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Cosmic Explorer Beamtube Experiment (CEBEX): Skin-Effect Heat Trace (SEHT) Reference Design

LIGO Laboratory

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1 Introduction

The purpose of this memo is to sketch out a potential design for a Skin-Effect Heat Trace (SEHT) system for the Cosmic Explorer (CE) Beam-tube EXperiment (CEBEX) system. This "reference" design is not binding upon the contractor. The scope of this memo is specifically the system, thermal and mechanical design and not the electrical design.

Since the intent of the CEBEX system is to serve as a technology pathfinder and testbed for the anticipated future CE gravitational wave observatory, the solution should be scalable and practical for 80 km.

2 Pipe and Tube terminology

In the heat tracing and pipeline literature, the process or transport "pipeline" is often referred to as a pipe. In the gravitational-wave observatory literature our vacuum tube is a beam "tube". Consequently, the CEBEX vacuum tube is referred to as the "beamtube".

In the skin-effect heat trace literature the ferromagnetic heating tube/pipe is often referred to as a tube. Since the term "heat pipe" refers to a passive two-phase heat transfer device, the SEHT heating pipe will be referred to as a "heat tube".

3 Unique aspects of a CEBEX SEHT System

The CEBEX SEHT application has five important design considerations that differ from a typical process-pipeline installation:

1) The heated vacuum beamtube is designed and constructed to the ASME BPVC section VIII requirements (rather than ASME B31.1 as is typical for process pipelines), so SEHT attachments must be compatible with its pressure-boundary design;
2) The beamtube contains no process fluid to redistribute heat, so the system must achieve the required wall-temperature distribution directly;
3) Frequent (every ~30 meters) expansion-joint bellows interrupt the otherwise continuous beamtube wall. Their thin, convoluted 304L construction limits heat conduction, requiring explicit design of heating and electrical continuity at each joint;
4) Ultra-High Vacuum (UHV) cleanliness of the interior impose requirements on the frangibility and handling of the insulation materials; and
5) Gravitational-Wave (GW) interferometer vibration requirements impose constraints on attachment methods and allowable materials (which may affect thermal boundary conditions).

The first three are the responsibility of the contractor to address, whereas the last two are the responsibility of the LIGO Laboratory to address.

4 CEBEX System Description

The CEBEX vacuum system (1.2-meter diameter by 122-meter ultra-high vacuum beamtube; Figure 1) is intended to demonstrate high-strength, low-alloy (HSLA) steel as a viable material for vacuum system construction, due to extremely low hydrogen diffusion (compared to stainless steel) and corrosion resistance (compared to mild steel). It is to be installed and operated in a laboratory building currently under construction on the LIGO Hanford Observatory grounds. Vacuum pumps,

gauges, instrumentation and clean dry air venting system will be incorporated by the LIGO Laboratory.

A heating system capable of baking the vacuum system in situ to a temperature of 150C is required to remove water and hydrocarbons from the interior surface and achieve < 10^{-9} torr pressure. This heating system, using the skin-effect heating technology, is the subject of this reference design.

The dimensions of the CEBEX beamtube segments (Figure 2, Figure 3, Figure 4) are:

- 1219.2 mm (48 in) OD
- 4.7625 mm (3/16 in) thick
- 14.5 m (570.87 in) long
- high-strength, low-alloy (HSLA) steel

The spool pieces have the same diameter and thickness as the beamtube segments.

The dimensions of the bellows (Figure 5) are:

- 1209.7 mm (47.625 in) ID
- 686 mm (27 in) overall length
- U-shaped convolutions
    - 2.0 mm (0.079 in) thick
    - 63.5 mm (2.5 in) pitch
    - 76 mm (3.0 in) depth
- 76 mm (3.0 in) wide tangents
- 76 mm (3.0 in) wide cuffs, 3.81 mm (0.15 in) thick

The dimensions of the spools (Figure X) are:

TBW

The beamtube segments and the spools are supplied from the factory with four heat tubes welded to the beamtube segment or spool. These heat tubes are 1” NPS, schedule 40.

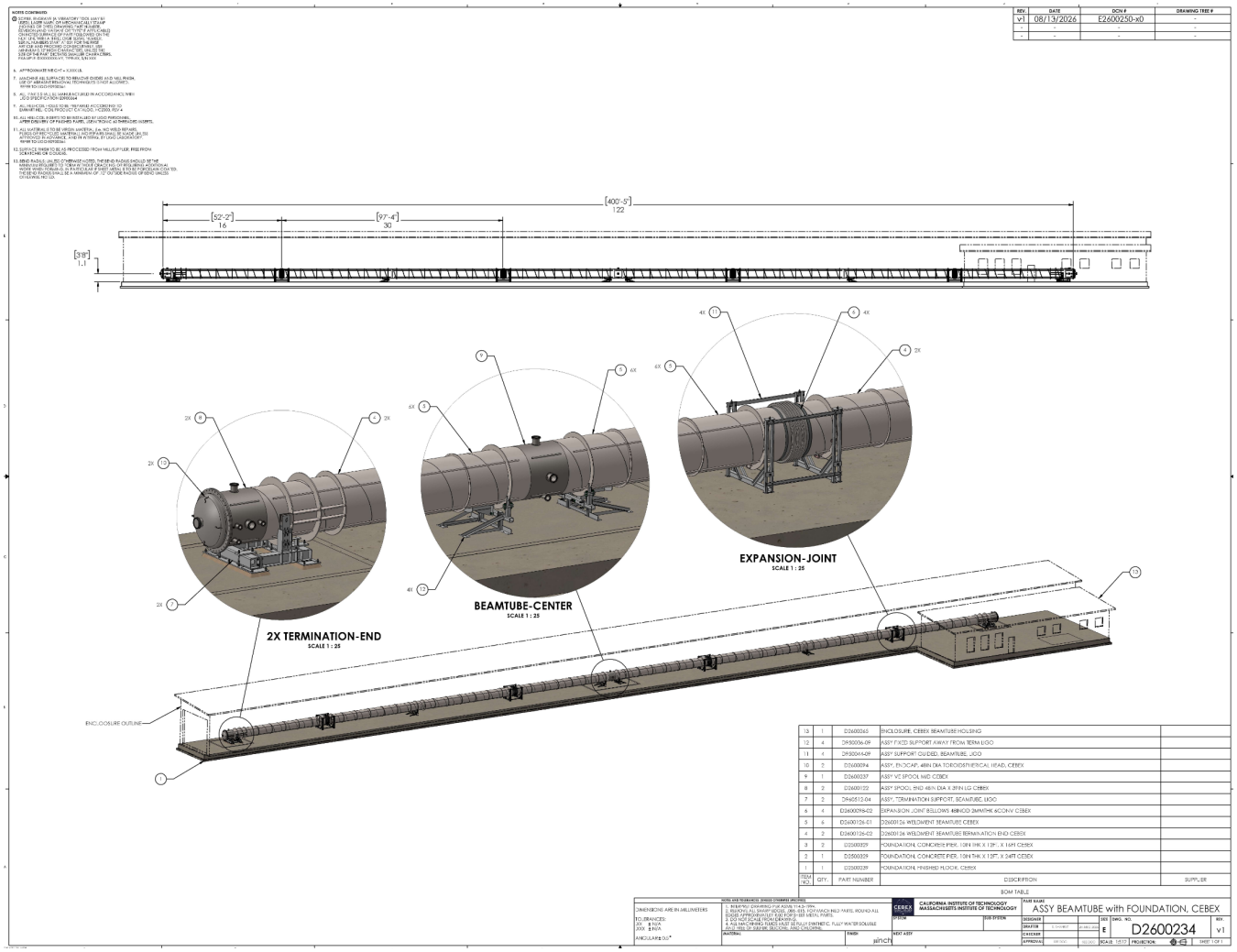


Figure 1 CEBEX Vacuum System Assembly (LIGO-D2600234)

Beamtube is housed in a climate-controlled building (phantom) purpose-built for the project. Off of the main hallway are offices, shop space, utilities, also restroom and break areas. Highlight bubbles (Left to Right) show the beamtube termination support and end chamber spool (with removable end cap), center-tube spool with fixed supports, an example of a bellows expansion joint with cable guided support.

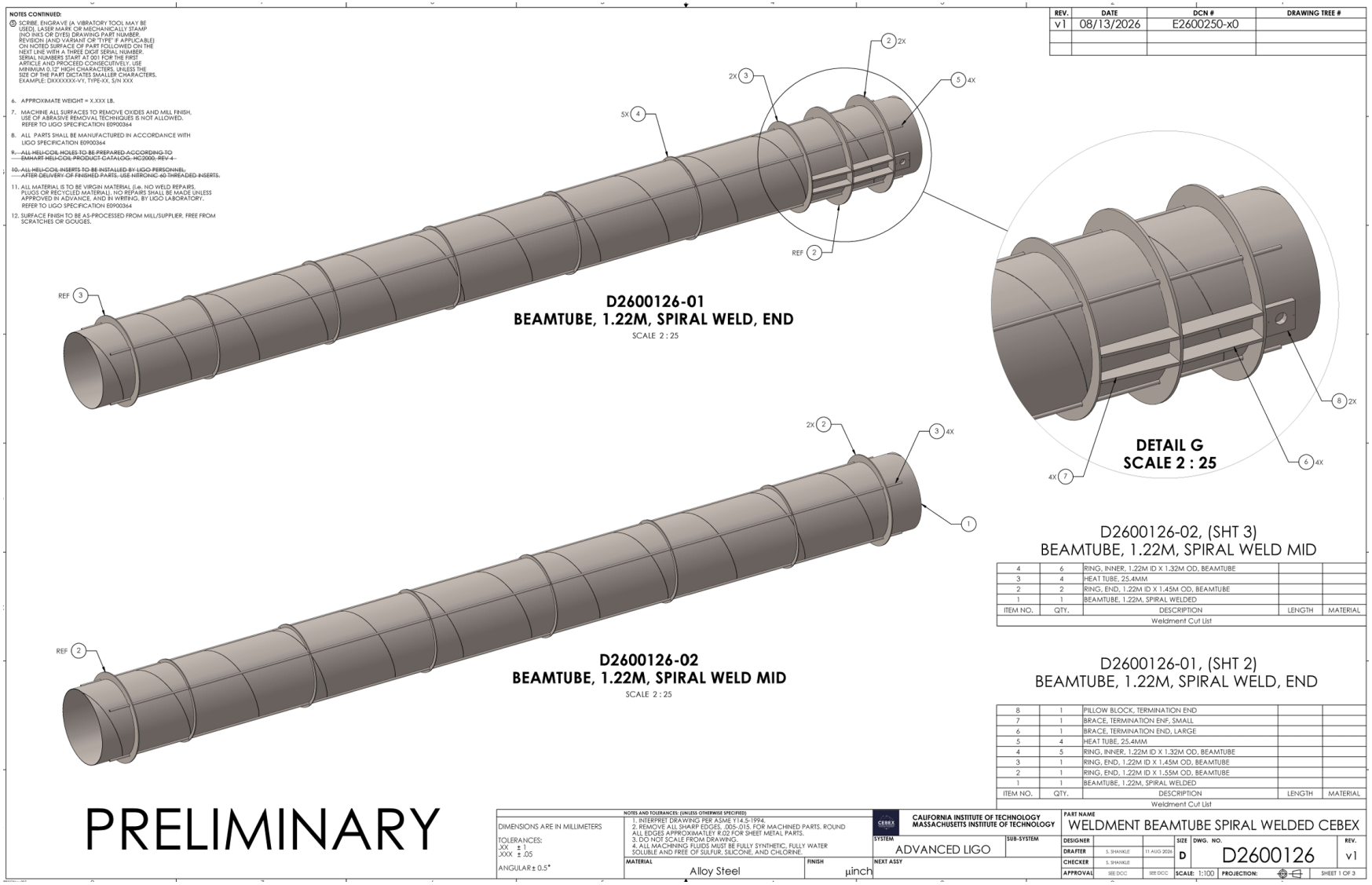


Figure 2 CEBEX Beamtube (LIGO-D2600126, sheet 1 of 3)

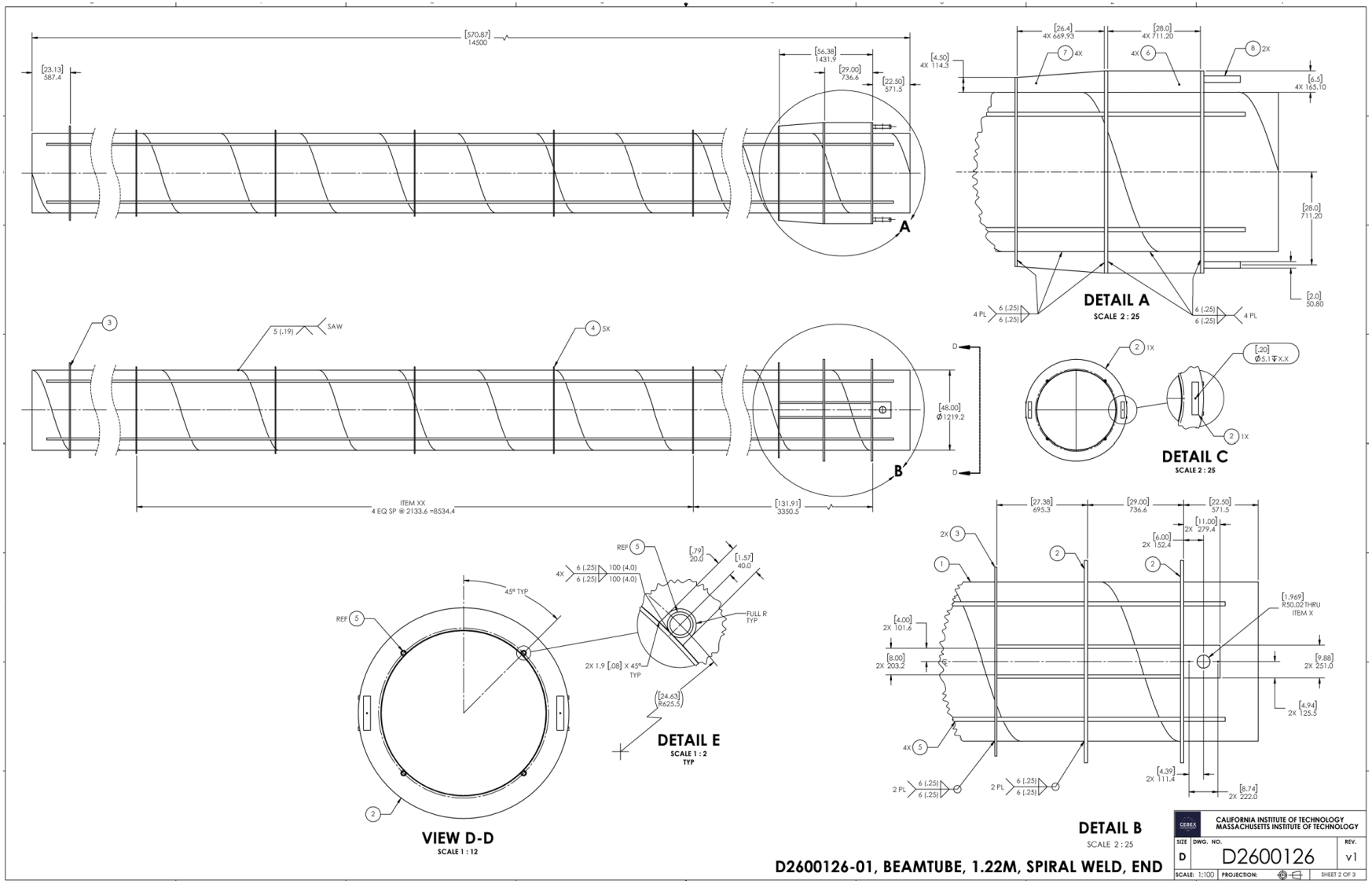


Figure 3 CEBEX Beamtube (LIGO-D2600126, sheet 2 of 3)

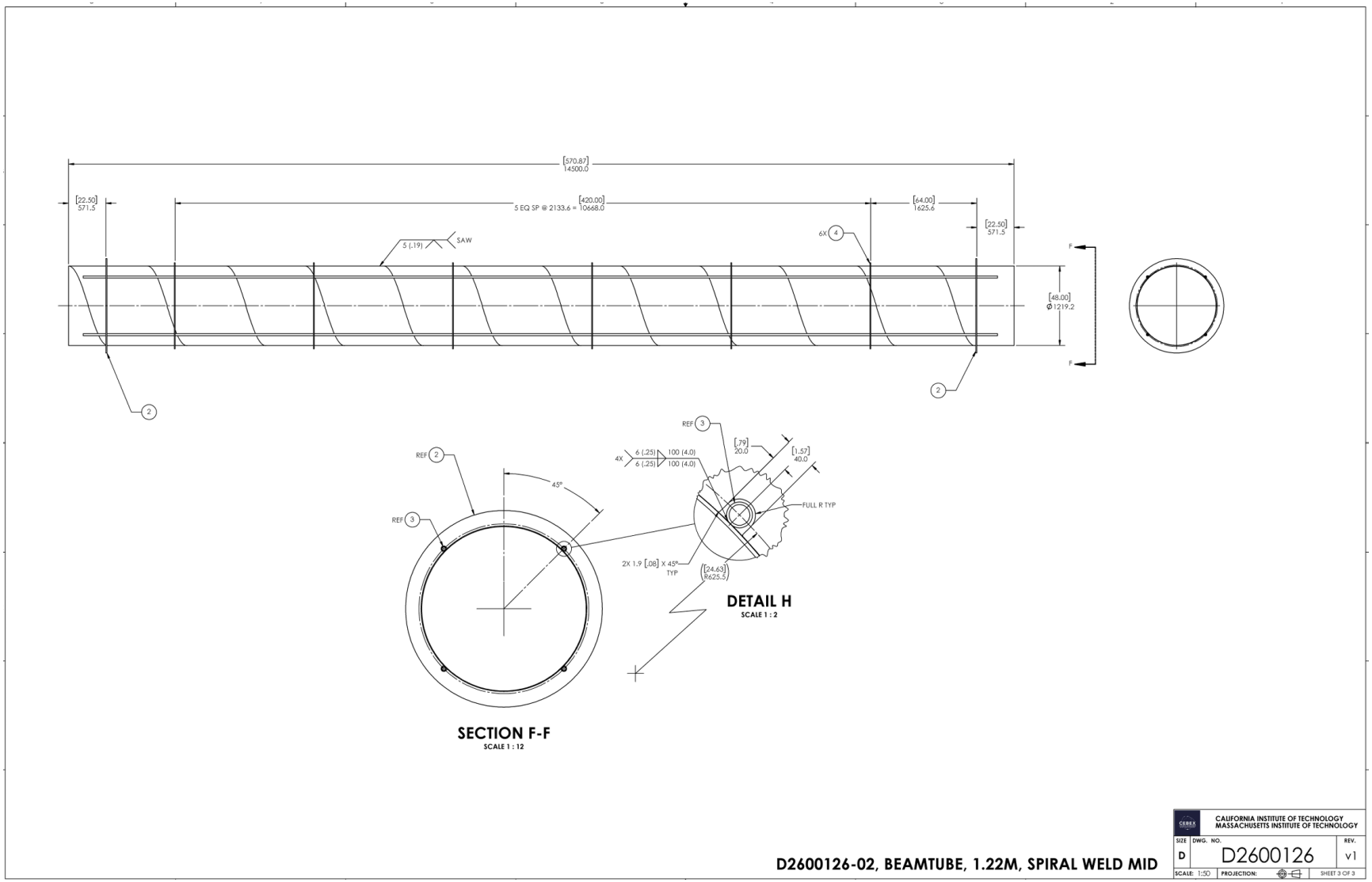


Figure 4 CEBEX Beamtube (LIGO-D2600126, sheet 3 of 3)

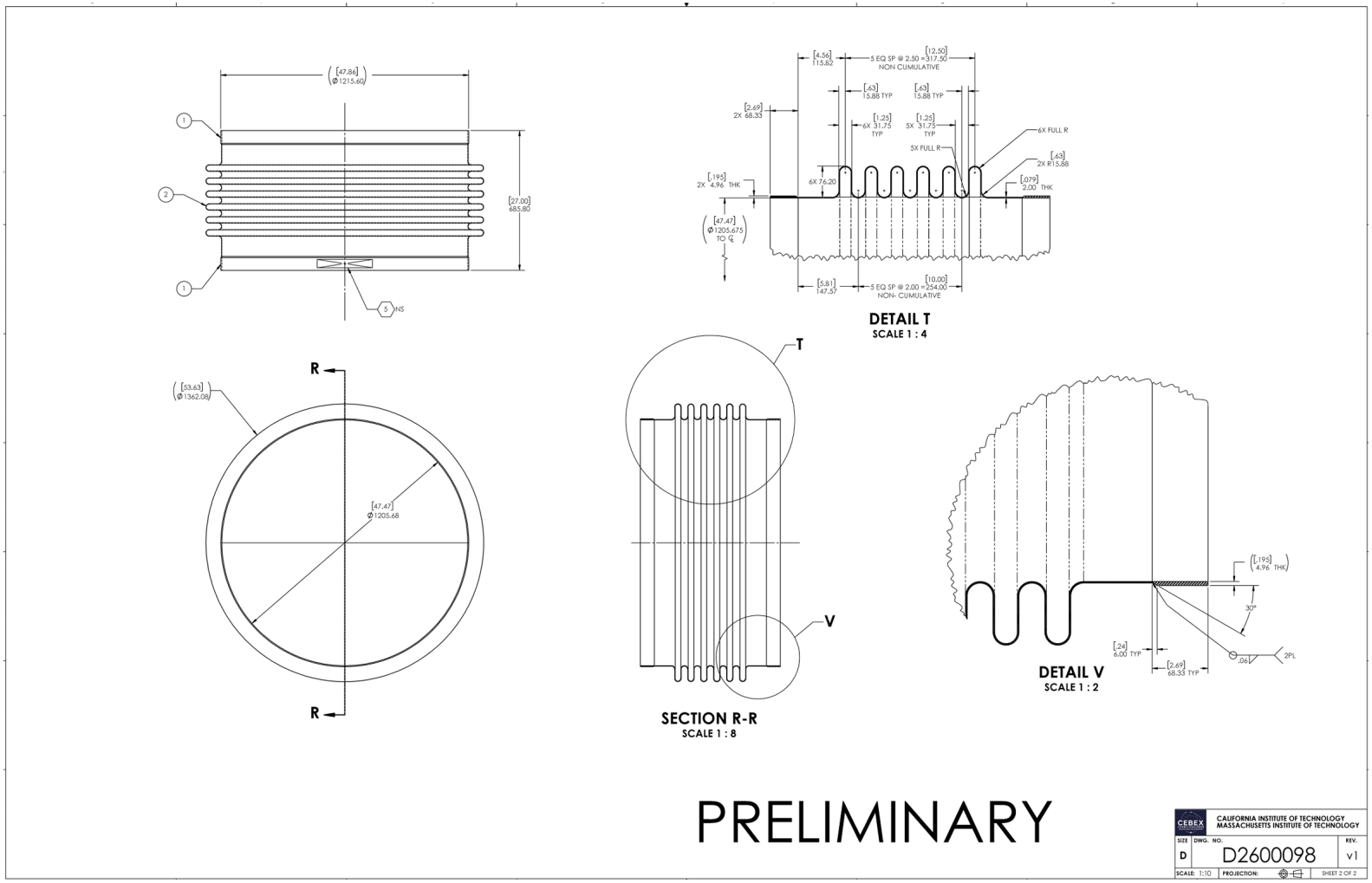


Figure 5 CEBEX Bellows (LIGO-D2600098, sheet 2 of 2)

5 Basic SEHT System Requirements

Note that contractor performance requirements are addressed in this companion document:

CEBEX SEHT Statement of Work (SOW), LIGO-E2600309

1) Lifetime:
   The CEBEX SEHT system shall have a minimum installed service life of five years and shall remain capable of completing at least 20 bake-out cycles, each having a duration of up to one month, without replacement of non-consumable components.
2) Temperature requirements (to be achieved when under vacuum):
   a. The inner surfaces of all of the vacuum system components (beamtube, spools, end caps and bellows) must achieve a temperature of 150C minimum.
   b. Required soak duration after all required surfaces reach 150C is 1 month.
   c. The maximum temperature of any component must not exceed 250C.
   d. The maximum permitted axial and circumferential temperature variation is 100C
   e. The maximum allowable ramp-up and cooldown rate is 15C/hr
   f. The maximum time to ramp up to 150C (from an ambient of 22C) is 2 days.
   g. The maximum time to ramp down (from an ambient of 22C) is 5 days.
   h. The design ambient-temperature range is 15C to 30C
3) Heat tube requirements:
   a. four heat tubes running longitudinally, equally spaced circumferentially (at 45°, 135°, 225° and 315° from top-dead-center to avoid vacuum ports),
   b. stitch or continuously welded to the beamtube without compromising the vacuum integrity of the beamtube and in accordance with ASME Boiler and Pressure Vessel Code (BPVC)
   c. Weld repairs to the beamtube are not allowed
4) Cable:
   a. A sacrificial scuff ring or scuff jacket should be specified to ensure the dielectric remains undamaged during installation.
   b. Certification of the skin effect conductor to the test requirements outlined in IEEE STD 844
   c. Capable of operating at a sustained temperature of ≥ 250C
5) Thermal Insulation:
   a. The entire system shall be enclosed in thermal insulation, designed to minimize thermal gradients and achieve the temperature requirements
   b. The thermal insulation should be moisture tolerant and rodent resistant.
6) Bridging the Expansion Joint Bellows:
   a. The SEHT implementation must not increase the expansion joint bellows stiffness (which has an axial spring rate of 0.54 MN/m) by more than 10%.
   b. Must accommodate the full bellows motion (± 88 mm)
7) Electrical Power Requirements:
   a. 60 Hz transformer with multiple taps to select an appropriate voltage for the as-installed system
   b. The CEBEX facility has a Main Distribution Panel (MDP) with a busbar operating on a 480Y/277V, 3 phase, 4 wire electrical system. A busbar tap intended for the Bake-Out power and controller is available through a100AF/100AT fixed mount Circuit

Breaker and a Switch (480Y/277V, 100AF, 3PH, 4W). If necessary the 100 amp breaker and switch can be upgraded.

8) System Control Requirements:
   a. The SEHT system shall provide automatic, closed-loop temperature control for each independently powered heating zone.
   b. The control system shall execute a programmable bake-out sequence comprising a controlled temperature ramp-up, soak at the specified bake-out temperature, controlled ramp-down and automatic completion and recording of the bake-out cycle.
   c. An independent, fail-safe high-temperature protection function shall disconnect power before any vacuum-system component exceeds 250 °C. Reset following an overtemperature trip shall require deliberate operator action.
   d. The controller shall monitor and alarm or trip, as appropriate, for:
      (a) High and low temperature;
      (b) Excessive temperature difference or rate of rise;
      (c) Temperature-sensor failure;
      (d) High or low load current;
      (e) Loss of supply voltage or phase;
      (f) Ground-fault/leakage current;
      (g) Transformer overtemperature;
      (h) Contactor or power-controller failure;
      (i) Loss of controller power or communications;
   e. The system shall include local emergency shutdown.
   f. The controller shall support load sequencing or power limiting so that the total demand does not exceed the available Main Distribution Panel (MDP) and transformer capacity.
   g. All process values, alarms, trips, operator actions, setpoints, and cycle status shall be time-stamped and recorded.
   h. Temperature sensing shall be accomplished with a fiber optic Distributed Temperature Sensing (DTS) system with a spatial resolution of 0.5 m. Temperature sensing may be collocated with each of the four skin-effect supply cables.
   i. Temperature sensing for the purpose of control and alarming should be independent from the DTS system.

6 CEBEX SEHT System Design

The CEBEX facility has a Main Distribution Panel (MDP) with a busbar operating on a 480Y/277V, 3 phase, 4 wire electrical system. A busbar tap intended for the Bake-Out power and controller is available through a100AF/100AT fixed mount Circuit Breaker and a Switch (480Y/277V, 100AF, 3PH, 4W)[1].

The most elegant and reliable electrical configuration is to group the 4 heat tubes into two independent, two-pipe series circuits powered by a custom multi-tap isolation transformer. Each pair of heat tubes are to be 180 degrees apart. Structuring the system this way delivers symmetrical

[1] One-Line Diagram, Dwg No. E701, pg 12 of 17, Meier Architecture Engineering, LIGO-D2500332.
AF = Amp Frame, AT = Amp Trip, 3PH = three phase, 4W = four wire, 480Y/277V = wye-configured system providing 480 volts between phase wires, and 277 volts from any single phase to neutral

heating even if one circuit is switched off for maintenance (preventing unsymmetric thermal stresses), avoids any risk of short-circuiting, and allows balancing the upstream electrical grid.

Based on the preliminary sizing/design, assuming a 60 Hz supply, the effective AC resistance is 0.0018 Ω/m and the required supply is 202A at 89V for each of the two circuits. Consequently, the circuit breaker and switch will need to be upgraded.

With each of the four heat tubes dissipating ~75 W/m, the beamtube, spool pieces and expansion joint bellows will reach the 150C (minimum) bake-out temperature. Two pairs of heat tubes will be wired in series, effectively creating two ~244 m long circuits. Feeding two independent single-phase circuits from a standard 3-phase 480V supply can create a phase imbalance. To prevent imbalance, we will need a Scott-T Transformer Configuration: A specialized winding connection that takes a 3-phase 480V input and converts it into two separate single-phase circuits that are 90 degrees out of phase.

- Transformer Type: Dry-type, isolation transformer with a Scott-T winding configuration.
- Total Power Rating: Minimum 45 kVA (this provides a healthy 20–25% engineering safety margin above the 36 kW continuous thermal load).
- Primary (Input) Voltage: 480V, 3-Phase, 60 Hz.
- Secondary (Output) Voltages: Two independent, single-phase outputs (90° apart).
- Target Operating Points (Per Phase Output):
    - Nominal Output: 18 kW continuous
    - Calculated Nominal Current: ~97 Amps
    - Calculated Nominal Secondary Voltage: ~186 Volts
    - Required Secondary Tap Schedule: To allow on-site adjustments for the steel's magnetic permeability and conductor impedance variations, secondary taps: 165V, 175V, 185V (Nominal), 195V, 205V

The SEHT System Schematic (LIGO-D2600282) is shown in Figure 6. Note that the number and locations of Resistance Temperature Devices (RTDs) used for temperature controller feedback and alarming/tripping is not defined. Also note that the number and locations of the fiber-optic runs of the Distributed Temperature Sensing (DTS) system are also undefined.

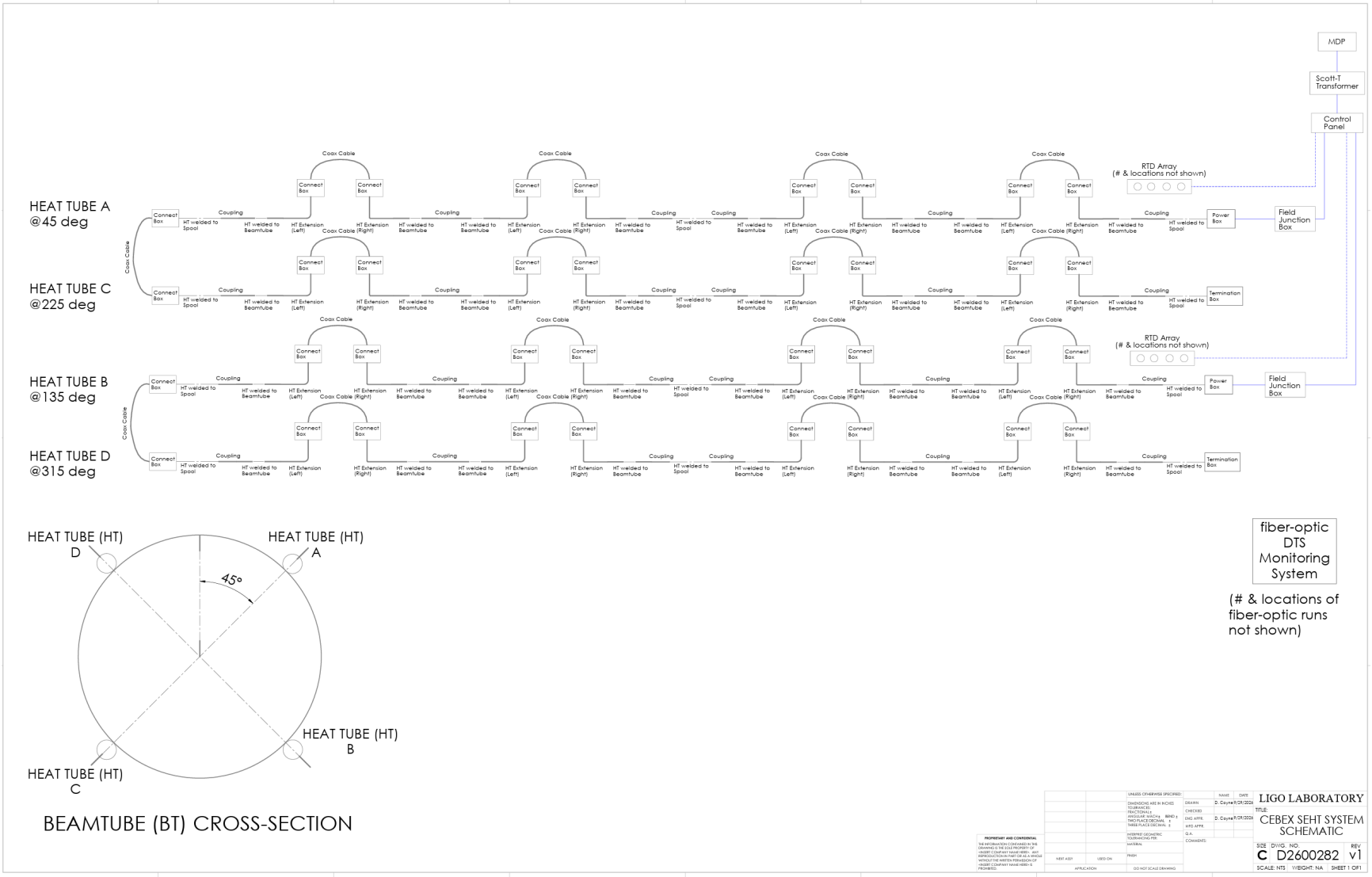


Figure 6 SEHT System Schematic (LIGO-D2600282)

7 Heat Tube Welds to Beamtube

Welding 50 mm long stitches on alternate sides at a pitch of 4 per meter has been shown by finite element analysis to be adequate to transfer the heat to the beamtube. In order to minimize the risk of weld burn-through, and a heat-affected zone extending through a relatively thin vacuum wall, laser welding is preferred.

The heat tube is terminated 150 mm short of the tube ends to allow for field welding of the tube. Welding of the pipe to the tube is terminated 450 mm short of the tube end to allow for installing and welding heat tube:

- sleeve inserts/couplings,
- pull boxes,
- power box
- termination box

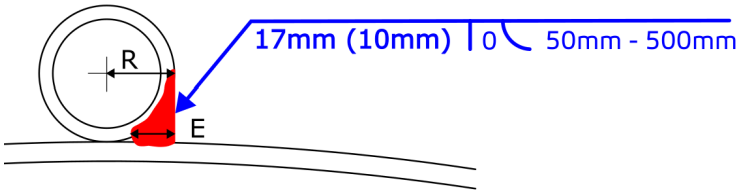
The applicable welding standards for the heat tube (a structural, non-pressurized attachment) are:

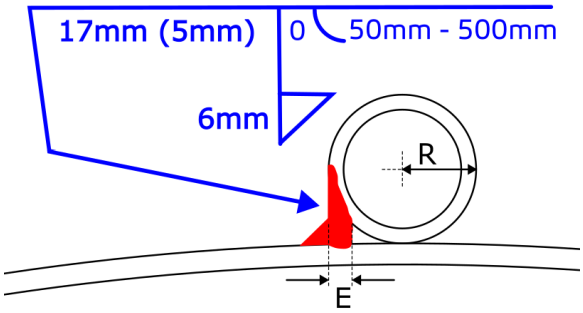
- ASME B31.3 (Process Piping), and
- AWS D1.1

For structural considerations, the design throat of a Partial Joint Penetration (PJP) weld cannot exceed the thickness of the thinner base metal part being joined. Attempting to deposit enough heat and filler metal to achieve a thicker throat in a single pass risks burn through the pipe wall. Since the heat tube wall thickness is 0.133" and the beamtube wall thickness is 0.1875", the maximum allowable effective throat (for structural considerations) is limited to 0.133". This is far less cross-section than the Flare-Bevel Groove welds assumed in the thermal analyses (see Table 1). However, since the heat tube is not structural, one can increase the weld throat (though not the root penetration depth) by making multiple passes.

In order to improve the thermal conduction at each weld, the Flare-Bevel Groove Weld should be overlaid with a Fillet Weld, as shown in Table 1.

Table 1 Heat Tube Welding to the Beamtube

Horizontal, Flush-Filled, Flare-Bevel Groove Weld	 Effective throat (E) = 10 mm (5R/8) if welded horizontal Since the throat exceeds the pipe wall thickness, the WPS should call out multiple passes.

Vertical or Overhead, Flush-Filled, Flare-Bevel Groove Weld with overlaid Fillet Weld	 Effective throat (E) = 5 mm (5R/16) Since the throat exceeds the pipe wall thickness), the WPS should call out multiple passes.

8 Conductors

SEHT Conductor: For our high temperature application (~150C), the insulation should be a fluorocarbon. A sacrificial scuff jack (scuff ring or scuff jacket) should be specified to ensure the dielectric remains undamaged during installation. Certification of the skin effect conductor to the test requirements outlined in IEEE STD 844 is required[2].

Power Conductor: Because of the exposure temperature in the power connection box, the conductor used to connect to the field junction box should have the same temperature and voltage rating as the skin effect conductor.

The maximum expected (targeted) operating temperature (on the basis of finite element analyses) is 250C.

9 Bridging the Expansion Joint Bellows

Rigid heat tubes cannot simply go straight across the expansion joint bellows; The heat tubes are too stiff and would resist the expansion of the beamtube. In addition, the expansion joint bellows have 3” high convolutions so the heat tracing must extend radially outward to bridge over the expansion joint bellows.

9.1 Required Movement

Since at this point in time we do not know whether the CE beamtube will be comprised of austenitic stainless steel (e.g. 304L like the LIGO beamtube) or high-strength carbon steel (e.g. ASME SA-737, which is the current plan for CEBEX) the selected method of bridging over the bellows expansion joint should ideally work for both beamtube options. The principal difference is the axial movement range of the bellows. Based on the LIGO Observatory beamtube design, the axial movement is ±88 mm.

[2] IEEE STD 844, IEEE Recommended Practice for Electrical Impedance, Induction and Skin Effect Heating of Pipelines and Vessels

9.2 Maximum distance between conductive links to the beamtube

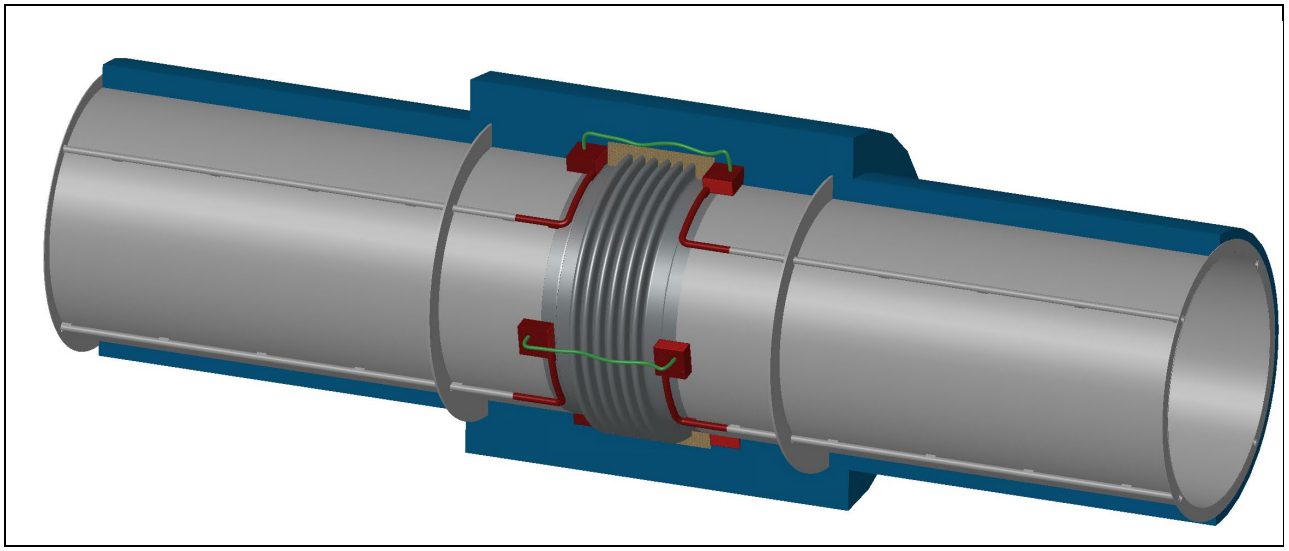
A study of the allowable distance between stitch welds of the heat tube to the beamtube indicates that the heat tube (and thus the electrical cable) will exceed likely allowable operational temperature of the electrical cable (250C) unless the distance between the welds (conductive contact points) is ≤ 333 mm. Since the overall length of the CEBEX bellows is 686 mm, or 533 mm between the cuffs, cantilevering the heat tube over the bellows results in excessive temperature even is a conductive heat strap is used on the cantilevered end.

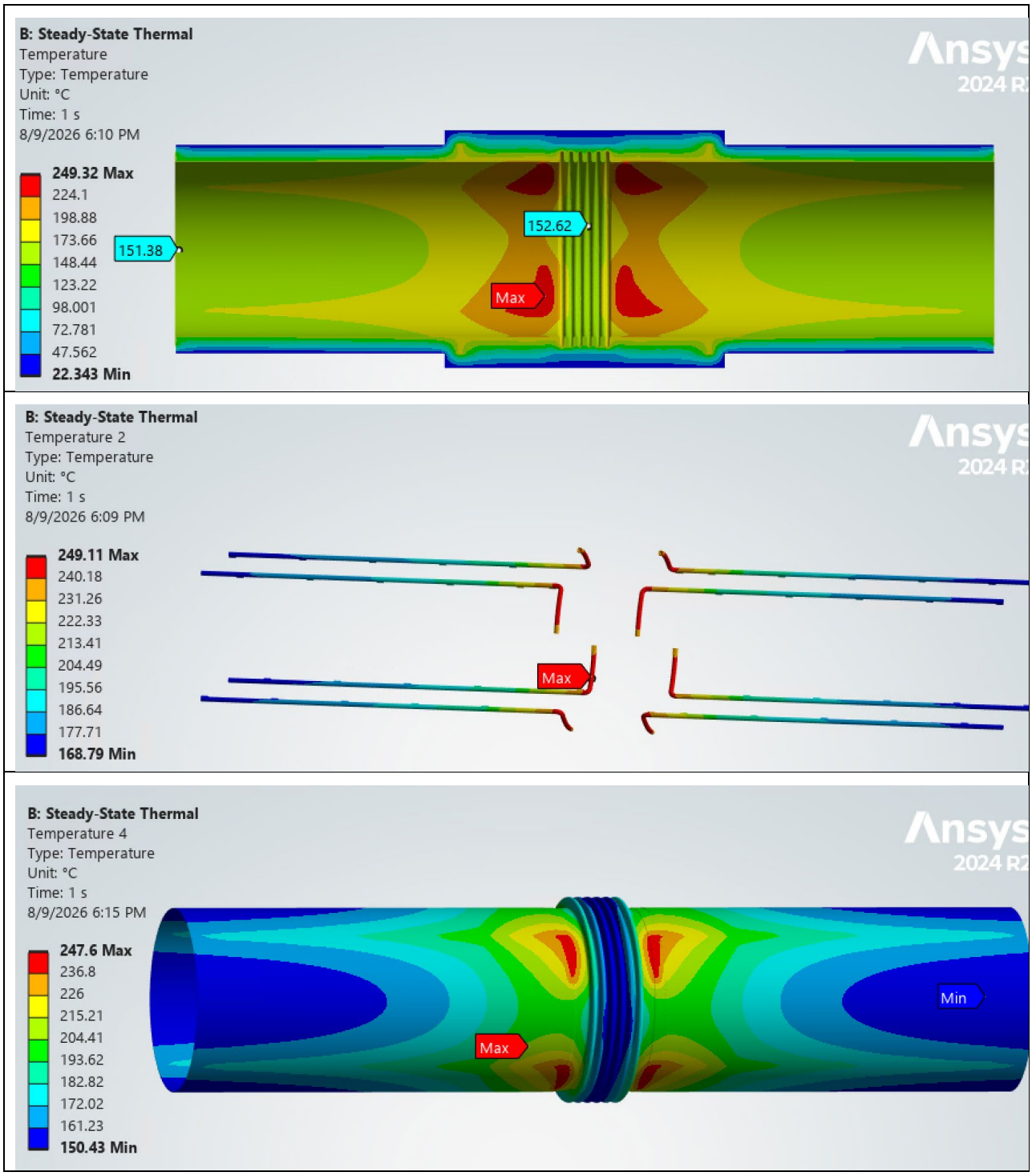
9.3 Required Insulation Around the Bellows Region

The bellows are thin (2 mm thickness), not very thermally conductive (304L stainless steel) and convoluted (so a long conduction path). Heat conduction alone from the beamtube sections into the bellows can achieve the minimum bake out temperature of 150C in the bellows if significantly more thermal insulation is deployed around the bellows and the heat tubes are routed along the perimeter of the expansion-joint bellows (0.315 m circumferentially along the bellows cuff). The predicted steady-state temperature distribution is shown in Figure 7:

- 67 W/m for heat tubes
- Heat tube (supply cable) maximum temperature = 249C
- Bellows temperature range – 152C to 231C
- Beamtube temperature range – 151C to 226C

The vacuum surfaces achieve a minimum of 150C and the supply cable is (just) within the operational maximum temperature of 250C.

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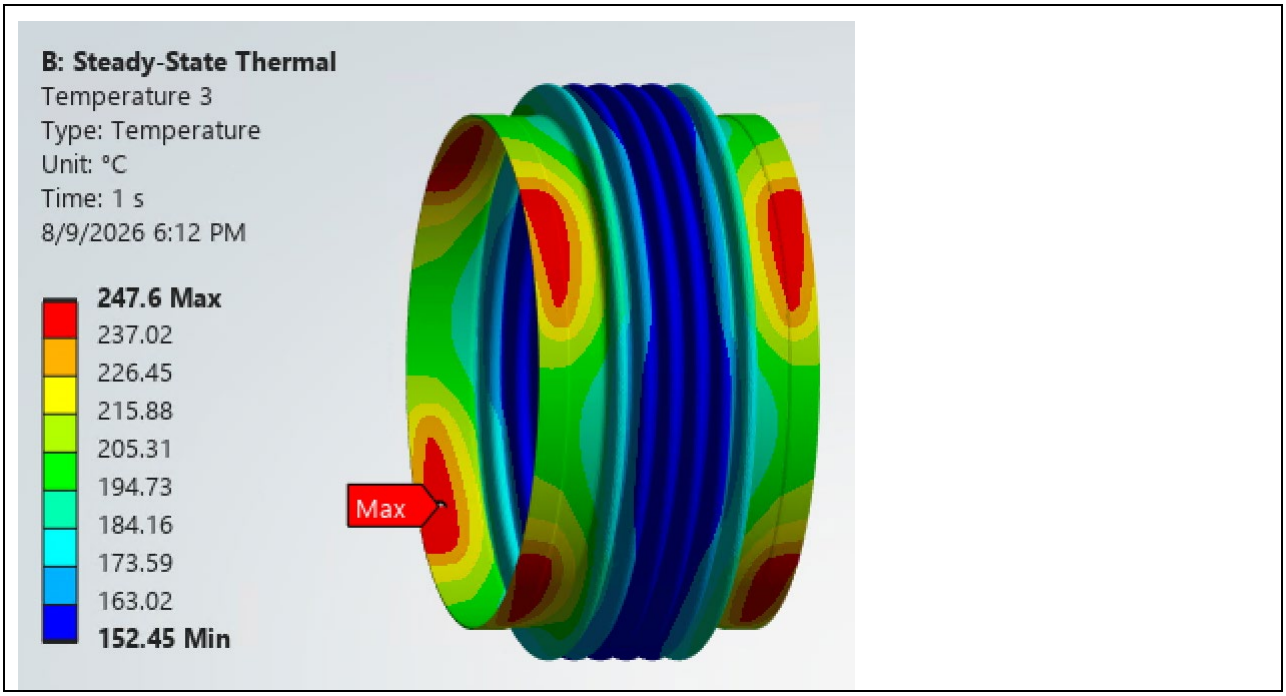

Figure 7 Heat Tube Along the Bellows Cuff

Note that while the configuration with the heat tube along the bellows cuff works in simulation, it has no margin to the maximum operating temperature of the current supply cable. Perhaps by curving the heat tube (instead of a 90 degree elbow), as depicted in Figure 8, the peak temperature can be lowered somewhat (TBD).

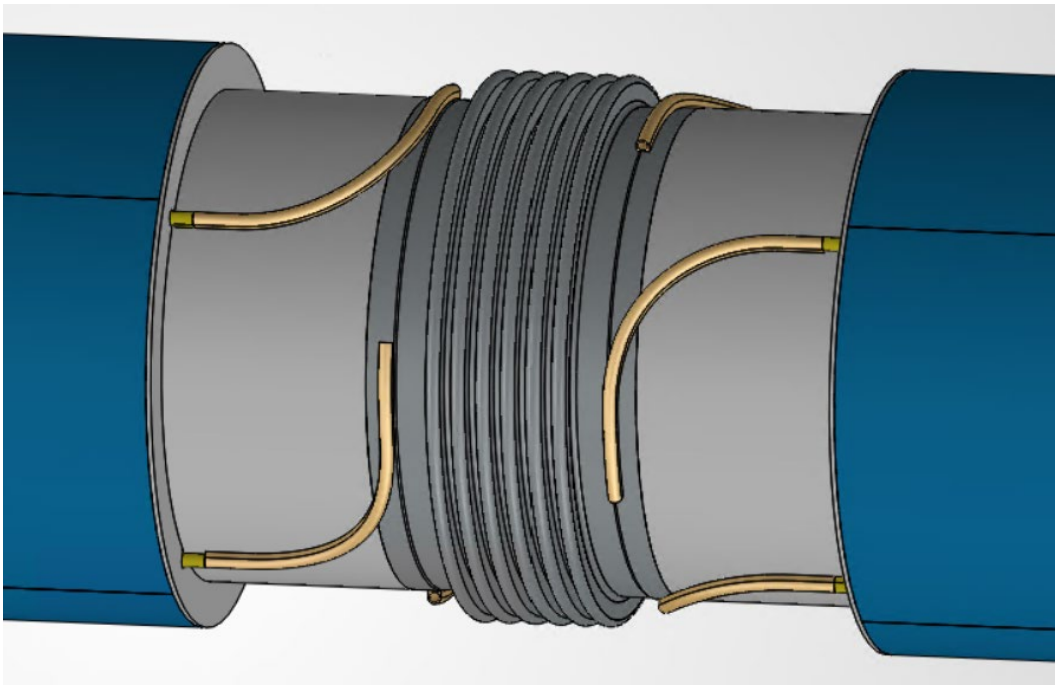

Figure 8 Curved Heat Tube Extension to the Bellows Cuff

10 End Cap Temperature Control

Whereas the future CE Observatory will have large gate valves at the ends of each beamtube, the CEBEX vacuum system has domed end caps (doors) which must remain accessible. Temperature control of the end caps can be accomplished with separate resistance wire tracing, to be provided by the LIGO Laboratory.

11 Support Structure Conductive Isolation

The load path of every beamtube support is thermally insulated.

If additional thermal isolation of the support structure attachments is required, the LIGO Laboratory will provide this isolation.

12 Insulation

The entire beamtube is to be insulated with curved segments (lagging) comprised of Foamglas One (48 inch ID x 4.5 inch thick). This insulation will need channels for the heat tubing and the beamtube stiffeners. Given the large temperature gradient across this insulation, two layers may be required to prevent cracking and spallation.

The four instances of the expansion-joint bellows require Aerogel (or Pyrolgel XTE or similar) insulation which is conformed to convolutions and extending to a diameter of 57 inches.

An additional thickness of Foamglas One is required over the expansion-joint bellows and the adjacent large diameter stiffeners on each side of the bellows (57 inch ID x 8 inches Thick x ~80 inches long).

13 Temperature Monitoring

Long pipeline systems often employ a fiber-optic based Distributed Temperature Sensing (DTS) technology analogous to time domain reflectometry. While system specifications vary, this set is representative:.

- Sensing length ~ 16 km
- Measure entire sensing length every 10s
- Accuracy of ±1C
- Measurement range: -65C to +300C
- Spatial resolution of 0.5m
- Passive along tube (no power required)
- Numerous vendors
- Feedback to heat trace power supply

Although it is technically feasible to run the DTS fiber within the heat tube, a better arrangement for controlling or verifying beamtube temperature is to run the DTS fiber separately beneath the insulation.

A reasonable route for the fiber-optic DTS runs is between the four heat tube runs, perhaps as a single 488 meter long fiber.

A skin-effect heat-tracing system can use DTS measurements in a closed feedback loop to regulate heating power, and advanced pipeline systems have been designed to do so. However, DTS is

commonly used only for supervisory monitoring, alarming, thermal-profile verification, and hotspot detection, while ordinary point RTDs or thermocouples provide the actual control feedback.

14 Temperature Regulation

Temperature regulation will be achieved by transformer voltage tap selection and current/voltage control by feedback from Resistance Temperature Devices (RTD) deployed on the beamtube.

15 Electronic Control

15.1 Full Feedback Control

Heating power can be changed by altering the applied voltage/current or by changing the fraction of time the circuit is energized. Possible control methods include:

- Contactor on/off control;
- Time-proportioned or duty-cycle control;
- Primary-side SCR/thyristor voltage control;
- Staged transformer or heating circuits;
- Motor-operated transformer tap changing; or

Any of these control methods are acceptable and up to the contractor to recommend.

15.2 Lower Cost Alternative

An alternative low-cost architecture could be:

1) Select the transformer tap during commissioning.
2) Operate normally at fixed voltage and current.
3) Use DTS or a limited number of temperature sensors for monitoring and recording.
4) Provide a simple high-temperature controller that disconnects power if the normal operating limit is exceeded.
5) Provide an independent, manually reset overtemperature cutoff for protection against exceeding 250 °C.
6) Require operator supervision and periodic review of the temperature distribution during each bake-out.

This is open-loop temperature operation with closed-loop safety protection. It avoids continuous voltage regulation, automatic transformer tap changing, and a sophisticated DTS feedback algorithm, while still protecting the equipment.

An even better low-cost option is fixed-tap operation with simple on/off contactor control from one or more representative temperature sensors. That is technically closed-loop, but it is far less expensive and complex than proportional SCR control. DTS could still verify that the coldest location has reached 150C and that no location is overheating.

We would have to demonstrate the fixed-tap approach under two bounding cases:

- Maximum heat loss: lowest ambient temperature and specified adverse insulation condition, demonstrating that every required component reaches at least 150C.

- Minimum heat loss: highest ambient temperature and best insulation condition, demonstrating that no component approaches 250C.

If a single transformer tap cannot satisfy both cases with adequate margin, simple thermostat cycling or two-stage tap/power selection would be practical and less expensive than a fully variable control system.

16 Bill Of Materials (BOM)

Component	Number or Amount
Scott-T Transformer	1
Control Panel	1 unit (2 circuits)
EMT & Wiring from MDP to Transformer, Control Panel and Field Junction Boxes	As needed
RTD Arrays	2 (1 array per circuit; RTD quantity TBD)
Field Junction Boxes	2
Power Boxes	2
Heat Tube (HT) Couplings	24
Heat Tube (HT) Extension (Right)	16
Heat Tube (HT) Extension (Left)	16
Coax Cable (jumper over bellows)	16
Connect Boxes	36
Coax Cable (jumper around end cap)	2
Termination Boxes	2
Skin-Effect Conductor	488 meters
Bellows Insulation (Pyrogel XTE, Dashamlabs Aerogel or similar)	4 instances (conformed to convolutions and extending to a diameter of 57 inches)
Beamtube (BT) Insulation (Foamglas)	Surrounding the Beamtube (BT): 48” ID x 4.5” Thickness, with cutouts for the Heat Tube (HT), BT Stiffeners and HT Extensions (near the bellows)
Additional Bellows Insulation (Foamglas)	57 inch ID x 8 inches Thick x ~80 inches long
Fiber-optic DTS Monitoring System	1 unit (≥ 2 fiber runs)