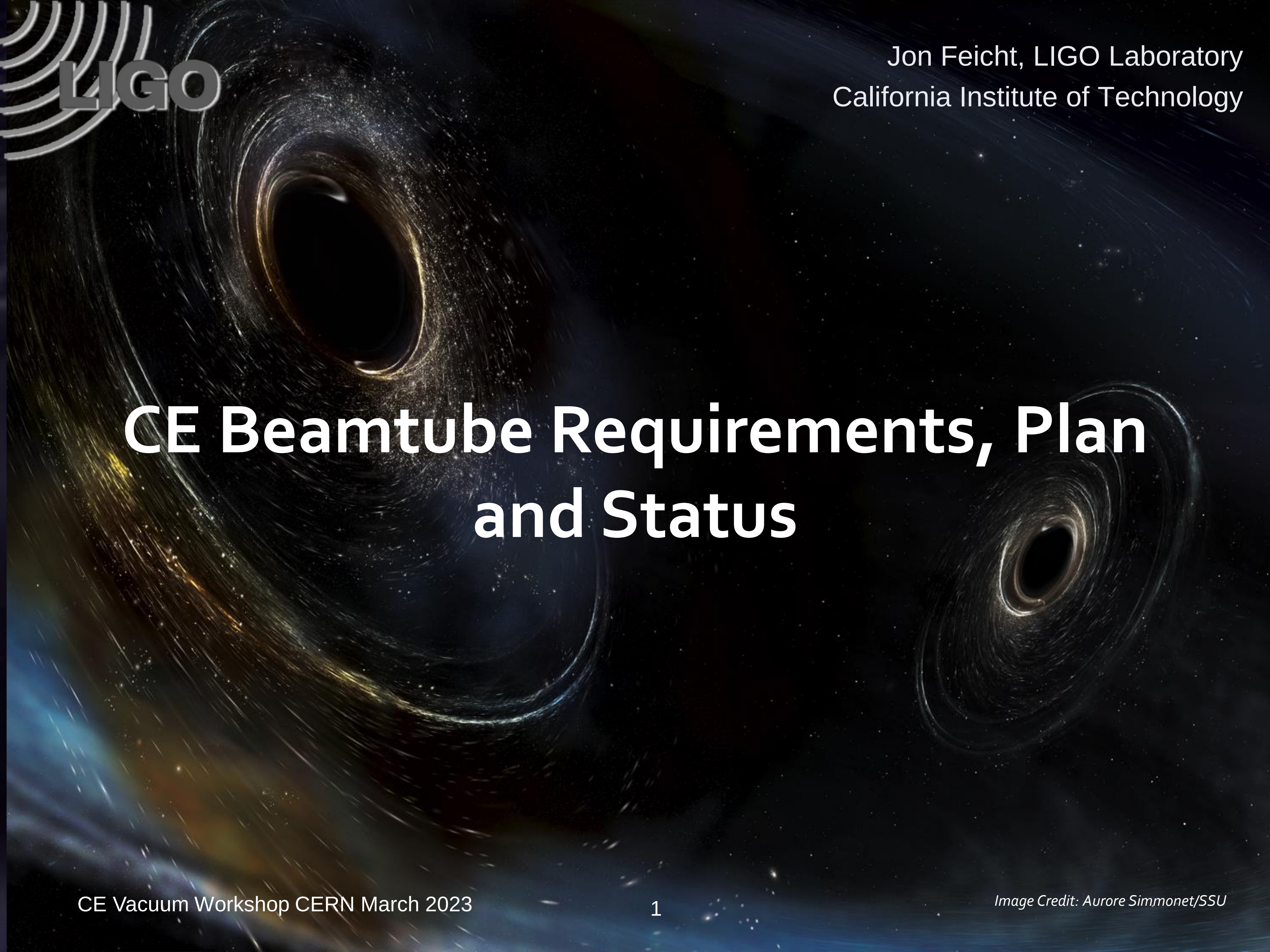
Jon Feicht, LIGO Laboratory
California Institute of Technology



CE Beamtube Requirements, Plan and Status

Image Credit: Aurore Simmonet/SSU

3rd Generation Gravitational Wave Detector NSF vacuum workshop Jan 2019

3rd Generation Detector Vacuum System Design Workshop held in 2019.
Final report publicly available at https://dcc.ligo.org/LIGO-P1900072

Participants in the *NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Instrumentation,* LIGO Livingston, Jan. 28-31,2019

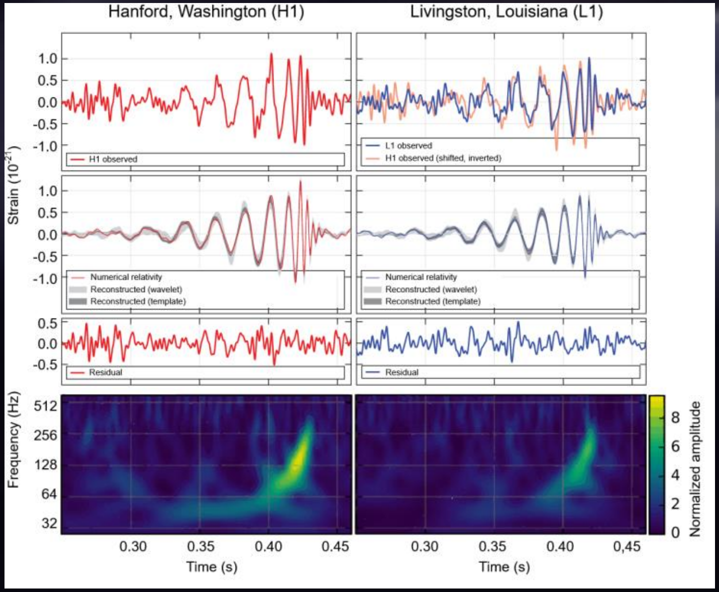
Attendee	Affiliation
Curtis Baffes	FNAL
Alex Chen	FNAL
Paolo Chiggiato	CERN
Bob Childs	MIT PSFC
Dennis Coyne	LIGO Caltech
Fred Dylla	AIP (retired)
James Fedchak	NIST
Jon Feicht	LIGO Caltech
Joseph Giaime	LIGO Livingston
Daniel Henkel	Henkel Consulting
Hsiao-Chaun (Dick) Hseuh	BNL
Albert Lazzarini	LIGO Caltech
Yulin Li	Cornell University
Yev Lushtak	Cornell University
Enrico Maccallini	SAES
Dennis Manos	William & Mary
Scott McCormick	LIGO Livingston
Gerardo Moreno	LIGO Hanford
Dave Morrissey	MSU
Tetsuro Nakamura	MiraPro
John Noonan	ANL
David Ottoway	Adelaide University
Richard Oram	LIGO Livingston
Harry Overmier	LIGO Livingston
Antonio Pasqualetti	Virgo
Matt Poelker	Jefferson Lab
Tommaso Porcelli	SAES
David Reitze	LIGO Caltech
Fulvio Ricci	Virgo
Chandra Romel	LIGO Hanford
Yoshio Saito	KAGRA
Bruce Strauss	DOE
Tom Swain	VAT
Ryutaro Takahashi	KAGRA
Martin Tellalian	McDermott
Takayuki Tomaru	KEK
Rainer Weiss	LIGO MIT
Michael Zucker	LIGO MIT

Topics

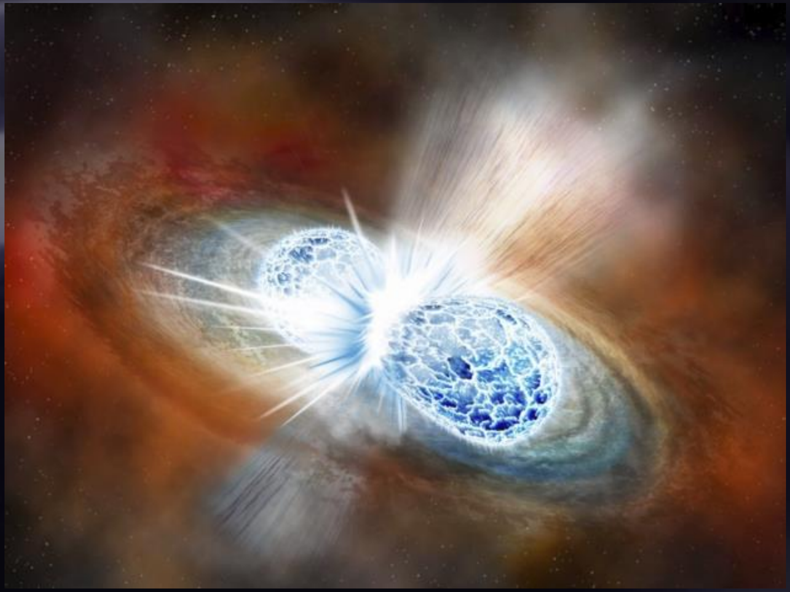
- 2015 - Gravitational Wave Astronomy 1st Detection and Multi-Messenger event
- Rational for building CE
- Design Trade Space: Improving Detector Sensitivity
- Scaling to 40 km beampipes
- Beamtube Requirements
    - Mechanical Design
    - Vacuum Conditions
- Outgassing Research
    - Water and hydrogen
    - Coatings
    - LTREX chamber
- Alternate Materials and Concepts
    - Carbon Steel
    - Nested (coaxial) System
- Summary and Status

Gravitational Wave Astronomy

- Predicted by general relativity- acceleration of mass.
- Distortion of space-time “strain waves”. Measure 10^{-19} m change in LIGO arms.
- First detection September 14th 2015- Black hole pair “inspiral”.
- Neutron star pair- August 17 2017- First GW+EM signals “multi-messenger”.



GW150914



GW170817

Rational for CE ?

- **CE would be a "3rd generation" GW detector**
  - **Major upgrade vs LIGO, 10x increase arm length 4 km -> 40 km**
  - **10x increase in strain sensitivity (scales with L). See farther back in time.**
  - **Larger "volume" of observation. Potential 1000x increase in detection frequency.**
  - **Ground based detector similar to LIGO, leverages > 20 yrs. of operational experience.**
  - **Minimal reliance on "new" technologies that may not become available.**
  - **Minimal increase in noise sources, same overall design as LIGO.**

Trade Space-Increased GW Detector Sensitivity

- Increase length of arms-the current CE proposal (ΔL/L)
  - Sensitivity scales with L .
  - Noise sources stay approximately constant.
  - Many cost drivers- land, materials, earthwork, site topology (30 m earth curvature), seismic.
  - LISA: Move to space. "Free" vacuum, unlimited room, explore much lower frequencies. Trade is complexity and costs, mission life and redundancy. JWST cost $10B, a cost growth about 1000%, 15 years behind schedule. Add $1B to launch.
- Increase "N" number of arm transits (add path length and photon density)
  - Optics reflectivity determines N, for LIGO about 200 trips, cavity finesse. Coatings about 15 ppm XMNS currently with ~10 ms arm storage time. Optical losses accumulate as N increases, also don't want light storage time close to GW period, so this approach has limits.
  - Reflective coatings are near state of the art, but also want coatings with lowest Brownian (thermal) noise possible .....significantly "better" coatings under intense research, 2x improvement?
- Reduce noise sources-other options (thermal, seismic)
  - Cryogenics- increased complexity, optics are now the vacuum pumps (cryofilms- optical scattering noise).
  - Lower (vacuum) arm pressure –> lower forward scattering-reduced phase noise , XUHV not practical.
  - Better suspensions (seismic), lower coating defects, larger or different test masses, scattering, etc. R&D.
- Increase laser/arm power (quantum noise)
  - A-LIGO arm power goal 800 kW <10 mm beam. Optics damage threshold ? Lossy areas/defects in coating "burn", increased radiation pressure, thermal lensing, shot noise, laser stability (need for length measurement).
  - Molecular films and particles (scatter and ablation, vaporize dust particles (loss and scatter).

See https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf for a discussion of trades associated with alternate CE detector designs

Concentrate on arm length trade

- 40 km arms will add 10x strain sensitivity
  - "See" cosmic events from 1st epoch of time.
  - Measure strain < 10^{-22} ΔL $4X10^{-18}$m.
  - Minimal new technology drivers (optics, coatings, etc.).

- Vacuum system becomes technology and cost driver
  - 90M liter UHV system.
  - Where to build and how to manage the 30 meter height change (earth curvature/40 km).
  - Cost of SST (Cr, Ni) is volatile (surcharge, cost escalation risk). Alternate materials?
  - Most requirements (diameter, vacuum levels, straightness are similar to the existing LIGO system.
  - Can we bake such a large system?

A wave's strength is measured by the *strain* induced in the detector,

$$h = \Delta L / L$$

We can calculate expected strain at Earth;

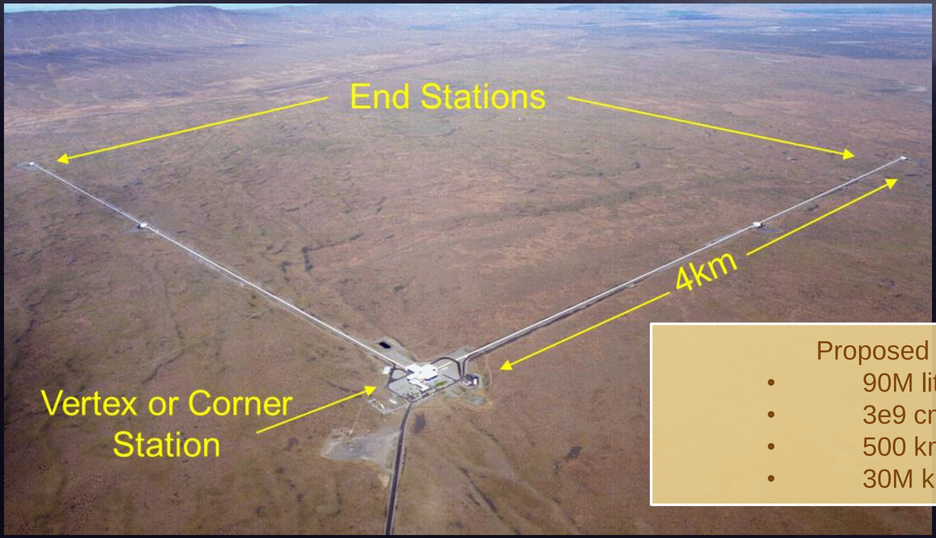
$$|h| \approx 4p^2 GMR^2 f_{orbit}^2 / c^4 r \approx 10^{-22} \left(\frac{R}{20\mathrm{km}}\right)^2 \left(\frac{M}{M_Q}\right) \left(\frac{f_{orbit}}{400\mathrm{Hz}}\right)^2 \left(\frac{100\mathrm{Mpc}}{r}\right)$$

Existing interferometer arms are 4,000 meters long,

$$DL = h \times L \approx 10^{-22} \times 4,000\, m \approx 4 \cdot 10^{-19}\, m$$

Scaling to 40 km

- **40 km system largest cost driver will be the the vacuum system**
  - **Cost scaling: Beamtubes (8 km) were $76M (1994) estimated $700M in 2028.**
  - **Chromium and nickel are commodities, price can be volatile. LIGO Contractor would not commit to FFP.**
  - **Are there alternate materials?**
  - **Can we eliminate the concrete enclosure?**
  - **What about bakeout?**
  - **We will assume an above-ground facility.**



Proposed CE beamtube 80 km

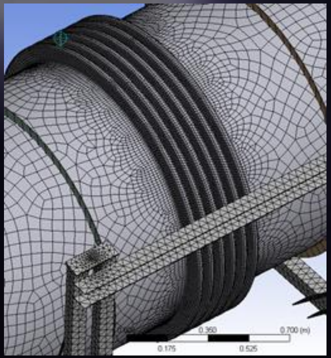
- 90M liter x10^{-9} Torr
- 3e9 cm^2 of surface area
- 500 km of welds
- 30M kg of material (1.27 cm wall)

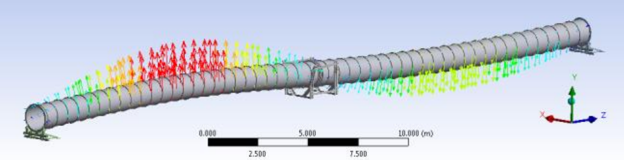
Beamtube requirements- Mechanical

- 1.2 meter pipe-80 km total length (two arms)
- 1 meter clear aperture through the arm (alignment, straightness)
  - Straightness to 5 mm rms (beam transmission, diffraction). Differential GPS ~ 10mm/10km resolution? Concrete foundation.
  - Arms orthogonal to 5 mrad (max sensitivity, antenna directivity).
  - Low vibration (phase noise from scattered light). Low optical scatter surface, optical baffles. Seismic noise response.
  - Modal analysis. Suspension systems: bellows, anchor points, no stick-slip, bowing. Stresses-cycle fatigue (particularly w/alt. materials like aluminum-also post weld).
  - Bellows and anchor points to accommodate thermal expansion, atm. pressure, etc. Keep tube aligned. LIGO ΔL/temp ~3.5 meter.
  - Flanges for large gate valves, pumps, etc. Need to be compatible with standard SST construction.
  - Resist atm. pressure, buckling, vibrational modes, operational lifetime, etc. Support rings if thin wall or guard vac if nested.
  - Enclosure required? Accidental or malicious damage, ballistics, wind noise or resonance (Aeolian), lightning, corrosion?
- Beamtube materials costs (M's of kg). Cost of Cr and Ni also heat treatment if using SST (H_2).

Hydrofomed bellow and 48" GV

Modal analysis

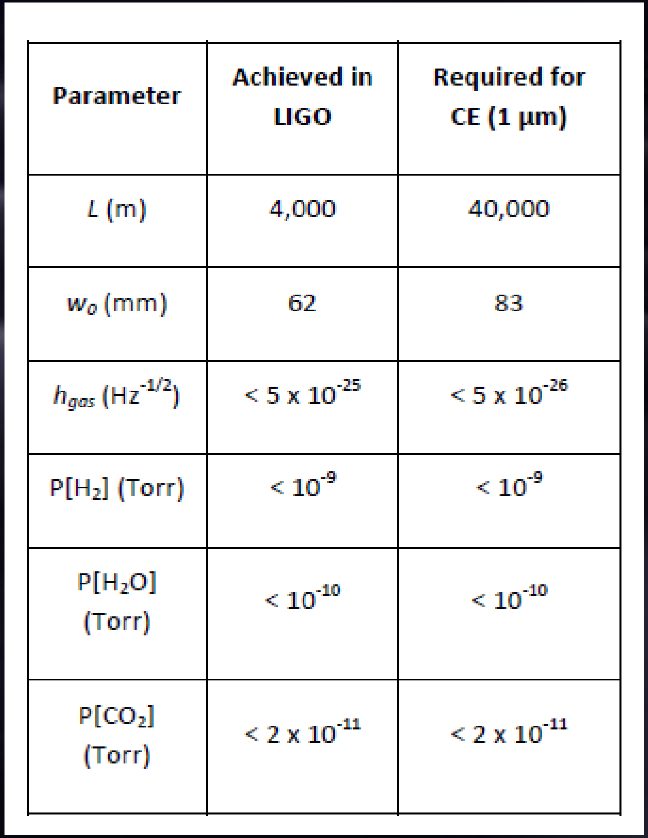




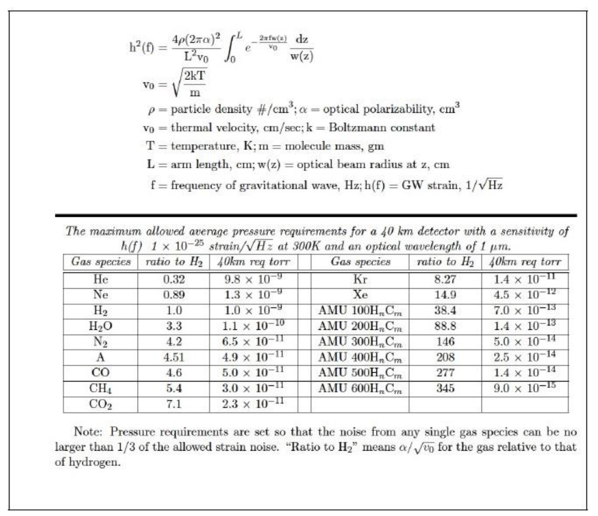
Suspension and cover

Beamtube requirements- Vacuum

- Vacuum requirements similar to LIGO
  - H_2 1e13- Torr-liter/sec-cm².
  - H_2O 1e-16 Torr-liter/sec-cm².
  - Low hydrocarbon flux.
  - Leak rate < 1e-10 Torr-liter/sec He
- Molecule size->polarization. Gas interaction scatter over path length. Phase noise, lowers h(f). Want both # density and amu low.
- Hydrogen diffusion, SST or Aluminum or Steel.
- Water expected to dominate spectrum.
- Keeping HC pressure low. Cleaning w/low waste stream-> low VOCs, ODP, phosphates, etc. Keep parts clean post cleaning-how?
- Bakeout required? Pumps, getters? Pump distribution? (no vibration)
- Low reflectance at 1 µm (laser frequency) desirable. Scattered light noise.



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



$$\mathrm{h}^2(\mathrm{f}) = \frac{4\rho(2\pi\alpha)^2}{\mathrm{L}^2\mathrm{v}_0}\int_0^L e^{-\frac{2\pi \mathrm{f} \mathrm{w}(z)}{\mathrm{v}_0}}\frac{\mathrm{dz}}{\mathrm{w}(\mathrm{z})}$$

$$\mathrm{v}_0 = \sqrt{\frac{2\mathrm{kT}}{\mathrm{m}}}$$

ρ = particle density #/cm³; α = optical polarizability, cm³

v_0 = thermal velocity, cm/sec; k = Boltzmann constant

T = temperature, K; m = molecule mass, gm

L = arm length, cm; w(z) = optical beam radius at z, cm

f = frequency of gravitational wave, Hz; h(f) = GW strain, $1/\sqrt{\mathrm{Hz}}$

The maximum allowed average pressure requirements for a 40 km detector with a sensitivity of h(f) 1×10^{-25} strain/$\sqrt{Hz}$ at 300K and an optical wavelength of 1 µm.

Gas species	*ratio to H_2*	*40km req torr*		*Gas species*	*ratio to H_2*	*40km req torr*
He	0.32	9.8×10^{-9}		Kr	8.27	1.4×10^{-11}
Ne	0.89	1.3×10^{-9}		Xe	14.9	4.5×10^{-12}
H_2	1.0	1.0×10^{-9}		AMU 100H_nC_m	38.4	7.0×10^{-13}
H_2O	3.3	1.1×10^{-10}		AMU 200H_nC_m	88.8	1.4×10^{-13}
N_2	4.2	6.5×10^{-11}		AMU 300H_nC_m	146	5.0×10^{-14}
A	4.51	4.9×10^{-11}		AMU 400H_nC_m	208	2.5×10^{-14}
CO	4.6	5.0×10^{-11}		AMU 500H_nC_m	277	1.4×10^{-14}
CH_4	5.4	3.0×10^{-11}		AMU 600H_nC_m	345	9.0×10^{-15}
CO_2	7.1	2.3×10^{-11}				

Note: Pressure requirements are set so that the noise from any single gas species can be no larger than 1/3 of the allowed strain noise. "Ratio to H_2" means $\alpha/\sqrt{v_0}$ for the gas relative to that of hydrogen.

Partial pressure requirements are similar to those achieved in LIGO

Issue: Dealing with water outgassing

- Water *is* the problem.
- Distribution of binding energies
- Mid-range energies are the problem, high/low energies irrelevant.
- Either raise T (bake) or lower binding energy
- Coatings to lower energy?
- Many in the collaboration are studying this.

“Sojourn” time at room temperature vs energy*

E_b [kcal/mol]	E_b [eV]	τ_a
1.4	0.06	1.2 x 10^{-12} s
3.5	0.16	5 x 10^{-11} s
9.5	0.41	1.2 x 10^{-6} s
14.3	0.62	5.5 xo^{-3} s
19	0.83	15 s
21	0.93	15 min
23	0.98	2 h
24	1.04	8 x 10^{4} s ~ 1 d
28	1.24	2 x 10^{8} s ~ 10 years
35	1.55	7 x 10^{13} s ~ 20,000 years

physisorption

weak chemisorption

Water on SST ~ 1 eV

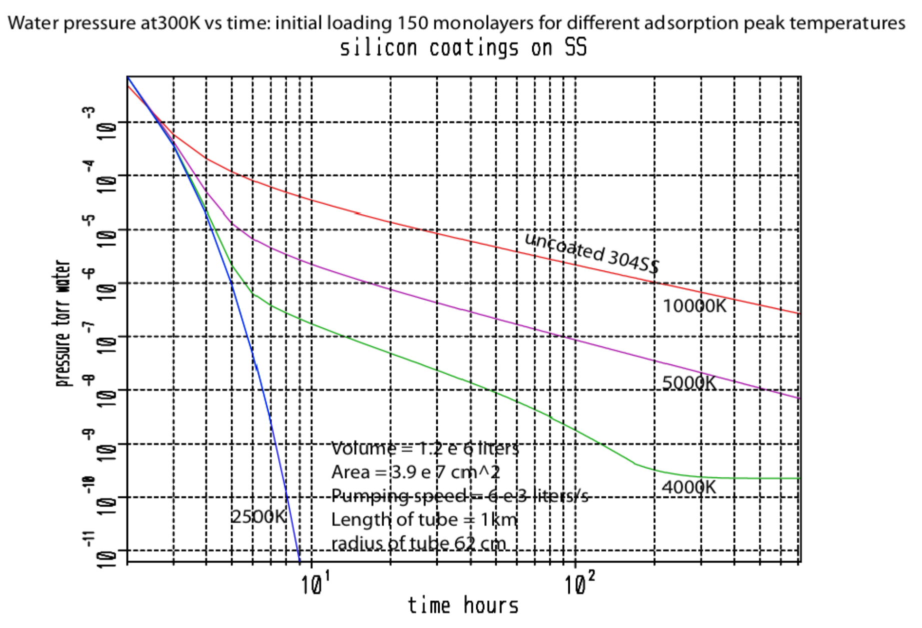
strong chemisorption

$$\tau_a = 1/\sigma = 10^{-13}\exp(E_b/kT)$$

*Excerpt from G. Vandoni, CERN

Pumpdown vs peak binding energy. Why coatings or other surface modifications could improve water desorption

- **The 1/t behavior of water pressure vs time. Typically wait >10^6 sec at RT.**
- **Water binding energy on SST is around 1eV (24 kcal/mol).**
- **If a coating reduced the peak energy < 4000 or 5000 K, bakeout would be unnecessary.**
- **Dubinin-Radushkevich Isotherm model shown (Weiss).**
- **Low-temperature bakeout-both Hanford and Livingston often 40C ambient temperature "summer bakeout" helps.**
- **Good p(t) models required.**



A hydrophobic coating could make bakeout unnecessary

LTREX experiment: An outgassing system using a residual section of LIGO beamtube

8m section of beamtube in storage at LLO ~ 20 yr

Tube being converted into UHV vacuum system

Delivery to Caltech

Installation

- 1.1 x 7.5 meter section of residual LIGO beamtube that stored at LLO since site construction. Removed from storage, flanges and end caps installed. Differentially pumped o-ring flanges. Helium leak testing and UHV performance verified. Mild (non-acid) cleaning processed to preserve surface chemistry. Matches LIGO beamtube surface- same low hydrogen air baked SST.

- Will be used for outgassing tests and dry-gas venting experiments and to verify isotherm models. Can we do a brief vent w/o rebake?

- Scale-up of Vortex tabletop system.

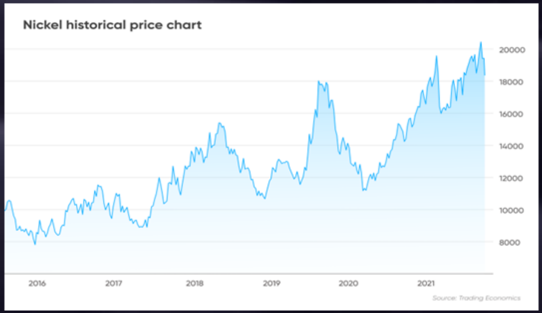
Currently under vacuum 8x10^{-9} Torr and being prepared for 150 C bakeout

Alternate Construction methods

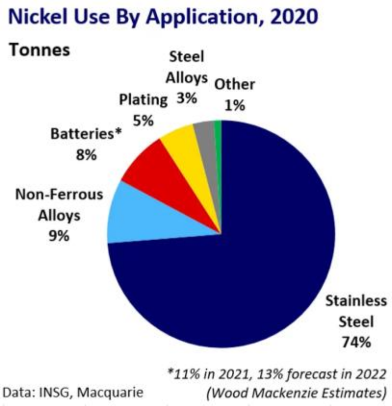
(how to beat the commodities market)

- **Cheaper materials, alternate construction methods and/or processing**
  - **Ni is a commodity, used in SST, superalloys, also batteries including Li-ion, magnets, etc.**
  - **SST typically sells with a market surcharge.**
  - **Evaluate mild steel for beamtube (Park, et. al).**
  - **Use a low temperature (or skip) bakeout (LIGO electrical costs were $1M/arm).**
  - **Are there coatings that reduce water desorption time?**
  - **Eliminate expense of concrete enclosure (BTE)?**
  - **A 1-meter diameter vacuum valve costs $300k. Expect 1 valve/10km. Simplify?**
  - **Nested system: use very thin inner wall, i.e. use less of the expensive stuff.**

SST follows nickel price-surcharges



Source: Trading Economics



*11% in 2021, 13% forecast in 2022 (Wood Mackenzie Estimates)

Data: INSG, Macquarie

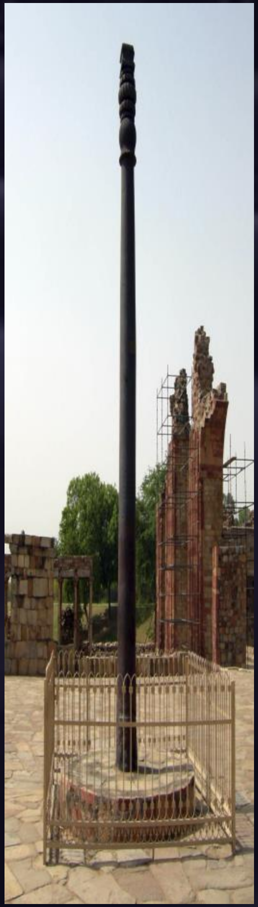
Mild steel research summary

- Hydrogen bulk content and diffusion rate verified.
- Outgassing tests: CERN, NIST, others.
- Mild steel pipe: Preliminary report complete (Henkel). Boutique mill can easily provide standard material, possibly tweak alloy if warranted.
- Magnetite coating: Needs development: how to efficiently make coating, verify outgassing rate. Some preliminary results encouraging.
- SST to mild steel transitions ~ 7×10^{-6}m/m-C CTE mismatch. Will make numerous CFF connections to std. vacuum equipment. Need to evaluate and manage.
- Scaling test of 20-40m beamtube, particularly induction heating test (LHO?)
- Vacuum component vendors typically do not allow mild steel fabrication in their shops due to “free-iron” contamination of the SST parts.

Carbon (mild) steel pipe

- Gas/Petroleum pipeline
  - Inexpensive- estimated saving $300M vs SST.
  - Available- 80 km is actually “small” order.
  - Shipped from factory with rail transport to site. (LIGO tube was made on-site).
  - QA system in place (fuel gas pipeline safety-US DOT).
  - No helium leak testing- revive LIGO leak test system?
  - ½” thickness- 380 kg/m. Tube is stable to atm pressure, buckling, resistant to mechanical damage.
  - No support rings needed. Suspension system (and cover) design TBD.
  - Corrosion? (epoxy, but what happens if it covers a vacuum leak?)
  - Magnetite (Fe_3O_4). Outgassing and optical scatter, mild corrosion protection.
  - Other coatings?

Helium leak test system for 20m LIGO tubes



Iron pillar of Delhi
400 AD
$FePO_4$
“Parkerized”
Coca-Cola

Carbon steel pipe

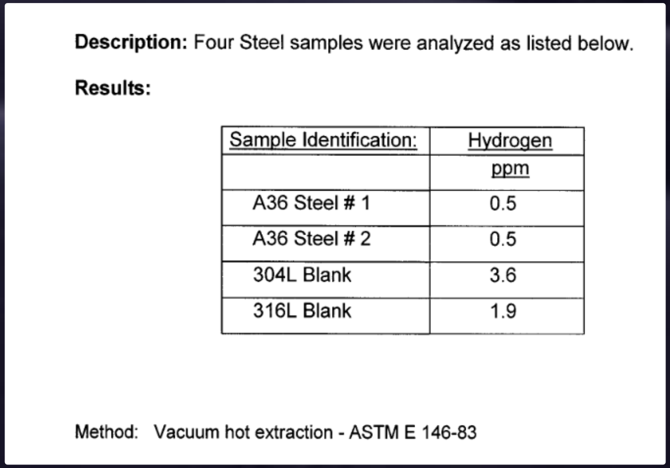
- **Pipe factory**
  - Nominal ½" wall thickness. 48" diameter.
  - Self supporting (no stiffening rings needed).
  - Spiral welded (LIGO same).
  - Low hydrogen outgassing.
  - Surfaces options.
    - Bare (corrosion "bad rust")?
    - Silica (CVD process) ?
    - Magentite (Fe_3O_4 "good rust")?
    - External-epoxy coating. Outgassing?
    - Magnetic, can be induction heated.

24m sections of spiral welded steel pipe.
This mill makes about 500km/year*

D. Henkel (invited talk 3/27@13:30) surveyed pipe mills

Hydrogen outgassing stainless steel vs carbon steel comparison

- H2 diffusion from bulk
  - Hydrogen dissolved in the metal when molten.
  - t=0 concentration starts with the material manufacture
  - SST requires vacuum degassing or air oxidation to reduce H2 diffusion
  - LIGO beamtube SST was oxidized prior to rolling
- Mild steel has extremely low intrinsic hydrogen
  - Vacuum degassing lowers dissolved gas, mainly hydrogen
  - Old textbook H2 values obsolete.
  - Mild steel lower H2 diffusion than the best LIGO SST
  - Verified low H2 concentration and diffusion rate
    - Park et.al JVST A 26 (5) 2008
    - NIST (Fedchak)
    - CERN



Description: Four Steel samples were analyzed as listed below.

Results:

Sample Identification:	Hydrogen ppm
A36 Steel # 1	0.5
A36 Steel # 2	0.5
304L Blank	3.6
316L Blank	1.9

Method: Vacuum hot extraction - ASTM E 146-83

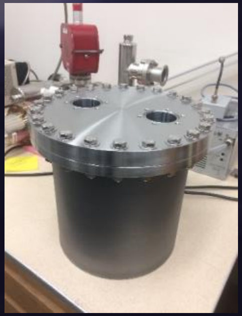
H2 concentration A36 mild vs 304L stainless steel using vacuum hot-extraction testing method

Low intrinsic hydrogen in mild steel verified

Silica coatings-Silane decomposition

- CVD process.
- Silane precursor SiH_4
- Proprietary process.
- CERN reports hydrogen uptake in the strips.
- Does improve outgassing but at what cost/benefit?
- Layer probably too thick (JRF).
- Dust and particulates.
- Practical on huge beamtube sections?

Above: Test strips (mild steel and SST) coated with silica. Below: A36 steel test chamber was also coated. The chamber is at now at NIST.

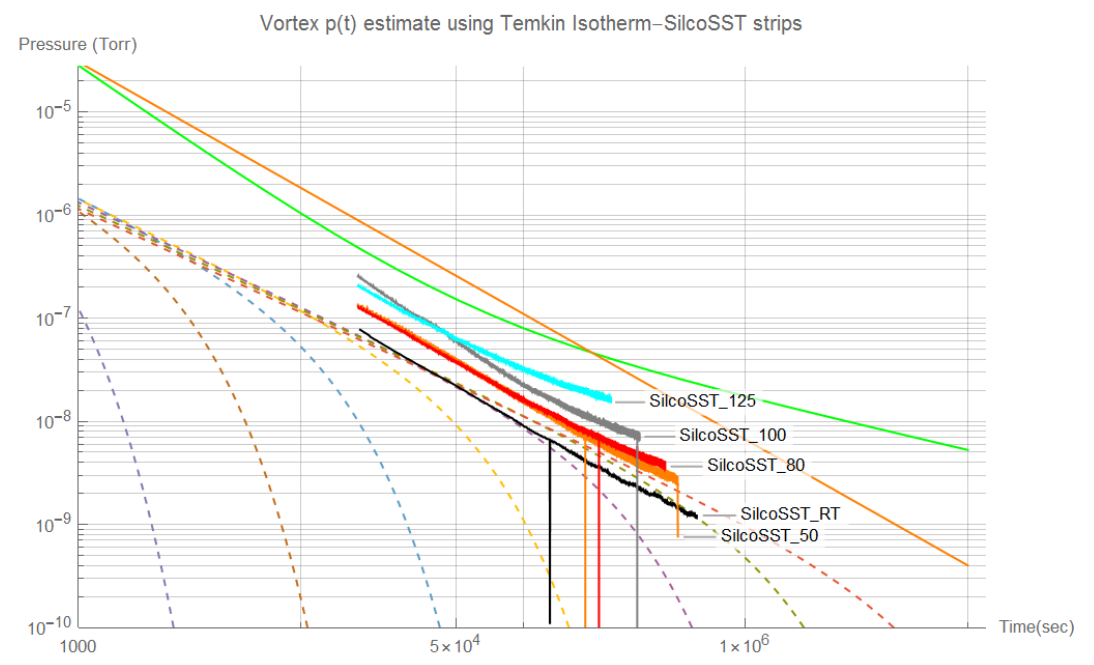


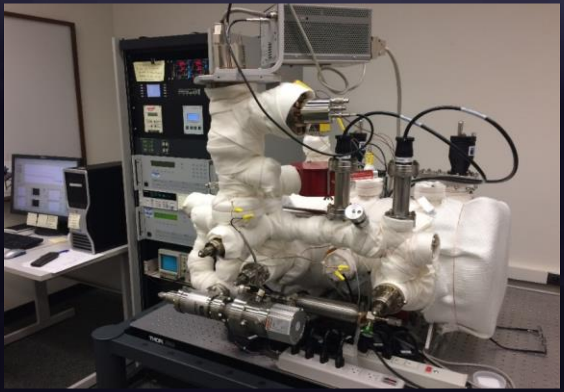
Strips being prepared for Silane CVD coating

Si-based coating reduces outgassing ≤10x.
Helpful but CVD process too complex for this application

Thermal outgassing: Temkin Isotherm model E_0=10.6 kcal/mol, E_1=25kcal/mol . CIT benchtop system

- Temkin Isotherm.
- T=300K.
- Dashed lines are p(t) at various energies.
- Green, Orange lines are Li/Dylla* models for SST pumpdown, show 1/t behavior.
- Still looks like stainless?
- Possible explanation in Y2000 patent?

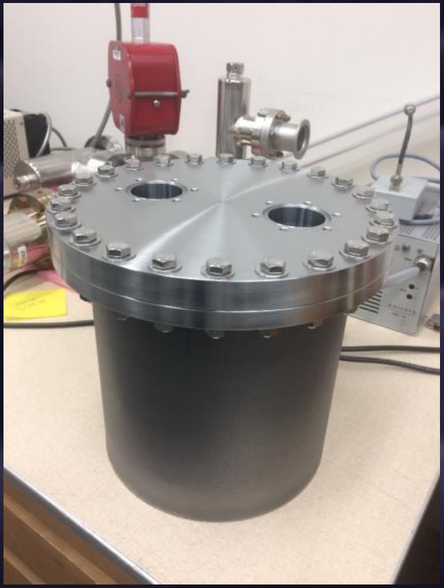


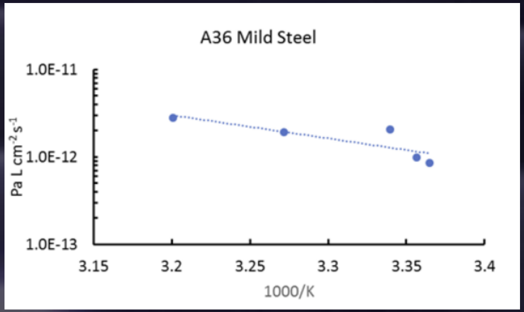


Vortex thermal outgassing system at CIT

* Minxu Li *and* H. F. Dylla , Journal of Vacuum Science & Technology A **12**, 1772 (1994)

Outgassing tests at NIST



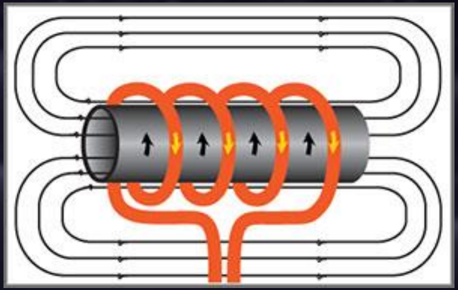


Mild-steel vacuum test chamber made from A36 mild steel. H2 outgassing measured by NIST using spinning rotor gauge. Technique described in J. Fedchak, JVST B **39**, 024201 (2021).

Invited talk J. Fedchak 3/28 @ 09:00

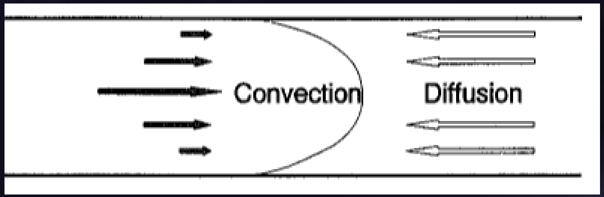
Traveling Bakeout System?

- Thought experiment
  - Heat pipe with traveling heater while flowing ultra-dry gas to prevent recontamination
  - Temperature and flow rates?
  - How to heat the pipe.
  - Practicality?



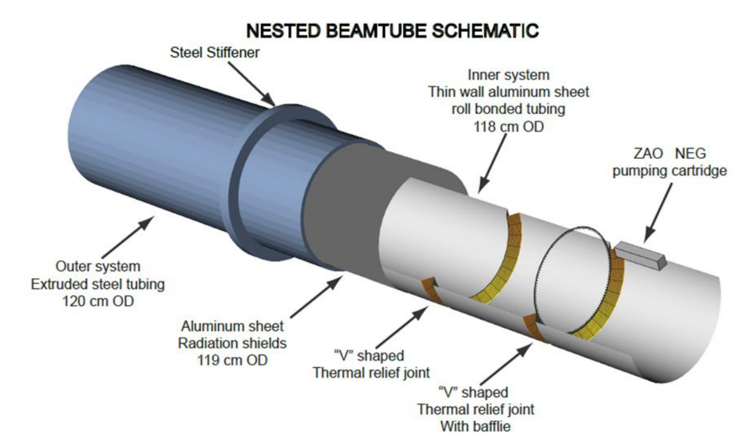
- RF Induction heating (the easy part)
  - Eddy current and magnetic hysteresis loss.
  - Works best on magnetic materials.
  - 10-30 kHz for pipe.
  - Turn-key for pipeline heating.
  - Purge with ultra-dry (< ppb) air.
  - Low conductance so vacuum ineffective.

- Now the hard part....
  - Back-contamination with water vapor.
  - Balance flow rate out with diffusion back in.
  - Common technique in semiconductor gas systems.
  - Flow rate may be unmanageable. Throttle ?.
  - Active research. Model and scale tests.



Nested System

- **Complex but has several unique features**
  - Steel outer pipe (thickness TBD) with thin (1/2 mm) aluminum inner pipe (could also be thin steel).
  - Modest vacuum (10^{-4} Torr) in annular gap.
  - Thin inner liner resistively heated to bake (same as LIGO).
  - Aluminum is excellent vacuum material. Reflectivity at 1μ?
  - Spiral formed and cold welded (new technology).
  - Gap vacuum: Thermal insulation, crush of inner tube, allows some leaks in inner liner.
  - Complex thermal/electrical isolation, valves need to be developed, unique feedthroughs and ports, manage 2x CTE mismatch between inner and outer systems.
  - Updated design (May 2022) both tubes are steel.
  - ZAO Getter pumps-require feedthroughs to heat. Water speed?
  - Hide ZAO getter behind baffle.

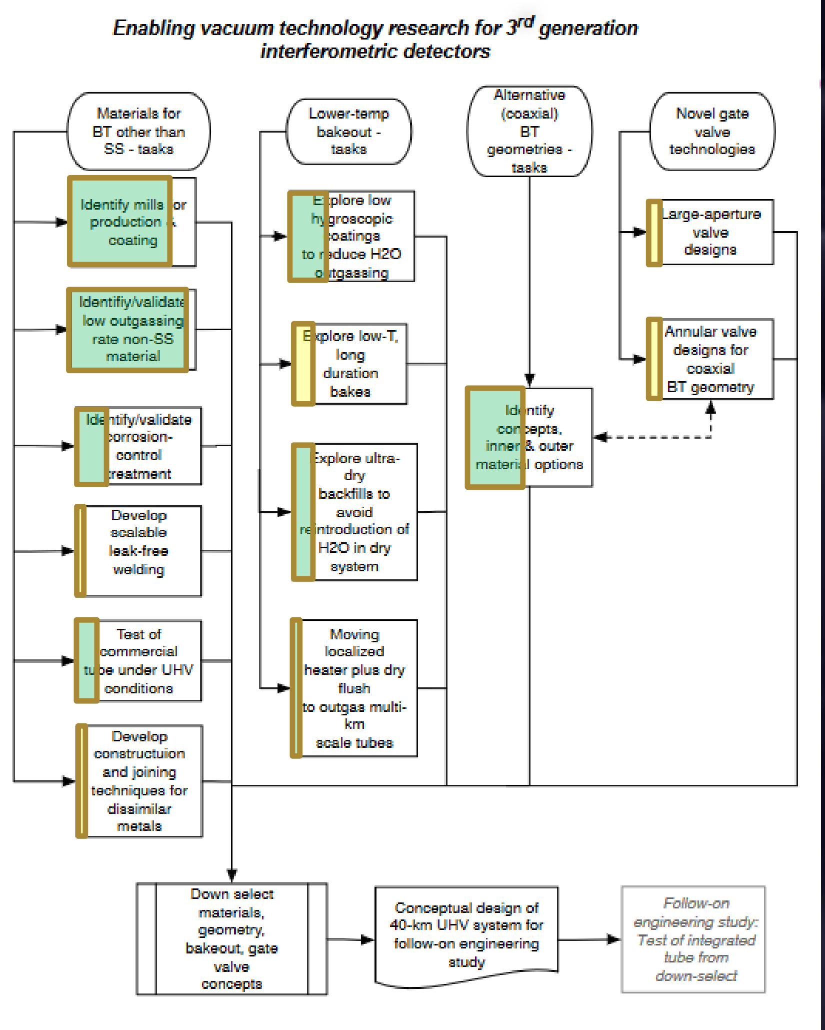


Proposed by R. Weiss

Summary

- Tasks started
  - Mild steel outgassing characterization.
  - Hydrogen content A36 steel.
  - Pipe mill inquiries and tube mfg. details.
  - Silica coatings prepared, tested.
  - Tube travelling heater/bake funded.
  - LTREX experiments underway.
  - Ultra-dry air benchtop tests started (Vortex).
  - Coaxial alternate system conceptual design.
  - Back-diffusion modelling.

- Tasks needing effort
  - Welding and joining methods-dissimilar metal.
  - Alternate coatings.
  - Gate valve(s)-design details.
  - Coaxial system-design details.



Enabling vacuum technology research for 3^{rd} generation interferometric detectors

Materials for BT other than SS - tasks

Identify mills for production & coating

Identifiy/validate low outgassing rate non-SS material

Identify/validate corrosion-control treatment

Develop scalable leak-free welding

Test of commercial tube under UHV conditions

Develop constructuion and joining techniques for dissimilar metals

Lower-temp bakeout - tasks

Explore low hygroscopic coatings to reduce H2O outgassing

Explore low-T, long duration bakes

Explore ultra-dry backfills to avoid reintroduction of H2O in dry system

Moving localized heater plus dry flush to outgas multi-km scale tubes

Alternative (coaxial) BT geometries - tasks

Identify concepts, inner & outer material options

Novel gate valve technologies

Large-aperture valve designs

Annular valve designs for coaxial BT geometry

Down select materials, geometry, bakeout, gate valve concepts

Conceptual design of 40-km UHV system for follow-on engineering study

Follow-on engineering study: Test of integrated tube from down-select