I. Experience with discharging the ETMY test mass at LHO in August 2014
II. Future work in developing the ionizer
III. The poor state of our knowledge of the charging on the test mass

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I. We made two attempts to discharge the ETMY at LHO. The first was on August 7 and the second on August 8, 2014. The conditions of the two tests are described in **Table 1.**

Table 1 Conditions in the two tests

parameter	test1	test2	comments
pressure on needles torr	300	130	
voltage on needles rms 60Hz kV	30 variac 3kV	13 variac 1.3kV	voltage set to avoid discharge
pressure in input line psi	20	1->5	
pressure in storage dewar psi	100	100	
sampled + ion current amp 0.01 of main flow	$5x10^{-9}$	$1.7x10^{-8}$	
sampled – ion current amp 0.01 of main flow	$5x10^{-10}$	$2.5x10^{-9}$	
initial pressure in chamber torr	4×10^{-8}	4×10^{-8}	after both tests pressure in chamber returned to original value within 12hours
final pressure in chamber torr	42	28	
final pressure in ionizer output torr	45	45	
filling time minutes	29	51	stopped test1 when ionizer got too cold
gas flow while filling atm*liters/sec	2	0.75	
gate valve chamber opening	full open	1/10 or less	test2 flow limited by "O" ring labyrinth
gas inlet Nupro valve opening	full open	full open	
pressure in ionizer before gas input torr	$2.0x10^{-3}$	2.0×10^{-3}	
pressure in ionizer and fill lines before gas input torr	$2.0x10^{-3}$	$2.0x10^{-3}$	after liquid N_2 trap was filled
Liquid N_2 and reheater on input fill line	only liqN_2	both	

It is now clear that we need to know more about the variables in the ion production and injection to tune the discharging process. One of the criteria we have used for success is to achieve near equality in the number of positive and negative ions in the ionizer. This can be done over a small range of nitrogen pressure on the needles and gas flow rates past the needles. Neither of the two injections had equal ion currents as can be seen in **Table 1.** The first injection was done with the gate valve between the ionizer and the test mass chamber fully open while in the second test that gate valve was used as a flow regulator. In the first test the ion currents sampled in the electrometer were unequal and small. Nevertheless, the test mass was discharged between 40% to 1% of its initial charge depending on the ESD quadrant. In the second test both positive and negative ion currents were larger though still not equal as we reduced the flow by throttling the gate valve and reducing the input gas pressure. The hoped for additional improvement in discharge of the test mass was not realized. One could attribute this to the gate valve not being sufficiently open and the flow having to take a serpentine path around the “O” ring in the valve. Most likely, the ions got lost by being attracted to their image in the metal walls of the gate valve.

Figure 1 The ionizer attached to the ETMY chamber as configured for the second test. The instrument is described in T1100332 and G1100364. The new elements not part of the initial test on the MIT LASTI facility are the additional liquid nitrogen trap in the fill line and the gas reheating section between the trap and the entry into the ionizer. The additional trapping was to avoid oil and water frozen dust that could be at the bottom of the storage dewar from entering the test mass chamber. Prior measurement had determined that both the hydrocarbon and dust emission at the ionizer output was small enough to avoid contamination of the optics. The single post support bolted to the ground was effective.

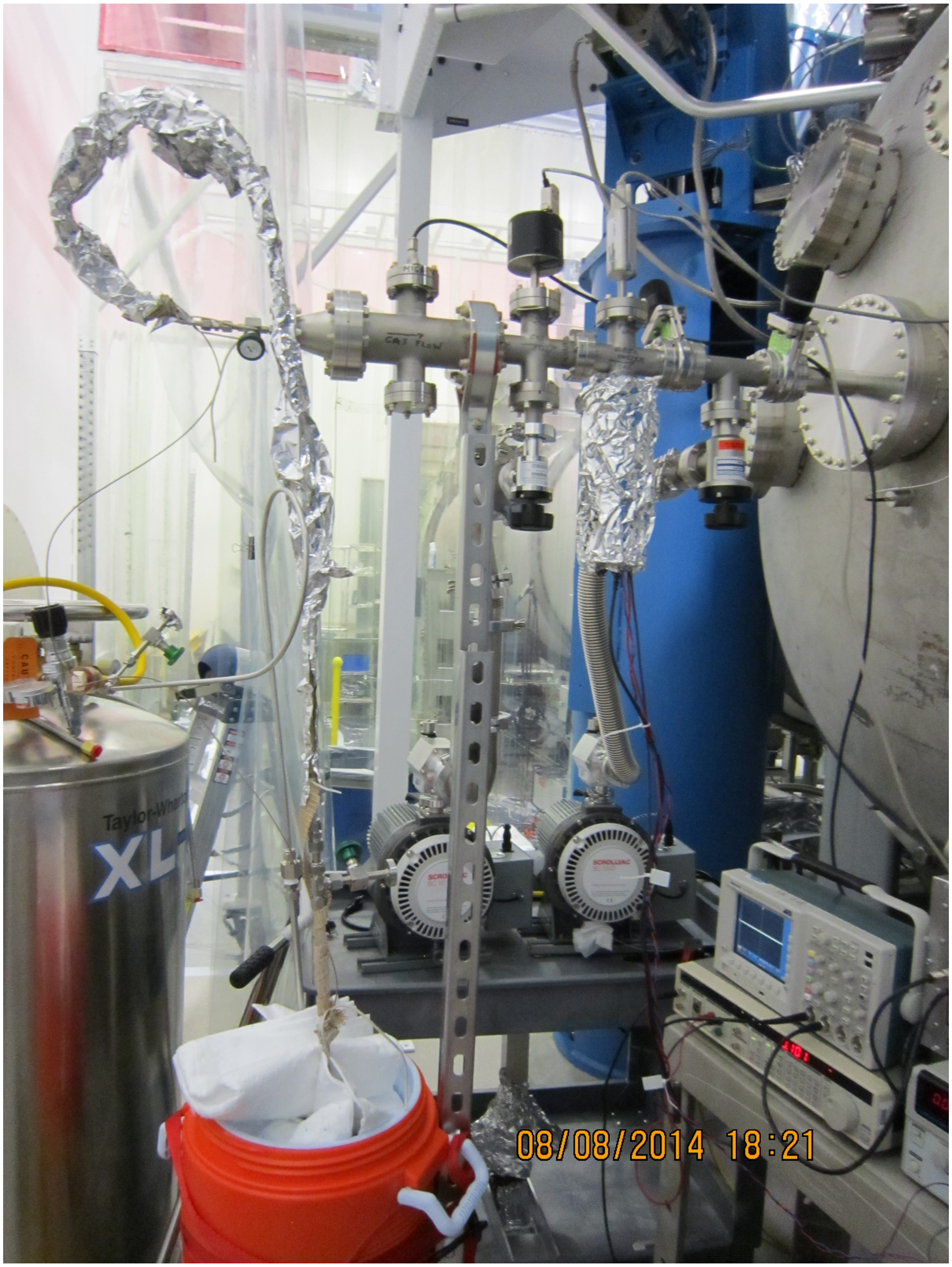

Figure 2 Side view of ionizer installation. Note the two right angle valves with horizontal black handles. The one on the left controls the pumping of the space between the needles and the apertures, while the one on the right is used to establish the flow through the ionizer before opening the system to the chamber. During the injection both valves are closed. The gate valve to the right of the Pirani gauge is always open. The gate valve on the chamber was completely open during test1 and only partially open in test2.

Figure 3 The instrumentation for the ionizer. The oscilloscope displays the 60Hz current between the needles and the vacuum shell (ground) as well as the currents of positive and negative ions that make it into the flow after the apertures. The sampled current is about 1/100 of the current in the flow. The variac controls the voltage on the needles.

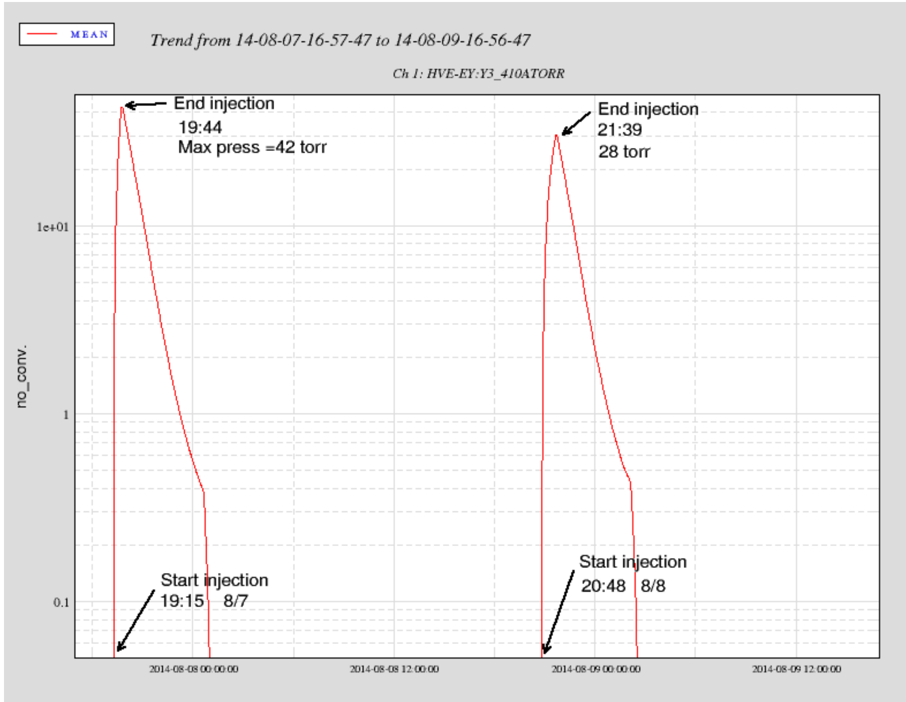

Figure 4 Pirani gauge on the test mass chamber showing pressure profile during the injection and subsequent rough pumping for both test1 and test 2.

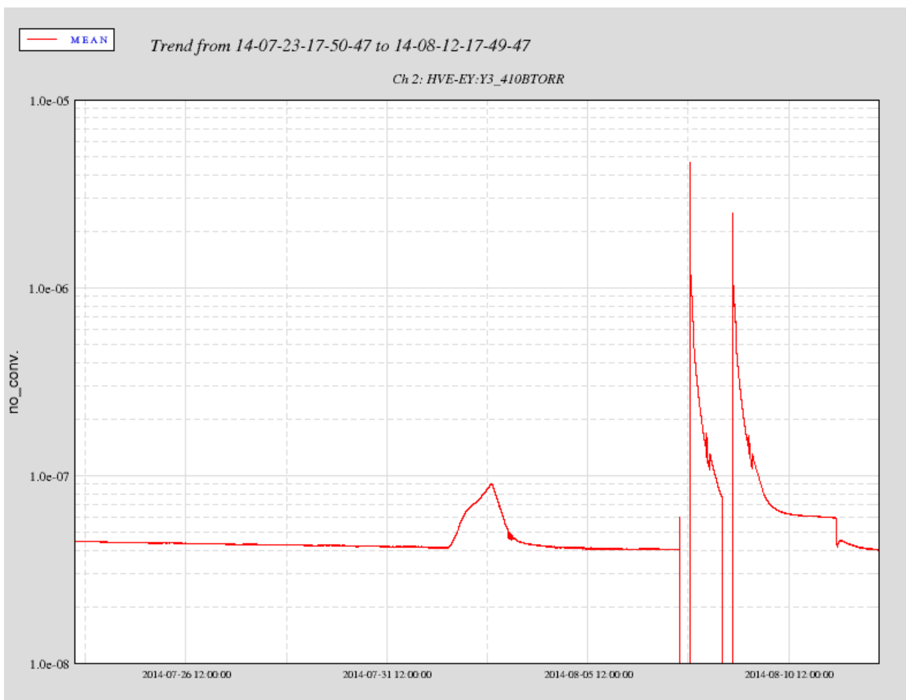

Figure 5 The discharge gauge measured chamber pressure before and after the two injections. In the trace before the first injection the chamber is maintained by its ion pump. The ion pump is closed off from the system before the first injection and turned on again at the downward step after the second injection. The pump out is with a turbo pump.

II. Work needing to be done to make the ionizer more robust

Before another attempt is made to discharge the test mass, a more reliable method needs to be developed to broaden the range of operating parameters to assure closer equality of the positive and negative ion currents. Nitrogen does not easily form negative ions. Negative molecular nitrogen ions have a short half life. More stable negative ions occur in clusters of several nitrogen molecules. The clusters have a small range of pressures and flow rates where they form. It is believed one can extend the range of pressures where the negative ions will form by applying both AC and DC potentials to the needles. Adding the DC bias to the AC power supply is easy and will be tried in September 2014 along with more experience in tuning the system. A clean (non-dust producing) flow meter will be placed in the nitrogen feeder line which will make it easier to establish the same flow conditions run after run. The tests do not require injection into the test mass chamber.

Another possible direction is to use a mixture of nitrogen and oxygen. Oxygen has well known negative ion states. Oxygen may be reactive to the VITON and may interact with the mirror coating. There is also the possibility that ozone would be generated which is known to harm VITON. Before embarking on using oxygen, samples of the coatings and VITON would need to be tested in the ionizer.

Bill Lee of Alpha Lab, a manufacturer of test equipment for the commercial electrostatic discharge industry, has suggested Argon as an alternative gas. The argon atom does not have negative ion states but, much as with molecular nitrogen, the dimers of Argon have negative ion states. Argon is not easily pumped by our ion pumps. If we use Argon, we would need to be sure that the bulk of the injected gas is pumped out by turbo pumps.

III. The current state of understanding of the charging on the mirrors

The LASTI tests showed the charge on the advanced LIGO test mass was small and, when charged deliberately, the charge was stable. In LASTI the test method was to measure the linear and quadratic part of the electrostatic drive force using small bias and control voltages; small enough so one could maintain longitudinal actuation even at a few torr pressure. The mirror was part of a Fabry-Perot cavity held on resonance with a PDH sensed servo system. The discharging experiments with the ionizer are described in T1100332. After the LASTI experience, it was considered unnecessary to continue the further development of the ionizer in part because it seemed it would never be needed.

The situation in Advanced LIGO is significantly different than in LASTI. There appear to be significant and disturbing amounts of charge on the test masses and, more seriously, there is growing evidence that the charge is on the test mass is not static. The ionizer discharging system is not appropriate for removing time varying charge. The two questions are then: why is there so much charge and then why would it vary?

The differences between the LASTI tests and Advanced LIGO that we know about are:

1) First contact was not used on the test mass at LASTI. There are significant electric fields generated when the first contact is removed from the mirror. This was known by people preparing and cleaning the mirrors who applied ion discharge gas to the glass after the first contact was removed. The electric fields on the mirror (as high as 10^4 volts/cm) were regularly measured before discharge. The electrometer to measure the remaining charge had a minimum sensitivity of 100V/cm which corresponds to surface charge densities of 10^{-11} coulombs/cm^2. The allowed surface charge density on the mirror is 1/100 to 1/1000 of the minimum measurable. A new more sensitive electrometer has been procured and, hopefully, all future charge densities from the first contact will be in the allowed range. Rich Abbott has reported that in all the post first contact discharging measurements, he has been involved with, the glass becomes **negatively** charged and the removed film is positively charged. If first contact is responsible for the charging, injected positive ions would suffice to discharge the test mass. Interestingly, the first charge measurements at LLO using the 4Hz excitation and pitch and yaw measurements with the optical lever imply (if the as built wiring is as drawn in the circuit diagrams), that the stored charge on the mirror was negative (the offset voltages are positive).
2) Green light was not applied to the mirror at LASTI. Though unlikely, two photon photo emission on the dielectric surface of the mirror needs only a quantum efficiency of 10^{-12} electrons/photon to explain the surface charge on the mirror. The estimate comes from the cavity locking experiments with green light done at LHO. The work function of SiO_2 is poorly known and probably also never will be known well as the surface potentials on dielectrics are notoriously difficult to measure being sensitive to adsorbed gas layers. The one value in the literature is 4.0 volts, just barely sufficient for two quanta of green light. Two photon photo effect is being measured currently at LHO. It should leave the surface positively charged as electrons get removed from the mirror – a possible indication that already rules out this cause of the charging.
3) Ion pumps were not on when the LASTI tests were done. We have never had occasion before these tests to determine if the ion pumps on the chambers are free of emitting UV photons or charged particles into the vacuum system. It is common experience that discharge gauges and ion pumps are sources of charged particles in a vacuum system. Test are in process at LHO to determine if the ion pumps are responsible for charging and also the variability in the charge.

The evidence for fluctuations in the charge comes primarily from the driven mass motion in pitch and yaw tests using the optical levers. There has been only one attempt at a direct longitudinal motion test at LLO (similar to those carried out at LASTI). The data of that test did not agree in detail with the optical lever tests although depending on the spatial distribution of the charge, the results could well be different.

We know several things about the variability. At LLO a series of driven pitch and yaw measurements were made over about a week which shows variations of easily 50% in the charge dependent offset voltages in both directions of more and less charge stored on the test mass. There may even be a pattern in the geometry with larger variations in some ESD quadrants than others. At LHO we had the alarming experience that after the partial discharge with the ionizer, subsequent measurements (made after the ion pump was turned on again) showed a return of the charge to pre-discharge values. At the time, one of the hypotheses was that had the charge on the test mass been positive, the negative ions required for the neutralization which are less stable than the positive ions, could have decayed and taken their electrons with them as they left the surface. This is no longer a likely hypothesis as the surface has been found to be negatively charged.

The understanding of both the large charge and, especially, the variability is still in a state of confusion.