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Process simulations for the LCLS-II cryogenic systems

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Abstract. Linac Coherent Light Source II (LCLS-II), a 4 GeV continuous-wave (CW) superconducting electron linear accelerator, is to be constructed in the existing two mile Linac facility at the SLAC National Accelerator Laboratory. The first light from the new facility is scheduled to be in 2020. The LCLS-II Linac consists of thirty-five 1.3 GHz and two 3.9 GHz superconducting cryomodules. The Linac cryomodules require cryogenic cooling for the super-conducting niobium cavities at 2.0 K, low temperature thermal intercept at 5.5-7.5 K, and a thermal shield at 35-55 K. The equivalent 4.5 K refrigeration capacity needed for the Linac operations range from a minimum of 11 kW to a maximum of 24 kW. Two cryogenic plants with 18 kW of equivalent 4.5 K refrigeration capacity will be used for supporting the Linac cryogenic cooling requirements. The cryogenic plants are based on the Jefferson Lab's CHL-II cryogenic plant design which uses the "Floating Pressure" design to support a wide variation in the cooling load. In this paper, the cryogenic process for the integrated LCLS-II cryogenic system and the process simulation for a 4.5 K cryoplant in combination with a 2 K cold compressor box, and the Linac cryomodules are described.

1. Introduction

The Linac Coherent Light Source II (LCLS-II), a collaborative project between SLAC National Accelerator Laboratory, Cornell University, Argonne National Laboratory, Lawrence Berkeley National Laboratory, Fermi National Laboratory and Thomas Jefferson National Accelerator Facility, is a 4 GeV continuous-wave (CW) superconducting linear electron accelerator to be installed in the existing two mile Linac facility at SLAC. The LCLS-II Project uses superconducting RF cavities housed in strings of cryomodules installed in the SLAC Linac tunnel. The LCLS-II Linac consists of thirty-five 1.3 GHz and two 3.9 GHz superconducting cryomodules. Two cryogenic plants (upstream and downstream) provide refrigerated helium, transported by the cryogenic distribution systems, to/from the cryomodules in a closed circuit. The cryogenic plant is located approximately at the mid-way point along the Linac in a dedicated cryoplant building as shown in figure1 and is separated from the Linac and Klystron gallery. Additional refrigeration and ancillary equipment and storage are located in adjacent outdoor space. The cryogenic distribution systems connect the surface-level cryogenic plant, at an interface box, to the below-ground cryomodules, through distribution boxes and penetrations from the Klystron gallery above the Linac tunnel.

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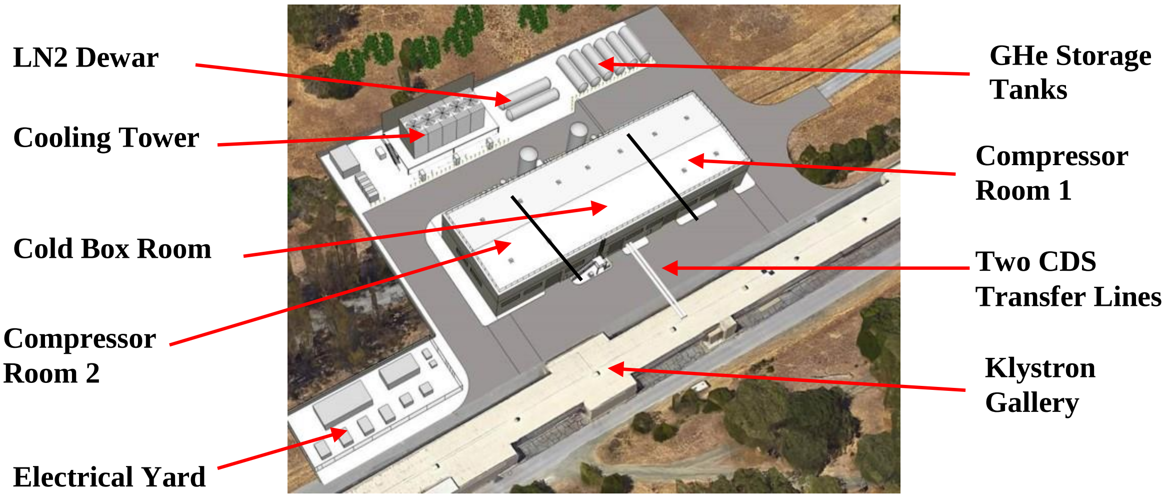

Figure 1: Cryoplant building layout.

2. Cryogenic System Design Capacity

The simplified flow diagram in figure 2 provides a schematic overview of the LCLS-II cryogenic system consisting of: (a) Linac Cryomodules, (b) Cryogenic distribution system and (c) Cryoplants. The LCLS-II Linac is split into two strings-the upstream Linac consisting of 17 cryomodules and the downstream Linac consisting of 20 cryomodules. In accordance with the project goals for the LCLS-II, the commissioning of the cryo-system will be done in two phases: (a) Phase 1 ("First Light Configuration"): In this phase of commissioning, the Linac will operate at a gradient of 14 MV/m (Gradient may be as high as 16 MV/m depending on the final cavity quality factor, Qo) with a nominal Qo of 2.7 $x10^{10}$ (Uncertainty in the Qo: $2x10^{10}$ to $3x10^{10}$). This phase will allow testing the performance of the cryomodules. (b) Phase 2 ("Nominal Beam Operations): In this phase, the Linac will operate at the baseline gradient of 16 MV/m and Qo of 2.7 $x10^{10}$ (Uncertainty in the Qo: $2x10^{10}$ to $3x10^{10}$). As per the current project plan, the entire Linac operation will be supported by a single cryoplant for the expected cryomodule performance. A second cryoplant was added to the project baseline to address the uncertainty in the cryomodule performance and for future upgrade.

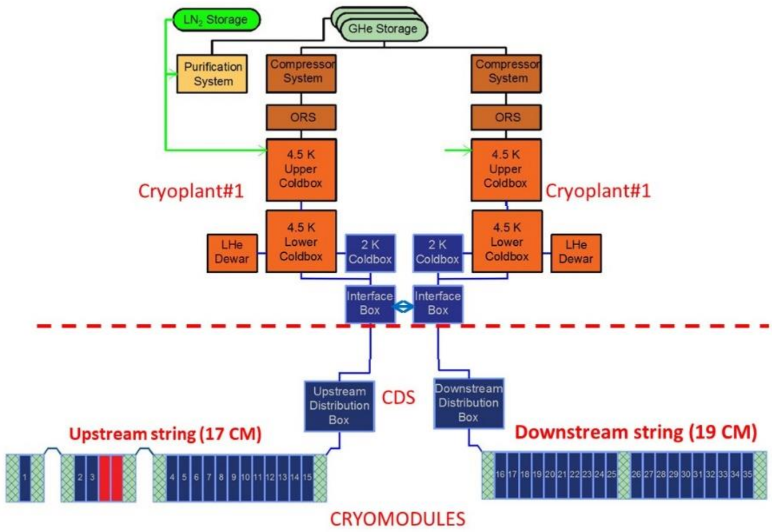

Figure 2: Schematic showing LCLS-II cryogenic systems layout.

The Linac cryomodules require cryogenic cooling for the super-conducting niobium cavities at 2.0 K, low temperature thermal intercept at 5.5-7.5 K, and a thermal shield at 35-55 K [1]. Figure 3 shows the combined refrigeration load on the cryoplant in terms of equivalent refrigeration capacity at 4.5 K for the first light and normal beam operation. The heat load at 2.0 K (figure 4) accounts for 80% of the total load on the cryoplant. The equivalent 4.5 K refrigeration capacity needed for the LCLS-II Linac operations range from a minimum of 11 kW to a maximum of 24 kW.

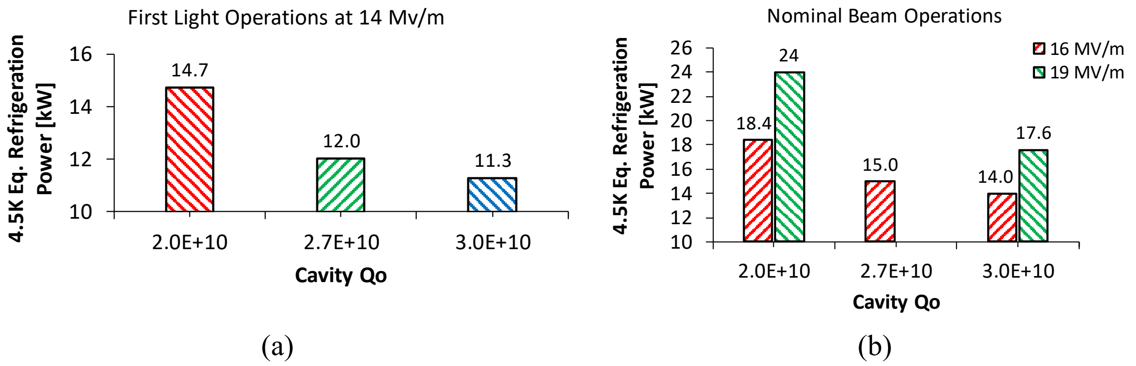

Figure 3: Variation in the Linac heat load in terms of the 4.5 K equivalent refrigeration power versus cavity Qo for (a) First Light and (b) Normal Beam Operation.

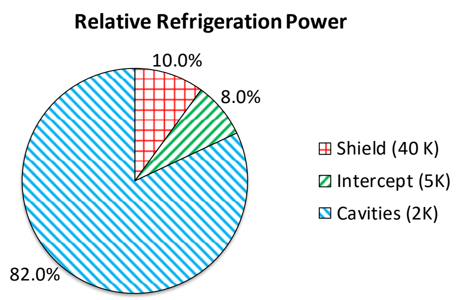

Figure 4: LCLS-II Linac Heat Load pie chart comprises of (1) Warm Shield at 40 K, (2) Intercepts at 5 K and (3) Cavities at 2 K. The 2 K heat load accounts for 80% of the total load on the cryoplant.

To meet the anticipated LCLS-II Linac heat load, two cryogenic plants based on the Jefferson Lab's CHL-II cryogenic plant, which uses the "Floating Pressure" design [2] to support a wide variation in the cooling load, will be used. Each LCLS-II cryogenic plant can provide an equivalent refrigeration capacity of 18 kW at 4.5 K. Table 1, presents a summary of the heat loads, exergy & the 4.5 K equivalent refrigeration power corresponding to the 4.5 K cold box design operating modes.

Table 1: 4.5 K Cold Box Operating Modes.

	Max Cap	Nom. Cap	Max. Liq.	Max. Ref	Max. Fill	4.5 K Standby
Warm Shield [kW]	15.2	10.1	10.1	15.2	15.2	10.1
Cold Intercept [kW]	1.3	0.9	0.9	1.3	1.3	0.9
Refrigeration [kW]	NA	NA	NA	9	NA	0.5
Liquefaction [g/s]	15	0	140	NA	45	NA
Sub-Atm [kW]	4.0	3.14	NA	NA	3.14	NA
Exergy [kW]	1199	844	1075	837	1215	169
4.5 K Eq. Ref. Power [kW]	18	12.7	16.2	12.7	18.3	2.55

3. LCLS-II Cryogenic System Process

The LCLS-II cryo-system process flow starts (shown in figure 5) from the warm compressor system which is grouped into a single high pressure (HP, supply pressure ≤ 20 bar), a single medium pressure (MP, suction pressure ≥ 2.5 bar) and three low pressure [suction pressure ≥ 1.05 bar] compressors. The HP, MP and the LP compressors require a total motor input power of 1865 kW (2500 hp, 1000 hp and 800 hp motor, respectively). The supply and return gas piping manifold from the compressor system to refrigerator is connected to the six 4,000 cubic feet (scf) gaseous helium storage tanks via a series of valves in the gas management system (GMS). Physically, the 4.5 K cold box is split into two vessels- the upper cold box and the lower cold box (in temperature level). The upper cold box vessel contains large helium gas and liquid nitrogen (LN2) heat exchangers, and it uses liquid nitrogen to cool the helium gas to 80 K. The liquid nitrogen feed to the heat exchanger is supplied by two external 20,000 gallons LN2 Dewar via a 132 gallon (500 liters) LN2 phase separator vessel inside the upper cold box. The 4.5 K cold box design requires the maximum LN2 consumption to be less than 140 g/s. The 80 K helium gas is then fed to the lower cold box which contains multiple turbine-expanders (T1, T2, T3 and T4) to lower the helium gas temperature from 80 K to 4.5 K. The Linac thermal shield is cooled with cold helium gas at 35 K from the outlet of turbine T1 and the return gas at 55 K is injected into the medium pressure stream. The Linac cold intercept is cooled with 5 K helium gas from the outlet of turbine-T4 and the return gas at 7.5 K is injected into the low pressure stream (between heat exchangers 9 and 10). The helium gas at the outlet of turbine T4 which is maintained above the helium critical temperature of 5.2 K is sub-cooled to 4.5 K in the heat exchanger (HX-SC) immersed in a liquid helium sub-cooler vessel in the lower cold box. The sub-cooled helium gas at 4.5 K and 3 bar is supplied to the cavity operating at 2.0 K. The helium required for the Linac at the three temperature levels are routed via multichannel transfer lines consisting of six inner transfer lines (Line A- 4.5 K supply, Line B-2 K return, Line C- 5.5 K supply, Line D – 7.5 K return, Line E – 35 K supply & Line F – 55 K return).

Figure 5(b) shows the six cryogenic lines (A to F) running between the cryoplants and Linac via the two interface boxes and the two distribution boxes. The interface boxes facilitate connection between the cryoplants and the transfer lines from distribution boxes using u-tubes with bayonet interfaces. Bayonet connections are also provided for connecting the internal six cryogenic circuits between the two interface boxes allowing both Linac strings to be connected to a single cryoplant (for the first light operation) or each Linac string to its respective cryoplant (for normal beam operations). The distribution box houses the low temperature 2-4 K heat exchanger where the 2 K vapor returning from the cryomodule in Line B cools the 4.5 K supply helium gas from the cryoplant to a lower temperature. For the 2 K Linac pump down, figure 5(a) depicts the 2.0 K cold box with six cold compressor stages (CC1 to CC6) out of which only five stages (CC1-CC5) will be used for the baseline Linac operations in a high-flow configuration. As shown in table 2, in the high-flow configuration, the cold compressor train is designed for a maximum flow of 215 g/s at suction pressure and temperature of 27 mbar and 3.5 K at the inlet to the 1st stage cold compressor. The sixth cold compressor stage is a provision allowed in the cold box design to operate the cold compressors in a low flow mode in the future. In the low-flow configuration, the cold compressor train is designed for a maximum flow of 132 g/s at a suction pressure and temperature of 27 mbar and 3.5 K at the inlet to the 1st stage cold compressor.

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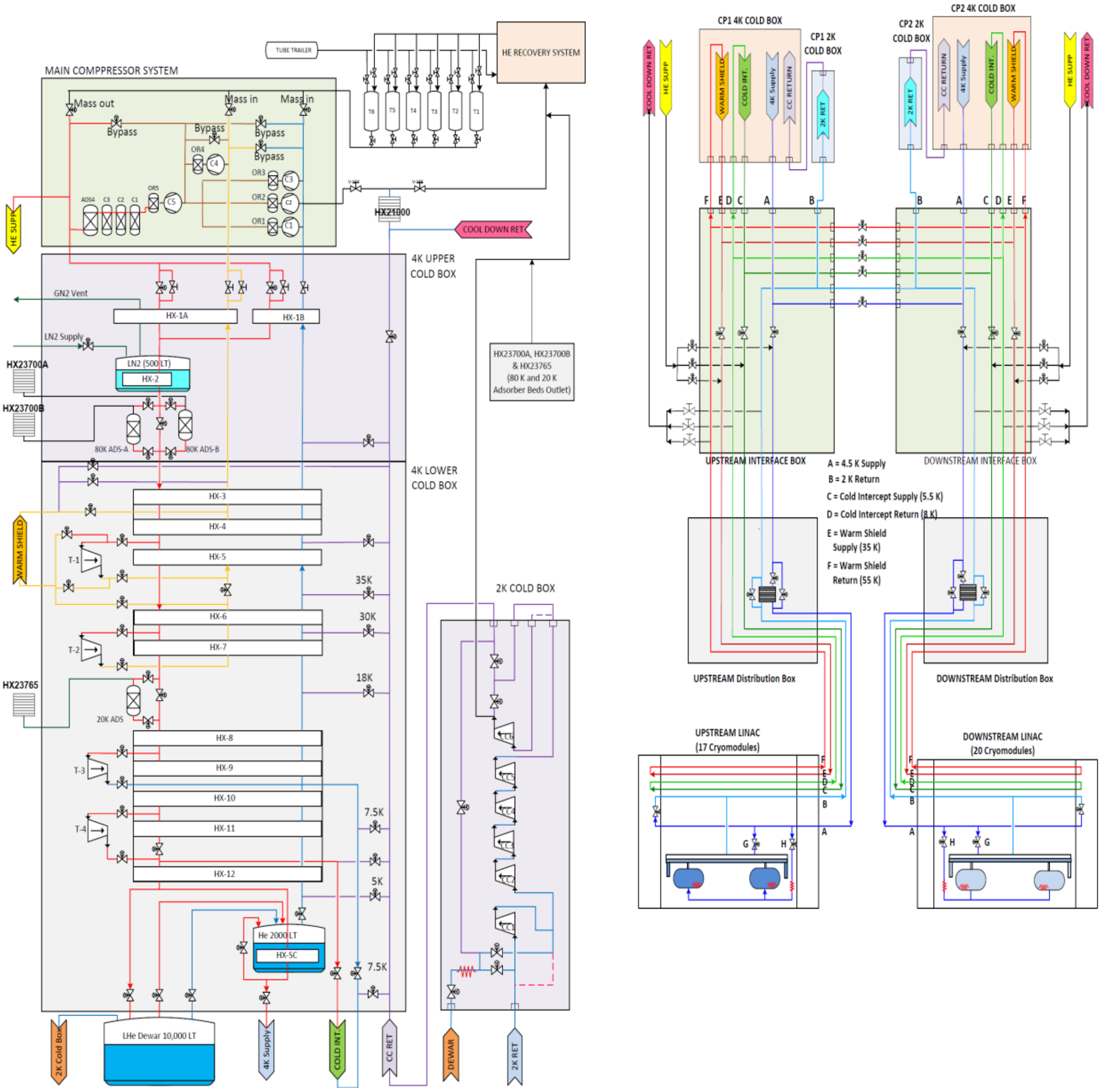

(a) **(b)**

Figure 5: LCLS-II Process Flow Diagram.

Table 2: 2 K Cold Compressor Specification.

Cold Compressor Config.	Modes	Mass Flow [g/s]	CC1 Suc. Press. [mbar]	CC1 Suc. Temp. [K]	CC Dis. Press [bar]	CC Dis. Temp [K]
	Max	215	27	3.5	1.2	< 30
	Min	150	28	3.6	1.2	< 30
	Max	132	27	3.5	1.2	< 30
	Min	100	28	3.6	1.2	< 30

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4. Cryo-System Process Model

The process model for the integrated LCLS-II cryo-system was developed in Excel® using the built-in VBA tool. The following approach was used for the process model: (1) The entire process model is split in small control volumes, (2) At the boundary of the control volumes boundary conditions-temperature and pressure are prescribed as “independent variables”, (3) Mass Flows (turbine mass flows) within each control volume starting from the “Cold End” (LINAC→Warm Compressor System) are computed using “Steady State Steady Flow Process” assumptions.

For simulating off-design conditions/turn down mode, the following approach was used: (1) The compressor (HP) discharge pressure/turbine inlet pressure is varied while ensuring that the computed turbine mass flow for each control volume satisfies the vendor provided design turbine flow coefficients, (2) The suction pressure of the HP and MP stages are solved given the mass flow from the cold box solution, (3) Heat exchanger UAs are estimated based on the vendor provided design UA and the reduction in the mass flow rate. The temperature boundary conditions are adjusted to match with the estimated UA, (4) Heat exchangers cooling curves are checked to ensure 2nd Law is not violated [i.e., no temperature reversal & crossing curves, inside the heat exchanger]. The process T-S diagram obtained from the process modelling for Mode 1: Maximum Capacity is shown in figure 6.

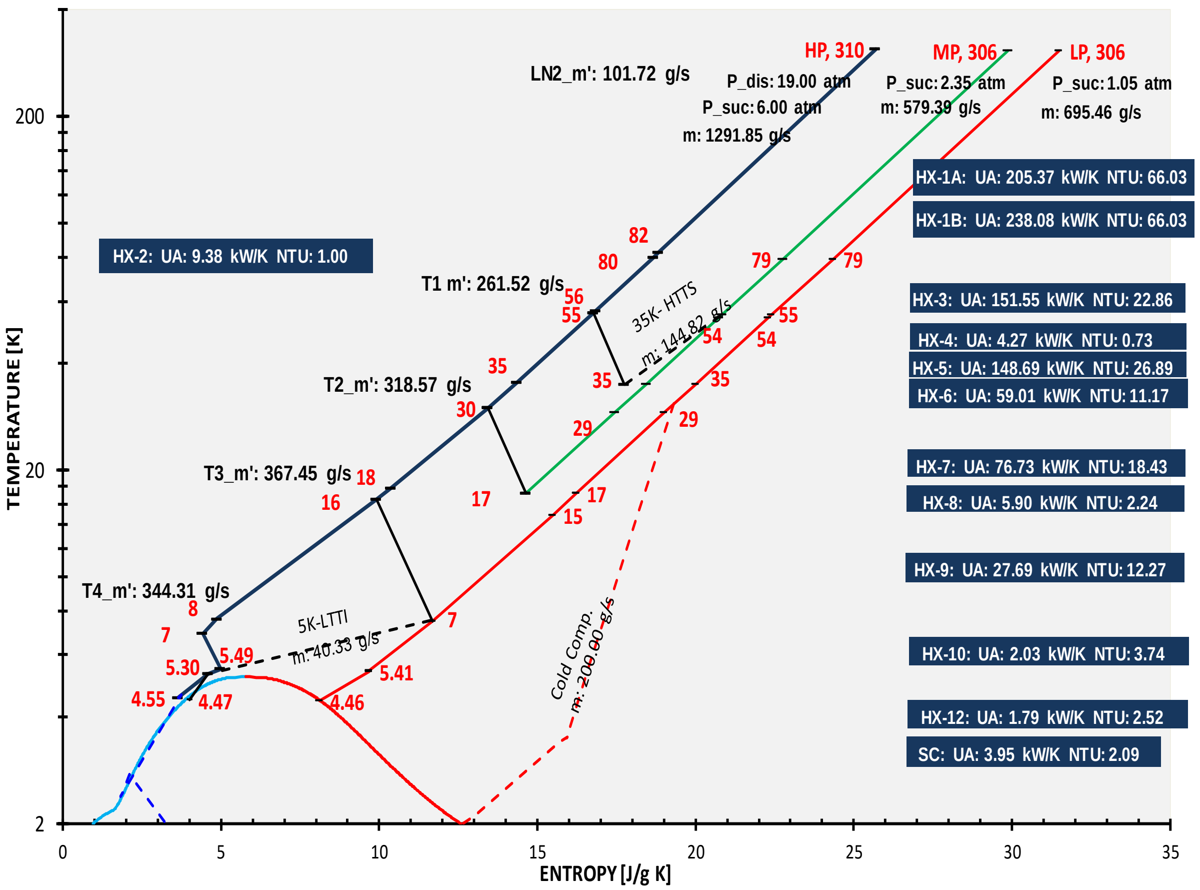

Figure 6: Mode 1, maximum capacity process TS diagram.

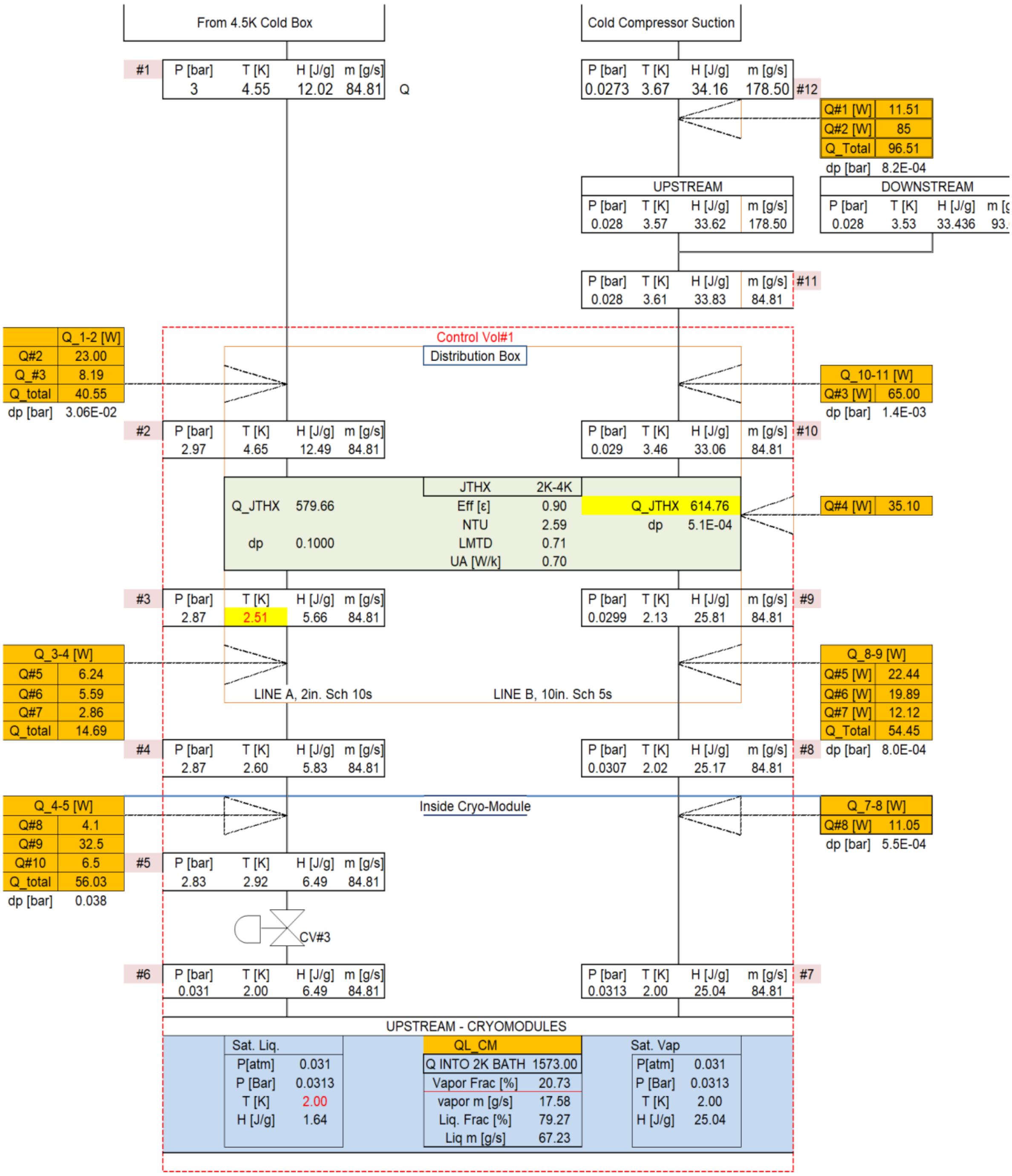

Figure 7: 2 K Process Model Example (E=16 Mv/m, Q_0 = 2.7x10^{10}, Upstream LINAC).

Figure 7 shows an example of the process modelling work done to establish the input conditions at the suction of the 2 K cold compressors. In the 2 K process model, the 2 K mass flow required for a given heat load is obtained from the energy balance for the control volume (represented by the red dash line indicated in the figure) drawn around the 2-4 K heat exchanger, the surface and tunnel transfer lines and the cryomodules. The heat loads on the transfer lines and the pressure drops were calculated and input in the process model [3].

Table 3 presents a summary of the 2 K process parameters-mass flow, cold compressor suction pressure temperature, density & volumetric flow for the given variation in the Linac heat loads (row 3) for varying cavity quality factor (row 2) and selected operating gradient (row 1). Rows 4 and 5 show the 2 K mass flow generated from each segment of the Linac. Row 7 indicates the configuration (high-flow or low flow) of the cold compressor for the given Linac heat load conditions.

Table 3: Summary of 2 K Operating Conditions at Cold Compressor Suction.

Rows		Description	First Light			Normal Beam Operation				
#1	LINAC CONDITIONS	Gradient (MV/m)	E = 14 MV/m			E = 16 MV/m			E = 19 Mv/m	
#2		Quality Factor, Q0	$2x10^{10}$	$2.7x10^{10}$	$3x10^{10}$	$2x10^{10}$	$2.7x10^{10}$	$3x10^{10}$	$2x10^{10}$	$3x10^{10}$
#3		CM 2 K Heat load [kW]	3.414	2.644	2.395	4.369	3.374	3.069	5.899	4.085
#4		2K Flow-Upstream Linac [g/s]	87	68	62	109	85	77	144	100
#5		2K Flow-Downstream Linac [g/s]	93	72	66	121	94	86	164	115
#6	2K Cold Box Configuration	Number of 2K Cold Box	1	1	1	2	1	1	2	2
#7		Cold Compressor Config.	H[1]	H[1]	H[1]	L[2]	H[1]	H[1]	H[1]	L[2]
#8	CP1-2K Cold Box Suction Conditions	CP1 2K CBX - 2K Max Flow [g/s]	180	140	128	109	179	163	144	100
#9		1^{st} CC Suction Pressure [mbar]	27.3	28.4	28.6	27.4	27.3	27.9	26	27.8
#10		1^{st} CC Suction Temperature [K]	3.66	3.81	3.87	3.67	3.67	3.72	3.54	3.73
#11	CP2-2K Cold Box Suction Conditions	CP2 2K CBX - 2K Mass Flow [g/s]	-	-	-	121	-	-	164	115
#12		1^{st} CC Suction Pressure [mbar]	-	-	-	26.8	-	-	24.6	27
#13		1^{st} CC Suction Temperature [K]	-	-	-	3.6	-	-	3.48	3.64
NOTES		1. High Flow Configuration								
		2. Low Flow Configuration								

5. Summary

An integrated process model was developed for the LCLS-II cryogenic system to simulate different operating modes of the cryogenic system. The process modeling capability served as a critical tool in defining the performance boundary for various components of the cryogenic system such as the 4.5 K Cold Box and the 2 K Cold Box. The process model developed for the LCLS-II cryogenic system was helpful in estimating the system performance under a wide variation in the Linac Heat Load (50% turn down). The process model results were also valuable in evaluating and cross checking vendor provided calculations.

6. References

[1] Cryogenic Heat Load, LCLS-II Engineering Note, LCLSII-4.5-EN-0179
[2] Ganni V, Knudsen P 2010 Optimal design and operation of helium refrigeration systems using the Ganni cycle Adv. Cryo. Eng. **55** (New York: American Institute of Physics) pp 1057-1071.
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