Beamtube Design, Fabrication, Assembly and Commissioning Tradeoffs

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LIGO Laboratory and Cosmic Explorer Consortium

CE - ET Beamtube Workshop III (BTW3)
LIGO Hanford
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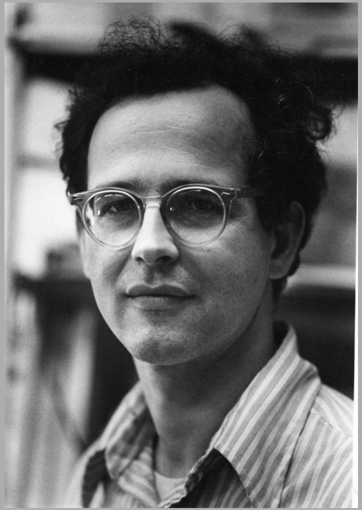
LIGO-G2502104

How This All Started



Rai Weiss, MIT

QUARTERLY PROGRESS REPORT

APRIL 15, 1972

No. 105

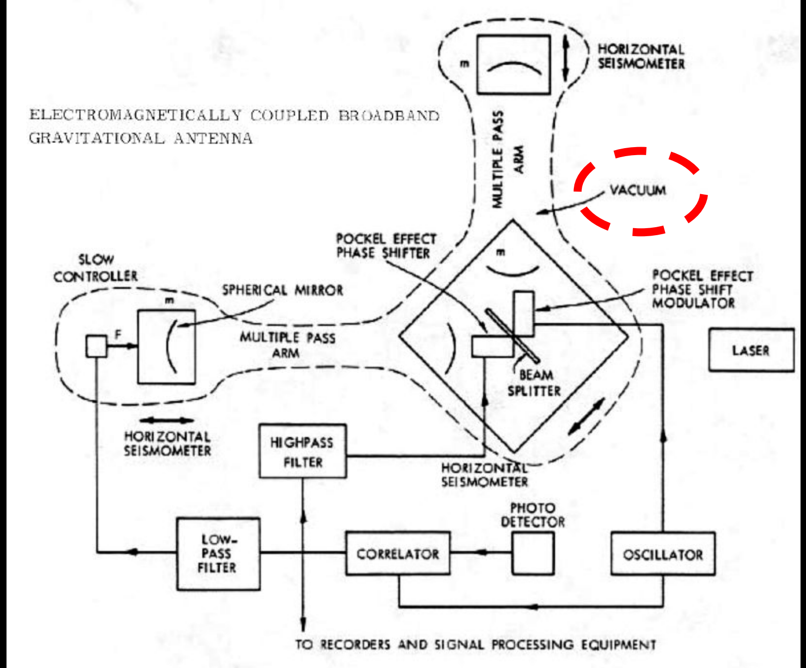


Fig. V-20. Proposed antenna.

Review: ET and CE Vacuum Drivers

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

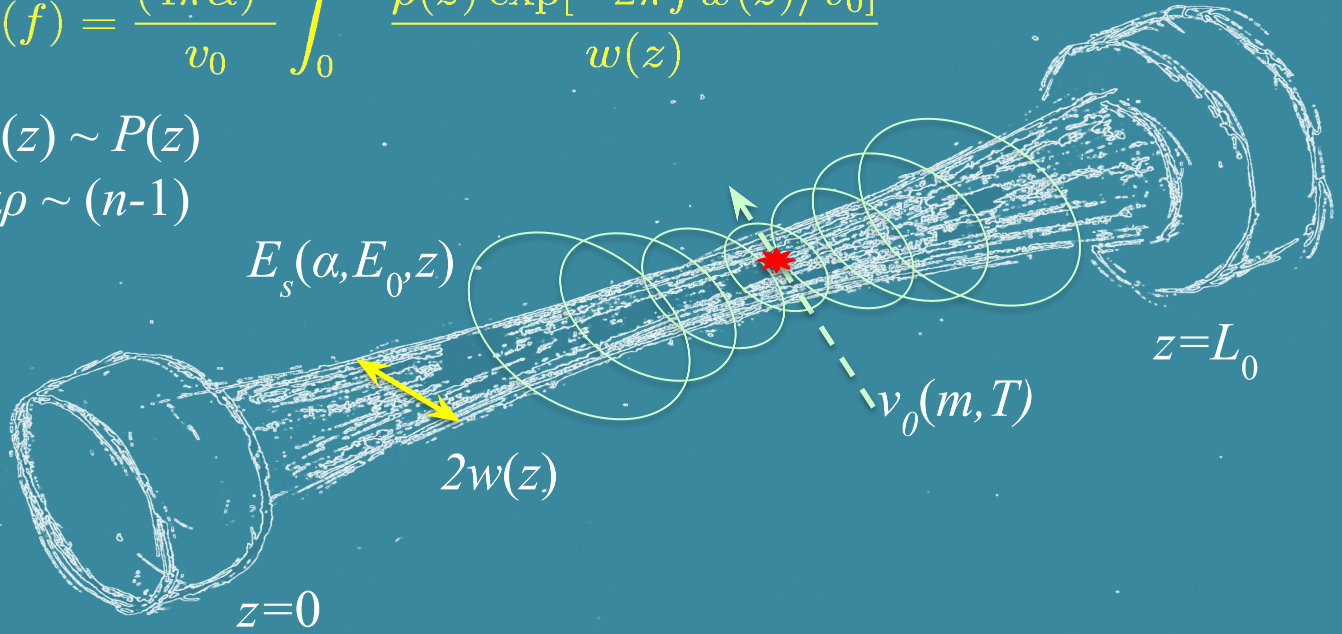
mainly applies to *beamtubes*

Light Scattering from Residual Gas

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

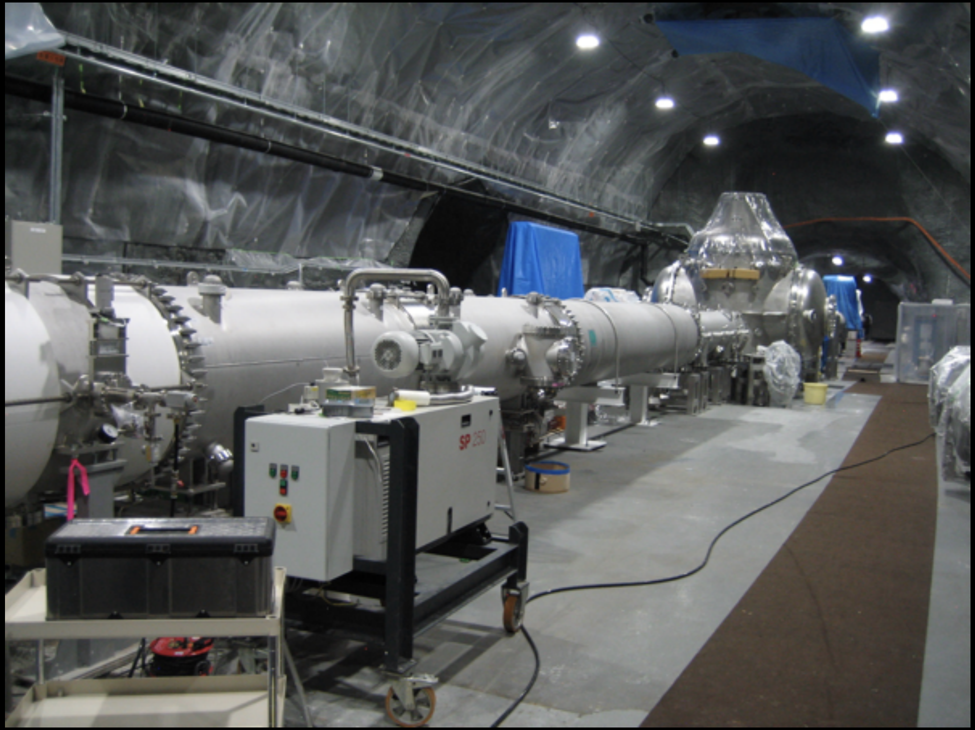
$\rho(z) \sim P(z)$

$\alpha\rho \sim (n\text{-}1)$



$S_L(f)$ = mean square deviation in L per unit bandwidth at signal frequency f

GEO600, KAGRA



Virgo, LIGO

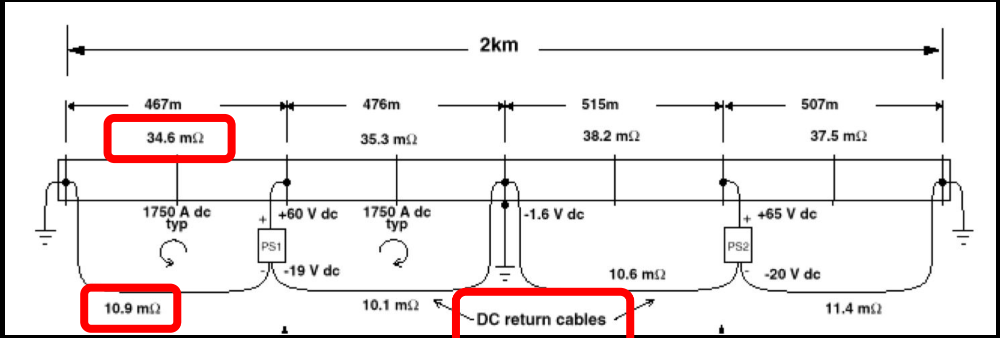
Example (Starting Point?): *How LIGO Did It*

- 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 cylinder
  - Discrete bellows every 40m
  - External stiffeners every 78 cm
  - Internal oxidized SS baffles
  - 20 m unit span/support interval
  - Butt-welded, 2 days/field joint
  - 100% He MSLD tested
  - 2 km sectors (gate valve pitch)
  - I^2R bake@160C, 3 weeks/sector
- 1997$ 47M / 16 km
  - 1997$ 3k/m
  - 1997$ 60/lb
- About 4.5 years/16km
  - Not including design/development
  - Sequential, by 2km sector

LIGO beamtube fab & field assembly

(by Chicago Bridge and Iron)

LIGO beamtube bakeout



2 layers fiberglass applied by hand

~2,000A DC

160°C for 3 weeks

Why not just a bigger LIGO/Virgo/Kagra/GEO?

$ COST & SCHEDULE 💀

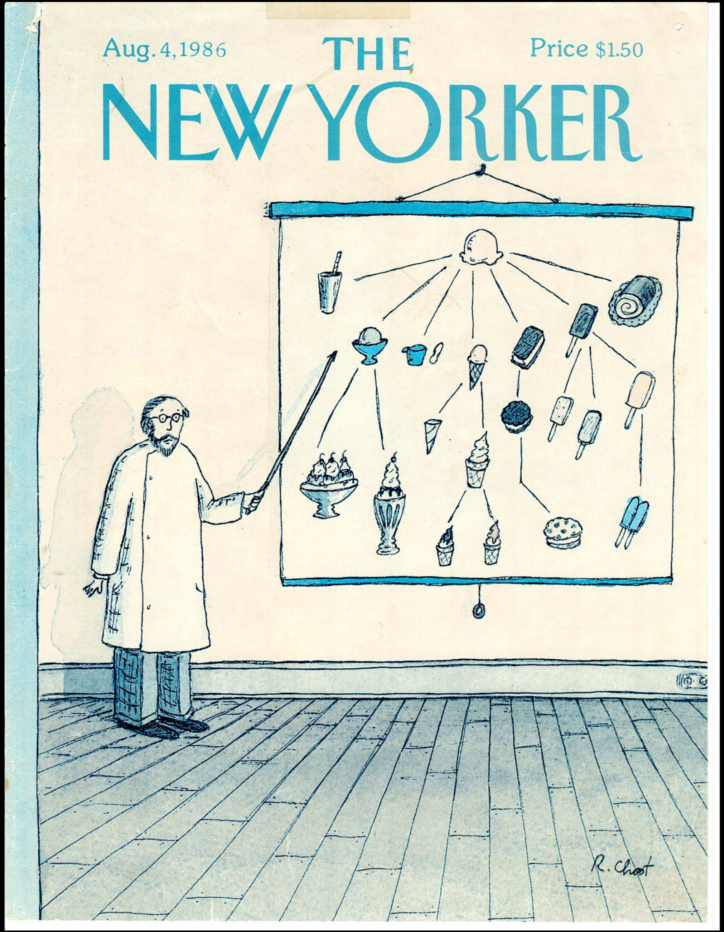
Scaling up existing design 10x could meet technical requirements
…but only if you also scale cost & construction duration

We seek LIGO-like UHV performance

- *at <1/2 the cost per unit length*
- *with total construction duration < 5 years*

"[A real engineer] … can do well for a dollar, what any bungler can do, after a fashion, for two." – *A. Wellington (1877)*

Choices, choices…



I. CE/ET BEAMTUBE MATERIAL OPTIONS
(See Carlo's talk earlier in this session)

- Air-fired austenitic stainless (e.g., 304L or 316L) *no longer the sole option*
  - Since 2019, joint CE/ET vacuum study group has vetted **mild steel** as a UHV material
    - + 5x cheaper than 304 by weight (raw material only)
    - + Intrinsically hydrogen-free (!)
    - + Thin walled (< 5 mm) sections should form & weld similar to austenitic SS
    - - High risk/complexity, extra process steps, maintenance burdens due to corrosion susceptibility
  - CERN has also now established **ferritic stainless** (low-nickel, e.g., 441) as a favorable option
    - + 2x cheaper than 304 by weight; in wide commercial use (e.g., car exhausts)
    - + Also hydrogen-free (!)
    - - Lower corrosion resistance than austenitic grades
    - - Extra precautions for welding & forming; potential risk of embrittlement
  - Thickwall mild steel (petroleum pipeline) ~ 10mm thick
    - + Super cheap, huge supply; CE or ET would be a small order
    - + No radial stiffeners needed (but expansion joints are essential)
    - - Corrosion protection?
    - - Leaktest through protective coatings?
    - - Weight (support cost)? Transport? Field welding?
    - *- R/L incompatible with I^2R bake → alternate degassing method required*

- *NOTE: raw material will likely comprise < 15% of total cost*
  - "Free" material can cost more, if it takes extra work or adds risk!
  - *Traditional 304 SS is by no means ruled out*
    - 450C air-firing to remove dissolved H is an extra step, but well proven by LIGO and Virgo (and comparatively inexpensive)

II. TUBE CONSTRUCTION METHODS

- Straight tubes: Spiral Welding (LIGO)
    - + Arbitrary unit length, long self-supporting span (20m +)
    - + Fast production
    - + Accepts wide variety of material skelp widths
    - - Greater total length of welds
    - - Specialized production machinery
- Straight tubes: Rolled longitudinal seam (Virgo)
    - + Simpler production tooling
    - - Unit length limited by roller tooling and/or skelp width
- Both: Discrete stiffeners and expansion joints straightforward, but labor-intensive & costly
- RAL introduced formed convolutions in the 1990’s (effectively all-bellows); used in GEO600
    - + Can use thinner material (as low as 0.9 mm)
    - + Obviates both radial stiffeners and expansion joints (but shorter component units)
    - - Elevates outgassing area, degrades conductance
    - - Complicates cleaning/drying
    - - Frequent supports or added “spine” required due to sag
- In 2022 CERN demonstrated intermittent formed convolutions as an alternative
    - + Same advantages but reduced area & conductance penalties
    - - Fabrication may limit unit length (roll- or hydro-forming)
    - - Self-supporting span still limited to ~ 10m (numerous supports or “spine” req’d)
- → Combine roll-forming convolutions with LIGO-like spiral weld?
    - *- Torsion of helical convolutions with expansion makes this impractical* ✘

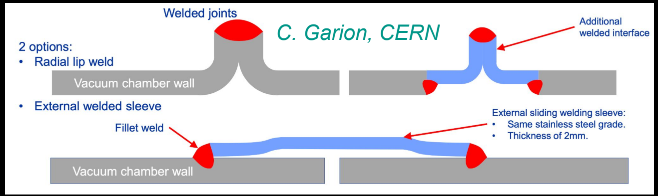

LIGO (1997)


GEO600 (2010)

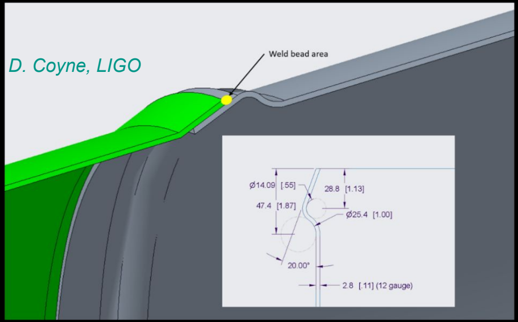

RAL (1992)

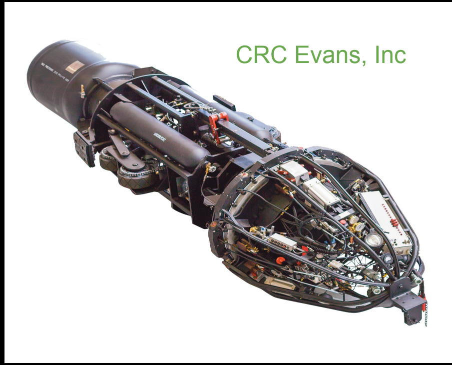

CERN VSC (2023)

III. Field Joint Options



- Butt welds are not easy or fast
  - LIGO fitup/weld/test took 2 days/joint
  - Relied on extreme skill, intense QA, long learning curve
- Joint alternatives: Flange, Sleeve, Socket?
  - Reduce joint prep time
  - Improve weld reliability
  - Improve repairability
  - Decrease alignment & fitup time
  - Reduce reliance on extreme skill pool
    - Allow multiple assembly fronts w/out compromising quality
- Extreme automation?
  - Robotic alignment, weld, leaktest?
  - Tooling investment may be reasonable at 80+ km





IV. Contamination


Detergent/hot water cleaning (LIGO/CBI)

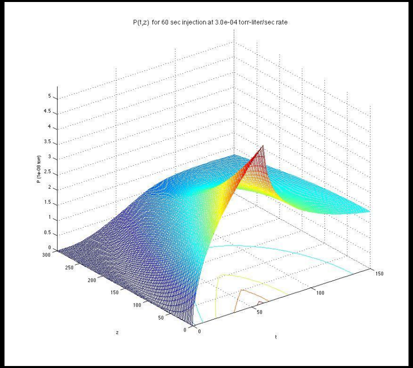

Traveling assembly cleanrooms (LIGO/CBI)

- Free iron, salts and chlorides
  - Seed corrosion in SS (intrinsic in mild steel…)
  - Constraint on supply chain, manufacturing, transport, tooling, installation
- Hydrocarbons
  - Phase noise requires P(HC) < 3×10^{-13} Torr (~300 AMU)
    - Detergent cleaning removes residues; FTIR sampling to confirm
    - Atmospheric re-exposure restores some HC's
      - In-situ sector bakeout (nominally for water) must also remove "re-acquired" HC's
  - Interferometer mirror contamination
    - Mitigated by conduction & pumping gradients, distance
- Particulates
  - Constraint on particles falling (or jumping?) through beam
    - Here too, limits are more stringent near optics than in beamtubes
  - Fab, transport, assembly require local cleanroom conditions

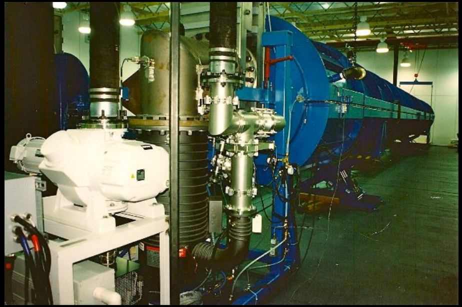
V. Leaks: Avoid, Test, Repair

- Leak localization & repair at ET/CE scale is problematic*
- Initial P(leak) << 1 per sector may be necessary
  - Fab to include component-level He MSLD
  - Field joints should include 100% testing
- Means to test full sectors for acquired leaks
  - Post-bake
  - During operational life
- Corrosion Susceptibility
  - Pit Corrosion
  - Stress-corrosion cracking (SCC)
  - Microbial-induced corrosion (MIC)
  - *Dependent on site environment*
- Fatigue Sensitivity
  - Thermal cycling
  - Bakeout
  - Seismic
- Impact, Abuse, Neglect…
  - System should be *REPAIRABLE* and *RECOVERABLE* after accident

*(ask how I know)



MSLD response vs. time and distance to leak (LIGO-T1200375)

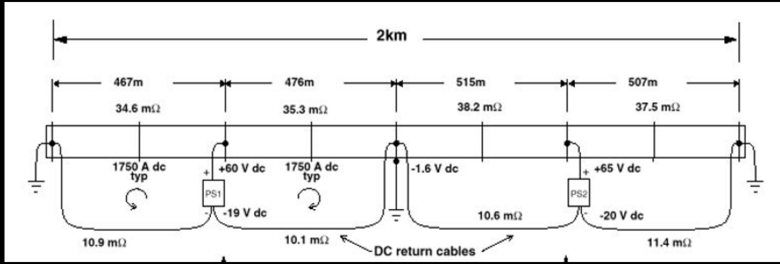


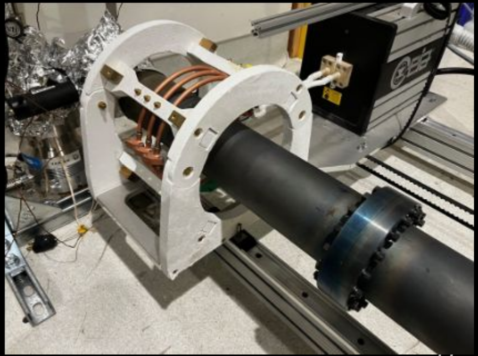
He leak test coffin (LIGO/CBI)

Field weld He leaktest (LIGO/CBI)

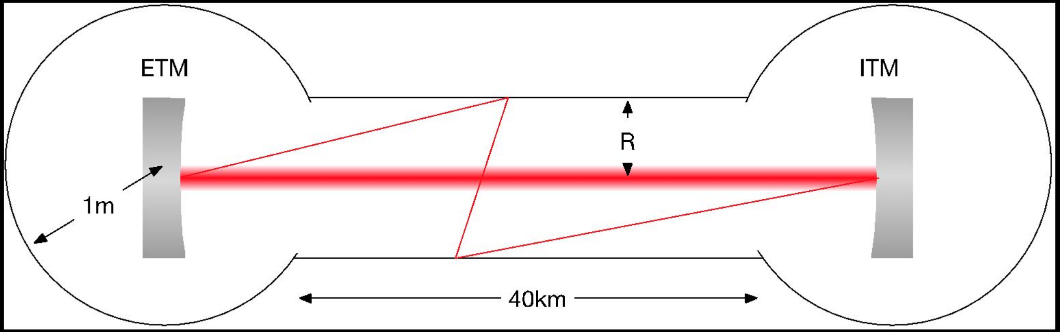
VI. Bakeout

- Water (and HC's) must be desorbed after assembly
- Was LIGO recipe (160C / 3 weeks) overkill?
  - post-bake $Q(H_2O) \sim 10^{-16}$ Tl/s/cm^2 , 10x better than required
  - 80C could simplify insulation and greatly reduce cost
- Baseline: DC electric I^2R (Joule) heating
  - ~ 250 kW/km for 160C with 150mm glass wool insulation
  - Cheap, easily installed, non-contaminating, environmentally sound insulation is an unsolved issue
  - DC return requires heavy cables
    - Tube walls > 5mm thick have too little impedance!
- Promising alternates
  - Traveling induction, ultra-dry viscous entrainment (CE/IBEX)
    - Incremental/continuous process could relieve need to pump & heat entire sector as a unit (low instantaneous power)
    - Can work for thick or thin walls
    - Relies on arresting re-adsorption in wake of heating
  - Plasma desorption (ET/MACBETH)
    - May be effective with much less power dissipation, insulation





VII. 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*

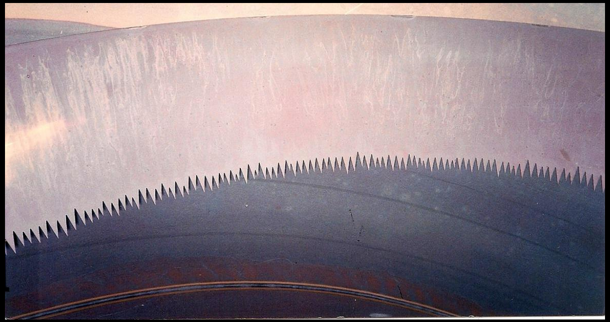
→ *Tube supports, isolation, mechanical eigenmodes can have dramatic effect*

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

…and the most difficult to change later

VII. Light scattering, baffles and vibration (cont'd)

- Tube & baffle optical scatter can in principle drive *everything:*
  - Minimum tube diameter & straightness
  - Material surface reflectance and texture
  - Integration sequence (baffle installation, alignment)
  - Tube mechanical compliance and eigenmodes
  - Tube support vibration and vibration isolation
- Possible mitigations
  - Preclude stick-slip or autogenous impulses by kinematic design
  - Universal tube support and/or baffle mechanical isolation
    - *COSTLY, especially if supports must be frequent*
  - "Extreme" local isolation (with restricted aperture)
- Modeling is notoriously difficult!
  - Depends on unknown/unknowable properties of future mirrors
  - Depends on projections of site seismicity & acoustics
  - Experimental constraints (e.g., LIGO as-built) have not been straightforward
- *Joint understanding of technical risk vs. engineering cost is critical*



Internal beamtube baffle (LIGO)

This is a top priority for our workshop!

View from 21,000 Feet

Immense progress since we first got together in early 2019! Many difficult problems have been isolated; some are even solved.

We have much more to learn, but can at least see all parts and how they interact.

To forge CE and ET, solutions must contribute to *efficient and cohesive system designs.*

This workshop is dedicated to sharing complementary expertise and perspectives across disciplines, in order to achieve this synthesis.

Enjoy the breakout sessions, and thank you for participating!

Destination LIGO: SEA-PSC from 21,000'

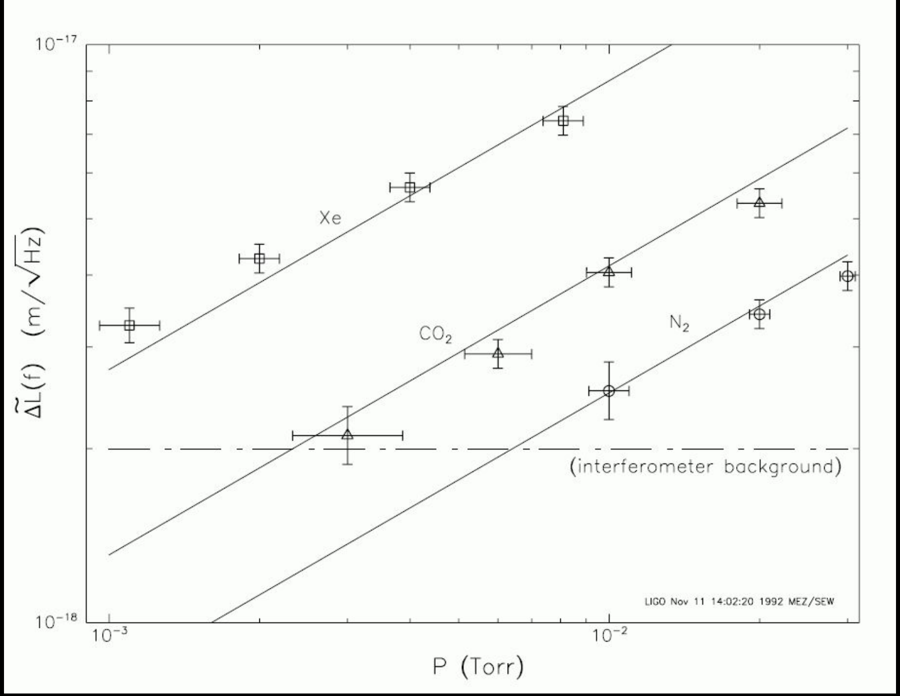
Residual Gas Scattering

Statistical model verified by interferometer experiment

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

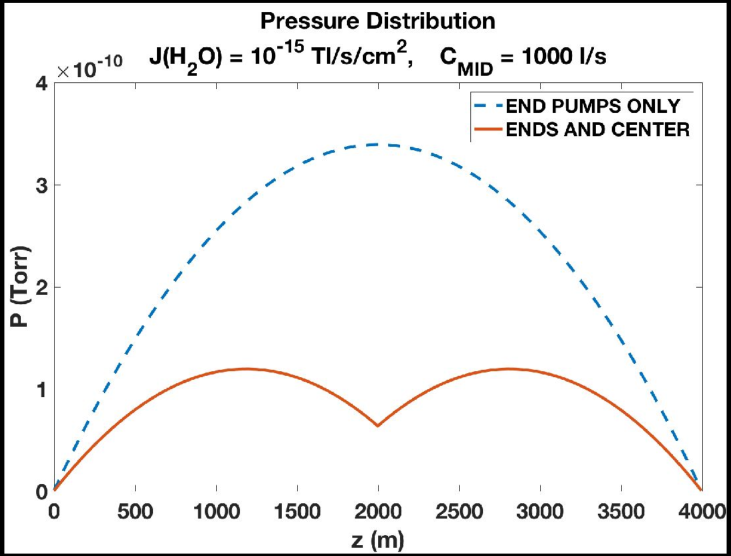
$$\Delta\tilde{L}(f) \equiv \sqrt{S_{\Delta L}(f)} = \sqrt{2 S_L(f)}$$

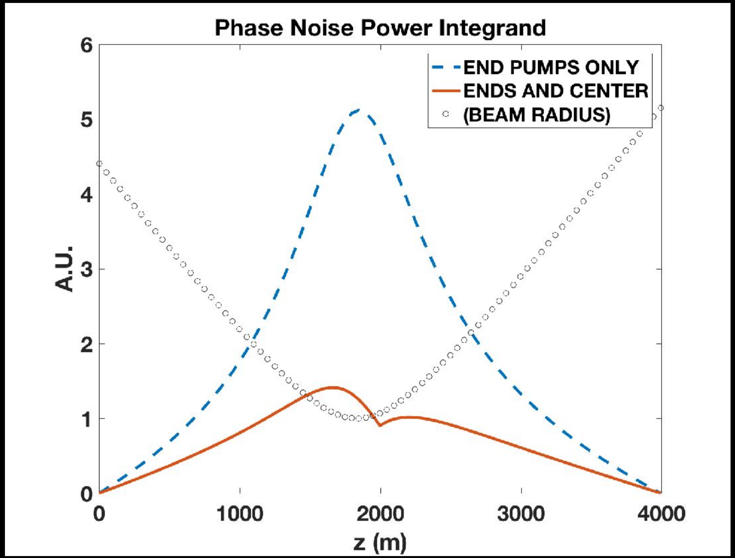
ρ = gas number density ~ pressure
α = optical polarizability ~ (index-1)/pressure
w = beam radius
v_0 = mean thermal speed
L_0 = arm length
ΔL = arm optical path difference



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

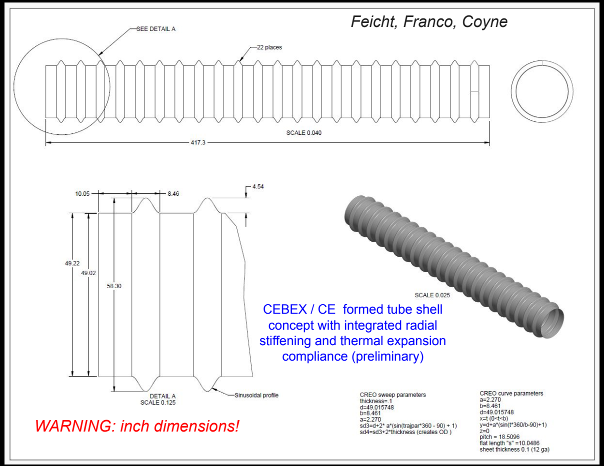
parameter	aLIGO	CE (1 µm)
L (m)	4,000	40,000
w_0 (mm)	62	83
h_{gas} ($Hz^{-1/2}$)*	$< 2 \times 10^{-25}$	$< 5 \times 10^{-26}$
P[H_2] (Torr)	$< 10^{-9}$	$< 10^{-9}$
P[H_2O] (Torr)	$< 10^{-10}$	$< 10^{-10}$
P[CO_2] (Torr)	$< 2 \times 10^{-11}$	$< 2 \times 10^{-11}$

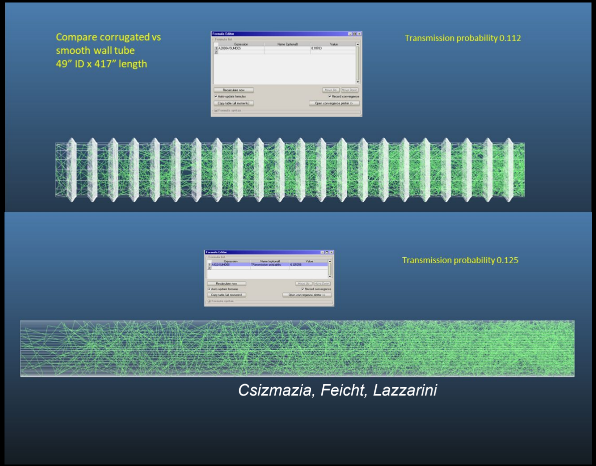
*3x safety margin

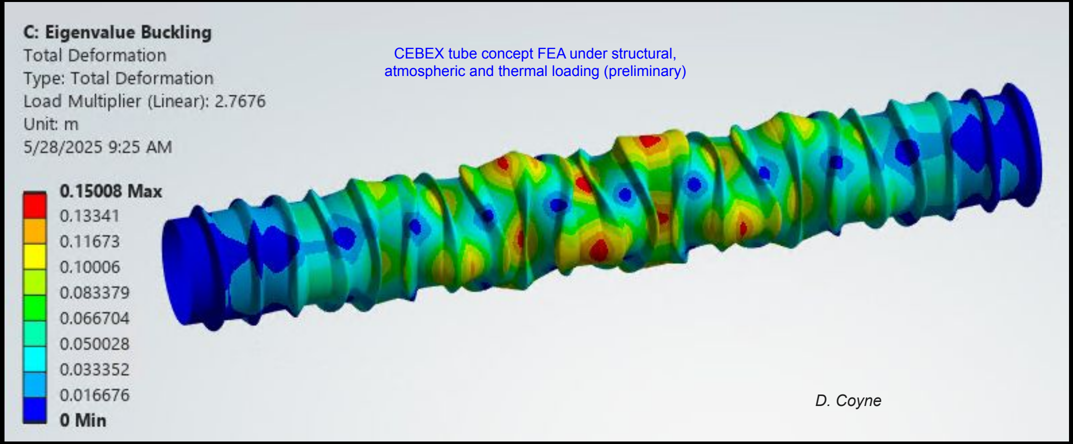
Assuming 40km x 1.2m ϕ tubes with 'LIGO-typical' outgassing, e.g.,
$J(H_2O) \sim 10^{-15}$ T l s^{-1} cm^{-2} and with
$J(H_2) \sim 5 \times 10^{-14}$ T l s^{-1} cm^{-2} ,
this could be achieved with one 1,000 l/s ion pump deployed each kilometer.

More fun with intermittent corrugations (teaser)

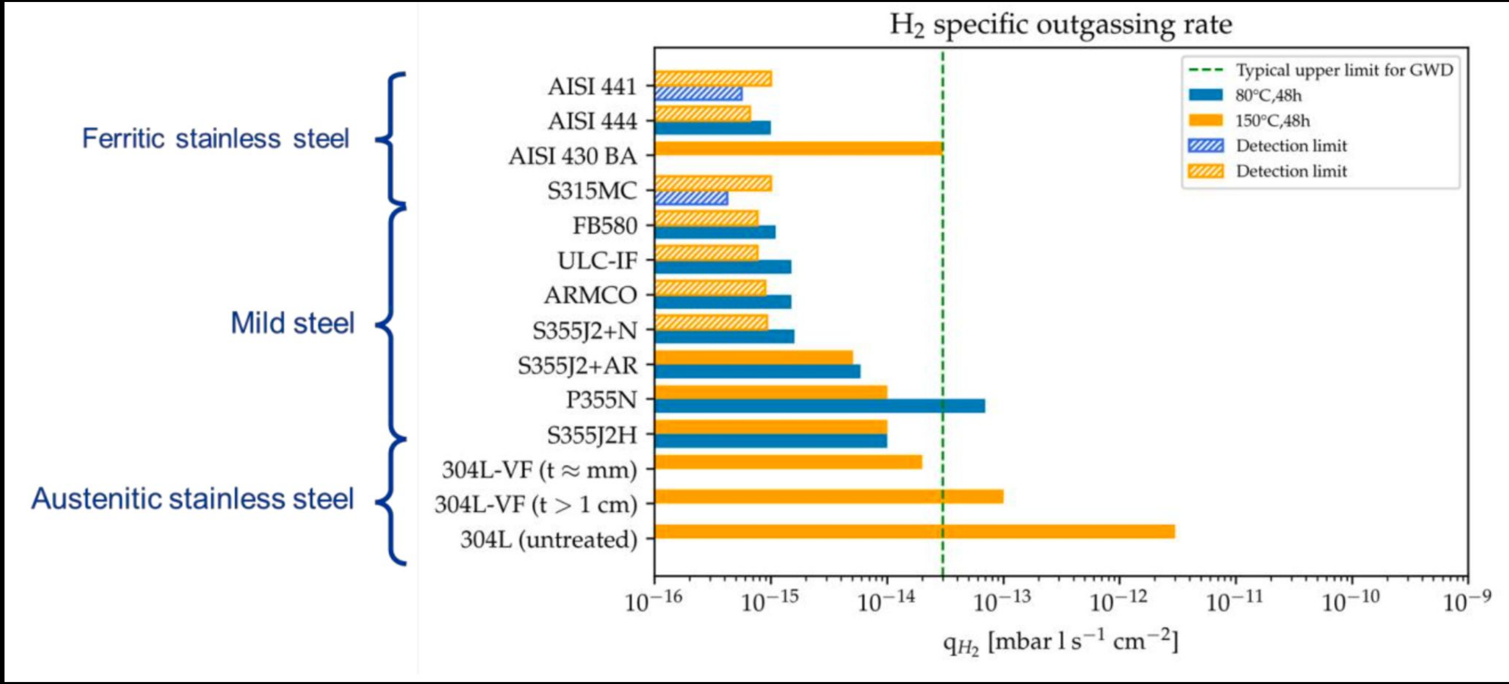
Coyne, Franco, Feicht







Hydrogen outgassing



C. Scarcia, CERN (2024)