Single-Event Effect Testing of the Cree C4D40120D Commercial 1200V Silicon Carbide Schottky Diode

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I. Introduction and Summary of Test Results

This study was undertaken to determine the single event effect (SEE) susceptibility of the commercial silicon carbide 1200V Schottky diode manufactured by Cree, Inc. Heavy-ion testing was conducted at the Texas A&M University Cyclotron Single Event Effects Test Facility (TAMU). Its purpose was to evaluate this device as a candidate for use in the Solar-Electric Propulsion flight project.

Devices exhibited reverse-bias current (I_R) degradation and/or catastrophic failure during heavy-ion irradiation. The threshold reverse voltage (V_R) bias for immediate catastrophic single-event failure is easy to determine; at much lower biases, no degradation occurs. The rapid increase in I_R at biases in between these two cases makes assessment of the maximum safe operating bias for a given space radiation environment extremely difficult: there is a broad region of biases for which catastrophic failure susceptibility is uncertain. I_R degradation did not recover in devices biased below the threshold for immediate catastrophic failure, suggesting that some thermal damage had occurred. A summary of results is given in Table I below.

Table 1: Summary of Heavy-Ion Test Results
(Beam properties are surface-incident as well as after transport via SRIM through 1 mil of parylene. LETs and ranges are for silicon carbide.)

Ion Species	Surface-Incident Energy *(MeV)*	Range *(μm)*	Surface-Incident LET *(MeV·cm^2/mg)*	Applied Reverse Bias *(V)*	Result
Kr	1032/918	90/78	30/31	175	No change in I_R during irradiation
				200	I_R increased as function of fluence
Ag	1289/1110	77/66	46/49	100	No change in I_R during irradiation
				200	I_R increased as function of fluence
				550	Immediate catastrophic failure
Xe	1512/1291	76/64	57/60	150	No change in I_R during irradiation
				175	I_R increased as function of fluence

II. Devices Tested

The sample size for this testing was 12 pieces. The device is manufactured by Cree, Inc. and is a 1200 V commercial silicon carbide Schottky diode, part #C4D40120D. The parts were packaged in TO-247 packages and comprises two diode die with a common cathode pin (see Fig. 1A for pin diagram). The internal NASA GSFC REAG ID# for this device is 13-033. In preparation for testing, parts were decapsulated with acid at GSFC by Ted Wilcox to expose the surface of one of the two die to permit ion beam penetration into the active region. A controlled 1-mil parylene coating was then deposited to prevent the bond wires from arcing under high voltage, and the package pins were additionally coated in hot glue. The parts were electrically characterized on site at TAMU before radiation testing. A picture of a decapsulated part mounted on a daughter card is shown in Fig. 1B. Appendix A gives the manufacturer's electrical specifications and the pre-irradiation characterization results. Nine parts tested in May, 2013, were characterized only for forward voltage drop; tests performed in June, 2013 were additionally characterized for reverse bias current at a low, 200 V_R, and at 1100 V_R, the maximum attainable bias the source-measuring unit could provide.

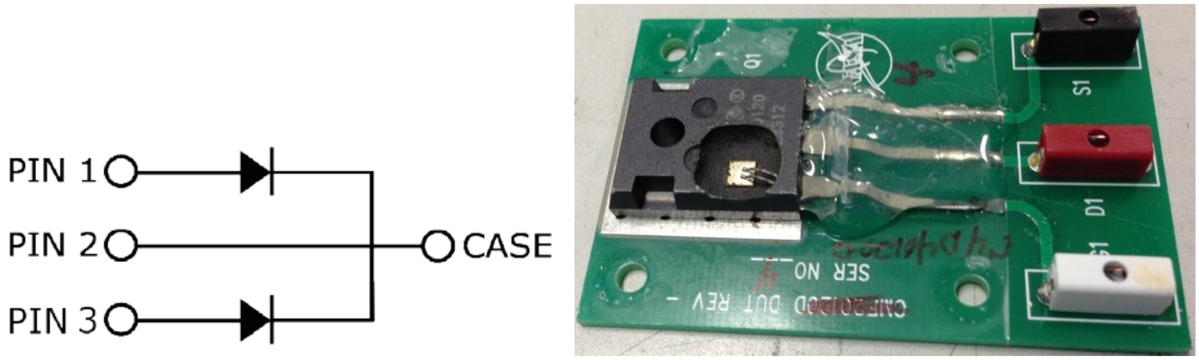

Figure 1. Pin-out of C4D40120D (left) and photograph of decapsulated TO-247 packaged DUT mounted on a daughter card (right).

III. Test Facility

Facility: Texas A&M University Cyclotron Single Event Effects Test Facility, 15 MeV/amu tune.
Flux: May, 2013 tests: $1x10^3$ ions/cm^2/s; June, 2013 tests: 40 – 70 ions/cm^2/s.
Fluence: Maximum fluence on passing runs = 3 x 10^5 ions/cm^2.
Ion species: Krypton, silver, and xenon. The table below shows the surface-incident beam properties for SiC, and the properties after passage through the 1 mil parylene coating.

Table 2. Ion Beam Properties (surface-incident and after passage through the parylene coating)

Ion	**Surface Energy/ After Coating *(MeV)***	**Surface LET/ After Coating *(MeV·cm²/mg)***	**Range/ After Coating *(μm)***
^{84}Kr	1032/918	30/31	90/78
^{109}Ag	1289/1110	46/49	77/66
^{129}Xe	1512/1291	57/60	76/64

IV. Test Setup

The power diode test circuit and block diagram are shown in Figures 2 and 3. For these tests, the GSFC Radiation Effects and Analysis Group (REAG) high-voltage power MOSFET motherboard was used as follows. A Keithley 2410 source meter provided the appropriate reverse bias voltage while measuring the diode reverse-bias current (I_R). A 500 Ω resistor is switched into series with the Keithley 2410 to protect it from sudden high-current transients; it is switched out during device characterization tests. A Keithley 2400 source meter is set to 0 V during irradiation in order to ground the gate circuitry on the motherboard (2400 and 2410 grounds are tied). DUTs are adapted to the motherboard using daughter cards as shown in Figure 1; the drain-source circuitry of the motherboard is connected to the daughter card via jumper wires, yielding the equivalent circuit shown in Figure 2. Diode reverse-bias current is limited to 21 mA and recorded via GPIB controller to a desktop computer at approximately 250 ms intervals. A Tektronix DPO4054 digital oscilloscope monitors voltage transients across the 1-Ω sense resistor via BNC cable. All equipment is plugged into a power conditioner.

Six DUTs can be mounted on the test board via daughter cards and individually accessed via dry Reed relays controlled by an Agilent DAQ 34907A data acquisition/switch unit and powered by a GW Instek PST-3202 power supply. All terminals of the devices not under test are then floating. Testing was conducted with the DUT centered within the 1 inch beam diameter. Ion exposures were conducted at normal incidence to the DUT in air. Photographs of the test setup and DUT test board are shown in Figure 4, and a list of the test equipment and calibration information is provided in Table 3.

The test setup is controlled via custom LabVIEW programs written by Alyson Topper and Hak Kim, MEI Technologies, for this test. One program controls the source measuring units (SMUs) and diode current sampling and recording. It is designed to perform a parametric analysis of each DUT prior to irradiation and following each beam run, recording if selected V_F as well as I_R at reverse-bias voltages of up to 1100 V. The second LabVIEW program controls the oscilloscope monitoring and transient capture.

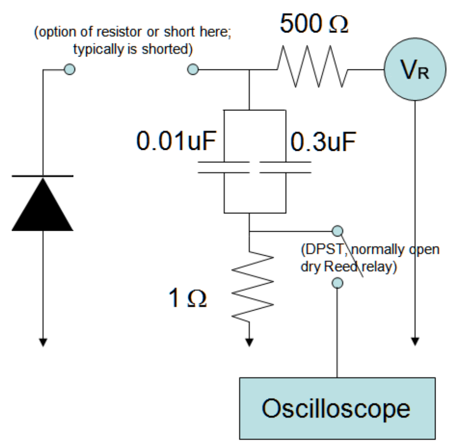

Figure 2. Equivalent test circuit for the C4D40120D Schottky diode.

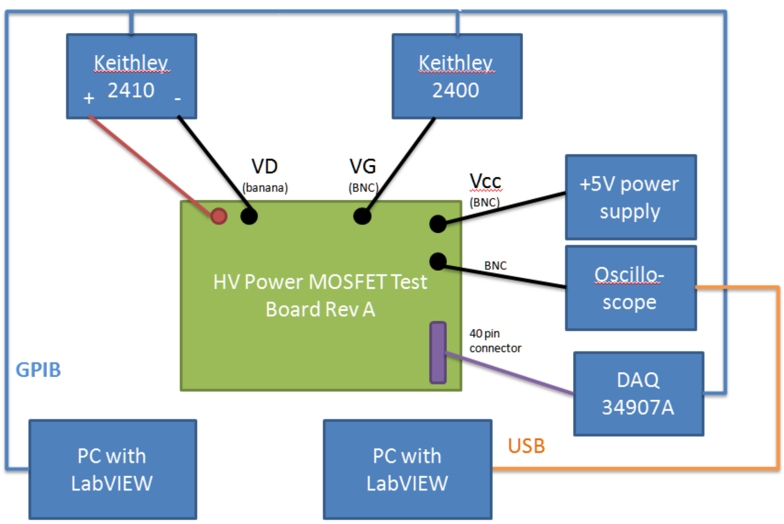

Figure 3. Block diagram of test setup in which the high-voltage power MOSFET test board is modified for diode testing: V_G is set to 0 V and shares common ground with the Keithley 2410, thereby grounding the gate circuitry on the motherboard. There is no gate contact to the daughter card/DUT; the diode is reverse-biased via the drain-source contacts.

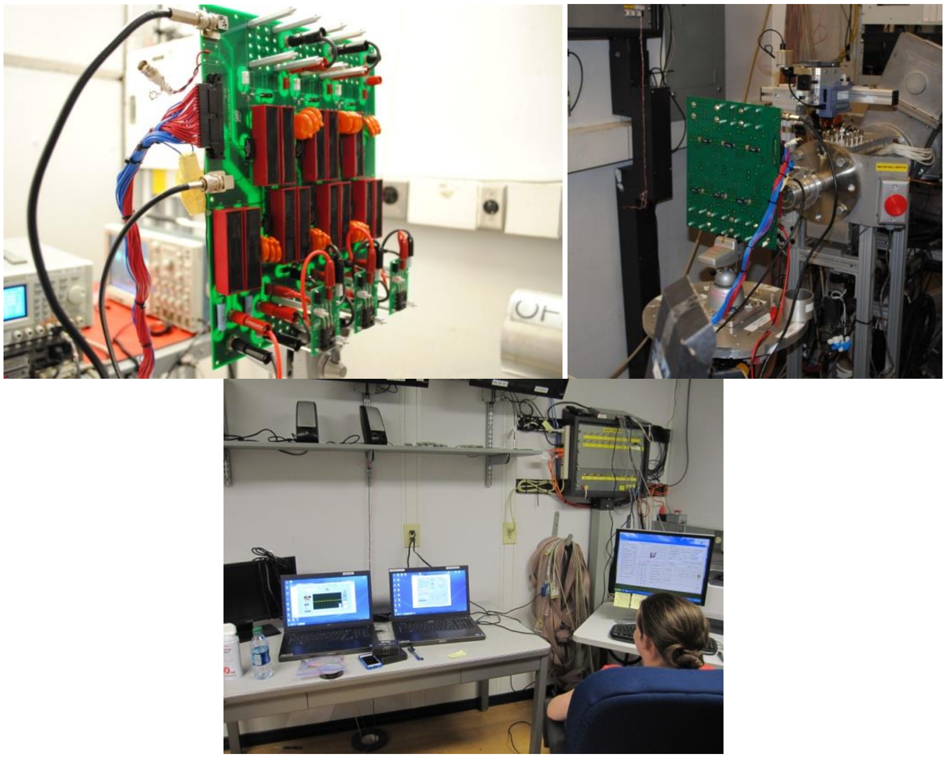

Figure 4. Top Left: Equipment in beam cave; Top Right: Test board being positioned for ion beam exposure. Bottom: Test/monitoring room setup.

Table 3. Test Equipment

Node	Make/Model	Serial No.	Calibration Due
V_G	Keithley 2400 source meter	1342769	8/8/2013
V_D	Keithley 2410 source meter Tektronix scope DPO4054	1247479 B020036	2/5/2014 11/30/2013
V_{CC}	GW Intek power supply	R1180020	2/7/2014
Other	2 Dell Precision laptops Power Conditioner Agilent DAQ 34907A Tektronix scope DPO4054	 SG41007993 B020036	 2/6/2013 11/30/2013

V. Test Results and Discussion

Tests were conducted at the Texas A&M University Cyclotron Single Event Effects Test Facility on May 7-8 2013, and on June 14, 2013. Test personnel were Megan Casey and Ted Wilcox (May, 2013), or Jean-Marie Lauenstein and Hak Kim (June, 2013). The monoenergetic ion beams used are listed in Table II above and include 10.0 MeV/u Xe, 10.2 MeV/u Ag, and 10.9 MeV/u Kr. All tests were conducted with the beam at normal angle of incidence to the DUT, which is worst-case for SEEs in vertical-field devices.

Prior to the initial beam run and following each run, the diode forward voltage and, for the June testing, reverse-bias current or peak reverse voltage (V_{RRM}) were measured to evaluate the device integrity. These tests revealed that some diodes had been damaged during the device preparation; it is therefore likely that some devices tested during the May campaign were similarly damaged. See figure captions accompanying striptape data in Appendix C. We believe that the overall findings of this study are still valid. Due to the current limit of the Keithley 2410 and to prevent device heating, V_F was measured at 50 mA rather than the 20 A manufacturer specification. Similarly, I_R was measured at the 1100 V maximum supply voltage the single Keithley 2410 could provide rather than at 1200 V. V_{RRM} was identified when below 1100 V.

As indicated in Table 1 in the Introduction above, devices exhibited reverse-bias current (I_R) degradation and/or catastrophic failure during heavy-ion irradiation. In June, samples were therefore irradiated under very low flux to identify single-event induced large increases in reverse-bias current. Due to this low flux and degradation of I_R, run fluences were typically an order of magnitude or more below those indicated as appropriate for power device single-event effect testing in military and JEDEC test standards (3×10^5 to 1×10^6 ions/cm^2). Below the threshold for immediate catastrophic failure, I_R increased as a function of fluence. This increase is larger for heavier ion species for a given fluence. This degradation of SiC diode reverse-bias current has been reported previously in the literature and hinders the ability to assess susceptibility to catastrophic failure at these bias conditions. A large sample size would be required to build confidence in the survivability of the device on orbit: whereas the degradation of current may be acceptable for a given circuit application, risk for single-event catastrophic failure remains uncertain.

The failure mode was single-event burnout. The location of the failure was in the active region of the die, as can be seen in Figure 5 below.

Table 1 in the Introduction provides a summary of the results, identifying the effects seen for a given bias and beam condition. When no impact was seen during the beam run, the highest bias condition for this result was provided; for degradation or catastrophic failure effects, the lowest bias condition tested that resulted in this effect is provided. Detailed results are provided in the Appendices. Device electrical specifications are provided in Appendix A, as well as on-site pre-run functional tests. The test-site data log is in Appendix B and striptape current measurements are plotted in Appendix C. Finally, Appendix D contains ion beam uniformity for the low-flux test conditions used in the June test campaign.

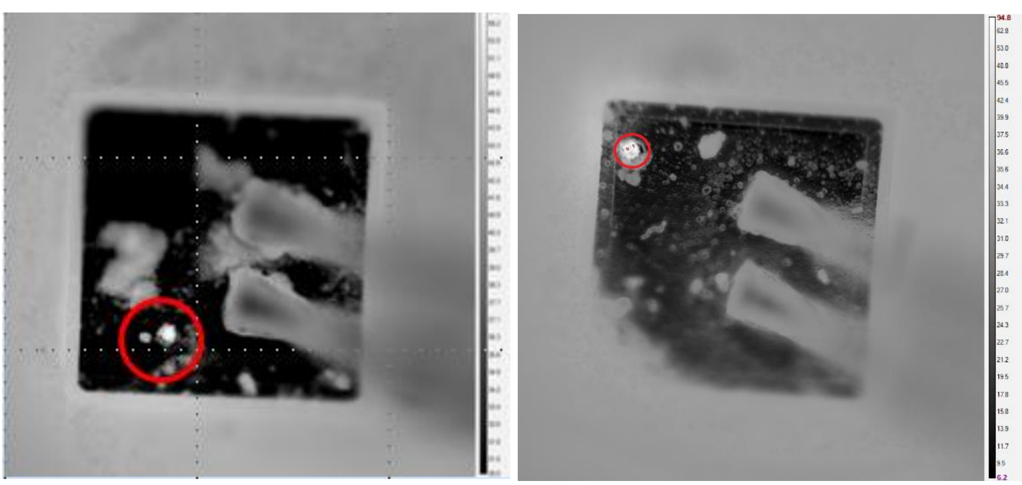

Figure 5. Infrared image of DUT 13 (left) and DUT 11 (right) revealing diode failure location (bright white spot encircled in red) is within the active region of the die.

Appendix A

Table A1. C4D40120D Manufacturer-Specified Electrical Parameters (Partial List)

Parameter	Condition	TYP	MAX	Units
Diode forward voltage (V_F)	I_F = 20 A	1.5	1.8	V
Reverse current (I_R)	V_R = 1200 V	35	200	μA
Repetitive peak reverse voltage (V_{RRM})	n/a	1200		V
Continuous forward current (I_F) leg/device	Tcase < 135 °C	27/54		A

Table A2. On-Site Pre Beam Run Aliveness Tests

Part SN#	V_F at 50 mA I_F *(V)*	I_R at 200 V_R *(A)*	I_R at 1100 V_R *(A)*
1	0.83		
2	0.83		
3	0.84		
4	0.84		
5	0.84		
6	0.83		
7	0.83		
8	0.83		
9	0.83		
10	0.83	1.61E-07	1.59E-04
11	0.83	3.66E-07	5.26E-05
12	0.83	2.12E-07	Failed (shorted)
13	0.83	2.13E-05	(hit max spec at 620 V_R)
14	0.82	5.21E-06	(hit max spec at 815 V_R)

Appendix B

Table B1. Raw test data. Beam diameter = 1"; Air gap = 30 mm.

NOTE: Ion characteristics are from TAMU's SEUSS software based on SRIM 1998, for silicon, at the surface of the die before energy loss to the parylene.

Run	Run Date	Time	S/N	socket	Ion	LET	Energy	Energy	Range	Flux	Fluence	Dose	Total Dose	V_R	V_F	V_{RRM}	P/F	Comments
#				#		MeV.cm2/mg	MeV/u	MeV	µm	#/cm2/s	#/cm2	rad(Si)	rad(Si)	V	V	V		
1	5/7/2013	0:49	3	6	Ag	42.2	11.8	1289	119.3	1085	3.00E+05	2.03E+02	2.03E+02	20	0.84			
2	5/7/2013	0:56	3	6	Ag	42.2	11.8	1289	119.3	1078	3.00E+05	2.03E+02	4.05E+02	100	0.84			
3	5/7/2013	1:03	3	6	Ag	42.2	11.8	1289	119.3	1087	3.00E+05	2.03E+02	6.08E+02	200	0.84			IR went from 2 to 4 uA during run, continued to rise to ~ 6
4	5/7/2013	1:09	3	6	Ag	42.2	11.8	1289	119.3	1088	3.08E+05	2.08E+02	8.16E+02	300	0.82			IR rose drastically and at a constant slope as the beam was on. We paused the beam temporarily and the current didn't change. Once the beam was turned back on, the current again continued to climb at the constant rate. At the end of the run, the current was constant at 1.47 mA. After power cycle, current is slowly increasing from 1.35 mA to 1.42 mA (when we turned off the power).
5	5/7/2013	1:21	3	6	Ag	42.2	11.8	1289	119.3	1077	3.00E+05	2.02E+02	1.02E+03	350	0.75			Current was slowly increasing from 1.8 mA once VR was applied. Once the beam was turned on, it continued to increase but at a faster rate than when the beam was off. After beam was turned off, rate of increase decreased, but current continued to increase to 9 mA when we turned the
6	5/7/2013	1:28	3	6	Ag	42.2	11.8	1289	119.3	1071	1.46E+05	9.88E+01	1.12E+03	400				Current increased as soon as power was applied. When it hit 21 mA, it remained constant. Keithley timed out in the middle of the run. Went downstairs to check on it and one of the Keithleys had turned itself off
7	5/7/2013	2:14	2	5	Ag	42.2	11.8	1289	119.3	1381	3.00E+05	2.03E+02	2.03E+02	200	0.83			
8	5/7/2013	2:20	2	5	Ag	42.2	11.8	1289	119.3	1372	3.00E+05	2.03E+02	4.06E+02	225	0.83			Current immediately started increasing when the beam turned on. Increased for a while after the beam was turned off, but then stabilized 1.14 uA.
9	5/7/2013	2:29	2	5	Ag	42.2	11.8	1289	119.3	1386	3.01E+05	2.03E+02	6.09E+02	250	0.83			Current increased during beam. Then when the beam turned off, the current dropped constantly.
10	5/7/2013	2:35	2	5	Ag	42.2	11.8	1289	119.3	1421	3.00E+05	2.03E+02	8.11E+02	300	0.82			Current increased during beam. Continued to increase a slower rate after the beam was turned off.
11	5/7/2013	2:43	2	5	Ag	42.2	11.8	1289	119.3	1230	8.91E+04	6.02E+01	8.71E+02	400	0.72			We stopped the run before the current reached 21 mA (realized it's a power limit on the 2410 -- any voltage >= 20 V cannot have a current greater than 21 mA).
12	5/7/2013	3:00	1	4	Ag	42.2	11.8	1289	119.3	1285	3.00E+05	2.03E+02	2.03E+02	150	0.83			Saw some weird current spikes, but current ended up where it started.
13	5/7/2013	3:06	1	4	Ag	42.2	11.8	1289	119.3	1081	3.00E+05	2.03E+02	4.05E+02	175	0.83			
14	5/7/2013	3:12	1	4	Ag	42.2	11.8	1289	119.3	1104	3.00E+05	2.03E+02	6.08E+02	200	0.83			
15	5/7/2013	3:18	1	4	Ag	42.2	11.8	1289	119.3	1295	3.00E+05	2.03E+02	8.10E+02	225	0.83			Current increased during the beam. After beam was turned off, current remained constant.
16	5/7/2013	3:24	1	4	Ag	42.2	11.8	1289	119.3	1169	3.00E+05	2.02E+02	1.01E+03	250	0.82			
17	5/7/2013	3:29	1	4	Ag	42.2	11.8	1289	119.3	1170	2.99E+05	2.02E+02	1.21E+03	300	0.8			
18	5/7/2013	3:35	1	4	Ag	42.2	11.8	1289	119.3	1172	9.79E+04	6.61E+01	1.28E+03	400	0.77			Current jumped up to 20 mA from 16 mA and LabView stopped the run. Turned off the beam.

Run	Run Date	Time	S/N	socket	Ion	LET	Energy	Energy	Range	Flux	Fluence	Dose	Total Dose	V_R	V_F	V_{BRM}	P/F	Comments
#				#		MeV.cm2/mg	MeV/u	MeV	µm	#/cm2/s	#/cm2	rad(Si)	rad(Si)	V	V	V		
58	5/7/2013	23:22	**4**	4	**Xe**	51.5	11.7	1512	119.7	2687	3.01E+05	2.48E+02	2.48E+02	**150**	0.84			
59	5/7/2013	23:26	**4**	4	Xe	51.5	11.7	1512	119.7	2804	2.98E+05	2.46E+02	4.94E+02	**175**	0.83			Current increased from 10 nA to 400 nA
60	5/7/2013	23:29	**4**	4	Xe	51.5	11.7	1512	119.7	2839	2.99E+05	2.47E+02	7.41E+02	**200**	0.83			Current continued to increase from 1 uA to 31 uA
61	5/7/2013	23:32	**4**	4	Xe	51.5	11.7	1512	119.7	2696	2.06E+05	1.70E+02	9.10E+02	**225**	0.83			Current increased from 56 uA to 200 uA
62	5/7/2013	23:39	**5**	5	Xe	51.5	11.7	1512	119.7	1151	3.00E+05	2.47E+02	2.47E+02	**150**	0.84			
63	5/7/2013	23:45	**5**	5	Xe	51.5	11.7	1512	119.7	1100	3.00E+05	2.48E+02	4.95E+02	**175**	0.84			Current increased from 1 nA to 350 nA
64	5/7/2013	23:52	**5**	5	Xe	51.5	11.7	1512	119.7	870.8	3.00E+05	2.47E+02	7.42E+02	**200**	0.84			Current increased from 1 uA to 29 uA
65	5/7/2013	23:58	**5**	5	Xe	51.5	11.7	1512	119.7	641.7	2.56E+05	2.11E+02	9.54E+02	**225**	0.83			Current increased from 51 uA to 200 uA
66	5/8/2013	0:09	**6**	6	Xe	51.5	11.7	1512	119.7	916.8	3.00E+05	2.48E+02	2.48E+02	**150**	0.83			
67	5/8/2013	0:16	**6**	6	Xe	51.5	11.7	1512	119.7	925.8	3.00E+05	2.47E+02	4.95E+02	**175**	0.83			
68	5/8/2013	0:23	**6**	6	Xe	51.5	11.7	1512	119.7	928	2.99E+05	2.47E+02	7.43E+02	**200**	0.83			Current increased from 7.5 uA to 72 uA
69	5/8/2013	0:32	**6**	6	Xe	51.5	11.7	1512	119.7	899.7	1.42E+05	1.17E+02	8.60E+02	**225**	0.83			Current increased from 96 uA to 200 uA
84	5/8/2013	4:24	**9**	4	**Kr**	27.8	12.3	1032	134	884.8	3.00E+05	1.34E+02	1.34E+02	**150**	0.83			100 nA
85	5/8/2013	4:32	**9**	4	Kr	27.8	12.3	1032	134	1289	3.00E+05	1.34E+02	2.68E+02	**175**	0.83			100 nA
86	5/8/2013	4:37	**9**	4	Kr	27.8	12.3	1032	134	1211	2.99E+05	1.34E+02	4.01E+02	**200**	0.83			Current increased from 100 nA to 1.9 uA
87	5/8/2013	4:43	**9**	4	Kr	27.8	12.3	1032	134	1196	3.00E+05	1.34E+02	5.35E+02	**225**	0.83			Current increased from 4.5 uA to 91 uA
88	5/8/2013	4:49	**9**	4	Kr	27.8	12.3	1032	134	1136	5.45E+04	2.43E+01	5.59E+02	**250**	0.83			Current increased from 134 uA to 200 uA. Beam was
89	5/8/2013	4:52	**8**	5	Kr	27.8	12.3	1032	134	1072	7.68E+03	3.43E+00	3.43E+00	**175**	0.84			750 nA. Lost flux and stopped run.
90	5/8/2013	4:59	**8**	5	Kr	27.8	12.3	1032	134	1446	3.00E+05	1.34E+02	1.37E+02	**175**	0.84			Current increased from 1.2 uA to 2 uA
91	5/8/2013	5:04	**8**	5	Kr	27.8	12.3	1032	134	1336	3.00E+05	1.34E+02	2.71E+02	**200**	0.84			Current increased from 4 uA to 9 uA
92	5/8/2013	5:12	**8**	5	Kr	27.8	12.3	1032	134	1330	3.00E+05	1.34E+02	4.05E+02	**225**	0.83			Current increased from 17.5 uA to 132 uA
93	5/8/2013	5:17	**8**	5	Kr	27.8	12.3	1032	134	1217	1.09E+04	4.88E+00	4.10E+02	**250**	0.83			Current increased from 184 uA to 200 uA. Beam was
94	5/8/2013	5:20	**7**	6	Kr	27.8	12.3	1032	134	1287	2.99E+05	1.34E+02	1.34E+02	**175**	0.83			Current increased from 25 nA to 80 nA
95	5/8/2013	5:25	**7**	6	Kr	27.8	12.3	1032	134	1252	2.00E+05	1.34E+02	2.67E+02	**200**	0.83			Current increased from 50 nA to 3.2 uA
96	5/8/2013	5:30	**7**	6	Kr	27.8	12.3	1032	134	1290	3.00E+05	1.34E+02	4.01E+02	**225**	0.83			Current increased from 7.2 uA to 97 uA
97	5/8/2013	5:36	**7**	6	Kr	27.8	12.3	1032	134	1288	5.12E+04	2.28E+01	4.24E+02	**250**	0.83			Current increased from 144 uA to 200 uA. Beam was
19	**6/14/2013**	3:19	**10**	2	**Ag**	42.2	11.8	1289	119.3	n/a	n/a	n/a	n/a	**650**				DUT not in position (still socket 1)
20	6/14/2013	3:20	**10**	2	Ag	42.2	11.8	1289	119.3	47.65	1.78E+02	1.20E-01	1.20E-01	**650**	0.82	0	Fail	Fail immediately on run
21	6/14/2013	3:30	**11**	3	Ag	42.2	11.8	1289	119.3	62.8	2.52E+02	1.70E-01	1.70E-01	**450**	0.83	378		Large increments in Ir during run
22	6/14/2013	3:35	**11**	3	Ag	42.2	11.8	1289	119.3	41.8	3.59E+02	2.42E-01	4.13E-01	**475**	0.79	378		Large increments in Ir during run
23	6/14/2013	3:35	**11**	3	Ag	42.2	11.8	1289	119.3	n/a	n/a	n/a	4.13E-01	**475**	0.78		Fail	No beam applied: current increased when Vr applied - then broke
23	6/14/2013	4:05	**14**	6	Ag	42.2	11.8	1289	119.3	43.92	3.15E+03	2.13E+00	2.13E+00	**375**	0.82	384		Prerad Vr bad; Very gradual increase in Ir during run; Ir=47.71 uA at Vr=200V
24	6/14/2013	4:15	**14**	6	Ag	42.2	11.8	1289	119.3	70.66	3.17E+02	2.14E-01	2.34E+00	**500**	0.73	36		Large increments in Ir during run
25	6/14/2013	4:20	**13**	5	Ag	42.2	11.8	1289	119.3	55.43	2.74E+02	1.85E-01	1.85E-01	**550**	0.74	0	Fail	Fail on run: about 3 immediate, consecutive steps in Ir

Appendix C

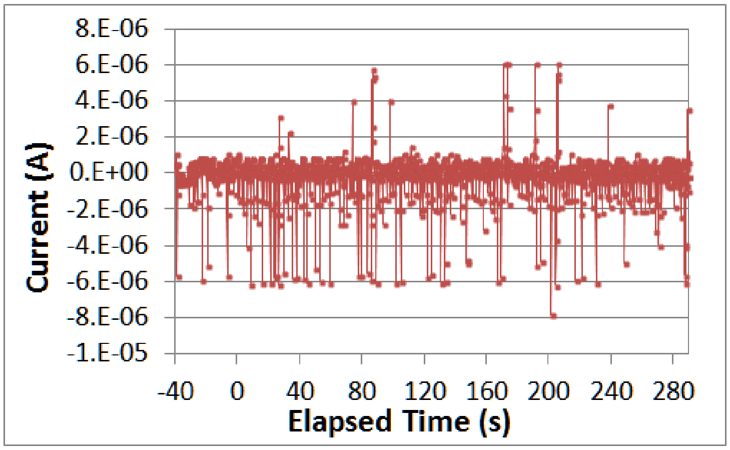

Figure C1. Strip tape data from DUT 3, run 2: 1289 MeV Ag.
V_R = 100 V. No damage was detected during the beam run; however, V_{RRM} was not measured after irradiation and is likely impacted.

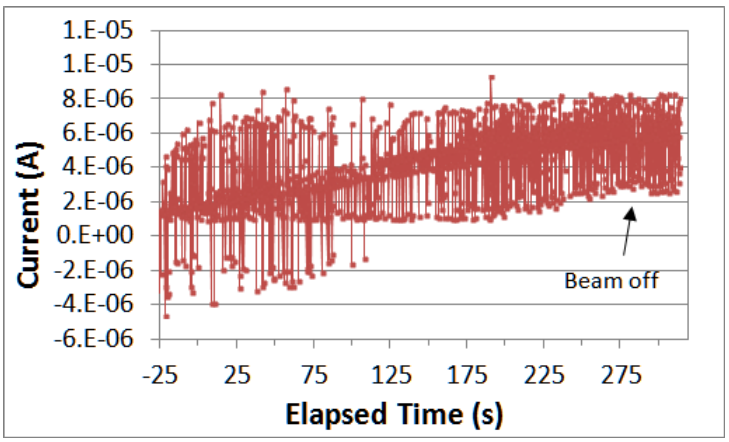

Figure C2. Strip tape data from DUT 3, run 3: 1289 MeV Ag.
V_R = 200 V. Small rise in reverse-bias current during irradiation.

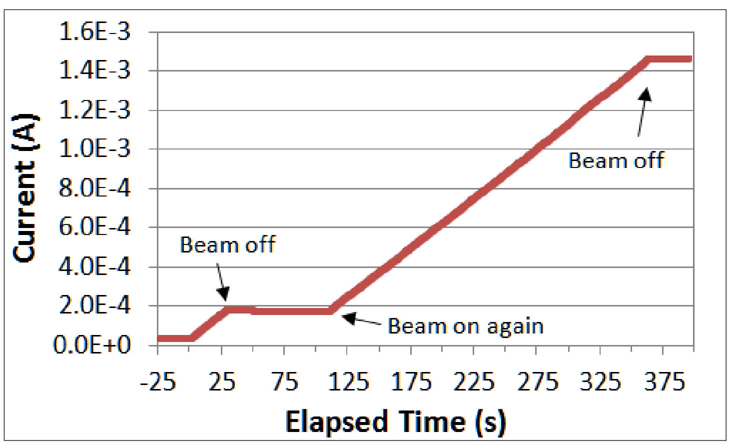

Figure C3. Strip tape data from DUT 3, run 4: 1289 MeV Ag.
V_R = 300 V. Increase in reverse-bias current occurs during irradiation; elevated current level persists when beam is shuttered.

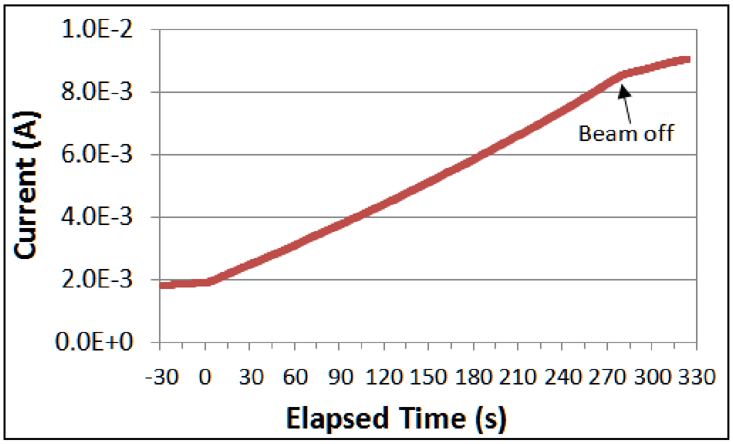

Figure C4. Strip tape data from DUT 3, run 5: 1289 MeV Ag. V_R = 350 V.
Note the current is increasing slightly prior to the beam turning on, indicating unstable damage from prior runs.

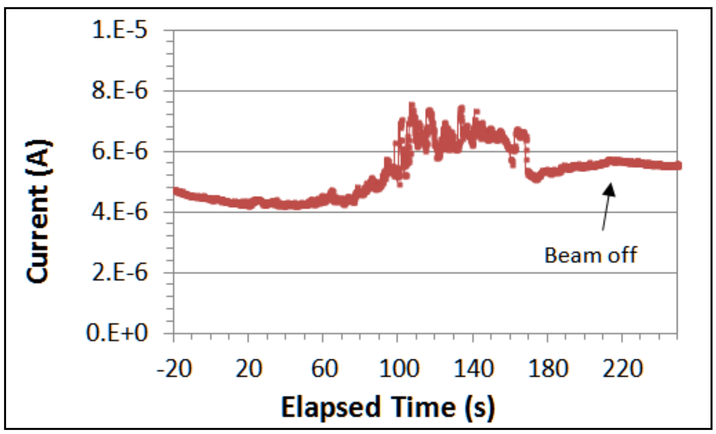

Figure C5. Strip tape data from DUT 2, run 7: 1289 MeV Ag. V_R = 200 V.
Elevated current during a portion of the run could be due to facility noise. It is likely that this device was damaged during preparation for testing, given the elevated pre-beam current. This device was not included in the Table 1 results summary.

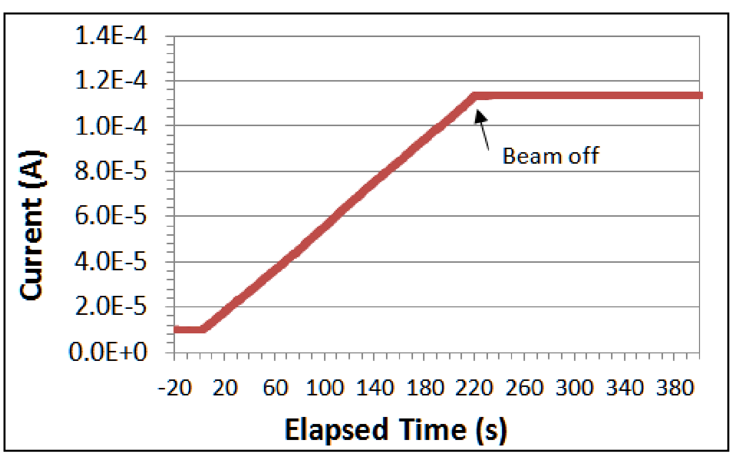

Figure C6. Strip tape data from DUT 2, run 8: 1289 MeV Ag. V_R = 225 V.
Elevated current does not recover after the beam is shuttered.

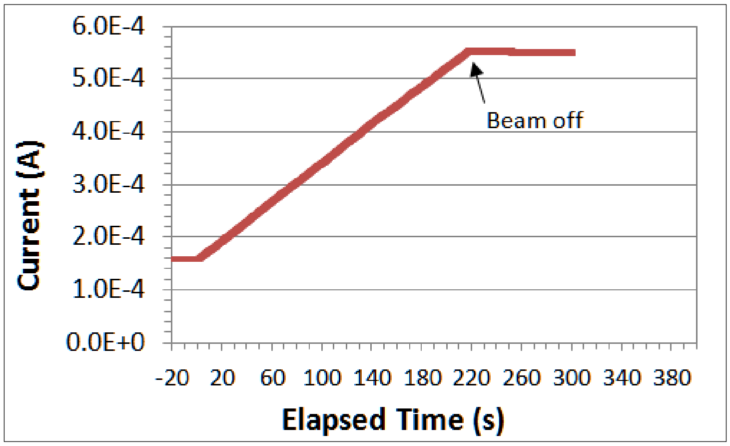

Figure C7. Strip tape data from DUT 2, run 9: 1289 MeV Ag. V_R = 250 V.

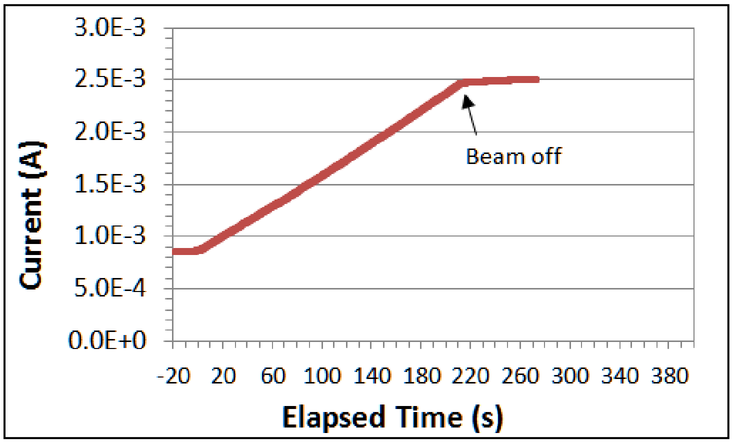

Figure C8. Strip tape data from DUT 2, run 10: 1289 MeV Ag. V_R = 300 V.

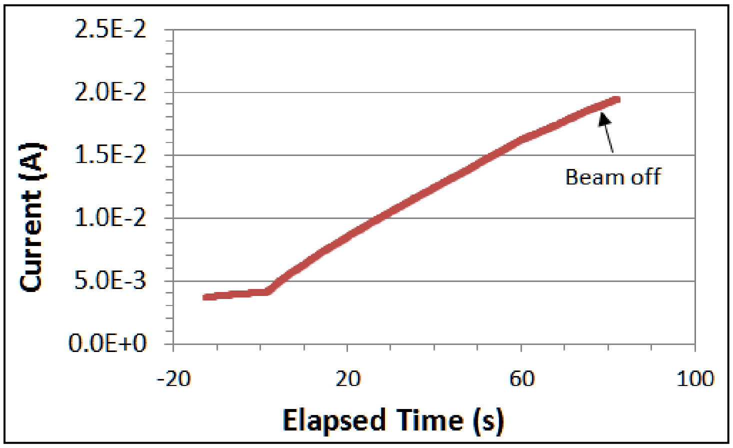

Figure C9. Strip tape data from DUT 2, run 11: 1289 MeV Ag. V_R = 400 V.

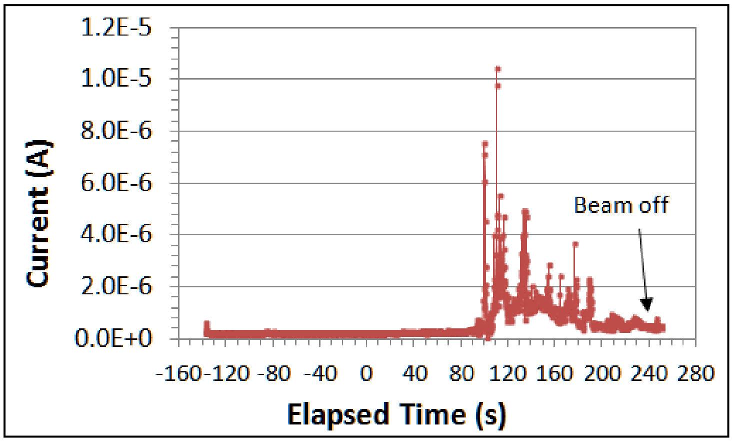

Figure C10. Strip tape data from DUT 1, run 12: 1289 MeV Ag. V_R = 150 V.
As in Figure C5, facility noise likely coupled into the drain current measurement during the run. Due to the noise on this and subsequent runs for this device, the DUT was excluded from analyses provided in Table 1.

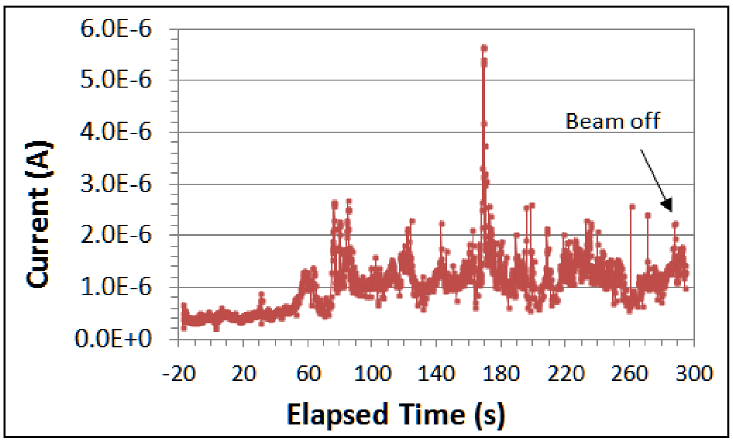

Figure C11. Strip tape data from DUT 1, run 13: 1289 MeV Ag. V_R = 175 V.

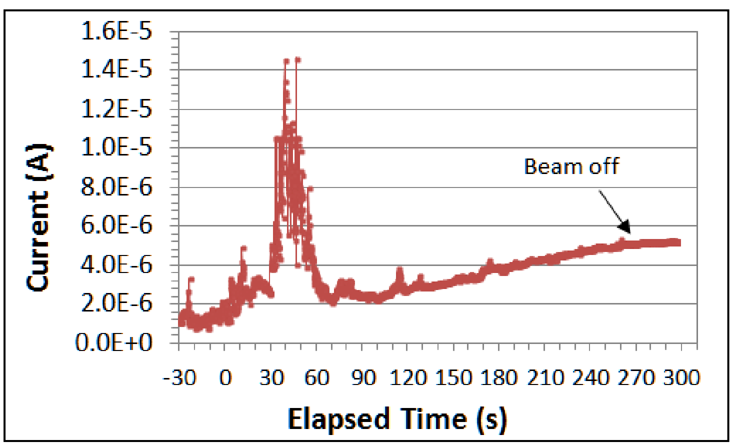

Figure C12. Strip tape data from DUT 1, run 14: 1289 MeV Ag. V_R = 200 V.

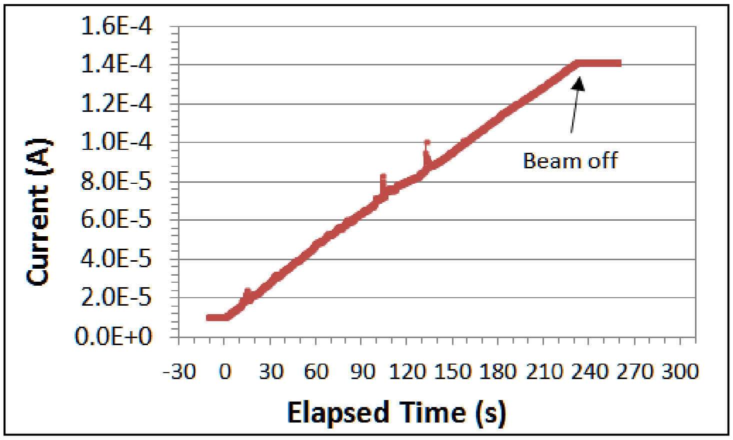

Figure C13. Strip tape data from DUT 1, run 15: 1289 MeV Ag. V_R = 225 V.

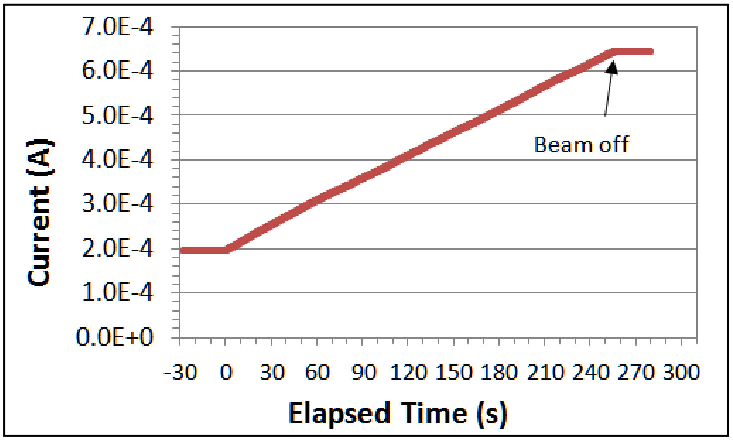

Figure C14. Strip tape data from DUT 1, run 16: 1289 MeV Ag. V_R = 250 V.

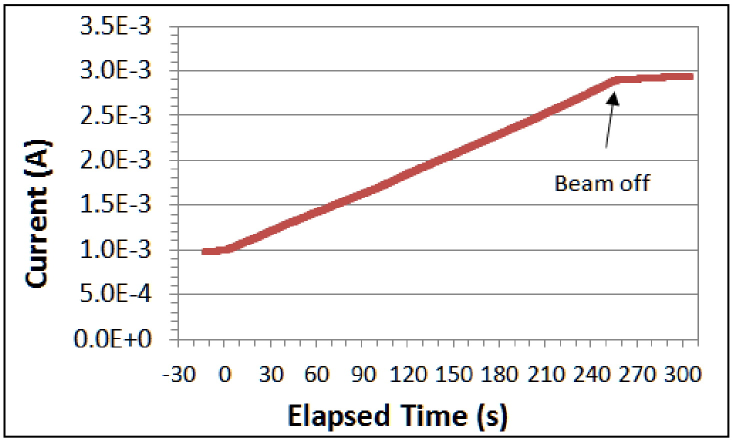

Figure C15. Strip tape data from DUT 1, run 17: 1289 MeV Ag. V_R = 300 V.

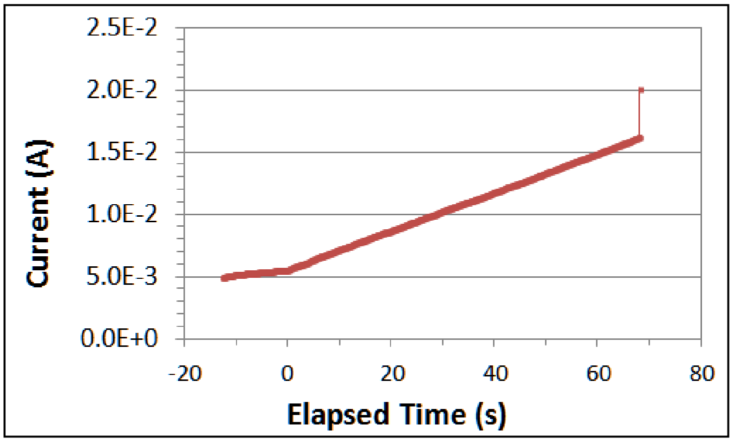

Figure C16. Strip tape data from DUT 1, run 18: 1289 MeV Ag. V_R = 400 V.

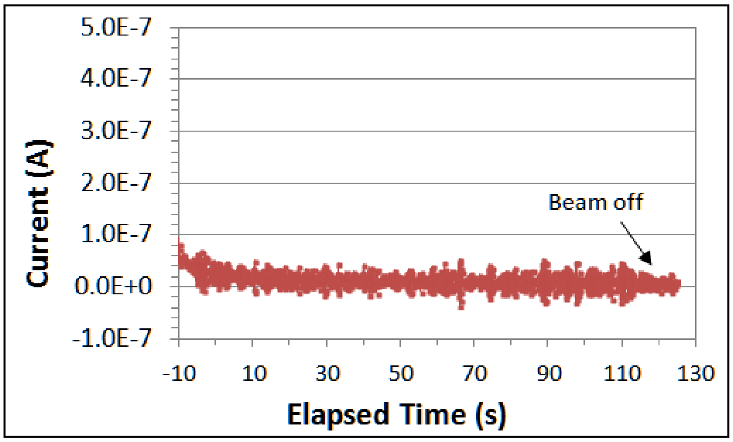

Figure C17. Strip tape data from DUT 4, run 58: 1512 MeV Xe. V_R = 150 V.

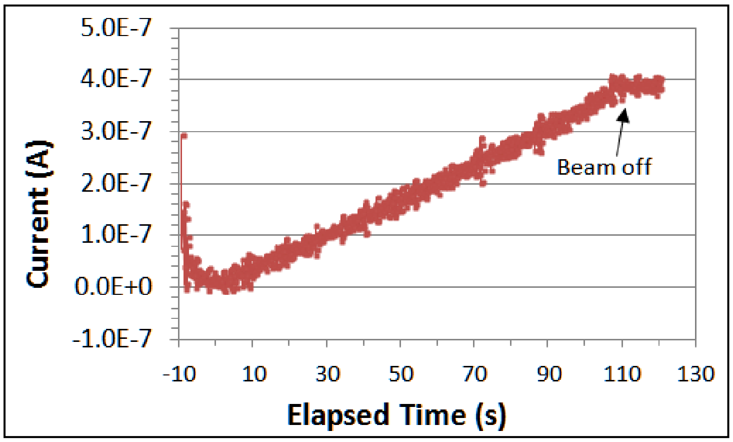

Figure C18. Strip tape data from DUT 4, run 59: 1512 MeV Xe. V_R = 175 V.

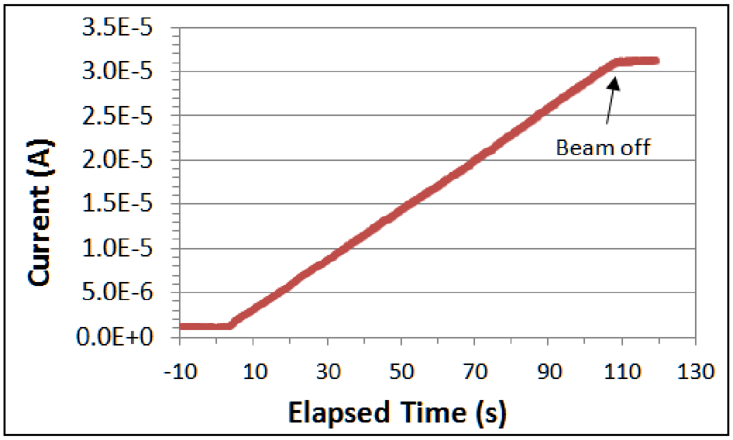

Figure C19. Strip tape data from DUT 4, run 60: 1512 MeV Xe. V_R = 200 V.

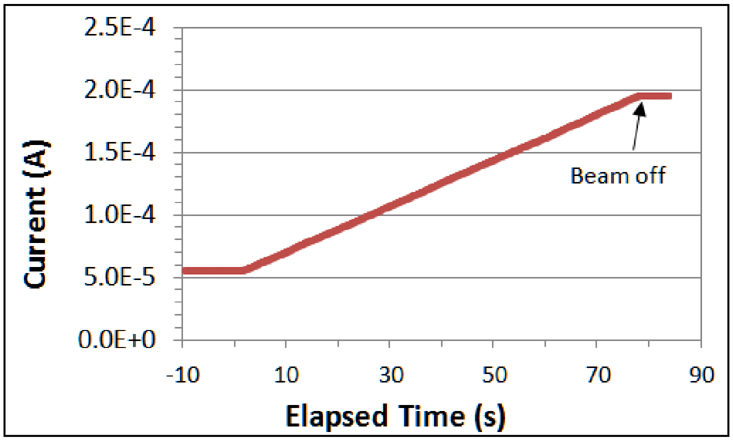

Figure C20. Strip tape data from DUT 4, run 61: 1512 MeV Xe. V_R = 225 V.

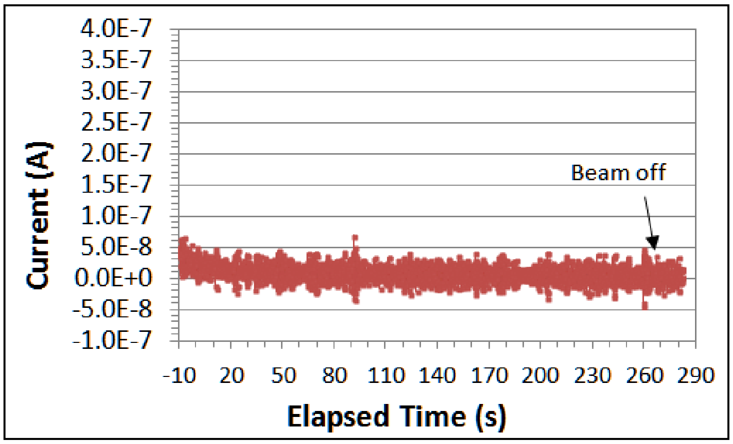

Figure C21. Strip tape data from DUT 5, run 62: 1512 MeV Xe. V_R = 150 V.

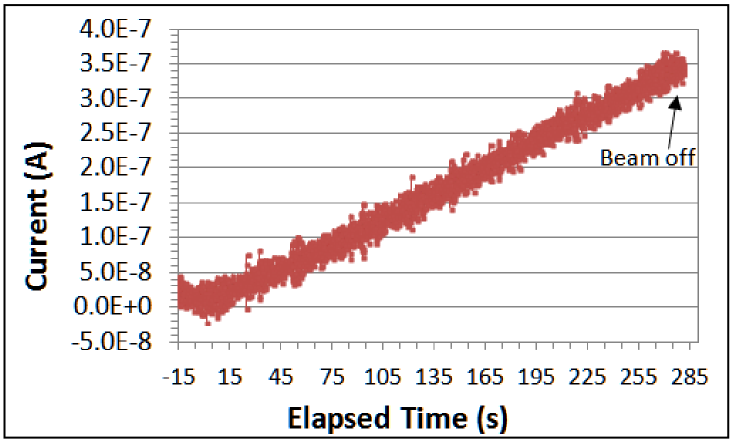

Figure C22. Strip tape data from DUT 5, run 63: 1512 MeV Xe. V_R = 175 V.

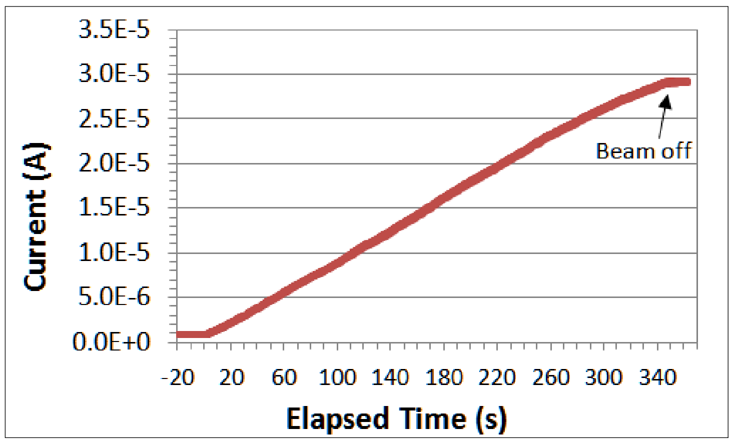

Figure C23. Strip tape data from DUT 5, run 64: 1512 MeV Xe. V_R = 200 V.

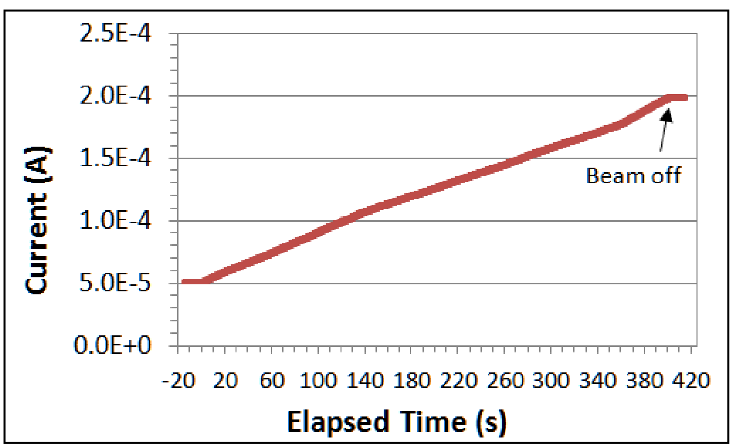

Figure C24. Strip tape data from DUT 5, run 65: 1512 MeV Xe. V_R = 225 V.

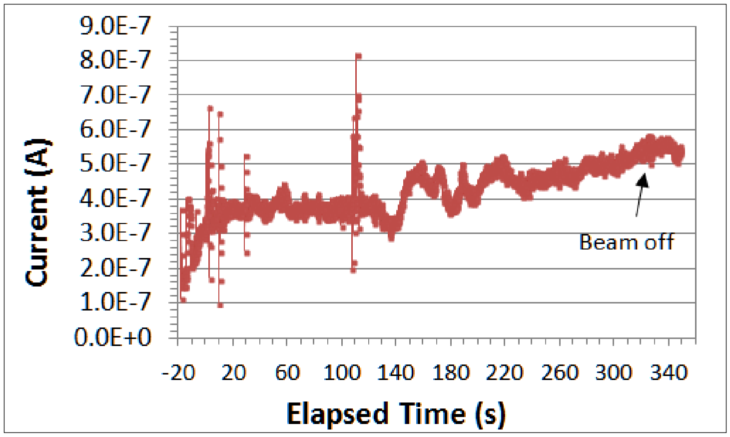

Figure C25. Strip tape data from DUT 6, run 66: 1512 MeV Xe. V_R = 150 V. This device was not included in Table 1 analyses due to the noise and current instability.

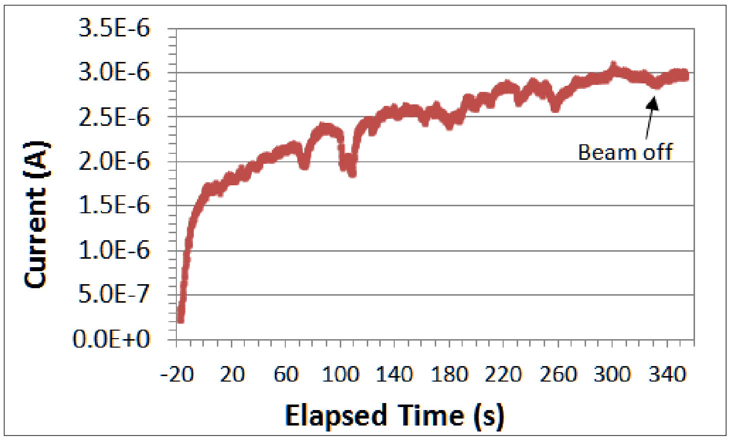

Figure C26. Strip tape data from DUT 6, run 67: 1512 MeV Xe. V_R = 175 V.

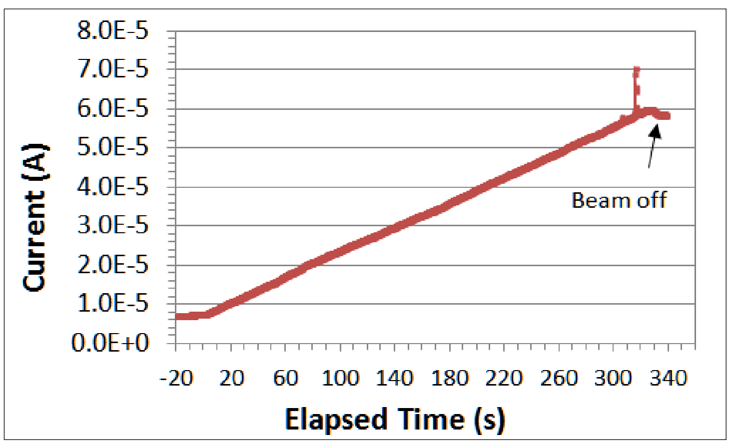

Figure C27. Strip tape data from DUT 6, run 68: 1512 MeV Xe. V_R = 200 V.

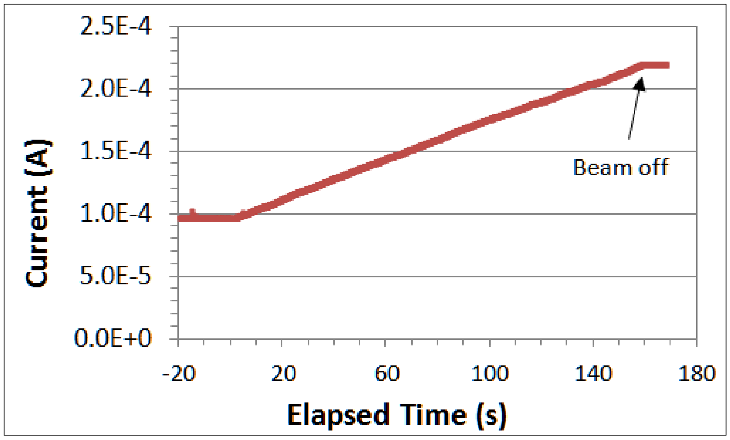

Figure C28. Strip tape data from DUT 6, run 69: 1512 MeV Xe. V_R = 225 V.

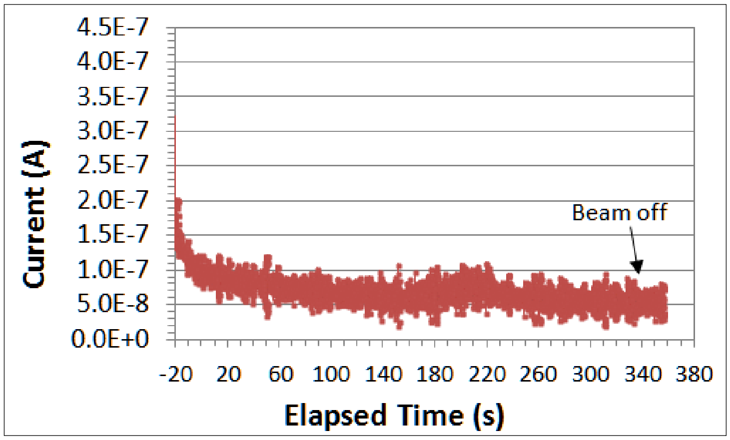

Figure C29. Strip tape data from DUT 9, run 84: 1032 MeV Kr. V_R = 150 V.

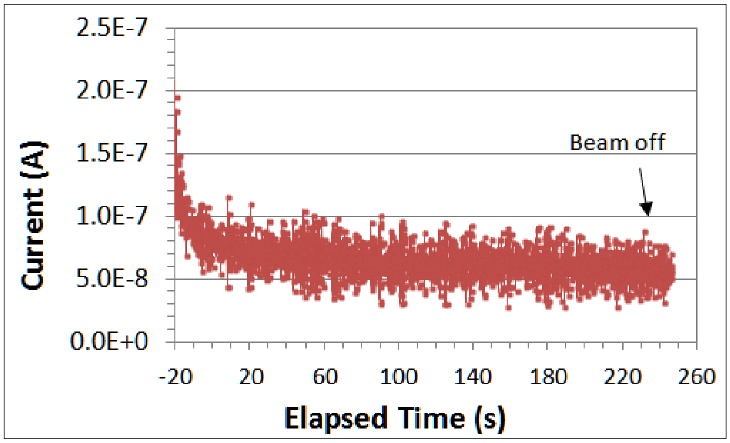

Figure C30. Strip tape data from DUT 9, run 85: 1032 MeV Kr. V_R = 175 V.

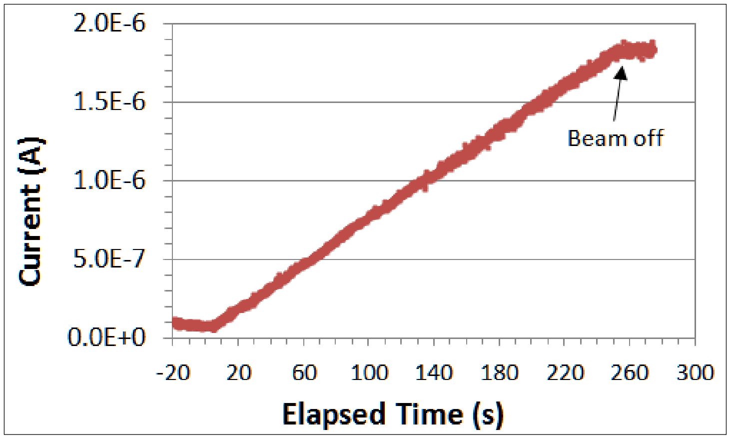

Figure C31. Strip tape data from DUT 9, run 86: 1032 MeV Kr. V_R = 200 V.

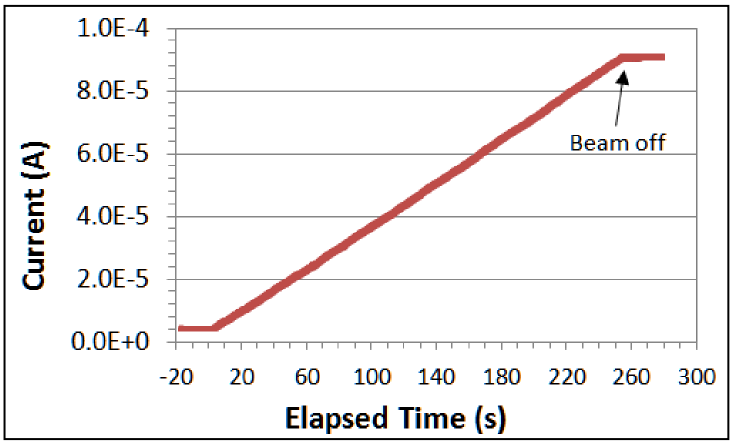

Figure C32. Strip tape data from DUT 9, run 87: 1032 MeV Kr. V_R = 225 V.

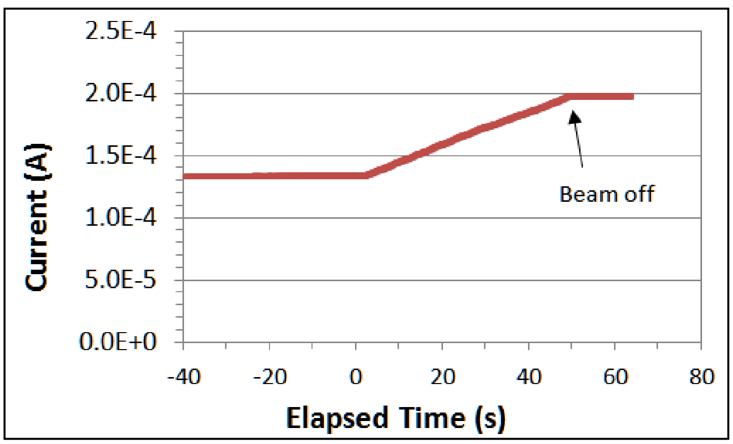

Figure C33. Strip tape data from DUT 9, run 88: 1032 MeV Kr. V_R = 250 V.

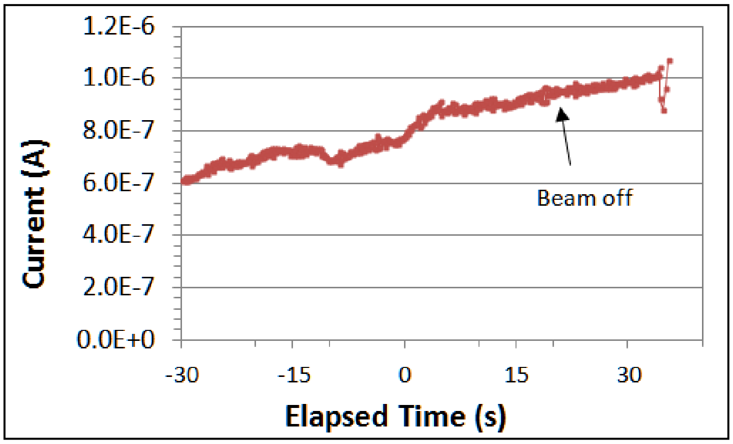

Figure C34. Strip tape data from DUT 8, run 89: 1032 MeV Kr. V_R = 175 V. This device was not included in Table 1 analyses due to the current instability occurring before the beam shutter was opened.

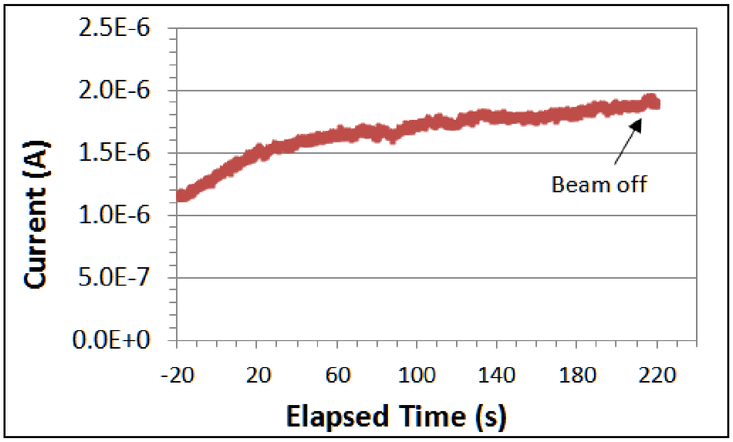

Figure C35. Strip tape data from DUT 8, run 90: 1032 MeV Kr. V_R = 175 V.

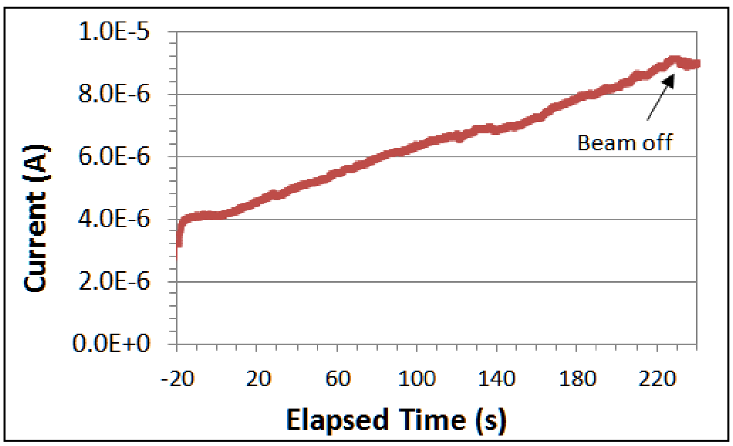

Figure C36. Strip tape data from DUT 8, run 91: 1032 MeV Kr. V_R = 200 V.

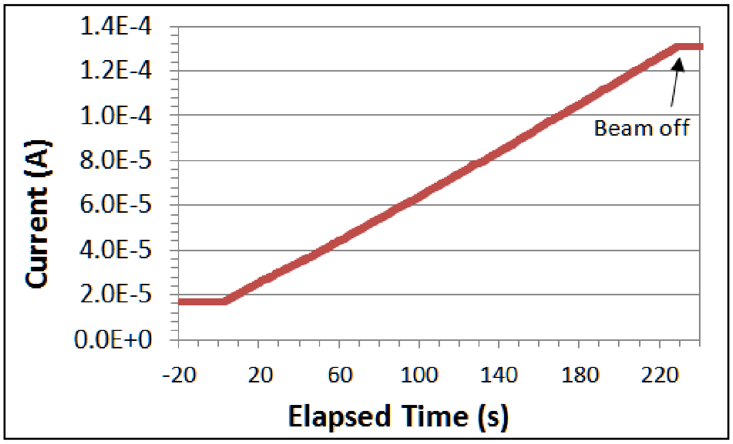

Figure C37. Strip tape data from DUT 8, run 92: 1032 MeV Kr. V_R = 225 V.

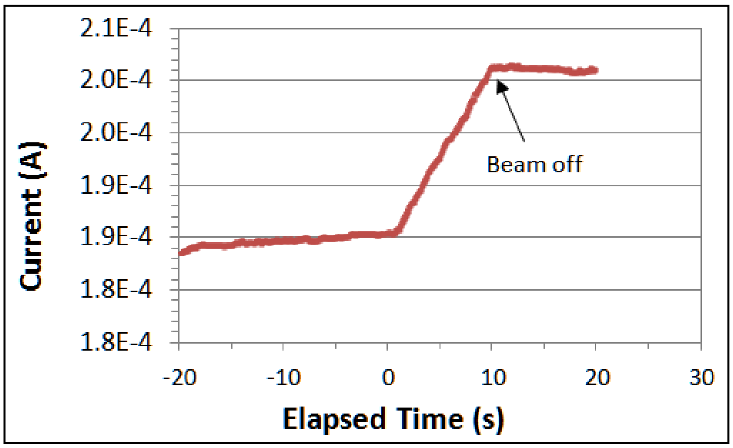

Figure C38. Strip tape data from DUT 8, run 93: 1032 MeV Kr. V_R = 250 V.

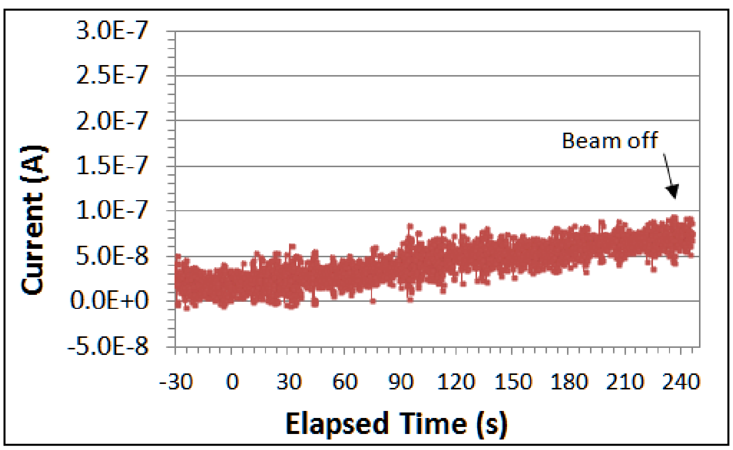

Figure C39. Strip tape data from DUT 7, run 94: 1032 MeV Kr. V_R = 175 V. This device shows a slight increase in reverse current as a function of fluence, unlike test results shown in Figure C30.

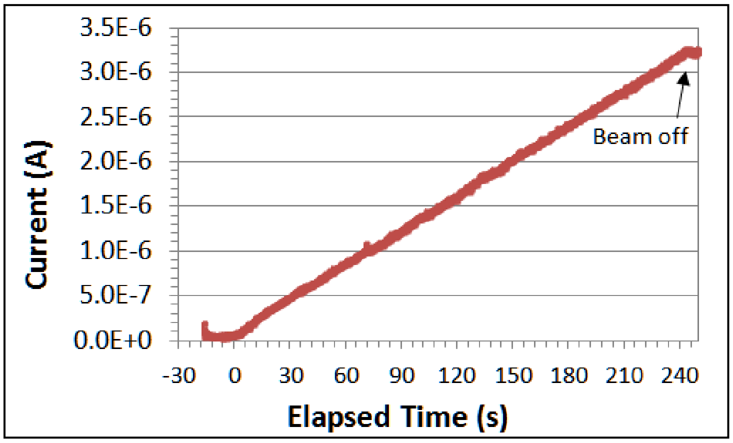

Figure C40. Strip tape data from DUT 7, run 95: 1032 MeV Kr. V_R = 200 V.

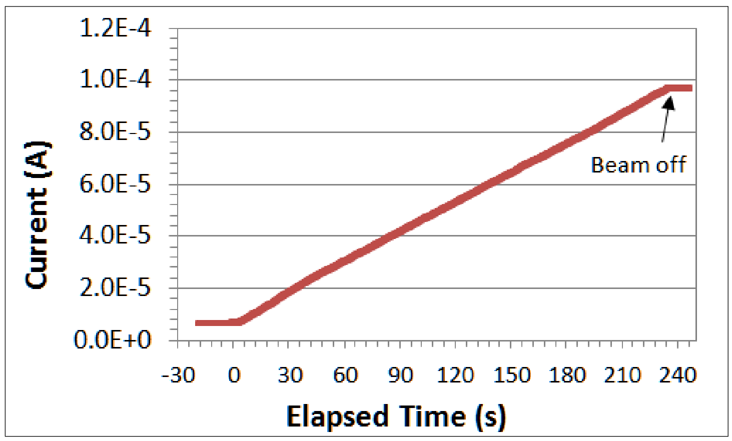

Figure C41. Strip tape data from DUT 7, run 96: 1032 MeV Kr. V_R = 225 V.

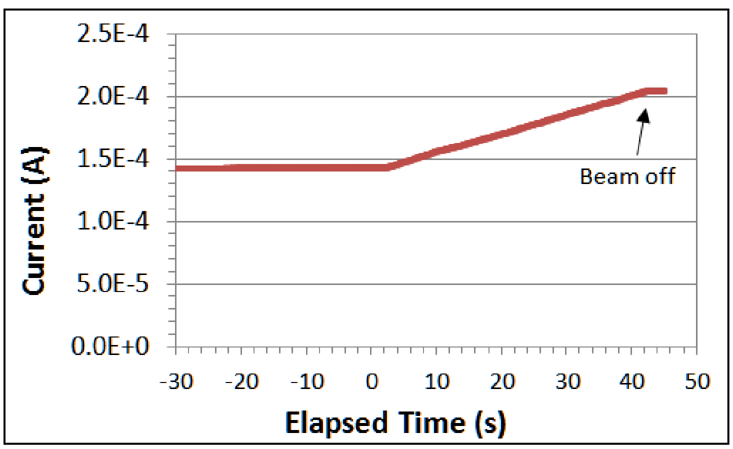

Figure C42. Strip tape data from DUT 7, run 97: 1032 MeV Kr. V_R = 250 V.

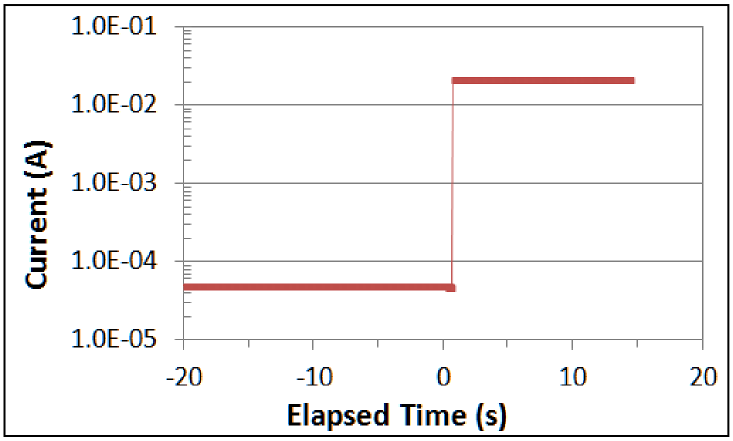

Figure C43. Strip tape data from DUT 10, run 20: 1289 MeV Ag. V_R = 650 V. Under these conditions, immediate catastrophic failure occurred during the beam run, resulting in I_R hitting compliance after a single ion strike.

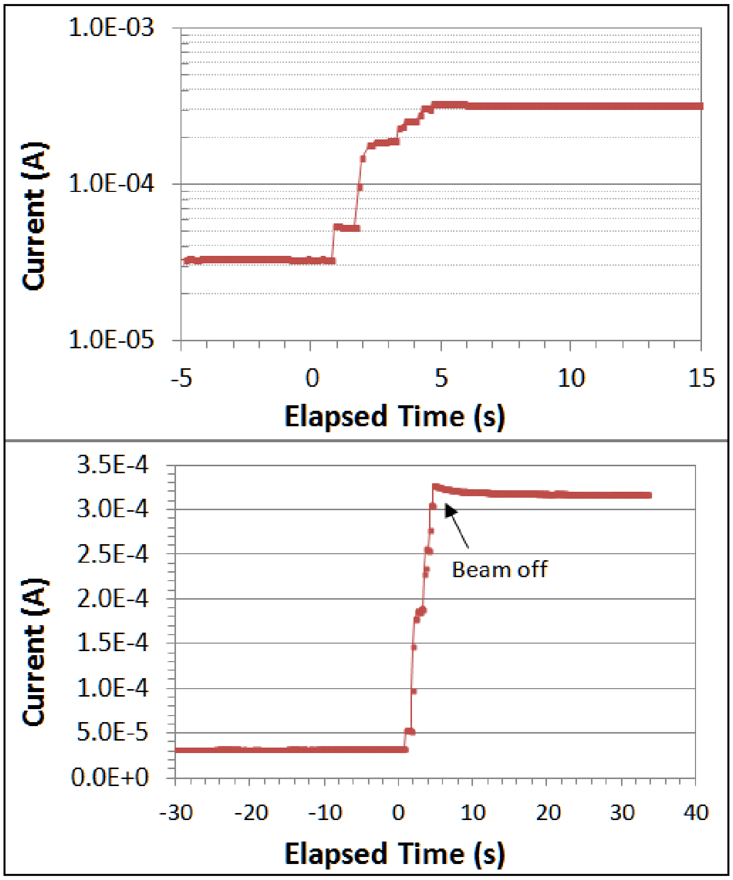

Figure C44. Log-linear (top) and linear (bottom) plots of strip tape data from DUT 11, run 21: 1289 MeV Ag. V_R = 450 V.
Low beam flux reveals current increments due to individual ion strikes.

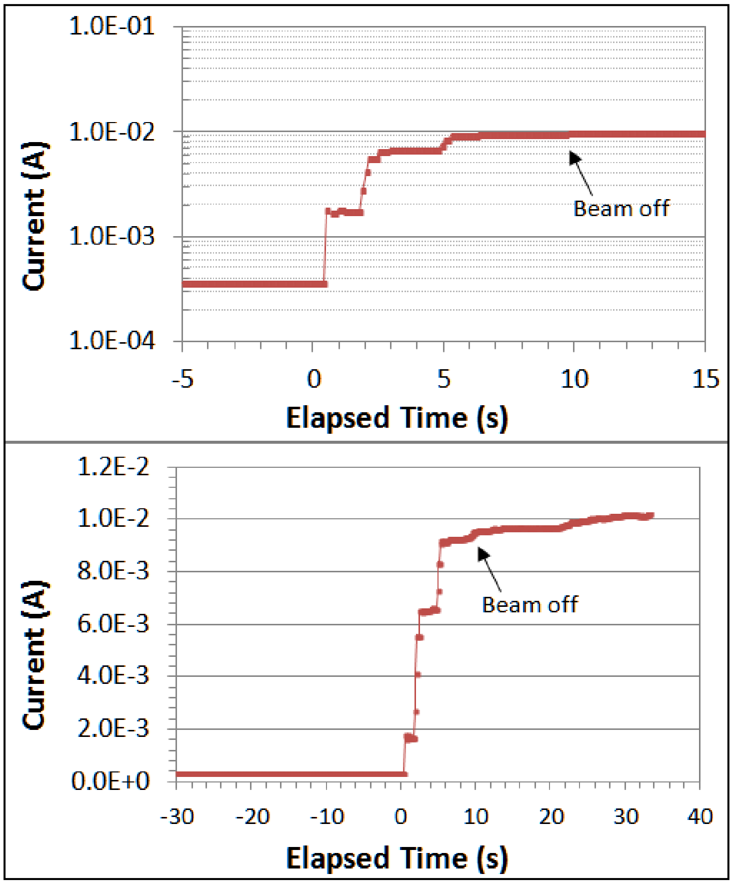

Figure C45. Log-linear (top) and linear (bottom) plots of strip tape data from DUT 11, run 22: 1289 MeV Ag. V_R = 475 V.
Current continues to climb after beam has been shuttered.

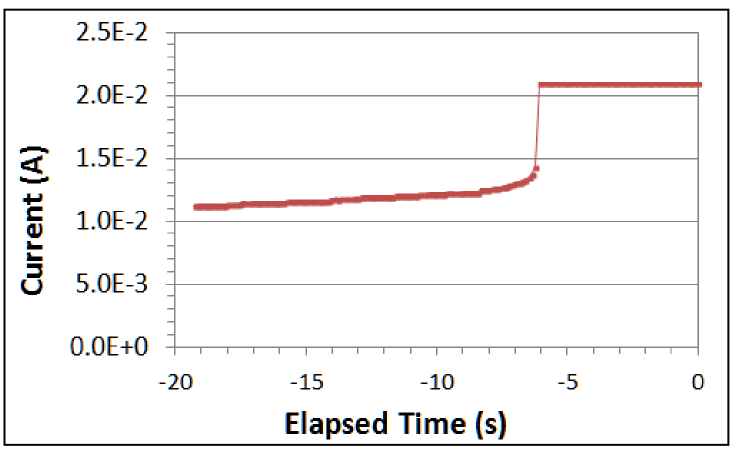

Figure C46. Strip tape data from DUT 11, run 23: V_R = 500 V.
Device failed catastrophically before beam was turned on.

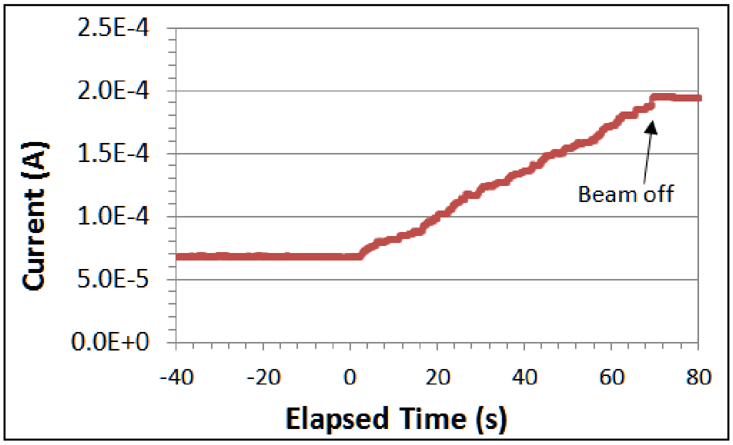

Figure C47. Strip tape data from DUT 14, run 23: 1289 MeV Ag. V_R = 375 V.

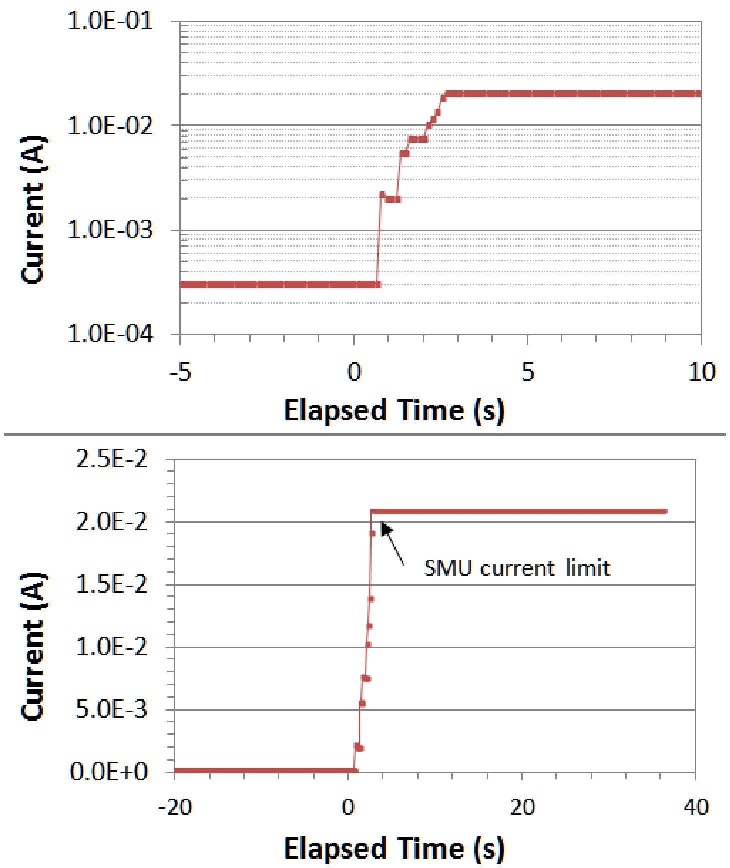

Figure C48. Log-linear (top) and linear (bottom) plots of strip tape data
from DUT 14, run 24: 1289 MeV Ag. V_R = 500 V.
Low beam flux reveals current increments due to individual ion strikes.

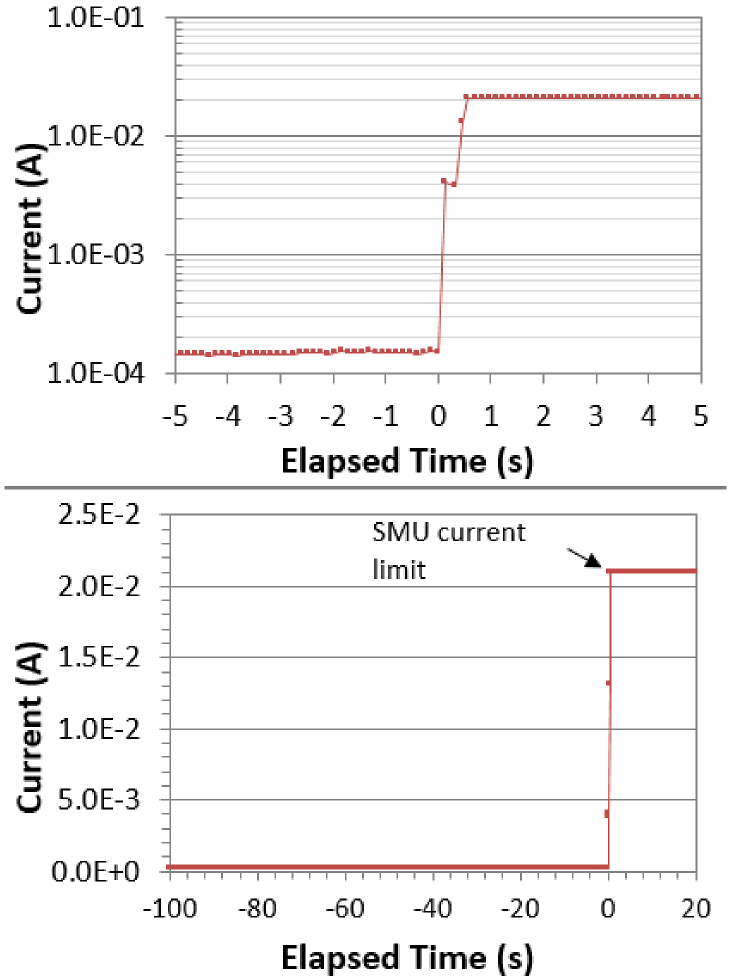

Figure C49. Log-linear (top) and linear (bottom) plots of strip tape data from DUT 13, run 25: 1289 MeV Ag. V_R = 550 V. Extended pre-beam current measurements demonstrate application of 550-V reverse bias does not degrade the device, despite this DUT having an out-of-spec breakdown voltage during pre-irradiation device characterization.

Appendix D

Table D1. TAMU Beam Log (Selected Sections) from June, 2013

Run number	Run start date and time	Run end date and time	Selected beam	Live time (s)	Aver. flux (ions/(cm^2-s))	Aver. flux error (%)	Overall uniformity (%)	Overall central shift (%)
19	13/06/14 03:17:57	13/06/14 03:18:22	Ag	11.90	42.05	7.1	89	5
20	13/06/14 03:22:11	13/06/14 03:22:23	Ag	3.73	47.65	12	71	24
21	13/06/14 03:30:06	13/06/14 03:30:31	Ag	4.02	62.80	10	77	13
22	13/06/14 03:35:46	13/06/14 03:35:59	Ag	8.57	41.84	8.4	82	9
23	13/06/14 04:07:47	13/06/14 04:09:19	Ag	71.78	43.92	2.8	95	4
24	13/06/14 04:16:43	13/06/14 04:17:19	Ag	4.48	70.66	8.9	78	20
25	13/06/14 04:22:13	13/06/14 04:22:39	Ag	4.95	55.43	9.5	88	3