Cosmic Explorer Beamtube EXperiment (CEBEX)

Back to basics

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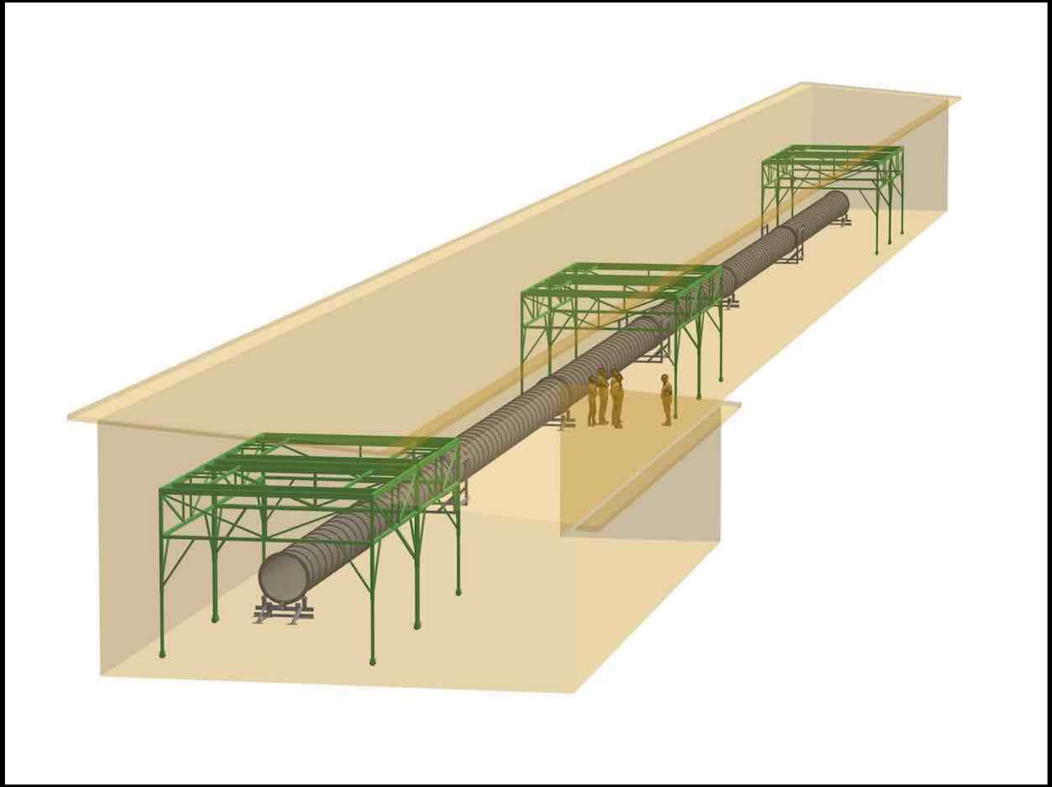
LIGO Laboratory and Cosmic Explorer Consortium

CE Project call
9 December, 2024

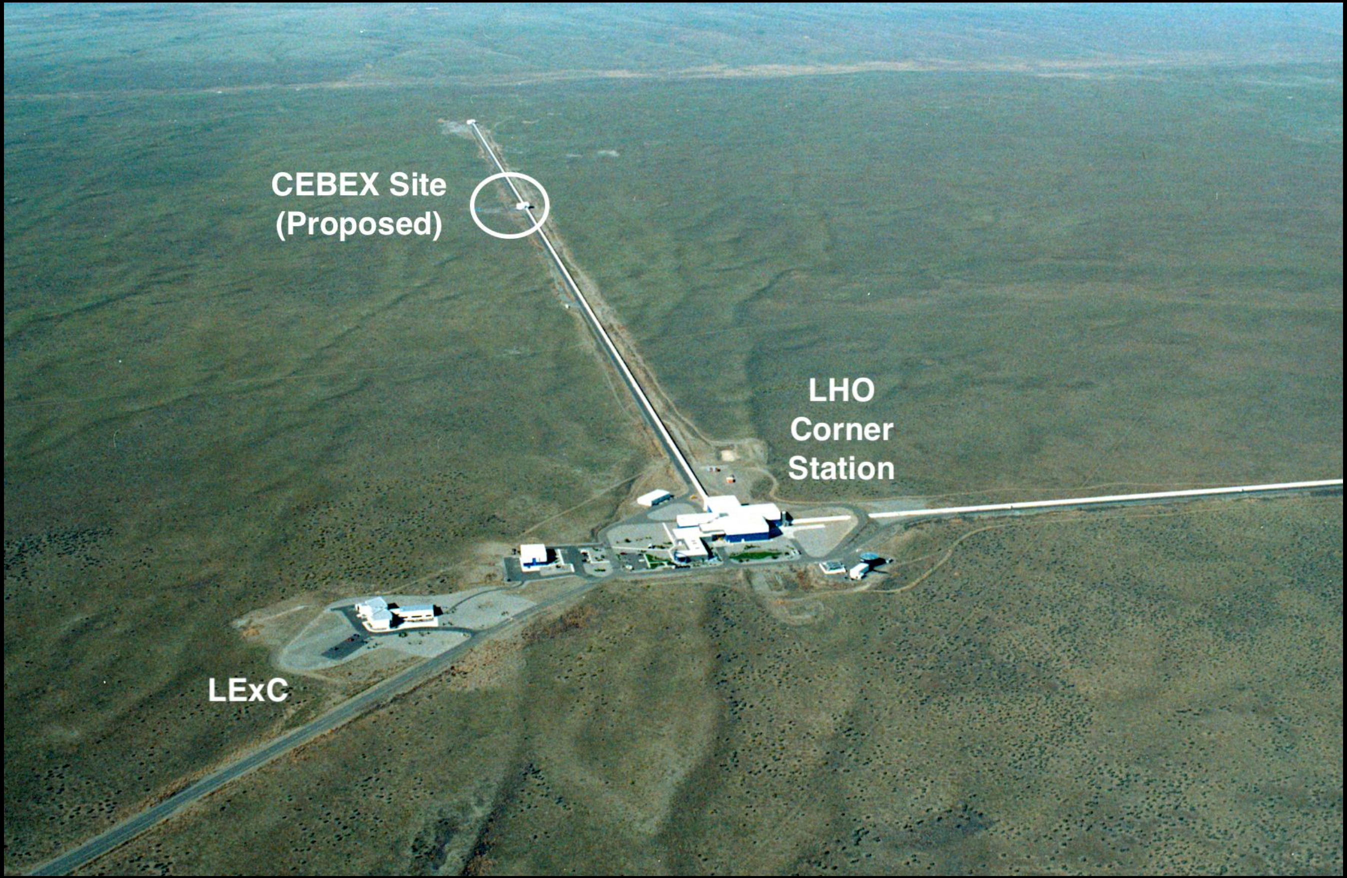
LIGO-G2402499

CEBEX concept

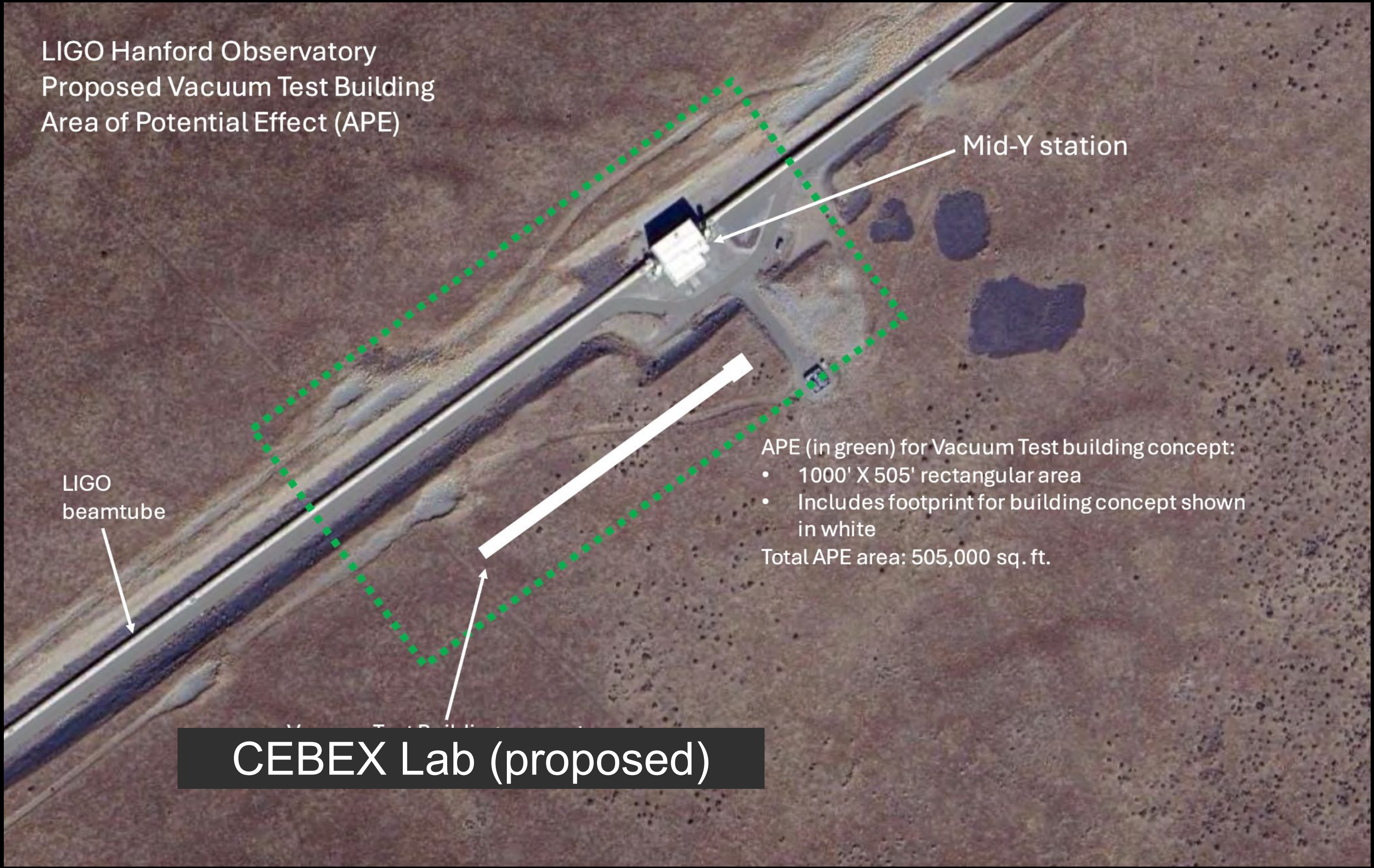


- US NSF award PHY-2422892
  CE beamtube technology pathfinder
- Complementary with CERN's *ET Pilot Sector* program
- 120m (400') x 1.2m (4') prototype UHV beamtube w/ instrumentation & bakeout
- New 140m x 7m x 6m lab to be constructed at LHO
- 4-5 full time staff + 2-4 FTE part-time
- Tube installation target:
  Late 2025
- To deliver CE conceptual design & parametric cost estimate
- Program authorized through Sept. 2028

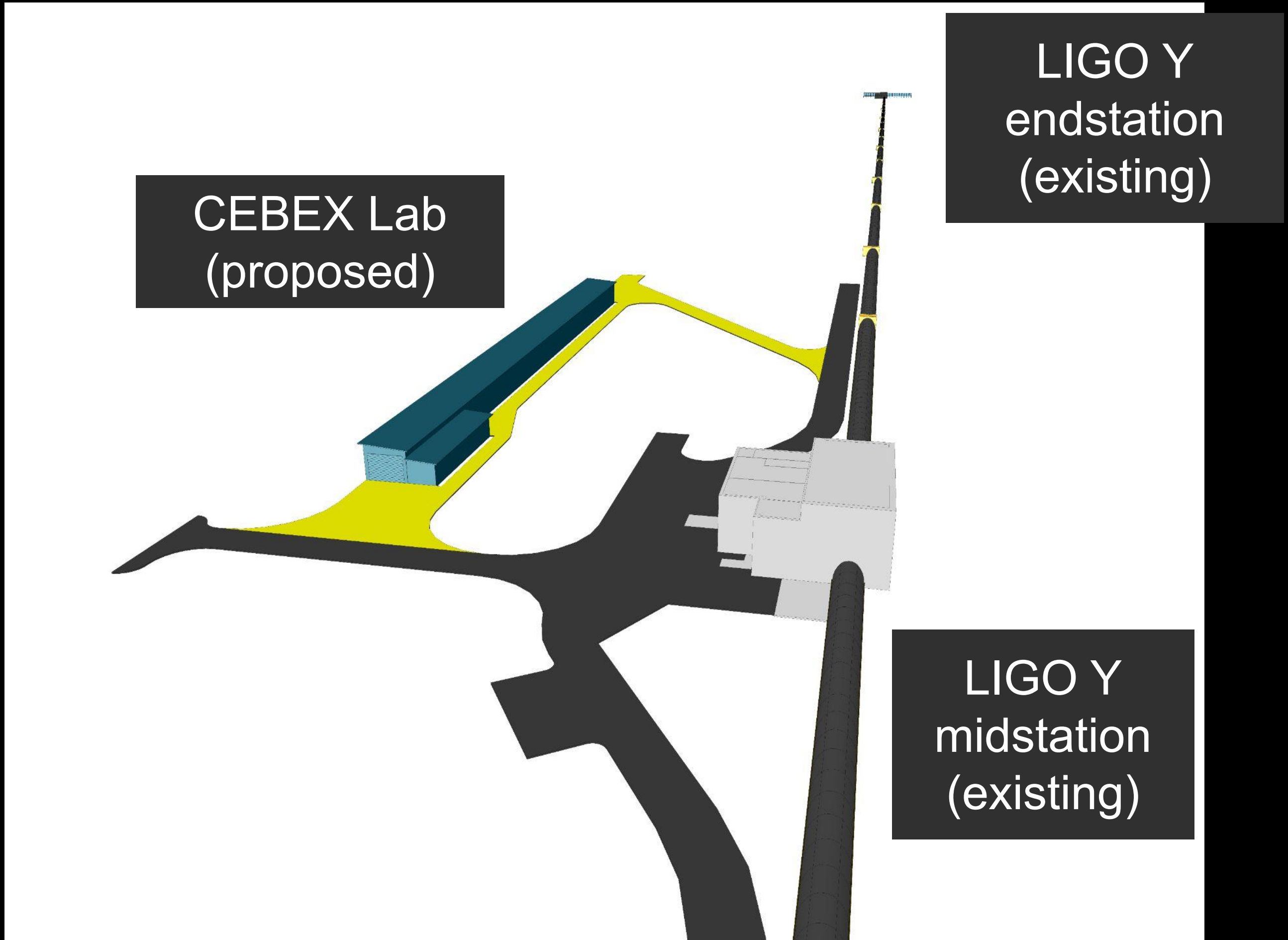
Proposed location



Proposed site layout and APE



Concept ISO view (looking SW)



CEBEX award action so far

- Lab construction
  - NSF pursuing DOE and Tribal Nations site approval (req'd for LHO construction)
  - A&E specification, commercial "Design & Build" RFP on track for December release
- Team construction
  - Core team (Lead, PM, Chief Eng., Chief Sci., Sr. Sci.) on part time loan from LIGO Ops
  - External p/t Sr. Mech. Eng., p/t Sr. Facilities Eng. (appointment pending)
  - Actively recruiting 4 fulltime CEBEX engineers, (3) Vacuum and (1) Mechanical
- Tube design, material, construction, field assembly
  - Under study- see below
- Tube bakeout/degassing
  - Depends on tube design
  - 2 main branches:
    - DC I^2R Joule heating (valve-isolated sectors) ← *baseline, like LIGO*
    - Traveling induction heat w/ viscous entrainment (no explicit valve isolation)

Review: ET and CE Vacuum Specs

Brownian recoil of mirrors due to gas molecule impact

$P(H_2) < 10^{-8}$ Torr

Contamination of optics leading to scattering, heating or damage

Mirror absorption: < 0.1 ppm change over operating life

Hydrocarbons: < 1 monolayer/10 years

Particles: < one 10 µm particle on any mirror

} mainly applies to *chambers*

Light scattering from residual gas

A function of molecular polarizability and thermal speed

$P(H_2) < 10^{-9}$ Torr

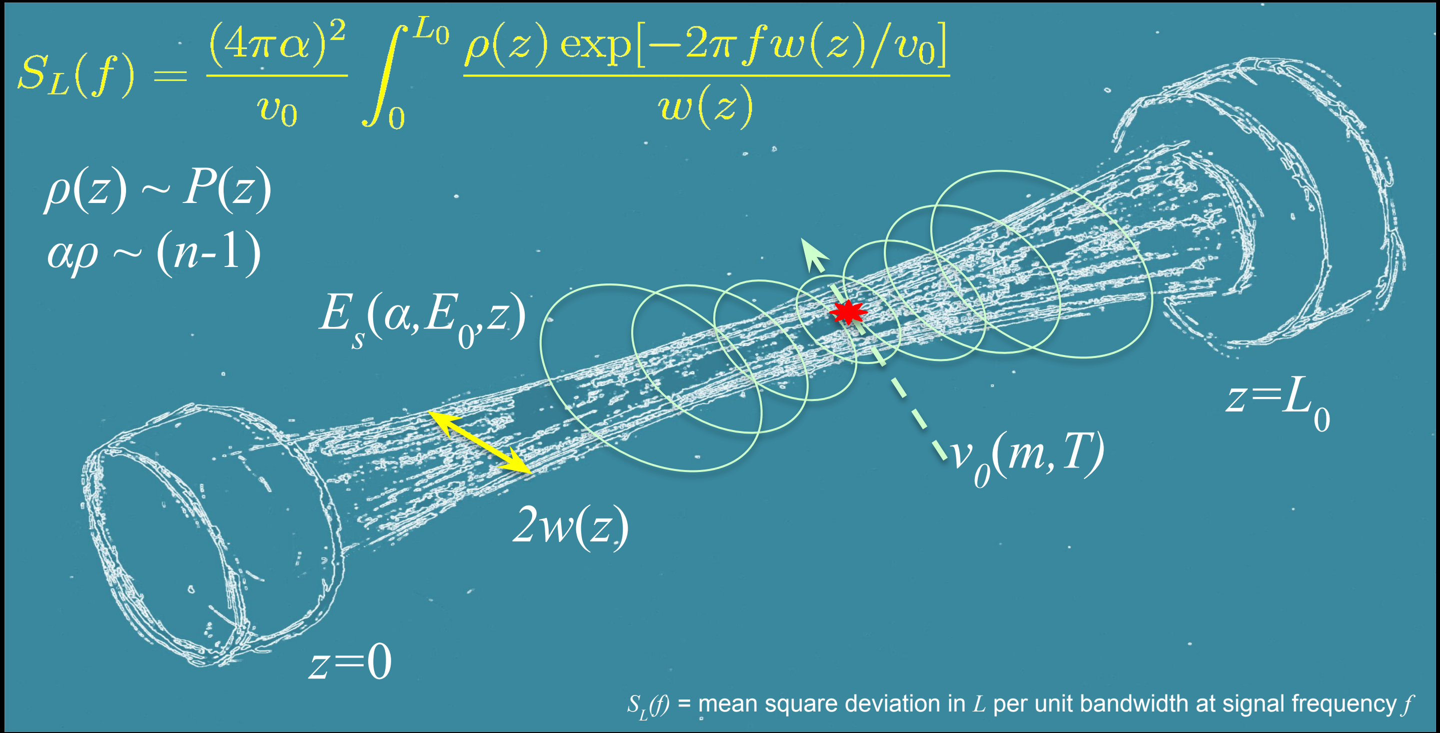
$P(H_2O) < 10^{-10}$ Torr

Light scattering from tube walls & internal baffles

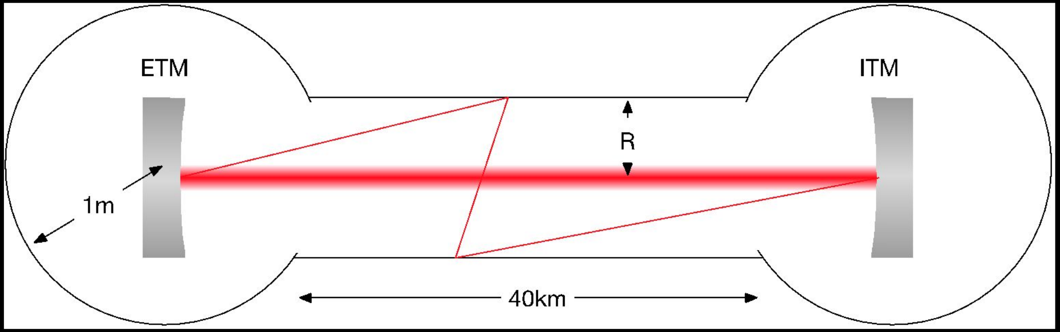
A function of everything in the world you could possibly imagine

} mainly applies to *beamtubes*

Light Scattering from Residual Gas



Beamtube Wall & Baffle Scattering



- Light scatters out of beam, strikes tube wall or baffle, re-scatters into beam
- Circulating IFO field's phase imprinted with mechanical noise of the tube wall
- A sensitive function of tube and baffle diameter
- Depends on parameters that are difficult to bound:
  - Mirror nano-topography (especially at long spatial wavelengths)
  - Baffle characteristics near grazing incidence
  - Tube support and wall vibration response
  - Ambient noise

→ *Optical baffles must be integrated with design*

→ *Tube wall finish & reflectance may be constrained*

→ *Tube supports, isolation, mechanical eigenmodes can have dramatic effect*

→ ***Tube diameter is among the first parameters to choose…***

…and the most difficult to change later

Other Practical Constraints

- Rapid, economical degassing (bakeout) to remove adsorbed water
  - Initially <u>and</u> after repair or accident
- Environmental resistance
  - 20-50 year planned lifetime
  - Thermal cycling, humidity, corrosion, steel-eating microbes (!)
  - Earthquakes, tornadoes, lightning strikes
  - Hunter's bullets (surface construction)
    - Standard deer (or kangaroo) rifle at 200m can pierce 13mm steel!
- Maintainability and Repairability
  - Access and life cycle renewal
  - Recovery from *planned* and *unplanned* vents
- Sustainability and environmental impact
  - Initially, in operation, and after retirement

The BIG ONES

$ COST & SCHEDULE 💀

Scaling up LIGO, Virgo, Kagra 10x would meet technical requirements

…but only if you also scale construction duration

We seek LIGO-like performance

- *at lower cost per unit length, and*
- *with total construction duration < 5 years**

**(just a guess)*

Starting point: *How LIGO Did It*

- 9,000 m^3 / site (x2)
- 30,000 m^2 / site (x2)
- 304L austenitic SS
  - Air fired at 450°C to deplete H
  - 3.2 mm thick
  - 1.245 m OD
  - Spiral welded
  - Discrete bellows
  - External stiffeners*
  - 20 m unit length
    - Butt welded
    - ~2 days / field joint
  - 2 km sector length
  - I^2R bake
- 1997$ 47M / 16 km
  - 1997$ 3k/m
  - ~ 1997$ 60/lb
- About 4.5 years/16km
  - Not including design, development

LIGO beamtube fab & field assembly

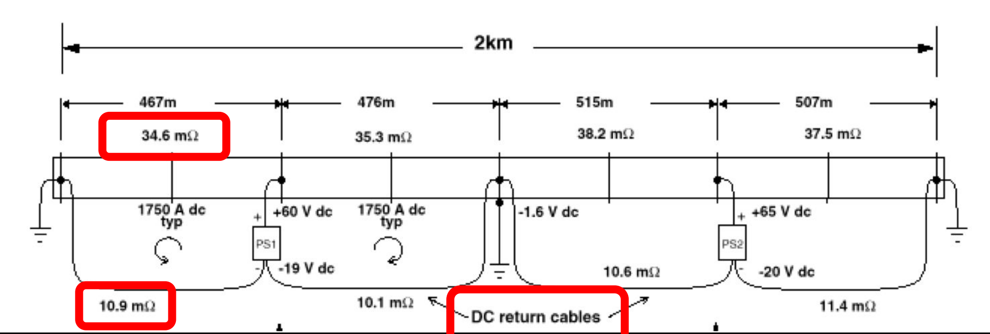
(by Chicago Bridge and Iron)







LIGO beamtube bakeout
(by LIGO)



2 layers fiberglass applied by hand

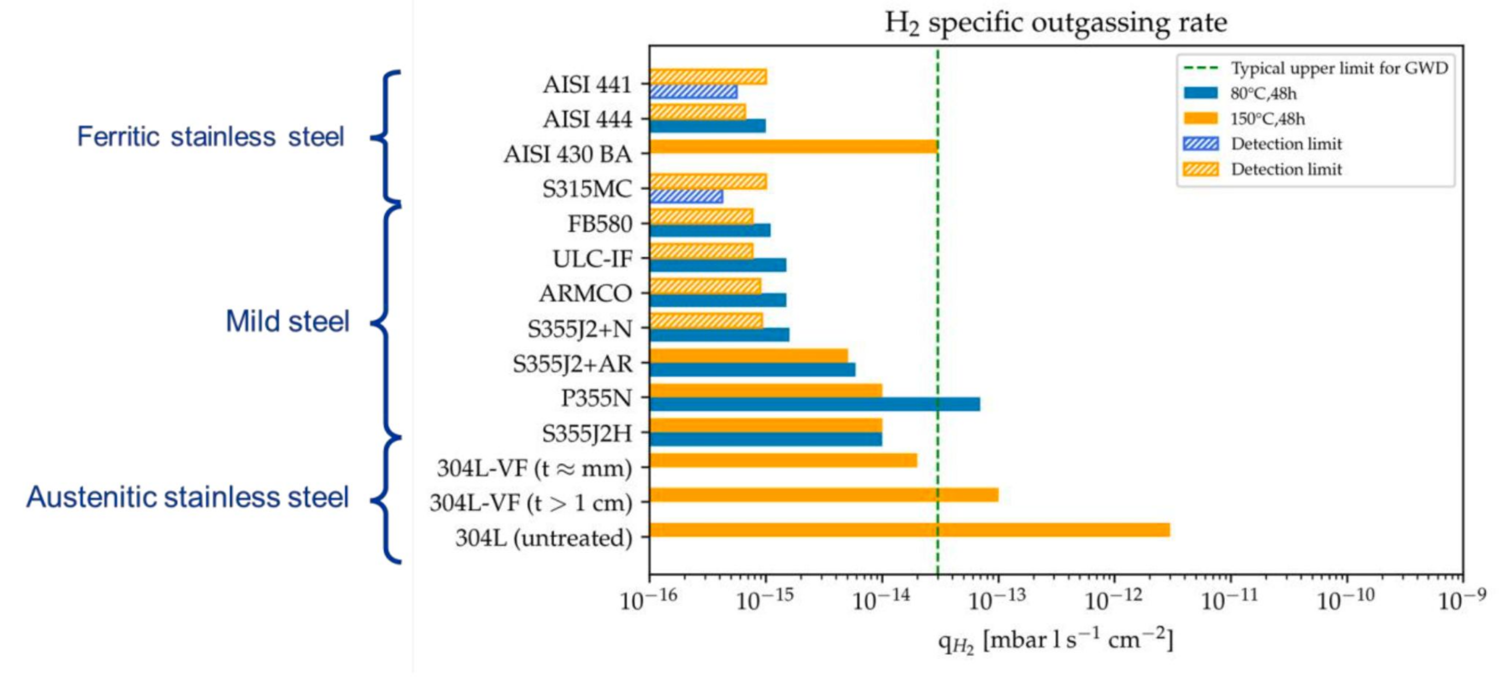
~2,000A DC

160°C for 3 weeks

‘That was then. This is now.’
I. TUBE MATERIAL

- Air-fired austenitic stainless (e.g., 304L or 316L) *no longer the sole option*
  - Since 2019 the joint CE/ET vacuum study group has proven mild steel as a viable UHV material
    - ~ 5x cheaper than 304 (raw material only)
    - Intrinsically hydrogen-free (!!)
  - CERN has also now established ferritic stainless (low-nickel, e.g., 441) as another option
    - ~ 2x cheaper than 304 (raw material only)
    - Also hydrogen-free (!!)
- Mild (‘carbon’) steel ±:
  - Petroleum pipeline, ~ 10mm thick, is super cheap; CE would be a small order!
    - + No radial stiffeners needed (but expansion joints are needed)
    - - Corrosion protection? Weight? Field welding? Transport?
    - *- R/L incompatible with practical I^2R bake*
  - Thin walled (< 5 mm) should be similar to SS options (except corrosion)
- Ferritic stainless steel ±:
  - + In common use, e.g., automotive exhausts
  - - Lower corrosion resistance than austenitic grades
  - - Welds & forms differently from austenitic or mild steel (risk?)
- *NOTE: raw material will likely comprise < 15% of total installed cost*
  - “Free” material can cost more, if it takes extra work
  - *Traditional old-school 304L is by no means ruled out at this point*

Hydrogen outgassing

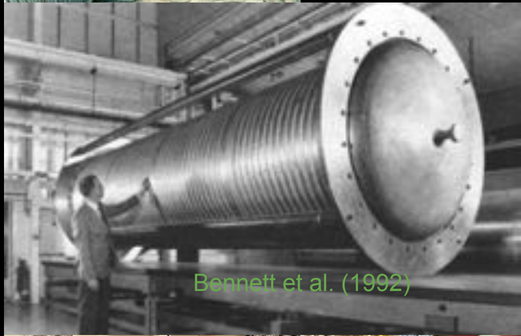


C. Scarcia, CERN (2024)

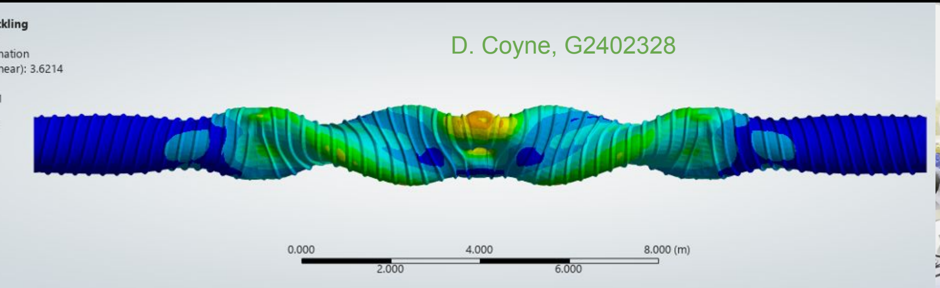
II. TUBE CONSTRUCTION

- Discrete stiffening rings and expansion joints are labor-intensive & costly
- RAL demonstrated formed convolutions in the 1990's (effectively, continuous bellows)
    - Used in GEO600
    - + Can use very thin material (0.9 mm)
    - + Obviates radial stiffeners and expansion joints
    - - Elevates outgassing area; susceptible to impact damage; needs frequent supports (sag)
- In 2022 CERN demonstrated intermittent formed convolutions as an alternative
    - + Reduces excess surface area, fab cost
- - Fabrication may limit unit length (profile is roll-formed or hydro-formed)
- → Combine roll-forming with LIGO-like spiral weld?
    - *- Torsion of helical convolutions during bakeout appears to be a serious issue*
- CEBEX may test more than one solution, depending on schedule
- *Industrial contacts are a critical ingredient*


GEO600 (2010)


Bennett et al. (1992)

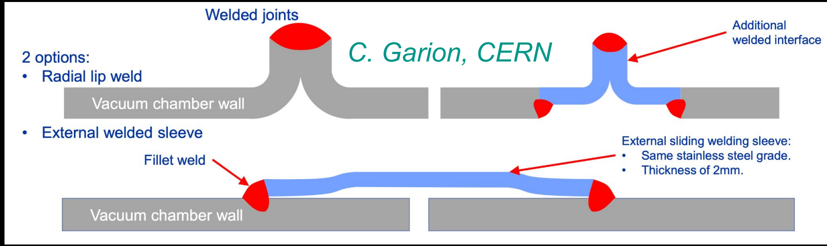

CERN VSC (2023)



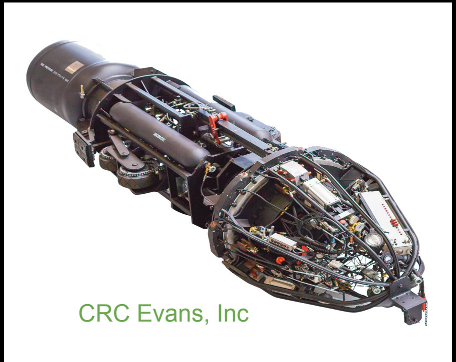
D. Coyne, G2402328


Pacific Roller Die, Inc.

III. Field assembly options



- Butt weld alternatives
  - Reduce joint prep
  - Improve weld reliability
  - Improve repairability

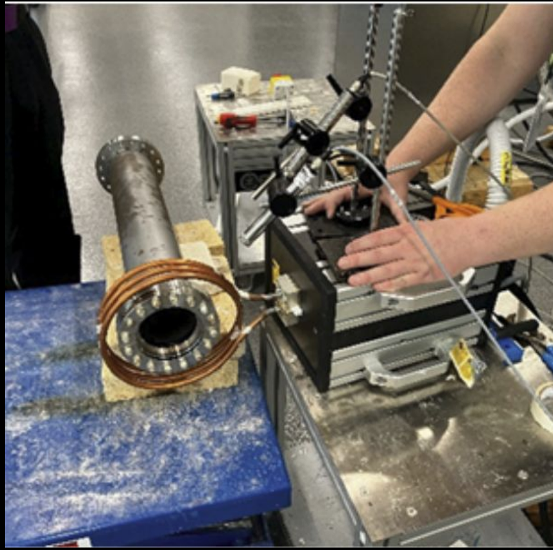


- Extreme automation
  - Robotic alignment, weld, leaktest
  - Tooling investment reasonable at 80km

- “Short” unit spools for field assembly (< 3m vs. 6 - 20m) ?
  - Can field joints be reduced from ~ 2 days to ~ 1h, including leak test?
  - Could open additional (fast, inexpensive) fabrication options
  - Multiple “assembly fronts” laying pipe (CBI had one crew)

IV. Bakeout

- CIT group looking into “traveling bake”
  - Tube heated locally by electric induction;=
    - AC coils travel along length of tube
  - Water vapor removed by viscous flow of ultra-dry air (PPB H_20)
  - May allow use of thick (low R/L) material
    - Full sector need not be valved/under vacuum
  - Never demonstrated– 4” test w/ heavy steel pipe in progress
- ET Pilot Sector and CEBEX will start with Joule heating
  - CEBEX reserves option to try more than one scheme



V. *Diameter, supports & baffles*

- Tube & baffle optical scatter drive everything:
  - Minimum tube diameter & straightness
  - Material reflectance and texture
  - Integration sequence (baffle installation, alignment)
  - Tube compliance and eigenmodes
  - Tube support vibration isolation
- Not feasible for CEBEX to probe the optical interaction itself
  - At best, we can test mechanical and vacuum performance of a proposed configuration calculated to be “adequate”
- Should we incorporate studies of tube support seismic isolation? Damping? Baffle configuration?
- *To ensure we vet the relevant parameter space, CE must reduce uncertainty in optical scattering projections (soon).*

SO… WHERE ARE WE???

Back on slide 12, we started out with:

- ~~304L austenitic SS~~ ??
  - ~~Air fired at 450°C to deplete H~~ ??
  - ~~1.245 m OD~~ ??
  - ~~3.2 mm thick~~ ??
  - ~~Spiral welded~~ ??
  - ~~Discrete bellows~~ ??
  - ~~External stiffeners~~* ??
  - ~~20m unit length~~ ??
    - ~~Butt welded~~ ??
    - ~~~2d / field joint~~ ??
  - ~~2km sector length~~ ??
  - ~~I^2R bake~~ ??

SO… WHERE ARE WE???

CEBEX decision tree (tentative)

- Material downselect target: *MAY ‘25*
  - CERN test vessels and ET Pilot Sector providing definitive baseline for ferritic SS
  - To 1st order, all mat’ls compatible with “thin” (< 5 mm, convoluted or stiffened) fabs
    - Thick wall (> 9 mm, unstiffened) *restricted to carbon steel*
- Fab & field joint downselect target: *AUGUST ‘25*
  - Thick wall option depends on unknowns that will take time to resolve, e.g.,
    - Viscous-flow bakeout
    - CS corrosion protection
    - M/L impact on logistics, supports, vibration isolation, expansion joints
  - → Need to maintain a thin-wall option as baseline (or at least in parallel)
  - Pursuing 2 options (or more) is possible, up to budget & schedule constraint
    - New CEBEX lab will accommodate parallel beamlines, or subdivided sector length
- Bakeout will begin with I^2R Joule heating as baseline
  - Insulation needs engineering– currently no clear solution that scales to CE
  - Review of alternate bakeout option(s) expected mid-2026

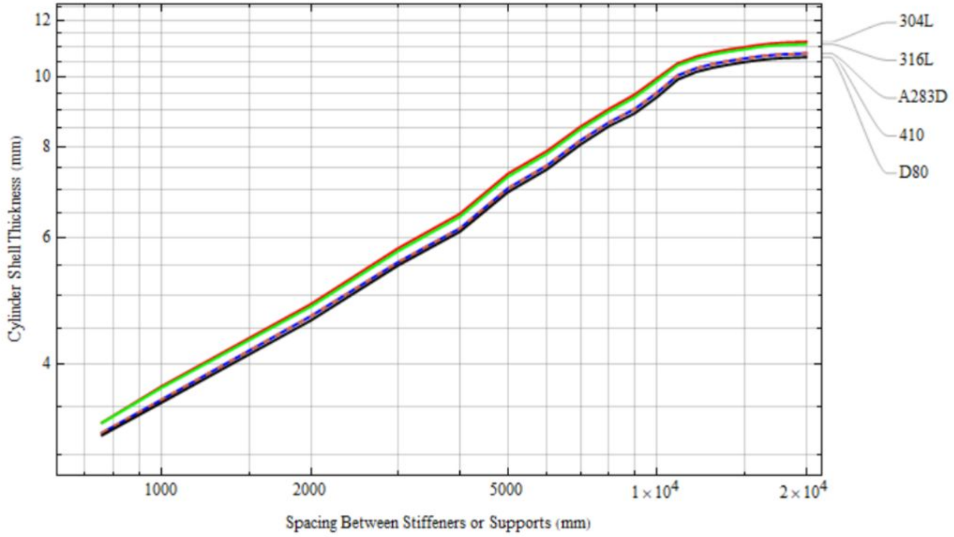
Onward

- We're about a year behind the ET Pilot Sector program at CERN
  - This is an advantage (and great motivation)
  - CERN program is now expected to be authorized additional 2 years
    - Will run in parallel with CEBEX; complementary and collaborative
    - Receiving additional funds to test convoluted & spiral fabrication
- We need to build up our team at LHO quickly
  - Part-time old-timers making do, but LIGO ops remains their priority
- A lot of pivotal engineering decisions are needed in the next year
- Scattering (geometry, vibration & baffles) drive design and cost–
  - ***NEED AGGRESSIVE SUPPORT FROM CE OPTICS TEAM TO MAKE CEBEX AS RELEVANT AS POSSIBLE!***
- 3G GW Beamtube Workshop III @ LHO: **6-9 May 2025**

Unstiffened Tubes

D.Coyne, G2402328 (11/6/2024)

- Gingin Beam Tubes
  - 406 mm OD x 72 m x 3 mm thick, 304 SS, unstiffened
  - 90C max temperature in the summer (no explicit bake out)
  - After ~20 yrs of service one tube collapsed (buckled)
  - Eccentricity (ovality) of up to 12 mm in diameter
  - ASME BPVC Div. 1 requires 3.7 mm thickness
  - FEA linear eigenbuckling factors
    - 1.94 atm perfect cylinder
    - 1.77 atm with eccentricities



Shell Thickness Required for 20 m Tube Length per Division 1

*@ 1.23 m OD→

Material	Tube shell thickness (mm): 20 m Tube Length	Tube shell thickness (mm): 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

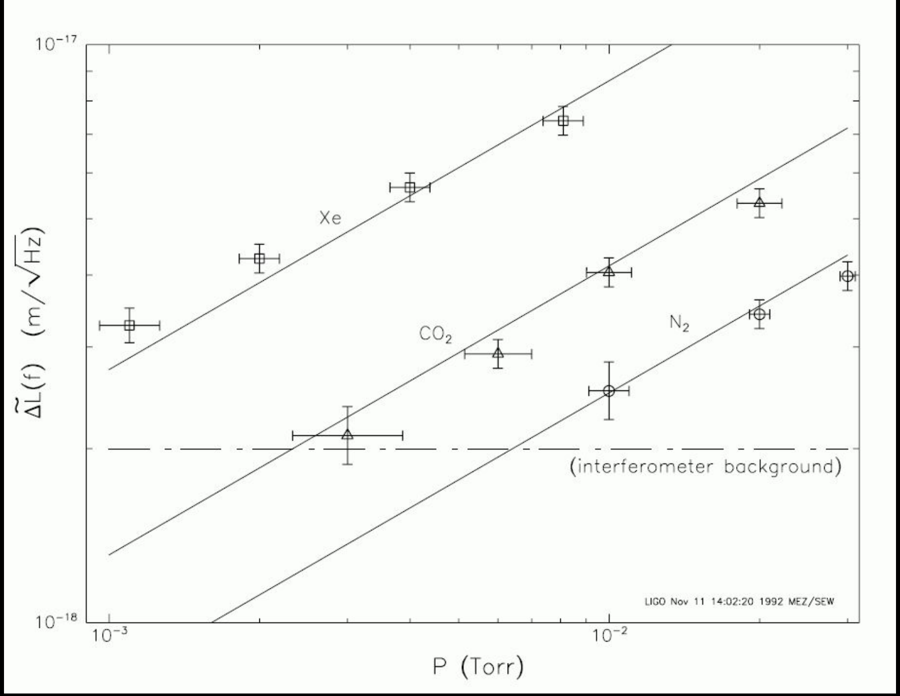
Residual Gas Scattering

Statistical model verified by interferometer experiment

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz$$

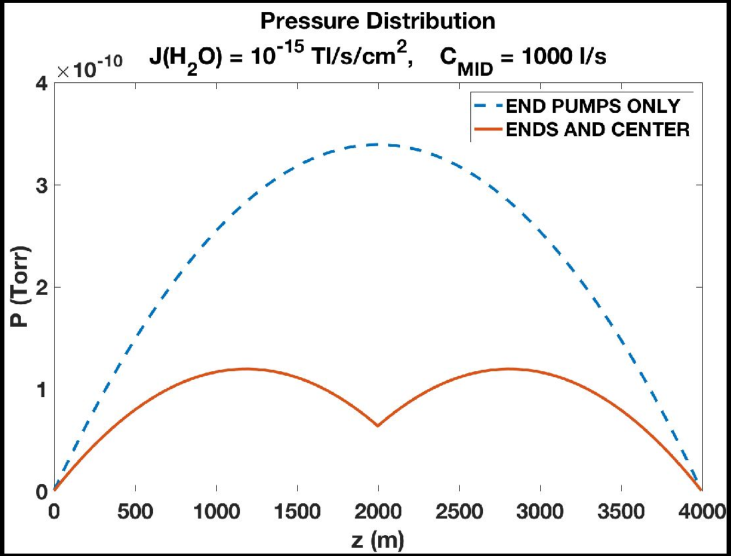
$$\Delta\tilde{L}(f) \equiv \sqrt{S_{\Delta L}(f)} = \sqrt{2S_L(f)}$$

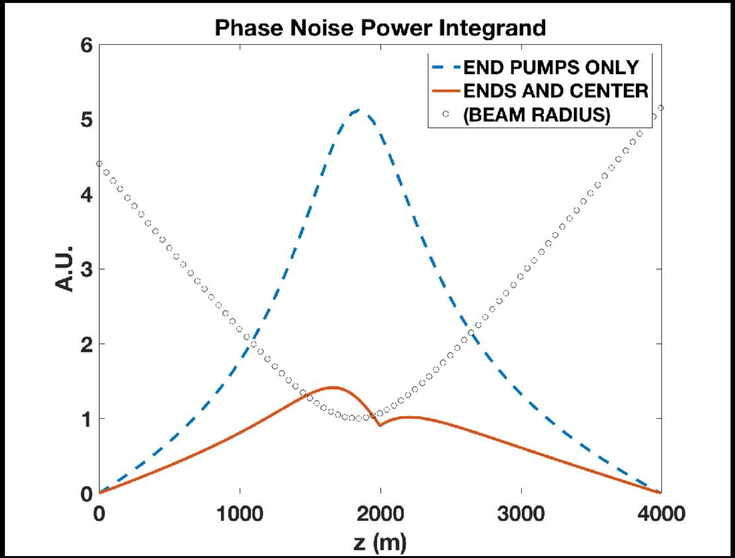
ρ = gas number density ~ pressure
α = optical polarizability ~ (index-1)/pressure
w = beam radius
v_0 = mean thermal speed
L_0 = arm length
ΔL = arm optical path difference



S. Whitcomb and MZ, Proc. 7th Marcel Grossmann Meeting on GR, R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

Gaussian laser beam diameter varies → *pressure gradients matter*





Sample parameters for CE design operating at 1 micron laser wavelength

parameter	aLIGO	CE (1 μm)
L (m)	4,000	40,000
w_0 (mm)	62	83
h_{gas} ($Hz^{-1/2}$)*	$< 2 \times 10^{-25}$	$< 5 \times 10^{-26}$
P[H_2] (Torr)	$< 10^{-9}$	$< 10^{-9}$
P[H_2O] (Torr)	$< 10^{-10}$	$< 10^{-10}$
P[CO_2] (Torr)	$< 2 \times 10^{-11}$	$< 2 \times 10^{-11}$

*3x safety margin

Assuming 40km x 1.2m ϕ tubes with 'LIGO-typical' outgassing, e.g.,
$J(H_2O) \sim 10^{-15}$ T l s^{-1} cm^{-2} and with
$J(H_2) \sim 5 \times 10^{-14}$ T l s^{-1} cm^{-2} ,
this could be achieved with one 1,000 l/s ion pump deployed each kilometer.