Implementation and Validation of a Long-Term Measurement System for Single Event Burnout at High Altitude

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***Abstract*— In electrified aircraft, cosmic radiation can be a potential hazard to power electronic systems like drive train inverters and dc/dc converters. As the increased failure rate at high altitudes usually requires a voltage derating, a detailed knowledge on the failure rate of the individual power semiconductors is necessary to enable an optimal compromise between failure rate and power density. This data is usually gained by accelerated measurements, which could omit certain influences of the high altitude. Therefore, this paper presents the implementation of a fully automatic long-term measurement system for the determination of the failure rate due to single event burnout under real conditions for power semiconductors.**

***Index Terms*-- Cosmic Radiation, Electric Aircraft, Measurement System, Power Devices (Si / Wide Band Gap), Reliability, Single Event Effect**

I. Introduction

Particles from cosmic radiation can interact with semiconductor devices at the atomic level and have unpredictable effects in electronic components [1]. These effects are called Single Event Effect (SEE) and have different impacts. In case of a high radiation environment, such as in aircraft, certain precautions must therefore be taken. In power electronics, effects like the Single Event Burnout (SEB) or the Single Event Gate Rupture (SEGR) can occur, resulting in a destruction of the component [2, 3]. For an electric aircraft, this can lead to the failure of a propulsion unit as a worst case scenario. To reduce the probability of failures, the inverter topology can be designed with respect to its fault tolerance [4]. To obtain a meaningful failure rate for the entire system while at the same time enabling high power density, the failure rates of the power semiconductors must be known. Accelerated measurements of the FIT rate of Si and SiC semiconductors are state of the art and have already been published, including a description of the measurement setup [5, 6]. This requires the availability of a special neutron source which can reproduce the natural neutron radiation spectrum. However, only few of such facilities are available worldwide and the waiting times are usually long. Alternative sources of radiation like high energy proton radiation are being investigated for their similarity to the SEE studies [7], but especially for wide-bandgap semiconductors like SiC or GaN the validity of such measurements is not proven. In contrast, a long-term measurement offers the advantage that the natural cosmic radiation is available at any time, but as the radiation level is much lower compared to accelerated measurements. As a consequence, a high number of devices under test and a long duration are necessary.

General design guidelines and requirements for neutron radiation tests are given in [8]. The reference neutron radiation spectrum was set for New York, USA. The spectrum on earth differs mostly in terms of a constant amplification factor depending on the geomagnetic location and the altitude. For determining the FIT rate of power semiconductors at high altitudes, such as in aircraft applications, natural neutron radiation on earth has a similar spectrum. Compared to accelerated neutron beams, there are deviations, especially at high energies [9]. The here proposed measurement serves to determine the failure rate more realistically and highlight the deviations by comparing them to reference measurements with identical components. The construction of a long-term test offers a lot of challenges which, as well as suitable test-locations, are presented [8, 9].

II. Construction of the Long-Term Measurement

The general test procedure as described in [6] and [9] is based on biasing the Devices Under Test (DUT) with a High Voltage (HV) in the area of their rated voltage up to the breakdown voltage. This is done to gain a sufficiently high failure rate. The gate of the DUTs are connected to their source for permanent turn off. In case of a neutron radiation induced failure, a short circuit current will occur. The individual device should then be disconnected (e.g. with a fuse), to prevent a full burn-out of the device which could damage the other DUTs or the measurement system. The failure can either be detected by a current- or by a voltage-measurement, which will change after the fuse was triggered. In summary, the test setup has to provide the high bias voltage, measurement system for detecting the failure, a storage for the measured data and communication system for remote control and evaluation, and safety related systems.

A special challenge is the supply of high voltage at high altitude. The operation of devices at an altitude of more than 2000 m above sea level is usually only specified for special devices. Operation of high voltage sources with reduced voltage and power is therefore recommended. Additional care is taken during the development of the measurement setup to ensure that sufficient safety mechanisms are in place. The structure of the measurement setup is shown in Fig. 1.

The experimental setup is connected to the grid with a main switch, which has auxiliary contacts to deactivate the

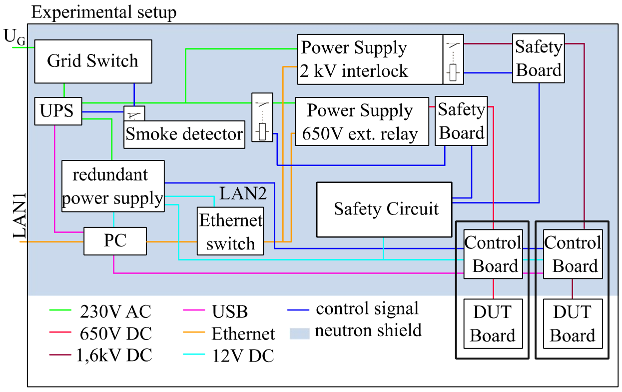

Figure 1: Simplified structure of the setup

Uninterruptible Power Supply (UPS) as well. The UPS is also deactivated by a smoke detector with auxiliary contacts.

A. UPS

If a grid failure occurs, the UPS provides a controlled shut down of the experimental setup. The UPS provides the input voltage for the HV sources and the redundant 12 V supply. The redundant supply ensures the operation of the PC, the ethernet switch, the measurement setup and the safety circuit.

B. PC

The PC controls the overall setup, including tasks like controlling the HV sources, the communication to the Control Boards, as well as evaluating the UPS, send status updates etc. After the start-up sequence, the PC is an observer and reports the status of the measurement. The measurement also runs without a PC, but the measurement is not monitored and it is not possible to react to discrepancies in the individual Control Boards.

C. Safety board

Because the experiment works fully autonomously with high voltages of up to 2 kV, safe operation must be guaranteed even in the event of a fault. A safety circuit with two separated HV discharge resistors, each with a HV relay is implemented. Simple HV relays have no auxiliary contacts, therefore monitoring for safe operation must be performed. Before the system starts a check sequence controls whether all HV relays are closed. After the start, only when both HV relays are open, the HV sources will be enabled. As backup check, a thermal fuse on the HV resistor can permanently shut down the HV source. Further checks in the safety circuit such as door switches ensure safe operation of the measuring system.

D. Control Board

The Control Board, which is shown in Fig. 3, has various functions and automatically records measurement data such as the number of functioning DUTs, the DUT test voltage, the sum of the leakage current of the DUTs and the temperature.

The fault current of a failed DUT is limited by the Control Board so that a failure of a DUT does not affect the parallel Control Boards. The fault current blows fuse F1 so that the DUT is disconnected from the high voltage

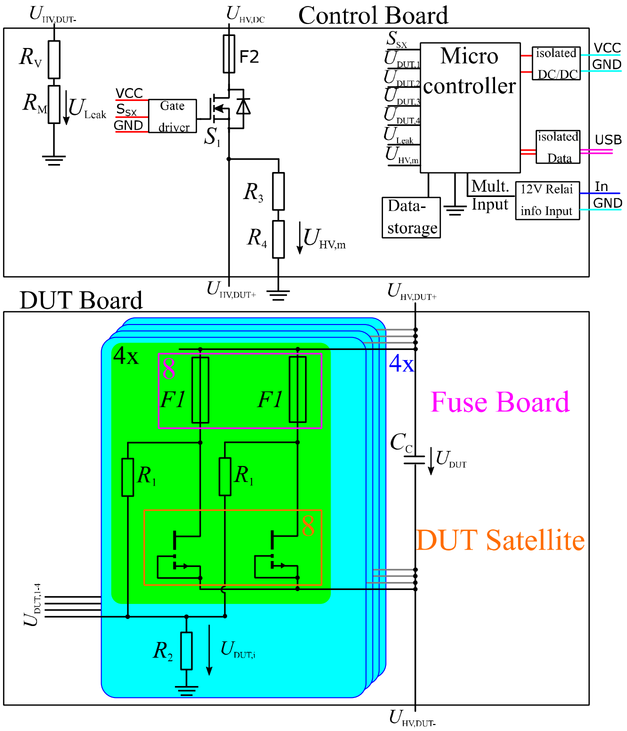

Figure 2: Stackable measurement setup of the FIT rate with safety precautions

supply. Due to the current measurement, the high fault current triggers a time-delayed disconnection of the voltage by the IGBT S1 and a possible arc is thereby extinguished. After a short time, the IGBT S1 is switched on again. If a failure current still occurs, the process is repeated. After five attempts, the IGBT S1 will remain permanently switched off and the fault will have to be rectified manually or the user will have to switch it on again. If the IGBT S1 is faulty (or permanently switched on for other reasons), the HV fuse F2 will disconnect the Control Board on which the error occurred.

E. DUT, DUT-Satellite & Fuse Board

For each individual Control Board there is a DUT Board, on which 128 DUTs are placed as compact as possible. For this purpose, eight fuse boards are used in each case to keep the distances as small as possible despite the voltages of up to 2 kV. In order to be able to test devices with different footprints, separate plug-in boards are used for the individual DUT-Satellites. With this arrangement the space required to measure 128 DUTs is about 325 mm x 180 mm x 65 mm.

III. IMPLEMENTATION AND PREPARATION OF THE MEASUREMENT

The DUT Board, shown in Fig. 4, is designed as compact as possible for the measurement system. On the top of the DUT Board are the DUT-Satellite Board. Each DUT Board belongs to one Control Board, shown in Fig. 5 inside of the server rack. This saves the measurement data, monitors the measurement and communicates with the PC. The structure of the entire measuring system was made similar to the system presented in [9]. An open 800 mm x

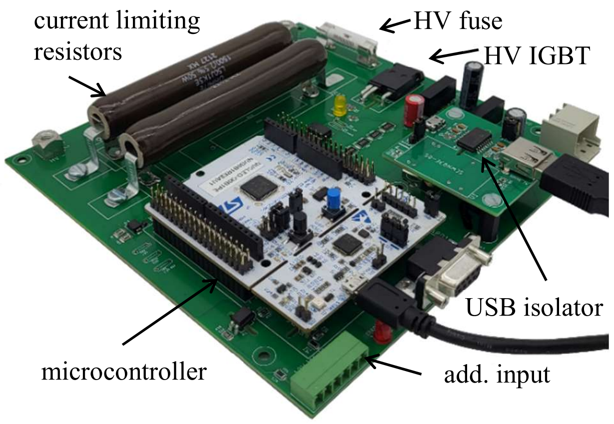

Figure 3: Control Board

800 mm server rack is the base and the top and side are neutron shields. The DUTs are placed on the top of the server rack, while all other components are placed inside of the shielded rack, which is shown in Fig. 5.The PC communicates via a serial interface and requests the status

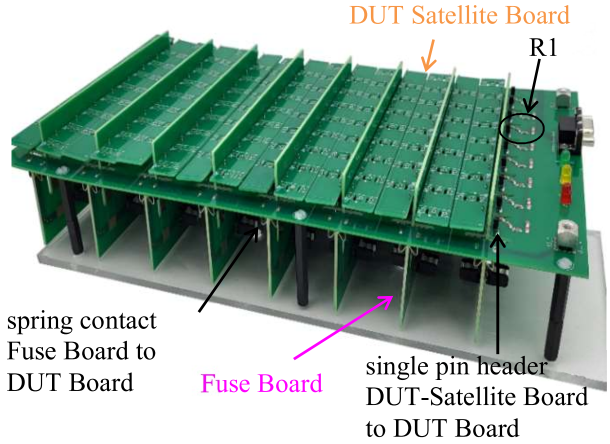

Figure 4: DUT Board combination with Fuse & DUT-Satellite Board

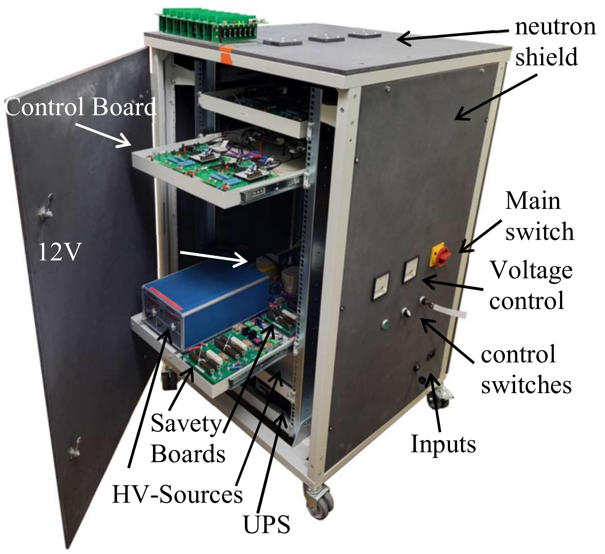

Figure 5:Overall design of the measuring system

of the Control Boards and the measurement data of the test daily. The Control Boards is storing a time stamp, the supply voltage U_{HV} and all measurement voltages $U_{\mathrm{DUT},i}$. Additional the ambient temperature at the DUTs and the leakage current of all DUTs.

Since a long-term measurement requires a high number of test specimens, this test setup offers the possibility of testing several DUT Boards/Control Boards with identical test specimens. It is only necessary to ensure that the DUTs have an identically long test time and that no interruptions of different lengths have taken place. This is possible because of the individual Control Boards, which disconnect themselves from the supply voltage in the event of errors without affecting other measurements.

For the evaluation, the time stamps of the measurements must be synchronized and then the failure times t_i determined. With this information, the FIT rate is calculated according to the equation:

$$\bar{\lambda}_{Chip} = \frac{k \cdot 10^9}{\sum_{i=1}^{k} F \cdot t_i + (n-k) \cdot F \cdot t_k} \quad (1)$$

With k corresponding to the number of failed DUTs, t_i corresponding to the time difference between start of the measurement and the failure of the DUT and t_k corresponding to the measurement time. The acceleration factor F results from the test location $\dot{\Phi}_0$ and the reference neutron flux $\dot{\Phi}_{ref}$ [8].

$$F = \frac{\dot{\Phi}}{\dot{\Phi}_{ref}} = \frac{DUT\ neutron\ flux}{12.96\ \mathrm{n/cm^2h}} \quad (2)$$

The neutron flux at the device $\dot{\Phi}$ can be reduced by other materials such as concrete. This can be taken into account with the following equation.

$$\dot{\Phi} = \dot{\Phi}_0 \cdot e^{\frac{-x}{0{,}37m}} \quad (3)$$

This equation [8] serves as an estimate for the influence of a 30 cm thick concrete ceiling (with associated roofing, ceiling, and flooring material, ductwork, etc. in an industrial building). In order to include the chip area of the DUT, this area must be represented in cm^2 like the neutron flux.

$$\bar{\lambda} = \frac{\bar{\lambda}_{Chip}}{A_{Chip}} \quad (4)$$

The error rate should be specified with a confidence limit as described in [10].

IV. Monitoring of the Measurement System

The measurement system includes a remote PC that monitors the test bench controlled by a self-developed software. In order to detect errors within the software, a watchdog is monitoring the subsystems of the program and restarts subprograms in the event of crashes and sends out

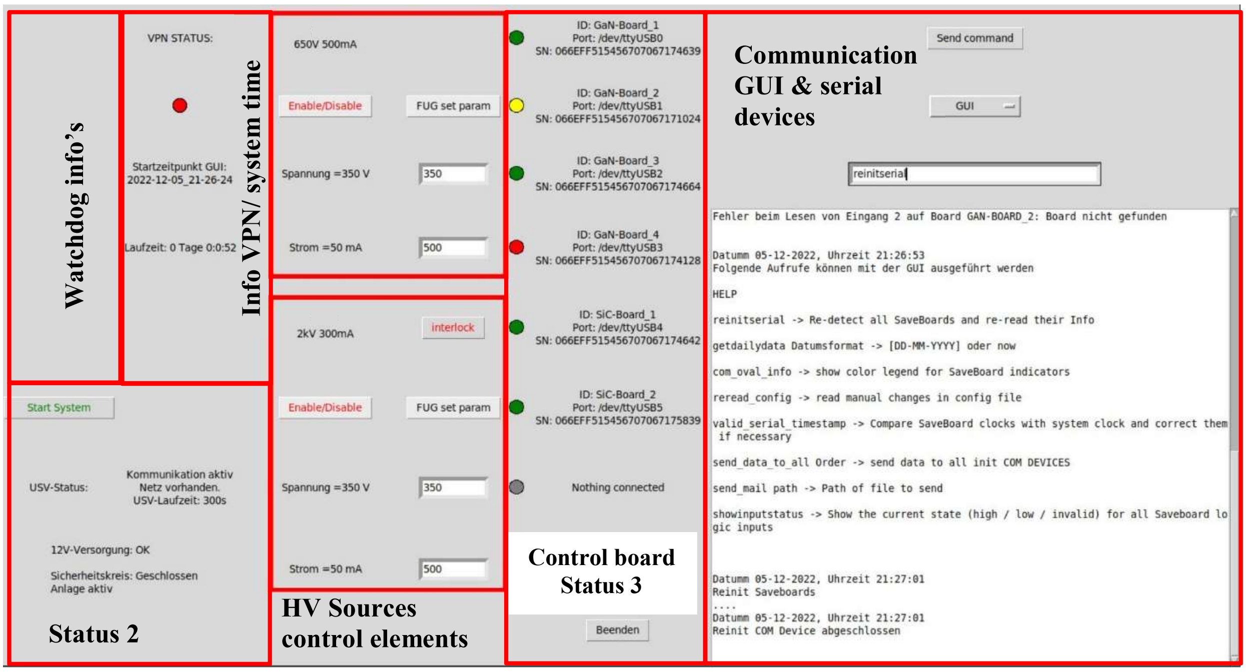

Figure 6: Overview of the GUI of the measurement platform

a warning. The GUI is separated into parts and shown in Fig. 6.

A subprogram monitors and activates the VPN connection. In addition, this subprogram sends the emails pending in the mail storage and monitors the UPS log data.

There is one subsystem for each HV source, so status/control is not lost if other subsystems fail. Changes about the connection status are saved in the mail storage.

One subsystem communicates with the Control Boards. This subsystem is acquiring the Status 3 and saves changes in the mail storage. The inputs of the additional 12 V signals are acquired, so that the status of the security system (door switches/key switch/HV discharge modules/ 12 V power supply) are shown in the GUI. Additional daily backups are created and stored.

One subsystem is refreshing the GUI.

V. VALIDATION OF THE EXPERIMENTAL SYSTEM

In a manual test, the measurement system was tested with an actively switched on power semiconductor to simulate a failed DUT. The test setup is able to detect a failing DUT with a maximum test voltage of 2 kV, with the fault current blowing fuse F1. The arc is extinguished automatically, before the microcontroller switches the HV IGBT off and so disconnects the DUT-Board from the high voltage. However, the voltage exceeding the nominal fuse rating due to missing alternatives, the fuse can cause its glass package to break even with the additional safety measures. The counting system of the DUTs works with sufficient accuracy. Please note that the VCR (Voltage Coefficient of Resistance) of the SMD resistors used must be taken into account in the measurement. Otherwise the resulting tolerance would be too large for the measurement.

In the first test under real conditions in the laboratory, the target is $5 < k < 10$ failures of the DUTs with a test duration of $t_k = 30$ days. Other assumptions are an acceleration factor $F = 1$, no influence of the ceiling is assumed $x = 0$ m, and the chip area of the DUTs is $A_{\text{Chip}} = 1\ \text{cm}^2$ (see eq. 3).

$$n = k \cdot \left(\frac{10^9}{\bar{\lambda}_{Chip} \cdot F \cdot t_k} + \frac{1}{2} \right)$$

Due to the many dependencies, the error rate is difficult to determine. For this test, $U_{nom} = 600\ V$ Si MOSFETs with known error rates from accelerated measurements are used. The error rates are in the range of 1 to 10000 at a voltage $U_{DC}/U_{nom} = 0.67$ to 0.8, as shown in Fig. 7. With an expected FIT rate $\bar{\lambda}_{Chip}$ between 70 k and 150 k, 5 up to 10 DUTs should fail according to the exponential extrapolated confidence interval. As the initial function $f(z) = z \cdot e^z$ was chosen for the extrapolation. z was substituted to $z(x) = a \cdot log(b \cdot x) + c$ .The extrapolated confidence interval is shown in Fig. 7. The reserve is a multiplication/division with a voltage-dependent exponential function out of the range of the known measured FIT rate.

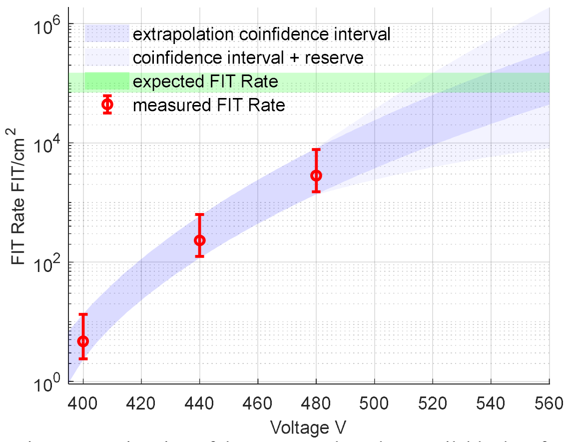

Figure 7: Estimation of the error rate based on available date from accelerated tests

A DC voltage of 550 V is selected and 100 DUTs are tested. In addition, a second Control Board and DUT Board without DUTs is tested at maximum DC voltage of 2 kV to test the PCB and HV components at maximum voltage without coating.

The software currently requests the status periodically with a time interval of 100 ms. During the test phase there were sporadic interruptions in the communication. After reconnecting, the HV sources were automatically deactivated. This was fixed after maintenance.

VI. EVALUATION OF THE MEASUREMENT RESULTS

The Measurement are currently in progress and the test system is shown in Fig. 8. After 21 days measuring time three DUTs are failed, the FIT rate is about $\bar{\lambda}_{Chip} = 60$ k and shown in Fig. 9. Otherwise, there were no unusual characteristics in the measurement data during this measurement. In the second Control Board / DUT Board with 2 kV DC voltage, the leakage current and the source current are monitored and no abnormalities occurred.

Figure 8: Test of the measurement system

It is therefore assumed that, if no problems continue to occur, this system with coating and a lower voltage of 1.65 kV is suitable for long-term testing.

The failure rate of the DUTs is currently under the expected range and about 4-5 DUTs will fail if the process continues identically. The confidence interval is still slightly large due to only two occurred failures.

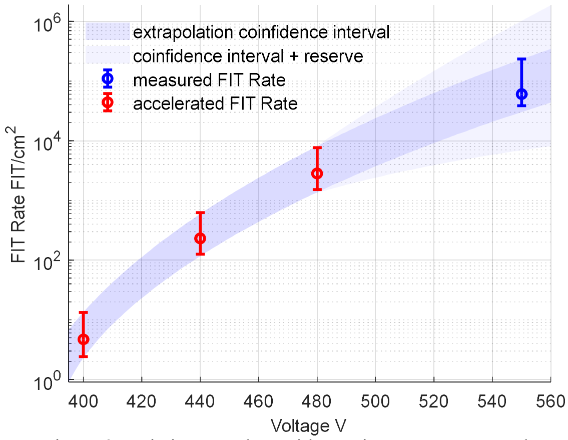

Figure 9: Existing FIT data with preview measurement data

VII. CONCLUSION

This paper presents a fully automatic long-term measurement platform for single event burnout measurements at high altitudes. The measurement system can monitor up to 1024 DUTs on an area of about 800 mm x 800 mm with up to 2 kV DC voltage. The focus is on the most compact design and safe and maintenance free operation. Particular attention is given to the challenges at high altitude and safe operation due to the high cosmic radiation. The development, function tests of the measurement parts and the implementation in a compact prototype are completed. The first test phase is promising and provides expected results. The software and hardware have been developed and described in the paper.

VIII. ACKNOWLEDGEMENT

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