**Fraunhofer-Institut
für Naturwissenschaftlich-
Technische Trendanalysen (INT)**

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Survey of Total Ionising Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE

TN6.7
SEE Test Report for
SiC Schottky Diode
STPSC6H12

Manufacturer:
ST Microelectronics

Date code/Lot code: 75604RDJ VY 75

Report no.	**Version**	**Date**	**NEO no.**
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Document Approval

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Version history

Table 1: Revision history

Version	Date	Changed by	Changes
0.1	2019-03-15	Steffens	Initial draft, Sections 1-5, Appendices A+B
1.0	2019-05-03	Steffens	Final Draft
	-	-	

Table of contents

List of figures

List of tables

1 Introduction

1.1 Scope

The Fraunhofer Institute for Technological Trend Analysis (INT) carried out a series of Single Event Effects tests with protons and heavy ions on SiC Schottky Diode STPSC6H12 from ST Microelectronics for the ESA project "Survey of Total Ionizing Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE" (ESA-TOPSIDE, AO/1-8148/14/NL/SFe) under contract number 4000113976/15/NL/RA.

This reports documents the preparation, execution and the results of these tests.

1.2 Applicable Documents

[AD1] ITT/AO/1-8148/14/NL/SFe "Statement of work: Survey of Total Ionizing Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE"

[AD2] Proposal for ITT/AO/1-8148/14/NL/SFe, Fraunhofer INT

1.3 Reference Documents

[1] Website of Fraunhofer INT: http://www.int.fraunhofer.de

[2] Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, B.N. Taylor and C.E. Kuyatt, NIST Technical Note 1297, 1994, http://www.nist.gov/pml/pubs/tn1297/index.cfm.

[3] ESCC Basic Specification No. 25100, issue 2, October 2014

[4] Datasheet of SiC Schottky Diode STPSC6H12, "STPSC6H12, 1200 V power Schottky silicon carbide diode", ST Microelectronics, DocID024631 Rev 5, September 2016

[5] TN3.13 "SEE (HI) Test Plan STPSC6H12 (Schottky Diode)", Issue 1, Revision 1, 2017-07-25

[6] TN3.14 "SEE (p) Test Plan STPSC6H12 (Schottky Diode)", Issue 1, Revision 1, 2017-07-25

[7] Casey et. al., "Schottky Diode Derating for Surviability in a Heavy Ion Environement", IEEE TNS vol. 62, no.6, pp. 2482-2489 (2015)

[8] Website of the HIF Facility at UCL: http://www.cyc.ucl.ac.be/HIF/HIF.php , last accessed: 2019-01-17

[9] SRIM 2013, www.srim.org, detailed in Ziegler et. Al., "SRIM - The stopping and range of ions in matter (2010)", Nuclear Instruments and Methods in Physics Research Section B, Volume 268, Issue 11-12, p. 1818-1823.016-12-08)

[10] Website of the PSTAR database at NIST, https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

[11] Website of SPENVIS, https://www.spenvis.oma.be/

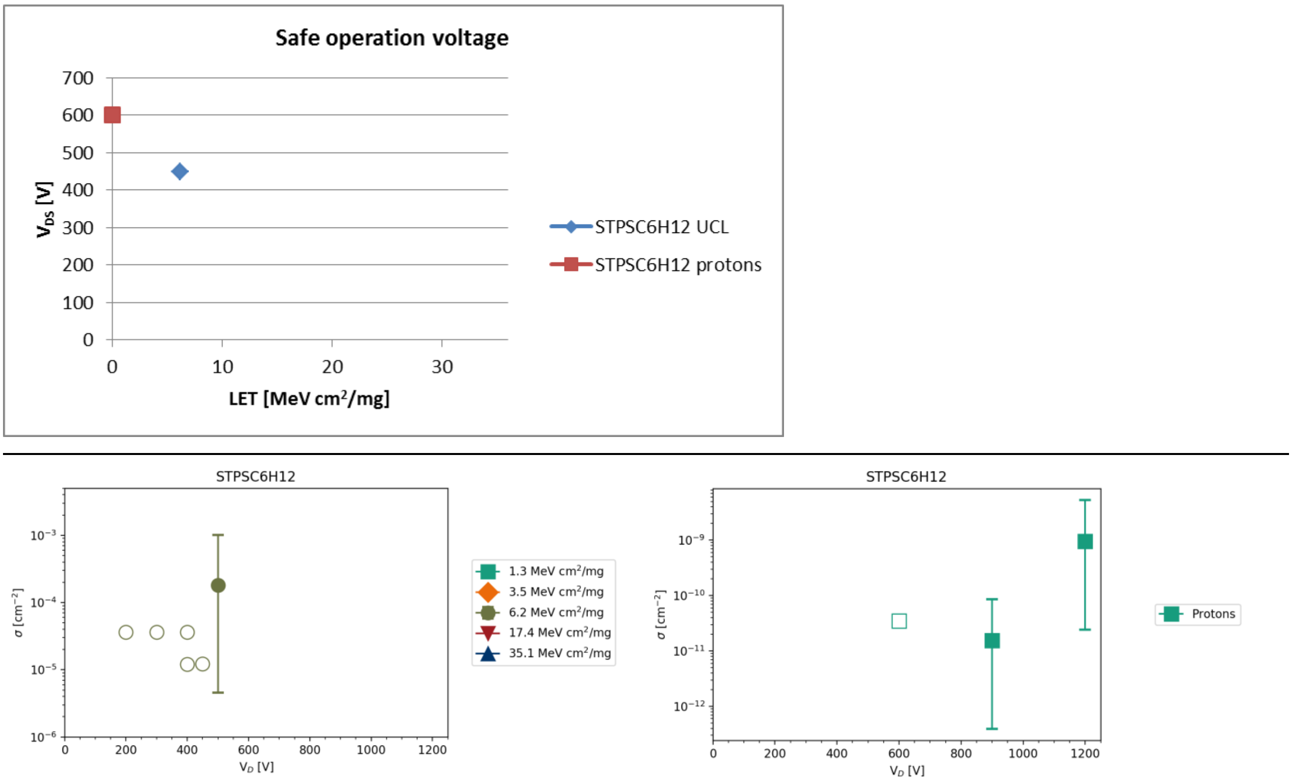
2 Summary

Table 2: Summary

Test Report Number	072/2018
Project (INT)	NEO-14-086
Customer	European Space Agency (ESA), contract number 4000113976/15/NL/RA
Contact	Project Coordinator: Stefan Höffgen (INT) ESA Technical Project Officer: Marc Poizat (ESA/ESTEC)
ESA project / contract number	AO/1-8148/14/NL/SFe 4000113976/15/NL/RA
Device under test	STPSC6H12
Family	SiC Schottky Diode
Technology	Silicon Carbide- Junction Field Effect Transistor
Package	TO247-3
Date code / Wafer lot	75604RDJ VY 75
SN	UCL: #5, #6 JULIC: #1, #2
Manufacturer	ST Microelectronics
Irradiation test house	Fraunhofer INT
Radiation source	UCL: Heavy Ions, JULIC: Protons
Irradiation facility	UCL, JULIC
Generic specification	ESCC 25100 Iss. 2
Detail specification	MIL-STD-750-1 w/CHANGE 5, Method 1080.1
Test plan	TN3.13 "SEE (HI) Test Plan STPSC6H12 (Schottky Diode)", Issue 1, Revision 1, 2017-07-25 TN3.14 "SEE (p) Test Plan STPSC6H12 (Schottky Diode)", Issue 1, Revision 1, 2017-07-25
Single/Multiple Exposure	Multiple
Parameters tested	Reverse current
Dates	UCL: 2018-04-16 – 2018-04-17 JULIC: 2017-09-19 – 2017-09-20

2.1 Overview of results

Figure 1: Safe operating voltage and cross sections across the campaigns In the cross section plots, filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run.



Tests with the SiC Schottky Diode STPSC6H12 showed high vulnerability with respect to the heavy ions even at low LETs and with the protons. Due to time and device limitations, only tests at one LET were performed and a limited set of runs was performed with protons.

The safe operating voltage in Figure 1 indicates the maximum voltage for which the DUTs passed the respective runs. The cross sections in Figure 1 give an impression on the test statistics and voltage levels tested.

From these tests, the safe operation voltage when exposed to Aluminium ions (LET = 6.2 MeV cm²/mg) is 450 V. While this seems like a fairly low voltage rating for a fairly low LET, this is in line with the results obtained with the other SiC devices investigated in this project.

The devices passed at 600 V when testing with 45MeV protons (approx. 39 MeV energy when entering the DUT package). However due to time restriction the next highest level tested was already at 900 V, so the threshold for destructive effects should be between 600 V and 900 V at this proton energy.

2.2 Comments

- **Decapsulation:**
    - Of 8 decapsulated devices, 7 passed the functional tests and were considered for the coating process. However out of these 7, only 3 (S/N #5,#6,#7) passed the functional tests after the parylene coating process. The DUTs tested at UCL are from this set of device.
- **All campaigns:**
    - Huge sensitivity in conjunction with a limited number of devices led to major deviations from the intended test plan.
    - Destructive events could not be mitigated.
- **Tests at UCL:**
    - Tests were performed only with one LET (Aluminium ions).
- **Tests at JULIC:**
    - Tests were performed with packaged devices.

3 Sample preparations

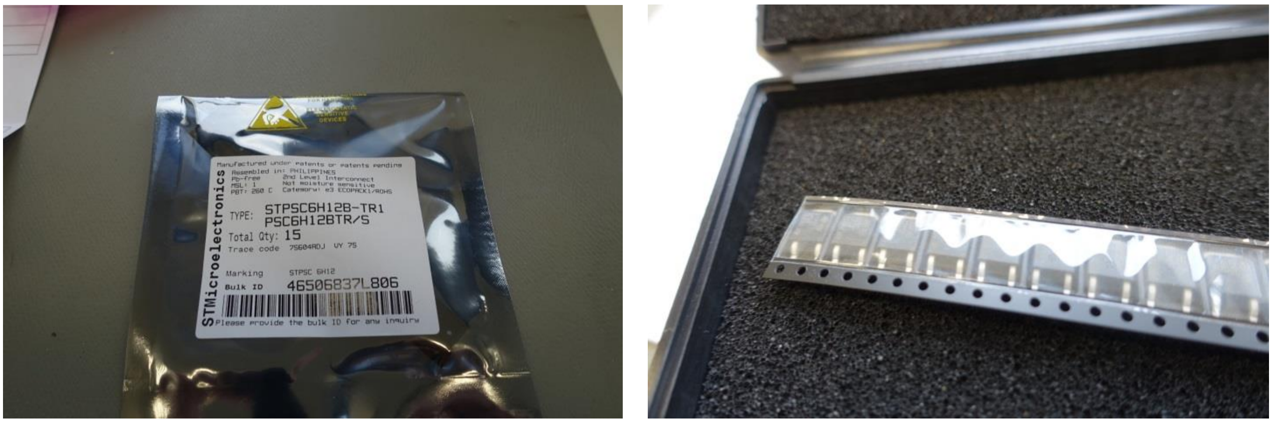
3.1 Sample shipment

A total of 15 Samples were provided by STMicroelectronics via ESA for the conduction of these tests. The parcel contained devices with one identification code (75604RDJ VY 75). Due to the devices being so-called “commercial-off-the-shelf” (COTS) devices, it is not clear whether this identifies the wafer or just the packaging).

Table 3: Sample shipment

Samples received	Samples sent back
March 2017	still at INT

Figure 2: The ESD package with the samples



3.2 Sample identification/ marking

The samples were soldered to adapter pins, to ease the mounting to the board, exchanging, plugging and storage of the samples.

The samples were colour marked to differentiate the samples between each other and to separate the samples of the different campaigns or types.

Table 4: Sample marking: Only DUTs used in the tests of this report are shown.

Condition	S/N	Color Code	Comment
UCL	5	🟩	decap, coated
	6	🟦	decap, coated
JULIC	1	🟥	non-decap

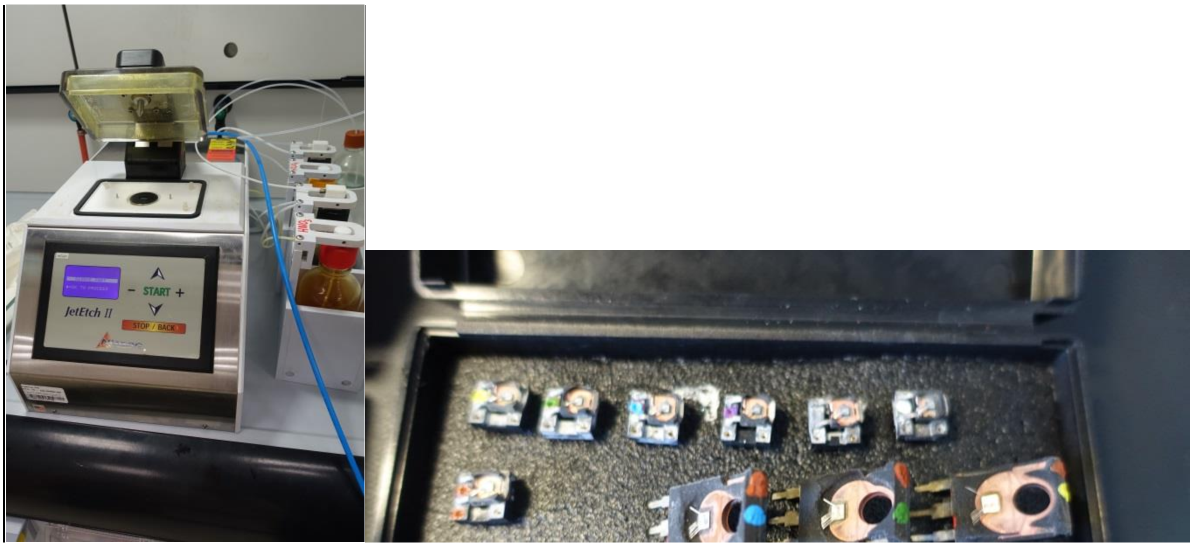
2	🟥	non-decap

3.3 Sample decapsulation and preparation

In preparation for the heavy ion test campaign at UCL, the DUTs were decapsulated and parylene coated.

DUT decapsulation was performed at INT using a Nisene JetEtchII (Figure 3). The JetEtch II uses spray of acid, in our case a 2:1 micture of sulfuric to nitridic acid, to remove the capping layers covering the dye and the active region of the device without inducing mechanical stress on the device. decapsulation was performed with the device already soldered onto their respective socket adapters.

Figure 3: DUT decapsulation. Left side: Nisene JetEtch II at INT. Right side: batch of decapsulated STPSC6H12 with sample markings



For etching, sulfuric acid at a flow of 5 ml/min was applied for 360 s at a temperature of 90°C.

After decapsulation the functionality of all DUTs was checked. Due to the missing insulation provided by the package material, only tests at low voltage to prevent corona discharges were performed. 7 out of 8 succesfully decapsulated devices passed these functional tests and were considered for the coating process.

Parylene coating was performed by the “Advanced Chip & Wire Bonding” group, department “System Integration and Interconnection Technologies (SIIT)”, at Fraunhofer IZM in Berlin.

Tests of the reverse current performed at INT after receiving the coated samples, are shown in Figure 4. Only 3 out of 7 devices passed this test and were considered for the SEE tests. One device (#4) did not return data as the SMU compliance was already reached at -10 V.

Figure 5 shows microscopic images of one DUT (#5) after parylene caoting and after the tests at UCL wherein this DUT showed destructive failure. The surface of the DUT does not show signs indicating this destructive failure.

Figure 4: Functional tests after paralene coating. One device (#4) did not return data as the SMU compliance was already reached at -10 V.

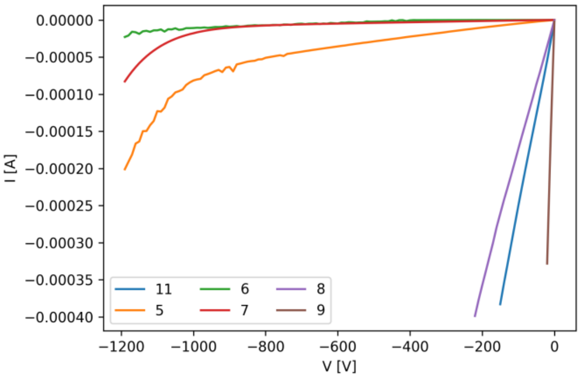
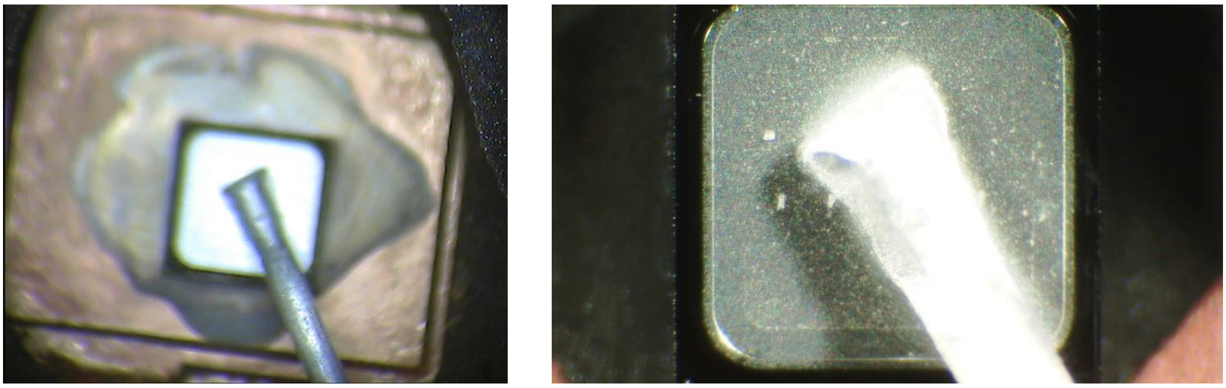


Figure 5: Die pictures. Images were taken with different optical microscopes. The camera used before the tests has a lower quality and resolution.



DUT #6 before tests at UCL

DUT #6 after tests at UCL

3.4 Sample safekeeping

The samples were stored in an Electro-Static Discharge (ESD) box (Figure 3) to handle them safely during the test, the interim storage after the last measurement and the final shipment.

4 Setup and Measurements

The test approach and setup covered in this section is mostly independent of the facility.

The tests performed with Heavy ions or protons aimed primarily at determining the safe operating voltage range rather than getting detailed cross sections for each setting and LET. This is mostly due to the high sensitivity of most of the SiC devices studied in this project to even moderate LETs.

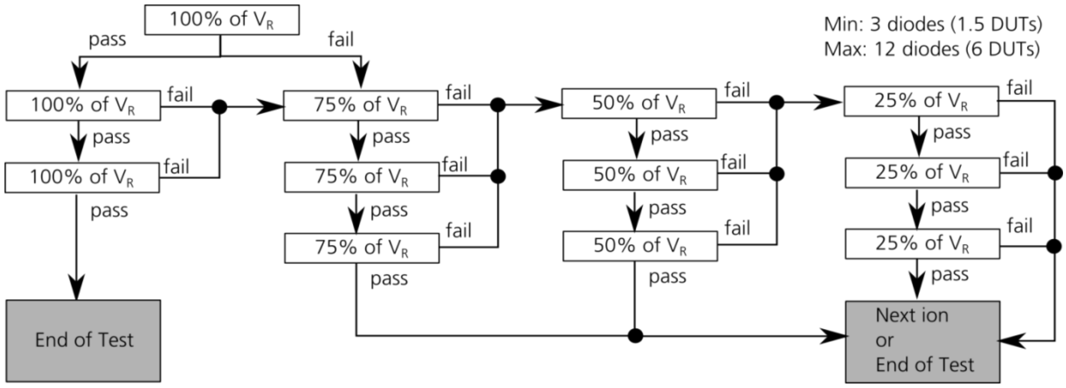
Due to a limited number of devices and having destructive failures which could not be mitigated, the required number of 3 samples to check the pass compliance of each test is not reached in any case.

4.1 Intended test program

The test logic is shown in Figure 6. As there are no applicable test standards or MIL test methods concerning Schottky diode SEE tests, the intended test logic follows mostly the approach for silicon Schottky diodes of Casey et. al. [7].

However during the tests and due to the high sensibility of the SiC diodes, this test program was in the end not followed.

Figure 6: Intended Test program



After each test step, a post-irradiation-stress-test is planned with the reverse voltage sweeped to its maximum rating.

4.2 Test Board and Detection Circuit

A custom-build printed-circuit board (Figure 8) was manufactured to

- bias the samples according to the circuit-layout of the irradiation test plan [5] [6]
- fix the samples at the radiation source
- switch between the samples and connect the respectively active sample to the external setup
- detect destructive events

To reduce the number of parts required for testing, the two diodes in each DUT are biased separately (Figure 7). No mitigation of destructive events is foreseen.

Figure 7: Detection Circuit

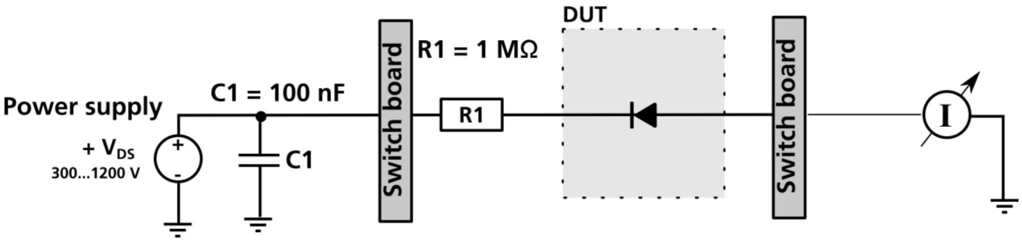
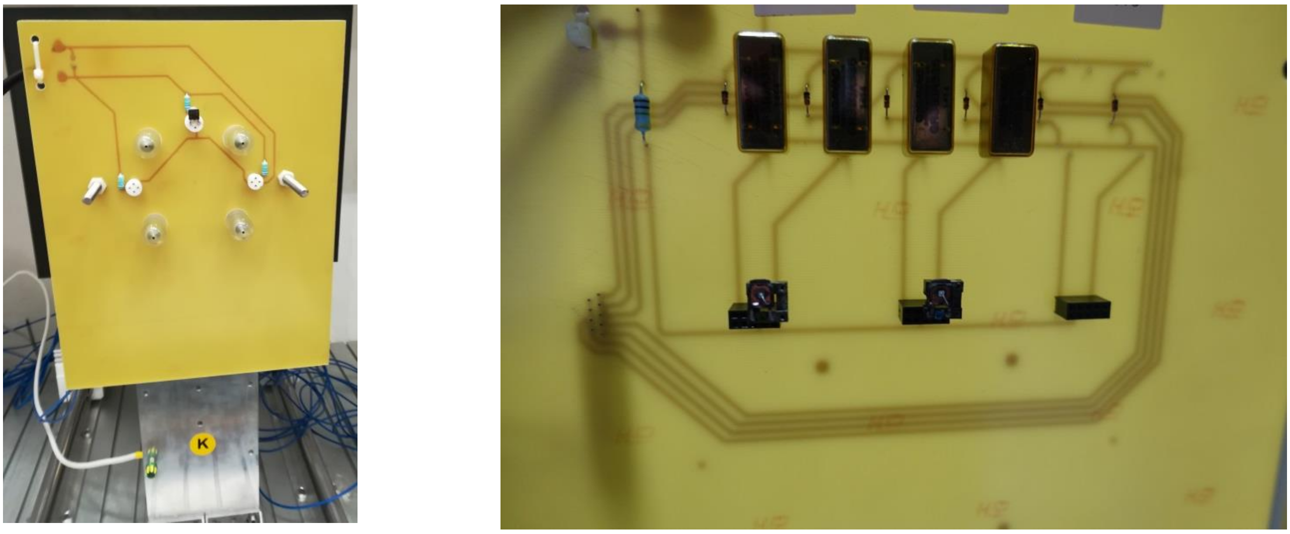


Figure 8: Test board layout. Left side: proton tests at JULIC, Right side: Heavy ion tests at UCL



The boards used for the Heavy Ion and proton tests are functionally identical, but the proton board featured additional holes for four ionization chambers. The DUT was then positioned off-center from the beam, such that all ionization chambers and the DUT position are at the same distance from the center, thus allowing to calculate the proton flux at the DUT position without a fixed installation at the facility which would allow to do that. As a drawback, only one DUT position on the board could be used at a time.

For protons the board was at a distance of 1.8 m from the beam line exit window. Due to interaction in air and the exit window, the proton beam with initial energy 45 MeV was then broadened and reduced in energy to approx. 39 MeV.

The DUTs were exposed to the protons non-delidded, thus when passing the package and hitting the sensitive volume of the devices, the proton energy is further reduced.

Calculations of the LETs in SiC are shown in the respective sections of the campaigns.

4.3 Measurement parameters

Parameters are continuously monitored during the runs. V_D is only indicated at the respective runs, I_D are shown in the appendices.

Table 5: Measurement parameters. Based on [4], taken from [5][6]

No.	Characteristics	Symbol	Remark
1	Reverse Voltage	V_D	Set according to test flow
2	Reverse Current	I_D	Monitored, typ. 100 µA @ 1200 V, max. 400 µA @ 1200 V

4.4 Measurement equipment

The test equipment is shown in Table 6 - Table 7 and Figure 9 - Figure 10.

The due date of the calibration can change from campaign to campaign if a new calibration was performed in the time between.

Table 6: UCL: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2018	V_D, I_D
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix
Triple Output Power Supply	Agilent	E3631A	E-PS3-002	n/a	Power supply of relais

Figure 9: UCL: Measurement equipment/setup (including equipment for MOSFET/JFET tests)

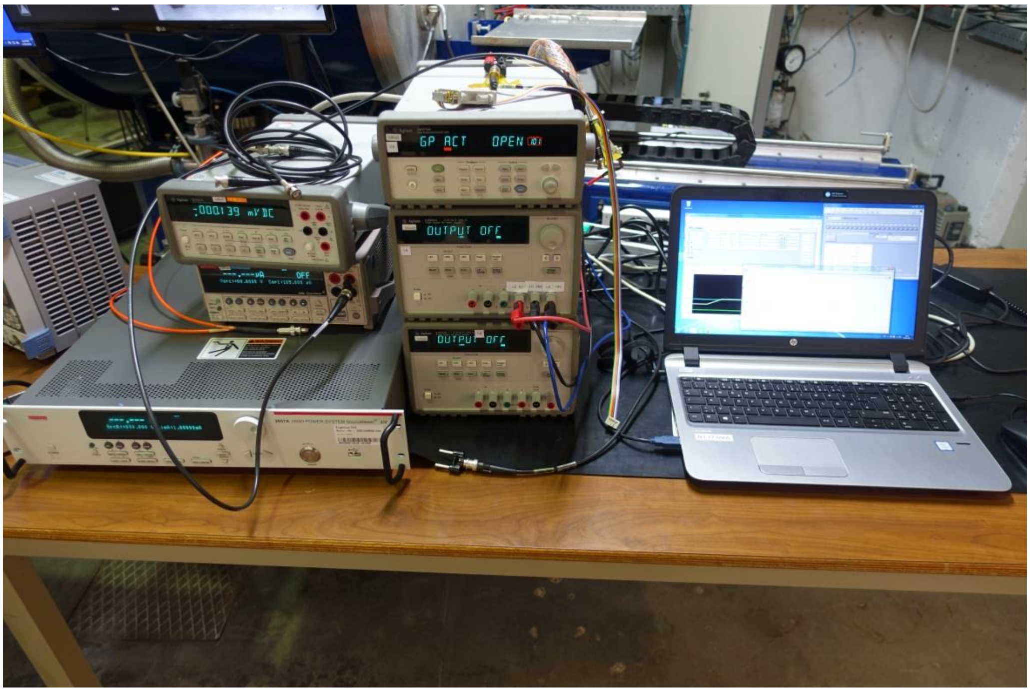
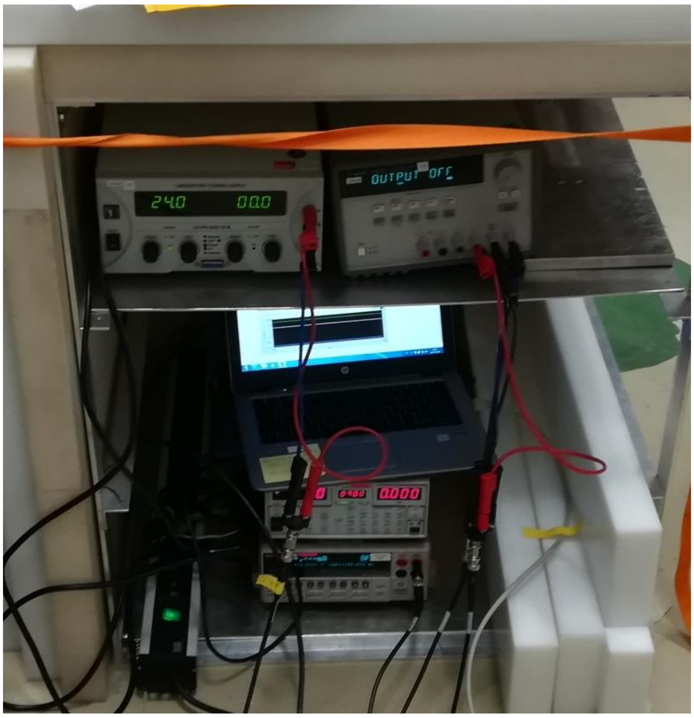


Table 7: JULIC: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
5 kV Power supply	Keithley	2290E-5	E-PS1-030	10/2017	V_R, I_R
Laboratory Power Supply	EA	EA-PS-3032-10B	E-PS1-001	n/a	Control of relais

As only one DUT was on the board, no switch matrix was included in the setup, and the power supplies were only used to power the relais, not for switching between DUTs.

Figure 10: JULIC: Measurement equipment/setup (including equipment for MOSFET/JFET tests)



4.5 Measurement procedures

Bias conditions of diode were fixed for each step. When no destructive events occurred during a run, a post-irradiation-stress test was scheduled. In some instances across the campaigns, that PIGS test might not have been performed. These instances are commented in the respective sections.

5 Tests at UCL

5.1 Facility

The main heavy ion test was performed at the HIF facility of the CYCLONE cyclotron of the Université catholique de Louvain (UCL) in Louvain-la-Neuve.

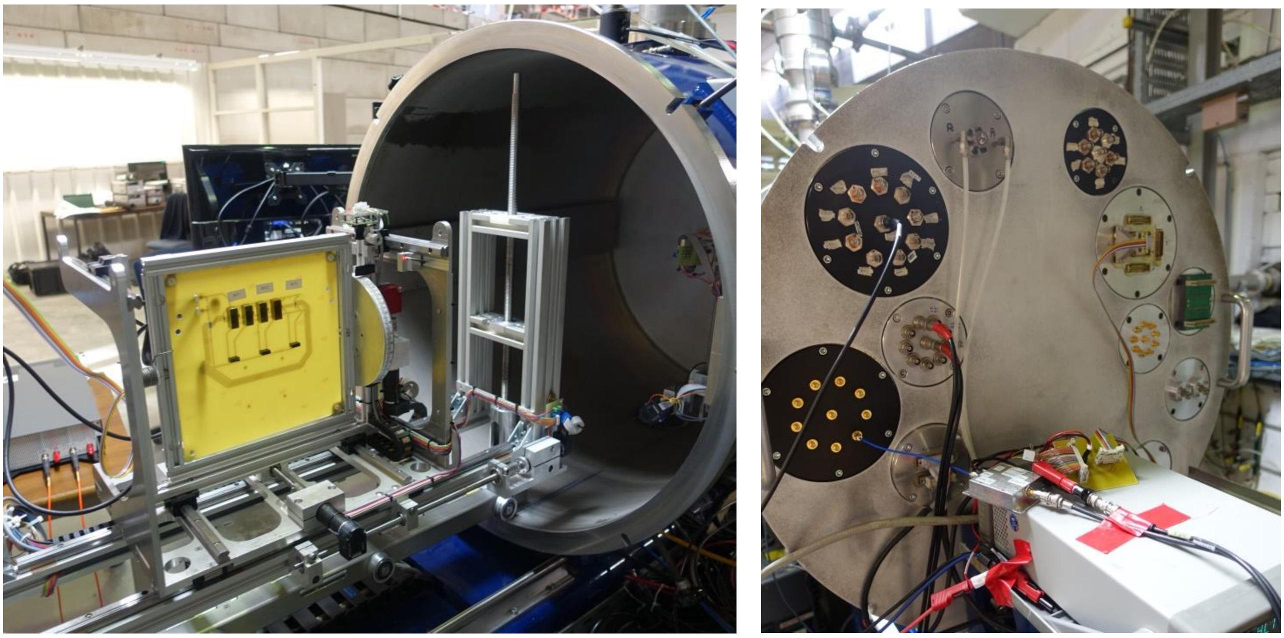
The facility can provide selected heavy ion beams from Carbon to Xenon in a particle cocktail with mass/charge ratio of approx. M/Q=3.3, allowing to switch from ion species to ion species quickly within the cocktail.

The experimental setup at the facility consists of the main vacuum chamber with a sample holder, which is moveable in x- and y-direction and can be tilted along one axis.

Feedthroughs can be used to connect boards within the enclosure with outside instrumentation (Figure 11).

Users can start and stop the irradiation from the user station next to the test chamber, other beam parameters like the particle flux can only be set by an operator.

Figure 11: UCL vacuum chamber with electrical feedthroughs. Two SHV cable feedthroughs, one DB9 feedthrough and one SMA feedthrough were used to connect the board with the outside instrumentation.



5.2 Beam parameters

The resulting total energies of the respective ions, as well as their LET and range in Silicon are provided by UCL [8]. However this data is not valid for Silicon Carbide.

SRIM 2013 [9] simulations by Fraunhofer INT show the respective values for the heavy ion beams provided by UCL under normal incidence in Silicon Carbide covered by a 10 µm Parylene layer. Detailed data and a comparison to the data in blank Silicon Carbide is included in the test plan [5].

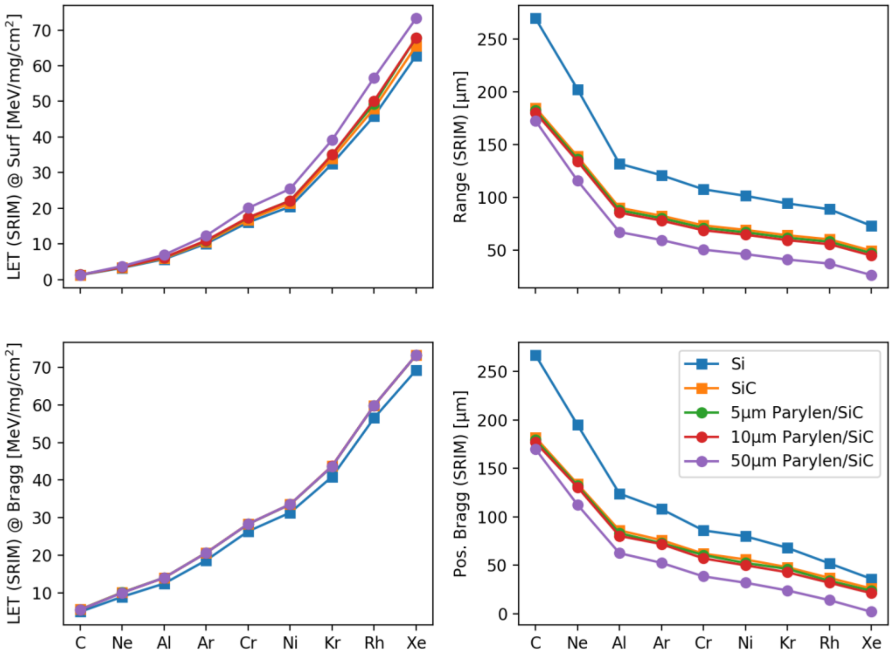
Tests with the STPSC6H12 were performed only with Aluminum.

Table 8: UCL: Ion energies, LETs and ranges in Silicon Carbide covered by 10 µm Parylene: Shown are the ions available at UCL [8]. Only LETs highlighted in bold font were actually used. In this case, only Aluminum. LET and range data are based on SRIM2013 [9] simulations done at Fraunhofer INT.

Ion	Energy [MeV]	LET ^{SRIM} @ Surface [MeV cm2/mg]	Range ^{SRIM}* [µm]	LET ^{SRIM} @ Bragg Peak [MeV cm2/mg]	Depth of Bragg Peak* [µm]
C	131	1.33	180.22	5.49	176.90
Ne	238	3.49	134.13	10.02	130.70
Al	**250**	**6.20**	**85.42**	**13.99**	**80.30**
Ar	379	10.95	77.91	20.63	71.90
Cr	513	17.41	68.74	28.34	57.10
Ni	582	22.09	64.53	33.55	50.00
Kr	769	35.06	59.36	43.77	42.80
Rh	972	50.14	55.57	59.84	32.00
Xe	995	67.81	44.79	73.27	21.20

* Range and position of Bragg peak is given within the Silicon Carbide layer.

Figure 12: Plot of LETs and Ranges in Silcon Carbide at UCL. Additional data with Paralene layers and data for Silicon are included. Thin Paralene layers have limited impact.



5.3 Geometry

The board is attached to the moveable board holder (Figure 11) which can be fully retracted from the chamber for ease of access. Tests are then performed with the chamber sealed and evacuated.

5.4 Irradiation steps

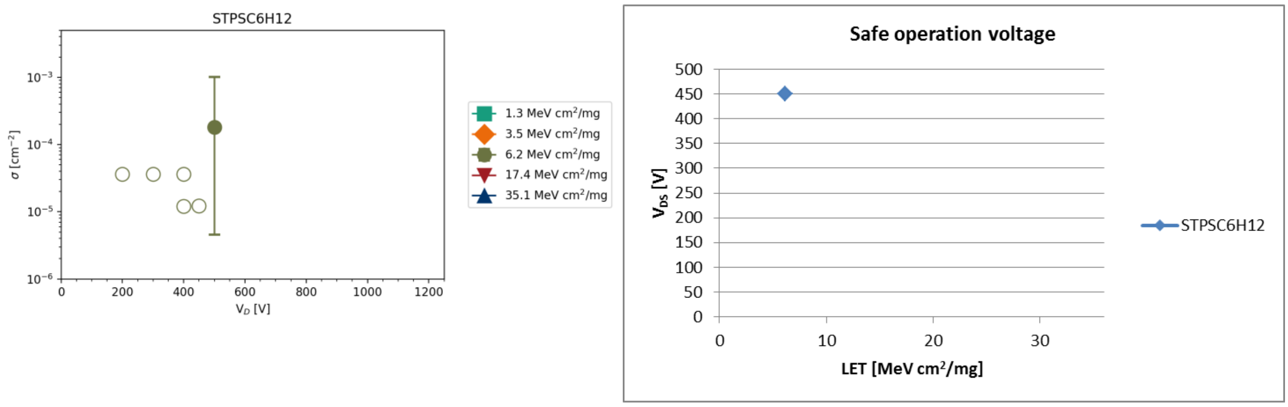
The log file of the tests performed at UCL can be found in Appendix B.B.1 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section B.

Table 9: UCL: Irradiation steps of SiC Schottky Diode STPSC6H12. Numbers indicate the DUT serial number from Table 4. Table cells without numbers indicate that no run was performed under these conditions. Green or red background color indicate PASS or FAIL respectively. If a DUT fails at some voltage, all higher voltages are also indicated as fail. Yellow color (if applicable) indicates mixed results (e.g. 1 DUT passing, 1 DUT failing at the same level) or non-conclusive results with the device showing some damage not clearly attributable to a fail.

	C		Ne		Al		Cr		Kr	
V_R [V]	1.3		3.5		6.2		17.4		35.1	
	in-situ	Post	in-situ	Post	in-situ	Post	in-situ	Post	in-situ	Post
200					🟩 5	🟩				
300					🟩 5	🟩				
400					🟩 5, 6	🟩				
450					🟩 6	🟩				
500					🟥 5	🟥				
600										
750										
900										
1050										
1200										

5.5 Results

Figure 13: Overview of results: Heavy Ions at UCL. The first three images show the cross section results for various settings of V_D. Filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run. The right side image shows the safe operating voltage for Aluminium ions.



Tests with the SiC Schottky Diode STPSC6H12 showed high vulnerability with respect to the heavy ions even at low LETs. Due to time and device limitations, only tests at one LET were performed.

The safe operation voltage when exposed to Aluminium ions (LET = 6.2 MeV cm^2/mg) is only 450 V.

While this seems like a fairly low voltage rating for a fairly low LET, this is in line with the results obtained with the other SiC devices investigated in this project.

To save more time, several runs were performed at even lower total fluence of 1E5 ions/cm^2. However after a destructive event at some voltage a run to 3E5 ions/cm^2 was always performed to confirm the lower voltage level. A device which passes a run up to 3E5 ions/cm^2 without errors has an upper limit of the cross section of σ_{upper} = 1.23E-5 cm^{2,} assuming 95%CL and 10% flux uncertainty.

Table 10: Results: Heavy Ions at UCL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

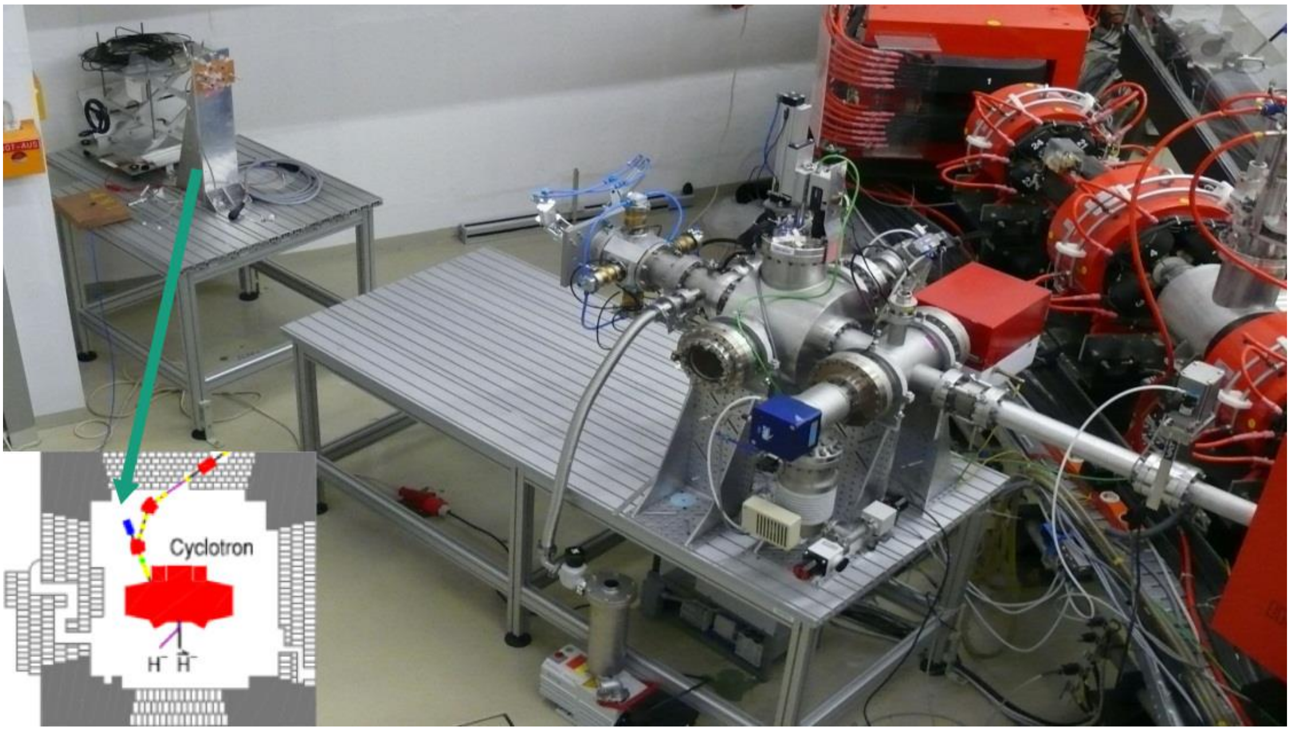
#	Ion	DUT #	V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Comment
105	Al	5	200	1.02E5	0	0	3.62E-5	Current in the device getting lower with time, likely not related to radiation
106	Al	5	300	1.02E5	0	0	3.63E-5	
107	Al	5	400	1.01E5	0	0	3.64E-5	
108	Al	5	500	5.54E3	4.57E-6	1.80E-4	1.01E-3	Destructive failure at indicated fluence
109	Al	5	400	3.06E5	0	0	1.20E-5	Current in the device getting lower with time, likely not related to radiation
110	Al	6	400	3.02E5	0	0	1.22E-5	Current in the device getting lower with time, likely not related to radiation

6 Tests at JULIC

6.1 Facility

Proton tests were performed at the JULIC injector cyclotron of the Forschungszentrum Jülich (FZJ, Research Centre Jülich). JULIC is the injector cyclotron of the Cooler Synchrotron COSY.

Figure 14: Beam line and irradiation site at the JULIC injector cyclotron, FZ Jülich



The initial energy of the proton beam is fixed to 45.0 MeV inside the cyclotron (vacuum). Usually the device under test (DUT) is placed at 1.8 m distance from the exit window of the beam. After passing the exit window of 1 mm aluminium and the air the mean proton energy is reduced to 39.3 MeV at the surface of DUT (Figure 15 and Figure 16). The maximum current of the beam is 10 µA (i.e. $6.24 \cdot 10^{13}$ p^+/s). The beam has a Gaussian profile with at FWHM of about 7 cm at the surface of the DUTs.

The dose is measured online with Farmer Ionisation Chambers 30010 (measurement volume of 0.6 cm^3) from PTW and an electrometer Multidos T10004 from PTW. Typically this type of ionisation chamber (IC) is used as an absolute dose-meter in high energy photon, electron, or proton-radiation therapy. The ionisation chambers are calibrated with a Co-60 gamma reference field against national standards by the manufacturer. The PMMA cap of the chamber further reduces the energy to 30.5 MeV inside the chamber.

The dose D given by the IC is related to the particle fluence Φ by the linear energy transfer (LET):

$$D = \underbrace{\frac{1}{\rho} \cdot \frac{\mathrm{d}E}{\mathrm{d}x}}_{\mathrm{LET}} \cdot \Phi$$

The conversion factor is obtained by a numerical simulation by MULASSIS (Geant4). For the experimental setup a fluence $\Phi = 10^{10}$ p^+/cm^2 at the exit window produces a dose D = 24.38(15) Gy(air) in the ionization chamber. Alternatively, the LET (also called stopping power) of protons in different materials can be looked up at PSTAR [10].

Figure 15: Schematic setup of the beam exit window at JULIC and the ionization chamber. The DUT is placed in same distance as the IC.

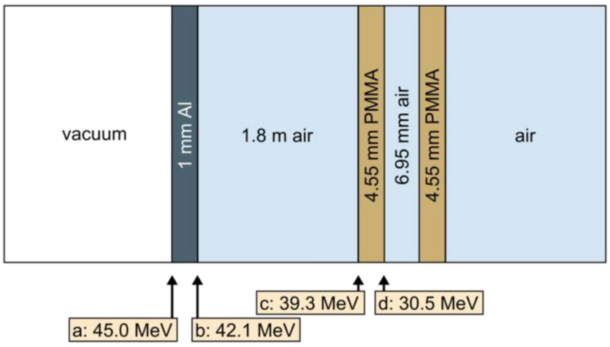
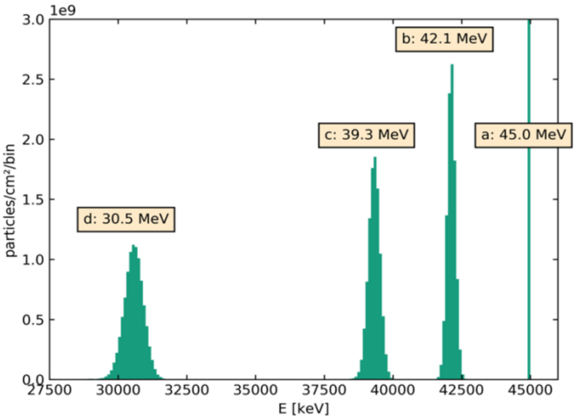


Figure 16: The initial proton energy of 45.0 MeV gets reduced to 39.3 MeV at the position of the IC/DUT. The PMMA cap of the chamber further reduces the energy to 30.5 MeV, calculation by MULASSIS (Geant4) on SPENVIS [11].



For the current tests, packaged Silicon Carbide devices were irradiated with the protons. Thus to calculate the LET on the die, additional simulations were performed with GRAS (Geant4).

6.2 Beam parameters

To receive the impact in terms of proton energy and LET on the Silicon Carbide die with packaged DUTs, radiation transport simulations have to be made. Simulation were performed with GRAS and a combination of MULASSIS and SRIM. Details on the approach and intermediate results are given in Appendix C.1. We see more of an impact on package thickness and nearly no impact of the package material. Thus here we will give a summary of the results just by thickness of the package.

Table 11: Results of simulations of the LET with package thickness. Details on the approach and intermediate results are given in Appendix C.1

Thickness	**0.5 mm**		**1 mm**		**2 mm**		**3 mm**	
LET_{GRAS} [MeV cm^2/mg]	0.012		0.008		0.005		0.003	
LET_{SRIM} [MeV cm2/mg]	0.013		--		--		0.016	
Atomic recoil	**Silicon**	**Carbon**	**Silicon**	**Carbon**	**Silicon**	**Carbon**	**Silicon**	**Carbon**
Peak LET_{SRIM} [MeV cm^2/mg] at max. recoil	12.30	5.81	12.16	5.81	11.86	5.80	11.31	5.80
Range [µm]	2.01	6.6	1.96	6.3	1.84	5.7	1.72	5.1

While the results from GRAS and SRIM are not identical, the proton induced LET is well below 0.02 MeV cm^2/mg in any case. The LETs of the recoil nuclei in SiC vary strongly with the LET of Si at or below 12.3 MeV cm^2/mg and the LET of C around 5.8 MeV cm^2/mg.

The thickness of the actual package of the DUTs is around 2 mm, however for the overall data evaluation we identify the proton data with an LET of 0.01 MeV cm^2/mg.

6.3 Geometry

The DUT was positioned off-center from the beam, such that all ionization chambers and the DUT position are at the same distance from the center, thus allowing to calculate the proton flux at the DUT position without a fixed installation at the facility which would allow to do that. As a drawback, only one DUT position on the board could be used at a time. The beam still was incident normally (90°) to the surface of the DUT.

6.4 Irradiation steps

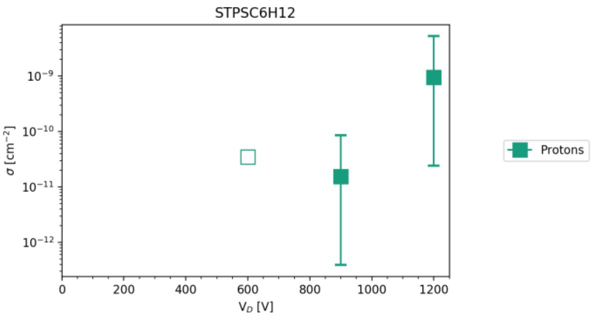
The log file of the tests performed at JULIC can be found in Appendix C. Table 12 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 6.5

Table 12: JULIC: Irradiation steps of SiC Schottky Diode STPSC6H12. Numbers indicate the DUT serial number from Table 4. Table cells without numbers indicate that no run was performed under these conditions. Green or red background color indicate PASS or FAIL respectively. If a DUT fails at some voltage, all higher voltages are also indicated as fail. Yellow color (if applicable) indicates mixed results (e.g. 1 DUT passing, 1 DUT failing at the same level) or non-conclusive results with the device showing some damage not clearly attributable to a fail.

	Proton	
	E_{init} = 45 MEV	
V_R [V]	in-situ	POST
600	🟩 3	🟩 3
900	🟥 2	
1200	🟥 1	

6.5 Results

Figure 17: Overview of results: Protons at JULIC. Filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run.



Only three devices and thus diodes were available for these tests, two of which failed at 1200 V and 900 V respectively. The next lowest voltage level tested was at 600 V and the device passed the tests up to approx. 1e11 p/cm^2. This result was not confirmed by another device however.

Table 13: Results: Heavy Ions at UCL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	DUT #	V_DS, V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
45	p	#1	1200	1.05E+09	2.41E-11	9.52E-10	5.31E-09	FAIL	Destructive failure at rather low fluence
46	p	#2	900	6.48E+10	3.91E-13	1.54E-11	8.6E-11	FAIL	--
47	p	#3	600	1.05E+11	0	0	3.51E-11	--	--

A Fraunhofer INT

A.1. About the institute

The Fraunhofer Institute for Technological Trend Analysis INT provides scientifically sound assessments and counselling on the entire spectrum of technological developments. On this basis, the Institute conducts Technology Forecasting, making possible a long-term approach to strategic research planning. Fraunhofer INT constantly applies this competence in projects tailor-made for our clients.

Over and above these skills, we run our own experimental and theoretical research on the effects of ionizing and electromagnetic radiation on electronic components, as well as on radiation detection systems. To this end, INT is equipped with the latest measurement technology. Our main laboratory and large-scale appliances are radiation sources, electromagnetic simulation facilities and detector systems that cannot be found in this combination in any other civilian body in Germany.

For more than 40 years, INT has been a reliable partner for the Federal German Ministry of Defence, which it advises in close cooperation and for which it carries out research in technology analysis and strategic planning as well as radiation effects. INT also successfully advises and conducts research for domestic and international civilian clients: both public bodies and industry, from SMEs to DAX 30 companies.

Further information can be found on the website [1].

A.2. Business unit Nuclear Effects in Electronics and Optics

The Business Unit „Nuclear Effects in Electronic and Optics (NEO)“ at Fraunhofer INT investigates the effects of ionizing radiation on electronic, optoelectronic, and photonic components and systems. Its work is based on more than 40 years of experience in that field.

NEO performs irradiation tests based on international standards and advises companies regarding radiation qualification and hardening of components and systems. The knowledge obtained in years of radiation testing is also used for the development of new radiation sensor systems. These activities are performed either at irradiation facilities installed at INT or at partner institutions to which our scientists have regular access.

A multitude of modern equipment to measure electrical and optical parameters is available. Furthermore our institute runs a precision mechanical workshop and an electronic laboratory. This enables us to conduct most of the irradiation tests without help or equipment of the customer.

The activities within NEO are:

- Investigations of the effects in all kinds of radiation environments
- Performance, analysis, and evaluation of irradiation tests done at Fraunhofer INT and external facilities

- Ensuring the operability of components and systems in typical radiation environments, such as space, nuclear facilities, medicine, or accelerators
- Consulting users and manufacturers on the use of products in radiation environments by selecting, optimizing and hardening
- Measurement of the radiation effects on optical fibers and fiber Bragg gratings (FBG)
- Development of radiation sensors based on optical fibers, FBGs, oscillating crystals, UV-EPROMs, and SRAMs
- Participation in the development of international test procedures for IEC, IEEE, NATO, and IAEA
- Since 2013 all services of the business unit are certified according to ISO 9001

A.3. Irradiation facilities

Fraunhofer INT operates several irradiation facilities on site that are dedicated to perform irradiation tests. For that purpose the design and operation characteristics are highly optimised from many decades of experience and to comply with all relevant standards and test procedures.

Furthermore Fraunhofer INT accesses regularly external facilities, partly with dedicated irradiation spots for exclusive use to Fraunhofer INT.

These irradiation facilities are:

- Co-60 irradiation sources on site to simulate the effect of total dose
- Neutron generators on site to simulate the displacement damage of heavy particles
- 450 keV X-ray irradiation facility on site
- Laser induced single event test system on site
- Dedicated proton irradiation spot at the injector cyclotron of FZ Jülich to simulate the effects of solar and trapped protons
- External Co-60 irradiation sources for high dose and high dose rate irradiations

The facilities used in the context of this work will be described in detail in the following sections.

A.4. QM-Certificate

DNV·GL

MANAGEMENT SYSTEM CERTIFICATE

Certificate No:
126306-2012-AQ-GER-DAkkS

Initial certification date:
13. February 2013

Valid:
14. February 2019 - 12. February 2022

This is to certify that the management system of

Fraunhofer
INT

Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen INT
Appelsgarten 2, 53879 Euskirchen, Germany

has been found to conform to the Quality Management System standard:

ISO 9001:2015

This certificate is valid for the following scope:

Scientific research on the effects of nuclear and electromagnetic radiation as well as application and development of methods for their characterization

Place and date:
Essen, 14. February 2019

DAkkS
Deutsche
Akkreditierungsstelle
D-ZM-18453-01-00

For the issuing office:
DNV GL - Business Assurance
Schnieringshof 14, 45329 Essen, Germany

Thomas Beck
Technical Manager

Lack of fulfilment of conditions as set out in the Certification Agreement may render this Certificate invalid.
ACCREDITED UNIT: DNV GL Business Assurance Zertifizierung und Umweltgutachter GmbH, Schnieringshof 14, 45329 Essen, Germany.
TEL: +49 201 7296-222. www.dnvgl.de/assurance

B Appendix: Tests at UCL

B.1. Logfile / Test steps

In case of device failure the fluences in this table indicate the fluence provided by the facility not the fluence until failure which may differ by some additional seconds of beam.

#	Run (UCL)	Date	Time	Ion	Device Type	Device	Position on board	DUT #	V	beam time [s]	fluence [cm-2]	comment
104	132	17.04.	22:18	Al	Schottky	STPSC6H12	#1	5	200			device not in beam
105	133	17.04.	22:22	Al	Schottky	STPSC6H12	#1	5	200	195	1.02E+05	
106	134	17.04.	22:27	Al	Schottky	STPSC6H12	#1	5	300	101	1.02E+05	
107	135	17.04.	22:30	Al	Schottky	STPSC6H12	#1	5	400	102	1.01E+05	
108	136	17.04.	22:33	Al	Schottky	STPSC6H12	#1	5	500	11	1.02E+04	
109	137	17.04.	22:37	Al	Schottky	STPSC6H12	#2	6	400	58	3.06E+05	
110	138	17.04.	22:40	Al	Schottky	STPSC6H12	#2	6	450	227	3.02E+05	

B.2. Measurements

Figure 18: Run# 105, STPSC6H12, Al-250, 1.0e+05 ions/cm2 , DUT 5.0, VD= 200.0 V

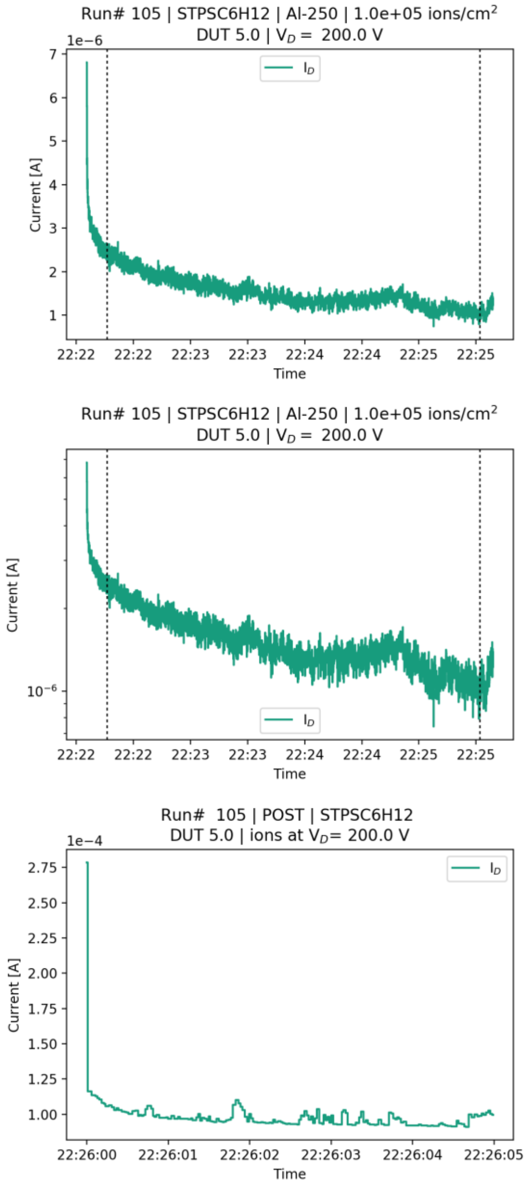


Figure 19: Run# 106, STPSC6H12, Al-250, 1.0e+05 ions/cm2 , DUT 5.0, VD= 300.0 V

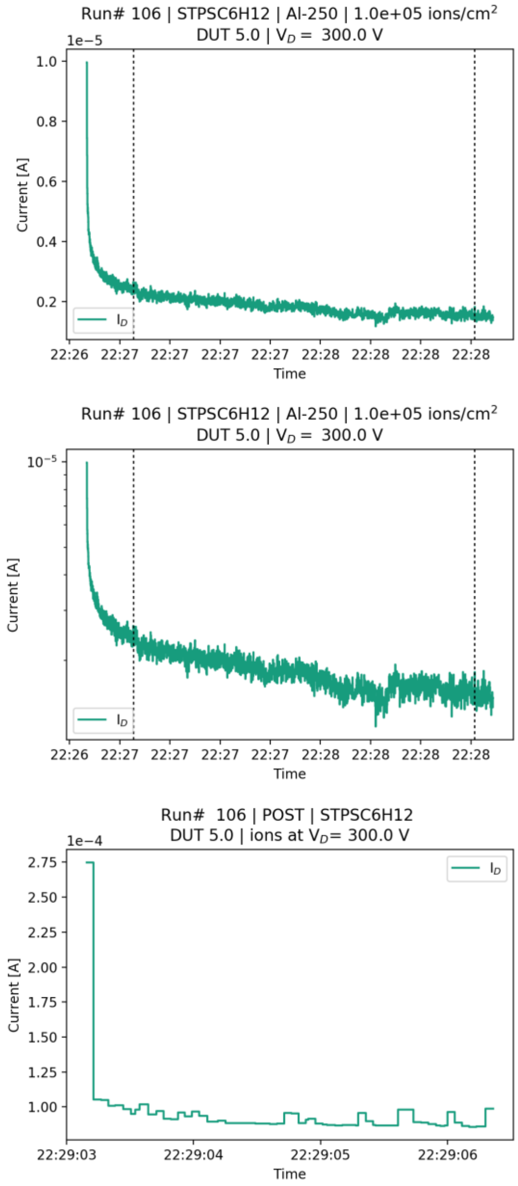


Figure 20: Run# 107, STPSC6H12, Al-250, 1.0e+05 ions/cm2 , DUT 5.0, VD= 400.0 V

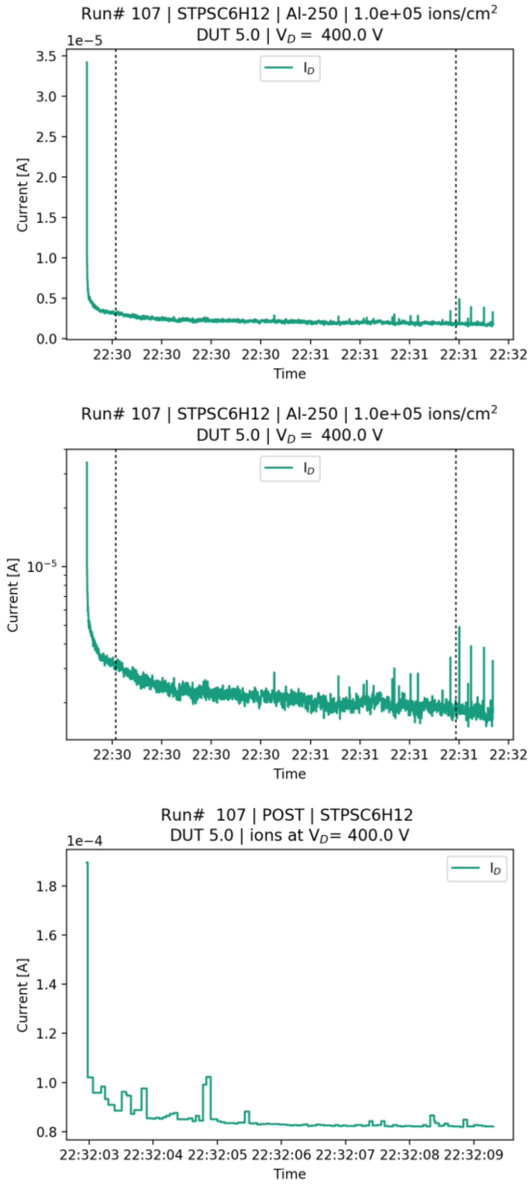


Figure 21: Run# 108, STPSC6H12, Al-250, 1.0e+04 ions/cm2 , DUT 5.0, VD= 500.0 V

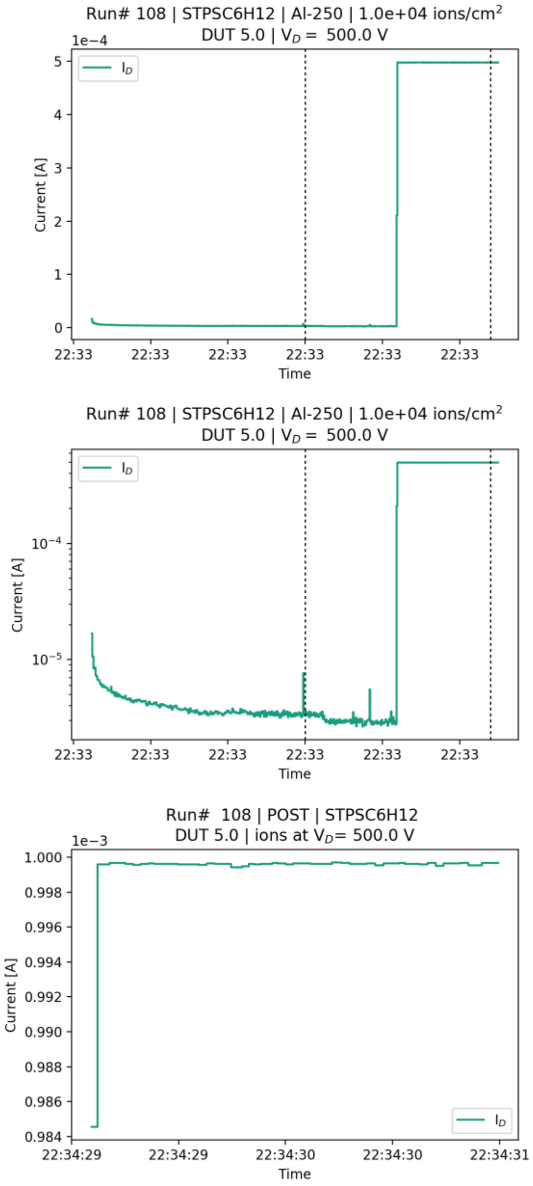


Figure 22: Run# 109, STPSC6H12, Al-250, 3.1e+05 ions/cm2 , DUT 6.0, VD= 400.0 V

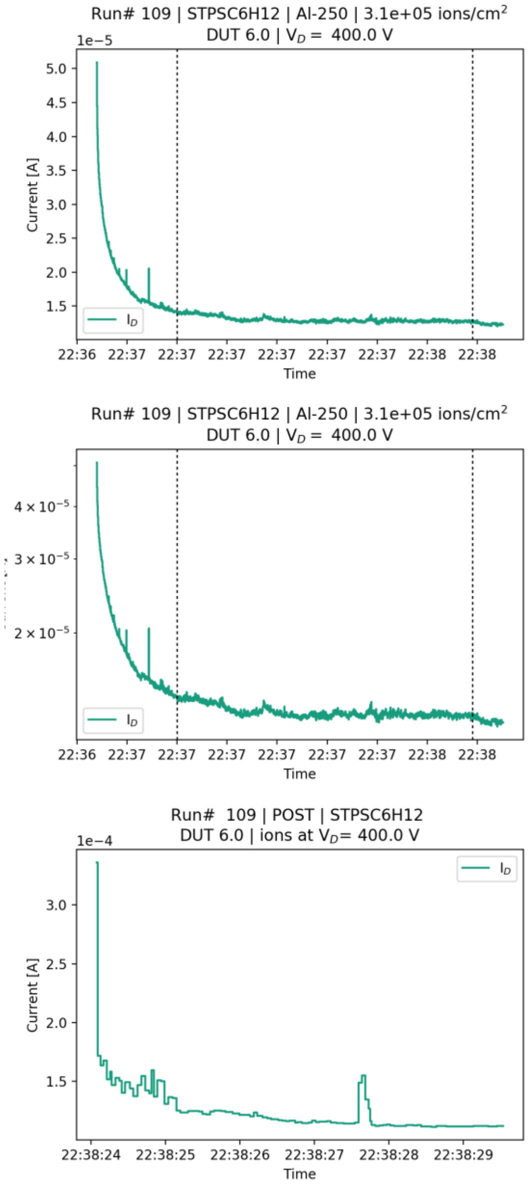
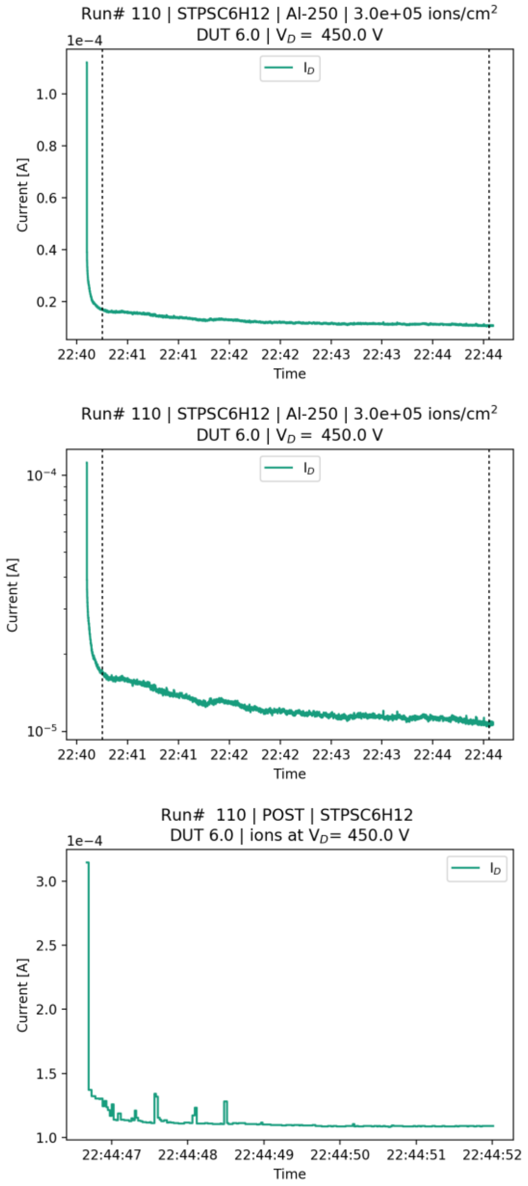


Figure 23: Run# 110, STPSC6H12, Al-250, 3.0e+05 ions/cm2 , DUT 6.0, VD= 450.0 V



C Appendix: Tests at JULIC

C.1. LET estimation

To receive the impact in terms of proton energy and LET on the Silicon Carbide die with packaged DUTs, radiation transport simulations have to be made:

1) The setup (beam exit window, air gap, package, die) were simulated with GRAS in standalone version 3.03 for 1E7 protons. The average LET at the layer boundary from the package to the silicon carbide was evaluated by GRAS. This gives the average LET in MeV/cm. Rare events e.g. maximum recoil energy transfer, are few in these simulations. For the results in Table 11, this was then devided by the density $\rho = 3210$ mg/cm^3 to give the LET in units of MeV cm^2/mg.
2) The setup (beam exit window, air gap, package, die) were simulated with MULASSIS in standalone version 1.26 for 1E7 protons. The proton energy at the layer boundary from the package to the silicon carbide was evaluated by MULASSIS. With this proton energy, the maximum recoil energy to Silicon and Carbon atoms in SiC were calculated with $E_{ion}(E_p) = \frac{4\, m_p m_{ion}}{(m_p+m_{ion})^2} \cdot E_p$. SRIM 2013 [9] simulations were then performed with the respective particles and maximum kinetic energy in Silicon Carbide. From the SRIM ionization curve the LET can then be calculated. This LET gives information on the recoils happening inside the SiC layer and is not restricted to the layer "surface" (although only extreme values were considered).

For these simulations, the 1 mm Aluminum exit window and 1.8 m of air were taken into account, such that the spread of the proton energy on the DUT package and the transport simulations through the package in the LET calculations is included. Package thickness for all materials was takes as 0.5, 1, 2 and 3 mm. The 3 mm was not simulated for Aluminum package (which was on the scale of 0.5 mm).

Alternatively the above geometry could be simulated only with SRIM. This has however some major drawbacks, when looking at a 100 µm layer at the end of the target of length >1.8 m as then only particles incident on ±50 µm around the center are evaluated.

Information on the plastic package of the materials was not readily available for the use in SRIM or GRAS, as both require the atomic stoichiometry of the materials. For the sake of the Monte Carlo simulations this does not have to be chemically exact, but has to reflect the likelihood of interacting e.g. with a Silicon, if an interaction with a random nucleus takes place.

For some devices in this project, information was given in the Material Content Data Sheet. A value of 2.37 g/cm^3 was assumed for the density of the plastic mold and the stoichiometry for the example of SiC MOSFET C2M0080120D was estimated to be around Si:O:C:H = 1.6 : 3.6 : 1.2 : 1, thus the estimate for the chemical sum formula to be used in the simulations to be Si3-O7-C2-H2.

*Table 14: Mold material of example C2M0080120D. Values indicated with * are estimates.*

Name	CAS	Stochiometry	Density [g/cm3]	Molar mass [u]	Mass in Mold [mg]
Silicon Dioxide	7631-86-9	SiO_2	2.6	60.0843	1640.71
Epoxy Resin	29690-82-2	$C_{33}H_{42}O_9X_2$	1.12 *	582.68 *	189.62
Anhydride	2421-28-5	$C_{17}H_6O_7$	1.57 *	322.23 *	159.68
Carbon Black	1333-86-4	C	1.7	12.01	5.99

Table 15: Results of GRAS simulations of the LET with package thickness. The GRAS results are the average "surface" LETs on the layer boundary from the package to SiC and would include error information. Error estimates are not given but are < 0.001 MeV cm²/mg in any case).

	LET_{GRAS} [MeV cm²/mg]			
Name	0.5 mm	1 mm	2 mm	3 mm
Al	0.012	0.008	0.004	--
Si1-O2-C1-H1	0.012	0.008	0.005	0.003
Si3-O7-C2-H2	0.012	0.008	0.005	0.003
Si545-O1220-C512-H597-P3-B1	0.013	0.009	0.005	0.004

Table 16: Intermediate results of MULASSIS simulations of the proton energy with package thickness. Little variation is seen based on the package material.

	E(p) [MeV] at boundary Package → SiC			
Name	0.5 mm	1 mm	2 mm	3 mm
Al	37.72	36.08	32.64	---
Si1-O2-C1-H1	37.77	36.18	32.85	29.17
Si3-O7-C2-H2	37.80	36.24	32.97	29.38
Si545-O1220-C512-H597-P3-B1	37.77	35.75	32.83	29.15
Average	37.76	36.06	32.82	29.23
LETSRIM [MeV cm2/mg]	0.013	--	--	0.016

Table 17: Results of SRIM simulations of the LET with package thickness. The SRIM results are the maximum LETs of the Silicon or Carbon recoil nuclei. The values given are the peak values, i.e. not necessarily at the beginning of the track, in the material. The average energies from Table 16 were used for the calculation of the recoil energies.

	Silicon				**Oxygen**			
	0.5 mm	1 mm	2 mm	3 mm	0.5 mm	1 mm	2 mm	3 mm
Max. Energy of Recoil Atom (180°) [MeV]	5.05	4.82	4.39	3.91	10.79	10.30	9.38	8.35
Peak LET_{SRIM} [MeV cm^2/mg] at max. recoil	12.30	12.16	11.86	11.31	5.81	5.81	5.80	5.80
Peak at track length [µm]	0	0	0	0	4.5	4.1	3.3	2.8
Range [µm]	2.01	1.96	1.84	1.72	6.6	6.3	5.7	5.1

C.2. Logfile / Test steps

In case of device failure the fluences in this table indicate the fluence provided by the facility not the fluence until failure which may differ by some additional seconds of beam.

#	Date	Time	Ion	Device Type	Device	DUT #	V_DS, V	beam time [s]	fluence [cm-2]
45	20.09.	10:58	p	Schottky	STPSC6H12	#1	1200	8	2.1e9
46	20.09.	11:05	p	Schottky	STPSC6H12	#2	900	172	6.7e10
47	20.09.	11:13	p	Schottky	STPSC6H12	#3	600	247	1.0e11

C.3. Measurements

Figure 24: Run# 045, STPSC6H12, p, 2.1e+09 p/cm2 , DUT 1, VD= 1200.0 V

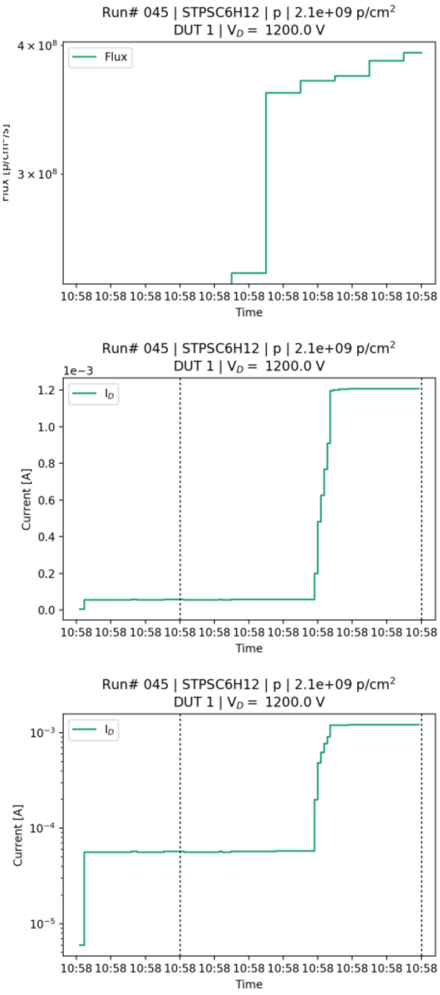


Figure 25: Run# 046, STPSC6H12, p, 6.7e+10 p/cm2 , DUT 2, VD= 900.0 V

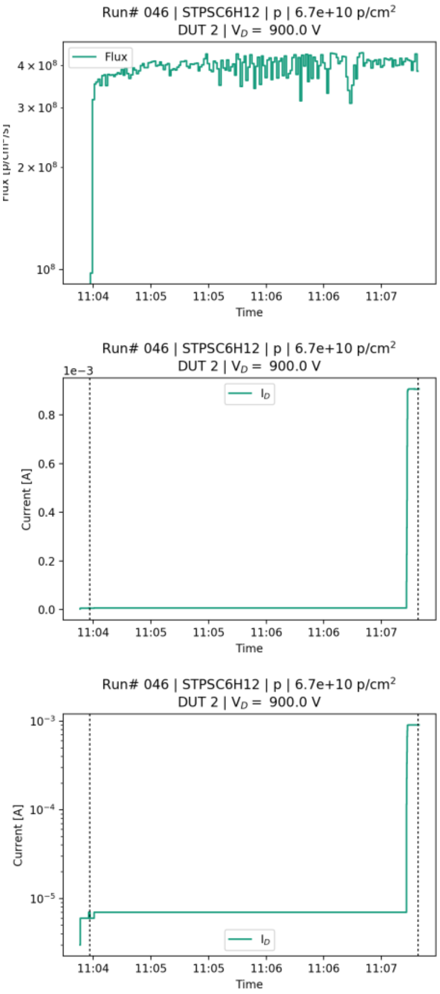


Figure 26: Run# 047, STPSC6H12, p, 1.0e+11 p/cm2 , DUT 3, VD= 600.0 V