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MEASUREMENTS OF PROMPT RADIATION INDUCED CONDUCTIVITY OF ALUMINA AND SAPPHIRE

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Abstract

We performed measurements of the prompt radiation induced conductivity in thin samples of Alumina and Sapphire at the Little Mountain Medusa LINAC facility in Ogden, UT. Five mil thick samples were irradiated with pulses of 20 MeV electrons, yielding dose rates of $1\text{E}7$ to $1\text{E}9$ rad/s. We applied variable potentials up to 1 kV across the samples and measured the prompt conduction current. Analysis rendered prompt conductivity coefficients between $1\text{E}-10$ and $1\text{E}-9$ mho/m/(rad/s), depending on the dose rate and the pulse width for Alumina and $1\text{E}-7$ to $6\text{E}-7$ mho/m/(rad/s) for Sapphire.

ACKNOWLEDGEMENTS

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Introduction

Ionizing radiation can render a dielectric material conducting by producing electron-hole pairs in the material [1-4]. The electrons and holes are quickly trapped, but possess some mobility during their lifetime and increase the conductivity of the dielectric. An increase of conductivity that persists only during the radiation pulse is called the *prompt conductivity*. There may also be a *delayed conductivity* that decays slowly after exposure to radiation.

Alumina can refer to several forms of aluminum oxide, Al_2O_3 . Sapphire refers to a single crystal (rhombohedral) form of this compound. In this report, the “alumina” sample is the rough and impure substance. Both samples are 5 mils thick.

Sapphire applications among other uses include substrates in electronics such as silicon on sapphire. Alumina has many industrial uses including alumina capacitors. [5]

Several series of shots were performed at different dose rates and pulse widths. Each series of shots swept through bias voltages, with zero bias clearing shots between each shot.

Figure 1 shows a side view cross-section of the RIC test fixture for the dielectric samples. This configuration is a stack of two separate cells which are irradiated together. Each cell consists of a center electrode, two dielectric layers, and ground planes on the outer surface of each dielectric. The RIC cell nearest the electron beam is called the upper RIC cell (URC), and the cell below it the lower RIC cell (LRC).

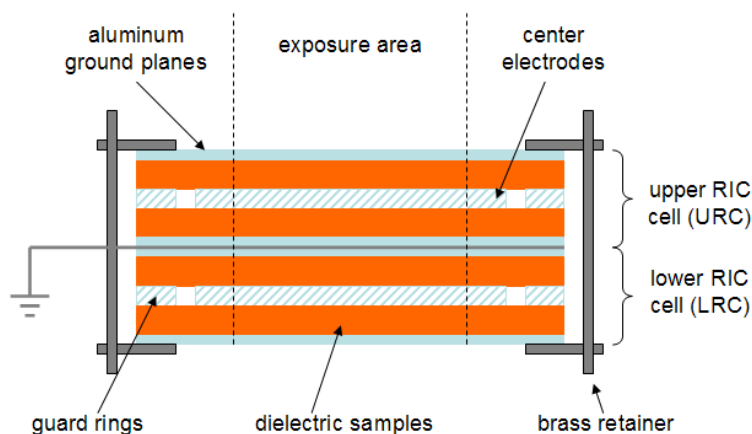


Figure 1 A RIC cell test fixture.

The Alumina or Sapphire layers are formed from 127 micron thick discs, about 2.5 centimeters in diameter, and are placed on either side of a 30 micron center aluminum electrode. Two 15 micron

outer aluminum electrodes serve as the cell ground planes. The guard rings minimize the electric field distortion at the edge of the center electrodes. Bias voltages were applied to the center electrodes and the guard rings. The bias of the lower cell was made equal to that of the upper cell, with opposite polarity.

Current is driven through the dielectric layers from their conductivity and the applied bias, and directly from the attenuation and divergence of the electron beam. The conductivity consists of the dark or static conductivity σ_0 , the prompt RIC σ_p , and the delayed RIC σ_d . The net current is the sum

$$I = Vd(\sigma_0 + \sigma_p + \sigma_d) + I_{dd} \quad (1)$$

where V is the bias, and d the sample thickness. The delayed conductivity may contain several terms with different decay constants, representing traps of different depths. In addition, there is a direct drive current I_{dd} produced by the electron beam in the absence of bias.

This cell design, including dielectric layers above and below a center electrode, greatly reduces the direct drive current, I_{dd} by balancing the charge gained or lost from the center electrode on either side. Even with this technique, the direct drive current is a substantial part of the total, and it can be difficult to determine the contribution of the prompt RIC.

A typical RIC cell test fixture is pictured in Figure 2. The busses for applying the guard ring voltages (LGR and UGR) and the center electrode biases (URC and LRC) are labeled.

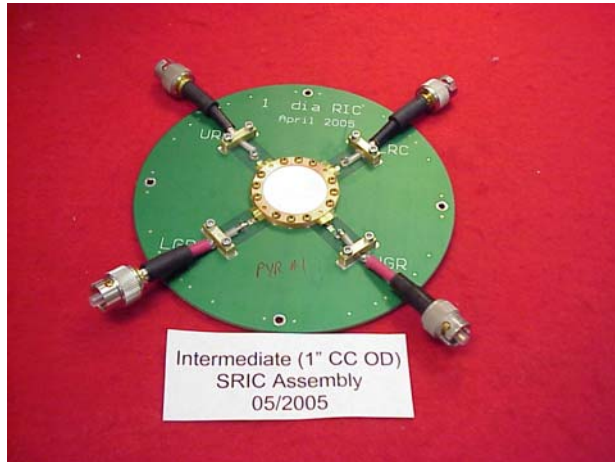


Figure 2 A typical RIC cell

The average measured capacitance of the RIC cells containing Alumina is 665 pF. This is for one two-sided cell, either the URC or the LRC. The area of the center electrode is $A_{tot} = 5.06 \text{ cm}^2$, but the irradiated area was collimated to 1.98 cm^2 . The average measured capacitance for the RIC cells containing sapphire is 734 pF.

The test chamber that housed the RIC cell was evacuated to $2\text{E-}4$ Torr to eliminate any effects due to air ionization. Radiation entered the test chamber through a collimated aperture. Figure 3 shows the front side of the test chamber and the aperture hole in the center of the fixture. The aperture was smaller in diameter than the dielectric samples. This assures that only the central area of the dielectric was struck by radiation and that the guard rings did not receive radiation exposure.

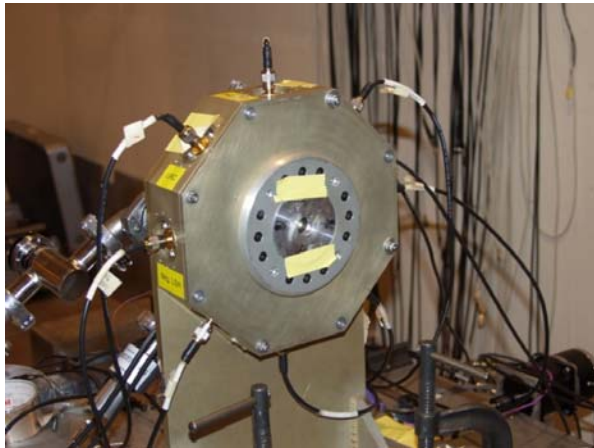


Figure 3 The vacuum experimental chamber
It is shown in the foreground with high voltage cables exiting through vacuum feed through connectors.

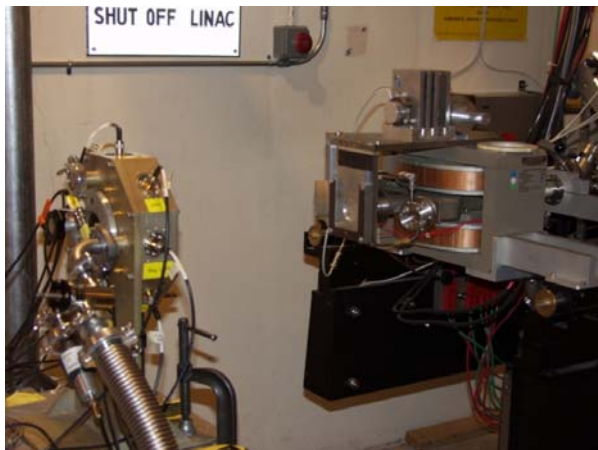


Figure 4 The experiment chamber with high voltage cables.
In the background is the front of the Medusa Linear Accelerator at the LMTF at Hill AFB near Ogden Utah.

Electron Beam Characteristics

If a radiation source is not capable of providing consistent or repeatable output, including its spectrum, pulse width, and fluence, 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 with the same conditions was approximately 1% shot to shot.

The nominal electron energy for the LINAC is 20 MeV. The radiation pulse can be varied from 10 ns to 50 μ s. For most of these experiments the radiation pulse width was about 0.5 μ s FWHM. Some additional experiments were performed with a pulse width of about 50 ns. The dose rate range for these experiments was $1\text{E}7$ to $1\text{E}9$ rad(Si)/s. For electron beam dosimetry, silicon calorimeters were supplemented with TLDs, PIN diodes, and PCDs. Measurement accuracy at the LINAC, including dosimetry and recording instruments, is estimated to be about $\pm 10\%$.

The electron beam differential energy spectrum is shown in Figure 5. The average electron kinetic energy for this spectrum is 19.2 MeV.

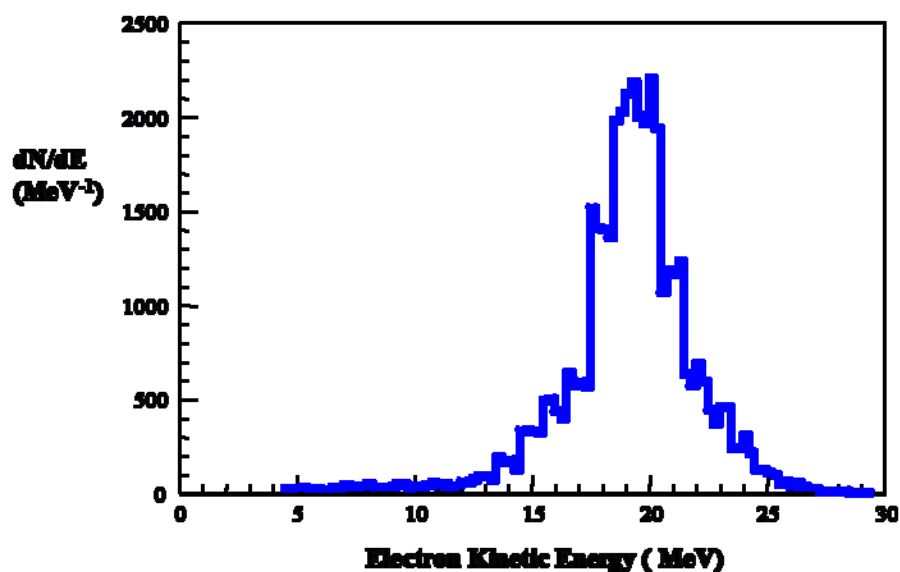


Figure 5 The LINAC electron energy spectrum.

The range of 20 MeV electrons in silicon or Alumina is about 5 cm. This is much greater than the total thickness of the test fixture (about 0.7 cm), so the dose should be nearly constant in all four Alumina or Sapphire layers.

A few typical radiation waveforms are shown in Figure 6. Most pulses are relatively flat, but some series of shots regularly exhibit peaks in the early or late times.

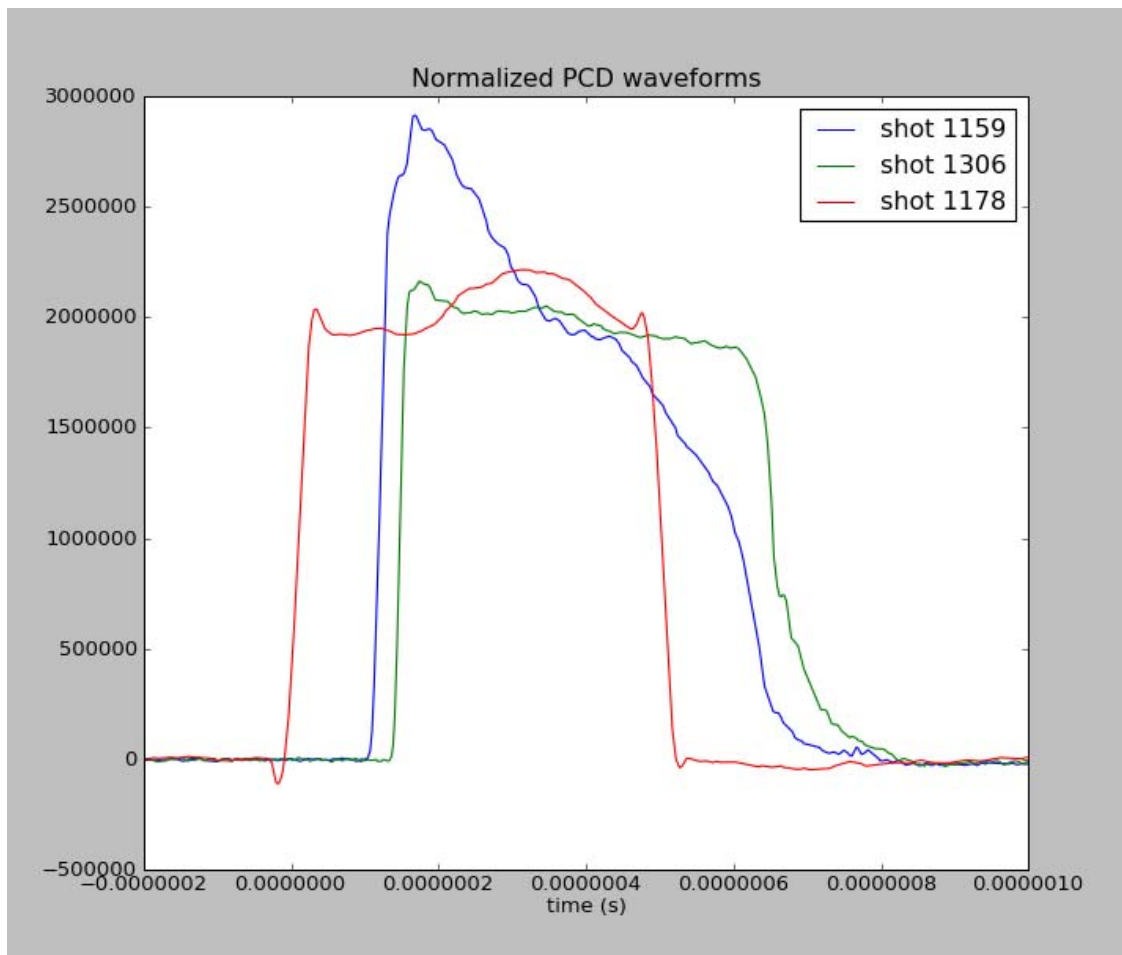


Figure 6 Some typical electron pulse time waveforms

The LINAC pulse has a microstructure with many short pulses of 40-80 ps duration at a rate of about 1.3 GHz. 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.

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 7 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 figure 7 that the electron energy peaks at around 19-20 MeV for both spectra and falls rapidly above 25 and below 15 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.

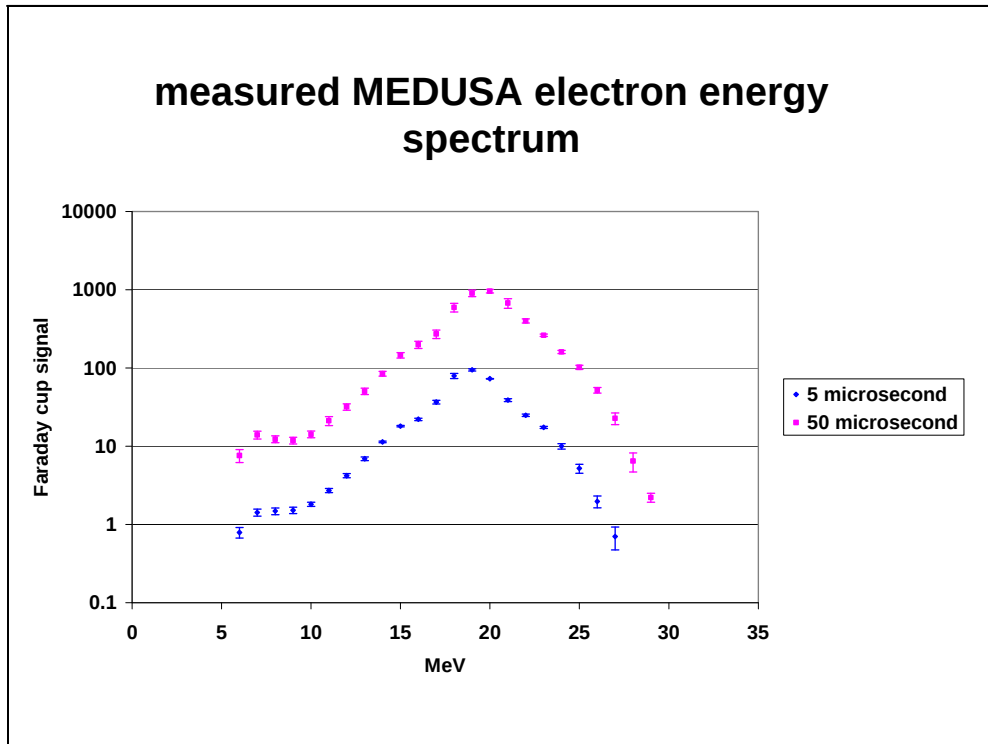


Figure 7 Electron energy spectra measured at different pulse width

Procedures

We included an aluminum scatter plate of 0.80 cm thickness on the front of the LINAC. We collimate the electron beam so only the dielectric samples are exposed to the beam, assuring that instrumentation cables are not exposed. The diameter of the collimator is tailored to a size such that guard rings are not exposed to direct radiation.

The response of different individual samples of the same type, on the same shot could vary. Though the dielectric samples are fabricated in the same manner there may be slight differences.

The radial location for the experiment is established by first assuring our experiment 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 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 dielectric samples aligns to the back cross hairs by being securely bolted in a rigid position within the vacuum chamber.

We established the desired axial position away from the LINAC beam port for each pulse length by mounting the silicon calorimeter in the position where the samples will be during testing. We find the axial position that provides the desired dose for a particular pulse width.

Next we exposed the dielectric samples at zero bias and record the current through the measurement circuit during the radiation pulse. Then we put bias on the samples and step through a series of exposures at various increasing bias levels (+/-). Typically we recorded several results at each bias level and alternate bias conditions (+ or -) on each dielectric sample.

When dielectrics are irradiated with photons or electrons, space charge (or trapped charge) can build up within the material sample. The accumulation of fixed trapped space charge will distort the internal field. The trapped charge effect becomes severe as the field strength approaches that produced by the externally applied bias. [6]

Discharge of the trapped charge after each data recording was accomplished by multiple zero bias irradiations until the recorded current signal returned the initial zero bias conditions. [7] Polarities of the applied bias typically were reversed at each bias voltage

The radiation is shielded and collimated such that virtually no radiation will strike any coaxial instrumentation or bias cables exiting the test chamber. Also, the test board and buried traces are minimized by restricting the area and circuit traces and attachments to that sufficient to mount the dielectric test cells, and to instrument and supply bias to the samples. The Tungsten collimator no doubt produces some Bremsstrahlung radiation at the high electron energies of the LINAC. This radiation strikes some of the traces and cabling. This produces only a small source of error because the background measurements are small compared to the measurements on the test samples.

Air can become conductive when ionized by radiation, which might provide a leakage path to discharge the voltage in our RIC samples. Sometimes experimenters coat all metal or conductors that will be under voltage with dielectric materials. While this can often eliminate most leakage induced by radiation it could potentially introduce possible charging effects, particularly in electron beam experiments.

We chose to place our samples in a vacuum chamber to eliminate the possibility of any air ionization effects. We used a 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 allowed the collimated electron beam to transit our thin front window of 0.00254 cm Titanium and the thin vacuum chamber housing back cover and “get lost” in the LINAC facility room. Our background response was very low compared to our test response.

Environment at the Test Fixture

Since we do not simultaneously measure the dose with the silicon calorimeter and expose the test samples, we must assure ourselves we know the environment at the samples. One fact in our favor is that through repeated diagnostic measurements we have shown that 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 typically calibrate two PIN diodes and two PCDs behind the test object 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. Our measurements of prompt radiation induced conductivity in fiberglass are available in a previous report [8]. Measurements of Radiation Induced Conductivity in Kapton are reported in another SAND Report [9]. Dosimetry techniques and uncertainties at the Medusa LINAC are detailed in a SAND report [10].

Dosimetry

To scale the TLD doses to the RIC cell dose, an MCNP run was used to determine the relative dose in the RIC cell layers and the TLD. The nominal alumina density of 4.0 g/cc was used for the calculations.

Layer	Dose (MeV/src)	Dose (MeV cm ² /g)	Ratio
URC1	9.11E-2		
URC2	9.07E-2		
URC average	9.09E-2	1.79	1.04
LRC1	8.95E-2		
LRC2	8.96E-2		
LRC average	8.96E-2	1.76	1.03
LiF TLD	4.15E-1	1.71	

MCNP predicts the doses in the URC and LRC are virtually identical, which is a little surprising, since there is a systematic difference in the responses. There is, however, a significant factor of 1.6 difference between the dose in the Alumina and the dose in the TLD.

In addition, the ratio of dose in Si vs. Dose in LiF at the TLD position is 1.12. The spreadsheet values are reported in rad(Si), so we must also divide by this value to get dose in the alumina or Sapphire.

Analysis

A diagram of the measurement circuit for a single cell (either the URC or LRC) is shown in Figure 8. The dielectric samples are represented by a fixed capacitance C_s , which is the sum of the parallel capacitances of the two layers. R_{cell} is due to the dark conductivity, and R_{ric} is the variable radiation induced resistance. The direct drive current source across the sample, due to slight imbalances in the beam current in upper and lower dielectric regions of a cell, is labeled I_{dd} . This source is responsible for

the current in the circuit when the cell is unbiased by either the external bias applied or any internal trapped charge bias.

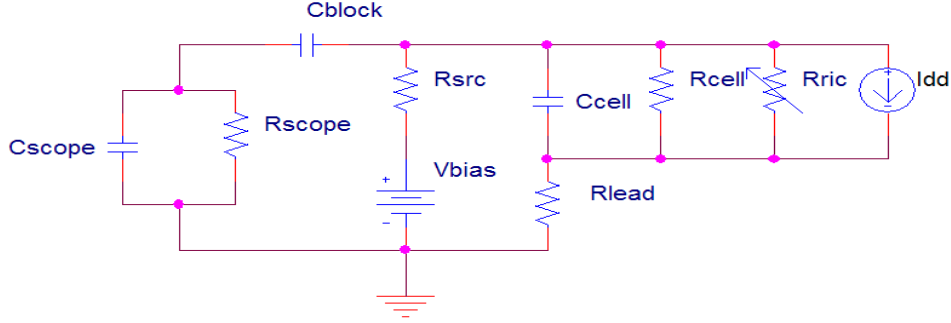


Figure 8 Equivalent Electrical Measurement Circuit

The blocking capacitor is selected so that the RC decay time is much greater than the radiation pulse width, so it can be considered a source of constant DC voltage V_C . The measured potential $V_R(t)$ across R_{scope} is used to determine the current through the circuit. Abbreviating $V_{bias} = V_B$, a loop rule gives $V_B = V_R + V_C$. Assuming the material is Ohmic, and denoting R_{scope} as R , the current in the circuit is

$$I = \frac{V_C}{R_{ric}} + I_{dd} = -\frac{V_R}{R}. \quad (2)$$

In general, both linear and non-linear current characteristics have been found for RIC in insulators. We can use (2) by absorbing all nonlinearity in the RIC conductivity R_{ric} , for instance by allowing it to depend on the electric field. Using these two relations we can relate V_R to V_B :

$$V_R = \frac{V_B}{1 - \frac{R_{ric}}{R}} - \frac{R_{ric} I_{dd}}{1 - \frac{R_{ric}}{R}}. \quad (3)$$

If the RIC resistance is constant, it can be determined from the linear relationship between the bias voltage and the measured voltage in (3). The advantage of this is the direct drive component only appears in the constant term. The dose rate dependence of prompt RIC in solids (where the conductivity is from fast electrons) is often modeled as

$$\sigma_p = k_c \dot{D}^\Delta \quad (4)$$

Where $\dot{D}$ is the dose rate, k_c is a constant RIC coefficient, and Δ is a parameter between 0.5 and 1. This makes the units of k_c the somewhat awkward $\text{mho}/(\text{rad/s})^\Delta$. Instead of assuming a power law, we can gain more flexibility by allowing the RIC coefficient k to depend on any of the experiment parameters,

and taking $\Delta = 1$, so $\sigma_p = k(\dot{D}, D, E, \dots)\dot{D}$. It is this k , with units of mho/(rad/s), we refer to as the RIC coefficient.

Since the RIC cell is a triode configuration, there are two paths through dielectric layers from the center electrode to ground. The resistance through one branch can be written as

$$R_1 = \frac{d}{A\sigma_1} = \frac{d}{Ak\dot{D}_1} \quad (5)$$

with an identical relation for the second branch. The total resistance through the cell is

$$R_{ric} = \frac{R_1 R_2}{R_1 + R_2} = \frac{d}{Ak(\dot{D}_1 + \dot{D}_2)} = \frac{d}{2A\sigma} \quad (6)$$

where the effective conductance σ depends on the average dose rate in the two dielectric layers.

From (3), the conductance can be found from the slope m of V_B vs. V_R :

$$\sigma = -\frac{d}{2AR} \frac{m}{1-m} \quad (7)$$

If $m \ll 1$ then (7) becomes

$$\sigma \approx -\frac{dm}{2AR} \quad (8)$$

and the intercept in (3) becomes proportional to the scope resistance R :

$$V_R = mV_B + RI_{dd} \quad (9)$$

For a narrow range of dose rates, the conductivity should be nearly linear (k should be constant), and the RIC coefficient can be found from (6) and (9) as

$$k = \frac{1}{\dot{D}} \frac{d}{2AR} \frac{m}{m-1} \quad (10)$$

The only assumption is that $k(\dot{D})$ varies slowly enough to make the linear approximation (10) locally valid. Since the dose rate will vary from shot to shot, we can define $\mu = m/\dot{D}$ and (assuming $m \ll 1$) use

$$\frac{V_M}{\dot{D}} = \mu V_B + \frac{I_{dd} R}{\dot{D}} = \mu V_B + \beta \quad (11)$$

to determine the slope μ . The RIC coefficient k is then determined by

$$k = \frac{d}{2AR} \frac{\mu}{1 - \mu \dot{D}} \quad (12)$$

where we use the average dose rate for $\dot{D}$.

Dose Rates

Dose rates were determined with a combination of total dose data from TLD's and a Silicon Calorimeter. Using only the front collimator, dose measurements were taken with a TLD at the sample position and at the back window, where it would be located during the RIC shots. The ratio of the dose measurements in the RIC cell plane and at the back window, around a factor of two, is used scale the TLD measurements to the dose at the sample location.

We performed these measurements offsetting the entire apparatus at depths of 0", 2" and 4" from the front of the linear accelerator. Over this range, the measured dose decreases by a factor of three, showing significant beam divergence.

To relate the TLD dose measurements to the dose in the Alumina and Sapphire, we performed calculations using MCNP.

Alumina Results

Several series of shots were performed at different dose rates and pulse widths. Each series of shots swept through bias voltages, with zero bias clearing shots between each shot. A typical shot series for alumina is summarized in the table below.

Table 1 Test Summary

Alumina Shot #'s	Nominal Dose Rate (rad (Si)/s)	Nominal Pulse Width (ns)
4144-4154	9.0E6	495
4157-4167	4.1E7	496
4170-4180	9.1E7	495
4184-4194	3.1E8	496
4197-4207	7.8E8	495
4210-4220	7.6E8	57.3
4222-4232	3.2E8	57.2
4234-4244	9.1E7	57.2

The results for conductivity are shown in figure 9.

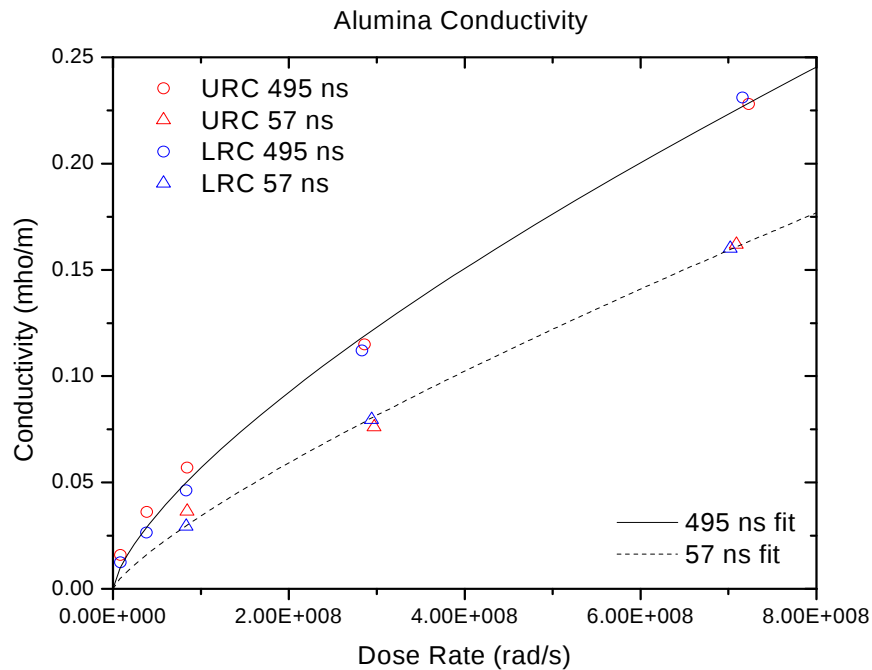


Figure 9 Alumina conductivity

The URC and LRC values are quite close, though the LRC conductivity was consistently lower at the lower dose rates. The URC and LRC data were considered together for the fit. The fits for the conductivity of the form

$$\sigma_{RIC} = k_{PL} \dot{D}^{\Delta} \quad (1.13)$$

are shown in table 2.

Table 2 Fits for Conductivity

Cell	k_{PL}	Δ
495 ns	1.334E-7	0.703651
57 ns	1.667E-8	0.789129

The subscript PL indicates the constant coefficient for the power law. The dose rate and pulse width dependent prompt conductivity coefficients k defined by the relation

$$\sigma_{RIC} = k(\dot{D}, \tau) \dot{D} \quad (1.14)$$

are shown in figure 10.

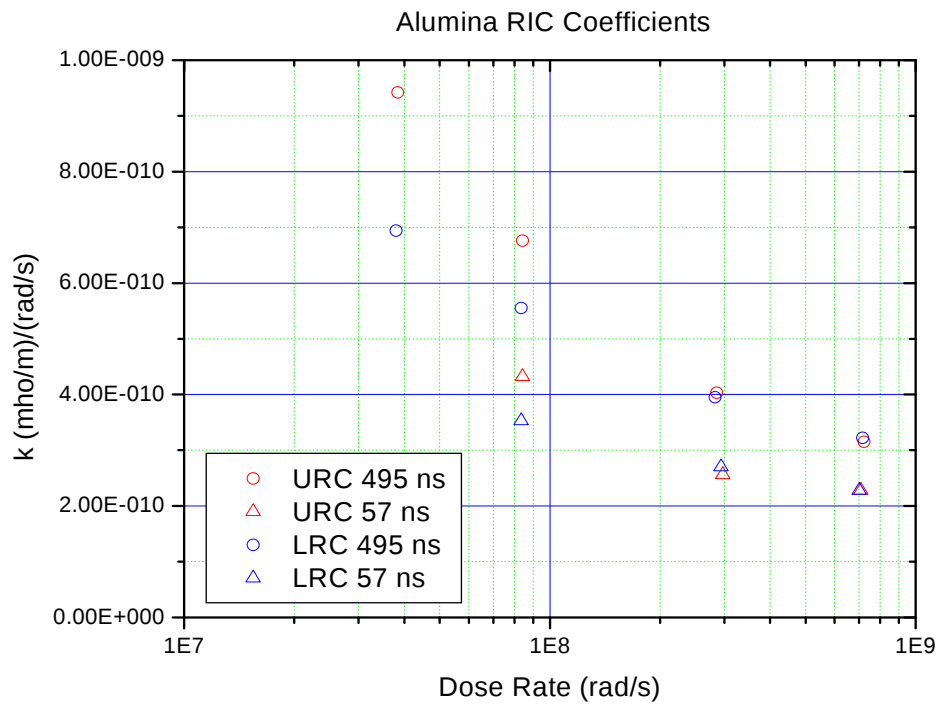


Figure 10 Alumina RIC Coefficients

Sapphire Results

The measured conductivities for the sapphire samples are shown in figure 11.

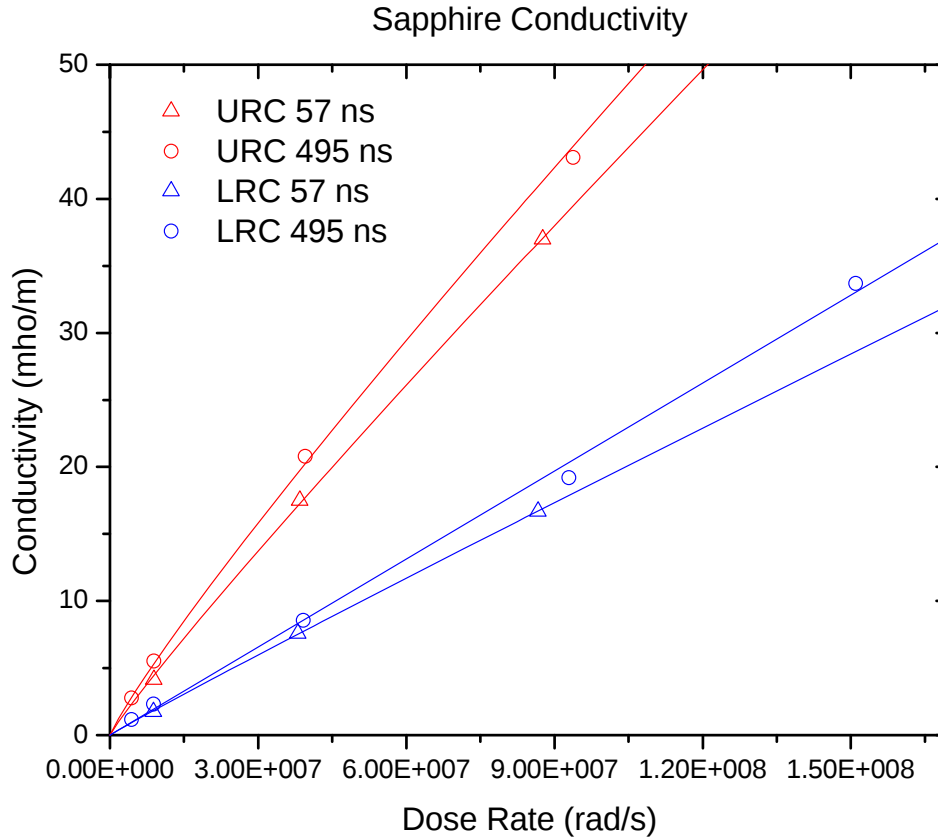


Figure 11 Sapphire Conductivity

This level of discrepancy between the URC and LRC was not seen for the alumina sample. Since the conductivity is two orders of magnitude greater, this may be indicative of sensitivity to crystal defects in the particular samples. However, in this case there is very little difference between the two pulse widths. It appears that at this higher conductivity the current saturates very rapidly.

The fit parameters for Sapphire are given in table 3. Since the dose rate varies by an order of magnitude, the fits are sensitive to many digits of the exponent.

Table 3 Fit Parameters for Sapphire

Cell	k_{PL}	Δ
URC 495 ns	3.142E-6	0.896322
URC 57 ns	1.620E-6	0.926585
LRC 495 ns	2.011E-7	1
LRC 57 ns	3.019E-7	0.971040

Note that the power law fit for the 495 ns LRC data yielded an exponent slightly greater than one (about 1.05). It doesn't seem likely this is real behavior, so we constrained the fit to be no greater than linear in dose rate.

The corresponding RIC coefficients are shown in figure 12.

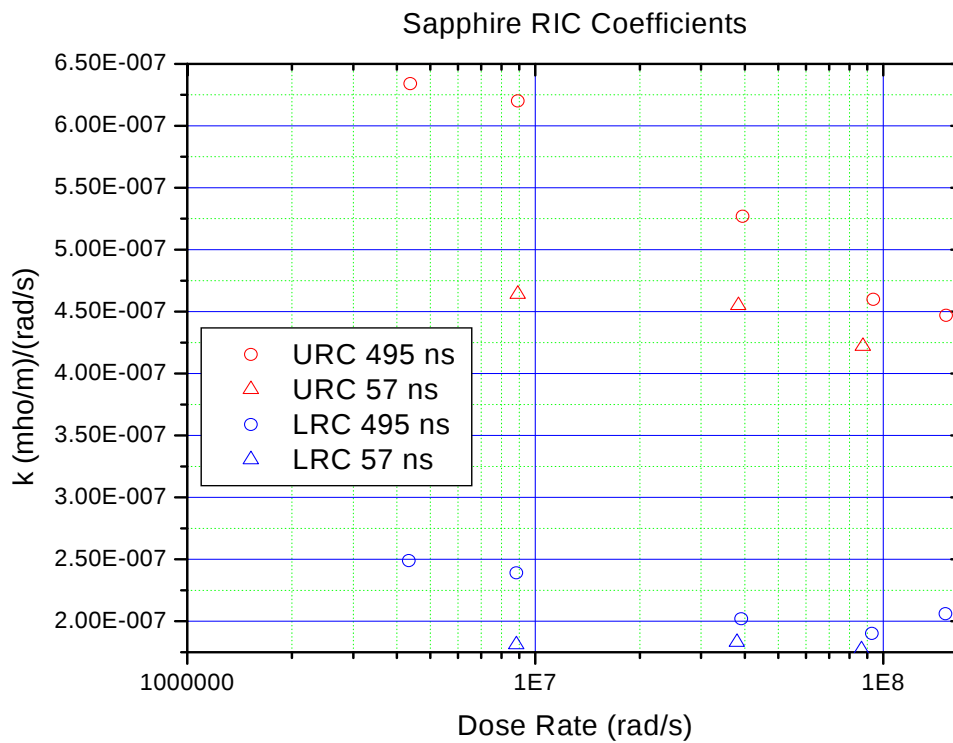


Figure 12 Sapphire RIC Coefficients

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