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SUPERCONDUCTING CAVITY CRYOMODULE DESIGNS FOR THE NEXT GENERATION OF CW LINACS: CHALLENGES AND OPTIONS*

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Abstract

The designs of nearly all superconducting RF (SRF) linacs over the last several years, with one notable exception being CEBAF at Jefferson Lab, have assumed pulsed beam operation with relatively low duty factors. These include the XFEL at DESY, the ILC, the original configuration for Project X at Fermilab, as well as several others. Recently proposed projects, on the other hand, including the LCLS-II at SLAC, the newly configured low and medium energy sections for Project X, and FRIB at Michigan State, to name a few, assume continuous wave or CW operation on quite a large scale with ambitious gradients and cavity performance requirements. This has implications in the cavity design as well as in many parts of the overall cryomodule due to higher dynamic heat loads in the cavities themselves and higher heat loads in the input and high-order-mode (HOM) couplers. Piping internal to the cryomodule, the effectiveness of thermal intercepts, the size of integrated heat exchangers, and many other aspects of the overall design are also affected. This paper will describe some of these design considerations as we move toward the next generation of accelerator projects.

CRYOMODULE DESIGN OVERVIEW

Many cavity types are being used in various superconducting RF linac designs around the world – single and multiple spoke, half and quarter-wave, and elliptical resonators operating in pulsed or CW mode spanning frequencies from a few megahertz to several gigahertz, operating nominally at 4.5 K or 2 K. In spite of their variety, they contain many common design features. All have an outer vacuum shell, a cold mass (the cold components within the cryomodule) support system, one or more layers of magnetic shielding, one or more thermal shields, multi-layer insulation, cryogenic piping, cavity tuning systems, input and HOM couplers, beam vacuum gate valves, and instrumentation. In addition there are features unique to each design – active alignment systems, cavity position monitoring systems, internal heat exchangers, cold-to-warm-transitions, active magnetic elements, current leads, and many others.

The goal here is to describe some of the options available to both pulsed and CW mode cryomodule designers, focusing on things that guide the design process and ultimately lead to a design choice. Most of the time there is no right or wrong choice. More often than not, final design features are a compromise between many factors.

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OVERALL CONFIGURATIONS

The size and shape of the overall cryomodule is determined by many factors. Lattice requirements determine the number of cavities, whether there are internal magnetic elements, and the amount of beam instrumentation, if any, all of which determine the overall length of the final assembly. The cavity shape, assembly preferences, and ease of maintenance determine whether the vacuum vessel is round or rectangular. Generally, elliptical cavities are installed in round vacuum vessels and half or quarter-wave resonators in rectangular vessels, but there are exceptions. Rectangular vessels are often thought to facilitate maintenance operations by allowing the internal structure to be removed in-situ.

Segmentation, the degree to which cryomodules share common cryogenic piping and vacuum space, also plays a strong role in the overall cryomodule design. The XFEL at DESY is an example of course segmentation with the cryogenic piping and insulating vacuum being shared by multiple cryomodules. CEBAF at Jefferson Lab is an example of fine segmentation with the cryogenic piping and insulating vacuum separated at each cryomodule interconnect. In this case the only line common to all cryomodules in the string is the beam vacuum.

Figures 1 and 2 show cryomodules for the XFEL and FRIB at Michigan State University respectively.

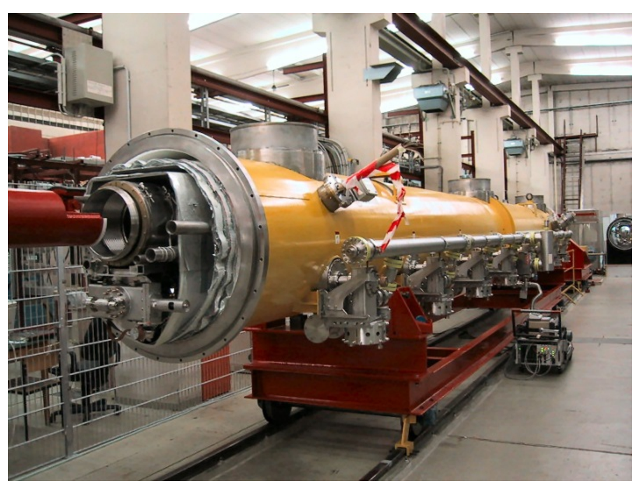

Figure 1: 1.3 GHz cavity cryomodule at DESY.

SUPPORT SYSTEMS

The structural support system serves to support the 4.5 K or 2 K cold mass accurately and reliably within the cryomodule assembly and to insulate it from heat radiated and conducted from the environment at 300 K. These two requirements are generally at odds with one another.

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Structural forces acting on the cold mass come in the form of static weight, shipping and handling loads, forces generated due to cooldown, and internal forces due to fluid flow and ambient ground motion. The requirement for thermal efficiency implies the use of composite materials, high-strength low thermal conductivity metal or a combination of both.

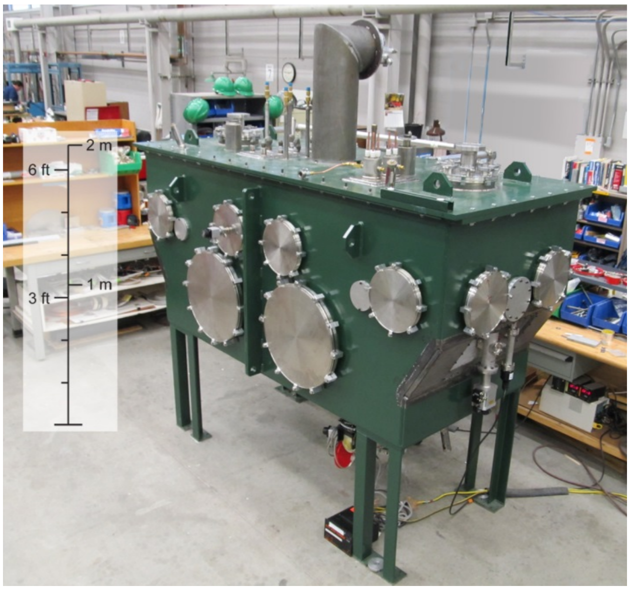

Figure 2: FRIB technology demonstration cryomodule.

Most of the active cryomodule designs today use one of two support types. XFEL cryomodules use three composite support posts similar to those originally developed for the SSC magnet program to support the thermal shield and a large gas helium return pipe which in turn supports the remaining internal parts of the cold mass assembly [1][2]. Also widely used are tension members, often made of high strength stainless steel connected to the cavity at one end and the vacuum vessel at the other. They often utilize some form of adjusting scheme to allow alignment of the cavity string after insertion into the vacuum vessel. Most half and quarter-wave cavity structures use this scheme as do all of the cryomodules in CEBAF and the 12 GeV upgrade at Jefferson Lab. Most Jefferson Lab cryomodules also employ a space frame concept that allows the entire internal assembly to be completed prior to insertion into the vacuum vessel [3].

THERMAL SHIELDS AND INSULATION

All superconducting accelerator devices, whether magnets or RF cavity cryomodules, employ means of reducing radiation heat transfer between the inner surface of the vacuum vessel and the cold mass. Left unchecked, radiation heat transfer to the internal cold surfaces could easily exceed 1 kW per meter of length. One or more thermal shields wrapped in multi-layer insulation (MLI) are very effective at reducing this to manageable levels. There is generally an outer thermal shield operating between 30 and 80 K depending on cryogenic system details with 40 to 60 layers of MLI. Occasionally a lower temperature shield operating between 5 and 20 K is also used to further reduce thermal losses. If so, it generally has a thinner MLI blanket made up of 10 to 20 reflective layers. The effectiveness of the MLI is directly related to the insulating vacuum. The better the vacuum, the better the MLI performs.

Thermal shields are most often an annular shell or flat sheets of aluminum or copper connected to a cooling supply integral to the cryogenic system. These shields serve as heat sinks, intercepting heat radiated from warmer surfaces and transferring that heat to the cryogenic system before it reaches the cold surfaces. The material choice is largely driven by cost, weight, and ease of manufacture. Aluminum tends to cost and weigh less, but usually requires the use of stainless steel to aluminum transition joints for connection to other piping. Copper, on the other hand, is more costly and heavier, but is easily soldered and brazed. Either material is effective.

In addition to thermal shields and MLI, many systems employ separate discreet intercepts on input couplers, conduction cooled current leads, and parts of the support structure to reduce the overall heat load on the low temperature elements even further.

MAGNETIC SHIELDING

Magnetic fields present in a superconducting cavity during cooldown become trapped in the cavity until it is warmed up again, seriously degrading cavity performance. To mitigate this during operation, magnetic shielding is incorporated into the cryomodule design in one or more places. A shell of room temperature mu-metal often lines the inside surface of the vacuum vessel and serves to shield the cold assembly from the Earth's field and low level magnetic elements in the surrounding area. If there are no magnetic elements inside the cryomodule and if high-Q in the cavity is not required, this single layer of shielding may be adequate. Single layer shields are also used immediately surrounding the cavity helium vessel. Installed here, cryogenic grade mu-metal can be used to enhance the overall performance of the shield. It is also possible to install shielding inside the helium vessel, minimizing the amount of material required and reducing the number of penetrations in the shield itself.

If higher performance is needed, especially for high-Q cavities, two or even more layers of shielding can be used to reduce the effect of stray fields even further.

CRYOGENIC PIPING

At a minimum, an SRF cryomodule would contain supply and return lines for the internal cold elements and similar lines for a single thermal shield. More often than not though, systems being designed and built now operate at 2 K and need an intermediate temperature cooling circuit for intercepts, even if a second thermal shield isn't employed. Also, 2 K operation requires the addition of a helium pumping line, usually a fairly large line running the length of the cryomodule at or near the top. Adding a circuit for cooling thermal intercepts adds another supply

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and return, bringing the total now to at least seven separate lines.

The size of these various lines is determined by pressure and flow requirements of the overall system. Designers of systems operating at 2 K with a helium pumping line need to be cognizant of the flow velocity through that pipe. Measurements suggest that a maximum flow rate of 5 m/sec reduces the likelihood that liquid droplets will be carried away with the pumped vapor, decreasing the overall efficiency [4]. Total capacity is also a factor in the design of this pipe because it serves as the pressure relief line for the entire cavity string. Another consideration, not directly tied to standard fluid flow, is heat transport. In a 2 K cavity system, each cavity helium vessel is connected to the helium gas return by one or more "chimneys" which transport heat out of the cavity to the return header. In systems operating in the CW regime, heat loads can be significantly higher than in similar pulsed systems. In order not to be a limiting factor these chimneys should be sized for no more than 1 to 1.4 W/cm^2 [5].

TUNERS

Tuners are used on each cavity assembly to adjust frequency changes due to manufacturing errors, cooldown shrinkage, Lorentz forces, internally generated displacements due to fluid flow, and displacement from outside the cryomodule from ground motion. The type of tuner and how it acts on the cavity depends on the cavity type. Elliptical cavities most often use either a lever tuner or blade tuner. Spoke cavities, at least those used at Fermilab, also use a lever style tuner. Quarter and half-wave resonators use a variety of tuning schemes that deform the entire cavity structure or oftentimes a localized diaphragm at one end of the cavity. No matter the configuration, the tuner acts to deform all or part of the cavity to change the resonant frequency from a few Hz to several kilohertz. Tuners often have two methods of operation – slow and fast. The basic function of the tuner, lever, blade, diaphragm, etc. functions slowly and is operated infrequently during startup or changes in operating conditions. If a fast tuning capability is needed, piezo-electric cartridges are employed that function at much higher frequencies, albeit with much smaller displacements and subsequently a smaller tuning range.

COUPLERS

Like many other cryomodule features, the design of input couplers vary widely, but have many common features. Input couplers may be coaxial or waveguide with either one or two ceramic windows. Two windows are thought to provide a measure of safely for the cavity in the event one window fails. Two windows also facilitate adopting cold and warm coupler halves. The cold half can be installed on the cavity in the cleanroom allowing it to remain clean for the entire assembly operation. Two windows imply one major complication in necessitating a separate vacuum system for the space between the two windows. Nearly all couplers need bellows to provide varying degrees of flexibility required for cooldown (Fig. 3).

Couplers for CW operation often have more rigorous requirements for their ceramic windows due to their higher average power and might also incorporate air, helium or even water cooling.

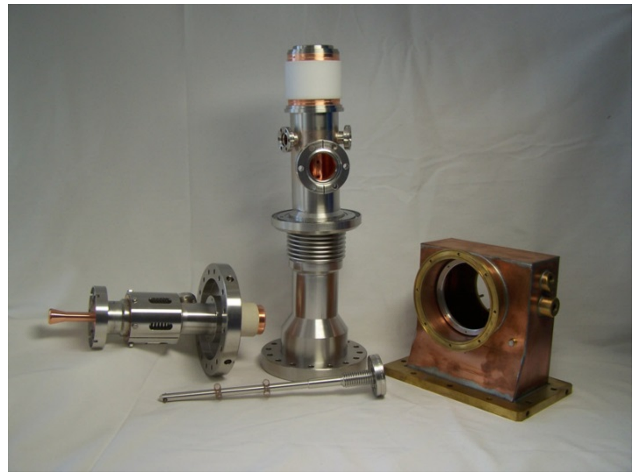

Figure 3: ILC coaxial input coupler.

SUMMARY

Superconducting RF linac projects are in varying stages of design, manufacture, installation, and testing in laboratories around the world. In spite of their differences all share many common features. They remain challenging due to cleanliness requirements, high RF power, the need to reduce thermal losses, multipacting, mode extraction, tuning, alignment, and above all, cost. But, for now at least, they seem to be the dominant direction being taken in accelerator research, taking full advantage of the cooperative spirit of an international community of scientists and engineers.

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