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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

TN6.1
SEE Test Report for
SiC MOSFET
C2M0080120D

Manufacturer:
Cree

Date code/Lot code: W14315

Report no.	Version	Date	NEO no.
066/2018	1.0	2019-05-08	NEO-14-086
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Customer	Project management
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Document Approval

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Version history

Table 1: Revision history

Version	Date	Changed by	Changes
0.1	2019-03-08	Steffens	Initial draft, Section 1-5, Annexes A+B
1.0	2019-05-08	Steffens	Initial release
	-	-	

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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 MOSFET C2M0080120D from Cree 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 MOSFET C2M0080120D, “C2M0080120D Silicon Carbide Power MOSFET C2M™ MOSFET Technology N-Channel Enhancement Mode”, Cree, Rev. B

[5] Datasheet of SiC MOSFET C2M0080120D, “C2M0080120D Silicon Carbide Power MOSFET C2M™ MOSFET Technology N-Channel Enhancement Mode”, Cree, Rev. C, 10-2015

[6] TN3.1 “SEE (HI) Test Plan C2M0080120D (SiC MOSFET)”, Issue 1 Rev. 3, 2017-07-25

[7] TN3.7 “SEE (p) Test Plan C2M0080120D (SiC MOSFET)”, Issue 1 Rev 2, 2017-07-25

[8] MIL-STD-750-1 w/CHANGE 5, Method 1080.1, “Single-Event Burnout and Single-Event Gate Rupture”, 2015

[9] P. Oser et. al., "Effectiveness Analysis of a Non-Destructive Single Event Burnout Test Methodology", IEEE TNS, vol. 61, no. 4, pp. 1865-1873 (2014).

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

[11] 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)

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

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

[14] Website of the GANIL facility for irradiation of electronic components: https://www.ganil-spiral2.eu/en/industrial-users-2/applications-industrielles/irradiation-of-electronic-components/

2 Summary

Table 2: Summary

Test Report Number	066/2018
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	C2M0080120D
Family	SiC MOSFET
Technology	SiC MOSFET N-channel enhancement mode
Package	TO-247-3
Date code / Wafer lot	W14315
SN	UCL: #14, #15, #19, #25, #26 GANIL: #24 JULIC: #1, #2, #3 (previously Gamma irradiated)
Manufacturer	Cree
Irradiation test house	Fraunhofer INT
Radiation source	UCL and GANIL: Heavy Ions, JULIC: Protons
Irradiation facility	UCL, GANIL, JULIC
Generic specification	ESCC 25100 Iss. 2
Detail specification	MIL-STD-750-1 w/CHANGE 5, Method 1080.1
Test plan	TN3.1 "SEE (HI) Test Plan C2M0080120D (SiC MOSFET)", Issue 1 Rev. 3, 2017-07-25 TN3.7 "SEE (p) Test Plan C2M0080120D (SiC MOSFET)", Issue 1 Rev 2, 2017-07-25
Single/Multiple Exposure	Multiple
Parameters tested	SEB, SEGR
Dates	UCL: 2018-04-16 – 2018-04-17 GANIL: 2018-06-06 – 2018-06-07 JULIC: 2017-09-19 – 2017-09-20

2.1 Overview of results

Figure 1: Safe operating voltage across the campaigns

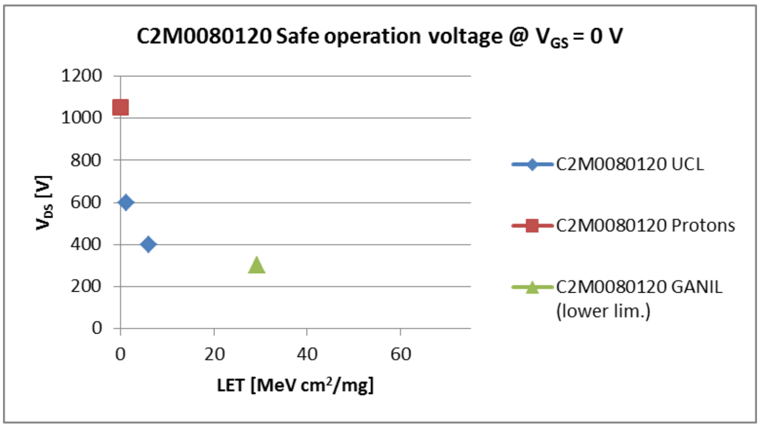
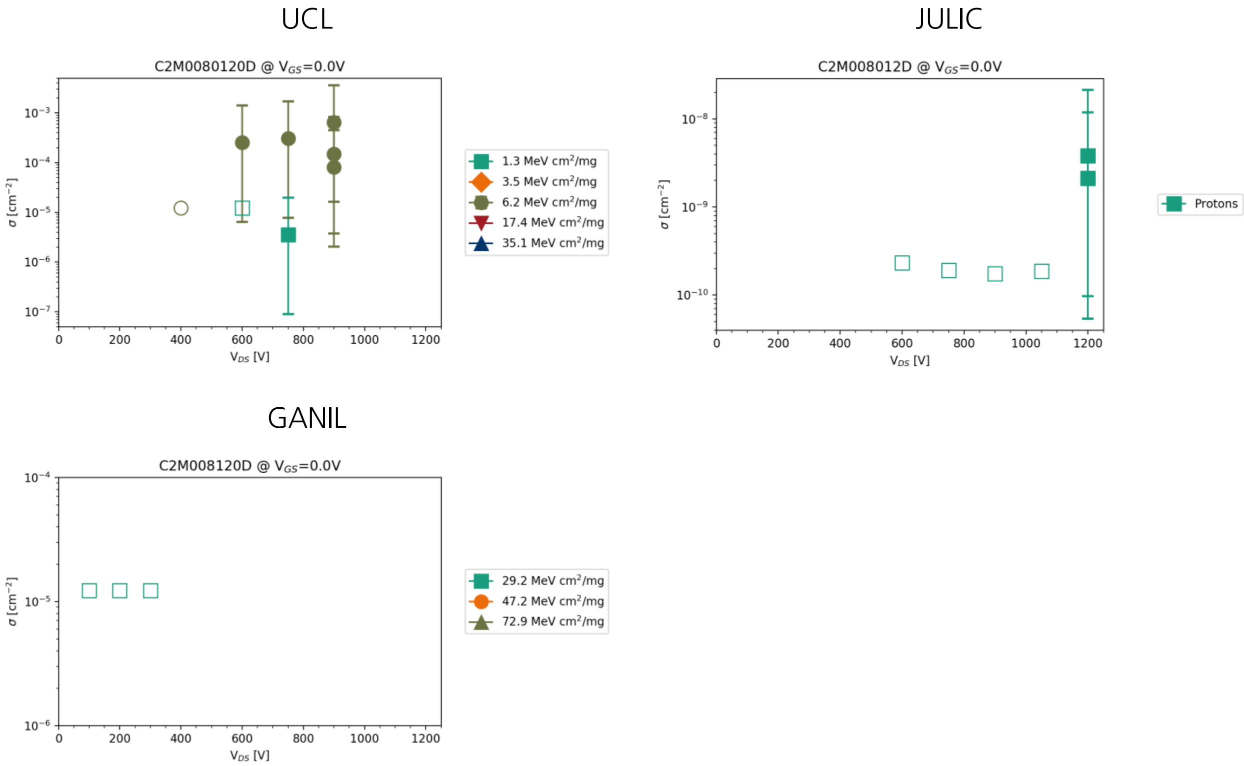


Figure 2: Cross sections at V_{GS} = 0 V for each campaign. Filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run.



With heavy ions at UCL the SiC MOSFET C2M0080120D showed high vulnerability with respect to the heavy ions even at low LETs and with the protons. At several instances the response to the heavy ion flux occurred nearly instantaneous with the start of the beam.

In the UCL tests, safe operation can be attributed to the 400 V level with Aluminium ions and the 600 V level of Carbon atoms. Higher LET ions were not used, as the necessary derating to safely operate the DUTS and the fluence until failure were already fairly low at Aluminium.

With protons of initial energy 45 MeV, the devices could not be operated at 1200 V free of destructive effects. One run performed at 1050 V with ~2E10 p/cm^2 passed.

At GANIL, no degradation or destructive events were seen up to 300 V, so 300 V can only be the lower limit of the safe operation area. However in comparison with the UCL results, the upper limit should be < 400 V.

2.2 Comments

- **Decapsulation:**
  - With the C2M0080120D, it was not possible to open the devices with the JetEtch alone. Thus the top 0.5 mm of the package was removed by drilling at the mechanical workshop of INT under ESD-safe conditions and the remainder of the package was removed with H_2SO_4 at 200°C for 600 s at an acid flow of 5 ml/min.
  - Of the 13 decapsulated devices, only 7 passed the functional tests and were considered for the coating process. This comparatively large fraction of rejects is most likely due to the large temperature during etching. Also of all SiC devices investigated in this project the C2M0080120D had the lowest operating junction and storage temperatures (up to 150°C).
  - One additional sample failed after the parylene coating process. Thus only 6 devices in total were available for the heavy ion campaigns at UCL and GANIL.
- **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:**
  - Especially in the first runs of the campaign device failures were not clearly seen as such and thus several runs with an already failed device were performed.
  - Also tests at V_{GS} > 0 V were most likely performed with a device with some damage on the gate, which might invalidate the results of these runs.
- **Tests at JULIC:**
  - The voltage level of 1050 V at V_{GS}=0V could not be confirmed with a second DUT.
  - Tests were performed with packaged DUTs.
  - Test devise were previously tested with Co-60 to 1 Mrad(Si).
- **Tests at GANIL:**
  - The tests at GANIL with the C2M0080120D were performed near the end of the beam time and only limited data could be taken. No PIGS tests were performed.
  - Test were only performed at voltages $V_{DS} \leq 300$ V and $V_{GS} = 0$ V with one LET.

3 Sample preparations

3.1 Sample shipment

A total of 30 Samples were procured by INT at a commercial supplier (Digi-Key Electronics) for the conduction of these tests for ESA. The parcel contained devices with one identification code (W14315). 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 ordered	Samples received	Samples sent back
December 2015	December 2015	still at INT (partially used for other tests in this project)

Figure 3: 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.

Figure 4: Sample marking

Table 4: Sample marking: Due to a limited number of samples, the DUTs tested with protons were previously used for a 1 Mrad(Si) TID campaign. Only DUTs used in the tests of this report are shown.

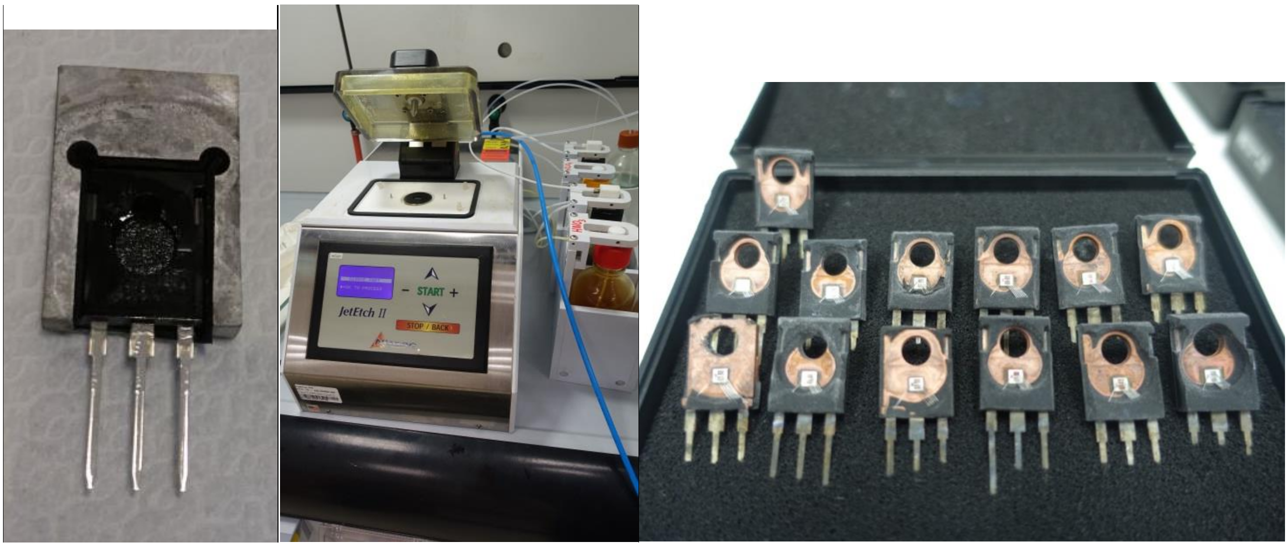
Condition	S/N	Color Code	Comment
	14		decap, coated
	15		decap, coated
UCL	19		decap, coated
	25		decap, coated
	26		decap, coated
GANIL	24		decap, coated
	1		non-decap, previously used for TID
JULIC	2		non-decap, previously used for TID
	3		non-decap, previously used for TID

3.3 Sample decapsulation and preparation

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

DUT decapsulation was performed at INT using a Nisene JetEtchII (Figure 5). The JetEtch II uses spray of acid, in our case fuming nitric 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 5: DUT decapsulation. Left side:Inset used for etching with a C2M0080120D showing the drill hole ,Center: Nisene JetEtch II at INT. Right side: batch of decapsulated C2M0080120D



With the C2M0080120D, it was not possible to open the devices with the JetEtch alone. Tested with a variety of acid mixtures of H_2SO_4 and HNO_3 at acceptable temperatures, no material removal was possible. Tests with H_2SO_4 at an acid temperature of 200°C, above the rated junction temperature, showed some progress. The material removal showed an acceptable rate once the surface layer of the package was removed, but the time required to get there was not acceptable.

Thus the top 0.5 mm of the package was removed by drilling at the mechanical workshop of INT (left side of Figure 5) under ESD-safe conditions and the remainder of the package was removed with H_2SO_4 at 200°C for 600 s at an acid flow of 5 ml/min.

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. Of the 13 decapsulated devices, only 7 passed these functional tests and were considered for the coating process. This comparatively large fraction of rejects is most likely due to the large temperature during etching. Also of all SiC devices investigated in this project the C2M0080120D had the lowest operating junction and storage temperatures (up to 150°C).

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 drain and gate threshold voltages performed at INT after receiving the coated samples, are shown in Figure 6 and led to the exclusion of one further sample (#16) from the tests.

In total 6 out of 13 decapsulated samples qualified for the heavy ion tests and were used at UCL and GANIL.

Figure 6: Functional tests after parylene coating

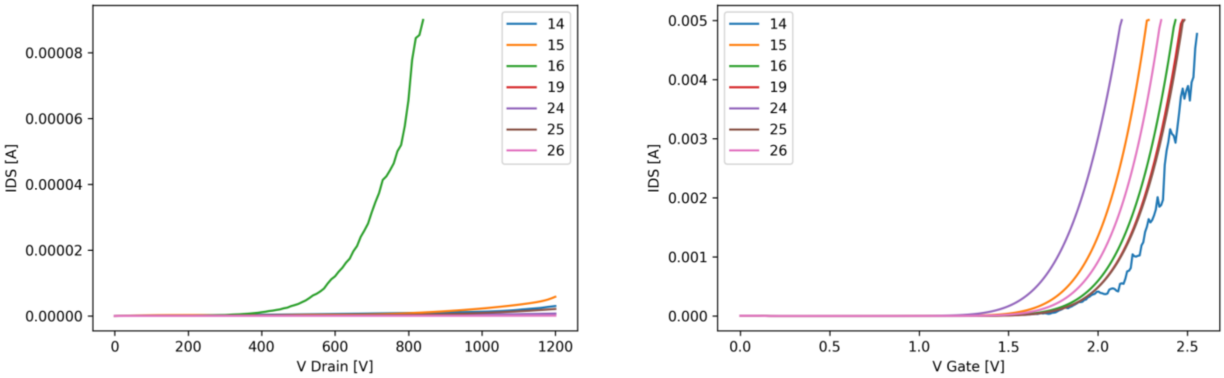
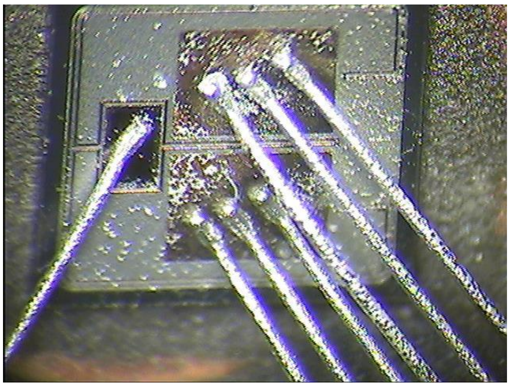
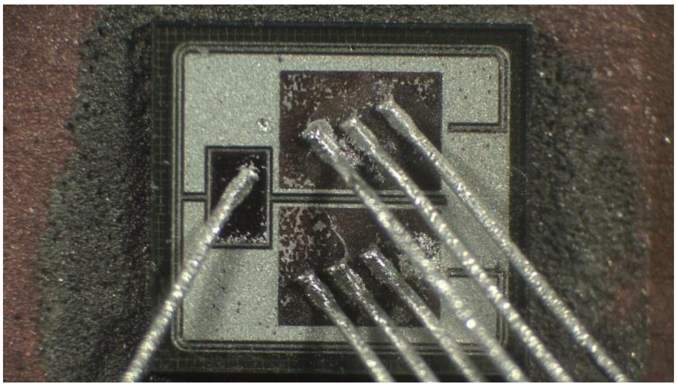


Figure 7: Die pictures. Images were taken with different optical microscopes. The camera used before the tests has a lower quality and resolution.



DUT #19 before tests at UCL



DUT #19 after tests at UCL

Figure 7 shows microscopic images of one DUT (#19) after parylene coating 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.

3.4 Sample safekeeping

The samples were stored in an Electro-Static Discharge (ESD) box (Figure 4) 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 area (applicable range of V_{DS} and V_{GS} for safe operation) 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 first steps in the intended test program foresaw tests at zero gate voltage to check for Single-Event Burnout (SEB), which should be independent of gate voltage. Starting at 50% of the rated V_{DS}, the drain source voltage would be increased in steps of 150 V due to beam time limitation. Afterwards the Single-Event Gate Rupture (SEGR) susceptibility would be tested for some V_{DS} settings starting at lower V_{DS} to cover any dependence on V_{DS}.

Due to increased sensitivity of the devices to even moderate LETs and V_{DS}, the actual tests did not follow this plan.

Table 5: Intended test program

#	V_{DS} [V]	V_{GS} [V]	#	V_{DS} [V]	V_{GS} [V]	#	V_{DS} [V]	V_{GS} [V]
1	600	0	6	600	-5	7	600	-10
2	750	0						
3	900	0	8	900	-5	9	900	-10
4	1050	0						
5	1200	0	10	1200	-5	11	1200	-10

After each test step, a post-irradiation-gate-stress- (PIGS) test is planned with the drain at maximum rated voltage and the gate sweeped to its maximum rating.

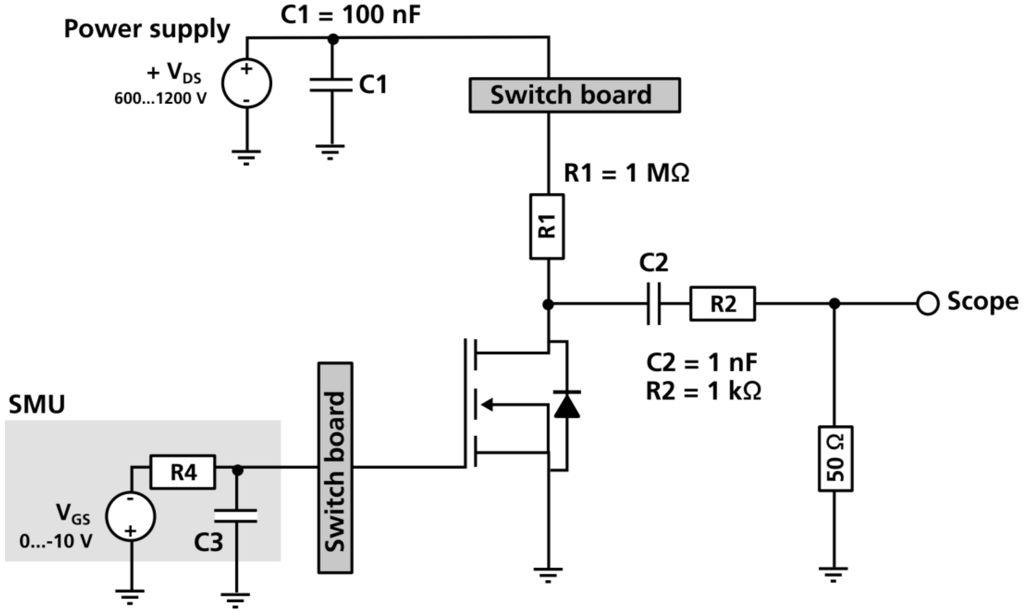
4.2 Test Board and Detection Circuit

A custom-build printed-circuit board (Figure 9) was manufactured to

- bias the samples according to the circuit-layout of the irradiation test plan [6] [7]
- fix the samples at the radiation source
- switch between the samples and connect the respectively active sample to the external setup

- detect and mitigate destructive SEB by using the voltage drop across a resistor in case of a SEB.

Figure 8: SEB / SEGR Detection Circuit



In Figure 8, the SEB circumvention should be governed by Resistor R1. Increased current will lead to an immediate voltage drop over R1 and consequently a decrease of the voltage on the MOSFET. This should set the voltage below the SEB threshold voltage and thus act like a power shutdown on the device.

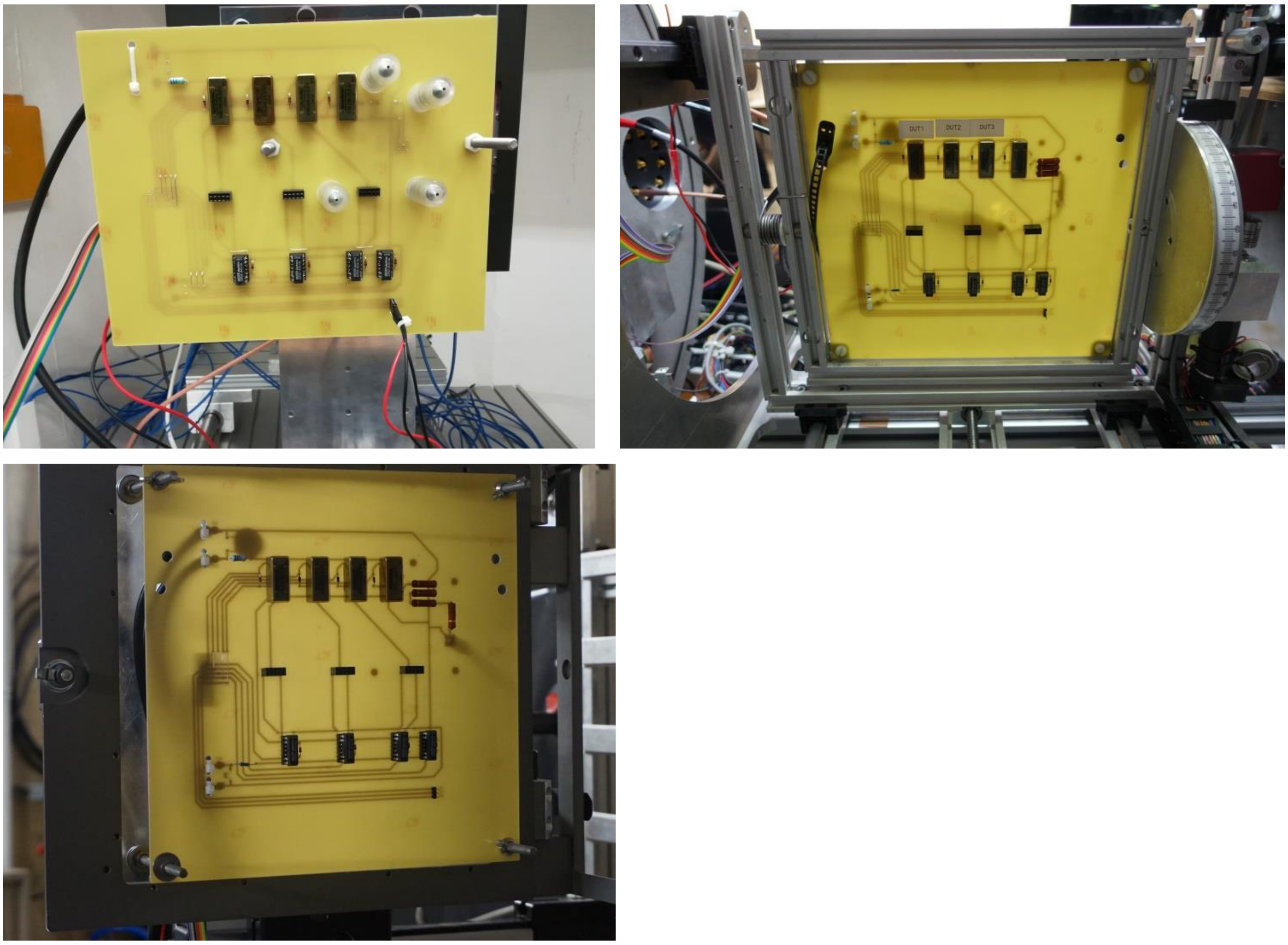
Capacitor C2 is used for DC decoupling of scope. C2 and R2 set the transient characteristics of signal due to SEB charge. The dimension of C2 should be small enough so that in case of a SEB and immediate voltage drop on MOSFET, the charge provided by C2 could not further damage the device.

No circumvention or protection was included on the gate, as SEGR cannot be circumvented and the DUT would be destroyed anyway.

This setup expanded on the setup proposed by P. Oser et. al. [9].

However, in the actual tests this design did neither circumvent nor mitigate destructive SEB, thus the devices were destroyed on each SEB event.

Figure 9: Test board layout Top left side: proton tests at JULIC, top right side: Heavy ion tests at UCL, bottom: Heavy ion tests at GANIL



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 in package, 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_{DS} and V_{GS} are only indicated at the respective runs, I_{DS} and I_{GS} are shown.

Table 6: Measurement parameters. Based on [4], taken from [6][7]

No.	Characteristics	Symbol	Remark
1	Drain-Source Voltage	V_{DS}	Set
2	Drain-Source Current	I_{DS}	Monitored for SEB Limits at V_{DS}=1200 V, V_{GS} = 0 V: typical 1 µA, max = 100 µA
3	Gate-Source Voltage	V_{GS}	Set
4	Gate-Source Current	I_{GS}	Monitored for SEGR

4.4 Measurement equipment

The test equipment is shown in Table 7 - Table 9 and Figure 10 - Figure 12.

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

Table 7: 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	VDS, IDS
System Source Meter	Keithley	2400	E-SMU-002	10/2019	VGS, IGS
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix for VDS and VGS relais
Triple Output Power Supply	Agilent	E3631A	E-PS3-002	n/a	Power supply of of relais
Triple Output Power Supply	Agilent	E3631A	E-PS3-003	n/a	Power supply for Line driver (SEB transients to oscilloscope)
Line driver	INT	--	--	--	Amplification of device output to transport signal

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
					over long cables
Digital Oscilloscope	Rohde & Schwarz	RTO2044	E-DSO-004	VB	intended for capturing of SEB transients, no results

Figure 10: UCL: Measurement equipment/setup

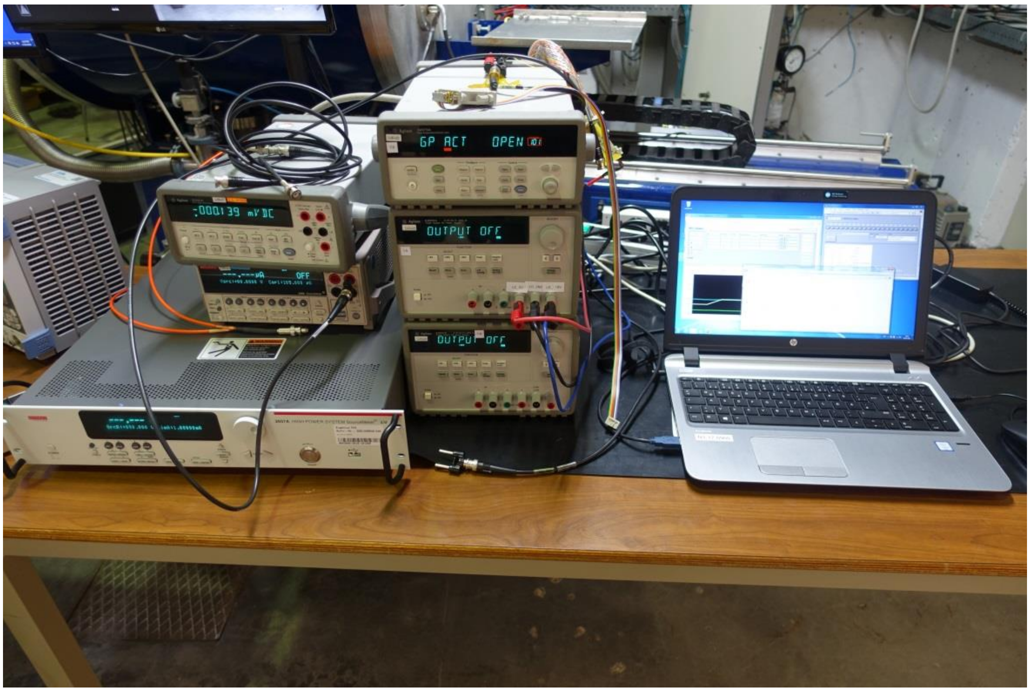


Table 8: GANIL: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2020	VDS, IDS
System Source Meter	Keithley	2400	E-SMU-002	10/2019	VGS, IGS
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix for VDS and VGS relais

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
Triple Output Power Supply	Agilent	E3631A	E-PS3-001	n/a	Power supply of of relais
Triple Output Power Supply	Agilent	E3631A	E-PS3-002	n/a	Power supply for Line driver (SEB transients to oscilloscope)
Line driver	INT	--	--	--	Amplification of device output to transport signal over long cables
Digital Oscilloscope	Rohde & Schwarz	RTO2044	E-DSO-004	VB	intended for capturing of SEB transients, no results

Figure 11: GANIL: Measurement equipment/setup

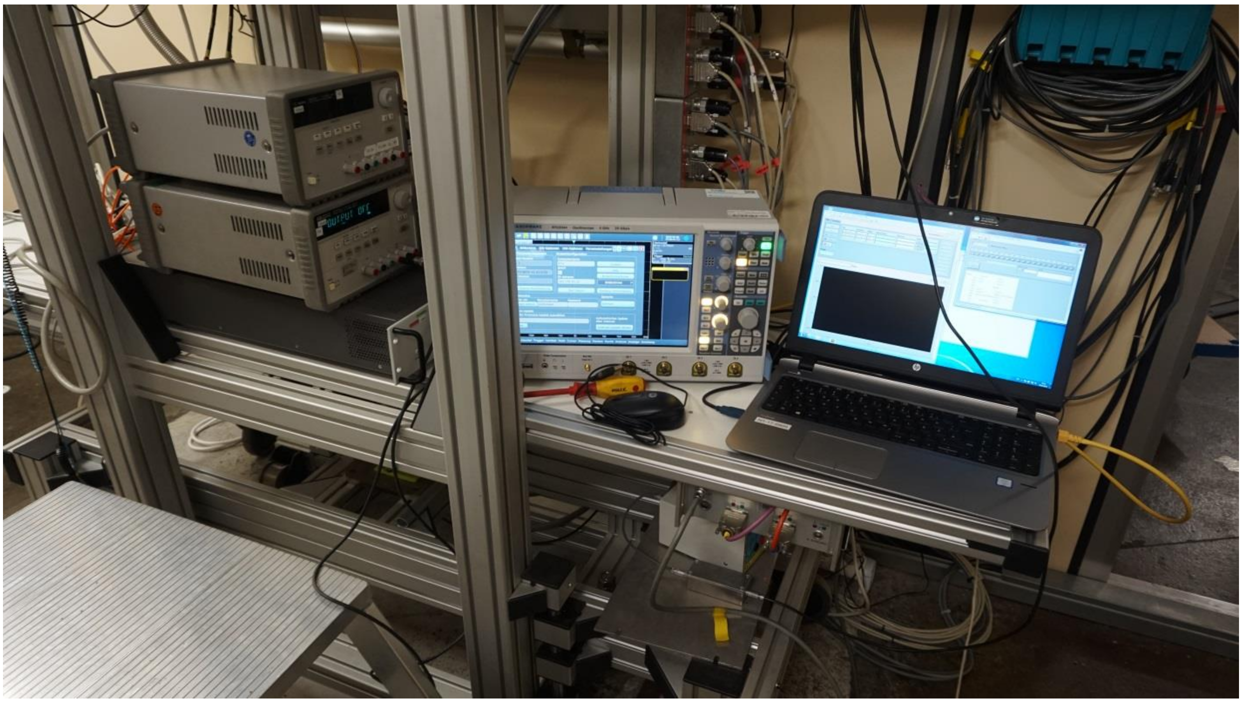
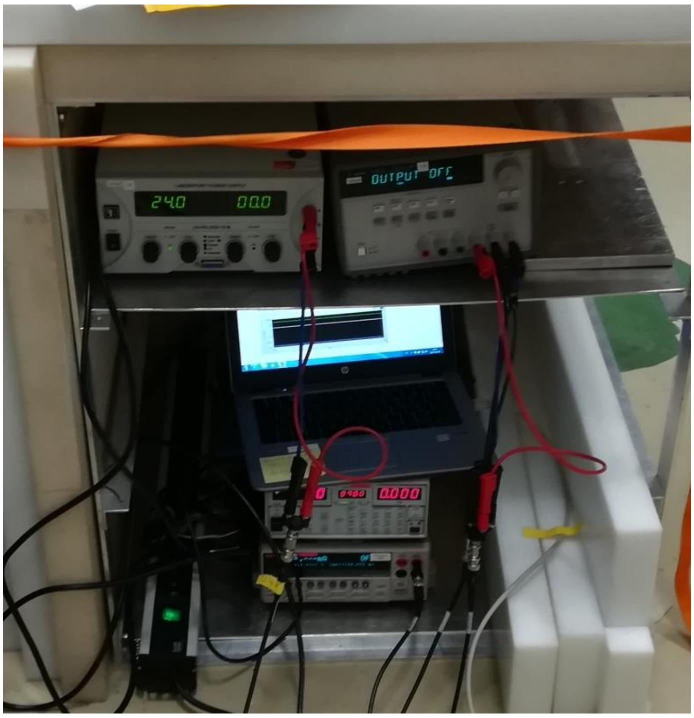


Table 9: JULIC: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
5 kV Power supply	Keithley	2290E-5	E-PS1-030	10/2017	VDS, IDS
System Source Meter	Keithley	2400	E-SMU-002	10/2017	VGS, IGS
Laboratory Power Supply	EA	EA-PS-3032-10B	E-PS1-001	n/a	Control of relais for switching VGS
Triple Output Power Supply	Agilent	E3631A	E-PS3-001-	n/a	Power supply for Line driver (SEB transients to oscilloscope)
Line driver	INT	--	--	--	Amplification of device output to transport signal over long cables
6 GHz Oscilloscope	Agilent	infiniium 54855A DSO	E-DSO-001	VB	intended for capturing of SEB transients, no results

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 12: JULIC: Measurement equipment/setup



4.5 Measurement procedures

Bias conditions of the drain and gate were fixed for each step. When no destructive events occurred during a run, a PIGS 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.

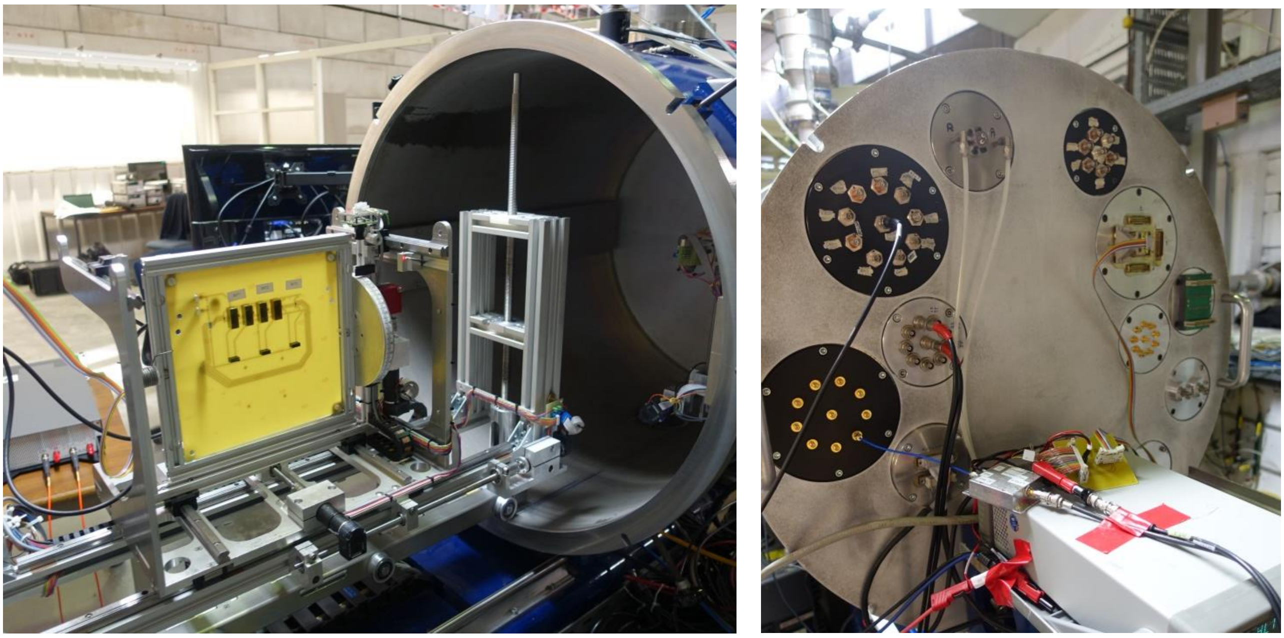
The facility can provide selected heavy ion beams from Carbon to Xenon in a particle cocktail with mass/charge ratio of approx. M/Q=3.3, allowing to switch from ion species to ion species quickly within the cocktail.

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 13).

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 13: 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 [10]. However this data is not valid for Silicon Carbide.

SRIM 2013 [11] 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 [6].

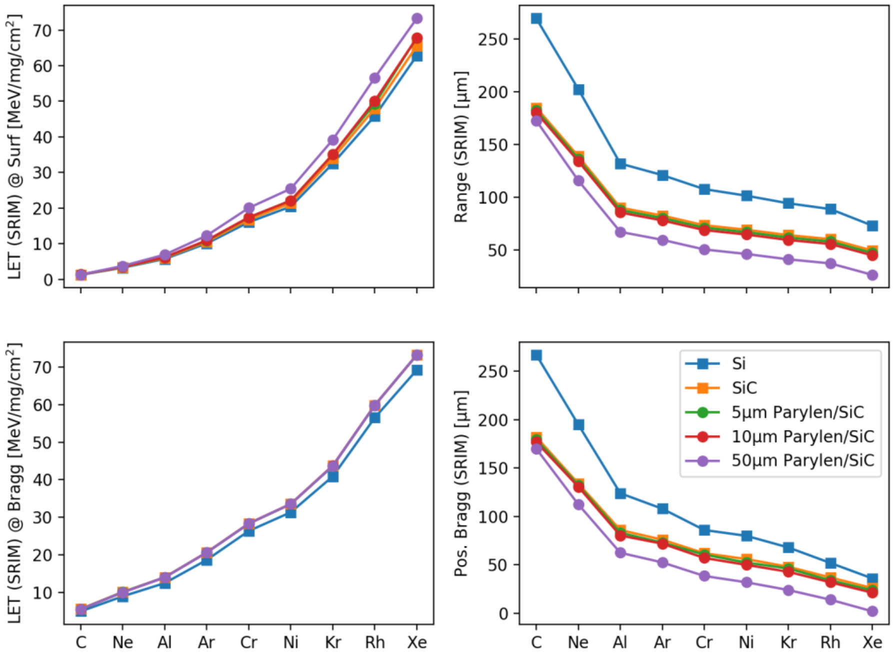
Tests with the C2M0080120D were only performed with ions marked in bold letters in Table 10.

Table 10: UCL: Ion energies, LETs and ranges in Silicon Carbide covered by 10 µm Parylene: Shown are the ions available at UCL [10]. LETs highlighted in bold font were actually used. LET and range data are based on SRIM2013 [11] 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 14: Plot of LETs and Ranges in Silcon Carbide at UCL. Additional data with Parylene layers and data for Silicon are included. Thin Parylene layers have limited impact.



5.3 Geometry

The board is attached to the moveable board holder (Figure 13) 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

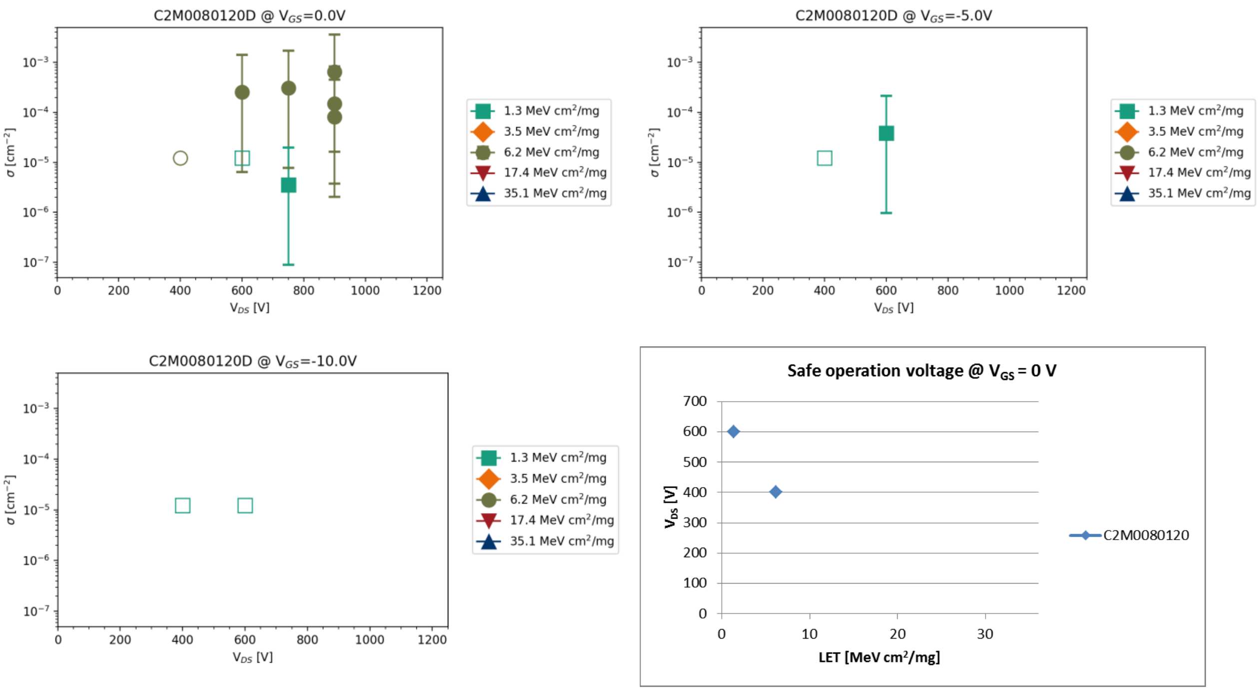
The log file of the tests performed at UCL can be found in Appendix B. Table 11 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 5.5.

Table 11: UCL: Irradiation steps of SiC MOSFET C2M0080120D. 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_DS [V]	V_GS [V]	1.3		3.5		6.2		17.4		35.1	
		in-situ	PIGS	in-situ	PIGS	in-situ	PIGS	in-situ	PIGS	in-situ	PIGS
400	0					25, 26	25, 26				
600		25, 26	25, 26			14	14				
750		26	none			14, 19	14, 19				
900						14, 15	14				
1050											
1200											
400	-5	25	25								
600		25	25								
900											
1200											
400	-10	25	25								
600		25	25								
900											
1200											

5.5 Results

Figure 15: Results: Heavy Ions at UCL. The first three images show the cross section results for various settings of V_{GS}. 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 bottom right image shows the safe operating voltage at V_{GS} = 0 V.



The SiC MOSFET C2M0080120D showed high vulnerability with respect to the heavy ions even at low LETs and a reduced target fluence of 3E5 ions/cm^2 . At several instances the response to the heavy ion flux occurred nearly instantaneous with the start of the beam. Especially in the first runs of the campaign this was not clearly seen as such and thus several runs with an already failed device were performed. Later several additional runs were performed with DUTs which show some gate damage from previous runs, but who also were not clearly identifiable as a gate rupture. However, in this case, gate rupture was clearly seen at a later run.

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.

In these tests, safe operation can be attributed to the 400 V level with Aluminium ions and the 600 V level of Carbon atoms. Higher LET ions were not used, as the necessary derating to safely operate the DUTS and the fluence until failure were already fairly low at Aluminium.

With carbon atoms most of the tests passed, however DUT #26 in run #9 failing at approx. that level indicates, that this may be due to the low target fluence and the devices might have failed if they had been exposed to the ions longer.

Table 12: 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)

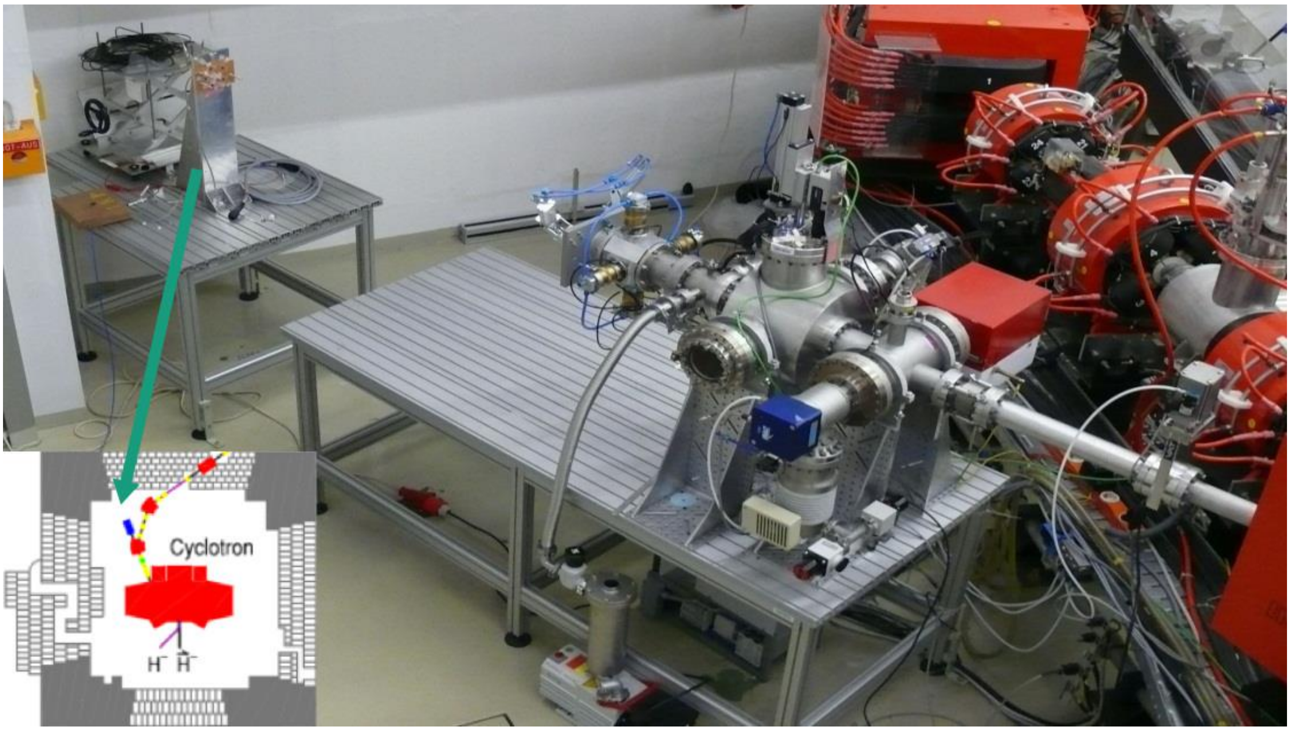
#	Ion	DUT #	V_DS, V	V_GS	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
1	Al	14	600	0	3.92E+03	6.45E-06	2.55E-04	1.42E-03	SEB	Immediate destructive failure. Runs #2-#4 performed with same device, thus discarded
5	Al	19	750	0	3.28E+03	7.71E-06	3.04E-04	1.70E-03	SEB	Immediate destructive failure
6	Al	25	400	0	> 3.01E+05	0	0	1.22E-05	--	--
7	Al	26	400	0	> 3.02E+05	0	0	1.22E-05	--	--
8	C	26	600	0	> 3.02E+05	0	0	1.22E-05	--	--
9	C	26	750	0	2.81E+05	9.02E-08	3.56E-06	1.99E-05	SEB, SEGR	Destructive failure at indicated fluence. Within data sampling accuracy the drain and gate fail simultaneously
10	C	25	600	0	> 3.02E+05	0	0	1.22E-05	SEGR @ PIGS	No failure during the run, but device shows largely increased current during PIGS
11	C	25	400	-5	> 3.02E+05	0	0	1.22E-05	?	Some device damage in gate
12	C	25	400	-10	> 3.02E+05	0	0	1.22E-05	?	Some device damage in gate
13	C	25	600	-5	2.60E+04	9.75E-07	3.85E-05	2.14E-04	SEGR	Some device damage in gate, huge jump in gate current, not observed anymore in PIGS
14	C	25	600	-10	> 3.03E+05	0	0	1.22E-05		Some device damage in gate.

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 16: 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 17 and Figure 18). 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 [13].

Figure 17: Schematic setup of the beam exit window at JULIC and the ionization chamber. The DUT is placed in same distance as the IC.

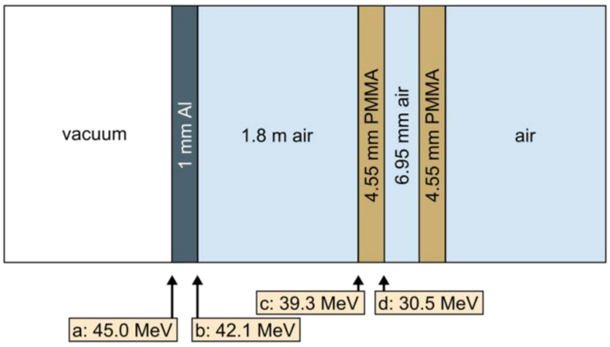
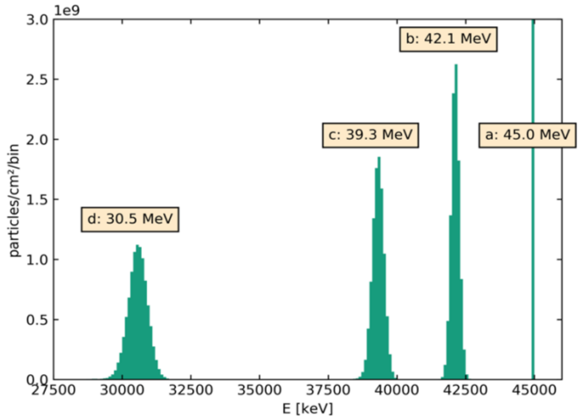


Figure 18: The initial proton energy of 45.0 MeV gets reduced to 39.3 MeV at the position of the IC/DUT. The PMMA cap of the chamber further reduces the energy to 30.5 MeV, calculation by MULASSIS (Geant4) on SPENVIS[12].



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

Thickness	0.5 mm		1 mm		2 mm		3 mm	
LET_{GRAS} [MeV cm²/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 cm²/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 cm²/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 cm2/mg and the LET of C around 5.8 MeV cm²/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 cm²/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 14 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 6.5.

The beam was not interrupted for all tests with DUT #3 (runs #4-#8). Start time of beam is thus identical. Fluences are calculated from the fluxes over the measurement time of the respective DUT.

The tests at V_{GS} = -10 V were performed with an already damaged device and are thus neglected in the results section.

Table 14: JULIC: Irradiation steps of SiC MOSFET C2M0080120D. 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	
V_DS [V]	V_GS [V]	E_{init} = 45 MEV in-situ	E_{init} = 45 MEV PIGS
400	0		
600	0	3	
750	0	3	
900	0	3	
1050	0	3	3
1200	0	1, 3	
400	-10		
600	-10		
900	-10		
1200	-10	2	

6.5 Results

Figure 19 and Table 15 shows the cross section results for the tests with the fairly low energetic protons at JULIC.

The safe operating voltage for V_{GS} = 0 V was found at 1050 V. In comparison, the Heavy ion results (Section 5.5) showed a safe operation voltage of only 600 V at LET = 1.3 MeV cm^2/mg.

As there was no other device left to confirm the result at 1050 V, the failure and the large cross section at 1200 V was confirmed instead with the last remaining device.

Figure 19: Results: Protons at JULIC. The cross section results for various settings of V_{GS}. 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.

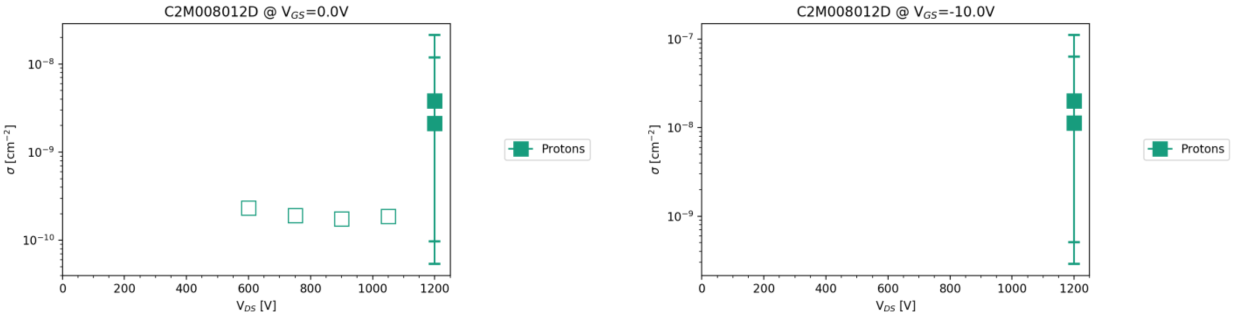


Table 15: Results: Protons at JULIC - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	DUT #	V_DS, V	V_GS	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
1	p	#1	1200	0	2.61E+08	9.7E-11	3.83E-09	2.13E-08	SEB	Nearly instantaneous
2	p	#2	1200	-10	4.98E+07	5.08E-10	2.01E-08	1.12E-07	SEB	Nearly instantaneous , SEGR within timing accuracy approx. 0.3 s delay
					8.79E+07	2.88E-10	1.14E-08	6.34E-08	SEGR	
4	p	#3	600	0	1.58E+10	0	0	2.33E-10	--	
5	p	#3	750	0	1.93E+10	0	0	1.91E-10	--	
6	p	#3	900	0	2.11E+10	0	0	1.75E-10	--	
7	p	#3	1050	0	1.98E+10	0	0	1.87E-10	--	
8	p	#3	1200	0	4.70E+08	5.39E-11	2.13E-09	1.19E-08	SEB	Nearly instantaneous

7 Tests at GANIL

7.1 Facility

Additional heavy ion tests were performed at the G4 cave at GANIL, Caen, France.

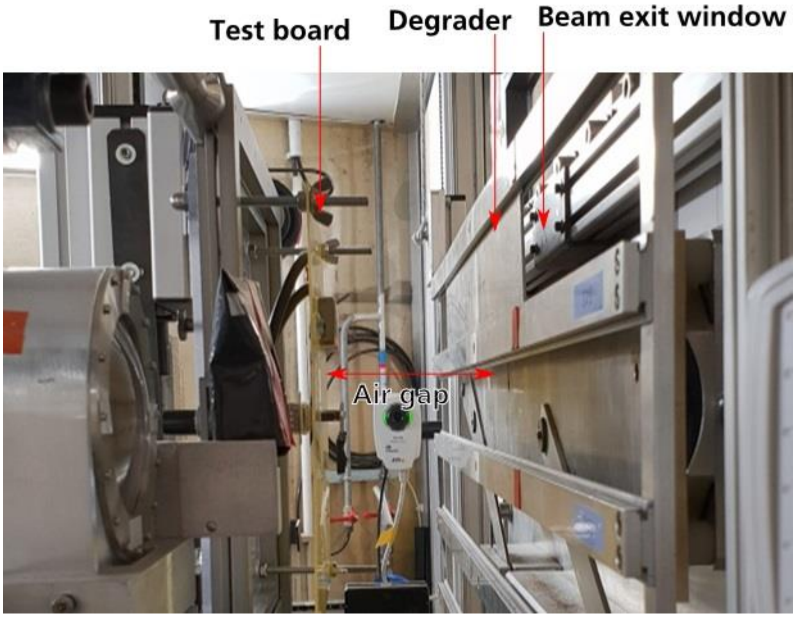
GANIL offers the irradiation of electric components with heavy ions over a wide LET range.

The facility can provide selected heavy ion beams from Argon to Lead with a larger kinetic energy per nucleon than is available e.g. at UCL. The available ion at the time of our tests was Xenon.

The experimental tests at the facility take place in air and the setup consists of a sample holder, which is moveable in x-,y- and z-direction and variable degraders that can be put between the beam exit window and the DUT. By inclusion or variation of the degrader and by varying the air gap between exit window and DUT, the LET in Silicon can be tuned from approx. 26.5 MeV cm²/mg to 64.3 MeV cm²/mg and the corresponding ranges of the ions in Silicon go from 685 µm to 35 µm over that LET range.

DUT alignment is done with the help of a laser system.

Figure 20: Test setup at GANIL. Ion LETs can be set by variation of the degrader and the air gap.



7.2 Beam parameters

The resulting total energies of the respective ions, as well as their LET and range in Silicon are provided by GANIL [14]. However this data is not valid for Silicon Carbide.

SRIM 2013 [11] simulations by Fraunhofer INT in Table 16 show the respective surface LET values for the Xenon beam provided by GANIL under normal incidence in Silicon Carbide covered by a 10 µm Parylene layer with the air gap and degrader settings used in the experiments. For comparison, the values in Silicon provided by GANIL are included in the table. The devices used for these tests were de-lidded, so packages were not included in the simulations.

Table 16: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [14], Values in SiC are calculated by INT and given with one digit

Degrader [mm Al]	Air gap [mm]	LET (Si) [MeV.cm²/mg]	Range (Si) [µm]	LET_{SURF} (SiC) [MeV.cm²/mg]	Range (SiC) [µm]
0	150	27.76	640.33	29.2	430
0.4	95	42.03	226.23	47.2	141
0.5	180	60.12	65.68	72.9	30

7.3 Geometry

The board is attached to the moveable board holder (Figure 20). Tests are then performed in air.

7.4 Irradiation steps

The tests at GANIL with the C2M0080120D were performed near the end of the beam time and only limited data could be taken. No PIGS tests were performed.

Table 17: GANIL: Irradiation steps of SiC MOSFET C2M0080120D. 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.

		Xe, 0 mm Al, 150 mm Air		Xe, 0.4 mm Al, 95 mm Air		Xe, 0.5 mm Al, 180 mm Air	
		29.2		47.2		72.9	
V_DS [V]	V_GS [V]	in-situ	PIGS	in-situ	PIGS	in-situ	PIGS
100	0	24					
200		24					
300		24					
1200							

The log file of the tests performed at GANIL can be found in Appendix D. Table 17 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 7.5.

7.5 Results

Anticipating destructive failures at low fluences, the tests started at V_{DS} = 100 V and went as high as V_{DS} = 300 V and test fluences of 3E5 ions/cm^2. Tests were only performed at voltages V_{GS} = 0 V with one LET.

Neither destructive events nor degradation was seen up to these points. Thus we can only conclude a lower limit of 300 V for the safe operating voltage at LET = 29.2 MeV cm^2/mg.

In comparison with the UCL results, the upper limit should be < 400 V, which was identified as the safe operation area at LET = 6.2 MeV cm^2/mg.

Figure 21: Results: Heavy ions at GANIL. The cross section results for various settings of V_{DS}. 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. No effects were observed.

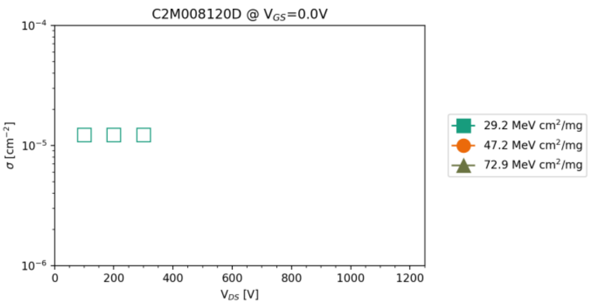


Table 18: Results: Heavy Ions at GANIL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	Al [µm]	Air [mm]	DUT #	V_DS, V	V_GS	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
512	Xe	0	150	24	100	0	> 3.00E+05	0	0	1.23E-05	--	
513	Xe	0	150	24	200	0	> 3.00E+05	0	0	1.23E-05	--	
514	Xe	0	150	24	300	0	> 3.00E+05	0	0	1.23E-05	--	

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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].

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

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.

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QM-Certificate

DNV·GL

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Certificate No:	Initial certification date:	Valid:
126306-2012-AQ-GER-DAkkS	13. February 2013	14. February 2019 - 12. February 2022

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Essen, 14. February 2019

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B Appendix: Tests at UCL

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_DS, V	V_GS	beam time [s]	fluence [cm-2]
1	11	16.4.	15:19	Al	MOSFET	C2M0080120D	#1	14	600	0	354	3.02E+05
2	12	16.4.	16:03	Al	MOSFET	C2M0080120D	#1	14	750	0	159	3.03E+05
3	13	16.4.	16:07	Al	MOSFET	C2M0080120D	#1	14	900	0	145	3.03E+05
4	14	16.4.	16:31	Al	MOSFET	C2M0080120D	#2	15	900	0	140	3.04E+05
5	15	16.4.	17:04	Al	MOSFET	C2M0080120D	#1	19	750	0	58	1.15E+05
6	16	16.4.	17:28	Al	MOSFET	C2M0080120D	#2	25	400	0	505	3.01E+05
7	17	16.4.	17:40	Al	MOSFET	C2M0080120D	#3	26	400	0	306	3.02E+05
8	18	16.4.	18:08	C	MOSFET	C2M0080120D	#3	26	600	0	307	3.02E+05
9	19	16.4.	18:15	C	MOSFET	C2M0080120D	#3	26	750	0	318	3.01E+05
10	20	16.4.	18:23	C	MOSFET	C2M0080120D	#2	25	600	0	293	3.02E+05
11	21	16.4.	18:30	C	MOSFET	C2M0080120D	#2	25	400	-5	299	3.02E+05
12	22	16.4.	18:39	C	MOSFET	C2M0080120D	#2	25	400	-10	299	3.02E+05
13	23	16.4.	18:47	C	MOSFET	C2M0080120D	#2	25	600	-5	157	3.03E+05
14	24	16.4.	18:52	C	MOSFET	C2M0080120D	#2	25	600	-10	158	3.03E+05

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Measurements

Figure 22: Run# 001, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 14, VDS= 600.0 V, VGS= 0.0 V

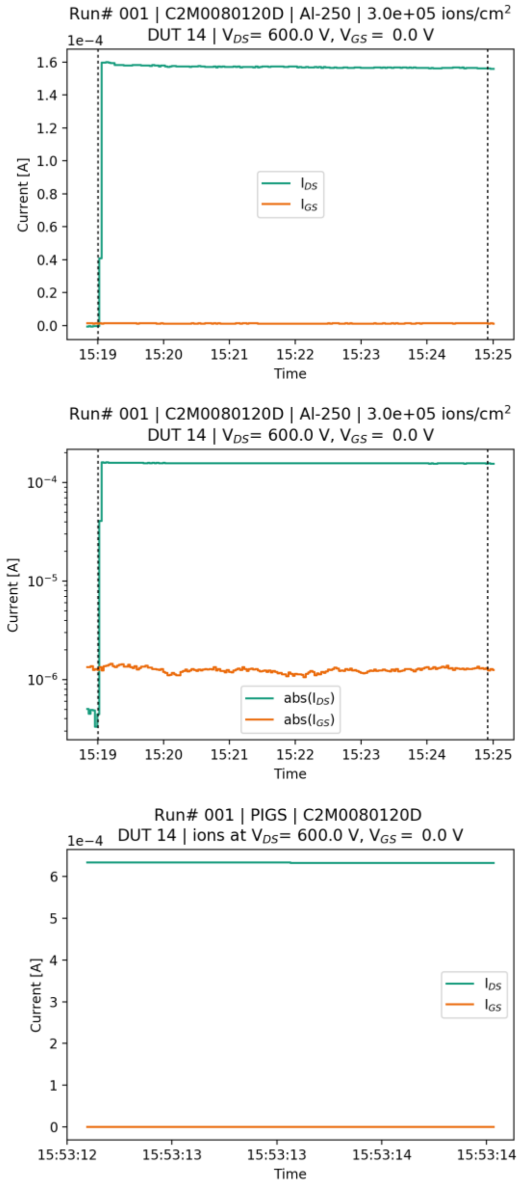


Figure 23: Run# 002, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 14, VDS= 750.0 V, VGS= 0.0 V

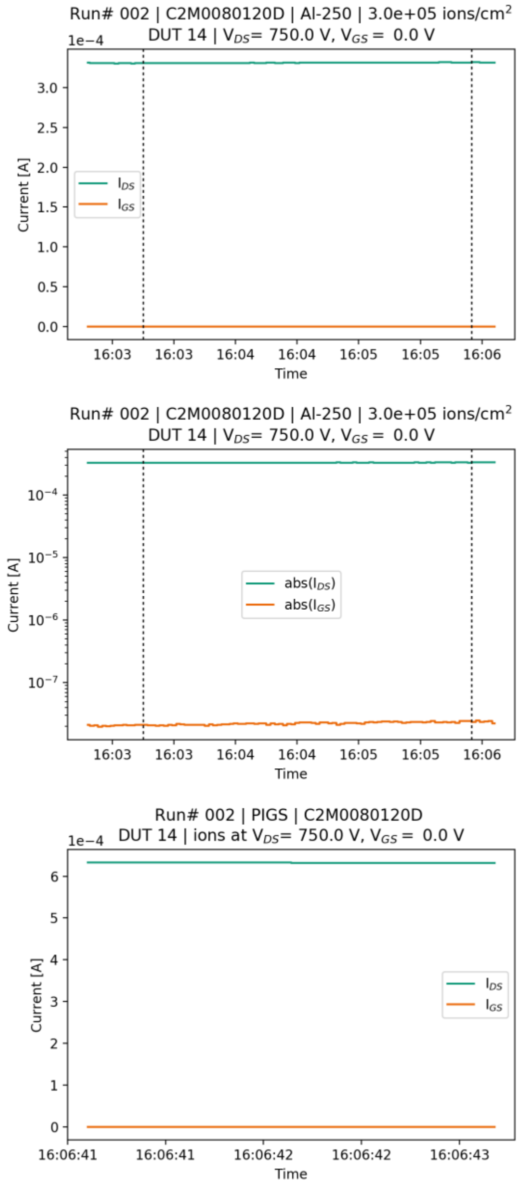


Figure 24: Run# 003, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 14, VDS= 900.0 V, VGS= 0.0 V

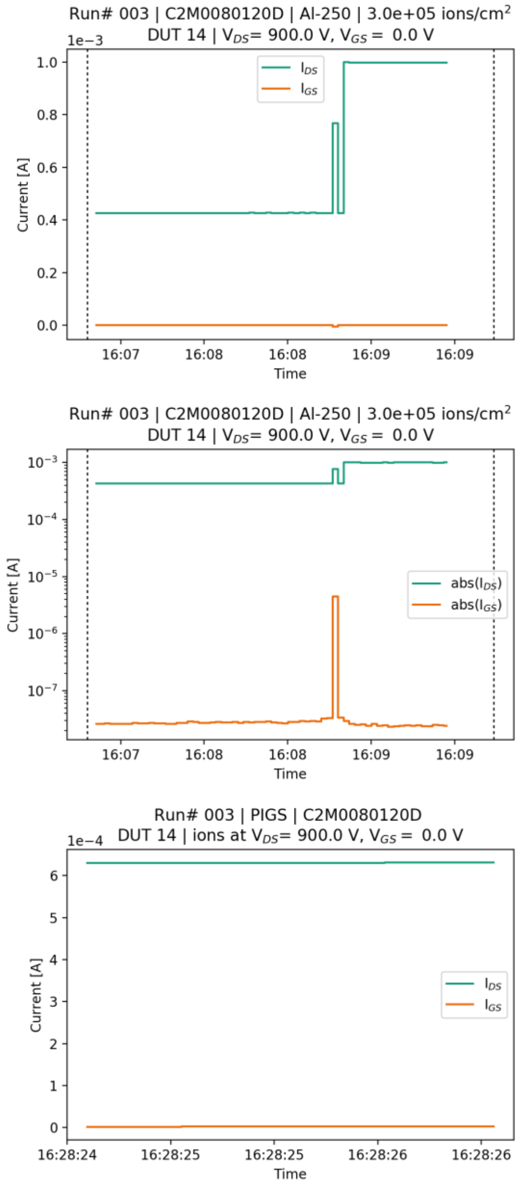


Figure 25: Run# 004, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 15, VDS= 900.0 V, VGS= 0.0 V

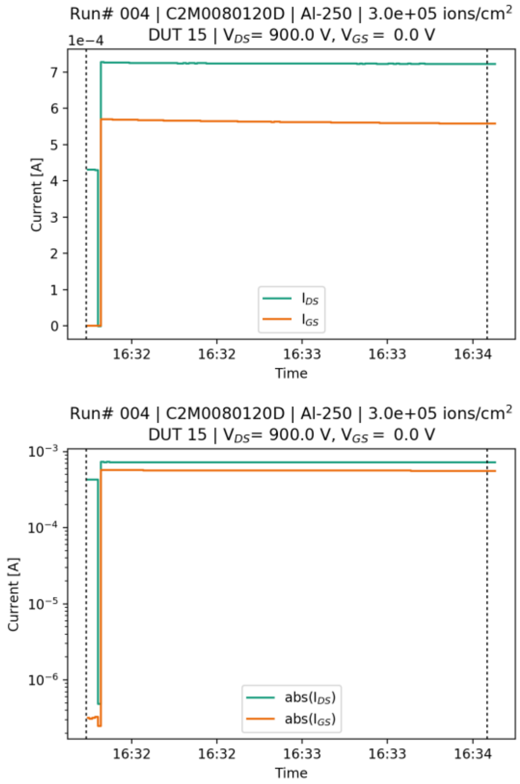


Figure 26: Run# 005, C2M0080120D, Al-250, 1.1e+05 ions/cm2 , DUT 19, VDS= 750.0 V, VGS= 0.0 V

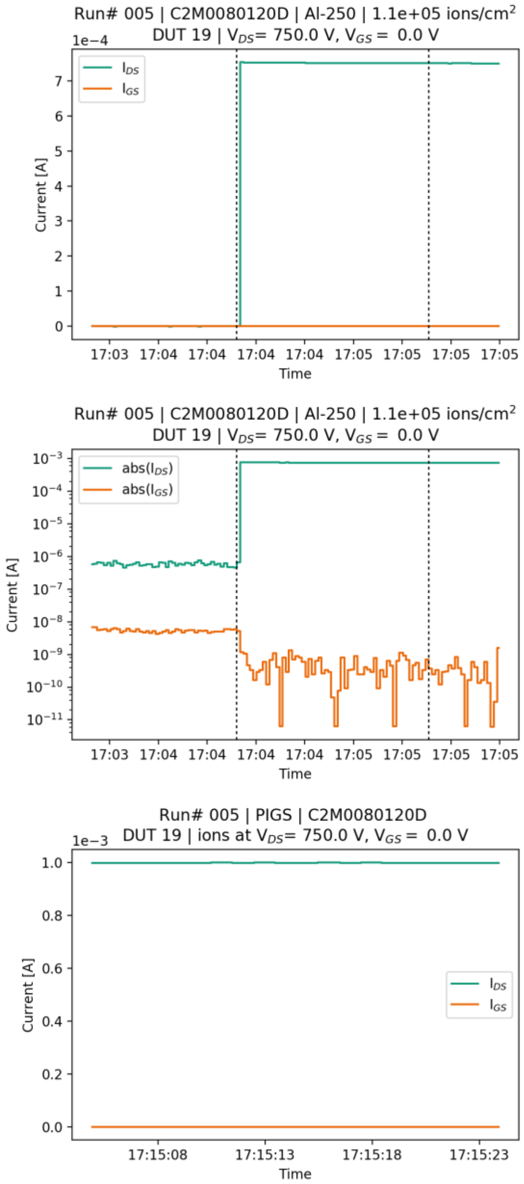


Figure 27: Run# 006, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 25, VDS= 400.0 V, VGS= 0.0 V

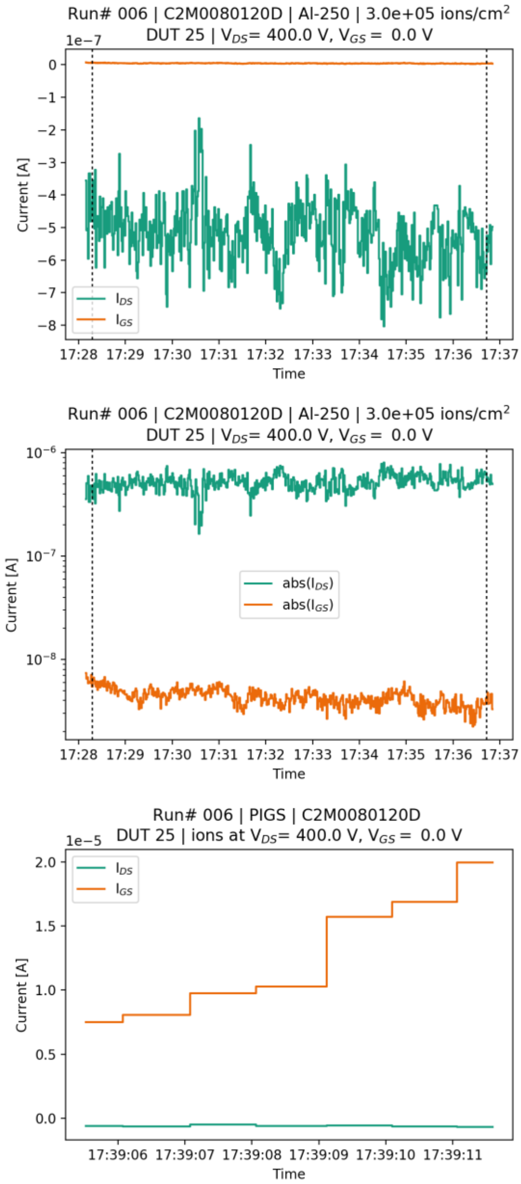


Figure 28: Run# 007, C2M0080120D, Al-250, 3.0e+05 ions/cm2 , DUT 26, VDS= 400.0 V, VGS= 0.0 V

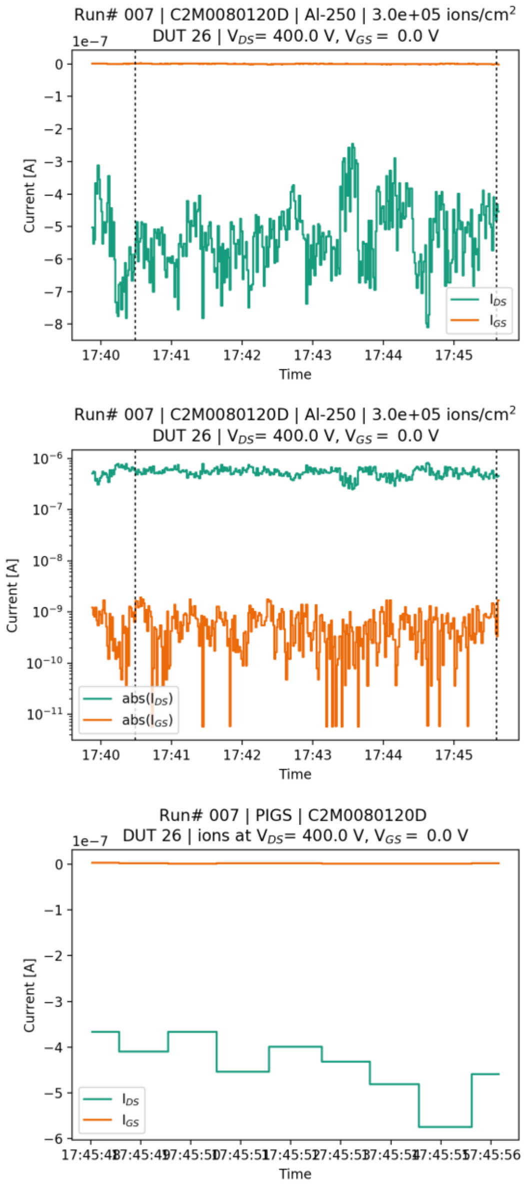


Figure 29: Run# 008, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 26, VDS= 600.0 V, VGS= 0.0 V

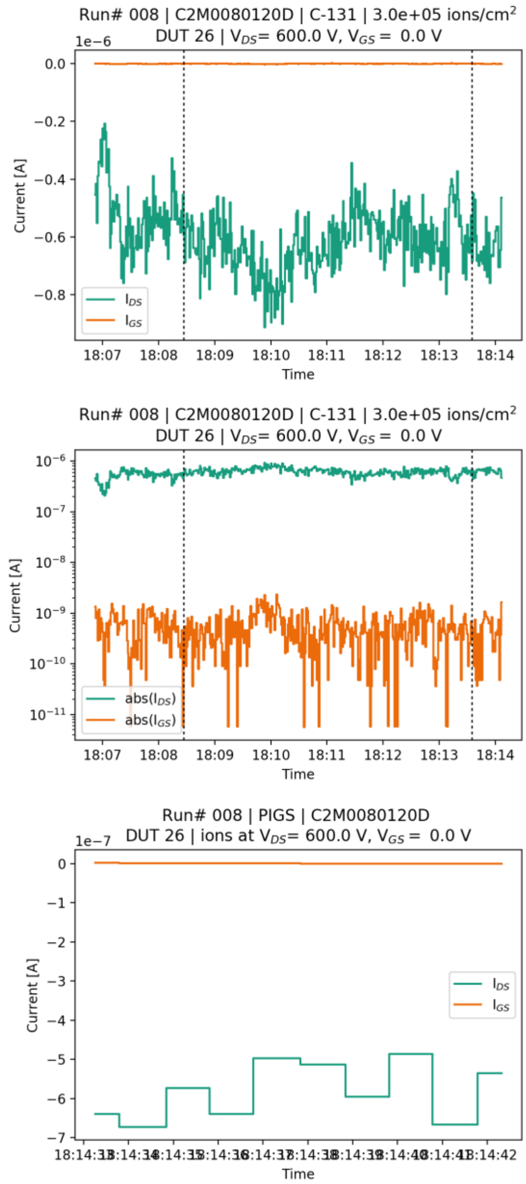


Figure 30: Run# 009, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 26, VDS= 750.0 V, VGS= 0.0 V

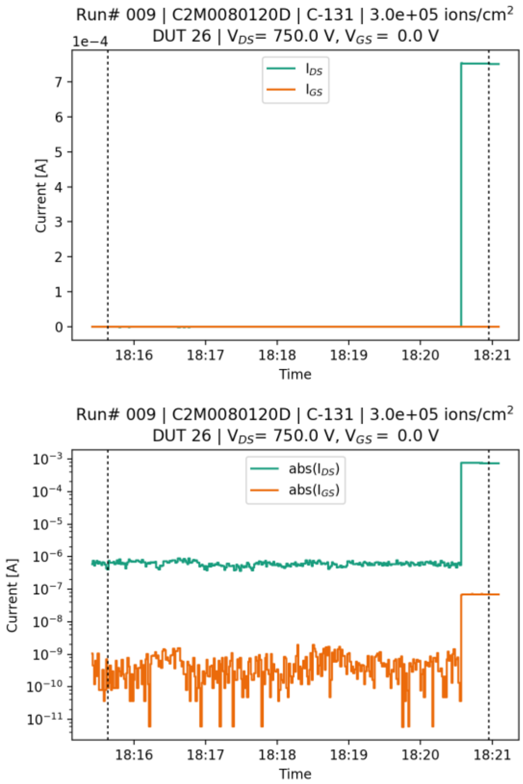


Figure 31: Run# 010, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 25, VDS= 600.0 V, VGS= 0.0 V

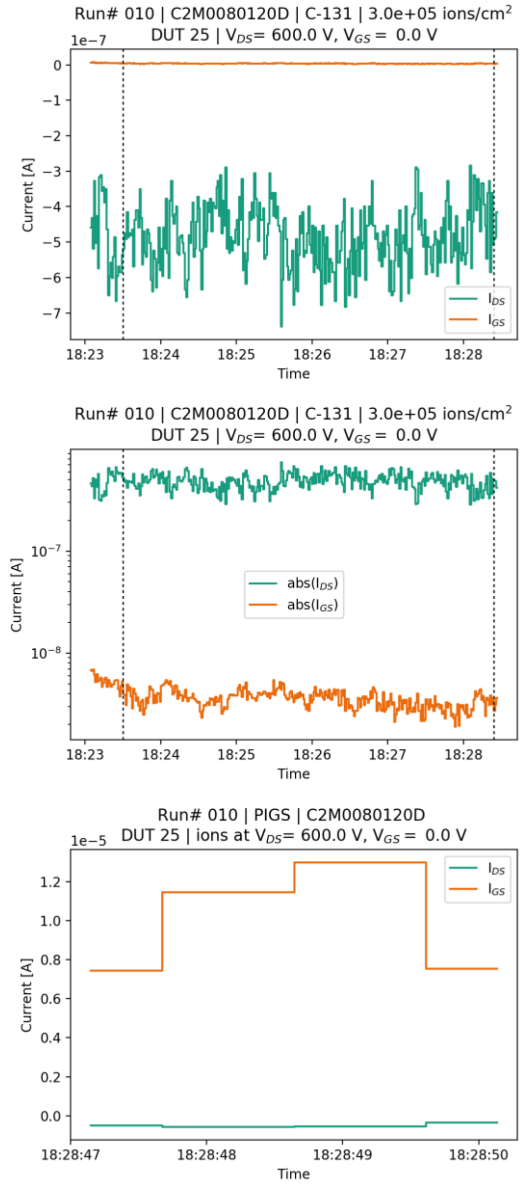


Figure 32: Run# 011, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 25, VDS= 400.0 V, VGS= -5.0 V

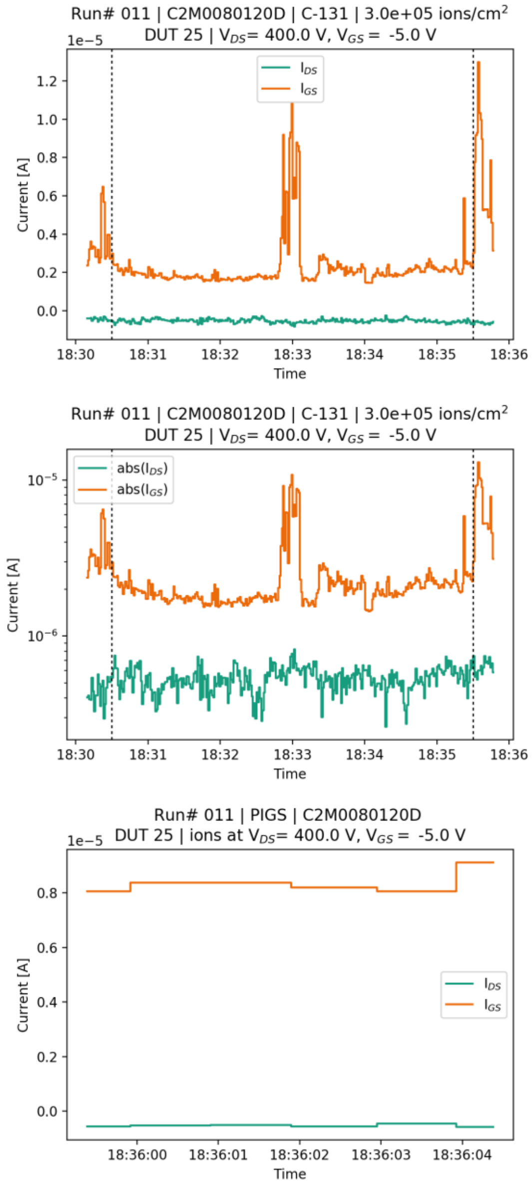


Figure 33: Run# 012, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 25, VDS= 400.0 V, VGS= -10.0 V

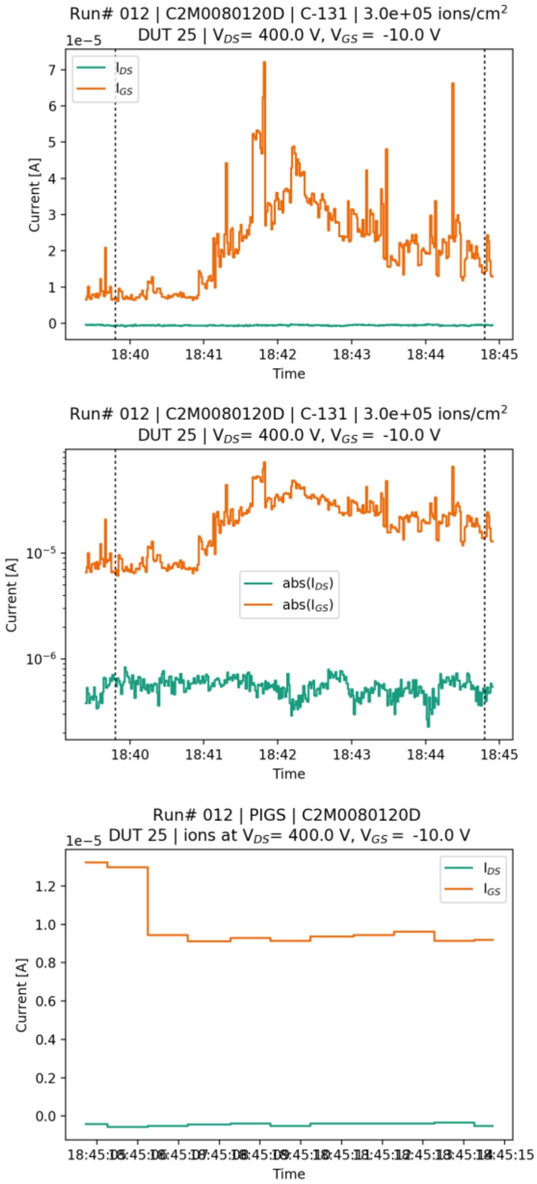


Figure 34: Run# 013, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 25, VDS= 600.0 V, VGS= -5.0 V

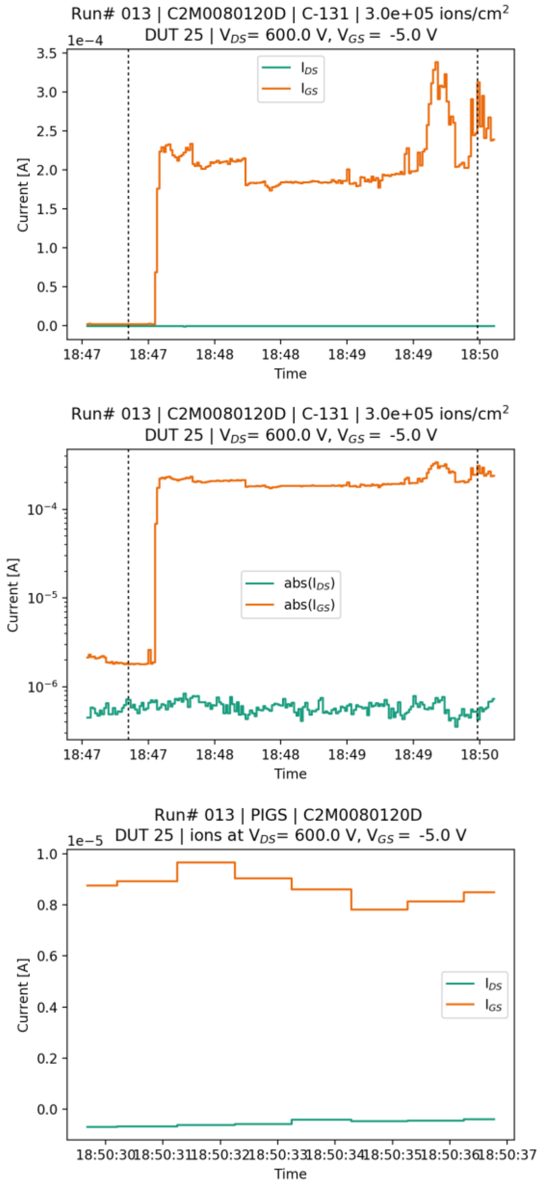
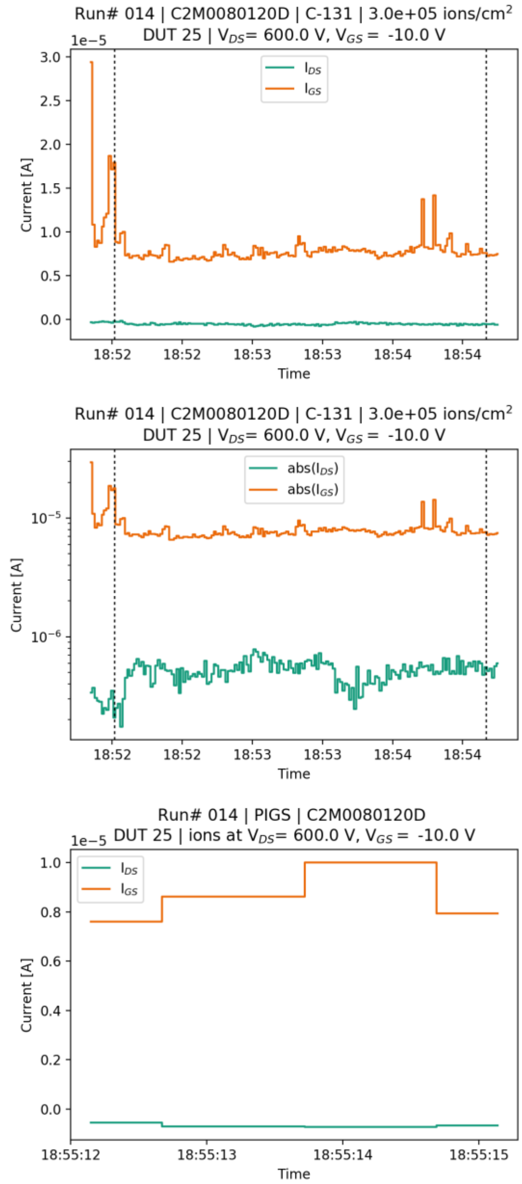


Figure 35: Run# 014, C2M0080120D, C-131, 3.0e+05 ions/cm2 , DUT 25, VDS= 600.0 V, VGS= -10.0 V



C Appendix: Tests at JULIC

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) was 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 13, this was then divided by the density ρ = 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) was 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 [11] 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.

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Table 19: 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	SiO2	2.6	60.0843	1640.71
Epoxy Resin	29690-82-2	C33H42O9X2	1.12 *	582.68 *	189.62
Anhydride	2421-28-5	C17H6O7	1.57 *	322.23 *	159.68
Carbon Black	1333-86-4	C	1.7	12.01	5.99

Table 20: 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 21: 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

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Table 22: 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 21 were taken for 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

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	V_GS	beam time [s]	fluence [cm-2]
1	19.09.	13:52	p	MOSFET	C2M0080120D	#1	1200	0	698	1.0e11
2	19.09.	14:25	p	MOSFET	C2M0080120D	#2	1200	-10	232	1.1e11
3	19.09.	14:38	p	MOSFET	C2M0080120D	#2	1200	-10	224	1.0e11
4	19.09.	15:07 *	p	MOSFET	C2M0080120D	#3	600	0	454	1.6e10
5	19.09.	15:07 *	p	MOSFET	C2M0080120D	#3	750	0	575	1.9e10
6	19.09.	15:07 *	p	MOSFET	C2M0080120D	#3	900	0	652	2.1e10
7	19.09.	15:07 *	p	MOSFET	C2M0080120D	#3	1050	0	636	2.0e10
8	19.09.	15:07 *	p	MOSFET	C2M0080120D	#3	1200	0	18	5.6e8

* Beam was not interrupted for runs #4-#8. Start time of beam is thus identical. Fluences are calculated from the fluxes over the measurement time of the respective DUT.

Measurements

Figure 36: Run# 001, C2M008012D, p, 1.0e+11 ions/cm2 , DUT 1, VDS= 1200.0 V, VGS= 0.0 V

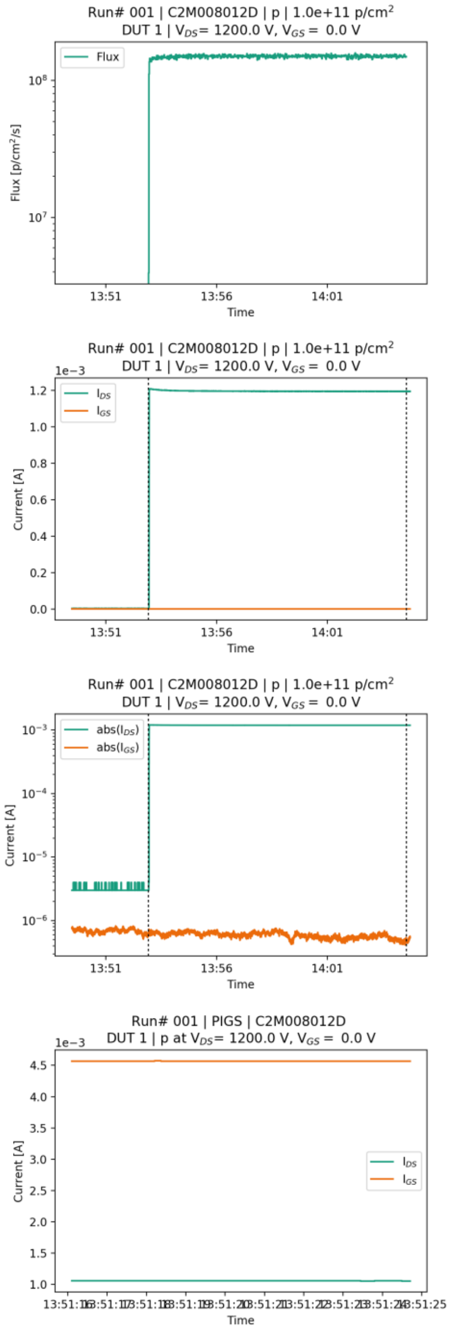


Figure 37: Run# 002, C2M008012D, p, 1.1e+11 ions/cm2 , DUT 2, VDS= 1200.0 V, VGS= -10.0 V

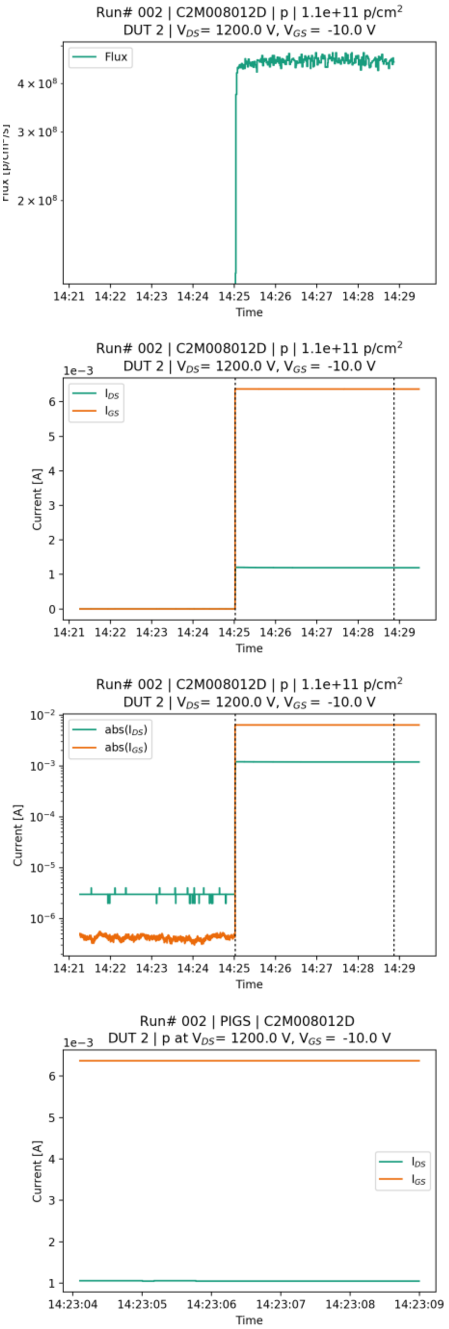


Figure 38: Run# 003, C2M008012D, p, 1.0e+11 ions/cm2 , DUT 2, VDS= 1200.0 V, VGS= -10.0 V

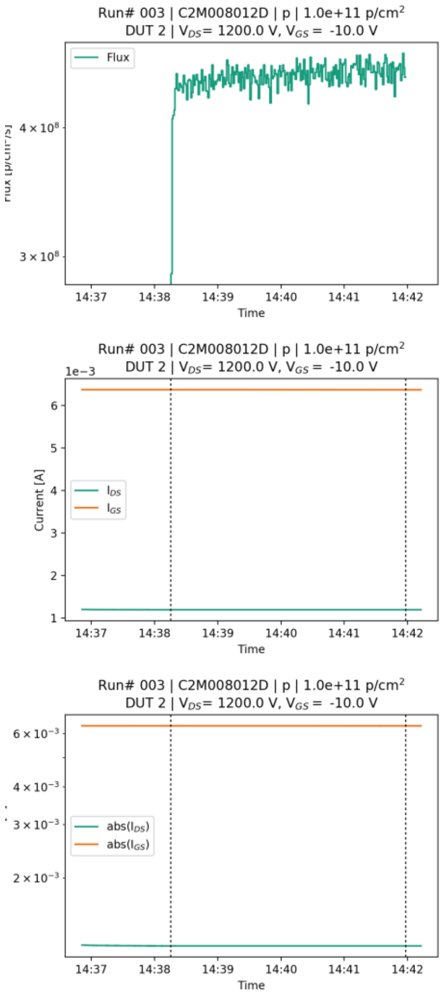


Figure 39: Run# 004, C2M008012D, p, 1.6e+10 ions/cm2 , DUT 3, VDS= 600.0 V, VGS= 0.0 V

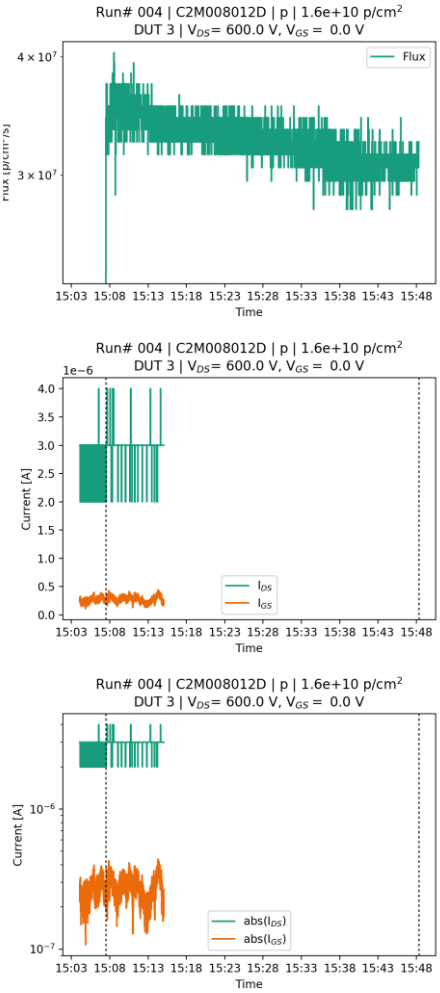


Figure 40: Run# 005, C2M008012D, p, 1.9e+10 ions/cm2 , DUT 3, VDS= 750.0 V, VGS= 0.0 V

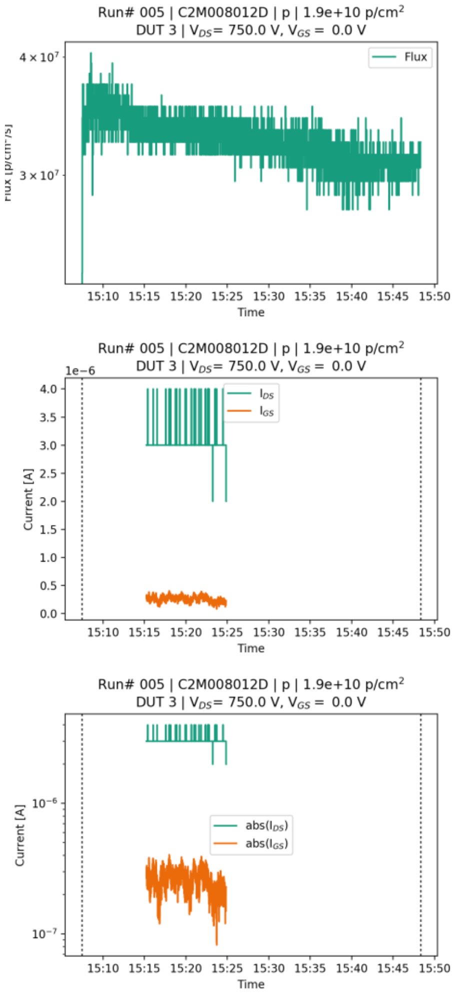


Figure 41: Run# 006, C2M008012D, p, 2.1e+10 ions/cm2 , DUT 3, VDS= 900.0 V, VGS= 0.0 V

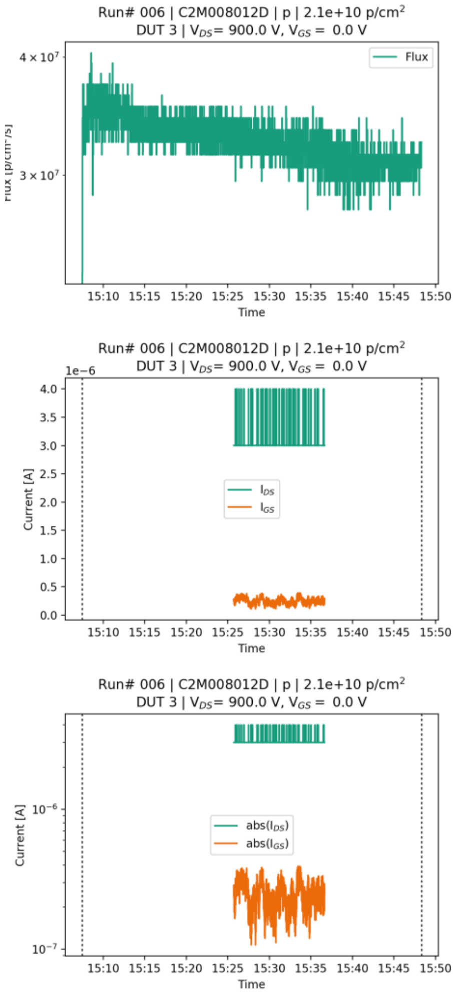


Figure 42: Run# 007, C2M008012D, p, 2.0e+10 ions/cm2 , DUT 3, VDS= 1050.0 V, VGS= 0.0 V

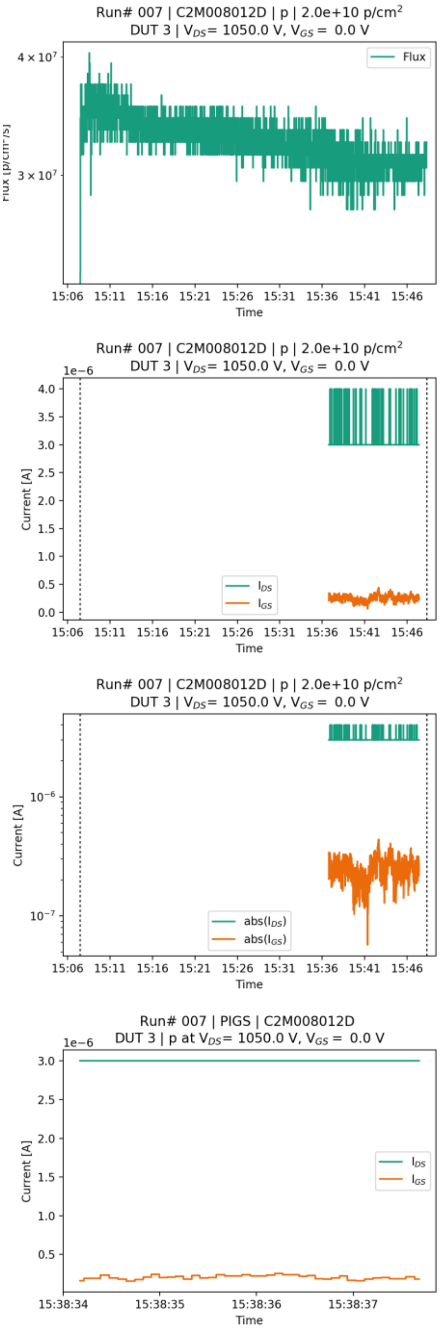
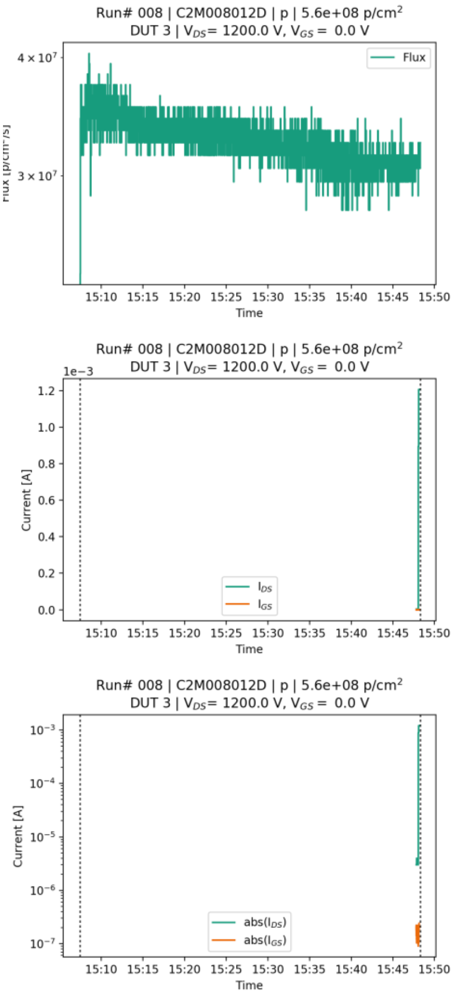


Figure 43: Run# 008, C2M008012D, p, 5.6e+08 ions/cm2 , DUT 3, VDS= 1200.0 V, VGS= 0.0 V



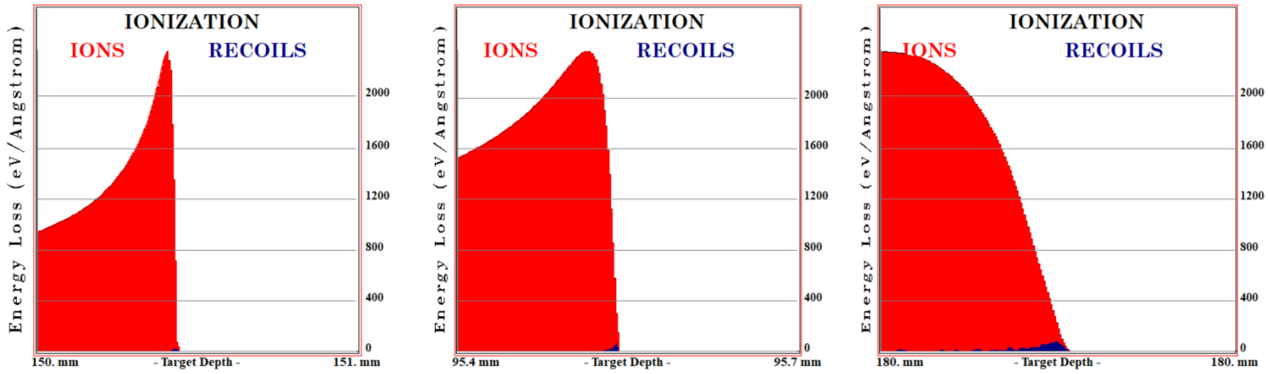
D Appendix: Tests at GANIL

LET estimation

To receive the impact in terms of LET on the Silicon Carbide die, radiation transport simulations have to be made. A major difference to the proton LET estimations, is that the tests were performed on decapsulated devices, so the package is not taken into account.

For these simulations, the 10 µm stainless steel exit window, a variable amount of air gap, and if applicable an Aluminum degrader was included in simulations with SRIM2013. The incident particles were 49.1 MeV/n Xenon ions (isotope mass = 136 u).

Figure 44: SRIM2013 simulations of the Ganil Xenon tests on SiC



a) 0 mm Al, 150 mm air b) 0.4 mm Al, 95 mm air c) 0.5 mm Al, 180 mm air

The views of the ionization curves in Figure 44 start at the surface of the silicon carbide layer, so e.g. at 95.410 mm in Figure 44 b), although only one digit is displayed.

The LET in MeV cm^2/mg can be directly calculated from the Energy loss in eV/Å by unit conversion (1 eV/ Å = 100 MeV/cm) and division by the SiC density of 3.21 g/cm^3 = 3210 mg/cm^3.

Table 23: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [14], Values in SiC are calculated by INT and given with one digit

Degrader [mm Al]	Air gap [mm]	LET (Si) (MeV.cm^2/mg)	Range (Si) [µm]	LET$_{SURF}$ (SiC) [MeV.cm^2/mg]	Range (SiC) [µm]
0	150	27.76	640.33	29.2	430
0.4	95	42.03	226.23	47.2	141
0.5	180	60.12	65.68	72.9	30

Logfile / Test steps

#	Date	Time	Ion	Al [µm]	Air [mm]	Device Type	Device	Position on board	DUT #	V_DS, V	V_GS	beam time [s]	fluence [cm-2]
512	07.06.	17:15	Xe	0	150	MOSFET	C2M008120D	#3	24	100	0	57	3.00E+05
513	07.06.	17:17	Xe	0	150	MOSFET	C2M008120D	#3	24	200	0	54	3.00E+05
514	07.06.	17:18	Xe	0	150	MOSFET	C2M008120D	#3	24	300	0	50	3.00E+05

Measurements

Figure 45: Run# 512, C2M008120D, Xe 0 mmAl, 150 mm Air, 3.0e+05 ions/cm2 , DUT 24, VDS= 100.0 V, VGS= 0.0 V

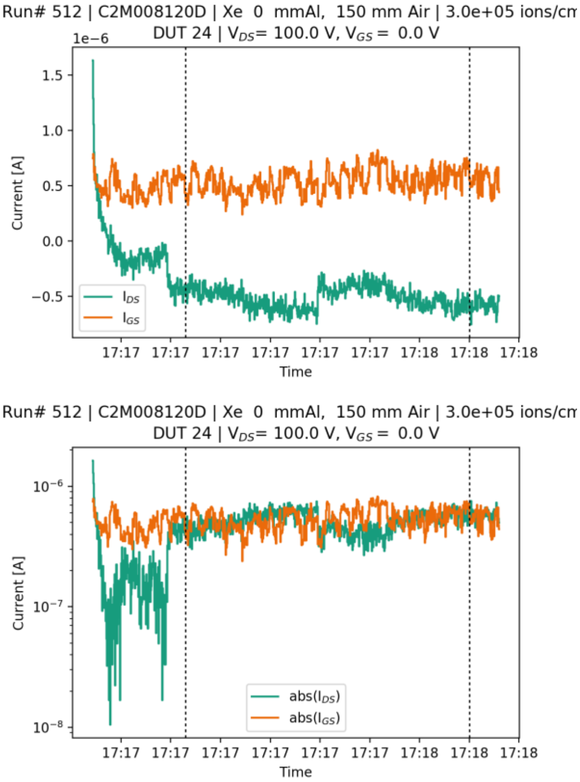


Figure 46: Run# 513, C2M008120D, Xe 0 mmAl, 150 mm Air, 3.0e+05 ions/cm2 , DUT 24, VDS= 200.0 V, VGS= 0.0 V

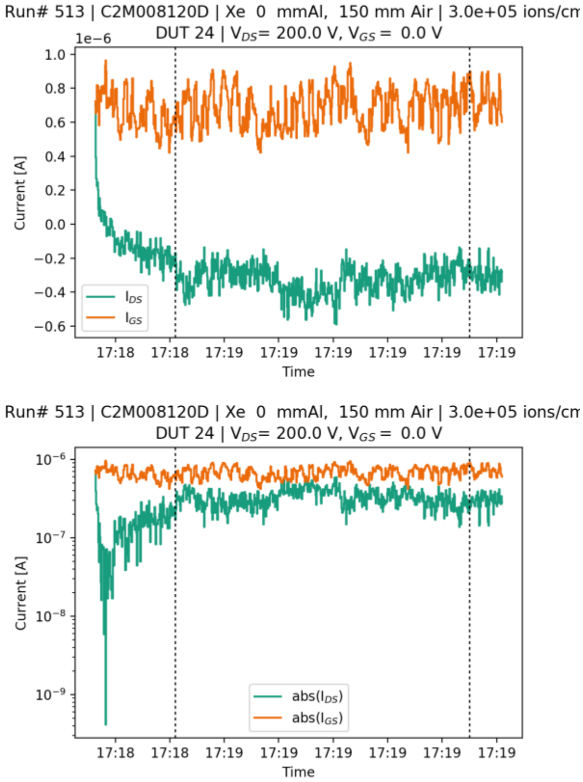


Figure 47: Run# 514, C2M008120D, Xe 0 mmAl, 150 mm Air, 3.0e+05 ions/cm2 , DUT 24, VDS= 300.0 V, VGS= 0.0 V