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Report on the Effect of Radiation on Resistors and Capacitors for the HV filter circuit of the Endcap VPT

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04/08/2004

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Introduction

This report looks at the effects of gamma radiation on components (RS 176-7956 10 MΩ 0.25w resistors, and the Farnell 498-385 1nF 2kV passive electronic capacitors). The aim of these experiments was to record the change in performance so as to predict their behaviour in a hostile environments. The importance of these tests arises from their use in the HV filter for the VPT in the Endcap calorimeter of CMS.

Since these components would be tested destructively, it was imperative to obtain as much data as possible. This information was obtained from two media:

- *The Capacitance and Conductivity of the capacitors as well as the Resistance and Parasitic Capacitance of the resistors was measured with an Impedance Meter*
- *Leakage current of the capacitor at 1000V.*

This report describes in its first chapter the methodology used for the measurements, each subsequent chapters would be dedicated to the degree of radiation received by the components, after which a comparison between the results would be made. Finally, it will be dynamically tested the leakage current of a sample capacitor while under irradiation.

In order to carry out the experiments, two facilities at Brunel University capable of delivering gamma radiation using ^{60}Co were used. For the first part, it was used the high dose rate facility, due to the need of irradiating the components to an equivalent of ten years of operation (~345 kGy) in a relatively short time. The second facility was used for the studies under comparable irradiation rate to simulate the operation conditions. This last facility, being nearly 1000 times weaker than the first one, provided the extra advantage for allowing electronic equipment to be left in the cell, without the risk of getting damaged.

Chapter 1 Methodology

In order to study the trends, a set of 10 nominally identical capacitors and 9 resistors were tested. However, this raised the problem of providing the correct method for identification.

It was important therefore, that the method in which each sample should be identified, complied with the next requirements:

- *The method should not be intrusive, i.e. adding or removing anything that could, under some condition, affect the performance of the component before or after the radiation has taken place.*

- *The identification should be clear, unique and permanent (at least for the duration of the study), i.e. the method of identification should not degrade with radiation, to the point that identification between samples becomes impossible.*

With this in mind, it was concluded that the samples should be contained individually on recipients as well as its identification; therefore, the component was not labelled, or marked in any other way. The identification was written with graphite pencils on pieces of paper (all the same size). This method provided, not only the compliance for the restrictions above, but also the means of protection against lost, and accidental damage during transport, storing, and handling.

For the measurement of the leakage current on the capacitors, the circuit shown in Figure 1 was used.

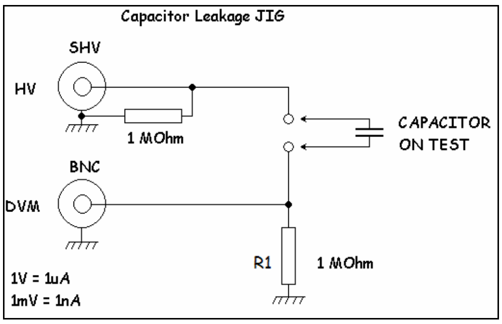

Figure 1: Capacitor Leakage circuit

Figure 1 shows the circuit diagram for the measurement of the current through the capacitor. The current also passes through R1, which generates a voltage proportional to the current (Ohms Law). However, it is important to notice that since the voltmeter (KEITHLEY 191 Digital Multimeter) has an input resistance of 10MΩ, the calculation of the current should therefore, account for the systematic affects this introduces.

The circuit was installed in a metal box for shielding against electromagnetic waves on the environment (lighting, communication signals, etc…). This box also contained a bag of silica gel to reduce the humidity inside the box.

Each capacitance was loaded to 1000V DC using a CANBERRA HV Power Supply, Model 3002. Measurements were then recorded each minute from time 0 to 10’. Thus, allowing the charging time to greatly exceed five RC time constants.

The impedance characteristic, of each component, was measured with an Impedance Analyser from HP model 4192A LF. To ensure the values measured were repeatable, it was decided to test each component ten times. The level of this repeatability is demonstrated in the Appendix, where it can also be seen the reasons of displaying the results obtained as this paper does.

In order to obtain as much consistency as possible, measurements were done when the lab temperature ranged between 19 to 21 degrees Celsius.

For the identification, storing, and manipulation of the samples, tubes of approximately 2.5 cm in diameter and 10 cm long were used. They were transparent, allowing seeing its identification written with graphite pencils on a piece of paper stored inside it.

Finally, the results displayed on this paper, reflects marginal bands obtained from the measurements. These bands are the **high band**, which shows the absolute maximum value obtained from the experiments, and the **low band**, which shows the absolute lower value obtained from the experiments. They demonstrate real variations, within tolerance, of the individual component values from nominal.

Chapter 2: Unirradiated Component Data

Since the aim of this report was to study the effects of radiation on the components, it is obviously clear the need to perform the measurements on the components before any damage is done to them.

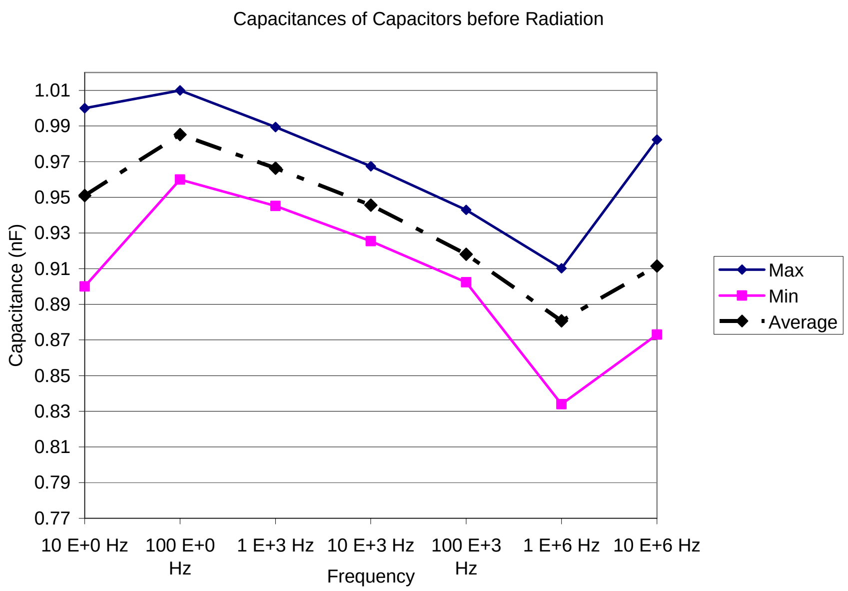

Figure 2 Capacitance of the Capacitors Before Radiation

Figure 2 and Figure 3, shows the characteristics of the capacitors in the frequency domain. It should be pointed out, that roughly all the samples follow the same trend, even if, they diverge on a vertical translation, this is clearly shown on the behaviour of the bands where it can be seen that the effects of the frequency was very similar.

On the other hand, the conductance from these capacitors increased linearly with frequency. This was expected, due to the fact that, the impedance of a capacitor is inversely proportional to the frequency, hence, as the frequency rises, the impedance should decrease, or in this case, the conductivity (the real part of the impedance, and inversed proportional to the resistance) would rise with the frequency.

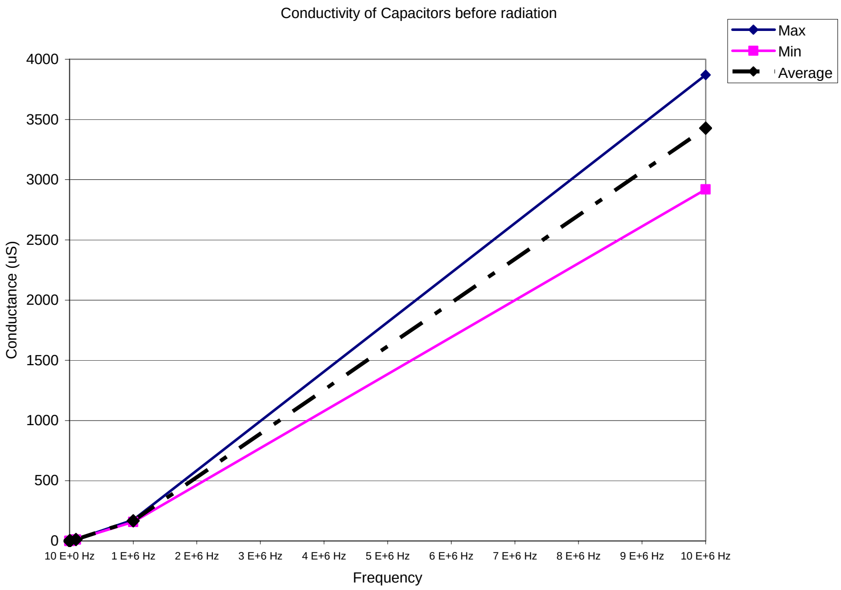

Figure 3 Conductivity of Capacitors Before Radiation

For the studies of the leakage current, it was used the circuit shown above in Figure 1; when powered, it was noticed a jump in the voltage registered on the DVM which drop rapidly over a short period of time, and after the 5th minute, the fall of the voltage gradually changed to an asymptotic behaviour. It is safe to mention that the time elapsed was considerably grater than the RC constant ($\tau \approx 9 \cdot 10^{-4} s$), so as to say that the voltage registered on the DVM was in deed due to the leakage current of the capacitor. Figure 4 shows the leakage current of the unirradiated capacitors, as well as the leakage current of the circuit when no capacitors were connected.

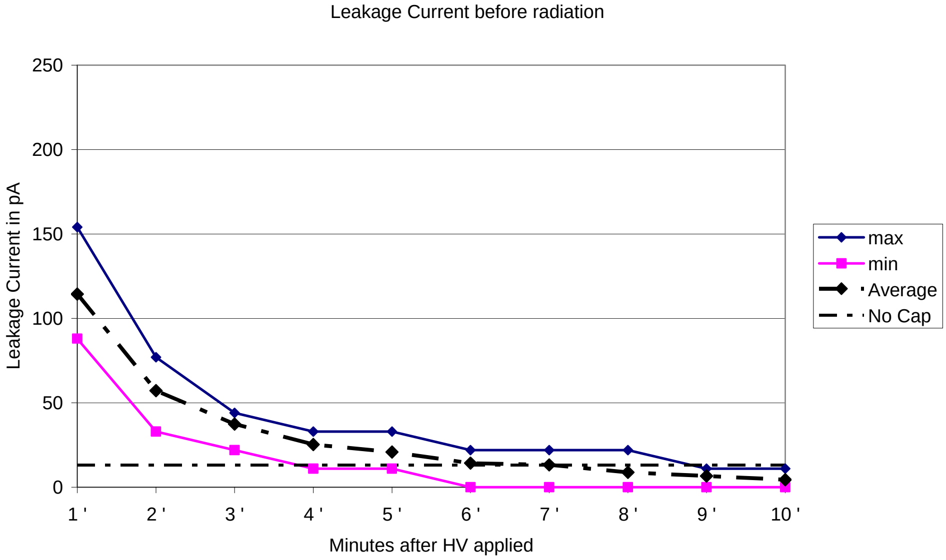

Figure 4 Leakage Current at 1000V of capacitors before Radiation

Finally, it should also be mentioned, that the minimum voltage detected, was comparable to the noise level of the DVM, and it was suggested that part of the voltage observed, was due to the intrinsic noise of the resistors on the circuit. However, it could prove useful to compare how these measurements changes depending on the radiation dose the components receive.

Chapter 3: First Irradiation

After the first dose of radiation was completed, it was calculated that the components received 25.9 kGy of Gamma radiation at rate of 116 Gy/hour and cell temperature of 18 C.

The components were then subject to the same experiments described on the previous chapter, so as to compare the effects of such dose.

Capacitor

After the first dose of radiation, measurements where taken and the results are shown below

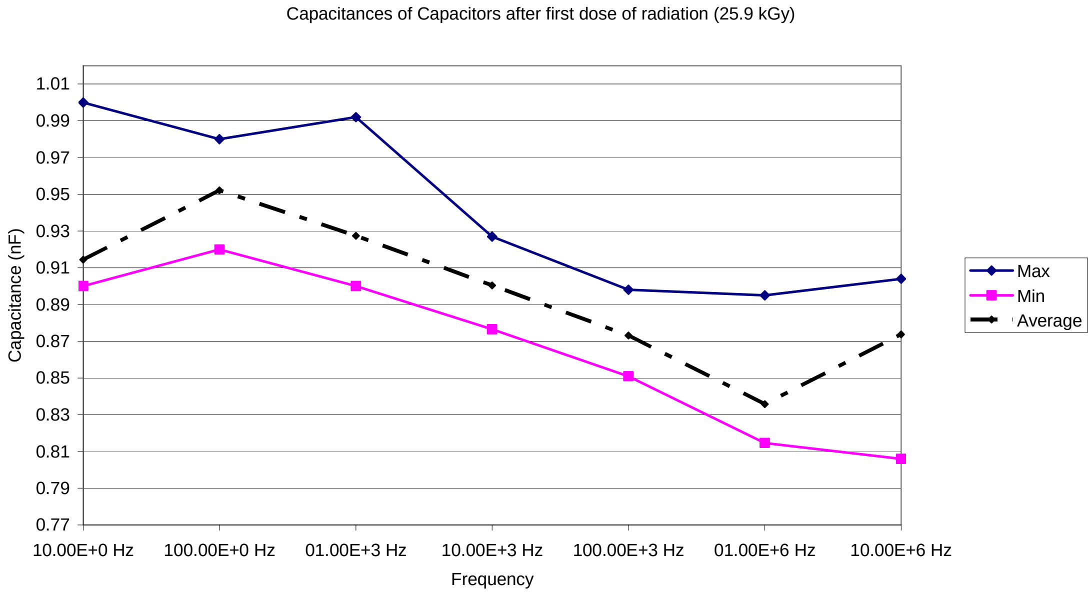

Figure 5 Capacitance of the Capacitors after first irradiation

Figure 5 shows that even if the capacitance of the capacitors differs slightly from the control model (the model obtained from the measurements before radiation); they do share the same trend. It is important to mention again that, measurements of the impedance were dependent on variables outside of control: such as temperature, humidity, and even the temperature of the impedance meter.

Because of this, it was expected different measures under the same radiation dose; therefore, each measurement was repeated, to ensure these factors had little influence on the results, as well as, ensuring repeatability. This figure shows the same behaviour all way through and variations within the tolerance of each components and Impedance Analyser. From these results, it could be agreed that after the first dose of radiation, the capacitors have suffered little or no change to their capacitances.

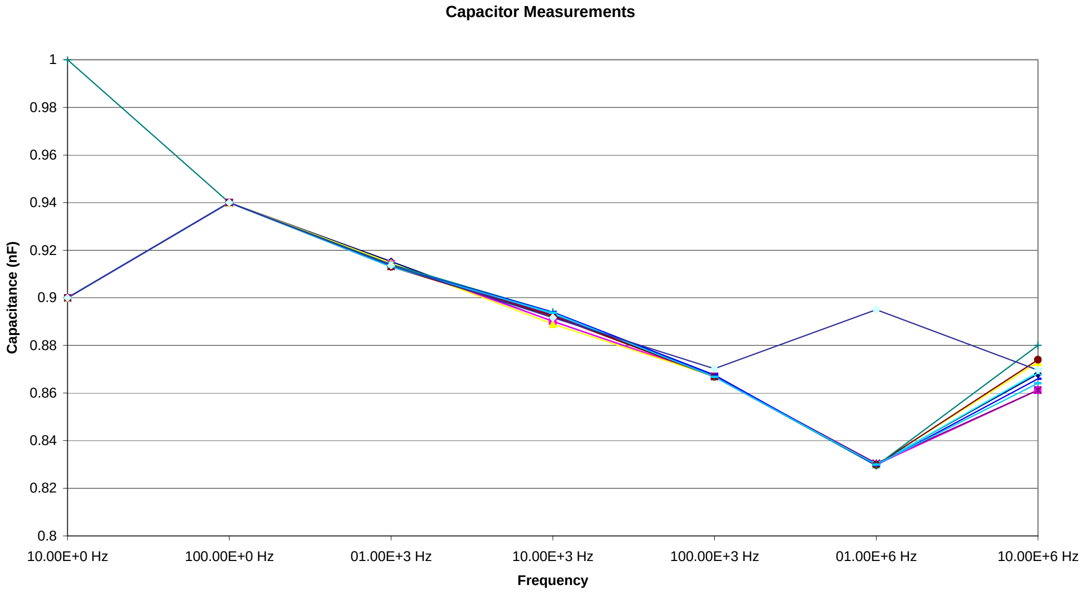

Figure 6: Results of repeated measurement of capacitor 1

The same argument could be applied to the conductivity of these capacitors, shown in Figure 7, however, even if they have increased, it does not rise for over 10%, which represent a decrease of the Ohmic Resistance by the same amount. However, the average conductance has remained with little or no change.

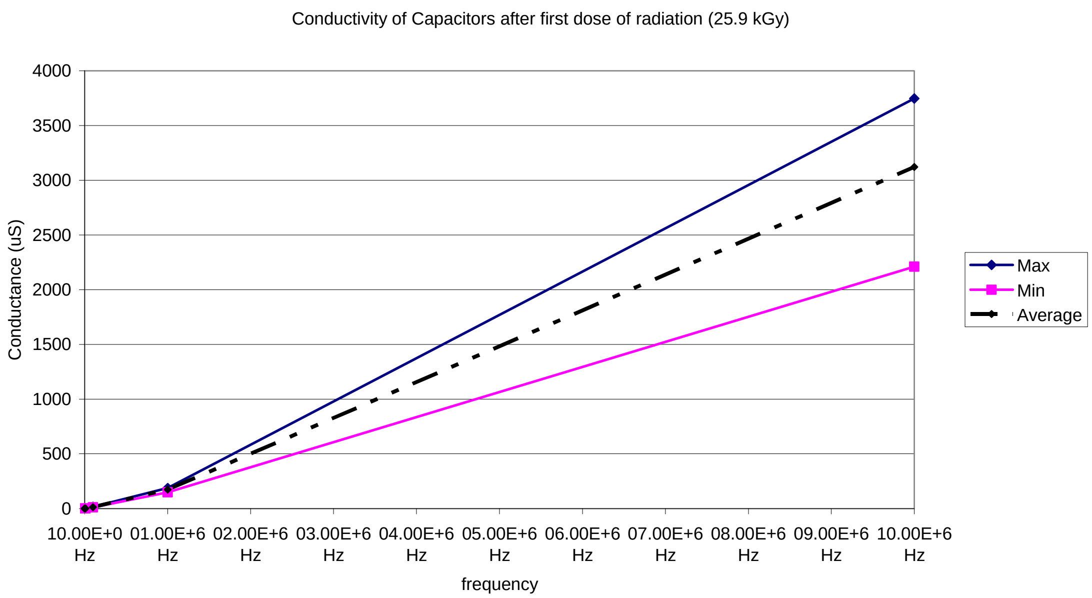

Figure 7 Conductivity of Capacitors after first dose of radiation

Figure 8 shows the leakage current after the first dose of radiation. These charts compared with the leakage before radiation, show again, the preservation of the behaviour of the components. This could be due to that, the first dose of radiation was not very high; in fact, this dose of radiation was well within the radiation resistance of the capacitors.

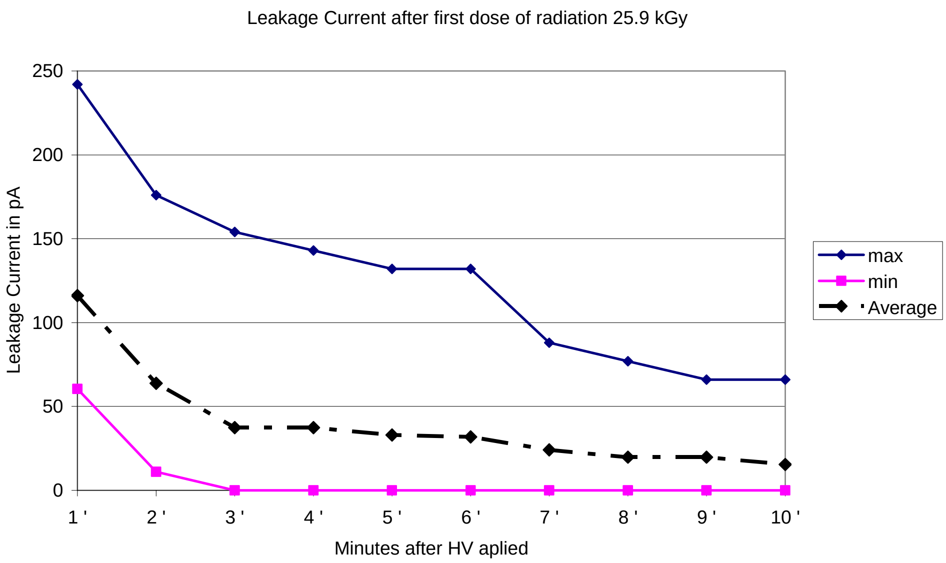

Figure 8 Leakage Current at 1000V after First Dose of Radiation

Resistors

Once the capacitors were tested, it was agreed that the resistors should have the same rigorous testing, and in spite not having previous data with which to compare these results to a control model, it would prove useful for future comparisons with higher irradiation dosed models.

This decision was taken after observing that the characteristics of the resistor varied with frequency. Figure 9 shows the parasitic shunt capacitance of the resistors, which, after 100 Hz it rises from a nominal 0 to a maximum of 0.2pF and then at 10 kHz it declines to an almost constant value of 0.15pF. These capacitive effects are very small, but it might explain why the conductance of real resistors also changes with frequency. As the frequency increases, the impedance due to the shunt capacitances reduces which in effect increases the conductivity of the resistor at high frequencies.

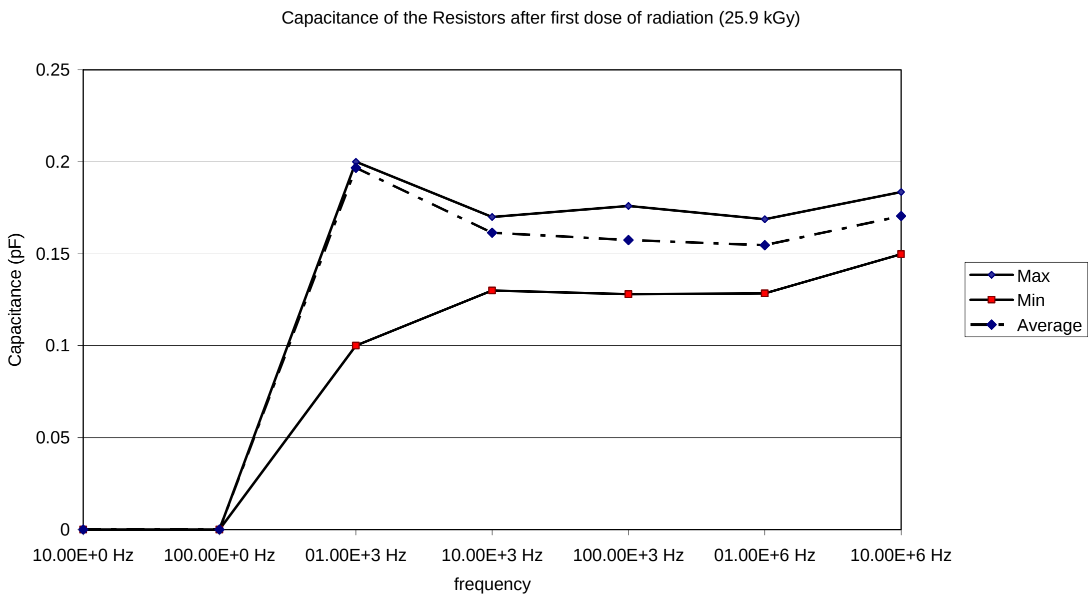

Figure 9 Shunt Capacitance of Resistors after first dose of Radiation

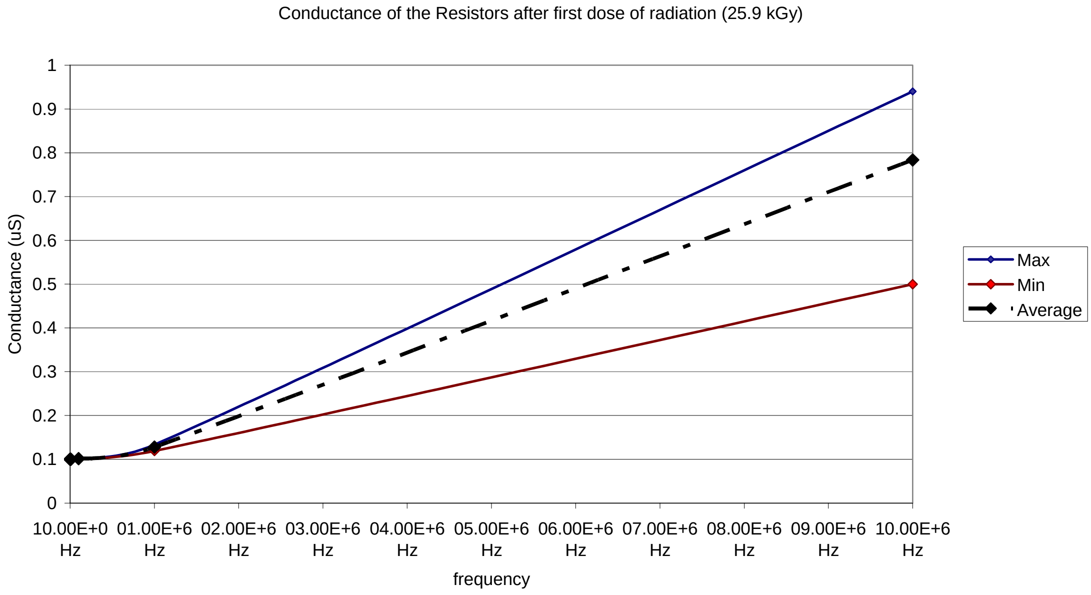

Figure 10 Conductance of the Resistors after first dose of Radiation

Figure 10 shows this change as a rise of the conductance of the resistors with frequency, in other words, as the frequency rose, the impedance decreased. As it has been seen on previous charts, the conductivity of these components and frequency are directly dependant. Moreover, the capacitor's conductances also share this behaviour, hence, it is believed, that if these tests were done prior to the first dose of radiation, one could have expected results of this fashion.

Chapter 4: Second Irradiation

On the preparation for the second does of radiation, it was estimated that, due to the volume of the metal box, in which the individual containers held the components, the timer required for achieving a high dose of radiation was going to be impractical. To solve this problem, it was concluded, to change the containers to ones of a much smaller size.

This new cylindrical containers, had an approximate diameter of ½ cm and 5 cm in length. Therefore, it was possible to provide accommodation for a more even irradiation. It was also concluded for practical reasons, to separate the containers containing the resistors, from the capacitors, in two metal boxes

After the second and final dose of radiation was completed, it was calculated that the components received 319 kGy of Gamma radiation at a rate of 1.04 kGy/hour and room temperature of 17 C, raising the total dose to 345 kGy.

The components were then remeasured to see the effects of a large dose have on their properties.

Capacitor

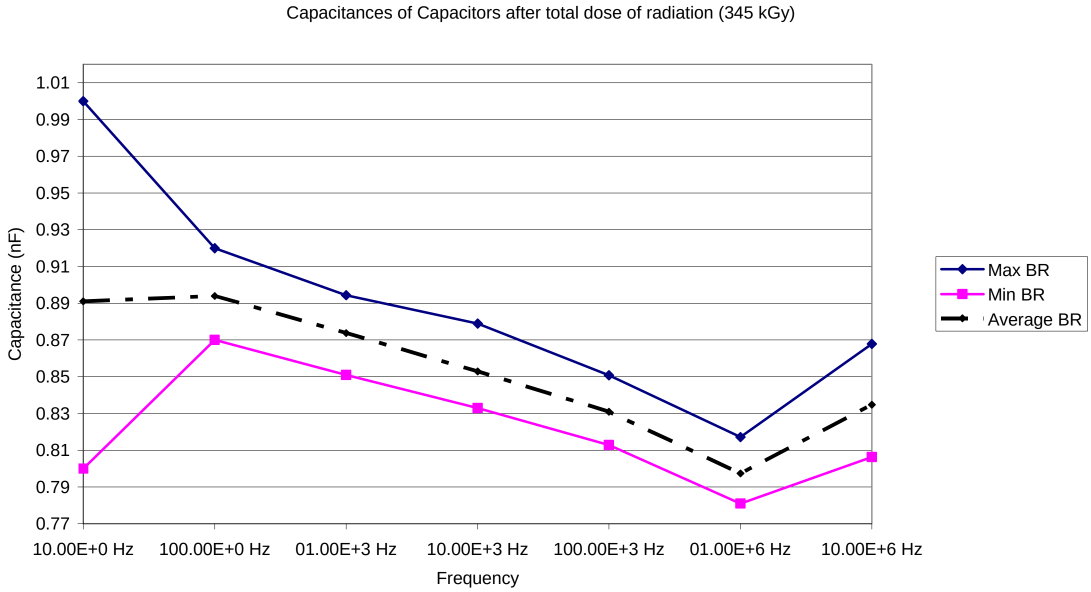

Figure 11: Capacitance of Capacitors after second irradiation

From Figure 11, it can be seen the maximum and minimum limits of the capacitance of the capacitors. This limits reflects a reduction in such capacitances due to the radiation that the components where subject to. This reduction was on the order 10% at 10 Hz on the lower limit, with no change on the maximum limit; however, at higher limits, this differences drop to less than 5% in both limits.

On the other hand, the conductance of the capacitors shown in Figure 12, reflect big differences but only at very high frequencies. These differences were rated at 25% at 10 MHz for the high band and 66% on the lower band. However, it is advised to remember, that these bands are only indicative of the values measured, and has no relation with the frequency of occurrence.

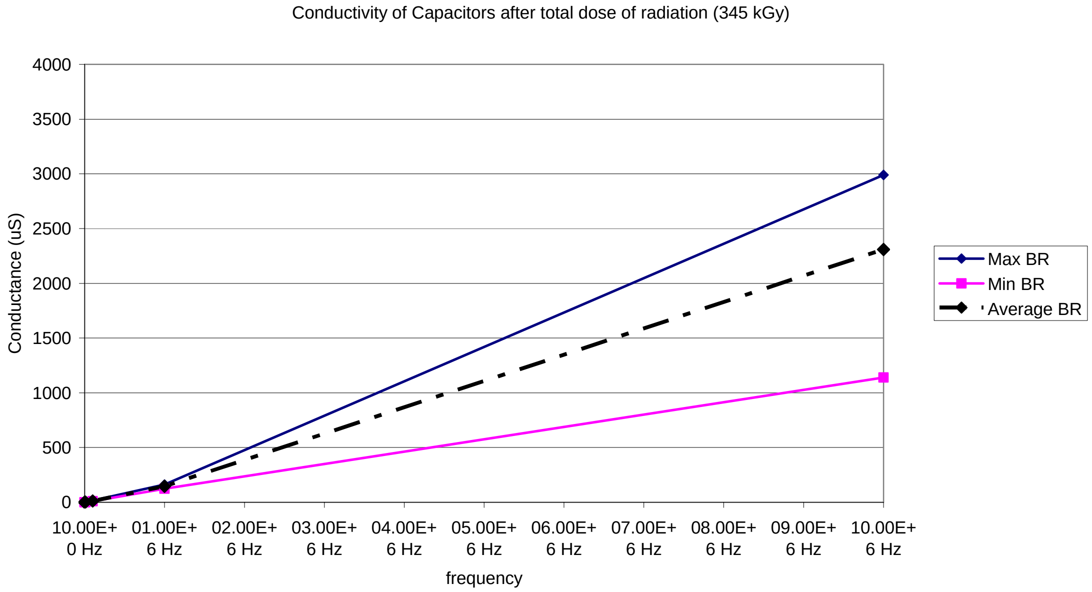

Figure 12: Conductivity of Capacitors after second dose of radiation

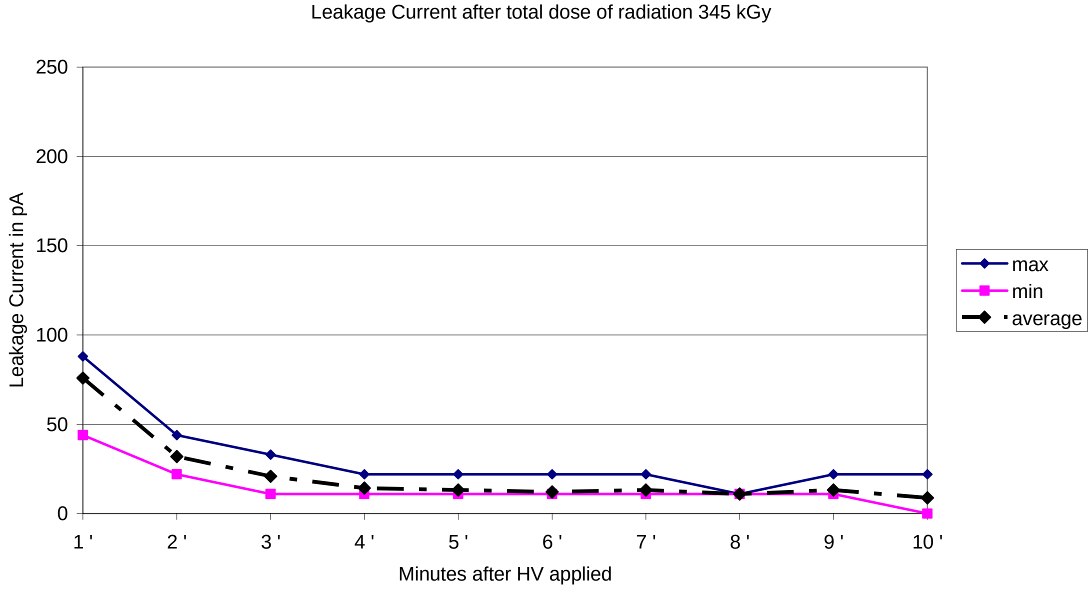

Figure 13: Leakage Current after second dose of radiation

Even if it has been shown that the parameters of the initial values of the components have been adversely affected, Figure 13 shows an improvement with a decrease of the leakage current.

Resistors

In contrast with the capacitors, the shunt capacitance of the resistors in Figure 14 shows a narrowing of the tolerance band at intermediate and high frequencies. What it is considered as interesting, is that the effect of the shunt capacitances flattens along the frequency axis, thus allowing a manageable model of the component for the studies of the frequency response of the HV filter. However, it is recommended to refer to the conclusion for further explanation of these results.

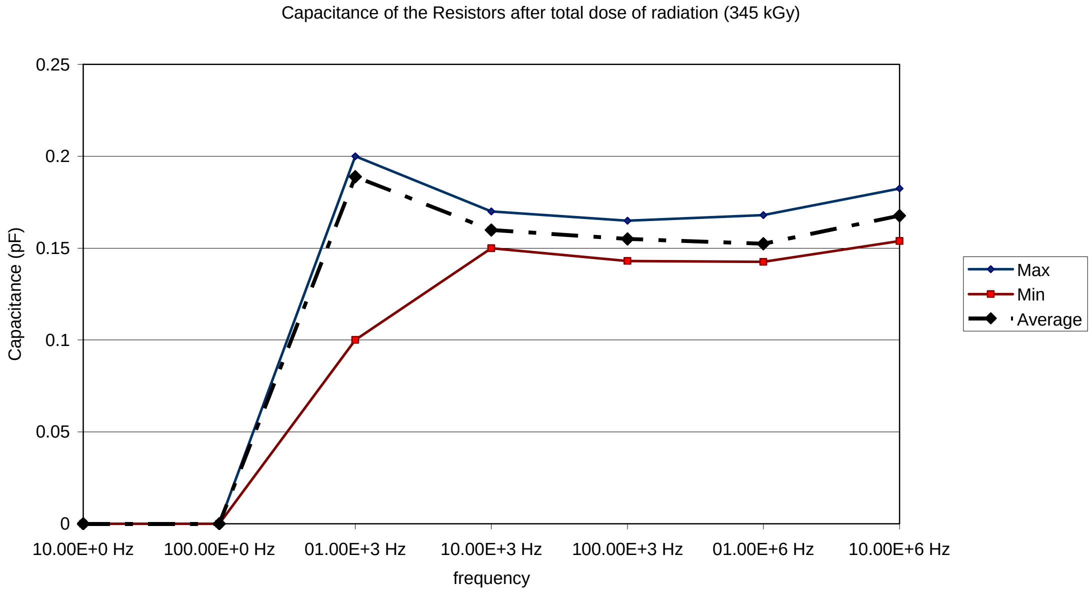

Figure 14: Capacitance of Resistors after second dose of radiation

On the other hand, the differences on the capacitances did not reflect the similarities that the resistors and capacitors shared on their conductivities. Figure 15 shows once again, the same behaviour of the conductance of the resistor to the capacitors. The lower and high bands suffered a widening as a function of the frequency; however, these bands have decreased their values by 5% for the higher band and 20% for the lower band at 10 MHz.

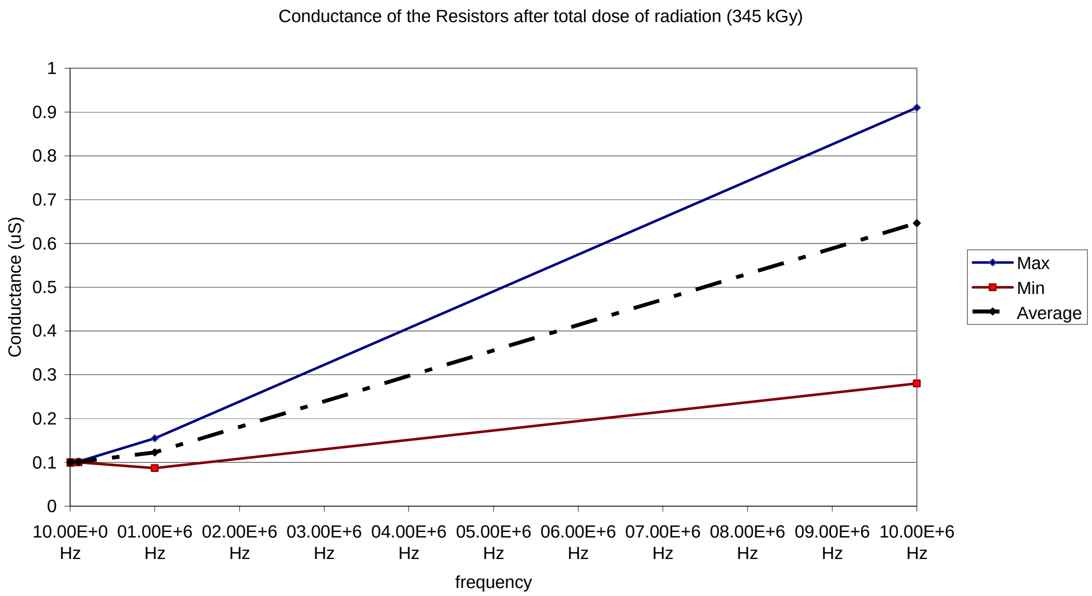

Figure 15: Conductivity of Resistors after second dose of radiation

Chapter 5: Leakage Current During Irradiation

This chapter discuss the measurement of the leakage current of a Farnell 498-385 1nF 2kV capacitor during irradiation.

Experiment

The leakage current on the capacitors was measured using the circuit shown in Figure 1 and mounted as shown in Figure 16

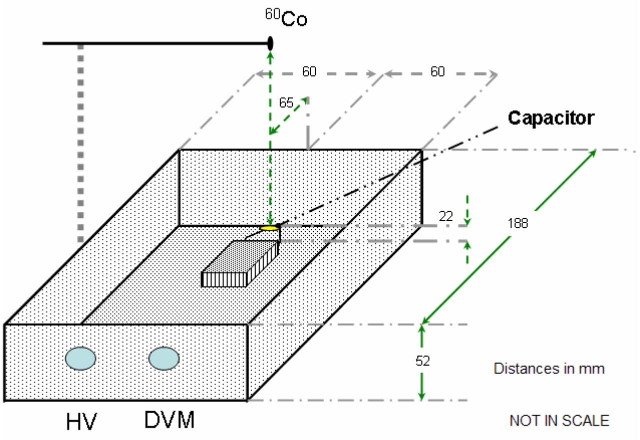

Figure 16: Jig Setup for Dynamic Testing

The circuit is mounted on a metal box. Figure 16 shows the dimensions of the box and the relative position of the source from the capacitor relative position between the source and the capacitor

As in the previous experiment, the capacitor was loaded to 1000V DC using a CANBERRA HV Power Supply, Model 3002. An “Intelligent Digital Multimeter” Thurlby 1905a was programmed to record measurements every 15 seconds.

The experiment was divided in three tests. The first test consisted on studying the leakage current during irradiation without a capacitor. On the second one, the capacitor was installed. Finally, the third test consisted of replacing the capacitor with wires of the same characteristics as the capacitor leads.

Once each test was ready to start, the circuit was powered and left to stabilise for at least ten minutes. Then the program on the DVM was run to start recording, and after an estimated time (or number of measurements) the mechanism that winds the source was activated. Finally after approximately three minutes, the mechanism was wound back in order to remove the source.

Confirmation of some effect of radiation, was observed, when there was a coherent change on the measurements at the estimated time

Results

As it can be seen from Figure 17 the first obvious result was a sudden rise in the leakage current when the source was exposed, proving that, radiation and leakage current do have a relation. The second observation was the time delay between the reactions of the three different modes, this was due to the human mechanical effect: although using a chronograph to know went to start winding the mechanism which took the source to the testing area, and vice-versa, the speed at which this was done could not be possible to control precisely, and hence synchronising the time-position of the source for all the tests.
Because of this, and in order to appreciate better the effect of radiation, some irrelevant data was omitted in favour of time synchronisation; as it can be seen in Figure 17. Secondly, due to the same reasons explained above, it is suggested to omit the analysis of the “transient” i.e. during the processes of winding and unwinding the source.

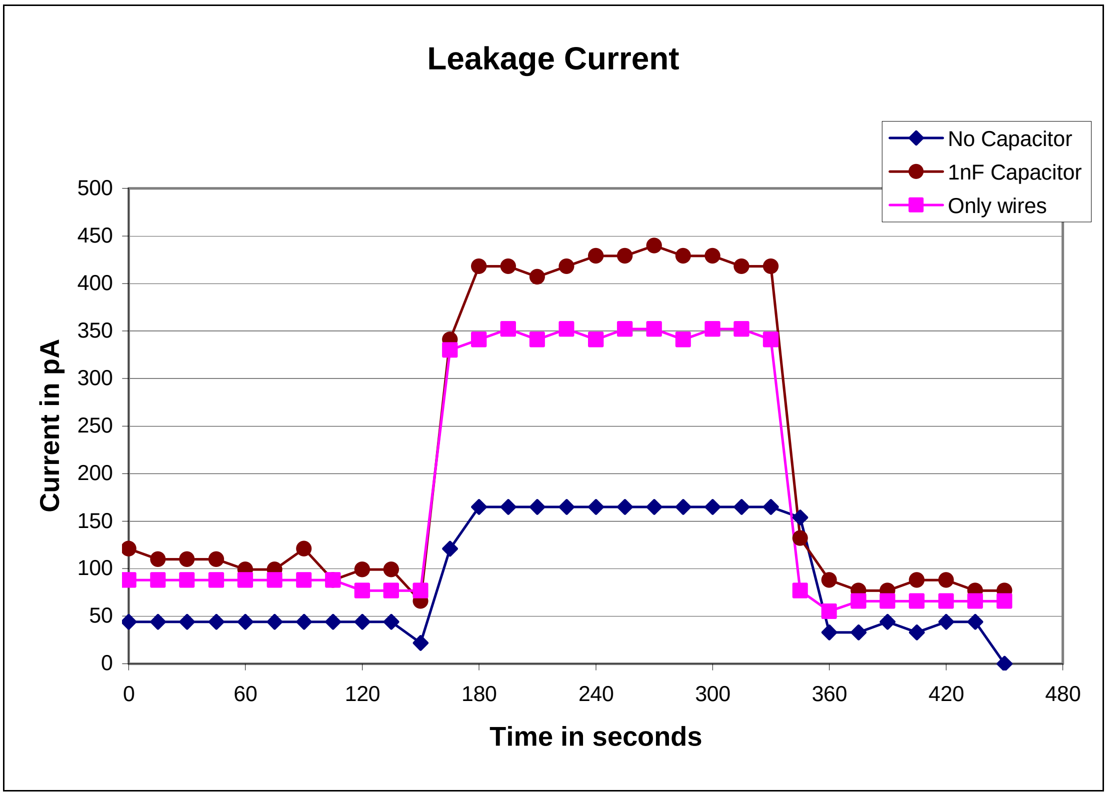

Figure 17

As mentioned above, it is clear that radiation does have an effect on the current passing through the circuit; however, this current should not be attributed only to the increased of leakage of the capacitor. Using superposition laws, Figure 17 shows the contributions of the capacitor and the wires, when the base measurements have been subtracted.

Figure 17 also shows that the leakage is greater with the capacitor than in any other case, however, it also shows that the wires of the capacitor contribute significantly to the leakage current. We hypothesize that, this is due to that the air around the wires being ionised with the radiation, and hence producing another route for the current to flow. Therefore, the contribution of the capacitor alone could be extracted from the two charts and it is shown on Figure 19.

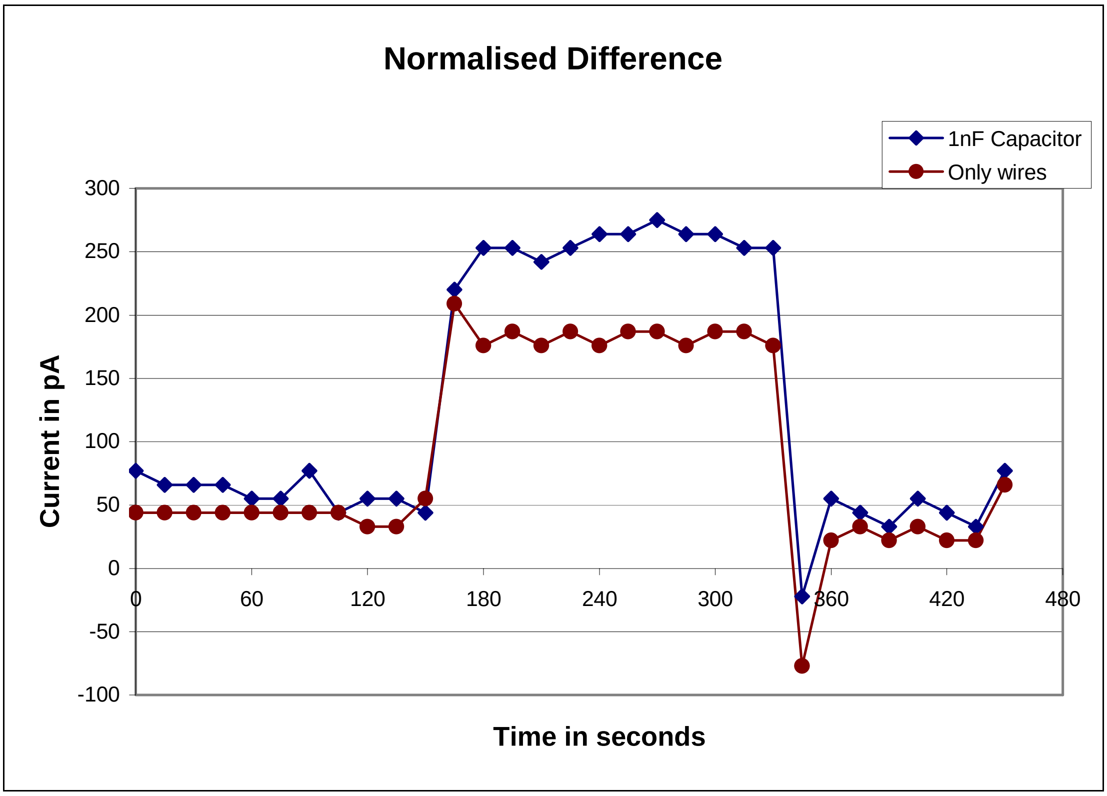

Figure 18

Finally, Figure 19 shows contribution of the capacitor alone; the average per region in the continuous line, and the "real" values in dots.

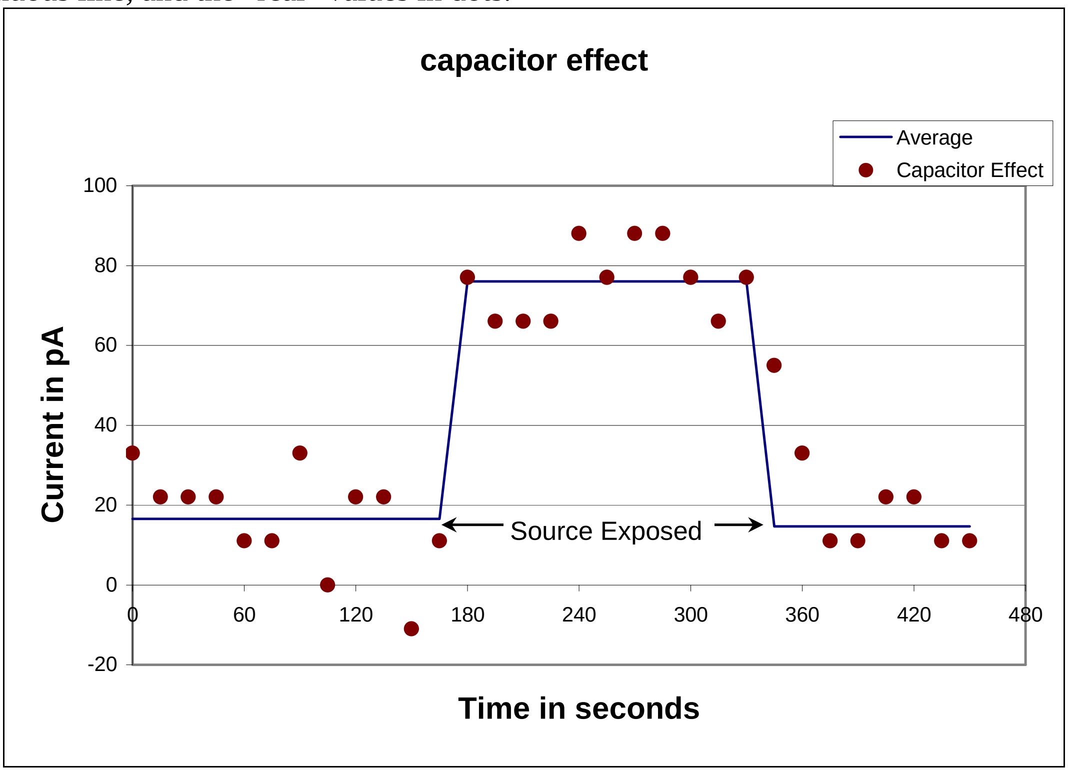

Figure 19 Additional Leakage Current due to capacitor alone

Chapter 6: Studies of recovery

This chapter studied a phenomenon raised by P. Osmokrovic [1], when he mentioned on his paper that capacitor would recover from irradiation. These theories were very interesting so we decided to conduct experiments to prove weather the theories applied to the capacitors studied on this report or not.

Measurements were taken 3 and 15 weeks after the final full dose of radiation and compared to the values obtained from the measurements before the components were irradiated.

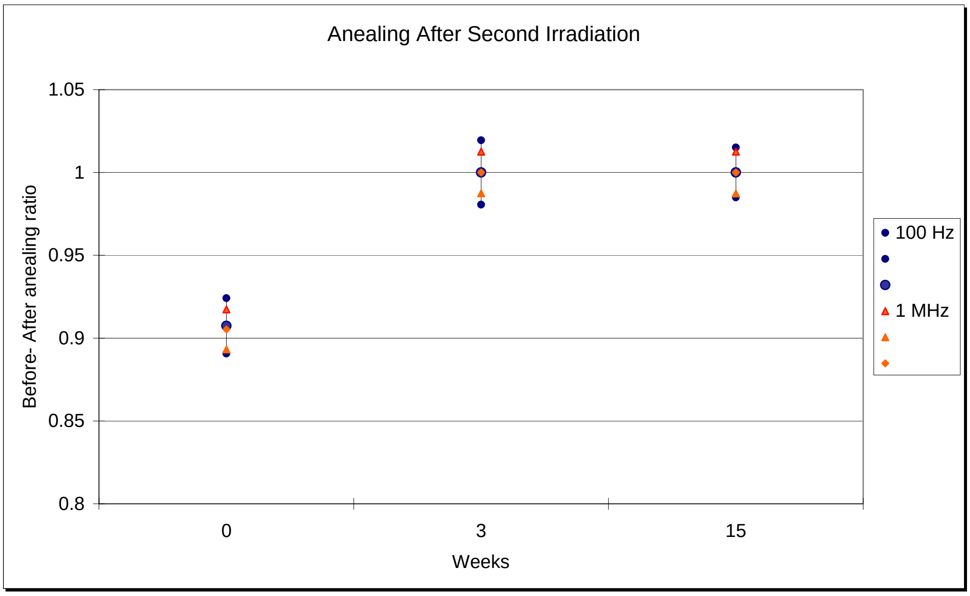

Figure 20 Recovery

Figure 20 shows the process of recovery of the capacitor after being subject to 345 kGy of gamma radiation. The data plotted on this figure is the mean $mean \pm 1\sigma$ of all the capacitors. It shows that most of the annealing takes place during the first four weeks, with very little change during the subsequent weeks. The frequencies studied (100Hz and 1MHz) were selected for this analysis due to that they are reasonable distant to each other, as well as being the points with more variations observed on the measurements.
This analysis concludes that these capacitors do recover after irradiation, and that any significant recovery takes place during the first weeks.

[1] P. Osmokrovic et all, **Radioactive resistance of elements for over-voltage protection of low-voltage systems,** *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 140, Issues 1-2, April 1998, Pages 143-151*

General Observations

About the Higher and Lower Bands

The benefits on this method for displaying the measurements obtained, raises from the simplification of the information shown. However, this simplification omits the frequency of a particular result, and hence reflecting the average, which was rarely the average of the bands, but some value between them. Even though, in some cases it showed that the margin of error was very slim, and that the data acquired varied very little in respect to the particular test of a component across the other components.

The values considered for these bands, where not from a particular sample, but from the maximum and minimum valued measured. I.e. these bands enveloped the whole experimental data enclosing the totality of the measurements.

About the observation on the effects of the radiation

The results shown are very encouraging on the fact that even if there was a 20% difference in some cases, the overall change has not reached an order in magnitude; therefore, it could be concluded on the stability and tolerance of theses components to radiation.

About the reliability of the experiments and data acquired

It is a fact that gradual radiation over a period of time has effects different to those from strong radiation on a shorter period, even if the radiation dose is the same. However, due to the length needed for the gradual radiation to which the components will be subject to, makes this experiment unviable. It is therefore, that the results obtained from this paper, should be only considered as a guide.

About external factors

It is important to mention again, that measurements of the impedance was dependant on variables outside of control, such as temperature humidity, and even the temperature of the impedance meter. These factors might have altered considerably the results from the measurements, explaining the appearance of widening on the gaps between the bands.

About Leakage Current Corrections

Corrections were taken to compensate for the leakage current observed without a capacitor due to instrumental error, noise and leakage on the circuit. This current generally approximated to 20pA, but the actual value was taken just before each testing each sample, to ensure consistency.

COMPARISON WITH PREVIOUS STUDIES

Comparing the results obtained from these experiments to those of Martin Torbet at RAL published in his report on CMS ECAL Endcap - Irradiation tests on HV filter components, on the 10th of November 2000, it could be concluded that:

1. In the case of the resistors conductance, there was no difference on the results for a frequency of 0-300kHz. However, Mr. Torbet's report did not study the effects of frequency on the measurements of the conductance, thus making impossible comparing the effects on the conductance or shunt capacitance, at intermediate and high frequencies, for the 10MΩ resistor.

2. Similarly, comparison on the effects of frequency on the capacitance and conductance of the capacitors, where not possible due to the lack of a base to compare them with. Even though, the evidence seen on this paper reinforces Mr. Torbet 's report on not only the changes seen between components, but the effects radiation have on the capacitances, as well as how much some capacitors have changed by radiation. In addition, his measurements at 300 kHz have a mean across the capacitor range of .925nF approximating the results of this investigation, which were .91nF at that same frequency before radiation. Furthermore, after the full dose of radiation, the results were even closer, matching to .87nF.

3. Finally, there was a good correlation between Mr. Torbet's report and the present one, on the study of leakage currents at 1kV each. The difference being that this report focused on the first ten minutes of the experiments and the former one for the next 20 minutes. Thus, the comparison could be made for t=10 minutes, at which, both reports show the same results.

Other sources where investigated to complete the comparisons with this paper. However, since Lambert et al [2], in 1975, no other publication was found. The group shows in their report a very comprehensive study of the effect of radiation across a wide range of components; however, Lamberts' report lacks the frequency analysis exposed in this paper, thus, making comparison impractical.

P. Osmokrovic et al[3], explain in their paper that the decrease of the capacitance was due to the formation of ionised structures on the dielectric, which somehow affects the partial screening of the electric field. With time, these structures recombine producing a recovery of the Capacitance. Although Osmokrovic's experiments were based on poly-carbon capacitors, this effect was too interesting to ignore. After three weeks the capacitances were measured again and a slight recovery was noticed; further readings were taken 12 weeks later, and when compared with the previous data, it was concluded that most of the recovery happened during the first 3 weeks.

[2] K. P. Lambert, H. Schönbacher and M. Van de Voorde, **A comparison of the radiation damage of electronic components irradiated in different radiation fields,** *Nuclear Instruments and Methods, Volume 130, Issue 1, 1 December 1975, Pages 291-300*

[3] P. Osmokrovic et all, **Radioactive resistance of elements for over-voltage protection of low-voltage systems,** *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 140, Issues 1-2, April 1998, Pages 143-151*

Conclusion

This paper reported on the effects of the radiation on nine RS 176-7956 10 MΩ 0.25w resistors, and ten Farnell 498-385 1nF 2kV capacitors.
Before and after each dose of radiation, the components had their conductivity and capacitance tested on Impedance Analyser from HP, model 4192A LF. Also, the capacitors were tested for leakage using a circuit shown on Figure 1, where the leakage current was calculated from the voltage measured across the resistor R1 for a period of 10 minutes.

The drop of the capacitance after the 345kGy can be seen in Table 1.

Table 1: Percentage drop of Capacitance

	Frequency						
	10.E+0 Hz	100.E+0 Hz	1.E+3 Hz	10.E+3 Hz	100.E+3 Hz	1.E+6 Hz	10.E+6 Hz
C 1	9.0	7.1	8.1	8.4	8.4	9.5	9.6
C 2	0.0	8.3	8.5	8.9	8.8	9.3	4.5
C 3	10.0	9.9	9.7	9.8	9.8	10.2	12.4
C 4	4.3	10.1	9.9	11.9	9.7	10.0	11.0
C 5	3.2	9.9	10.2	10.1	9.9	10.2	6.0
C 6	6.3	9.5	10.0	10.0	9.9	10.8	8.3
C 7	15.8	10.8	10.6	10.3	10.0	10.3	7.0
C 8	9.1	9.5	9.9	9.8	9.7	9.9	9.2
C 9	2.2	8.6	9.6	9.6	9.4	9.8	8.9
C 10	2.2	8.7	9.2	9.4	9.4	4.3	6.4

The resistors did not show significant changes at frequencies below 1 MHz, however, at 10 MHz, the story is another one, with the conductance dropping a maximum of 40 % at the lower limits, 20% on the average and 5% on the higher limits.

It was also studied the annealing process in order to investigate if the capacitors would recover after being irradiated. And it was concluded that these recoveries do happen but most of it during the first 3 weeks.

Then, it was measured the leakage current on a single capacitor while on radiation. Measurements were taken using an “Intelligent Digital Multimeter” Thurlby 1905a, which was programmed to record every 15 seconds, with the aim of investigating how the component would operate under the conditions it would be subject to. The result showed a small increase on the leakage current at 1kV during irradiation due to the capacitor alone.

Further analysis was conducted to appreciate the effect radiation had on each capacitor, and also the overall on all the samples. These results can be appreciated on page 22 in the appendix section. From this analysis this paper concludes that radiation do have an effect on the operation of such components, as well as in their life expectancy, as damage was inflicted with the dose and that it is asymptotic with a near to constant degradation.

Further experiments could investigate how the components operate, as well as, how long would they last before they are rendered useless at different dose rates. However, the time constrains could prove such research unfeasible.

Appendix

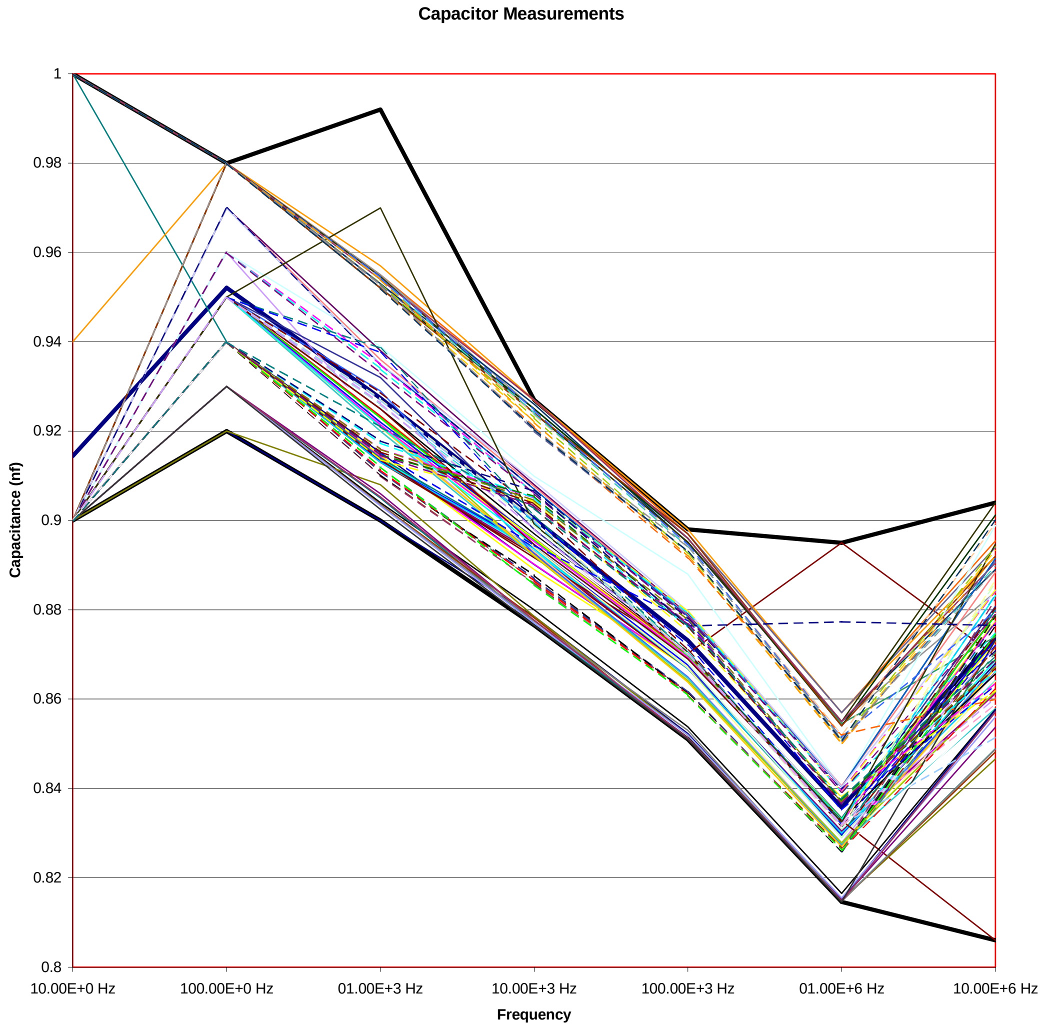

Figure 21 Complete set of capacitance measures on the capacitors after 26 kGy

Figure 21 shows the complete set of measurements for the capacitors for after the first dose of radiation. This includes the ten tests per capacitor, for all the ten capacitors. In bold black thick lines the maximum and minimum bands, proving that if fact all the measurements fell between these bands. By taking a detailed look at the graph it is also possible to notice that the measurements are divided in close groups. These groups correspond to individual capacitors showing also that the instrumental errors are very small, except from some exceptional peaks by some capacitors at some specific test. All in all, this graph is representative on the repeatability of the tests. The amount of data shown on this graph is obviously overwhelming, thus, concluding in the decision of displaying the measurements results as it has been displayed.

Radiation effect on the capacitors

The following pictures show the normalized capacitance of the capacitors, $C'_i(f_k,R) = \dfrac{C_i(f_k,R)}{C_i(f_k,R_0)}$; where F_K is the testing frequency, R is the radiation level and R_0 refers to the test before radiation.

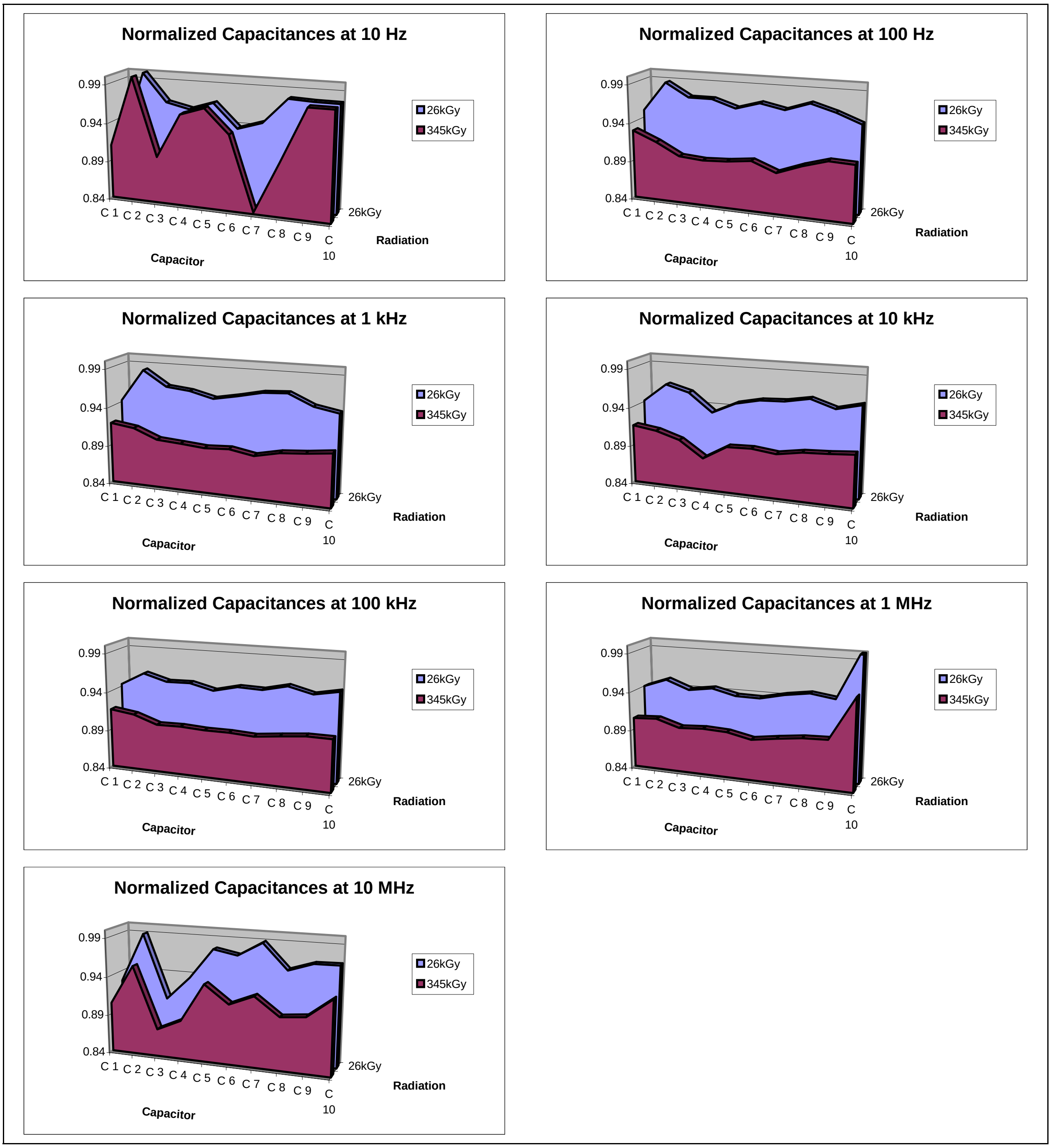

Figure 22: Effects of radiation on the capacitors