adjacent to the inlet to the CHL cold compressors. The change in pressure at this location will be related to the total mass flow coming from the linacs. In addition, the proposal includes placing sensors at the ends of each linac to monitor the highest absolute pressure. For the north linac, use the injector modules. All of the sensors would be placed on the CM end can nearest the desired location. Existing purge lines enable the installation of the sensors using VCR fittings.

The plan is to use calibrated sensors that can be verified on the benchtop to understand any systematic differences. For installations with a C100 CM, the heater and liquid level response can be used as a cross check against pressure readbacks. Over time, these six pressures can be monitored to ensure that operating limits for individual CMs are maintained.

References:

[1] Helium Cryogenics, Van Sciver
[2] https://logbooks.jlab.org/entry/3348758
[3] https://logbooks.jlab.org/entry/3348923

[4] https://logbooks.jlab.org/entry/3348423
[5] https://logbooks.jlab.org/entry/3351191