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PRE-STANDARD

Process management for avionics – Atmospheric radiation effects – Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects

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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

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The text of this PAS is based on the following document: | This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:

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107/59/NP	107/71/RVN

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will transform it into an International Standard.

This PAS shall remain valid for an initial maximum period of three years starting from 2007-09. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn

IEC/PAS 62396 consists of the following parts, under the general title *Process management for avionics – Atmospheric radiation effects:*

- Part 2: Guidelines for single event effects testing for avionics systems
- Part 3: Optimising system design to accommodate the Single Event Effects (SEE) of atmospheric radiation
- Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects
- Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects

1 Scope and object

This PAS is intended to provide guidance on Atmospheric Radiation effects on high voltage, nominally above 200 V. Avionics electronics used in aircraft operating at altitudes up to 60 000 feet (18,3 km). It is intended to be used in conjunction with IEC/TS 62396-1. This PAS defines the effects of that environment on high voltage electronics and provides design considerations for the accommodation of those effects within avionics systems.

This PAS is intended to help aerospace equipment manufacturers and designers to standardise their approach to Single Event Effects on high voltage Avionics by providing guidance, leading to a standard methodology.

Details are given of the types of Single Event Effects relevant to the operation of high voltage Avionics electronics, methods of quantifying those effects, appropriate methods to assist design and to demonstrate the suitability of the electronics for the application.

1.1 Normative references

The following referenced documents are indispensable for the application of this document, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/TS 62396-1, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

2 Terms and definitions

For the purpose of this document, the terms and definitions given in IEC/TS 62396-1 apply.

3 Potential high voltage single event effects

A N-channel power MOSFET can have two different types of catastrophic effects induced by the deposition of charge from a single energetic particle, Single Event Burnout, SEB and Single Event Gate Rupture, SEGR. In addition to this kind of power MOSFET, other power devices, such as Insulated Gate Bipolar Transistors (IGBTs), bipolar power transistors and diodes, which have large applied voltage biases and high internal electric fields, are susceptible to SEB. In SEB, the penetration of the source-body-drain region by the deposited charge can forward bias the thin body region under the source. If the bias applied to the drain exceeds the local breakdown voltage of the parasitic bipolar elements, the single event induced pulse initiates avalanching in the drain depletion region that eventually leads to destructive burnout SEB. SEGR applies to N and P channel MOSFETS. It is explained via the transient plasma filament created by the energy deposition track when the MOSFET is struck through the thin gate oxide region. As a result of this transient track filament, there is a localized increase in the oxide field which can cause the oxide to break down, leading first to gate leakage and finally to gate rupture. As a consequence of the atmospheric neutrons, SEB is the major threat to high voltage electronics.

Although at the outset, this threat to the power system in an aircraft from SEB may appear to be remote or even far-fetched, the experience of breakdowns in the high voltage electronics on electric trains in Europe before 1995 shows that SEB can be real and has happened in the field. In this case, European and Japanese manufacturers of high voltage semiconductors noticed that some of their devices were undergoing burnout failures in the field during normal operation of newly developed train engines [1, 2][1]. The diodes and GTO thyristors (Gate Turn Off Thyristors) used on the trains were rated at 4 500 V, and were normally operated at (50 to 60) % of rated voltage. They were designed for terrestrial use for > 35 years, so when the failures first appeared in the field after only a few months, this was puzzling. The failure mode was investigated in great detail and eventually a set of experiments, carried out at three different locations (salt mine, top-floor laboratory and basement), the results convinced the investigators that the cause of the failures was cosmic ray neutrons. Since that time, the manufacturers of these very high voltage devices have been careful in recommending the voltage at which the devices can be operated safely without SEB.

In addition, these manufacturers have followed the methodology established by an experienced radiation effects group [3] by carrying out tests in the WNR beam at Los Alamos National Laboratory to characterize the response of their devices to a simulated high-energy neutron environment. Because the atmospheric neutron flux is higher by about a factor of 300 at aircraft altitudes compared to sea level, it is clear that the same effect can occur in high voltage electronics in aircraft. The reason that, as far as is known, such failures have not been experienced previously in the field in aircraft power electronics, is that the bus voltage used in aircraft systems has always been low enough to preclude SEB or SEGR.

Generally, the highest voltage used in aircraft power systems has been 270 V, and a practical lower onset limit for most high voltage devices is 300 V. This practical lower limit stems from the fact that with SEB, there is a threshold voltage for the effect to occur; if Vds is kept below the threshold voltage, there will be no SEB. Thus, for 270 V operation devices rated at 400 or 500 V would be used, resulting in a situation in which the devices are being operated at a derating factor of 67,5 % and 54 % respectively. Since the devices are being used at < 300 V and with a derating factor of < 70 %, these conditions are sufficient to preclude any single event burnout in the high voltage electronics.

However, in advanced designs for avionics systems, significantly higher voltages are being considered for the bus voltage in order to reduce the overall weight of the system. The voltage will thus be >300 V, and in fact 600 V has often been mentioned as a practical bus voltage. Thus, in order to preclude SEB from occurring in the high voltage electronics of such advanced avionics systems, a sufficiently low derating factor will have to be used, and the adequacy of the derating factor will have to be demonstrated through testing.

4 Quantifying single event burnout in avionics for high voltage devices

Thus, the problem becomes that avionics vendors may be asked to provide systems that will operate at higher voltages, for example, 600 V, and there is virtually no guidance for them to use in developing the designs that will avoid the potential of SEB in the high voltage devices such as power MOSFETs and IGBTs.

In reality, the situation with SEB in high voltage electronics is relatively similar to that of single event upsets, SEU, in low voltage devices (< 5 V) such as random access memories (RAMs), microprocessors and FPGAs. The threat of SEU from atmospheric neutrons in the low voltage devices has been dealt with very extensively in the technical literature and in IEC/TS 62396-1. The approach in IEC/TS 62396-1 is that the rate of the single event effect, in this case SEU, in the devices, can be estimated by the following equation:

$$\text{SEE rate per device (per hour)} = 6\,000\ (\text{n/cm}^2\text{h}) \times \text{SEE cross section (cm}^2\text{ per device)} \quad (1)$$

[1] Numbers in square brackets refer to the bibliography.

The 6 000 n/cm^2 per hour flux is a nominal value for the cosmic ray neutrons with Energy > 10 MeV, at 40 000 ft (12,2 km) altitude and 45° latitude. It may be adjusted for different altitudes and latitudes using data in Annex D of IEC/TS 62396-1. For RAMs especially, a great deal of SEU cross section data has been published, allowing users of the standard to estimate the SEU rate, and some SEU cross section data is also available for microprocessors and FPGAs.

The same Equation (1) can also be used for SEB rates in high voltage devices provided that SEB cross sections are known for specific devices operated at a specified voltage. This standard recommends the use of Equation (1) for calculating SEB rates even though it is recognized that this is conservative. There is very little published data on the SEB cross sections, but the data that does exist [3 and 6] suggests that the SEB cross section is significantly reduced at lower neutron energies compared to for example 200 MeV. Thus a more realistic neutron energy threshold for calculating the SEB rate (energy at which the SEB cross section is similar to that at high energy, for example, 200 MeV) might be 50 MeV rather than 10 MeV. However, this level of conservatism will be allowed in the interest of maintaining consistency with IEC/TS 62396-1. The available SEB cross section data is documented in Clause 6.

For avionics applications, it should be recognized that assuming the HV electronics will be operating at a single voltage is unrealistic. First, the airplane power system is expected to experience power transients and spikes during flight. The transients typically last for less than 1 s during which time Vds could increase from 270 V to 350 V. The cascading power spikes can increase the voltage to even higher levels above nominal, although the duration is much shorter, usually < 100 µs.

Secondly, the details of the operation of high voltage equipment may be important in evaluating its susceptibility to SEB. For example, in the case of certain types of DC-DC converters, the voltage across the MOSFET is not continuous. The MOSFET cycles between off and on states, and the voltage across the MOSFET during the off state is higher than during the on state due to an inductive voltage associated with the mechanism that allows the magnetic energy to be discharged [11]. The highest voltage across the MOSFET is during the off state, but its magnitude depends on several operational parameters of the converter (for example, Vin, Vout and output current). Thus, a true evaluation of the SEB susceptibility should take into consideration the voltage across the MOSFET throughout the complete duty cycle and set of operating conditions of the converter. Other high voltage components may have similar variations in their operating conditions.

The use of the WNR beam to perform accelerated SEB testing of very high voltage devices [3] has spurred considerable additional testing of the very high voltage devices (> 2 kV) by the microelectronics companies that manufacture these devices. This testing has used the WNR facility as well as other sources of neutrons. The other neutron sources include the quasi mono-energetic neutron beam created by a proton beam on a lithium target (for example, at the Svedberg Laboratory in Sweden) or high elevation research stations (Sphinx Laboratory at Jungfraujoch, Switzerland, 11 300 ft (3,4 km) high). However, the results of such testing are usually considered proprietary and not published, or if a few are published, it is in an obscure publication [4, 5]. In addition, for these vendors having ground level applications, their results are often put into the format of a FIT (Failure in Time) rate, 1 FIT being equal to one failure in 10^9 device-hours of operation (see [3]).

The key points are that none of these very high voltage devices are relevant to avionics applications and that some vendors treat their SEB data as proprietary. However, the familiarity of these HV electronics vendors with the overall SEB issue from neutrons means that if they also manufacture lower voltage devices, devices that may be relevant to avionics applications, they may have SEB data, but this data will be considered proprietary.

5 Relevant SEB data and applying it to avionics

5.1 SEB data from heavy ion testing is not relevant

It is surprising that when it comes to SEB induced by high-energy protons and neutrons, there are only two IEEE papers [3, 6] that discuss this subject and present useful data, despite the fact that the first evidence of proton-induced SEB in MOSFETs was documented in a 1988 report [7]. Since the 1988 report, almost all data published concerning SEB in power devices has been based on single event effects testing using heavy ions to simulate the cosmic rays rather than with protons and neutrons. The results of the heavy ion testing is not relevant to the situation with high energy neutrons and protons. This heavy ion SEB data could theoretically be used if the SEB cross section induced by the heavy ions were measured, but in most cases this is not done, only the values of Vds and Vgs are presented, at which no SEB occurs.

However, even if heavy ion SEB cross sections were known, applying them to avionics applications would be extremely conservative, and would result in highly conservative SEB rates for avionics applications. For example, just looking at the Vds threshold value at which no SEB occurs, in a 500 V device that was tested with both high energy protons and heavy ions, the threshold was 330 V with WNR neutrons and 300 V with heavy ions. In addition, for a 400 V device, the threshold was 280 V with WNR neutrons and 220 V with heavy ions. Thus, the heavy ion results are overly conservative and there is really no substitute for SEB cross sections in high voltage devices measured using a high energy neutron or proton source.

5.2 SEB from high energy neutron and proton testing

SEB cross section data from tests using high energy neutron and proton with 400 V and 500 V MOSFETs are shown in Figure 1. The data comes from testing by Boeing [3, 6] and Fermilab, the Fermi National Accelerator Laboratory [8]. For some of the parts, the SEB cross sections are similar to one another at some values of Vds, but for other parts, there are some distinct differences. This figure includes data taken by Boeing on various specific devices using both the WNR neutron beam as well as 149 Me V protons (Harvard Cyclotron). The Fermilab data in Figure 1 was obtained using 200 Me V protons from the Indiana University Cyclotron Facility (IUCF). None of these Fermilab devices are identified as a specific part type.

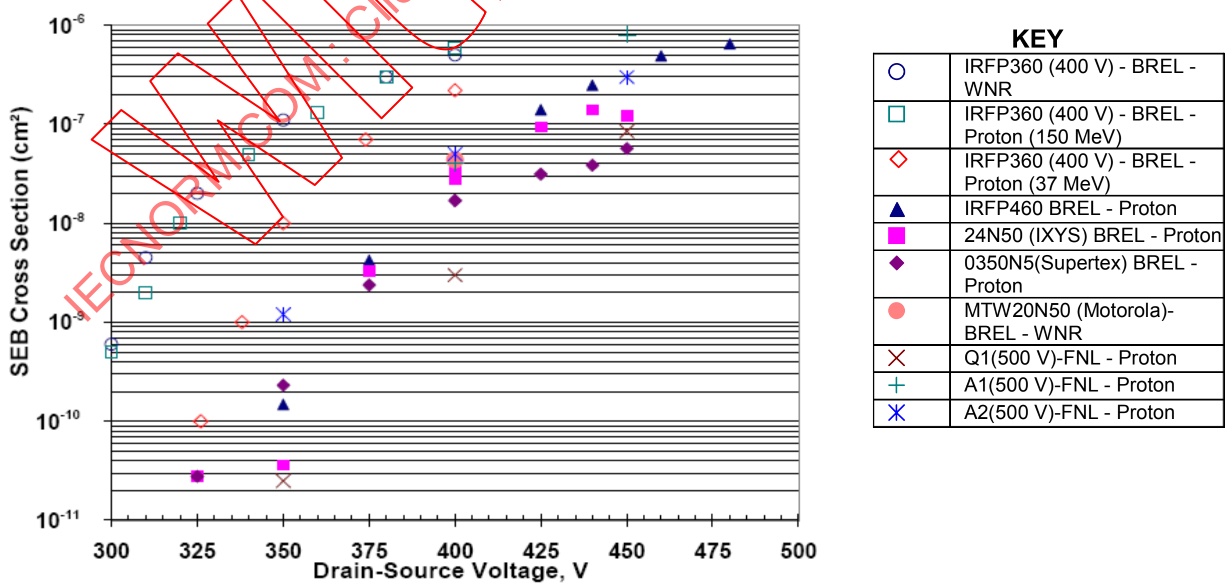

Figure 1 – SEB cross sections measured in 400 V and 500 V MOSFETs for WNR and proton beams

In looking at Figure 1, it is clear that the voltage threshold for the 400 V IRFP360 is < 300 V. In [6], the threshold is given as 280 V, meaning at 280 V there will be no SEB events, but at higher voltages, there will be. Figure 1 also shows that the SEB response of the IRFP360 is very similar when using the WNR neutron beam and a 150 MeV proton beam. However, when using lower energy protons, for example, 37 MeV protons, the SEB response is far too low compared to that with the WNR beam, for some values of Vds being too small by 1 to 2 orders of magnitude.

For the four different 500 V MOSFETs tested by BREL, the SEB cross sections are generally within an order of magnitude of one another, even though there may be significant differences between them, such as the size of the die and the maximum allowable current. At some values of Vds, the SEB cross sections are actually quite close for several of the devices. Of the three devices tested by FNL, one of these, Q1, exhibits a markedly smaller SEB cross section than all of the other devices, while the response of the other two devices, A1 and A2, are much closer to the response of the devices tested by BREL.

In Figure 2, we present similar data for higher voltage parts, mostly 1 000 V MOSFETs and two 1 200 V IGBTs. This data shows that there appears to be greater variation in the SEB cross section with the higher voltage devices compared to the 500 V MOSFETs in Figure 1. SEB cross section data exists on one part, the IRFPG50, using both 200 MeV protons and WNR neutrons. There is fairly good agreement between the two sets of measurements, with the proton SEB curve higher than the neutron curve by a factor of 2 to 3.

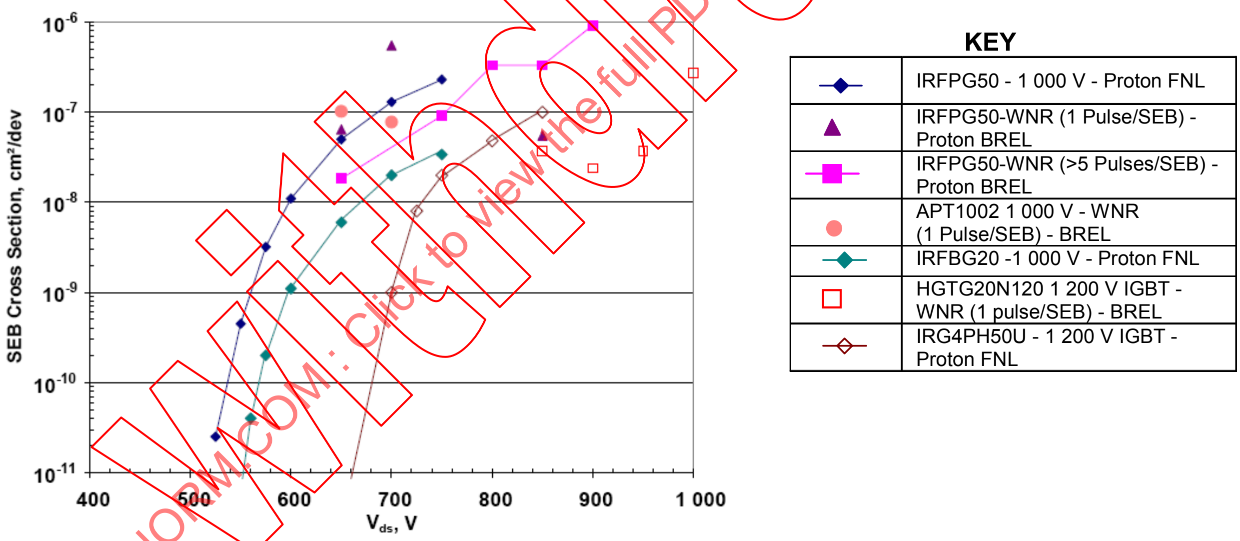

Figure 2 – SEB cross sections measured in 1 000 V MOSFETs and 1 200 V IGBTs with WNR neutron and 200 MeV proton beams

Two sets of SEB measurements were made with the WNR neutrons and these illustrate the importance of having good statistics (adequate number of burnout pulses) in calculating the SEB cross section. The SEB neutron curve that seems to parallel the proton curve was made on a single part with the burnout protection mechanism on the test card still operational, so that numerous burnout pulses could be counted during each neutron exposure. After the burnout protection mechanism was no longer operational, each burnout pulse destroyed the test sample, so there was only one burnout pulse per device. Since there were only a few samples available of each part type, the SEB cross section was based on a very small number of burnout pulses. For that reason, the SEB cross sections based on such a small number of pulses are not considered to be very accurate.

Although Figure 2 contains data on only two 1 200 V IGBTs (the open symbols in the figure), it clearly shows that the SEB cross sections for these devices are lower than those for 1 000 V MOSFETs by at least a factor of 10 and possibly more at lower voltages. However, since this is based on only two data points, such a generalization cannot be applied to other specific devices.

It also should be emphasized that most of the data in Figure 2 for the 1 000 V to 1 200 V devices are on devices from one vendor, International Rectifier, IR. The figure also includes data on one device from Harris and one from APT, but this not adequate for the figure to be viewed as being representative of the SEB behaviour of comparable devices from all of the vendors that produce such devices. A similar caution needs to be applied to Figure 1, although this figure clearly has a wider range of high voltage manufacturers included in it. Figures 1 and 2 should be viewed only as giving the overall behaviour of the SEB cross section curve as a function of applied voltage. These figures cannot be used in place of data obtained from the testing of actual devices that are being considered for use in specific systems.

5.3 Calculating the SEB Rate at Aircraft Altitudes

With the SEB cross sections shown in Figures 1 and 2, we can give examples of how to calculate the SEB rate for power devices. If it is assumed that a 500 V MOSFET is needed to operate at 400 V within an aircraft, from Figure 1 we see that an upper bound SEB cross section would be ~5×10^{-8} cm^2/dev, so that the SEB rate at 40 000 ft (12,2 km) would be, following Equation (1), 3×10^{-4} Burnout/dev·h. However, a much more reliable scenario would be to limit the MOSFET operating voltage to 300 V, in which case an upper bound on the SEB cross section would be 3×10^{-11} cm^2/dev leading to an upper bound SEB rate at 40 000 ft (12,2 km) of 2×10^{-7} Burnout/dev·h. However, with better data or by extrapolating the limited data in Figure 1 more carefully, much lower values for the SEB cross section could be obtained. For example, a SEB cross section that is at least a factor of 10 lower than 3×10^{-11} cm^2/dev could be obtained, or even more drastic, it could be assumed that 300 V is below the SEB threshold, in which case, there would be no SEB at 300 V. This emphasizes the importance of having good SEB cross section data on specific parts of interest in order to obtain SEB rates that we can have confidence in.

For advanced avionics systems that might operate at 600 V, from Figure 2 we observe that a reasonable value for the SEB cross section of a 1 000 V MOSFET would be 1×10^{-8} cm^2/dev. This would lead to SEB rate of 6×10^{-5} Burnout/dev·h in the nominal neutron environment (IEC/TS 62396-1, 40 000 ft (12,2 km) and 45 degrees latitude). However, in looking at Figure 2, we could also extrapolate the upper bound values to obtain an upper bound estimate on the SEB cross section that is an order of magnitude larger, in which case it would lead to a SEB rate of 6×10^{-4} Burnout/dev·h. For the 1 200 V IGBTs, the data on the IRG4PH5OU would indicate that 600 V is below the threshold of this specific device in which case no SEB would be expected from the atmospheric neutrons. The very limited data on the other IGBT, the HGTG20N120, is not adequate to allow extrapolation to voltages below 850 V so no conclusion may be drawn as to the SEB susceptibility of this device at 600 V. Therefore, again, these examples emphasize the importance of having good SEB cross section data on specific parts of interest in order to obtain SEB rates, in which we can have confidence.

5.4 Measurement of high voltage component radiation characteristics, EPICS

EPICS, Energetic Particle Induced Charge Spectroscopy, is primarily a non-destructive technique [9] to determine the charge or current response of high voltage devices under applied voltage to radiation. The technique was developed to assist in the understanding of the mechanisms behind charge multiplication within high voltage electronic devices and can also be used to determine derating margins for devices operating at high applied voltages.

The basis of the measurement technique is shown for a high voltage diode in Figures 3a and 3b using a charge and current measurement technique respectively. The high voltage (labelled 1 in the figures) is provided with a suitable storage capacitor. In the charge measurement technique, a Charge Sensitive Amplifier, CSA (A in Figure 3a) is used in combination with a multi channel pulse height analyser to record the radiation induced event charge at different applied voltages. Alternatively, the radiation induced event current may be measured using transformer current probes (B) of differing current ranges in combination with for example a digital oscilloscope (A in Figure 3b) employing suitable input sensitivity to provide a wide current monitor range.

The results are normally plotted as the number of events per charge or current interval in a logarithmic scale against the logarithm of the charge or current. In Figure 4, for results taken at TRIUMF using the arrangement of Figure 3b, the X axis is the logarithm to base 10 of the event current in milliamperes. The technique has the benefit that each measured event contributes to the graph. A typical EPICS plot for current measurement under simulated atmospheric neutron radiation (TRIUMF) of a 1 200 V diode is shown in Figure 4 where the curves at each applied voltage have been normalised to the same fluence ($3,5 \times 10^9$ neutrons per cm^2) at each voltage. Above 300 mA (2,5 on the logarithmic scale) the diodes potentially burn out, this is a measure of the critical current (charge). As the applied voltage increases the number of events rises, the event cross-section is rising and the peaks move to the right (increasing current and charge). For an applied voltage of 900 V there were no Single Event Burnout, SEB events, at a neutron fluence of 10^9 neutrons per cm^2. This equates to a neutron cross-section of less than 10^{-9} cm^2 at 900 V. The EPICS technique can be used in a similar way to measure the SEE response of power MOSFET, IGBT and bipolar transistors in order to determine voltage margins and cross-sections for SEB, Single Event Burnout.

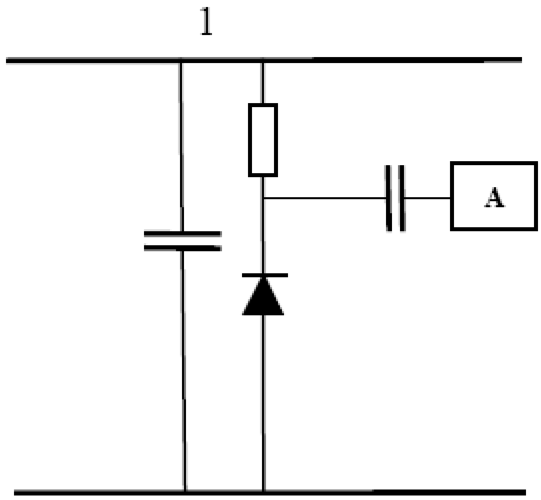

Figure 3a – Application of EPICS to the measurement of radiation event induced charge

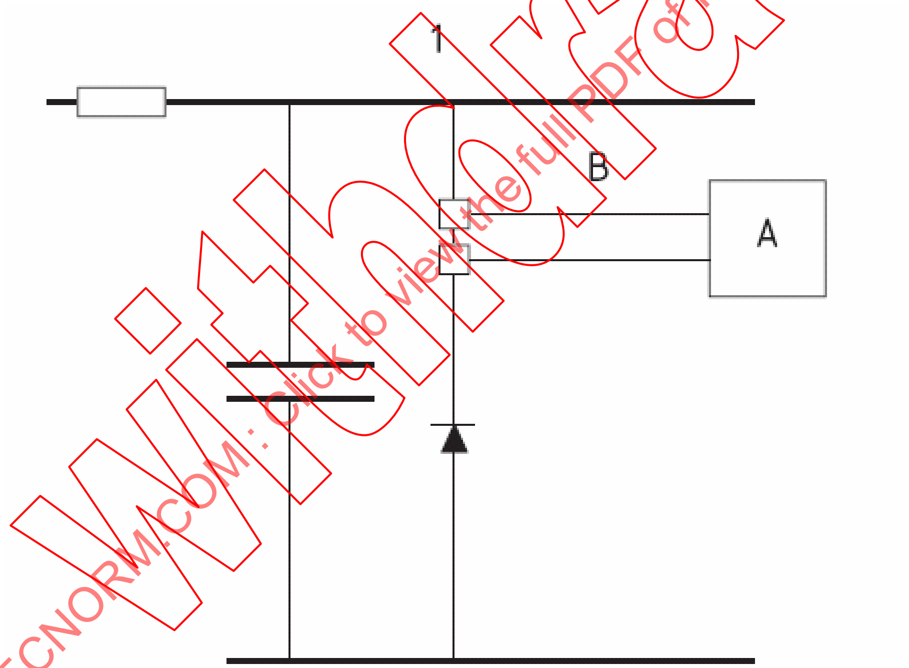

Figure 3b – Application of EPICS to the measurement of radiation event induced current

Figure 3 – Application of EPICS to the measurement of radiation event induced charge and current