DESIGN OF AN ERL LINAC CRYOMODULE*

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INTRODUCTION

The Cornell Energy Recovery Linac (ERL) will nominally operate cw at 1.3 GHz, 2 ps bunch length, 100 mA average current in each of the accelerating and decelerating beams, normalized emittances 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 TTF technology, but must have several unique features dictated by the ERL beam parameters. The main deviations from TTF are that the HOM loads must be on the beamline for sufficient damping, that the average power through the RF couplers is relatively low, and that cw beam operation introduces higher cryogenic heat loads. Several of these challenges were addressed for the Cornell ERL Injector, from which valuable fabrication and operational insight is being gained [2,3].

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. Details of a few aspects of the design at this early stage of development are presented below.

MECHANICAL SUPPORTS

A unique feature used in the Cornell ERL Injector cryomodule that proved very useful was to have accurately machined mating surfaces between all mechanical links from the beamline up to the support cylinders at the top ports of the vacuum vessel. Simple bolting together of components then yields an “automatic” alignment accuracy of ±0.2 mm with no adjustments required. This accuracy is more than sufficient for the ±1.0 mm alignment tolerance of SRF cavities. The added cost of precise machining of the cold mass components will be small given a machining sequence with precise finish cuts only at the final step. This is true even for large components such as the Gas Return Pipe (GRP) and the Vacuum Vessel (VV), where numerous shops are tooled for such jobs at high accuracy and low cost [4].

Given this cold mass “bolt up” alignment scheme, the sag of the GRP and VV under load must be taken into account for final beamline alignment. In standard TTF technology, there are 3 supports linking the GRP and the VV. The suspended cold mass for the ERL Linac is estimated to be 4000 kg. ANSYS modeling shows that portions of a 3-support GRP would sag about 0.2 mm and the VV about 0.7 mm after optimizing top port and bottom footer locations. This would consume nearly all of the ±1.0 mm beamline tolerance with no further margin for error. Adding reasonable stiffening ribs to the GRP and VV gives little improvement. Thus the design was changed to have 4 supports linking the GRP and the VV and the GRP wall thickness increased from 9.53 mm to 17.45 mm. The small reduction in He gas pumping area due to increasing the wall thickness still leaves ample margin for typical ERL heat loads. Having 4 supports also allows the GRP to be split into 2 sections with a bellows in between, thus reducing the net thermal contraction along its length as the GRP can be fixed at 2 locations per module. The results of the ANSYS model are shown in Figs. 2 and 3 where the GRP now sags 0.077 mm and the VV 0.194 mm, thus consuming only about 25% of the ±1.0 mm beamline alignment tolerance.

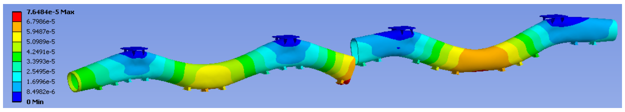

Figure 2: ANSYS model showing a maximum 77 μm deflection of the GRP when fixed at the top plates and the 4000 kg cold mass evenly distributed among 21 bottom supports.

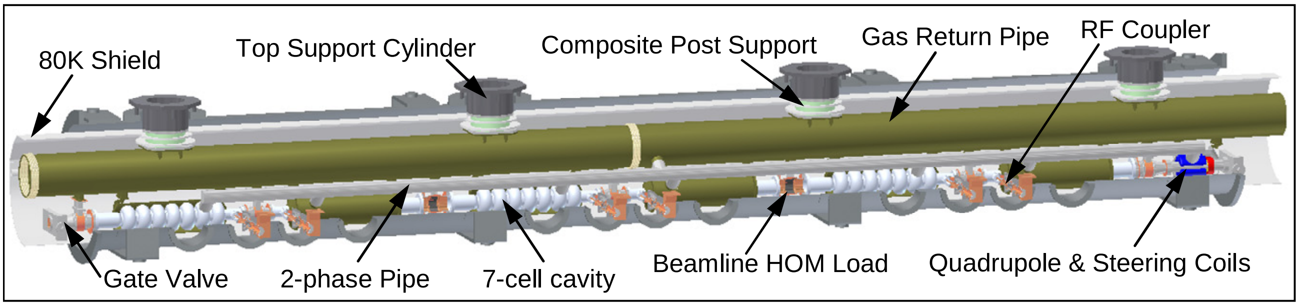

Figure 1: A cut-away CAD model showing the main features of the ERL Linac cryomodule.

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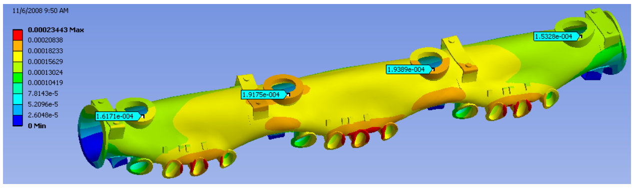

Figure 3: ANSYS model showing a maximum 194 μm deflection of the Vacuum Vessel when loaded by the GRP at the top ports and supported by 4 bottom footers.

CRYOGENIC HEAT LOADS

The thermal boundaries of the ERL Linac cryomodule follow closely to that of standard TTF layout. 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 80K, which in turn absorb the heat load from the 300K Vacuum Vessel. One difference from the TTF layout is the ERL's need for high bandwidth beamline HOM loads. This necessitates a significant temperature gradient along the beamline between cavities since the 200 W HOM RF power should be dissipated at as high a temperature as possible.

Intermediate Temperature and Cryoplant Load

For the ERL Injector, the choice of 80K as the intermediate temperature was a matter of convenience for the heat exchangers that used LN_2. To explore the optimal intermediate temperature, as well as document the heat loads of the full module, all of the module components were modeled in ANSYS using nonlinear material properties. The various static and dynamic heat loads include: conduction along the composite support posts, radiation from 300K to the intermediate shield, radiation from the intermediate shield to 1.8K, HOM load conduction along the beamline and through supports to the GRP, RF coupler conduction and power loss, and cavity RF and conduction loss. At present, the quadrupole is assumed to have the same heat load as an SRF cavity.

Shown in Fig. 4 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 120K. The calculations assume a refrigeration COP as the inverse product of the Carnot efficiency and a practical efficiency. The practical efficiencies are taken as 0.23 for 1.8K and as 0.3 for 5K and the intermediate temperature. The SRF cavity is taken to have $Q=2\times10^{10}$, $R/Q=804\ \Omega$, and an accelerating voltage of 13 MV per cavity, giving a dissipation of 10.5 W per cavity at 1.8K. It is seen from Fig. 4 that 80K turns to be the broad optimal intermediate temperature to minimize the summed static and dynamic wall-plug power to about 5 MW. The refrigeration plant would typically incorporate an additional 50% overhead capacity for unforeseen contingencies. The largest cryogenic loads are the dynamic cavity and HOM load dissipations. As figures of merit, this accounting has static loads per module of 3.4 W at 1.8K, 43 W at 5K, and 37 W at 80K.

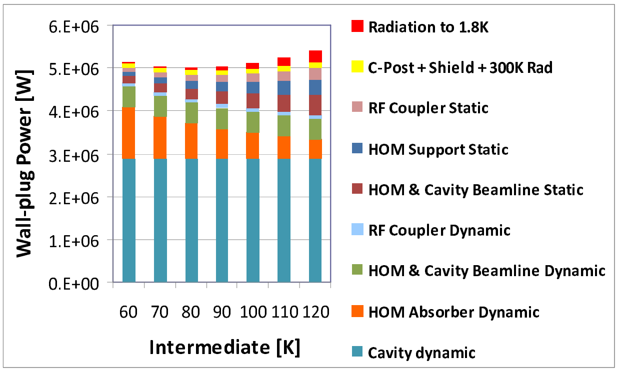

Figure 4: ANSYS modeled wall-plug refrigeration power for a 64-module ERL linac as a function of the intermediate intercept temperature.

Beampipe Plating

An aspect of the heat load explored in this heat load study was the beampipe plating in the HOM load. For the ERL Injector, these stainless steel components received a 10 μm thick copper plating with RRR~30 to reduce RF loss while keeping the static heat conduction low. To quantify this plating optimization, the stainless beampipe was modeled as having a 110 mm inner diameter, 105 mm long, 1.5 mm thick wall, propagating 200 W of HOM power in the TE_{11} mode at 1.6 GHz, and thermal boundaries of 80K at the HOM RF absorber and 5K at the load-cavity interface flange. The SRF cavity's Nb RRR=40 beampipe was then attached with 3 mm thick wall and 186 mm length to the 1.8K helium vessel. This scenario gives an RF wall dissipation of about 3 W in bare stainless steel and 0.3 W with Cu plating present. The 2D ANSYS model then gives a wall-plug refrigeration power for the bare stainless case of 271 W with no RF and 817 W with HOM RF. The wall-plug power for the Cu plated case is 792 W with no RF and 842 W with RF. Thus, having the stainless beampipe unplated requires less net refrigeration power for both the static case without beam and the dynamic case with beam. Though more RF power is dissipated in the case without Cu plating, the nonlinear thermal conductivity of stainless between 80K and 5K directs most of the heat to the 80K sink rather than the 5K sink. Leaving the stainless beampipe unplated also simplifies HOM load fabrication. The additional effects of beam image wall currents should be taken into account, but in the above analysis having all of the HOM power in the TE_{11} mode at 1.6 GHz over-estimates RF wall loss, and there will be some percentage of weekly machine down time, both of which increases the benefit of leaving the beampipe as bare stainless steel.

80K and 5K Shields

Another aspect of insight from the thermal modeling concerns the use of tough-pitch copper straps (RRR~50) as heat sinks. For the ERL Injector, such straps were used to link the grade 1100 aluminum 80K shield to a stainless 80K manifold running the length of the module. As shown in Fig. 5, the ANSYS model predicts a 17K

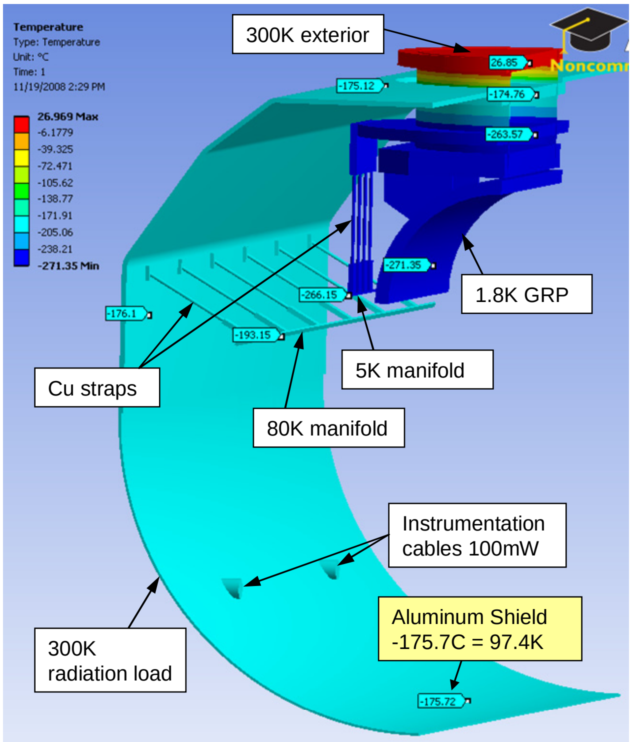

Figure 5: ANSYS model of the ERL Injector shield using copper straps between the shield and the 80K manifold.

temperature rise along the straps, which are conducting heat mainly due to the 13 W radiation load from 300K onto the shield. There is a further temperature rise due to contact impedance between the aluminum shield and a silver-plated copper ferrule soldered to the end of the strap. These contributions explain measurements that show that the Injector shield resides at about 110K. Further modeling shows that replacing the copper straps with an aluminum manifold integral to the aluminum shield, as used in TTF technology and shown in Fig. 1, reduces the temperature rise to less than 1K. Thus, such a configuration will be used in the ERL Linac modules and any future versions of the Injector.

The case of having a second radiation shield at 5K was also modeled, and shown to save only 690 W operational wall-plug power per module. Given estimates of electricity cost as compared to materials and labor to include a 5K shield, the payback time is about 10 years, which does not justify the added complexity of having a 5K shield interleaved between 80K HOM loads.

OTHER MODULE COMPONENTS

Numerous components of the ERL Linac cryomodule are at the beginning of their development process, such as the SRF cavity [5]. Another component is the beamline HOM load. The design implemented in the Cornell Injector consisted of 3 different types of RF absorbing tiles soldered to substrates and bolted into a housing. This design could be made to perform acceptably given corrections to the fabrication process and a slightly different selection of materials. But it would also be attractive to reduce the cost and complexity associated with the numerous unique materials, plating, brazing, and welding operations. A simplified HOM load will be the subject of development efforts, central to which will be an RF absorbing material configured as a unitary cylinder as shown in Fig. 1. Further, this material must have an adequate RF absorption bandwidth from 1 GHz to 100 GHz. Such a material has yet to be identified.

Another important component to develop is the RF input power coupler. Given the expected average power of only 2 kW per coupler, a simplification of the Injector coupler design should be straightforward. The new design will also incorporate more mechanical flexure of the inner and outer conductors to accommodate coarser alignment tolerance and greater CTE contraction differences between the beamline and the VV coupler port. If ongoing tests of cavity microphonic control give high confidence that the average power will indeed be 2 kW or less, an aggressive coupler design could follow in which the warm window is replaced by a simple Amphenol 7/16 coax connector. Semi-rigid coax could then be routed from the VV port to a cold window adapter. This would significantly reduce the complexity of the RF coupler and the cost by about half.

An aspect of the Linac cryomodule to be analyzed and configured is the He flow from the cavity to the 2-phase pipe and then to the GRP. The heat conduction through the He vessel chimney should be <1 W/cm^2 to keep the superfluid from boiling. At present, this chimney is allotted a 74 cm^2 area, which provides a factor of 7 safety margin for the expected 10.5 W heat flow from the cavity. Further analysis will verify the locations of connections between the 2-phase pipe and the GRP for minimal cavity temperature variation, presently estimated to be one connection at the module midpoint, as shown in Fig. 1.

A unique feature of the ERL Injector that will also be incorporated into the Linac is the use of roller bearings on the composite posts and rails inside the VV for insertion of the cold mass. This proved to be a quick and easy insertion method without the overhead necessitated by the familiar “Big Bertha” cantilever method.

Design of this cryomodule and its components will continue over the next couple of years, with a proto-type expected to be assembled and tested in the 2012 time frame.

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