DESIGN AND CONSTRUCTION OF THE MAIN LINAC CRYOMODULE FOR THE ENERGY RECOVERY LINAC PROJECT AT CORNELL

G.R. Eichhorn#, B. Bullock, J. Conway, Y. He, G.H. Hoffstaetter, M. Liepe, T. O'Connell, P. Quigley, D. Sabol, J. Sears, E. Smith, V. Veshcherevich
Cornell Laboratory for Accelerator-based Science and Education (CLASSE), Cornell University, Ithaca, NY 14853, USA

Abstract

Cornell University has been designing and building superconducting accelerators for various applications for more than 50 years. Currently, an energy-recovery linac (ERL) based synchrotron-light facility is proposed making use of the existing CESR facility. As part of the phase 1 R&D program funded by the NSF, critical challenges in the design were addressed, one of them being a full linac cryomodule. It houses 6 superconducting cavities, operated at 1.8 K in continuous wave (CW) mode, with individual Higher Order Modes (HOMs) absorbers and one magnet/ beam position monitor section. Pushing the limits, a high quality factor of the cavities ($2x10^{10}$) and high beam currents (100 mA accelerated plus 100 mA decelerated) are targeted. We will present the design of the main linac cryomodule (MLC) being finalized recently, its cryogenic features and report on the status of the fabrication which started in late 2012.

INTRODUCTION

The potential for excellent quality of X-ray beams, generated by a low-emittance electron beam, motivated the design of a 5-GeV superconducting ERL [1] at Cornell University. Starting with 10 MeV electrons produced by a photo-injector with currents of up to 100 mA [2], the beam will be accelerated in two main linac sections to 5 GeV before it enters several undulators feeding the X-ray beam-lines.

The existing CESR ring is then used to return the beam and inject it into additional undulators, before it gets decelerated to 10 MeV again inside the two main linac sections. A more detailed description can be found in [3].

This paper will focus on the MLC, designed and now fabricated under an NSF funded R&D phase, 64 of which will form the main linac of the proposed ERL.

The general layout of the cryomodule prototype is shown in Fig. 1. The almost 10 m long module houses 6 superconducting cavities, operated in CW mode at 1.8 K. These 7-cells, 1.3 GHz cavities with an envisaged Q of $2x10^{10}$ will provide an energy gain of 16 MV/m [4]. Each cavity is fed by a 5 kW RF power input coupler [5].

Due to the high beam current combined with the short bunch operation a careful control and efficient damping of the HOMs is essential, leading to the installation of dampers next to each cavity [6]. The series linac module will have a quadrupole/ steerer superconducting magnet section behind the 6 cavity string, making the transition to the adjacent module.

This magnet section will be omitted in the prototype describe further on as it, in contrast to the other components, technically does not represent a challenge.

MECHANICAL AND THERMAL DESIGN

The mechanical concept foresees that all components within the cryomodule will be suspended from the Helium Gas Return Pipe (HGRP). The radiation and convection heat loads are reduced by operating the shield at 40 K and wrapping it with 30 layer multilayer insulation (MLI) blankets, in a vacuum environment.

The magnetic shield, which is made of 0.5 mm Mu-metal sheets, will be mounted to the exterior of the 40 K thermal shield to screen the Earth's field and any other stray magnetic field from the cavities.

Cold Mass Support System

The beam-line string is suspended under the HGRP which acts as the beam-line backbone and is supported by three support posts to the vacuum vessel (see Fig. 2 & 3).

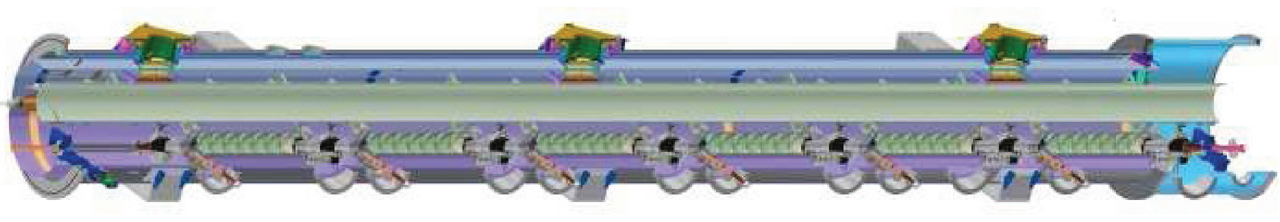

Figure 1: CAD model of the cryomodule prototype.

#r.eichhorn@cornell.edu

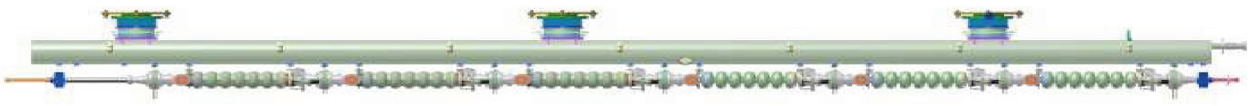

Figure 2: Beam-line suspended under the HGRP.

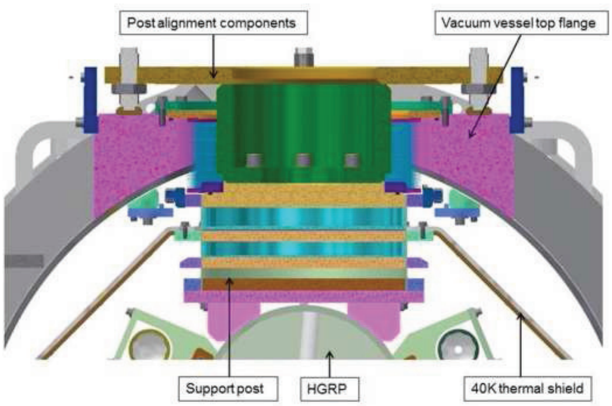

Figure 3: Cold mass support system.

The support system provides precision alignment and thermal insulation of the beam-line string.

Helium Gas Return Pipe

The HGRP is made of a Grade 2 Titanium pipe, with an outer diameter of 280 mm and a wall thickness of 9.5 mm. The HGRP also provides the low flow impedance needed for the large mass flow rate of helium gas evaporated from the cavity vessels to the liquefier, without excessive pressure drop over a half linac length of 350 meters.

Post

The post has a same design as those used in the TTF cryomodule (see Fig. 4), which is an assembly of a low thermal conduction composite material pipe (G10 fiberglass pipe) and four stages of shrink-fit aluminum and stainless steel discs and rings. The two stainless steel disc/ring sets are connected respectively to the room temperature and to the 2 K cold mass environments. The two aluminium disc/ring sets provide thermal intercepts at 40 K and 5 K, with the 40 K set also providing structural support to the 40 K thermal shield.

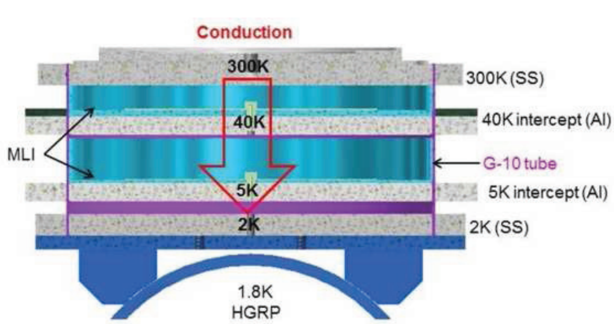

Figure 4: Thermal design of the post.

Between the 5 K and 40 K stages, there are insulation discs and rings made of alternating layers of double aluminized Mylar (DAM) and reeway spunbonded polyester (RSP).

Vacuum Vessel

The vacuum vessel is 965.2 mm in diameter. It has ports for support posts, input RF power couplers, tuner access, instrumentation, gate valve actuator, vacuum pump-out, safety relief, and cryogen valves. There are rails for the installation of the cold mass.

The vessel cylinder is made of carbon steel (A516 GR70, chosen for cost reasons over the stainless) and the flanges that use O-ring seals are made of stainless steel 304L. For the prototype the interior of the carbon steel portion will be painted with low vapor pressure vacuum compatible epoxy, while the exterior will be painted with marine paint product.

Alignment

The HGRP defines the reference for the precision alignment of the beam-line string. Relative vertical alignment is ensured by precision machining on the interfacing surfaces of the supports, with a single machine tool setup at the final stage after all welding is done and a vibration stress relief is performed. The transverse and longitudinal alignment is obtained by the alignment pins on the support plates, see Fig. 5. The alignment key or a flexible cavity support allows the beam-line components to slide longitudinally relative to the HGRP during cool-down or warm-up.

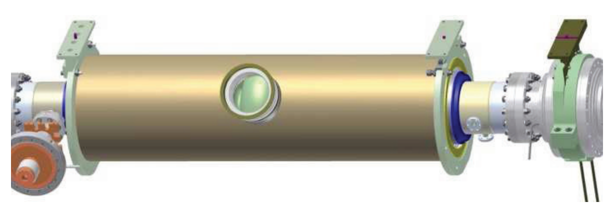

Figure 5: Beam-line support plates with pin/key for alignment.

To accommodate the HGRP thermal contraction at cold relative to the vacuum vessel, the two side posts are slide-able over the top flanges while the central post is locked in position. The central position of the side posts are pre-shifted at room temperature and will be concentric to the vacuum vessel flange at cold. The alignment and push screws on the suspension brackets provide the positional adjustment of the cold mass at room temperature. The rather complex arrangement is shown in Fig. 6.

ISBN 978-3-95450-143-4

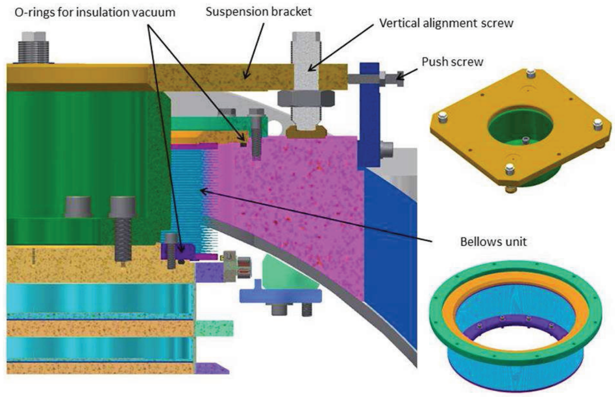

Figure 6: Post alignment components.

Thermal Shield

The thermal shield is made of aluminum AL 1100-H14, with the upper section being 6.35 mm thick and the lower section being 3.175 mm thick. They are connected with fasteners as a rigid assembly with a good thermal contact. Reinforcement rings on the bottom sheets serve to increase the mechanical stability (See Fig. 7).

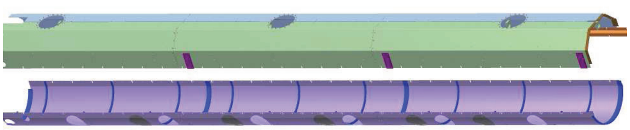

Figure 7: Upper and lower sections of the thermal shield.

To avoid excessive stress due to asymmetric cooling during cool-down process, some slots are machined off at the upper-lower joint section to unload the force (See Fig. 8).

CYOGENIC DESIGN

The cryogenic scheme of the module consists in principle of three different loops as shown in Fig. 9. The cryogenic considerations were discussed in paper [7].

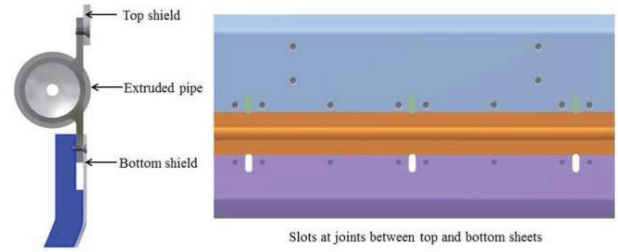

Figure 8: Joints between top and bottom sheets.

1.8 K Loop

The cavities will be cooled by liquid helium. Sub-cooled to 1.8 K by pumping the He-atmosphere down to 16 mbar ensures an optimum operation regime for the superconducting cavities.

To minimize the pressure drop over the whole linac string, a big aperture (280 mm diameter) for the HGRP was chosen. Connected to the HGRP at a single point is a 100 mm diameter 2-phase helium manifold. The 2-Phase 1.8 K pipe feeds helium to the helium vessel of cavities and the magnets through seven chimneys. It should be mentioned that the diameter of this pipe is strongly increased (compared to the ILC cryomodule design) to accommodate CW operation, by allowing adequate surface area for evaporation and a sufficiently large cross-section for gas flow to avoid generation of waves on the liquid surface which could result in pressure fluctuations affecting frequency tuning of the cavities. See Fig. 10.

The size of the 75 mm diameter pipe connecting between each cavity helium vessel and the 2-phase line is dictated by a maximum superfluid helium heat transport of about 1 W/cm^2 at this temperature.

5 K-6.5 K Loop

The 5 K-6.5 K is used to cool the intercept all transitions to warmer temperatures in order to assure a minimal heat transfer to the 1.8 K system. The 5 K coolant supply will be distributed at a pressure somewhat

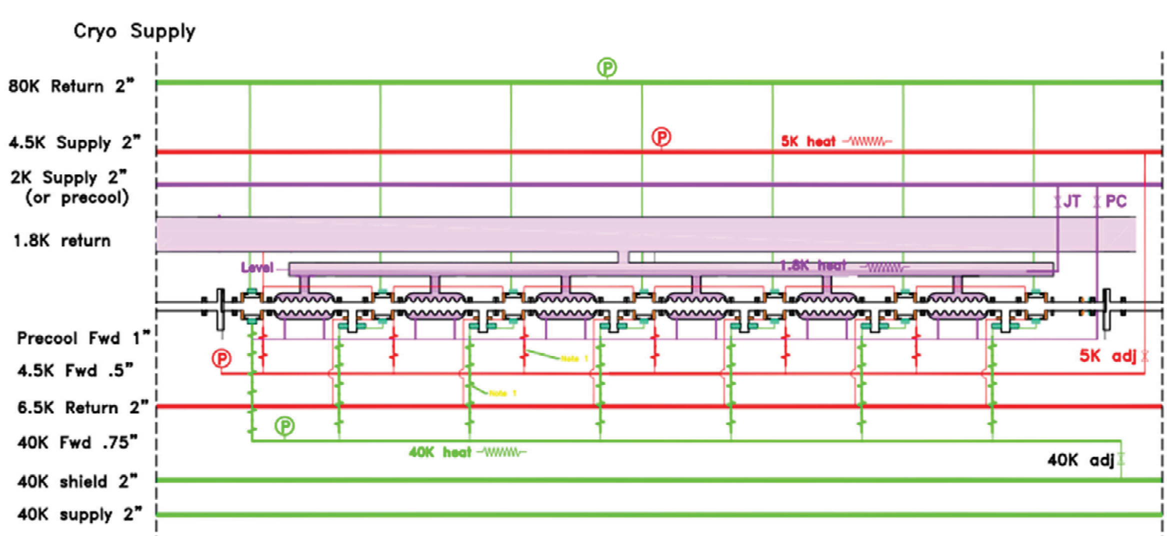

Figure 9: Diagram of the cooling loops in the module.

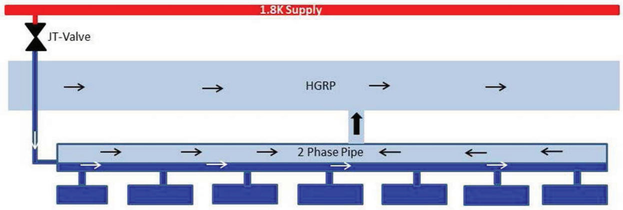

Figure 10: 1.8K flow chart.

above the critical point for liquid helium (around 3 bar), where helium gas conveniently has an increased heat capacity. The choice of temperature rise between supply and return is a compromise between reducing the mass flow of gas through the refrigeration system to improve refrigeration efficiency and keeping the outlet temperature low enough to not degrade superconducting properties of the cavities.

For the prototype, a baffle is used for redirecting the flow from the middle chimney to the downstream end of the HGRP before flowing to the upstream end.

40 K-80 K Loop

A 40-80 K loop provides cooling for the coupler intercepts, cools the thermal radiation shield of the module and removes the heat generated in the HOM absorbers, the operation temperature of the later was chosen for efficiency reasons. As shown in Fig. 9, the loads are partially in parallel, partially in series. As the expected heat load especially at the HOM absorbers (due to its principle character) are expected to vary individually on a scale of 0 to 400 W, concerns were raised on the thermal stability of this arrangement. Based on findings on an earlier cryomodule built for the injector [8] a careful investigation on the stability of parallel flows was performed, being reported in another paper [9].

Piping System

A number of cryogenic piping run along the module, as shown in Fig. 11.

Six lines of 50 mm diameter run through the entire half-linac. Due to the fact that this half linac will be 350 m long, the pressure drop even with these large diameter

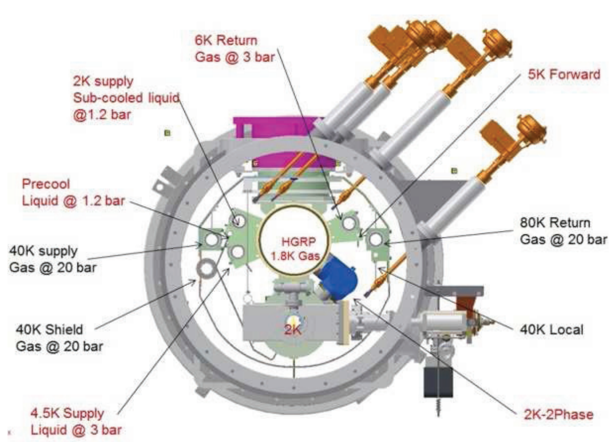

Figure 11: Cross-section of the module.

lines would be significant. To keep the diameter reasonable, local manifolds of smaller diameters help delivering the cryogens. Four valves (1.8 K, pre-cool, 4.5 K, and 40 K) located at the entrance of each cryomodule will manage the flow division amongst the modules.

The 1.8 K and 6 K pipes are mounted on the HGRP with G10 brackets fixed on one end and sliding on the other supports. The 40 K and 80 K pipes are mounted with G10 brackets on the thermal shield, with lateral supports on both ends of the shield.

MECHANICAL AND THERMAL ANALYSES

A series of ANSYS finite element analyses (FEA) were performed to evaluate the cryomodule design mechanical stability and thermal behavior.

Structural Analysis of the HGRP

Structural analysis was performed to evaluate the vertical displacement of the HGRP. With a 1 ton weight force of the beamline string, the maximum vertical displacement of the HGRP would be 0.1 mm and the natural frequency would be 88 Hz. This simulation, the results of which are shown in Fig. 12 indicates that a 3-posts support system is well suited to ensure an acceptable vertical displacement and vibration characteristics.

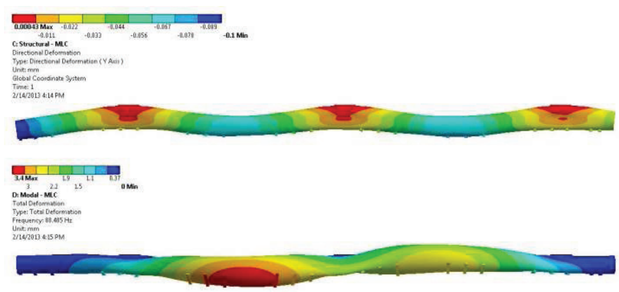

Figure 12: Structural analysis of the HGRP showing vertical displacement and the lowest mechanical eigenmode.

Structural Analysis of the Vacuum Vessel

Through the structural analysis and design optimization process, it was decided that the U-foot to support the vessel is placed under each top flange. Along with the stiffening rings bridging the top flange and the U-foot, the integral reinforced structure increases the stability of the vessel and minimize the vessel deformation.

Thermal Analysis of the Thermal Shield

The thermal shield will be cooled by the 40 K delivery line which is connected to one side, shown in Fig. 13. As a result, the cool-down process will be asymmetric requiring a more detailed analysis about the temperature gradient, deformation and thermo-mechanical stresses on the shield during the cool-down process.

ISBN 978-3-95450-143-4

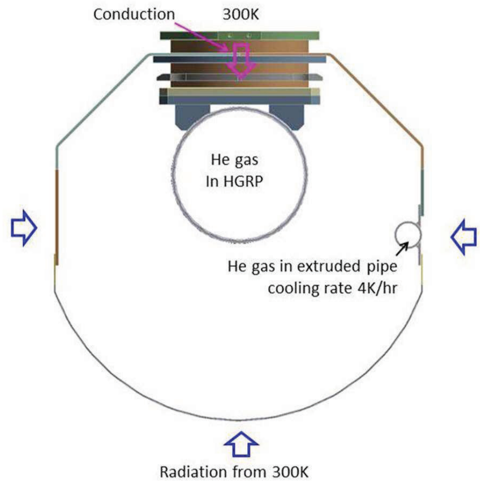

Figure 13: Asymmetric cooling of the 40 K thermal Shields.

Static heat loads includes conduction through the support post and radiation from room temperature vacuum vessel. With 30 MLI blankets covered on the shield, the radiation heat fluxes from room temperature are assumed to be 1.25 W/m^2. In the extruded pipe for the 40 K helium gas delivery, a convective heat transfer coefficient of 0.11 W/cm^2-K was estimated. The variation with gas temperature, hence a function of time with a known cooling rate, was taken into account. The simulated results indicated that with a slow cooling rate of 4 K/hour, the temperature gradient reaches a maximum of 15 K on the entire shield, occurring 20 hours after the start of the cool down, shown in Fig. 14 & 15. Once fully cooled down, the steady state maximum temperature gradient will be only 2.6 K, shown in Fig. 16.

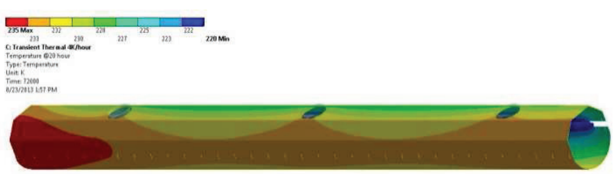

Figure 14: Temperature distribution on the shield at 20 hours after cool-down started.

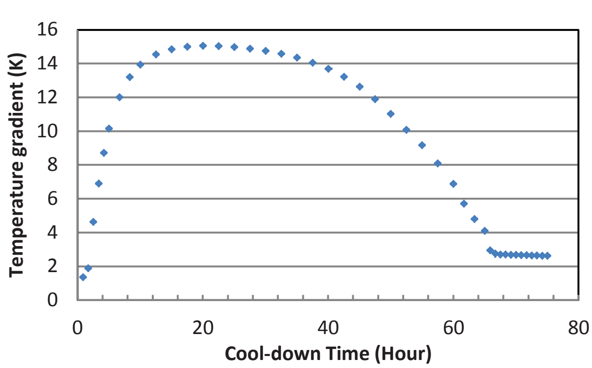

Figure 15: Temperature gradient on 40 K shield as a function of time during cool-down.

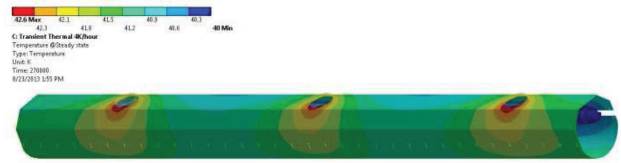

Figure 16: Temperature distribution of the shield at steady state.

Static thermo-structural analysis was performed to study the stresses at the worst scenario when the temperature gradient over the shield reaches the maximum. The thermal shield will be bent during cool-down with a maximum relative deformation of 4.6 mm (see Fig. 17). The maximum stress will be about 60 MPa occurring at the corner of the slots.

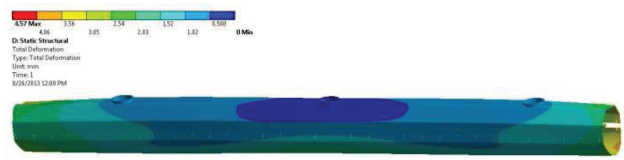

Figure 17: Shield deformation when the temperature gradient reaches the maximum.

Thermal Analysis of the Post

Thermal and thermo-structural analysis of the post provided the heat inleak to the cryogenic systems due to the conduction through the. The heat load through each post is estimated to be 8.58 W to 40 K, 0.54 W to 5 K and 0.05 W to 1.8 K, respectively (see Table 1).

Table 1: Heat Inleak (W) from Each Post

	In	Out
Heat from 300K flange	9.17	
Heat to 40K system		8.58
Heat to 1.8K system		0.05
Heat to 5K-6.5K system		0.54

Vibration Analysis

FEA Modal analyses were performed to evaluate the mechanical stability of the thermal shield (see Fig. 18) and individual piping lines (see Fig. 19) in the module. The location and stiffness of piping supports were considered in the design to make sure the resonant frequencies are higher than 60 Hz.

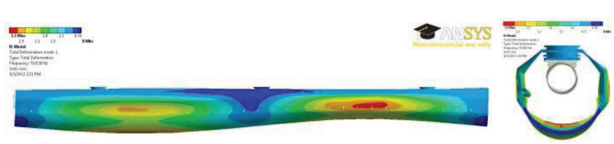

Figure 18: Lowest mechanical eigenmode of the thermal shield.

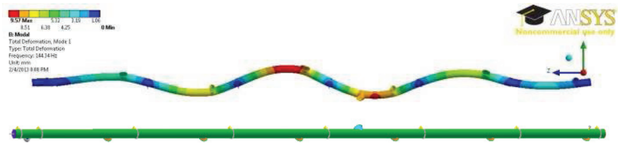

Figure 19: Lowest mechanical eigenmode of 2-phase pipe and the model showing the supports.

STATUS AND OUTLOOK

On the frontier of superconducting radiofrequency accelerating cavities, we were able to achieve extremely high quality factors resulting in remarkable low cryogenic losses in CW operation.

Towards construction of a Main Linac Cryomodule prototype, major parts have been procured or already fabricated in house. The prototype design foresees that it could be a spare module in the series Linac that the final welding or connection for the cryogenic pipes will be made in-situ. In addition, the design also allows easy dismounting of the whole assembly for replacing some components. The assembly sequence is that the beam-line string will be assembled in the clean room, and then attached to the HGRP. Once the cold mass is assembled, it will be rolled into the vacuum vessel on its rail system (see Fig 20).

The cryomodule prototype assembly process will start in November 2013 and is scheduled to be finished and ready for test by the end of 2014.

ACKNOWLEDGMENTS

We would like to thank Tom Peterson, Serge Claudet and John Weisend II for their help and their review during the design phase.

This work has been supported by NSF awards PHY-0969959 and DMR-0807731 and DOE award DOE/SC00008431.

REFERENCES

[1] M. Tigner, "A Possible Apparatus for Electron Clashing-Beam Experiments, Nuovo Cimento", 37 - 3, 1965, p. 1221.
[2] B. Dunham et al., "Record High-average Current from a High-brightness Photoinjector", App. Phys. Lett. 102 (2013) 034105.
[3] G. H. Hoffstaetter, S. Gruner, M. Tigner, et al., Cornell ERL Project Definition Design Report (June 2013); http://erl.chess.cornell.edu/PDDR
[4] R. Eichhorn et al., "High Q Cavities for the Cornell ERL Main Linac", Proc. of the SRF 2013 conference, Paris.
[5] V. Veshcherevich et al., "Input Coupler for Cornell ERL Main Linac", Proc. of the SRF 2013 conference, Paris.
[6] R. Eichhorn et al., "Cornell's Beam Line Higher Order Mode Absorbers", Proc. of the SRF 2013 conference, Paris.
[7] Eric Smith et al., "Cryogenic Distribution System for the Proposed Cornell ERL Main Linac", IPAC 12
[8] M. Liepe et al., "Design of the CW Cornell ERL Injector Cryomodule", Proc. of the 2007 Part. Acc. Conf., 2007, p. 2572.
[9] R. Eichhorn et. al., "Managing Parallel Cryogenic Flows to the Thermal Intercepts in the Cornell ERL", Advances in Cryogenic Engineering, in press.

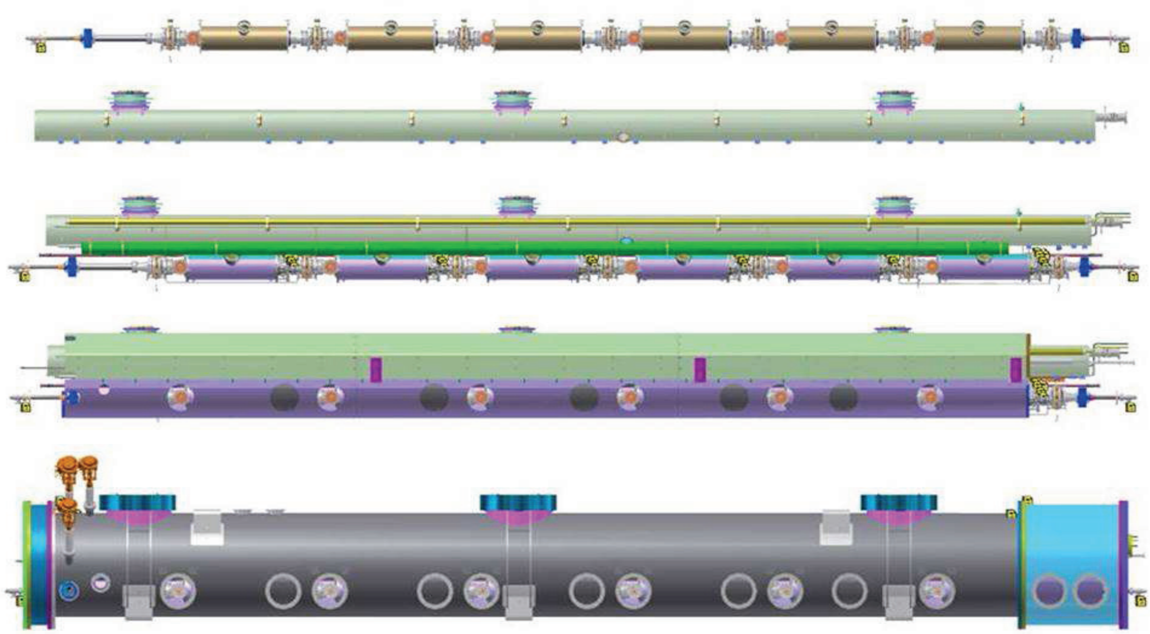

Figure 20: MLC prototype assembly sequence.

ISBN 978-3-95450-143-4