CRYOGENIC HEAT LOAD OF THE CORNELL ERL MAIN LINAC CRYOMODULE*

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INTRODUCTION

The proposed Cornell Energy Recovery Linac (ERL) will operate cw at 1.3 GHz, 2 ps bunch length, 100 mA average current in each of the accelerating and decelerating beams, normalized emittance of 0.3 mm-mrad, and energy ranging from 5 GeV down to 10 MeV, at which point the spent beam is directed to a dump [1]. The cw duty and low emittance drive the choice of using superconducting RF. The cryomodule for the ERL will be based on TTC technology, but must have several unique features dictated by the ERL beam parameters. The main deviations from TTC are that the HOM loads must be on the beamline for sufficient damping, that the peak and average power through the RF couplers is relatively low, and that cw beam operation introduces much higher SRF cavity heat loads.

The cryogenic plant will be a significant portion of the ERL cost and an accurate prediction of the heat load is crucial to facility planning. The main linac cryomodule is in the process of being designed, but the configuration of the components is sufficiently known to allow a preliminary calculation of the heat loads. A cut-away CAD model showing the main features of the ERL linac cryomodule is shown in Fig. 1. The present design incorporates six 7-cell SRF cavities, beamline HOM loads, one quadrupole, one set of X-Y steering coils, gate valves at each end, and is 9.82 m long.

Presented below are the results of thermal modeling using nonlinear material properties to provide an itemization of the cryomodule heat loads. The wall-plug power for the cryoplant will be estimated using COP's provided by major helium-refrigeration vendors. The optimal intermediate temperature will be shown to be about 100K.

MODULE LAYOUT

The thermal boundaries of the ERL linac cryomodule follow closely to that of standard TTC technology. To minimize the heat load to the refrigeration plant, all of the 1.8K components are surrounded by 5K intercepts, and the 5K intercepts likewise surrounded by "intermediate" intercepts in the vicinity of 100K, which in turn absorb the heat load from the 300K vacuum vessel. To explore the optimal intermediate temperature, all of the module components connected to this cooling loop were modeled over the range of 60K-160K for the intermediate temperature, which will be summarized in the last section.

In the following there will be dynamic heat loads and static heat loads. The static loads are those that exist without beam or RF, with all of the module components held at their design operational temperatures. The dynamic loads are the additions to the static load arising from the steady state beam and RF.

MATERIAL PROPERTIES AND REFRIGERATION COP

Material properties over the temperature range of 1.8K-300K were gathered from several sources [2-4]. The non-linear properties were entered in ANSYS material property files and used in most of the calculations.

The Coefficient of Performance (COP) for the cryoplant is the power required from the wall-plug to absorb power at a given low temperature. An approximation of the COP is typically given by

$$\mathrm{COP}(T) = {P(293\mathrm{K})}\big/{P(T)} = 1\big/{\eta_C(T)\cdot\eta_p}\ , \text{ where} \tag{1}$$

$$\eta_C(T) = T\big/{293\mathrm{K} - T} \tag{2}$$

is the Carnot efficiency, and η_p is a "practical" efficiency that is a catch-all term accounting for the mechanical non-idealities that come into play in a refrigeration system. After extensive discussions with several major helium-refrigeration vendors, the parameters listed in Table 1 were considered to be reasonable for a modern cryoplant.

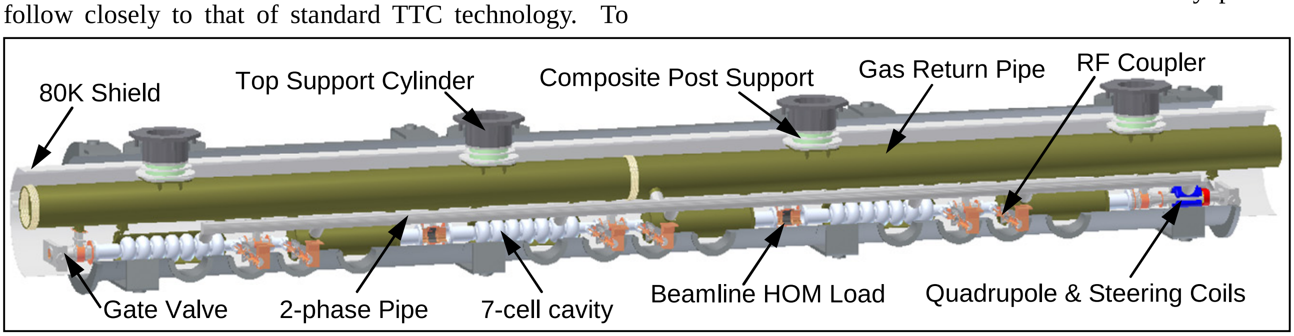

Figure 1: A cut-away CAD model showing the main features of the ERL Linac cryomodule.

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Table 1: Efficiencies and COP's of a modern cryoplant

Temperature [K]	η_C	η_p	COP
1.8	0.006	0.230	720.3
5	0.017	0.300	196.7
60	0.250	0.168	23.9
70	0.304	0.168	19.6
80	0.364	0.168	16.4
90	0.429	0.168	13.9
100	0.500	0.168	11.9
110	0.579	0.168	10.3
120	0.667	0.168	8.9
130	0.765	0.168	7.8
140	0.875	0.168	6.8
150	1	0.168	6.0
160	1	0.168	6.0

SRF CAVITY

The largest heat load in the module is the dynamic RF loss of the superconducting cavities to their helium baths when the cavities are powered to their operating gradient. The present SRF cavity design has R/Q_0=804 Ω, $Q_0=2\times10^{10}$, shunt impedance $R=1.61\times10^{13}$ Ω, operating gradient E=16.2 MV/m, and active length of 0.8 m. This gives a voltage gain of V=13 MV per cavity. The power dissipation to the 1.8K helium bath per cavity is then

$$P = V^2/R = 10.4 \text{ [W]} . \tag{3}$$

Using the COP(1.8K)=720.3 per Table 1, the wall-plug power is 7.3 kW per cavity. A single-turn Cornell ERL linac will have 64 modules with 6 cavities each, giving a total of 384 cavities The dynamic wall-plug power is then 2.8 MW for the linac cavities, which will be about half of the total cryoplant load. Of course, if the average cavity Q performance were to be less, the wall-plug power will increase proportionally and could easily deplete the typical 50% over-capacity built into the cryoplant. Thus, achieving the target SRF cavity gradient and Q in the installed modules is of great importance.

HOM LOADS

The higher order modes (HOMs) spawned in the SRF cavities by the 2 ps long ERL beam have been estimated to generate about 200 W per cavity, distributed over a broad band of frequencies. The Cornell ERL design utilizes beamline HOM loads with RF absorbers cooled to the module's intermediate temperature. There will be an HOM load between each of the 6 cavities in a module and outboard of the end cavities, for a total of 7 HOM loads per module.

HOM Absorber Dynamic Power

Conservatively assuming that all 7 loads in a module absorb 200 W each at the intermediate temperature T, the dynamic HOM wall-plug power for the full linac is then $P_{dynamic} = 7\cdot 64\cdot 200\text{W}\cdot \text{COP}(T) = 1.07\text{ MW}$ for T=100K.

Static Load to the GRP

The HOM loads are suspended from the 1.8K Gas Return Pipe (GRP) by a support post with their beamline flanges attached to a cavity. The central portion of the HOM body is maintained at the intermediate temperature. There is a static heat leak between the GRP and the HOM load body. In the initial linac module design (as well as the ERL Injector module [5]), the support post was made of thin-walled stainless steel with a 5K copper shim placed between the steel support and the titanium GRP. The ANSYS model of this configuration is shown in Fig. 2. A plot of the full linac wall-plug refrigeration power for the summed dynamic HOM absorbers and static GRP supports is shown in Fig. 3. It is seen that for this component, a higher intermediate temperature reduces the dynamic load, but increases the static load.

The static load for the HOM support can be reduced by replacing the stainless steel with a support comprised of 1/16″ thick G-10 plates bolted to stainless steel plates, as shown in Fig. 4. This modification has no 5K intercept, yet reduces the net static load by about ½. Such a support has been prototyped and tested for stress-strain and maintaining its alignment precision down to 77K, for all of which it performed well.

Cavity-HOM Load Beamline

The beamline between the cavity helium vessel and the HOM load absorber contains a 5K intercept on the HOM load flange. There is then a static heat load to 1.8K from the 5K intercept, and to 5K from the intermediate temperature of the HOM absorber. There is also a dynamic load from the wall loss of the 200 W HOM RF power propagating along the beamline. The RF loss in the RRR=400 niobium held between 1.8K and 5K is negligible. The HOM load has a stainless steel shell with an optional 10μm thick RRR=30 copper plating on the interior. The copper plating reduces RF loss, but increases the static loss. For the RF loss, it is assumed that the HOM power is propagating in the TE_{11} mode at 1.6 GHz in a 110 mm diameter beam tube that is 105 mm long. For bare stainless, this gives a wall loss of about 3 W. For the case with copper plating, the wall loss is about 0.3 W. This is a conservative estimate for both cases since the actual HOM frequencies will be a distribution mostly above 1.6 GHz, further from the TE_{11} cutoff of 1.597 GHz and have less wall loss.

The axisymmetric beamline configuration between the cavity helium vessel and the HOM load absorber was modeled in ANSYS in 2D, as shown in Fig. 5. This model does not include the cavity RF coupler port, which will be discussed in a later section. The 2D treatment allows a small mesh on the HOM load interior to accurately model the 10 μm thick copper plating. Shown in Fig. 6 is the wall-plug refrigeration power consumed by this portion of the beamline for the full linac. Here, it is assumed that the module quadrupole is equivalent to an SRF cavity, giving $7\cdot 2\cdot 64 = 896$ such beamline transitions for the linac.

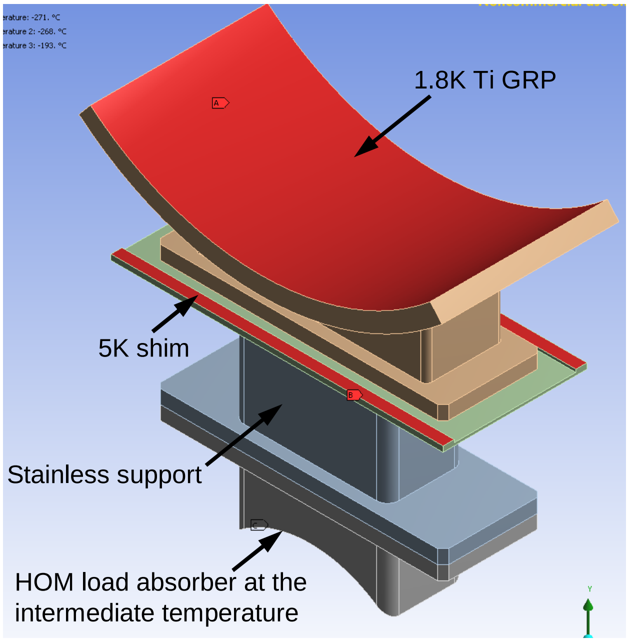

Figure 2: ANSYS model of the thermo-mechanical connection between the HOM body and the GRP.

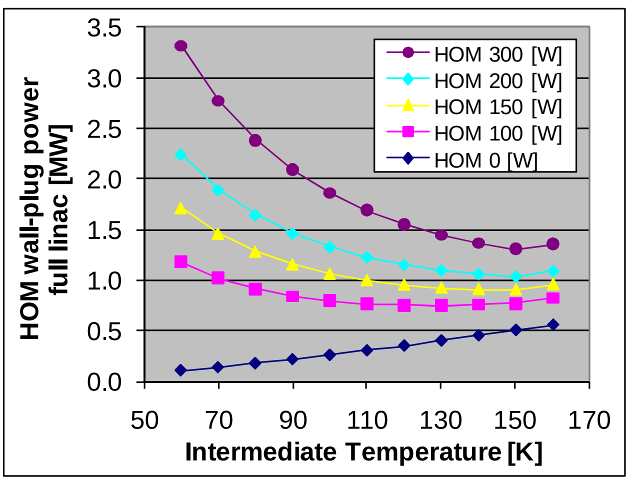

Figure 3: Linac wall-plug refrigeration power for the summed dynamic HOM absorber and static GRP support.

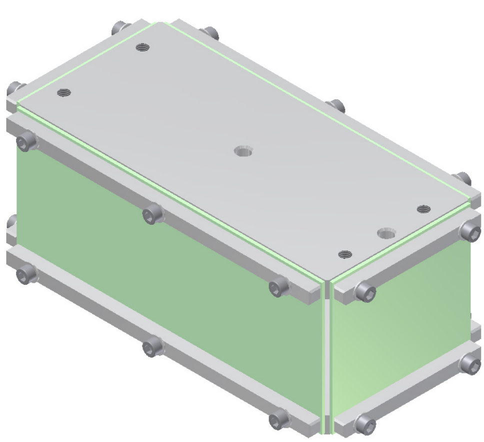

Figure 4: An alternate HOM support post comprised of 1/16″ thick G-10 plates bolted to stainless steel plates.

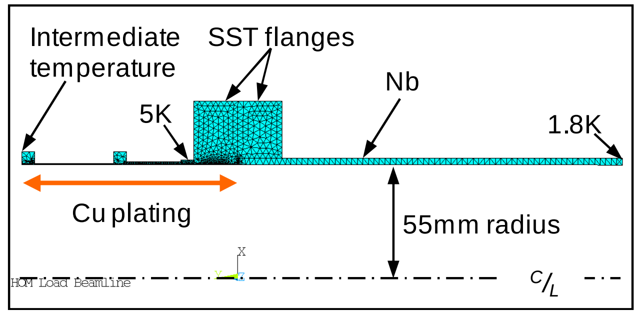

Figure 5: ANSYS 2D model of the axisymmetric beamline configuration between the cavity helium vessel and the HOM load absorber.

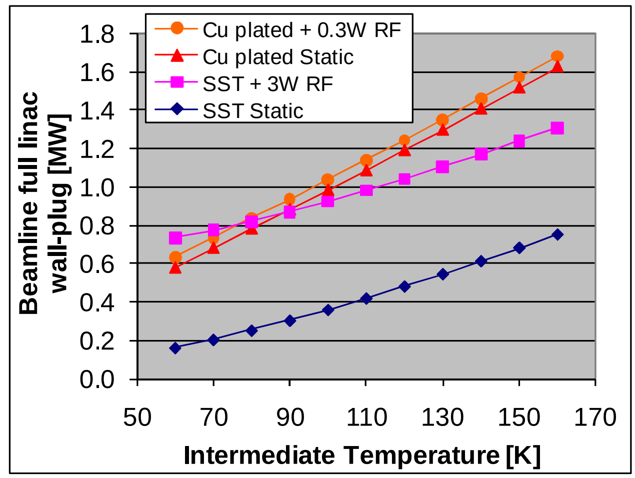

Figure 6: Wall-plug refrigeration power for the beamline between the cavity helium vessel and the HOM load absorber for the full linac.

Note in Fig. 6 that the static loss for the cases with copper plating generally exceeds the summed static and dynamic loss for the case with bare stainless steel. Though more RF power is dissipated in the case without Cu plating, the nonlinear thermal conductivity of stainless steel directs most of this dynamic heat to the intermediate sink rather than the 5K sink. The temperature profile along the beamline without plating shows no excessive heating due to the 3 W RF loss, even in the bellows section with 0.2 mm thick wall. Thus, the HOM load could be simplified by omitting most of the copper plating, although it may be best to plate the thin-walled bellows in the event that a high-frequency RF mode is trapped there and could overheat the bellows.

COMPOSITE SUPPORT POST AND THERMAL RADIATION

In TTC technology, the cold mass inside the vacuum vessel hangs from support posts comprised of a G-10 tube with press-fit disks and rings connected sequentially to 1.8K, 5K, the intermediate temperature, and finally to 300K. The radiation shield that is connected to the intermediate temperature is also supported by this composite post. For radiation from 300K to 80K, it has been shown that 30 layers of multi-layer insulation (MLI) on the shield will reduce the radiation load to about 1 W/m^2, or an (effective) emissivity of ε=2.23×10^{-3}. The present linac module design has four composite posts. A 1/8th symmetry ANSYS model of the post and shield is shown in Fig. 7. The contribution of these components to the cryoplant power is about 142 kW for an intermediate temperature of 100K and varies modestly with intermediate temperature, as will be seen in the summary plots in the final section of this paper.

To address the cost vs. benefit of including a 5K shield as is used in standard TTC technology, the radiation loads from the intermediate shield to either a 5K shield or directly to the 1.8K portions of the cold mass were estimated. For radiation from 80K to 1.8K, it has been shown that 10 layers of MLI placed on the 1.8K components will reduce the radiation load to about 0.05 W/m^2, or an emissivity of ε=2.14×10^{-2}. Shown in Fig. 8 is a model representing 1/7th of the linac module components nominally at 1.8K. The wall-plug power for the 80K radiation load to these components for the full 64-module linac is about 52.4 kW, whereas a 5K shield would consume about 8.3 kW, saving 44.1 kW. Estimating the added hardware and labor cost of a 5K shield to be about $30k per module, and using a projected electricity cost of $0.2/kWhr with 100% machine up time, the payback time for installing a 5K shield would be about 25 years. This payback time scale does not justify the added complexity of a 5K shield, especially considering that the shield would have to be segmented to conform around the beamline HOM loads residing at the intermediate temperature.

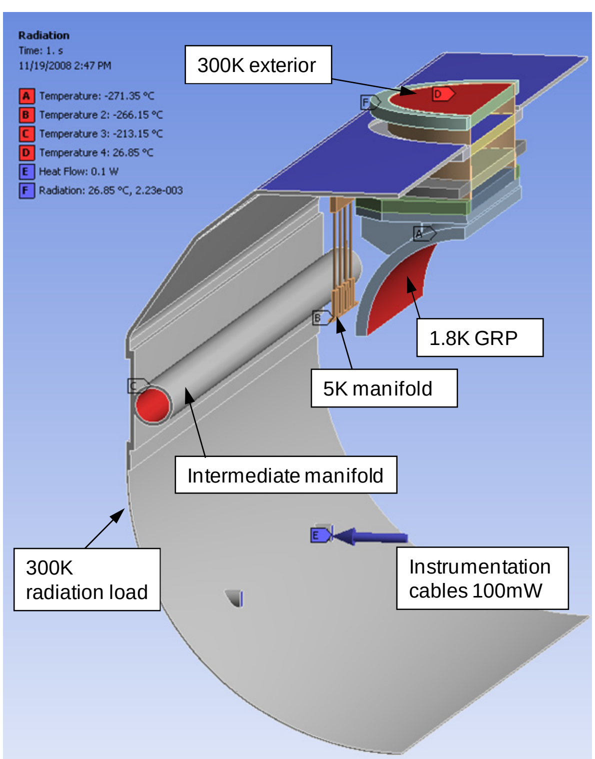

Figure 7: ANSYS model of 1/8th of the ERL linac module intermediate shield and composite support post.

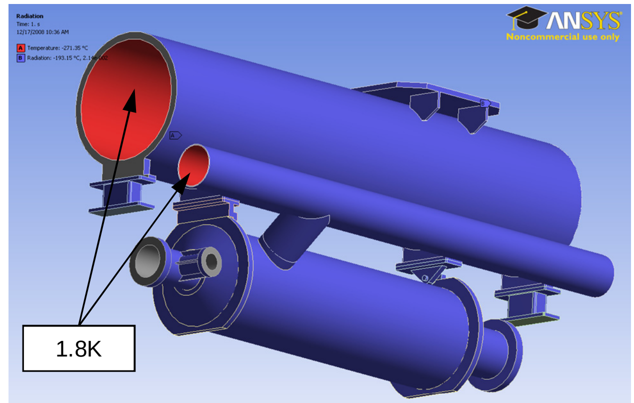

Figure 8: ANSYS model of 1/7th of the ERL linac module components nominally at 1.8K.

RF COUPLER

The RF coupler to the cavity is a coaxial antenna with the center conductor made of solid copper and the outer conductor made of copper-plated stainless steel, except for a small portion of the outer conductor being a Nb port on the cavity beampipe, as shown in Fig. 9. There are thermal intercepts on the outer conductor at 5K and at the intermediate temperature. At this time, the static and dynamic heat loads of the coupler have been estimated analytically, as opposed to numerical simulation. The contribution of the RF coupler to the cryogenic heat load is included in the total linac heat load that is presented in the final section of this paper.

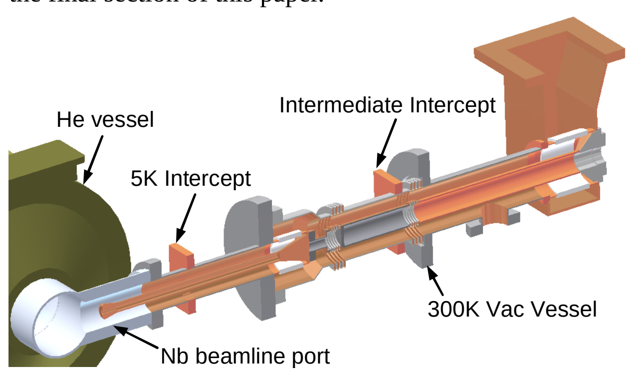

Figure 9: CAD model section view of the RF coupler attached to the SRF cavity.

SUMMARY

Analyses of the cryogenic heat loads for most of the components of an evolving ERL linac cryomodule design [6] have been presented. One cryomodule component that has not been analyzed is the quadrupole, for which is its assumed here to have the same heat loads as an SRF cavity. Shown in Fig. 10 is a bar graph summarizing the results of the thermal models, plotting refrigeration wall-plug power for a 64-module ERL linac as the intermediate temperature is varied from 60K to 160K. It is seen that an intermediate temperature of 100K is the fairly broad minimum of net wall-plug cryoplant power of 5.7 MW.

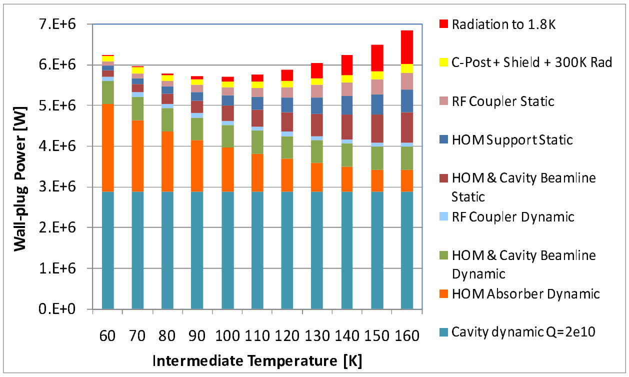

Figure 10: Wall-plug refrigeration power for a 64-module ERL linac as a function of the intermediate intercept temperature.

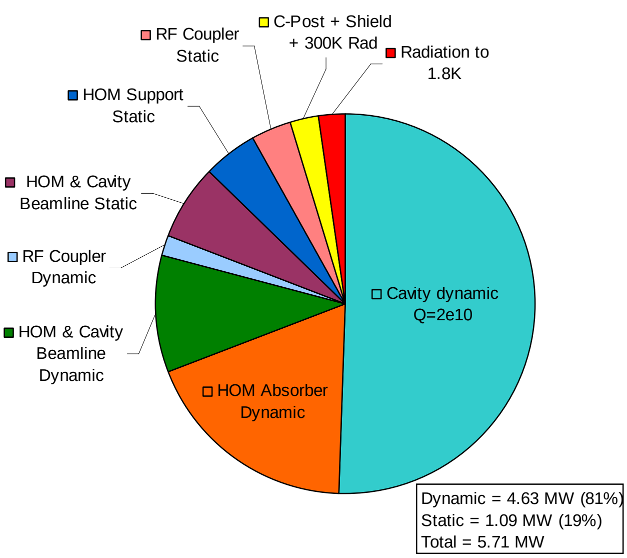

Figure 11: Distribution of wall-plug power loads for 64 cryomodules with a 100K intermediate temperature and cavity Q_0=2×10^{10}.

Table 2. Summary heat loads per module and full linac.

Per module		Wall Plug
1.8K Static [W]	5.68	4091
1.8K Dynamic [W]	68.99	49692
1.8K Total [W]	74.67	53782
5K Static [W]	64.27	12640
5K Dynamic [W]	25.65	5045
5K Total [W]	89.92	17685
100K Static [W]	32.58	389
100K Dynamic [W]	1455.49	17369
100K Total [W]	1488.07	17757
Module wall plug [W]		89225
# modules	64	
Linac Total [W]		5.71E+6
Safety Factor	1.5	
Linac Total · Safety Factor [W]		8.57E+6

A pie chart of the distribution of wall-plug power loads for the 100K intermediate temperature case is shown in Fig. 11. The SRF cavity dynamic load is about 50% of the total load, with the dynamic HOM load being next largest. The cw operation of the ERL linac obviously makes the dynamic heat loads the largest contributors. Note in Fig. 11 that the beamline HOM loads at 100K contribute the most to the static heat load.

If the average cavity Q performance were to be halved to Q_0=1×10^{10}, then the cryoplant power would increase to 8.6 MW with the SRF cavity being about 67% of the total load. Such an increase in wall-plug power could in itself consume all of the 50% overhead capacity typically incorporated into refrigeration plants for unforeseen load contingencies.

As figures of merit, the heat loads per cryomodule at the various temperatures are listed in Table 2, along with the wall-plug conversions using the COP's per Table 1, the wall-plug total for the full linac, and the cryoplant capacity using a safety factor of 50%. These values are consistent with other TTC cryomodules, where the main differences are a higher 1.8K static load due to the beamline HOM loads and a much higher dynamic load due to cw operation.

The design of the ERL linac cryomodule will continue, with more accurate analysis of the heat loads of components such as the quadrupole, RF coupler, and pneumatic gate valves. Also to be quantified are the parameters of the various helium supply and return cooling circuits, such as the pressure differentials, mass flow, heat transfer, gas temperature rise, and so on.

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