Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen (INT)

Fraunhofer INT

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

TN6.3
SEE Test Report for
SiC Schottky Diode IDW10G120C5B

Manufacturer: Infineon

Date code/Lot code:

D1012B5 / HAA527 (UCL/GANIL/JULIC) and D1012B5 / HAO714 (CERN)

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068/2018	2.0	2019-06-07	NEO-14-086
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Customer	Project management
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Document Approval

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Version history

Table 1: Revision history

Version	Date	Changed by	Changes
0.1	2019-03-12	Steffens	Initial draft, Sections 1-5, Appendices A+B
1.0	2019-05-10	Steffens	Initial Release
2.0	2019-06-07	Steffens	Removal of empty Section 9, Fixed header of Appendices, Added remark on total fluences in tests at CERN (2.2, 8.5)

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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 Schottky Diode IDW10G120C5B from Infineon for the ESA project "Survey of Total Ionizing Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE" (ESA-TOPSIDE, AO/1-8148/14/NL/SFe) under contract number 4000113976/15/NL/RA.

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

1.2 Applicable Documents

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

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

1.3 Reference Documents

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

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

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

[4] Datasheet of SiC Schottky Diode IDW10G120C5B, "IDW10G120C5B 5th Generation thinQ!™ 1200 V SiC Schottky Diode", Infineon, Final Datasheet Rev. 2.0 2014-06-10

[5] TN3.3 "SEE (HI) Test Plan IDW10G120C5BFKSA1 (Schottky Diode)", Issue 1 Revision 4, 2018-04-15

[6] TN3.9 "SEE (p) Test Plan IDW10G120C5BFKSA1 (Schottky Diode)", Issue 1 Revision 1, 2017-07-25

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

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

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

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

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

[12] 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/

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

[14] 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

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

2 Summary

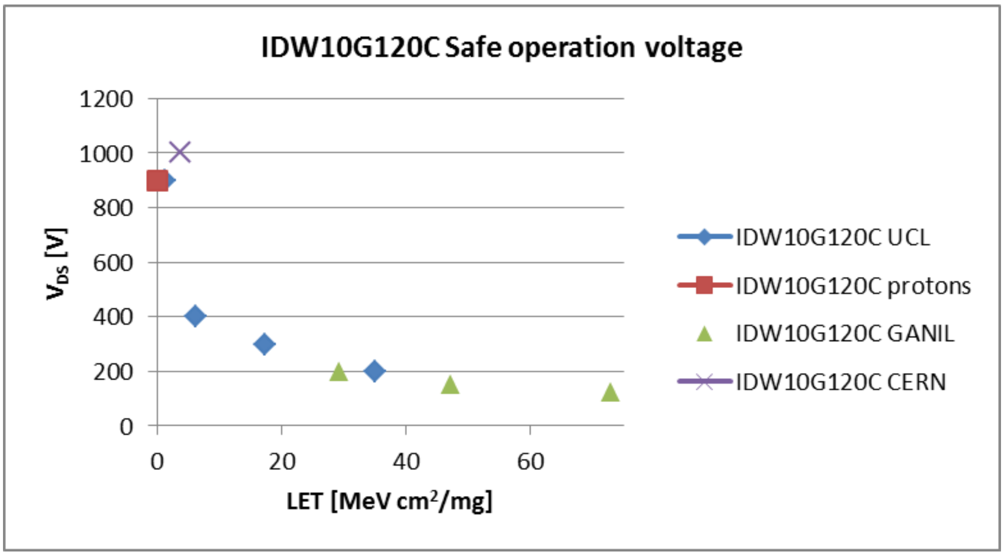
Table 2: Summary

Test Report Number	068/2018
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	IDW10G120C5B
Family	SiC Schottky Diode
Technology	NPN high voltage bipolar transistor
Package	Hermetic TO220 Isolated Metal Package
Date code / Wafer lot	D1012B5 / HAA527 (UCL/GANIL/JULIC) and D1012B5 / HAO714 (CERN)
SN	UCL: #11, #12, #13, #14, #15, #16 GANIL: #17, #18, #19 CERN: #3 (delivery #2) JULIC: #1, #2 (previously Gamma irradiated)
Manufacturer	Infineon
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	TN3.3 "SEE (HI) Test Plan IDW10G120C5BFKSA1 (Schottky Diode)", Issue 1 Revision 4, 2018-04-15 TN3.9 "SEE (p) Test Plan IDW10G120C5BFKSA1 (Schottky Diode)", Issue 1 Revision 1, 2017-07-25
Single/Multiple Exposure	Multiple
Parameters tested	Reverse current
Dates	UCL: 2018-04-16 – 2018-04-17 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



The heavy ion tests at UCL with the SiC Schottky Diode IDW10G120C5B were performed with 4 different LETs at a reduced target fluence of 3E5 ions/cm^2. Considering the rather low number of devices, that number of LETs was only achievable by testing each of the two diodes per package separately, thus effectively doubling the number of available devices. We see no correlation that diode #2 in any package is more likely to fail if diode #1 already failed thus this approach was used in all campaigns.

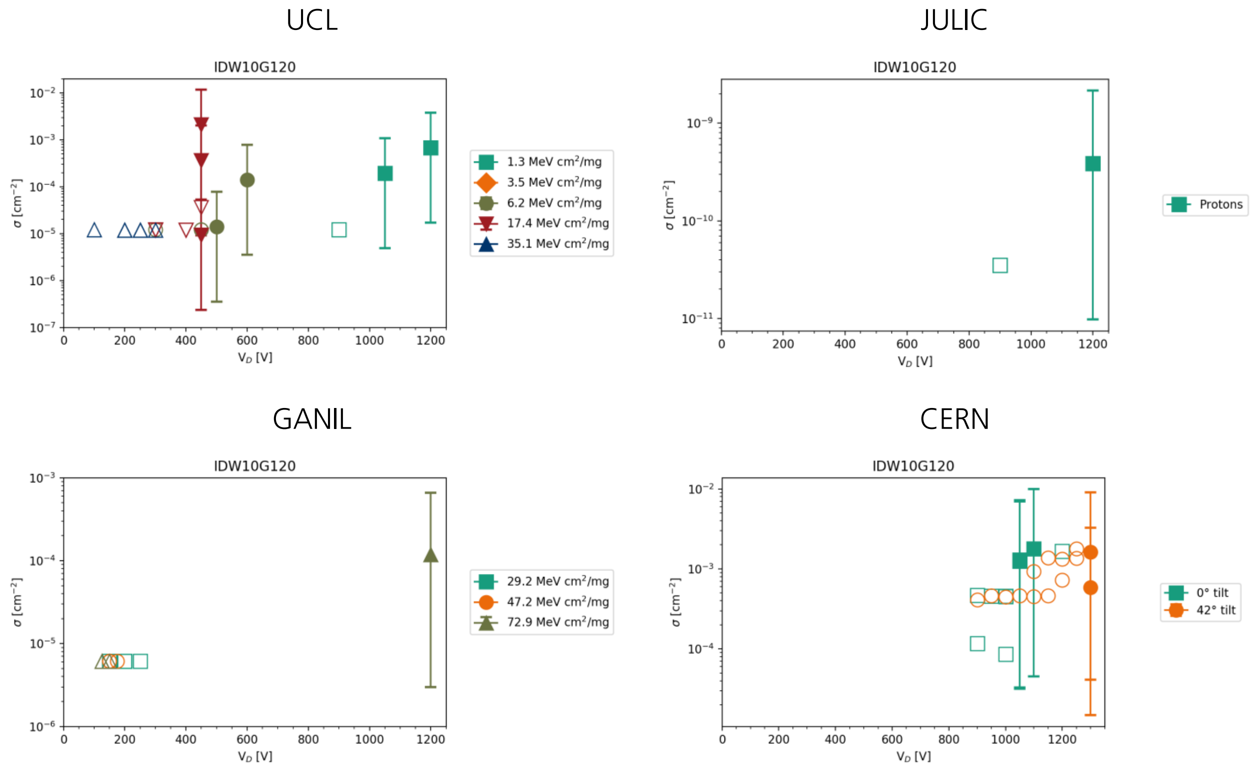
The voltage achievable for a safe operation up to the target fluence decreases from 900 V with carbon ions (LET = 1.3 MeV cm^2/mg) down to 200 V with Krypton (LET = 35.1 MeV cm^2/mg).

The voltage achievable for a safe operation with the GANIL Xenon ions decrease down to 125 V at these larger LETs and the proton, UCL and GANIL results give roughly an overall trend of the minimum voltage for safe operation.

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 1000 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.

Additionally, in tests with tilted devices at CERN the DUTs could be operated at voltages larger than the nominal rating without failing, however the fluences achieved at CERN are comparatively low.

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 JULIC:**
  - Tests were performed with packaged DUTs.
  - Test devices were previously tested with Co-60 to 1 Mrad(Si).
- **Tests at CERN:**
  - Tests were performed with packaged DUTs.
  - The effective fluences across the tests were <4.3E4 ions/cm². This very 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.

- Additional tests with tilted devices were performed. In these the DUTs could be operated at higher voltages without failures than at normal incidence.

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 (D1012B5 / HAA527) 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 D1012B5 / HAO714. 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

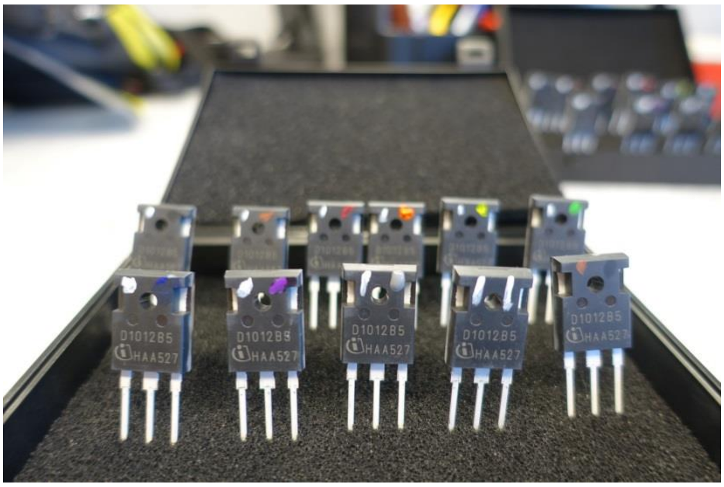
Figure 3: The ESD package with the samples

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



3.3 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.

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.

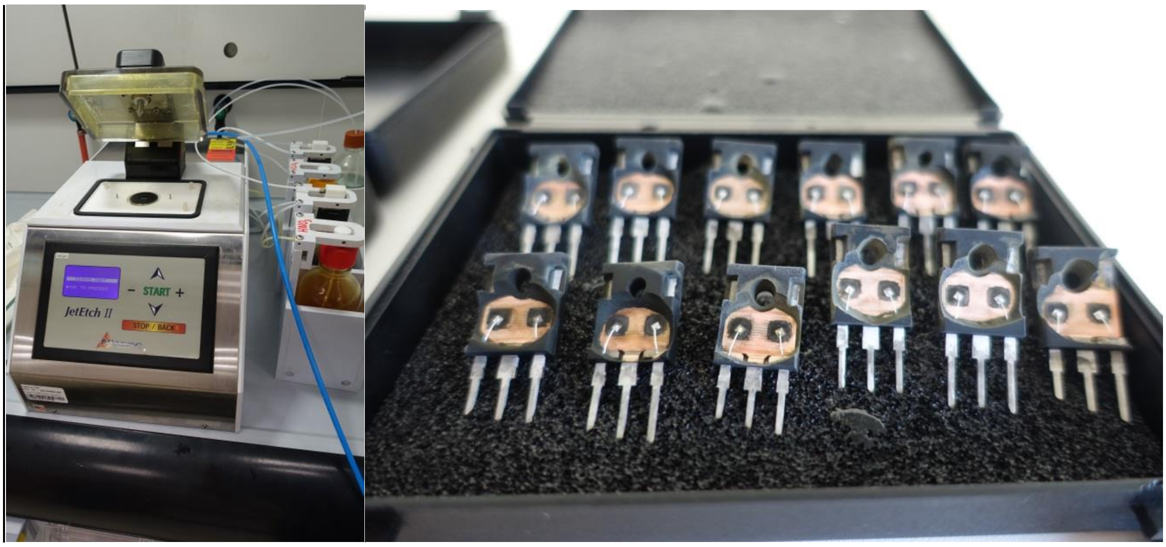
Condition	S/N	Color Code	Comment
D1012B5 / HAA527			
UCL	11		decap, coated
	12		decap, coated
	13		decap, coated
	14		decap, coated
	15		decap, coated
	16		decap, coated
GANIL	17		decap, coated
	18		decap, coated
	19		decap, coated
JULIC	1		non-decap, previously used for TID
	2		non-decap, previously used for TID
D1012B5 / HAO714			
CERN	3		non-decap

3.4 Sample decapsulation and preparation

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

DUT decapsulation was performed at INT using a Nisene JetEtchII (Figure 5). The JetEtch II uses spray of acid, in our case a 2:1 micture of sulfuric to nitridic acid, to remove the capping layers covering the dye and the active region of the device without inducing mechanical stress on the device. Decapsulation was performed with the device already soldered onto their respective socket adapters.

Figure 5: DUT decapsulation. Left side: Nisene JetEtch II at INT. Right side: batch of decapsulated IDW10G120C5B



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.

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

Tests of the reverse current performed at INT after receiving the coated samples, are shown in Figure 6. Two diodes are in each package and these were tested separately. Although device #17 deviates from the other tested devices, it is still well within the datasheets limits of max. 40 µA per leg. Thus all devices were considered for the SEE tests.

Figure 6: Functional tests after paralene coating

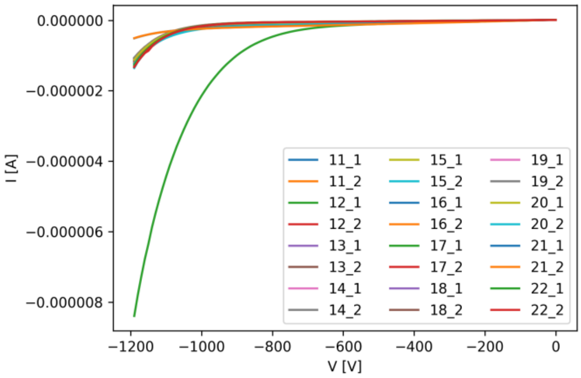
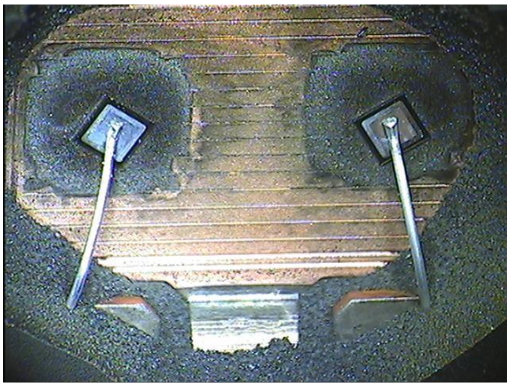
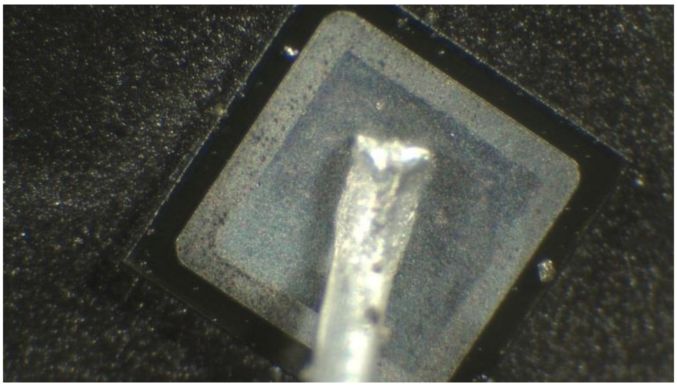
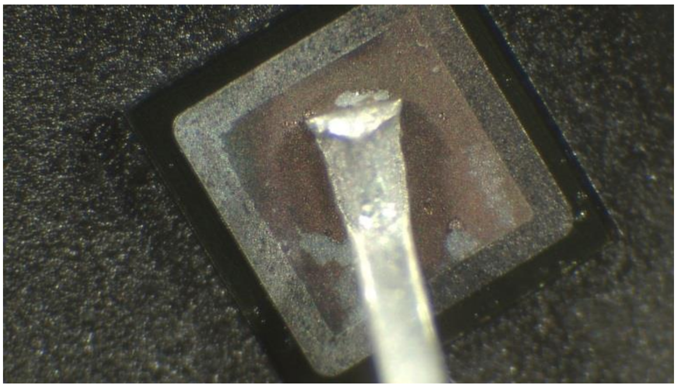


Figure 7: Die pictures. Images were taken with different optical microscopes. The camera used before the tests has a lower quality and resolution.



DUT #11 before tests at UCL





DUT #11 after tests at UCL (Top: left diode, bottom: right diode)

Figure 7 shows microscopic images of one DUT (#11) 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.

3.5 Sample safekeeping

The samples were stored in an Electro-Static Discharge (ESD) box (Figure 5) to handle them safely during the test, the interim storage after the last measurement and the final shipment.

4 Setup and Measurements

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

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

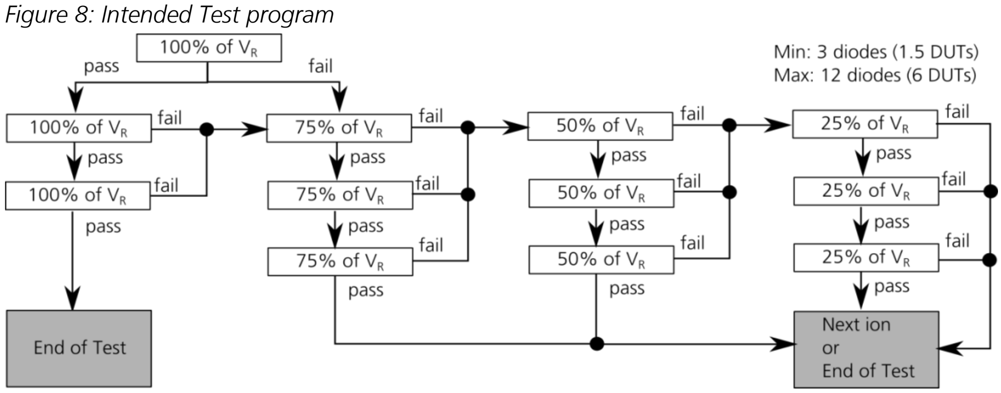
Due to a limited number of devices and having destructive failures which could not be mitigated, the required number of 3 samples to check the pass compliance of each test is not reached in any case.

4.1 Intended test program

The test logic is shown in Figure 8. As there are no applicable test standards or MIL test methods concerning Schottky diode SEE tests, the intended test logic follows mostly the approach for silicon Schottky diodes of Casey et. al. [7].

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

Figure 8: Intended Test program



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

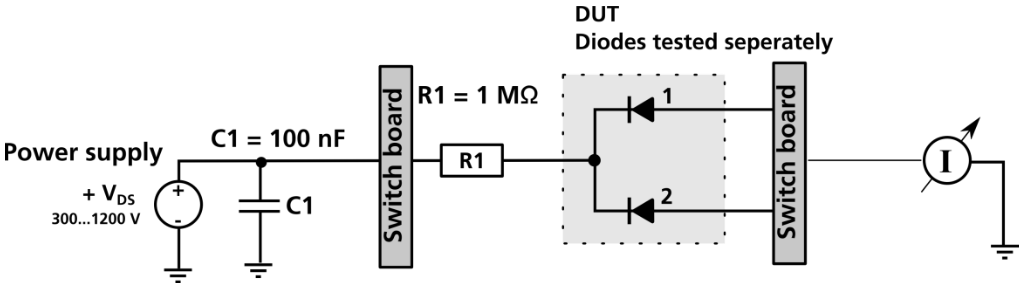
4.2 Test Board and Detection Circuit

A custom-build printed-circuit board (Figure 10) was manufactured to

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

To reduce the number of parts required for testing, the two diodes in each DUT are biased separately (Figure 9). No mitigation of destructive events is foreseen.

Figure 9: Detection Circuit



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

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

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

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

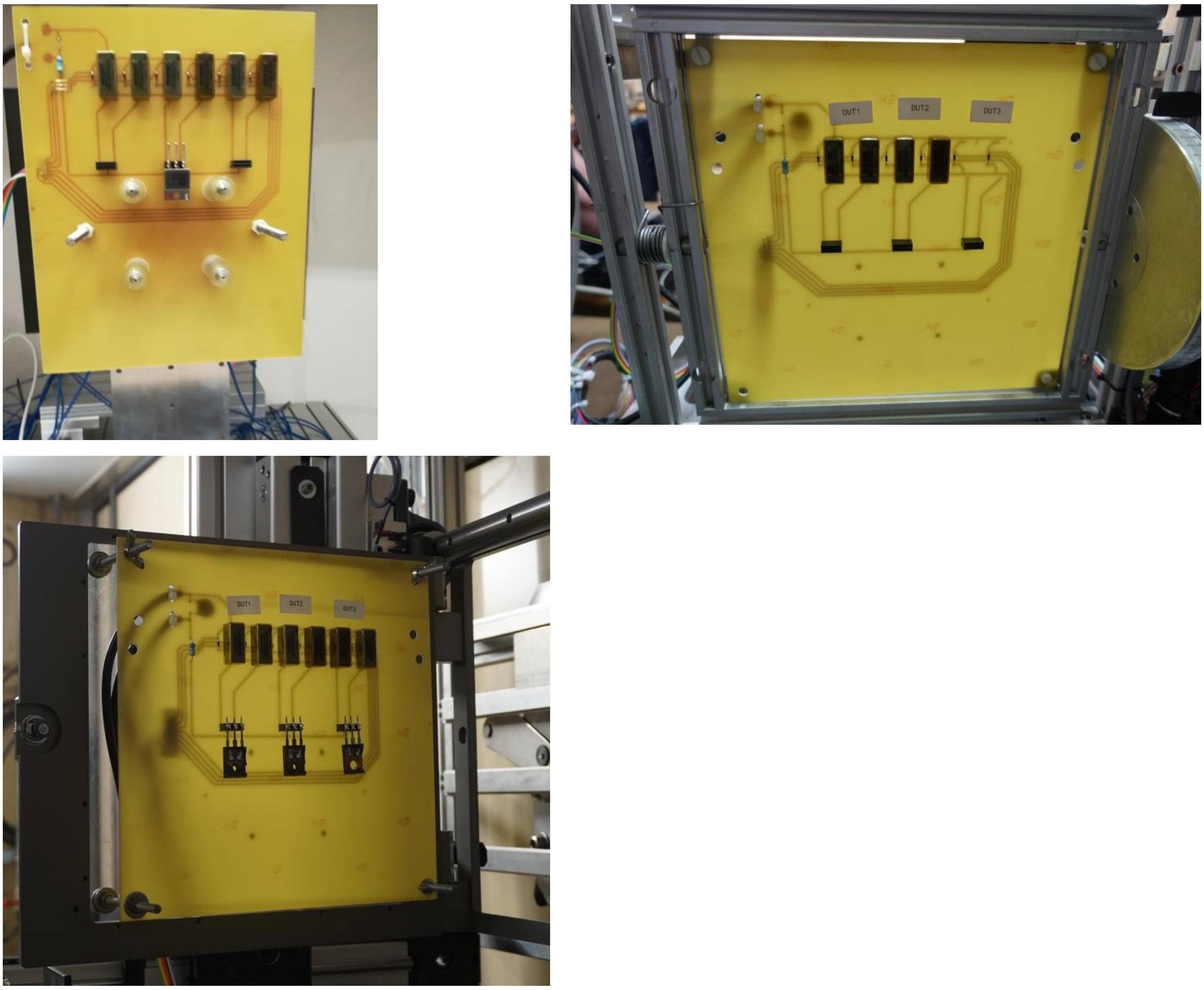
4.3 Measurement parameters

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

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

No.	Characteristics	Symbol	Remark
1	Reverse Voltage	V_D	Set according to test flow
2	Reverse Current	I_D	Monitored, typ. 3 µA @ 1200 V, max. 40 µA @ 1200 V per Leg

Figure 10: 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



4.4 Measurement equipment

The test equipment is shown in Table 6 - Table 9 and Figure 11 - Figure 14.

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

Table 6: UCL: Measurement equipment and instrumentation

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

Figure 11: UCL: Measurement equipment/setup (including equipment for MOSFET/JFET tests)

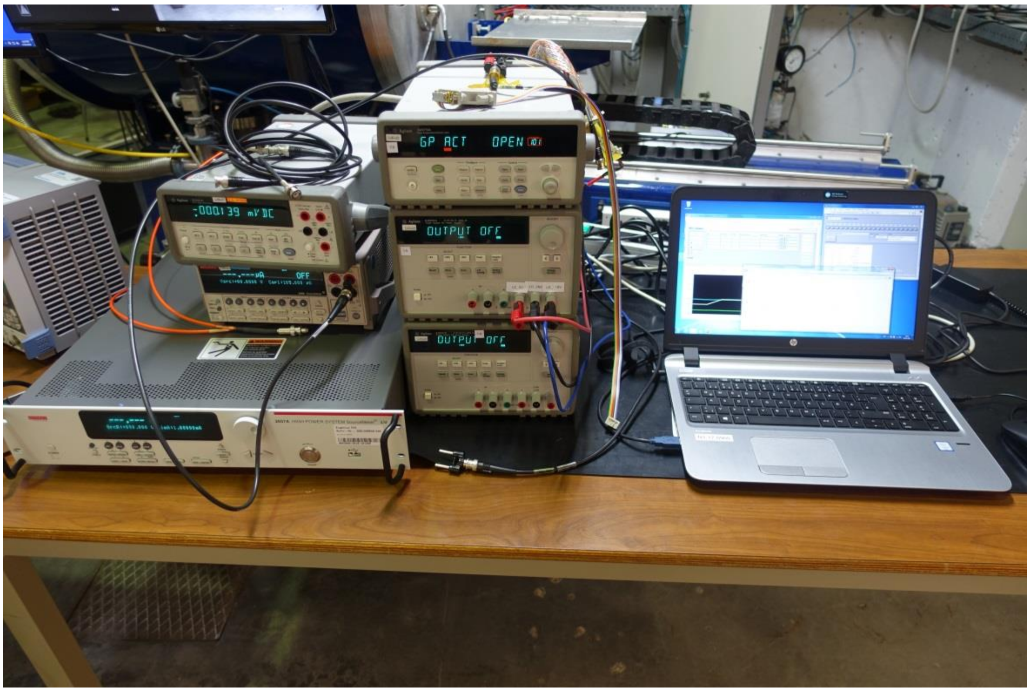


Table 7: GANIL: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2020	V_D, I_D
Data	Agilent	34970A	E-SMF-002	n/a	Switch matrix

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
Acquisition/Switch unit					
Triple Output Power Supply	Agilent	E3631A	E-PS3-001	n/a	Power supply of of relais

Figure 12: GANIL: Measurement equipment/setup (including equipment for MOSFET/JFET tests)

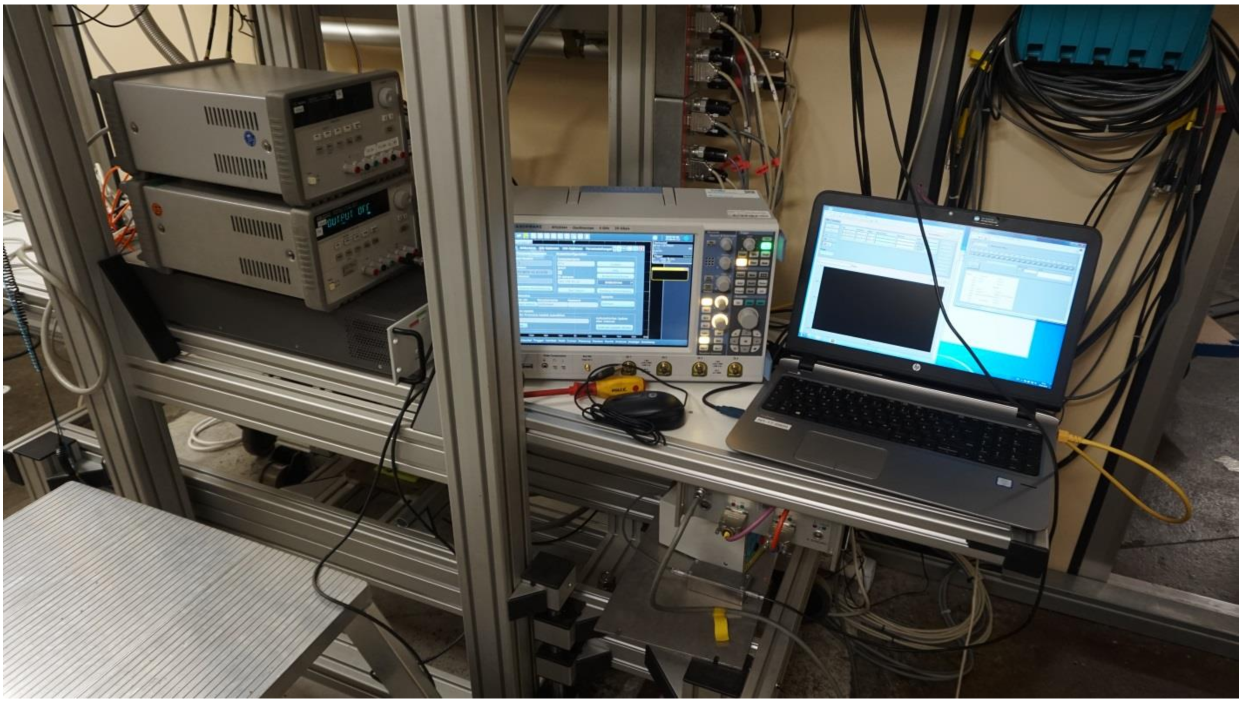


Table 8: CERN: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
High Power System Source Meter	Keithley	2657A	E-SMU-012	03/2020	V_D, I_D
Data Acquisition/Switch unit	Agilent	34970A	E-SMF-002	n/a	Switch matrix
Triple Output Power Supply	Agilent	E3631A	E-PS3-001	n/a	Power supply of relais

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
Step motor	ISEL	LES4	--	n/a	Moving samples along 1 direction
Linear guide	ISEL	IT116 G	--	n/a	Moving samples along 1 direction

Figure 13: CERN: Measurement equipment/setup.

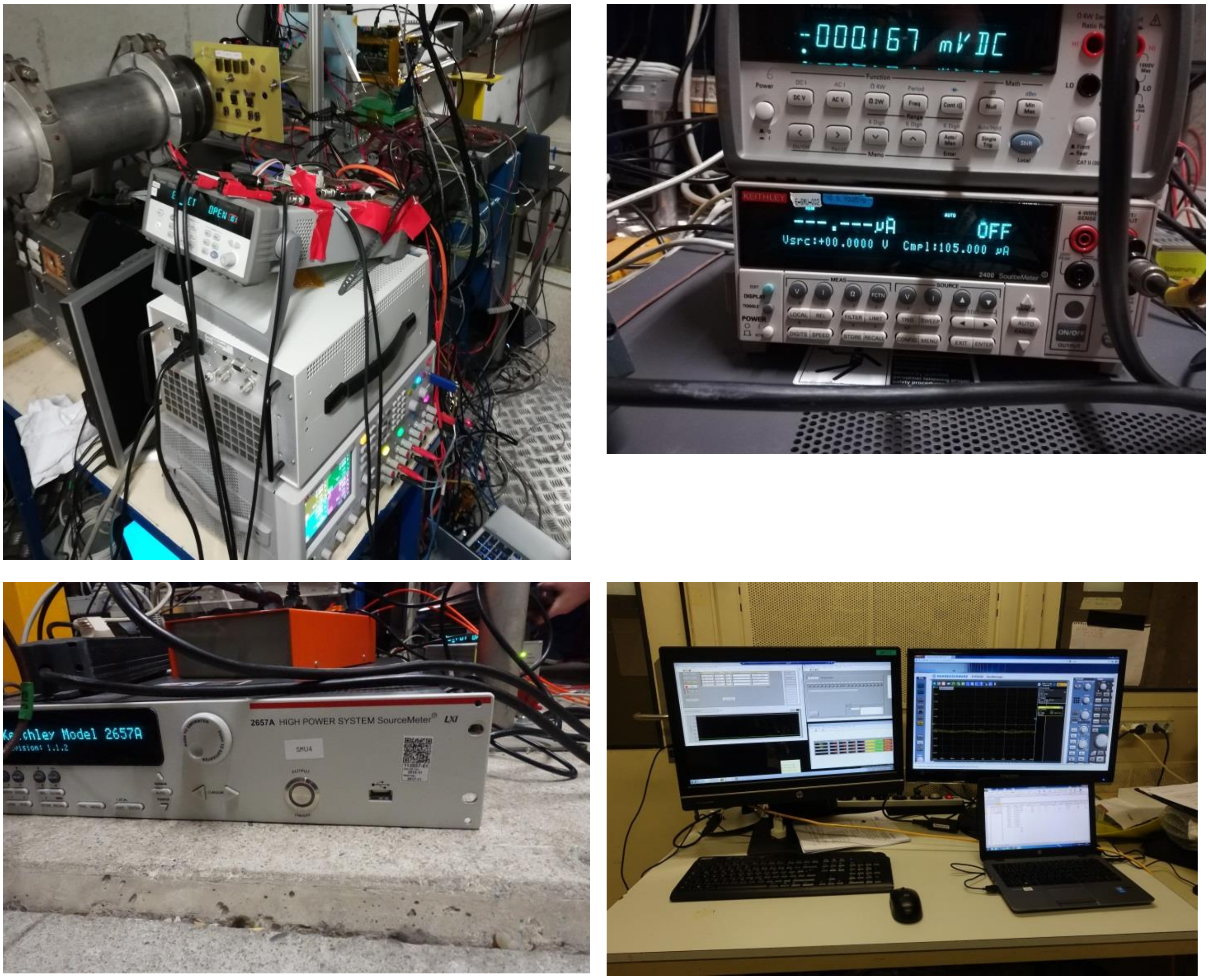


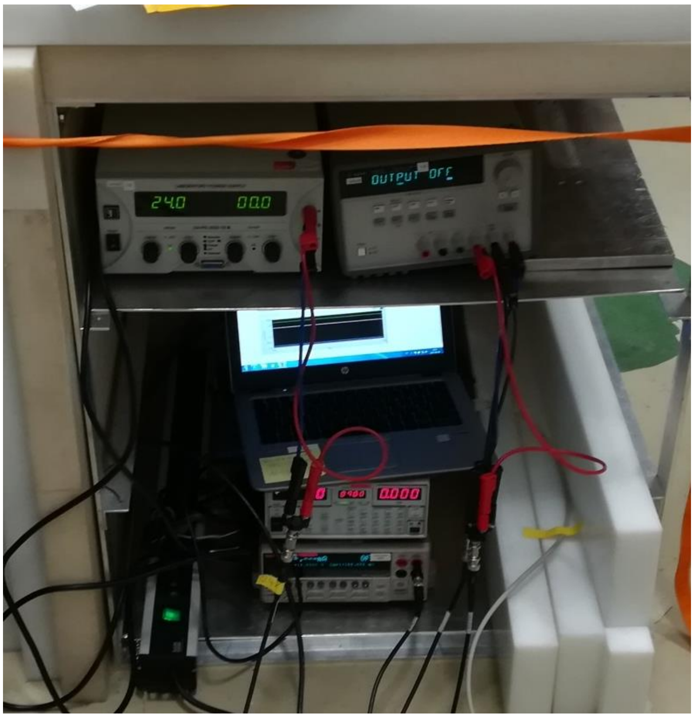
Table 9: JULIC: Measurement equipment and instrumentation

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
5 kV Power	Keithley	2290E-5	E-PS1-030	10/2017	V_D, I_D

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
supply					
Laboratory Power Supply	EA	EA-PS-3032-10B	E-PS1-001	n/a	Control of relais

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

Figure 14: JULIC: Measurement equipment/setup (including equipment for MOSFET/JFET tests)



4.5 Measurement procedures

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

5 Tests at UCL

5.1 Facility

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

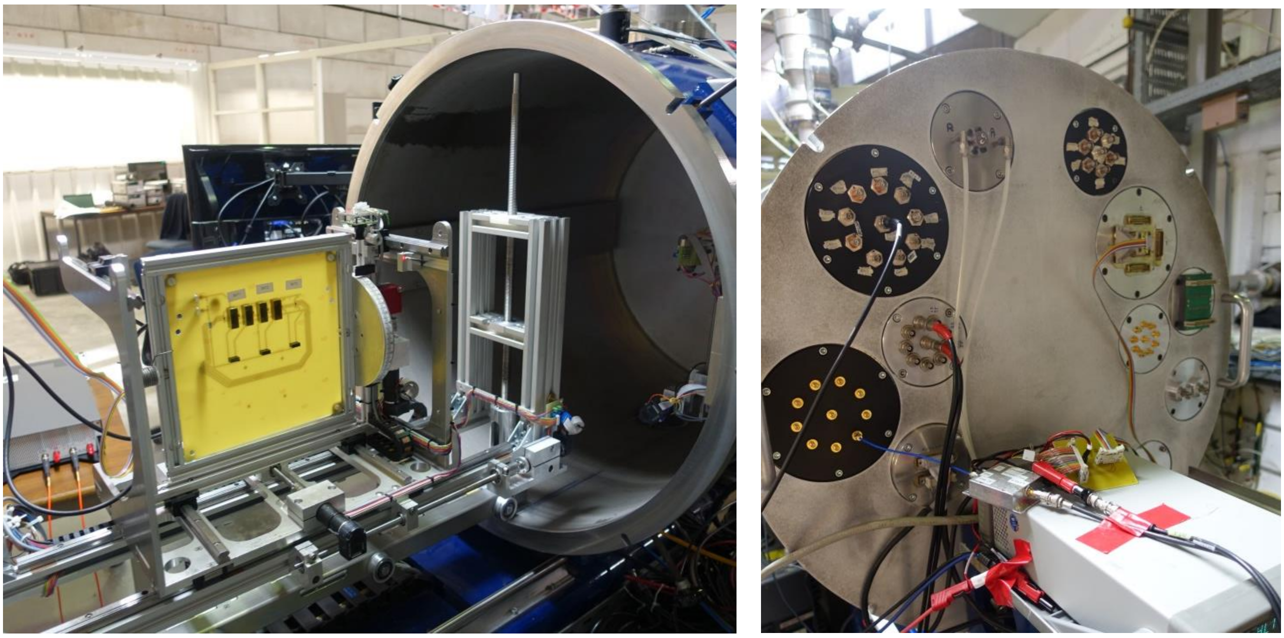
The facility can provide selected heavy ion beams from Carbon to Xenon in a particle cocktail with mass/charge ratio of approx. M/Q=3.3, allowing to switch from ion species to ion species quickly within the cocktail.

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

Feedthroughs can be used to connect boards within the enclosure with outside instrumentation (Figure 15).

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



5.2 Beam parameters

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

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

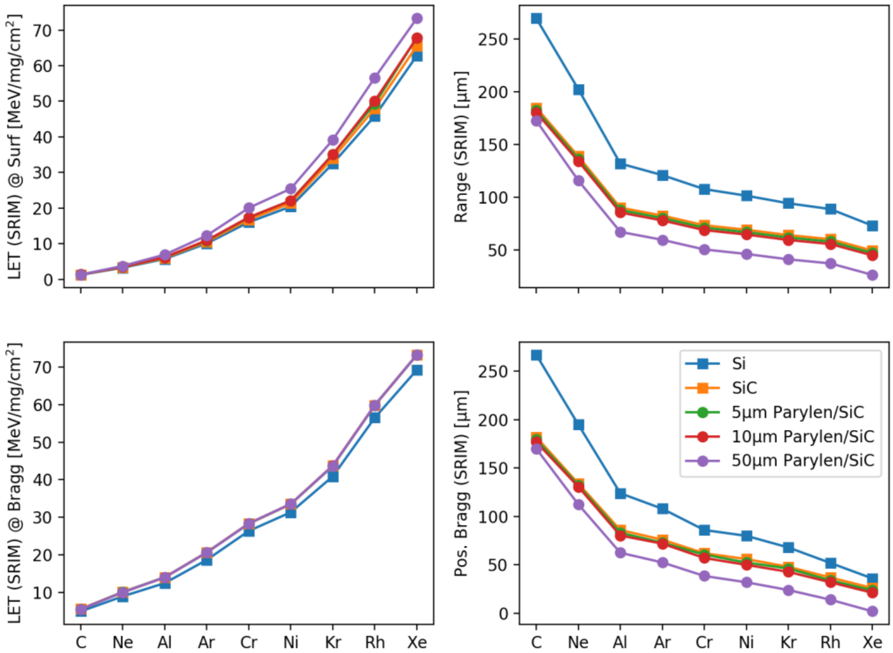
Tests with the IDW10G120C5B were only performed with ions marked in bold letters in Table 10.

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

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

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

Figure 16: Plot of LETs and Ranges in Silcon Carbide at UCL. Additional data with Paralene layers and data for Silicon are included. Thin Paralene layers have limited impact.



5.3 Geometry

The board is attached to the moveable board holder (Figure 15) which can be fully retracted from the chamber for ease of access. Tests are then performed with the chamber sealed and evacuated.

5.4 Irradiation steps

The log file of the tests performed at UCL can be found in Appendix B. Table 11 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**.

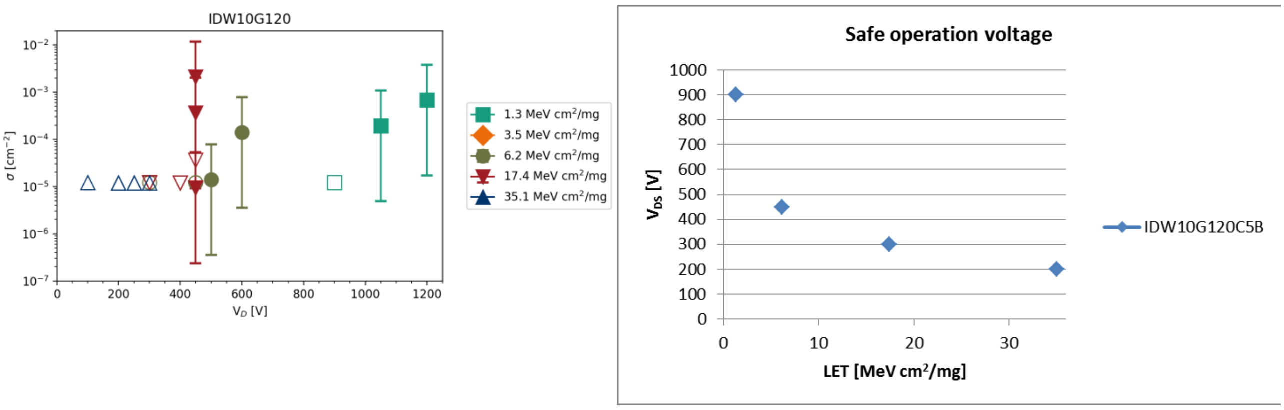
Fraunhofer INT

Table 11: UCL: Irradiation steps of SiC Schottky Diode IDW10G120C5B. Numbers indicate the DUT serial number from Table 4. Table cells without numbers indicate that no run was performed under these conditions. Green or red background color indicate PASS or FAIL respectively. If a DUT fails at some voltage, all higher voltages are also indicated as fail. Yellow color (if applicable) indicates mixed results (e.g. 1 DUT passing, 1 DUT failing at the same level) or non-conclusive results with the device showing some damage not clearly attributable to a fail.

	C		Ne		Al		Cr		Kr	
V_R [V]	1.3		3.5		6.2		17.4		35.1	
	in-situ	Post	in-situ	Post	in-situ	Post	in-situ	Post	in-situ	Post
100									15.2	
200									15.2, 16.1	
250									16.1, 16.2	
300					11.2		13.1, 14.2		15.2	
400							14.2, 15.1			
450					11.2, 12.1		13.1, 13.2, 14.1			
500					11.2					
600					11.1					
900	12.2									
1050	12.1									
1200	12.2									

5.5 Results

Figure 17: Overview of results: Heavy Ions at UCL. The left image shows the cross section results. Filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run. The right image shows the safe operating voltage. At low voltages, markers for LET 17.4 are overlapped by the 35.1 markers.



The heavy ion tests at UCL with the SiC Schottky Diode IDW10G120C5B were performed with 4 different LETs at 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.

Considering the rather low number of devices, that number of LETs was only achievable by testing each of the two diodes per package separately, thus effectively doubling the number of available devices. We see no correlation that diode #2 in any package is more likely to fail if diode #1 already failed.

The voltage achievable for a safe operation up to the target fluence decreases from 900 V with carbon ions (LET = 1.3 MeV cm^2/mg) down to 200 V with Krypton (LET = 35.1 MeV cm^2/mg). LETs are given in SiC according to Table 10.

Within the runs we see some indication, that there may be an intermediate voltage range beyond that safe operation voltage in which destructive events are less likely, but instead lead to a step of the leakage current of the device.

Table 12: Results: Heavy Ions at UCL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	DUT #	V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
61	Al	11.1	600	7.1E3	3.57E-6	1.41E-4	7.85E-4	FAIL	Destructive failure at indicated fluence
62	Al	11.2	300	3.02E5	0	0	1.22E-5	--	
63	Al	11.2	450	3.01E5	0	0	1.23E-5	--	Several steps in leakeage current observed.
64	Al	11.2	500	7.08E4	3.57E-7	1.41E-5	7.87E-5	FAIL	Destructive failure at indicated fluence. Several steps in leakeage current observed prior to this.
65	Al	12.1	450	3.04E5	0	0	1.21E-5	--	--
66	C	12.2	900	3.03E5	0	0	1.22E-5	--	--
67	C	12.2	1200	1.45E3	1.74E-5	6.87E-4	3.83E-3	FAIL	Destructive failure at indicated fluence
68	C	12.1	1050	5.18E3	4.89E-5	1.93E-4	1.08E-3	FAIL	Destructive failure at indicated fluence
69	Cr	13.1	300	3.02E5	0	0	1.22E-5	--	--
70	Cr	13.1	450	1.06E5	9.18E-6	9.42E-6	4.30E-5	FAIL	Run#70 was stopped after a fluence of 1.02E+05 cm-2 for a post test which the device passed. However after an additional fluence of approx 4E3cm-2 the device failed.
71	Cr	13.1	450						
72	Cr	13.2	450	2.65e+03	9.55e-06	3.77e-04	2.10e-03	FAIL	Destructive failure at indicated fluence
73	Cr	14.1	450	4.66e+02	5.43e-05	2.14e-03	1.19e-02	FAIL	Destructive failure at indicated fluence
74	Cr	14.2	300	3.06e+05	0	0	1.20e-05	--	--
75	Cr	14.2	400	3.10e+05	0	0	1.19e-05	FAIL	Leakage current gradually increases, then shows a pronounced jump in current ..
76	Cr	15.1	400	3.06e+05	0	0	1.20e-05	FAIL	Destructive failure at indicated fluence
77	Kr	15.2	100	3.05e+05	0	0	1.21e-05	--	--
78	Kr	15.2	200	3.09e+05	0	0	1.19e-05	--	--

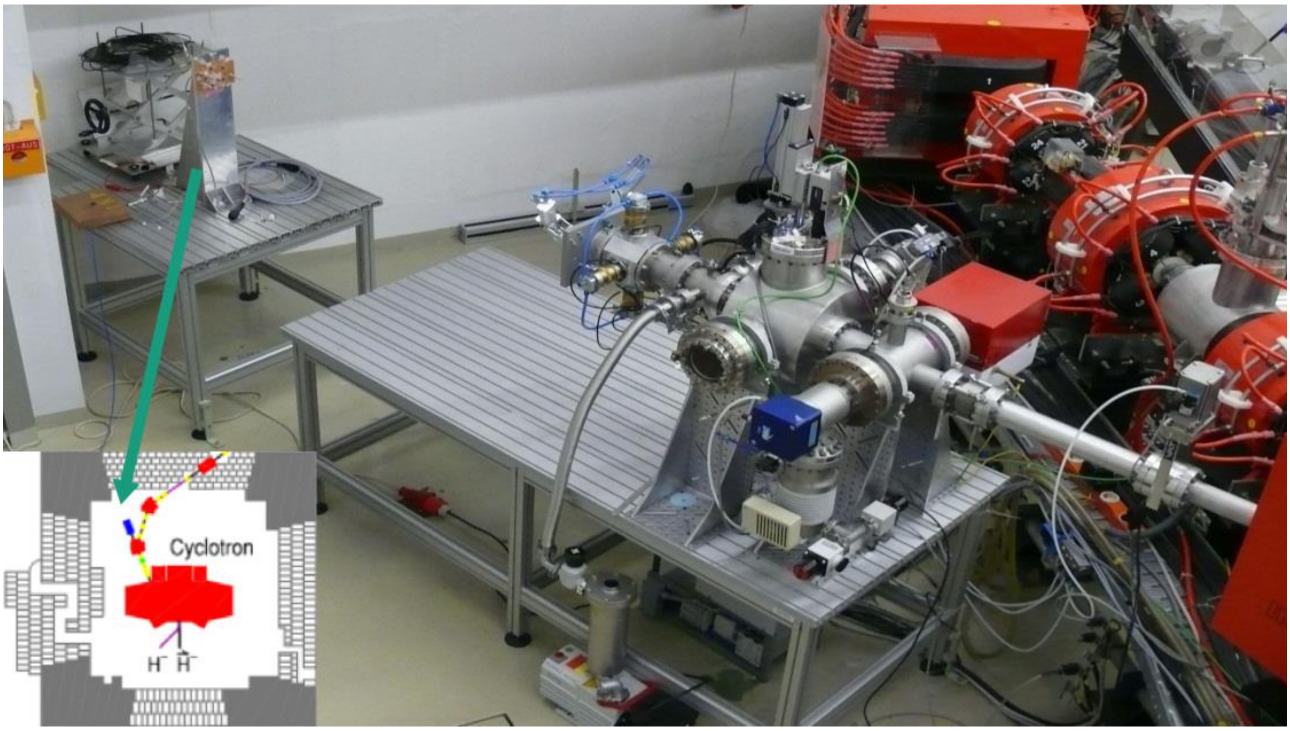
79	Kr	15.2	300	3.07e+05	0	0	1.20e-05	FAIL	Continuous leakage increase by approx 2 orders of magnitude. Fails in post test
80	Kr	16.1	200	3.06e+05	0	0	1.20e-05	--	--
81	Kr	16.1	250	3.07e+05	0	0	1.20e-05	FAIL	Slight continuous increase of leakage current. Fails in post test
82	Kr	16.2	250	3.09e+05	0	0	1.19e-05	FAIL	Slight continuous increase of leakage current. Fails in post test

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 18: 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 19 and Figure 20). 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):

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

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 [11].

Figure 19: Schematic setup of the beam exit window at JULIC and the ionization chamber. The DUT is placed in same distance as the IC.

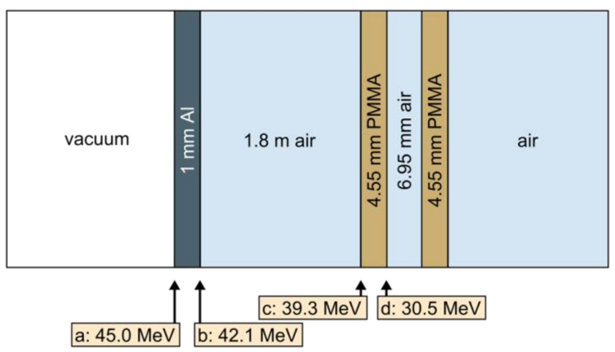
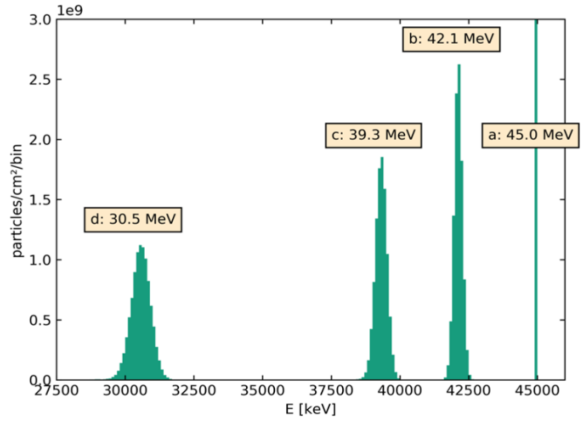


Figure 20: The initial proton energy of 45.0 MeV gets reduced to 39.3 MeV at the position of the IC/DUT. The PMMA cap of the chamber further reduces the energy to 30.5 MeV, calculation by MULASSIS (Geant4) on SPENVIS[10].



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 13: 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 cm^2/mg in any case. The LETs of the recoil nuclei in SiC vary strongly with the LET of Si at or below 12.3 MeV cm2/mg and the LET of C around 5.8 MeV cm^2/mg. For the overall data evaluation we identify the proton data with an LET of 0.01 MeV cm^2/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

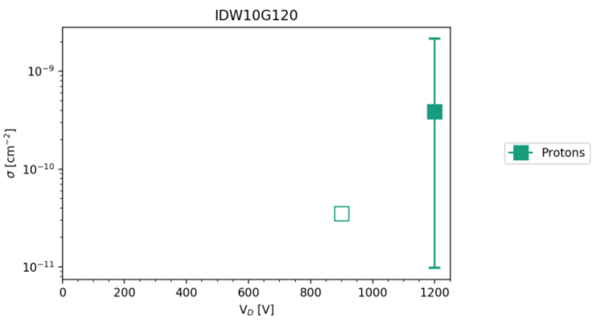
The log file of the tests performed at JULIC can be found in AppendixC. Table 14 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 6.5

Table 14: JULIC: Irradiation steps of SiC Schottky Diode IDW10G120C5B. 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_R [V]	E_{init} = 45 MEV	
	in-situ	POST
900	1.2, 2.1, 2.2	1.2, 2.1, 2.2
1200	1.1	

6.5 Results

Figure 21: Overview of results: Protons at JULIC. The test at 900 V was verified with 3 diodes (in 2 packages). Filled symbols mark the cross section in case of device failures and error bars mark the upper lower limits. Open symbols mark the cross section upper limit in case no failure was observed during a run.



Tests with this device were verified with 3 diodes at 900 V and a fluence of approx. 1e11 p/cm² per run. There were no voltages tested between 900 V and 1200 V, but the safe operating voltage is at least as high as found in the heavy ion tests with carbon (LET = 1.3 MeV cm²/mg) in Section 5.5.

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

#	Ion	DUT #	V_DS, V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
34	p	1.1	1200	2.59E+09	9.79E-12	3.87E-10	2.15E-09	FAIL	Breakdown at indicated fluence.
35	p	1.2	900	1.05E+11	0	0	3.5E-11		--
36	p	2.1	900	1.05E+11	0	0	3.51E-11	--	--
37	p	2.2	900	1.05E+11	0	0	3.51E-11	--	--

7 Tests at GANIL

7.1 Facility

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

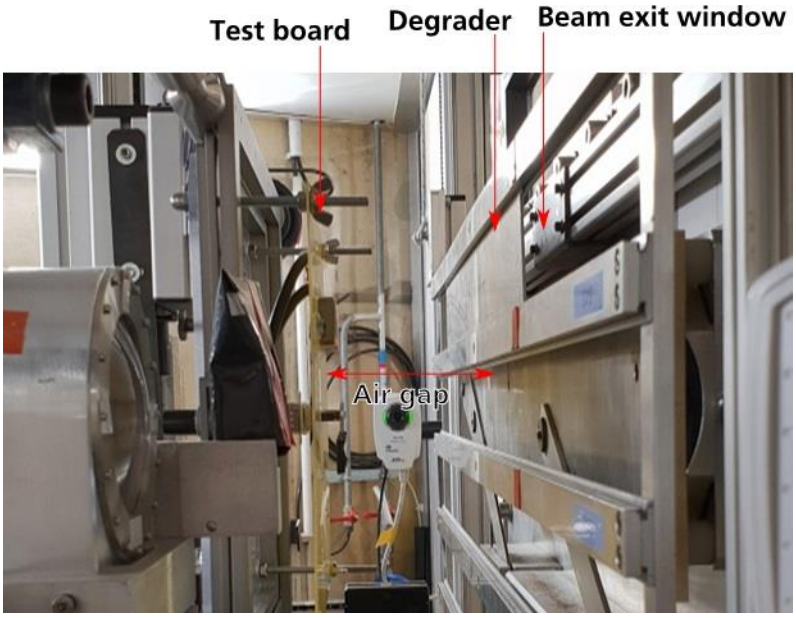
Additional heavy ion tests were performed at the G4 cave at GANIL, Caen, France.

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 22: 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 [12]. However this data is not valid for Silicon Carbide.

SRIM 2013 [9] simulations by Fraunhofer INT in Table 16 show the respective surface LET values for the Xenon beam provided by GANIL under normal incidence in Silicon Carbide covered by a 10 µm Paralene layer with the air gap and degrader settings used in the experiments. For comparison, the values in Silicon provided by GANIL are included in the table. The devices used for these tests were de-lidded, so packages were not included in the simulations.

Table 16: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [12], 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 22). Tests are then performed in air.

7.4 Irradiation steps

The tests at GANIL with the IDW10G120C5B were performed near the end of the beam time and only limited data could be taken. No PIGS tests were performed.

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

Table 17 shows an overview over the test indicating pass and fail results. A detailed evaluation of the results is shown in Section 7.5.

Table 17: GANIL: Irradiation steps of SiC Schottky Diode IDW10G120C5B. 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	POST	in-situ	POST	in-situ	POST
100	0						
125	0					19.1, 19.2	19.1, 19.2
150	0	17.2, 18.1	17.2, 18.1	17.2, 18.2	17.2, 18.2	18.2	18.2
175	0			17.2	17.2		
200	0	17.1, 17.2	17.1, 17.2				
250	0	18.1	18.1				
300	0						
1200	0					19.2	

7.5 Results

In all tests with this device up to voltages of 200 V, no destructive SEE was observed when the DUT was in beam. At higher LETs in runs #140 and #142, the POST test was below the threshold of 100 µA, which we arbitrarily set to identify clear failures. Therefore to be on the safe side, we'd identify the next lowest voltage setting to define the safe operation voltage.

Figure 23: 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.

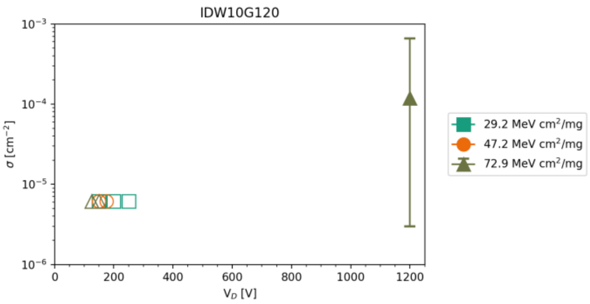


Table 18: Results: Heavy Ions at GANIL - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	Al [µm]	Air [mm]	DUT #	V_DS, V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
134	Xe	0	150	17.1	200	6.01E+05	0	0	6.14E-06	--	--
135	Xe	0	150	17.2	200	6.00E+05	0	0	6.15E-06	--	--
136	Xe	0	150	17.2	150	6.00E+05	0	0	6.15E-06	--	--
137	Xe	0	150	18.1	150	6.00E+05	0	0	6.15E-06	--	--
138	Xe	0	150	18.1	250	6.00E+05	0	0	6.15E-06	Degr.	Slight degradation during irradiation. DUT fails POST test.
139	Xe	400	95	17.2	150	6.00E+05	0	0	6.15E-06	--	--
140	Xe	400	95	17.2	175	6.00E+05	0	0	6.15E-06	--	--
141	Xe	400	95	18.2	150	6.00E+05	0	0	6.15E-06	--	--
142	Xe	500	180	18.2	150	6.00E+05	0	0	6.15E-06	--	--
143	Xe	500	180	19.1	125	6.00E+05	0	0	6.15E-06	--	--
144	Xe	500	180	19.2	125	6.00E+05	0	0	6.15E-06	--	--
145	Xe	500	180	19.2	1200	8.46E+03	2.99E-06	0.000118	0.000659	FAIL	Desctructive failure at indicated fluence.

8 Tests at CERN

8.1 Facility

Tests at CERN took place at the H8 beam line [13] 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 [14].

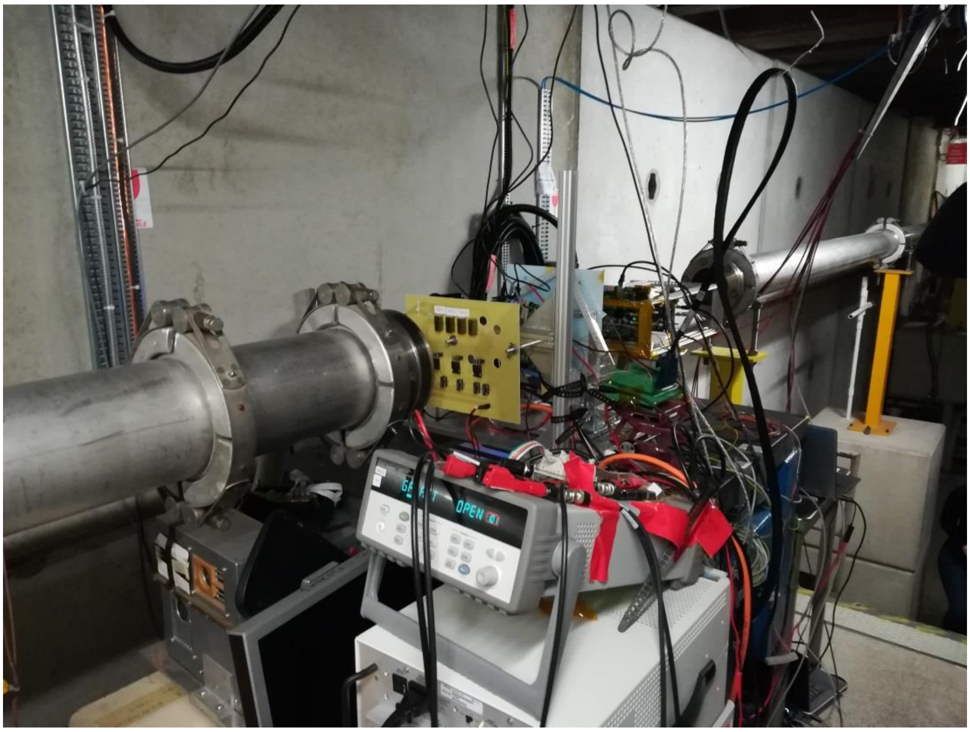
The ion beam is ultra-energetic and thus highly penetrating, which has several practical advantages for testing:

- 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 24: 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 [14][15]. 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. [15]

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 Section8.5 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 [14] 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 [14] 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.

Additional runs were performed with the DUT tilted by 42° to the beam (angle determined by measurement). As 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 than at 0° incidence is invalid, we cannot properly give an expression of LET for these runs.

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.

First, the beam was incident normally on the DUTs. In addition, tests with the DUT at 42° to the beam were performed. For this the whole motor unit was turned at an 42° angle as tilting would not be possible with the frame holder and motor.

8.4 Irradiation steps

Table 19: CERN: Irradiation steps of SiC Schottky Diode IDW10G120C5B. 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°	
V_DS [V]	in-situ	PIGS	in-situ	PIGS
900	1.2, 2.1		3.1	
950	1.2		3.1	
1000	1.2, 2.1, 2.2		3.1	
1050	2.1, 2.2		3.1	
1100	1.2		3.1, 3.2	
1150			3.1, 3.2	
1200			3.1, 3.2	
1250			3.1, 3.2	
1300			3.1, 3.2	

8.5 Results

At normal incidence of the ions, the tests with the IDW10G120C5B at CERN failed repeatedly at 1050 V and passed 1000 V, so the latter is assigned the safe operation voltage, however no POST tests were performed leaving a chance that the devices may have failed already at lower voltages. Failures are immediate and at no single test a quasi-continuous degradation could be seen.

At first glance there is a difference to the previous tests in the increased voltage of safe operation of 1000 V. This value was 900 V with the lowest LET at UCL and with protons. However at UCL the next highest test voltage was at 1050 V and with protons even at 1200 V. Thus when taking this into account the different values assigned to the safe operation voltage are not conflicting but could be due to the voltage steps in the previous tests.

Tests at CERN were performed with DUTs from a different lot as the previous tests, so lot-to-lot variability could also play a role, although here it is not very evident.

Additional tests were performed with the DUT at a 42° angle to the beam. According to ESCC25100, using an effective LET when tilting is not valid for SEB or SEGR tests of power devices. Given the ultra-energetic ions in this tests, it is safe to assume that the sensitive volume is still penetrated fully in these tests. An effective LET would however in any case give a 1.4-times (at 42°) larger LET and thus having a larger safe operating voltage is the opposite of the naïve expectation.

The effective fluences across the tests were <4.3E4 ions/cm². This very low fluence might be an explanation for the increased "safe operation" levels observed in these tests compared to the other test campaigns.

Figure 25: 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.

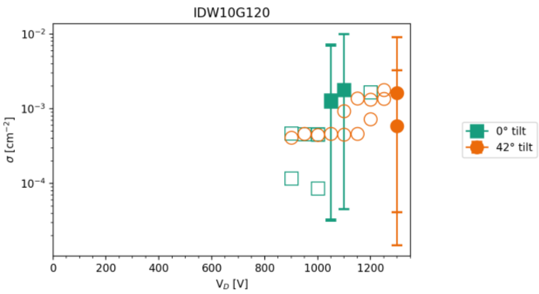


Table 20: Results: Heavy Ions at CERN - Calculated cross sections Calculated with the formulae in ESCC25100 with CL=0.95 and flux uncertainty of 10% (approx. worst case)

#	Ion	Tilt [°]	DUT #	V_DS, V	Failure fluence [cm-2]	σ lower [cm2]	σ [cm2]	σ upper [cm2]	Effect	Comment
019	Xe	0	1.2	900	7.89E+03	0	0	4.67E-04	--	No POST test
020	Xe	0	1.2	950	8.03E+03	0	0	4.60E-04	--	No POST test
021	Xe	0	1.2	1000	8.03E+03	0	0	4.60E-04	--	No POST test
022	Xe	0	1.2	1100	5.60E+02	4.52E-05	1.79E-03	9.95E-03	FAIL	Destructive failure
023	Xe	0	2.1	900	3.15E+04	0	0	1.17E-04	--	--
024	Xe	0	2.1	1000	4.27E+04	0	0	8.64E-05	--	--
025	Xe	0	2.1	1050	7.73E+02	3.27E-05	1.29E-03	7.20E-03	FAIL	Destructive failure
026	Xe	0	2.2	1000	8.16E+03	0	0	4.52E-04	--	--
027	Xe	0	2.2	1050	8.00E+02	3.16E-05	1.25E-03	6.96E-03	FAIL	Destructive failure
036	Xe	42	3.1	900	8.99E+03	0	0	4.10E-04	--	--
037	Xe	42	3.1	950	8.00E+03	0	0	4.61E-04	--	--
038	Xe	42	3.1	1000	8.24E+03	0	0	4.48E-04	--	--
039	Xe	42	3.1	1050	8.00E+03	0	0	4.61E-04	--	--
040	Xe	42	3.1	1100	8.19E+03	0	0	4.51E-04	--	--

041	Xe	42	3.1	1150	8.00E+03	0	0	4.61E-04	--	--
042	Xe	42	3.1	1200	5.09E+03	0	0	7.24E-04	--	--
043	Xe	42	3.1	1250	2.05E+03	0	0	1.80E-03	--	--
044	Xe	42	3.1	1300	6.13E+02	4.13E-05	1.63E-03	9.08E-03	FAIL	Destructive failure
045	Xe	42	3.2	1100	3.95E+03	0	0	9.35E-04	--	--
046	Xe	42	3.2	1150	2.69E+03	0	0	1.37E-03	--	--
047	Xe	42	3.2	1200	2.77E+03	0	0	1.33E-03	--	--
048	Xe	42	3.2	1250	2.72E+03	0	0	1.36E-03	--	--
049	Xe	42	3.2	1300	1.71E+03	1.48E-05	5.86E-04	3.26E-03	FAIL	Destructive failure

A Fraunhofer INT

A.1. About the institute

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

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

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

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

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

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

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

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

The activities within NEO are:

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

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

A.3. Irradiation facilities

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

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

These irradiation facilities are:

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

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

A.4. QM-Certificate

DNV·GL

MANAGEMENT SYSTEM CERTIFICATE

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

Initial certification date:
13. February 2013

Valid:
14. February 2019 - 12. February 2022

This is to certify that the management system of

Fraunhofer INT

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

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

ISO 9001:2015

This certificate is valid for the following scope:

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

Place and date:
Essen, 14. February 2019

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

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

Thomas Beck
Technical Manager

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

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B Appendix: Tests at UCL

B.1. Logfile / Test steps

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

#	Run (UCL)	Date	Time	Ion	Device Type	Device	Position on board	DUT #	V	beam time [s]	fluence [cm-2]
61	89	17.04.	14:59	Al	Schottky	IDW10G120	#1	11.1	600	109	1.13E+04
62	90	17.04.	15:05	Al	Schottky	IDW10G121	#1	11.2	300	661	3.02E+05
63	91	17.04.	15:18	Al	Schottky	IDW10G122	#1	11.2	450	487	3.01E+05
64	92	17.04.	15:29	Al	Schottky	IDW10G120	#1	11.2	500	151	7.89E+04
65	93	17.04.	15:41	Al	Schottky	IDW10G120	#2	12.1	450	230	3.04E+05
66	94	17.04.	16:02	C	Schottky	IDW10G120	#2	12.2	900	444	3.03E+05
67	95	17.04.	16:12	C	Schottky	IDW10G120	#2	12.2	1200	22	1.08E+04
68	96	17.04.	16:17	C	Schottky	IDW10G120	#2	12.1	1050	13	6.61E+03
69	97	17.04.	16:43	Cr	Schottky	IDW10G120	#1	13.1	300	614	3.02E+05
70	98	17.04.	16:59	Cr	Schottky	IDW10G120	#1	13.1	450	301	1.02E+05
71	99	17.04.	17:07	Cr	Schottky	IDW10G120	#1	13.1	450	5	9.00E+03
72	100	17.04.	17:10	Cr	Schottky	IDW10G120	#1	13.2	450	5	8.15E+03
73	101	17.04.	17:16	Cr	Schottky	IDW10G120	#2	14.1	450	8	1.43E+03
74	102	17.04.	17:19	Cr	Schottky	IDW10G120	#2	14.2	300	61	3.06E+05
75	103	17.04.	17:21	Cr	Schottky	IDW10G120	#2	14.2	400	61	3.10E+05
76	104	17.04.	17:45	Cr	Schottky	IDW10G120	#1	15.1	400	62	3.06E+05
77	105	17.04.	18:09	Kr	Schottky	IDW10G120	#1	15.2	100	61	3.05E+05
78	106	17.04.	18:11	Kr	Schottky	IDW10G120	#1	15.2	200	62	3.09E+05
79	107	17.04.	18:13	Kr	Schottky	IDW10G120	#1	15.2	300	60	3.07E+05
80	108	17.04.	18:16	Kr	Schottky	IDW10G120	#2	16.1	200	61	3.06E+05
81	109	17.04.	18:18	Kr	Schottky	IDW10G120	#2	16.1	250	61	3.07E+05
82	110	17.04.	18:22	Kr	Schottky	IDW10G120	#2	16.2	250	60	3.09E+05

B.2. Measurements

Figure 26: Run# 061, IDW10G120, Al-250, 1.1e+04 ions/cm2 , DUT 11.1, VD= 600.0 V

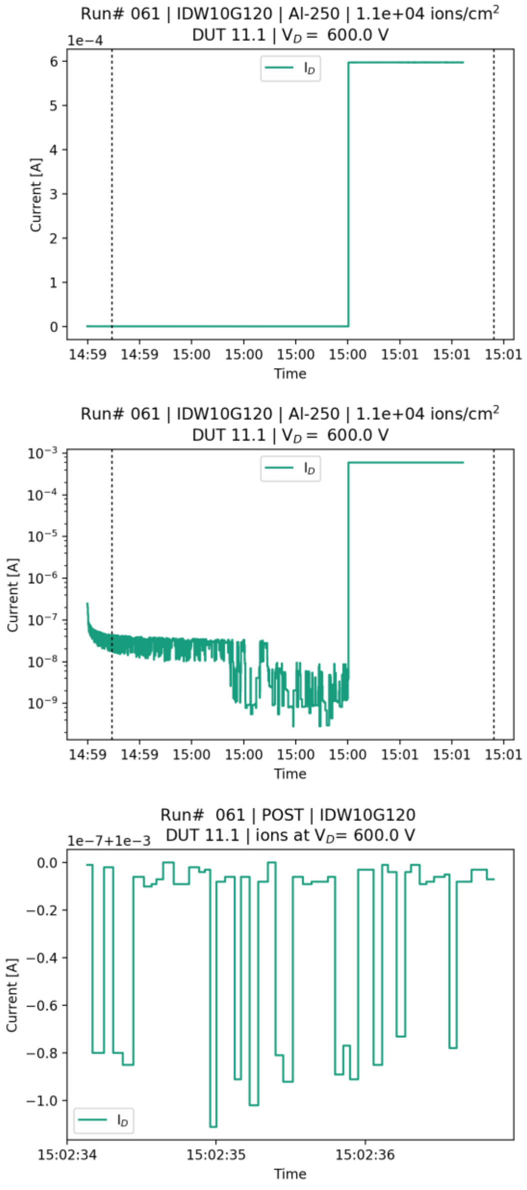


Figure 27: Run# 062, IDW10G121, Al-250, 3.0e+05 ions/cm2 , DUT 11.2, VD= 300.0 V

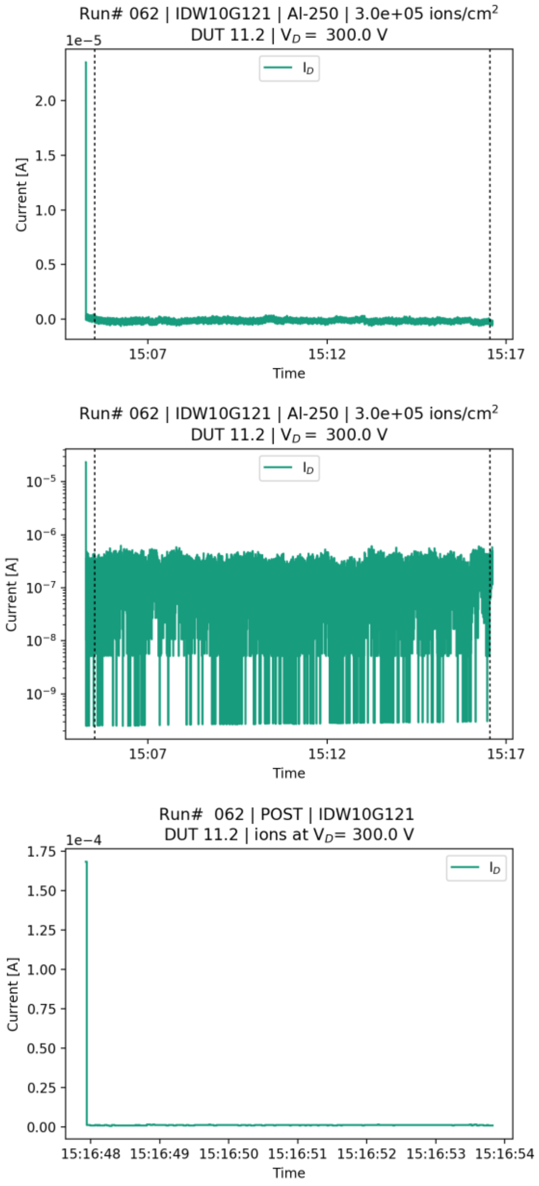


Figure 28: Run# 063, IDW10G122, Al-250, 3.0e+05 ions/cm2 , DUT 11.2, VD= 450.0 V

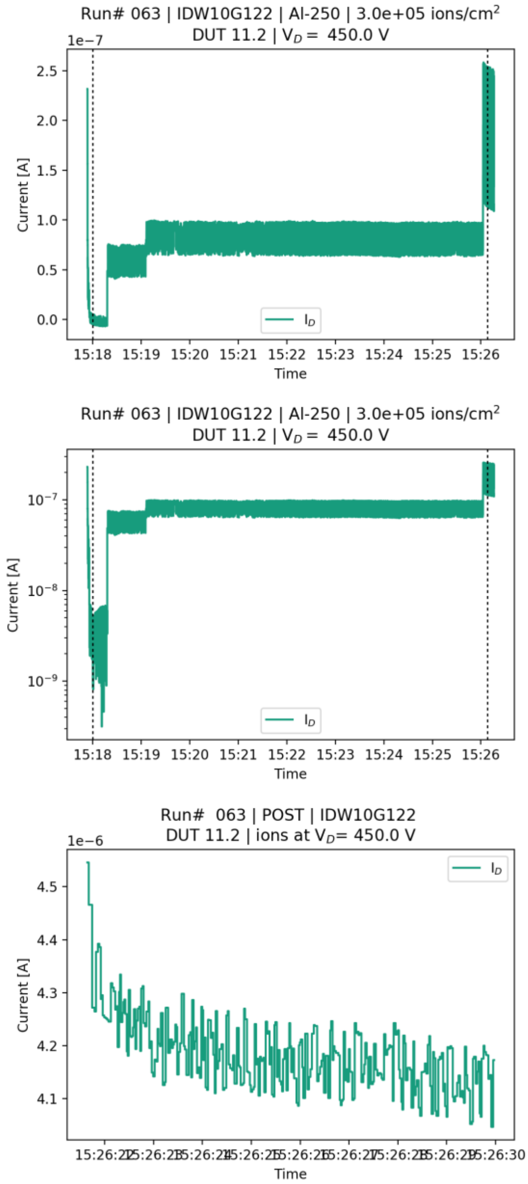


Figure 29: Run# 064, IDW10G120, Al-250, 7.9e+04 ions/cm2 , DUT 11.2, VD= 500.0 V

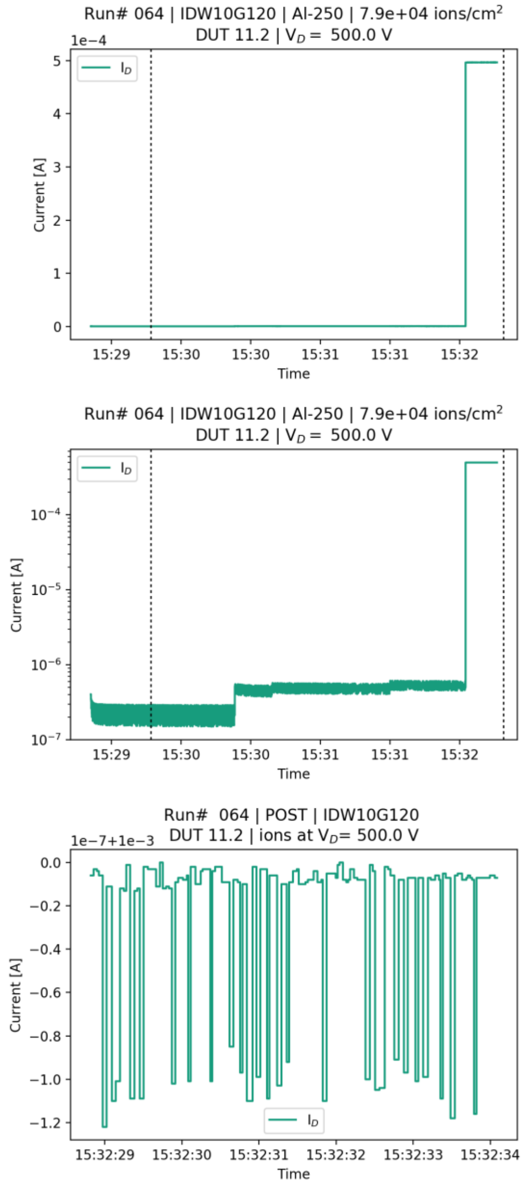


Figure 30: Run# 065, IDW10G120, Al-250, 3.0e+05 ions/cm2 , DUT 12.1, VD= 450.0 V

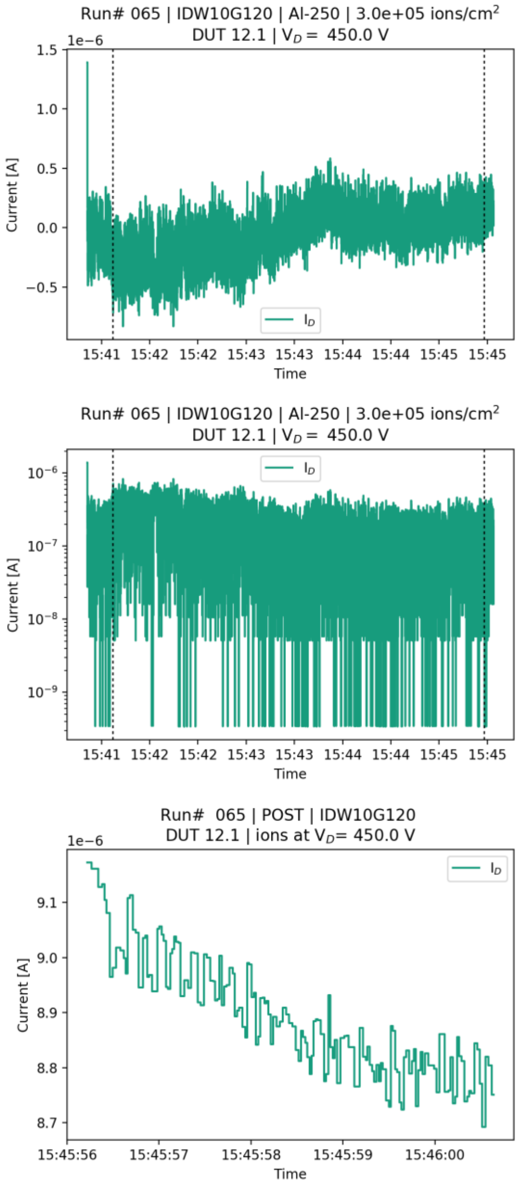


Figure 31: Run# 066, IDW10G120, C-131, 3.0e+05 ions/cm2 , DUT 12.2, VD= 900.0 V

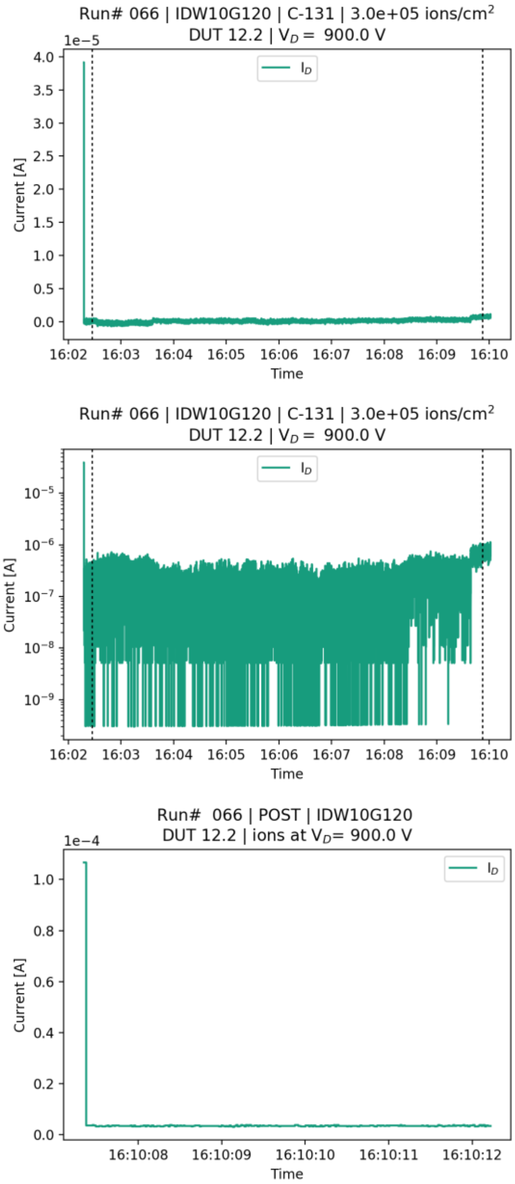


Figure 32: Run# 067, IDW10G120, C-131, 1.1e+04 ions/cm2 , DUT 12.2, VD= 1200.0 V

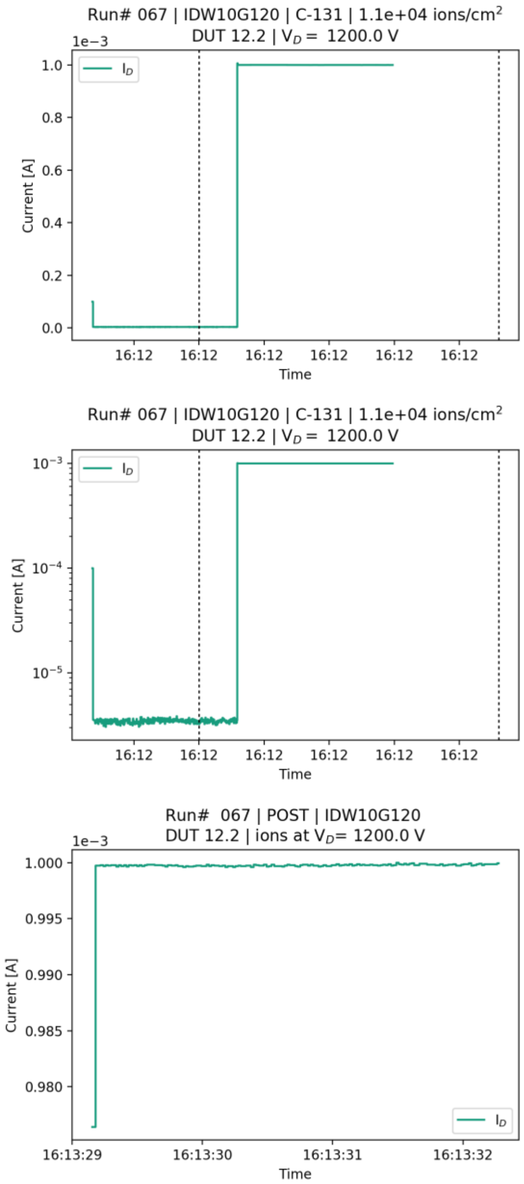


Figure 33: Run# 068, IDW10G120, C-131, 6.6e+03 ions/cm2 , DUT 12.1, VD= 1050.0 V

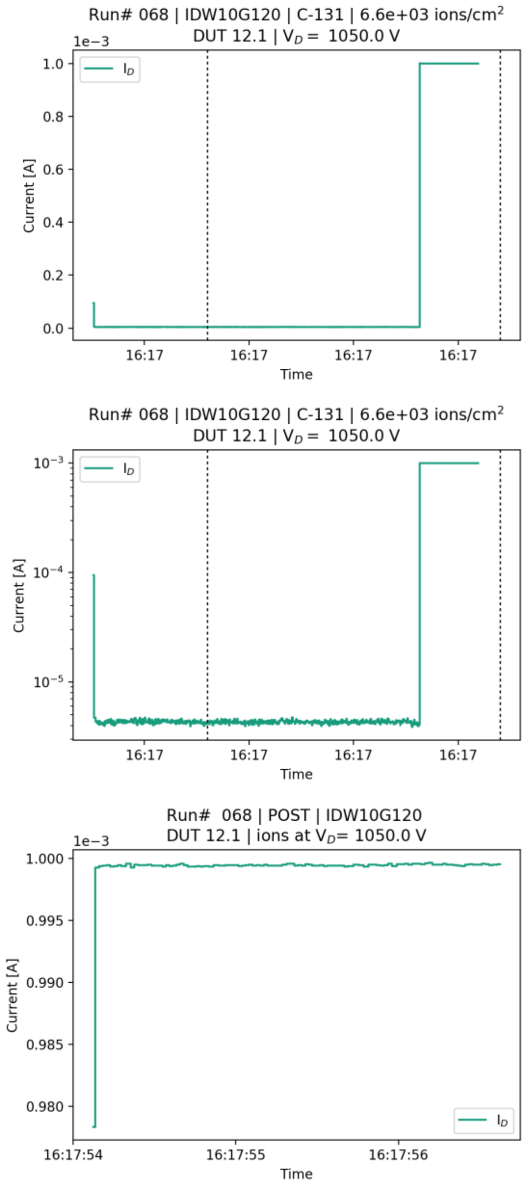


Figure 34: Run# 069, IDW10G120, Cr-513, 3.0e+05 ions/cm2 , DUT 13.1, VD= 300.0 V

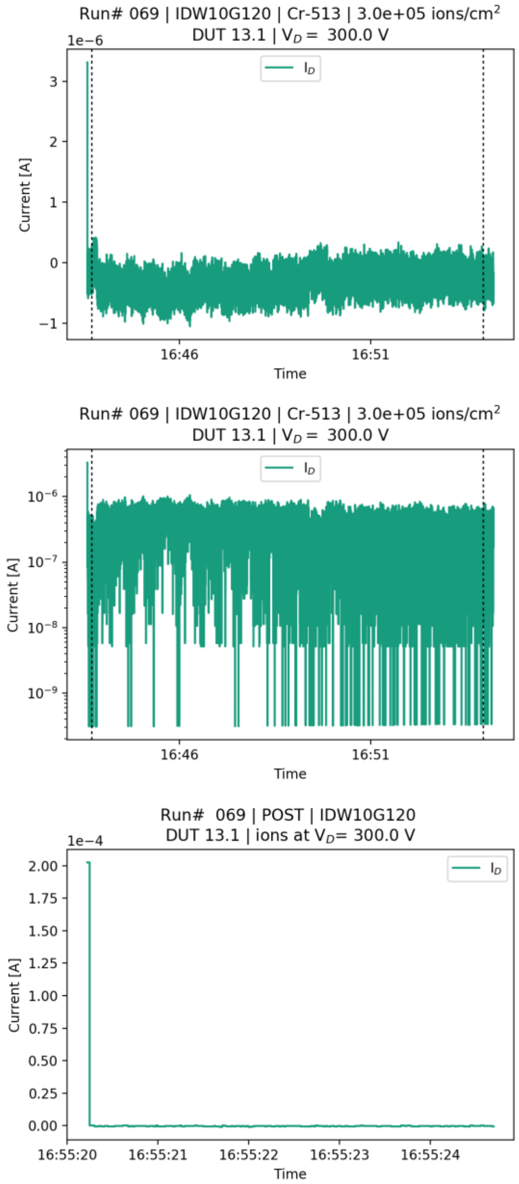


Figure 35: Run# 070, IDW10G120, Cr-513, 1.0e+05 ions/cm2 , DUT 13.1, VD= 450.0 V

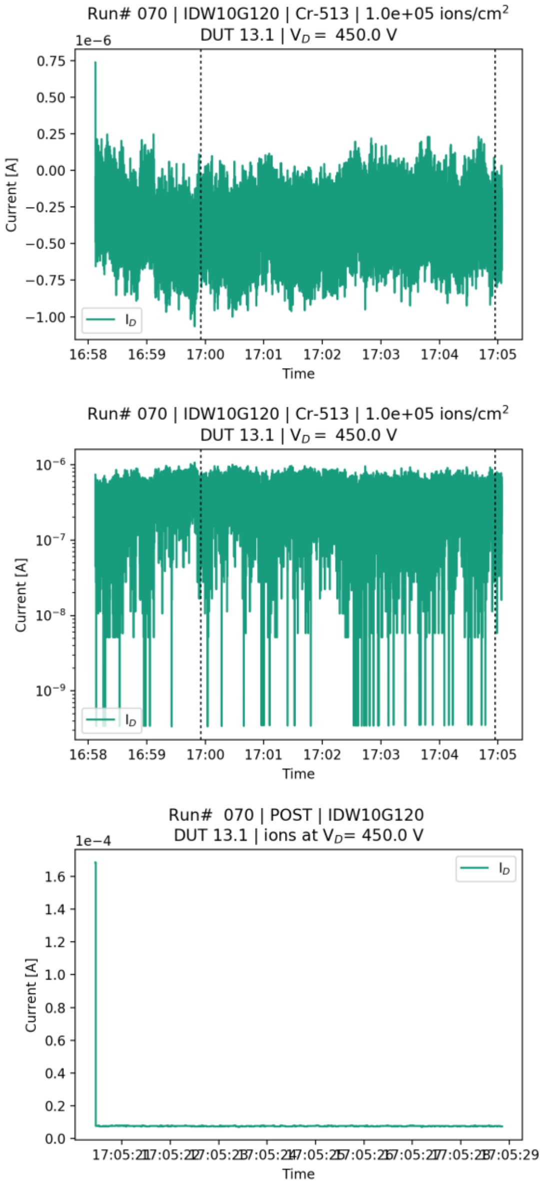


Figure 36: Run# 071, IDW10G120, Cr-513, 9.0e+03 ions/cm2 , DUT 13.1, VD= 450.0 V

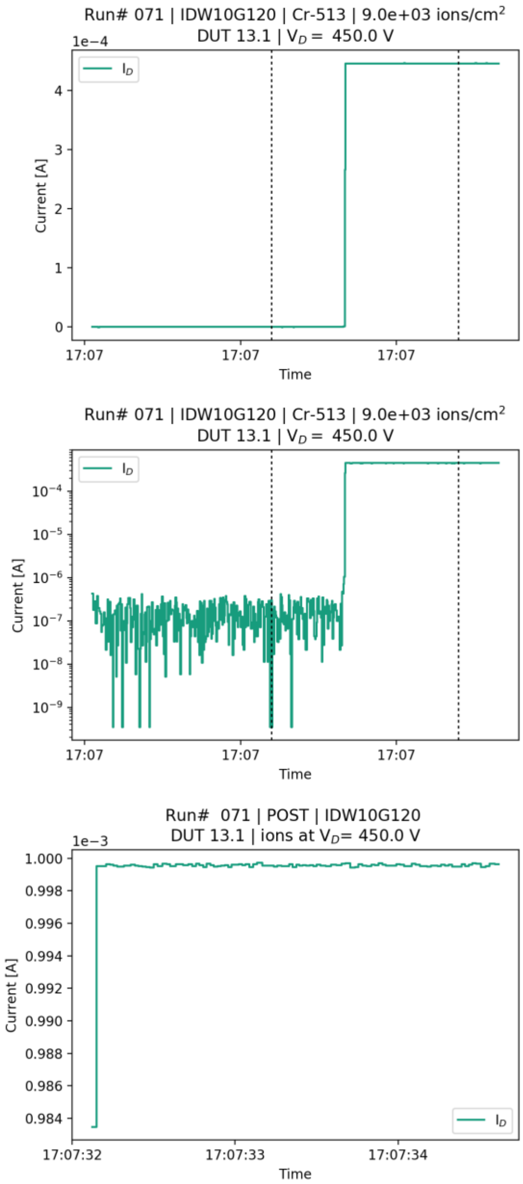


Figure 37: Run# 072, IDW10G120, Cr-513, 8.2e+03 ions/cm2 , DUT 13.2, VD= 450.0 V

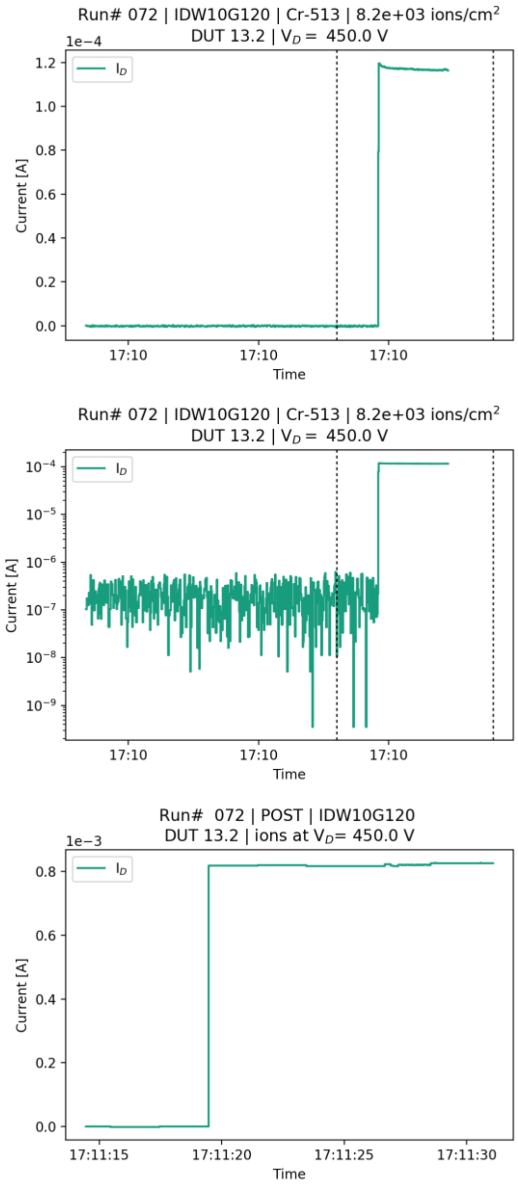


Figure 38: Run# 073, IDW10G120, Cr-513, 1.4e+03 ions/cm2 , DUT 14.1, VD= 450.0 V

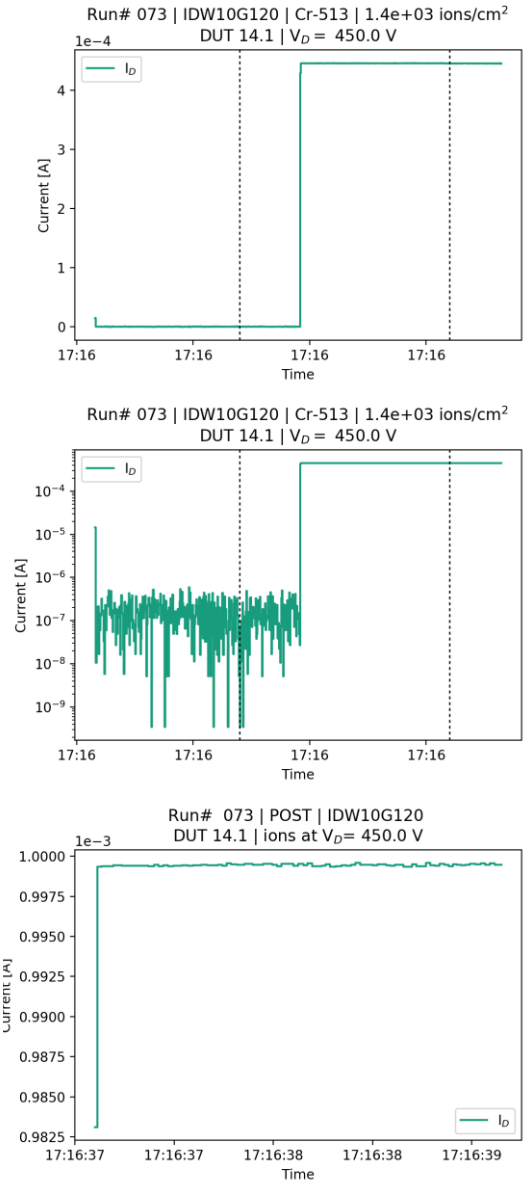


Figure 39: Run# 074, IDW10G120, Cr-513, 3.1e+05 ions/cm2 , DUT 14.2, VD= 300.0 V

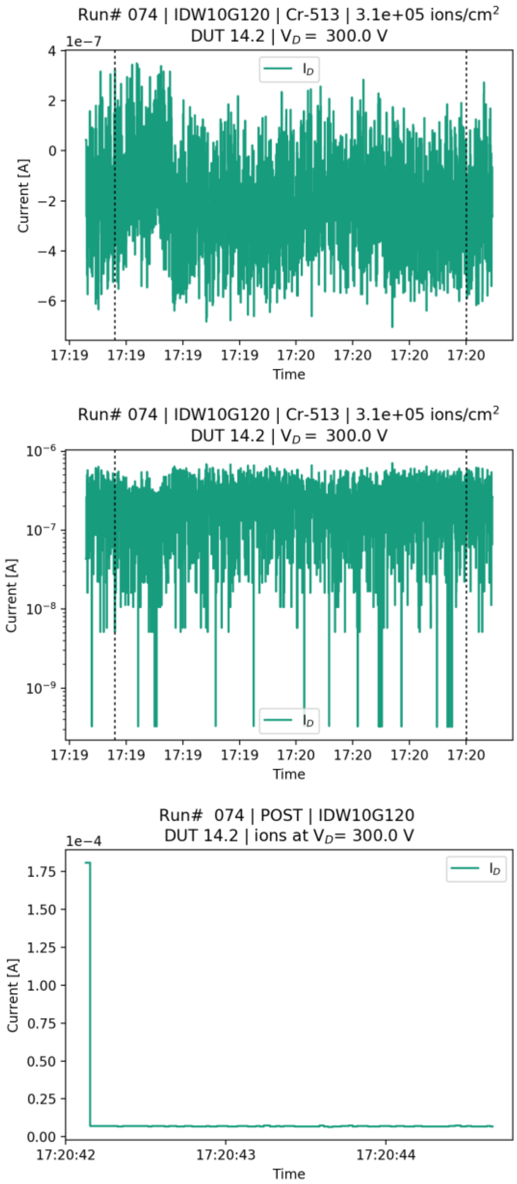


Figure 40: Run# 075, IDW10G120, Cr-513, 3.1e+05 ions/cm2 , DUT 14.2, VD= 400.0 V

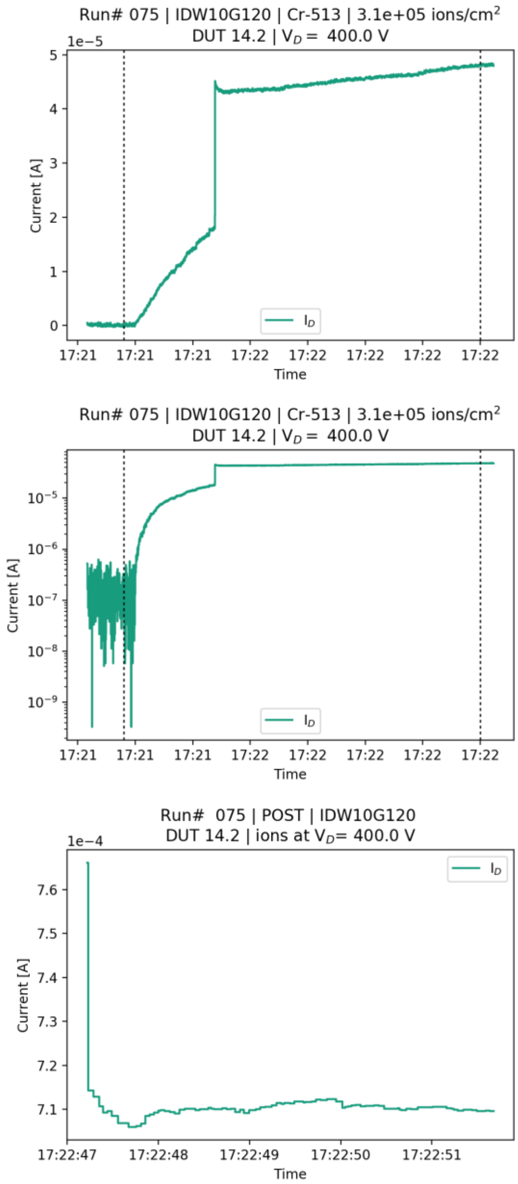


Figure 41: Run# 076, IDW10G120, Cr-513, 3.1e+05 ions/cm2 , DUT 15.1, VD= 400.0 V

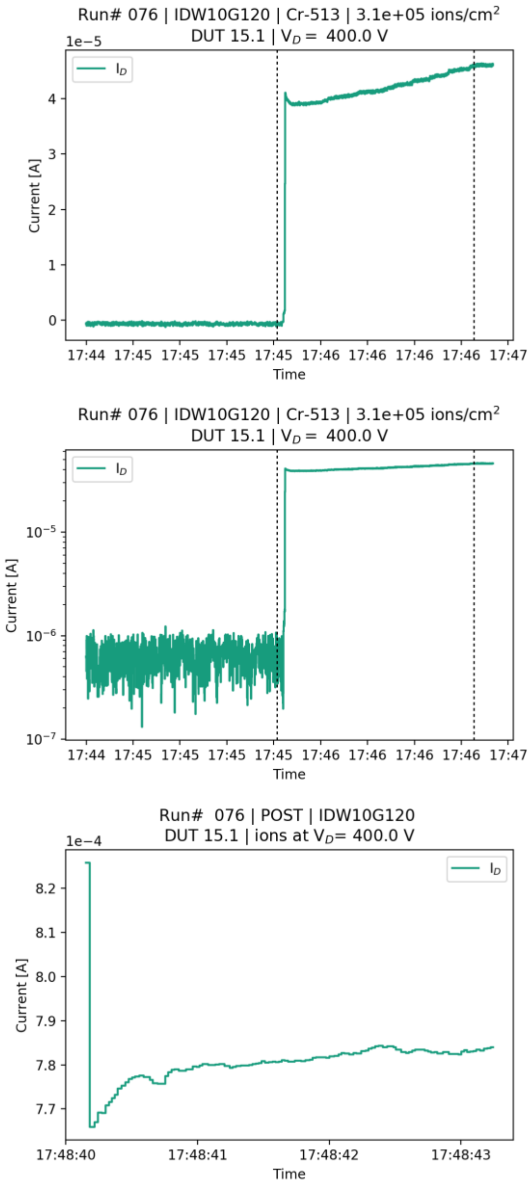


Figure 42: Run# 077, IDW10G120, Kr-769, 3.0e+05 ions/cm2 , DUT 15.2, VD= 100.0 V

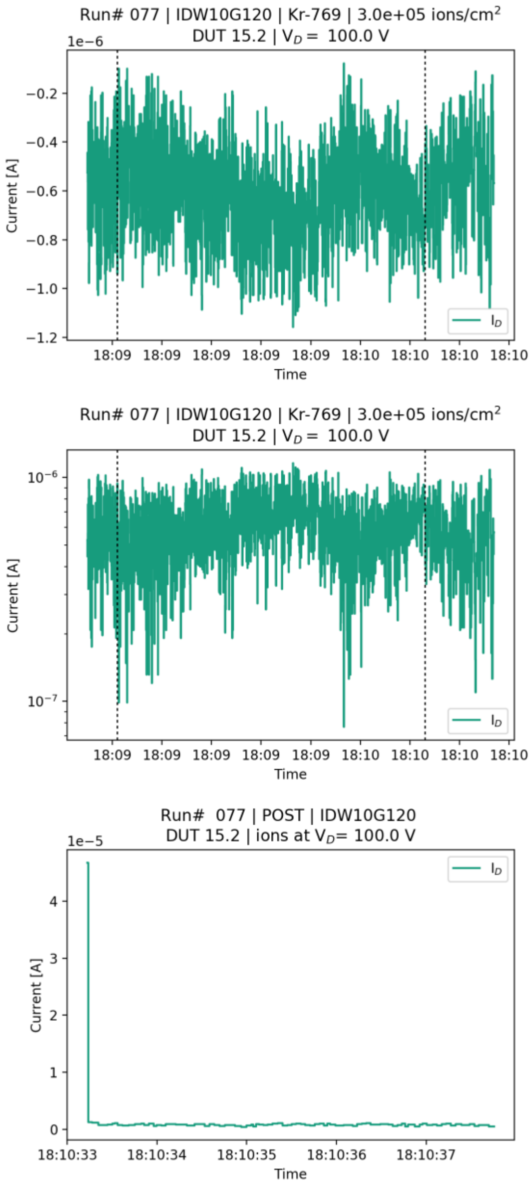


Figure 43: Run# 078, IDW10G120, Kr-769, 3.1e+05 ions/cm2 , DUT 15.2, VD= 200.0 V

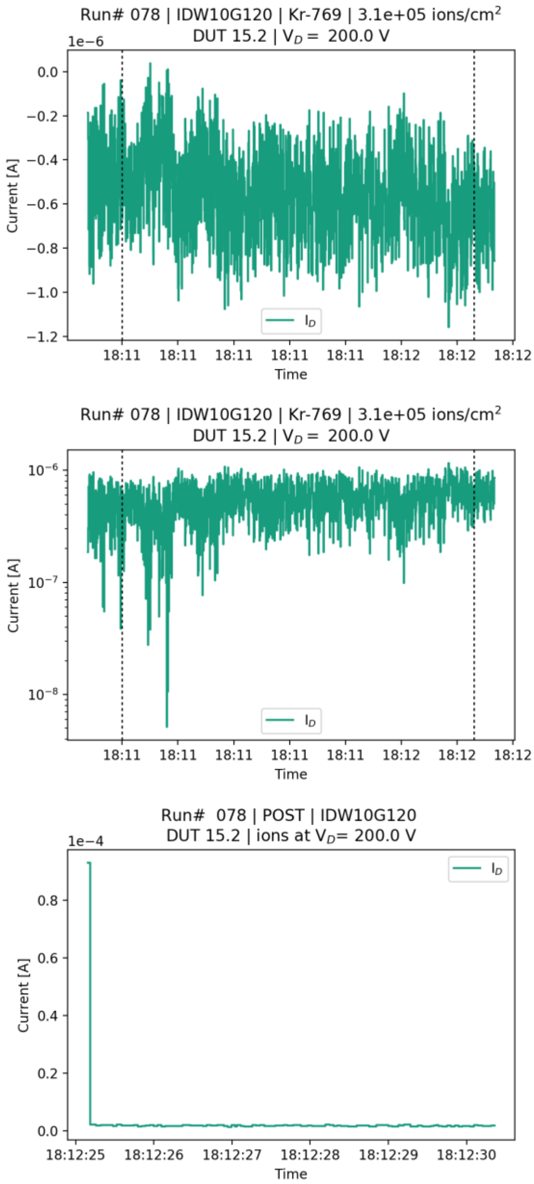


Figure 44: Run# 079, IDW10G120, Kr-769, 3.1e+05 ions/cm2 , DUT 15.2, VD= 300.0 V

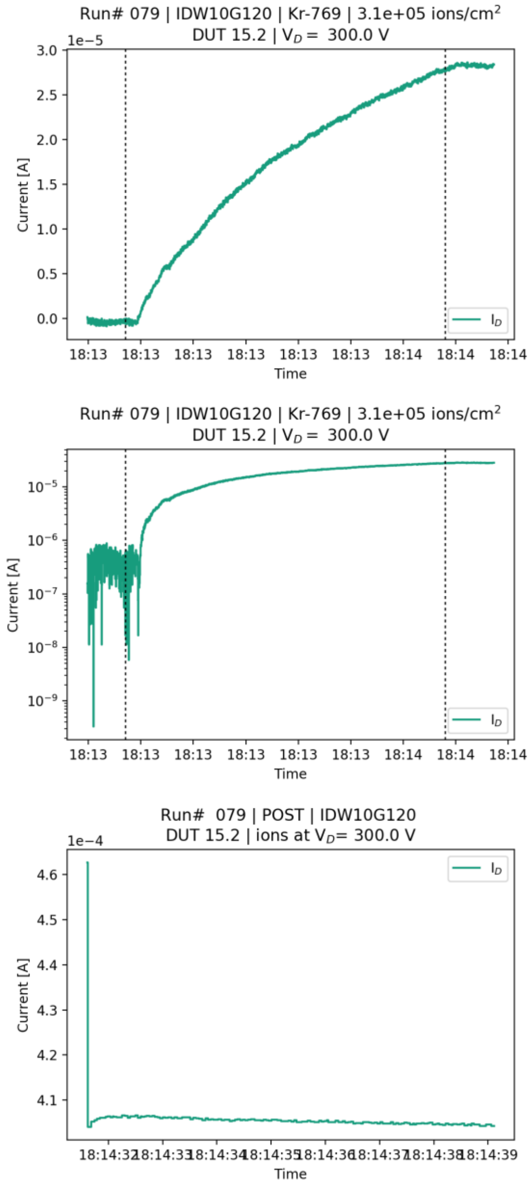


Figure 45: Run# 080, IDW10G120, Kr-769, 3.1e+05 ions/cm2 , DUT 16.1, VD= 200.0 V

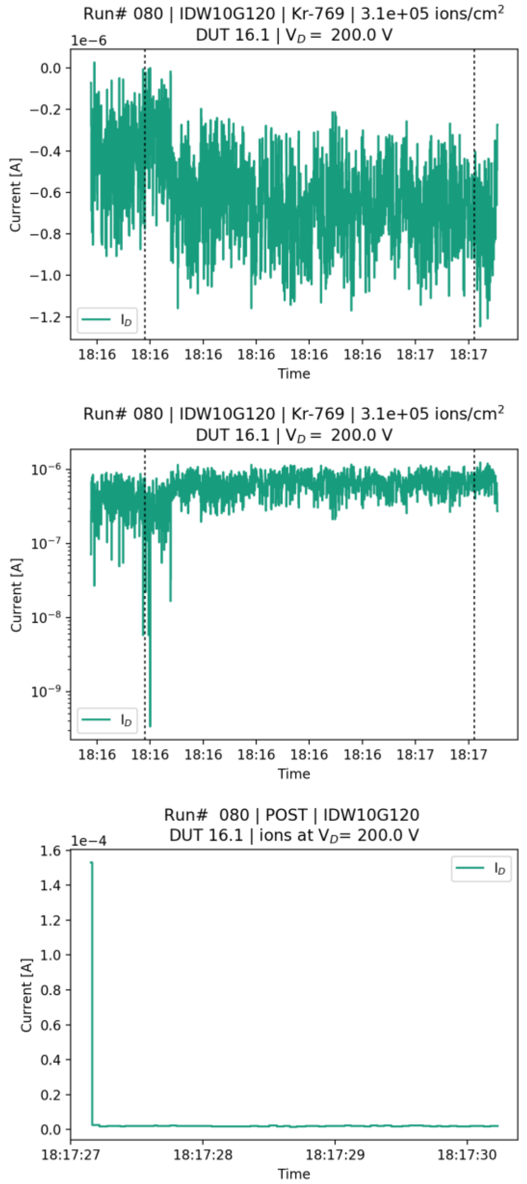


Figure 46: Run# 081, IDW10G120, Kr-769, 3.1e+05 ions/cm2 , DUT 16.1, VD= 250.0 V

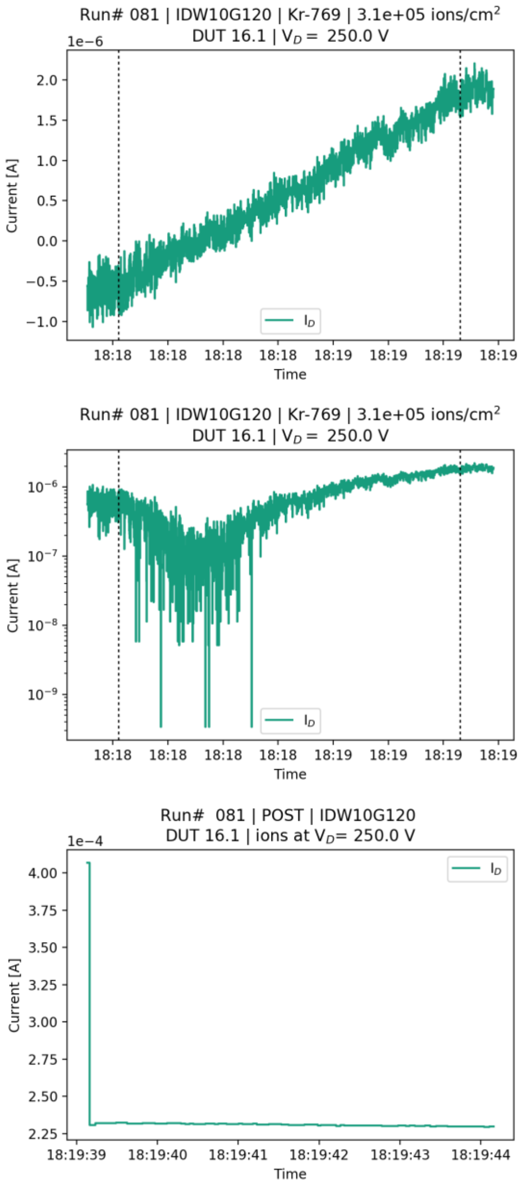
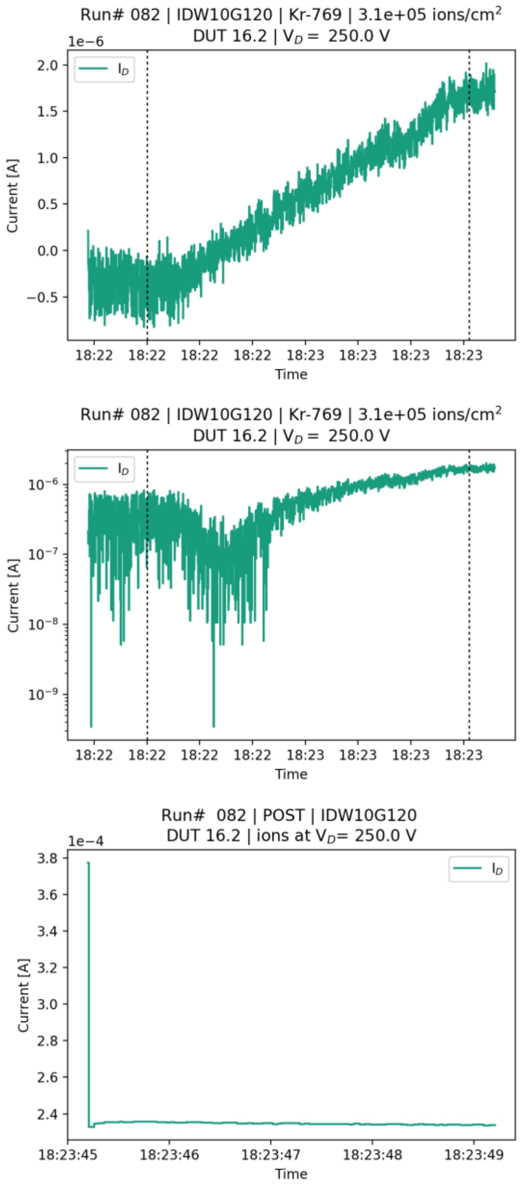


Figure 47: Run# 082, IDW10G120, Kr-769, 3.1e+05 ions/cm2 , DUT 16.2, VD= 250.0 V



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 13, 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 [9] simulations were then performed with the respective particles and maximum kinetic energy in Silicon Carbide. From the SRIM ionization curve the LET can then be calculated. This LET gives information on the recoils happening inside the SiC layer and is not restricted to the layer "surface" (although only extreme values were considered).

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

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

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

For some devices in this project, information was given in the Material Content Data Sheet. A value of 2.37 g/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.

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*Table 21: 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 22: 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 23: 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 24: 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 23 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	beam time [s]	fluence [cm-2]	
33	20.09.	08:54	p	Schottky	IDW10G120	1.1	1200	263	1.1e11	DUT unbiased
34	20.09.	09:13	p	Schottky	IDW10G120	1.1	1200	11	3.5e9	
35	20.09.	09:18	p	Schottky	IDW10G120	1.2	900	257	1.1e11	
36	20.09.	09:28	p	Schottky	IDW10G120	2.1	900	265	1.1e11	
37	20.09.	09:38	p	Schottky	IDW10G120	2.2	900	253	1.1e11	

C.3. Measurements

Figure 48: Run# 033, IDW10G120, p, 1.1e+11 p/cm2 , DUT 1.1, VD= 1200.0 V

DUT unbiased during run

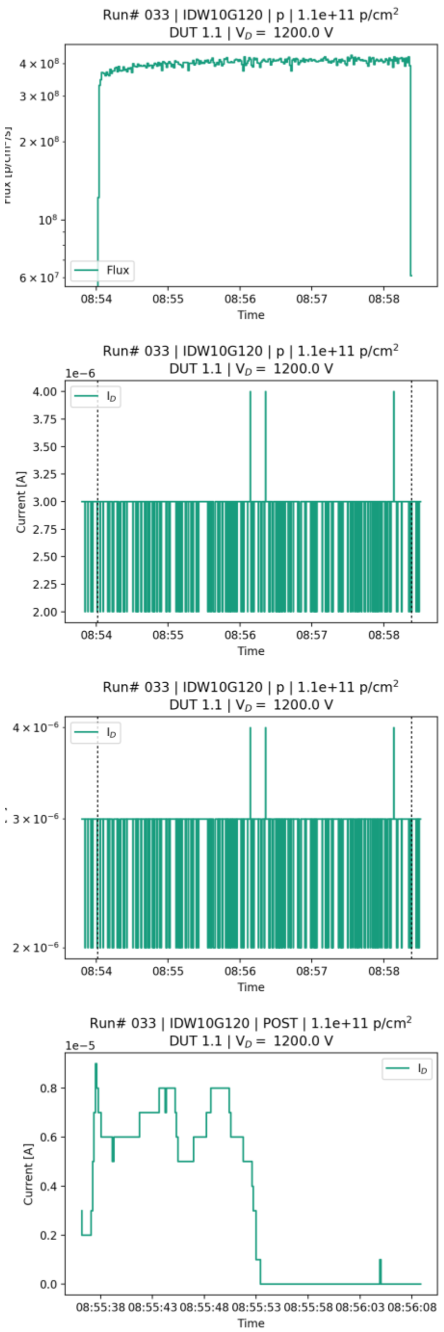


Figure 49: Run# 034, IDW10G120, p, 3.5e+09 p/cm2 , DUT 1.1, VD= 1200.0 V

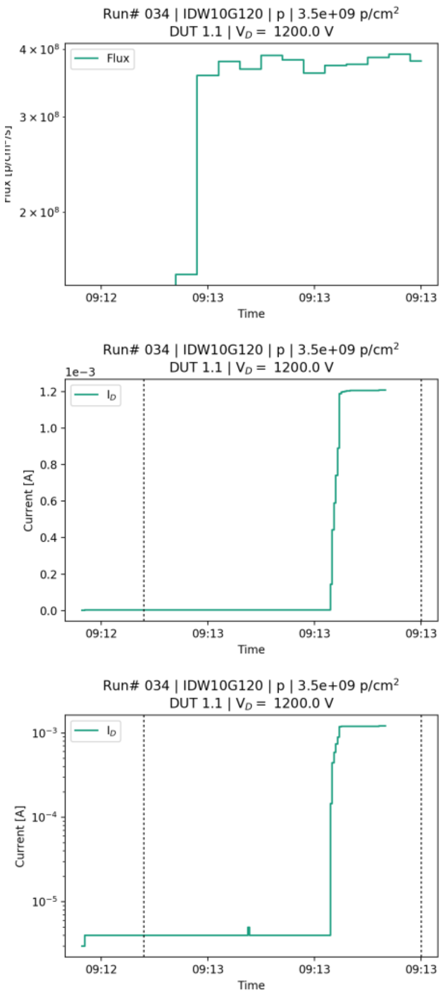


Figure 50: Run# 035, IDW10G120, p, 1.1e+11 p/cm2 , DUT 1.2, VD= 900.0 V

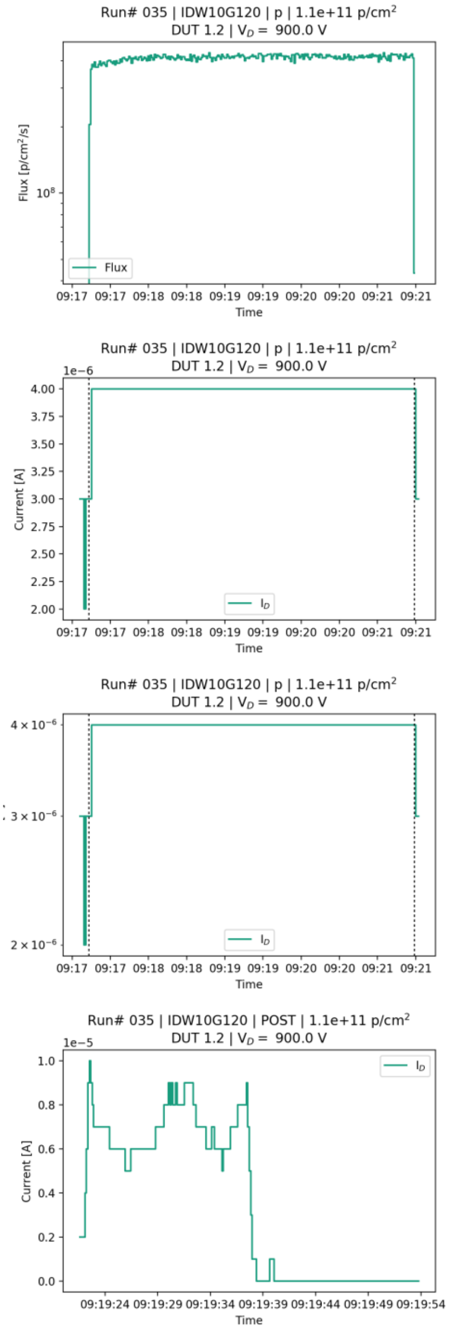


Figure 51: Run# 036, IDW10G120, p, 1.1e+11 p/cm2 , DUT 2.1, VD= 900.0 V

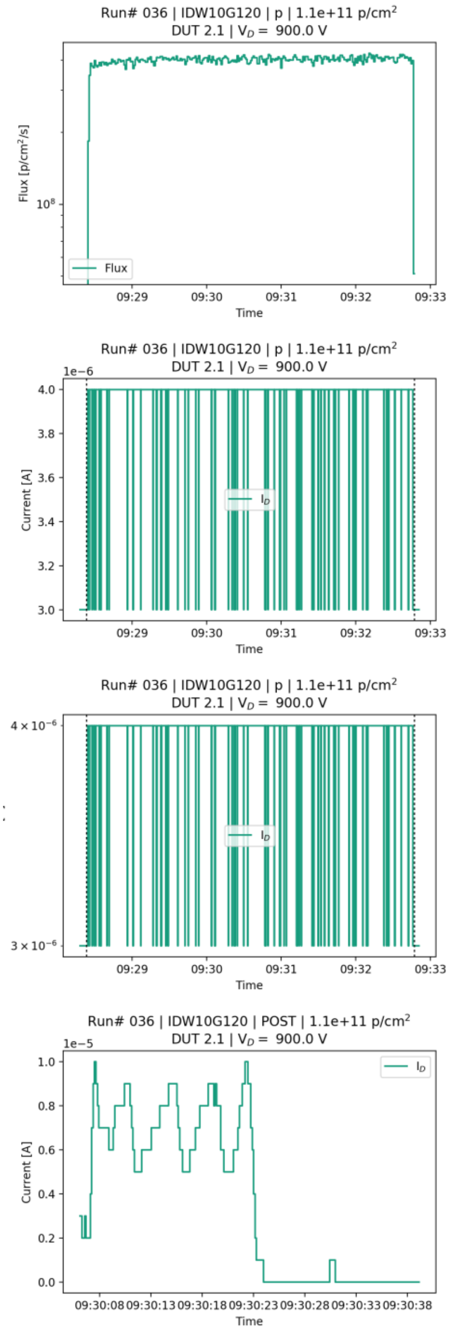
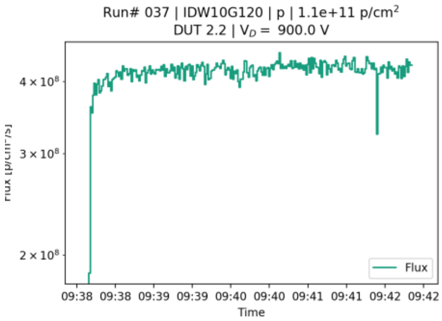
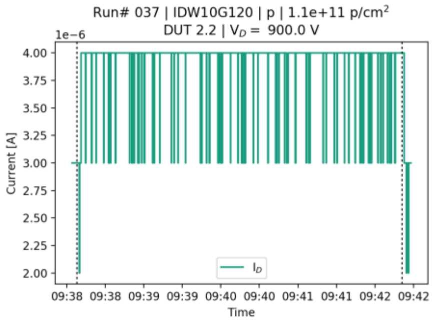
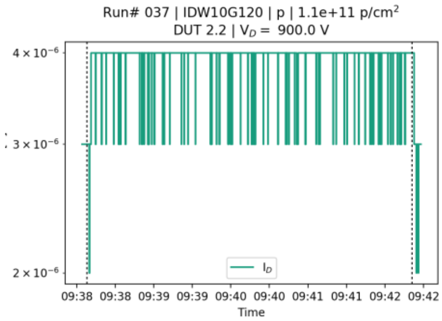
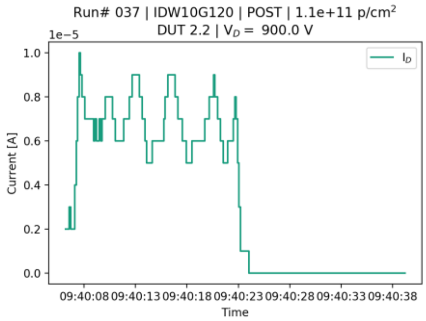


Figure 52: Run# 037, IDW10G120, p, 1.1e+11 p/cm2 , DUT 2.2, VD= 900.0 V









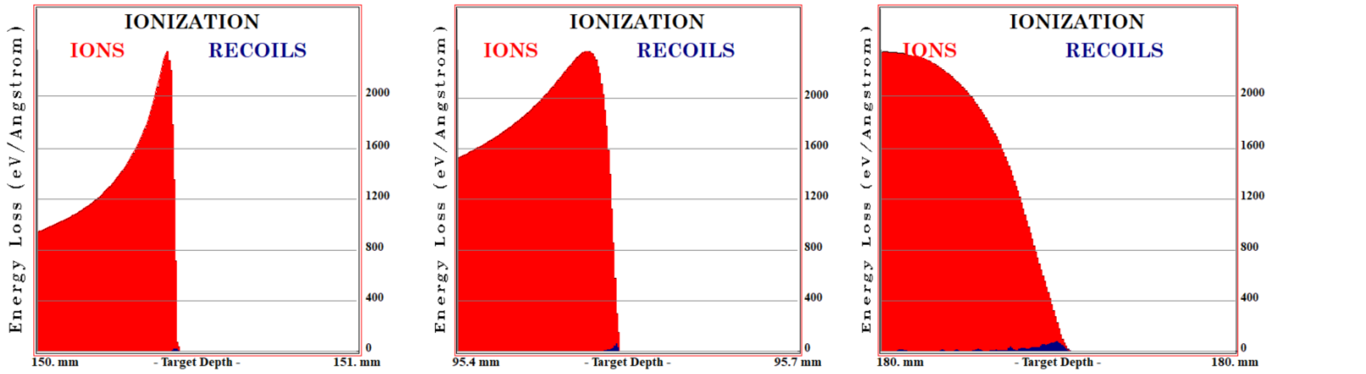
D Appendix: Tests at GANIL

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 53: 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 53 start at the surface of the silicon carbide layer, so e.g. at 95.410 mm in Figure 53 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 25: GANIL: Beam characteristics. Values in Silicon are provided by GANIL [12], 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	beam time [s]	fluence [cm-2]
134	06.06.	12:02	Xe	0	150	Schottky	IDW10G120	#1	17.1	200	299	6.01E+05
135	06.06.	12:15	Xe	0	150	Schottky	IDW10G120	#1	17.2	200	112	6.00E+05
136	06.06.	12:23	Xe	0	150	Schottky	IDW10G120	#1	17.2	150	116	6.00E+05
137	06.06.	12:27	Xe	0	150	Schottky	IDW10G120	#2	18.1	150	105	6.00E+05
138	06.06.	12:28	Xe	0	150	Schottky	IDW10G120	#2	18.1	250	103	6.00E+05
139	06.06.	12:33	Xe	400	95	Schottky	IDW10G120	#1	17.2	150	117	6.00E+05
140	06.06.	12:37	Xe	400	95	Schottky	IDW10G120	#1	17.2	175	112	6.00E+05
141	06.06.	12:39	Xe	400	95	Schottky	IDW10G120	#2	18.2	150	118	6.00E+05
142	06.06.	12:43	Xe	500	180	Schottky	IDW10G120	#2	18.2	150	115	6.00E+05
143	06.06.	12:46	Xe	500	180	Schottky	IDW10G120	#3	19.1	125	119	6.00E+05
144	06.06.	12:50	Xe	500	180	Schottky	IDW10G120	#3	19.2	125	122	6.00E+05
145	06.06.	12:53	Xe	500	180	Schottky	IDW10G120	#3	19.2	1200	5	2.28E+04

D.3. Measurements

Figure 54: Run# 134, IDW10G120, Xe 0 mmAl, 150 mm Air, 6.0e+05 ions/cm2 , DUT 17.1, VD= 200.0 V

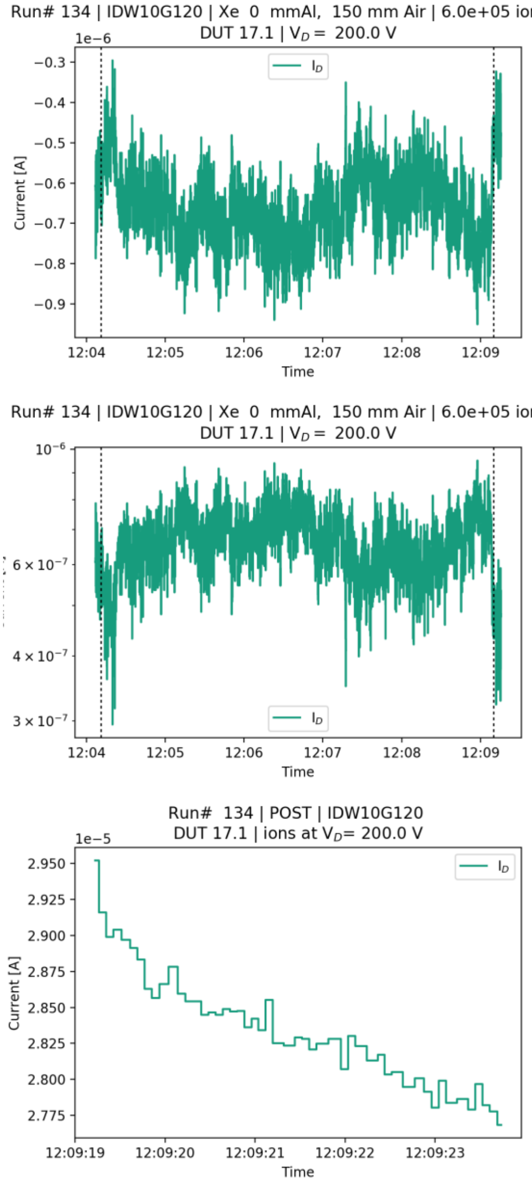


Figure 55: Run# 135, IDW10G120, Xe 0 mmAl, 150 mm Air, 6.0e+05 ions/cm2 , DUT 17.2, VD= 200.0 V

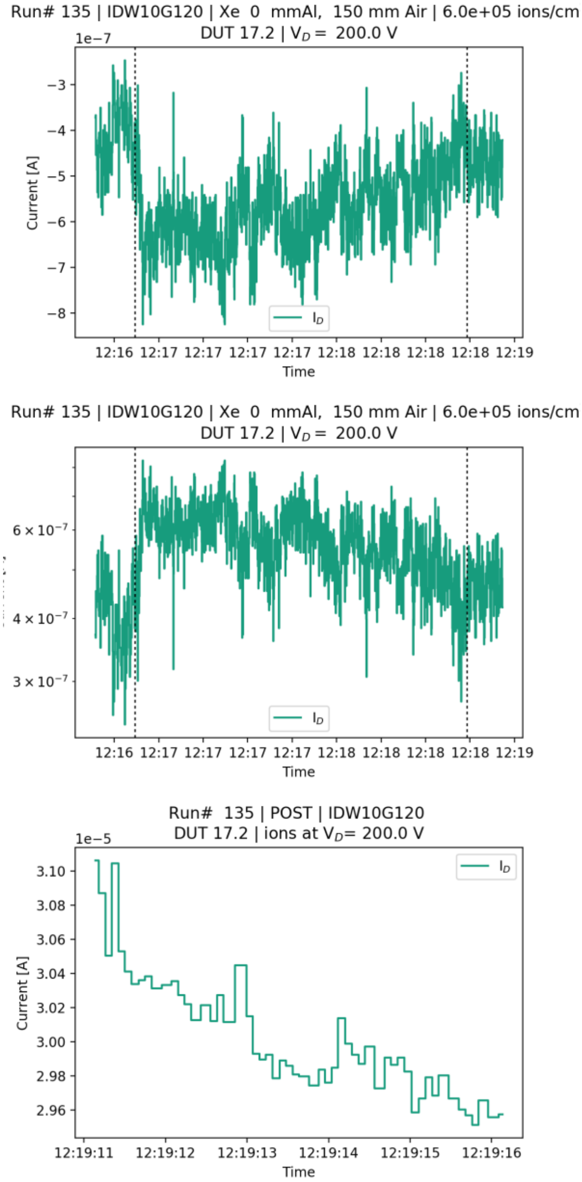


Figure 56: Run# 136, IDW10G120, Xe 0 mmAl, 150 mm Air, 6.0e+05 ions/cm2 , DUT 17.2, VD= 150.0 V

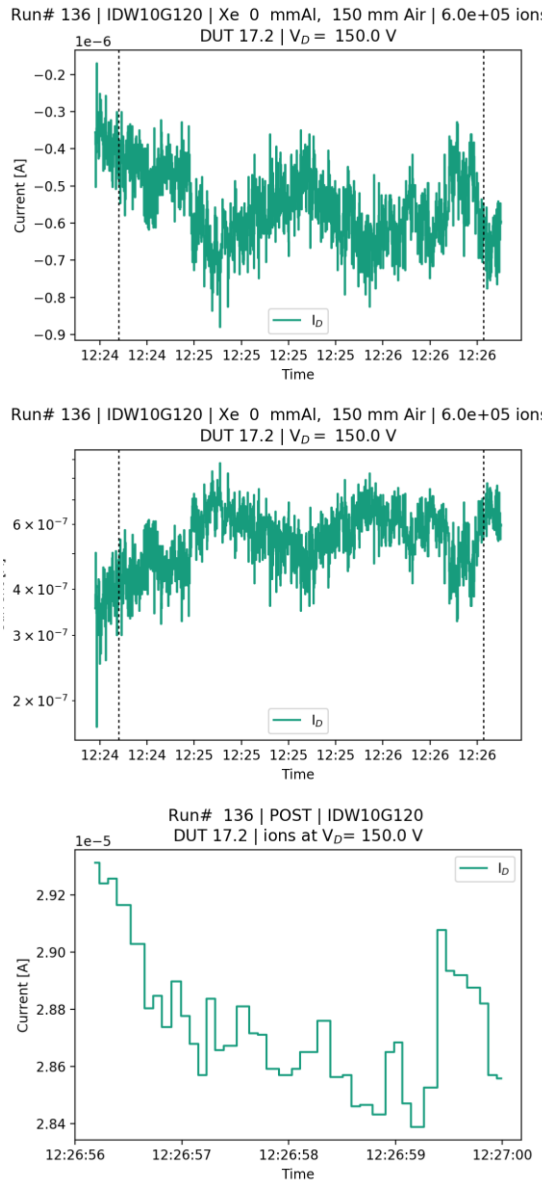


Figure 57: Run# 137, IDW10G120, Xe 0 mmAl, 150 mm Air, 6.0e+05 ions/cm2 , DUT 18.1, VD= 150.0 V

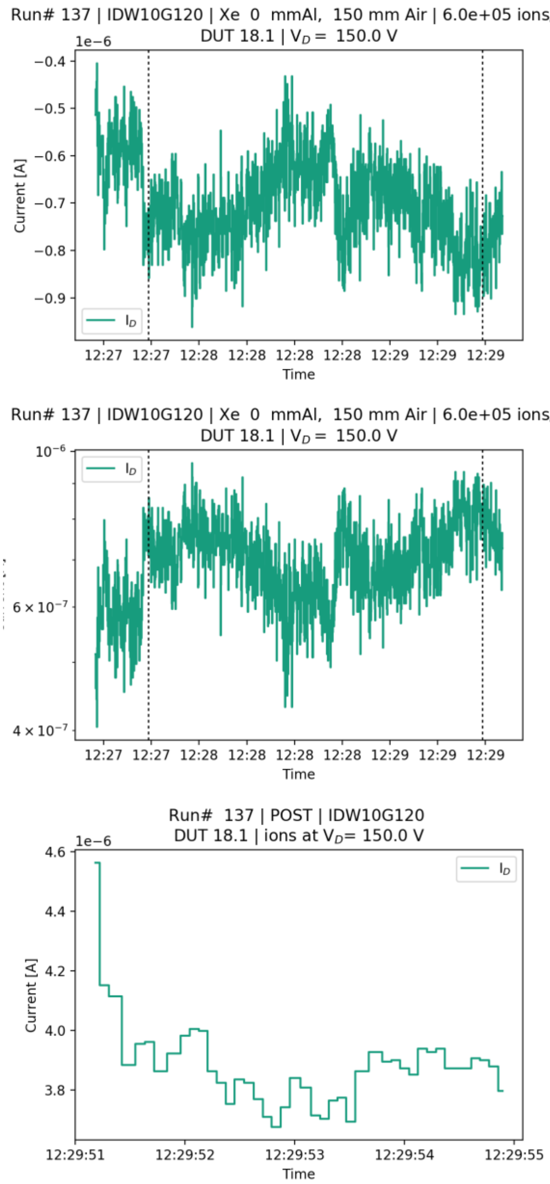


Figure 58: Run# 138, IDW10G120, Xe 0 mmAl, 150 mm Air, 6.0e+05 ions/cm2 , DUT 18.1, VD= 250.0 V

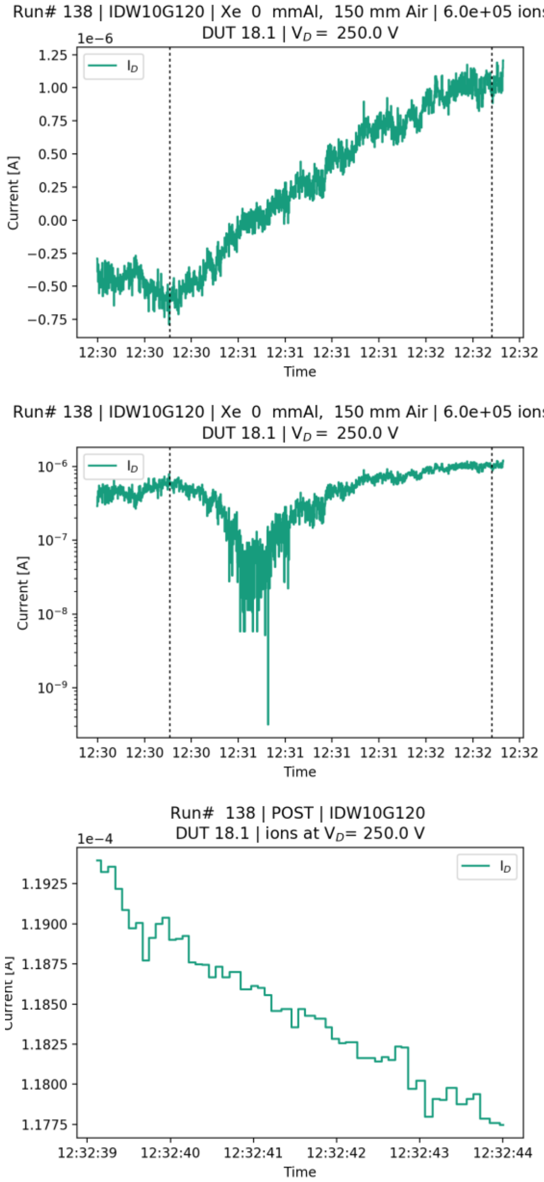


Figure 59: Run# 139, IDW10G120, Xe 400 mmAl, 95 mm Air, 6.0e+05 ions/cm2 , DUT 17.2, VD= 150.0 V

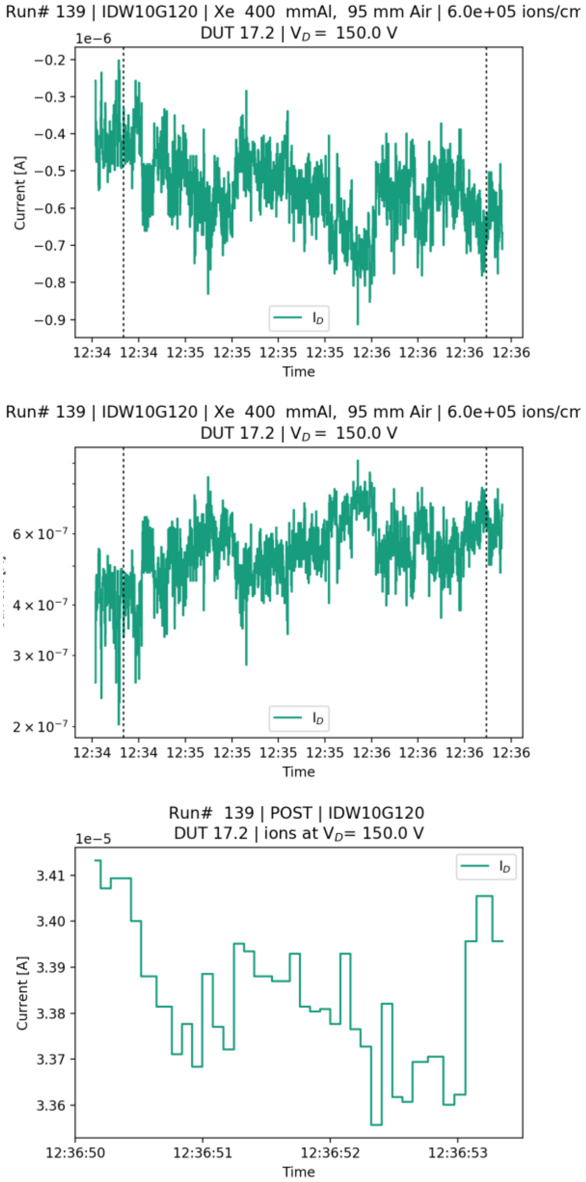


Figure 60: Run# 140, IDW10G120, Xe 400 mmAl, 95 mm Air, 6.0e+05 ions/cm2 , DUT 17.2, VD= 175.0 V

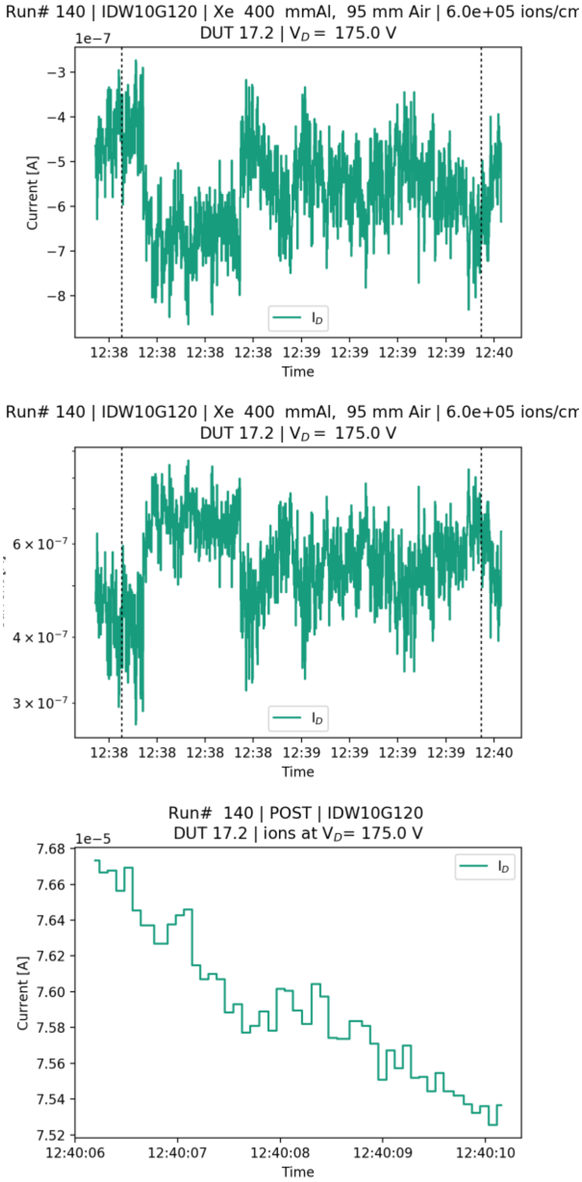


Figure 61: Run# 141, IDW10G120, Xe 400 mmAl, 95 mm Air, 6.0e+05 ions/cm2 , DUT 18.2, VD= 150.0 V

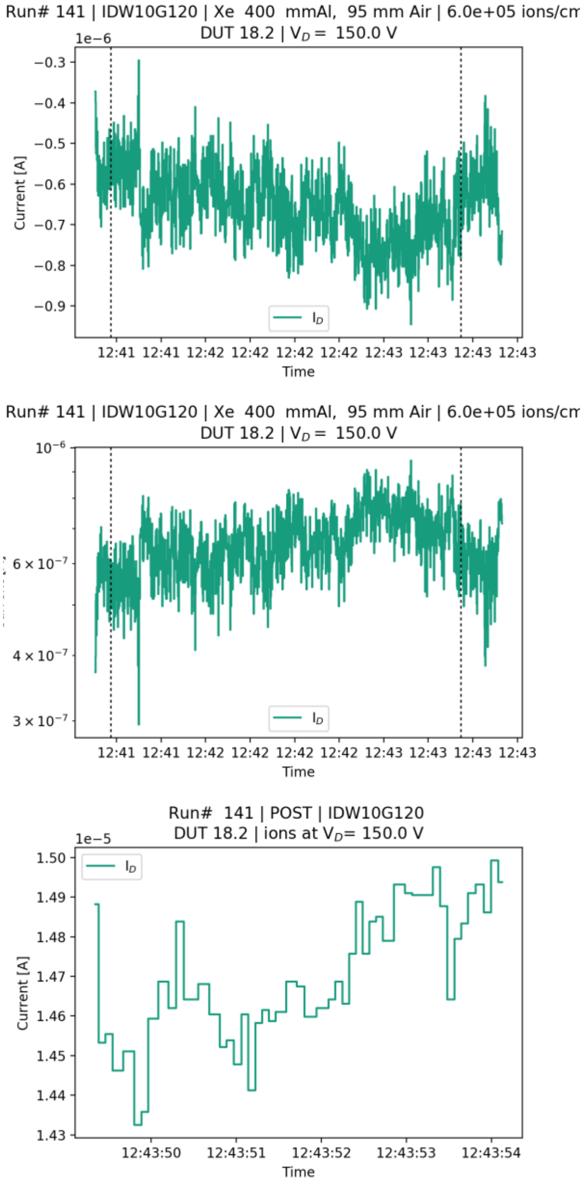


Figure 62: Run# 142, IDW10G120, Xe 500 mmAl, 180 mm Air, 6.0e+05 ions/cm2 , DUT 18.2, VD= 150.0 V

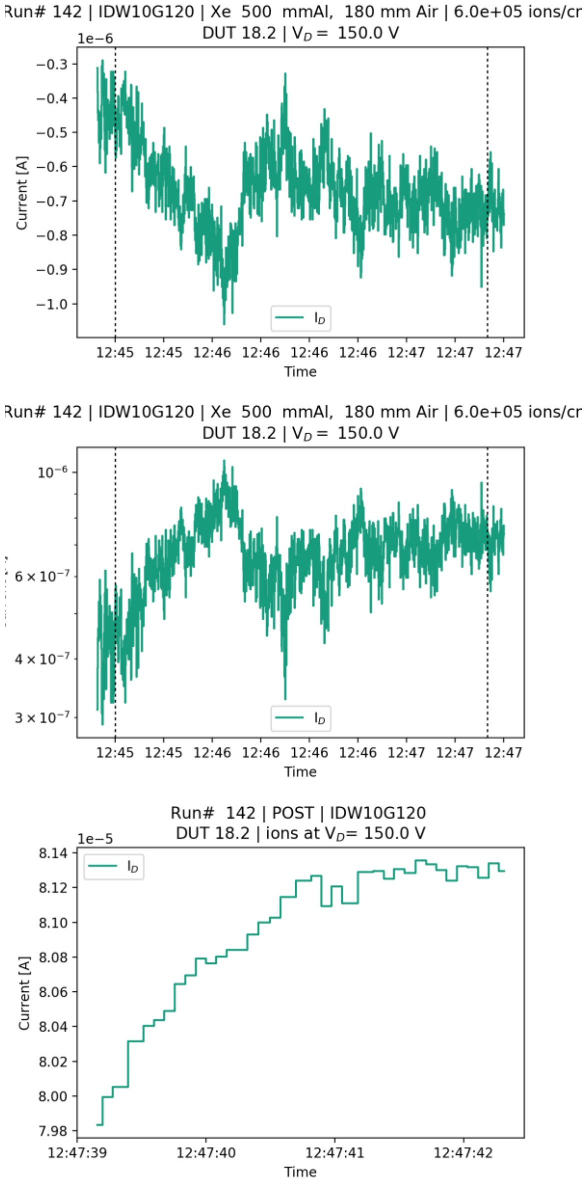


Figure 63: Run# 143, IDW10G120, Xe 500 mmAl, 180 mm Air, 6.0e+05 ions/cm2 , DUT 19.1, VD= 125.0 V

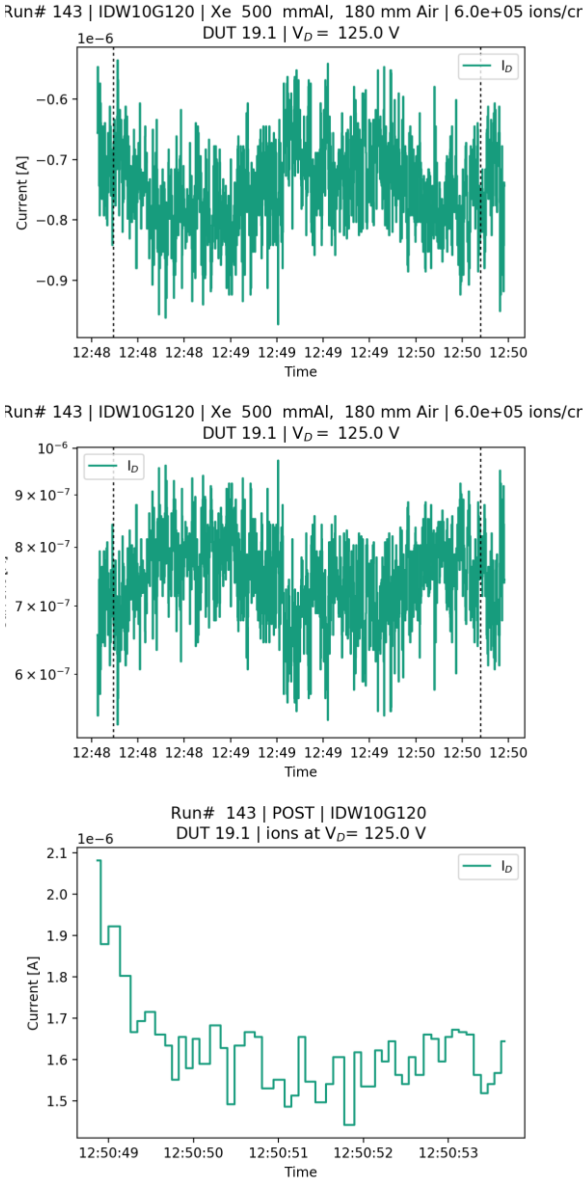


Figure 64: Run# 144, IDW10G120, Xe 500 mmAl, 180 mm Air, 6.0e+05 ions/cm2 , DUT 19.2, VD= 125.0 V

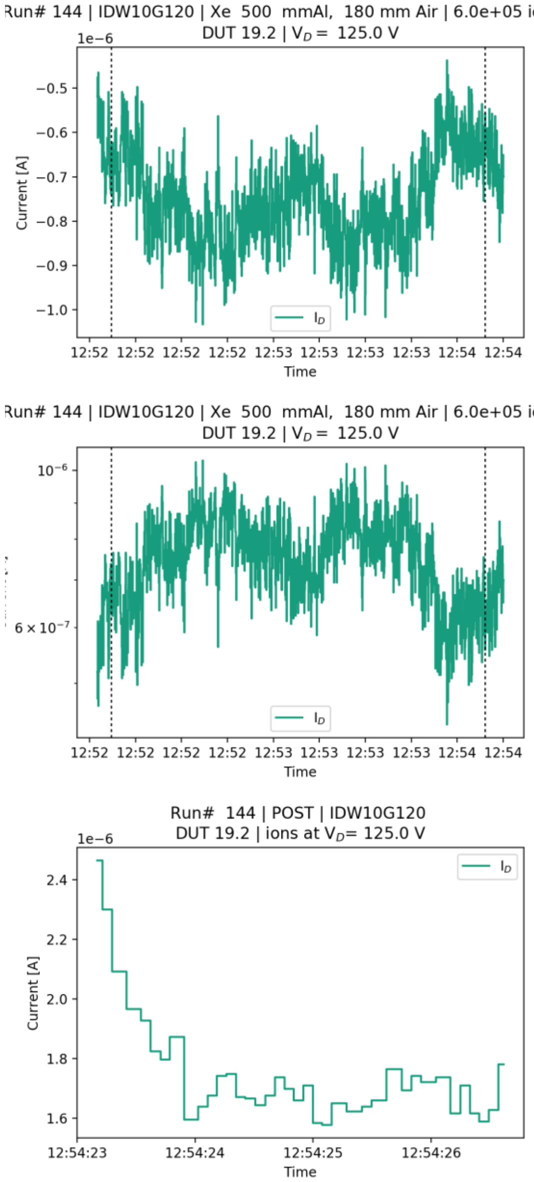
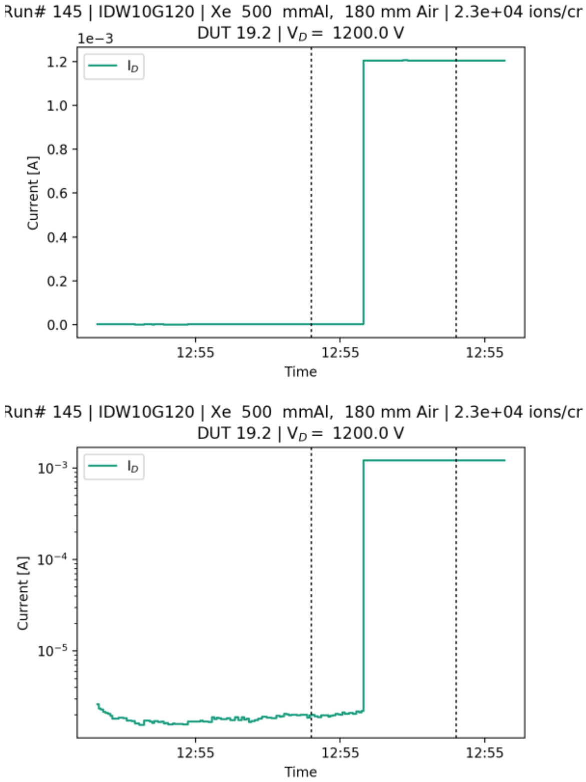


Figure 65: Run# 145, IDW10G120, Xe 500 mmAl, 180 mm Air, 2.3e+04 ions/cm2 , DUT 19.2, VD= 1200.0 V



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.

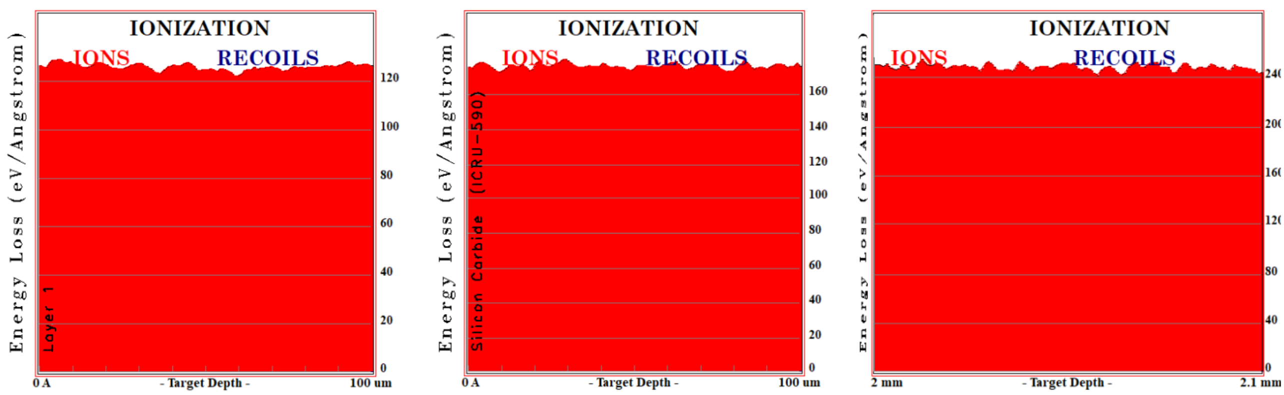
The LET values for silicon were simulated with FLUKA up to energies > 100 GeV/n and with SRIM up to 10 GeV/n by Rubén García Alía et al. and reported in [14]. There different LET values were considered, one unrestricted value taking into account all ionization caused by the beam (approx. 6.3 MeV cm²/mg) and a volume-restricted value covering the area of a 9.3 MeV/n Silicon particle track (approx. 3.7 MeV cm²/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 [14] 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 66 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 cm²/mg for Si and (5.47 ± 0.05) MeV cm²/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 cm²/mg (image not shown).

Figure 66: 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 [14] 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(Θ). 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	beam time [s]	fluence [cm-2]
019	01.12.	13:22	Xe	0	Schottky	IDW10G120	1.2	900	2.96E+02	7.89E+03
020	01.12.	13:28	Xe	0	Schottky	IDW10G120	1.2	950	3.01E+02	8.03E+03
021	01.12.	13:33	Xe	0	Schottky	IDW10G120	1.2	1000	3.01E+02	8.03E+03
022	01.12.	13:39	Xe	0	Schottky	IDW10G120	1.2	1100	2.10E+01	5.60E+02
023	01.12.	13:40	Xe	0	Schottky	IDW10G120	2.1	900	1.18E+03	3.15E+04
024	01.12.	14:55	Xe	0	Schottky	IDW10G120	2.1	1000	1.60E+03	4.27E+04
025	01.12.	15:25	Xe	0	Schottky	IDW10G120	2.1	1050	2.90E+01	7.73E+02
026	01.12.	15:28	Xe	0	Schottky	IDW10G120	2.2	1000	3.06E+02	8.16E+03
027	01.12.	15:33	Xe	0	Schottky	IDW10G120	2.2	1050	3.00E+01	8.00E+02
036	01.12.	17:24	Xe	42	Schottky	IDW10G120	3.1	900	3.37E+02	8.99E+03
037	01.12.	17:30	Xe	42	Schottky	IDW10G120	3.1	950	3.00E+02	8.00E+03
038	01.12.	17:36	Xe	42	Schottky	IDW10G120	3.1	1000	3.09E+02	8.24E+03
039	01.12.	17:40	Xe	42	Schottky	IDW10G120	3.1	1050	3.00E+02	8.00E+03
040	01.12.	17:45	Xe	42	Schottky	IDW10G120	3.1	1100	3.07E+02	8.19E+03
041	01.12.	17:50	Xe	42	Schottky	IDW10G120	3.1	1150	3.00E+02	8.00E+03
042	01.12.	17:56	Xe	42	Schottky	IDW10G120	3.1	1200	1.91E+02	5.09E+03
043	01.12.	18:00	Xe	42	Schottky	IDW10G120	3.1	1250	7.70E+01	2.05E+03

044	01.12.	18:01	Xe	42	Schottky	IDW10G120	3.1	1300	2.30E+01	6.13E+02
045	01.12.	18:03	Xe	42	Schottky	IDW10G120	3.2	1100	1.48E+02	3.95E+03
046	01.12.	18:05	Xe	42	Schottky	IDW10G120	3.2	1150	1.01E+02	2.69E+03
047	01.12.	18:07	Xe	42	Schottky	IDW10G120	3.2	1200	1.04E+02	2.77E+03
048	01.12.	18:09	Xe	42	Schottky	IDW10G120	3.2	1250	1.02E+02	2.72E+03
049	01.12.	18:11	Xe	42	Schottky	IDW10G120	3.2	1300	6.40E+01	1.71E+03

E.3. Measurement

Figure 67: Run# 019, IDW10G120, Xe 0 °,, 7.9e+03 ions/cm2 , DUT 1.2, VD= 900.0 V

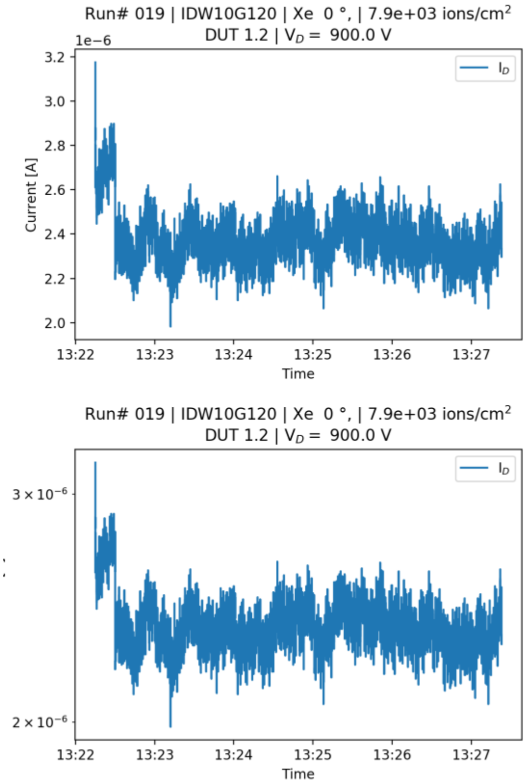


Figure 68: Run# 020, IDW10G120, Xe 0 °,, 8.0e+03 ions/cm2 , DUT 1.2, VD= 950.0 V

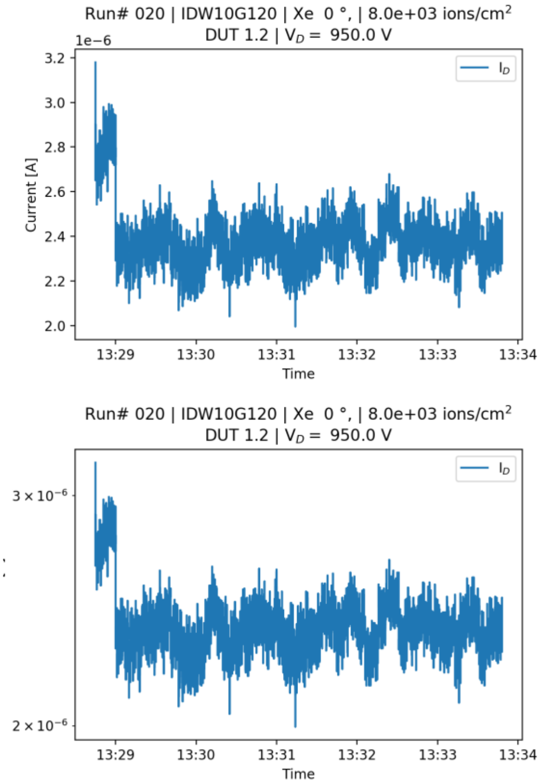


Figure 69: Run# 021, IDW10G120, Xe 0 °,, 8.0e+03 ions/cm2 , DUT 1.2, VD= 1000.0 V

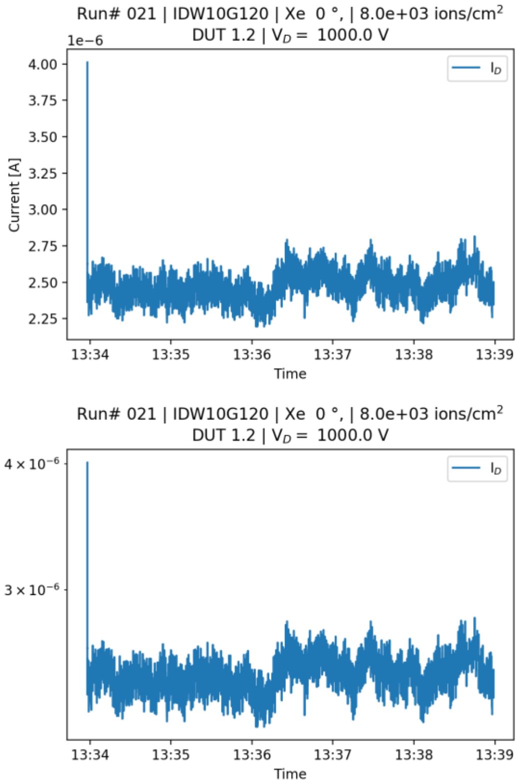


Figure 70: Run# 022, IDW10G120, Xe 0 °,, 5.6e+02 ions/cm2 , DUT 1.2, VD= 1100.0 V

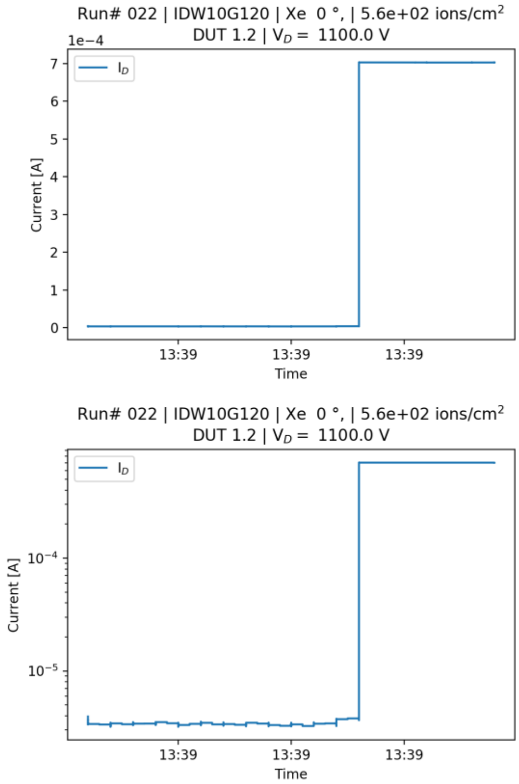


Figure 71: Run# 023, IDW10G120, Xe 0 °,, 3.1e+04 ions/cm2 , DUT 2.1, VD= 900.0 V

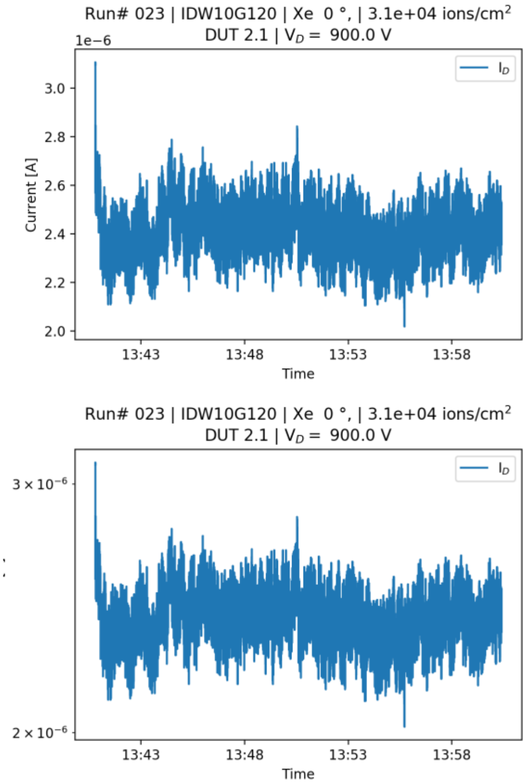


Figure 72: Run# 024, IDW10G120, Xe 0 °,, 4.3e+04 ions/cm2 , DUT 2.1, VD= 1000.0 V

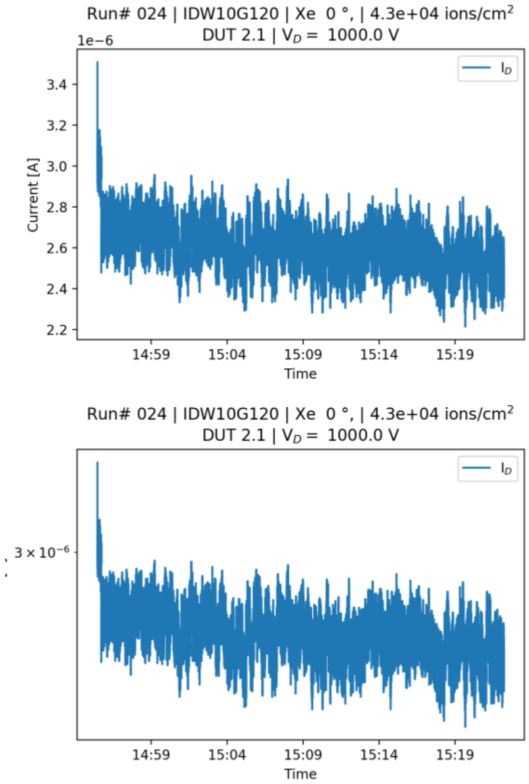


Figure 73: Run# 025, IDW10G120, Xe 0 °,, 7.7e+02 ions/cm2 , DUT 2.1, VD= 1050.0 V

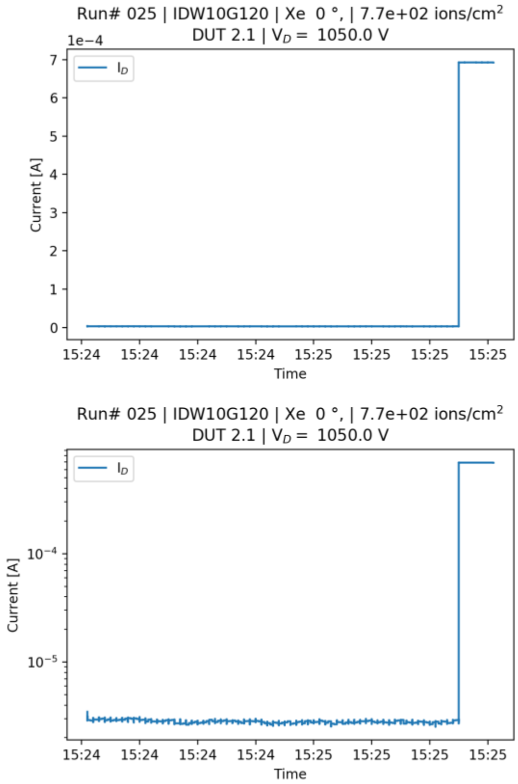


Figure 74: Run# 026, IDW10G120, Xe 0 °,, 8.2e+03 ions/cm2 , DUT 2.2, VD= 1000.0 V

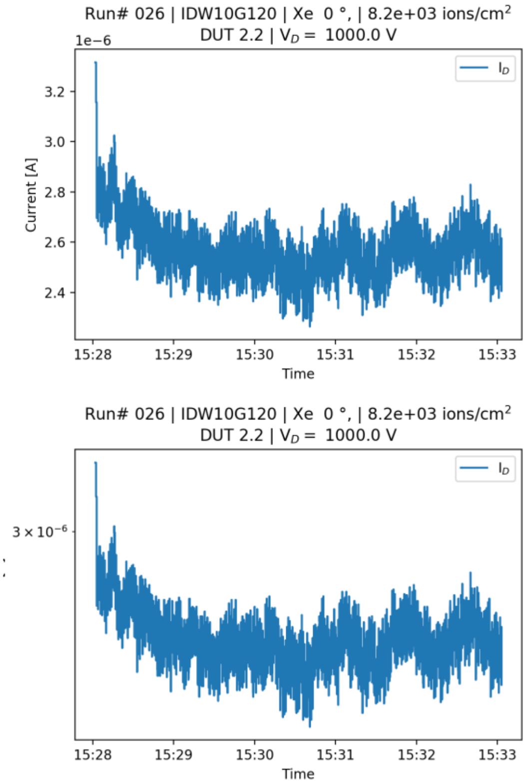


Figure 75: Run# 027, IDW10G120, Xe 0 °,, 8.0e+02 ions/cm2 , DUT 2.2, VD= 1050.0 V

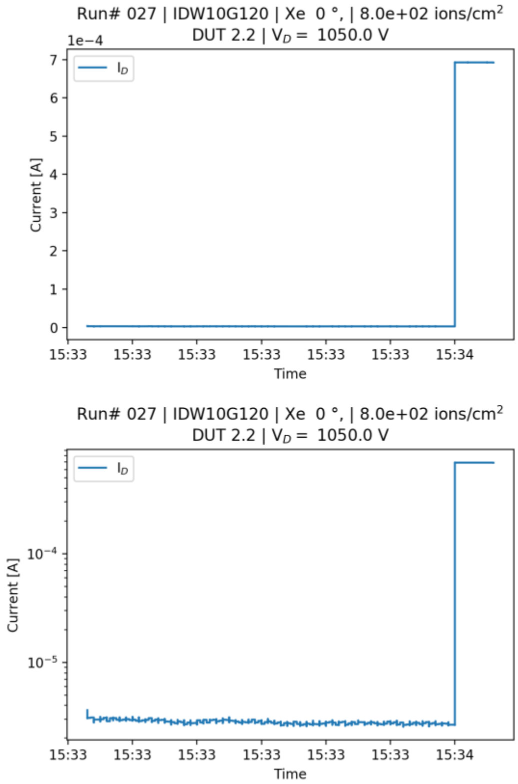


Figure 76: Run# 036, IDW10G120, Xe 42 °,, 9.0e+03 ions/cm2 , DUT 3.1, VD= 900.0 V

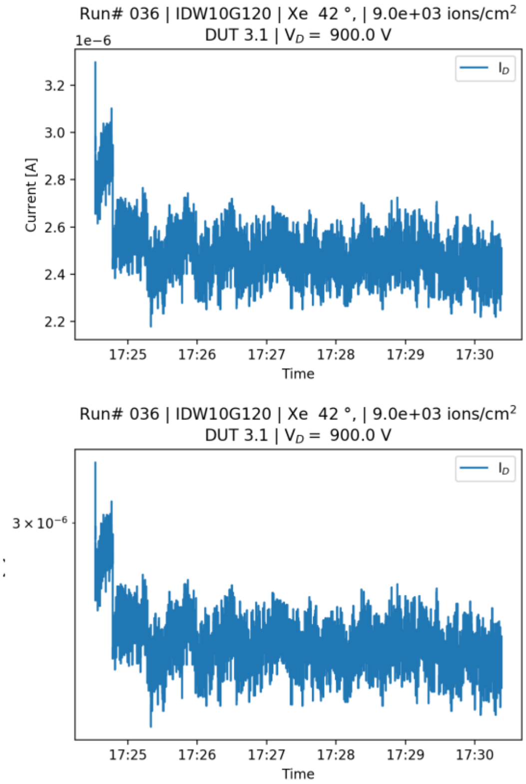


Figure 77: Run# 037, IDW10G120, Xe 42 °,, 8.0e+03 ions/cm2 , DUT 3.1, VD= 950.0 V

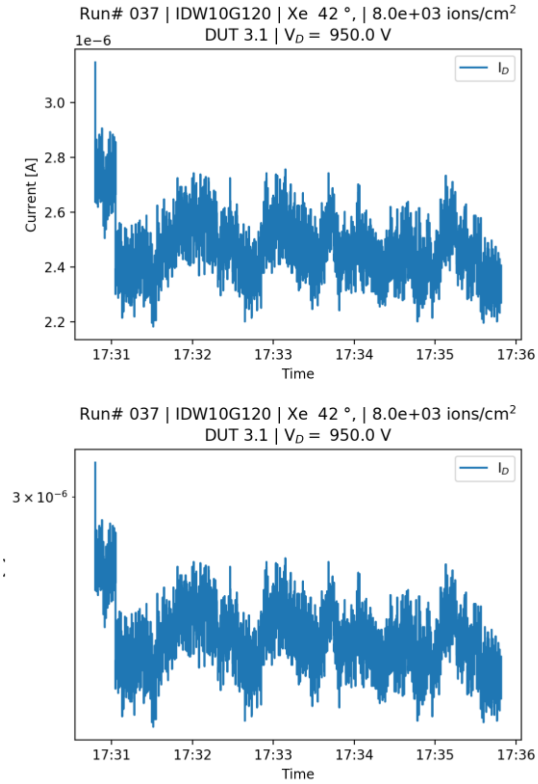


Figure 78: Run# 038, IDW10G120, Xe 42 °,, 8.2e+03 ions/cm2 , DUT 3.1, VD= 1000.0 V

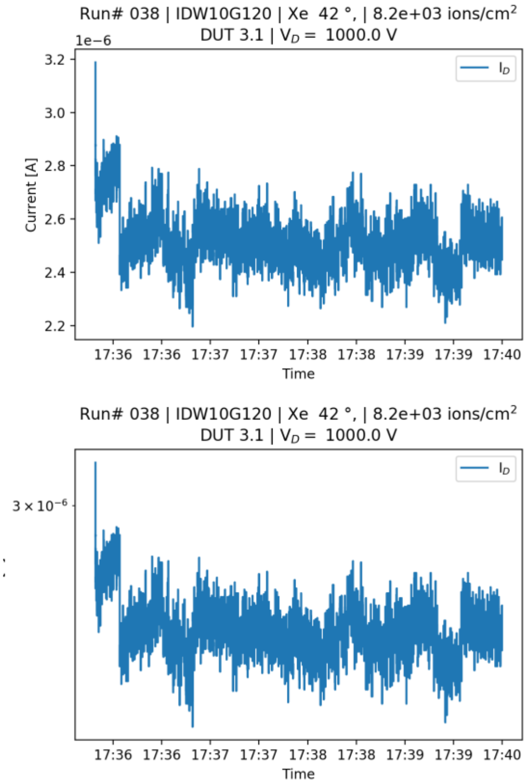


Figure 79: Run# 039, IDW10G120, Xe 42 °,, 8.0e+03 ions/cm2 , DUT 3.1, VD= 1050.0 V

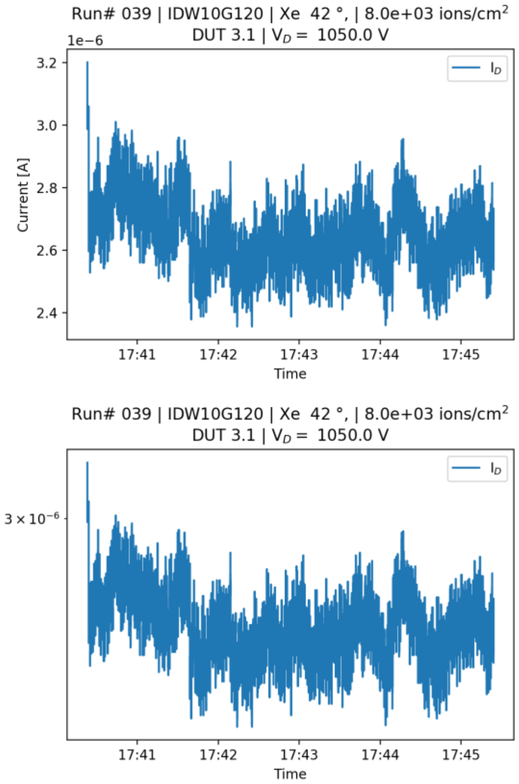


Figure 80: Run# 040, IDW10G120, Xe 42 °,, 8.2e+03 ions/cm2 , DUT 3.1, VD= 1100.0 V

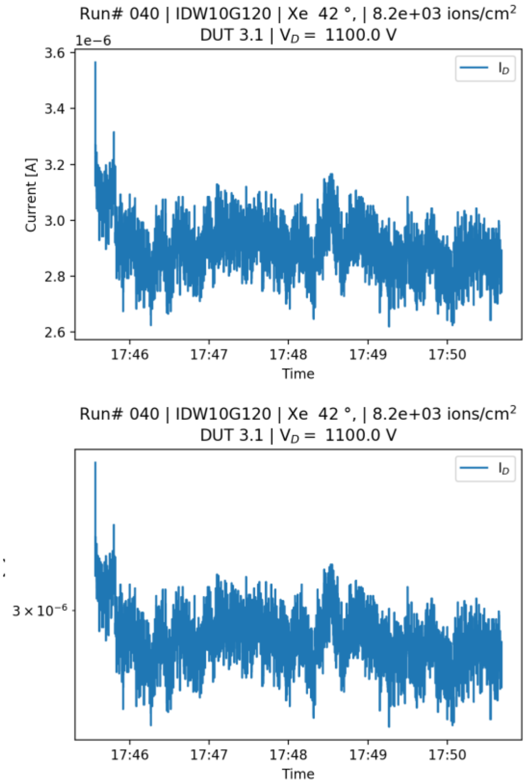


Figure 81: Run# 041, IDW10G120, Xe 42 °,, 8.0e+03 ions/cm2 , DUT 3.1, VD= 1150.0 V

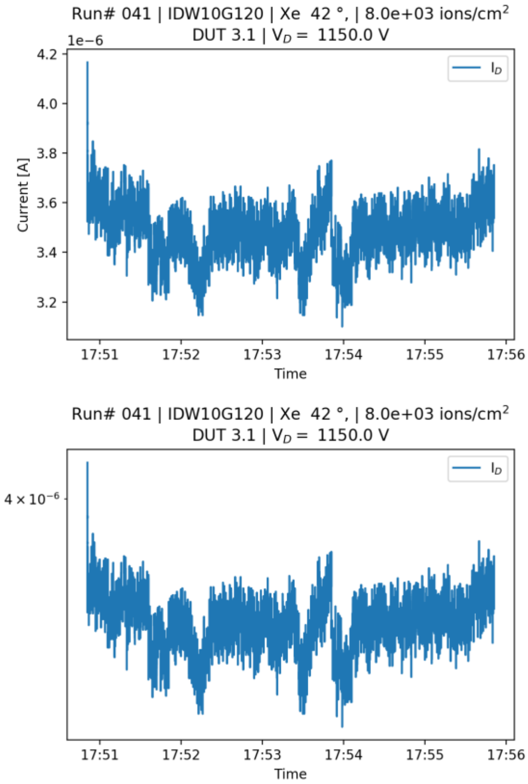


Figure 82: Run# 042, IDW10G120, Xe 42 °,, 5.1e+03 ions/cm2 , DUT 3.1, VD= 1200.0 V

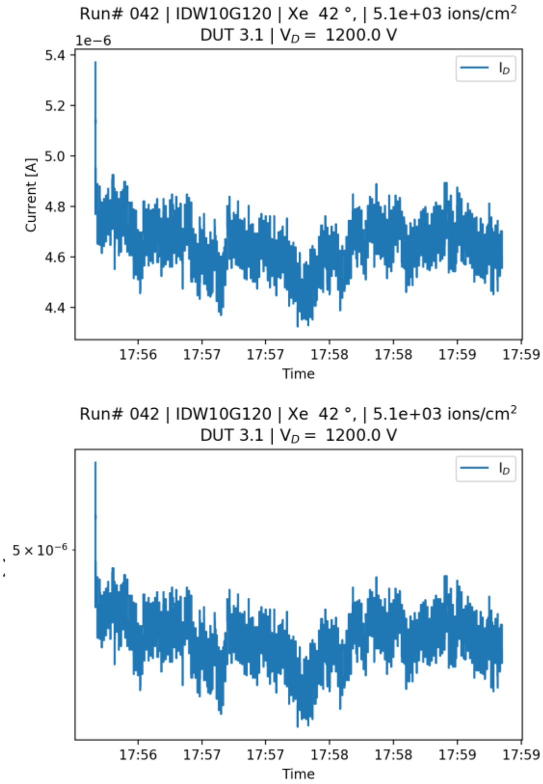


Figure 83: Run# 043, IDW10G120, Xe 42 °,, 2.1e+03 ions/cm2 , DUT 3.1, VD= 1250.0 V

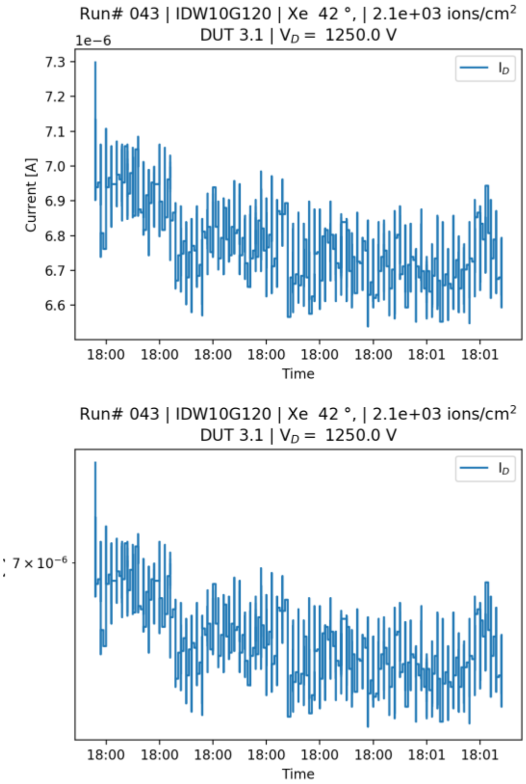


Figure 84: Run# 044, IDW10G120, Xe 42 °,, 6.1e+02 ions/cm2 , DUT 3.1, VD= 1300.0 V

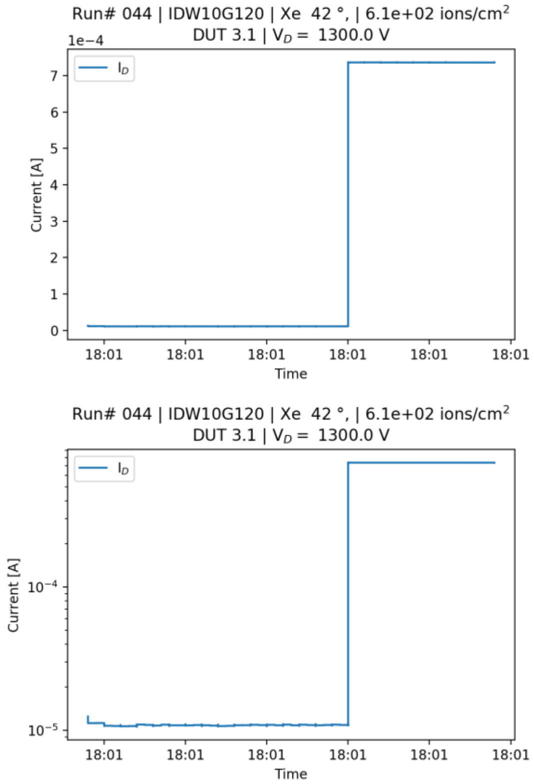


Figure 85: Run# 045, IDW10G120, Xe 42 °,, 3.9e+03 ions/cm2 , DUT 3.2, VD= 1100.0 V

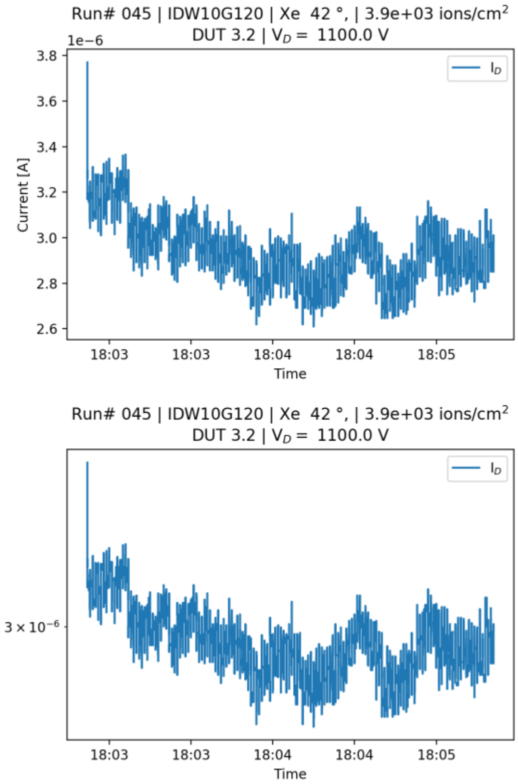


Figure 86: Run# 046, IDW10G120, Xe 42 °,, 2.7e+03 ions/cm2 , DUT 3.2, VD= 1150.0 V

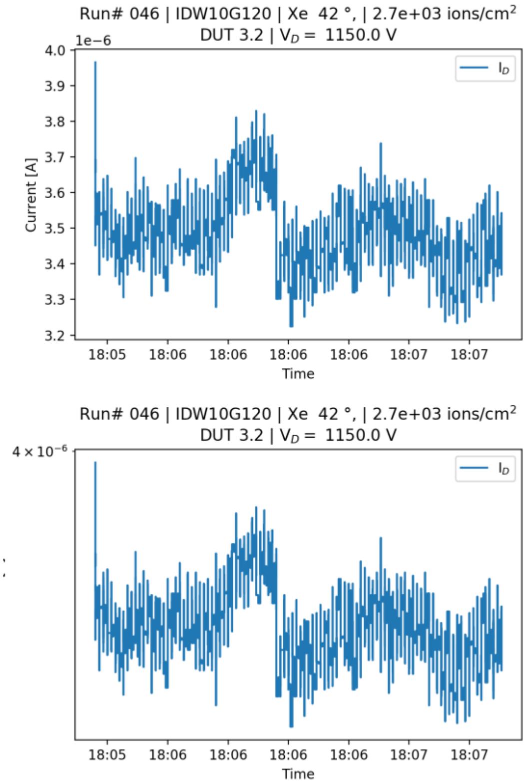


Figure 87: Run# 047, IDW10G120, Xe 42 °,, 2.8e+03 ions/cm2 , DUT 3.2, VD= 1200.0 V

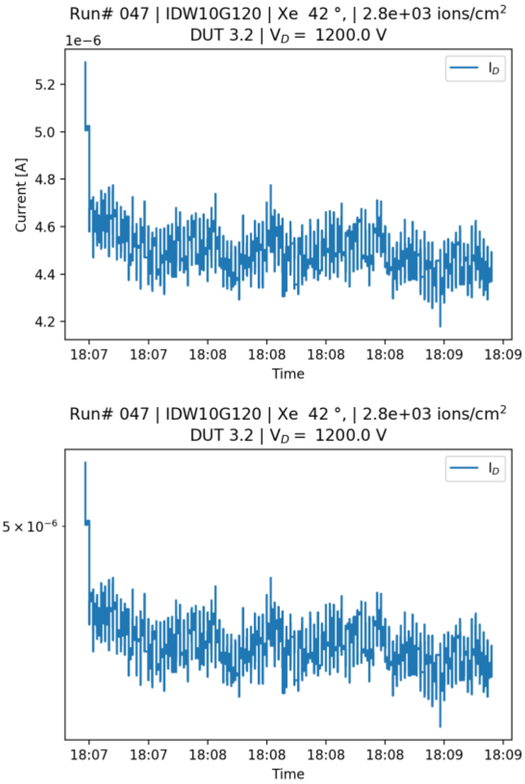


Figure 88: Run# 048, IDW10G120, Xe 42 °,, 2.7e+03 ions/cm2 , DUT 3.2, VD= 1250.0 V

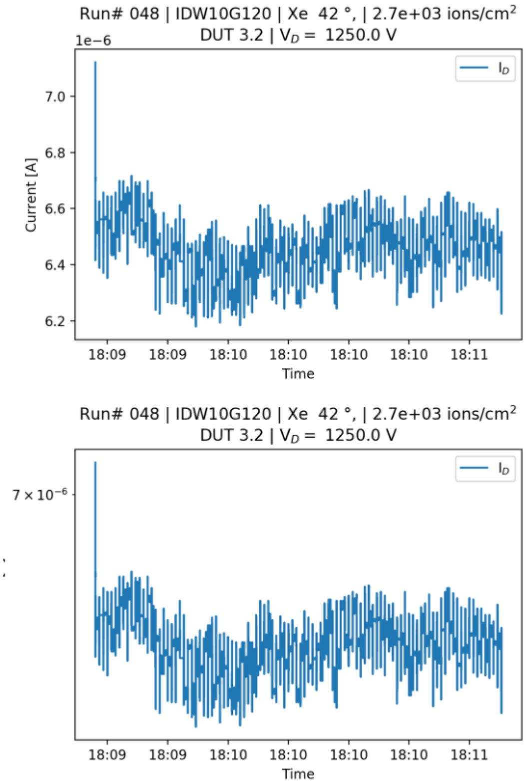


Figure 89: Run# 049, IDW10G120, Xe 42 °,, 1.7e+03 ions/cm2 , DUT 3.2, VD= 1300.0 V