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A TEST PROTOCOL TO SCREEN CAPACITORS FOR RADIATION-INDUCED CHARGE LOSS

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Abstract

This report presents a test protocol for screening capacitors' dielectrics for charge loss due to ionizing radiation. The test protocol minimizes experimental error and provides a test method that allows comparisons of different dielectric types if exposed to the same environment and if the same experimental technique is used. The test acceptance or screening method is fully described in this report. A discussion of technical issues and possible errors and uncertainties is included in this report also.

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1 INTRODUCTION

Electronic systems that require hardening to nuclear threats, and in particular ionizing radiation, use capacitors for important aspects of circuit design. Capacitors are used for energy storage and release, as parts of filters for input and outputs, for signal conditioning, and for power supply decoupling. During radiation, the capacitor leakage resistance decreases. Therefore, the time constant of the circuit will also decrease. If the capacitor is in a critical timing circuit, the timing circuit may produce errors that affect system performance. Whenever possible, a designer of radiation hard circuits should choose capacitors made with dielectric materials that exhibit low prompt transient conductivity and minimal delayed conductivity.[1, 2]

Since capacitors are critical components in hardened electronic circuit design, we have developed and quantified a test or experimental method that allows relatively unambiguous comparison of the performance of advanced capacitor technologies in ionizing dose rate environments with respect to capacitor charge loss or discharge. Other investigators have measured capacitor charge loss in the past[3-6.]

Using the standard semi-classical electron model from solid state physics, we find that allowable energy states for the electrons in the solid are not continuous or nearly continuous, but contain gaps or forbidden regions. The nearly continuous regions are referred to as bands and forbidden regions as band gaps. A full or nearly full band is called the valence band and an empty or nearly empty band the conduction band. If a band is full, then there are no nearby states (in energy and momentum) for an electron to move into. Hence the valence band electrons are unable to absorb energy from the electric field and participate in electrical conduction. An electron in the conduction band has many nearby empty states that it can move into upon absorption of a small amount of energy and therefore conduction occurs.

For a dielectric (insulator) the band gap is large relative to room temperature thermal energies, and the valence band is full and the conduction band is empty, leaving no electrons available to participate in the conduction process. However, in the presence of ionizing radiation where the energy from the radiation that can be imparted to an electron exceeds that of the band gap, an electron may transition to the conduction band and electrical conduction will take place.

By definition, all dielectric materials become electrically conductive when exposed to ionizing radiation. Capacitor dielectric materials are no exception. In addition to the electrons, now that the valence band has some vacancies, conduction can also take place there. The change energy and momentum of vacancies (holes) can be expressed as the motion of positive charge often referred to as holes. This conductivity does not persist indefinitely. Eventually the electrons in the conduction band will lose their energy and return to a vacancy in the valence band. This process is often referred to as electron-hole recombination. The amount of radiation-induced conductivity (RIC) can vary widely with dielectric material type depending on its band gap, lifetime before recombination, scattering, and other factors. Depending on the nature of the material and scattering processes, conduction may cease very quickly after radiation or persist for 100s of ns. If there are impurities in the dielectric, they may produce isolated states within the band gap, often referred to as traps. An electron or hole may leave its band and enter this isolated state, where it will cease to contribute to the conduction process. (In the case of a hole trap the impurity contributes an electron to the valence band, thus filling a vacancy.) If some of these traps are near the band edge the trap may be only metastable at room temperature and the electron or hole may return to the conduction process until eventually recombining or trapping again. This often slow process can produce a delayed conductivity that persists long after the irradiation has ceased. For these studies we not only characterized the prompt charge loss (or conductivity) that occurs during the radiation pulse, but often observed the occurrence of a delayed component of charge loss (or conductivity) after the radiation pulse.

Capacitor discharge can appear linear for low doses or small ranges of ionizing dose, but the actual behavior of discharge is non-linear with dose, often expressed as an exponential. Most of the time, it is wise to choose capacitors whose charge loss is small and can be approximated as linear in the regime of the radiation requirement. This requires that the chosen capacitor types have a fairly small percent of charge loss for hardened systems with high radiation requirements.

The test protocol described in this report is most appropriate for screening capacitors for charge loss caused by ionizing radiation. It can be used to identify capacitors whose radiation response is adequate to meet system radiation requirements. This can be done experimentally.

2 THE TEST PROTOCOL

The protocol for how we performed the capacitor charge loss measurements is given below: First a description of the test facility and our hardware is given. The test protocol is most appropriate for screening capacitors for charge loss caused by ionizing radiation.
It can be used to separate capacitors whose radiation response is inadequate from those that can meet system radiation requirements. This can be done experimentally. A full description of the accuracy possible with this testing is included

(1) TEST FACILITY: Our chosen test facility was the LINAC at LMTF near Ogden, UT. This LINAC was operated at a nominal 20 MeV. We used the electron beam to irradiate our capacitor samples. We recommend a pulse width between 5 and 10 microseconds at a dose rate of about 1E9 rad/s for initial characterization of charge loss per unit dose which provides a dose of 5 to 10 kilorads. We used an aluminum scatter plate of 0.80 cm thickness on the front of the LINAC to assure uniformity of the beam over the collimated exposure area. If another LINAC is used, we recommend radiation pulses ≥2 microseconds. We also recommend LINAC energies of 10 – 20 MeV.

(2) COLLIMATION: We collimated the electron beam so essentially only the capacitor samples were exposed to the beam thus assuring that instrumentation cables were not exposed. The diameter of the collimator was tailored to the size required to expose two to three capacitors at a time. The diameter varied from 1.2 to 2.0 cm. The collimator was constructed of Tungsten and was 1.6 cm thick. The collimator should be thick enough to essentially stop all primary electrons from the LINAC. Some scattered and fluoresced electrons and photons will be present, but a sufficient collimator thickness minimizes the radiation present outside the collimated area.

(3) VACUUM CHAMBER: We used a vacuum chamber to house the capacitor samples and the circuit board on which the capacitors were mounted. The vacuum chamber was evacuated to a pressure of 2E-4 Torr. Pressures below 1m Torr render gas RIC negligible. The vacuum chamber is shown in Figure 1 and drawings of the vacuum chamber are in the appendix to this report. The vacuum chamber had a front window of 0.0025 cm thick Titanium. The electron beam was allowed to transit through the relatively thin vacuum chamber and “get lost” in the facility room housing the LINAC.

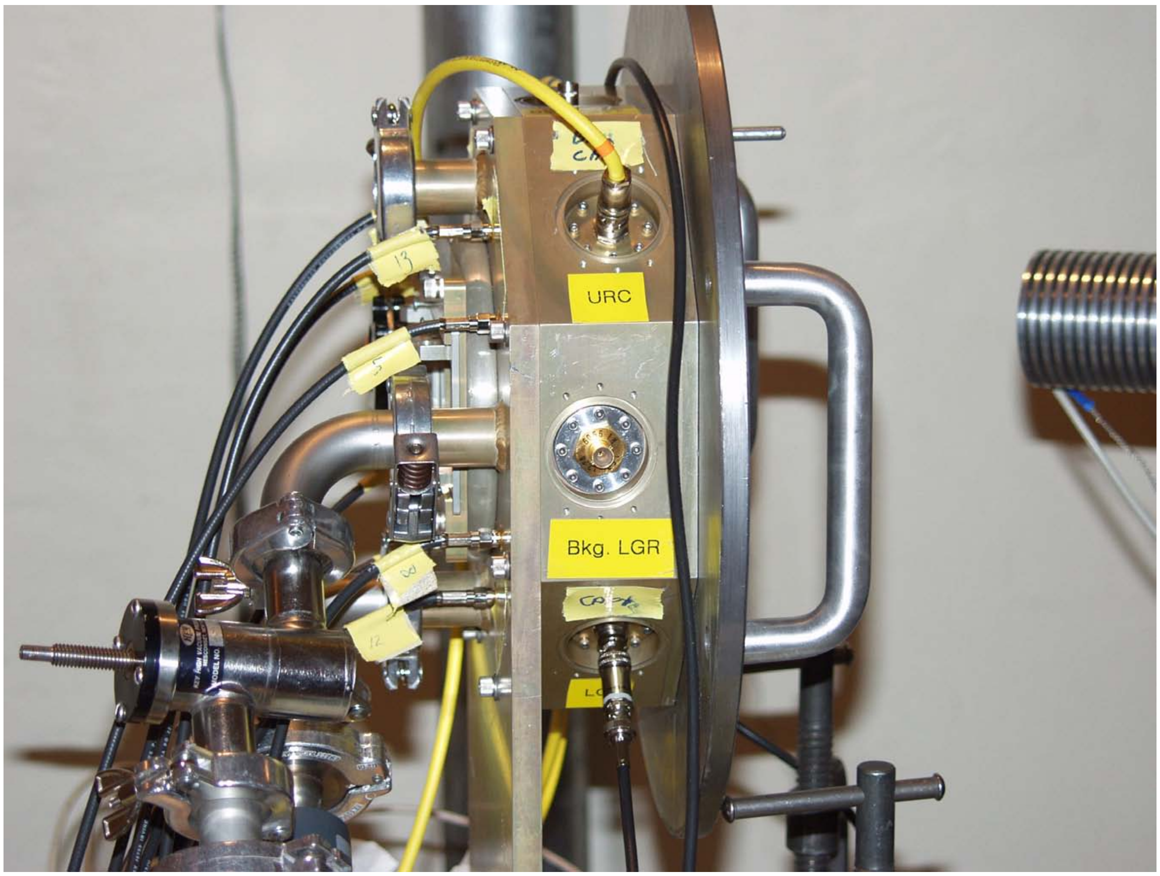

Figure 1 Custom Vacuum Test Chamber for Capacitor Testing

(4) CIRCUIT BOARDS: Our circuit boards were designed with buried traces and minimal conductor area and attachments to mount and instrument the capacitors and supply bias to the capacitors. Buried traces and minimal trace area minimize the radiation-induced response of the test board itself. An example of a test board is shown in Figure 2. At the center of the circuit board are mounted three test capacitors of identical type which were tested simultaneously. The exposure area or collimated area is shown in Figure 2 as a circle drawn around the three capacitor samples. Note that a single background capacitor was mounted outside the exposure area on the same board (left of center in picture) to assure that a background signal was recorded on each experimental shot.

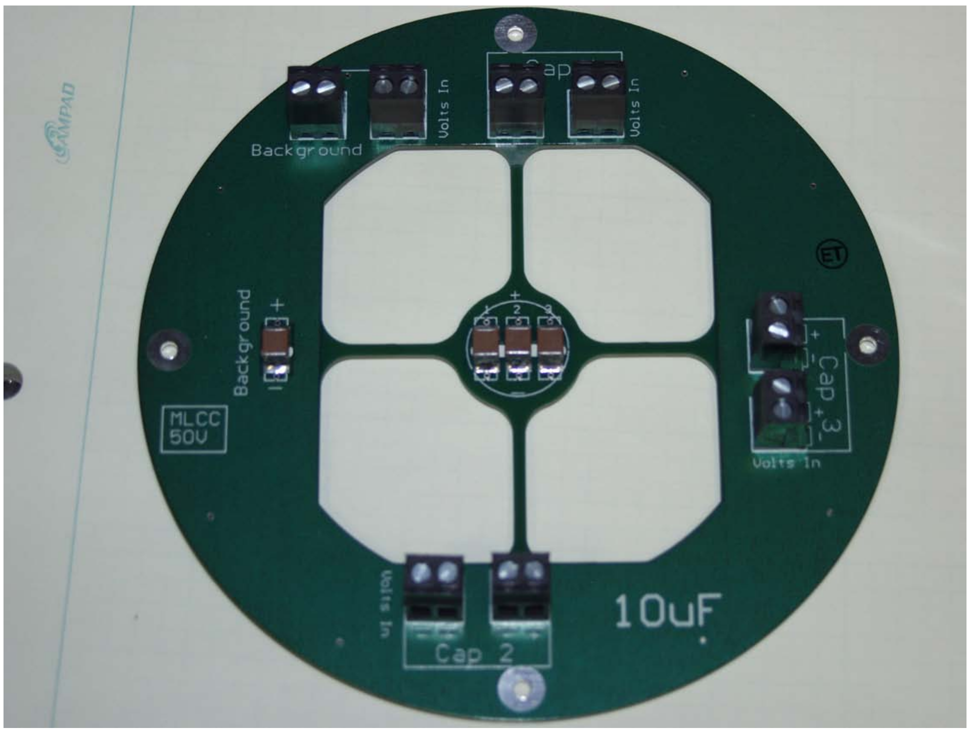

Figure 2 Test capacitors mounted on special test board

(5) EQUIPMENT: Power was supplied to the capacitors using Power Design model C500 Power Supplies. The power supplies used were precision power supplies although less precise supplies that can fully charge the capacitors can be used. After fully charging all the capacitors simultaneously (each with an individual power supply), power was disconnected before the experiment. Capacitor charge loss before and after the short LINAC exposure was monitored using very high impedance (>1E16 ohm) Keithly model 6517A Electrometers. Vacuum feed through triaxial connectors and low loss triaxial cables were used to connect to the electrometer.

(6) DOSIMETRY: For dosimetry we relied on custom silicon calorimeters for the absolute dose measurement. We calibrated the LINAC source for each pulse width and axial distance from the LINAC. The LINAC proved to be virtually repeatable shot to shot at the same location on subsequent shots. Never-the-less, we established correction factors for each capacitor type for both PIN diodes and PCDs so dose corrections could be made as necessary on each LINAC shot or exposure. We chose silicon calorimeters over

TLDs as TLDs can have some issues with accuracy at higher doses and dose rates. The experimental procedure or steps used to characterize capacitor charge loss are described below:

(1) The radial location for the experiment is established by first assuring our experiment (the capacitors' fixture or board) is aligned with the center of the LINAC beam. This is accomplished using the low power alignment laser supplied by the LMTF and mounted on the back wall of the facility. Without our vacuum fixture in place we burn a bubble like spot in a plastic film to establish the center of the LINAC beam. The laser is then aligned to this center position. We then move our vacuum fixture in place and align the laser to the back of our fixture which has cross-hair indicators. The circuit board with capacitors aligns to the back cross hairs by being securely bolted in a rigid position within the vacuum chamber.

(2) Next we establish the desired axial position away from the LINAC beam port for each pulse length, by mounting the silicon calorimeter in the exact position where the capacitors will be during testing. We find the axial position that provides the desired dose (say 10 kilorads) for a particular pulse width.

(3) We then use "throw away" capacitors of the type to be tested to calibrate both PIN diodes and PCDs behind the capacitors to establish a correction factor. Note the calorimeter can be reinserted as a check at this point, but the LINAC is so repeatable this step has not been proven to be necessary. The calibration is performed for multiple shots. Each time the fixture is moved axially or the capacitor type is changed we recalibrate the dose measurement system.

(4) Next we put in new capacitors of the same type and close vacuum chamber and draw a vacuum to 2E-4 Torr.

(5) At vacuum we charge all the capacitors using separate power supplies for 30 minutes in order to assure that they are fully charged.

(6) We first obtain a record of the non-radiation discharge behavior. We trigger instrumentation and record voltage (capacitor charge) for approximately 30 seconds with the power supplies connected. We then disconnect the power supplies and for 14 minutes 30 seconds monitor the capacitors discharge characteristics.

(7) We then recharge capacitors for 30 minutes. Of course in actual use the capacitors may not be in a fully charged state during radiation.

(8) We next trigger instrumentation and record capacitor charge for approximately 30 seconds with power supply connected. We then disconnect the power supplies for 30 seconds at which time the LINAC is fired. Recording continues for another 14 minutes. (Note: the first 2 seconds of readings after the radiation pulse are defined as prompt.)

(9) (Note: if the early time behavior of the capacitor charge loss is important these recording times can be greatly shortened as the Keithly electrometer records 1E5 points regardless of the recording time. The minimum recording time for the Keithly is one point per 8ms. If faster recording time is required then scopes will have to be used.)

(10) Typically we repeat the measurement 2 to 3 times at the same location, dose and pulse width.

3 DISCUSSIONS OF TECHNICAL ISSUES, ERRORS, AND UNCERTAINTIES

3.1 Radiation Source Errors and Uncertainties

If a radiation source in not capable of providing consistent or repeatable output including spectrum, pulse width and flux, then the difficulty of performing repeatable and interpretable experiments is greatly magnified. We chose the Medusa LINAC at the Little Mountain Test Facility (LMTF) because it is capable of producing repeatable and predictable radiation output over long periods of time (such as reproducible pulsing over a week of experiments). We found through repeated testing that our dosimetry consisting of silicon calorimeter, PIN diode and PCD diamond detectors gave consistent repeatable readings shot to shot for the same conditions such as fixed distance from the source and fixed pulse width. The variation at the same conditions was approximately 1% shot to shot. We chose not to use very short pulses (<1 microsecond) as there is a leading edge on the radiation pulse that is a bit variable that had the potential to introduce uncertainties in the delivered dose in our test capacitors. By using pulse widths of 2 to 10 microseconds we effectively made the leading edge a very small part of the overall pulse.

Figure 3 shows the Medusa LINAC in background and our vacuum test chamber, associated cabling and vacuum system in the foreground. The nominal electron energy for the LINAC is about 20 MeV. The LINAC can provide radiation pulses of varying widths up to 50 microseconds. The pulse shape is basically rectangular for pulse widths from 2 to 50 microseconds. Since we wanted to work with a defined consistent pulse shape, the duration of the pulse and LINAC capabilities meant we performed our experiments in the 1E9 to 1E10 rad(Si)/s range. This allowed capacitor measurements to be made in a dose rate/dose range where the capacitor charge loss is approximately linear for most capacitor types.

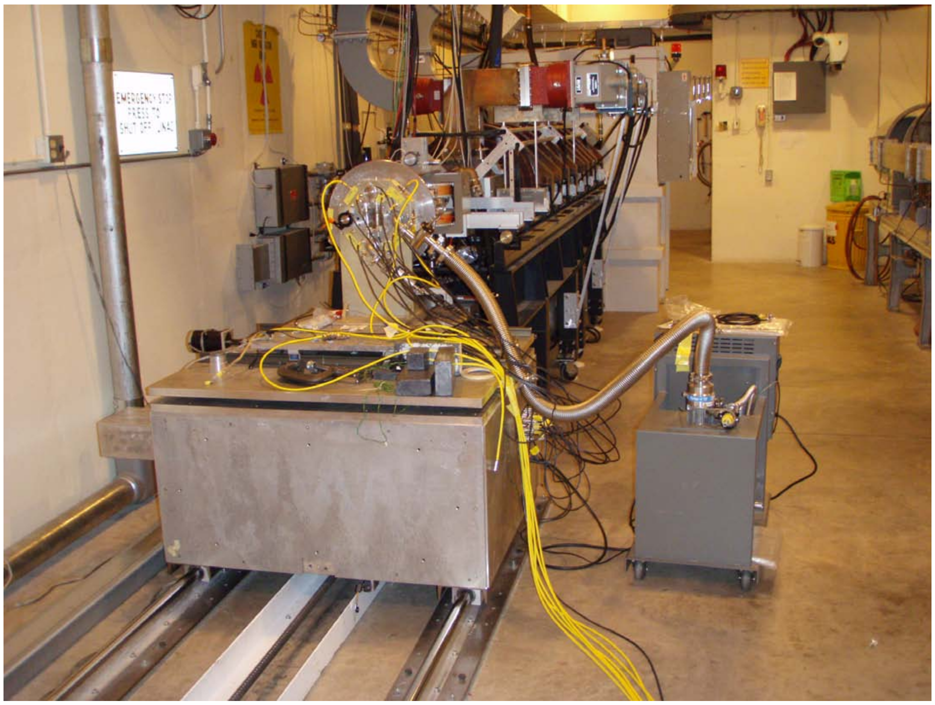

Figure 3 LINAC at LMTF (Little Mountain Test Facility) in Ogden, Utah with Vacuum Chamber and Cabling

The LINAC pulse has microstructure such that there are many short pulses of about 40-80 ps duration at a rep rate of about 1.3 GHz during the longer several microsecond pulse. We have not found any reports that this microstructure creates any problems for testing when ionizing dose or dose rate drives the response. An extremely fast circuit could respond to the microstructure. For capacitors used in such applications, this procedure will still provide accurate charge loss data to support circuit design. However, circuit-level testing with temporal characteristics similar to threat conditions should be conducted. Circuit-level testing with high-frequency microstructure on the radiation pulse could lead to spurious results.

We investigated the LINAC spectrum as the pulse width of the LINAC was changed. A plot of the Medusa LINAC electron energy spectrum is shown in Figure 4 for both 5 and 50 microsecond pulses. The measurement was made by using bending magnets to divert electrons of nearly discrete energy to a 30 degree port. The response was recorded with a Faraday Cup. It can be seen in the figure that the electron energy peaks at around 19-20 MeV for both spectra and falls rapidly above 25 and below 10 MeV. The spectrum was measured between 5 and 30 MeV. Given that the spectral shape is nearly identical at 5 and 50 microsecond pulse widths, there are not any significant uncertainties associated with experiments performed at different pulse widths on the LINAC that are caused by spectral variations.

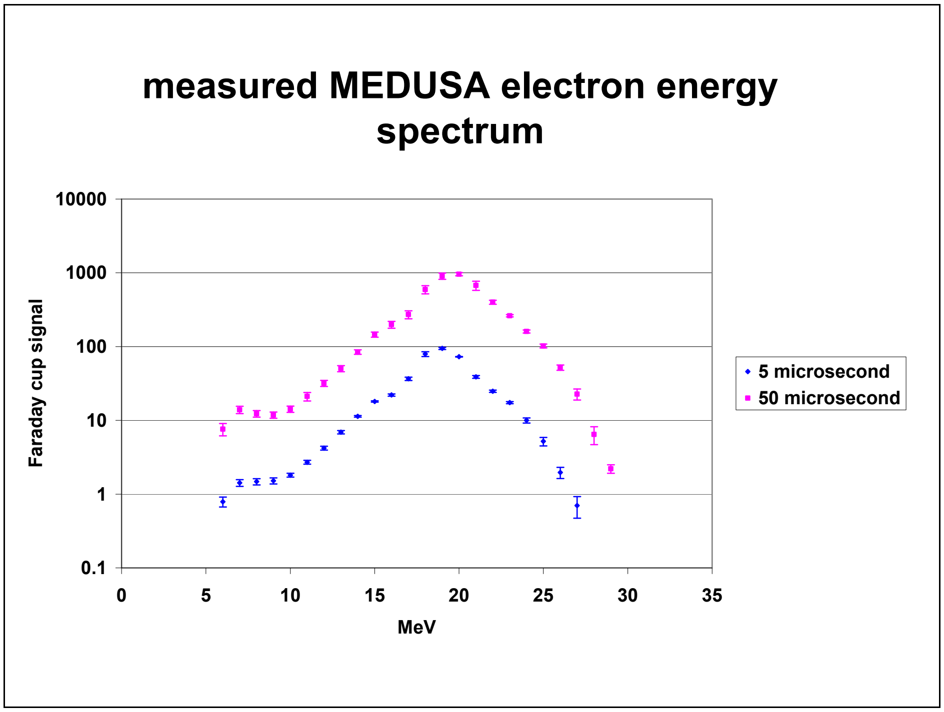

Figure 4 MEDUSA LINAC Electron Energy Spectra for 5 and 50 μs Pulses

3.2 Dosimetry Errors and Uncertainties

We used Si calorimeters as our base dose diagnostic. Si calorimetry is recommended rather than the thermoluminecient dosimetry (TLDs) frequently used in radiation testing. Experiments show that the CaF_2 TLD and calorimetry readings diverge at high doses. An example of divergence is shown in figure 5. CaF_2 TLD response is complex and is subject to general sources of systematic error, including trap saturation, space charge effects in e-beam testing etc. Therefore, Si calorimeter techniques are recommended over CaF_2 TLDs. The overall RMS error associated with our Si calorimeter was 7%. This error included the amplifier, Yokogawa DL750 digitizer, the thermocouple hardware and reading technique. In comparison, the error associated with the recording of voltage (indicator of charge loss) on the electrometer was about 2%.

Note that where possible simultaneous calorimetry measurements at the various intended capacitor locations should be taken while characterizing the exposure environment to establish systematic ratios in the expected dose.

Calculations show that for 20 Mev electrons, the dose into 0.10 cm of Si is 1.31 Mev-cm^2/g and the dose into 0.089 cm of CaF_2 is 1.33 Mev-cm^2/g. The calculated values are essentially identical for deposited dose in realistic thicknesses of both the Si calorimeter and the CaF_2 TLD.

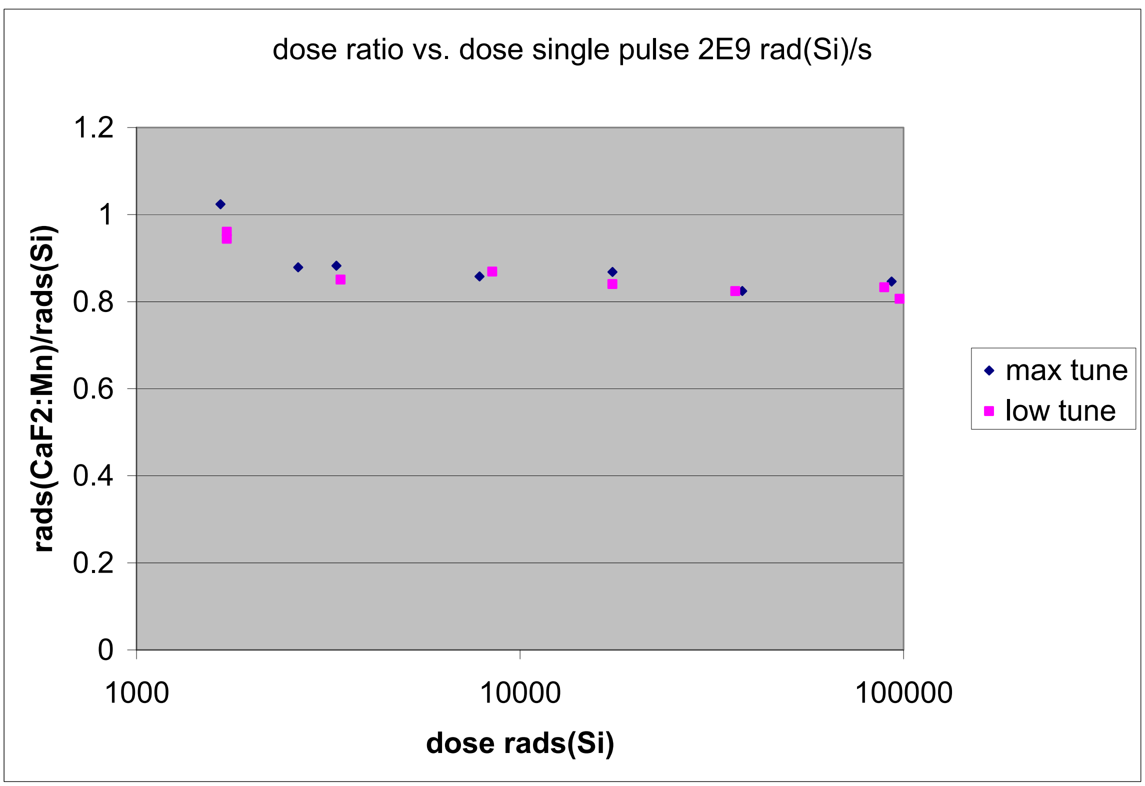

Figure 5 TLDs vs. silicon calorimeters

Lithium Fluoride (LiF) TLDs are also sometimes used as dosimeters in radiation effects testing, but are known to have problems at high dose and high dose rates. In one study we performed on LINAC dosimetry techniques we found the LiF measurements to be problematic and unreliable. Figure 6 presents a comparison of several diagnostic methods. The methods include PIN diodes, Faraday cup, neutron-damaged transistor, diamond detectors (PCDs), silicon calorimeter and LiF thermoluminescent detectors (TLDs).

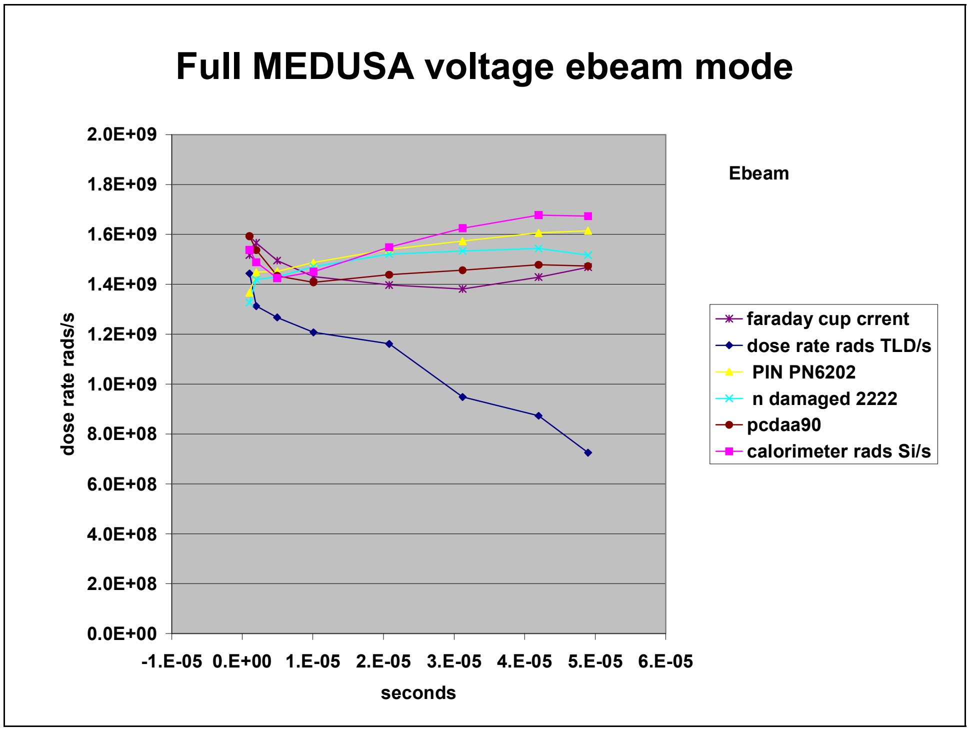

Figure 6 Comparison of various diagnostic techniques for Medusa LINAC

It can be seen that at least the shape of all diagnostics with the exception of the TLDs generally agree. It should be noted that one would expect some differences because of geometry and material differences between the various diagnostics. For instance PIN diodes, the damaged transistors, and the silicon calorimeter are all silicon based diagnostics and they track each other very well (top three curves). The Faraday cup plotted response is just below the silicon diagnostics and is a measure of beam current and not affected by material cross section. The PCD is a carbon based material and likely it's spectral response would be slightly different than the silicon-based diagnostics. The LiF response is an outlier.

It is likely that LiF and perhaps even CaF_2 can have a problem if there are too many carriers generated and there are not enough traps present. The sensitivity (and dose measuring) ability of TLDs can be affected and change when the number of carriers becomes a significant fraction of the traps. Lifetimes, trapping efficiencies and other factors will determine how well a dosimeter performs. The dosimeter can be stressed at high dose rates or lower dose rates for longer times as long as the radiation pulses are shorter than the lifetimes of the processes occurring. This under-reading behavior can be termed a saturation effect. We chose to use the silicon dosimeter as our base diagnostic. Based on the evidence we uncovered we trust this technique accurately records dose (Si) to within 7% accuracy. We further corrected our silicon calorimeter shot to shot for the very small (1-2%) source output variation of the LINAC using calibrated PIN diodes and PCDs in fixed positions just behind our test capacitor samples.

3.3 Technical Issues and Uncertainties Associated with Different Capacitor Types

The previous section discussed dosimeters, and stated we are measuring dose silicon at the capacitor location to within 7%. Now the fact that the silicon calorimeters perform well means that this measured silicon dose can be used to relate or translate to different dielectric materials using radiation transport codes that track both photons and electrons and calculate dose to any material. The procedure would be to first calculate the dose in silicon for representative silicon calorimeter geometry including any surrounding materials such as the scatter plate for the nominal Medusa LINAC energy spectrum appropriate to the experiments. Then, using the electron fluence (and LINAC spectrum) that results in a matched dose in the silicon calorimeter, another radiation transport code calculation would be performed to determined the dose in the dielectric material of the capacitor. After this result is in hand, the charge loss per unit dose for a particular type capacitor can be determined by dividing the measured charge loss by the dose in the dielectric material for the particular capacitor type.

Since different capacitors have different dielectric material such as SiO_2, various ceramics, glasses, etc., the atomic numbers of the dielectric materials can vary widely. For example silicon has an atomic number of 14 and Tungsten (W) has an atomic number of 74. In a high energy electron environment such as a LINAC, the deposited dose in Si versus W might vary by 30% or more due to stopping power differences. If tests were performed at an X-ray source the difference in deposited energy for the same spectrum and pulse width could be an order of magnitude or more different. It is critical to perform the radiation transport calculations to determine true charge loss per rad (material).

If the purpose of testing capacitors is to qualify the capacitors to a particular radiation requirement, then radiation transport calculations must be performed for the various x-ray and gamma-ray environments into realistic system geometries. Then the result can be translated to measured charge loss using the procedure described above. There may be cases particularly for X rays where dose enhancement effects are important and must be considered to obtain the correct dose to the dielectric material of interest. If the geometry model is correct and coupled radiation transport is used, the dose enhancement effects will be included. Packaging and other materials around a capacitor including housing and dielectric potting can affect the dose or dose rate the capacitor receives. The entire system typically needs to be modeled.

Since capacitor geometries can be complex such as alternating layers of metal and dielectric materials, and since ceramic and glass mixtures for dielectrics may contain many elements, both sectioning for engineering analysis and materials analysis techniques for material properties may be required. All these procedures: reverse engineering, determining the elements within a material, and the radiation transport modeling are straightforward and it is known how to do these procedures. They will always be time consuming and costly, but likely necessary, for qualification of capacitors to radiation environments when margins are low.

3.4 Uncertainties of Air Conductivity Effects

It is well known that air can become conductive when ionized by pulsed radiation. It is often difficult to quantify this effect. Air ionization might provide a leakage path which would discharge the voltage from our capacitor samples. Sometimes experimenters coat all metal or conductors under voltage with dielectric materials. While this can often eliminate most leakage induced by radiation it could potentially introduce possible charging effects particularly in the electron beam testing.

We chose to place our samples and circuit board in a vacuum chamber to eliminate the possibility of any air ionization effects. We made the chamber large enough in diameter and thin enough such that essentially no collimated scattered or reradiated (Bremsstrahlung) radiation of any significance could ionize trapped air within cables outside our experiment. We used triaxial vacuum feed through connectors and triaxial low loss cable to connect to the high impedance electrometer. We allowed the collimated electron beam to transit our thin front window of 0.00254 Titanium and the thin vacuum chamber housing back cover and "get lost" in the LINAC facility room. Our background capacitor response was low compared to our test capacitor response. Figure 7 shows the background capacitor response compared to three test capacitors for a single typical experiment.

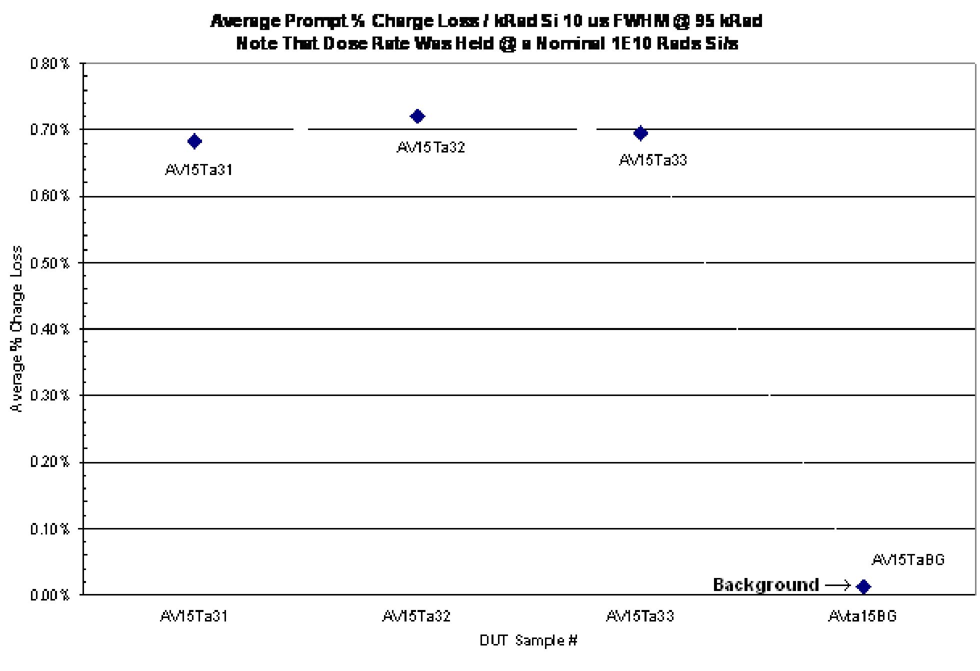

Figure 7 Prompt Charge Losses in Kyocera Capacitor

The background response was about 1% of these test capacitors. This does not prove there were no air ionization effects, but the upper bound of the effects has to be small. Experts in air conductivity state that at vacuum levels at or below 1E-3 Torr radiation induced conductivity (RIC) in gases is not a concern even at higher dose rates than we used for our testing[7]. At the vacuum level of 2E-4 Torr which we used in our capacitor experiments, RIC in air is not a factor in our measurements. The threshold for concern due to RIC in air is ≤ 1m Torr[7].

3.5 Uncertainties Associated with Charge Trapping or Polarization

Trapped charge effects have been reported as an error or uncertainty in measuring capacitor discharge.[1] Trapped charge can cause a reduction in capacitor discharge rates after previous irradiations. Trapped charge produces an internal electric field. This field can become compensated by the addition of electrons from the bias circuitry. When the capacitor is irradiated again by pulsed radiation, trapped charge can recombine releasing compensating electrons which can result in a current flow even at zero bias (0 Volts). In our measurements we disconnected the bias about 30 seconds before the radiation pulse. We also always fully recharged the capacitor over a period of 30 minutes before the next test exposure.

We did not note any significant effects we could attribute to trapped charge since when we repeated our measurements on the same capacitor at the same conditions (we typically did this 3 times), we did not note any change in prompt charge loss. While we observed charge trapping at zero bias, this trapped charge appeared to be neutralized or minimized as long as the capacitors were biased. Repeated experiments did not produce different responses for charge loss shot to shot.

Our instrumentation sampling rate was low, so if there was a small trapped charge response at the beginning of the pulse we potentially could have missed it. We find this unlikely however as the sampling was basically random in time and over couple hundred experiments we never observed any effects attributable to trapped charge.

There were, however, major differences between our test technique and that of those who reported the trapped charge effects including the radiation source, radiation type, capacitor types, bias conditions, pulse widths, soak times, energy spectrum, and purpose of the experiments. It was beyond the scope and resources of this project to determine the source of the differences in results.

We established the soak times for the capacitors by doing laboratory soaks on the capacitors and then comparing the discharge characteristics of capacitors after soaks between 5 minutes and 24 hours. We found a 30 minute soak to essentially fully charge the capacitors such that the discharge was very similar to longer soaks. We found no issue with dielectric polarization for the types of capacitors we examined for which the test results are published in another SAND report.[8]

3.6 Issues with Radiation Response of Instrumentation and Circuits

The radiation was shielded and collimated such that virtually no radiation struck any coaxial instrumentation or bias cables exiting the test chamber. Also the test board and buried traces were minimized by restricting the area and circuit traces and attachments to that sufficient to mount the capacitors, and to instrument and supply bias to the capacitors. An example of a test board was shown in Figure 2. At the center of the board are mounted three test capacitors of identical type which were tested simultaneously. The exposure area is shown as a circle drawn about the capacitors. This exposure area was defined by collimation of the electron beam. Note that a background capacitor was mounted outside the exposure area (on left in picture) to assure that a background signal was recorded on each shot with the appropriate voltage on the background capacitor matching conditions on the test capacitors. The electron beam was allowed to exit the vacuum chamber and "get lost" in the room housing the LINAC.

The Tungsten collimator would no doubt produce some Bremsstrahlung radiation at the high electron energies of the LINAC. This radiation no doubt strikes some of the traces and cabling. This produces a small source of error because the background measurements were small compared to the measurements on the test capacitors.

3.7 Uncertainties Associated with Capacitor Parts

For a particular type of capacitor we typically recorded data on about 9 parts. We found the response of individual capacitors to be very repeatable shot to shot (1-2%). The response of different individual capacitors of the same type, on the same shot could vary up to 5%. We did not attempt to control the lot or manufacturing of the capacitors. We used commercial product. For example for the AV15Ta capacitor for all samples tested even including tests at different pulse widths between 20 and 50 microseconds the three sigma error bars on charge loss that encompassed all data were +/- 10%.

3.8 Uncertainties Associated with Knowing the Radiation Environment at the Capacitor Test Sample

Since we do not simultaneously measure the dose with the silicon calorimeter and expose the test capacitors, we must assure ourselves we know the environment at the capacitors. One fact in our favor is that through repeated diagnostic measurements we have shown the Medusa LINAC produces repeatable results at the same axial location and same pulse width. To ensure we are getting the environment and dose we expect, we calibrate two PIN diodes and two PCDs behind the test capacitors such that we obtain correction factors for each of the four diagnostic devices mounted in fixed positions. The correction factors differ slightly with axial position and pulse width, so we always obtain calibration factors for each test condition. These are used to correct slight differences in machine performance shot to shot at the same location (typical variation 1-2% or less) for all testing of capacitors.

The silicon calorimeter is mounted in the exact center point for the capacitors and at the same axial position as the capacitors are later placed. These items are rigidly mounted in place. Any additional dosimeters such as LiF, CaF_2, or alanine are mounted within the same type housing as the silicon calorimeter. We do not introduce any uncertainty or error beyond the 7% error in recording the silicon calorimeter with this procedure. Of course we are measuring an environment (essentially) rather than the actual dose in the various dielectric materials and geometries associated with different capacitor types. Because of the tight nature of the capacitor response, even though the three capacitors are in different locations within the collimated beam, the exposure is uniform. Other indications that the beam is uniform include irradiated film samples. The translation procedure from a measured environment to actual dose in a particular capacitor dielectric has been previously discussed.

We examined the effect of different radiation pulse widths or dose rates for exposures of the same dose. Since the pulse width is changing, but the dose is being held constant, obviously the dose rate is also varying. Figure 8 below shows that for the Kyocera/AVX electrolytic 15 microfarad capacitor that varying the dose rate or pulse width by a factor of five did not change the percent charge loss at constant dose. The dose rate was varied between about 1E9 and 5E9 rad (Si)/sec. The charge loss percent per krad remain constant over the range examined. The error bars shown are for 3 standard deviations over the entire data set at all pulse widths. All data fall within 3 standard deviations (97%).

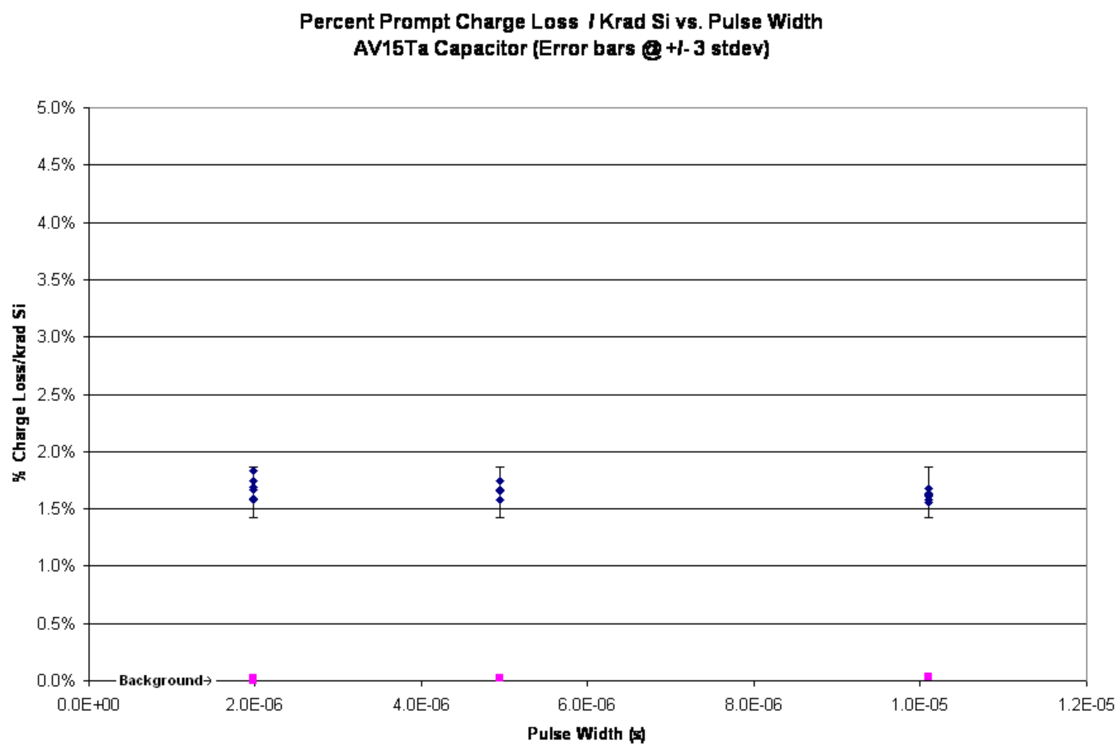

Figure 8 Percent Prompt Charge Loss for Kyocera/ AVX Electrolytic Capacitor

3.9 Grounding and Shielding Technical Issues

There are no technical issues with grounding or shielding for our test method. The housing of the vacuum chamber is ground, and we use high-quality low- loss triaxial cables and vacuum triaxial connectors especially compatible with the Keithly Electrometer. Circuit board ground is internal to the circuit board and adapted to the cable grounds that are circumferentially grounded to the vacuum chamber. We are not measuring high frequency signals so issues associated with high frequency do not impact these experiments.

3.10 Issues with Testing Outside the Linear Charge Loss Region

It is well known[1] that at high doses and dose rates, the loss of charge in a capacitor can be non-linear. The charge loss can become exponential and has been described by the equation $Q = Q_o \exp(-D/D_o)$ where Q is charge, Q_o the initial charge on the capacitor, D is dose in dielectric material, and D_o is the discharge characteristic of the particular capacitor typically a fitted parameter. For small changes in charge the response is nearly linear. We suggest that screening tests be performed in the quasi-linear regime. It is not recommended that capacitors be chosen for system qualification if the capacitor's response is non-linear at the radiation requirement of dose or dose rate if at all possible.

An example of non-linear response for a capacitor is shown in Figure 9 for the Murata X7R Capacitor at doses between 1E4 and 1E5 rad (Si). If it is necessary to use a capacitor in the non-linear range of charge loss then the charge loss must be characterized at and above the requirement dose.

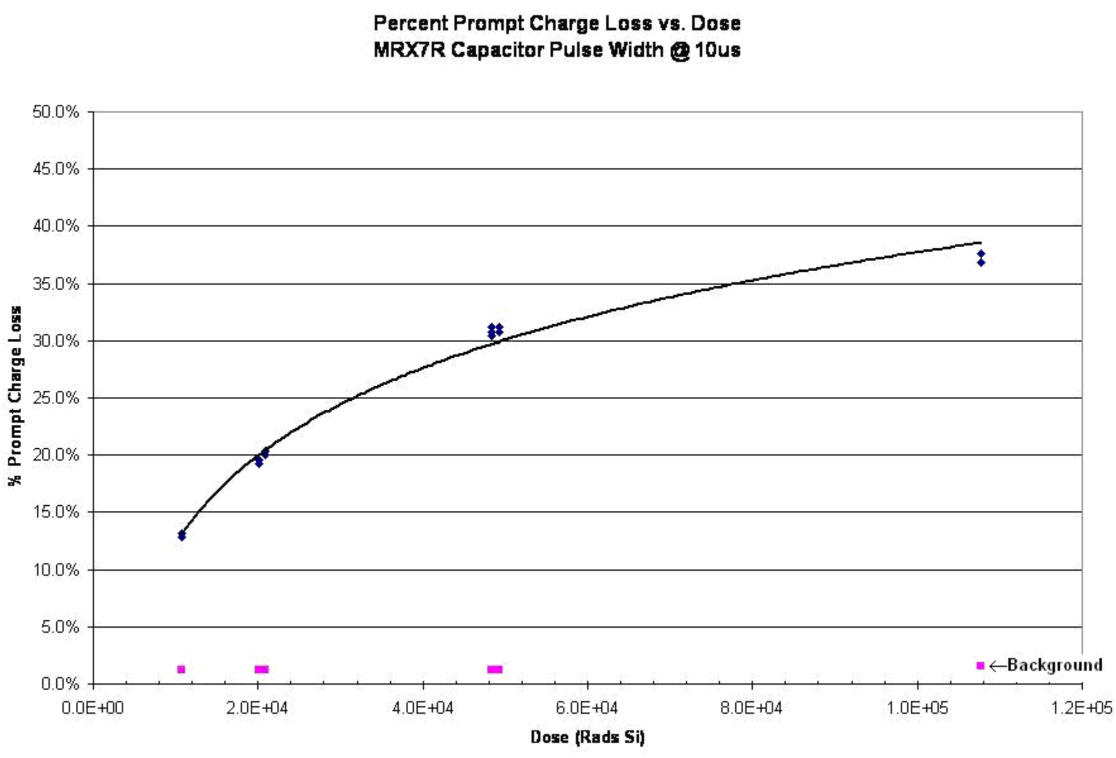

Figure 9 Capacitor Response Compared to Background

3.11 Issues with Number of Parts and Tests Needed

The numbers of parts that should be tested for charge loss measurements depends entirely on the desired operating margin, the specific use of the capacitors, and the variability of capacitor response lot to lot and capacitor to capacitor. We envision our test method as a screening method for early part selection. Our method allows side by side comparisons of different capacitor types without necessarily employing reverse engineering or complicated modeling. Since even in the LINAC testing, actual dose can vary by about 30% in different dielectric materials, it would be senseless to obtain extremely tight statistics on a capacitor unless required. In this case the dose levels are translated to actual dose in the relevant and particular dielectric material within the capacitor type using reverse engineering and radiation transport computer modeling.

As a screening tool, testing about 9-10 capacitors of each type is sufficient to characterize relative charge loss between various capacitor types. We found the measured capacitor charge loss in the linear regime of charge loss to be repeatable within +/- 10% for most capacitor types. We recommend that at least three LINAC pulses or tests be performed at each test condition so repeatability can be judged. We would also recommend testing these parts at least two different doses (5 and 10 kilorads) and at two different dose rates (such as 1E9 and 3E9 rads/s). Likely the charge loss will be in the quasi-linear regime for these conditions. If the part has a much higher dose requirement, it can be tested at the higher dose conditions; however, the measured charge loss in C/rad at this higher dose will be in the non-linear regime, so predictions of charge loss at other dose and/or dose rates from these data may be inaccurate.

Since charge loss characteristics for different capacitor types can vary an order of magnitude, knowing the charge loss characteristics to about 10% seems adequate for screening. Our test method allows measurement accuracy well within the 10% number so generally part to part variation can add more uncertainty than the described test method. It is a good thing that the test method does not control the uncertainty in the data.

If the capacitor is a critical part in a system where system performance may be affected, qualification of the capacitor part (if high margins do not exist) will require the more complicated procedures of dose translation by coupled photon-electron transport codes and reverse engineering as previously described to translate test results to requirements. Additionally this situation (inadequate margin) will require an experiment design with adequate part numbers and lot sampling techniques. The whole purpose of our procedure for screening capacitors for radiation-induced charge loss is to avoid this expensive and complicated qualification process.

4 SUMMARY

We have developed and evaluated a test method that minimizes uncertainty when measuring capacitor charge loss caused by pulsed ionizing radiation. We have described the uncertainties in the measurement technique. Radiation transport calculations that provide dose calculations are necessary for qualification of capacitors to radiation requirements unless very large performance margins exist.

For screening purposes, different capacitor types can be characterized for charge loss and selections made of those that are candidates for use in a particular radiation environment. The characterization of charge loss experimentally using this procedure would be accurate within 30%. The 30% difference is mainly due to electron beam stopping power in different dielectric materials versus our silicon calorimetry. Radiation transport calculations can improve the accuracy to about 10-15% by resolving the electron beam energy deposited in different dielectric materials.

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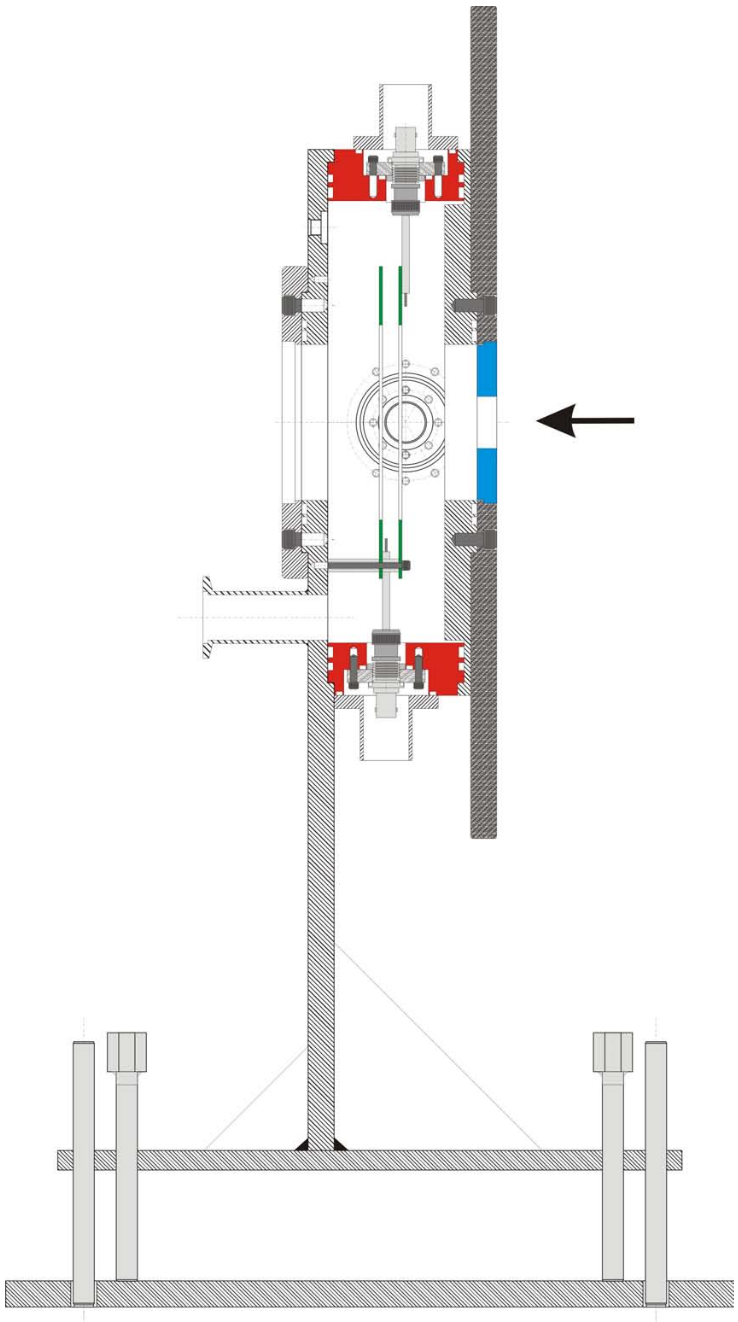
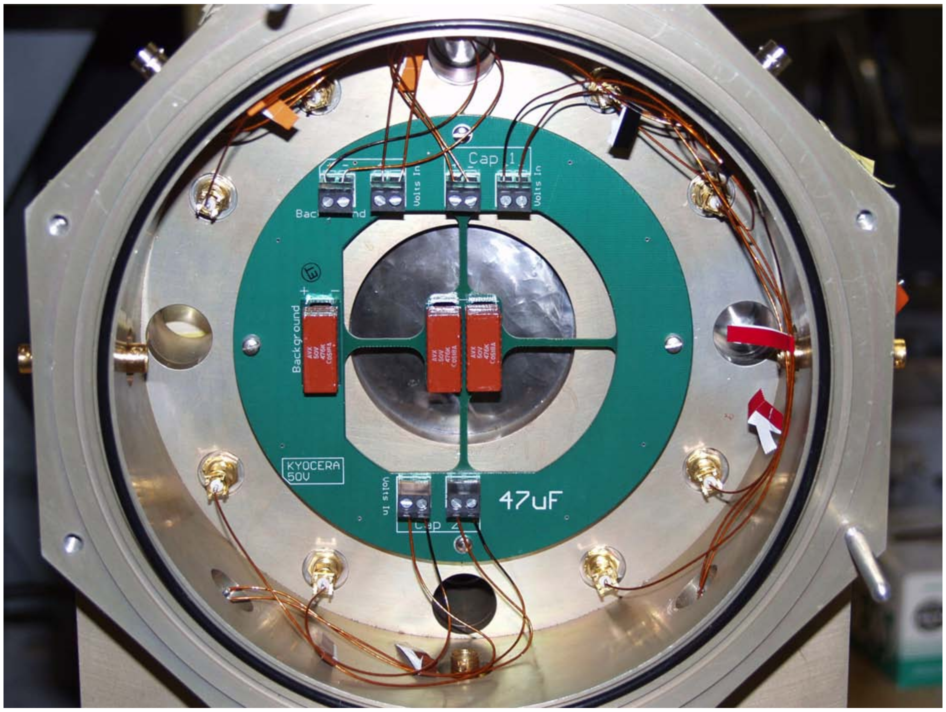
APPENDIX



1. Cross Section of Mounted Vacuum Chamber



2. View of Capacitor Test Board within Vacuum Chamber

3. Some of the Instrumentation for Capacitor Testing

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