Vacuum Problems

M. Zucker
LIGO-G1500936
LIGO Management Advance @ Caltech
7/22/2015

Outline

- LLO Y tube status
  - Tube weld repairs
  - LGV7 neutralization
  - Water assay
  - Status of mitigation & risk reduction
- LGV11
  - What's known
  - What's suspected
  - Impact on O1 (+)
  - Repair concepts
  - Repair recovery (bake) concepts
- Things we should be doing
  - Way too many


AMERICAN

LLO Y Beamtube Leaks Redux

- Excess air was discovered in the LLO Y arm early 2012
  - Likely onset reconstructs to 10/2008
    - No known coincident event
    - Undetected/ambiguous due to inadequate instrumentation (colocated with pumping)
  - Approximately constant air influx of 2.6×10^{-4} Tl/s since onset
- Combined leak hunt campaign:
  - Visual inspection (requiring complete insulation removal)
  - Pressure gradient reconstruction (T1200263)
    - Modulate valves at ends of tube to change pumping boundary conditions
    - Monitor pressure gradients, reconstruct source location given tube conductance
    - Typical test duration ~ 1 week (tube aperture blocked)
    - ~ 100m position resolution @ 10^{-5} Tl/s rate
  - Turbo-assisted He mass-spectrometer leak detection (T1200375)
    - Brute force; poly bag sections 1 to 18m long, fill bag with He, monitor tube interior for He
    - Subdivide & retest if zone tests positive (cleanup after a positive takes very long)
    - Most "signal" disappears down tube; mass spectrometer only sees small sample
    - Strong attenuation with distance (sampling ports @ 250m intervals; SNR loss ~ 5:1 at 250 m)
    - Time constants far from "normal" leak testing; instrument drift & backgrounds problematic
    - With time & care, ~ cm resolution @ sensitivity < 10^{-7} Tl/s achieved
- Pressure gradient implied location "near" tube center (Y ~ 2km)

LLO Y Beamtube Leaks (cont'd)

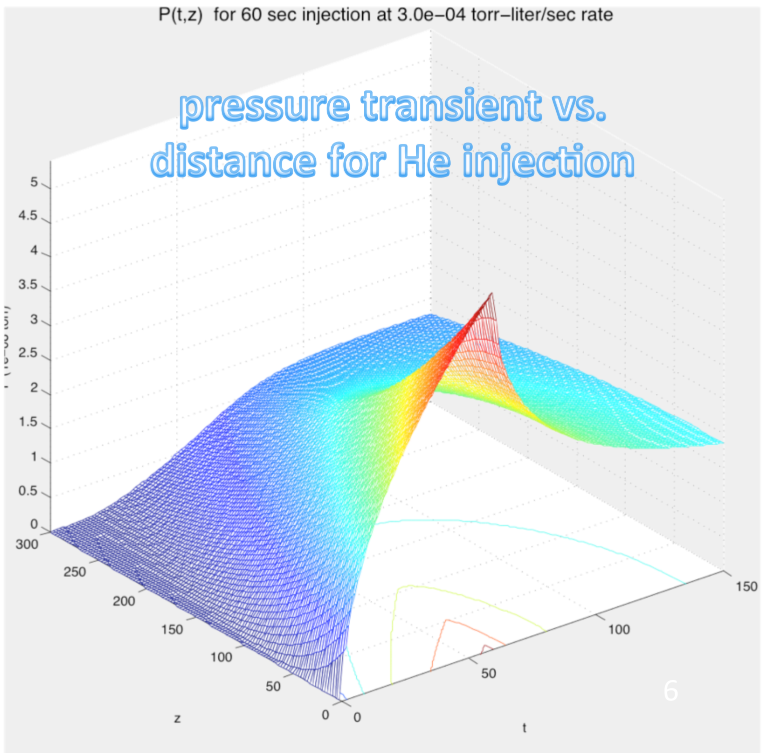
- Primary leak located by He MSLD and sealed* December 2012
  - Evidence of historical rodent nesting under insulation
  - Evidence of historical rain leakage from enclosure roof (also natural condensation)
  - Two smaller (< 10^{-5} Tl/s) leaks subsequently also located and sealed--
    - one nearby (presumably correlated)
    - another 300m away (presumed independent) under a mud dauber wasp nest
  - These leaks were all:
    - On *welds*
    - Associated with evidence of *moisture*
    - Located near *animal excretion residues* (i.e., chloride contamination)
- Outside corrosion & welding consultants brought in
  - Inconclusive wrt cause, but confirmed no structural risk to tube integrity
  - Corrosion strongly suggested, but not proven; *no direct visual or chemical evidence*
  - Stress (or stress-corrosion cracking) is *not* an apparent factor

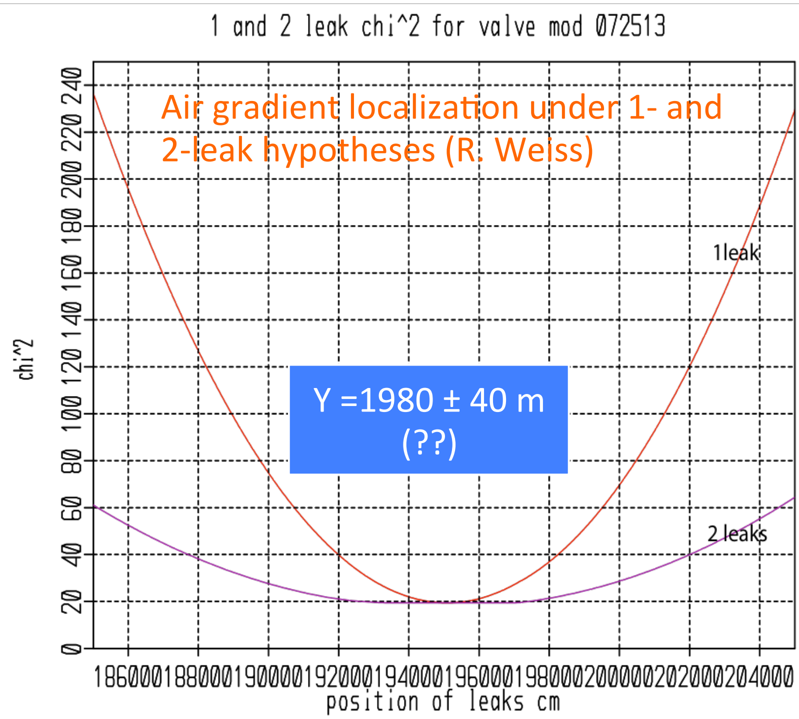
**with VacSeal silicone-based penetrant*


mouse latrine


evacuated "fothering" patch


mud dauber nest


P(t,z) for 60 sec injection at 3.0e−04 torr−liter/sec rate
pressure transient vs.
distance for He injection
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
300
250
200
150
100
50
0
z
0
50
100
150
t



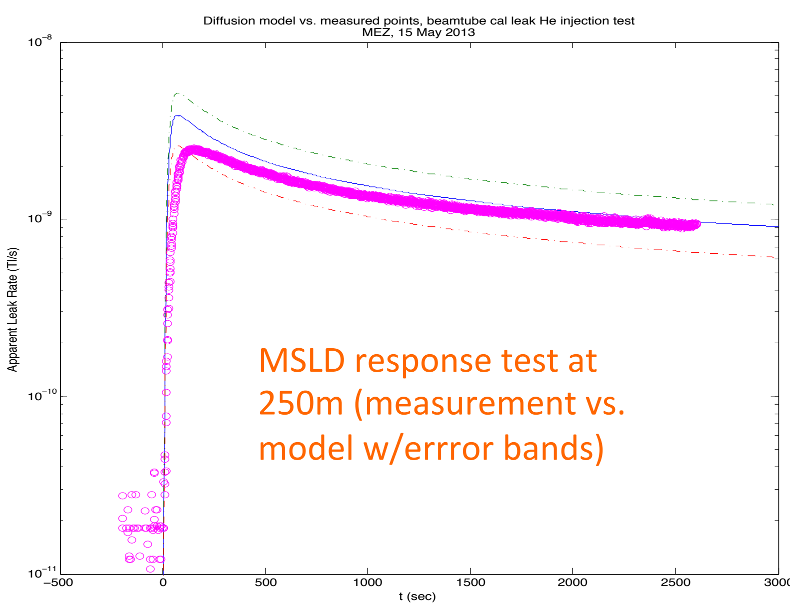


Figure 2: Leak detector response to 30 second calibrated injection of helium test gas at $z = 250$ meters (pink circles). Also plotted is predicted response from diffusion model (solid blue) and approximate standard error margins (dash-dot red and green).

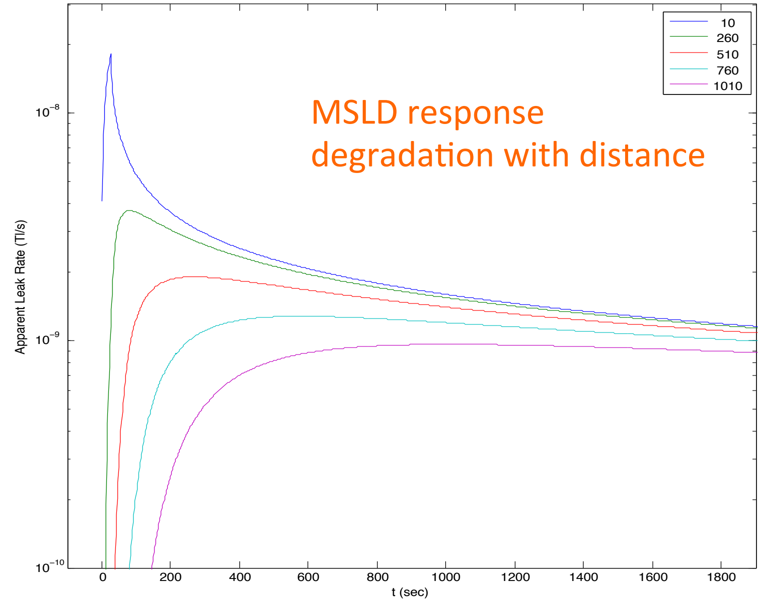


Figure 1: Model leak detector response for He test injections as described in text, assuming different injection positions z ranging from 10m (blue) to 1.01 km (purple). The actual test (Fig. 2) was performed at $z = 250$m (green).

LLO Y Beamtube Leak (Part II)

- Air still coming in
- 4e-5 Tl/s source remained "at large"
  - Gradient reconstruction repeatedly implicated tube midsection
  - Successive refinements to gradient method (R. Weiss, T1300702)
    - Included more sensors
    - Regressed effects of temperature, electrometer zero drift
    - Allowed multi-leak solutions
    - Used more robust statistical algorithm
  - Reduced position error to ±50m, *solutions always included midpoint*

  however...

  - ...exhaustive He MSLD bag tests on middle km (esp. GV7 gate valve) showed no leaks, with high measurement confidence (< 10^{-7} Tl/s)
- Started considering "strange" (delayed, virtual) mechanisms (?)
  - Long time constant (to evade MSLD) + known total rate → constrained solution
  - Seemed to require hidden storage volume or reservoir of permeable substance
  - Where could gas hide ? gate valve stem?
  - Crazy stuff, but *'once you have eliminated the impossible...'*

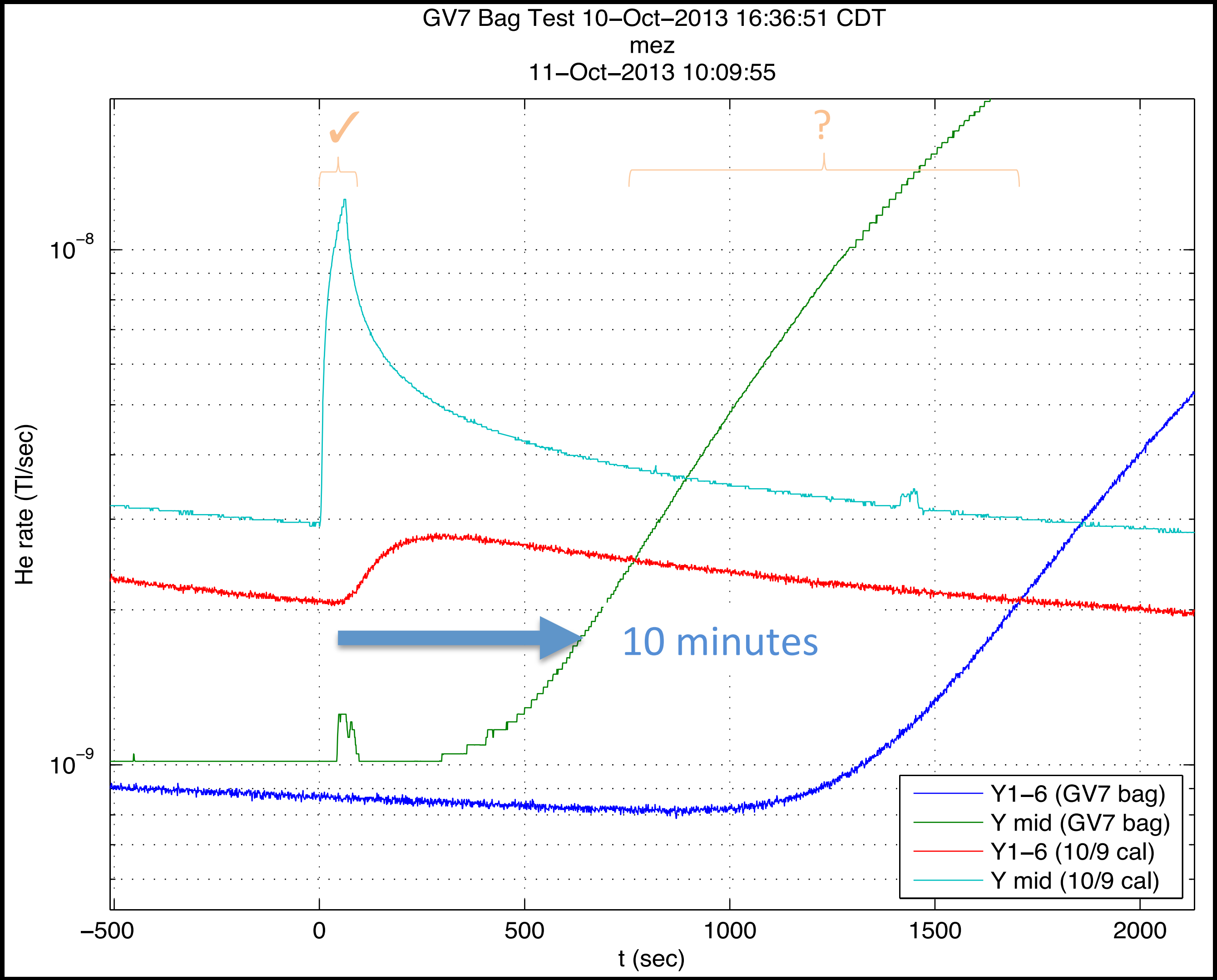
GV7 `Enhanced Interrogation’

- Resorted to aggressive tests on GV7
  - Test 1 (He): Out-wait the time constant(s)
    - Two MSLD sample points, one 550m away to rule out flanking/background sniff
  - Test 2 (Argon): Replace air around valve and watch internal composition change
    - Look for both presence of test gas *and* replacement/reduction of air inside tube
- Results both convincing and bizarre:
  - Gas outside the valve stem gets in
  - Composition inside mirrors outside

  but…
  - Very long delay for He to enter
  - Delay 10-100x longer still for Ar
- Weiss: **“The Leak from Hell”**

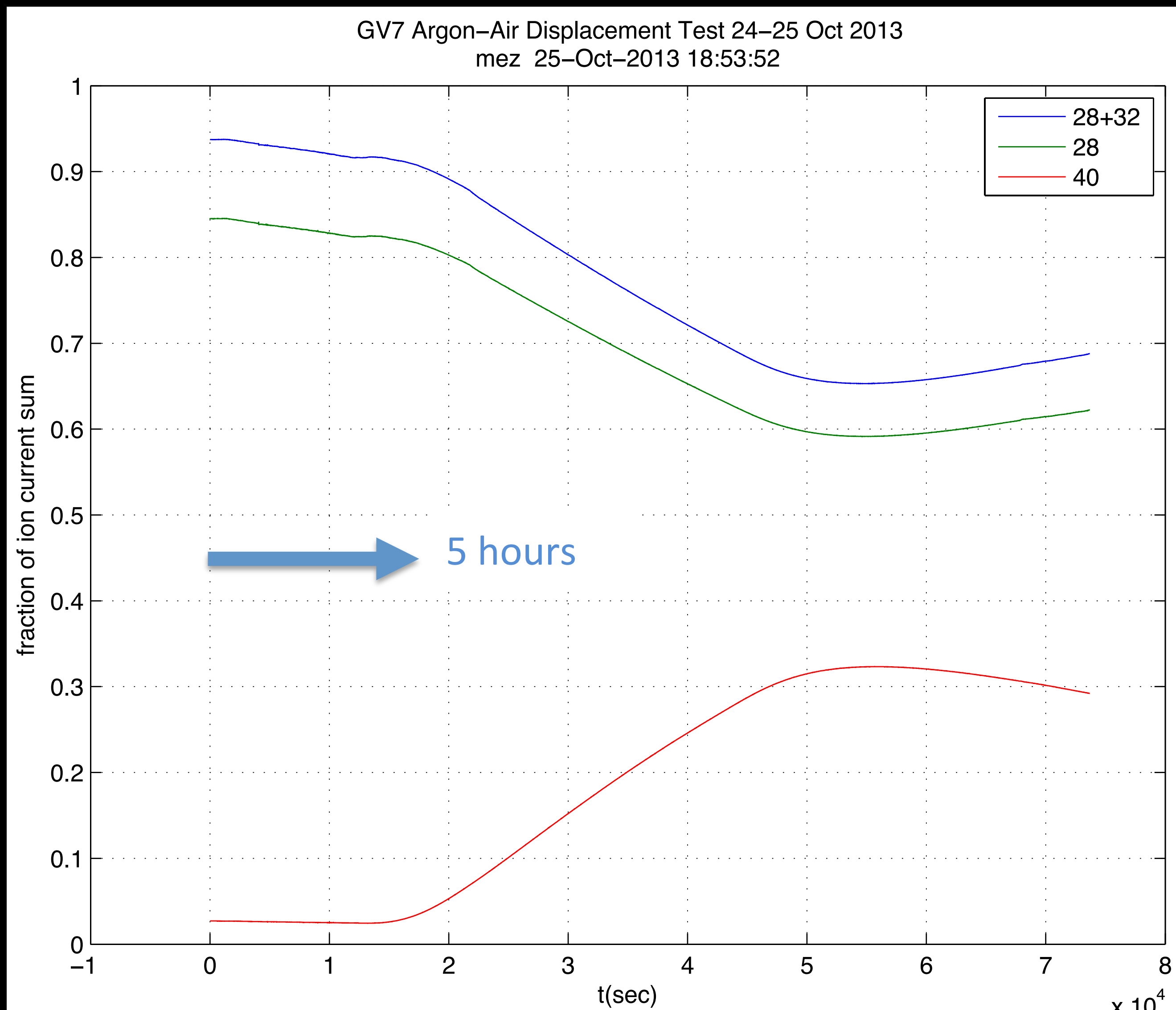
He Response: "Direct leak" vs. GV7

He MSLD responses measured adjacent to GV7 (green) and 550m north (blue). For comparison, corresponding responses are also plotted (cyan and red, respectively) for a direct 60-second timed He injection of 1.8e-7 Tl/s near the valve location. In all cases t=0 corresponds to the start of He flow. The delayed GV7 response is unequivocal, but also inconsistent with a simple leak.



Air displacement over GV7 stem

RGA ion currents for argon and components of air are plotted vs. time as a fraction of the total ion current, which summed contributions from N_2 (28), O_2 (32), H_2O(18), and Ar(40) (but did not include H_2 or other species).



"Delayed Leak" Models

- Long thin channel ?
  - $\tau \sim L^2/Dv$ *and* $F \sim vD^3/L$
  - → $D \sim 0.3$ mm for $L \sim 1$m (maybe plausible), ***but…***
  - gas diffusion → $\tau \sim m^{1/2}$ (only 3:1 between Ar and He)
- Discrete series leaks w/ dead volume(s) between?
  - e.g., $V \sim 5$ l and $\tau \sim 1{,}000$ s → $F_1 \sim F_2 \sim$ 5e-3 l/s , $P_{mid} \sim .01$ Torr
  - If limit is viscous (choked flow), rate ~ *P*, ***but…***
  - molecular mass dependence of τ is *even weaker*
- Permeation/percolation?
  - Weld or gasket *fissure* which is *plugged* with liquid, e.g., condensate or *lubricating grease?*
  - →Expect bulk diffusion $\tau \sim a^2 m^{1/2}$ (Ar : He ~ 20:1)
- Is it important? Maybe…
  - Risk of future "evolution"
  - Potential failure mode for *other valves***

*** wait for it..*

Test of Ar diffusion through a sample of valve mechanism lubricant

From R. Weiss, LIGO-**T1400183**

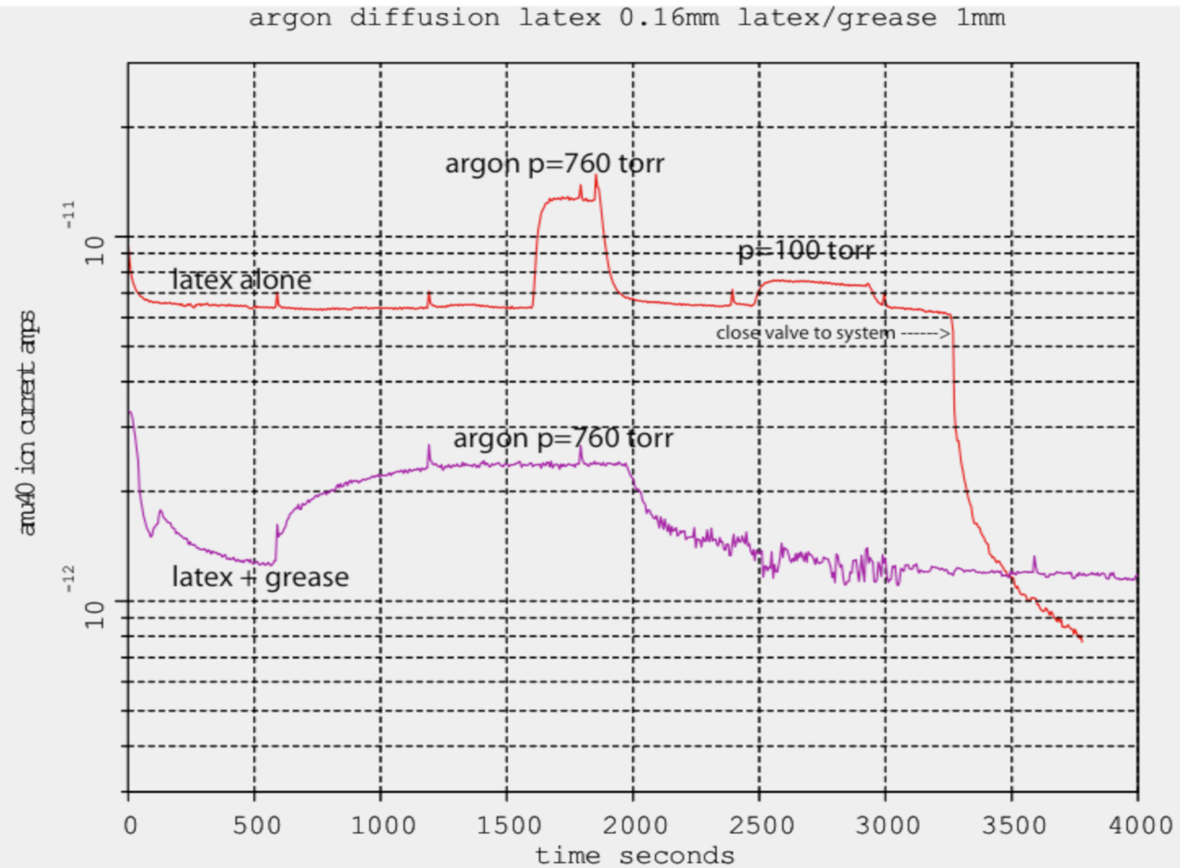


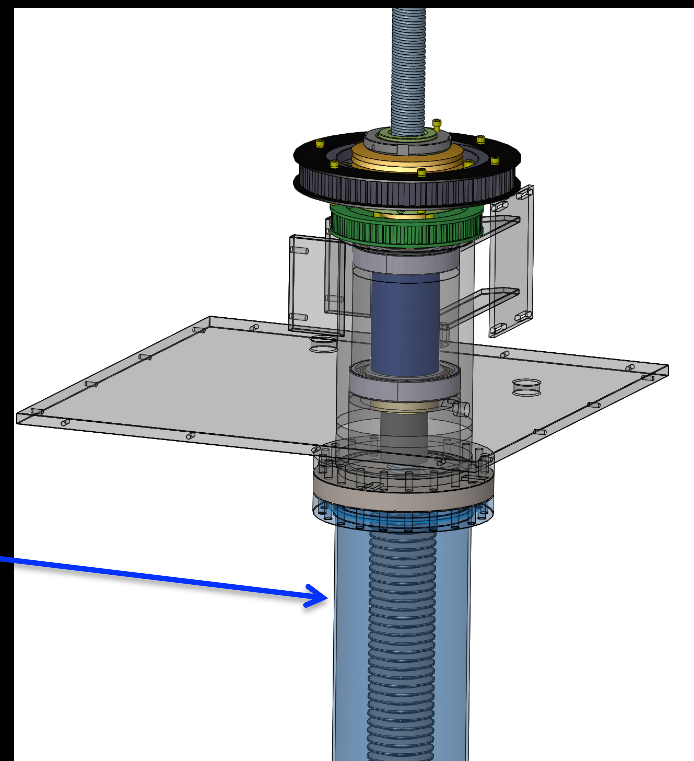
Figure 3 The permeation by Argon through the 0.16mm latex at pressures of 760 and 100 torr in red and the permeation of Argon with an additional 1mm layer of grease in violet. The curve for the latex alone has an argon background due to the chamber V2 which is removed by closing the valve between V1 and V2 at 3200 seconds. The combined latex and grease has a flow of 1.4 x 10^{-5} torr liters/sec with 760 torr of Argon on the grease. Again, using a surface area of 5 $cm^{2,}$ the permeation constant is 5.3 x 10^{-10} cc@stp/sec cm torr. The diffusion time constant for argon in the grease is 600 seconds leading to a diffusion constant for Argon of 8.3 x 10^{-6} cm^2/sec.

Valve Repair Options

- Out-pump it ? ✖
  - Conductance limited; only two 10” ports available nearby
  - IFO is most sensitive near this location (laser beam waist)
  - “Grease theory” → *leak rate could spontaneously change!*
- Vent and fix it ? ✖
  - Requires re-bakeout of entire tube
  - Very costly (large % of LIGO annual budget)
  - Too time consuming (~ year(s) ?)
- Pull an external vacuum? ✔ …but…
  - No cutting, welding or disassembly allowed
  - “Captured” seals, “as-built” (rough) sealing surfaces
  - Weight constraints
  - Trapped grease, plastics

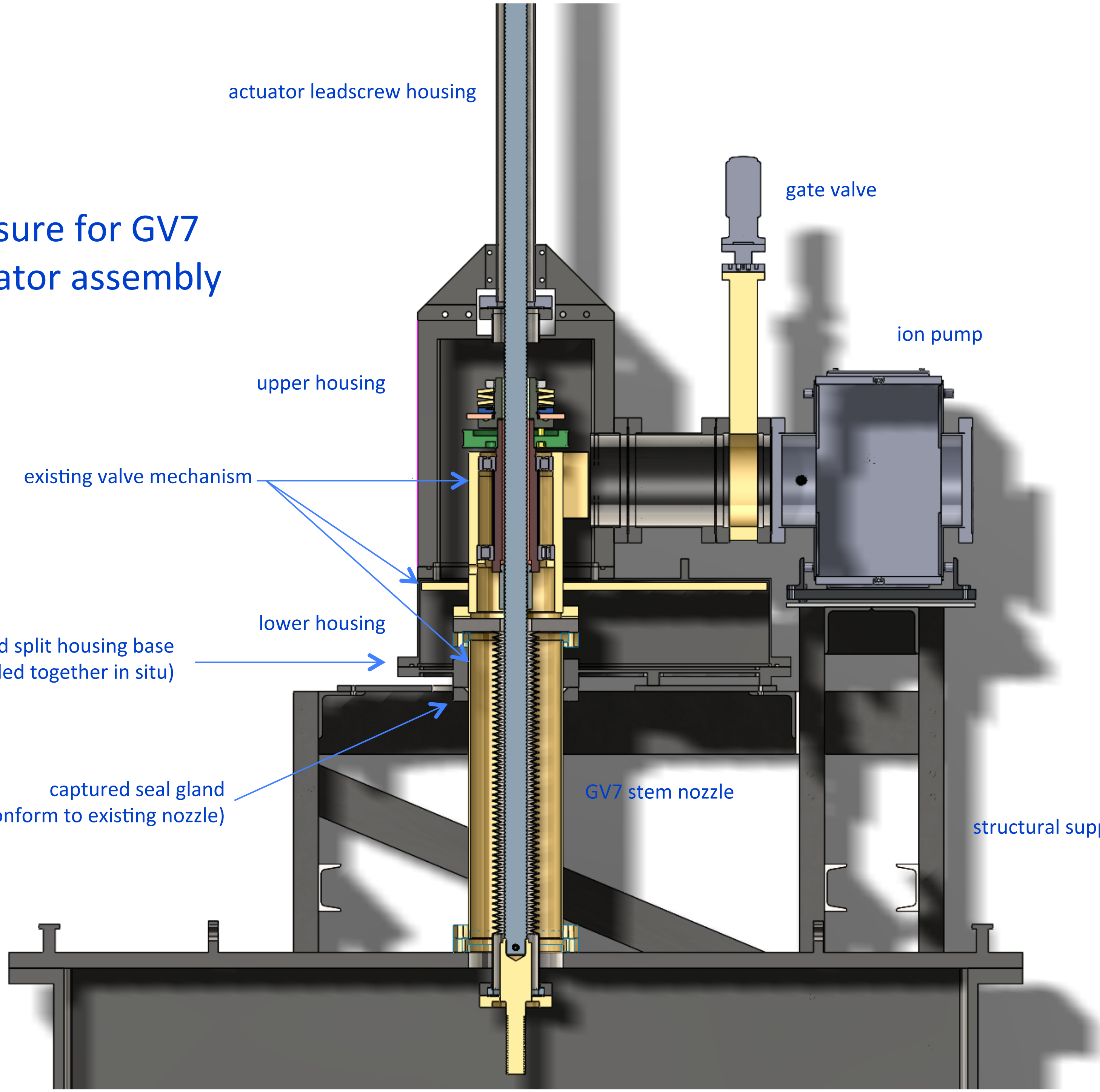
→ Unique engineering challenge

GV7 sarcophagus concept



Vacuum enclosure for GV7 stem/actuator assembly

K. Mason 5/1/2014



Split plate & captured seal engineering

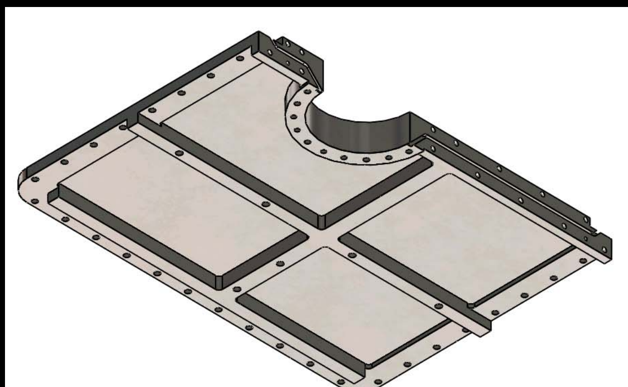
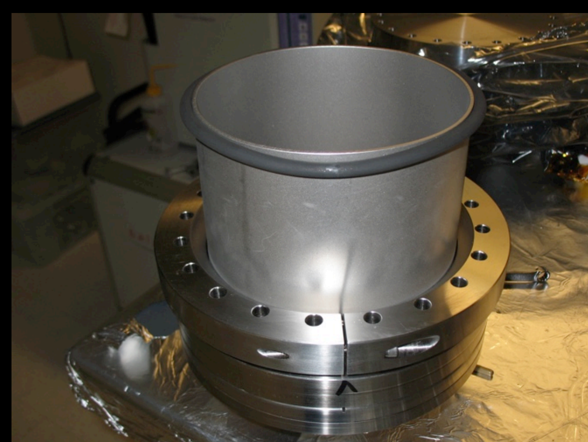
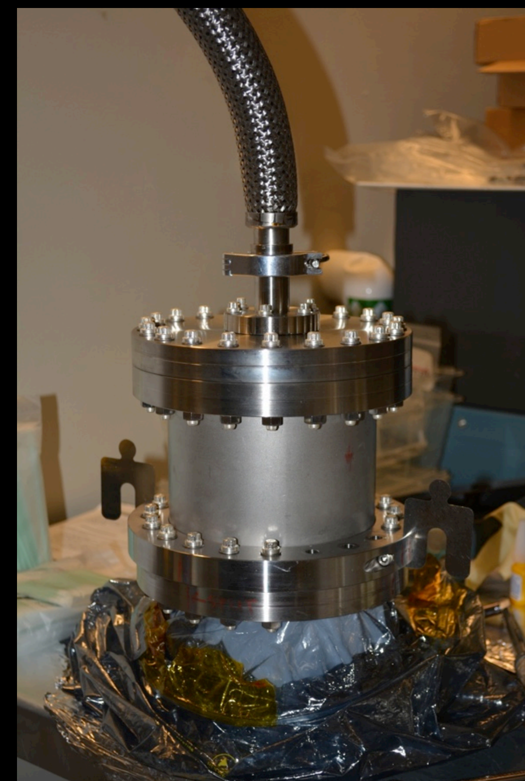
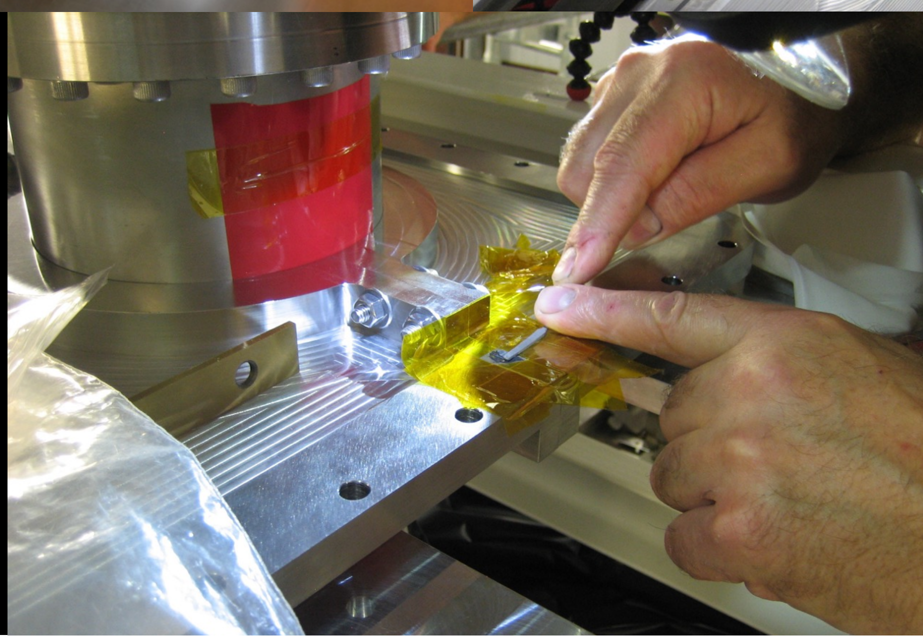


Plate joint/crossed seal test

O-ring field weld & seal gland leak test



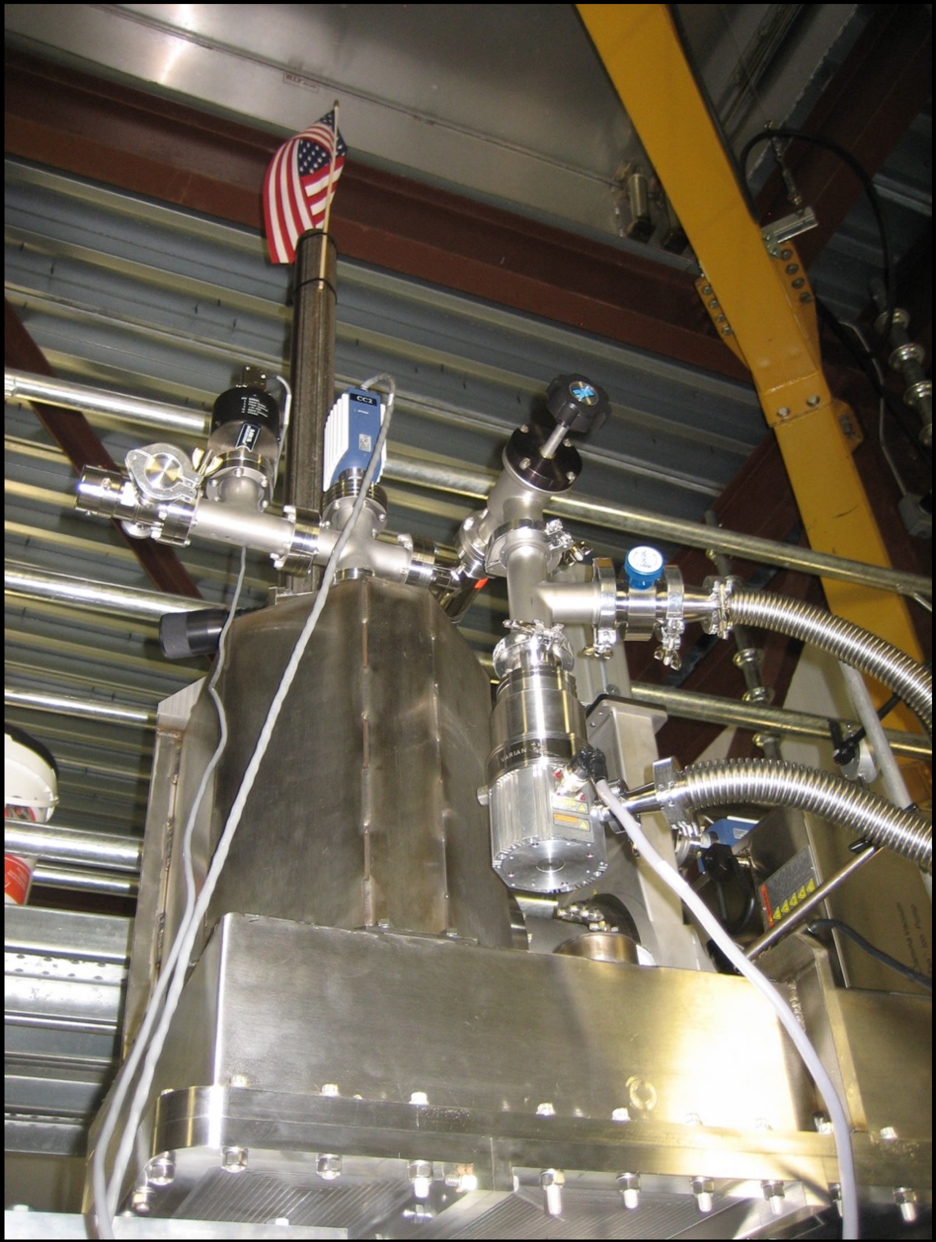




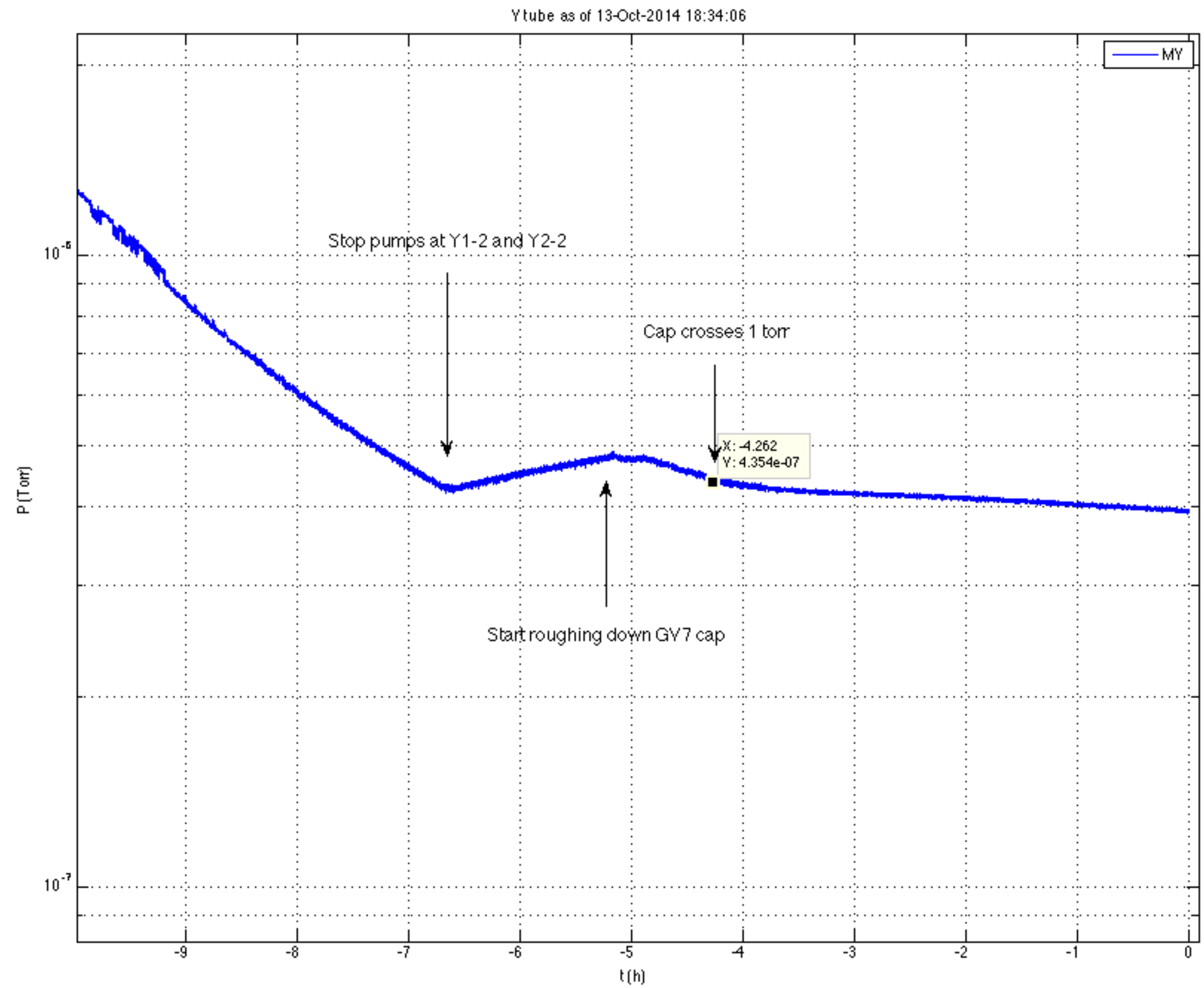
GV7 sarcophagus installation

GV7 sarcophagus installation

GV7 sarcophagus installation

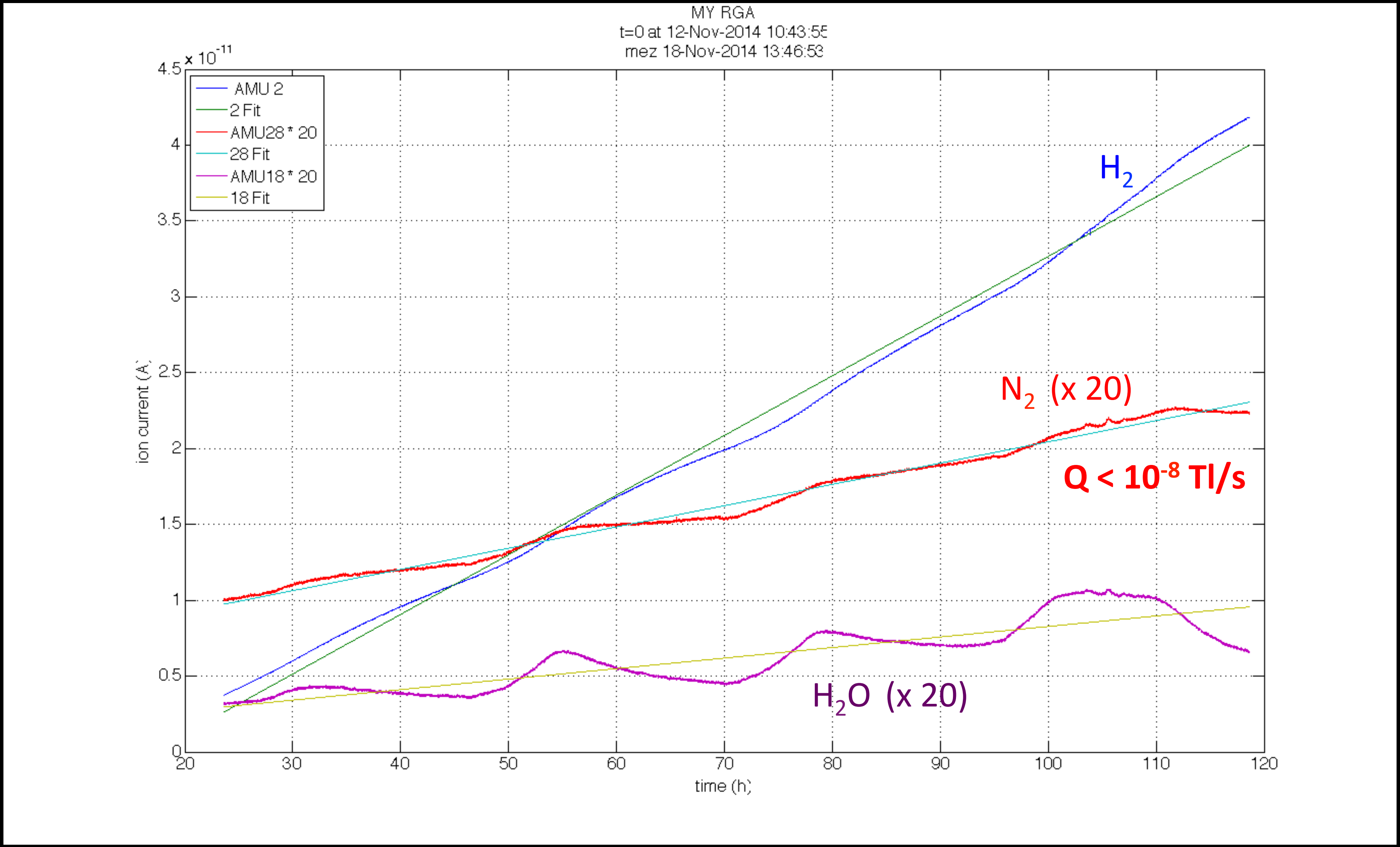


IT WORKED…



Ytube as of 13-Oct-2014 18:34:06
MY
Stop pumps at Y1-2 and Y2-2
Cap crosses 1 torr
X: -4.262
Y: 4.354e-07
Start roughing down GV7 cap
P (Torr)
t (h)

LLO Y ARM ACCUMULATION (AFTER GV7 CONTAINMENT)

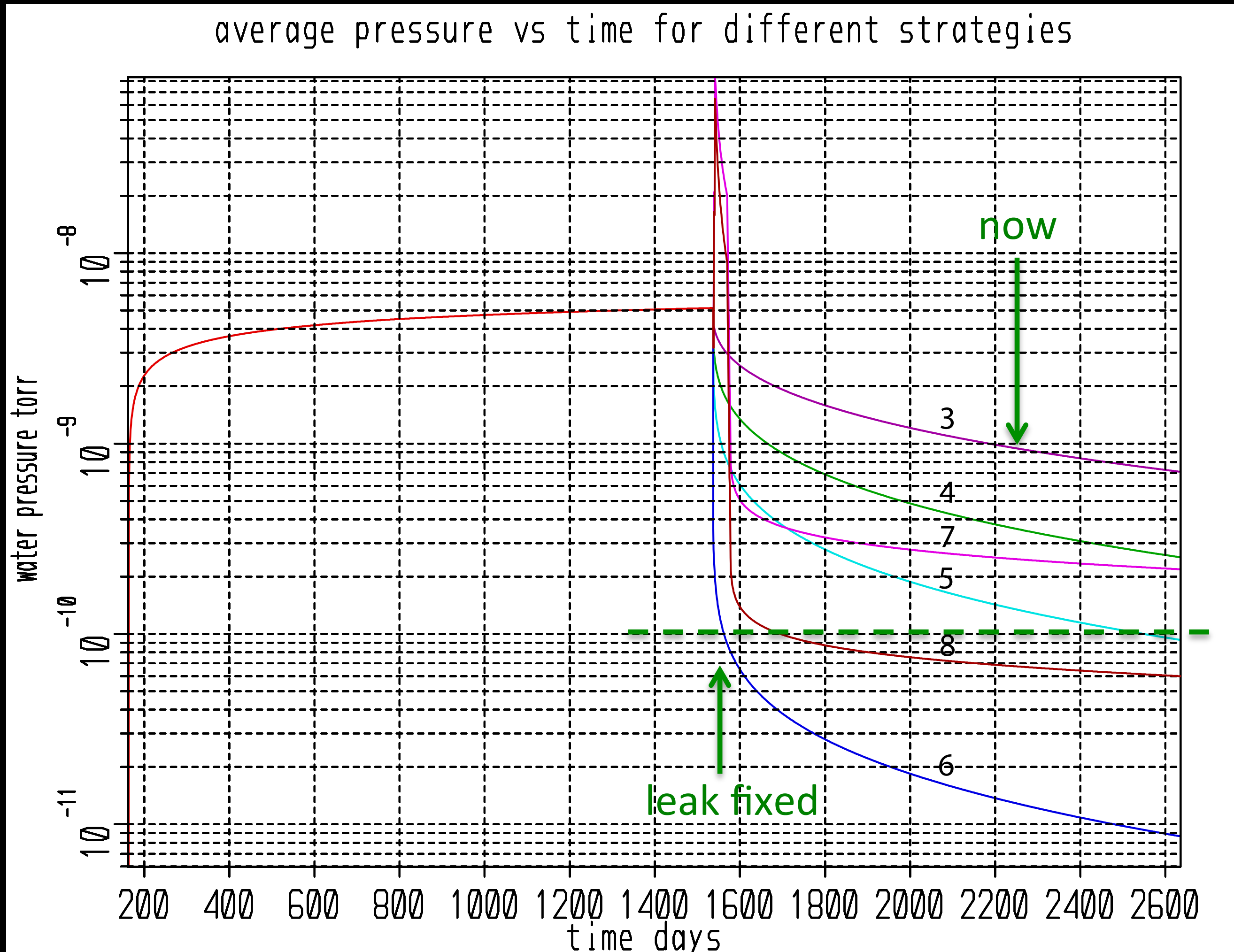


(LIGO-T1400723)

Some Good Breaks…

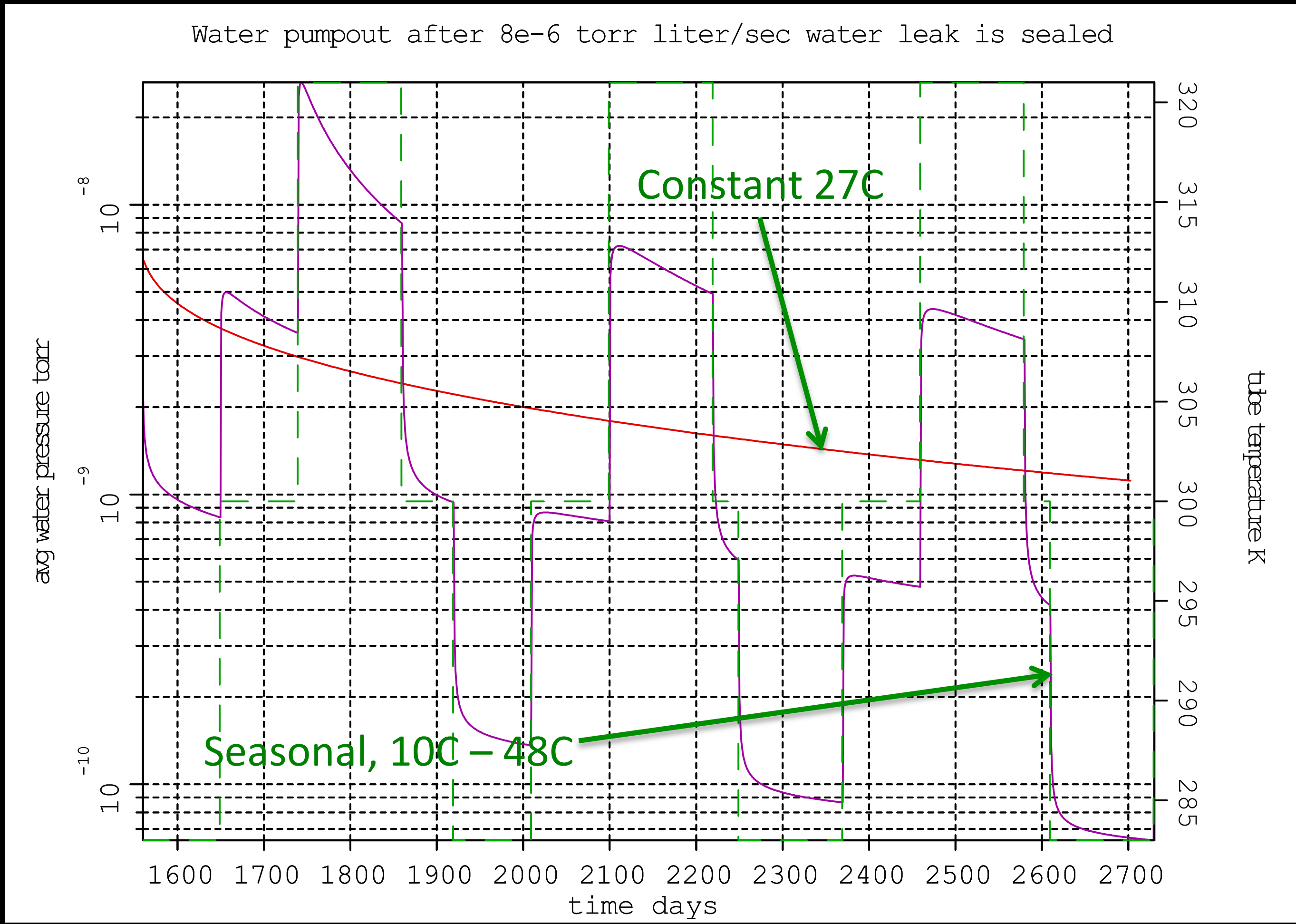
- Sarcophagus pumpdown was quick
  - Maintained solely on ion pump within 2 days
  - Steady-state stem P < 10^{-7} Torr, despite contamination
- *LOWER residual water vapor desorption* than calculated based on leak exposure
  - We expected $x10^3$ increase in water desorption due to 4 years of air leakage
  - In reality only x100; *not a threat to aLIGO sensitivity (with added pumps)*
  - Part of the answer: we underestimated the 48C "mini-bake" occurring naturally each summer– *potentially critical for future repair scenarios*

Modeled desorption of water adsorbed from atmospheric leakage (assuming constant T)



R. Weiss, T1200399

Modeled desorption with step-approximated seasonal temperature profile included (preliminary)



R. Weiss, 6/9/2015

Big Picture: Recovery Program So Far

- Removed old beamtube bakeout insulation (both sites) ✓
- Install temp, RH, pressure sensors & network (LLO) ✓
- Install AC power along both LLO arms ✓
- He MSLD test ~~LLO Y tube~~ *stopped after 3200 m (leak free)* ✓
- Develop & install BTE Dehumidification plant (LLO) ✓
- Upgrade BTE joint caulking (LLO done ✓, LHO pending)
- Install ion pumps to mitigate sorbed gas at LLO *(in progress)*
- Inspect and clean steel of chlorides *(in progress,~ 75% both sites)*
- ~~Install new insulation (both sites)~~ *deferred, not req'd. (next slide)*
- ~~Cap & neutralize GV7~~ ✓

Σ (EAC) ~ $M2.8 (vs. $M3.8 budgeted)

To Insulate, or Not To Insulate?

- Original bake insulation t= 150 mm, R = 4.3 m^2 K/W, τ_{therm} = 15 h
  - When new, *diurnal* ΔT of tube wall attenuated by ~ ¼ (*seasonal* ΔT unaffected)
  - Fiberglass, foil & paper; destroyed at both sites by insects, rodents & rain leaks
  - Removed & discarded to allow cleaning and inspection
  - Intent (until recently) was to replace with something 'similar,' but vermin-proof
  - Sought to specify its functional requirements…
- Study undertaken of direct and secondary effects
  - Metal fatigue: No insulation needed
    - > 300 years fatigue life at 80C p-p daily (4x actual)
  - Vacuum: Insulation doesn't help (much)
    - Seasonal cycle (28C p-p) dominates gas evolution
    - Summer PM H_2 peak slightly affected; but insulation *not* a cost-effective mitigation
- Most important effect studied: optical scattering
  - Old insulation had side effect of damping some tube wall modes
  - Coating defect on early ETM's enhanced scattering

    NEW ETM'S FREE OF THIS DEFECT-

    REPLACEMENT CONSIDERED AFTER O1
  - Again, insulation would be a weak countermeasure (at best)
    - Dominant 14 Hz bulk mode is unaffected (need another approach if it's an issue)
    - 30-50 Hz modes have safety margin, particularly if/when improved ETM's are installed
    - Local damping at optical interaction zone(s) more effective, if needed

- Replacing *original* insulation (were it deemed appropriate) potentially very costly
  - >$1M per site (est.)
  - Sites out of action >4 months
  - Interference with future tube diagnostics/leak testing/repairs
- LIGO TRB convened in May 2015 to weigh risks & benefits
  - Decided to defer action, keep tubes bare after cleaning is completed
  - Directed to consider alternatives in light of actual performance issues, if any

About $800k budgeted for insulation now redirected to Lab staffing and other shortfalls

WARNING

Material beyond this point may not be suitable for sensitive viewers.

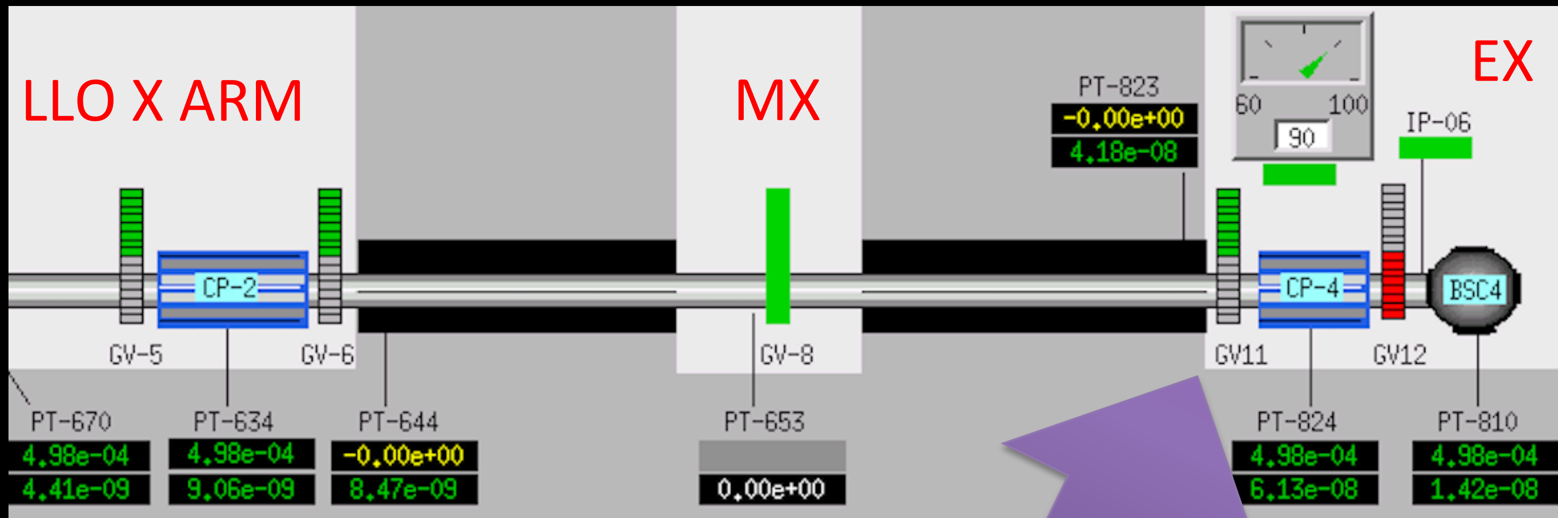
Some Breaks, Not So Good…

(Just when you think it's safe…)

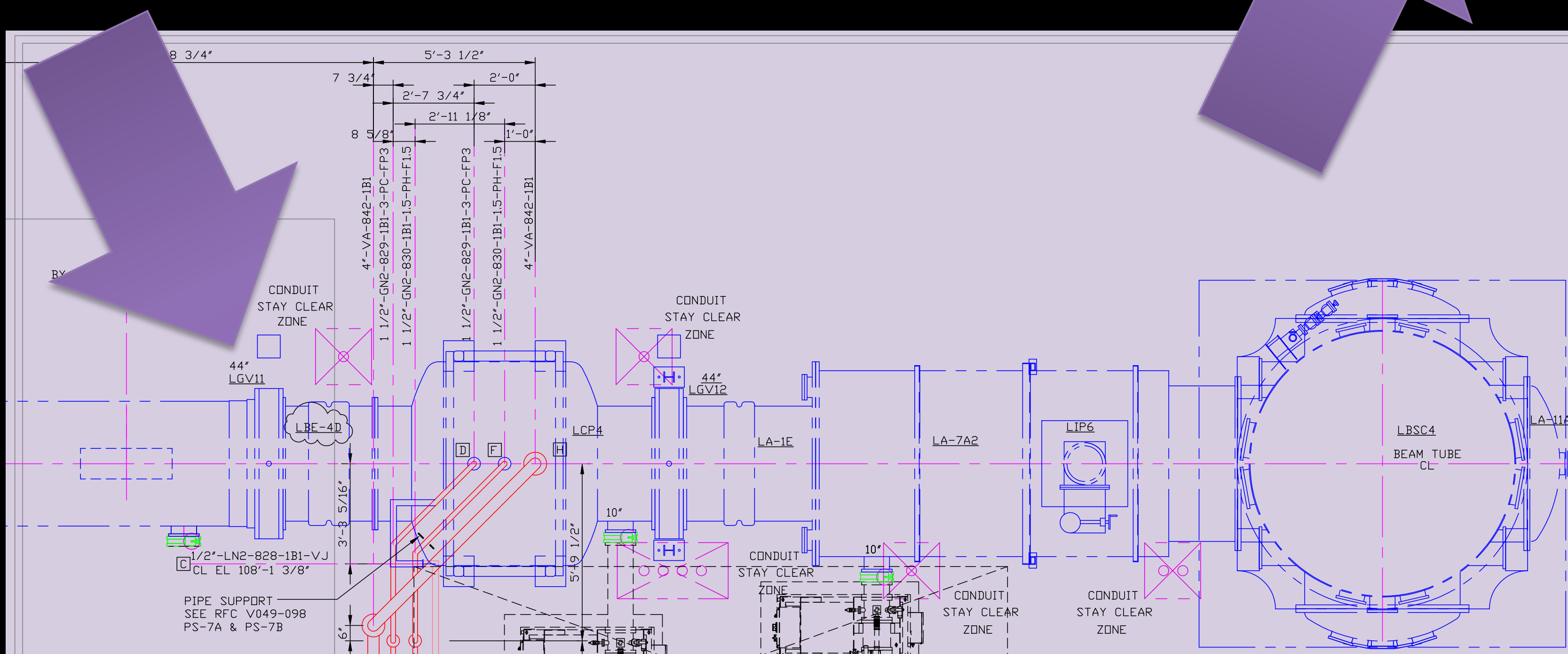
- Another valve found leaking (LGV11)
- Retarded He response, i.e., another "diffusion-moderated" stem leak; see G1500110
- Slower leak than LGV7, but *not stable:*
- Grew x3 in 1.5 years
- Interval included 8 strokes; unclear if correlated, but suspicious
- Now Q_{air} ~ 4 x 10^{-6} Tl/s
- LGV11 bounds a cryo trap–

  cannot be abandoned (unlike GV7)

Where it is

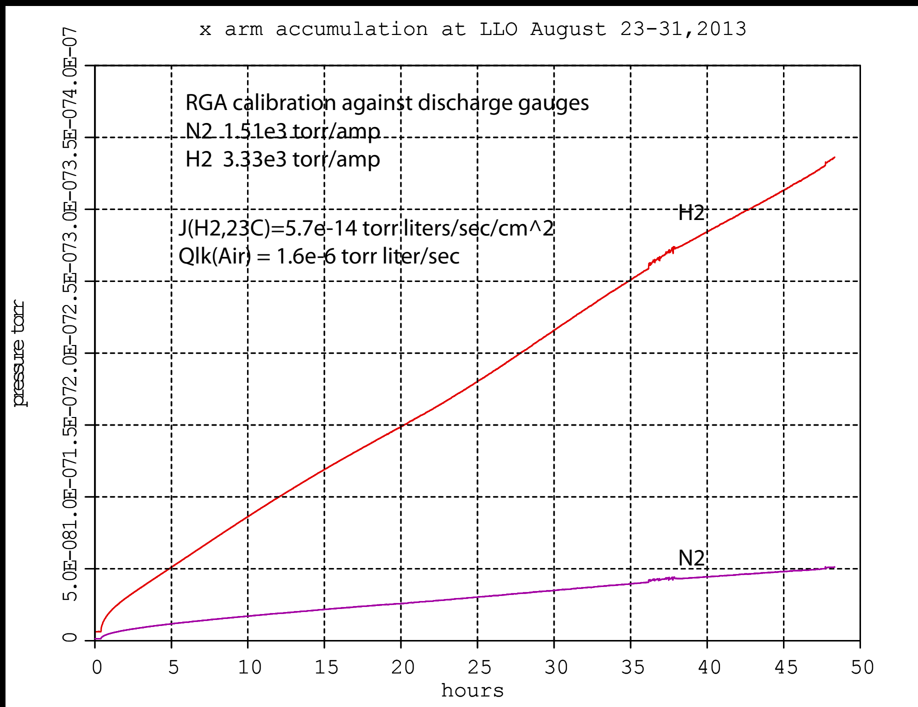


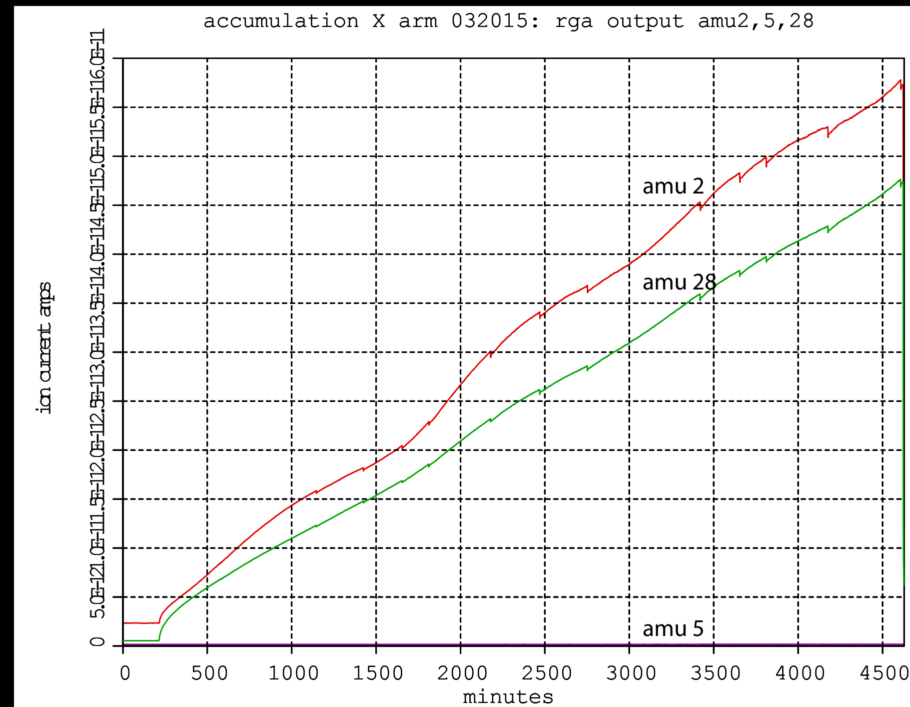
LLO X ARM
MX
EX
PT-823
-0.00e+00
4.18e-08
60
100
90
IP-06
CP-2
CP-4
BSC4
GV-5
GV-6
GV-8
GV11
GV12
PT-670
4.98e-04
4.41e-09
PT-634
4.98e-04
9.06e-09
PT-644
-0.00e+00
8.47e-09
PT-653
0.00e+00
PT-824
4.98e-04
6.13e-08
PT-810
4.98e-04
1.42e-08



5'-3 1/2"
7 3/4"
2'-0"
2'-7 3/4"
2'-11 1/8"
8 5/8"
1'-0"
4"-VA-842-1B1
1 1/2"-GN2-829-1B1-3-PC-FP3
1 1/2"-GN2-830-1B1-1.5-PH-F1.5
CONDUIT
STAY CLEAR
ZONE
44"
LGV11
LBE-4D
LCP4
44"
LGV12
LA-1E
LA-7A2
LIP6
LBSC4
BEAM TUBE
CL
LA-11A
1/2"-LN2-828-1B1-VJ
CL EL 108'-1 3/8"
PIPE SUPPORT
SEE RFC V049-098
PS-7A & PS-7B

Apparent change in rate between 8/2013 and 3/2015





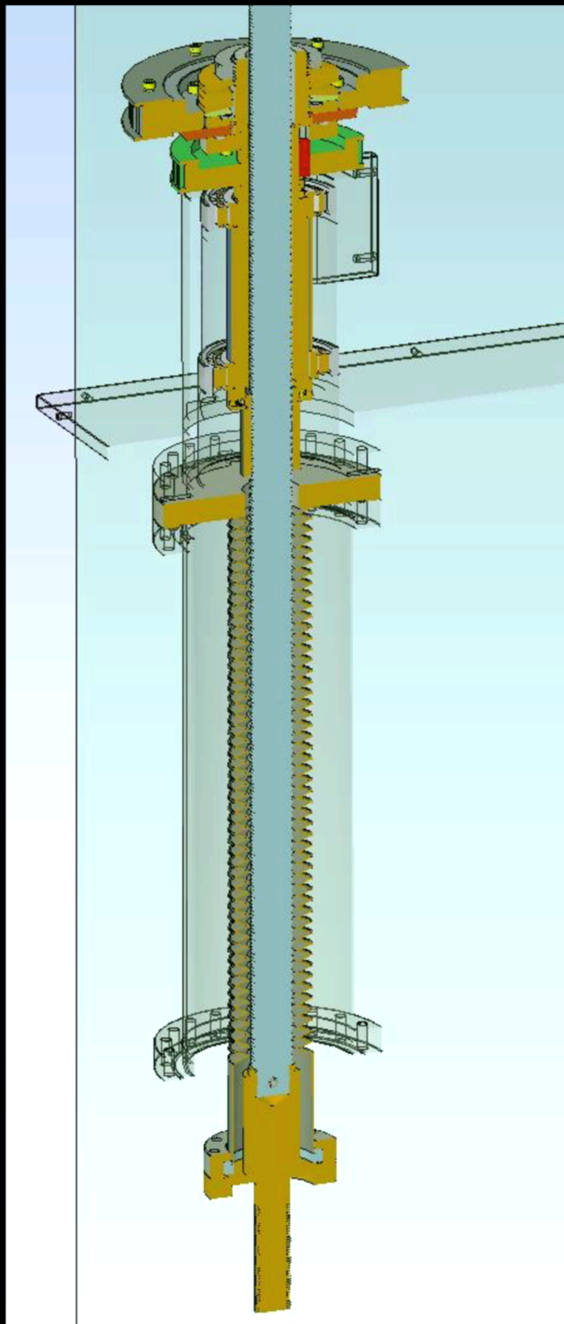
T1300757 (8/29/13)
Included BSC4 (EX) , CP3, CP4
5 GV's open (GV2 closed)
Q(air) ~ 1.5e-6 Tl/s

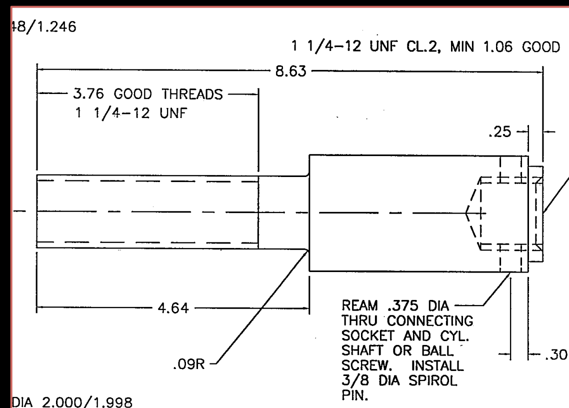
GV-11 STROKES 2013-present:
09-19-13 closed
01-13-14 open
02-28-14 closed
03-01-14 open
04-23-14 closed
04-25-15 open
08-02-14 closed
09-02-14 open
➔ 4 CYCLES BETWEEN MEASUREMENTS
(63 total cycles since installation)

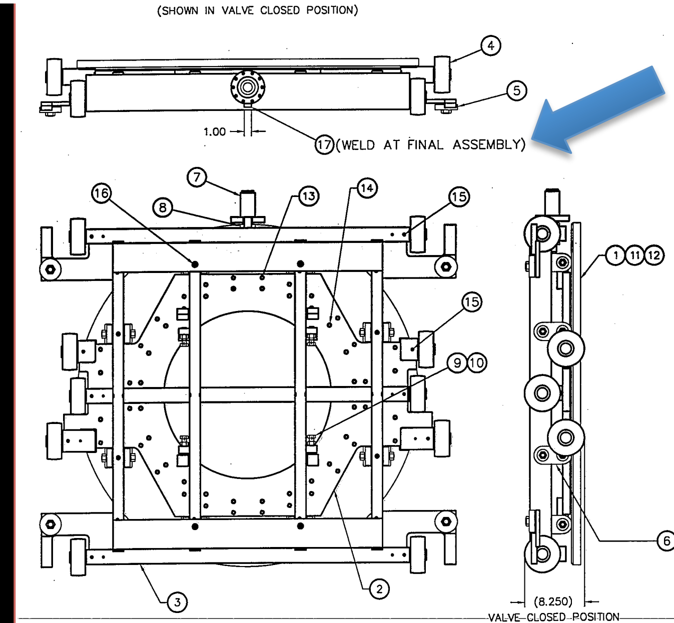
T1500126 (3/16/2015)
Included CP3, CP4
3 GV's open (GV5 & GV12 closed)
Q(air) ~ 4e-6 Tl/s

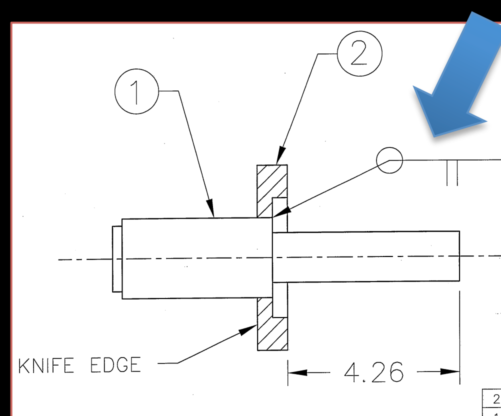
GNB Valve Anatomy

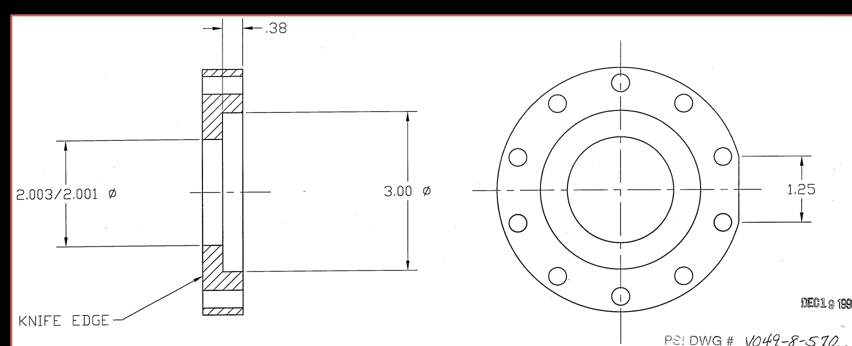
Valve Construction: Weak Link?

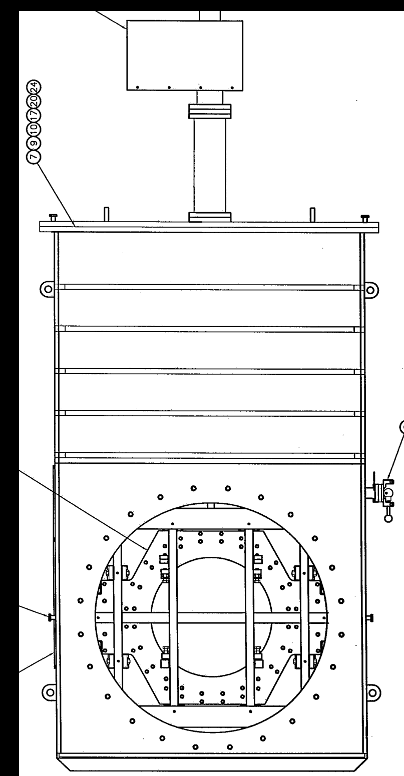












Near term impact of GV11 leak

- O1-3 noise impact (next page)
- Operations risk
  - CP4 cannot be isolated w/out closing GV11
  - Until now, this was required in a hurricane emergency (i.e., possible extended loss of power & site access; about 1 per 3 years, historically)
    - Trap "passive" hold time ~ days
    - LN_2 storage can extend to ~ month w/ manual filling
    - Uncontrolled trap warmup, gate open, would saturate tube with decades of integrated water and hydrocarbons (probable disaster)
  - For now, we have "adjusted" the risk threshold for CP4
    - If we do close it, not sure how risky to reopen, or how to minimize that risk…
- "New reality"
  - Revised "Bayesian prior"
    - 2 of 24 valves are leaking!
  - Probability/rate appears to increase with age and with each stroke
  - We have started to defer or curtail useful and important work that might require cycling a large valve (including valve diagnostics!)

THIS IS UNACCEPTABLE FOR THE LONG TERM

Leak impact in 3 pumping scenarios

(IP's at ends disabled due to charging; Y arm slightly wet)

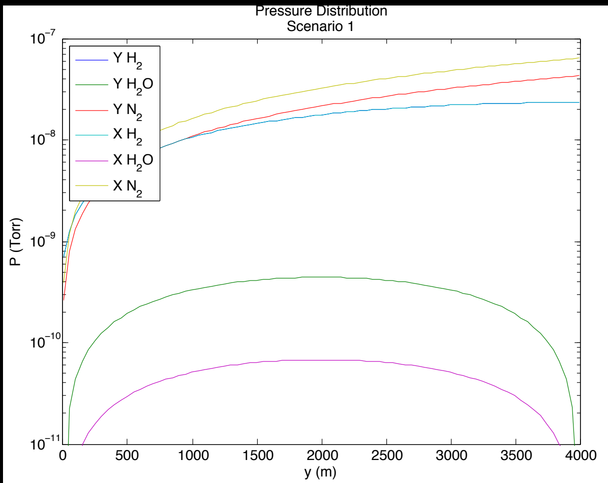


Figure 2: Pressure distribution, no added pumps.

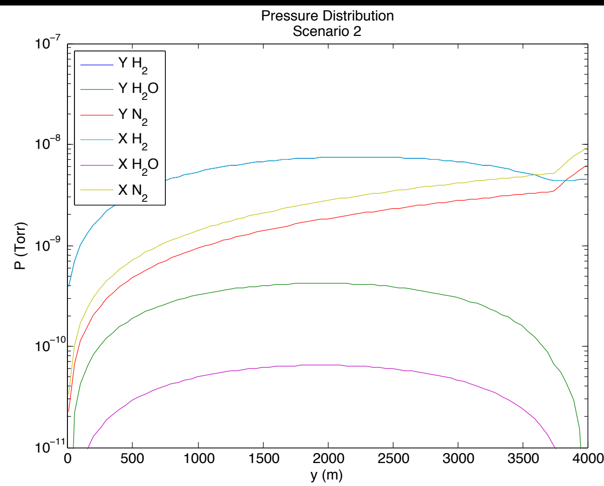


Figure 3: Pressure distribution, ion pumps at 3.75km.

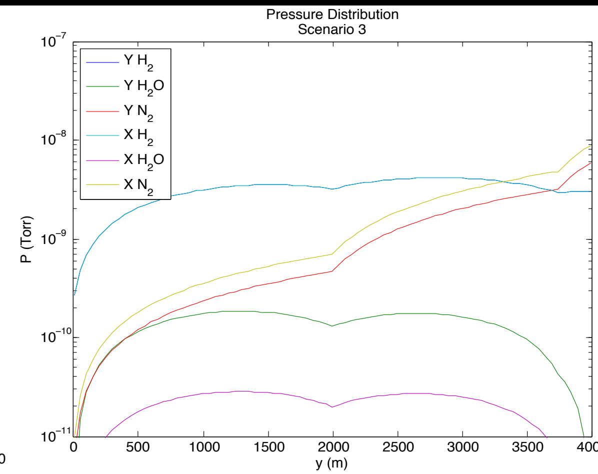


Figure 4: Pressure distribution, ion pumps at 2km and 3.75km

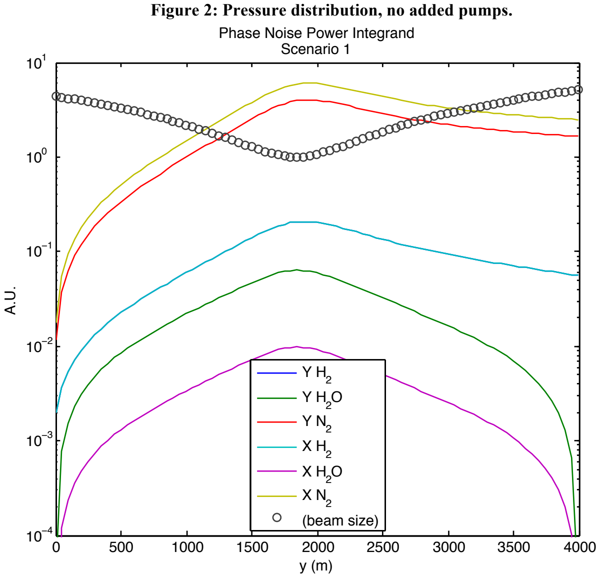


Figure 5: Phase noise integrand, no added pumps.

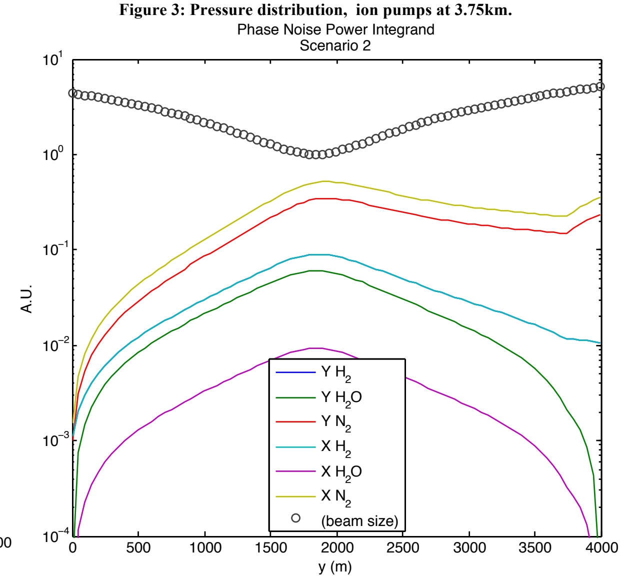


Figure 6: Phase noise integrand, pumps at 3.75km.

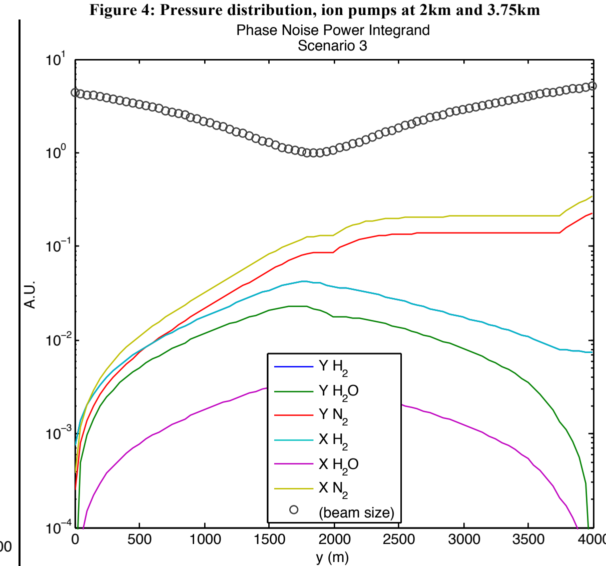


Figure 7: Phase noise integrand, pumps at 2km and 3.75km.

From LIGO-T1500210-v1

Index noise by arm & gas species with LGV11 leak

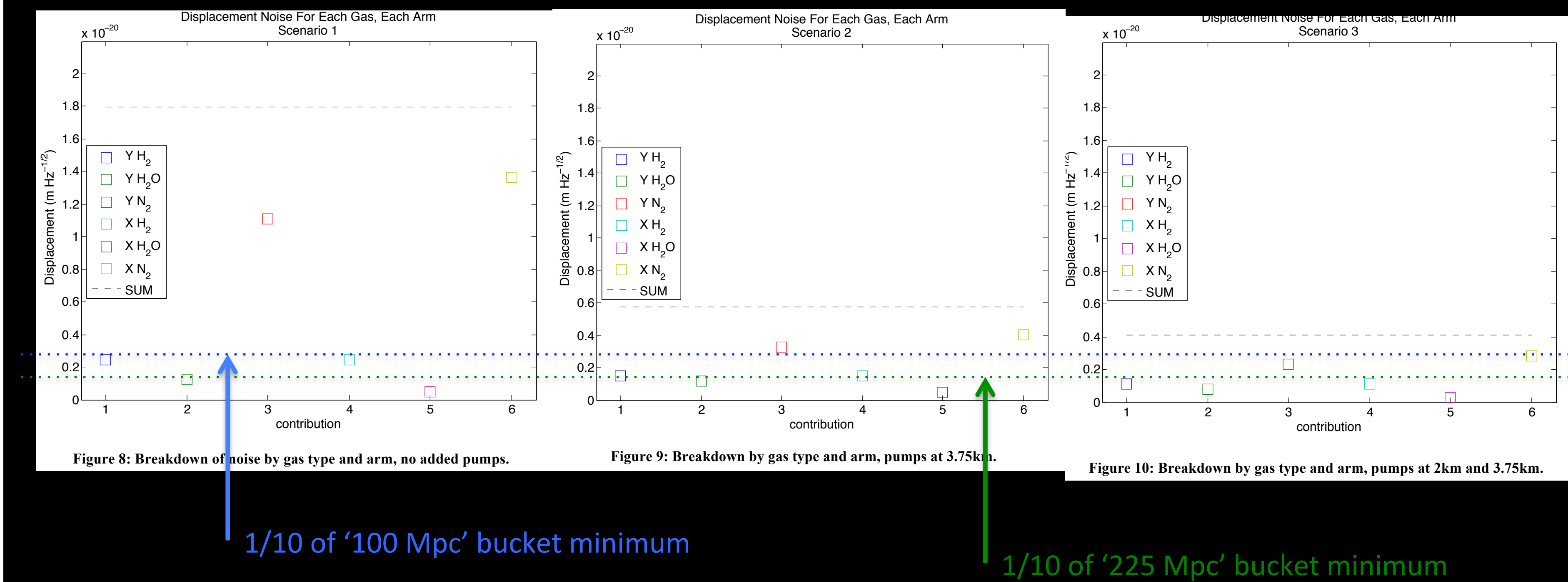


Figure 8: Breakdown of noise by gas type and arm, no added pumps.

Figure 9: Breakdown by gas type and arm, pumps at 3.75km.

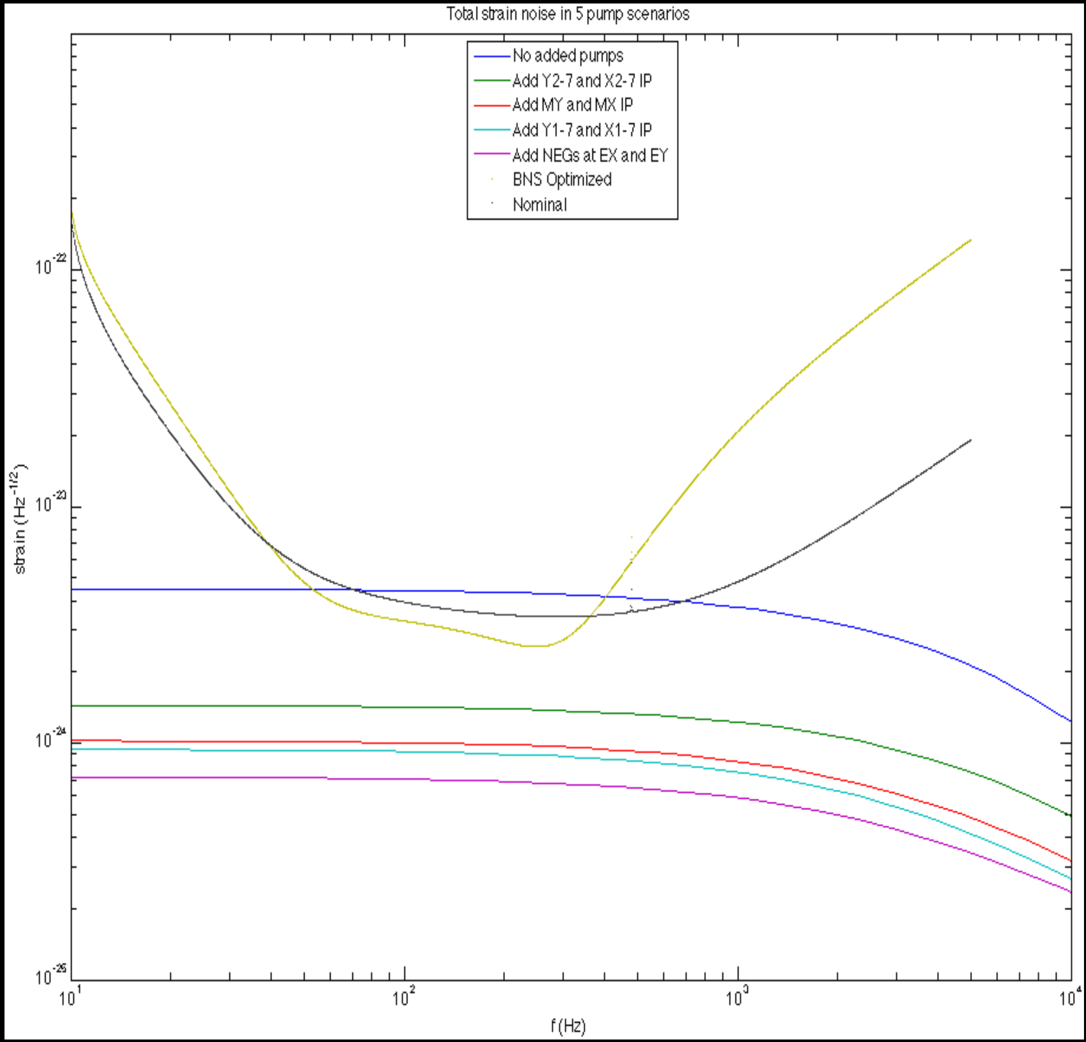
Figure 10: Breakdown by gas type and arm, pumps at 2km and 3.75km.

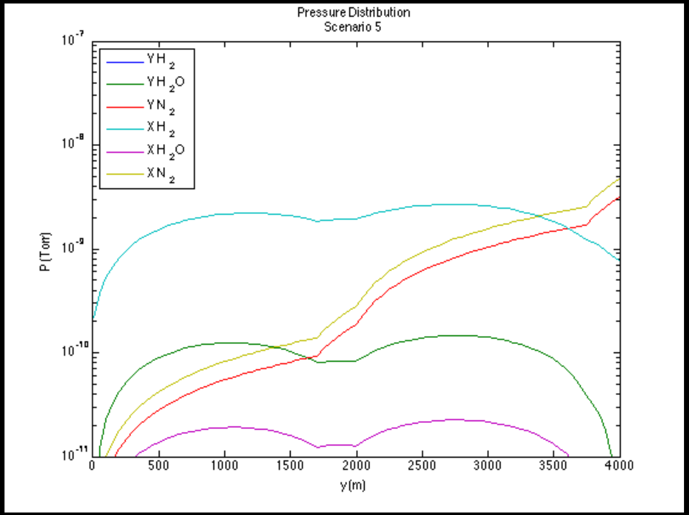
➔ *difficult to get gas index noise < 1/10 of design bucket minimum without fixing the leak, and/or restoring full pump speed at ends*

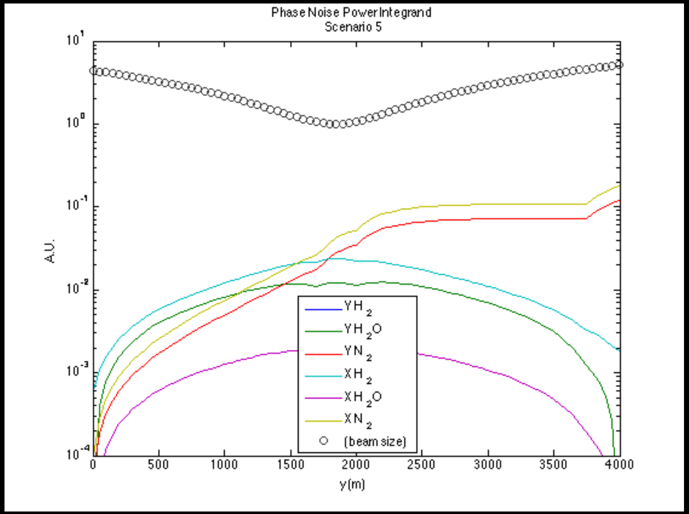
(1/3 of bucket minimum is achievable, maybe ok)

Index phase noise w/GV11 leak

(ion pumps at 1.75, 2, 3.75 km + NEGs at ends)







Gate Valve Repair Options: *Rock or Hard Place?*

- 29 years ago, we chose to risk a "one-off bakeout" design. This means

  "LIGO BEAMTUBES MUST REMAIN UNDER HARD VACUUM FOR THE LIFE OF THE FACILITY"

  – Tough choice, but we had to build to cost, or go home!
  – Durable/reusable bake capacity (like, e.g., Virgo*) was not affordable.
  – OTOH, we (optimistically) expected to *need* 10^{-10} Torr H_2O within 10 years , so bake was *required*
  – (also, a specified 20-year design life seemed generous …)
- From an engineering standpoint, best answer is to *revisit and break this constraint*
  – Capability to repair your mistakes is a 'fundamental right' for ground-based experiments!
  – It (now) seems reasonable to expect more gate valve stem leaks
  – Based on what little we know, stem faults could accelerate catastrophically (grease bubble scenario)
  – We also see, and should thus expect, other failure modes (besides bad valves and rodents)…
    - Catastrophic viewport failures at Virgo and HPLF
    - Truck collisions and lightning strikes on our BTE
    - Brush fires and Cat 5 hurricanes
    - Rifle rounds through buildings & disgruntled employees
    - Safety valve failures and human errors (lots)
- We also DON'T REALLY KNOW the consequences of air exposure from the current state!

As a matter of principle:

LIGO SHOULD HAVE MEANS TO PERFORM A CONTROLLED TUBE VENT AND RECOVERY

LIGO SHOULD ALSO HAVE A PLAN TO RECOVER FROM AN ACCIDENTAL TUBE VENT

Gate Valve Repair Options: *Rock or Hard Place? (ii)*

- Even if we resolve to proceed, and secure funding and staff, it will take time and effort to develop this missing capability. We may have to act sooner; are there fallbacks?

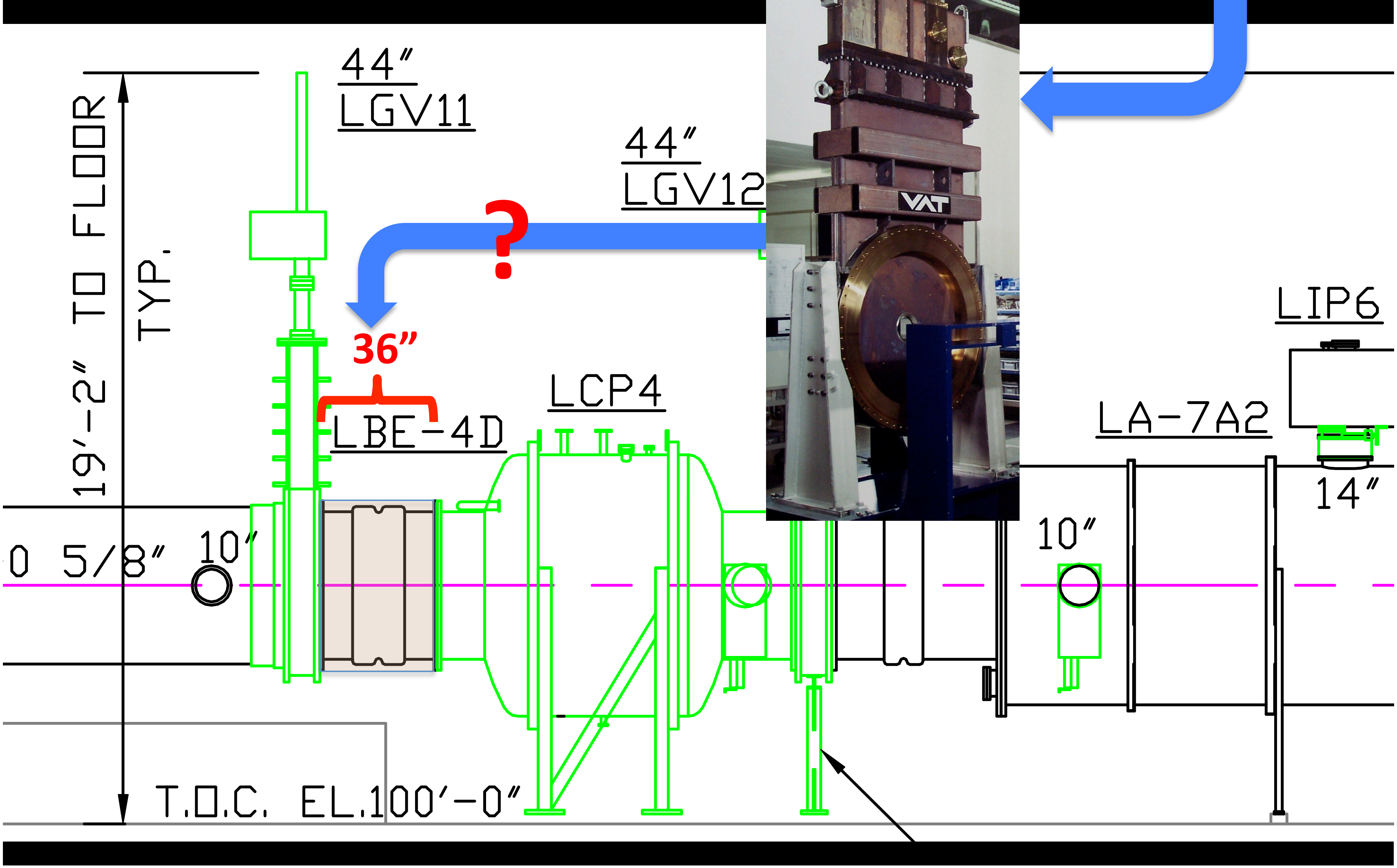
- Plan B: "Living Dead" sarcophagus
  - Encapsulate & evacuate the valve stem while *maintaining valve function*
  - Replace or modify drive components that won't survive (?)
  - *Much more complicated* engineering problem than GV7 sarcophagus
  - High risk of accidental dump or contamination during procedure
  - Continued deterioration with future valve operation possible (probable?)
  - ➔repair likely to fail, contaminate tube with HC, and obstruct future action

- Plan C: "Last Lick, then Kick"
  - Close valve one last time; regenerate & vent CP
  - Cut in and install a new valve *in series* with the failed one
  - Pump out dead space, reopen faulty valve, & encapsulate/disable in open state (a la GV7)
  - Similarly complicated engineering
  - Similar risk of accidental dump or HC contamination (but stable after it's open)

"Sometimes it's better to fall flat on your face, than to bend over too far backward..."

-James Thurber

possible series valve position (TBR)



Gate Valve Repair Options: *Rock or Hard Place? (iii)*

Plan A: *Develop & test backfill and recovery protocol,* THEN :

- A1: Vent tube and fix the valve
  - Backfill tube, release bonnet , & crane out mechanism
  - Repair (somehow), reinstall & test
  - Pump down & bake (as required)
    - + *May* figure out what is wrong with this (all?) valves
    - - Extended tube vent (more water adsorbed for a given concentration)
    - - Risk of guessing wrong about how to repair, parts to replace
    - - Still the same old shi++y gate valve when you're done
- or… A2: Vent tube and replace the valve entirely
  - Backfill tube & remove bad gate valve
  - Install replacement valve & test
  - Pump down & bake (as required)
    - + Can probably figure out what is wrong, once it's out on the test bench
    - - Extended tube vent (more water adsorbed)
- or…A3: Close valve once (Plan C style), then gut & cap it, leave empty shell
  - Close bad valve one last time; regenerate & vent CP
  - Cut in and install a new valve *in series* with the failed one (BT still under vacuum)
  - Quickly vent beamtube & reopen failed valve
  - Crane out failed mechanism, then cap & reinstall bonnet on *empty shell*
  - Pump down & bake (as required)
    - + Can probably figure out what is wrong, once guts are out on the bench
    - + Very short tube vent required
    - - Need space for series valve

Gate Valve Repair Options: *Rock or Hard Place? (iv)*

How can we buy time?

- Control atmosphere around the valve stem
  - Install "non-vacuum" sealed enclosure
  - Backfill with dry air or other gas
    - Tempting to try gases with less index noise… but they have high permeation rates, maybe little to gain
  - May use a flexible membrane sealed over valve ("Fothering" in maritime parlance)
    - Must reinforce to take atm
  - Could pump in emergency
    - Dangerous, but…
    - If leak accelerates, nothing to lose

Refresher: Original I^2R Bakeout to Desorb Water

- Glass wool insulation, R = 4.3 m^2K/W, t = 15 cm
- I_{DC} = 2,000 A (surplus FNAL magnet supplies)
- Soak ~ 4 weeks @ 150ºC
- Cryopumps every 250 m; ports later valved off

- Final $J(H_20) < 2e\text{-}17$ Tl/s/cm
- FY97$6.5M for both sites

➔*OVERKILL*

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

Revisiting the $J(H_2O)$ Requirement

- Consider 2- and 15- pump cases
  + cryopumps at ends

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

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

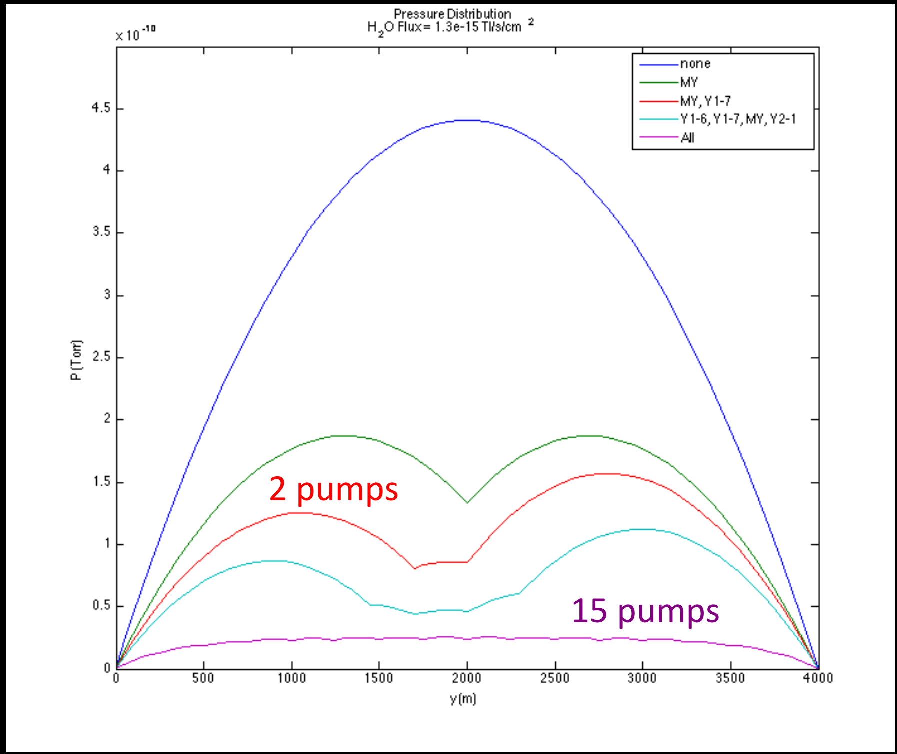
Then[2], for 2 pumps

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

and for 15 pumps

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

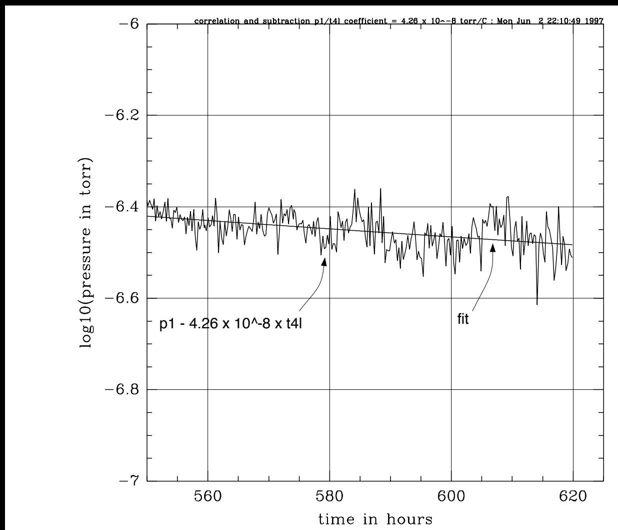
(no leaks, just autogenous water; F_i = 534 l/s)



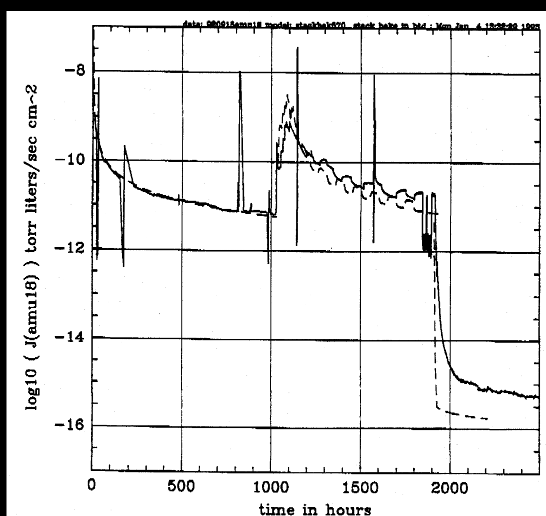
[1] *T1400177, Fig. 3, "BNS Optimized 125W"*
[2] *T1500202*

NB: $1\ T\ l\ s^{-1}\ cm^{-2} = 1.33 \times 10^3\ W\ m^{-2}$

Unbaked Water Outgassing (norm. to 1000 hours)



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



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

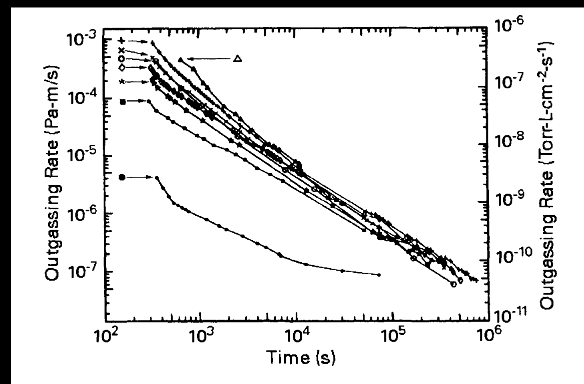
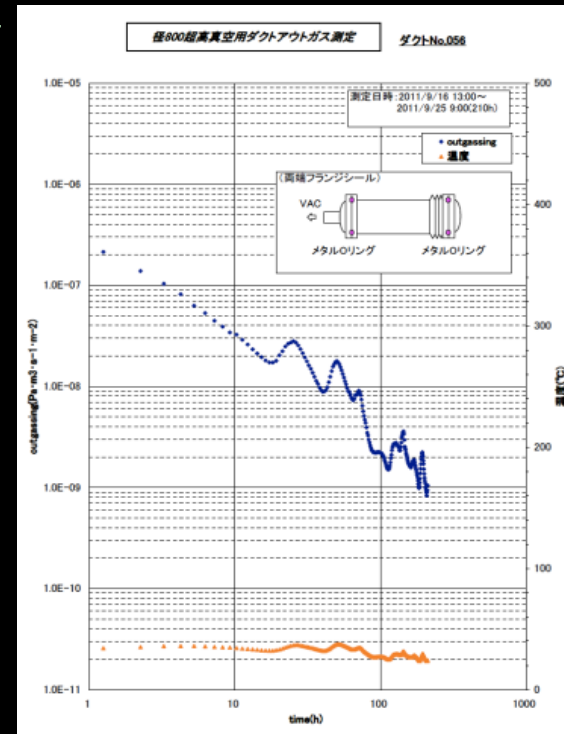


Fig. 4.5 Outgassing measurements for different H_2O exposures during venting of a 304 stainless steel chamber of inner surface area 0.4747 m^2. ○ Ambient air exposed, 7.8 ml absorbed; Δ 600 ml exposed, 16.8 ml absorbed; + 400 ml exposed, 9.2 ml absorbed; × 200 ml exposed, 7.2 ml absorbed; ◊ 100 ml exposed, 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.

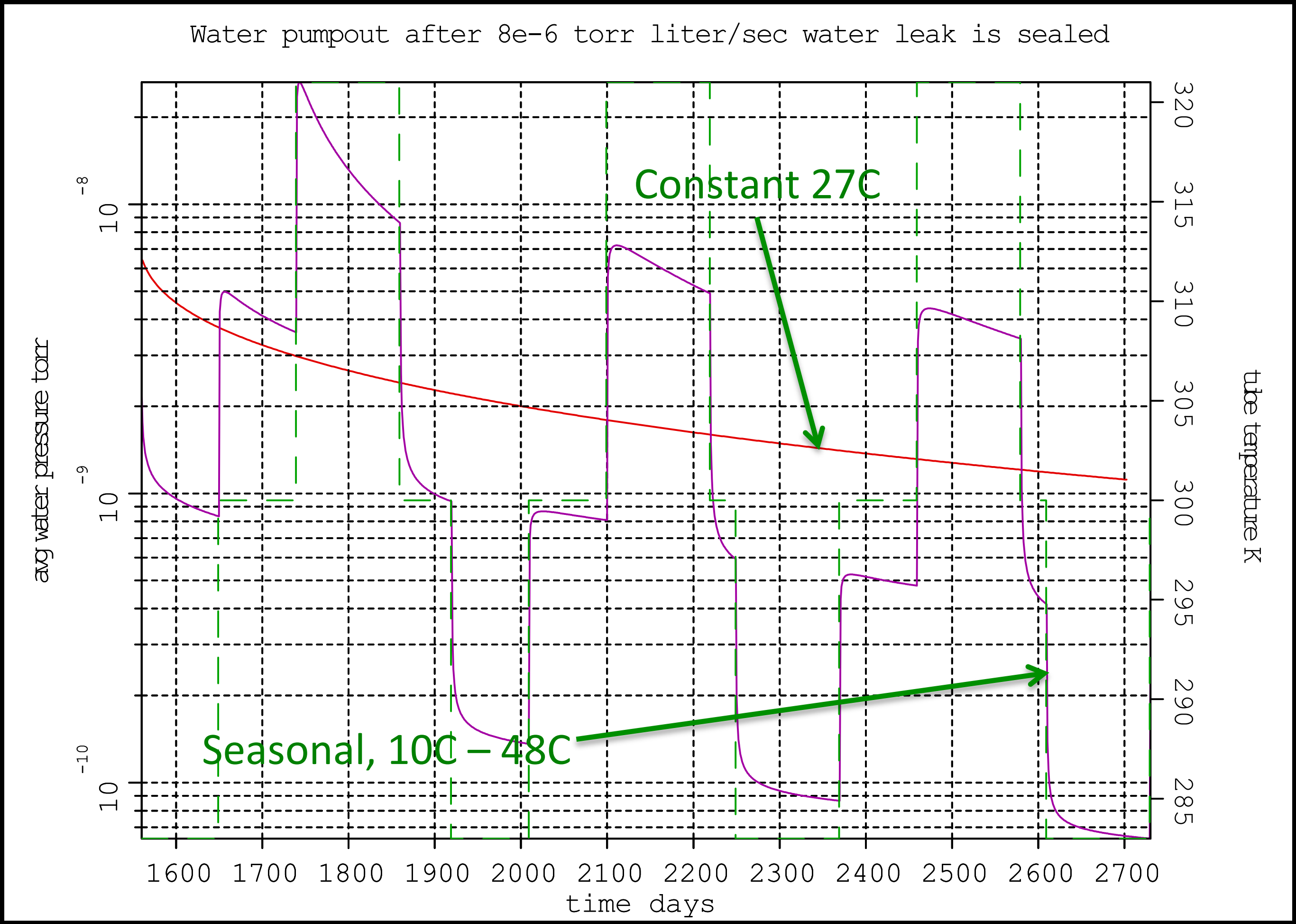
Li and Dylla (1993)
Electropolished 304L
10 ppm water content air re-exposure
$J(H_2O)$ ~ 4 x 10^{-12} T l s^{-1} cm^{-2} x (1000 h)/t



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

- Passive desorption @ ambient T too weak (t > 5 yr)
- Modest bake probably required
- For “controlled backfill” scenarios, can assist by:
    - Ultra-dry backfill (< 1 ppm, -75C dewpoint)
    - Minimize atm. exposure time
- *Summer heat helps*

Modeled desorption with step-approximated seasonal temperature profile included (preliminary)



R. Weiss, 6/9/2015

Easy-Bake A: Operation Endless Summer?

- Duct hot air through the BTE & heat tube by convection
- BTE compatible with > 50C internal temperature (60C? 80C?)
- Install pumps in local cooled enclosures at each pump port
- Relocate network, instruments, electrical outside temporarily
- Rent LNG space heaters & fans
- Blanket/electrically heat gates at endpoints

Possible Problems:

- BTE a poor insulator (R ~ 1.3 M^2 K/W); only in summer?
- LLO Y no longer has midpoint valve! :^((maybe have to replace it)
- Effect on BTE seam sealants?
- Maintenance/repair on guided supports & insulators?
- Max. T too limited to degas in tolerable period?

NEEDS STUDY

Easy-Bake B: Operation Viscous Breeze?

- Piecewise bake with reusable local heater & blanket sets
- Flow dry purge from completed toward future sections
- Viscous flow entrains vapor w/out (much) redeposition (?)
- Crew "leapfrogs" heated section to reposition blankets

Possible Problems:

- Flow gas, while rarified, still needs to be very dry
- Only effective (even theoretically) in narrow (*P,T,v*) regime
- Turbulence in wake of baffles ?
- Sustainable over module length?
- Continuous high-volume pumping (and production) required
- Total time to complete module in steps may be much longer
- *Never been tried*

NEEDS STUDY

Things to do (i)

- Complete & commission 3.75 km IP sets @ LLO, LHO
- Procure, build & install 2km, 1.75km IP sets @ LLO
- Complete & commission D3500 NEG's @ LLO, LHO
- Research & test new air-tolerant "HV Series" NEG's
- Develop, procure, fit UV baffles for 1200 and 2500 l/s IP's
- Develop & deploy GV11 environmental enclosure
- Develop protocol to check all large gates @ both sites
- Survey valve vendors & obtain specs & budgetary quotes
- Study economical bake scenarios & establish limits
- Study "industrial scale" dry backfill systems

Things to do (ii)

- Upgrade and extend water ad/desorption model
- Develop failsafe turbopump sets for unattended operation
- Fabricate & condition BT-representative sample chambers
- Build & characterize H_2O outgassing test system
- Bench characterize backfill and bakeout protocols
- Intermediate-scale qualification test
- Procure & deploy site valve(s), backfill and bake hardware
- Vent & fix/replace valve(s)
- Perform forensics on failed GNB valve(s)
- Recover & bake tube(s)

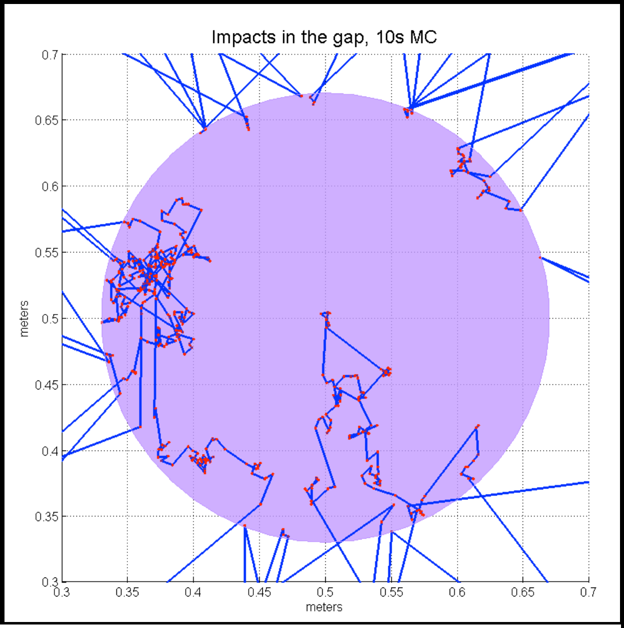
Troops & Treasure

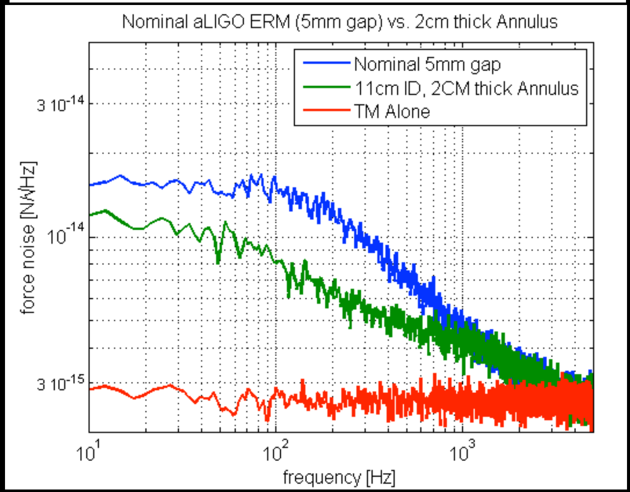
?

EXTRA SLIDES

Squeeze film damping

- Narrow gap between ETM and ESD reaction plate enhances viscous damping by residual gas
- Increases thermal noise at low frequencies
- Exacerbates penalty for *any vacuum problem* affecting pressure at end chambers
- Possible mitigations
  - Increased pumping
  - Repair leaks, reduce outgassing
  - Redesign ESD for larger gap



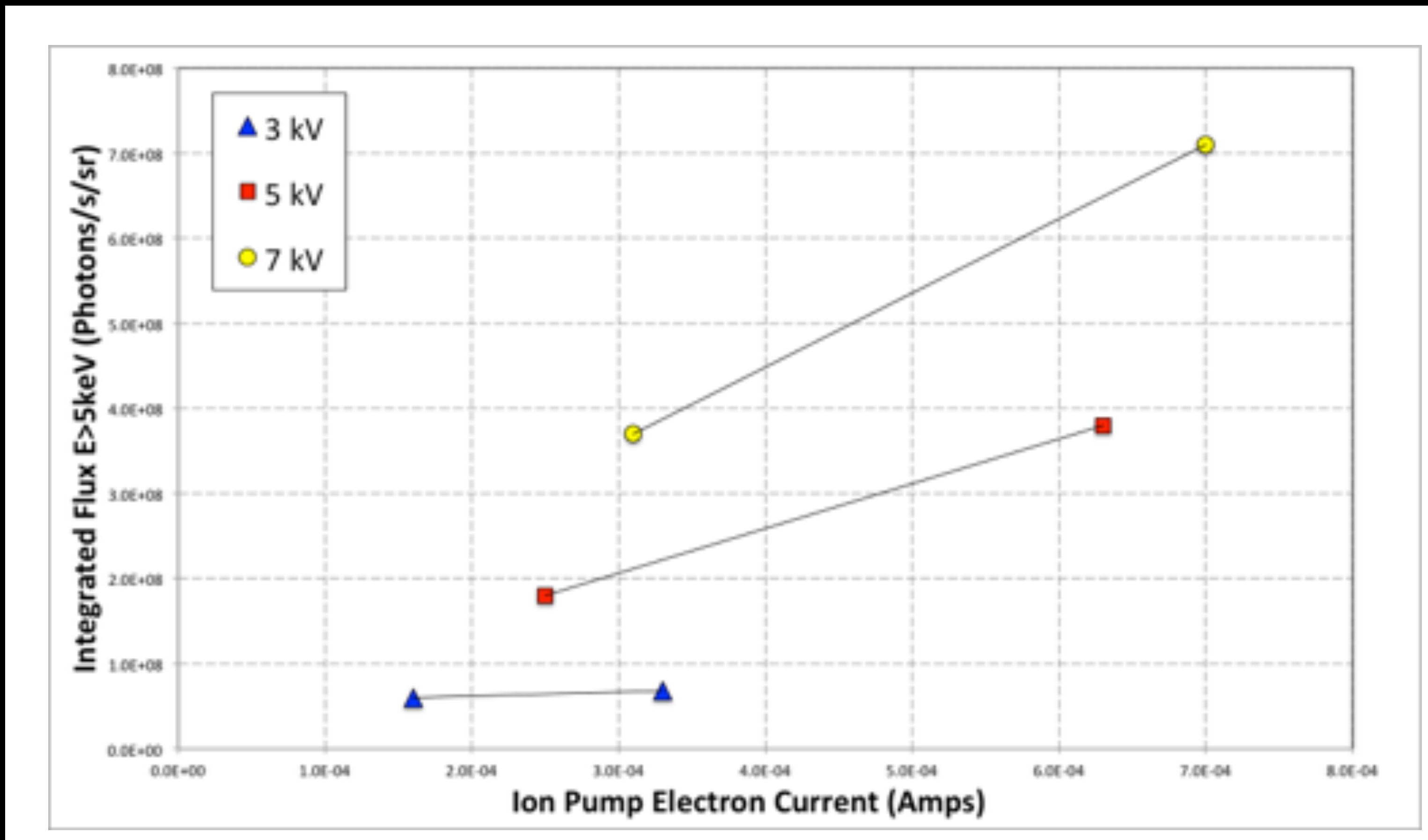


from LIGO-T0900582-v6 (10^{-8} torr H_2)

Electrostatic Test Mass Charging

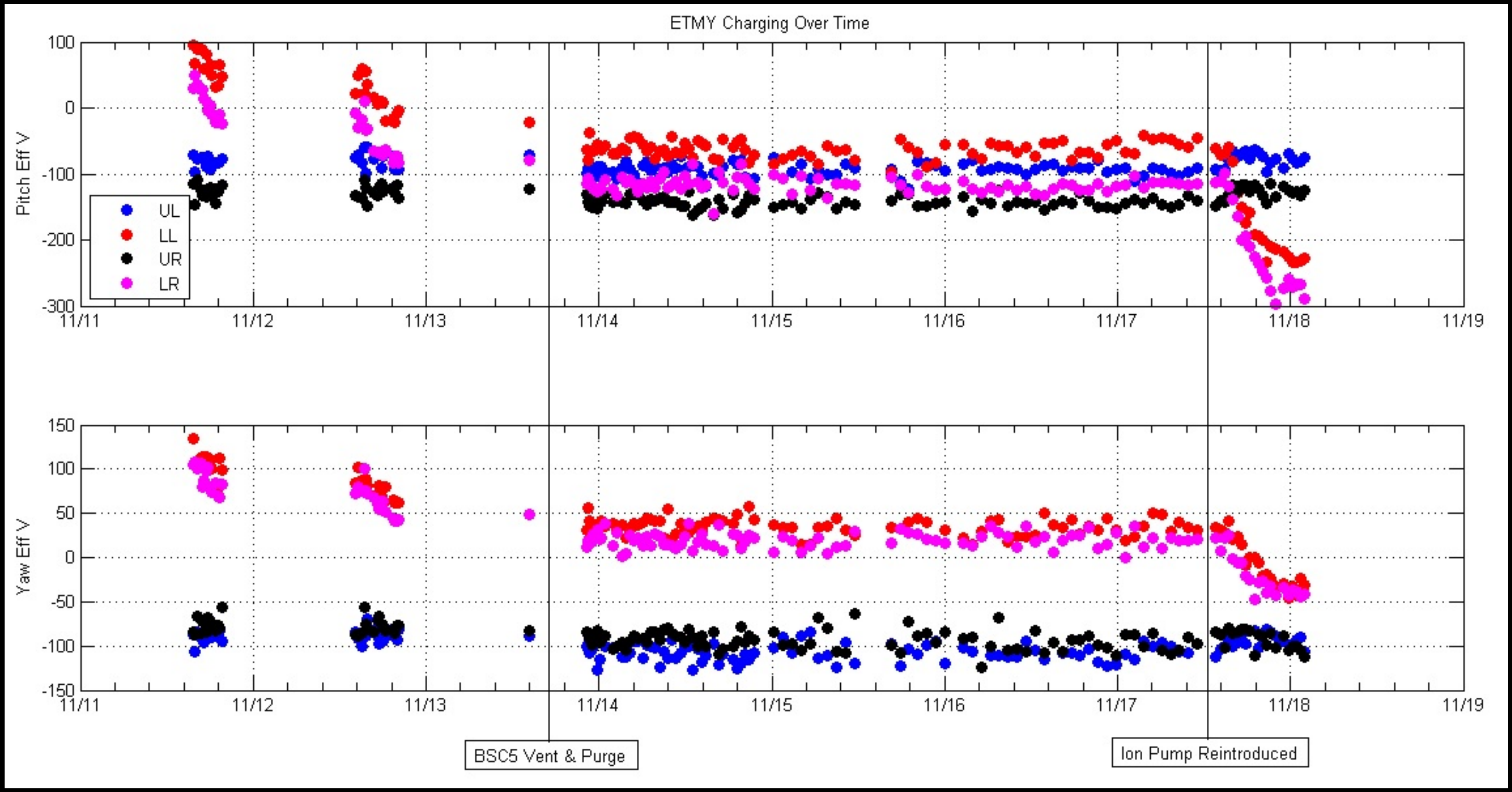
- Correlated w/ operation of ion pumps nearby
  - Theory: PE due to UV / soft X rays from discharge (no direct line of sight)
  - Induced $\sigma \sim 10^{-12}$ coulomb/cm^2 over hours-days
  - Effect on input TM's less; probably due to distance from local pumps
- Wreaks havoc
  - Interferes with electrostatic force drive operation
  - Couples V noise from nearby circuits & 'groundplanes'
  - Couples mechanical noise from image charges in nearby conductors
  - Intrinsic noise due to spontaneous charge dissipation & redistribution
- Interim solution: *seal off IP's at ends*
  - *no pumping of non-condensibles, except via beamtube*
  - Almost immediately hit both squeeze-film and gas index noise in rapidly improving noise budget
- In progress now:
  - Remote IP's (250m from end, on beamtube pumpout ports)
    - Reduced speed for noncondensibles
  - NEG pumps at ETM chambers
    - Reduced speed, limited life for gases other than H_2
    - Poor margin against detector outgassing, leakage
- Longer term:
  - Chevron UV baffle retrofit to IP nozzles
    - Degrades pump speed
  - Reengineer TMP's for continuous duty
    - ultra-low vibration, fault-tolerance, backstreaming safety

Ion Pump UV emission



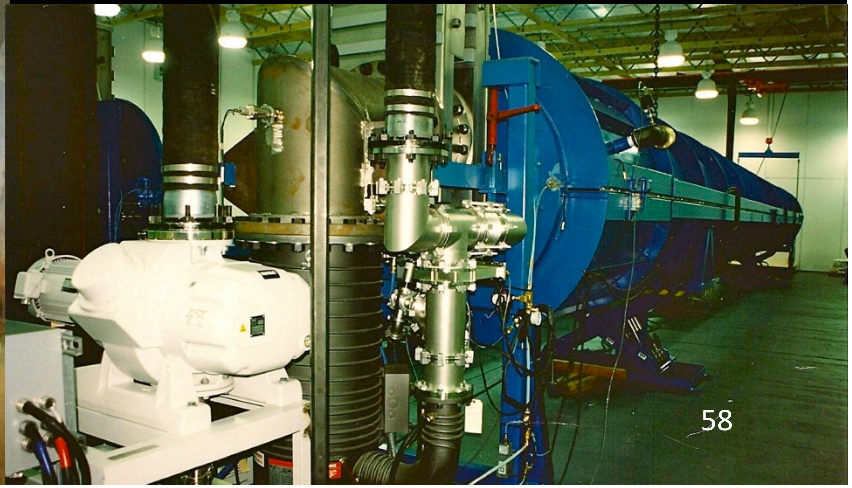
A. Kontos, 6/10/2015

IP charging evidence (LHO)



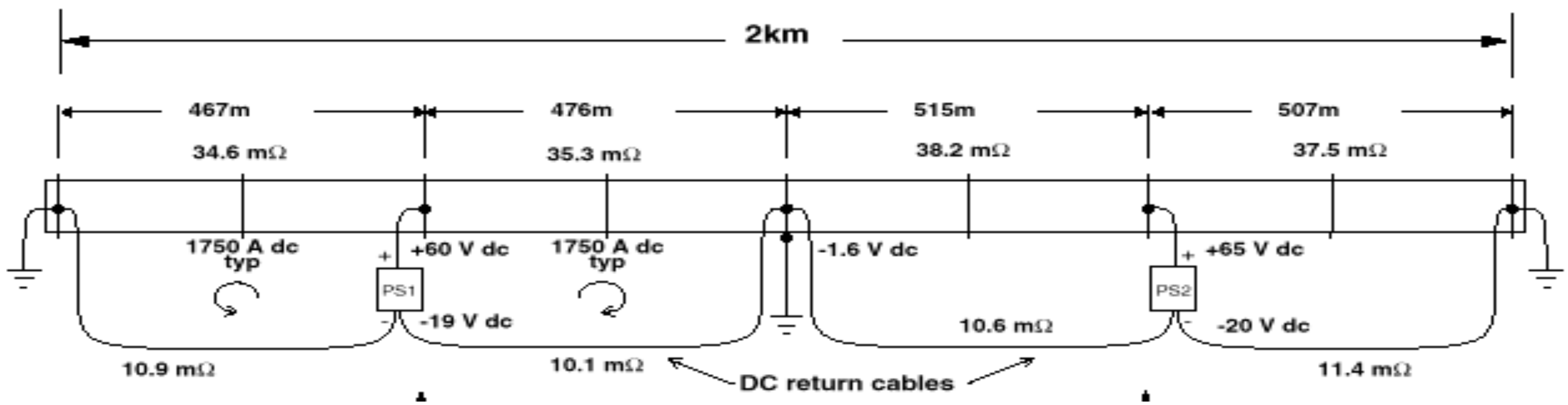
Beam Tube Overview

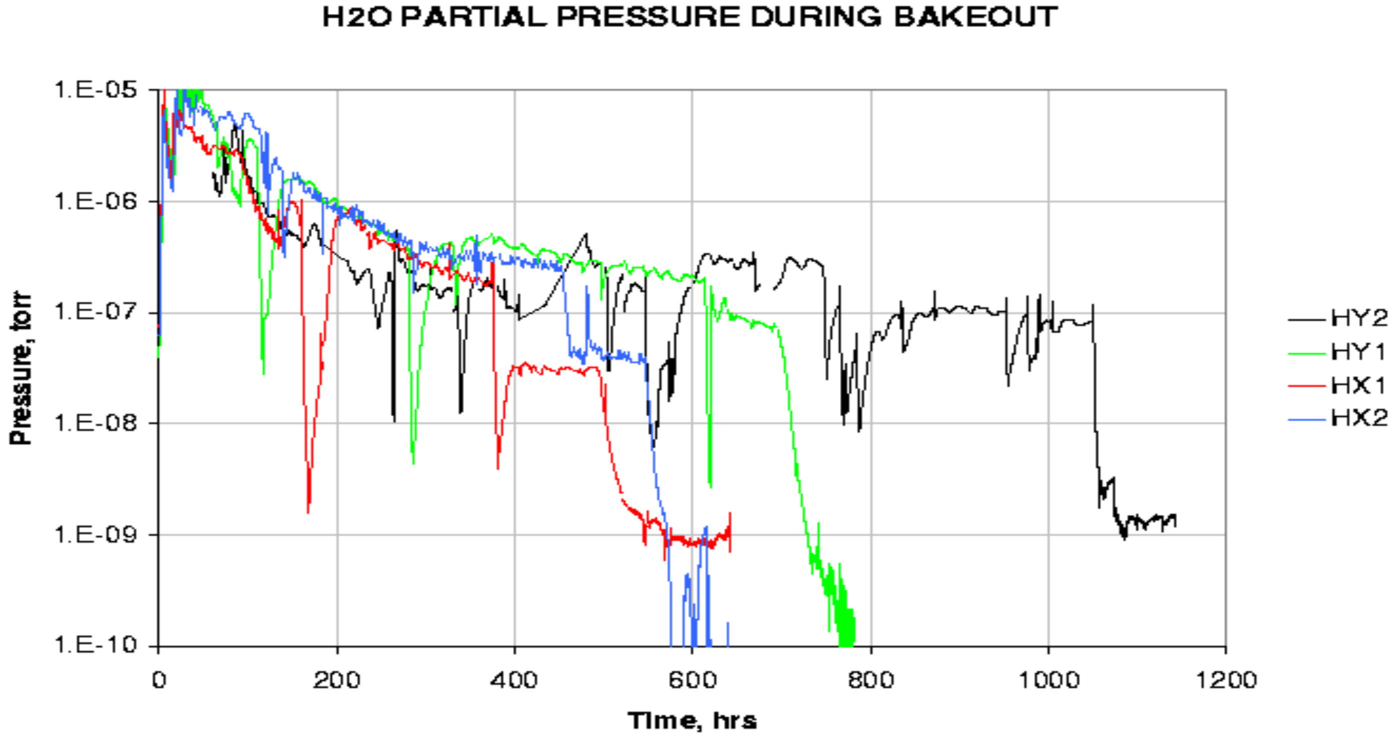
- 304L SS, 3.2 mm thick with external stiffeners
- raw coiled stock air baked 36h @ 455C to deplete hydrogen
  - $J_{H2} < 10^{-13}$ Tl/s/cm^2
  - process developed by LIGO
- prepared coil spiral-welded into 1.2m tube on modified culvert mill
- 16m sections cleaned, leak tested, and capped
- FTIR analysis 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



Field Assembly & welding

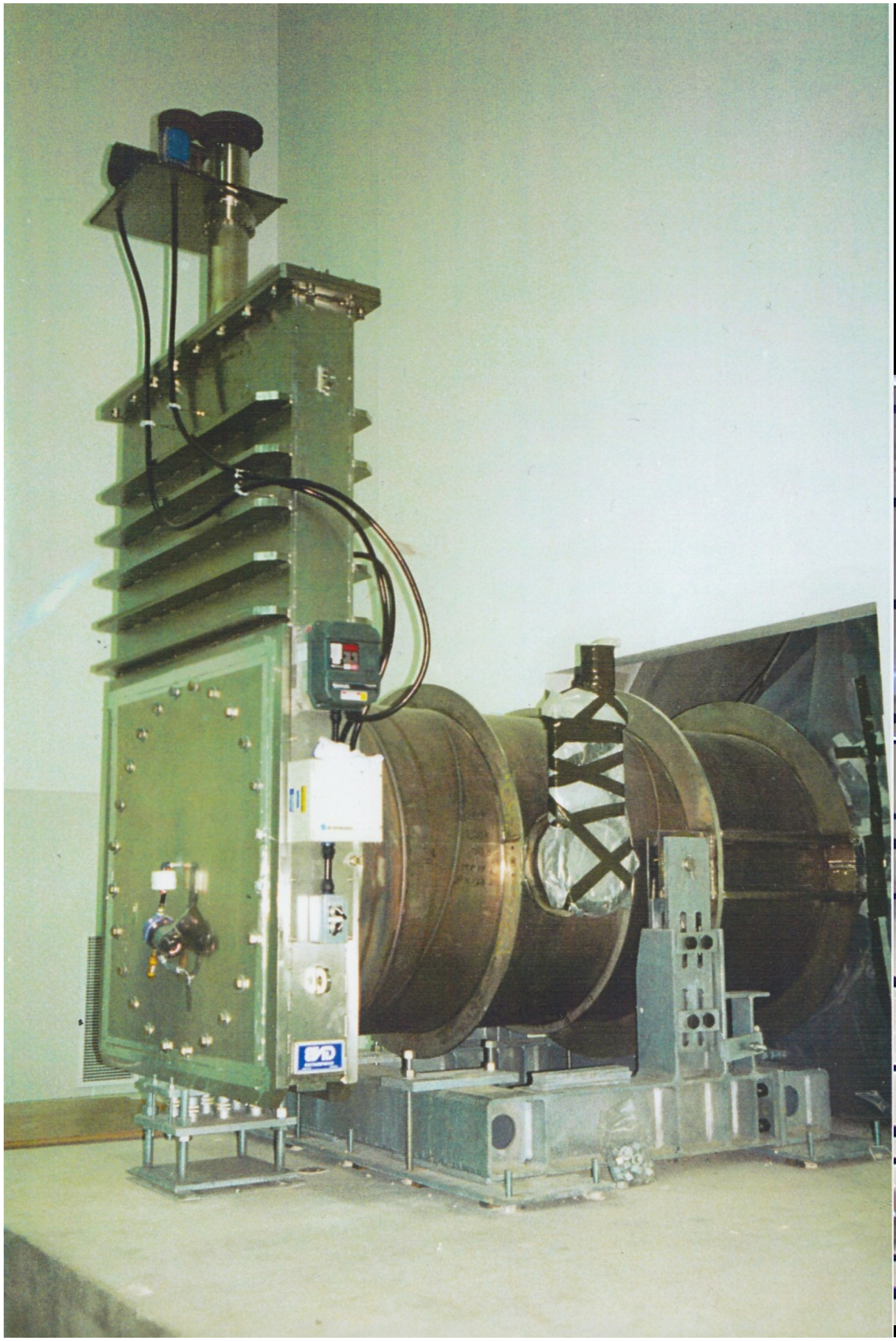
I^2R Bakeout to Desorb Water (cont'd)





Beamtube Gate Valves

- 44” clear aperture
- @ beamtube ends and midpoints
- Custom low-shock dual-seal electric design

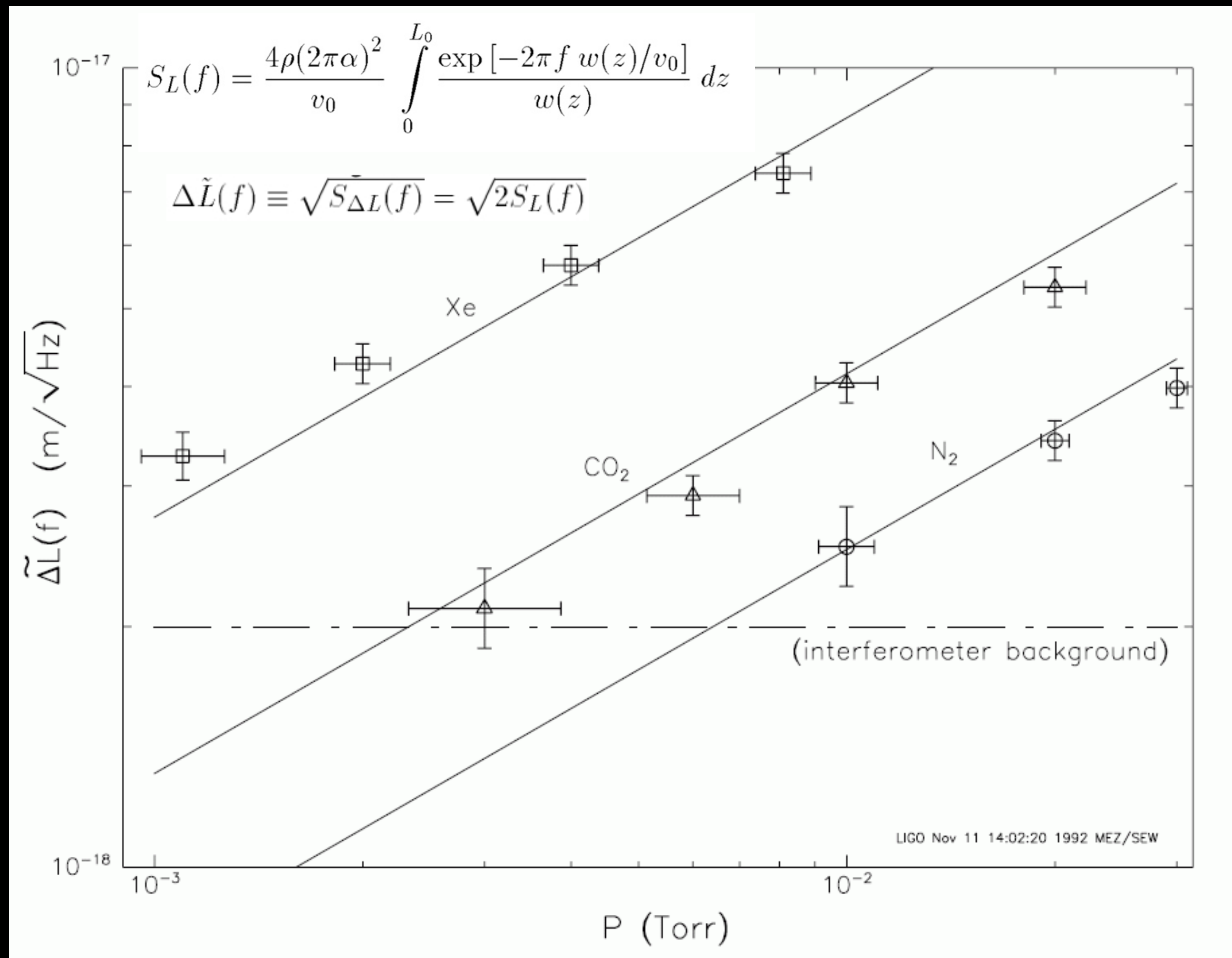


Residual Gas Index Fluctuation Noise

Statistical model verified by 40m 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)
w = beam radius
v_0 = most probable 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).

Residual Gas Pressure Limits in Beam Tubes

then *now*

Table 1: Residual gas phase noise factor and average pressure

Gas Species	$R(x/H_2)$	Initial Req (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	$9.0\text{x}10^{-12}$	$9.0\text{x}10^{-15}$

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