Cosmic Explorer

Beamtube Experiment (CE-BEX):

Design Specifications
& Tube Design Overview for CE

Beamtube Workshop #3 (29-Sep – 2-Oct 2025)

Caltech

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24-Sep-2025 v1

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LIGO-G2502099-v1

Scope

- Design
  - Beamtube/pipe segments
  - Circumferential joints between tube/pipe segments
  - Bellows (expansion joints), if needed
  - Support structures, including
    - Support configuration
    - alignment provisions
    - slab attachments
    - vibration isolation (**if required*)
  - Ports for pumps and instrumentation
  - Valving to isolate pumps & instruments
  - Valving to isolate BT sections
  - Baffle attachment
  - **Pumping & Instrumentation System

- Fabrication
  - ***Beamtube material (coil) processing (rolling, forming, welding, cleaning, …)
  - Beamtube/pipe segment manufacturing
  - Beamtube segment cleaning
  - Beamtube segment leak testing
  - Transport/logistics
- Assembly
  - In-situ installation
  - Alignment
  - Field circumferential joint welding
  - Bake-out system
  - Quality Assurance
  - Module Leak Testing

**Potentially big design driver; Awaiting WG#3 input*
***deferred scope for WorkShop#3*

****except material pre-processing (coil hydrogen degassing, surface passivation, etc.) which is covered in WG#1*

Assumptions & Interfaces

- Above ground
- Concrete slab interface for beamtube supports
- Enclosure assumed
  - impact and ballistic protection
  - mitigation of environmental factors (lightning, wind, snow, solar heating, …)
- Light Baffling
  - Separate baffles placed/secured in the beamtube interior
  - Potential requirements on beamtube interior surface reflective properties
- Simply repeating LIGO beamtube design/fab will fail:
  - Fab/Assy. Time scaling: LIGO BTs (8km) required > 1yr; Scaled to CE (80km) would require > 10 yr
  - Cost scaling: LIGO BTs (8 km) were $76M (1994); Estimate CE (80km) $700M in 2028

Structural evaluation with the ASME BPVC 2023 edition

Costs are always important.
However …

Long Term Reliability
is far more important than
Minimizing Cost

Beamtube Mechanical Requirements

- 80 km length (two 40km perpendicular arms)
- 1.245 m diameter (same as LIGO)
- 1.0 m clear aperture through internal baffles
  - *Tube straightness to ~10 mm (beam transmission, diffraction)
  - Determines allowable sag between supports
  - Determines alignment precision requirement (Standard differential GPS may not be adequate)
- *Seismic vibration isolation
- Capable of **150C bake
- Compliant with applicable codes for all load factors (ASCE, ASME, EJMA)
- ≥ ~50 year lifetime
- ≤ ~1 UHV leak per 10 years (10^{-9} Torr-L/s)

*Potentially significant design driver; Awaiting WG#3 input
**WG#1 considering lower temp. bake (~80C)

Structural evaluation with the ASME BPVC 2023 edition

- *See LIGO-E2500064 (in-process) for details*
- Plastic Collapse
- Local Failure
- Buckling
- Cyclic Fatigue
- Vessel Class 2

CE Pressure < 15 psig

	Class 1	Class 2
Allowable stress values	Section II, Part D, Subpart 1, Table 2A or Table 2B	Section II, Part D, Subpart 1, Table 5A or Table 5B
***Design margin against tensile ultimate strength**	3.0	2.4
***Design margin against yield strength**	1.5	1.5
Design Rules	The Design by Analysis rules in Part 5 cannot be used in lieu of the rules in Part 4.	Components for Class 2 pressure vessels may be designed using a combination of Part 4 or Part 5.

**N.B.: Design margin against buckling is at least 3.0 and generally higher for Division 1.*

Using buckling factor of 3 alone may not be sufficient – see examples below

Structural evaluation with the ASME BPVC 2023 edition

Load Case Combinations for Buckling Analysis

- D = deadload load = beamtube weight plus attachments such as pump ports, bellows, flanges, etc.
- P = Pressure load = 1 atm for CE
- T = Thermal load = compressive load from restraining the thermal expansion during a bake-out
- E = Earthquake load (defined by ASCE/SEI 7 standard)
- Loads not relevant to CE removed (i.e. static head loads, live loads, wind loads, snow loads)
- User Design Specification (UDS) may specify additional loads such as transport loads, cantilevered pump/instrumentation loads, etc.

Dominant Load when in Bake-out mode → (2)

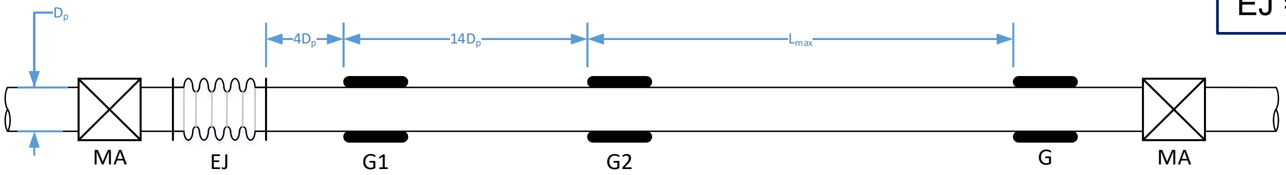
Load Case (k)	Load Combination
(1)	β_b (P + D)
(2)	0.88 β_b (P + D + T)
(5)	0.88 β_b (P + D) + 0.71 b_b E
(n)	per the User Design Specification (UDS)

β_b = buckling load factor

Beamtube Structural Support Layout/Configuration

MA = Main Anchor (or fixed support)
G# = Guided Support
EJ = Expansion Joint (aka Bellows)

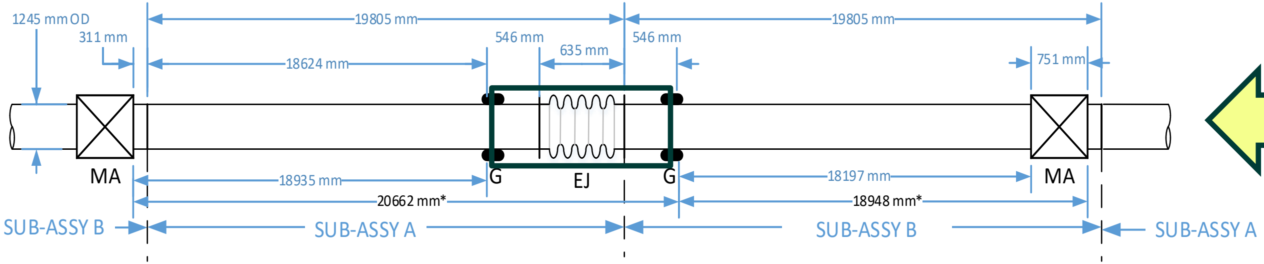
❑ EJMA Guidance



Beamtube Support Layout Options to Prevent Tube Squirm and Column Buckling

❑ CBI/LIGO Design

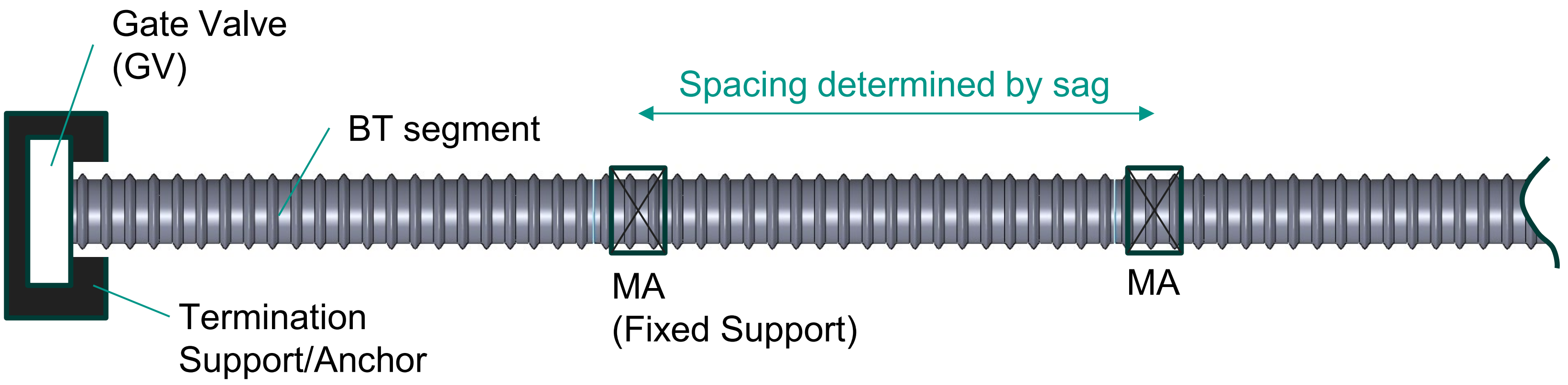
Fixed Support Spacing: bellows displacement capacity = bake-out BT expansion



CE Choice if ring-stiffened or thick-walled tube

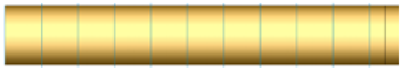
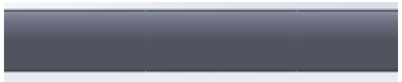
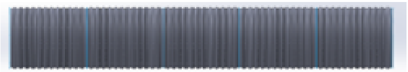
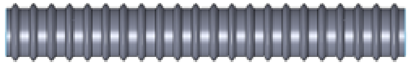
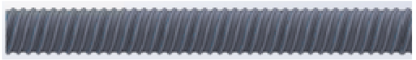
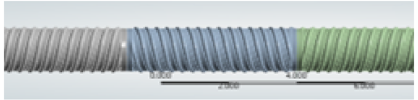
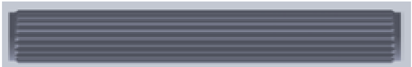
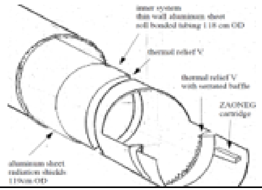
Dimensions shown are per LIGO and only for illustration, not prescriptive for CE

Beamtube Structural Support Layout/Configuration for Corrugated Tube



MA = Main Anchor (or fixed support)
No Guided Supports
No Expansion Joints (EJ, aka Bellows)

Beamtube Taxonomy

Group	Subgroup	Description	Sketch	Advantages	Disadvantages	Examples
Single-Wall		**Ring-Stiffened Tube** ✓		• Thin-walled cylinder (less material expensive if SS) • Proven technology	• Stiffening rings require additional welding • Requires EJs	LIGO VIRGO
Single-Wall		**Thick-Walled (unstiffened) Tube** ✓		• Simple construction (less fabrication expensive) • Common oil/gas pipe form	• Thick-walled (expensive if material is SS) • Requires EJs	KAGRA GinGin Oil/Gas pipelines
Single-Wall	**Circumferentially Corrugated**	**Continuously, U-shaped** ✓		• Thin-walled cylinder (less material expensive if SS) • Thermal expansion spread to many convolutions (higher cyclic fatigue life) • Common EJ form	• Requires short spacing between supports • Requires many circumferential welds • Many, highly deformed convolutions may lead to high UHV leak rate	GEO600 Expansion Joints
Single-Wall	**Circumferentially Corrugated**	**Sparsely, Sinusoidal** ✓		• Thin-walled cylinder (less material expensive if SS) • Thermal expansion spread to many convolutions (higher cyclic fatigue life)	• Shorter spacing between supports than ring-stiffened tube • Somewhat unconventional	Drainage tubing Infrastructure
Single-Wall	**Helically Corrugated**	**Single Chirality (handedness)** ✗		• Convolution forming and helical welding in a single operation (helix = skelp angle) • Convolution doesn't cross weld HAZ	• Significant axial-to-torsional coupling induces excessive stress • Somewhat unconventional	Drainage tubing Infrastructure
Single-Wall	**Helically Corrugated**	**Counter-rotating (Reversing Chirality)** ✗		• Convolution forming and helical welding in a single operation (helix = skelp angle) • Convolution doesn't cross weld HAZ	• Requires short (< 5m) segments, circumferentially welded together • Torsional coupling must be balanced between segments • Unconventional	
Single-Wall		**Longitudinally Corrugated** ✗		• Thin-walled cylinder (less material expensive if SS)	• Unconventional • Requires EJs	
Nested Cylinders ✗				• Exterior shell can be comprised of non-UHV material • Tolerant of small leaks in outer shell	• Unconventional • Complex construction • Differential pumping	

Structural Properties of Potential BT Materials

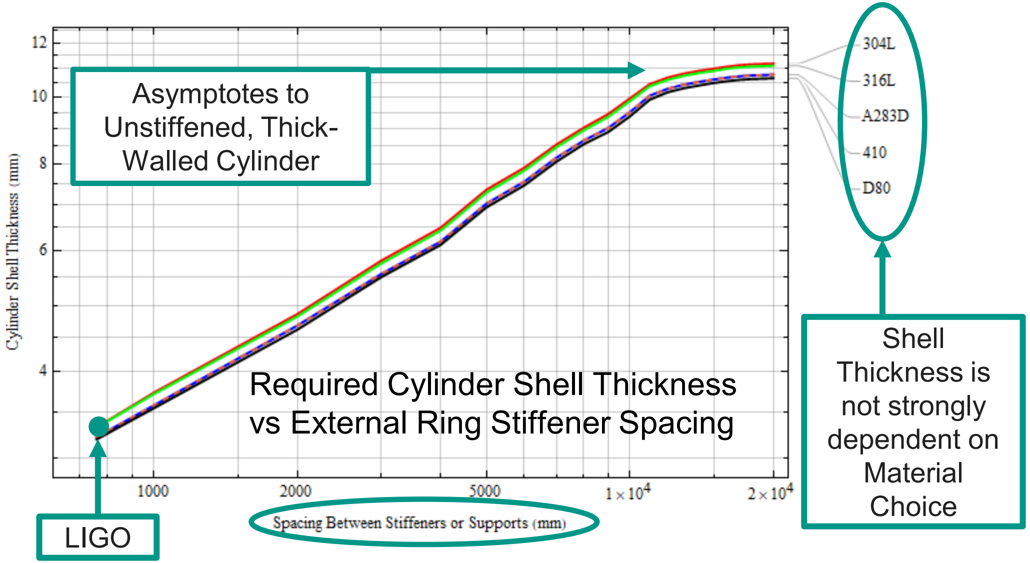
- Material pre-requisites
  - UHV compatible
  - Low hydrogen outgassing (inherently or with pre-processing)
  - Low particulate generation (with or without passivation layer, coating)
  - Weldability
- Extant GW BTs use austenitic stainless steel:
  - AISI 316L for GEO600
  - AISI 304L for all the others (LIGO, Virgo, Kagra) .
- Ferritic stainless steel (AISI 400 series) is also of interest
- Duplex stainless steels
  - mixed microstructure of both austenitic and ferritic phases
  - Superior strength, enhanced toughness (compared to ferritic), and lower cost due to less nickel content
- Low-carbon steel (aka mild steel) found to be UHV compatible (lower H2 outgassing rate than SS)
  - Trade pipe steel (API 5L) is readily available and less expensive

Grade			304/304L	304L	316L	410	A283D*	D80*
UNS			S30400	S30403	S31603	S41000	--	--
Type			Austenitic Stainless	Austenitic Stainless	Austenitic Stainless	Ferritic Stainless	Carbon Steel	Carbon Steel
Nominal Composition			18Cr-8Ni	18Cr-8Ni-C<.03	16Cr-12Ni-2Mo	Cr13	0.9Mn-0.4Si-0.27C-0.2Cu	0.98Mn-0.45Si-0.24C
ASTM Specification			SA-240	SA-240	SA-240	SA-240	SA-134	SA-672
Form			plate	plate	plate	plate	wld. pipe	wld. pipe
Elastic Modulus (GPa)		22C	195	195	195	201	202	202
		80C	191	191	191	196	199	199
		150C	186	186	186	192	195	195
Ultimate Tensile Strength, min (MPa)		22C	517	486	479	443	414	552
		80C	496	465	476	450	414	551
		150C	456	421	441	439	414	544
Tensile Yield Strength, Sy min (MPa)		22C	207	190	189	220	246	449
		80C	187	152	151	192	210	373
		150C	154	132	131	183	201	335
Allowable Stress (MPa)	Sect VIII, Div 1 Table 1A	22C*	138**	115**	115**	128	118 (NP)	158 (NP)
		80C	137**	115**	115**	127	118 (NP)	157 (NP)
		150C	130**	115**	115**	123	118 (NP)	156 (NP)
	Sect VIII, Div 2 Table 5A	22C*	138**	115** (127)	115** (126)	138 (147)	-- (164)	-- (300)
		80C	138**	115** (101)	115** (101)	128	-- (140)	-- (249)
		150C	138**	115** (88)	115** (87)	122	-- (134)	-- (223)
Poisson's Ratio			0.31	0.31	0.31	0.31	0.30	0.30
Density (kg/m^3)			8030	8030	8030	7750	7750	7750
Mean Coefficient of Thermal Expansion (CTE) x10^{-6} m/m/C		20C to 80C	16.0	16.0	15.0	11.0	11.9	11.9
		20C to 150C	16.6	16.6	16.6	11.4	12.4	12.4

NP – Not Permitted for ASME BPVC Section VIII, Division 1
-- Not listed in Table 5A for ASME BPVC Section VIII, Division 2
**actually at 40C*
***Use of these stresses may result in dimensional changes due to permanent strain; Sy/1.5 given in parentheses*

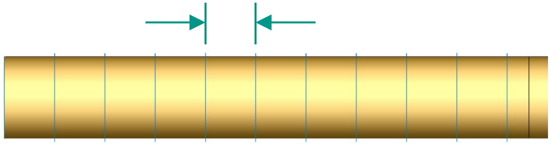
Material considerations in Structural Analyses: Ring-Stiffened and Thick-Walled Cylinders

- Ring-Stiffened and Thick-Walled Tube design is generally stiffness critical for adequate buckling factor
- Since all the materials of interest have similar values of elastic modulus, analyses are conducted for material with lowest yield stress (dual-rated 304/304L)



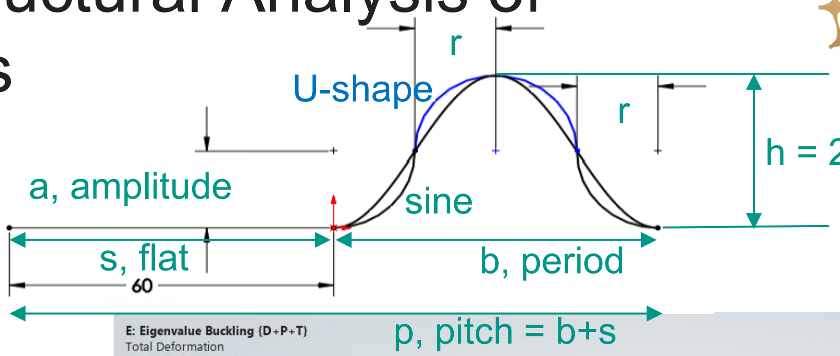
	Tube shell thickness (mm)	
Material	20 m Tube Length	758 mm Stiffener Spacing
304L	11.20	3.33
316L	11.12	3.32
410	10.79	3.22
A283D	10.79	3.22
D80	10.66	3.20
LIGO (304L)		3.23

Shell Thickness Required for 20 m Tube Length
(per ASME.2023.VIII.Division1)

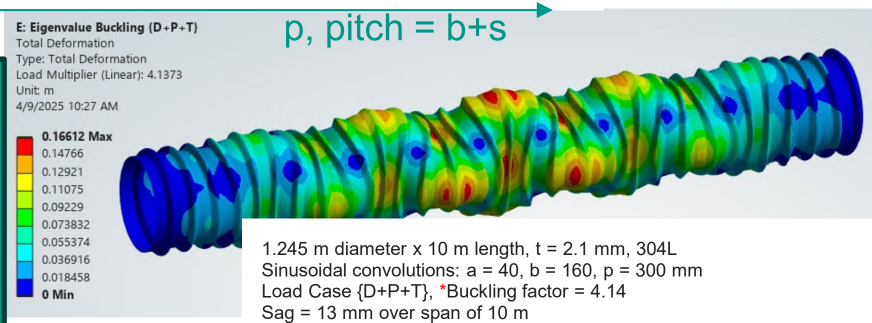


Considerations in Structural Analysis of Corrugated Cylinders

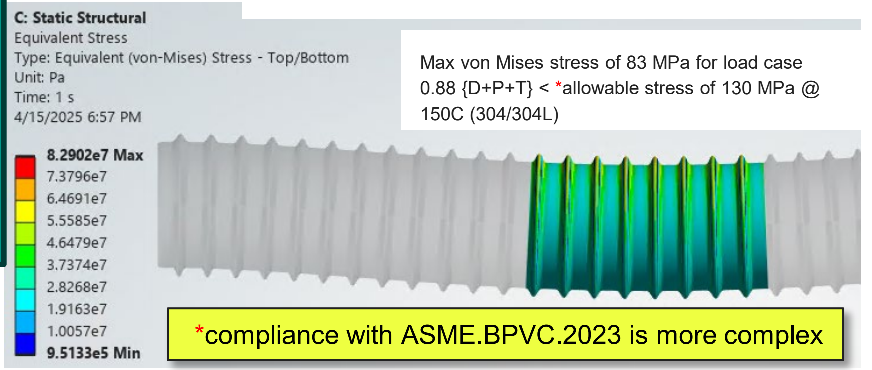
- ☐ Circumferentially Corrugated Tube design is generally stiffness critical for adequate buckling factor and acceptable sag
- ☐ We have a 7-dimensional design space:
  - ☐ Tube Material
  - ☐ Corrugation shape
  - ☐ L = length of unsupported span
  - ☐ a = corrugation amplitude
  - ☐ b = corrugation period
  - ☐ p = corrugation pitch
  - ☐ t = tube thickness
- ☐ We apriori choose:
  - ☐ 304L stainless steel material (lowest yield stress)
    - ☐ … but once other parameters are chosen we can explore material options
  - ☐ Sinusoidal shape since it is efficient for buckling while maintaining bending stiffness (and a triangular shape with bend radii to minimize stress is basically the same)
    - ☐ … but can adapt for manufacturing considerations



Corrugated Tube Example



1.245 m diameter x 10 m length, t = 2.1 mm, 304L
Sinusoidal convolutions: a = 40, b = 160, p = 300 mm
Load Case {D+P+T}, *Buckling factor = 4.14
Sag = 13 mm over span of 10 m



Max von Mises stress of 83 MPa for load case 0.88 {D+P+T} < *allowable stress of 130 MPa @ 150C (304/304L)

*compliance with ASME.BPVC.2023 is more complex

Conclusion

- The Beamtube will be a cost driver for the CE observatory
  - <u>Cost reduction (value engineering)</u>
  - <u>high confidence</u> for <u>long facility lifetime</u> is essential
- Simply repeating LIGO beamtube design/fab will fail
  - We need designs capable of <u>fast fabrication</u> and <u>fast field assembly</u> with <u>excellent QA</u>
  - <u>Automation</u> will likely be the key when scaling up to production
- From the design perspective we have at least four viable basic tube designs
  - Ring-stiffened cylinder
  - Thick-walled cylinder
  - U-shaped, continuously corrugated cylinder (i.e. continuous bellows)
  - Sine-shaped, sparsely corrugated cylinder