Vacuum Technology of the LIGO Interferometers

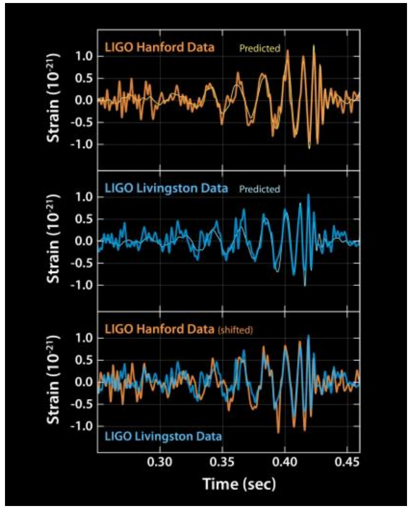
presentation to the

Southern California Chapter AVS

28 March 2017

Learn more about LIGO at https://www.ligo.caltech.edu/page/about

Ligo HANFORD and Ligo LIVINGSTON



Observatories are about 10 ms apart by gravity wave, a *long* way apart by geography

LIGO Project Timeline

- 1980s

LIGO 40m (1% scale) interferometer constructed at CIT (we will tour this facility later)

- 1990s

Funding from NSF, LIGO Hanford (94) and Ligo Livingston (95) construction begins

- 2000s

LIGO operational

- 2010-2015

LIGO offline for Advanced LIGO sensitivity upgrade

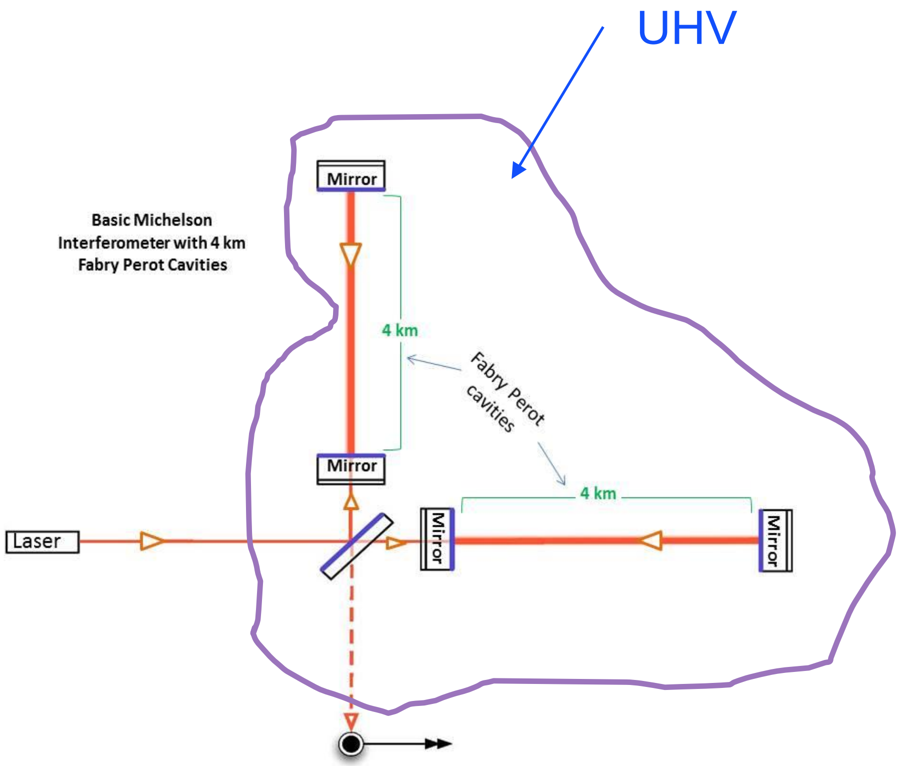
- 2016-present

A-LIGO operational, historic 1st observation of a GW event occurs

The LIGO vacuum systems have now been in service for 20 years

Why is a 4 km vacuum system required?

- Michelson interferometer sensitivity ~ L
- Want storage time in cavity ~ ½ GW period
- 150 km would be about optimum, but……..
  - » Too expensive $$$
  - » Earth curvature 1 meter/4 km, 1.7 km/150km
  - » Mirrors hang, consider g-vector
  - » Space-based system ideal, has its own problems
- Add Fabry-Perot cavity to increase path length
- Still represents 10^4 cubic meters of plumbing
- Pressure ~1e-9 Torr
- No vibration…. limits pump type (ion, getter, LN2 cold traps)



- Measure amplitude (null) not phase (time)
- Feedback control loop keeps signal at null
- Measure feedback signal
- Both sites signals should overlay but be 10 mS apart

Why is vacuum operation necessary ?

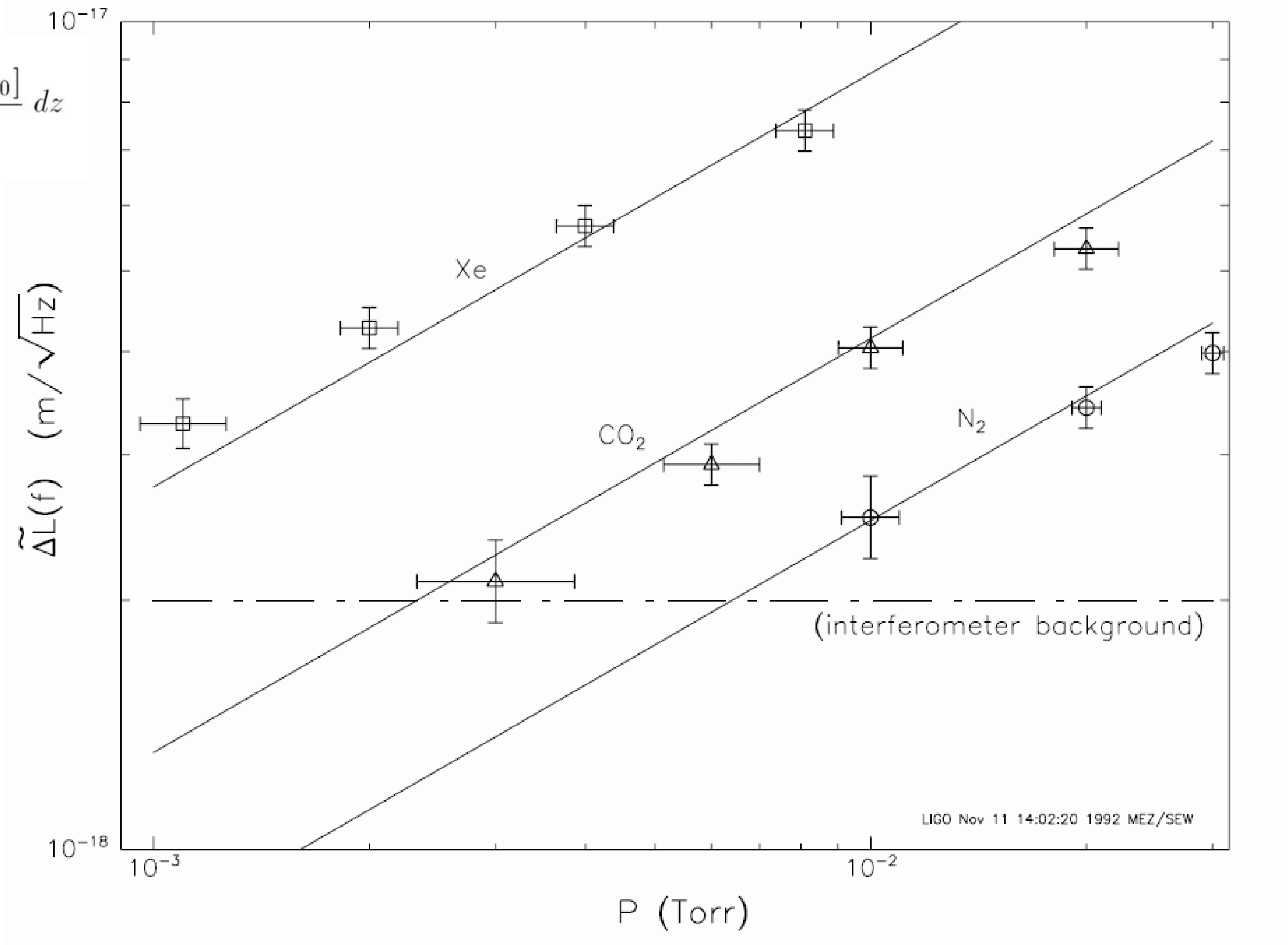
- Required to reduce phase noise
- Noise Sources
  - » Beam refraction due to gas density fluctuations
  - » Acoustic noise transmitted to mirrors
  - » Mirror absorption due to films ~ monolayers
  - » Requires operation at UHV

Residual Gas Index Fluctuation Noise

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

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

ρ = *gas number density (~ pressure)*
α = *optical polarizability (~ index)*
w = beam radius
v_0 = *most probable thermal speed*
L_0 = *arm length*
ΔL = arm optical path difference



From a vacuum engineering perspective, about all we can do to help is get the pressure as low as practically possible

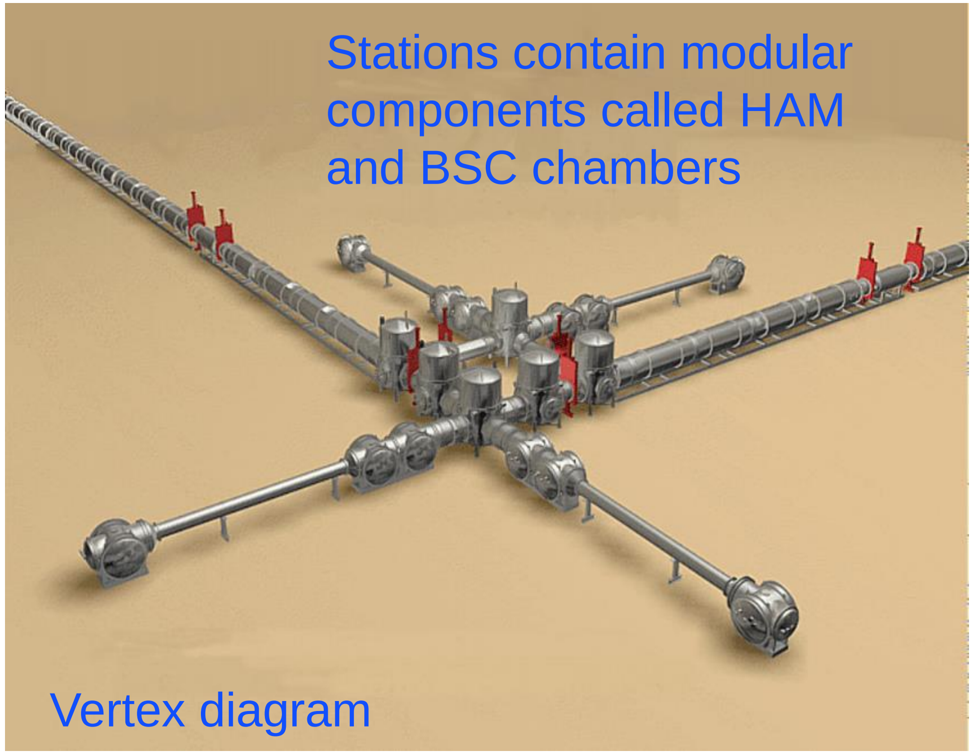
S. Whitcomb and MZ, *Proc. 7th Marcel Grossmann Meeting on GR,* R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

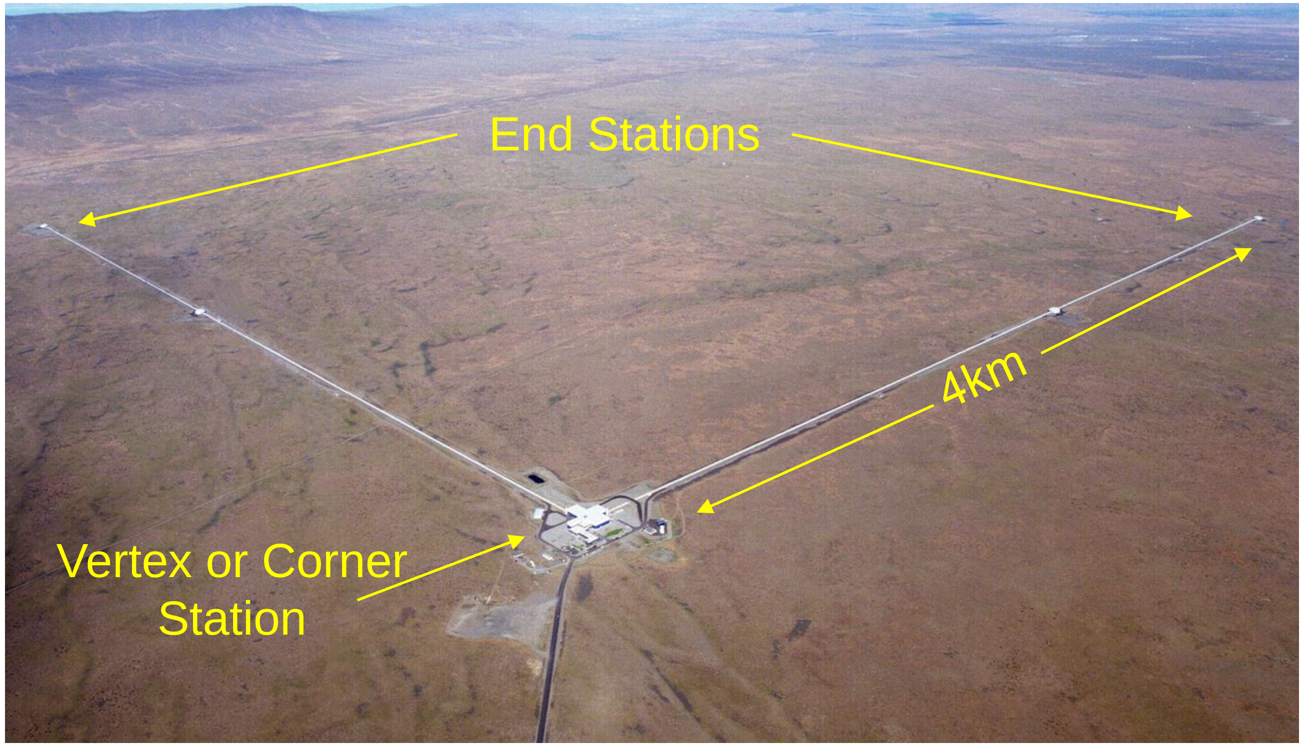
Vacuum system requirements

- Light scattering from residual gas
  - Function of molecular polarizability, transit speed and partial pressure
  - Primary goals for beam tubes:
    - ➔ $P(H_2) < 10^{-9}$ Torr
    - ➔ $P(H_2O) < 10^{-10}$ Torr
- No contamination of optics
  - Mirror absorption < 0.1 ppm
  - Hydrocarbons deposition < 1 monolayer/10 years
    - ➔ Aggressive cleaning and vacuum bake of every component
  - Particulates < one 10 µm particle on any mirror
    - ➔ ISO Class 5 or better clean room protocol for worker access, internal components, surface exposure, backfill/roughing speed
- Vibration-free environment
    - ➔ No mechanical, turbo or displacer-piston cryopumps during site observation

To our advantage, we do not have to contend with radiation, thermal, or ion/electron induced desorption, LIGO outgassing is passive at ambient temperature

LIGO Vacuum Chambers and Equipment





Corner and End Stations are connected by beam tubes which are 1.2m diameter x 4 km long, and are aligned (straight) to 5 mm rms. The arms are orthogonal to 5μ radians.

Essentially two vacuum systems that share one volume……?

1. Chambers (at the vertex and end stations)

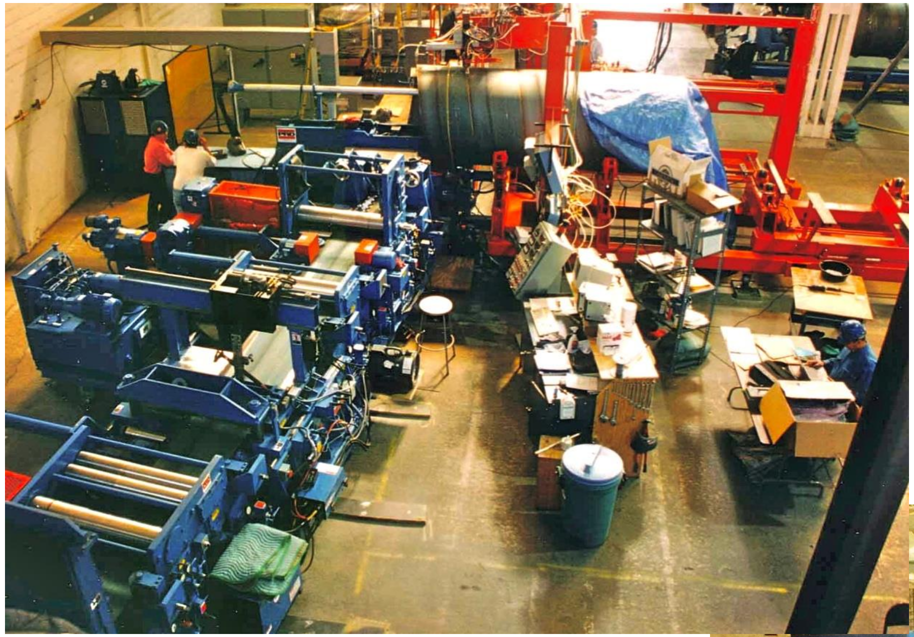
- Frequently opened
- Numerous penetrations; flanges, fittings, viewports, feedthrus
- Large doors
- House the electrical, mechanical and optical equipment
- Pumps, valves, backfill vents
- O-ring sealed
- Create a large water (and some crud) load

2. Beam tubes (which connect the stations)

- Designed never to be opened (i.e.vented)
- 1.2 m diameter x 4 km long
- 20 million liters volume (per site)
  - 600 million cm^2 surface area (per site)
  - 200 l/s char. conductance (thin tube ??)
  - All metal
  - Baked 150 C for 3 weeks, UHV with low H2 diffusion
  - Isolated by 44 Inch diameter gate valves

These two systems have very different purposes but are open to each other for months at a time during observation runs. How can they coexist?
Hint: 77 K

Beam tubes were fabricated by winding coiled sheet

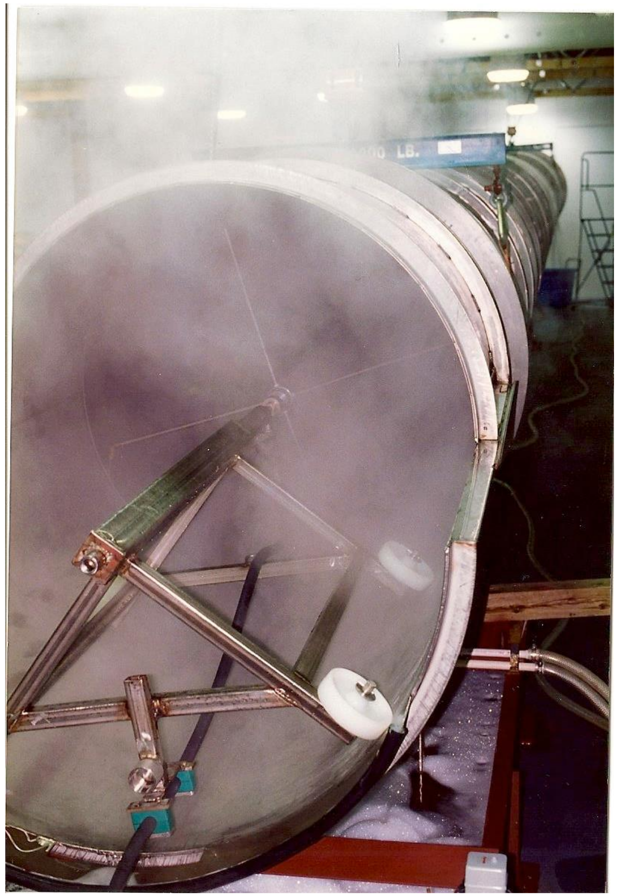


Spiral rolling and seam welding

- 304L SS, 3.2 mm thick with external stiffeners
- Raw coiled stock air baked 36h @ 455C to deplete hydrogen
  - $J_{H2} < 10^{-13}$ Tl/s/cm^2
  - process developed by LIGO
- Prepared coil spiral-welded into 1.2m tube on modified culvert mill
- 16m sections cleaned, leak tested, and capped
- FTIR analysis to confirm HC-free
- Sections butt-welded together in travelling clean room at sites
- Over 50 linear km of weld; no leaks
- Tubes designed never to be vented after installation
- CBI (Chicago Bridge and Iron) was fabricator

Adding the stiffener rings

Cleaning and leak testing a tube section



Steam/water/detergent cleaning followed by FTIR sampling

Helium leak testing a section of beam tube. Note large diffusion pump, Roots-backed forepump

LIGO

Field assembly of the beam tubes

Transport

Position

Field fitup

Butt weld

Leak check

Add next section

Completed beam tube joint

The unique color of the steel is due to the air-firing process used to reduce hydrogen diffusion

There are 50 km of weld bead per beam tube. The inner bead is autogenous, the outer bead low-hydrogen filler wire

Stiffening rings prevent buckling of the tube by air pressure. The tube is 3.2 mm thick

Beam tubes were aligned using dual-frequency differential GPS, 5 mm/4 km straightness*

See Rev. Sci. Instr. V 72, No. 7 p 3086, July 2001.

LIGO beam tubes

- 9000 m^3 volume
- 30000 m^2 surface area
- 50000 m of spiral welds
- ~10^{-9} Torr operating pressure

module length	2 km
25 cm diameter pump ports/module	9
radius of beam tube	62 cm
volume of module	4.831 x 10^6 liters
area of module	1.55 x 10^8 cm^2
initial pumping speed/surface area	1.94 x 10^{-5} liters/sec/cm^2
length/short section	1.90 x 10^3 cm
wall thickness	3.23 x 10^{-1} cm
stiffener ring spacing	76 cm
stiffening ring width	4.76 x 10^{-1} cm
stiffening ring height	4.45 cm
expansion joint wall thickness	2.67 x 10^{-1} cm
expansion joint convolutions	9
expansion joint longitudinal spring rate	1.5 x 10^9 dynes/cm

Beam Tube Bakeout….. I^2R using beam tube as the "R"

Insulate tube and conduct 2000 amps x 65 volts from end to end

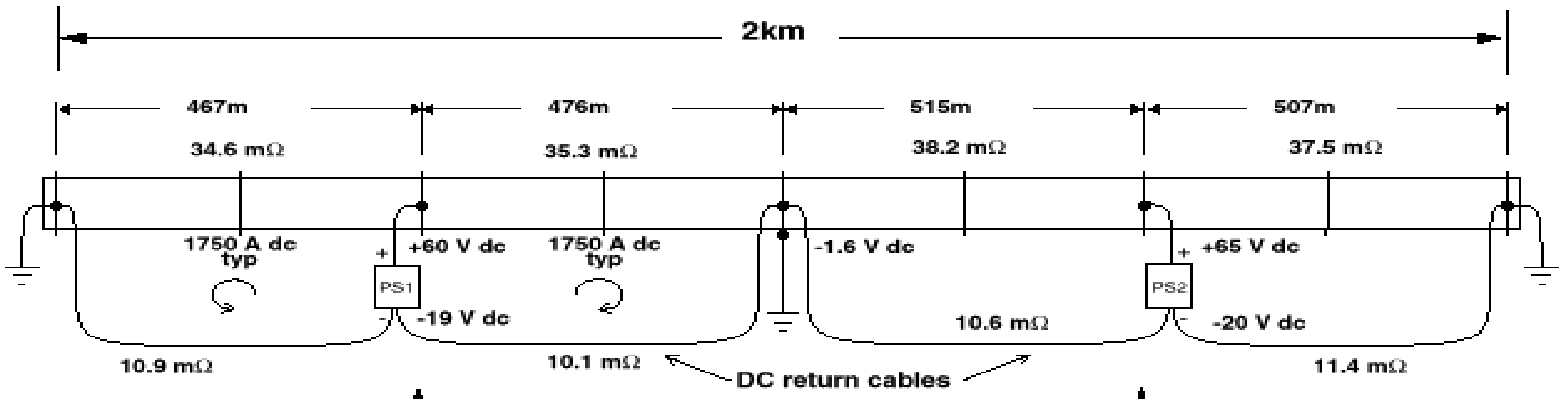
Tube with power cable junction box

"Portable" magnet supply from Fermilab. 13 kV primary power

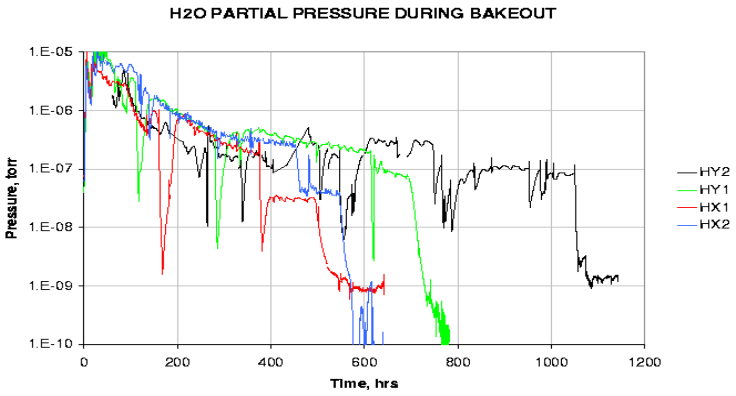
Bake for 3 weeks 160 C, $1M of electricity

I^2R Bakeout Schematic. Desorb Water

- Glass wool insulation
- I_{DC} = 2,000 A
- ~ 3 weeks @ 160°C
- Final J_{H_2O} < 2e-17 Tl/s/cm²
- Tubes never to be vented



Temporary cryopumps were used during bakeout 17, places, removed after bake



To avoid optical phase noise in laser path

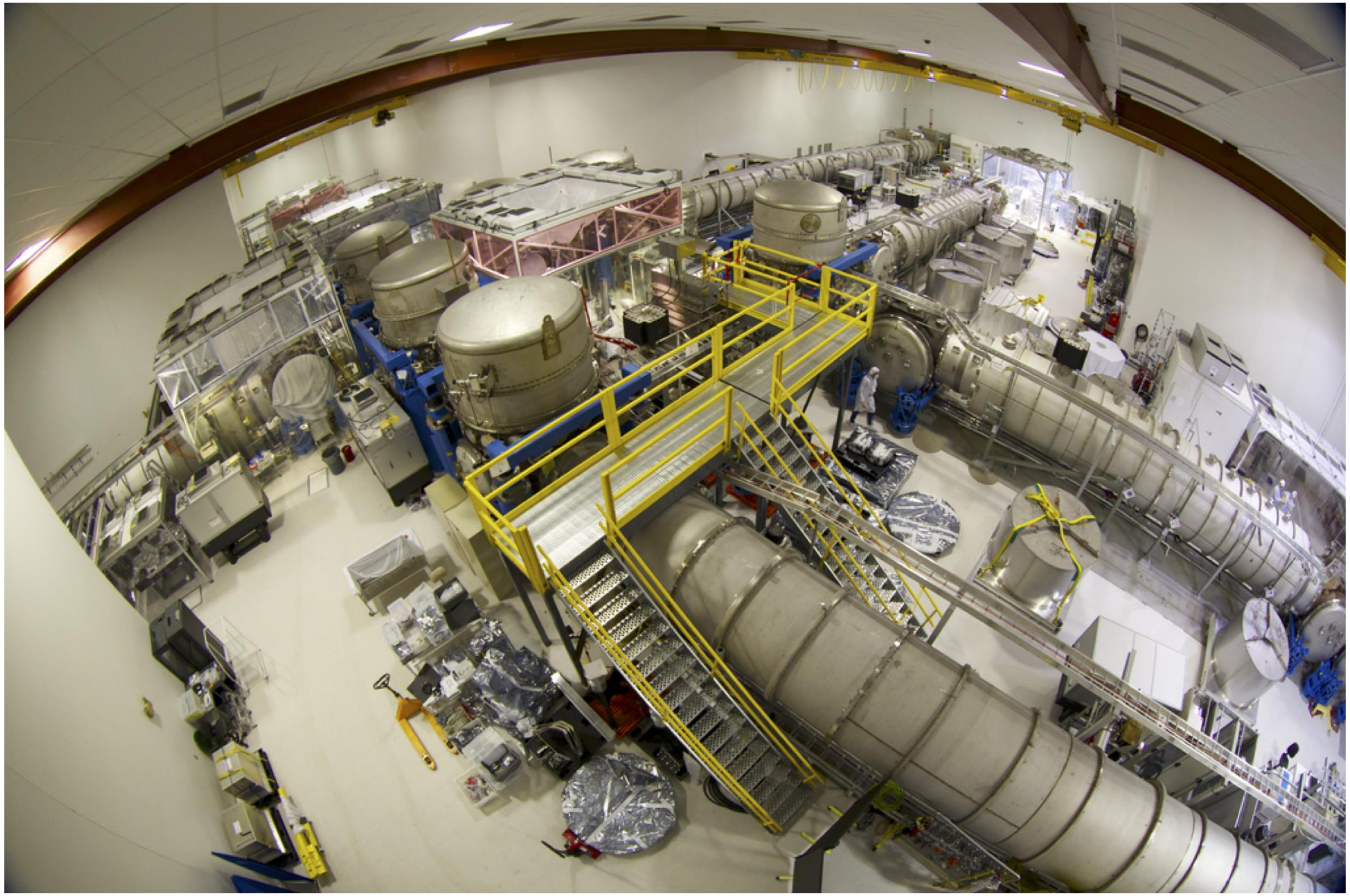
$$h(f) = 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

LIGO-G1300176

Table 1: Residual gas phase noise factor and average pressure

Gas Species	R(x/H_2)	Requirement (torr)	Goal (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}
AMU 100 hydrocarbon	38.4	7.3×10^{-10}	7×10^{-13}
AMU 200 hydrocarbon	88.8	1.4×10^{-10}	1.4×10^{-13}
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	2.5×10^{-11}	2.5×10^{-14}
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	9.0×10^{-12}	9.0×10^{-15}

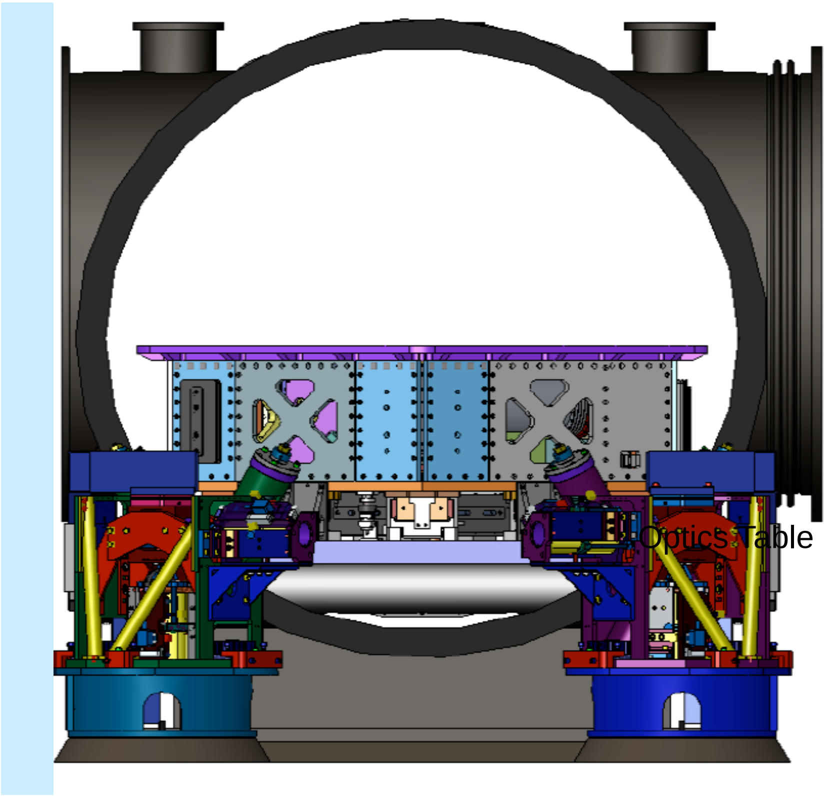
Vacuum equipment at the "Corner" or "Vertex"



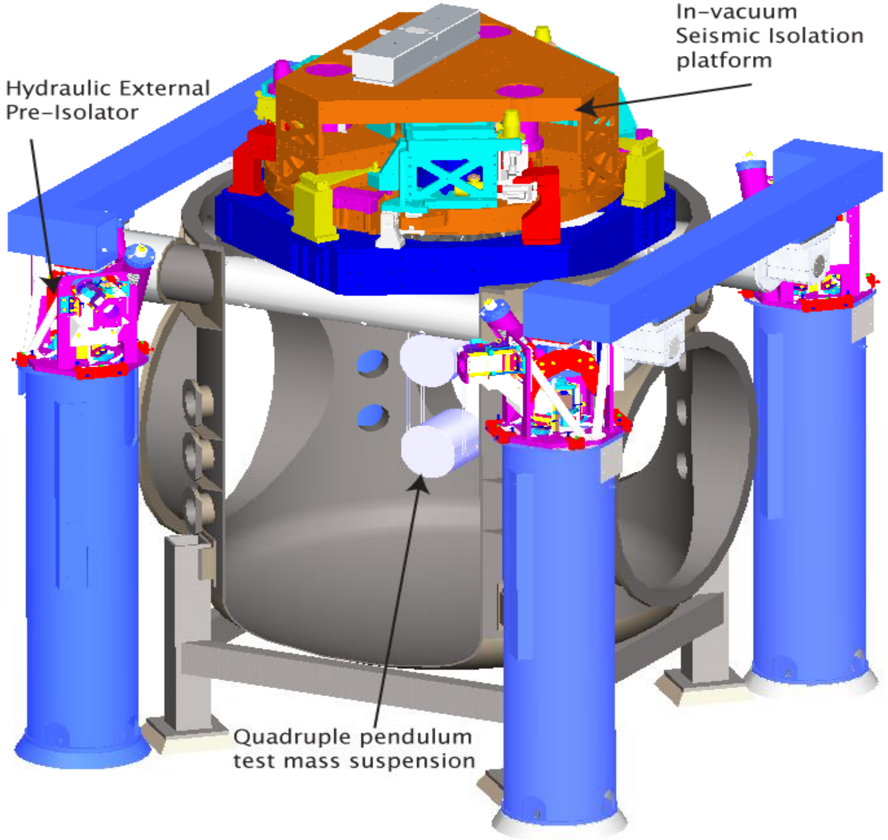
The corner stations are busy places…. they house the lasers, beam splitters, most of the diagnostic and control equipment, also monitor the laser signal for GW detection

The end stations have (fewer but similar) chambers that house the suspended mirrors, some diagnostic and vacuum control equipment, etc.

Two chamber types, modular construction



Horizontal access module “HAM”



Basic Chamber “BSC”

BSC Chambers at the Vertex

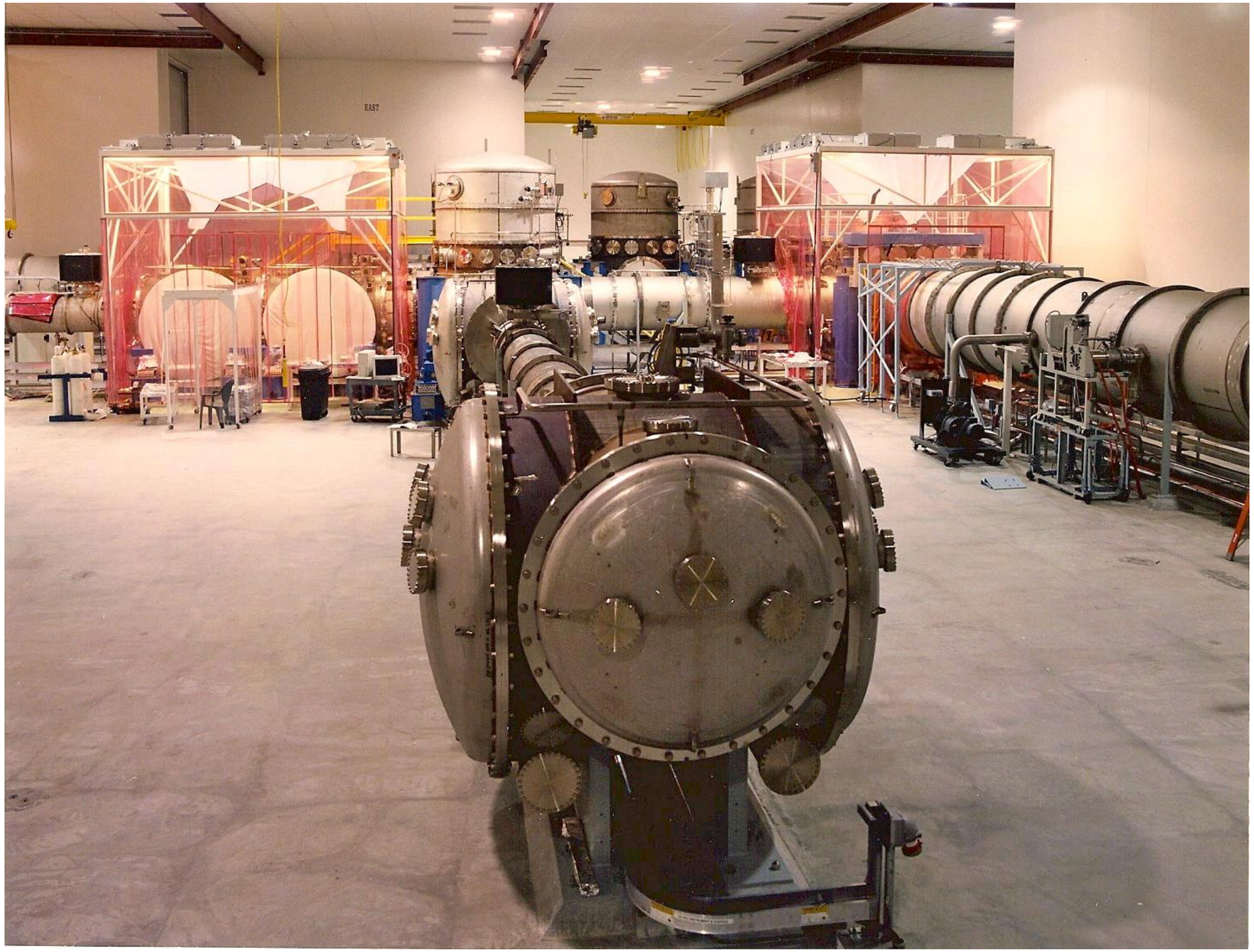
HAM Chambers

- House complex input/output optics

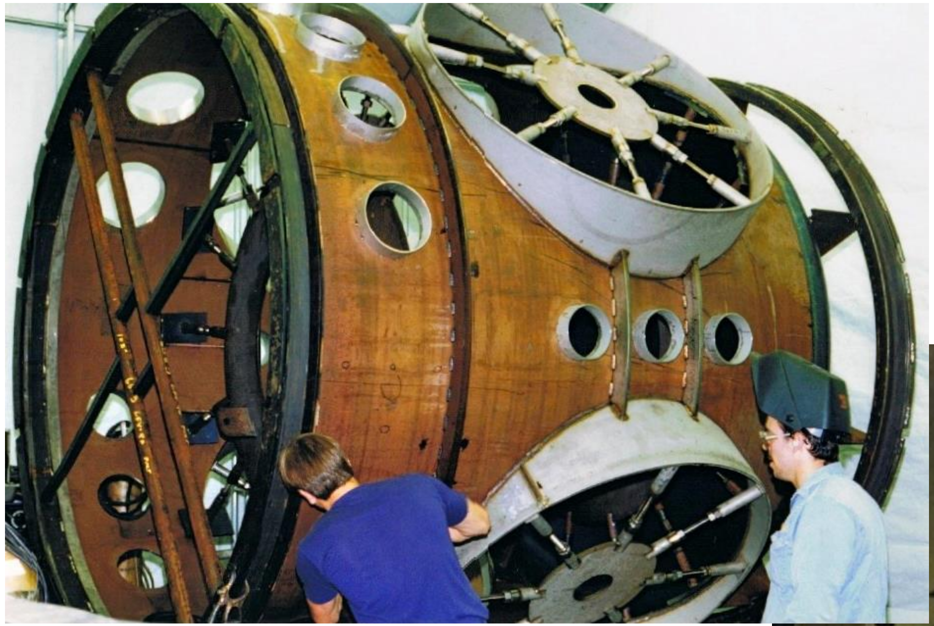
- 2.1m Ø x 2m W

- More than 70% of area are removable access doors

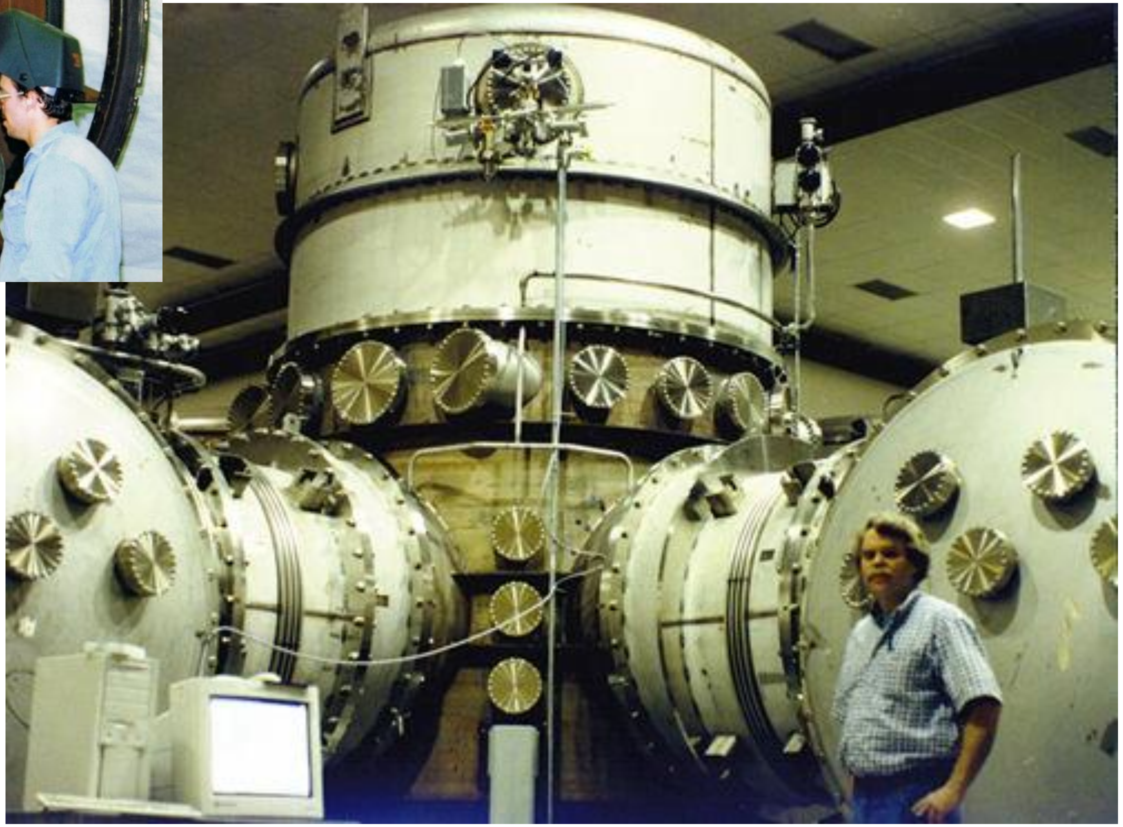
- O-ring seals



BSC chamber manufacture



- 2.8m Ø x 5.5m h for large cavity optics
- Upper third is a removable dome
- Thin (10-15mm) 304L SS shell with welded stiffeners, F&D heads
- Combination of GTAW and plasma welding
- Major weldments were stress-relieved

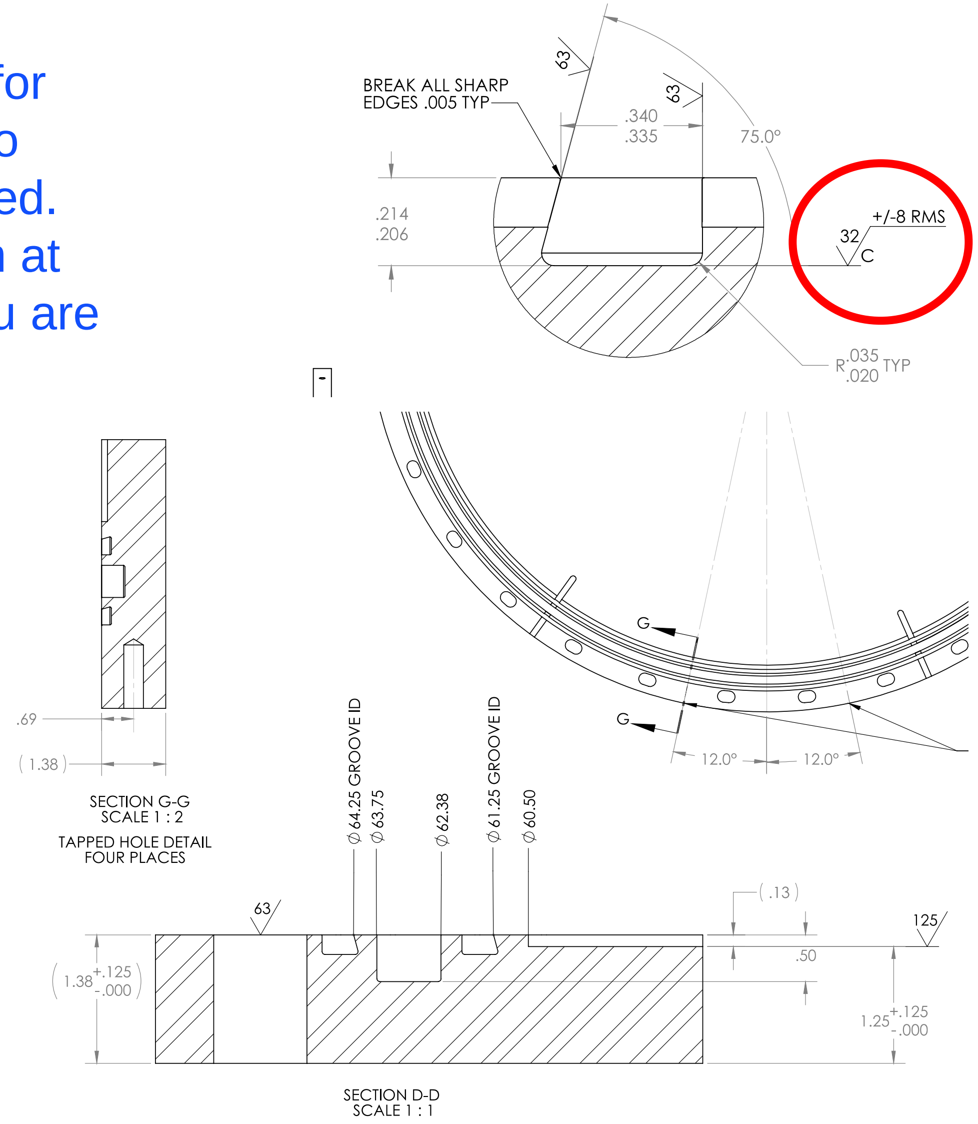


- Ports < 35cm Ø: ConFlat™
- Ports > 35cm Ø: Dual O-ring
  - Treated Viton elastomer
  - DRY (no grease)
  - Isolated pumped annulus between inner and outer seal
  - Permeation and damage tolerant

Differentially pumped flanges

Large metal sealed flanges would be impractical for the chambers seals, so o-ring seals were used. To reduce permeation, differential seals were specified. You can also see these in use on the 40m system at Caltech, just look for the pumpout tubes when you are on the tour.

- Dual o-ring
- Pumped annulus
- Vacuum maintained by *ion pump* (which is unusual….no vibration)
- Independent of main volume
- Gate valve disk also dual o-ring
- Seal faces single-point machined
- “Fluorel” o-rings, pre-processed



Chamber installation circa 1997

- Fabricated and cleaned off-site
- Delivered in sealed condition for installation

Chamber Bakeout

Conventional bakeout using heater blankets and heat tracing. 150 C

Mobile clean-rooms are used for contamination (particulate) control

Internal Equipment Installation

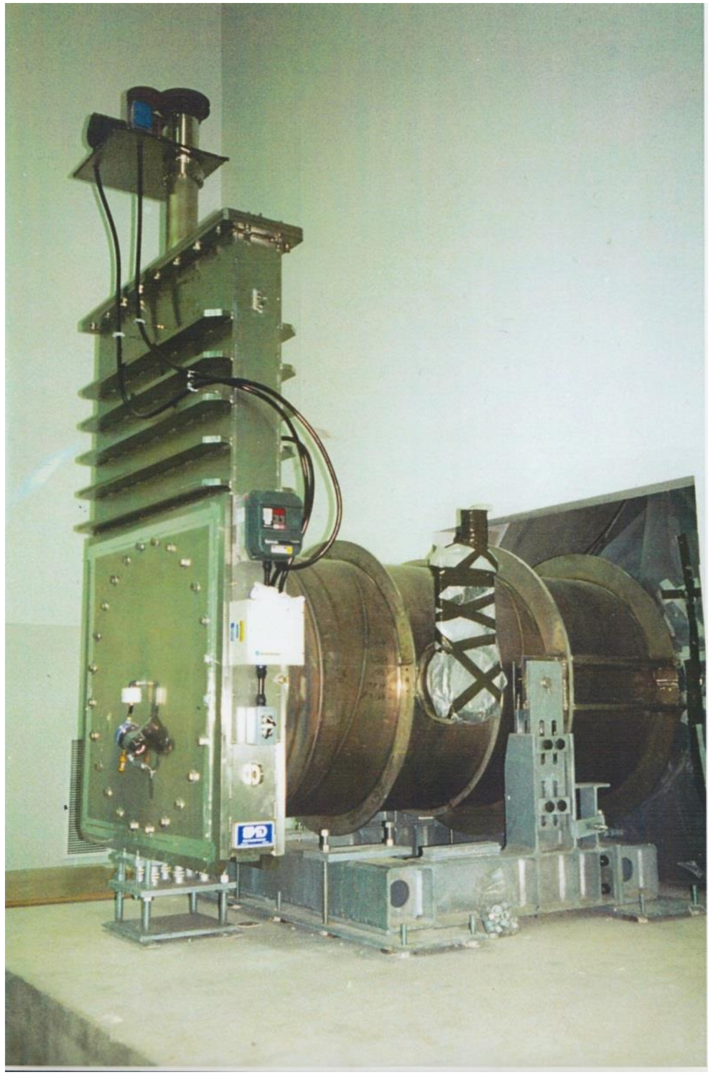
Strict part cleanliness and cleanroom techniques are required

LIGO

Large Gate Valves

There are approximately 17 large gate valves at each LIGO installation. These valves have a clear opening diameter of 44 or 48 inches depending on their location in the system. They were made in California by GNB

The bonnet plate and valve disk have dual o-ring, differentially pumped seals. A 60 l/s ion pump maintains the differential volume.



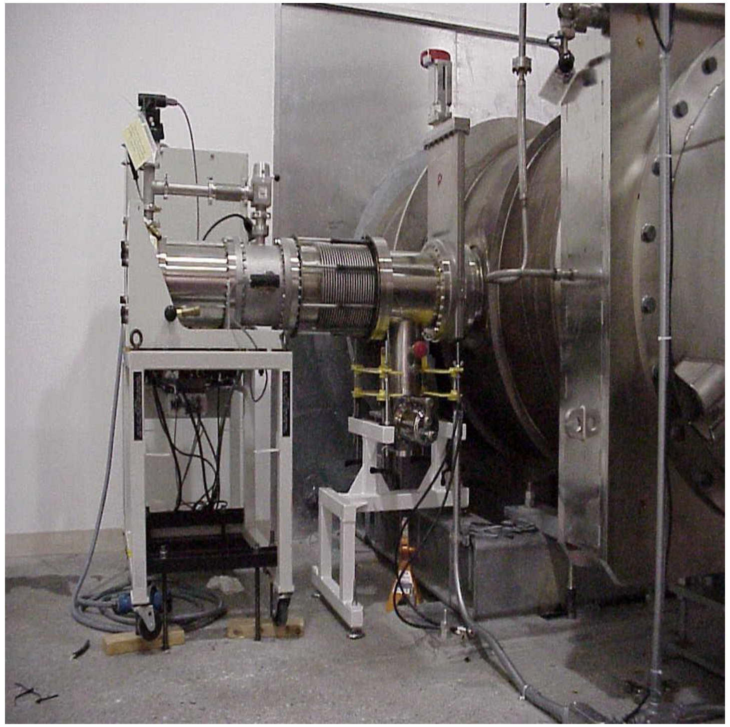
Valves are actuated by either a mechanical (screw drive) or pneumatic servo. A valve cycle takes about 4 minutes.

Large Gate Valve with bonnet open

- 44” & 48” ID gate valves used to isolate beamtubes, LN2 traps
- Double o-ring gates & bonnet seals with pumped annulus
- Two actuator varieties *electric* (ballscrew) and *pneumatic* (cylinder)

Pumping Systems

Roughing pumps and Roots blowers (background), also visible is backfill equipment -50 C dew point air dryer, + oil-free compressor

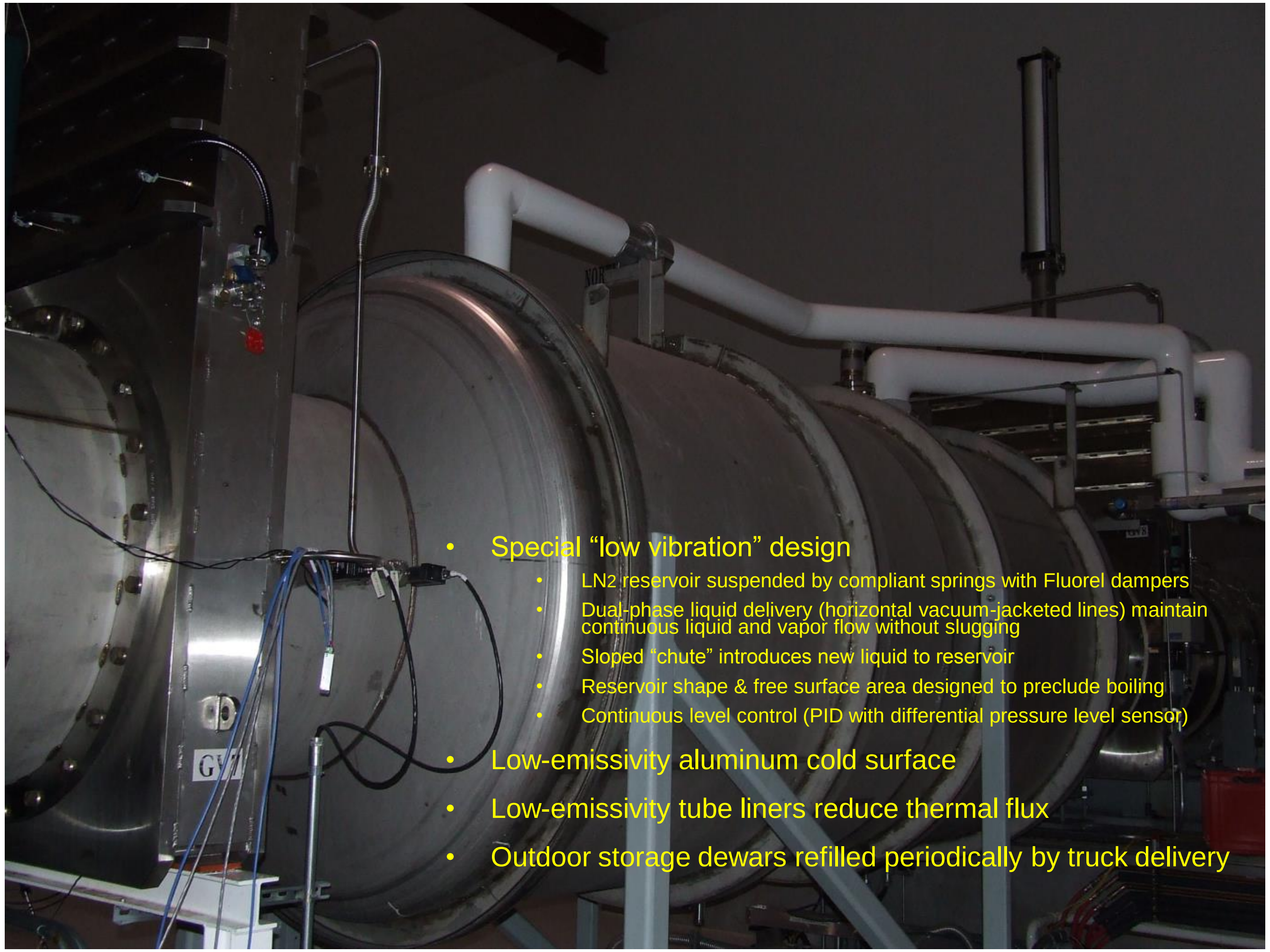


Maglev Turbopumps

2500 l/s ion pumps (16.5" Conflat flange) with Ta "Noble Diode" Cathode

Roughing and turbopumps are used for evacuation and achieving initial high vacuum in chambers. Ion pumps control H2 partial pressure. Getter pumps are being evaluated as well

Elephant in the room



- Special “low vibration” design
  - LN_2 reservoir suspended by compliant springs with Fluorel dampers
  - Dual-phase liquid delivery (horizontal vacuum-jacketed lines) maintain continuous liquid and vapor flow without slugging
  - Sloped “chute” introduces new liquid to reservoir
  - Reservoir shape & free surface area designed to preclude boiling
  - Continuous level control (PID with differential pressure level sensor)
- Low-emissivity aluminum cold surface
- Low-emissivity tube liners reduce thermal flux
- Outdoor storage dewars refilled periodically by truck delivery

The LIGO beamtubes are bounded by gate valves and coaxial 10^5 liter/second cryotraps. These traps protect the beamtube from the water loads introduced by the HAM and BSC chambers. The cryopumps have a unique design that reduces boiling noise.

Liquid nitrogen is fed from large external dewars, and transferred to pump by vacuum insulated lines.

End Station Cryopump Arrangement

LN_2 storage

(outdoors)

Coaxial

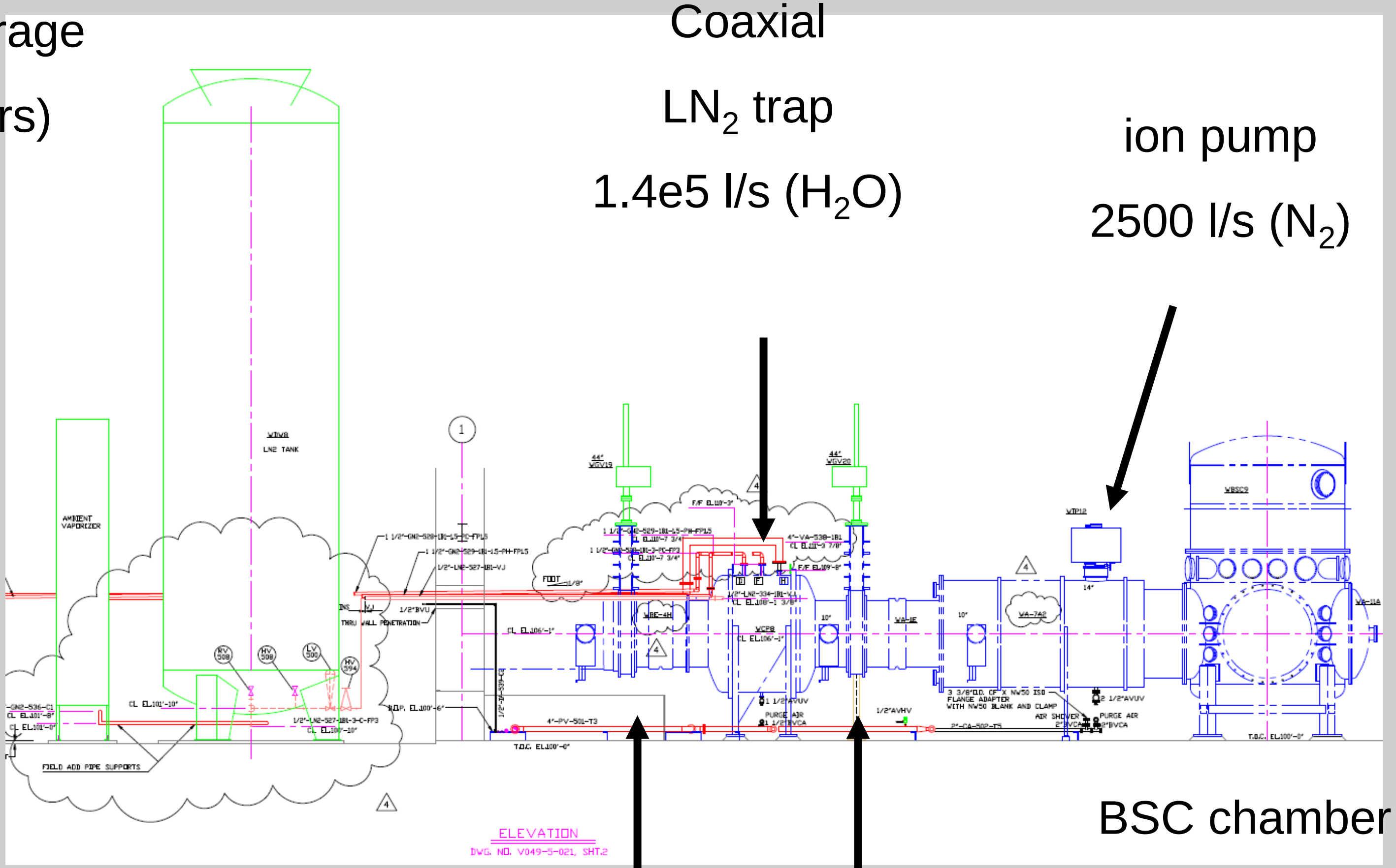
LN_2 trap

1.4e5 l/s (H_2O)

ion pump

2500 l/s (N_2)

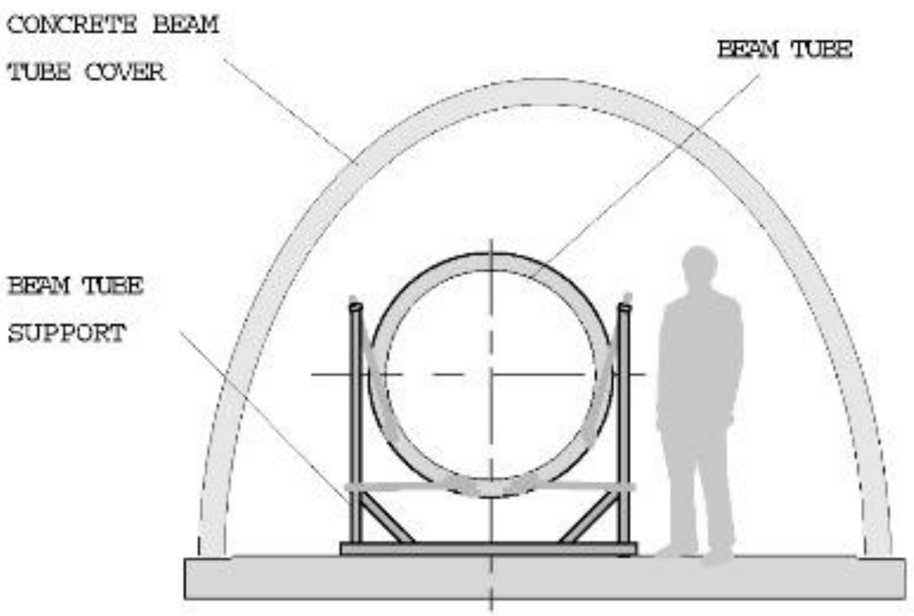
beamtube



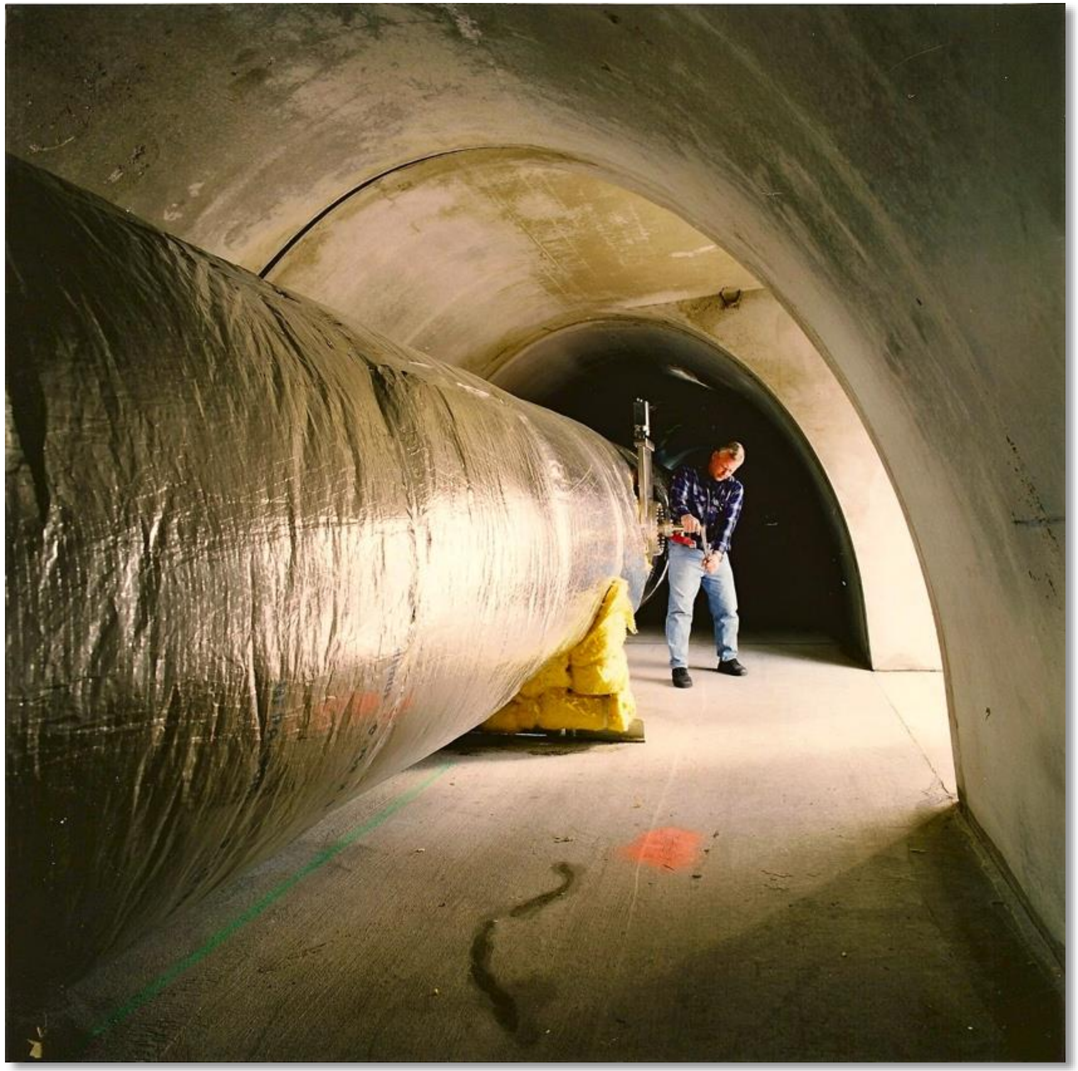
BSC chamber

1.2m Ø gate valves

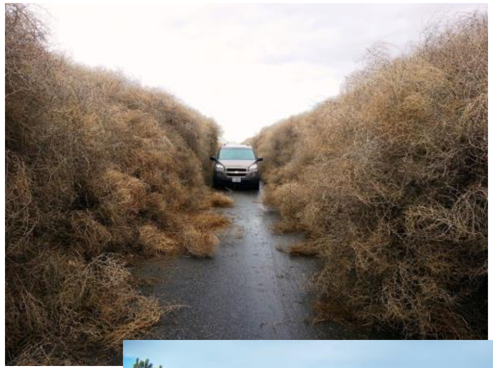
Concrete Enclosure



Enclosure is pretty spartan, minimal utilities, access doors, lighting, environmental control, etc.
Not a fun place to work in.

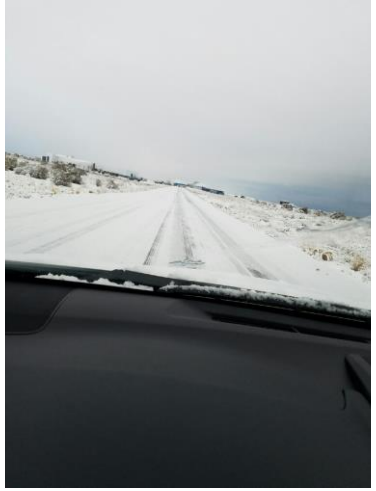


Enclosures doing their job



Tumbleweeds and range fires

Bullets

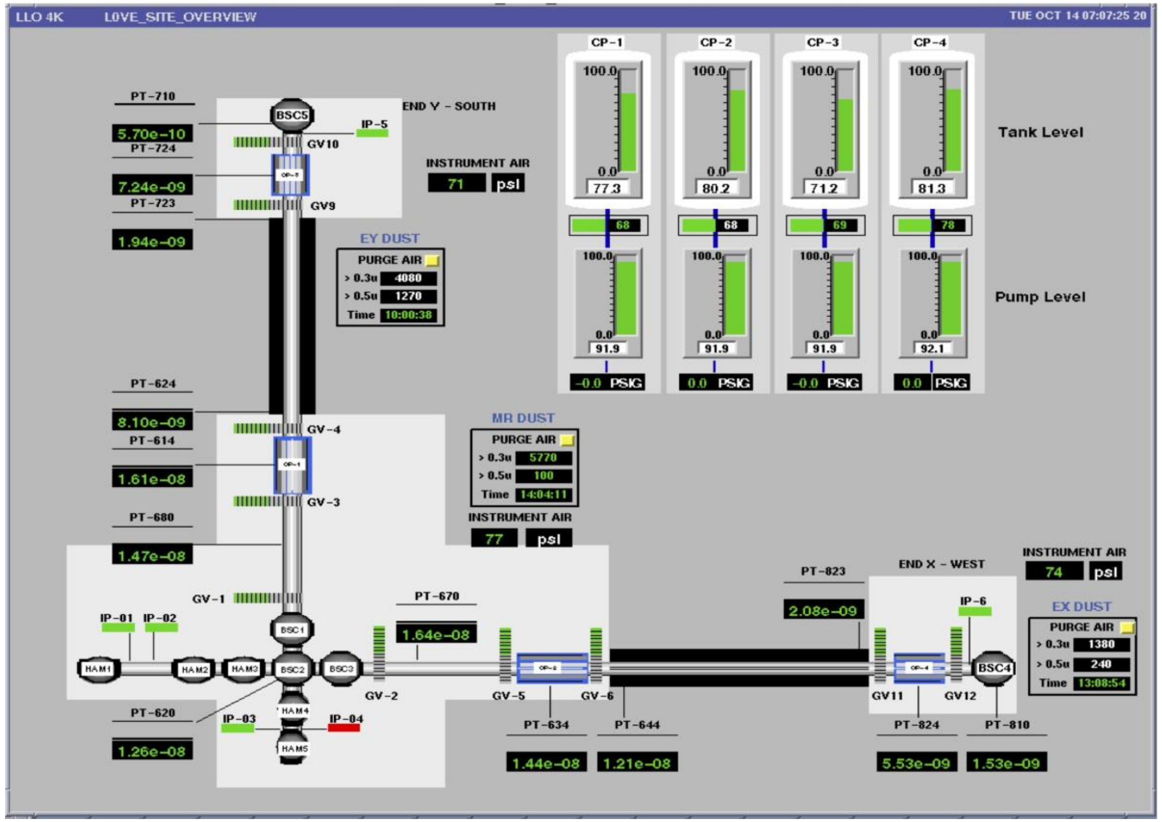


Icy Roads

Vacuum System Schematic and Gauging

4 km

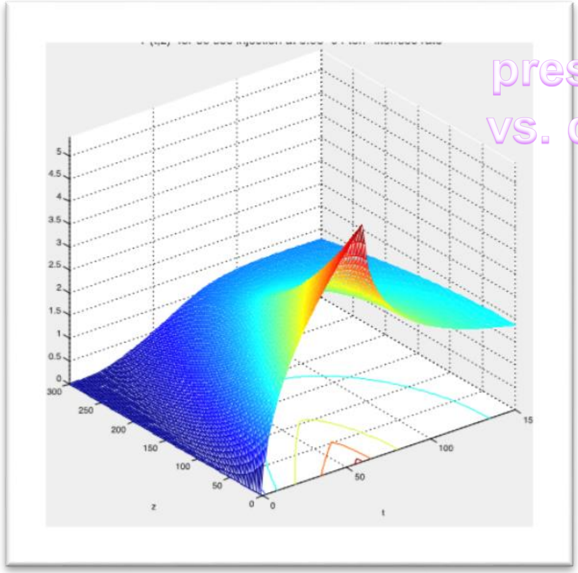
50 m



Gauging monitors pressure, cryopump levels, LN2 supply, etc. sends a text message if unusual condition occurs. Pressure monitored by cold-cathode (magnetron) gauges

Challenges: Leaks and corrosion

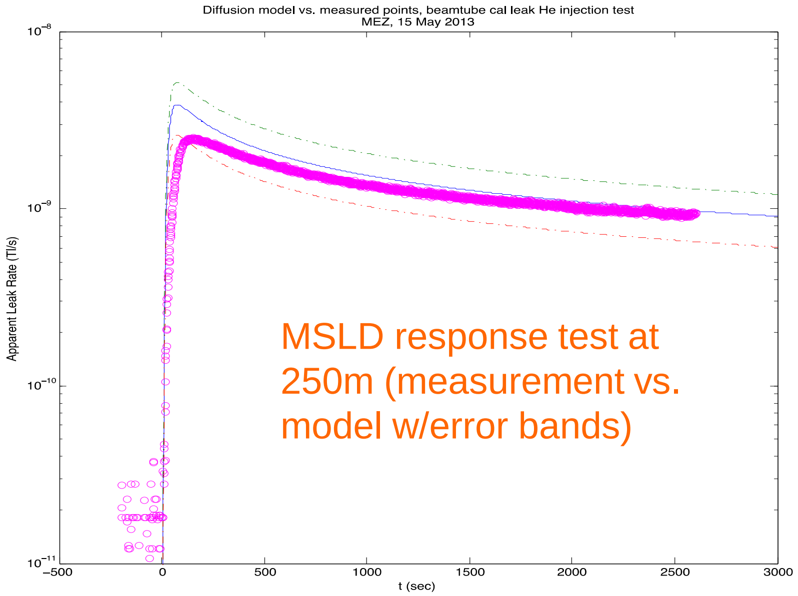
evacuated "fothering" patch



pressure transient vs. distance for He injection

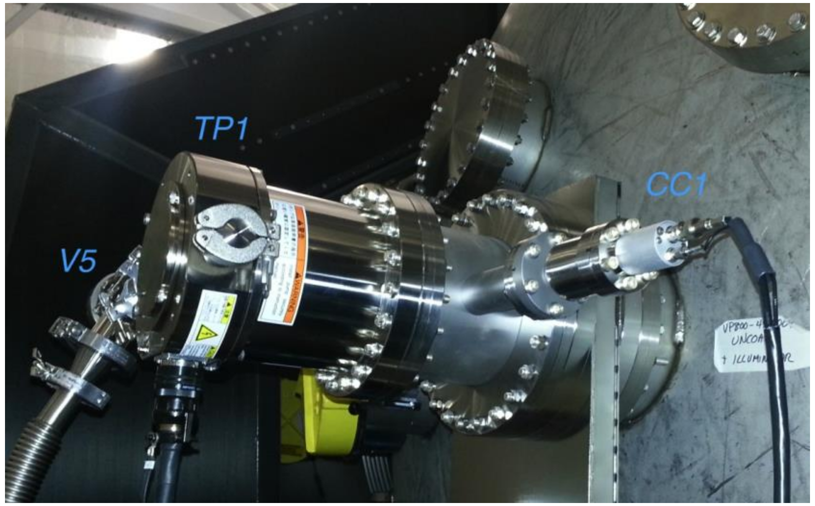
Cracks and corrosion create ~1e-6 TL/s leaks…sounds easy to find but……

Challenges: Leaks and Detection



MSLD response test at 250m (measurement vs. model w/error bands)

Figure 2: Leak detector response to 30 second calibrated injection of helium test gas at $z = 250$ meters (pink circles). Also plotted is predicted response from diffusion model (solid blue) and approximate standard error margins (dash-dot red and green).



500 l/s turbo for MSLD compression boost (K. Ryan)

MSLD response degradation with distance

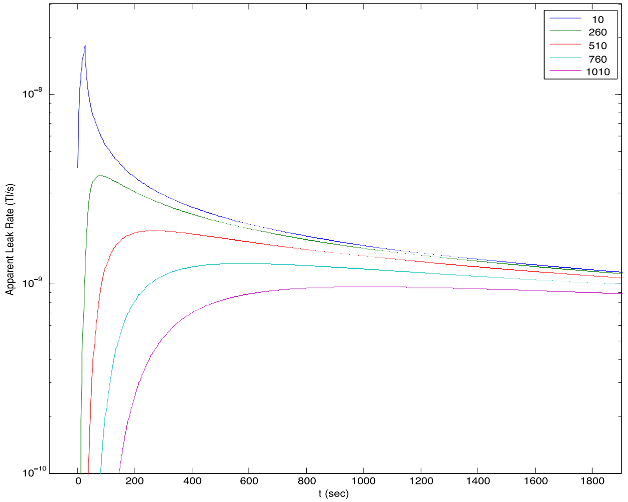
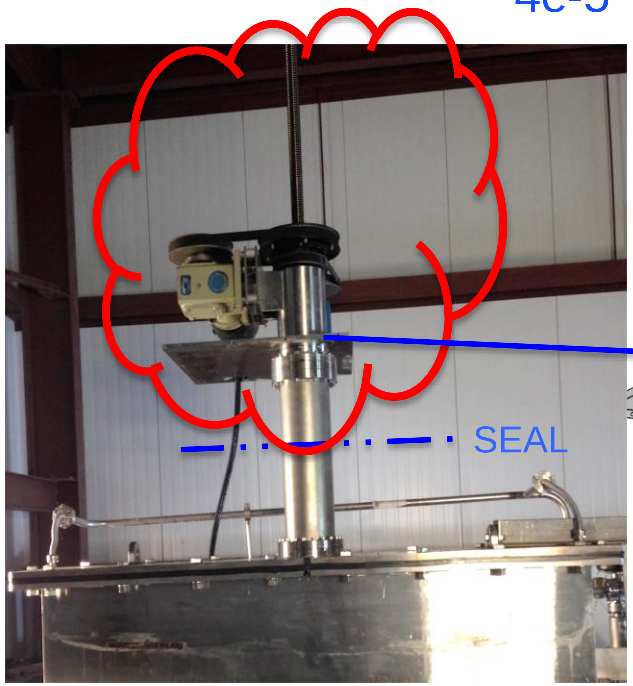


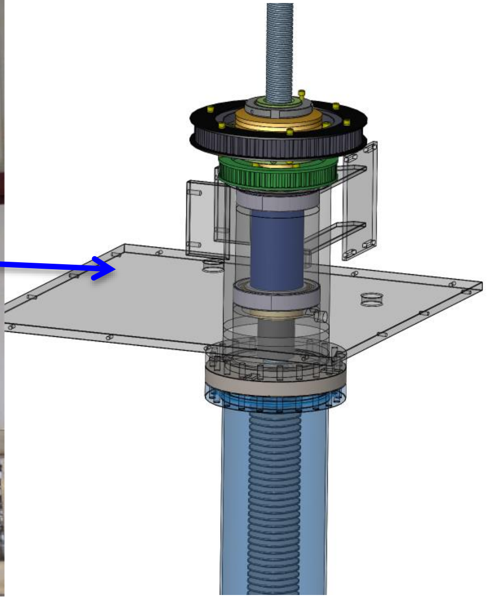
Figure 1: Model leak detector response for He test injections as described in text, assuming different injection positions z ranging from 10m (blue) to 1.01 km (purple). The actual test (Fig. 2) was performed at $z = 250$m (green).

Time constant of system makes Helium MSLD difficult, locating a leak extremely challenging, plus “where to start”?

Challenges: Valve bonnet leak

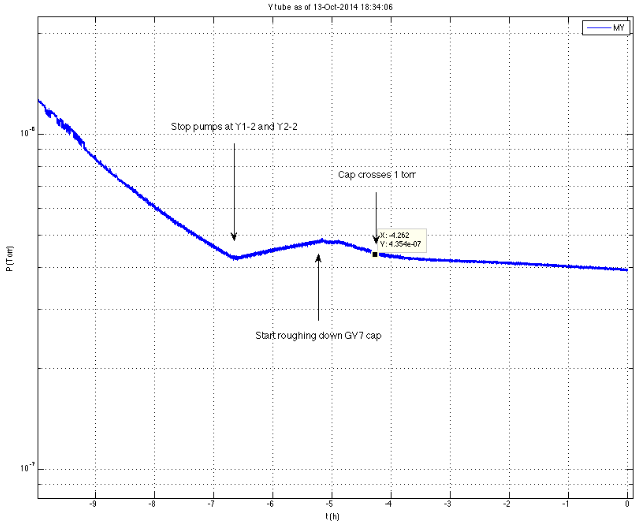
~ 4e-5 TL/s leak





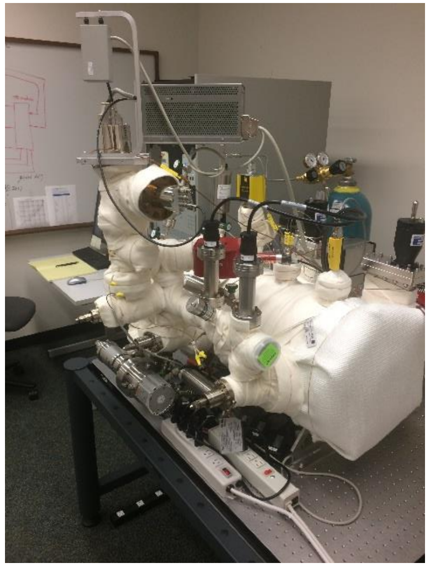
Odd time constant…. leaking through grease?

GV7 sarcophagus concept



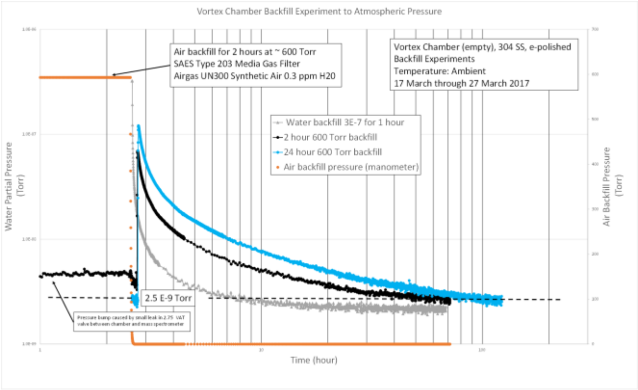
There is no mechanism to vent a beam tube, repair a valve and rebake, so what to do? Answer….design and install an enclosure to evacuate the volume *outside* the valve screw drive mechanism. Leak reduced, but valve now permanently inoperable (located at 2 km “mid-station”) in open position. Luckily…. this valve could be abandoned w/o compromising operations

Current Vacuum Research



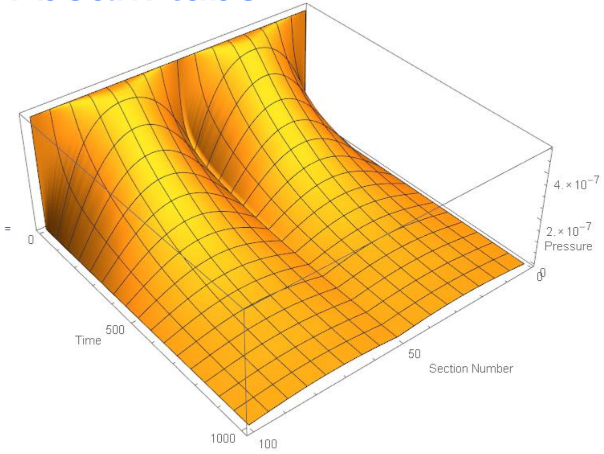
Vortex system

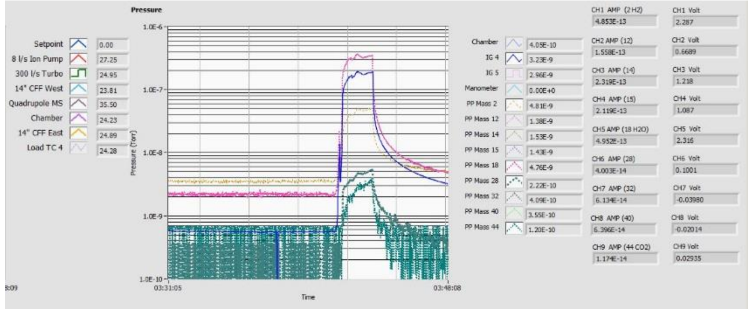
Steel surface modeling



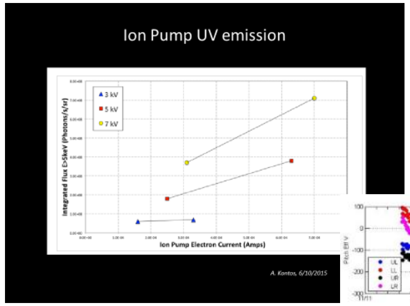
Dry gas backfill

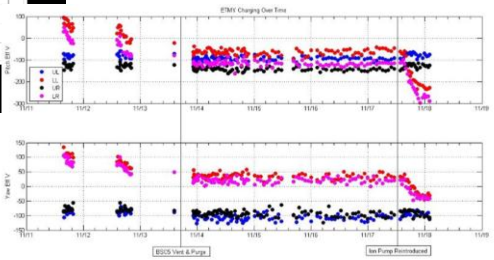
Molecular dynamics of beam tube



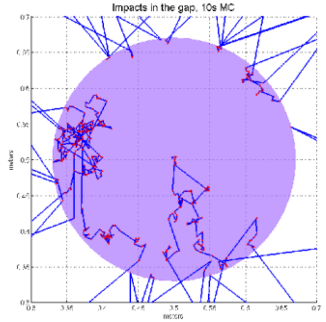


Water injection





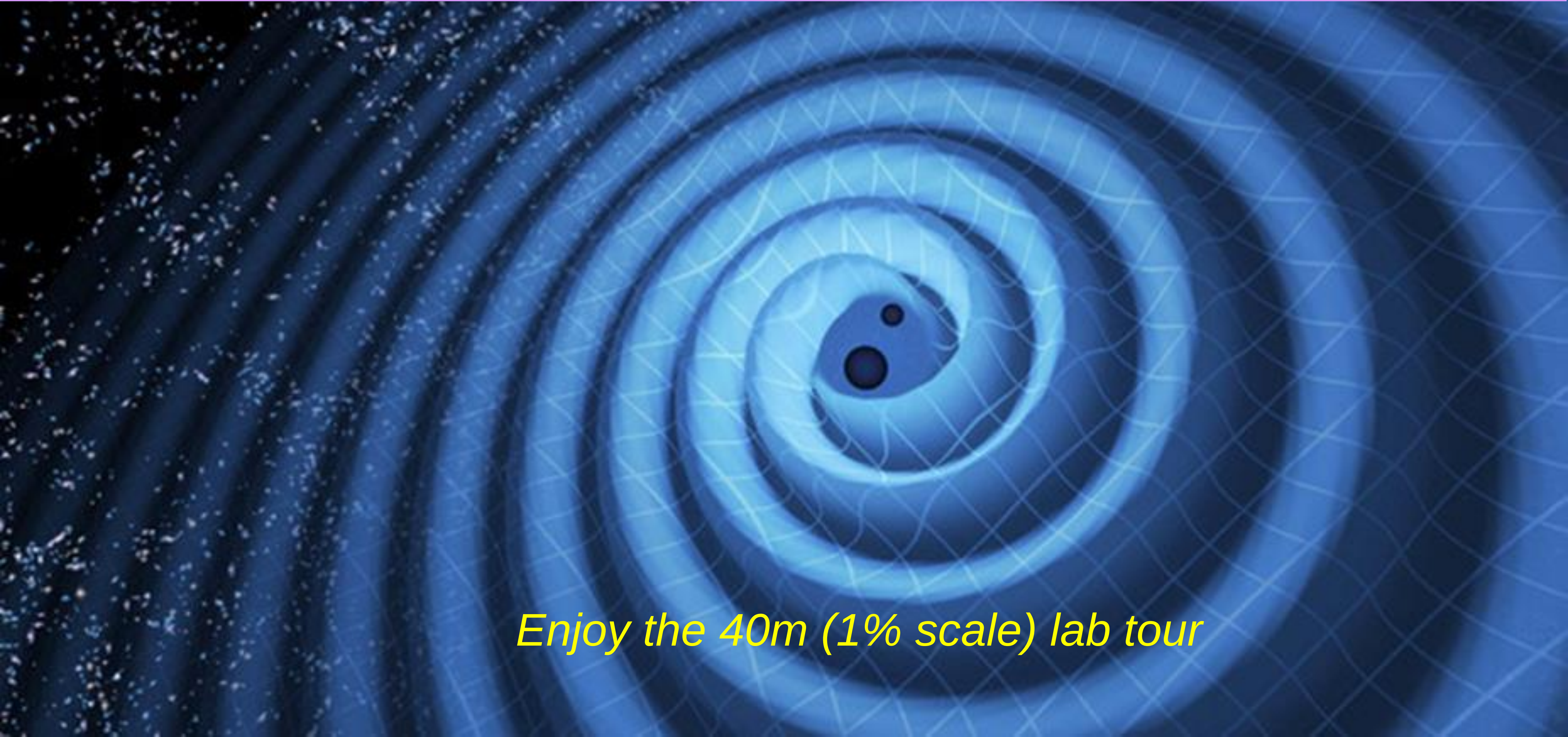
Ion pump UV induced charging



Squeeze film damping

LIGO

Thank you for visiting LIGO !



Enjoy the 40m (1% scale) lab tour