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Mechanical Design and Analysis of LCLS II 2 K Cold Box

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Abstract. The mechanical design and analysis of the LCLS II 2 K cold box are presented. Its feature and functionality are discussed. ASME B31.3 was used to design its internal piping, and compliance of the piping code was ensured through flexibility analysis. The 2 K cold box was analyzed using ANSYS 17.2; the requirements of the applicable codes—ASME Section VIII Division 2 and ASCE 7-10—were satisfied. Seismic load was explicitly considered in both analyses.

1. Introduction

The Linac Coherent Light Source II (LCLS-II), located at SLAC National Accelerator Laboratory (SLAC) in Menlo Park, CA, is a U.S. Department of Energy project tasked to design and build an x-ray free-electron laser facility for scientific research. The LCLS-II accelerator (Linac) design is based on superconducting radio frequency technology employing thirty-five 1.3 GHz SRF cryomodels and two 3.9 GHz SRF cryomodels in continuous wave operation. It requires a cryogenic system to support the cooldown of the cryomodels, to provide sufficient cooling capacity at design temperature levels, and to enable operation of the superconducting cavities and other cryogenic components within their respective operational conditions.

The cryogenic system consists of two helium cryoplants designed and procured by JLab. Each cryoplant consists of a 2 K coldbox system to achieve an operation temperature of 2 K in the RF cavities by reducing the pressure of liquid helium to 31 mbar. This paper presents the mechanical design and analysis of the two identical 2 K cold boxes.

2. 2 K Cold Box

2.1. Features of 2 K Cold Box

The 2 K cold box system is being designed at JLab. It consists of cryogenic cold compressors and the control system, vacuum jacket, internal piping, external utility piping, bayonets for cryogenic transfer lines and insulating vacuum pumps.

The 2 K operating temperature in the cavities is achieved by reducing the saturation pressure of the liquid helium bath using cold compressors. In the LCLSII 2 K cold box, 5 cold compressors are used in series to pump-down the cavities to a pressure as low as 31 mbar while the discharge side of the last



cold compressor is maintained slightly above the atmospheric pressure (approx. 1.2 bar) and is at a temperature of approx. 30 K. The discharge flow from the 2 K cold box is then routed to the 4 K cold box for refrigeration recovery.

2.2. Design of 2 K Cold Box

The design of the LCCLS II 2K cold box is largely based up on the FRIB 2 K cold box design. Both LCLS II 2 K cold boxes feature a large vacuum vessel topped by a 50.8 mm (2") thick flat plate, buttressed by a central column, that supports six cold compressors and associated piping. Multiple external bayonet arrangements permit modification of the flow path through the box so the nominal flow can be adjusted by approximately 24% without altering the internal piping. Figure 1 shows the overall 2 K cold box structure.

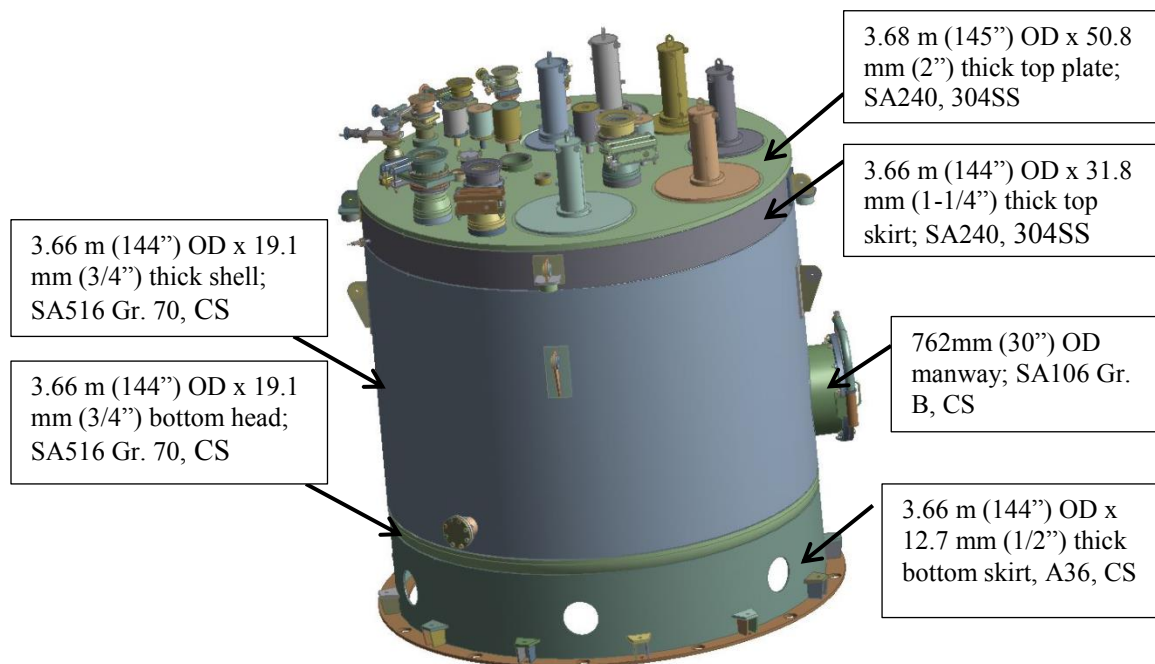


Figure 1. LCLS-II 2 K cold box.

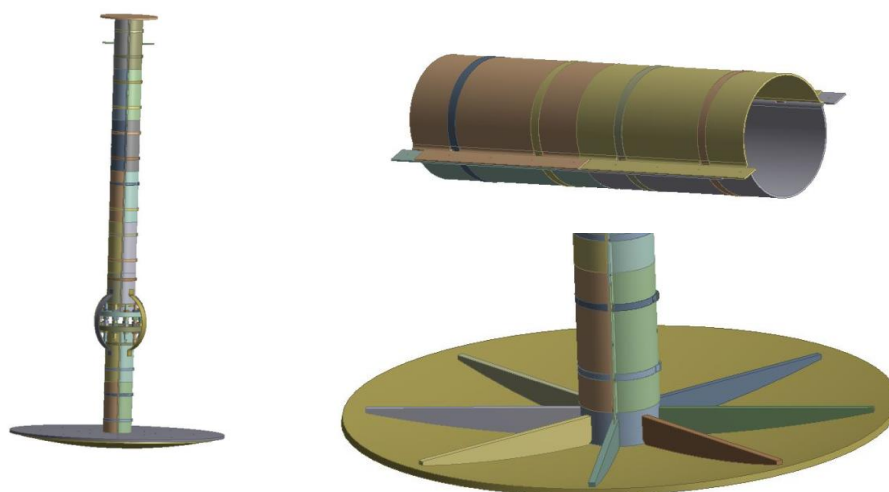


Figure 2. Mechanical Design of Center Column.

2.3. Design of Center Column

A center column is required to reduce the displacement on the top plate. It is made of two sections of 8" NPS Sch. 80 stainless steel (SS) pipe. Two sections are connected by tie rods and nuts for alignment purpose. To reduce its shrinkage, copper clamp shells are clamped to the outside surface of the center column. Four copper ribbons connect the copper upper and lower cylindrical sections. Copper foil is wrapped around the pipe to increase the surface contact between it and the copper cylindrical sections. Plates and radial gussets, "spider-ribs", are designed so the load can be evenly distributed to the vessel. Figure 2 illustrates the mechanical design of the center column.

The lowest temperature is calculated assuming a heat flux of 4 W/m^2 (0.4 W/ft^2) applied to the center column from cold piping system having a total height of 3.66 m (12 ft) [1]. This temperature, located at the center of the center column, is 295.2 K if an ambient temperature of 300 K is assumed.

3. Flexibility Analysis of Internal Piping System of 2 K Cold Box

3.1. Code Requirement

All piping is designed in accordance with ASME B31.3-2014 Process Piping and local requirements [2]. These local requirements include the 2013 California Building Code (CBC), its reference standard ASCE 7-10, and the Cryogenic Plant Seismic Design Criteria [3, 4, 5]. Flexibility analysis is therefore required for the internal piping system of 2 K Cold Box per ASME B31.3-2014. Bentley AutoPIPE is used to perform flexibility analysis. The piping is properly sized in accordance with the piping code. Figure 3 shows the overall layout of the internal piping system.

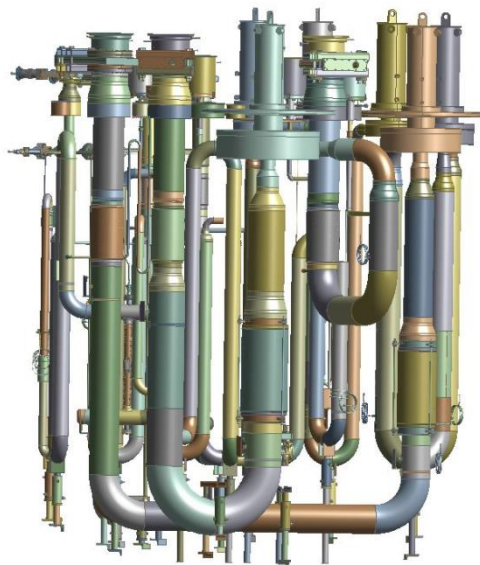


Figure 3. Internal Piping System of 2K Cold Box.

3.2. Allowable Stress of Flexibility Analysis

Per ¶ 302.3.5 of ASME B31.3-2014, the longitudinal stresses due to the sustained loads (S_L) shall not exceed the basic allowable stress at maximum metal temperature (S_h); the stresses due to the expansion loads shall not exceed the allowable displacement stress range (S_A). S_h is 115 MPa (16.7 ksi) per the code for 304L stainless steel piping; basic allowable stress at minimum metal temperature (S_c), is also 115 MPa (16.7 ksi). S_A is calculated as 173 MPa (25.1 ksi) from:

$$S_A = f(1.25S_c + 0.25S_h) = 173 \text{ MPa (25.1 ksi)} \quad (1)$$

where f [stress range factor] = 1.0.

Per ¶ 302.3.6 (a) of ASME B31.3, the sum of the longitudinal stresses due to the sustained loads (such as pressure and weight) and the stresses produced by occasional loads (such as wind or

earthquake) may be as much as 1.33 times the basic allowable stress S_h . Therefore, the allowable stress for occasional loads is 153 MPa (22.2 ksi).

3.3. Load Cases

The piping flexibility and loads on cold compressor nozzles as well as on the bayonets were checked for the shipping mode, the normal operation mode, and the normal operation plus seismic effect mode. There are two shipping cases: the first case is 1.5 g acceleration in two lateral directions plus the self-weight load; the second case is only ± 3 g vertical acceleration plus the self-weight [6]. For the normal operation mode, the following load cases were checked: gravity, thermal (process temperature), gravity and pressure (Δp of 0.41 MPa (60 psi)), gravity, pressure and thermal (process temperature). For the normal operation and seismic effect mode, 16 cases (gravity + pressure + thermal + seismic loads) were checked.

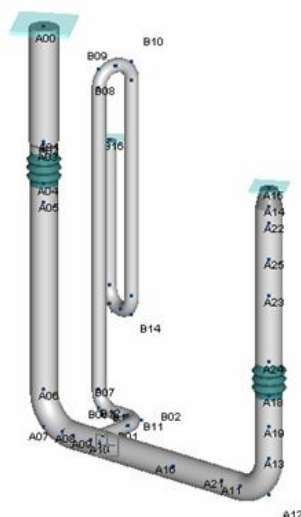


Figure 4. AutoPIPE Model of the Section Between Bayonet and the CC2 Inlet Nozzle for Normal Operation mode.

3.4. Results of Flexibility Analysis

The internal piping of the cold box was separated into 9 sections to simplify the analysis. Among them, the section between one of the three return flow inlet bayonets and the CC2 inlet nozzle has the highest stresses. Table 1 lists the stresses of this section at various modes. Figure 4 illustrates the AutoPIPE model that was used in flexibility analysis.

Table 1 Maximum Stresses of Flexibility Analysis.

Mode	Type of Stress	Stress (MPa)[ksi]	Percentage of Allowable Stress
Transportation	Maximum occasional stress	60.5 [8.78]	33%
Normal Operation	Maximum sustained stress	7.52 [1.09]	5%
Normal Operation	Maximum expansion stress	29.7 [0.43]	14%
Normal Operation + Seismic Load	Maximum occasional stress	62.1 [9.01]	34%

4. Finite Element Analysis of 2 K Cold Box

Finite element analysis (FEA) was performed to check the mechanical integrity of the cold box vessel under seismic load, vacuum pressure, weight, and cryogenic temperature. ANSYS 17.2 was utilized due to its ease of use. ASME Section VIII Division 2 and ASCE 7-10 were used for the allowable stresses and seismic load [7][4].

4.1. Finite Element Analysis Model

Figure 5 shows the FEA model used in the analysis. The original Computer Aided Design (CAD) model was simplified:

- The anchor structure was not included.
- The small open holes for control valves, feedthroughs, and other small nozzles were filled.
- The cold compressors were removed; their weight and the acceleration loads were applied to the model.
- The internal piping system was completely suppressed; its worst-case forces and moments on nozzles were applied at the appropriate locations.
- A 12' OD x 11'11" ID ring was created to simulate the 0.5" groove weld between the top plate and top skirt.
- A 12' OD x 11'11-1/2" ID ring was created to simulate the 0.25" groove weld between the top skirt and shell body.
- A 12' OD x 11'11-1/4" ID ring was created to simulate the 0.375" groove weld between the shell body and the bottom head.

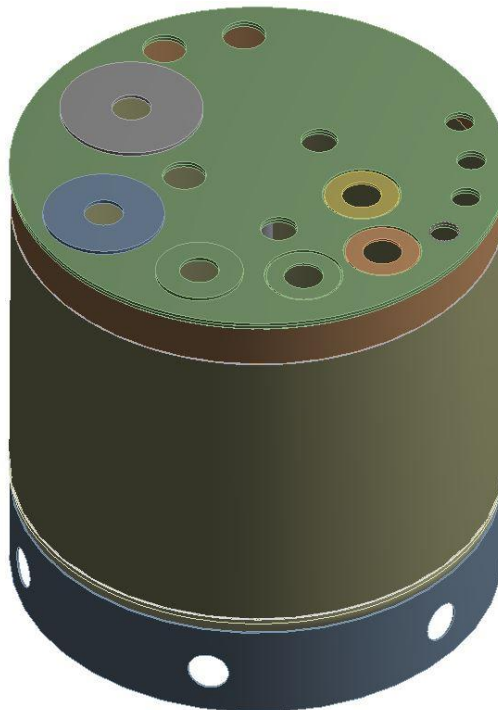


Figure 5. Finite Model of 2 K Cold Box Vessels.

4.2. Seismic Load

ASCE 7-10 and the LCLS II Cryogenic Plant Seismic Design Criteria were used to perform the seismic load calculation. The site seismic design parameters include Site Class C, SD1(1.013) and

SDS(1.968). The Risk Category for the Cryogenic Building and its associated components is II per Cryogenic Plant Seismic Design Criteria. Thus, the Seismic Importance Factor for the 2 K Cold Box is 1.0 (I_e) per Table 1.5-2, ASCE7-10.

The Cold Box vessel is a welded, steel-skirt-supported vertical vessel. It is classified as a non-building structure in ASCE 7-10. In accordance with Table 15.4-2, ASCE 7-10, the Response Modification Factor R is 2. However, since the Option 2 in the Cryogenic Plant Seismic Design Criteria is applied, it is reduced by a factor two [5]. Therefore, R is equal to 1.0, which is used in the seismic load calculation.

Table 2 summarizes the seismic design parameters and the calculated accelerations in both horizontal and vertical directions. It should be noted that the overstrength factor doesn't apply to the design of walls, including interior walls, of tanks or vessels.

Table 2 Seismic Load Calculation of Cold Box.

Parameter	Value	Unit	Name
S_{DS}	1.968	g	Design Spectral Acceleration for short periods
S_{D1}	1.012	g	Design Spectral Acceleration for 1 sec
I_e	1	NA	Importance Factor
R	1	NA	Response Modification Factor
ρ	1	NA	Redundancy Factor
Ω_0	1	NA	Overstrength Factor
C_s	1.968	g	Seismic Response Coefficient
Q_E/W	1.968	g	Horizontal Seismic Design Force
ASD Loads – without Overstrength Factor			
E_h	1.968	g	Horizontal Seismic Acceleration
E_{h1}	0.590	g	30% Orthogonal Acceleration
E_v	0.394	g	Vertical Seismic Acceleration

In Table 2, the parameters are defined as follows.

- D – the dead load or weight;
- $0.14S_{DS}$ – the vertical seismic acceleration;
- Q_E – effects of horizontal seismic forces, as required by Section 12.5.3 or 12.5.4, such effects shall result from application of horizontal forces simultaneously in two directions at right angle to each other.
- W – the effective seismic weight per Section 12.7.2

The allowable stress design (ASD) method was used to analyze the vessel structure. The two basic combinations according to 12.4.2.3, ASCE 7-10, are listed in the Table 3.

Table 3 Basic Load Combinations (ASD) with Seismic Load Effect.

Case No.	Code Requirement	Calculated ($Q_E = 1.968 W$, $\rho = 1$)
5	$(1.0 + 0.14S_{DS})D + 0.7\rho Q_E$	$1.28D \pm 1.38W$ (horizontal direction) $\pm 0.41W$ (30% orthogonal)
8	$(0.6 - 0.14S_{DS})D + 0.7\rho Q_E$	$0.32D \pm 1.38W$ (horizontal direction) $\pm 0.41W$ (30% orthogonal)

4.3. Boundary Conditions and Loads

The vacuum and the standard earth gravity as well as the seismic acceleration loads were applied to the vessel. The highest reaction loads from the AutoPipe were applied to the cold compressor nozzles and bayonets. The acceleration loads were applied to the internal piping system, the cold compressors, and the motors. The bottom skit surface was fixed in the model.

4.4. Allowable Stress

The material for the top flat head and the top 14" high skirt is SA-240 304/304L stainless steel. The shell body and the bottom head are made of SA516 Gr. 70 carbon steel. A36 carbon steel is used for bottom skirt, manway structures and anchor structures. The material properties in the Table 4 were used in the analysis.

Table 4 Material Properties [8].

Material	SA 240 304 SS	SA516 Gr. 70 CS	A36 CS
Young's Modulus (GPa) [psi]	195 [2.83E7]	203 [2.94E7]	203 [2.94E7]
Poisson's ratio	0.31	0.3	0.3
Density (kg/m ³) [lb/in ³]	8027 [0.29]	7750 [0.28]	7750 [0.28]

Table 5 Allowable Stress [7].

Stress Category	P _m	P _L	P _L + P _b	P _L + P _b + Q
SA240, 304SS (MPa) [ksi]	138 [20]	207 [30]	207 [30]	414 [60]
SA516 Gr.70 (MPa) [ksi]	138 [20]	207 [30]	207 [30]	414 [60]

Parameters in Table 5 are defined as follows:

- S – Allowable stress;
- P_m – Primary membrane stress $\leq S$ (Paragraph 5.2.2.4(e), ASME Section VIII Division 2);
- P_L – Primary local membrane stress $\leq 1.5S$ (Paragraph 5.2.2.4 (e), ASME Section VIII Division 2);
- P_b – Primary bending stress;
- Q – Secondary stress;
- (P_L + P_b) $\leq 1.5S$ (Paragraph 5.2.2.4(e), ASME Section VIII Division 2);
- (P_L + P_b + Q) $\leq 3S$ (Paragraph 5.5.6.1 (d), ASME Section VIII Division 2).

The 2K CB was analyzed per PART 5—Design by Analysis Requirements—of ASME Section VIII, Division 2 [4]. The allowable stresses for each stress category at room temperature are listed in Table 5.

4.5. Results of Finite Element Analysis

Both the stresses and displacements were found to be acceptable. Although the maximum displacement was 4 mm (0.16 in) on the top plate, the relative displacement in each cold compressor area was less than the cold compressor supplier required tolerance (1.6 mm). The maximum von-Mises stress on the vacuum vessel body was below the allowable stress as defined in Table 5. Because the von-Mises stress was lower than the allowable stress, there was no need to create a Stress Classification Line (SCL) per ASME VIII Section 2 to obtain the general primary membrane and bending stresses for comparison.

The overall stress of the center column was far below the allowable stress, but some local areas between the interface of the center column and radial gussets had high stresses (Figure 6). A stress classification line (SCL) was created per ASME Section VIII Section 2. The local membrane stress

was found to be below the allowable stress. There were several points at which primary local membrane stress plus primary bending stress was above the allowable stress as defined in Table 5, but the sum of the average membrane and primary bending stress was below the allowable stress. The local high stress on the center column was not a concern because it was due to stress concentration.

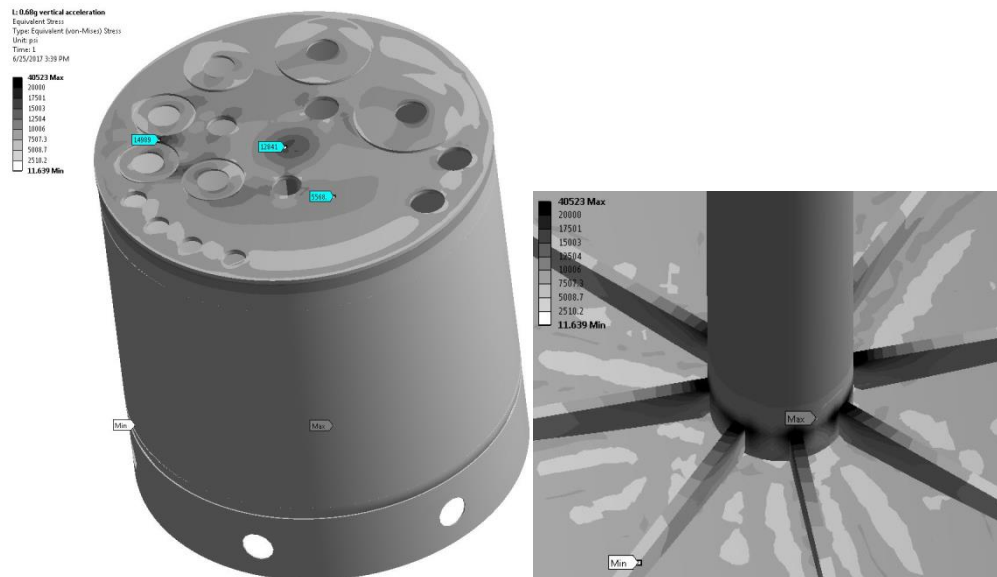


Figure 6. Overall Stress Contour with Zoom-in of the Peak Stress.

5. CONCLUSION

The design of the LCLSII 2 K cold box and the internal piping system conforms to the code requirements specified in ASME VIII Divisions 1 and 2, ASME B31.3, ASCE7-10 and LCLSII seismic requirements. The partial penetration welds—between the top plate and top skirt, between the top skirt and shell body, and between the shell body and bottom head—do not meet the ASME VIII Division 1 requirements. However, as these welds were simulated and analyzed per ASME VIII Division 2 and the design stress requirements from this division were satisfied.

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