The LIGO 4km Vacuum System: Design, Construction, Features & Faults

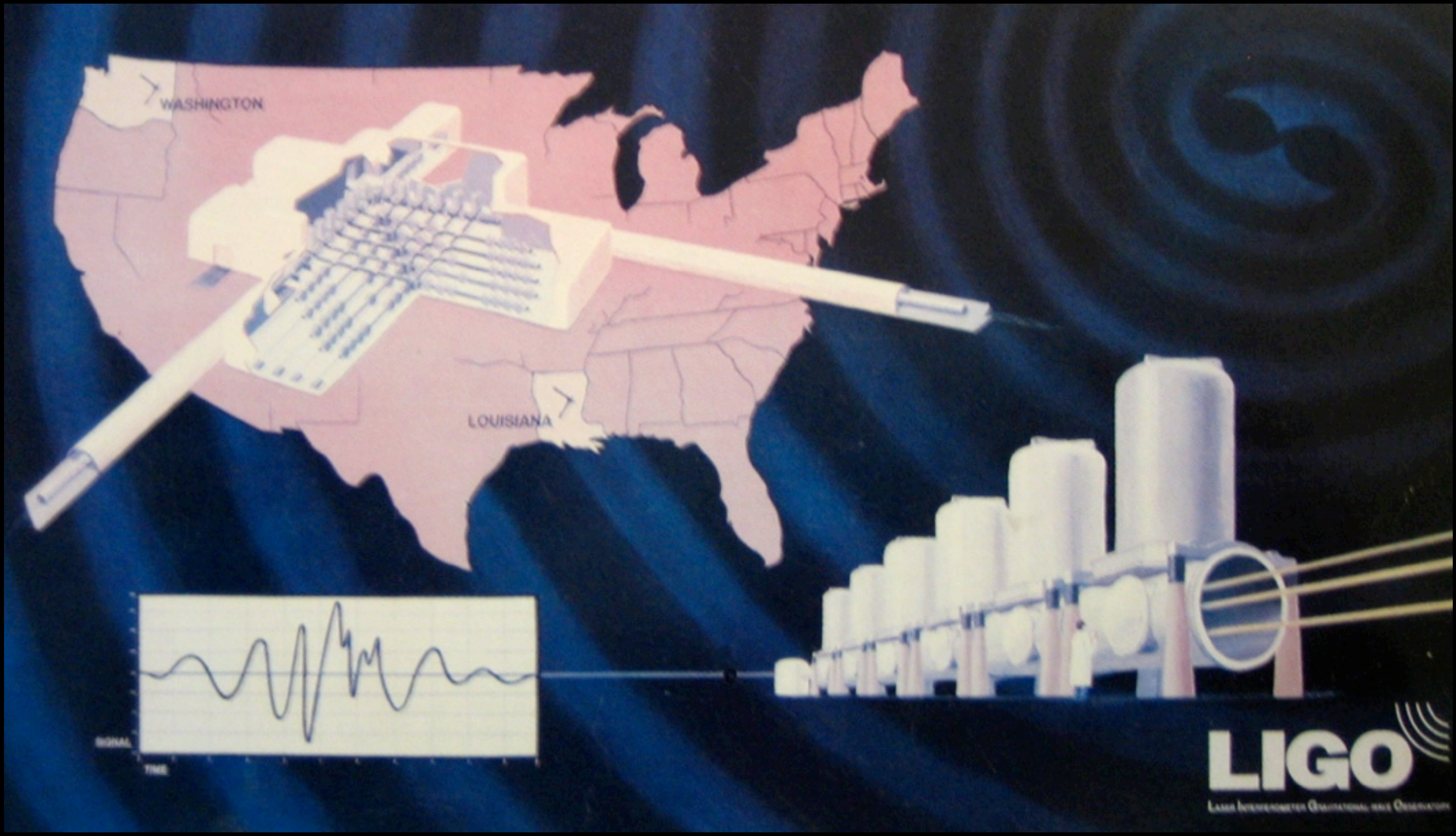
Mike Zucker, LIGO Caltech & MIT

NSF Workshop on Large UHV Systems for Frontier Scientific Research
LIGO Livingston Observatory
29-31 January, 2019

LIGO-G1900137

Image Credit: Aurore Simmonet/SSU

30 years ago…



Topics

Vacuum Equipment vs. Beamtubes

VE construction

Tube construction & Bakeout

Performance

Gotchas & Lessons Learned

LIGO is Really Two Vacuum Systems (at each site)

Chambers, pumps, instruments- "Vacuum Equipment"

- Houses detector apparatus
- Isolation (valves), access (doors)
- Electrical, mechanical, optical penetrations/interfaces
- Pumping & instrumentation
- Somewhat "conventional"
- *F:A* ~ 10^{-2} $ls^{-1}cm^{-2}$

Beam tubes

- Just a long hole in the air;
  Never to be vented
- Highly "unconventional"
  - 10 million liters (per site)
  - 300 million cm^2 (per site)
  - 200 l/s char. conductance
- *F:A* ~ 10^{-5} $ls^{-1}cm^{-2}$

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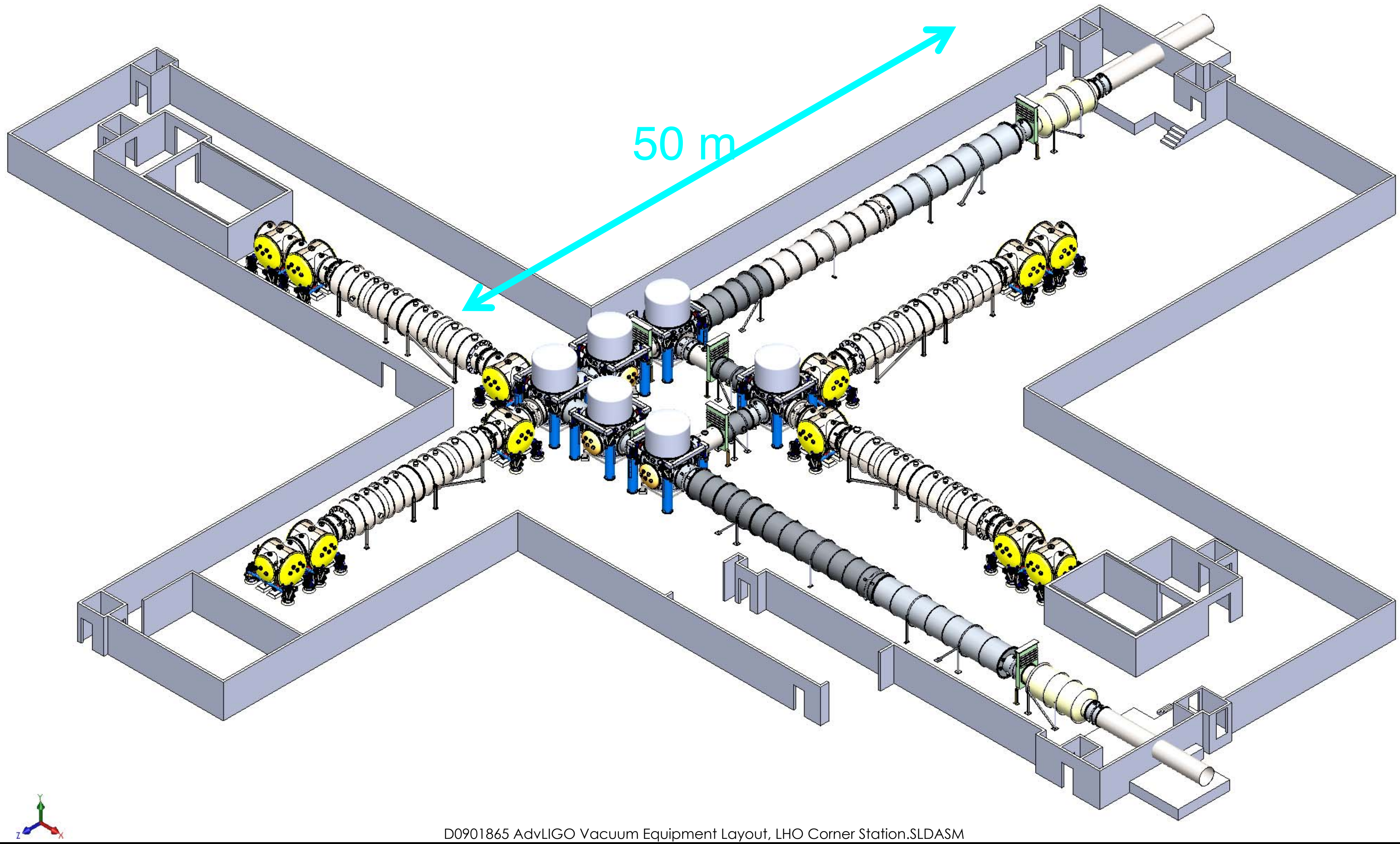
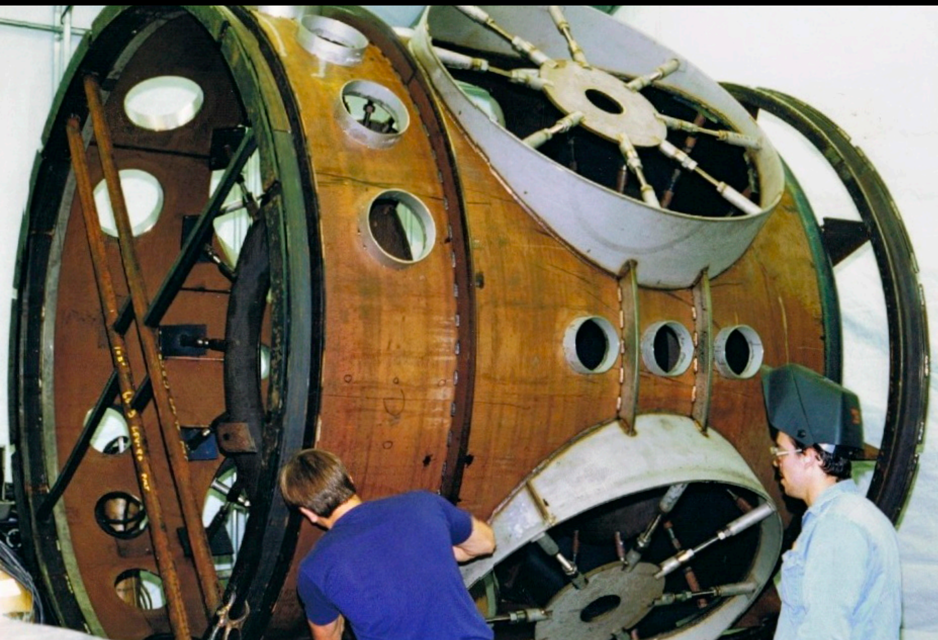
LIGO Vacuum Equipment, LHO Corner Station

Modular Vacuum Equipment Design

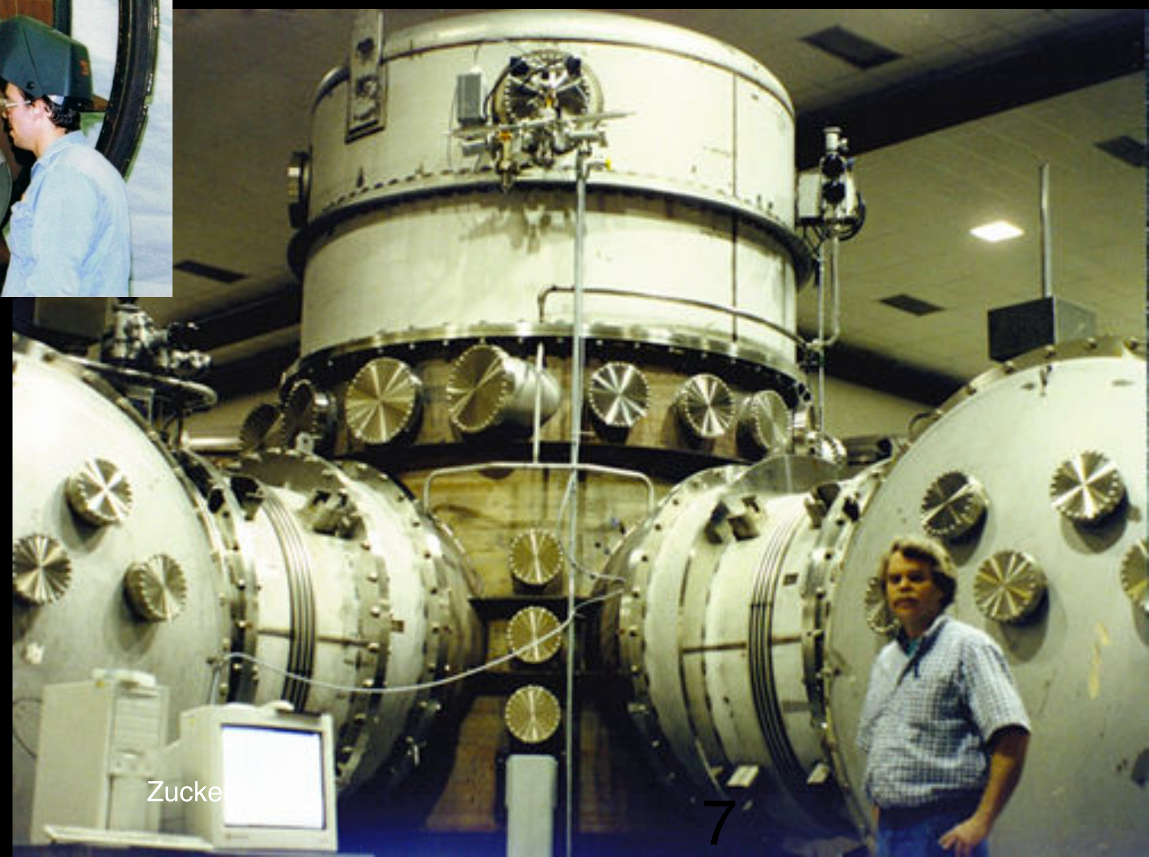


BSC chamber

(Boring Symmetric Chamber)



- 2.8m Ø x 5.5m h
- Upper third removable dome
- Thin (10-15mm) 304L SS shell with welded stiffeners, F&D heads
- Combination of GTAW and plasma welding



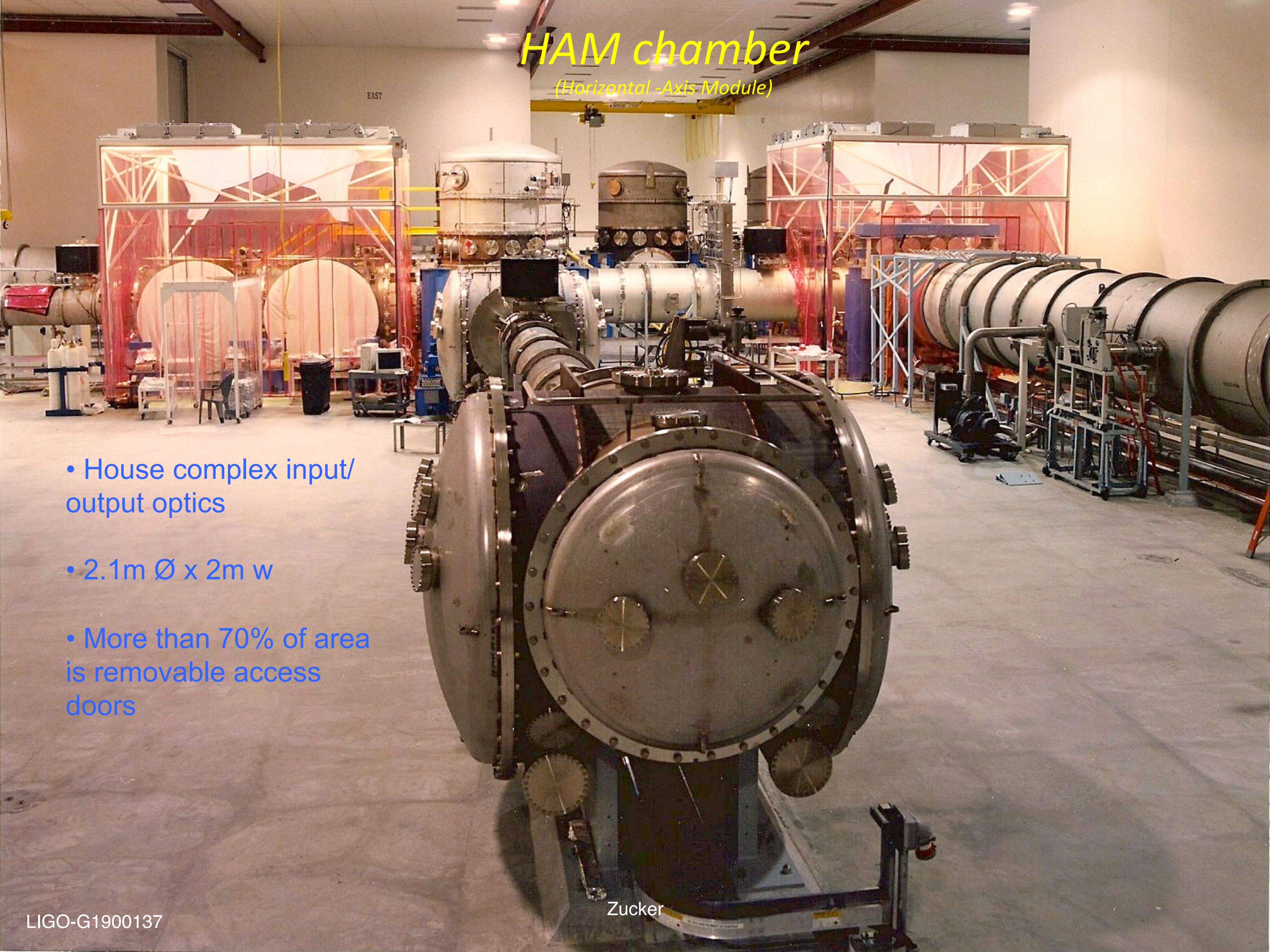
- Ports < 35cm Ø: ConFlat™
- Ports > 35cm Ø: Dual O-ring
  - Treated Viton elastomer
  - Isolated pumped annulus between inner and outer seal
  - Permeation and damage tolerant

BSC Equipment Installation

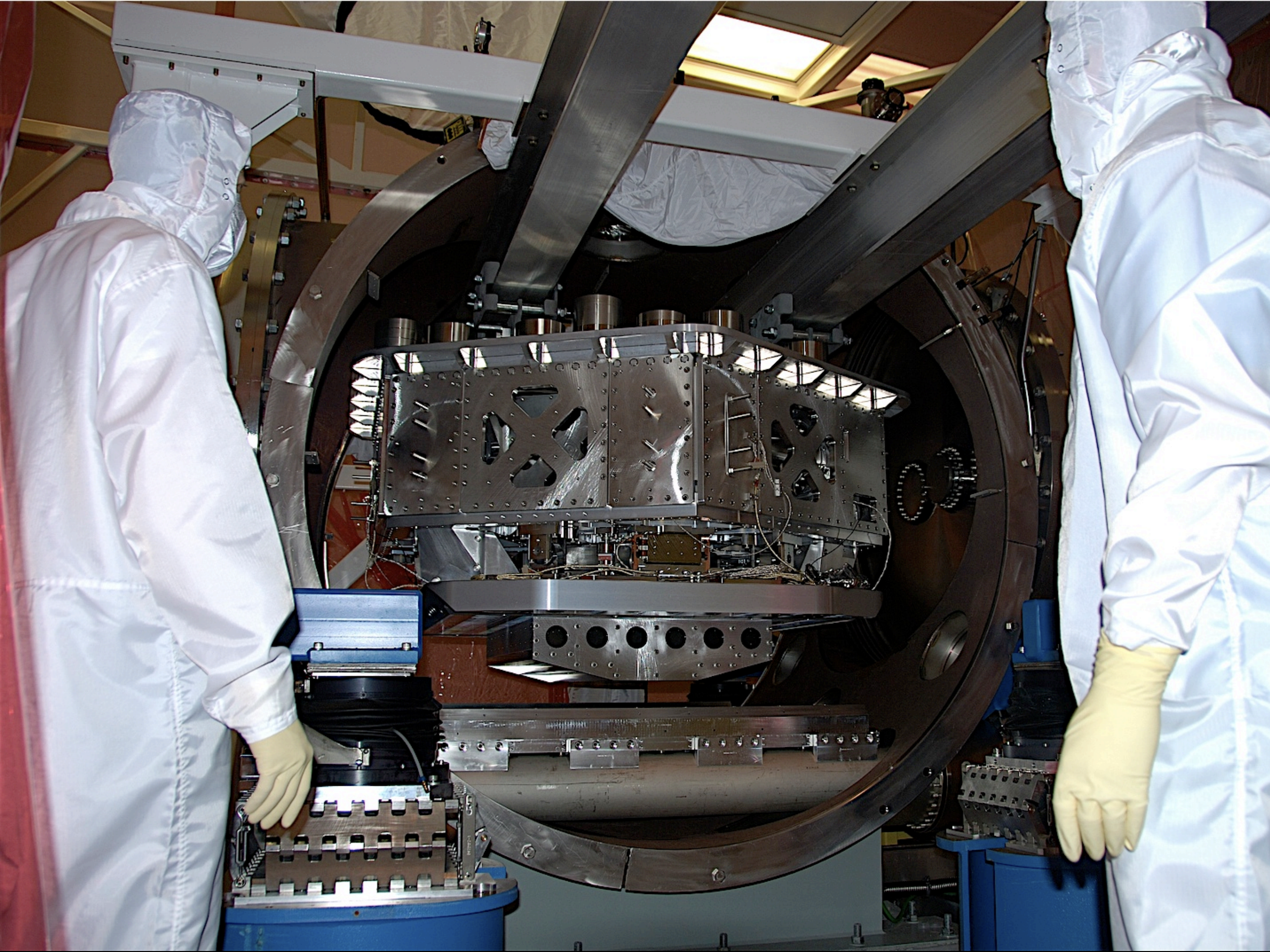
Livingston ETM Y BSC "Cartridge" Installation
21 Feb '14

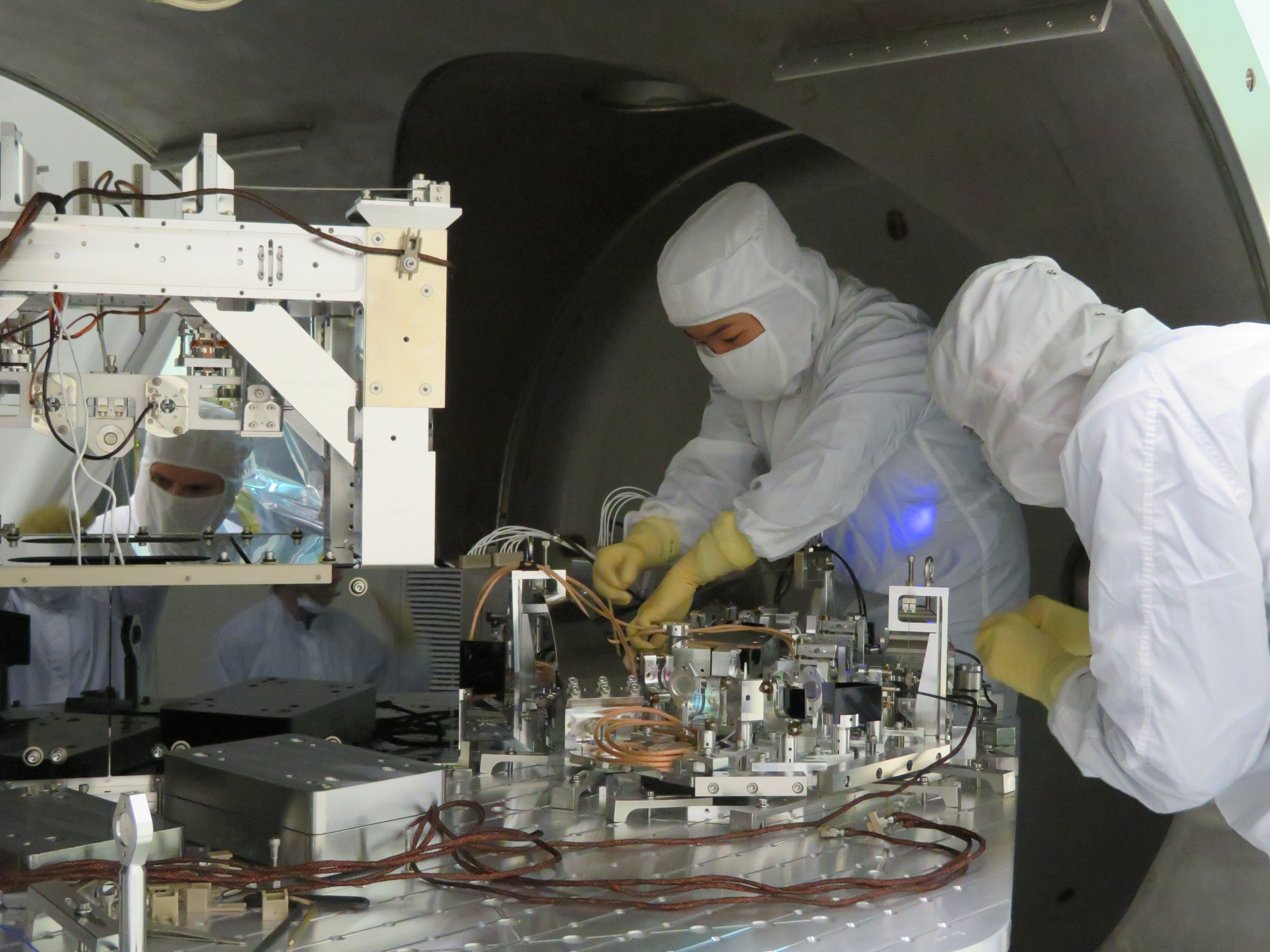
HAM chamber

(Horizontal -Axis Module)



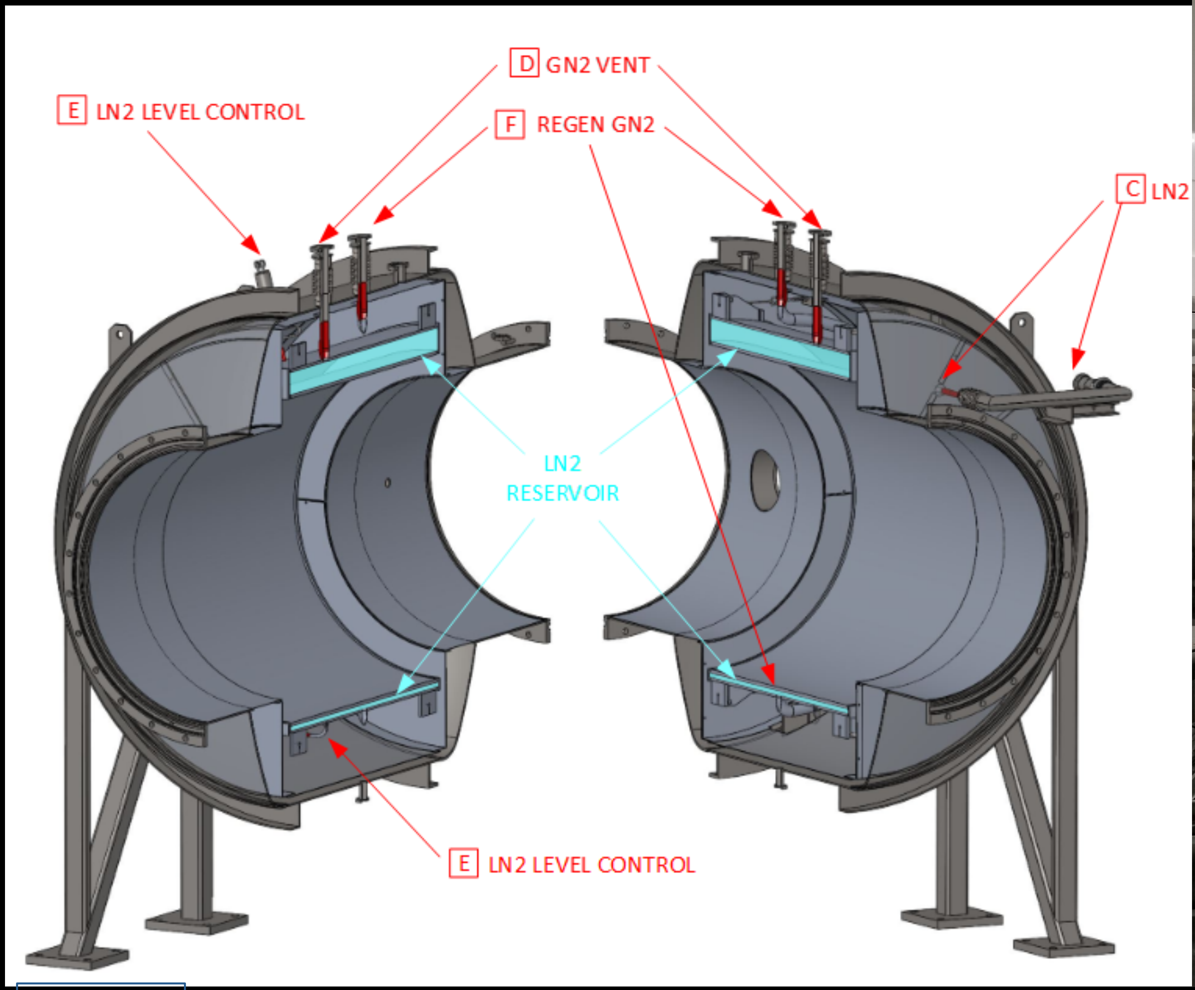
- House complex input/ output optics
- 2.1m Ø x 2m w
- More than 70% of area is removable access doors





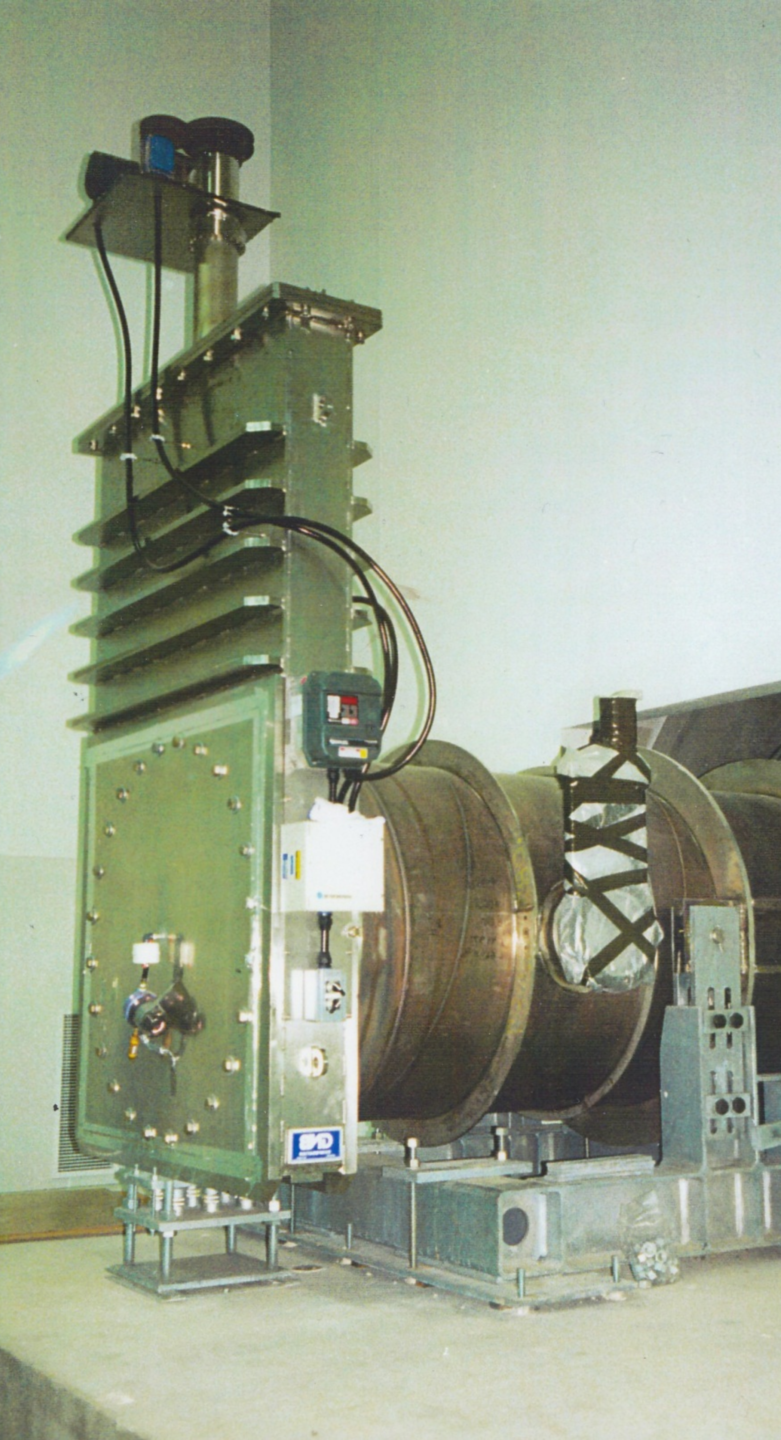

B2B-36
B5A-36

Passive 80K cryotraps pump water vapor released by detector components

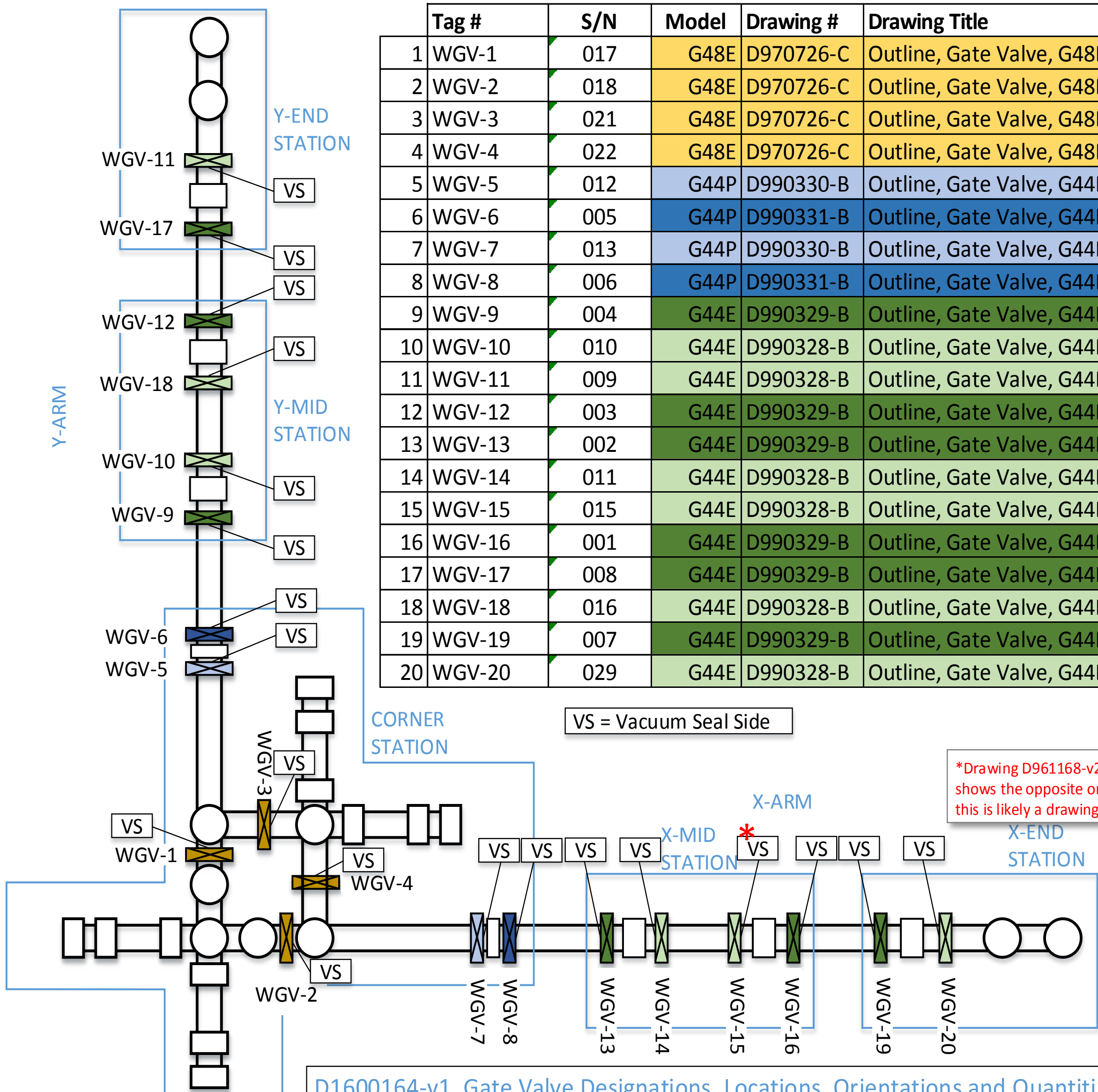


3D model
E. Sanchez

photo
G. Moreno




	Tag #	S/N	Model	Drawing #	Drawing Title
1	WGV-1	017	G48E	D970726-C	Outline, Gate Valve, G48ESB - FLG/FLG
2	WGV-2	018	G48E	D970726-C	Outline, Gate Valve, G48ESB - FLG/FLG
3	WGV-3	021	G48E	D970726-C	Outline, Gate Valve, G48ESB - FLG/FLG
4	WGV-4	022	G48E	D970726-C	Outline, Gate Valve, G48ESB - FLG/FLG
5	WGV-5	012	G44P	D990330-B	Outline, Gate Valve, G44P - FLG/FLG
6	WGV-6	005	G44P	D990331-B	Outline, Gate Valve, G44P - WLD/FLG
7	WGV-7	013	G44P	D990330-B	Outline, Gate Valve, G44P - FLG/FLG
8	WGV-8	006	G44P	D990331-B	Outline, Gate Valve, G44P - WLD/FLG
9	WGV-9	004	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
10	WGV-10	010	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG
11	WGV-11	009	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG
12	WGV-12	003	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
13	WGV-13	002	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
14	WGV-14	011	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG
15	WGV-15	015	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG
16	WGV-16	001	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
17	WGV-17	008	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
18	WGV-18	016	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG
19	WGV-19	007	G44E	D990329-B	Outline, Gate Valve, G44ESB - WLD/FLG
20	WGV-20	029	G44E	D990328-B	Outline, Gate Valve, G44ESB - FLG/FLG



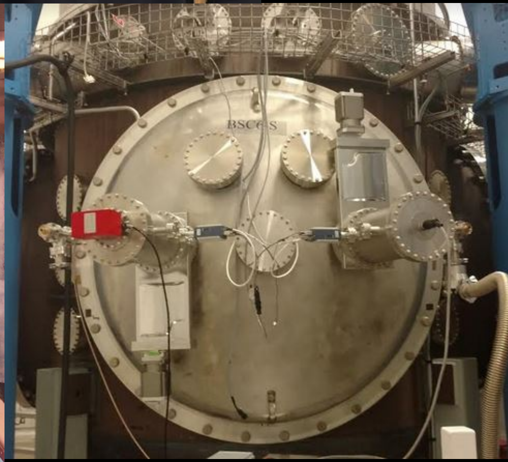
VS = Vacuum Seal Side

*Drawing D961168-v2 (PSI V049-5-004, Rev. 5) shows the opposite orientation of this GV, but this is likely a drawing error.

D1600164-v1, Gate Valve Designations, Locations, Orientations and Quantities
Sheet1: LHO

Pumping for Non-condensibles

- Maglev turbos for initial evacuation only
- Ion pumps assisted by NEGs in normal operation
- *NO rotating or vibrating machinery* allowed during interferometer operation



LIGO Beamtube

- 9000 m^3 volume/site
- 30000 m^2 area/site
- 50 km of spiral welds
- ~10^{-9} torr
- budget ~ \$40M (1997)
  \$2500/m
  \$50/lb

Beam Tube Properties

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

Residual Gas Pressure Limits in Beam Tubes

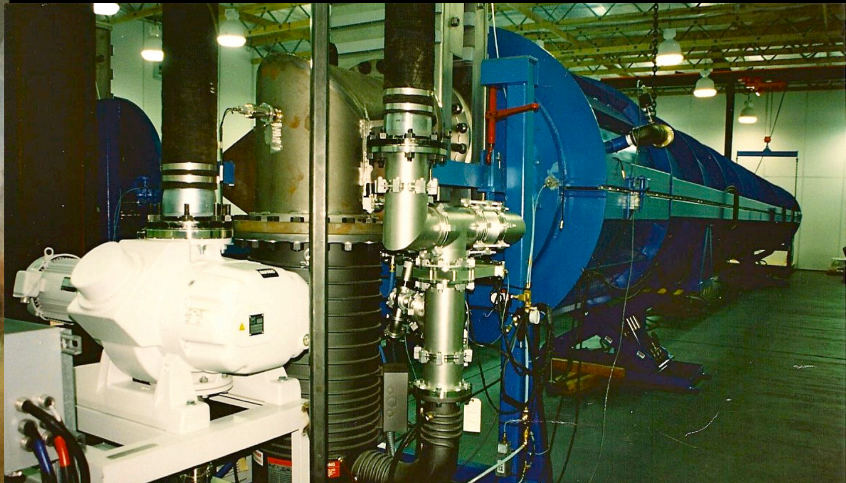
$$h(f) = 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

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	$1.4\text{x}10^{-10}$	$1.4\text{x}10^{-13}$
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	$2.5\text{x}10^{-11}$	$2.5\text{x}10^{-14}$
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	$9.0\text{x}10^{-12}$	$9.0\text{x}10^{-15}$

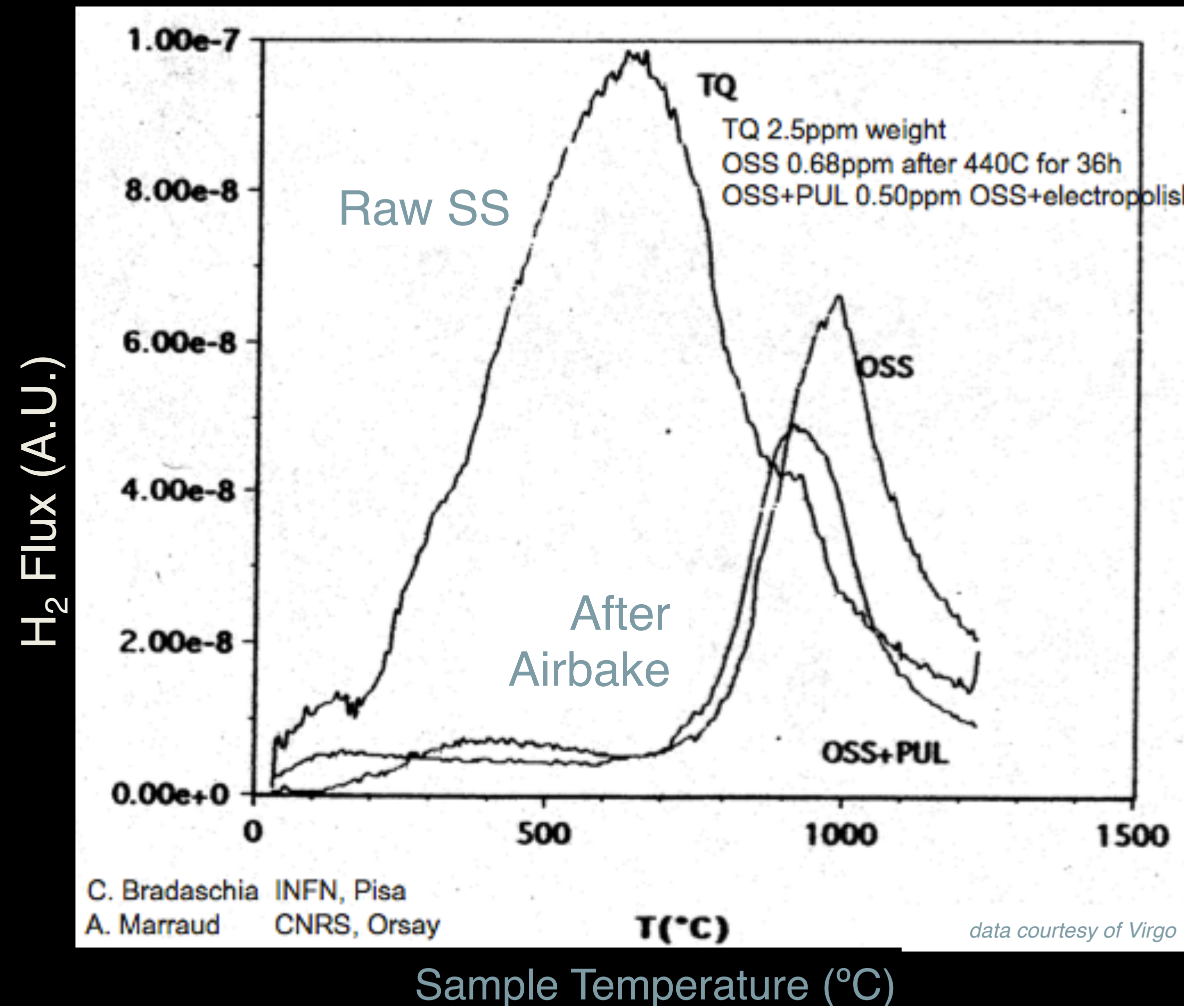
Beam Tubes

- 304L SS
- 3.2 mm thick with external stiffeners
- Raw stock air baked 36h @ 455C
  - Final J_{H2} < 1e-13 Tl/s/cm^2
- coil spiral-welded into 1.2m tube 16m long
  - method adapted from sewer pipe industry
- 16m sections cleaned, leak checked
- FTIR analysis to confirm HC-free
- sections field butt-welded together in travelling clean room
- Over 50 linear km of weld



Depleting Hydrogen from raw SS before tube fabrication: An economical alternative to high T vacuum bakeout

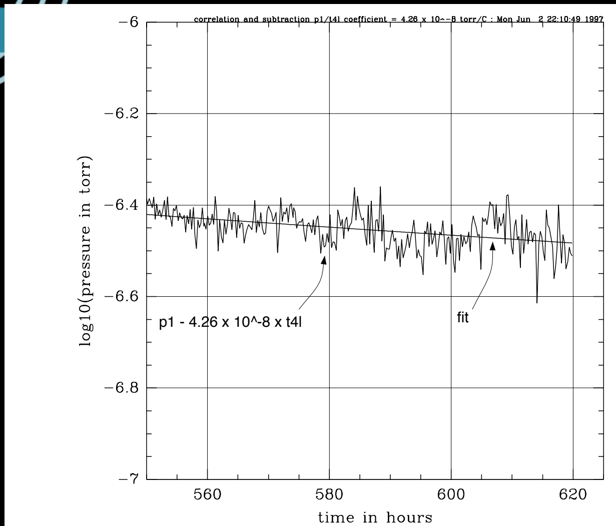
- SS sheet from mill is baked in air 36 hours at 455 ºC
- (Hotter treatment deemed inadvisable due to carbide formation)
- Total dissolved hydrogen is reduced ~ 3x
- Remaining H is tightly bound, high activation T
- Care is required in welding to avoid re-introduction of H



Leak Test “Coffin”

Beamtube Field Assembly

Unbaked Water Outgassing (norm. to 1000 hours)



Weiss et al, T970111
LHO beamtube
$J(H_2O) \sim 8 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t

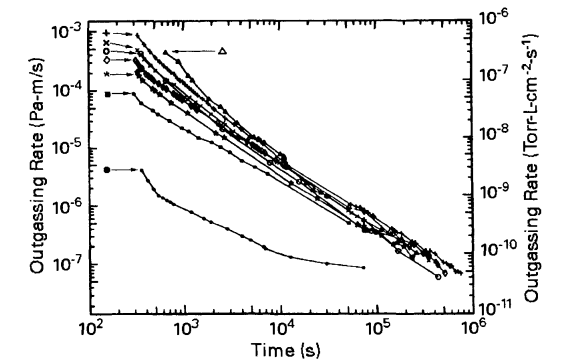
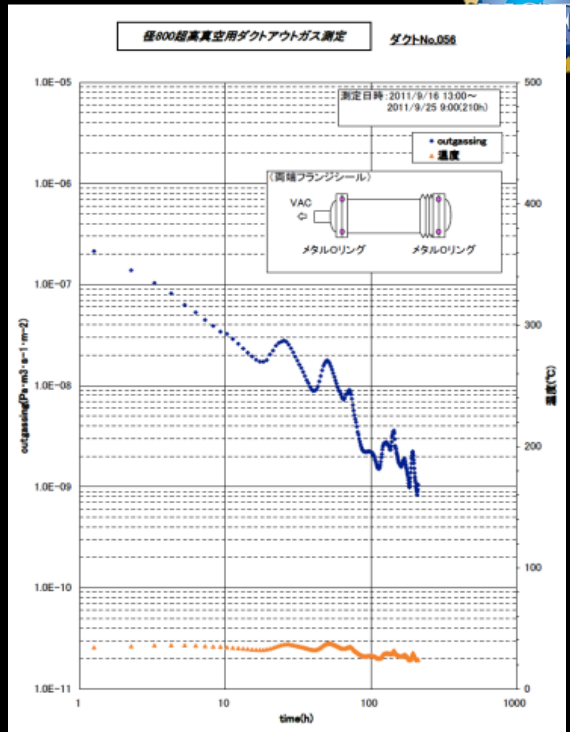
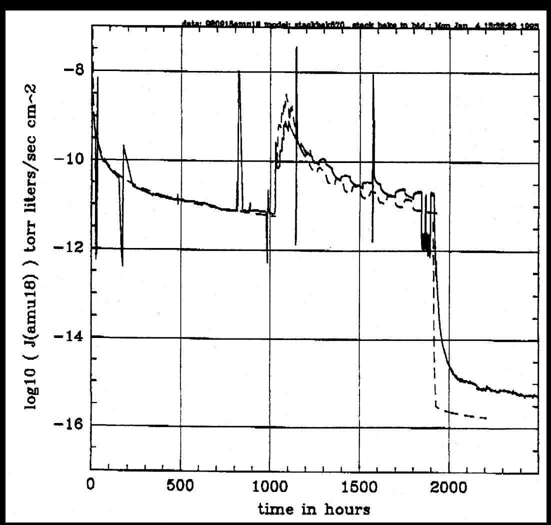


Fig. 4.5 Outgassing measurements for different H_2O exposures during venting of a 304 stainless steel chamber of inner surface area 0.4747 m^2. ○ Ambient air exposed, 7.8 ml absorbed; Δ 600 ml exposed, 16.8 ml absorbed; + 400 ml exposed, 9.2 ml absorbed; × 200 ml exposed, 7.2 ml absorbed; ◊ 100 ml exposed, 3.6 ml absorbed; ★ 10 ml exposed, 2.3 ml absorbed; ■ N_2 gas with <10 ppm H_2O exposed, 0.7 ml absorbed; ● dry N_2 gas exposed, 0.017 ml absorbed; Reprinted with permission from *J. Vac. Sci. Technol. A*, **11**, p. 1702, M. Li and H. F. Dylla. Copyright 1993, AVS–The Science and Technology Society.

Li and Dylla (1993)
Electropolished 304L
10 ppm water content air re-exposure
$J(H_2O) \sim 4 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t



Saito et al (KAGRA, 2011)
ECB 304L, 200C conditioning bake
-40C dewpoint (127 ppm) re-exposure
$J(H_2O) \sim 2 \times 10^{-13}$ T l s^{-1} cm^{-2} x (1000 h)/t

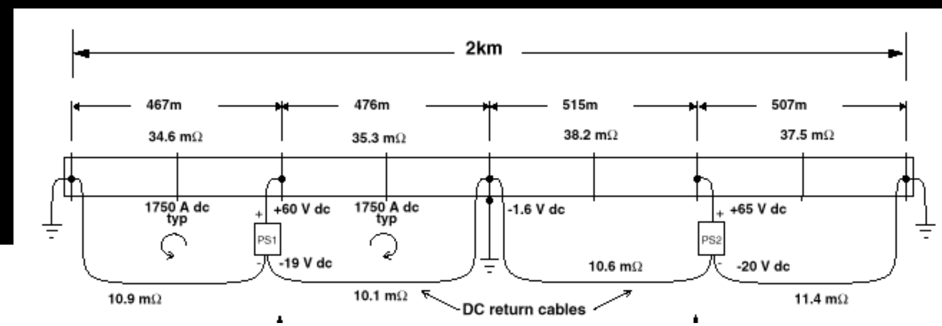


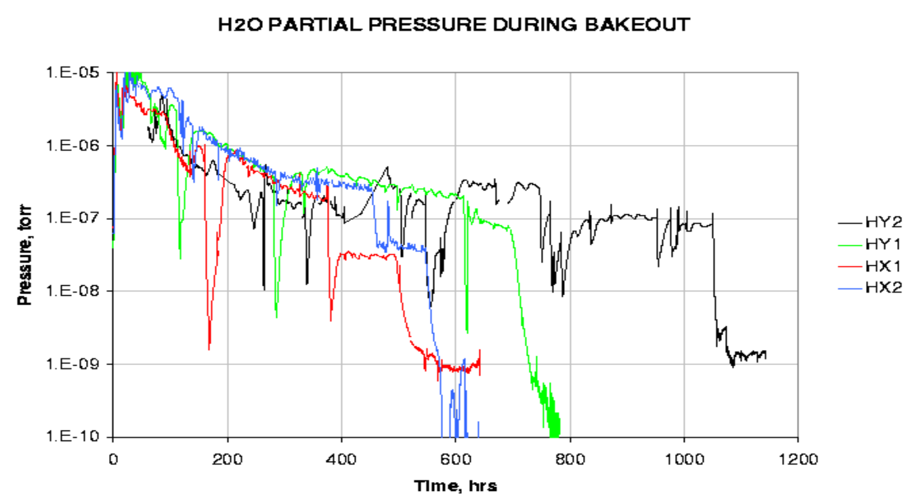
Weiss et al, T940090
BTD at CB&I
$J(H_2O) \sim 3 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t
(~ 10^{-16} T l s^{-1} cm^{-2} post-bake)

- Tolerable pressure for H_2O ~ 1/10 that for H_2
- Passive 1/t desorption with time too weak
- Low-temperature bakeout was required
  - LIGO used 1-shot bakeout to save cost
  - Tubes can never be re-exposed to atmosphere

I^2R Bakeout to Desorb Water

- I_{DC} = 2,000 A
- 3 weeks @ 160ºC
- Final J_{H2O} < 2e-17 Tl/s/cm^2





Bakeout Results (Hanford)

Beam Tube Bakeout Results

	Outgassing Rate corrected to 23 °C torr liters/sec/cm^2 (All except H_2 are upper limits)					
molecule	Goal*	HY2	HY1	HX1	HX2	
H_2	4.7	4.8	6.3	5.2	4.6	$\times 10^{-14}$
CH_4	48000	< 900	< 220	< 8.8	< 95	$\times 10^{-20}$
H_2O	1500	< 4	< 20	< 1.8	< 0.8	$\times 10^{-18}$
CO	650	< 14	< 9	< 5.7	< 2	$\times 10^{-18}$
CO_2	2200	< 40	< 18	< 2.9	< 8.5	$\times 10^{-19}$
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	$\times 10^{-19}$
$H_nC_pO_q$	50–2†	< 15	< 8.5	< 5.3	< 0.4	$\times 10^{-19}$

air leak	1000	< 20	< 10	< 3.5	< 16	$\times 10^{-11}$ torr liter/sec

*Goal: maximum outgassing to achieve pressure equivalent to 10^{-9} torr H_2 using only pumps at stations

†Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100–300 AMU

5/24/99 wea

Sounds great- but

WHAT WOULD WE DO DIFFERENTLY?

Photo credit: Hurricane Harvey and Richard Oram

20:20 Hindsight–

What Worked Well for LIGO

- Low-hydrogen steel airbake process
- Spiral-welded tube construction (with aggressive QA)
- I^2R bakeout heating
- Modular chamber & spool concept
- Soft-wall modular cleanrooms for installation
- Dual differentially-pumped O-rings on large flanges
- Passive LN_2 cryotraps
- Ion pumps
- Two highly proficient and cooperative subcontractors
  - Chicago Bridge and Iron (beamtubes)
  - Process Systems International (vacuum equipment)

20:20 Hindsight—

Not so much…

- Large gate valves
  - Have had two develop bizarre leakage through stem
  - Serious and increasing concerns about fragility of the mechanism
- Microbial-induced corrosion
  - Leaks caused by SS-eating bacteria in Louisiana
  - Tube environment was not climate-controlled
  - Vermin and moisture “disease vectors”
- But our biggest regret of all is…

20:20 Hindsight–

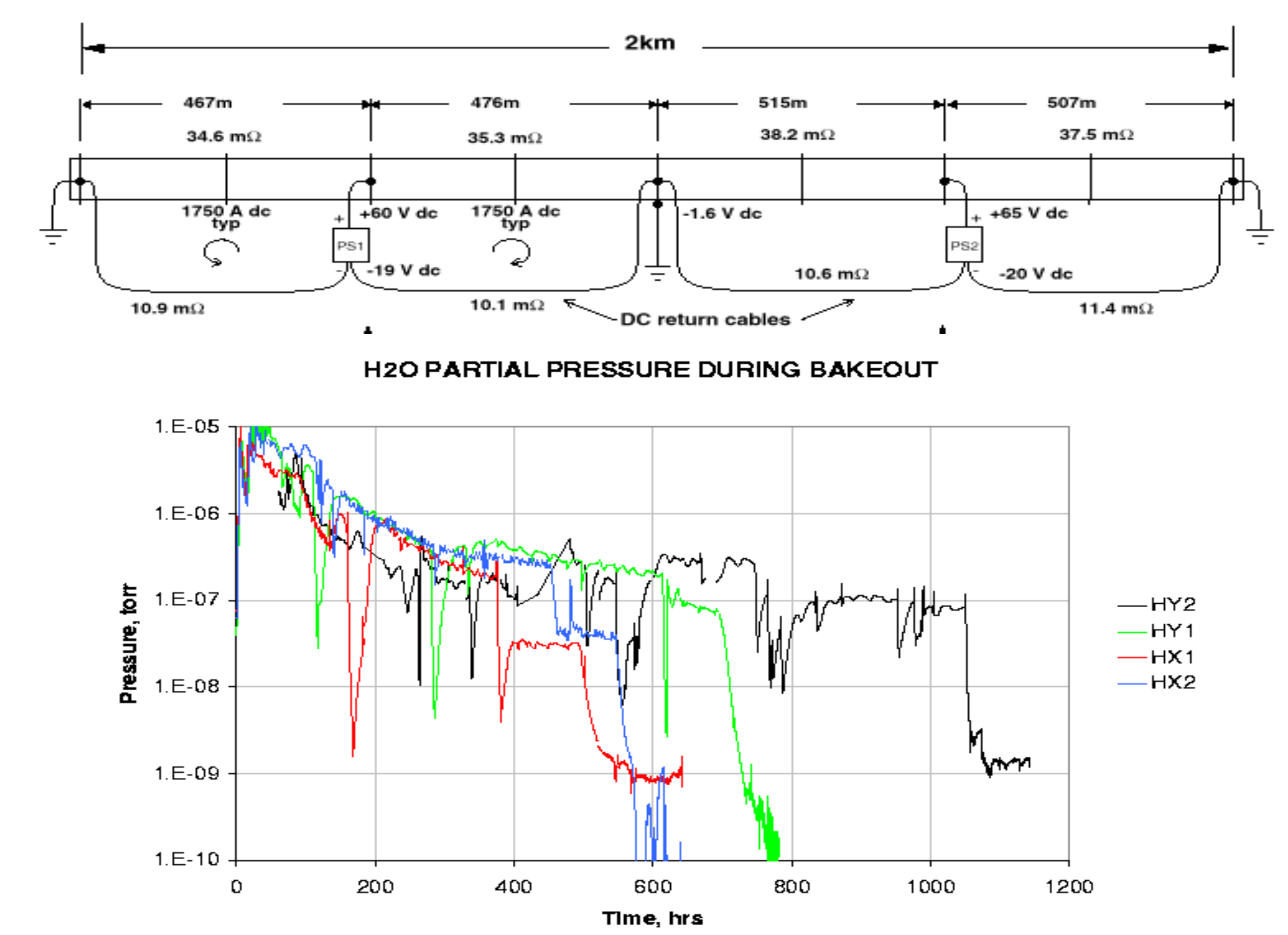
If I could turn back time…

- *Budget constraints left us no standing provision to vent, re-evacuate and re-bake beamtubes in case of future contingency*

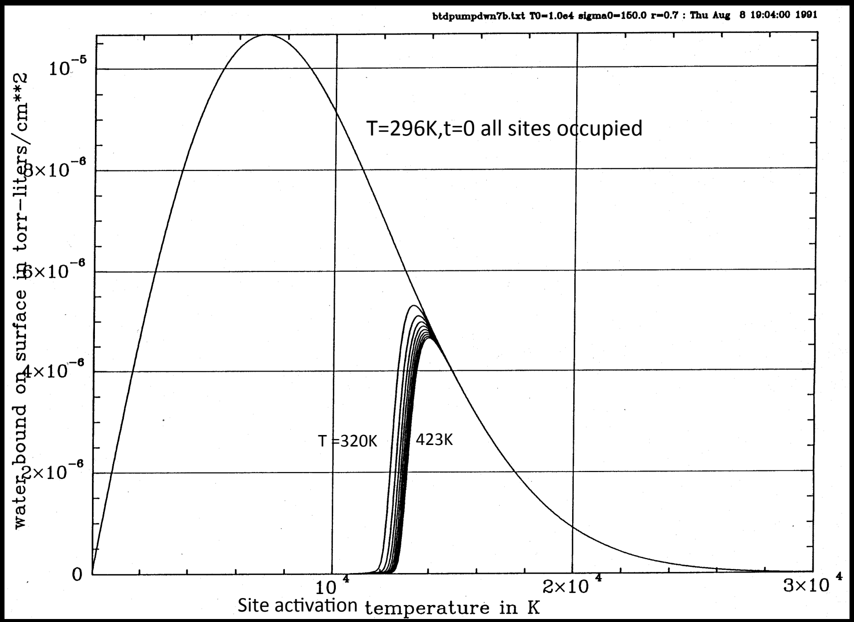

Thanks for your attention

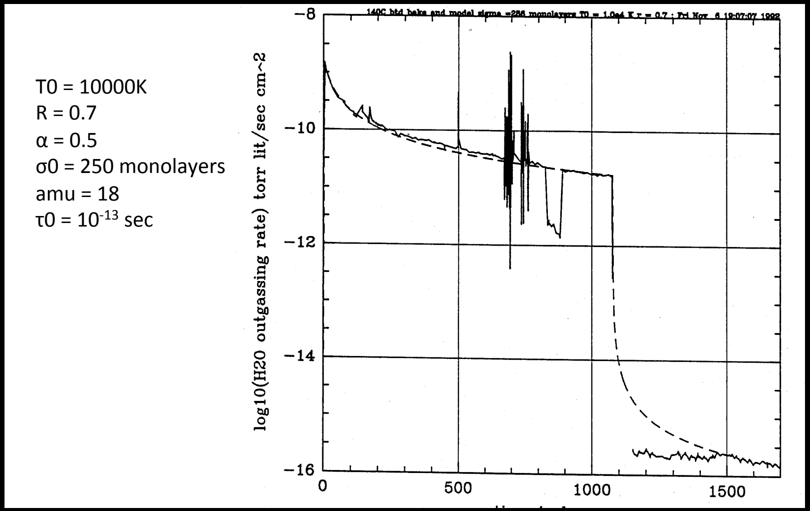
REFERENCE SLIDES

I^2R Bakeout to Desorb Water (cont'd)



“Dubinin-Radeschevich Isotherm” desorption model





Weiss et al, LIGO-T970111

Postbake measurements of module X1 at Hanford

March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$
$NO+C_2H_6$	$< 1.5 \times 10^{-19}$	$< 1.6 \times 10^{-13}$	$< 6.6 \times 10^{-19}$	$< 7.2 \times 10^{-13}$
$H_nC_pO_q$	$\sum$amu41,43,55,57 $< 1.2 \times 10^{-19}$	$< 2.2 \times 10^{-13}$	$\sum$amu41,43,55,57 $< 5.3 \times 10^{-19}$	$< 9.7 \times 10^{-13}$

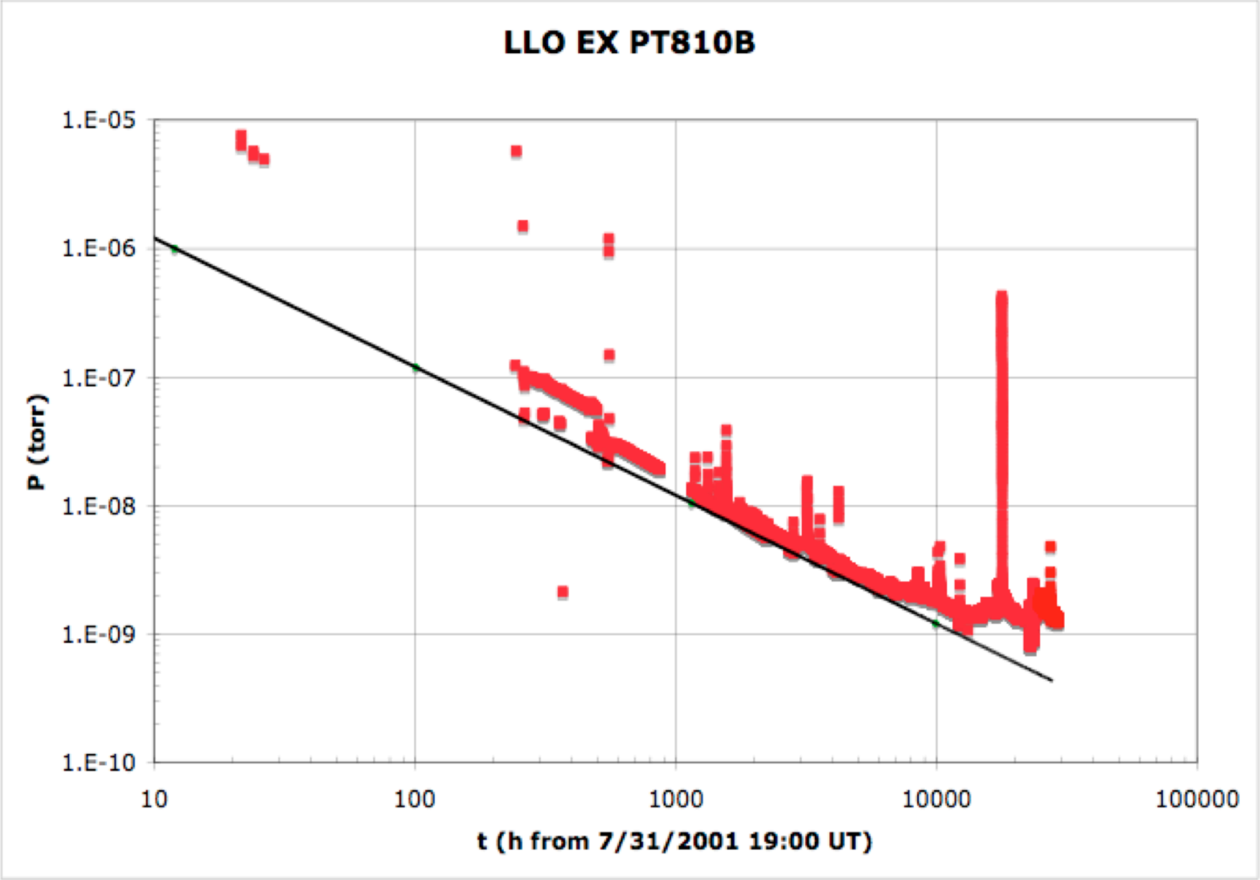
Volume = 2.4×10^6 liters and Area = 7.8×10^7 cm^2

** The equivalent air leak into the module Q < 3.5×10^{-11} torr liters/sec from amu 28.

Correction from 10C to 23C uses a binding temperature of 8000K for hydrogen and 10000K for all other molecules

The data shows the outgassing rates of the tube are acceptable. The higher temperature bake at 168C for a shorter time has accomplished a better result than the longer bakes at 150C.

End Station Pressure Evolution after Backfill



Effects of Pump Distribution on Required $J(H_2O)$

- Consider 4km aLIGO arm (1.2m ID) with 2 or 15 distributed pumps + cryotraps at ends

- Assign $S_h^{1/2}(H_20) < 0.1$ x min aL curve[1]

$$\rightarrow S_h^{1/2}(H_20) < 2.6 \times 10^{-25}\ \mathrm{Hz}^{-1/2}$$

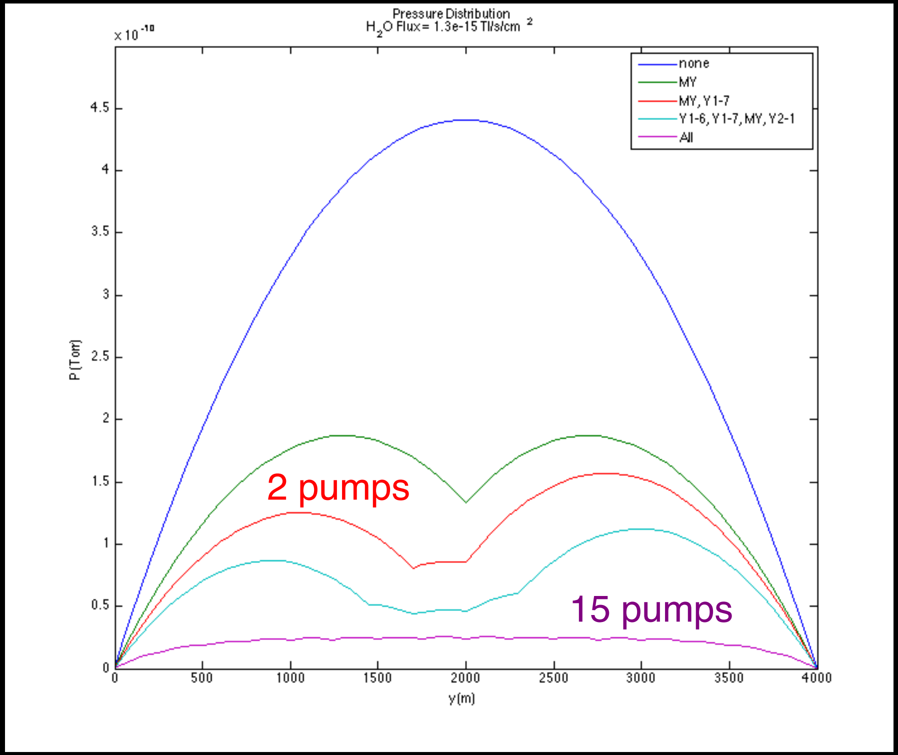
Then[2], for 2 pumps

$$J(H_2O)_{2p} < 2.0 \times 10^{-15}\ \mathrm{T\ l\ s^{-1}\ cm^{-2}}$$

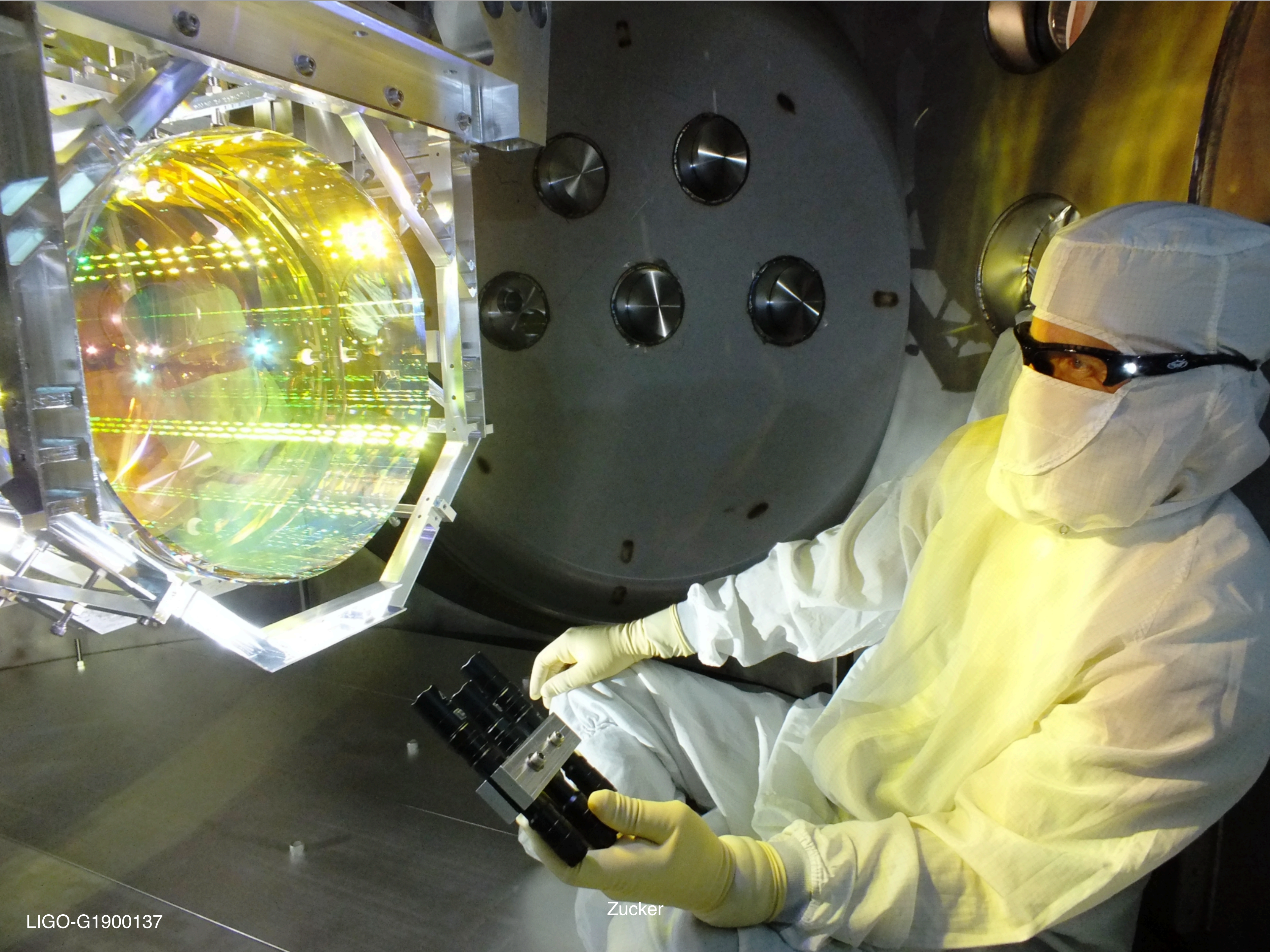
and for 15 pumps

$$J(H_2O)_{15p} < 4.3 \times 10^{-15}\ \mathrm{T\ l\ s^{-1}\ cm^{-2}}$$

(no leaks, just autogenous water; F_i = 534 l/s)



[1] T1400177, Fig. 3, "BNS Optimized 125W"
[2] T1500202



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LIGO-G1900137