Note on Vertical Test Results of Cavity TE1AES004

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Background

Cavity TE1AES004 is a single cell cavity manufactured by AES Corporation. It was initially processed (BCP) and tested at Cornell University, where it reached a maximum gradient of 25MV/m, limited by field emission and low Q_0 (1.4×10^9). It was then shipped to Fermilab/ANL for EP processing, HPR, assembly, and test.

Tests & Results

The first post-EP test cycle was performed from 9/25/08 to 10/7/08.Testing included Q_0 vs T measurements down to 1.5K, Q_0 vs E measurements at 2K, and testing of the single-cell diode thermometry system.

Results are shown in Figures 1 and 2. Measurements of cavity Q_0 as a function of temperature yield a residual resistance of about 2nΩ (this is using the 9-cell cavity geometry factor - it may be marginally different for a single cell cavity). During power tests at 2K, the cavity reached a maximum gradient of 33.1 MV/m, and was limited by Q-drop and field emission. At maximum gradient the incident power was about 240W, with a dissipation of 113W. The Q_0 at this point had dropped to just over 1×10^9 . The onset of field emission was 23 MV/m, with a maximum x-ray flux at maximum gradient of 3.3 mR/hr. Strong Q-drop begins at abut 26 MV/m, where the radiation reaches 0.1 mR/hr. The low field Q_0 was between 1.4-1.5 $\times 10^{10}$.

Measurements of cavity Q_0 and gradient at 2K were performed on three separate occasions, in support of thermometry system measurements. The results were consistent each time, as can be seen in Figure 2. No real processing of the field emission was observed.

After warmup, it was decided to attempt in-situ baking of the cavity at 120° C, in order to determine if the Q-drop was entirely due to FE loading, or surface oxides (in which case performance could be recovered by baking). This was accomplished using a makeshift baking system consisting of a heater tape and integrated controller with thermocouple. The heater tape was wrapped around the cavity, including the beam pipes, and the cavity was then covered with fiberglass insulation. The control thermocouple was mounted on the cavity surface at the equator near a heater tape, while two other thermocouples were mounted on the cavity at the equator, but as far as possible from a heater tape. It was surmised that this configuration would provide the best estimate of the thermal gradient over the cavity during baking. During operation, the controller was set to maintain a temperature of 120°C based on feedback readings from the control thermocouple. During baking, the secondary thermocouples measured a cavity surface temperature of about 115°C, indicating a reasonably uniform cavity temperature. The cavity was baked for about 49.5 hours, and actively pumped the entire time. The diode thermometry system was removed before baking began and replaced afterwards.

The cavity was re-tested during the period 10/23-28/08. The result of initial cable calibrations were questionable, indicating substantial differences in correction factors from previous calibrations performed during the last test cycle. Repeated calibrations produced reproducible (identical) results. While stable, repeatable calibration results should not, a priori, indicate a problem with the RF system, the significant change from previous calibrations (with an essentially identical configuration) was cause for concern. This concern was justified when erratic results were obtained while performing Q_0 measurements as a function of temperature on 10/23/08.

The next day, a careful evaluation of all of the high power RF components was performed, and it was found that the incident power cable from the patch panel to the Dewar top plate had a faulty connector that led to changes in attenuation resulting from handling. The cable was replaced and subsequent calibrations reproduced the earlier (10/3/08) correction factors to within 3%.

A Q_0 vs E run was then performed at 2K, as shown in Figure 3. Field emission began at about 16MV/m (to be compared with 23MV/m from the pre-baking test), again leading to a strong Q-drop. This time, the maximum gradient reached was only 23.8MV/m with a Q_0 of 1.4 $\times 10^9$. The radiation at maximum gradient had increased to 8.4mR/hr - an almost 3-fold increase, but at ~70% of the previous field. This increase in field emission is attributed to a leak in the cavity vacuum system that appeared during the warmup following the 1st test cycle. A “split-Conflat” flange on the pumping line was found to be the source of the leak; probably as a result of mechanical stress applied during test stand transport to this less-than-ideal joint design. It was temporarily repaired by changing the Cu gasket and constraining the flange halves with a SS hose clamp, before baking of the cavity commenced. This joint then remained leak tight throughout the following test cycle and subsequent warmup. A permanent fix (replacement of the “split” Conflat with a full Conflat flange) is underway.

During this Q_0 vs E run, heating of the cavity was observed. At a gradient of ~16MV/m (coincident with onset of FE), the Cernox sensor mounted on the bottom beam tube (approximately half way between the cavity lower iris and end flange) began to exhibit a temperature increase. This ΔT reached 70mK at ~24MV/m, right before the cavity reached a thermal instability (accompanied by a sharp drop in Q_0 and decreased gradient). The cavity was clearly heating up and only recovered when the field was reduced – essentially exhibiting “Q-switch” behavior. This effect was reproducible. The other three Cernox sensors (mounted on both end flanges, and on the upper beam pipe in a location analogous to the lower beam pipe one) did not show any temperature increases.

After this Q_0 vs E run, the Dewar was them pumped down from 2K to 1.5K in order to obtain Q_0 vs T data with the corrected cable configuration/calibration. After taking data at 1.48K, the Dewar was warmed up so that so data above the λ-point could be taken as well. The data are shown in Figure 4, along with data from the pre-baking test on 9/29, and data from a second set of measurements taken on 10/28. The data from this current run indicate a residual surface resistance somewhat higher than that measured during the pre-baking tests - ~6nΩ as opposed to the ~2nΩ measured previously.

During this test cycle some anomalous input cable heating was observed. The input cable in-Dewar segment attenuation changed by a few 10ths of a dB over the power range 0-50W. This required that this particular segment of cable be re-calibrated periodically (as a function of input power) during a measurement run. This is not a normal mode of operation. It was decided to perform a quick warmup of the Dewar, so that the input cable/connections could be evaluated.

Upon removal of the stand from the Dewar, the input cable connections were inspected. They were found to be tight, and the connectors themselves showed no evidence of breakdown (discoloration, "soot", etc.). Measurement of cable attenuation gave a value of 0.78dB – well within the expected range. Additional TDR measurements gave no indication of a cable fault. The cable was re-attached to the cavity and the Dewar cooled down again. Calibration of the RF cables yielded correction factors in excellent agreement (to within 2%) of the previous calibration.

A set of Q_0 vs T measurements from 4.4K to 2K were once again made, and are shown in Figure 4 along with previous data. The data from this run more closely match those of the pre-baking data taken on 9/29. However, during this set of measurements, and subsequent Q_0 vs E measurements, we once again observed some erratic behavior related to the input cable power correction factor, necessitating periodic re-calibration. As a result, there is some substantial uncertainty in the measured values of Q_0, and hence R_s, that may be larger than the systematic errors indicated by the error bars in Figure 4.

In Figure 5 are shown the data from the Q_0 vs E measurements. Except for a slightly higher low-field Q_0, the data are in general agreement with those taken before the cavity was warmed up to inspect the input cable connections. In Figure 6 we compare these data with the pre-baking data. Clearly the cavity performance has been degraded substantially by the additional field emission that resulted from the vacuum system leak. While it appears that the low-field Q_0 has improved as a result of the bakeout, it is not clear if unmitigated uncertainties or instabilities in the cable calibration are instead the cause of the improved Q_0 values. It is clear that the high-field Q drop is a direct consequence of the heavy field emission and baking is not likely to have had any positive effect there.

Summary

After being EP'd at ANL, cavity TE1AES004 improved somewhat in performance. The maximum gradient increased to 33MV/m from 25MV/m, but the low field Q_0 was about 25% lower (1.5×10^{10} vs 1.9×10^{10}); however that may be a consequence primarily of a slightly lower test temperature at Cornell. The cavity performance limit after EP was again strong FE, which led to a strong Q-drop. The onset of FE was about 23MV/m, an improvement from the 18MV/m recorded at Cornell. In both cases, the Q_0 dropped to about 1.4×10^9 at the respective gradient limits.

After the first round of post-EP tests, the cavity was baked in an attempt to determine if any of the Q-drop could be recovered. Unfortunately, during removal from the Dewar, the cavity vacuum system on the test stand developed a leak, which led to particulate contamination of the cavity. This manifested itself in a sharply reduced FE onset level, and higher overall radiation. This, coupled with some erratic behavior of the RF input cable, makes it difficult to ascertain the effect of the baking on either the residual surface resistance (R_s) or Q_0 at low fields. The high field Q_0 behavior is unchanged; a strong drop dominated by FE loading.

Subsequent investigation of the RF input cable and associated connectors after the last round of tests did not reveal any obvious cable damage or problems. Once again, the cable attenuation will be measured and TDR measurements performed. The input and transmitted power coupler have been removed from the cavity and inspected; neither show any visible signs of damage or compromised integrity.

Give the strong Q-drop associated with this cavity, and the relatively high levels of radiation for a single cell with substantial radiation shielding between it and the detector, it is possible that the cable heating could be the result of high levels of FE impacting the coupler region (the beamline flange at the top of the cavity, in this case). This is supported by the thermal instability observed at high field during the second thermal cycle (which was not present during the first post-EP test cycle). This instability indicates that some substantial heating of the cavity occurred, which required a sustained reduction in power/field in order for the cavity to recover.

During these tests of TE1AES004, the single cell diode thermometry system was exercised. While reporting of these results is not in the scope of this document, a few observations can be made. During the first thermal cycle, when the cavity reached 33MV/m, the diode thermometry did indicate the “strip-like” heating at high fields that is customarily associated with field emission source and impact points. During the second thermal cycle, this response was less clear, and the diodes seemed to register more of a global heating, especially in the lower regions of the cavity. If true, this might indicate a greater density of field emitters during the second test cycle, possibly as a consequence of the contamination introduced by the vacuum leak.

A Note on Field Emission

Even if we ignore the results from the second post-EP test cycle of cavity TE1AES004 (where we contaminated the cavity via the vacuum system leak), we note that every cavity that has been processed and/or assembled at FNAL/ANL for vertical test has shown rather poor field emission performance. In all cases where a cavity was first tested at FNAL after receipt from, e.g., JLab, and then re-assembled or re-processed, there has been a substantial degradation (decrease) in FE onset.

For example, the large-grain single cell used for initial VTS commissioning reached 27MV/m, with a FE onset of 20MV/m. When EP’d at ANL and re-assembled, it only reached 22MV/m, with a FE onset of 15MV/m. When cavity AES03 was tested after receipt from JLab, it reached 19.6MV/m with a FE onset of 12MV/m. After assembling the variable coupler onto it here at FNAL, it only reached 11.5MV/m, with a FE onset of 6-7 MV/m. Likewise, cavity A6 reached 39MV/m with a FE onset of 28MV/m when received from JLab, but after installation of the variable coupler, it only reached 21 MV/m, and had an initial FE onset of 6 MV/m. The HINS cavity also showed FE during all tests. Now, while this is not an overwhelmingly large data sample, the fact remains that cavity performance has been degraded by increased field emission every time a cavity is assembled and/or processed at FNAL/ANL.

So while some in the SRF field wish to declare that FE is no longer a problem, as they push towards an understanding of more fundamental limitations (pits, grain boundaries, Nb sub-oxides, etc.), we must recognize that, here at FNAL at least, field emission **IS** the performance limiting factor in cavities that are processed/assembled at FNAL/ANL facilities. This is not to be unexpected given that we as an institution are just beginning to develop the skills, techniques, processes, and procedures needed to perform this work. Not surprisingly, the demands of higher gradients (and surface fields) and larger cavity surfaces associated with the 1.3GHz program may not be adequately met by procedures or experience levels that are sufficient for the 3.9GHz cavity program.

Given our FE problems, it would be prudent to direct sufficient attention and resources to understanding the root causes of this issue, and towards implementation of solutions. If we do not, we will be unable to credibly contribute to any ILC S0 or Project X cavity processing and test activities, since we will be plagued by field emission, which will prevent us from addressing more fundamental cavity limits that lie at the upper end of cavity performance phase space.

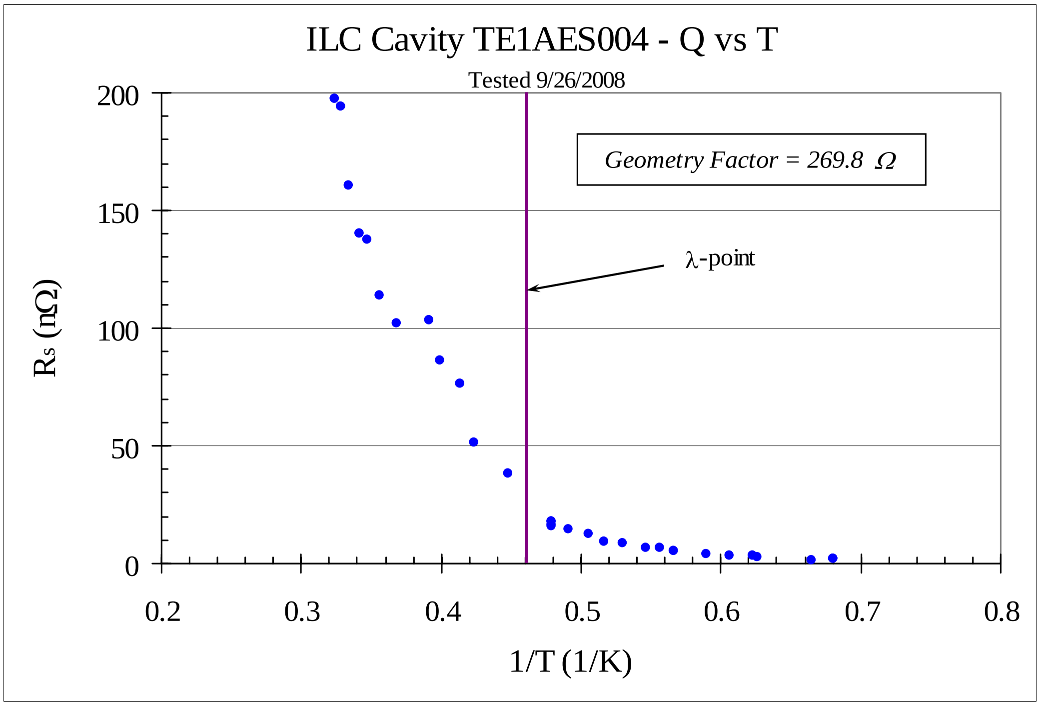

Figure 1.) R_s vs T, first post-EP test.

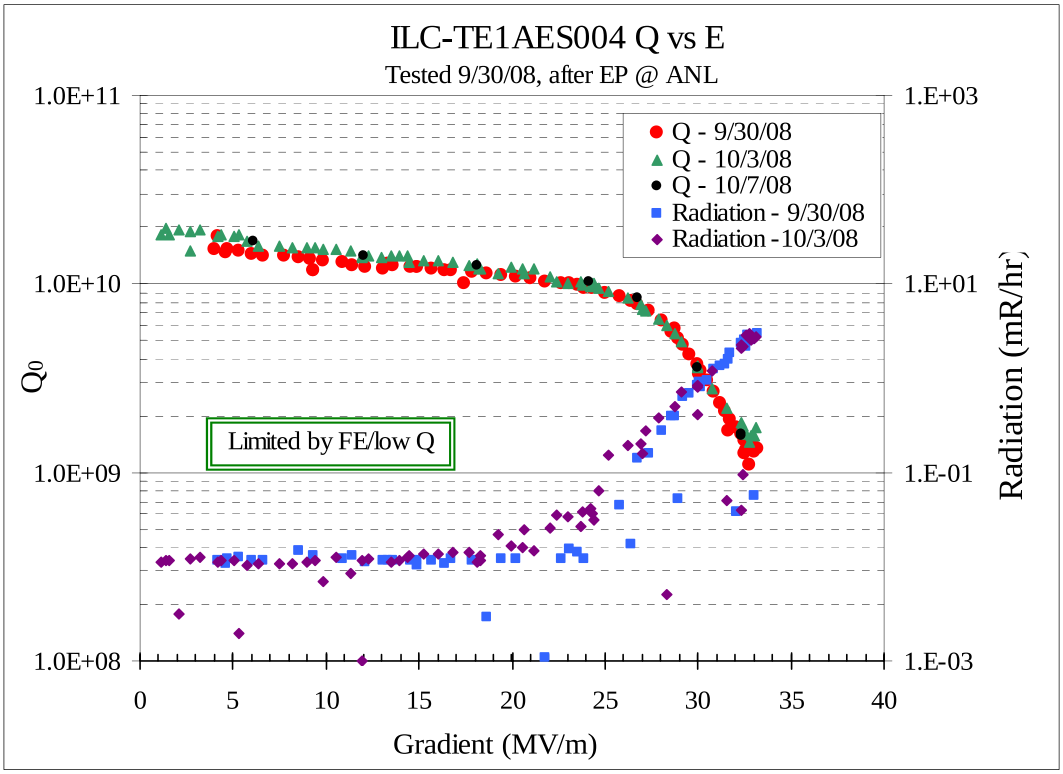

Figure 2.) Q_0 vs E for several power runs, over about a week, first post-EP test cycle.

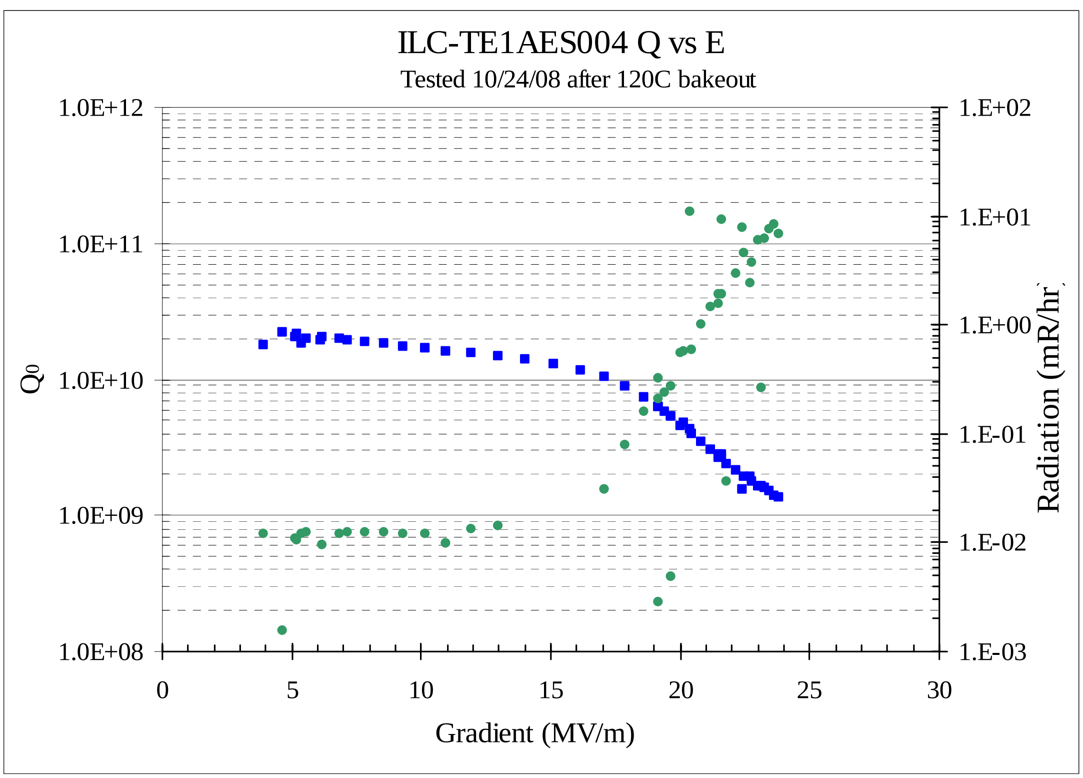

Figure 3.) Q_0 vs E run at 2K, after 120° C bakeout

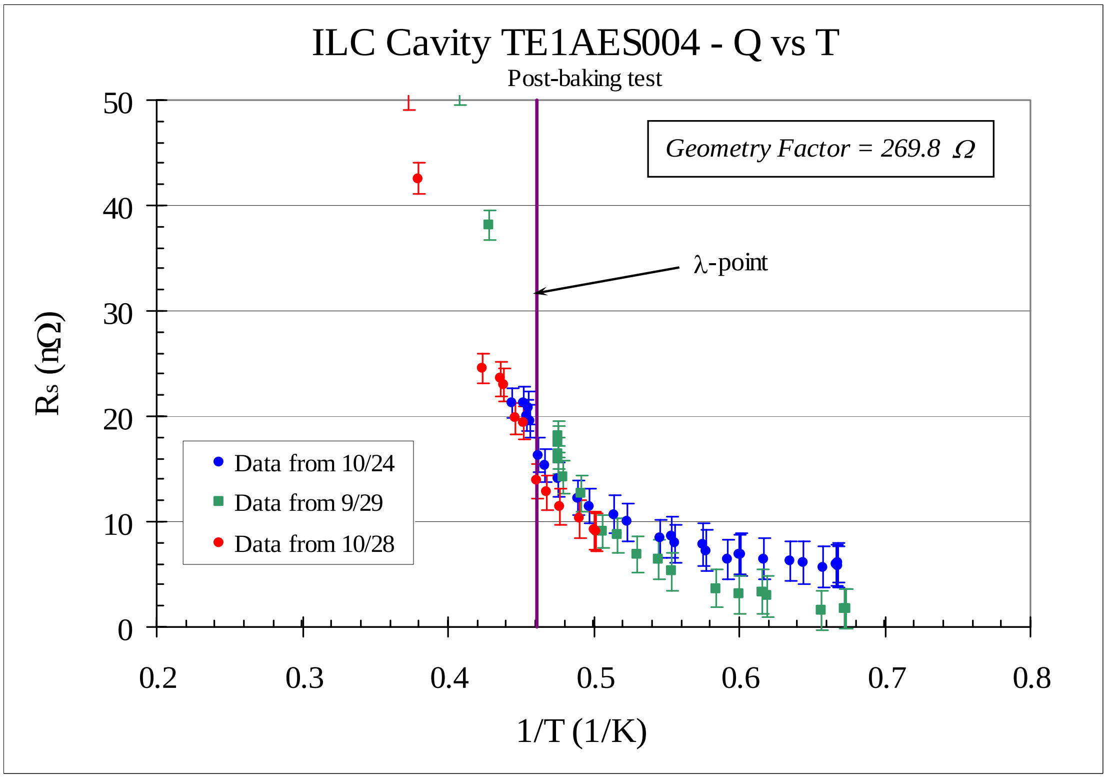

Figure 4.) R_s vs T data, before and after bakeout. Two post-bakeout runs are shown, indicating the uncertainty in R_s due to possible cable calibration issues.

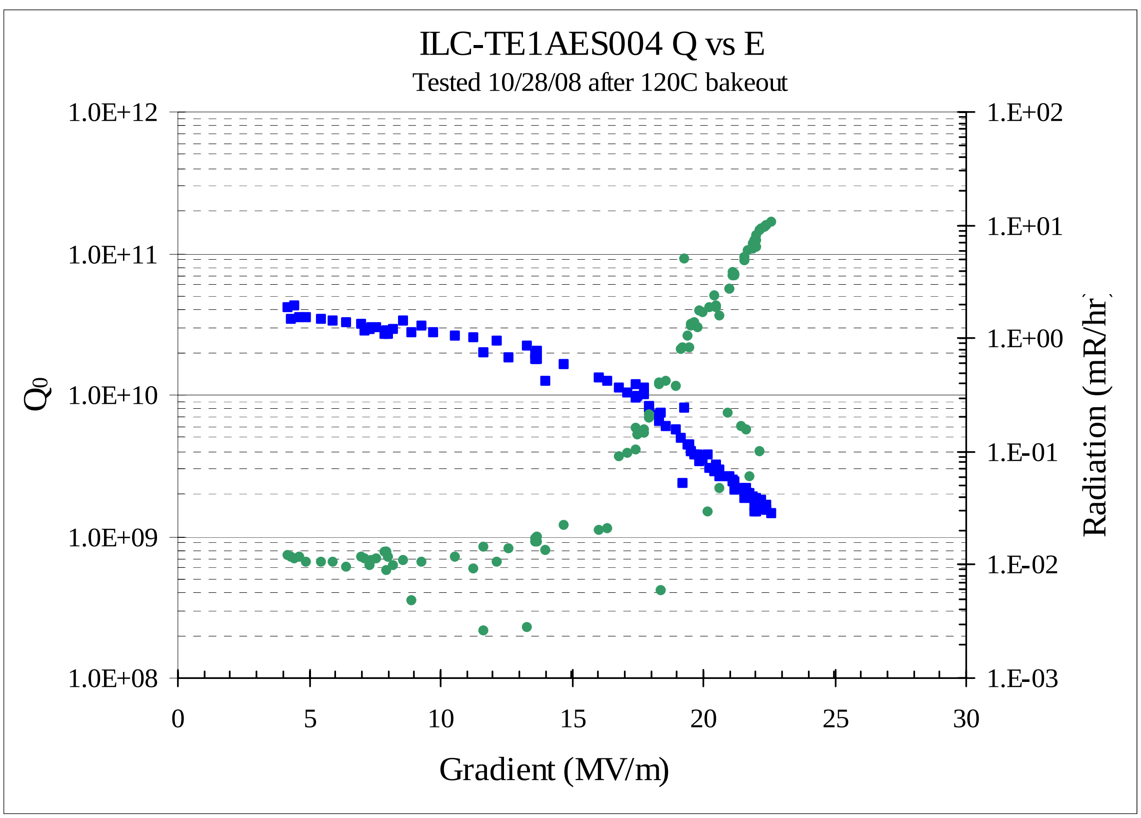

Figure 5.) Q_0 vs E run at 2K, after 120° C bakeout, and after thermal cycle to inspect input cable

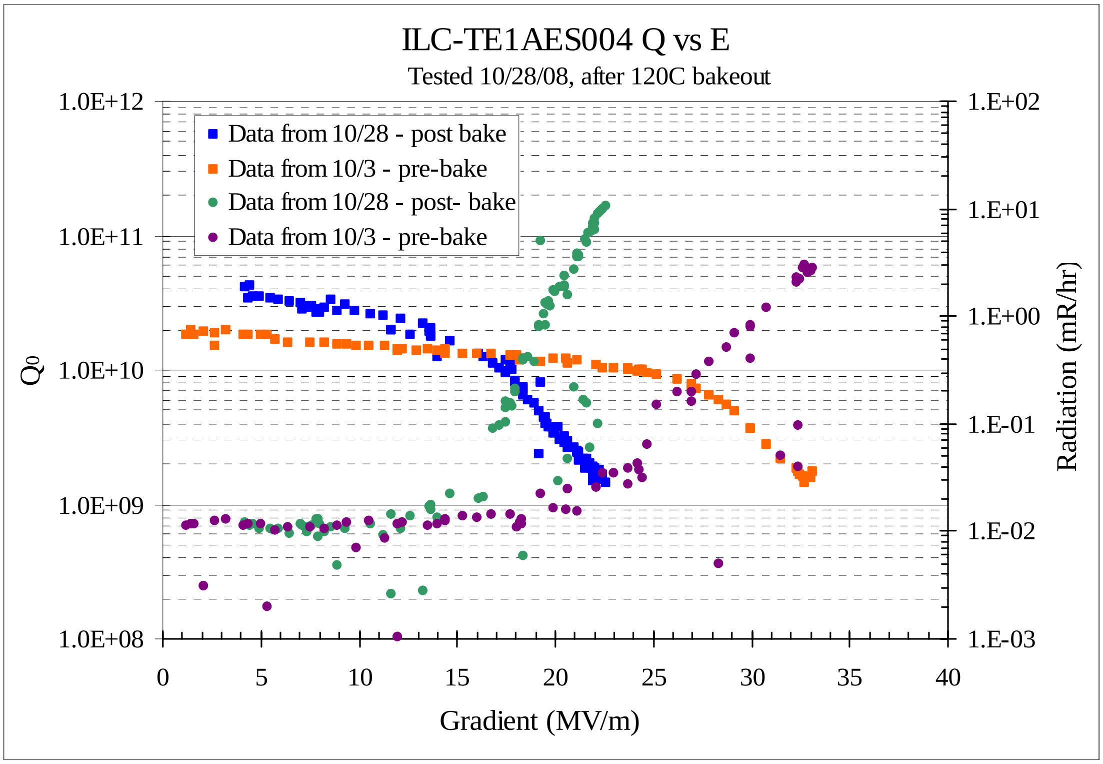

Figure 6.) Comparison of pre- and post-bake Q_0 vs E performance at 2K.