Cosmic Explorer
Beamtube Experiment (CE-BEX):

Beam Tube Principal Cost Drivers

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

Caltech
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28-Sep-2025 v1

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LIGO-G2502099-v2

Scope

- Includes:
  - Beam Tube
  - Beam Tube Supports
  - design, materials, stiffening provisions, pump ports, supports, manufacturing, cleaning, transportation, and leak testing
- Does not include:
  - Baffles
  - Slab (foundation)
  - BT enclosure
  - BT insulation
  - BT vacuum bake
  - Vacuum equipment (gate valves, pumps, controls, gauges, etc.)
  - Overall management oversight, cost of money, etc.

Caveats & Sources

- Caveats
  - Based on 1994 cost data from CBI for the LIGO Beam Tube
  - While this data is "ancient", it may still provide relative measures of cost
  - In addition, this estimate (captured in a Mathematica notebook, LIGO-T2400377) may provide the template for updating to current cost information
  - Proper escalation would require different escalation factors for the various elements of the estimate – this has not been done
- Sources
  - LIGO-C1900321, “Final Design Review Data Package, Beam Tube Module: CDRL 09, DRD 04, Draft Detailed Design prepared by the contractor, CB&I
  - C-type documents in the LIGO DCC are generally restricted to LIGO Lab personnel, but can be made available to LSC and perhaps the public (TBD)
  - Document LIGO-T2400377 also compares the CB&I estimate to the LIGO cost book

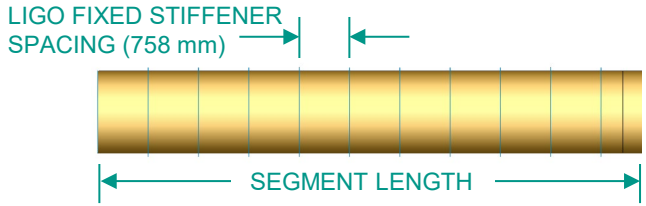
LIGO BT Costs

- Cost table compiled by Rai Weiss for a 2020 proposal to the NSF for CE seed funding for vacuum research
- Separation of Fixed and "Per km" costs
- Projection for a 40km interferometer in 2028 USD using an inflation rate of 0.023/year (factor of 2.166) – total cost for 80km = $635M

References: LIGO Cost Book, L.Jones notes, F.Asiri notes

Item	Total cost $M	Length dep cost
Management	5.5	~1.0
Design	0.83	
Tube factory	8.05	
Tube material	9.02	9.02
Bellows	0.77	0.77
Assembly	1.66	1.66
Leak check	0.87	0.87
Anchors+supports	3.05	3.05
Pump ports	1.83	1.83
Handling/shipping	0.92	0.92
Moblization/demobilization	0.46	
Installation in field	7.2	7.2
Insulation and bake	7.0	7.0
Acceptance tests	1.1	
CB&I profit (10%)	5.2	3.3
Beamtube enclosure design	0.64	
BTE QA and survey	0.32	0.32
BTE, berm, slab construction	18.6	18.6
TOTAL 1	72.4 16.8 fixed	55.5 3.47/km
Vac equipment for beamtube		
gate valves	0.72	0.72
ion pumps	0.24	0.24
cryo traps	0.80	
roughing pumps	0.24	0.16
turbo pumps	0.18	0.12
gauges, electronics	0.02	0.02
Total vac equip for beamtube	2.2 0.94 fixed	1.26 0.08/km
TOTAL 2	74.6 17.7 fixed	56.8 3.55/km

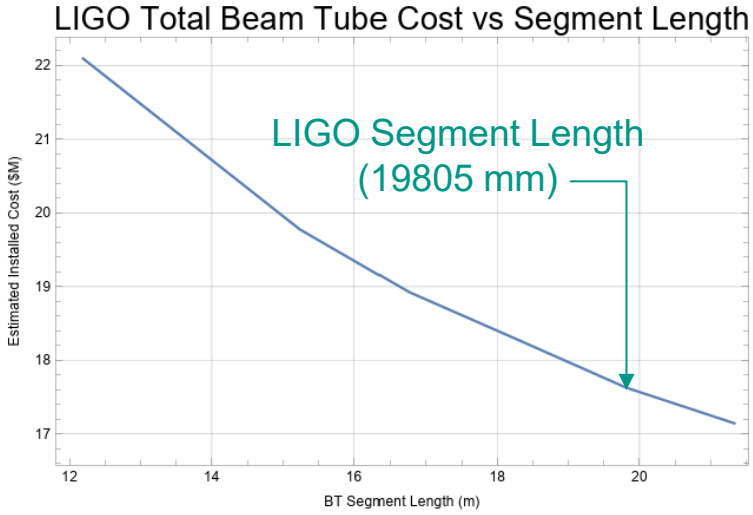
Tube Segment Length Impact on Cost (2 sites, 16 km, 1994 USD)

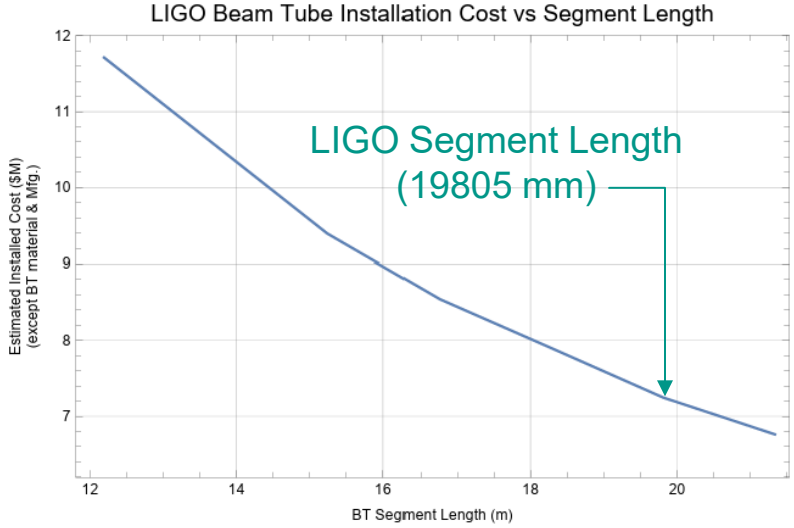


- Costs independent of tube segment length:
  - Coil mfg (average of 5 steel producers)
  - Spiral Welding manufacture
  - Stiffener costs (mfg and installation)
- Total Costs vs segment length:

- Install Costs dependent of tube segment length:
  - Short transport case (Portland, OR to Hanford, WA)

	40'	50'	55'	60'	65'	70'
Freight	74 714.5	59 956.1	71 930.3	74 928.7	72 741.9	91 927.6
Bellows	1 944 000	1 560 000	1 416 000	1 308 000	1 200 000	1 116 000
Supports	4 894 400	3 921 600	3 556 800	3 283 200	3 009 600	2 796 800
Tube Install	1 944 000	1 560 000	1 416 000	1 308 000	1 200 000	1 116 000
Leak Test	2 855 600	2 292 400	2 081 200	1 922 800	1 764 400	1 641 200





Tube Segment Length Impact on Cost (2 sites, 16 km, 1994 USD)

- Total Costs dependent of tube segment length:
  - Long transport case (Portland, OR to Livingston, LA)

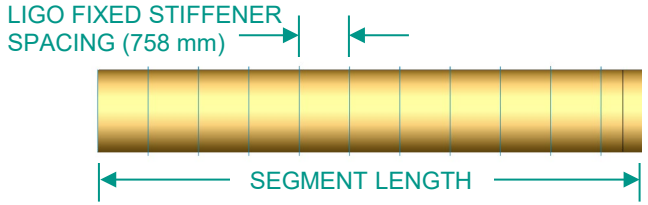
	40'	50'	55'	60'	65'	70'
Freight	4.3%	3.9%	4.8%	5.2%	5.2%	6.7%
Bellows	8.4%	7.6%	7.2%	6.8%	6.5%	6.1%
Supports	21%	19%	18%	17%	16%	15%
Tube Install	8.4%	7.6%	7.2%	6.8%	6.5%	6.1%
Leak Test	12%	11%	11%	10%	9.5%	9%
Stiffeners	4.4%	4.9%	5.1%	5.3%	5.5%	5.5%
Coil Mfg	24%	27%	28%	29%	30%	30%
Spiral Weld Mfg	17%	19%	19%	20%	21%	21%

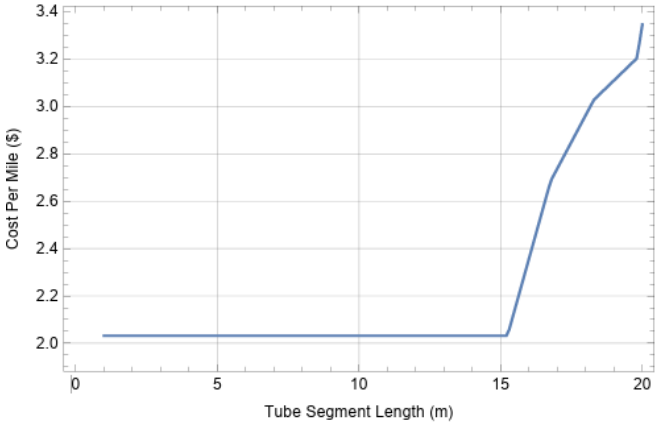
	40'	50'	55'	60'	65'	70'
Total Cost ($M)	23.0074	20.5084	19.8026	19.1943	18.5174	18.2669

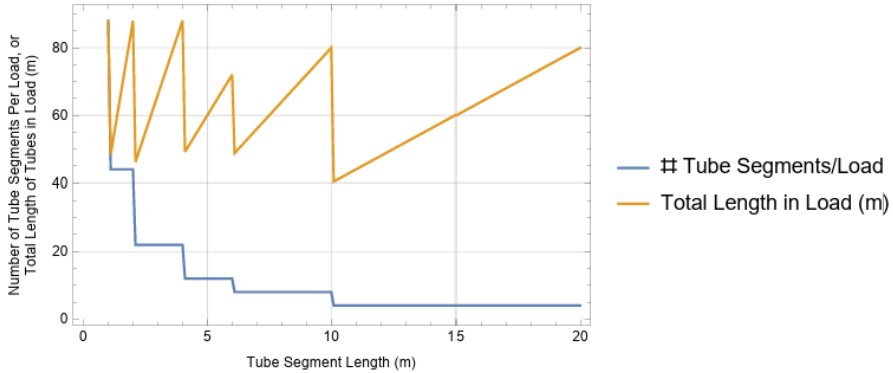
- Segment Lengths > ~20 m not considered because Freight costs rose dramatically

CE Cost (1994 USD) with LIGO Beamtube for varying tube segment length

- Freight
  - Heavy hauling (8.6x13.6x53 ft, <80,000 lb)
  - Packing density used to determine the number of transport loads:
    - > 4m long tubes, 2 rows x 2 levels)
    - ≤ 4m long tubes, stand up in 2 rows x 11

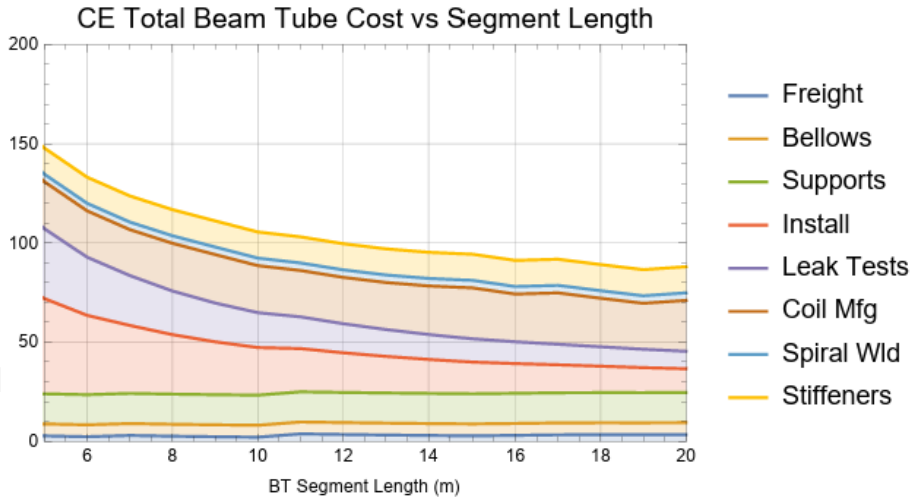






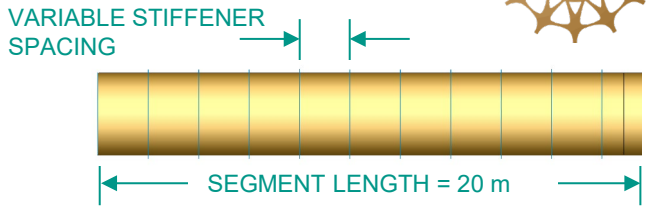
CE Cost (80 km, 1994 USD) with LIGO Beamtube for varying tube segment length (concluded)

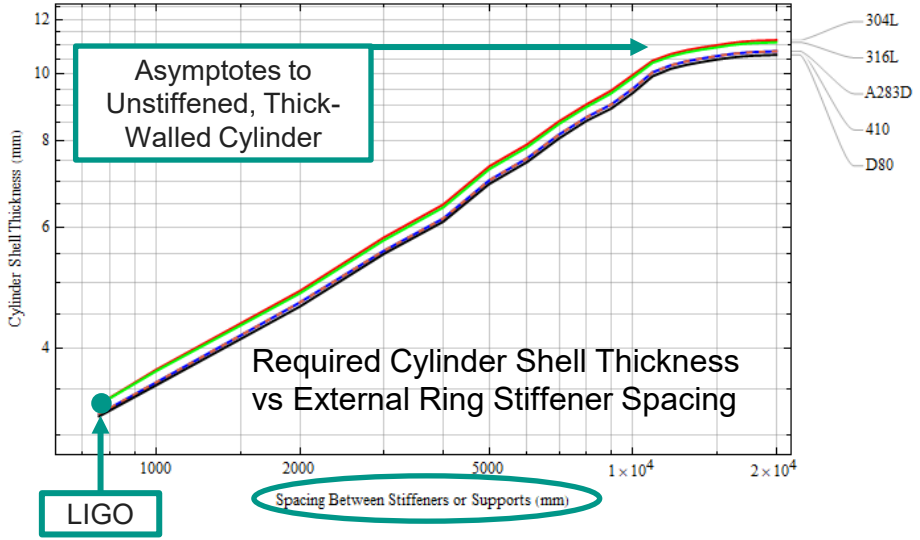
- Bellows (EJ)
  - In principle the EJ could be designed to handle the displacement of multiple BT segments, or optimized for shorter BT segments
  - I've estimated the number of EJs on the assumption that each EJ handles 40 m of tube
- Supports: Assumed 1 fixed & 1 guided support per EJ
- Pump Ports: Simply scaled by (CE Length)/(LIGO Length)
- Coil Mfg Costs (avg. of 5): coil material (304L), transport to/from bake facility, bake, transport to/from finishing mill, outgas test, level, slit, transport to tube mfg, less cost of 10% scrap steel
- Spiral Mill Costs (avg. of 3):
  - not quoted as a function of segment length
  - shorter segments would cost more due to the need to make more transverse cuts
- Stiffeners: material, fabrication, welding costs

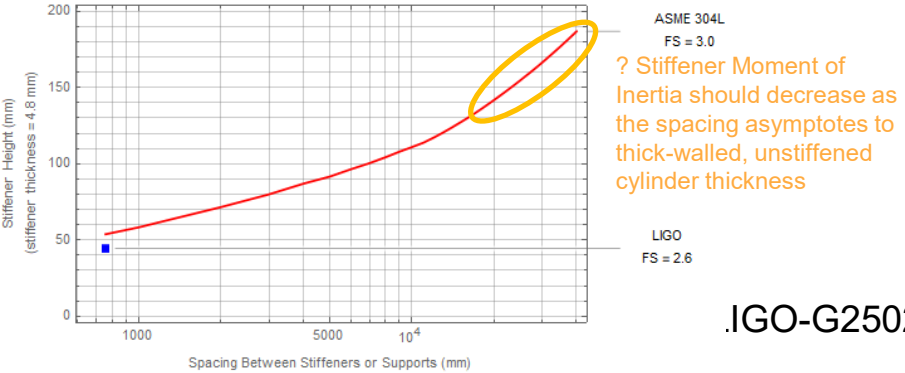


CE Cost (80 km, 1994 USD) with LIGO Beamtube for varying tube stiffener spacing

- Cylinder thickness and stiffener height (MOI) increases as stiffener spacing increases per ASME 2023.BPVC.VIII, Division 1
- Costs independent of stiffener spacing: Tube segment freight, Bellows, Supports, Leak Tests, Pump ports, Tube installation
- Assuming cylinder is formed by spiral welding (thick-walled is more likely slip rolled?)
- Assuming each 304L coil weight remains the same
- Stiffener
  - Material costs scaled by stiffener weight
  - Welding cost assumed constant per stiffener







? Stiffener Moment of Inertia should decrease as the spacing asymptotes to thick-walled, unstiffened cylinder thickness

CE Cost (80 km, 1994 USD) with LIGO Beamtube for varying tube stiffener spacing (concluded)

- The CB&I (LIGO) design seems optimal for a 304L ring-stiffened cylinder
- Corrugation fabrication cost (currently unknown) is offset by ~34% of baseline total
  - Stiffener cost of ~13.6%
  - Bellows cost of ~6.2%
  - Shell thickness reduction from 3.23 mm (LIGO) to 2.78 mm (CEBEX RFI) represents a cost of ~13.9%