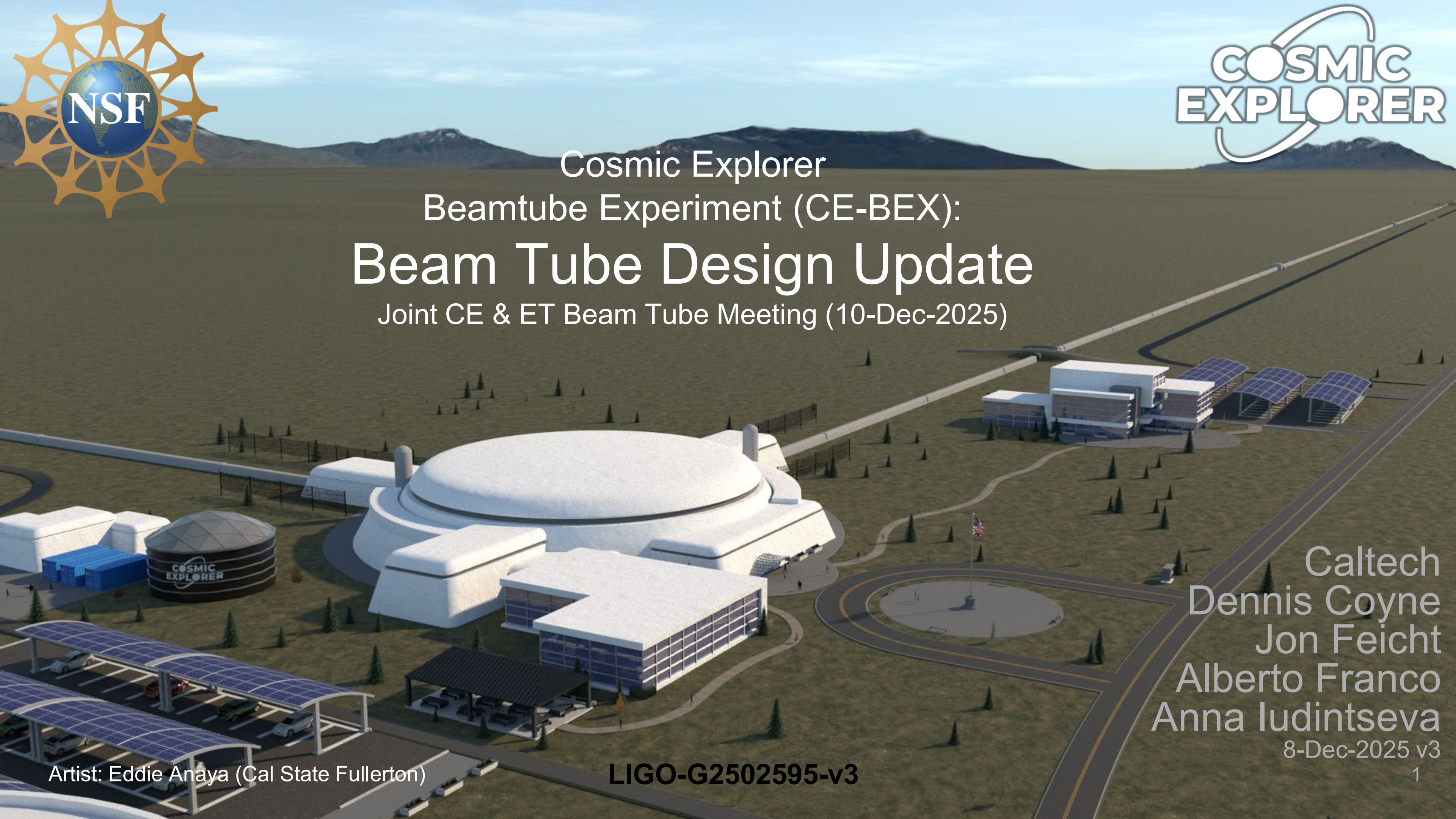


Artist: Eddie Anaya (Cal State Fullerton)

Cosmic Explorer Beamtube Experiment (CE-BEX): Beam Tube Design Update

Joint CE & ET Beam Tube Meeting (10-Dec-2025)

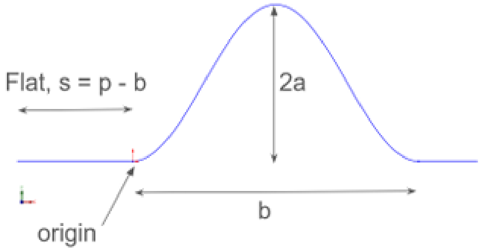
Caltech
Dennis Coyne
Jon Feicht
Alberto Franco
Anna Iudintseva

8-Dec-2025 v3

LIGO-G2502595-v3

No Manufacturing Interest in “Optimized” Cylindrical Corrugated Tube

- Sent out Request For Information (RFI, LIGO-L2500049) to ~20 companies
  - staggered, deep, sinusoidal corrugations



a*{sin[2*π*x/b-π/2]+1} from 0 to b

Fig. 6. Sinusoidal convolution profile generating equation.

- *Sinusoidal dimensions:*
  a = 58mm (2.3”),
  b = 215mm, (8.5”)
  p = 470mm (18.5”)

Sheet thickness =2.8mm (0.11”) (12 gauge)

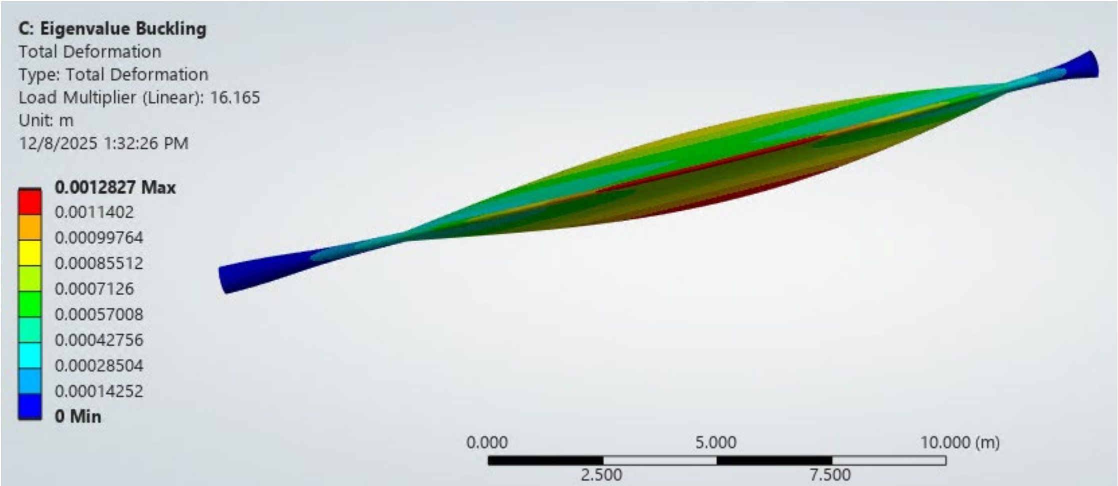
- Too different from standard manufacturing practice?
  → Apparently no interest or expression of capabilities to fabricate
- Exploring some alternatives:
  - Explore thick-walled, unstiffened, carbon steel “oil” pipe alternative
  - Explore commercially available corrugated pipe

Readily Available “Oil” Pipe

- Contingency Plan for an “Oil Pipe”
  - API-60x steel, 24” OD x 3/8” thick (schedule 20) x 100 m (609.6 mm x 9.5 mm thick)
  - Beamtube l/d ratio ~ 1/150 is perfect for 1-d diffusion model
  - Available either linear weld seam or spiral welded
- Proposed plan (LIGO-E2500307):
  - Carbon steel tube heads
  - CTE matched 304SS Conflat flanges
  - Steel Bellows
  - Heat tracing for bakeout
  - Cast Perlite for insulation
  - Distributed Temperature Sensing (DTS) using fiber optics

“Oil Pipe” appears to be Structurally Adequate

- API specified steels are not allowed in the ASME BPVC
- FEA results
  - based on similar material (A283D)
  - Coupled to a bellows at the end of a 20 m tube
  - 8 mm sag over 20 m
  - indicates adequate strength and buckling safety factor (~16x)



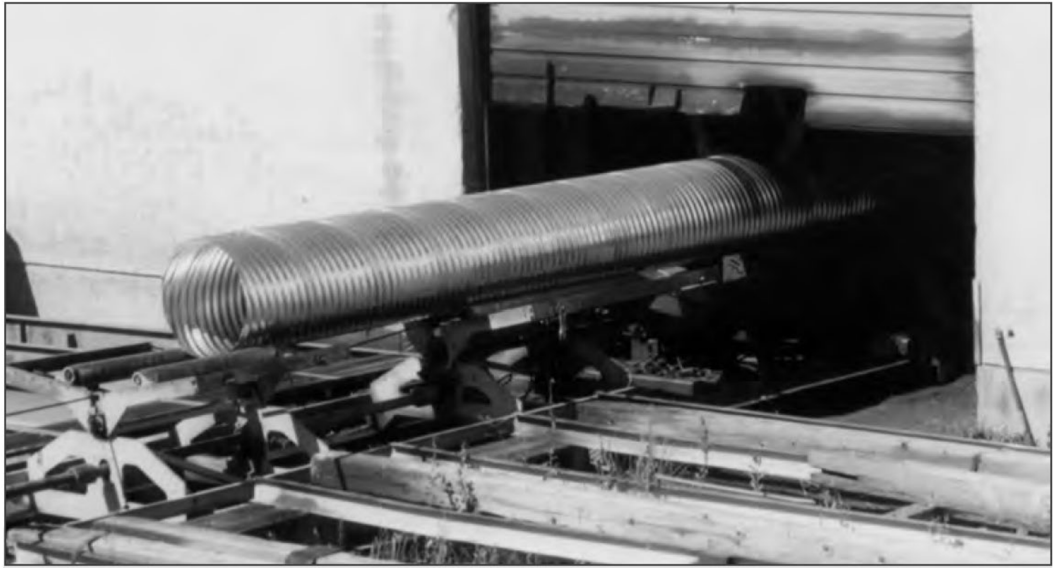
Commercially Available Corrugated Steel Pipe (CSP)

- References:
  - Corrugated Steel Pipe (CSP) Manual, National Corrugated Steel Pipe Assoc., cr 2018
  - ASTM specification A760M, "Standard Specification for Corrugated Steel Pipe, Metallic-Coated for Sewers and Drains"
- "Most shop-manufactured CSP is produced on a machine that forms helical corrugations; in such case, the seam may be either a continuous helical lock seam or a continuously helical welded seam …"
- "In contrast with CSP, structural plate pipe is always fabricated with annular corrugations and field bolted longitudinal and circumferential seams."
- Consequently, for CEBEX, our interest is only in helical corrugated CSP (not structural plate pipe)

… Helical Corrugation Redux

Reasons to Pursue Helically Corrugated and Welded Pipe

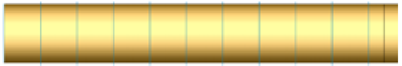
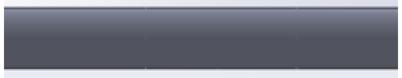
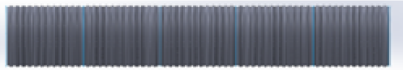
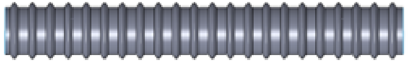
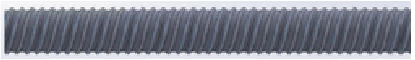
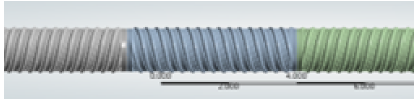
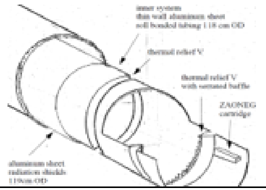
- Pro
  - Standard commercial CSP product
  - No high plastic deformation crossing the weld HAZ
    - May be the cause of unacceptable UHV leak failure rates (see LIGO-E2400425)
  - Eliminates the need for bellows and stiffeners
- Con
  - Requires alternating chirality sections of pipe/tube (i.e. LH, RH, LH, …) to compensate for the length-to-torsion coupling
  - However …
    - CE can afford two rolling machines with opposite handiness
    - CEBEX can be constructed to allow one end to rotate when performing the bake-out
      - Challenge becomes the design of this support and the transition to the CSP



Manufacturing of corrugated steel pipe.

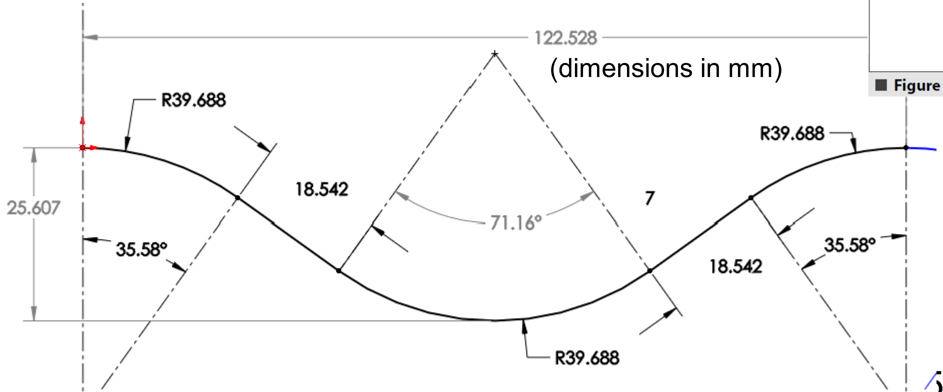
Beamtube Taxonomy

CURRENT FOCUS

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	

Standard Corrugation Profiles

- Arc & Tangent
  - Not very different from sinusoidal profile
  - Corrugations are continuous (no flat sections to easily interface to baffles
  - Only 3 profiles appropriate for large diameter CSP
- Ribbed
  - Sharp corners will induce high stresses



5” pitch x 1” height x .0598” thick

595-v3

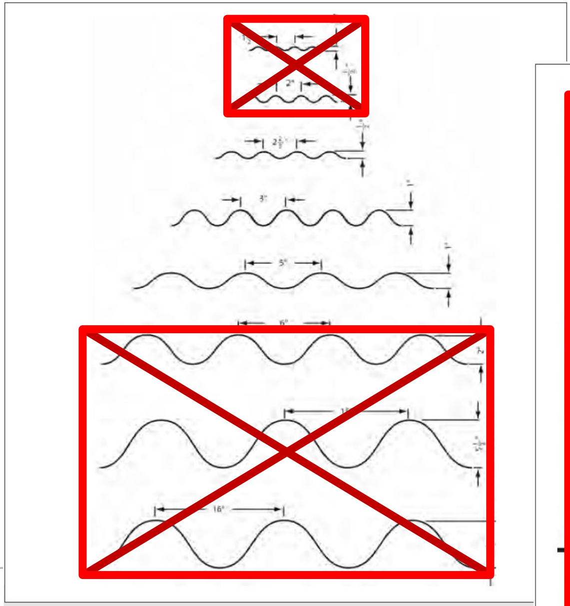


Figure 2.1 Arc and tangent corrugations.

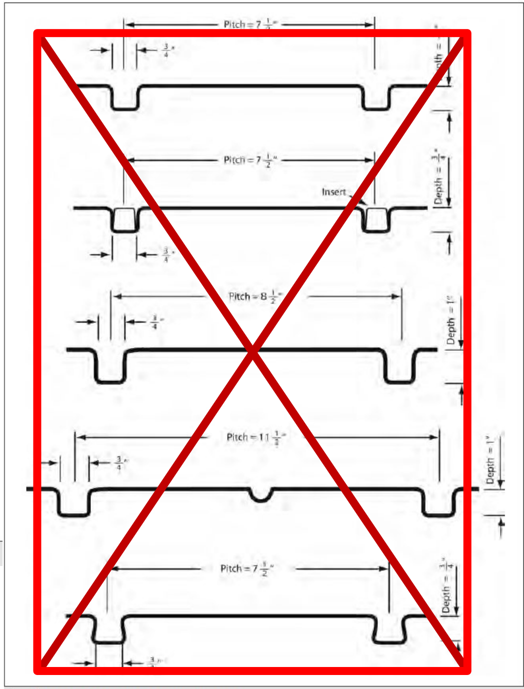


Figure 2.2 Spiral rib corrugations.

Standard CSP

A760/A760M – 10

TABLE 1 Pipe Sizes

Nominal Inside Diameter		Corrugation Sizes[A]				Ribbed Pipe			Minimum Outside Circumference[B]	
in.	mm	1½ by ¼ in. [38 by 6.5 mm]	2⅔ by ½ in. [68 by 13 mm]	3 by 1 in. [75 by 25 mm]	5 by 1 in. [125 by 25 mm]	¾ by ¾ by 7½ in. [19 by 19 by 190 mm]	¾ by 1 by 11½ in. [19 by 25 by 292 mm]	¾ by 1 by 8½ in. [19 by 25 by 216 mm]	in.	mm
4	100	X							11.4	264
6	150	X							17.7	441
8	200	X							24.0	598
10	250	X							30.2	755
12	300	X	X						36.5	912
15	375	X	X			X[C]			46.0	1148
18	450	X	X			X	X	X	55.4	1383
21	500		X			X	X	X	64.8	1620
24	600		X			X	X	X	74.2	1854
27	675		X			X	X	X	83.6	2091
30	750		X			X	X	X	93.1	2483
33	825		X			X	X	X	102.5	2561
36	900		X	X	X	X	X	X	111.9	2797
42	1050		X	X	X	X	X	X	130.8	3269
48	1200		X	X	X	X	X	X	149.6	3739
54	1350		X	X	X	X	X	X	168.4	4209
60	1500		X	X	X	X	X	X	187.0	4675
66	1650		X	X	X	X	X	X	205.7	5142
72	1800		X	X	X	X	X	X	224.3	5609
78	1950		X	X	X	X	X	X	243.0	6075
84	2100		X	X	X	X	X	X	261.7	6542
90	2250			X	X	X	X	X	280.3	7008
96	2400			X	X	X	X	X	299.0	7475
102	2550			X	X	X	X	X	317.6	7941
108	2700			X	X	X	X	X	336.3	8408
114	2850			X	X	X		X	355.0	8874
120	3000			X	X	X		X	373.6	9341
126	3150			X	X			X	392.3	9807
132	3300			X	X			X	410.9	10274
138	3450			X	X			X	429.6	10740
144	3600			X	X			X	448.3	11207

[A] An" X" indicates standard corrugation sizes for each nominal diameter of pipe.
[B] Measured in valley of annular corrugations. Not applicable to helically corrugated pipe.
[C] Additional size for Type IS pipe.

CLOSEST TO LIGO BEAM TUBE DIAMETER (1244 mm)

Preliminary FEA Results

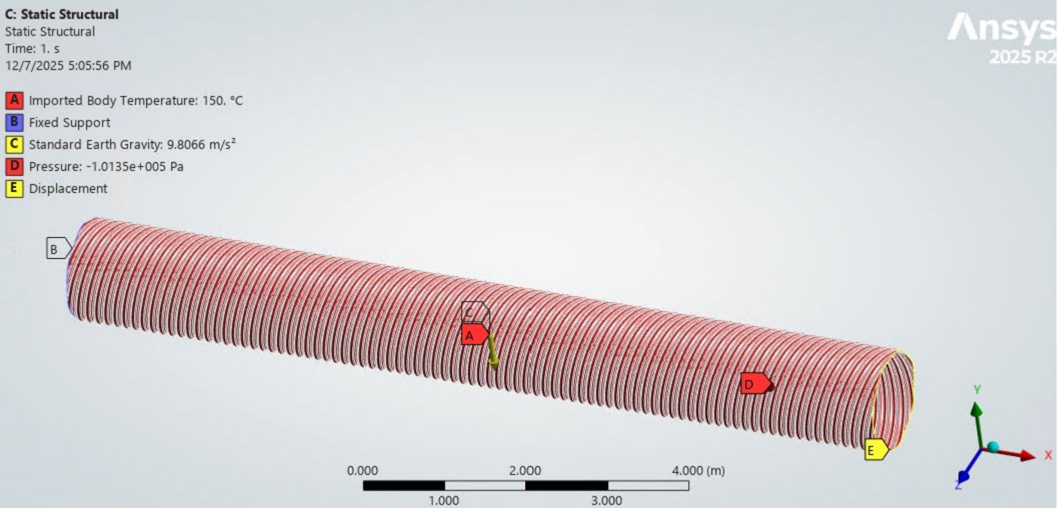
- No info yet on skelp edge prep (e.g. flat portion) for helical welding
- No info on re-rolling/forming ends for circumferential welds
- FEA Caveats:
  - Arc & Tangent profile is defined at the helix angle, not perpendicular to the skelp (helix angle is ~11 deg)
  - Mesh is coarse and with poor mesh quality (element distortion or skew) distortion
  - Single profile, corresponding to t = 1.52 mm (0.0598”), used for all thicknesses

Table 2.7

Sectional properties of 5 x 1 in. (Helical)

Specified Thickness	Uncoated Thickness T	Area of Section A	Tangent Length TL	Tangent Angle Δ	Moment of Inertia I	Section Modulus S	Radius of Gyration r	Developed Width Factor
(in.)	(in.)	(in.^{2}/ft)	(in.)	(Degrees)	(in.^{4}/in)	(in.^{3}/ft)	(in.)	
0.064	0.0598	0.794	0.730	35.58	0.0089	0.1960	0.3657	1.106
0.079	0.0747	0.992	0.708	35.80	0.0111	0.2423	0.3663	1.107
0.109	0.1046	1.390	0.664	36.30	0.0156	0.3330	0.3677	1.107
0.138	0.1345	1.788	0.616	36.81	0.0203	0.4210	0.3693	1.108
0.168	0.1644	2.186	0.564	37.39	0.0250	0.5069	0.3711	1.108

Notes: 1. Per foot of projection about the neutral axis. To obtain A or S per *inch* of width, divide the above values by 12.
2. Developed width factor measures the increase in profile. Dimensions are subject to manufacturing tolerances.
3. Actual Pitch = 4.9213 in. and Actual Depth = 1.0236 in. Dimensions shown on sketch are nominal.

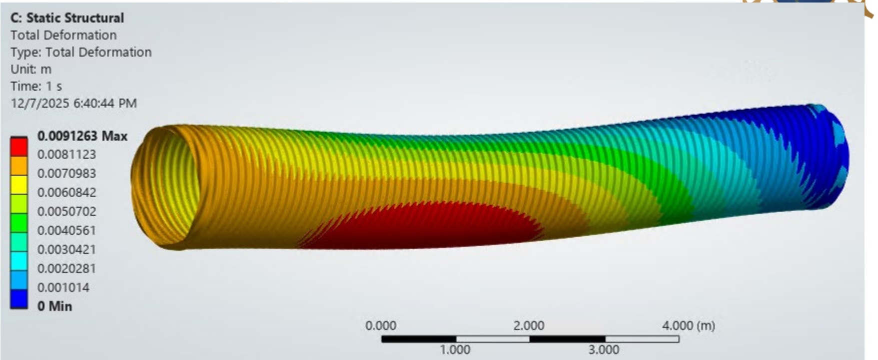


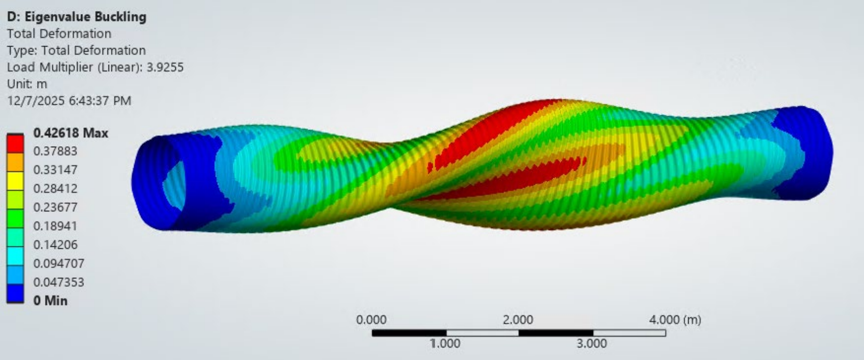
Preliminary FEA Results

Profile	Thickness mm (in)	Sag (mm)	Buckling Factor	Axial Spring (kN/m)
127 x 25	1.52 (.0598)	16.8	1.02	
	1.90 (.0747)	14.4	1.54	
	2.66 (.1046)	11.1	2.72	
	3.42 (.1345)	9.1	3.92	4,033
	4.18 (.1644)	8.0	5.04	
76 x 25	3.42 (.1345)	9.1	3.96	4,128

PROMISING

PROMISING

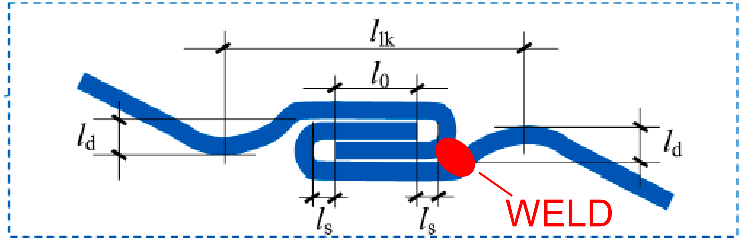




- 10 m length of Arc & Tangent profile
- LIGO Bellows for a 20 m long pipe:
  - 1,401 kN/m design maximum
  - 845 kN/m ± 10% as-built

Helical Lock-Seam vs Continuously Welded Seam

- ASTM A760M allows for either helical lock-seam or helical continuous weld
- Industry prefers the lock seam for buried applications
  - Lock-seam allows for easier, leak-resistant assembly, especially for large diameters, offering flexibility
  - Lock-seam also provides greater structural integrity, better stress distribution (reducing crack risk)
  - whereas continuous welds, while strong, can create potential leak points, require precise alignment, and are harder to manage on heavy gauges



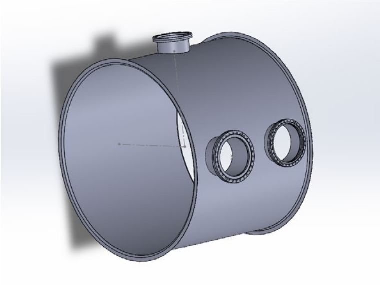
Notes: l_0 is the overlapping length; l_s is the reserved gap; l_d is the reserved offset distance; l_{lk} is the length of the lock-seam.

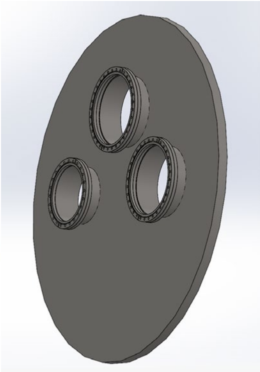
Lock-seam

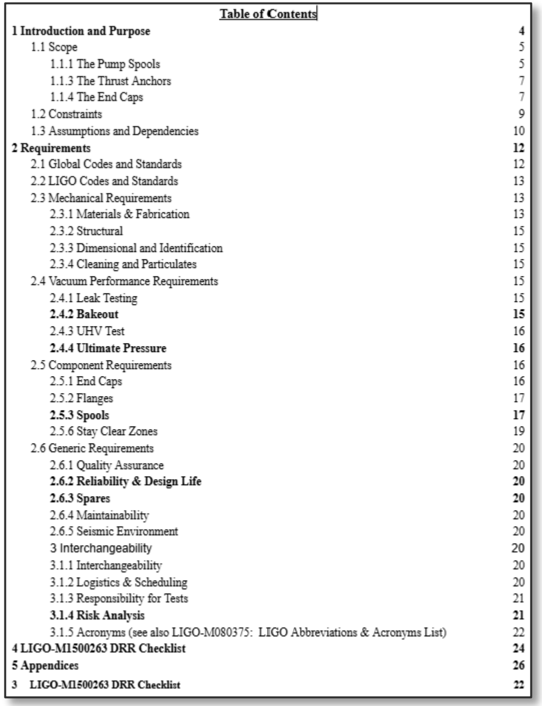
- Iff CSP manufacturers don't have (or don't want to add) a weld head to the CSP mill, then
  - Consider a weld processing step subsequent to the CSP forming mill
  - Fixed weld head coupled to a custom helically guided tube rotator/translator

Draft Requirements Document: Pump Spools, Beamtube Supports, Thrust Anchors, and End Caps (LIGO-E2500329)

- Design & Fabrication requirements for all components of the CEBEX structural system, including:
  - Quantities and types of port configurations
  - Dimensions
  - Vacuum performance







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