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EUROPEAN SPACE AGENCY
CONTRACT REPORT
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Survey of Total Ionising Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE

TN6.2
TID Test Report for
SiC MOSFET SCT20N120

Manufacturer: STMicroelectronics

Date code/Lot code:
GK 06NVY / CHN GK546 (UCL/GANIL/JULIC) and GK OU5VY / CHN GK706 (CERN)

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Version history

Table 1: Revision history

Version	Date	Changed by	Changes
0.1	2019-03-08	Steffens	Initial draft, Sections 1-5, Appendices A+B
1.0	2019-05-10	Steffens	Initial Release
2.0	2019-06-07	Steffens	Added remark on total fluences in tests at CERN

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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 SCT20N120 from STMicroelectronics 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 SCT20N120, "SCT20N120 Silicon carbide Power MOSFET: 20 A, 1200 V, 189 mΩ (typ., TJ=150 °C), N-channel in a HiP247™", STMicroelectronics, DocID026413 Rev 4, December 2015

[5] TN3.2 "SEE (HI) Test Plan SCT20N120 (SiC MOSFET)", Issue 1 Revision 4, 2018-04-15

[6] TN3.8 "SEE (p) Test Plan SCT20N120 (SiC MOSFET)", Issue 1 Revision 1, 2017-07-26

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

[8] 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).

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

[10] 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)

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

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

[13] 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/

[14] Website of the H8 beam line at CERN: sba.web.cern.ch/sba/BeamsAndAreas/resultbeam.asp?beamline=H8

[15] García Alía et al., "Ultraenergetic Heavy-Ion Beams in the CERN Accelerator Complex for Radiaiton Effects Testing", IEEE TNS, vol. 66, No. 1, p. 458, 2018. DOI: 10.1109/TNS.2018.2883501

[16] Fernánzet-Martinez et al., "Characterization of the Ultra-High Energy Xe beam of the CERN NAH8 line", Report for users – ongoing analysis

2 Summary

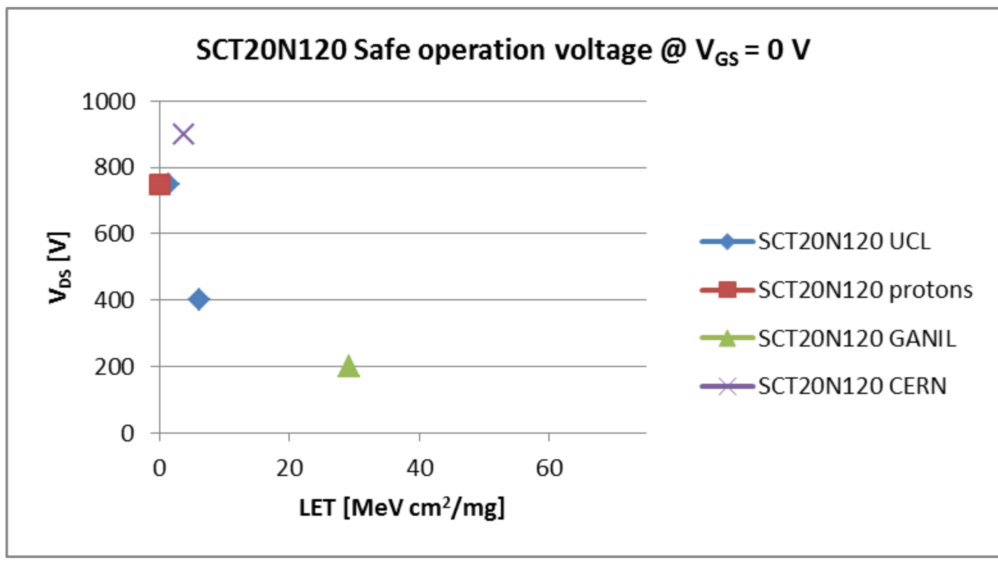
Table 2: Summary

Test Report Number	067/2018
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	SCT20N120
Family	SiC MOSFET
Technology	Silicon carbide Power MOSFET
Package	HiP247™
Date code / Wafer lot	GK 06NVY / CHN GK546 (UCL/GANIL/JULIC) and GK OU5VY / CHN GK706 (CERN)
SN	GK 06NVY / CHN GK546: • UCL: #11, #12, #13, #15, #16, #17 • GANIL: #22 • JULIC: #1, #2, #3 (previously Gamma irradiated) GK OU5VY / CHN GK706: • CERN: #1, #2, #4, #5, #6
Manufacturer	STMicroelectronics
Irradiation test house	Fraunhofer INT
Radiation source	UCL, CERN and GANIL: Heavy Ions, JULIC: Protons
Irradiation facility	UCL, CERN, GANIL, JULIC
Generic specification	ESCC 25100 Iss. 2
Detail specification	MIL-STD-750-1 w/CHANGE 5, Method 1080.1
Test plan	TN3.2 "SEE (HI) Test Plan SCT20N120 (SiC MOSFET)", Issue 1 Revision 4, 2018-04-15 TN3.8 "SEE (p) Test Plan SCT20N120 (SiC MOSFET)", Issue 1 Revision 1, 2017-07-26
Single/Multiple Exposure	Multiple
Parameters tested	SEB, SEGR

Dates	UCL: 2018-04-16 – 2018-04-17 CERN: 2017-11-30 – 2017-12-01 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



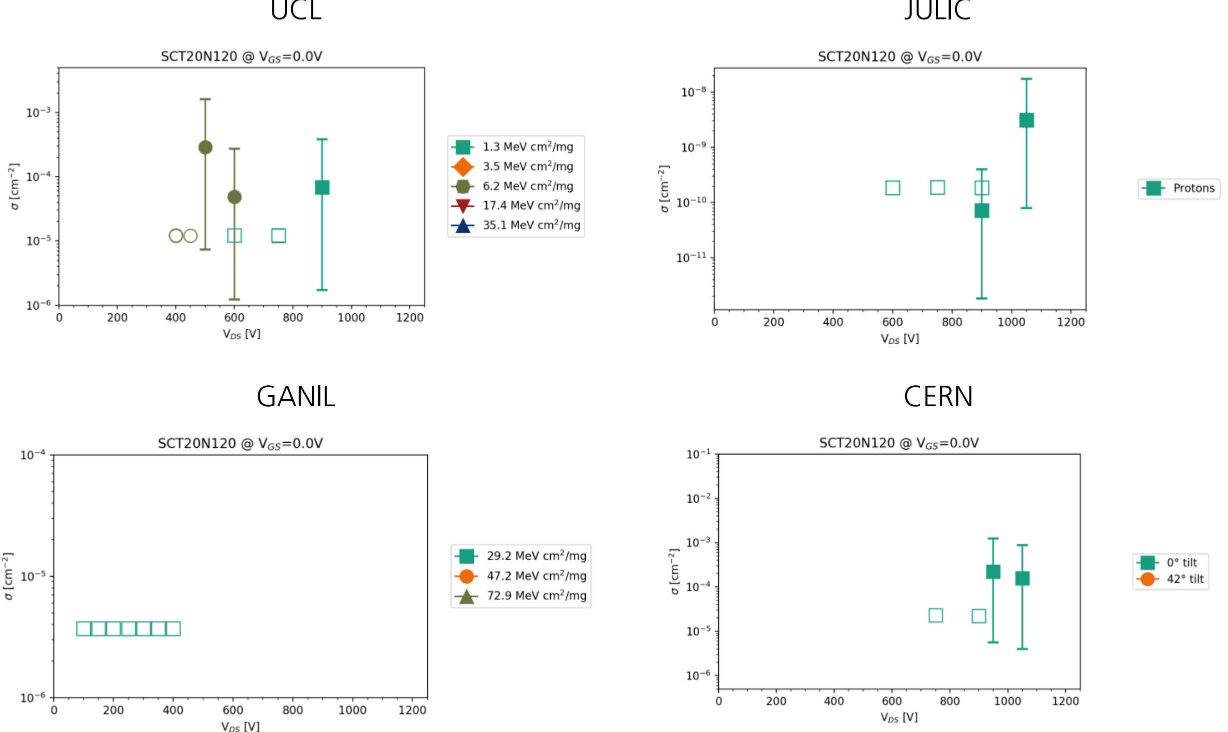
With heavy ions at UCL the SiC MOSFET SCT20N120 showed high vulnerability with respect to the heavy ions even at low LETs and a reduced target fluence of 3E5 ions/cm^2 .

In these tests safe operation can be attributed to the 400 V level with Aluminium ions (see comments) and the 750 V level of Carbon ions. 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.

At GANIL no degradation was seen up to 150 V and a slight degradation (~ 1µA) at 200 V. With each additional voltage increase, the degradation became more pronounced without the device ever clearly failing destructively. There was however no PIGS test performed in between runs and the increase in current even continues when the DUTs are not exposed to ions (see Figure 60 to Figure 63 on pages 74 - 76). To be on a safe side, we consider runs at 200 V and beyond a fail.

Tests at CERN were performed with DUTs from a different lot. A striking difference to the previous tests is the increased voltage of safe operation of 900 V. However when looking at all devices tested at CERN, all of them show a similar behaviour. Lot-to-lot variability might thus not be an explanation for this.

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.



2.2 Comments

- **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:**
  - Aluminium-Ions: Due to the gate getting gradually damaged at V_{DS} = 450 V without showing definitive SEGR, the safe operation voltage is taken as 400 V.
- **Tests at JULIC:**
  - Test were performed with packaged DUTs.
  - Test devices were previously tested with Co-60 to 1 Mrad(Si).
- **Tests at GANIL:**
  - The tests with the SCT20N120 at GANIL were performed with no PIGS tests in-between.
- **Tests at CERN:**
  - Test were performed with packaged DUTs.
  - The effective fluences across the tests were <6E5 ions/cm^2. The relatively low fluence might be an explanation for the increased "safe operation" levels observed in these tests compared to the other test campaigns.

- Most device failures occurred at the first spill of beam. Properly deducing the fluence of failure and thus the cross sections of the devices is not possible in these cases, so the cross sections in case of failures given for the CERN results should only be seen as a rough order of magnitude.

3 Sample preparations

3.1 Sample shipment

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 (GK06NVY/CHN GH546) and was used for the campaigns at UCL, GANIL and JULIC. For the campaign at CERN 20 additional samples were procured, but samples from the same batch were no longer available. For that campaign the identification code was GK OU5VY/CHN GK706. 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)
November 2017	November 2017	still at INT

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
GK06NVY/CHN GK546			
UCL	11		decap, coated
	12		decap, coated
	13		decap, coated
	15		decap, coated
	16		decap, coated
	17		decap, coated
GANIL	22		decap, coated
JULIC	1		non-decap, previously used for TID
	2		non-decap, previously used for TID
	3		non-decap, previously used for TID
GK OU5VY/CHN GK706			
CERN	1		non-decap
	2		non-decap
	4		non-decap
	5		non-decap
	6		non-decap

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.

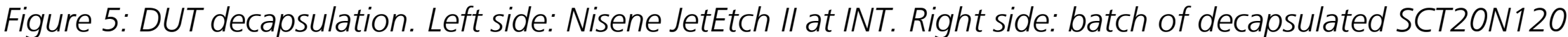
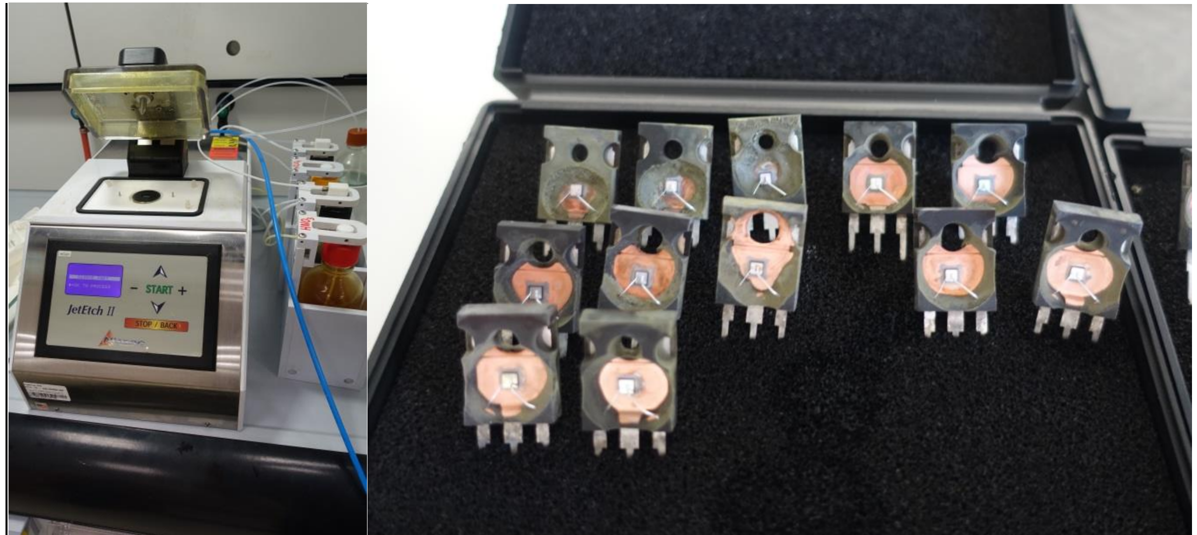


Figure 5: DUT decapsulation. Left side: Nisene JetEtch II at INT. Right side: batch of decapsulated SCT20N120



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

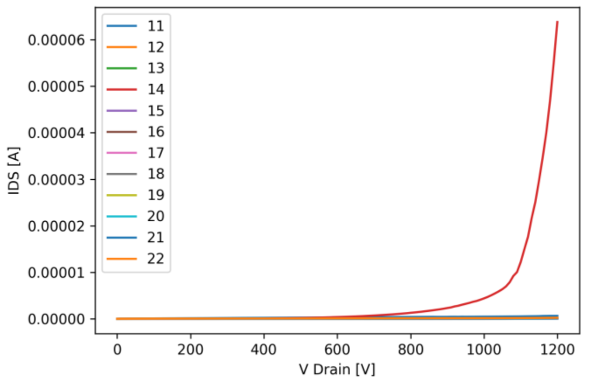
After decapsulation the functionality of all DUTs was checked. Due to the missing insulation provided by the package material, only tests at low voltage to prevent corona discharges were performed. All 12 decapsulated devices passed these functional tests and were considered for the coating process.

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 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 sample (#14) from the tests.

In total 11 out of 12 decapsulated samples qualified for the heavy ion tests.

Figure 6: Functional tests after Parylene coating



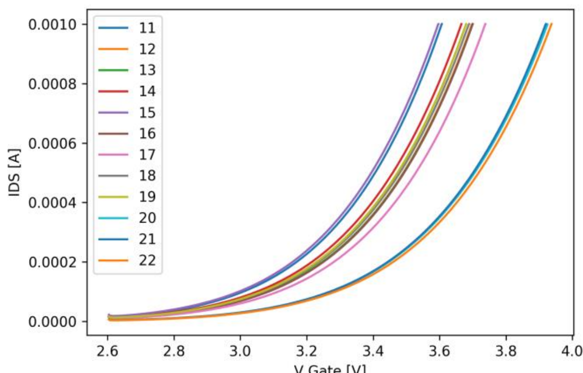
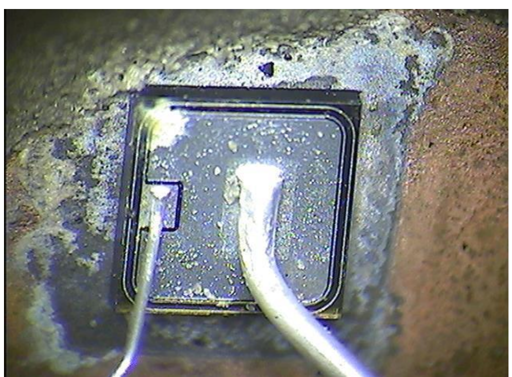


Figure 7: Die pictures. Images were taken with different optical microscopes. The camera used before the tests has a lower quality and resolution.



DUT #12 before tests at UCL

DUT #12 after tests at UCL

Figure 7 shows microscopic images of one DUT (#12) 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.

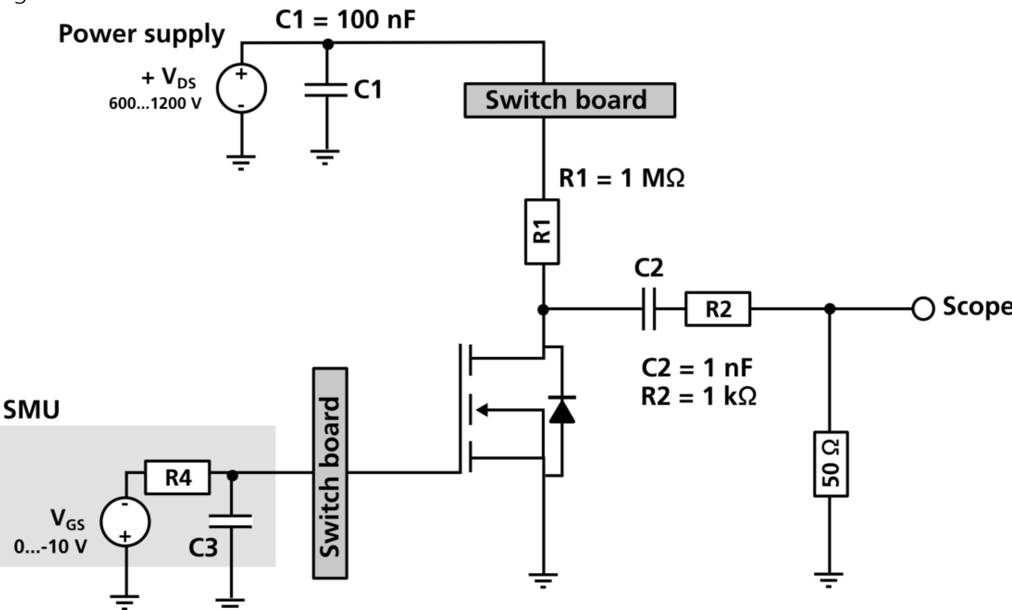
4.2 Test Board and Detection Circuit

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

- bias the samples according to the circuit-layout of the irradiation test plan [5] [6]
- 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.

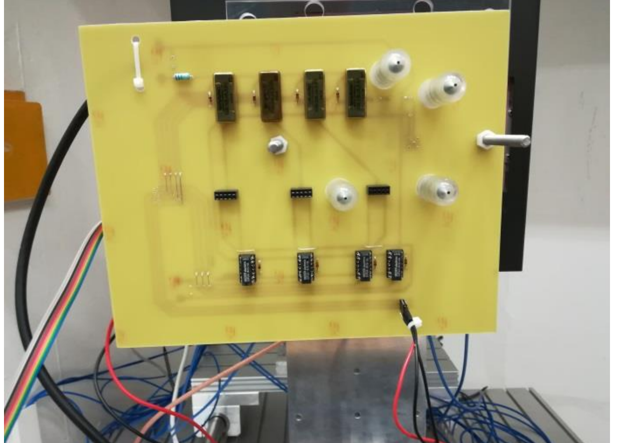
Capacitor C2 is used for DC decoupling of scope. C2 and R2 set the transient characteristics of signal due to SEB charge. The dimension of C2 should be small enough so that in case of a SEB and immediate voltage drop on MOSFET, the charge provided by C2 could not further damage the device.

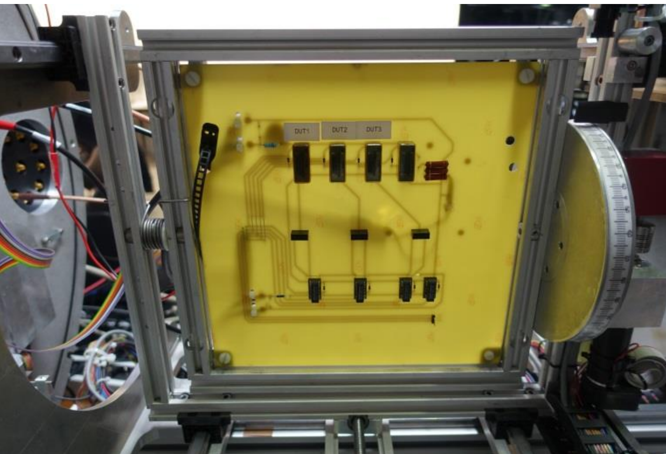
No circumvention or protection was included on the gate, as SEGR cannot be circumvented and the DUT would be destroyed anyway.

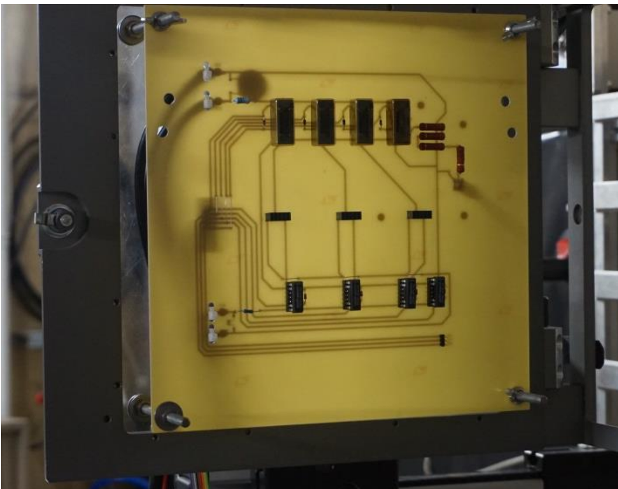
This setup expanded on the setup proposed by P. Oser et. al. [8].

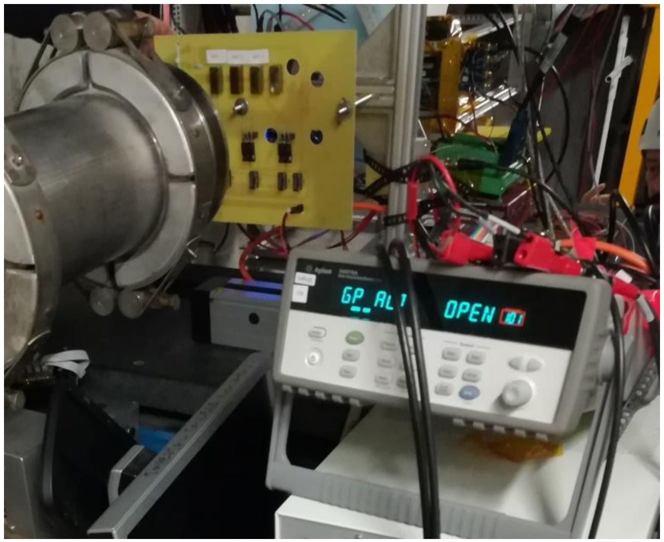
However, in the actual tests this design did neither circumvent nor mitigate destructive SEB, thus the devices were destroyed on each SEB event.

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









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.

At CERN the beam was shared with other experiments, but the INT setup was the first in line after the beam exit window. The installation at the beam line did not feature a moveable table, so a ISEL linear guide and step motor was used to achieve sample and board movement along one axis. With this, the samples were moved away from the beam to perform the PIGS tests.

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 in the appendices.

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

No.	Characteristics	Symbol	Remark
1	Drain-Source Voltage	V_{DS}	Set
2	Drain-Source Current	I_{DS}	Monitored for SEB
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 10 and Figure 10 - Figure 13.

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	V_{DS}, I_{DS}
System Source Meter	Keithley	2400	E-SMU-002	10/2019	V_{GS}, I_{GS}
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix for V_{DS} and V_{GS} 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)

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
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 10: UCL: Measurement equipment/setup

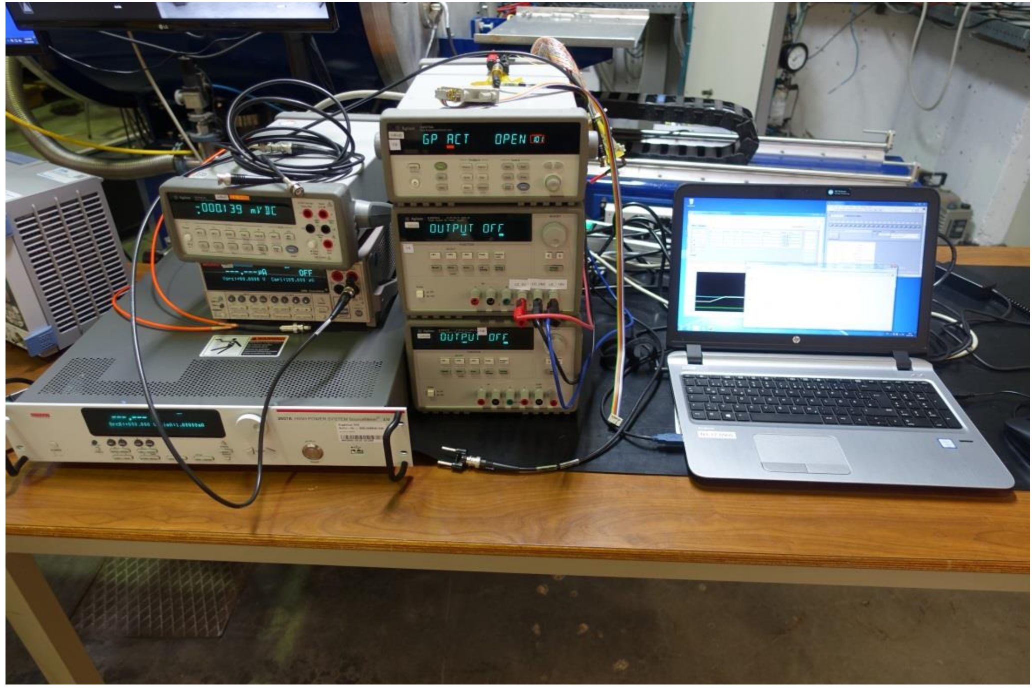


Table 8: GANIL: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2020	V_{DS}, I_{DS}
System Source Meter	Keithley	2400	E-SMU-002	10/2019	V_{GS}, I_{GS}

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix for V_{DS} and V_{GS} relais
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

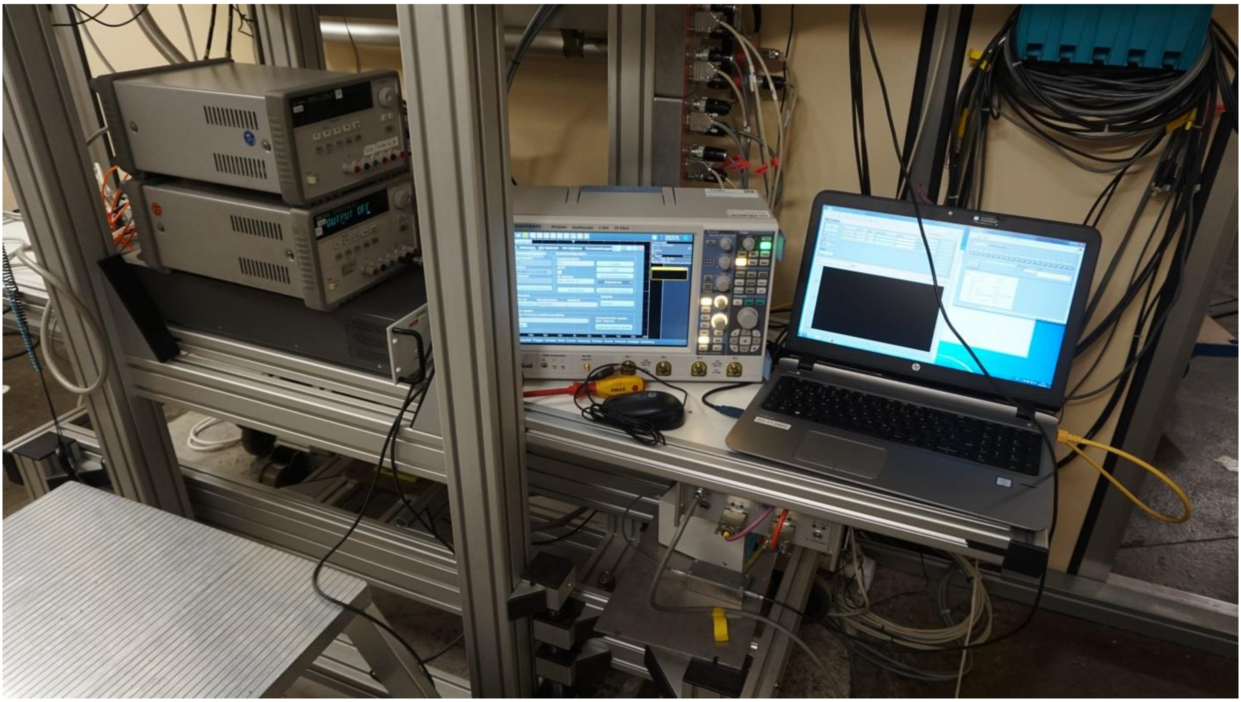
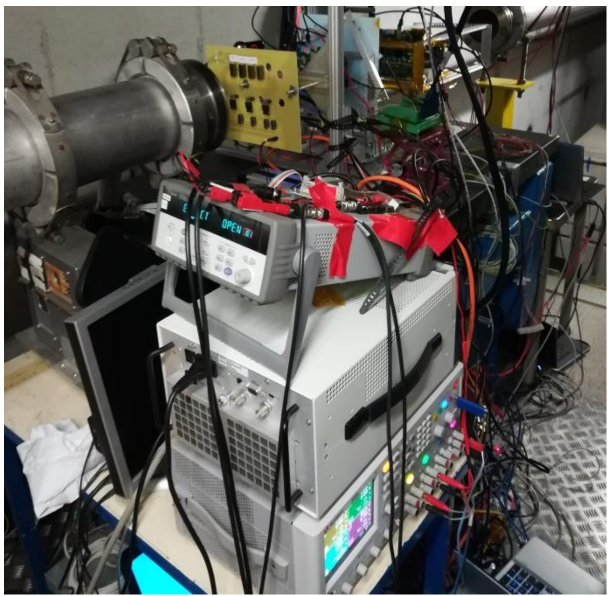
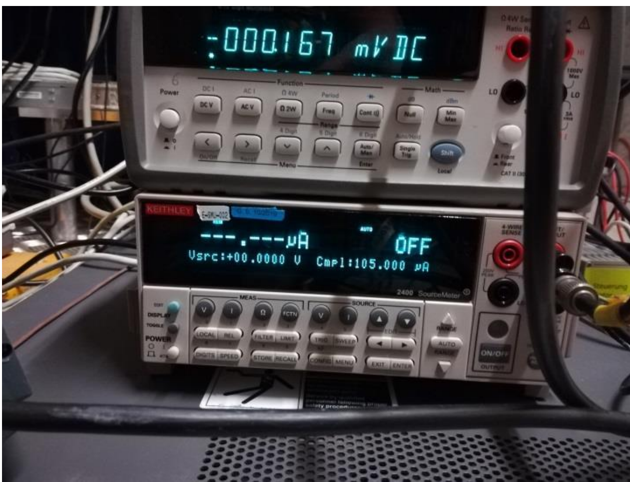


Table 9: CERN: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2020	V_{DS}, I_{DS}
System Source Meter	Keithley	2400	E-SMU-002	10/2019	V_{GS}, I_{GS}
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix for V_{DS} and V_{GS} relais
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	--	--	n/a	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
Step motor	ISEL	LES4	--	n/a	Moving samples along 1 direction
Linear guide	ISEL	IT116 G	--	n/a	Moving samples along 1 direction

Figure 12: CERN: Measurement equipment/setup.





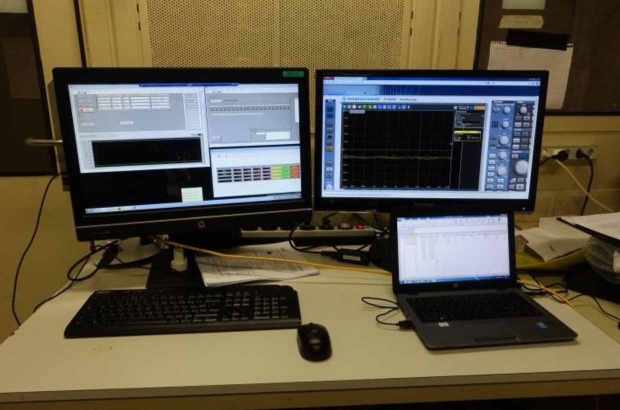
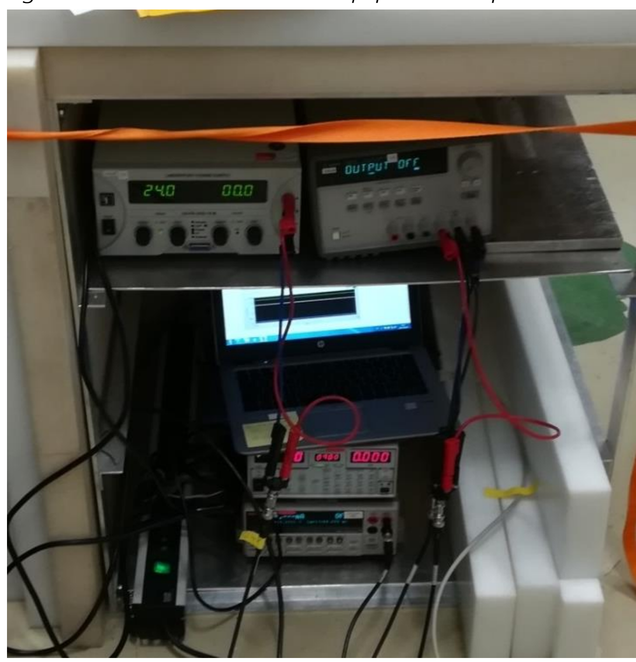


Table 10: JULIC: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
5 kV Power supply	Keithley	2290E-5	E-PS1-030	10/2017	V_{DS}, I_{DS}
System Source Meter	Keithley	2400	E-SMU-002	10/2017	V_{GS}, I_{GS}
Laboratory Power Supply	EA	EA-PS-3032-10B	E-PS1-001	n/a	Control of relais for switching V_{GS}
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 13: 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.

For the CERN campaign, the samples were moved out of the beam to perform the PIGS tests. At the other campaigns the beam was stopped for the PIGS tests.

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.

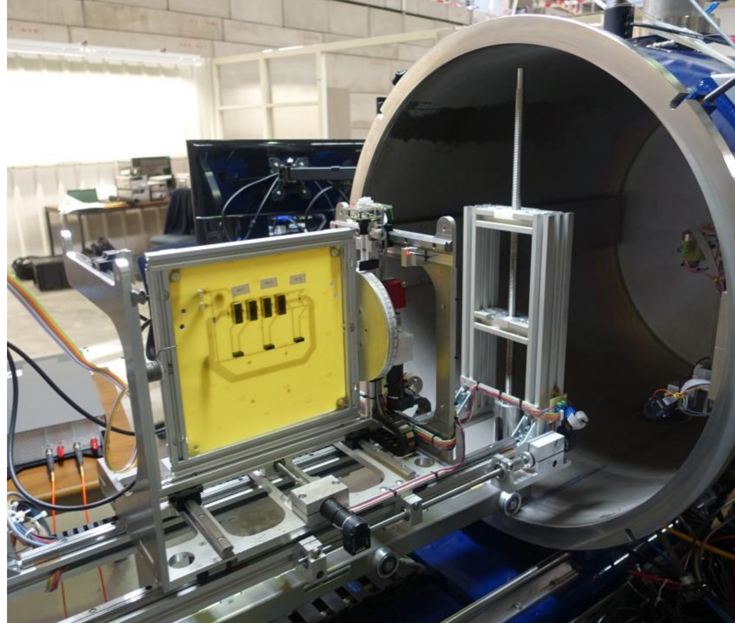
The facility can provide selected heavy ion beams from Carbon to Xenon in a particle cocktail with mass/charge ratio of approx. M/Q=3.3, allowing to switch from ion species to ion species quickly within the cocktail.

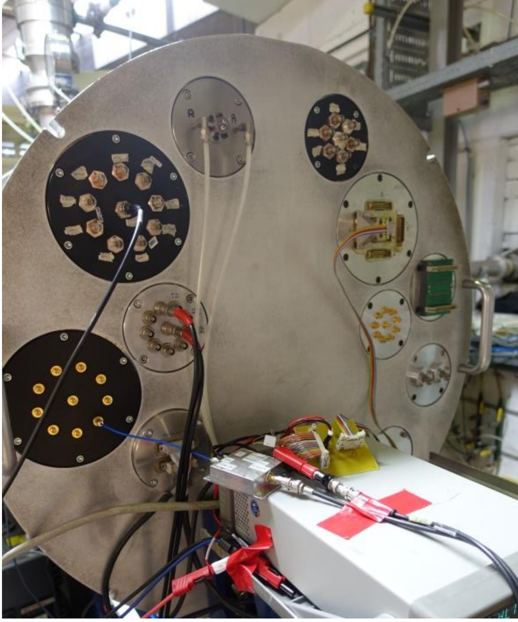
The experimental setup at the facility consists of the main vacuum chamber with a sample holder, which is moveable in x- and y-direction and can be tilted along one axis.

Feedthroughs can be used to connect boards within the enclosure with outside instrumentation (Figure 14).

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 14: 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 [9]. However this data is not valid for Silicon Carbide.

SRIM 2013 [10] 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].

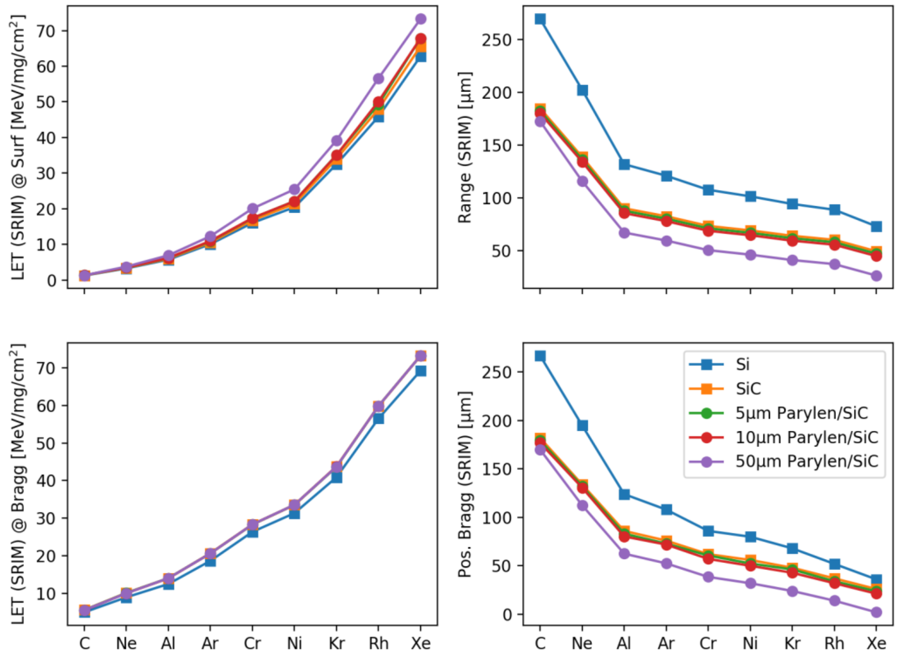
Tests with the SCT20N120 were only performed with ions marked in bold letters in Table 11.

Table 11: UCL: Ion energies, LETs and ranges in Silicon Carbide covered by 10 µm Parylene: Shown are the ions available at UCL [9]. LETs highlighted in bold font were actually used. LET and range data are based on SRIM2013 [10] 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 15: 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 14) 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 12 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 5.5.

Table 12: UCL: Irradiation steps of SiC MOSFET SCT20N120. 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					12,15,16					
450						17					
500						12					
600		11				13					
750		11, 12, 13									
900		11									
1050											
1200											
400	-5					15, 16					
450						17					
400	-10					15,16,17					
450						15, 16, 17					

5.5 Results

With heavy ions at UCL the SiC MOSFET SCT20N120 showed high vulnerability with respect to the heavy ions even at low LETs and a reduced target fluence of 3E5 ions/cm^2.

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 (see comments) and the 750 V level of Carbon ions. 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.

Figure 16: Overview of results: Heavy Ions at UCL Due to the gate getting gradually damaged at VDS = 450 V without showing definitive SEGR, the safe operation voltage is taken as 400 V. 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.

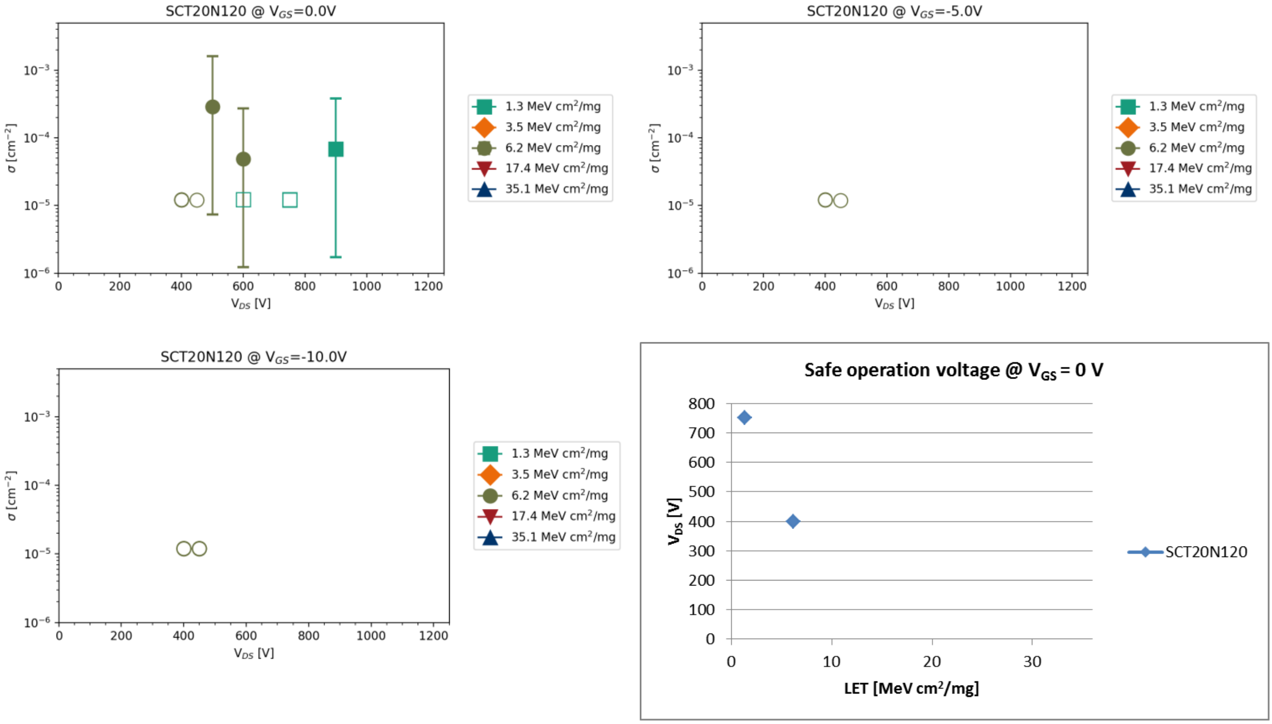


Table 13: Results: Heavy Ions at UCL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case). The failure fluence indicates the approximate fluence when the failure occured (if applicable).

run #	Ion	DUT #	V_{DS} [V]	V_{GS} [V]	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
15	C	11	600	0	> 3.03E+05	0	0	1.22E-05	--	--
16	C	11	750	0	> 3.04E+05	0	0	1.21E-05		--
17	C	11	900	0	1.46E+04	1.73E-06	6.85E-05	3.82E-04	SEB	Destructive failure at indicated fluence. Increase of gate current simultaneously to drain failure.
18	C	12	750	0	> 3.03E+05	0	0	1.22E-05	--	--
19	C	13	750	0	> 3.02E+05	0	0	1.22E-05	--	--
20	Al	13	600	0	2.05E+04	1.23E-06	4.88E-05	2.72E-04	SEGR, SEB	Destructive failure at indicated fluence. SEGR approx. 2 secs earlier than SEB
21	Al	12	400	0	> 3.02E+05	0	0	1.22E-05	--	--
22	Al	12	500	0	3.46E+03	7.32E-06	2.89E-04	1.61E-03	SEB, SEGR	Destructive failure at indicated fluence. Increase of gate current simultaneously to drain failure.

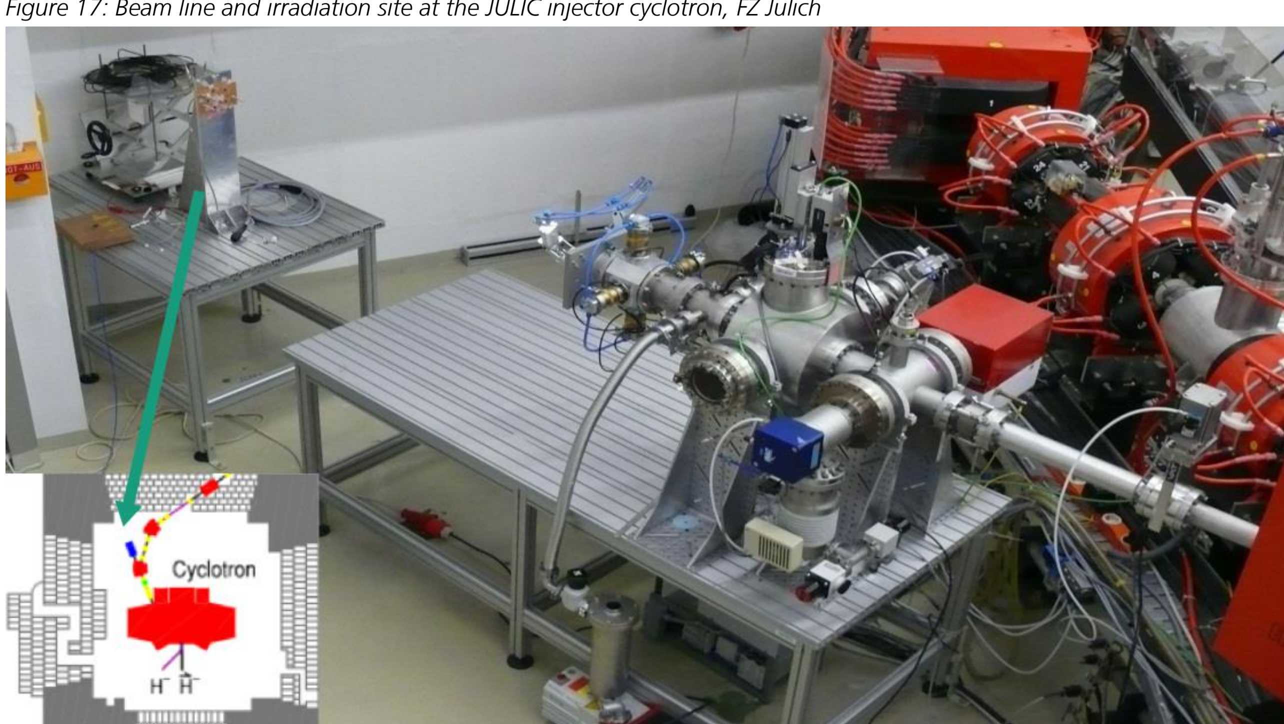
run #	Ion	DUT #	V_{DS} [V]	V_{GS} [V]	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
23	Al	15	400	0	> 3.02E+05	0	0	1.22E-05	--	--
24	Al	15	400	-5	> 3.03E+05	0	0	1.22E-05	--	--
25	AL	15	400	-10	> 3.04E+05	0	0	1.21E-05	--	Minor jump in gate current
26	Al	16	400	0	> 3.06E+05	0	0	1.21E-05	--	--
27	Al	16	400	-5	> 3.07E+05	0	0	1.20E-05	--	Minor jump in gate current
28	Al	16	400	-10	> 3.06E+05	0	0	1.21E-05	--	--
29	Al	17	400	-10	> 3.08E+05	0	0	1.20E-05	--	--
30	Al	17	450	0	> 3.05E+05	0	0	1.21E-05	SEGR	Stepwise increase of gate current
31	Al	17	450	-5	> 3.09E+05	0	0	1.19E-05		Pre-damaged gate, gate current in µA-range, single step in gate current observable
32	Al	17	450	-10	> 3.09E+05	0	0	1.19E-05		Pre-damaged gate, gate current in µA-range
33	Al	16	450	-10	> 3.06E+05	0	0	1.21E-05	SEGR?	Stepwise increase of gate current
34	Al	15	450	-10	> 3.07E+05	0	0	1.20E-05	SEGR?	Several steps in gate current including one strong instantaneous decrease

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 17: 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 18 and Figure 19). 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 [12].

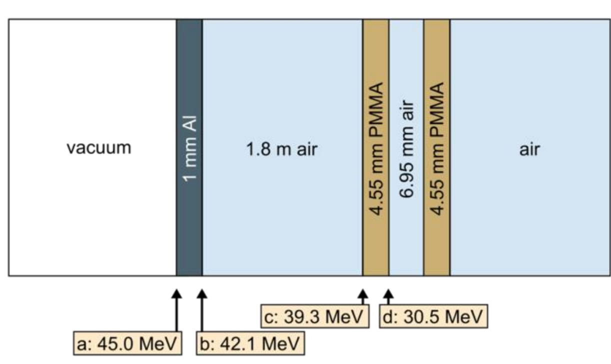


Figure 18: Schematic setup of the beam exit window at JULIC and the ionization chamber. The DUT is placed in same distance as the IC.

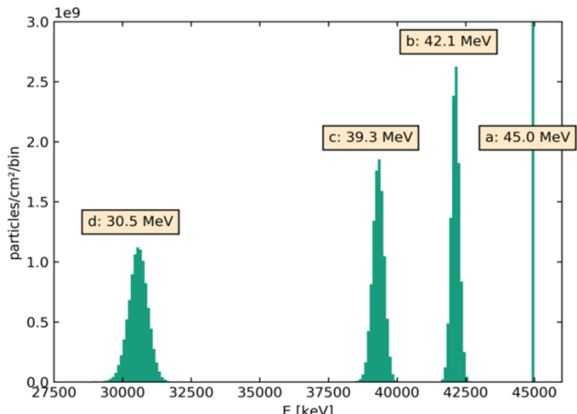


Figure 19: The initial proton energy of 45.0 MeV gets reduced to 39.3 MeV at the position of the IC/DUT. The PMMA cap of the chamber further reduces the energy to 30.5 MeV, calculation by MULASSIS (Geant4) on SPENVIS[11].

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 14: 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 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. For the overall data evaluation we identify the proton data with an LET of 0.01 MeV cm²/mg.

The thickness of the actual package of the DUTs is around 2 mm.

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 15 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 6.5

Table 15: JULIC: Irradiation steps of SiC MOSFET SCT20N120. 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	PIGS
400	0		
600		1,2,3	
750		1,2,3	1*, 2
900		2,3	2
1050		2	
1200			

* PIGS was performed in-beam

Tests were only performed with V_{GS} = 0 V.

6.5 Results

Figure 20 and Table 16 show the cross section results for the tests with the fairly low energetic protons at JULIC.

Figure 20: Results: Protons at JULIC. The cross section results for V_{GS} = 0 V are shown. 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.

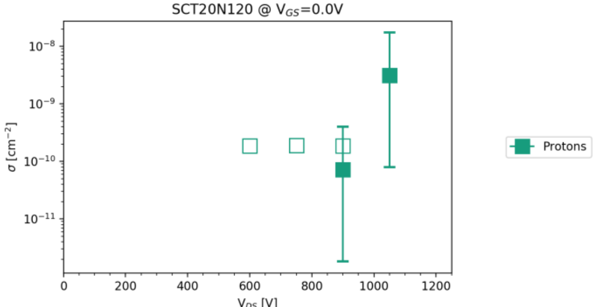


Table 16: Results: Protons at JULIC - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	DUT #	V_DS, V	V_GS	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
9	p	#1	600	0	1.98E+10	0	0	1.86E-10	--	
10	p	#1	750	0	1.97E+10	0	0	1.88E-10	--	
11	p	#2	600	0	1.99E+10	0	0	1.85E-10	--	
12	p	#2	750	0	1.96E+10	0	0	1.88E-10	--	
13	p	#2	900	0	1.97E+10	0	0	1.87E-10	--	
14	p	#2	1050	0	3.21E+08	7.89E-11	3.12E-09	1.74E-08	SEB	Desctructive failure at indicated fluence
15	p	#3	600	0	1.99E+10	0	0	1.85E-10	--	
16	p	#3	750	0	1.96E+10	0	0	1.88E-10	--	
17	p	#3	900	0	1.4E+10	1.8E-12	7.12E-11	3.97E-10	SEB	Desctructive failure at indicated fluence

One device was operated without destructive effect at 900 V over a fluence of approx. 2E10 p/cm^2. This could not be reproduced with a second device. The safe operating voltage for V_{GS} = 0 V was thus assumed 750 V, the next lowest step. In comparison, the same that was found for Heavy ion results (Section 5.5) at LET = 1.3 MeV cm^2/mg. The cross section is however several orders of magnitude lower and the test at 750 V was not reproduced with another device.

7 Tests at GANIL

7.1 Facility

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

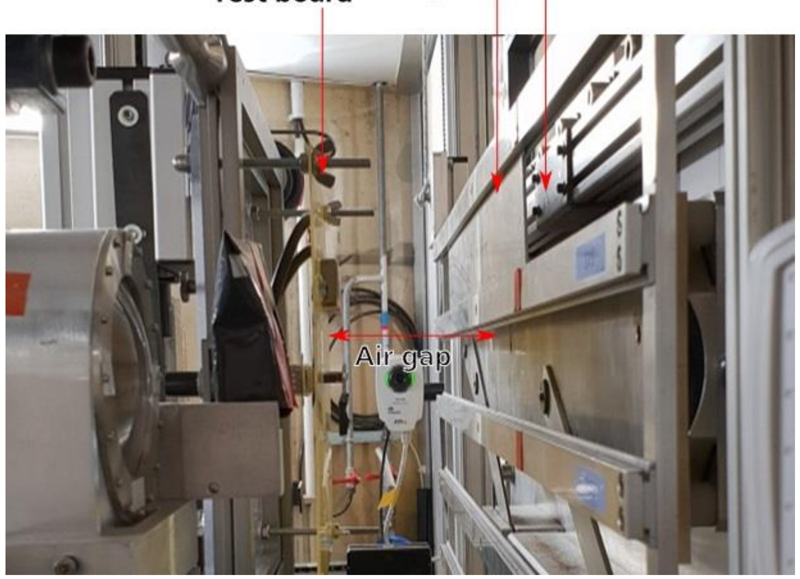
Additional heavy ion tests were performed at the G4 cave at GANIL, Caen, France.

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 aligned is done with the help of a laser system.

Figure 21: 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 [13]. However this data is not valid for Silicon Carbide.

SRIM 2013 [10] simulations by Fraunhofer INT in Table 17 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 17: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [13], Values in SiC are calculated by INT

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 21). Tests are then performed in air.

7.4 Irradiation steps

The tests at GANIL with the SCT20N120 were performed near the end of the beam time and only limited data could be taken. No PIGS tests were performed.

Table 18: GANIL: Irradiation steps of SiC MOSFET SCT20N120. 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	
V_DS [V]	V_GS [V]	29.2		47.2		72.9	
		in-situ	PIGS	in-situ	PIGS	in-situ	PIGS
100	0	22					
150		22					
200		22					
250		22					
300		22					

350	22		
400	22		
450			
600	22		

The log file of the tests performed at GANIL can be found in Appendix D. Table 18 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

The tests with the SCT20N120 at GANIL were performed with no PIGS tests in-between.

Starting at VDS = 100 V, no degradation was seen up to 150 V and a slight degradation (~ 1µA) at 200 V. With each additional voltage increase, the degradation became more pronounced without the device ever clearly failing destructively. The increase in current even continues when the DUTs are not exposed to ions (see Figure 60 to Figure 63 on pages 74 - 76).

To be on a safe side, we do not consider runs at 200 V and beyond a pass.

Figure 22: 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.

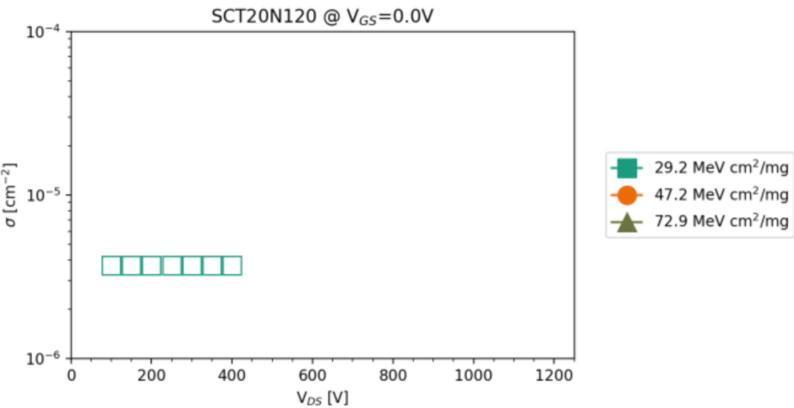


Table 19: Results: Heavy Ions at GANIL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	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
503	Xe	0	150	22	100	0	1.00E+06	0	0	3.69E-06	--	No PIGS test performed
504	Xe	0	150	22	150	0	1.00E+06	0	0	3.69E-06	--	No PIGS test performed
505	Xe	0	150	22	200	0	1.00E+06	0	0	3.69E-06	Degr.	Slight degradation. No PIGS test performed
506	Xe	0	150	22	250	0	1.00E+06	0	0	3.69E-06	Degr.	Degradation. No PIGS test performed
507	Xe	0	150	22	300	0	1.00E+06	0	0	3.69E-06	Degr.	Degradation. No PIGS test performed
508	Xe	0	150	22	350	0	1.00E+06	0	0	3.69E-06	Degr.	Degradation. No PIGS test performed
509	Xe	0	150	22	400	0	1.00E+06	0	0	3.69E-06	Degr.	Degradation. No PIGS test performed
510	Xe	0	150	22	450	0	--	--	--	--	Degr.	Pronounced degradation continued from previous runs. Due to pre-existing damage not reasonable to give cross sections. No PIGS test performed
511	Xe	0	150	22	600	0	--	--	--	--	Degr.	Pronounced degradation continued from previous runs. Due to pre-existing damage not reasonable to give cross sections. No PIGS test performed

8 Tests at CERN

8.1 Facility

Tests at CERN took place at the H8 beam line [14] from the T4 target of the SPS North Experimental Area with a Xenon beam of 30 or 40 GeV/n. The opportunity to test at this beam line was given in a joint effort from ESA and CERN [15].

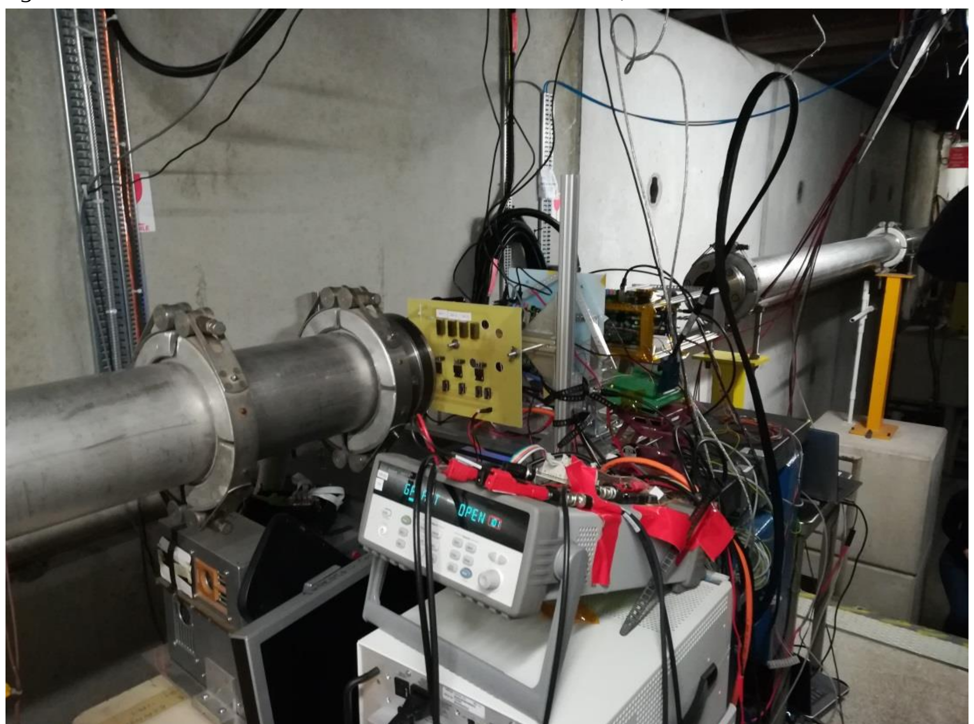
The ion beam is ultra-energetic and thus highly penetrating, which has several practical advantages for testing:

- The test can take place in air
- The DUTs do not need to be de-lidded
- Multiple test boards can be placed successively in the beam.

The INT test board was positioned first in line during all the tests, so energy reduction and thus LET modifications by other boards in the beam line does not occur.

The test site is not specifically intended for SEE tests of electronics, therefore additional infrastructure like a moveable frame holder are not installed.

Figure 23: Beam line and irradiation site at the H8 beam line, CERN.



8.2 Beam parameters

The beam was delivered in spills of approx. 8 s length at an interval of 30 – 50 s [15][16]. While the time-average flux is thus relatively low in the range of 1 - $2 \cdot 10^3$ ions/($cm^2 \cdot s$), the actual flux during the spill time is much higher.

The dosimetry on-site was recorded by CERN and preliminarily available during the campaign. The translation from the dosimeter readout to the actual particle flux and fluence was available after the campaign [16].

The total fluences given in Appendix E are based on the timestamps of the individual runs and the dosimetry information provided by CERN. Most device failures occurred at the first spill of beam. Properly deducing the fluence of failure and thus the cross sections of the devices is not possible in these cases, so the cross sections in case of failures given in Section 8.5 should only be seen as a rough order of magnitude.

The calculation of the LET for particles of these energies cannot be done easily e.g. with SRIM due to the interactions with matter at these energies. The LET values for silicon were simulated with FLUKA by Rubén García Alía et al. and reported in [15]. There different LET values were considered, one unrestricted value taking into account all ionization caused by the beam (approx. 6.3 MeV cm^2/mg) and a volume-restricted value covering the area of a 9.3 MeV/n Silicon particle track (approx. 3.7 MeV cm^2/mg). Comparisons with the ESA SEU monitor in [15] indicate that the volume-restricted LET is a more proper expression for the particle LET in Silicon.

We adopt the LET value of 3.7 MeV cm^2/mg for our tests although these were determined in Silicon and we would require the value in SiC. While we cannot show or prove this assumption here, indicative simulations with SRIM using 10 GeV/n Xenon ions (maximum possible energy) are shown in the appendix E.1.

8.3 Geometry

The test board was attached to a frame holder on a motor unit, allowing to shift the board along one axis. Three DUTs could be installed on the board and irradiated separately. For the PIGS or POST tests, the DUTs were moved out of the beam, which ran continuously except when installing new DUTs.

The beam was incident normally on the DUTs.

8.4 Irradiation steps

Table 20: CERN: Irradiation steps of SiC MOSFET SCT20N120. 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°		Xe, 42°	
				42.03	
V_DS [V]	V_GS [V]	in-situ	PIGS	in-situ	PIGS
750	0	1	1		
900		1,5	1,5		
950		5	5		
1050		1	1		
900	-5	2	2		
900	-10	2,6	2,6		
950		4,6	6		
1050		2	2		

8.5 Results

The tests with the SCT20N120 at CERN show that the device was operable at V_{DS} = 900 V for each V_{GS} = 0 V, -5 V or -10 V, but fails at 950 V (tested with V_{GS} = 0 V and -10 V).

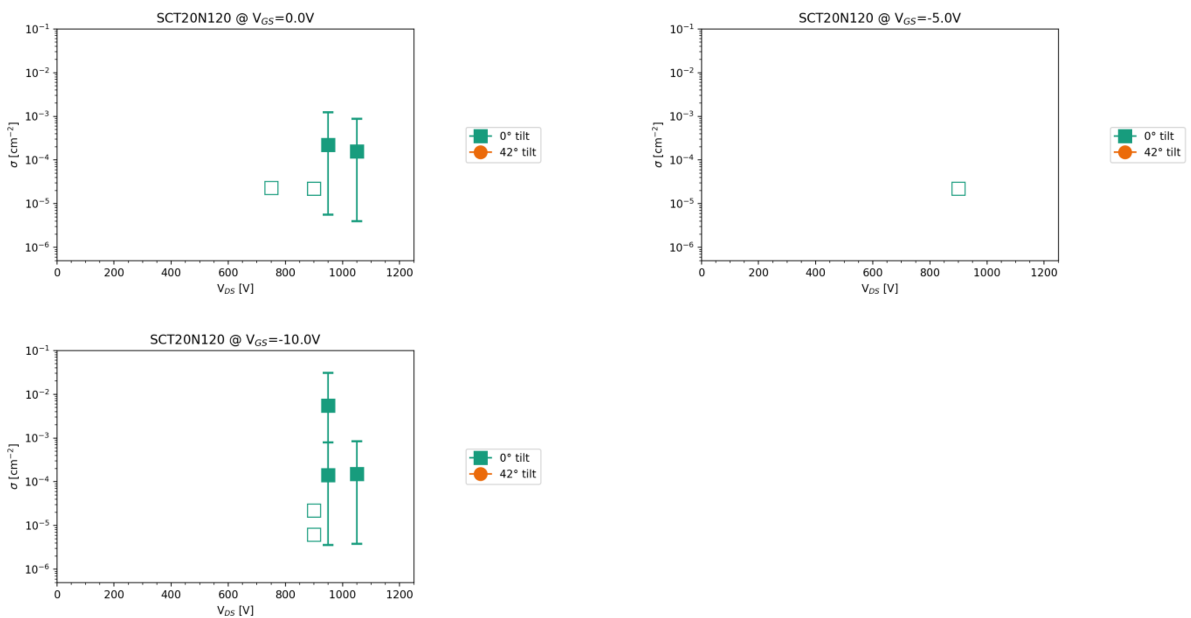
Failures are always immediate and destructive and we do not see a quasi-continuous degradation.

A striking difference to the previous tests is the increased voltage of safe operation of 900 V. This value was assumed as 750 V with the lowest LET of approx. 1.3 MeV cm^2/mg at UCL and with protons[1].

Tests at CERN were performed with DUTs from a different lot. However when looking at all devices tested at CERN, all of them show a similar behaviour. Lot-to-lot variability might thus not be an explanation for this.

[1] However in both campaigns no tests were performed at values between 750 V and 900 V.

Figure 24: Results: Heavy Ions at CERN. 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.



The effective fluences across the tests were <6E5 ions/cm2. The relatively low fluence might be an explanation for the increased "safe operation" levels observed in these tests compared to the other test campaigns.

Table 21: Results: Heavy Ions at CERN - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	Tilt [°]	DUT #	V_DS, V	V_GS	Fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
001	Xe	0	1	750	0	1.03E+05	0	0	2.31E-05	--	--
002	Xe	0	1	900	0	1.02E+05	0	0	2.21E-05	--	--
003	Xe	0	1	1050	0	4.26E+03	4.00E-06	1.58E-04	8.80E-04	SEB	Destructive failure at indicated fluence
004	Xe	0	2	900	-5	1.04E+05	0	0	2.22E-05	--	--
005	Xe	0	2	900	-10	9.76E+04	0	0	2.20E-05	--	--
006	Xe	0	2	1050	-10	5.93E+03	3.80E-06	1.50E-04	8.36E-04	SEB/SEGR	Destructive failure
007	Xe	0	4	950	-10	4.74E+03	3.62E-06	1.43E-04	7.96E-04	SEB/SEGR	Destructive failure, SEB/SEGR at same time
008	Xe	0	5	900	0	9.88E+04	0	0	2.21E-05	--	--
009	Xe	0	5	950	0	4.75E+03	5.63E-06	2.22E-04	1.24E-03	SEB	Destructive failure

010	Xe	0	6	900	-10	3.77E+05	0	0	6.15E-06	--	--
011	Xe	0	6	950	-10	2.73E+02	1.41E-04	5.56E-03	3.10E-02	SEB/SEGR	SEB followed by SEGR shortly after

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-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

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

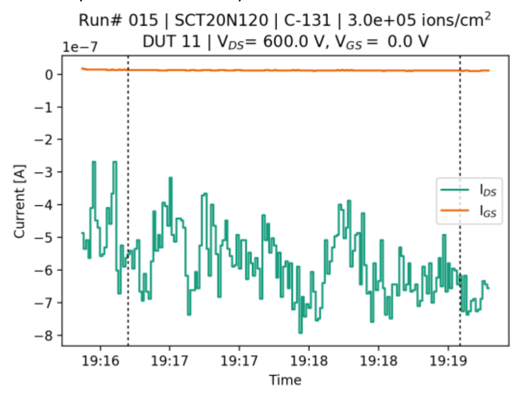
B.1. Logfile / Test steps

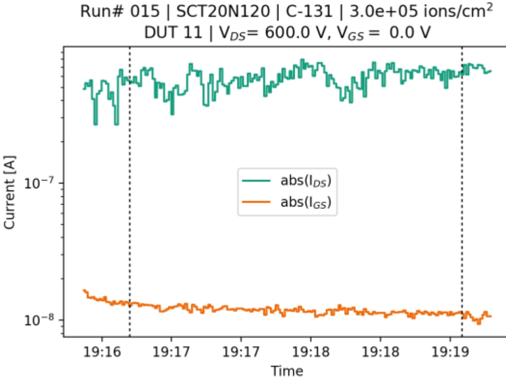
In case of device failure the fluences in this table indicate the fluence provided by the facility not the fluence until failure which may differ by some additional seconds of beam.

Run #	Run (UCL)	Date	Time	Ion	Device Type	Device	Position on board	DUT #	V_{DS} [V]	V_{GS} [V]	beam time [s]	fluence [cm-2]
15	25	16.4.	19:16	C	MOSFET	SCT20N120	#1	11	600	0	142	3.03E+05
16	26	16.4.	19:22	C	MOSFET	SCT20N120	#1	11	750	0	141	3.04E+05
17	27	16.4.	19:29	C	MOSFET	SCT20N120	#1	11	900	0	17	3.34E+04
18	28	16.4.	19:32	C	MOSFET	SCT20N120	#2	12	750	0	160	3.03E+05
19	29	16.4.	19:36	C	MOSFET	SCT20N120	#3	13	750	0	158	3.02E+05
20	30	16.4.	19:59	Al	MOSFET	SCT20N120	#3	13	600	0	18	3.53E+04
21	31	16.4.	20:02	Al	MOSFET	SCT20N120	#2	12	400	0	181	3.02E+05
22	32	16.4.	20:06	Al	MOSFET	SCT20N120	#2	12	500	0	10	1.29E+04
23	33	16.4.	20:20	Al	MOSFET	SCT20N120	#1	15	400	0	176	3.02E+05
24	34	16.4.	20:24	Al	MOSFET	SCT20N120	#1	15	400	-5	127	3.03E+05
25	35	16.4.	20:27	AL	MOSFET	SCT20N120	#1	15	400	-10	106	3.04E+05
26	36	16.4.	20:33	Al	MOSFET	SCT20N120	#2	16	400	0	57	3.06E+05
27	37	16.4.	20:36	Al	MOSFET	SCT20N120	#2	16	400	-5	56	3.07E+05
28	38	16.4.	20:38	Al	MOSFET	SCT20N120	#2	16	400	-10	60	3.06E+05
29	39	16.4.	20:42	Al	MOSFET	SCT20N120	#3	17	400	-10	61	3.08E+05
30	40	16.4.	20:45	Al	MOSFET	SCT20N120	#3	17	450	0	66	3.05E+05
31	41	16.4.	20:49	Al	MOSFET	SCT20N120	#3	17	450	-5	63	3.09E+05
32	42	16.4.	20:51	Al	MOSFET	SCT20N120	#3	17	450	-10	62	3.09E+05
33	43	16.4.	20:55	Al	MOSFET	SCT20N120	#2	16	450	-10	65	3.06E+05
34	44	16.4.	20:57	Al	MOSFET	SCT20N120	#1	15	450	-10	67	3.07E+05

B.2. Measurements

Figure 25: Run# 015, SCT20N120, C-131, 3.0e+05 ions/cm2 , DUT 11, VDS= 600.0 V, VGS= 0.0 V





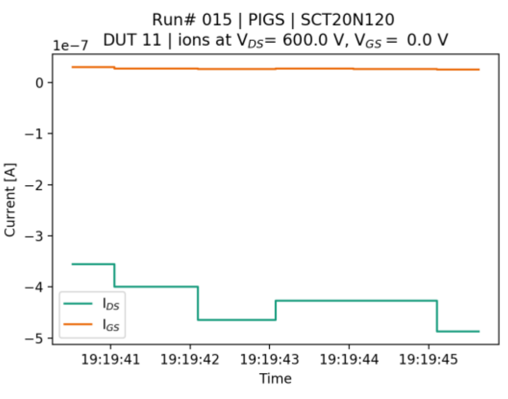
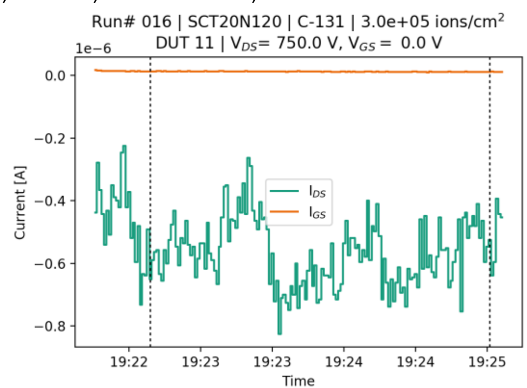
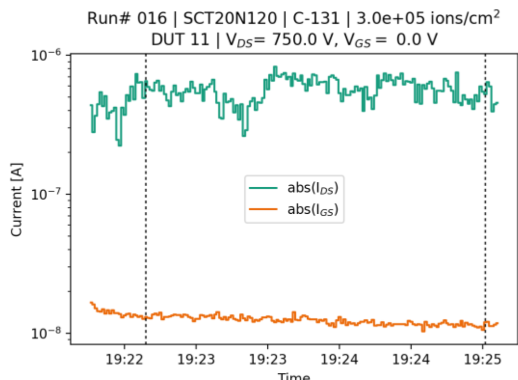


Figure 26: Run# 016, SCT20N120, C-131, 3.0e+05 ions/cm2 , DUT 11, VDS= 750.0 V, VGS= 0.0 V





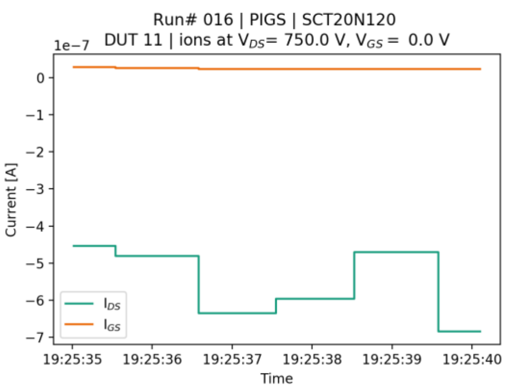
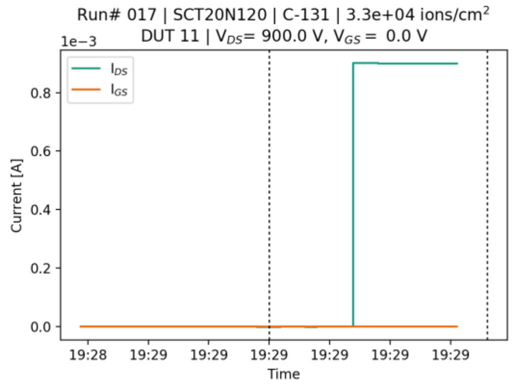
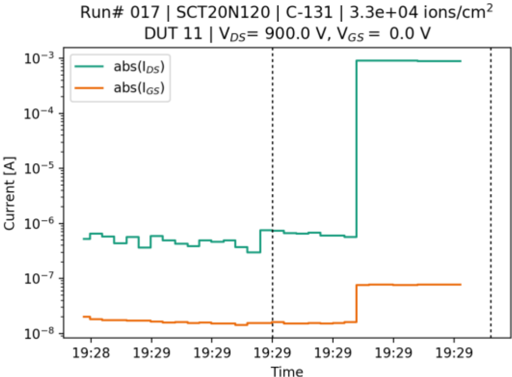


Figure 27: Run# 017, SCT20N120, C-131, 3.3e+04 ions/cm2 , DUT 11, VDS= 900.0 V, VGS= 0.0 V





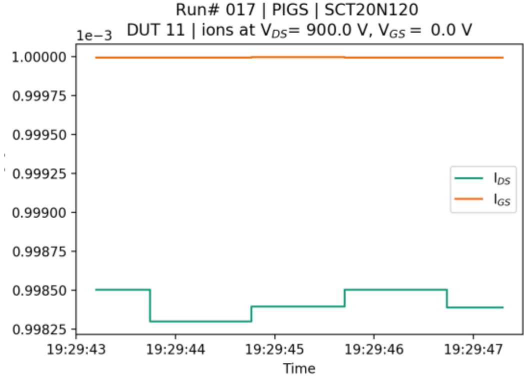
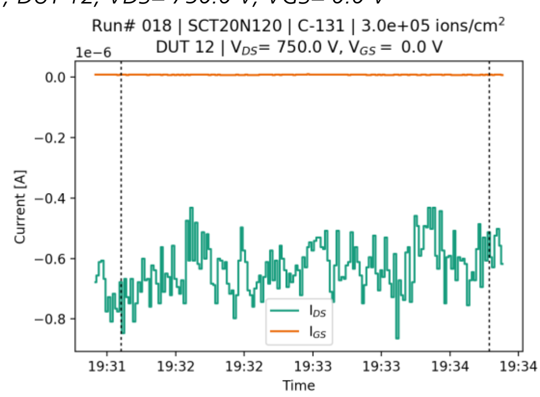
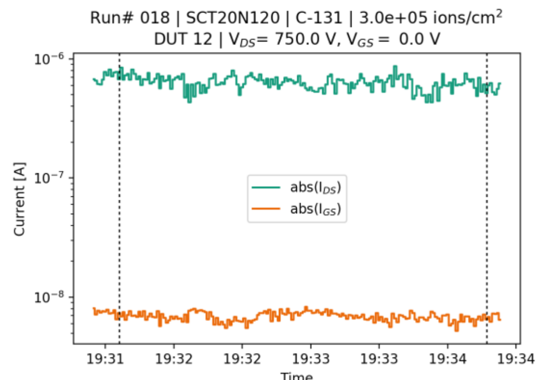


Figure 28: Run# 018, SCT20N120, C-131, 3.0e+05 ions/cm2 , DUT 12, VDS= 750.0 V, VGS= 0.0 V





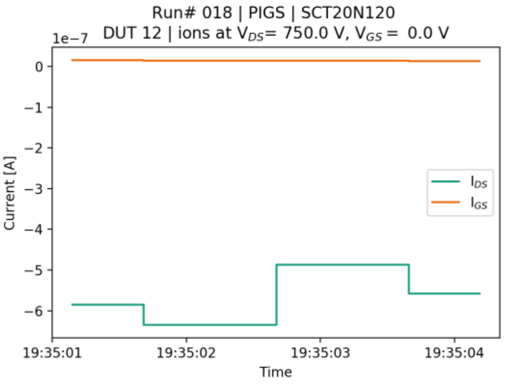
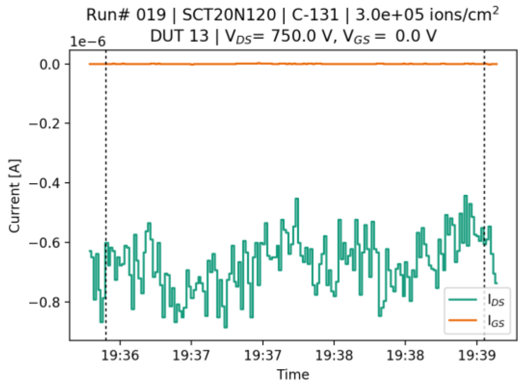
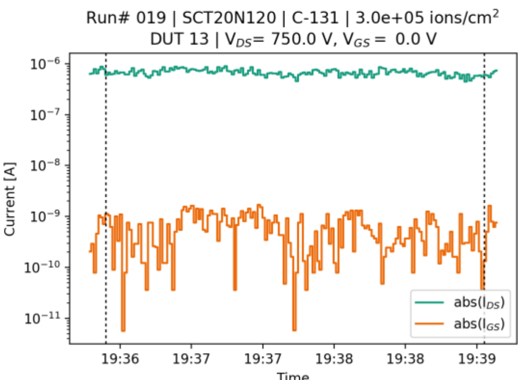


Figure 29: Run# 019, SCT20N120, C-131, 3.0e+05 ions/cm2 , DUT 13, VDS= 750.0 V, VGS= 0.0 V





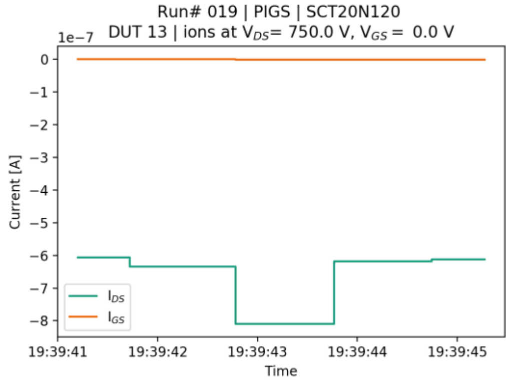
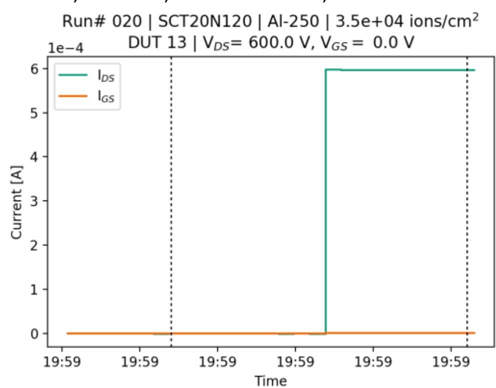
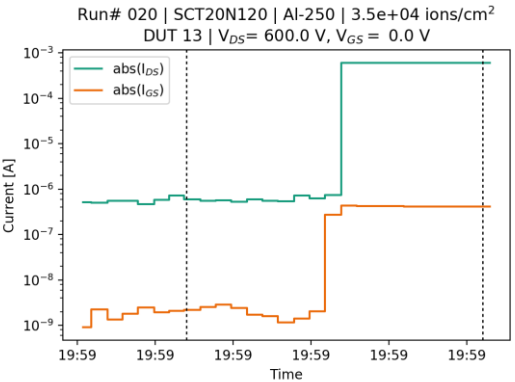


Figure 30: Run# 020, SCT20N120, Al-250, 3.5e+04 ions/cm2 , DUT 13, VDS= 600.0 V, VGS= 0.0 V





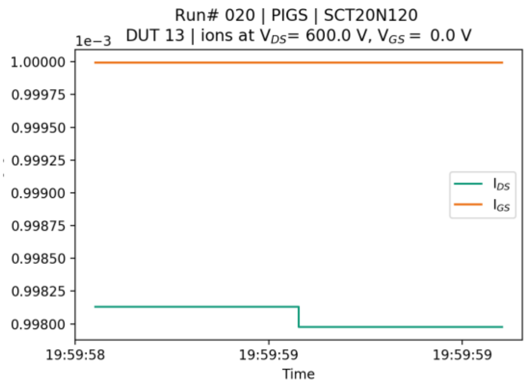
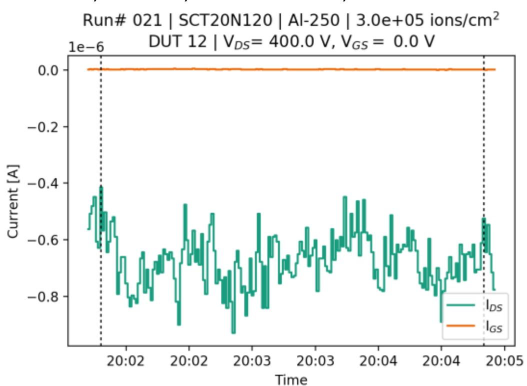
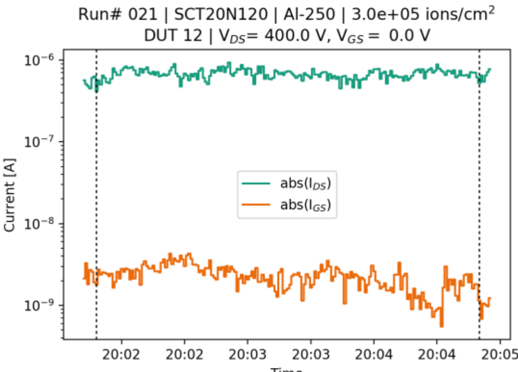


Figure 31: Run# 021, SCT20N120, Al-250, 3.0e+05 ions/cm2 , DUT 12, VDS= 400.0 V, VGS= 0.0 V





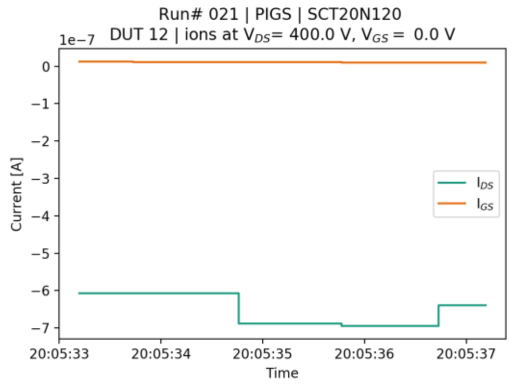
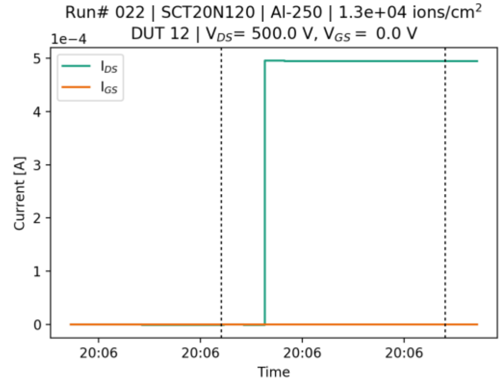
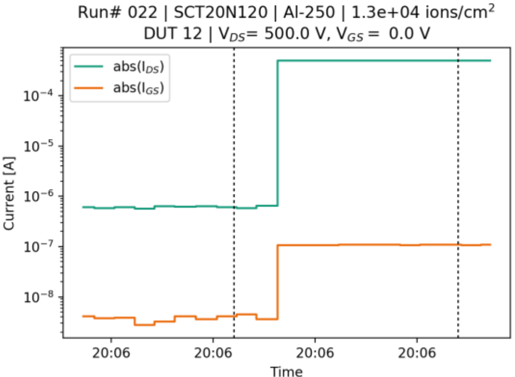


Figure 32: Run# 022, SCT20N120, Al-250, 1.3e+04 ions/cm2 , DUT 12, VDS= 500.0 V, VGS= 0.0 V





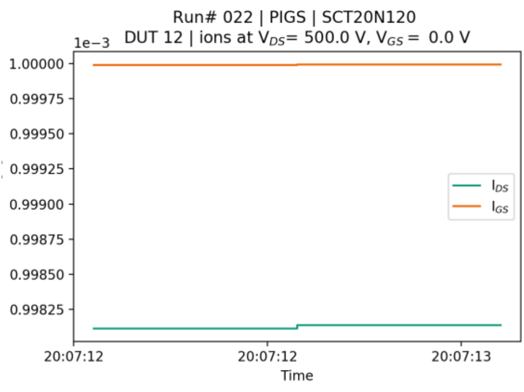
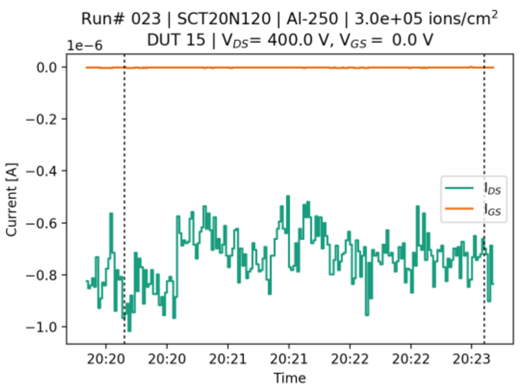


Figure 33: Run# 023, SCT20N120, Al-250, 3.0e+05 ions/cm2 , DUT 15, VDS= 400.0 V, VGS= 0.0 V



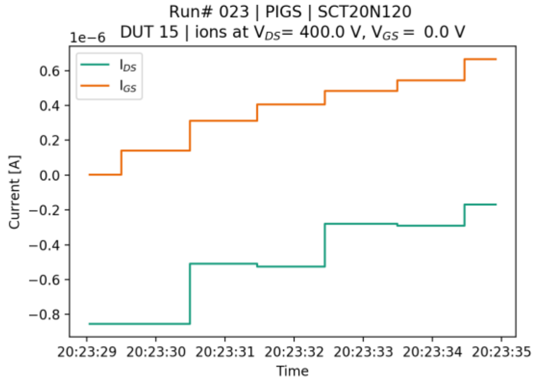
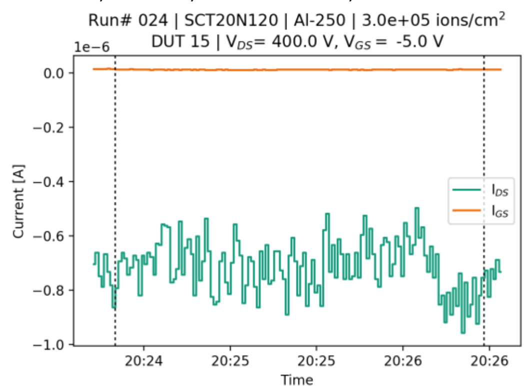
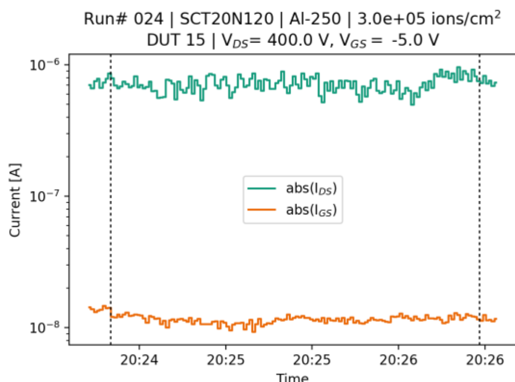


Figure 34: Run# 024, SCT20N120, Al-250, 3.0e+05 ions/cm2 , DUT 15, VDS= 400.0 V, VGS= -5.0 V





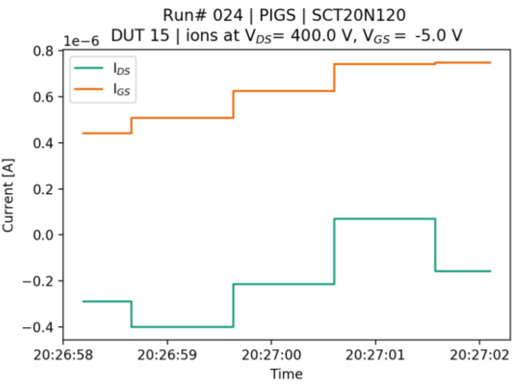
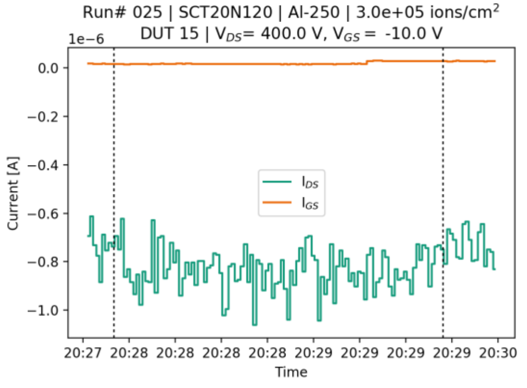
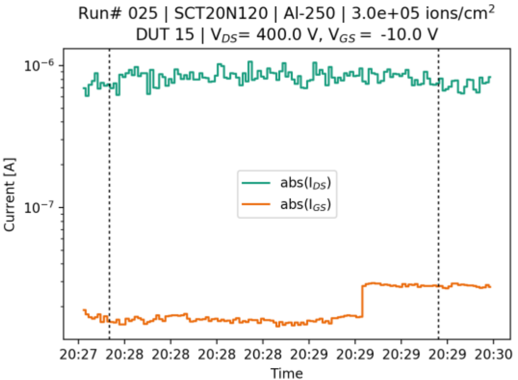


Figure 35: Run# 025, SCT20N120, Al-250, 3.0e+05 ions/cm2 , DUT 15, VDS= 400.0 V, VGS= -10.0 V





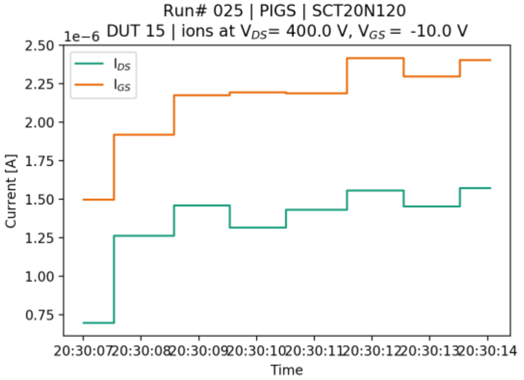
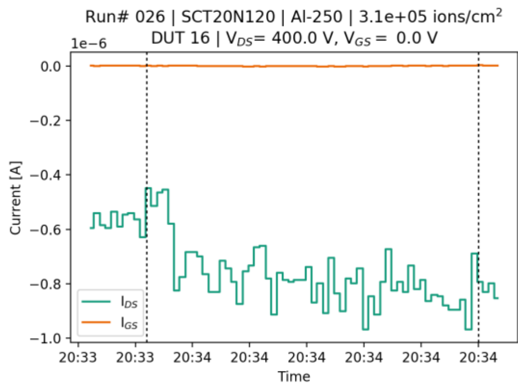
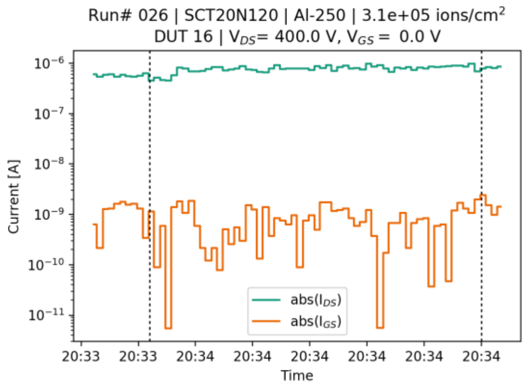


Figure 36: Run# 026, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 16, VDS= 400.0 V, VGS= 0.0 V





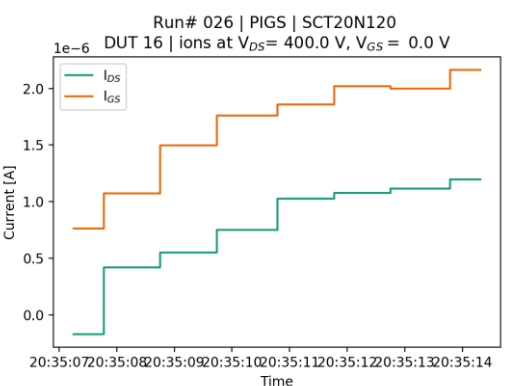
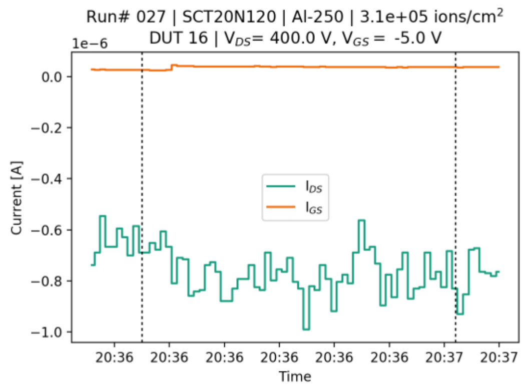
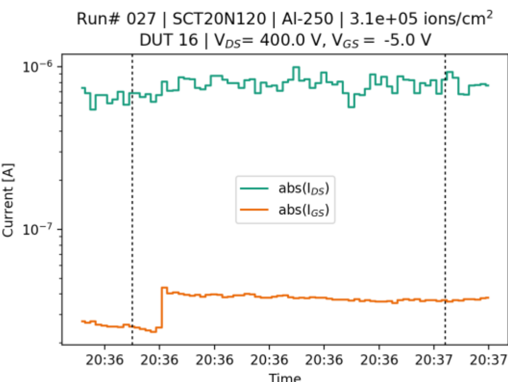


Figure 37: Run# 027, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 16, VDS= 400.0 V, VGS= -5.0 V





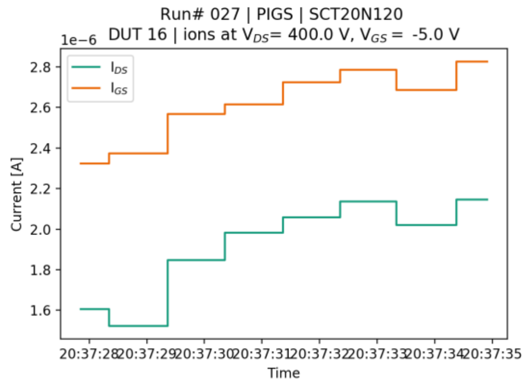
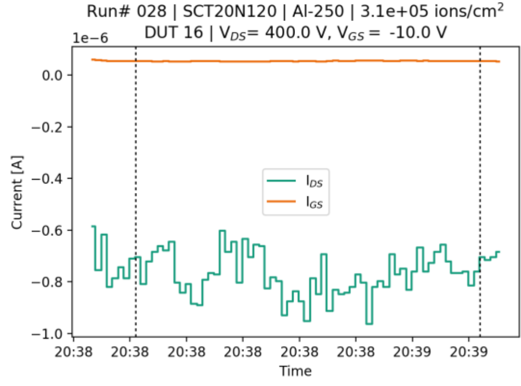
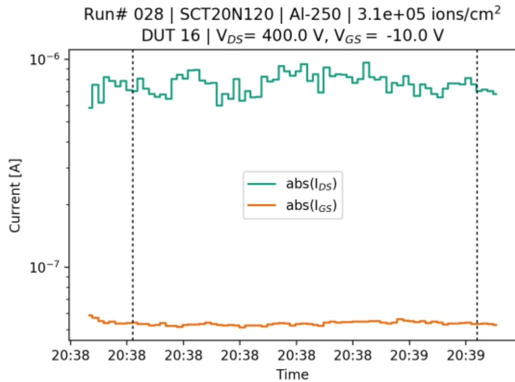


Figure 38: Run# 028, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 16, VDS= 400.0 V, VGS= -10.0 V





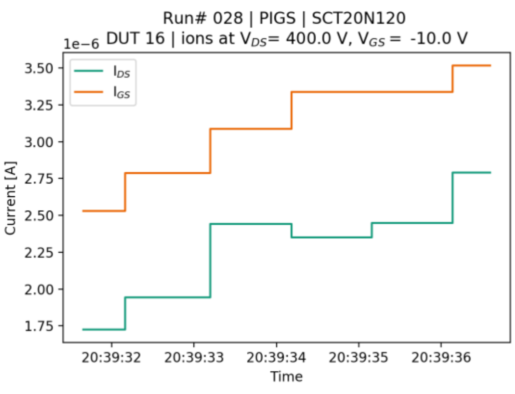
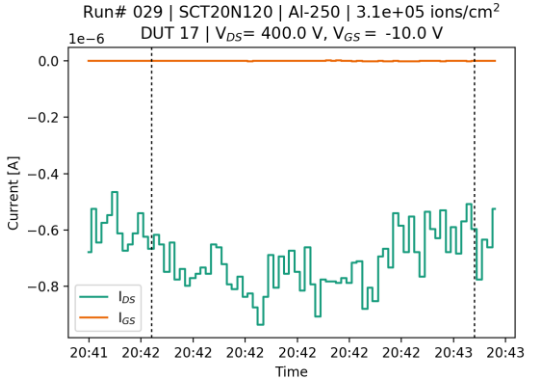
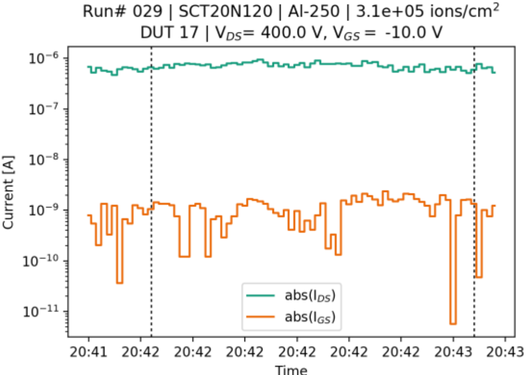


Figure 39: Run# 029, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 17, VDS= 400.0 V, VGS= -10.0 V





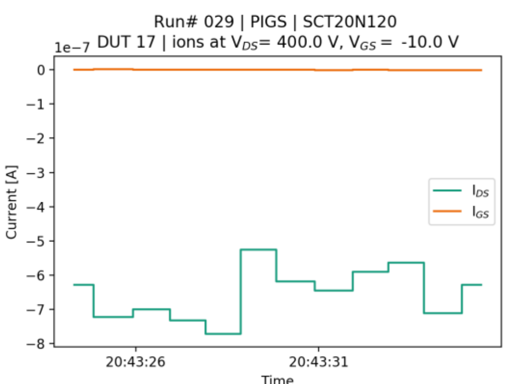
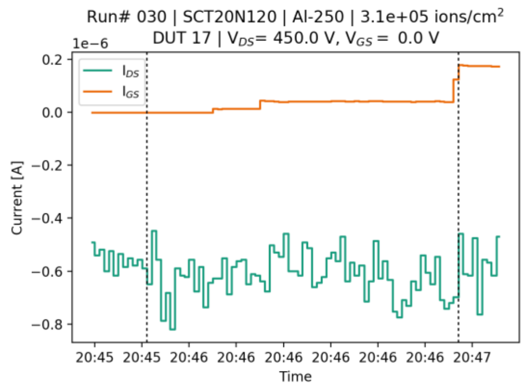
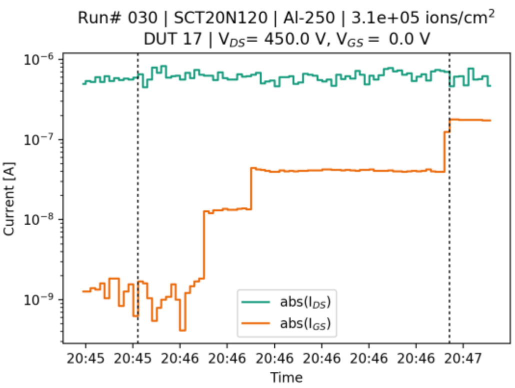


Figure 40: Run# 030, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 17, VDS= 450.0 V, VGS= 0.0 V





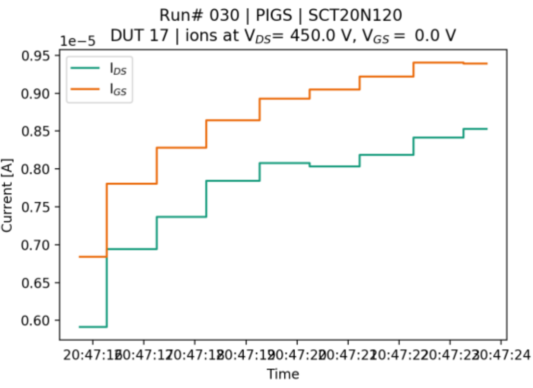
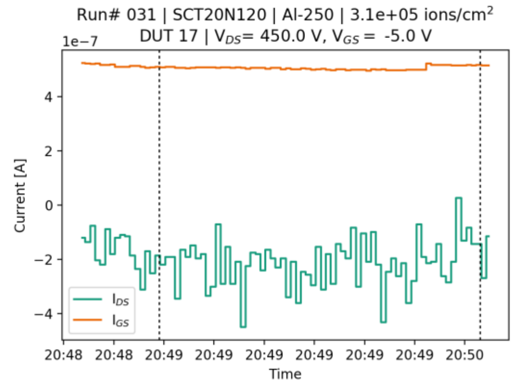


Figure 41: Run# 031, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 17, VDS= 450.0 V, VGS= -5.0 V



Run# 031 | SCT20N120 | Al-250 | 3.1e+05 ions/cm^2
DUT 17 | V_{DS}= 450.0 V, V_{GS} = -5.0 V

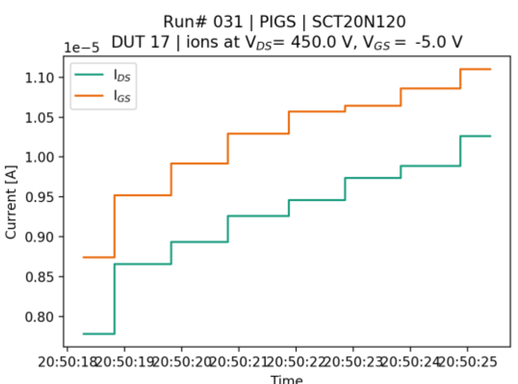
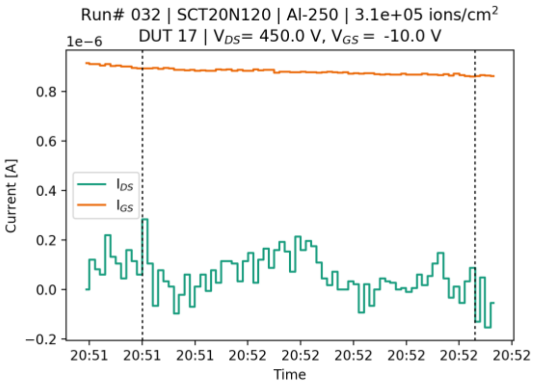
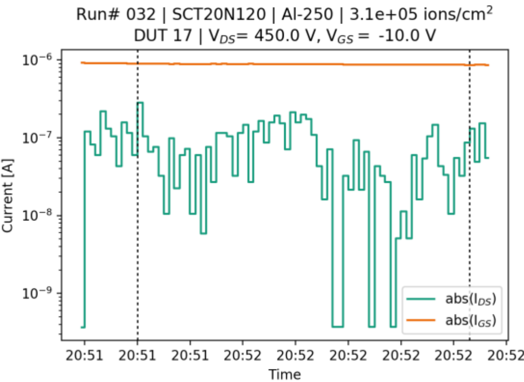


Figure 42: Run# 032, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 17, VDS= 450.0 V, VGS= -10.0 V





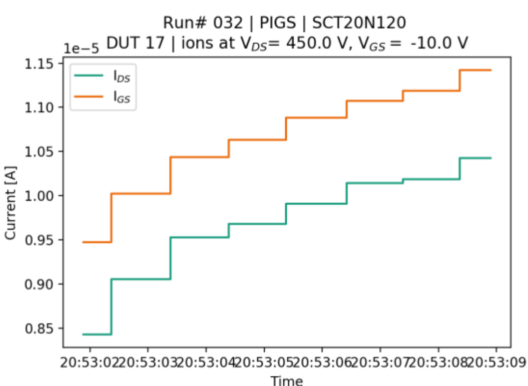
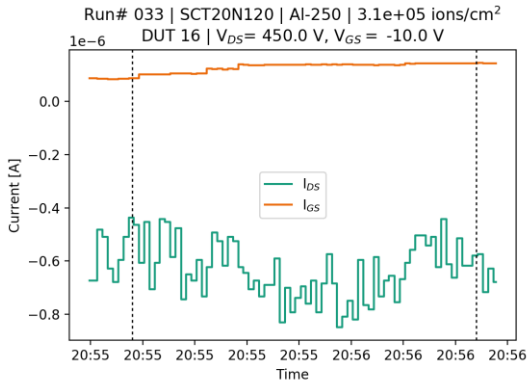


Figure 43: Run# 033, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 16, VDS= 450.0 V, VGS= -10.0 V



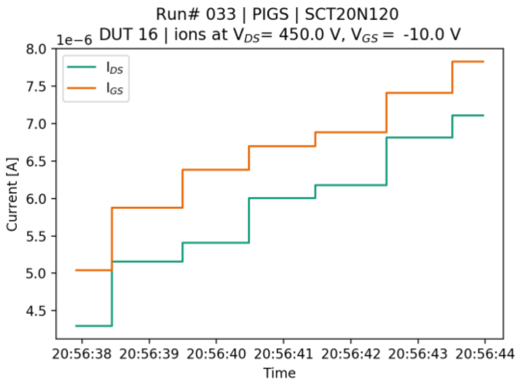
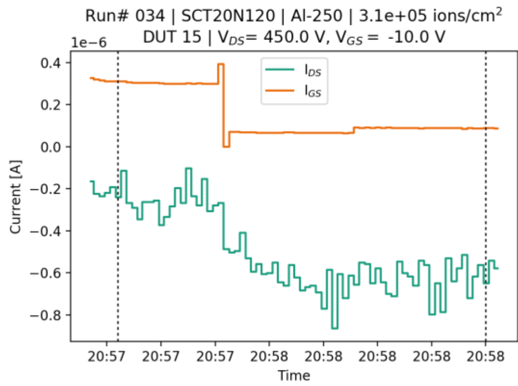
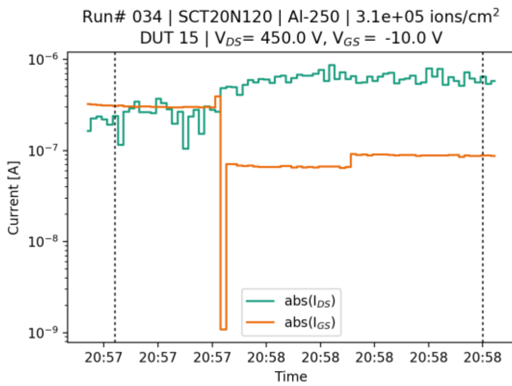
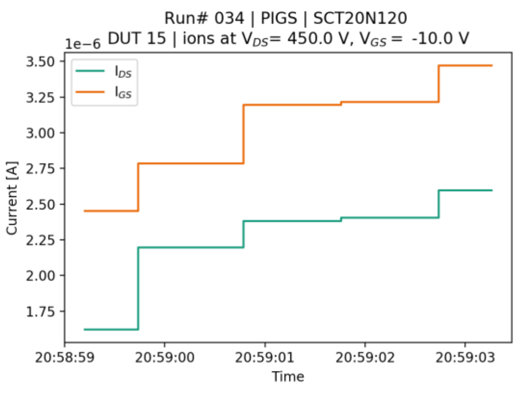


Figure 44: Run# 034, SCT20N120, Al-250, 3.1e+05 ions/cm2 , DUT 15, VDS= 450.0 V, VGS= -10.0 V







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 14, this was then devided by the density ρ = 3210 mg/cm³ to give the LET in units of MeV cm²/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 [10] 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/cm³ 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 22: 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 23: 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 24: 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 25: 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 24 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 cm²/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

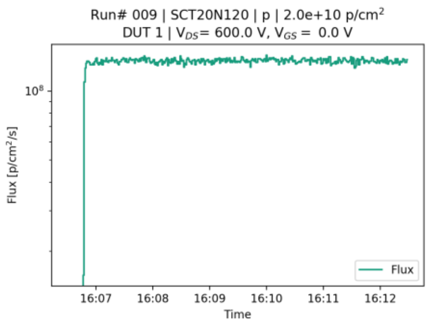
In case of device failure the fluences in this table indicate the fluence provided by the facility not the fluence until failure which may differ by some additional seconds of beam.

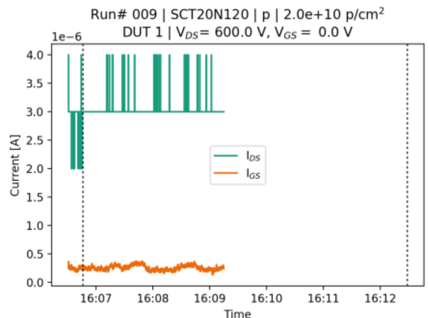
#	Date	Time	Ion	Device Type	Device	DUT #	V_DS, V	V_GS	beam time [s]	fluence [cm-2]
9	19.09.	16:06 *	p	MOSFET	SCT20N120	#1	600	0	148	2.0e10
10	19.09.	16:06 *	p	MOSFET	SCT20N120	#1	750	0	145	2.0e10
11	19.09.	16:20	p	MOSFET	SCT20N120	#2	600	0	152	2.0e10
12	19.09.	16:23	p	MOSFET	SCT20N120	#2	750	0	148	2.0e10
13	19.09.	16:26	p	MOSFET	SCT20N120	#2	900	0	150	2.0e10
14	19.09.	16:29	p	MOSFET	SCT20N120	#2	1050	0	9	1.0e9
15	19.09.	16:35	p	MOSFET	SCT20N120	#3	600	0	151	2.0e10
16	19.09.	16:38	p	MOSFET	SCT20N120	#3	750	0	145	2.0e10
17	19.09.	16:41		MOSFET	SCT20N120	#3	900	0	113	1.5e10

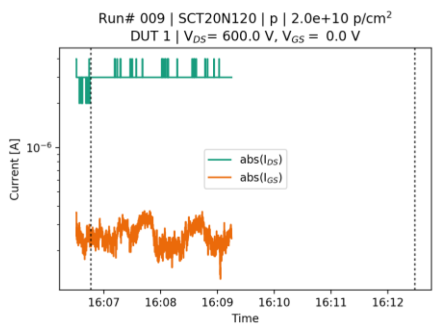
* Beam was not interrupted for runs #9-#10. Start time of beam is thus identical. Fluences are however calculated

C.3. Measurements

Figure 45: Run# 009, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 1, VDS= 600.0 V, VGS= 0.0 V







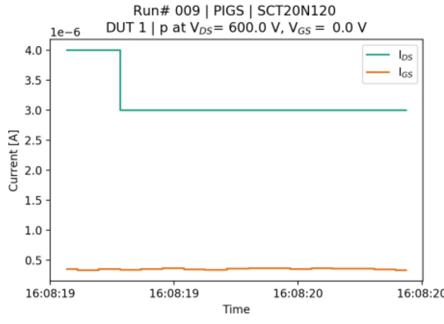
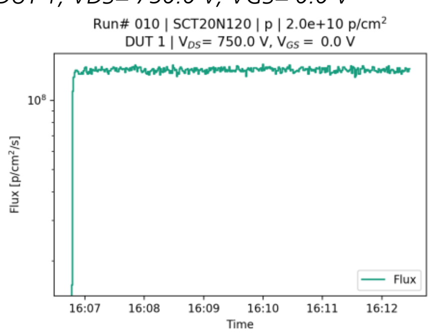
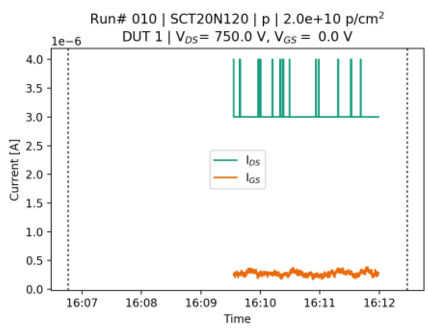
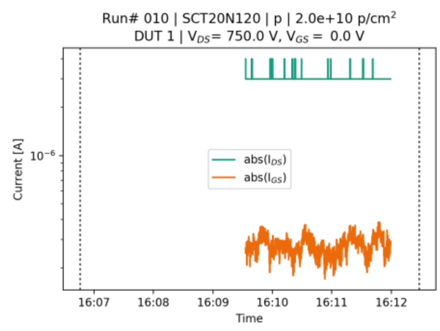


Figure 46: Run# 010, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 1, VDS= 750.0 V, VGS= 0.0 V







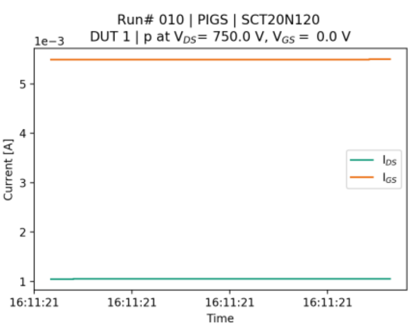
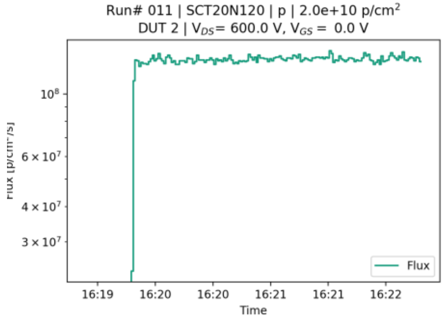
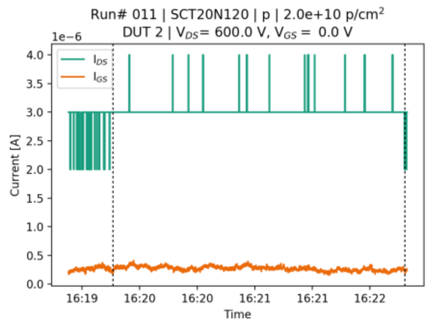
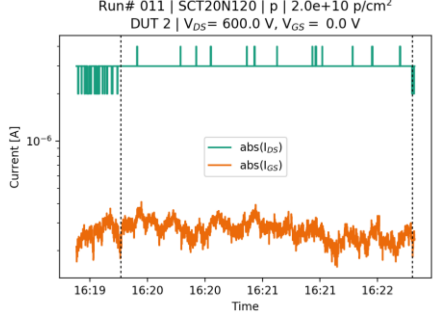


Figure 47: Run# 011, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 2, VDS= 600.0 V, VGS= 0.0 V







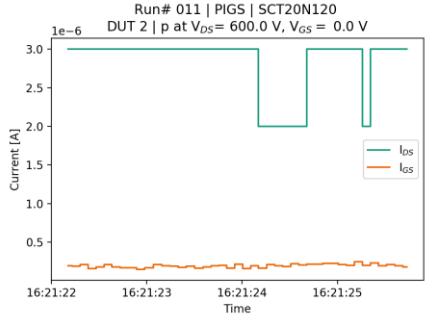
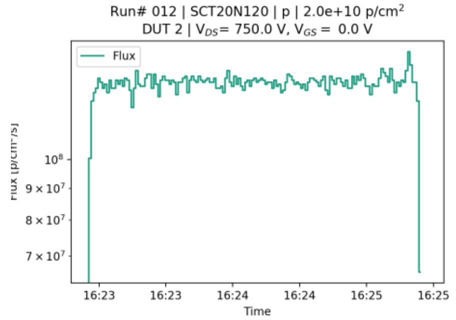
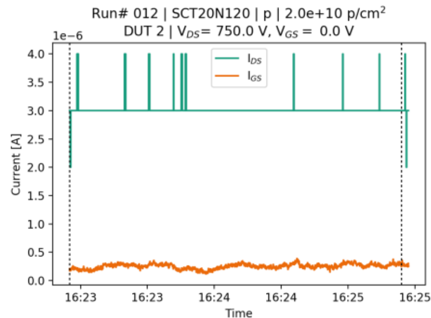
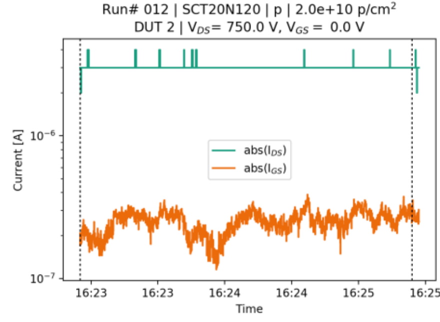


Figure 48: Run# 012, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 2, VDS= 750.0 V, VGS= 0.0 V







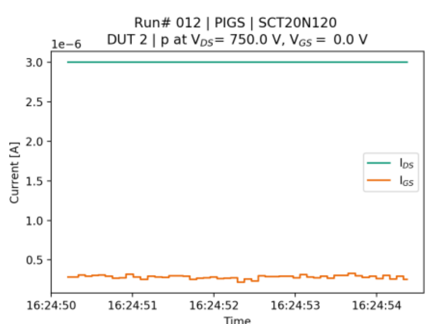
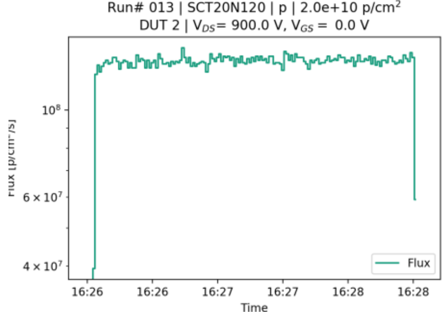
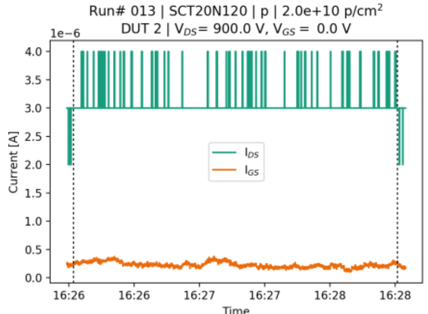
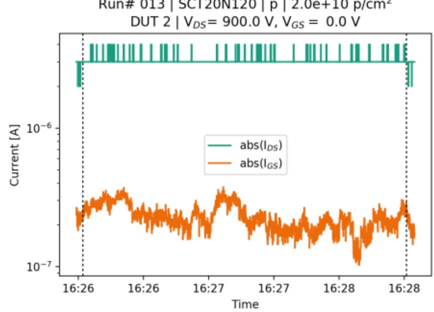


Figure 49: Run# 013, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 2, VDS= 900.0 V, VGS= 0.0 V







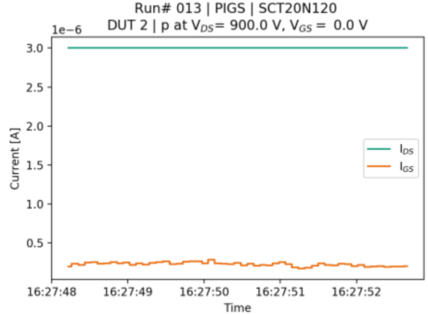
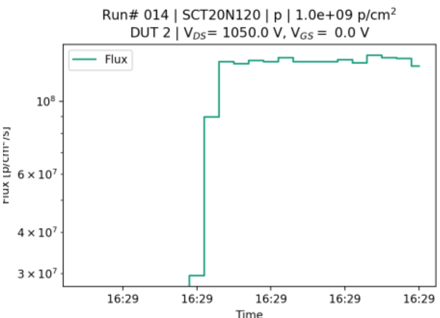
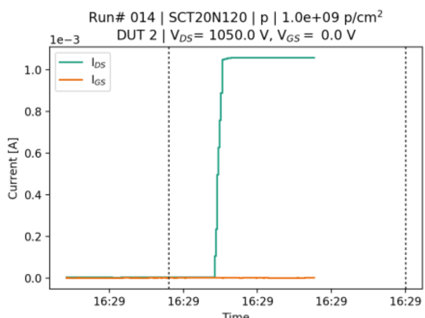


Figure 50: Run# 014, SCT20N120, p, 1.0e+09 ions/cm2 , DUT 2, VDS= 1050.0 V, VGS= 0.0 V





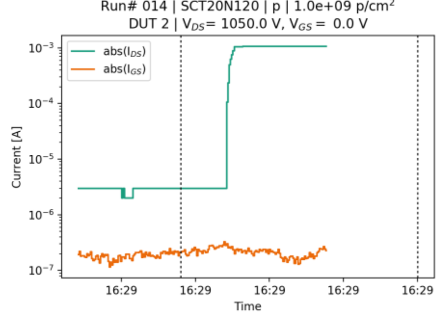
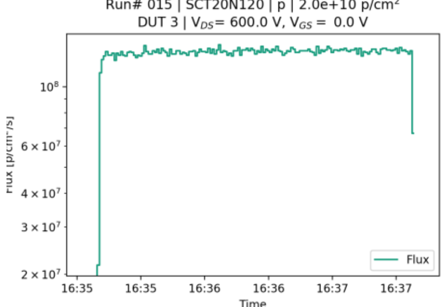
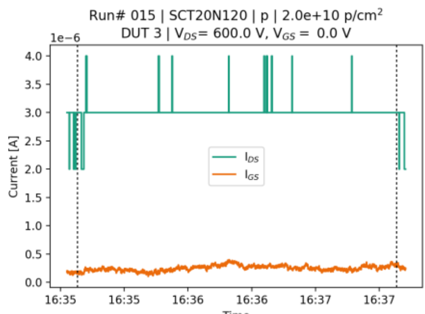
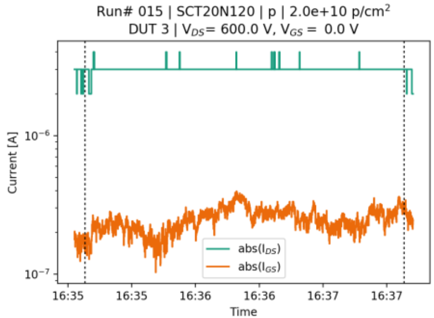


Figure 51: Run# 015, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 3, VDS= 600.0 V, VGS= 0.0 V







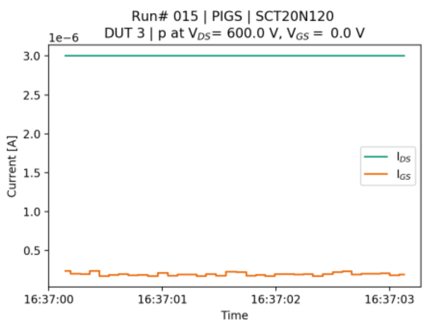
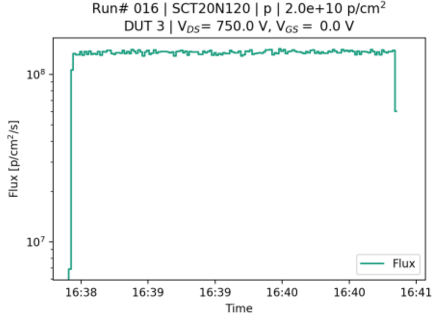
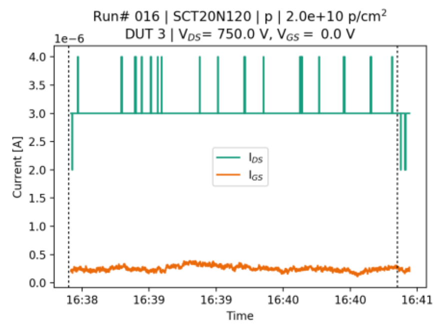
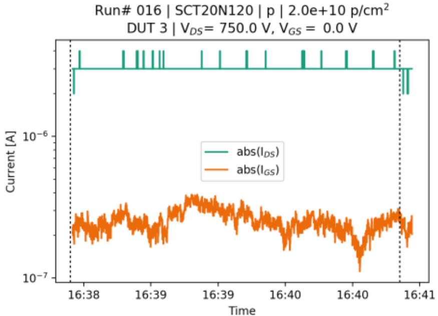


Figure 52: Run# 016, SCT20N120, p, 2.0e+10 ions/cm2 , DUT 3, VDS= 750.0 V, VGS= 0.0 V







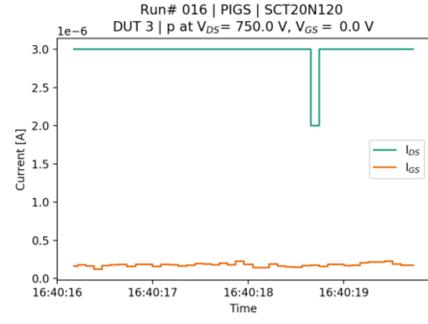
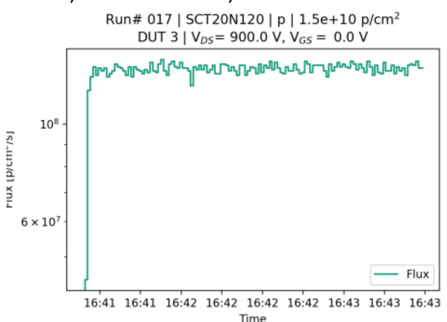
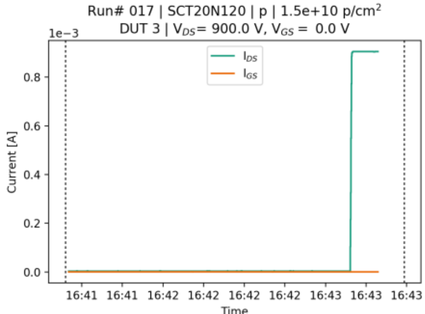
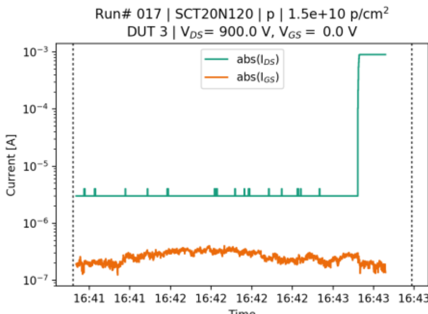


Figure 53: Run# 017, SCT20N120, p, 1.5e+10 ions/cm2 , DUT 3, VDS= 900.0 V, VGS= 0.0 V




Run# 017 | SCT20N120 | p | 1.5e+10 p/cm2
DUT 3 | VDS= 900.0 V, VGS = 0.0 V
1e−3
IDS
IGS
Current [A]
Time


Run# 017 | SCT20N120 | p | 1.5e+10 p/cm2
DUT 3 | VDS= 900.0 V, VGS = 0.0 V
abs(IDS)
abs(IGS)
Current [A]
Time

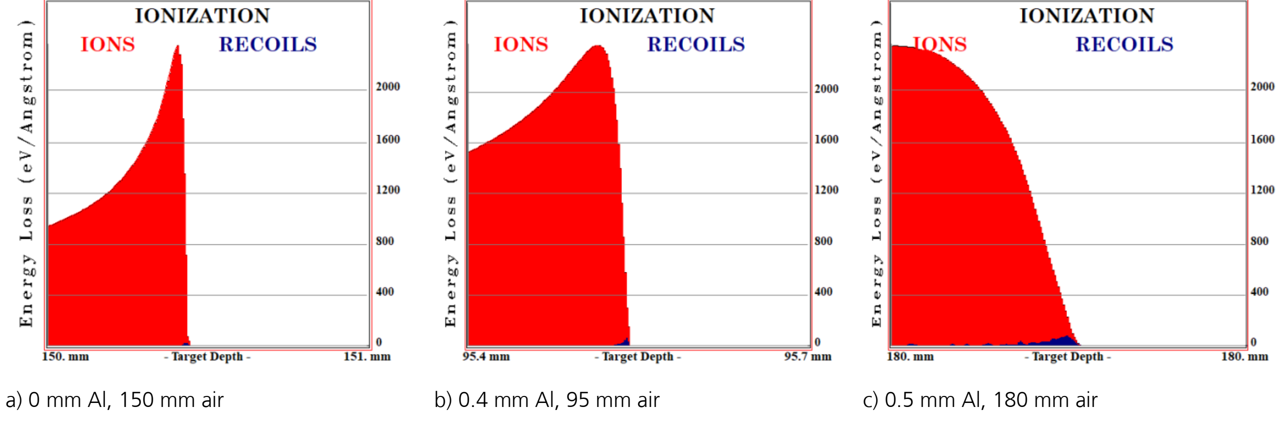
D Appendix: Tests at GANIL

D.1. 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 Aluminium degrader were included in simulations with SRIM2013. The incident particles were 49.1 MeV/n Xenon ions (isotope mass = 136 u).

Figure 54: 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 54 start at the surface of the silicon carbide layer, so e.g. at 95.410 mm in Figure 54 b), although only one digit is displayed.

The LET in MeV cm²/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/cm³ = 3210 mg/cm³.

Table 26: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [13], Values in SiC are calculated by INT and given with one digit

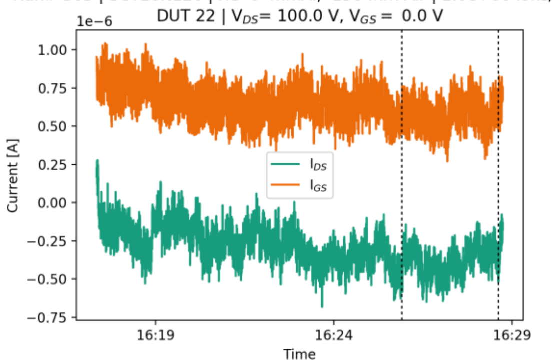
Degrader [mm Al]	Air gap [mm]	LET (Si) (MeV.cm²/mg)	Range (Si) [µm]	LET_{SURF} (SiC) [MeV.cm²/mg]	Range (SiC) [µm]
0	150	27.76	640.33	29.2	430
0.4	95	42.03	226.23	47.2	141
0.5	180	60.12	65.68	72.9	30

D.2. 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]
503	07.06.	16:24	Xe	0	150	MOSFET	SCT20N120	#2	22	100	0	163	1.00E+06
504	07.06.	16:28	Xe	0	150	MOSFET	SCT20N120	#2	22	150	0	210	1.00E+06
505	07.06.	16:32	Xe	0	150	MOSFET	SCT20N120	#2	22	200	0	289	1.00E+06
506	07.06.	16:38	Xe	0	150	MOSFET	SCT20N120	#2	22	250	0	307	1.00E+06
507	07.06.	16:45	Xe	0	150	MOSFET	SCT20N120	#2	22	300	0	289	1.00E+06
508	07.06.	16:50	Xe	0	150	MOSFET	SCT20N120	#2	22	350	0	325	1.00E+06
509	07.06.	16:57	Xe	0	150	MOSFET	SCT20N120	#2	22	400	0	352	1.00E+06
510	07.06.	17:06	Xe	0	150	MOSFET	SCT20N120	#2	22	450	0	122	3.00E+05
511	07.06.	17:09	Xe	0	150	MOSFET	SCT20N120	#2	22	600	0	60	3.00E+05

D.3. Measurements

Figure 55: Run# 503, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 100.0 V, VGS= 0.0 V



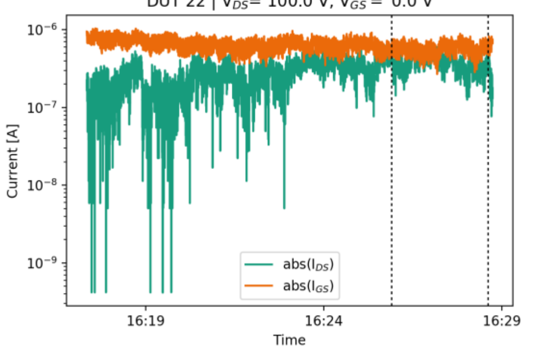
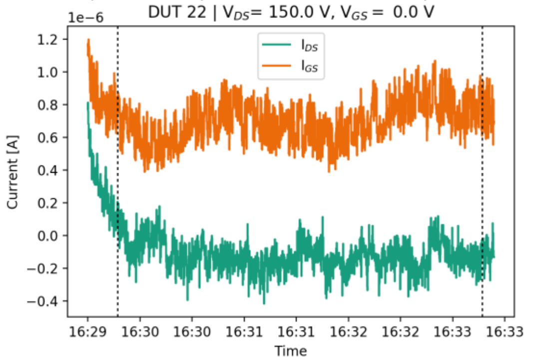


Figure 56: Run# 504, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 150.0 V, VGS= 0.0 V



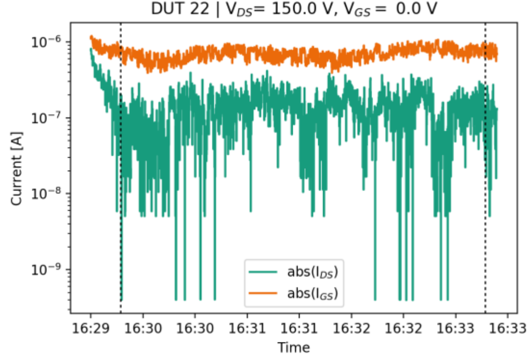
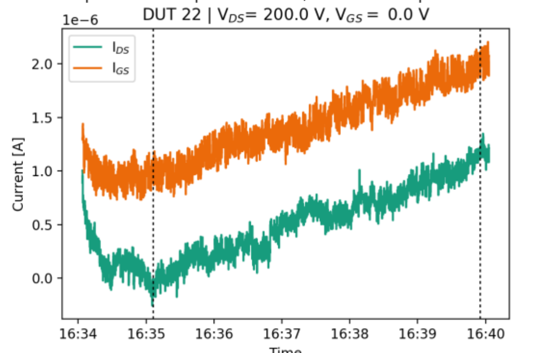


Figure 57: Run# 505, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 200.0 V, VGS= 0.0 V



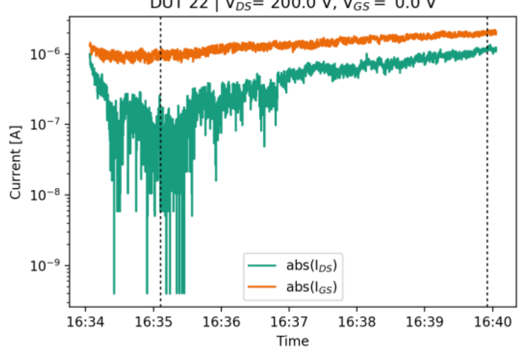
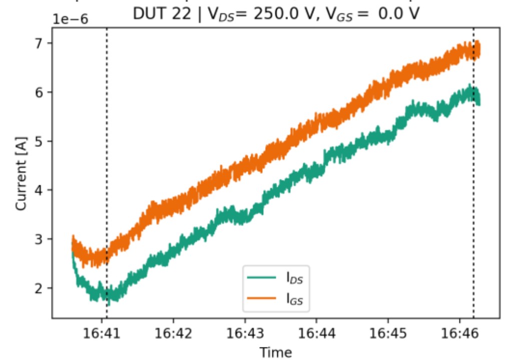


Figure 58: Run# 506, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 250.0 V, VGS= 0.0 V



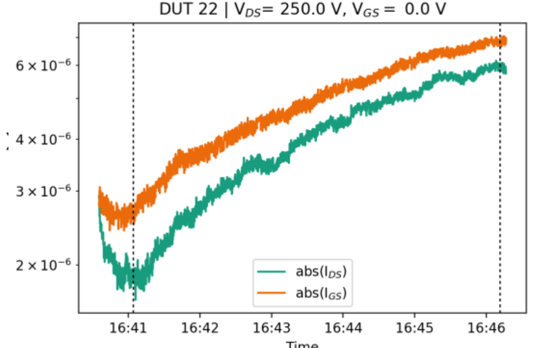
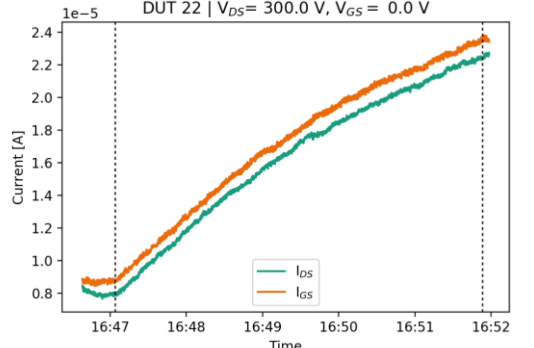


Figure 59: Run# 507, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 300.0 V, VGS= 0.0 V



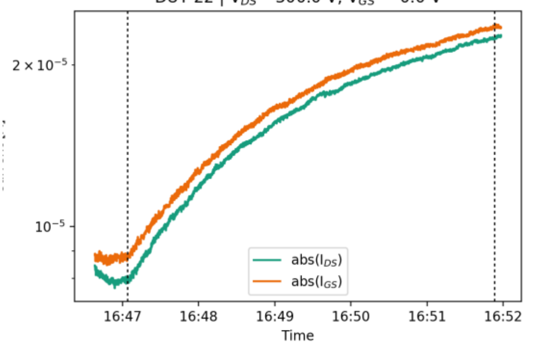
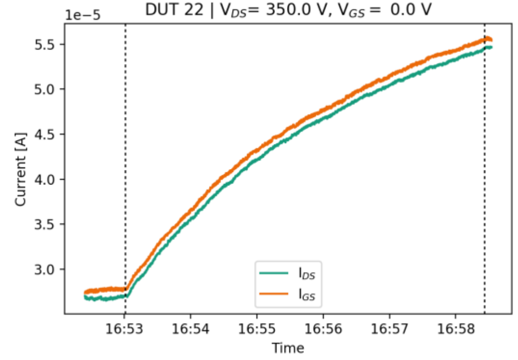


Figure 60: Run# 508, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 350.0 V, VGS= 0.0 V



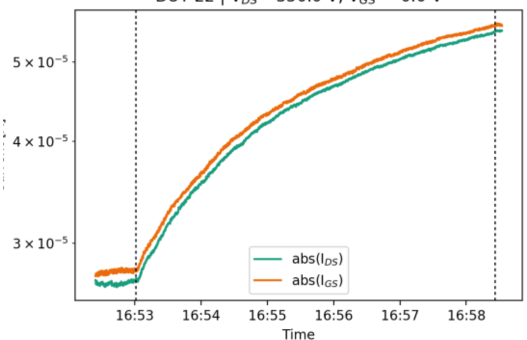
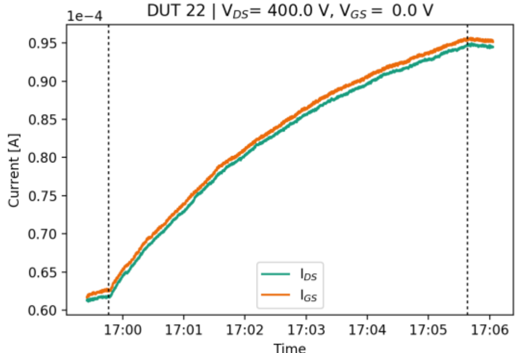


Figure 61: Run# 509, SCT20N120, Xe 0 mmAl, 150 mm Air, 1.0e+06 ions/cm2 , DUT 22, VDS= 400.0 V, VGS= 0.0 V



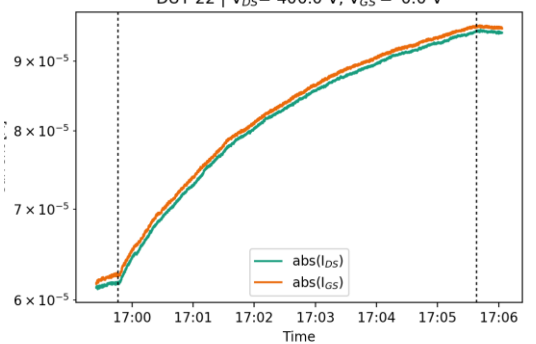
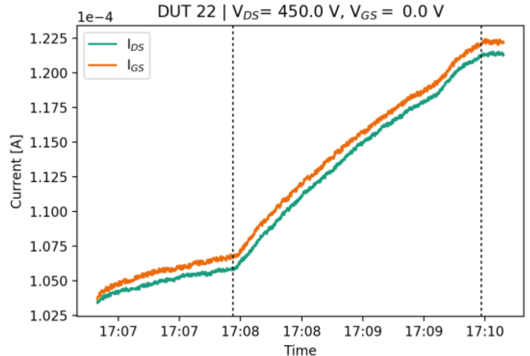


Figure 62: Run# 510, SCT20N120, Xe 0 mmAl, 150 mm Air, 3.0e+05 ions/cm2 , DUT 22, VDS= 450.0 V, VGS= 0.0 V



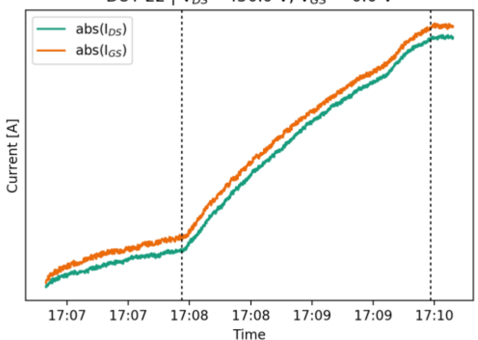
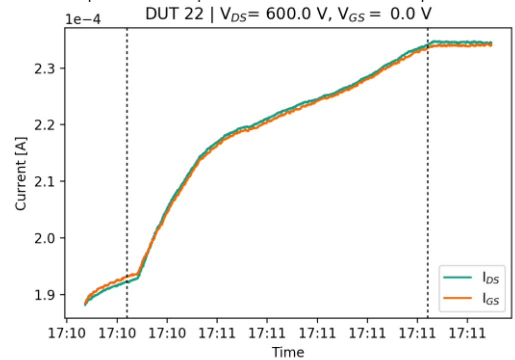
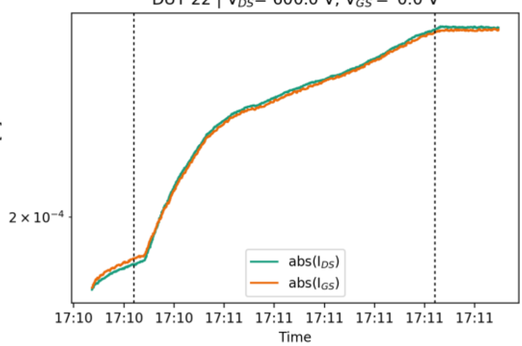


Figure 63: Run# 511, SCT20N120, Xe 0 mmAl, 150 mm Air, 3.0e+05 ions/cm2 , DUT 22, VDS= 600.0 V, VGS= 0.0 V





E Appendix: Tests at CERN

E.1. LET estimation

During the experiments (2017-11-30 – 2017-12-01) at the H8 beam line at CERN, the beam energy was set to 40 GeV/n. The calculation of the LET for particles of the energies cannot be done easily e.g. with SRIM. SRIM does not cover all interactions with matter at these energies and has a built-in limitation to ion energies of 10 GeV/n. Thus a realistic LET cannot be determined using SRIM.

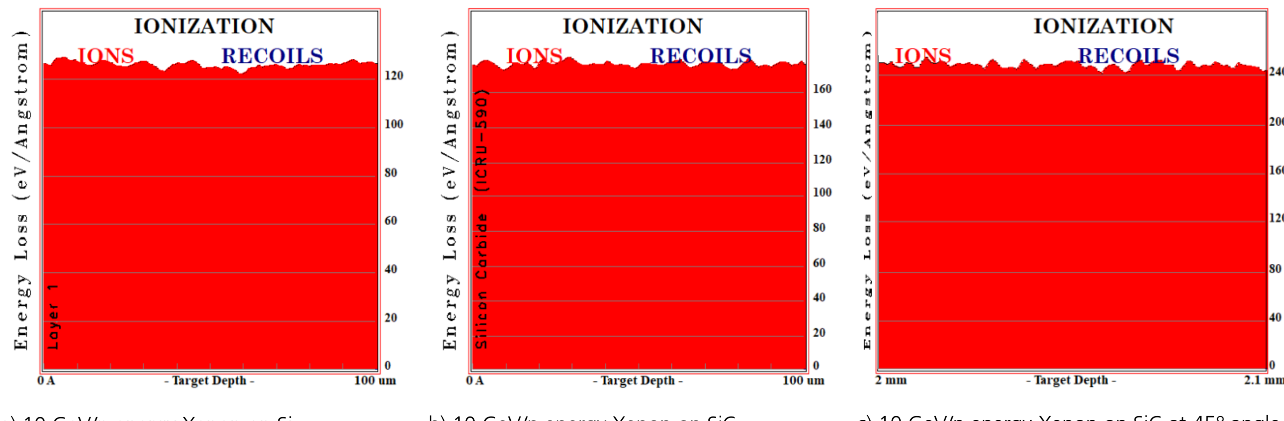
The LET values for silicon were simulated with FLUKA up to energies > 100 GeV/n and with SRIM up to 10 GeV/n by Rubén García Alía et al. and reported in [15]. There different LET values were considered, one unrestricted value taking into account all ionization caused by the beam (approx. 6.3 MeV cm^2/mg) and a volume-restricted value covering the area of a 9.3 MeV/n Silicon particle track (approx. 3.7 MeV cm^2/mg).

Up to energies of 10 GeV/n, the SRIM results closely follow the volume-unrestricted simulations in FLUKA. However, comparisons with the ESA SEU monitor in [15] indicate that the volume-restricted LET is a more proper expression for the particle LET in Silicon.

We will give only an approximation of the LET in SiC by looking at the similarity of results in Si and SiC with SRIM at 10 GeV/n energy. After that we compare simulations with and without a plastic package at that energy. Any air gap or beam exit window is ignored in these simulations, so the particles enter either the target material or a package immediately.

Figure 64 shows a constant ionization profile in a 100 µm layer of Si (left side) and SiC (right side). Taking the target density and the statistical fluctuations into account, the LETs amount to (5.43 ± 0.06) MeV cm^2/mg for Si and (5.47 ± 0.05) MeV cm^2/mg for SiC. Introducing a 2 mm plastic package (Si1-O2-C1-H1 as defined in Appendix C.1) in front of the SiC does not alter the LET at all and again gives (5.47 ± 0.05) MeV cm^2/mg (image not shown).

Figure 64: SRIM2013 simulations of Xenon ions of 10 GeV/n energy on Si and SiC



a) 10 GeV/n energy Xenon on Si b) 10 GeV/n energy Xenon on SiC c) 10 GeV/n energy Xenon on SiC at 45° angle

The Silicon LETs are in the same range as the SRIM-simulated ones from [15] and the unrestricted LETs simulated with FLUKA.

Finally we make two assumptions, both of which cannot be validated here:

1. If Si and SiC still yield the same results at 40 GeV/n, the LET would then be approx. 6.3 MeV cm^2/mg.
2. As mentioned above, measurements in Silicon showed that the volume-restricted LET is more representative for the particle LET in Silicon, however we have no indication about that in SiC. Assuming similar behaviour, then the more proper LET of the 40 GeV/n in SiC would still be identical to the value of approx. 3.7 MeV cm^2/mg in Silicon.

Thus in the end we assume the 40 GeV/m Xenon LET in SiC to be identical with the LET in Si based on the SRIM simulation results with Si and SiC at 10 GeV/n energy and assuming similarity at higher energies.

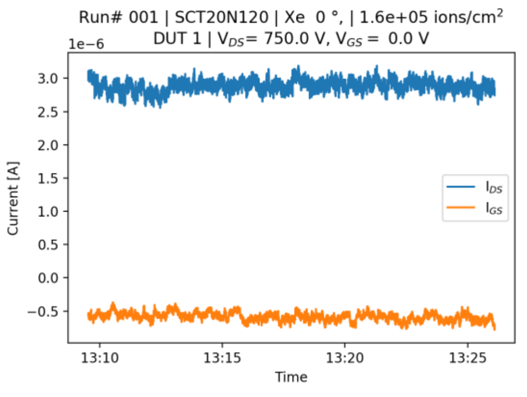
Additional simulations were performed with the ion beam directed under 45° angle to the SiC (tests were done at 42°). The SRIM results give an LET of (7.72 ± 0.07) MeV cm^2/mg, which follows the rule of effective LET proportional to $1/\cos(\Theta)$. However in general the concept of effective LET is not valid for power devices [3] and all data collected at these settings further implicate that assuming a larger LET is invalid.

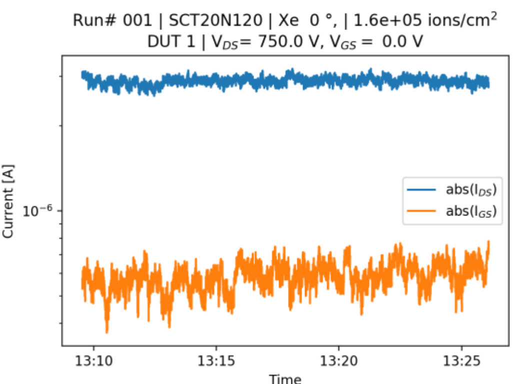
E.2. Logfile / Test steps

#	Date	Time	Ion	Tilt [°]	Device Type	Device	DUT #	V_DS, V	V_GS	beam time [s]	fluence [cm-2]
001	30.11.	13:10	Xe	0	MOSFET	SCT20N120	1	750	0	9.60E+02	1.60E+05
002	30.11.	13:33	Xe	0	MOSFET	SCT20N120	1	900	0	1.00E+03	1.67E+05
003	30.11.	13:54	Xe	0	MOSFET	SCT20N120	1	1050	0	3.80E+01	6.33E+03
004	30.11.	14:01	Xe	0	MOSFET	SCT20N120	2	900	-5	9.95E+02	1.66E+05
005	30.11.	14:20	Xe	0	MOSFET	SCT20N120	2	900	-10	1.00E+03	1.67E+05
006	30.11.	14:41	Xe	0	MOSFET	SCT20N120	2	1050	-10	4.00E+01	6.67E+03
006	30.11.	14:41	Xe	0	MOSFET	SCT20N120	2	1050	-10	4.00E+01	7.00E+03
007	30.11.	14:50	Xe	0	MOSFET	SCT20N120	4	950	-10	4.20E+01	1.67E+05
008	30.11.	15:49	Xe	0	MOSFET	SCT20N120	5	900	0	1.00E+03	4.50E+03
009	30.11.	16:11	Xe	0	MOSFET	SCT20N120	5	950	0	2.70E+01	6.00E+05
010	30.11.	16:16	Xe	0	MOSFET	SCT20N120	6	900	-10	3.60E+03	1.80E+02
011	01.12.	10:22	Xe	0	MOSFET	SCT20N120	6	950	-10	2.70E+01	1.60E+05

E.3. Measurement

Figure 65: Run# 001, SCT20N120, Xe 0 °,, 1.6e+05 ions/cm2 , DUT 1, VDS= 750.0 V, VGS= 0.0 V





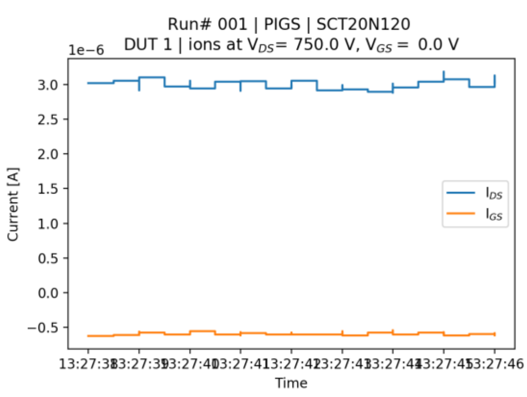
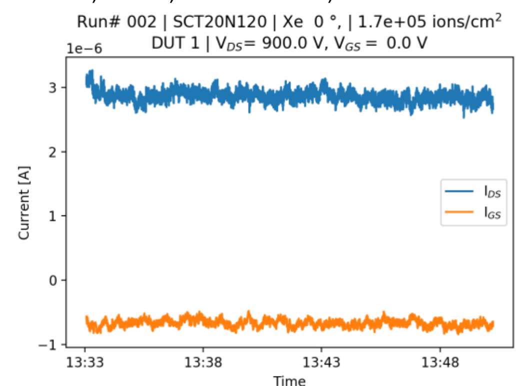
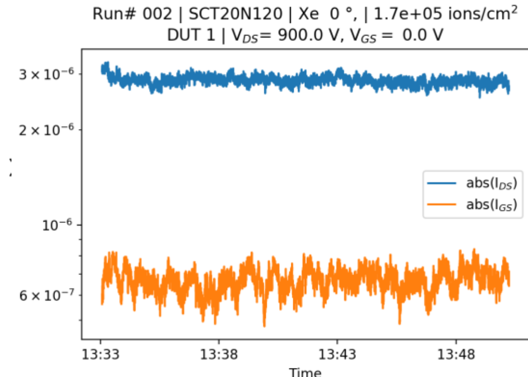


Figure 66: Run# 002, SCT20N120, Xe 0 °,, 1.7e+05 ions/cm2 , DUT 1, VDS= 900.0 V, VGS= 0.0 V





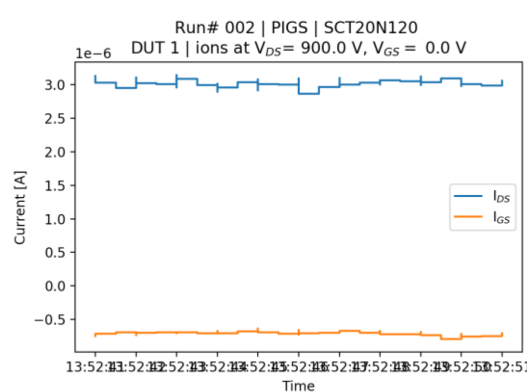
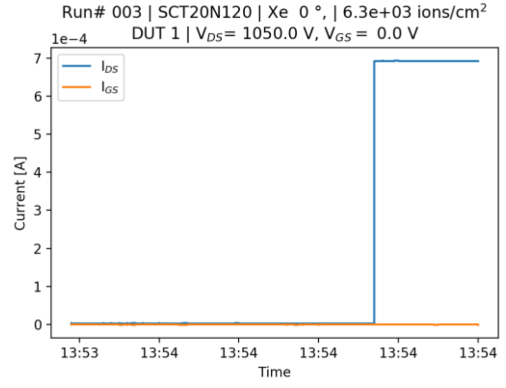
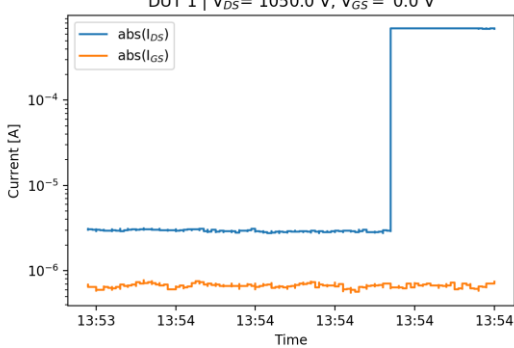


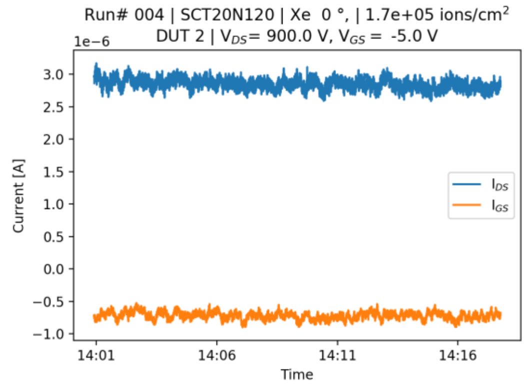
Figure 67: Run# 003, SCT20N120, Xe 0 °,, 6.3e+03 ions/cm2 , DUT 1, VDS= 1050.0 V, VGS= 0.0 V

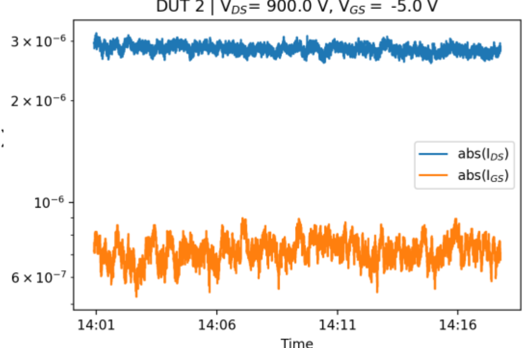




Run# 003 | PIGS | SCT20N120
DUT 1 | ions at V_{DS}= 1050.0 V, V_{GS} = 0.0 V

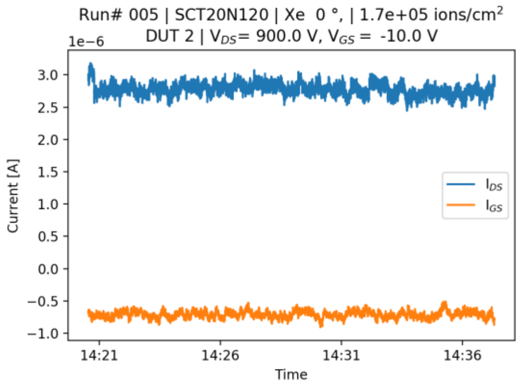
Figure 68: Run# 004, SCT20N120, Xe 0 °,, 1.7e+05 ions/cm2 , DUT 2, VDS= 900.0 V, VGS= -5.0 V





Run# 004 | PIGS | SCT20N120
DUT 2 | ions at V_{DS}= 900.0 V, V_{GS} = -5.0 V

Figure 69: Run# 005, SCT20N120, Xe 0 °,, 1.7e+05 ions/cm2 , DUT 2, VDS= 900.0 V, VGS= -10.0 V



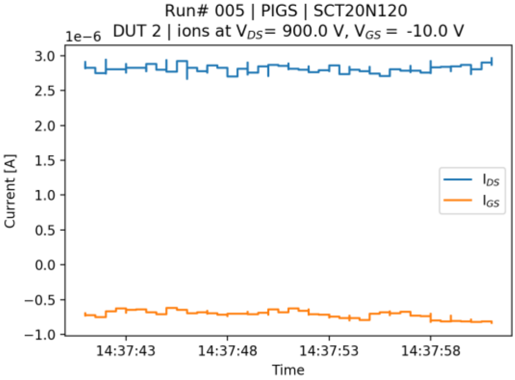


Figure 70: Run# 006, SCT20N120, Xe 0 °,, 6.7e+03 ions/cm2 , DUT 2, VDS= 1050.0 V, VGS= -10.0 V

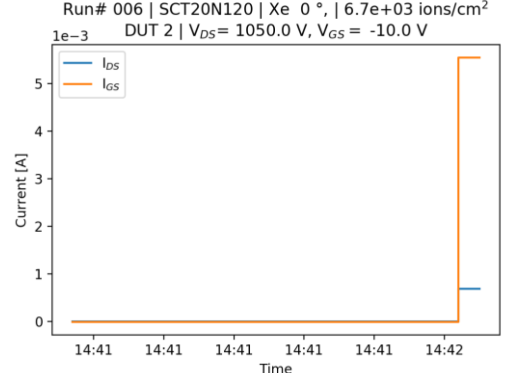


Figure 71: Run# 007, SCT20N120, Xe 0 °,, 7.0e+03 ions/cm2 , DUT 4, VDS= 950.0 V, VGS= -10.0 V

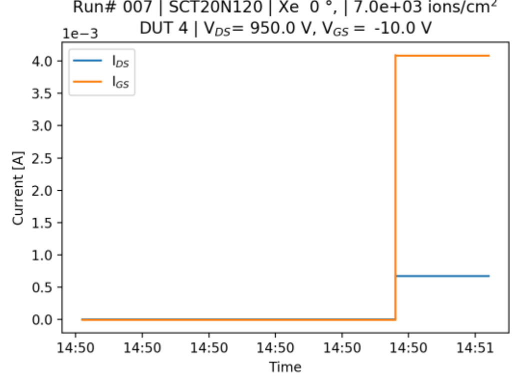
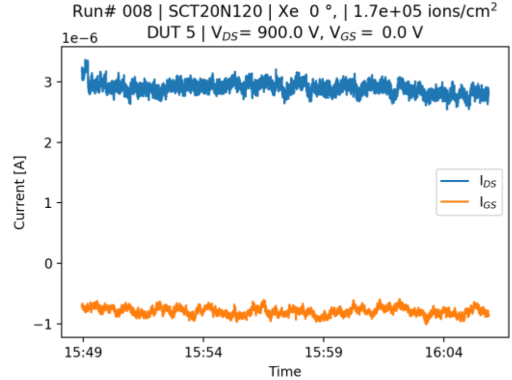
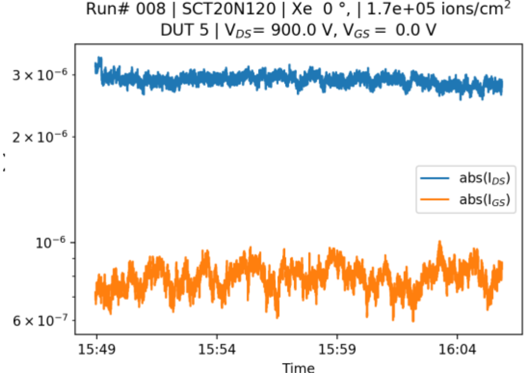


Figure 72: Run# 008, SCT20N120, Xe 0 °,, 1.7e+05 ions/cm2 , DUT 5, VDS= 900.0 V, VGS= 0.0 V





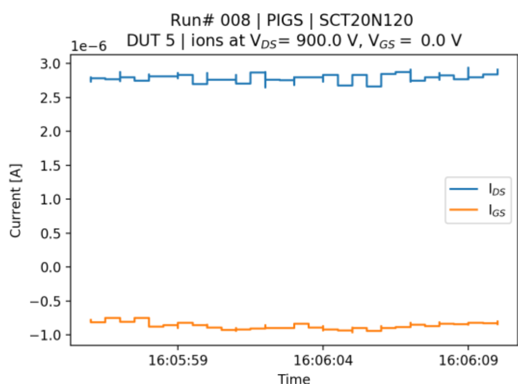
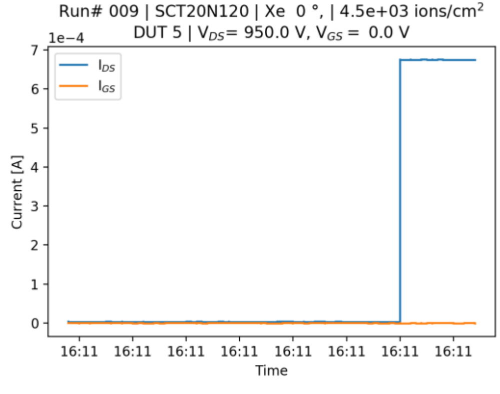


Figure 73: Run# 009, SCT20N120, Xe 0 °,, 4.5e+03 ions/cm2 , DUT 5, VDS= 950.0 V, VGS= 0.0 V



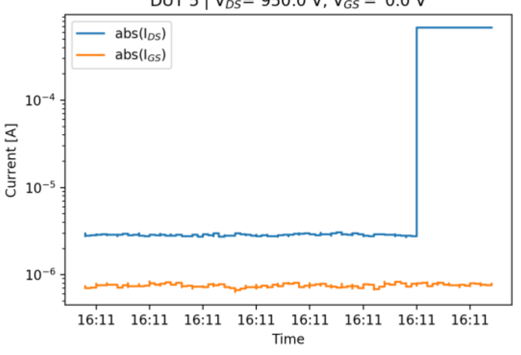
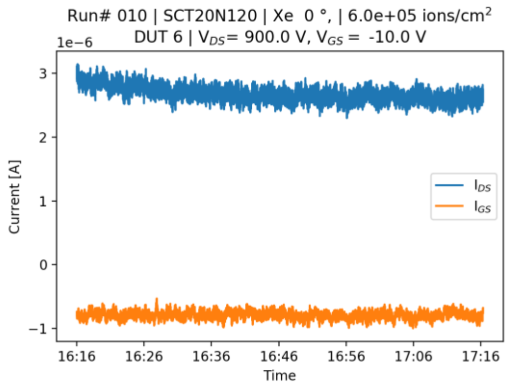
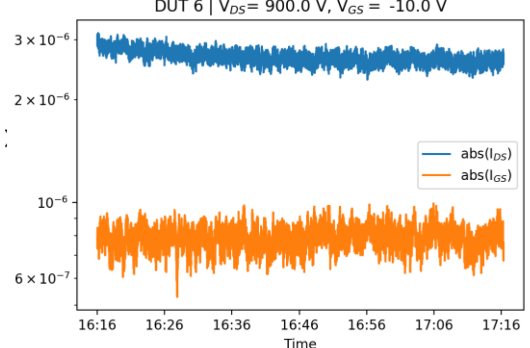


Figure 74: Run# 010, SCT20N120, Xe 0 °,, 6.0e+05 ions/cm2 , DUT 6, VDS= 900.0 V, VGS= -10.0 V





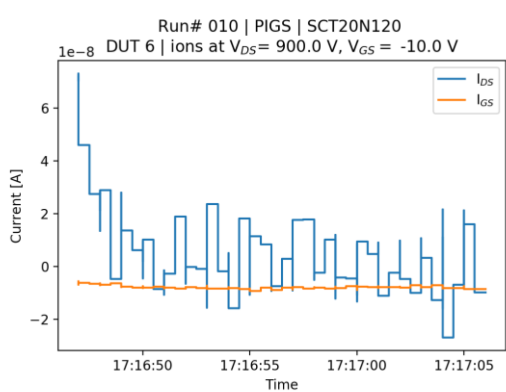


Figure 75: Run# 011, SCT20N120, Xe 0 °,, 1.8e+02 ions/cm2 , DUT 6, VDS= 950.0 V, VGS= -10.0 V