LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Maximum B-OSEM Current

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1 Introduction

Testing is required on the BOSEM assembly in order to establish coil current limits based on thermal considerations. These thermal considerations include:

- Maximum operating temperatures of the components and materials comprising the BOSEM assembly, and
- Hydrocarbon outgassing rates

The BOSEM report, T050111, contains data on temperature rise vs current, but no outgassing measurements. Moreover this testing was done at relatively high pressure (~50 mTorr) instead of < 0.1 mTorr needed to ensure that air conduction/convection is negligible. This memo reports on testing of the outgassing of BOSEMs in a test chamber and the interpretation of this data in terms of the maximum allowed drive current.

2 Device Under Test

The Device Under Test (DUT) is the BOSEM assembly (D060218-v2), depicted below.

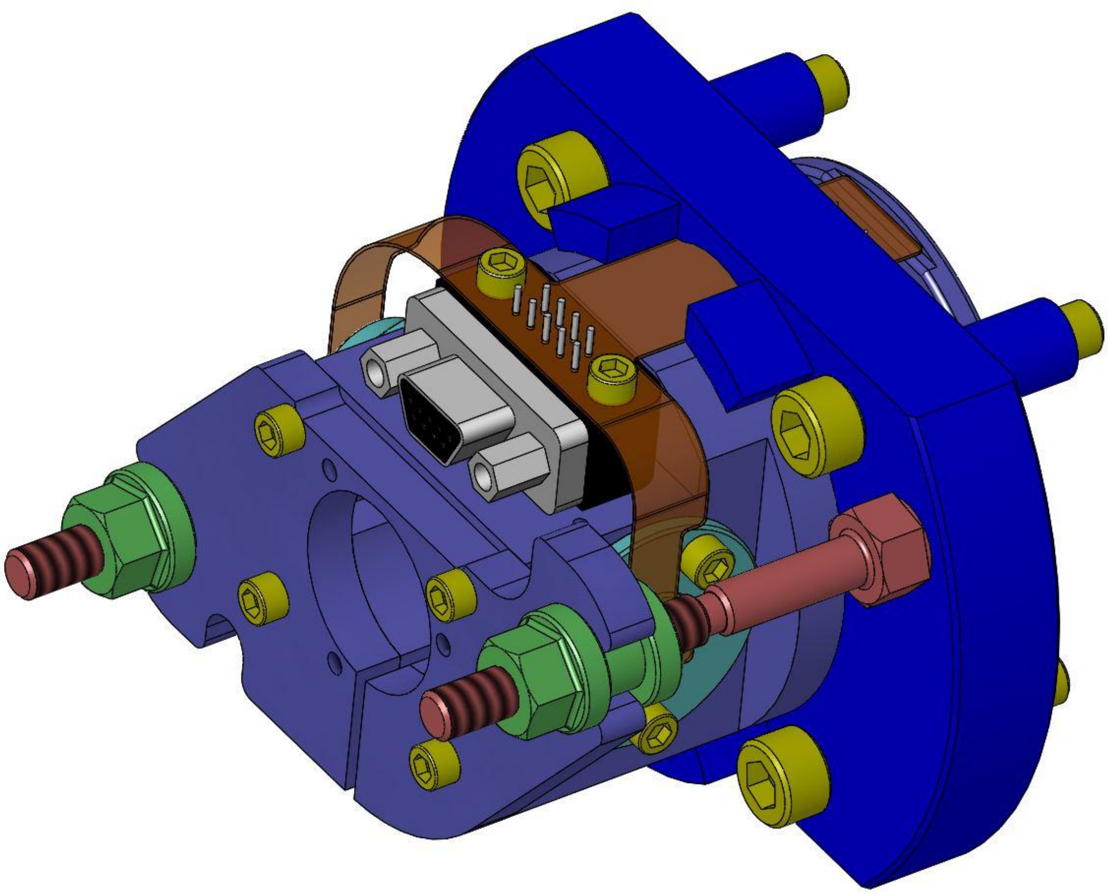

Figure 1: BOSEM Assembly

The eight (8) BOSEMS are wired in series, as indicated in the diagram below. These 8 BOSEMs are from a set of 10 which were shipped from LLO to CIT for this test (ICS shipment #7165). The 10 BOSEMs shipped were serial numbers 324, 328, 344, 346, 368, 386, 389, 396, 398 and 401.

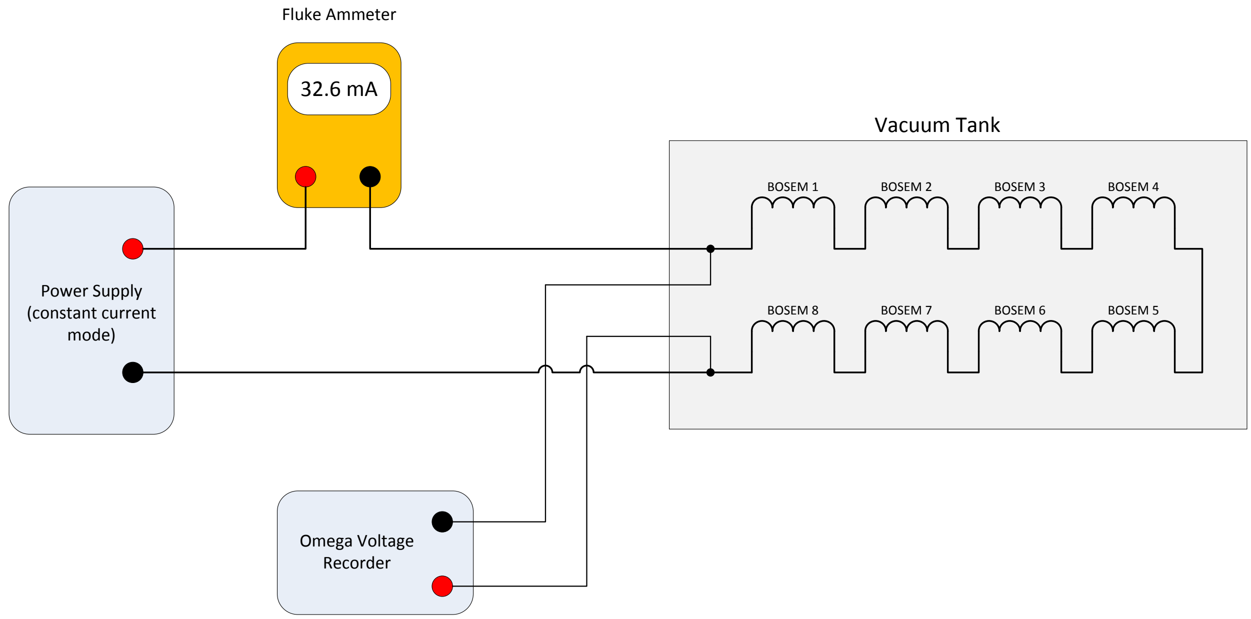

Figure 2: Test Wiring Diagram

The maximum BOSEM coil current is defined in section 4.5 of T050111-v6, “BOSEM Design Document and Test Report”, as 150 mA. However the maximum current capacity of the drive electronics (for a nominal 40 ohm load) is 200 mA (per section 3.1.3 of T080014-v2; e.g. range test for serial number S1000379-v5 demonstrated 190 mA).

3 Calibration of coil resistance to temperature

The 8 coils wired in series were placed into a temperature controlled air oven and the coil resistance was measured as a function of oven temperature, making sure that the coils had achieved equilibrium (steady state) temperature. The coil resistance was found to be very linear with temperature (as expected), as shown in Figure 3.

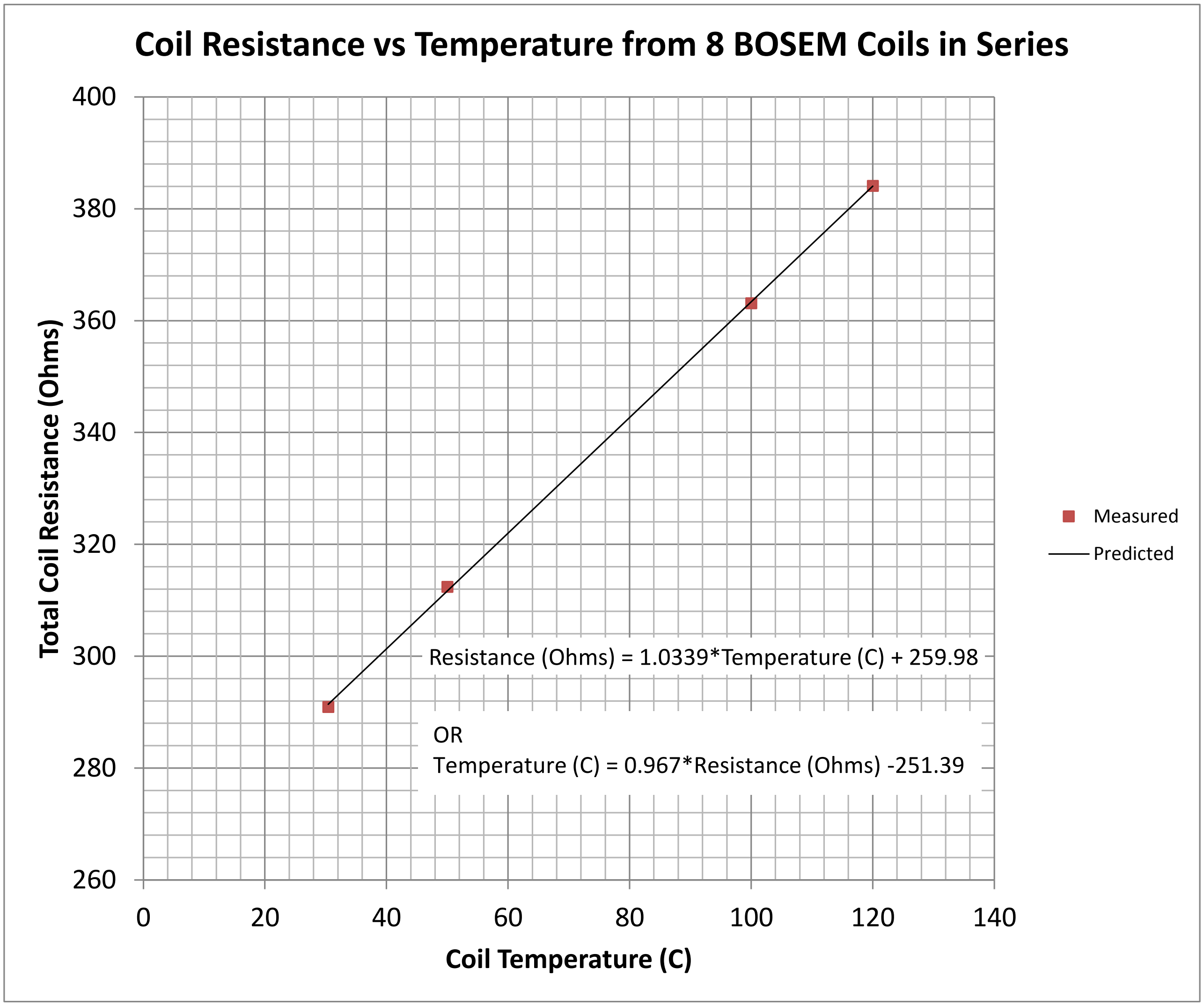

Figure 3: Coil Temperature vs Resistance

4 Coil temperature vs coil current in vacuum

In the test, two sets of four (4) BOSEMs are attached to a common aluminum bar (with dimensions ~0.375" x ~2.50" x ?"). These two sets are physically placed adjacent to one another and sitting on the inner cylindrical wall of the stainless steel vacuum chamber, as depicted in Figure 4.

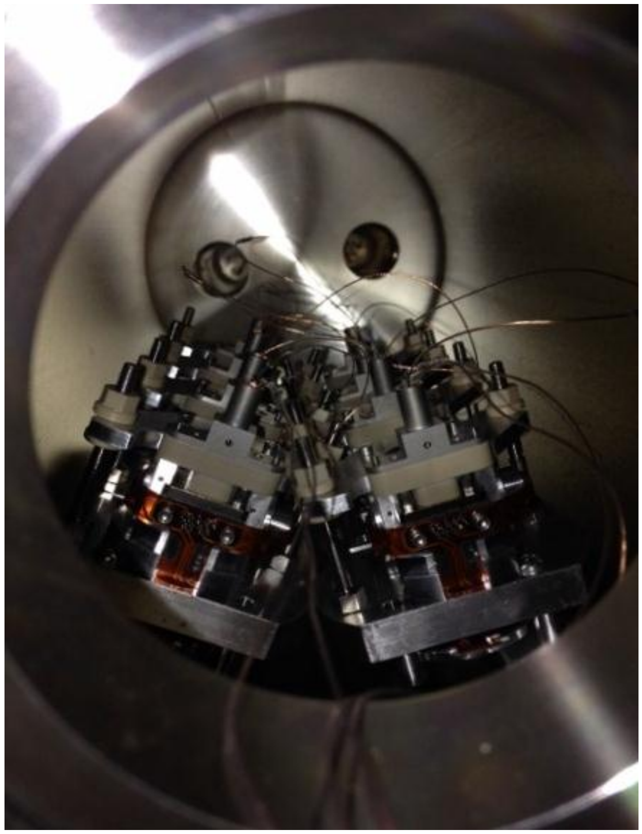

Figure 4: 8 BOSEM Assemblies in Vacuum Test Chamber

The partial pressures of air, water and hydrocarbons was monitored over time for a constant coil current. Once equilibrium was achieved (or close to it), as evidenced by the RGA response, the coil voltage and coil current were recorded. Then a new, higher coil current was set and the outgassing monitored until a new equilibrium was approached.

Using the calibration of coil resistance to coil temperature, we are able to infer the average coil temperature of the 8 in-vacuum BOSEMs, as indicated in Table 1 and Figure 5.

Table 1: Measured DUT Voltage vs Coil Current and inferred Coil Temperature

Actual Measured Current (mA)	Measured Voltage After Equilibrium (VDC)	Temp C	Ohms	Power (W) per BOSEM
50	14.223	23.7	284.5	0.09
100	30.987	48.3	309.9	0.39
150	53.724	95.0	358.2	1.01
200	88.99	178.9	445.0	2.22

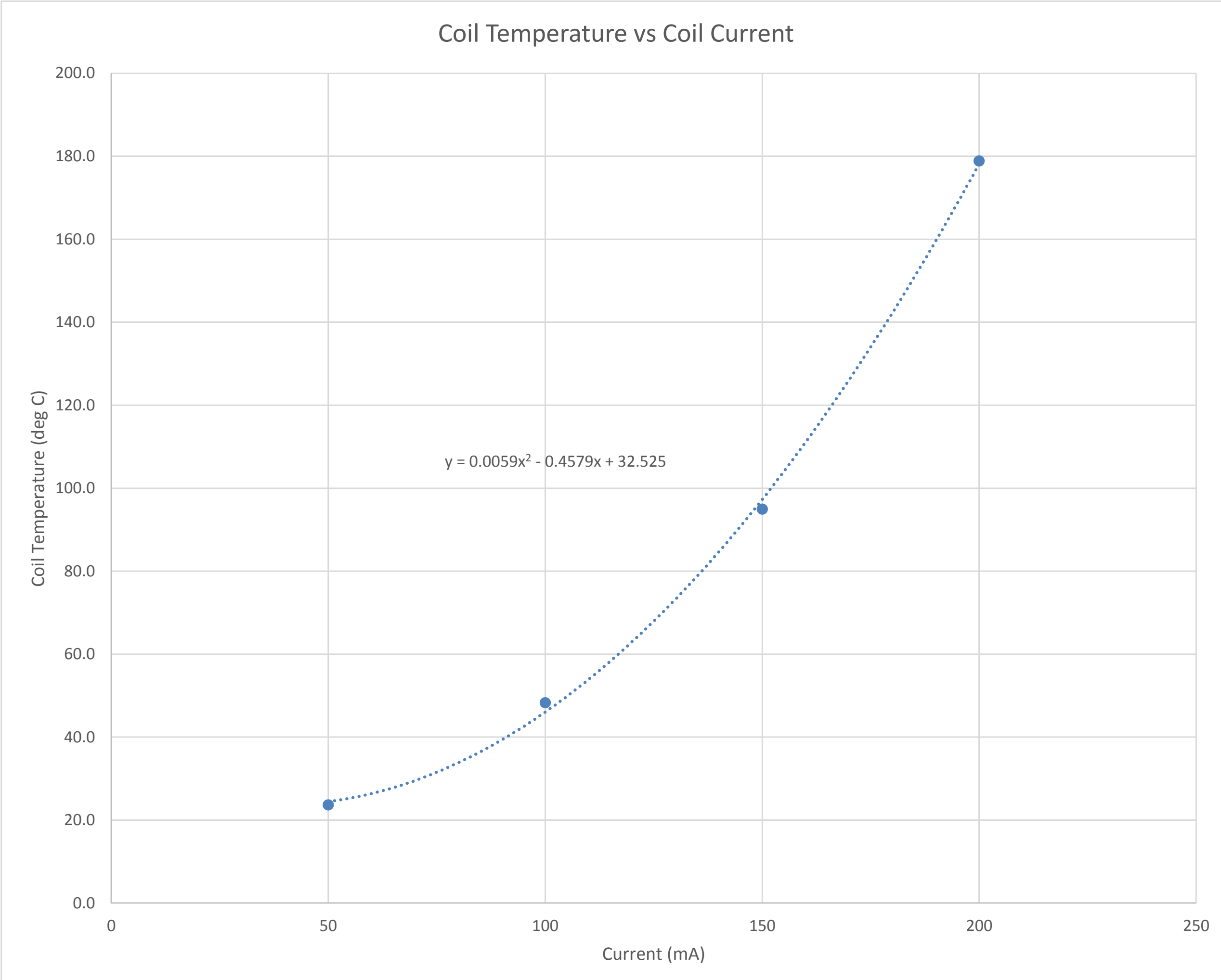

Figure 5: Coil Temperature vs Coil Current, in the In-Vacuum Test

In this test only coil current was applied; The IRLED was not powered. According to section 4.5 of T050111-v6, "BOSEM Design Document and Test Report", the continuous dissipation due to the IRLED is 50 mW, which is significant in comparison to the coil dissipation (at least up to ~100 mA of coil current). *[N.B.: The estimate of 833 mW of coil dissipation at 150 mA of coil current report in T050111-v6, is based on a nominal, room temperature, coil resistance of 37 ohms and did not take into account the increase in coil resistance with temperature.]*

⚠ According to section 5.2 of T050111-v6, the maximum temperature of the BOSEM is limited by:

- ~80C demagnetization for the ND35 magnets (Although this does not directly apply to the BOSEM assy, the magnets are close-coupled radiatively to the BOSEM and the surrounding/attached structures.) Note that the bake temperature for the NEO35 magnets (NdBFe) specified in E960022 is 80C.
- 125C storage, 120C operating for photodiode BPX65 (see E1000204 for data sheet)
- 150C storage, 125 operating for IR-LED OP232 (see E1000203 for data sheet)
- 125C for the Glenair connector

- 182C for the flexi-circuit

So these 8 BOSEMs which have been tested may have been destroyed! Electrical testing and evaluation will be performed on these 8 units before deciding whether they can be used in the interferometer (before they are placed back into the spares inventory).

The maximum operating temperature (based solely on damage/reliability concerns and not outgassing concerns) of the BOSEM appears to be limited to ~70C (with some small margin), by the demagnetization of the magnet which interacts with the BOSEM.

5 BOSEM outgassing vs coil current

Two in-vacuum, self-heating runs with the 8 BOSEMs were conducted. The first run sequenced through coil currents of 50 mA, 100 mA, 150 mA and 200 mA. The partial pressures of several AMUs are plotted vs time in Figure 6.

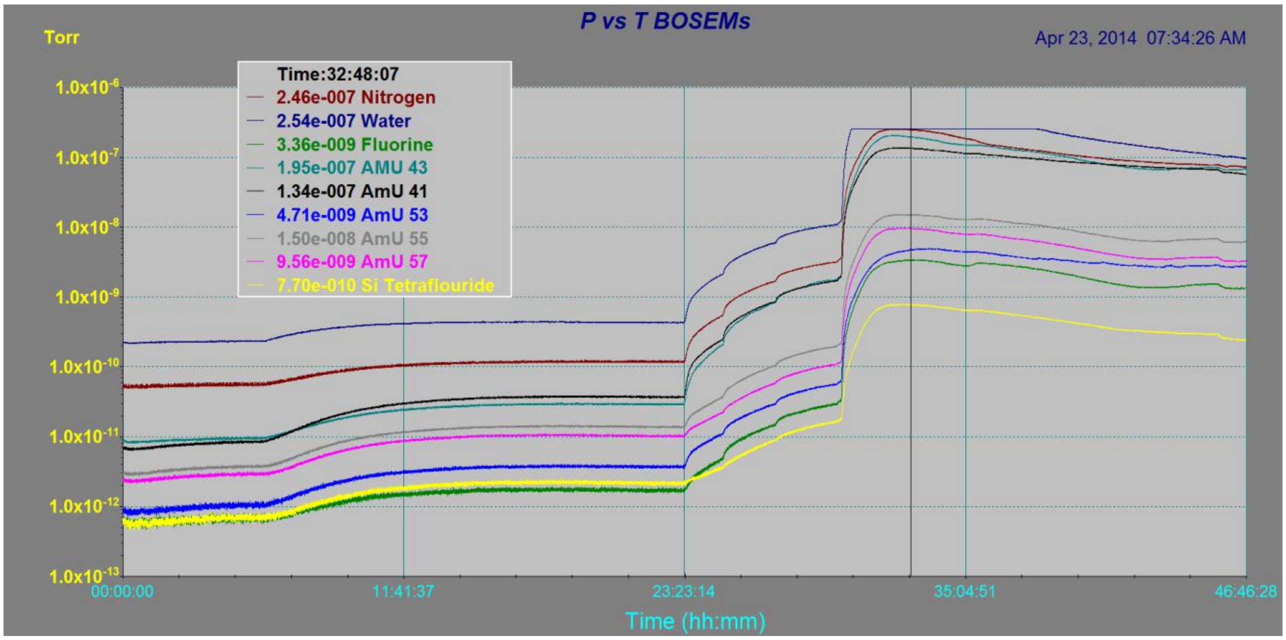

Figure 6: Partial Pressures vs time as coil current increased (50, 100, 150, 200 mA)

After cooling down to room temperature, a second, longer run at 200 mA was conducted to determine the rate of reduction of hydrocarbon outgassing over time. The partial pressures vs time are plotted in Figure 7, and in Figure 8. The non-monotonic behavior near the peak of the partial pressure traces is due attempts at adjusting the current drive back to 200 mA after it had drifted off the set point somewhat. In the later plot, only the traces after the peak are plotted, on a log-log scale. The rate of decrease follows a power law with time (t) an exponent of -1.2, i.e. $t^{-1.2}$. This is roughly consistent with a rate limited by outgassing t^{-1}. If the pump down was limited by diffusion the rate would be $t^{-½}$.

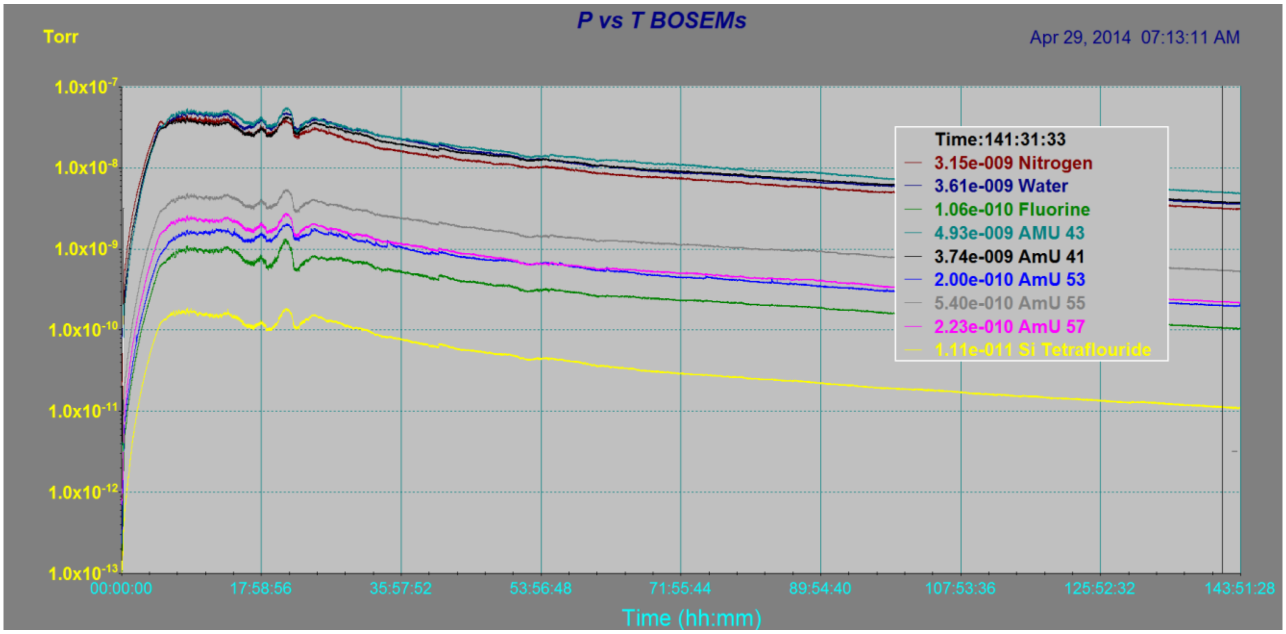

Figure 7: Partial pressures vs time for second run at 200 mA coil current

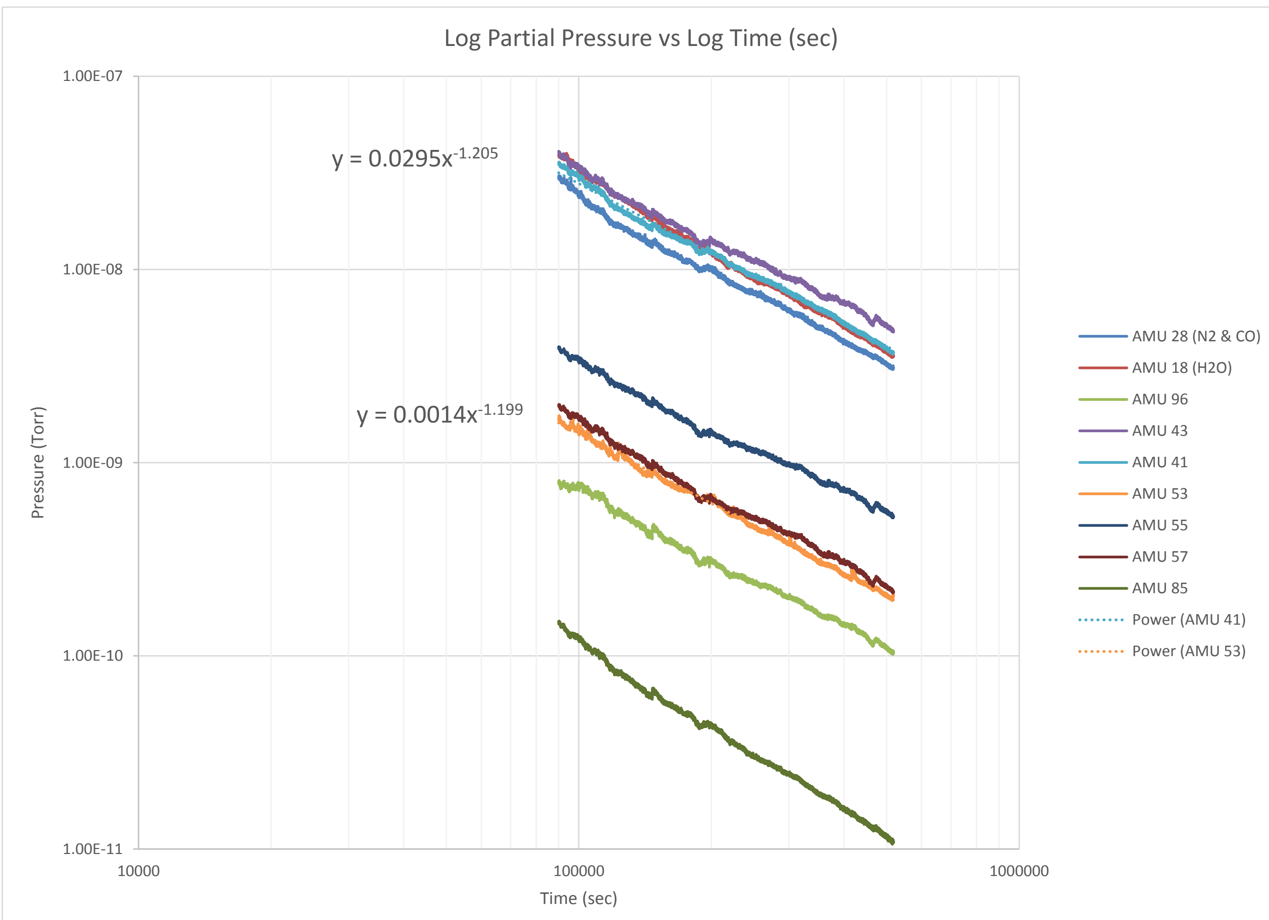

Figure 8: Log Partial Pressures vs Log Time (at 200 mA coil current)

The sum of the ‘flag’ hydrocarbon (HC) outgassing (see REF) as a function of coil temperature is plotted in Figure 9. At room temperature the HC outgas rate is limited by the RGA sensitivity at ~1 x 10^{-12} torr-L/s/BOSEM. The HC outgas rate rose to ~1.5 x 10^{-8} torr-L/s/BOSEM at 179C coil temperature. The HC outgas rate dropped to ~6 x 10^{-9} torr-L/s/BOSEM after 14 hrs at 179C. After colling back to room temperature, the BOSEMs were driven again at 200 mA. The HC outgas rate returned to ~4 x 10^{-9} torr-L/s/BOSEM and then declined to ~4 x 10^{-10} torr-L/s/BOSEM after 143 hrs at 179C. When the BOSEMs were cooled to room temperature again, the apparent HC outgas rate was high (~5 x 10^{-11} torr-L/s/BOSEM) but this is likely because the chamber walls were now dirty from the condensed hydrocarbon contaminants released from the BOSEMs (the chamber walls were not heated). Only a single calibration (Figure 10) was done for this testing and it preceded these two runs by 2 weeks. As a consequence the HC outgas rates are only approximate.

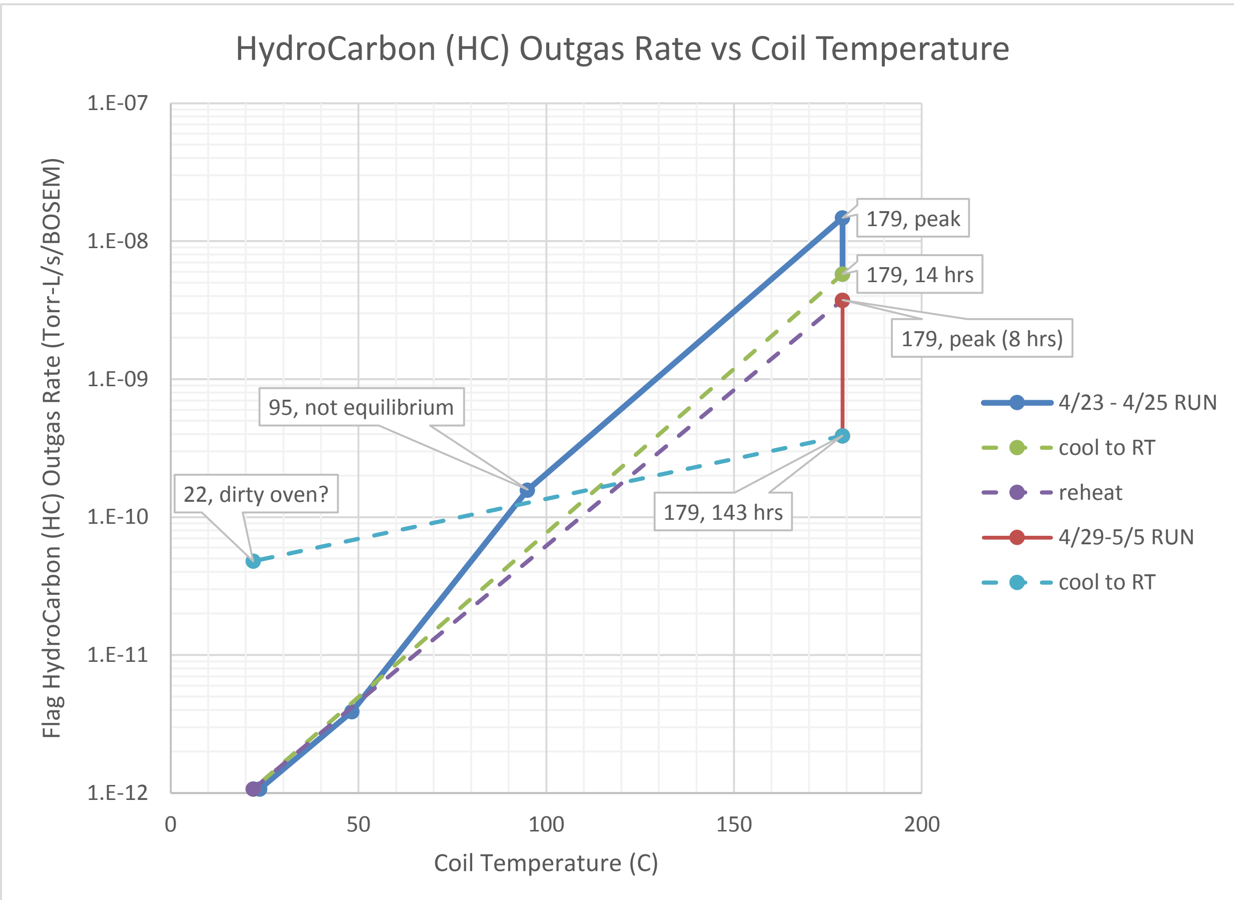

Figure 9: Hydrocarbon outgas rate vs coil temperature

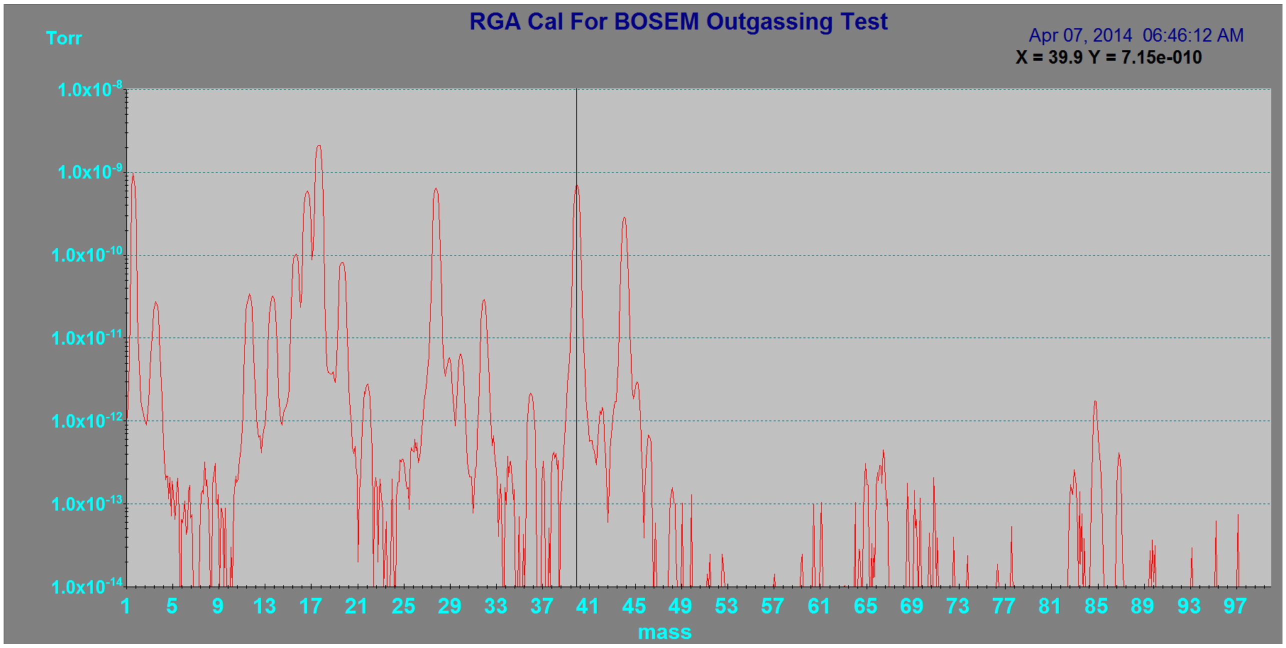

Figure 10: Calibration spectrum

6 Maximum allowed BOSEM HC outgas rate & coil temperature

The number of OSEMs is defined in document E1000042-v2, "OSEM Counts". There are 12 BOSEMs at the top stage of each quad. However we are likely only to use 8 at near maximum current for any given quad; 4 to vertically lift each of the suspension chains, and 2 for each suspension chain (so another 4) to effect a large yaw correction. A large pitch correction would require 1 additional BOSEM per chain. While it is possible then that 10 BOSEMs might be near max drive to correct a highly drooped, pitched and yawed TM, it is not likely that all three conditions are present simultaneously. Hence the assumption of ~8 high-current BOSEMs per Quad in the outgas rate calculation below.

The hydrocarbon partial pressure goal[1] is $P_{hc} = 1 \times 10^{-13}$ Torr. The hydrocarbon pumping rates[2] are S_c~6800 L/s for the corner station and S_e~1700 L/s for the end stations. There is one quad in each end station vacuum volume and 2 quads in the vertex vacuum volume. So the number of high-current BOSEMs is N_e=8 per end station vacuum volume and N_c=16 per corner station, vertex vacuum volume. If these BOSEMs were the sole, or dominant, contributors to the HC partial pressure, then the allowable HC outgassing rate per BOSEM, $f = \min\{ S_c P_{hc}/N_c, S_e P_{hc}/N_e\} = 2 \times 10^{-11}$ Torr-L/s/BOSEM. This corresponds to a BOSEM coil temperature of ~70 C (see Figure 9).

However there are other contributors to the HC partial pressure, so not all of the budget should be given to the BOSEMs. A factor of 5 reduction in outgassing rate (corresponding to 4×10^{-12} Torr-

[1] See for example T1301006-v2, "Hydrocarbons in the LLO LVEA on Dec 17, 2013"

[2] E0900398-v5, "Advanced LIGO residual gas estimate"

L/s/BOSEM) would correspond to a BOSEM coil temperature of 50C; this is the recommended maximum BOSEM coil temperature.

If we assumed that the thermal conditions for the BOSEMs installed in the quadruple pendulum suspension were identical to the thermal conditions in the vacuum chamber in the test reported above, then the allowed coil current would be 105 mA, the coil resistance (at 50C) would be 38.9 ohm and the applied voltage would be 4.08 V. However this is pessimistic, as explained in the next section.

7 Thermal Modeling

The thermal boundary conditions of the test do not match the conditions of a BOSEM assembled to a quadruple pendulum suspension. In order to interpret the test results, a model of the test conditions, and the conditions for an installed quad would be needed.

Of course the equilibrium temperature in vacuum in this test setup is not necessarily indicative of the equilibrium temperature of the BOSEMs when mounted to a quadruple pendulum suspension inside a LIGO BSC chamber. The equilibrium temperature depends upon a complex set of thermal boundary conditions as indicated in Figure 11. In the limit that the chamber insulation is very effective, and the penetrations through the chamber insulation (e.g. pump station plumbing) are minimal conductive heat losses, then the BOSEM temperature would rise to a very high level (and it would take a very long time). If the chamber thermal mass is extremely high then the BOSEM temperature would come to an equilibrium via radiative balance with an ambient at room temperature. In fact the situation is far more complex. The chamber insulation is not perfect, conductive loses through the plumbing and the chamber support stand are likely not negligible and the RGA head and pump station are heat sources as well.

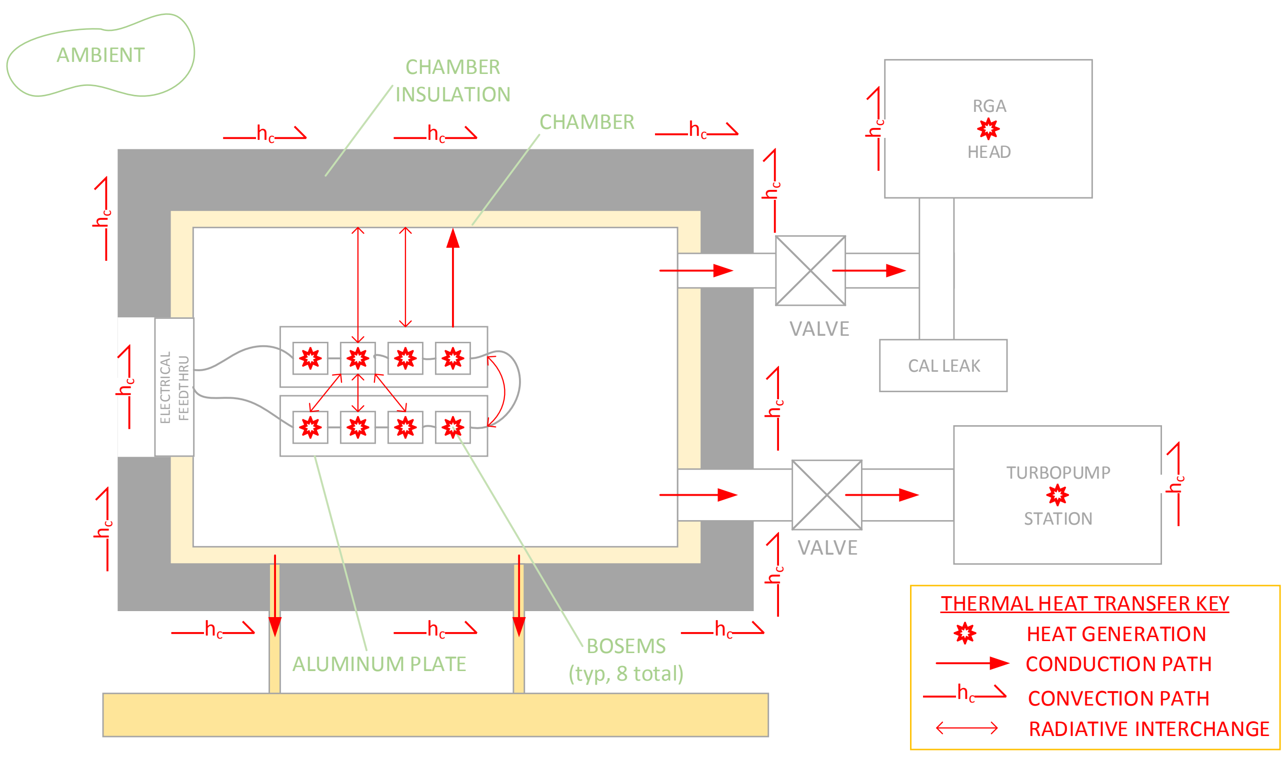

Figure 11: Simple schematic representation of the thermal conditions of the test

Consider a simpler case of a BOSEM not attached to anything (no conductive heat transfer), in vacuum (no convection) and surrounded by a constant temperature (22 C) environment that it radiates to. To simplify the radiative exchange, assume that only the surfaces that (mostly) face outward are effective. Furthermore since the outer surface area is dominated by aluminum, assume that the emissivity of the radiative surfaces is 0.10, appropriate for polished aluminum surfaces. Then the predicted temperature is 150 C, as shown in Figure 12.

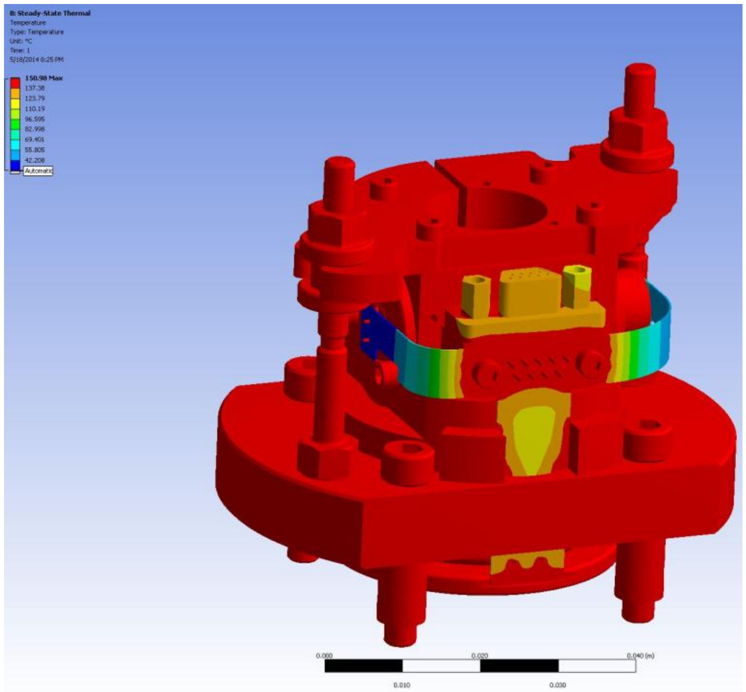

Figure 12: BOSEM with outer faces radiating to 22C ambient with emissivity of 0.10

Note that the peak temperature in this case is not as high as in the vacuum test conducted with the 8 BOSEMs. In the vacuum chamber test the 8 BOSEMs are clustered together. The central four BOSEMs face another warm BOSEM on 3 sides and so can't as effectively radiate heat. In addition, the stainless steel walls of the vacuum chamber will (in time) rise from the initial room temperature value to a warmer equilibrium temperature determined by the balance of radiation (and some conduction) from the BOSEMs to conduction through the insulation surrounding the chamber and conduction through the attachments to the chamber (plumbing to pumps, RGA, etc.). This increase in effective ambient temperature also decreases the efficacy of radiation from the BOSEM.

Now consider the situation of a BOSEM mounted in a quadruple pendulum suspension. We are principally concerned with the BOSEMs on the top stage, mounted to the "tablecloth" structure, since these are the BOSEMs with the highest current drive. The aluminum tablecloth structure is a reasonably good conductor and provides a significant radiative surface. The tablecloth structure is attached to the upper quad structure which in turn is clamped to the BSC ISI optics table. In this thermal model, the chamber walls, the BSC ISI optics table and the Quad pendulum upper structure are considered to be isothermal at 22 C. For simplicity I've just included the tablecloth structure. A single BOSEM is modeled in detail, and only the equivalent heat dissipation is included at the other 7 BOSEM locations at the upper stage. The BOSEM coil temperature at 200 mA is predicted to be only 34 C, as indicated in Figure 13.

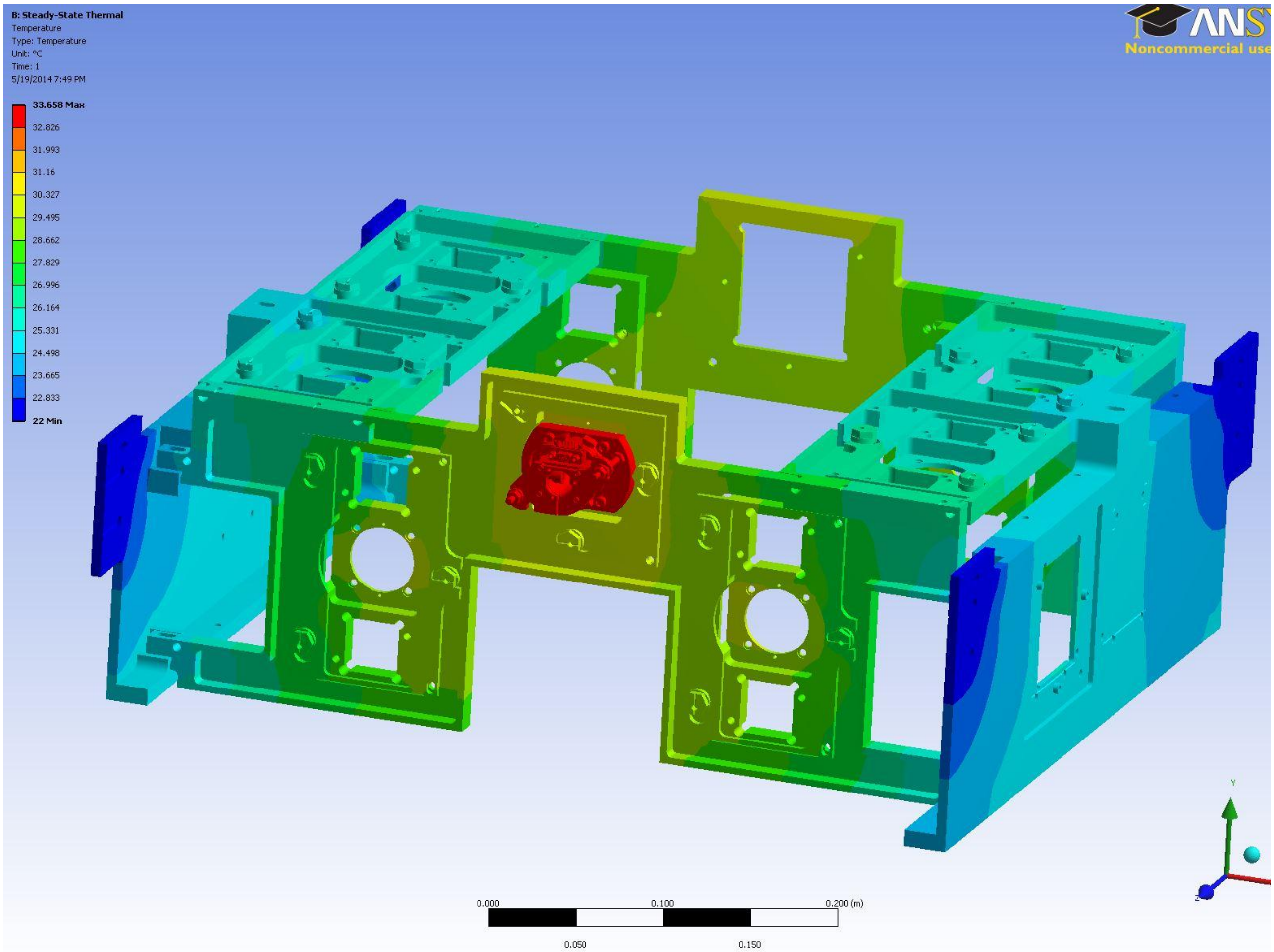

Figure 13: Predicted BOSEM coil temperature for 200 mA coil current

However note that a lot of assumptions have gone into this model. It is best to measure the actual coil temperature as a function of coil current for the in situ situation. This would require a temporary breakout box to allow measurement of the drive current and the voltage. The voltage to current ratio then gives the coil resistance and then Figure 3 can be used to infer the coil temperature.