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Energy Recovery Linac: Cryogenic System

R. Than

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R&D ERL: Cryogenic System

R. Than

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

Cryogenic System for the Energy Recovery Linac Facility

R. Than

Introduction

The ERL cryogenic system will supply cooling to a super-conducting RF (SCRF) gun and the 5-cell super-conducting RF cavity system that need to be held cold at 2K. The engineering of the cavity cryomodules were carried out by AES in collaboration with BNL. The 2K superfluid bath is produced by pumping on the bath using a sub-atmospheric warm compression system.

The cryogenic system makes use of mainly existing equipment relocated from other facilities: a 300W 4.5K coldbox, an 45 g/s screw compressor, a 3800 liter liquid helium storage dewar, a 170 m^3 warm gas storage tank, and a 40,000 liter vertical low pressure liquid nitrogen storage dewar. An existing wet expander obtained from another facility has been added to increase the plant capacity. In order to deliver the required 3 to 4 bar helium to the cryomodules while using up stored liquid capacity at low pressure, a new subcooler will be installed to function as the capacity transfer device.

A 2K to 4K recovery heat exchanger is also implemented for each cryomodule to recover refrigeration below 4K, thus maximizing 2K cooling capacity with the given sub-atmospheric pump. No 4K-300K refrigeration recovery is implemented at this time of the returning sub-atmospheric cold vapor, hence the 2K load appears as a liquefaction[1] load on the cryogenic plant.

A separate LN2 cooling loop supplies liquid nitrogen to the superconducting gun's cathode tip.

Cryo Modules

Besides the 2K cooling requirements, each cryomodule has a liquid nitrogen-shield and also requires 4 bar, 5K helium for intercepts on the fundamental power couplers (FPC) and other thermal transitions to ambient boundaries.

eCX 5-Cell Cavity Cryostat System

5-Cell Cavity Cryostat

The helium vessel/cavity has a liquid nitrogen-cooled heat shield operating at 80K. The cryostat consists of the 5-cell cavity string with a fundamental power coupler that is heat stationed with 3 bar, 5K helium, and at each end of the beam tube, helium flow heat intercepts are used for the thermal transitions from the cryogenic end to the ambient temperature ends.

<u>5-Cell cryostat: 2K Static Load</u>

The 2K static load is the heat leak into the 5-cell cavity and Titanium helium vessel. Preliminary boil-off measurements indicate that the static load is around 20W.

<u>5-Cell cavity: 2K Dynamic Load</u>

Predicted dynamic dissipation of the 5 cell at 2K is 40W.

<u>5-Cell cavity: Temperature Gradients</u>

Niobium wetted area 1.6 m^2.
Nominal surface heat flux: ~16 W/m^2
Kaptiza resistance: 1.5 cm^2-K/W
Kaptiza temperature gradient: ~ 2.4 mK

The interconnecting pipe between the cavity helium vessel and the liquid helium reservoir above introduces a temperature gradient between the liquid reservoir and cavity's helium. The interconnect has a crossection area of 205 cm^2. At a total load of ~ 60W, the cross sectional heat flux density is approximately 0.3 W/cm^2 throughout this interconnect. The interconnect is around 80 cm tall, and the resulting superfluid conductivity gradient at 2K at this flux is about 1 mK.

5-Cell cryostat 4.5 K Loads

Beam tube end bore thermal transition intercepts

The 10 inch diameter endbores have been designed to be cooled each with 0.15 g/s of 3 bar 4.5K helium and returned warm. This imposes a liquefaction load on the plant. The endbore intercepts, removes heat conducted down from the room temperature bore. Flows are controlled using industry standard mass flow controllers calibrated for helium.

5-Cell Fundamental Power Coupler Intercept Flow

A flow of 0.075 g/s of 3 bar 4.5K is required to flow through the intercept and cool the fundamental power coupler attached to the cavity. This flow is returned to the plant at room temperature and imposes a liquefaction load on the plant. Flow is controlled using an industry-standard mass flow controller calibrated for helium.

5-Cell Tuner Intercept Flow

Because the tuner is mounted inside the insulating vacuum space and because it is rather massive, cooldown will proceed slowly. A cooling / intercept circuit is also installed on the tuner. The cooling flow is thermally connected to 3 different locations on the tuner. A flow of up to 0.5 g/s of 3 bar 4.5K is available for this intercept. The flow can be turned off once the tuner is cold and is not expected to be a continuous load on the plant. This flow is returned to the plant at room temperature and imposes a liquefaction load on the plant. Flow is also controlled using an industry - standard mass flow controller calibrated for helium.

5-Cell Cavity's Separator / Liquid Reservoir Tank

An existing 500 liter reservoir tank installed on top of the 5 cell cavity cryostat that is being used for helium storage inventory to carry out initial cold emission tests without the plant will be kept to serve as the phase separator and reservoir. This helium reservoir is shielded by a liquid nitrogen-cooled shield. The calculated heat load by the manufacturer is 2W excluding the helium supply interface and the 4 inch helium vent vacuum break. The thermal transitions for these vacuum breaks is expected to add 4 W to the 2K load for a total of 6 W. The reservoir has a top fill valve for supply liquid to the cavity when filled.

5-Cell Cavity's 2K-4K RR heat exchanger

A refrigeration recovery heat exchanger is implemented to recover refrigeration from the low pressure stream, 2K against the high pressure, 4.5K liquid supply from the subcooler. The recovery heat exchanger is single-wrap Collins type wound copper fintube heatexchanger identical to the one used on Fermilab's 2K Teststand #4. Expected pressure drop is less than 1 mbar at 4 g/s flow.

5-Cell LN2-Cooled Shield Loads

The cavity is shielded with a liquid nitrogen cooled shield estimated at 120W. The liquid helium reservoir is also shielded with a liquid nitrogen cooled shield. The shields are connected in series with the cavity cryostat shield upstream of the helium reservoir.

5-Cell Cryostat System Instrumentation

Level indication

Redundant superconducting liquid level probes are mounted in the cavity's helium vessel volume. Another set of level probes is also mounted inside the 500-liter reservoir.

Temperature sensors

Two redundant sets of Cernox sensors are mounted inside the helium vessel space around the cavity. The Cernox sensors are packaged for high temperature environment to allow bake-out along with the cavity assembly.

Two redundant sets of Cernox sensors are mounted onto the helium reservoir's vessel wall also.

Pressure Indication

A capacitance diaphragm pressure sensor with 50 Torr range and another with a 2 bar range are used to measure pressure above the liquid reservoir space.

Pressure Safety

The 5-cell cavity maximum allowable working pressure is 159 kPa or 23 psi differential, (55 kPa gage or 8 psig with full vacuum on other side).

Helium side relief

- For the case of lost of insulating vacuum to air with MLI on helium vessel. The combined area of the cavity's helium vessel and upper reservoir is 6 m^2, at 6 kW/m^2 for a total of 36 kW.

- For the case of loss of vacuum on the beam tube side to air, with a 1.6 m^2 bare surface, the load is 60 kW. This case dictates.

The relief is a 4 inch burstdisk set at the MAWP.
A smaller relief valve set at 5 psig is installed to relief transients during cooldown.

Cavity UHV beam side

- For the case of failure of helium boundary, the beam tube side will flood with liquid helium. The reliefs are size to handle the expansion of helium due to 25 kW of heat input.

Two UHV burstdisks on a 1.5 inch tube also installed on either side of the cavity's string ahead of the isolation gate valves.

SCRF Gun Cryostat System

The Gun consist of a half-cell RF cavity inside a Titanium helium vessel with a cathode gun at one end of the cavity. A 140 liter helium reservoir is connected above the cavity via a 3 inch (75 mm) tube. The cavity is powered using two (2) FPCs, which require 5K cooling intercept flow. One separate helium stream intercepts, in a series arrangement, the heat leak on each end of the cavity flange interface to the beam tube and the high temperature superconducting solenoid. The gun's cathode tip is liquid nitrogen cooled.

2K refrigeration load

Static Load

The 2K static load is the heat leak into the cavity and Titanium helium vessel. The predicted load is 8 W.

Dynamic Load

Predicted dynamic dissipation of the Gun's cavity at 2K is 8W.

Gun cavity: Temperature Gradients

Niobium wetted area 0.25 m^2.
Nominal surface heat flux: ~60 W/m^2
Kaptiza resistance: 1.5 cm^2-K/W
Kaptiza temperature gradient: ~ 40 mK

The interconnecting pipe between cavity helium vessel and liquid helium reservoir above introduces a temperature gradient between the liquid reservoir and cavity's helium. The interconnect has a crossection area of 46 cm^2. At a total load of ~ 15W, the cross sectional heat flux density is approximately 0.3 W/cm^2 throughout this interconnect. The interconnect is around 60 cm tall, and the resulting superfluid conductivity gradient at 2K at this flux is about 1 mK.

4.5 K Loads

End Flange Intercepts (3 atm, 5K helium)

The end flange heat leak intercepts heat leak from the warm beam tube sections.
The predicted heat load is 2W for each intercept. The flow for these intercepts will be piped in series with the discharge going to cool the HTSC Solenoid magnet.

HTSC Solenoid Magnet

Heat leak to the magnet and cooling will be done using the flow coming from the end flange intercepts.
The predicted heat load for the helium load is approximately 3W. The power leads feeding the HTSC solenoid are heat stationed to the 80K LN2 shield.

Fundamental Power Coupler Lead Flows

There are two power couplers for the SCRF Gun. Each requires a 3atm 5K helium flow of 0.075 g/s for a total of 0.15 g/s. This flow will be returned warm to the plant, thus will be a liquefaction load on the plant. flow of 0.075 g/s each. There are two (2) thermal transition heat intercepts, using 5K helium to minimize loads to the 2K section.

Helium Supply and Vent Feedthrough Interface.

There will be a separate supply line and control valve for the cooldown line on the cavity. There will be one common supply line that will feed both the end flange heat intercepts/HTSC solenoid magnet and the two fundamental power coupler heat intercepts.

The 2K vent line will also serve as the relief line for the helium volume. The line will be sized for the worst case of either loss of insulating vacuum or loss of beam tube vacuum to air.

LN2 Cooled Loads

Liquid Nitrogen Shield

A liquid nitrogen-cooled shield intercepts the heat load to the cavity and the reservoir.

Gun Cathode Cooling

The heat generated in the cathode tip is cooled by liquid nitrogen loop. The heat dissipated is expected to be about 50W. The LN2 is supplied and returned through copper tubing to the cathode tip. The LN2 will be supplied from a phase separator through vacuum jacketed flexible lines connected to the cathode transport cart. To ensure boiling heat transfer, the flow rate will be adjusted to be above 2.5 g/s. Instream heaters will heat the flow to room temperature.

SCRF Gun Cryostat System Instrumentation

Level indication
Redundant superconducting liquid level probes are mounted in the helium vessel volume. Another set of level probes is also mounted inside the 500 liter reservoir.

Temperature sensors
Two redundant set of sensors are located inside the helium vessel space around the cavity.

Pressure Indication
A capacitance diaphragm pressure sensor with 50 Torr range and another with a 2 bar range are used to measure pressure above of the liquid reservoir space.

Heat Load Summary

	2K W	(5K,3 bar) Lique-faction g/s	4.5K Refrig. W	LN2 W
eCX Cavity Static	6			
eCX Cavity Dynamic	40			
eCX FPC		0.075		
eCX end transitions		2 x 0.075		
eCX Tuner		0.3 temporarily		
eCX LHe Reservoir	2			
eCX cryostat shields				400
HX 2K-4K JT valve vacuum break	6			

SCRF Gun Heat Load Summary

	2K W	(5K,3 bar) Lique-faction g/s	4.5K Refrig. W	LN2 W
Gun Cavity Static	8			
Gun Cavity Dynamic	7			
Gun LHe Reservoir	3			
End flange & solenoid		0.3		
Gun FPC's		2 x 0.075		
Gun cryostat shields				145
Gun HX 2K-4K JT valve vacuum break	3			

Distribution Transfer lines & valves

	2K W	(5K,3 bar) Lique-faction g/s	4.5K Refrig. W	LN2 W
4.5 K Transfer lines valves cryo plant interconnects			75	N/A

Pressure Safety

The gun cavity maximum allowable working pressure is also 159 kPa or 23 psi differential, (55 kPa gage or 8 psig with full vacuum on other side).

Helium side relief

- For the case of lost of insulating vacuum to air with MLI on helium vessel. The combined area of the cavity's helium vessel and upper reservoir is 2.4 m^2, at 6 kW/m^2 for a total of 14.4 kW.

- For the case of loss of vacuum on the beam tube side to air, with a 0.25 m^2 bare surface, the load is 9.6 kW. The first case dictates.

The relief is a 2 inch burstdisk set at the MAWP.
A smaller relief valve set at 5 psig is installed to relief transients during cooldown.

Cavity UHV beam side

- For the case of failure of helium boundary, the beam tube side will flood with liquid helium. The reliefs are size to handle the expansion of helium due to 9 kW of heat input from the warm beam tube section upstream of the gate valve.

Two UHV burstdisks each on a 1.5 inch tube are installed on the beamline within the gatevalve baoundaries. One on the gun's beam side ahead of the isolation gate valve. The other is installed in the space behind cold cathode tip.

Operations

Ballasting

Because the cryoplant's liquefaction capacity is less than the demand of the cryomodules, the system cannot be operated continuously at full load, rather the cavities have to stop operating at 2K and allow the plant to reliquefy helium stored in the warm gas storage tank during the run back into the liquid helium storage dewar.

With a 2K load of at least 75 W, the vacuum pump flow will be 4.3 g/s, and with a 0.8 g/s liquefaction load from the intercepts, the total liquefaction demand load is 5.1 g/s, which is higher than the net 3.0 g/s liquefaction capacity of the plant. The additional 2.1 g/s capacity will come from the low pressure storage dewar, using the subcooler as the transfer device.

With 2000 liters or 240,000 grams of reserve, the system can operate 24 hours, before stopping. If the cavities operate at the full capacity of the vacuum pump, 5.5 g/s, then the total demand is 6.3 g/s. The run time becomes 16 hours.

Reliquefaction of the equivalent of 2000 liquid liters from warn storage while keeping the cavities cold at 4.5K requires 50 hours.

Liquid nitrogen consumption

	LPH
5 Cell Cavity/Ballast Tank	14
SCRF Gun	6
Gun Cathode	2
1660S Coldbox	70
Future purifier	10
	102

Equipment Summary

Sub-atmospheric pumping System

A Roots blower backed by 2 liquid rings pumps are used to pump on the liquid helium bath to produce the 2K cooling. The system is capable of pumping 5.5 g/s with the bath held at 2K. The Roots blower is a Tuthill MB5400 belt geared down to 1900 rpm from the 2400 rpm max using a 40 HP motor. The blower is backed by two (2) Kinney KLRC-525 2- stage liquid ring pumps with 50 HP motors. A high to low by-pass valve controls the suction pressure at the pump from dropping below its setpoint. Coalescing element at the discharge of the each liquid ring pump prevents carry over of oil to the discharge line. The vacuum pump discharge will go to the low pressure (suction side) of the main helium plant.

4.5K Coldbox plant

The Process Systems International 300 W @ 4.5K model 1660S built in 1993, has 2 pairs of 3 inch (76 mm) diameter piston expanders, configured as a Collins cycle with liquid nitrogen precooling. The first expansion stage operates at an inlet of 50K, and the second expansion stage at an inlet of ~19K in liquefaction mode.

Wet expander

A 1985 Koch Process System wet expander consisting of a pair of 2 inch (50 mm) diameter piston has been added to the system, providing an additional 0.7 g/s liquefaction capacity to the plant.

Main compressor

The main helium compressor is a 1975 Sullair C20LA4.8-400HP screw compressor, complete with bulk oil separator. The oil demisting system consists of 2 parallel banks of 4 Balston coalescing elements in series: DX, BX, BX, BX. A 18 inch diameter charcoal bed is used for oil vapor removal. Flow throughput of the compressor is 45 g/s @ 1.05 atm.

Liquid helium inventory

Liquid helium inventory will be stored in an existing 3800 liters liquid helium storage dewar manufactured in 1992 by Cryofab. The dewar has 3 liquid fill and one vapor line as interface.

Gas Storage Tank

An existing 170 m^3 warm gas storage tank is used for inventory storage when the system is warm.

Subcooler

Because helium at 3 to 4 bar is required for the intercept flows in the cryomodules, the plant's high pressure flow is used to supply the cryomodules, instead of low pressure liquid from the storage dewar. The subcooler serves to condition the plant's warmer liquid helium to 4.5K and simultaneously serves to use-up liquid inventory from the main low pressure storage dewar.

Notes

1. Liquefaction load: The plant receives warm gas and liquefies this to liquid form, as oppose to a refrigeration load, where the plant receives cold 4.5 K vapor and reliquefies this cold vapor. A plant operating at same Carnot efficiency in liquefaction mode or refrigeration mode will have 1 g/s liquefaction capability for every 100 W of 4.5K refrigeration capacity.

Figure 1 Cryogenic system layout