STARS-3: Fully Integrated Communication Terminal and Equipment: Image Compression Camera

Work Package 1200: **Detailed Specification of Camera and ASICs**

IRIS-3 Characterization Report
Part 2: Radiation Tests

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issue	Date	description of change
1	08/08/2003	Preliminary version, total dose tests only
2	01/09/2003	Added distribution of increased power consumption over different supplies
3	27/10/2003	Final version, added heavy ion tests

Table of contents

Purpose

The purpose of this document is to report on the radiation tolerance evaluation of the CMOS active pixel sensor that was custom designed for the STARS-3 project. (ESTEC contract 13716/99/NL/FB)

Scope.

This document reports on the radiation tolerance evaluation of the devices that was performed in the scope of the STARS-3 project. It contains a description of the tests and the test conditions and an overview of the measurement results.

An earlier document describes the electro-optical evaluation, consisting of the establishment of the bias- and operating conditions and the electro optical evaluation to confirm the electro optical specifications. Together these two documents form deliverable D24 as foreseen in the contract 13716/99/NL/FB.

Abbreviations and acronyms

SEL	Single-Event Latchup
SEU	Single-Event Upset
TID	Total Ionizing Dose

Reference:

[RD1] LCDSSOG-FF-DL-2001-001 Electro-optical evaluation report for CMOS APS, Version 1, October 27, 2001

Applicable Documents

[AD1] Total Dose Steady-State Irradiation Test Method, ESA/SCC Basic Specification No.22900, Issue 4, April 1995

[AD2] Single Event Effects Test Method and Guidelines, ESA/SCC Basic Specification No.25100, Issue 1, October 1995

[AD3] IMEC P50314-IM-DL-0005 IRIS-3 Imager Test and Validation Plan, Draft Issue 0.4 March 5, 2001

1.Introduction

During the design phase, the specifications of the IRIS-3 image sensor were predicted, based upon experience and upon simulations wherever possible. However, assessment of the specifications implies production and measurement on real devices. This document reports on the radiation tolerance measurements that were made on the produced devices to verify and assess their performance.

2.Overview of tests

2.1.Test flow

The following list contains the test flow of the IRIS-3 image sensor samples.

- Dicing and packaging of first samples
- Operation and establishment of bias conditions (1)
- Electro-optical evaluation of samples from the production run. (1)
- Functional testing of digital core. (1)
- Total dose radiation tests with gamma radiation (2)
- Single event latchup radiation tests with heavy ion beam (2)

(1) described in the electro-optical characterisation report
(2) described in this report

2.2.Summary of radiation test results

- Total dose tolerance is 30 krad, and up to 80 krad with massively increased supply current
- No latchup was seen over the test range of beam flux 10 to 11000 ions/s/cm² with LET's of 14.1 MeV/mg/cm² to 55.9 MeV/mg/cm²
- SEU's started appearing at a beam flux of 100 ions/s/cm² (with LET=55.9 MeV/mg/cm²)
- Remaining defects were present after a total fluence of greater than 1.45×10^{6} ions/cm²

3.Total dose irradiation followed by characterisation of IRIS-3 chips

3.1.Test objectives

The aim of this test is the validation of the rad-tolerant design techniques employed in the IRIS-3.

3.2.Ancillary equipment

The devices under test are put on a dedicated circuit board, and are properly biased. No clock is applied during radiation and their output is not monitored.

3.3.Test procedure

First all six devices to be irradiated were characterised, at 22°C ambient temperature only.

The devices were irradiated to increasing doses. When a specific dose (see table) was reached, the devices were taken from the test setup and measured for dark current and current consumption. The dark current measured is at once a good test for device functionality, and for accumulated damage. The test started with two devices. As long as the devices tested are perceived to be still functional, they were re-inserted into the test set-up and tested up to the next dose of interest. Whenever devices passed the test at specific target doses and proceed, two new devices were inserted into the test rig, to accumulate dose from hence on. At the end of the test two devices had received a large, potentially lethal dose, two devices have had a slightly lower dose, and two have had again a lower dose.

All irradiated devices underwent characterisation (at 23°C ambient temperature only) as soon as possible after total dose exposure, and again after 24 and 48 hours. During the latter measurement process, two unirradiated control samples were taken from the output batch and re-characterised.

3.4.Irradiation conditions

This paragraph lists details specific to radiation tests.

Total dose levels

The following doses and dose rates have be used:

Total dose (for first devices, doses for additional devices in brackets)	Dose rate	Total number of devices being tested	Source
5krad	2.5krad/h	2	Co60
10krad	2.5krad/h	2	
20krad (10krad)	10krad/h	4	
40krad (30krad, 20krad)	20krad/h	6	
80krad (70krad, 60krad)	40krad/h	6	

Ambient conditions

The irradiations have been done at room temperature. There are no facilities at the test site to modify the temperature.

Biasing conditions during test and annealing

During irradiation all devices under test were statically biased, using the optimal bias currents and voltages as established in paragraph 3.2.1. The biasing is not monitored, due to the high number of bias signals involved. Past experience indicated that this is acceptable. All devices will have their own current-limited supply voltage and ground. There will be no explicit latch-up protection as latch-up is not expected during this test. Power supply current is not monitored. There is no in-situ testing.

During transport there is no bias: all IC pins will be shorted together. During annealing, the devices are biased, in the same fixture they were in during irradiation.

The biasing and power supply electronics were identical to those used in the IRIS-3 test system, with the bus transceivers replaced by simple wire bridges (testing is done with a slow readout speed so the transceivers are unneeded, and by removing them there is no risk of them going into latchup).

Irradiation facilities

The total dose irradation has been done at the facilities of the Université Catholique de Louvain, Belgium:

Institut de Physique Nucléaire et
Centre de Recherches du Cyclotron
Chemin du cyclotron, 2
B-1348 Louvain-la-Neuve

3.5. AD1 Compliance matrix

The following table gives an overview of the compliance of the total dose irradiation test plan with AD1.

AD1 paragraph	Item	compliance	comments/divergence from guidelines
3.1	radiation source	yes	-
3.2	radiation level	Partly	custom different levels
3.3	dose rates	Partly	custom different levels
3.4	Temperature	yes	-
3.5	measurement system	partly	Not all instruments used are calibrated, some instruments are built ad-hoc.
3.6	test fixture	yes	Standard commercial sockets to be used. No blank board will be irradiated. Biasing conditions to be described later.
3.7	test setup	yes	Remote testing, local verification of device functioning
3.7.3	bias	no	No bias monitoring. Bias based on typical use.
3.8	time intervals	no	Intervals will be as short as practically possible given the geographic distance between radiation site and test site.
4.1	general evaluation testing	No	Testing is ad-hoc, and specific to imagers.
4.3	sample selection	No	6 samples, 2 control samples, 1 lot.
4.4	sample serialisation	Yes	-
4.5	test sequence	No	Not until failure. Anneal temperature is 22°C. No

			accelerated ageing.

3.6 Total dose test results

3.6.1 Tabulated measurement results for all samples

1A

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	137.6	17.46668
5	130.6	21.83335
10	130.7	28.38336
20	139.6	37.1167
40	296.3	76.41674
80	354.0	109.1668

1Z

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	137.9	15.28335
5	136.8	19.65002
10	132.0	21.83335
20	137.6	34.93337
40	299.2	74.23341
80	353.0	91.70009

4E

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	84.7	13.10001
10	135.0	17.46668
30	156.4	26.20003
70	344.0	45.85005

7E

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	145.1	15.28335
10	137.2	17.46668
30	167.8	26.20003
70	365.0	39.30004

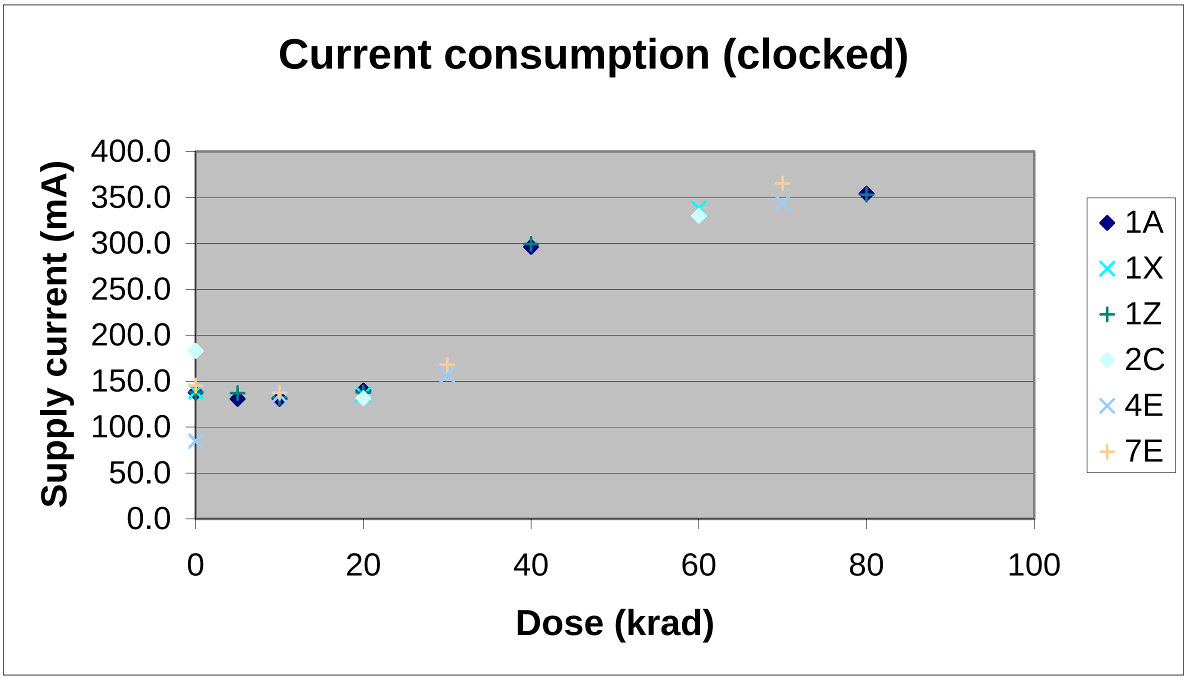
1X

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	138.8	15.28335
20	135.3	21.83335
60	338.0	54.58339

2C

Dose (krad)	Supply current (mA)	Dark current (mV/s)
0	183.1	19.65002
20	131.4	19.65002
60	330.0	52.40005

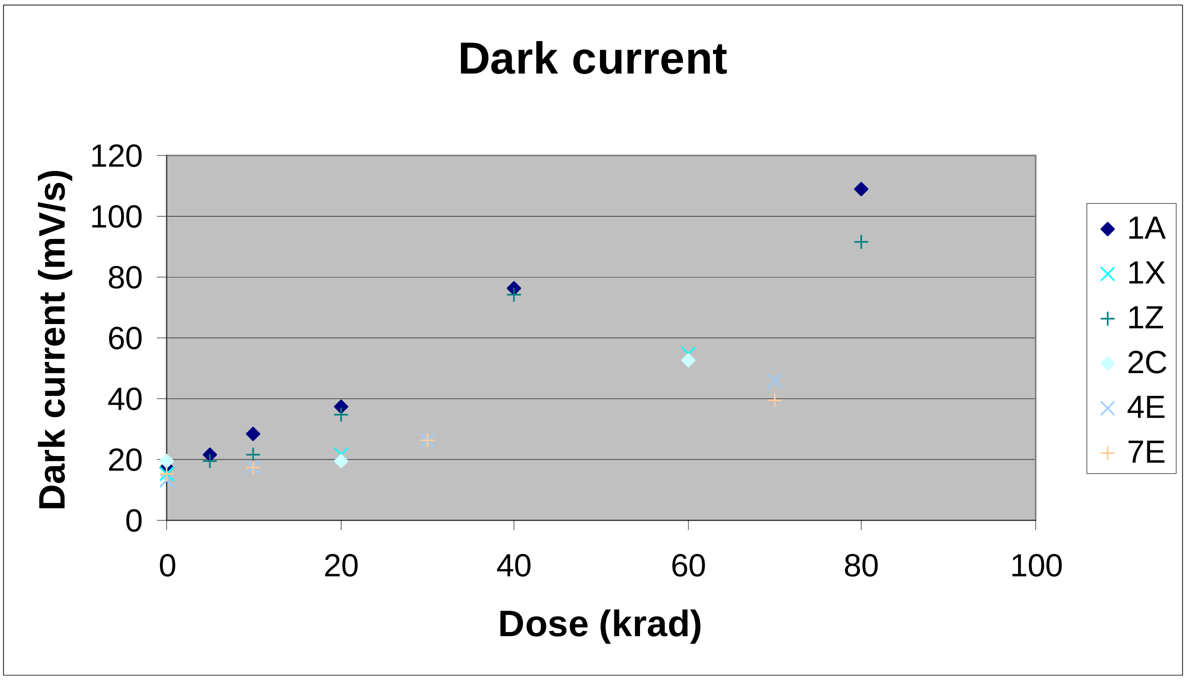
3.6.2 Current consumption vs. total dose



The current consumption radically increases (approximately doubles) between 30 and 40 krad total dose. The current consumption then appears to stabilize at this higher value, and the devices otherwise continue to operate normally until the maximum dose reached of 80 krad.

The current consumption after annealing remains identical, so the increase because of radiation damage is permanent.

3.6.3 Dark current vs. total dose



Dark current continuously increases with increased dose. This effect can be attributed partially to the radiation and partially to the increased die temperature because of increased current consumption (see 3.6.2). At the maximum reached dose of 80 krad the combined result of these effects is a ca. fivefold increase in dark current.

3.6.4 Dark current after annealing

Dark current measurements were made after annealing on both an unradiated sample and the 80 krad irradiated samples, at different temperatures:

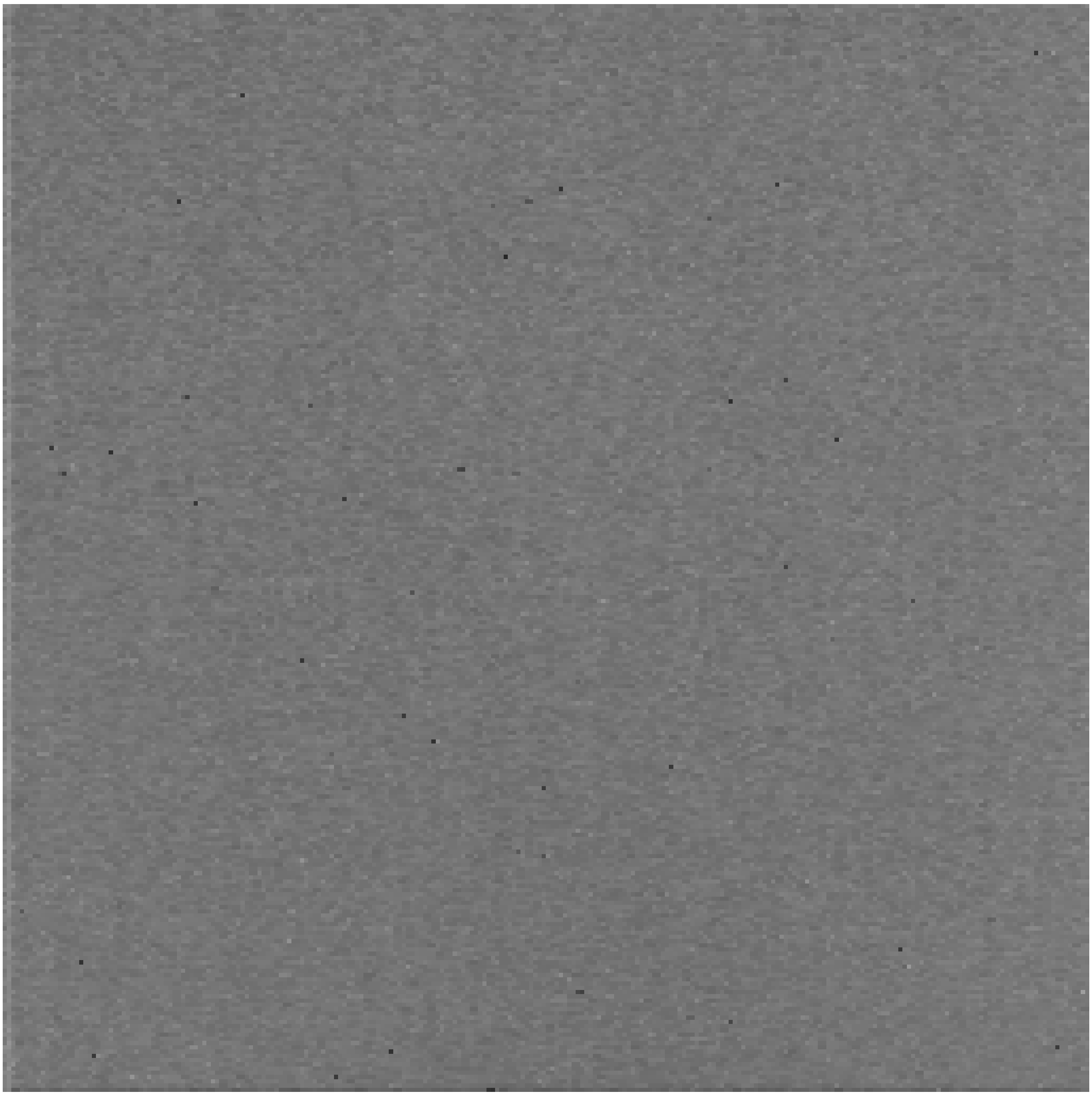
Sample	Dark current (mV/s)
24 hours after radiation, room temperature (22C)	
Unradiated	15.3
1A (80 krad)	72.1
1Z (80 krad)	72.1
48 hours after radiation, cooled with cooling spray (ca. -50C)	
Unradiated	<1

1A (80 krad)	15.3
1Z (80 krad)	17.5

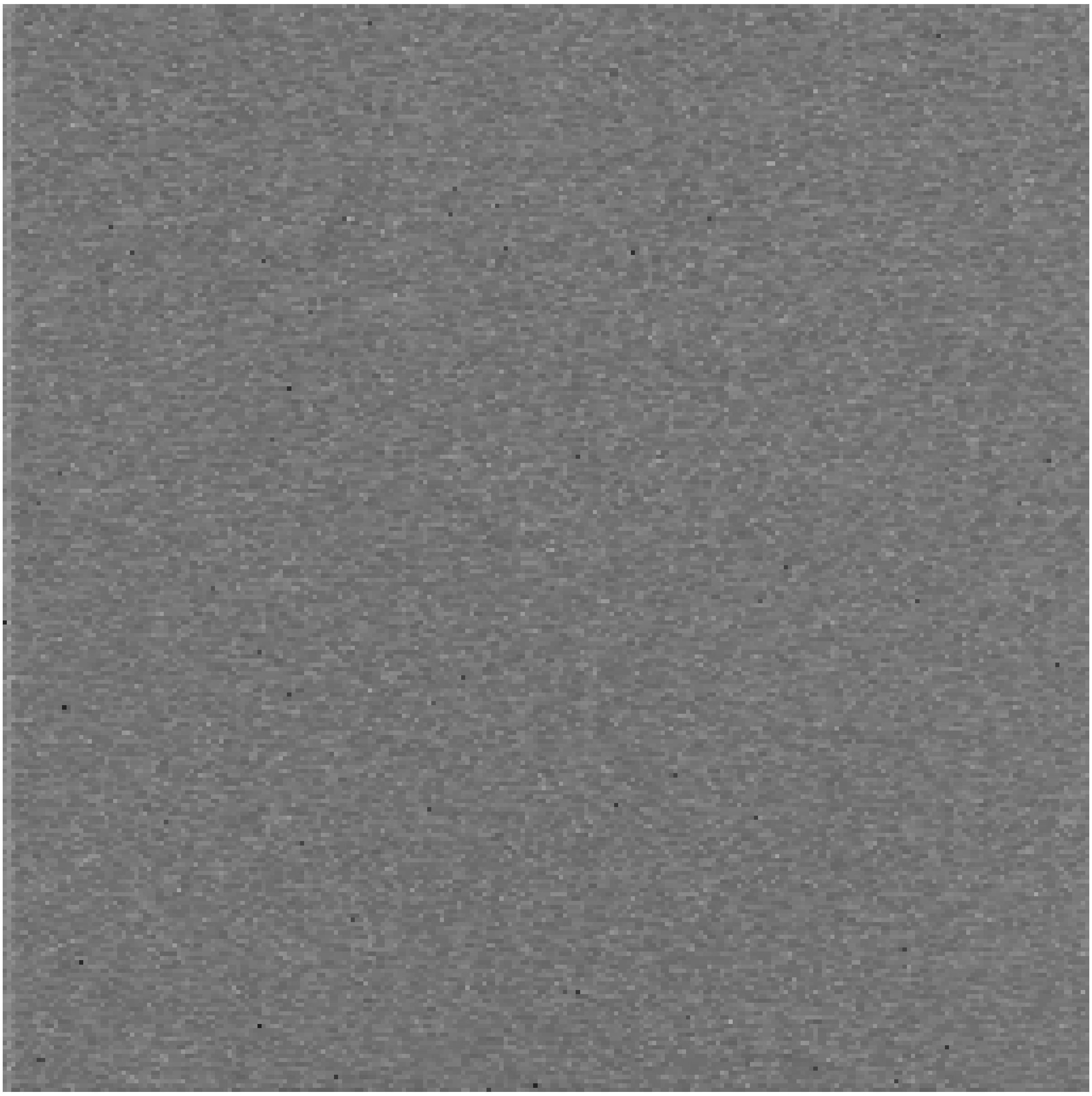
The room temperature measurements were made as soon after power-up as possible, to avoid heating up of the die. The dark current after annealing under these circumstances is ca. 30% lower than immediately after radiation. This can be caused both by annealing or by reduced temperature.

The measurements with cooling spray give an indication on the amount of dark current that is introduced by the radiation regardless of temperature effects.

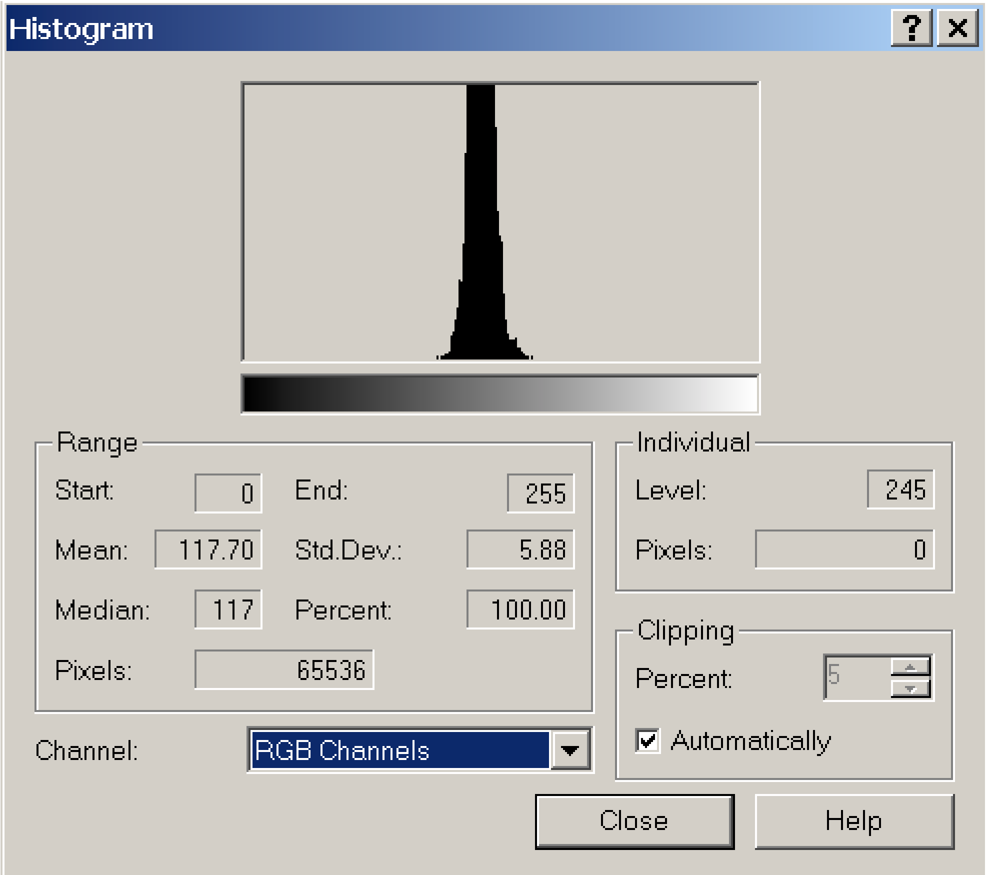
3.6.5 Sample images



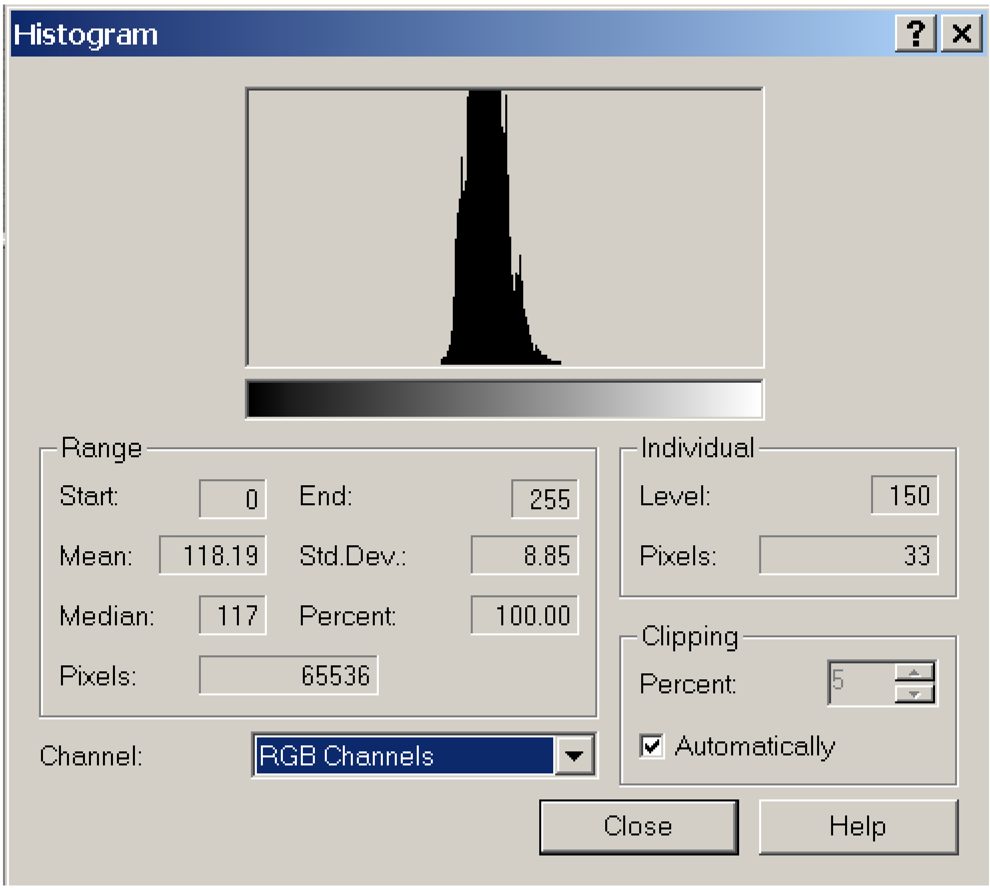
Dark image (256x256, exposure 255 lines) of sample 1A before radiation



Dark image (256x256, exposure 255 lines) of sample 1A after radiation with 80 krad and annealing. Image appears slightly more speckled than before radiation.

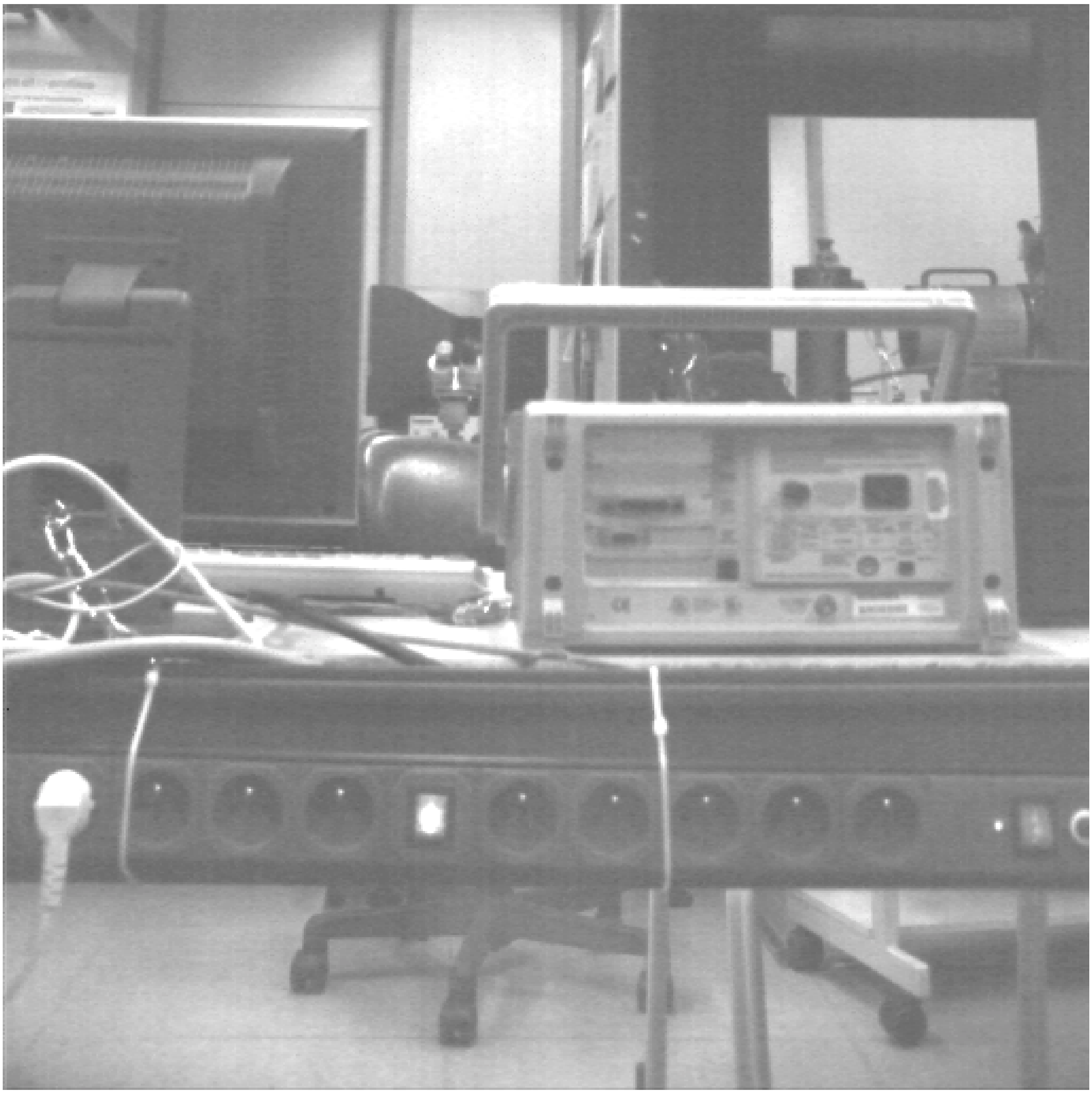


Histogram of above dark image before radiation.



Histogram of above dark image after radiation and annealing.

The histogram shows that the standard deviation of the dark current in this sample image has increased from 5.88 to 8.85. This quantifies the increased speckle.



Test image from sample 1A after 80 krad: the increased speckle is also visible here.

3.6.6 Conclusions of total dose tests

The devices are still operational after a total dose of 80 krad of gamma radiation, albeit with a doubled current consumption and increased dark current.

Upto ca. 30 krad the current consumption and dark current stay within their specified values. After 40 krad and above these parameters will go out of spec, but the devices remain functional and image quality acceptable until at least 80 krad.

4.Heavy ion latch-up testing on IRIS-3 chips

4.1.Test objectives

The main objective of this test is to assess the latch-up behaviour of the complete IRIS camera chip under operational conditions.

The second objective is to study possible imager degradation resulting from heavy particle irradiation. Expected effects are:

- overall increased dark current: this can be measured directly.
- locally increased dark current, i.e. dark current *spikes* or defective pixels.

If logistically possible, a third test objective will be the assessment of single event upsets.

4.2.Ancillary equipment and bias

The devices under test were put on a dedicated circuit board, properly biased, and constantly acquiring images and transmitting them over the RS-422 interface. The supply currents are monitored continuously on an oscilloscope, separately for the 3.3V digital (cell logic), 5V digital and 5V analog supplies.

Circuitry was added in the power supply circuit to automatically switch off the power as soon as the total supply current (IRIS-3 supply currents + interface electronics) exceeds a preset value I_{max}. This circuit exists completely of hardware (analog comparator) and hence suffers no 'blind' times caused by the measurement software running other processes.

4.3 Test procedure

During the test, power supply current is monitored. If the current exceeds a level I_{max}, the DUT is shut down. After a time T_{down}, the DUT is started again. The remote test PC logs these events with time of occurrence and the level of current before shut-down.

Two devices were tested: the devices with codes 1B and 5G. The device with code 1B was also a subject of the electro-optical evaluation IRIS-3 characterization report (part 1 of deliverable D24).

Images and camera status information packets were logged during the irradiation, and analyzed for information extraction regarding SEUs. Note that camera status packets contain detailed information on possible errors in the camera's controller logic. When the test software detected an error in the data, the DUT was reset.

After the irradiation, the devices tested were characterised at room temperature (23°C).

I_{max}	500mA (includes support/interface electronics)
T_{down}	20s

4.4.Test conditions

This paragraph lists details specific to radiation tests. Normally the test specifics are expected to be under control of CYCLONE personnel, and hence compliant with [AD2].

Irradiation beam, flux levels, and duration of exposure

Referring to [AD5], the composition of the heavy ion beam is:

- cocktail #1
- M/Q = 5
- LET = 1.7 to 56 MeV/mg/cm^2

After the devices are brought under the beam, the beam flux is varied (possible range: 10 up to 10^4 ions/s) to get a nominal response from the devices. The whole exposure procedure lasts a few hours, for each device individually.

The following heavy ion beams were used:

Ions	*M/Q*	*DUT energy [MeV]*	*Range [µm Si]*	*LET [MeV/mg/cm²]*
$^{40}Ar^{8+}$	5	150	42	14.1
$^{84}Kr^{17+}$	4.94	316	43	34
$^{132}Xe^{26+}$	5.07	459	43	55.9

The beam spot size was 25 mm, focussed on the center of the bare IRIS-3 die, which was therefore fully covered by the ion beam. Because of this narrow beam spot, in combination with the small range of the particles, the support electronics did not need shielding.

Ambient conditions

The ambient conditions at the test site are:

- vacuum chamber
- room temperature (approximately 20°C)

Irradiation facilities

The irradiation facility used is the ESA-coordinated Heavy Ion Facility at:

CYCLONE
Cyclotrone Research Center
Chemin du Cyclotron, 2
B-1348 Louvain-la-Neuve
Belgium

4.5 AD2 Compliance matrix

AD2 paragraph	Item	compliance	comments/divergence from guidelines
3.1	radiation source and dosimetry	yes	ESA HIF
3.2	test system	mostly	freedom of noise not proven
4.1	sample size	mostly	no die photograph
4.2.1	SEU	limited	no pre-study to identify bistable elements, no testing all registers on the chip; logging of self-test errors in chip output data housekeeping packets.
4.2.2	LU	yes	

4.6 Exposure overview

The two samples were exposed to beams of varying intensity, according to the following table: (the high beam fluxes were used to detect latchup, the low beam fluxes to analyze the SEU behaviour)

Sample	*Ion beam*	*LET [MeV/mg/cm²]*	*Beam flux [ions/s/cm²]*	*Time [s]*	*Total fluence [ions/cm²]*	*Remarks*
1B	Argon	14.1	3500	286	1.00E+06	SEU's, but no latchup
"	"	"	4000	500	2.00E+06	"
"	"	"	10000	1000	1.00E+07	"
"	Krypton	34	1000	900	9.00E+05	"
"	"	"	2000	450	9.00E+05	"
"	"	"	5000	120	6.00E+05	"
"	"	"	10000	60	6.00E+05	"
"	Xenon	55.9	3500	60	2.10E+05	"
"	"	"	11000	600	6.60E+06	Maximum flux, no latchup
"	"	"	500	30	1.50E+04	for SEU testing, no latchup
"	"	"	100	480	4.80E+04	"
"	"	"	10	960	9.60E+03	"
"	"	"	50	960	4.80E+04	"
Cumulative for sample 1B:				*6406*	*2.29E+07*	
5G	Xenon	55.9	11000	120	1.32E+06	Maximum flux, no latchup
"	"	"	100	1330	1.33E+05	for SEU testing, no latchup
Cumulative for sample 5G:				*1450*	*1.45E+06*	

4.6 Latchup test results

For these tests high beam fluxes were used, in an attempt to get the IRIS-3 device to show latchup events, and measure the average time until these events occur.

Although many SEU's were observed, including self-diagnosed state machine errors and aborted data acquisitions (see further), no abnormal increase in any of the supply currents was observed, even at the highest energy levels and beam flux available at the irradiation facility: Xenon (LET=55.9 MeV/mg/cm²) and 11000 ions/s/ cm². The total fluence reached (over all the measurements) for sample 1B was as high as 2.29 x 10^7 ions/cm², without any sign of latchup. A software reset command issued to IRIS-3 over the RS-422 interface was always able to restore IRIS-3 to normal operation.

The measured power supply currents were:

Sample	Supply	Imin (mA)	Imax (mA)	Powerup peak (mA)
1B	3.3V digital	40	60	230
"	5V digital	0	25	138
"	5V analog	44	50	65
5G	3.3V digital	40	60	155
"	5V digital	0	25	187
"	5V analog	44	51	65

Imin = minimum current during operation (idle and/or acquiring+reading out image data)
Imax = maximum current during operation (idle and/or acquiring+reading out image data)
Powerup peak current is listed separately and not included in Imax. This powerup peak current is the reason the overcurrent shutdown treshold was put at 500mA.

The 500mA overcurrent protection was never triggered, and it was visually verified that during operation none of the IRIS-3 supply currents exceeded the above Imax values, and the total supply current (including all support and measurement electronics) never exceeded 250mA. No latchup occurred.

4.6 SEU test results

During the latchup tests (with high beam fluxes) no latchup events were detected, but a large amount of SEU's were observed. These include:

- setting of the following self-diagnostic ErrorState bits:
  - ErrorState[2]: illegal command/packet detected
  - ErrorState[3]: liveness watchdog on command interface timed out and restarted FSMs
  - ErrorState[4]: liveness watchdog on data interface timed out and restarted FSMs
  - ErrorState[5]: FSM in image data acquisition entered illegal state
  - ErrorState[6]: error in main FSM

  (ErrorState[0] and ErrorState[7], both related to memory, were never observed; there were also no memory functions used and no memory was present)
- abortion of image data acquisition stream
- corruption of housekeeping data: this was observed only once (bit flipped in image height), and most likely occurred during the setting of this data before writing it into its triple-protected long-term storage; no other corruption of triple-protected long-term stored data was observed

The most obvious event to detect is the abortion of the image data acquisition stream. Some measurements were made on sample 1B with Krypton (LET=34 MeV/mg/cm²) to find a statistical relation between the beam flux and occurrence of this event:

Flux [ions/s/cm²]	*Time [s]*	*Average time [s]*	*Fluence [ions/cm²]*	*Average fluence [ions/cm²]*
1000	88	85	88000	85000
"	95		95000	
"	109		109000	
"	68		68000	
"	93		93000	
"	71		71000	
"	28		28000	
"	131		131000	
"	131		131000	
"	36		36000	
2000	55	39	110000	78000
"	62		124000	
"	23		46000	
"	56		112000	
"	30		60000	
"	15		30000	
"	34		68000	
"	79		158000	
"	20		40000	
"	16		32000	
5000	35	43	175000	215000
"	59		295000	
"	35		175000	
10000	17	14.33333	170000	143333.3333
"	20		200000	
"	6		60000	

The average time to abortion is directly related to the beam flux. On average, the data stream was aborted after a fluence of ca. 75000..100000 ions/cm².

A measurement was also made at relatively low beam flux intensitities to find:

- time to first detectable SEU (see above)
- beam flux at which detectable SEU's do not occur any more / are very rare

The following SEU's were detected:

Sample	*Flux [ions/s/cm²]*	*Time [s]*	*Fluence [ions/cm²]*	*Type of SEU*
1B	500	26	13000	Abort
"	100	23	2300	ErrorState[6] set
"	50	480	24000	Abort
"	50	480	24000	none occurred
"	10	960	9600	none occurred
5G	100	660	66000	Abort
"	100	40	4000	ErrorState[2] set
"	100	95	9500	ErrorState[6] set
"	100			bit flipped in image height (*)
"	100	150	15000	none occurred
"	100	180	18000	none occurred

(*) this data was wrong in the housekeeping from the very beginning; most likely this bit was flipped during the setting of this image parameter, before it was stored in its long-term, triple-protected storage register – this could be regarded as a SEU at time 0

At a beam flux of 10 ions/s/cm² no SEU's were observed. At a beam flux of 100 ions/s/cm², no SEU's were recorded at a fluence of less than 2300 ions/cm² (with the possible exception of the above bit flip).

In all cases the image data was OK (fully saturated white images), no bit flips occurred in the image data.

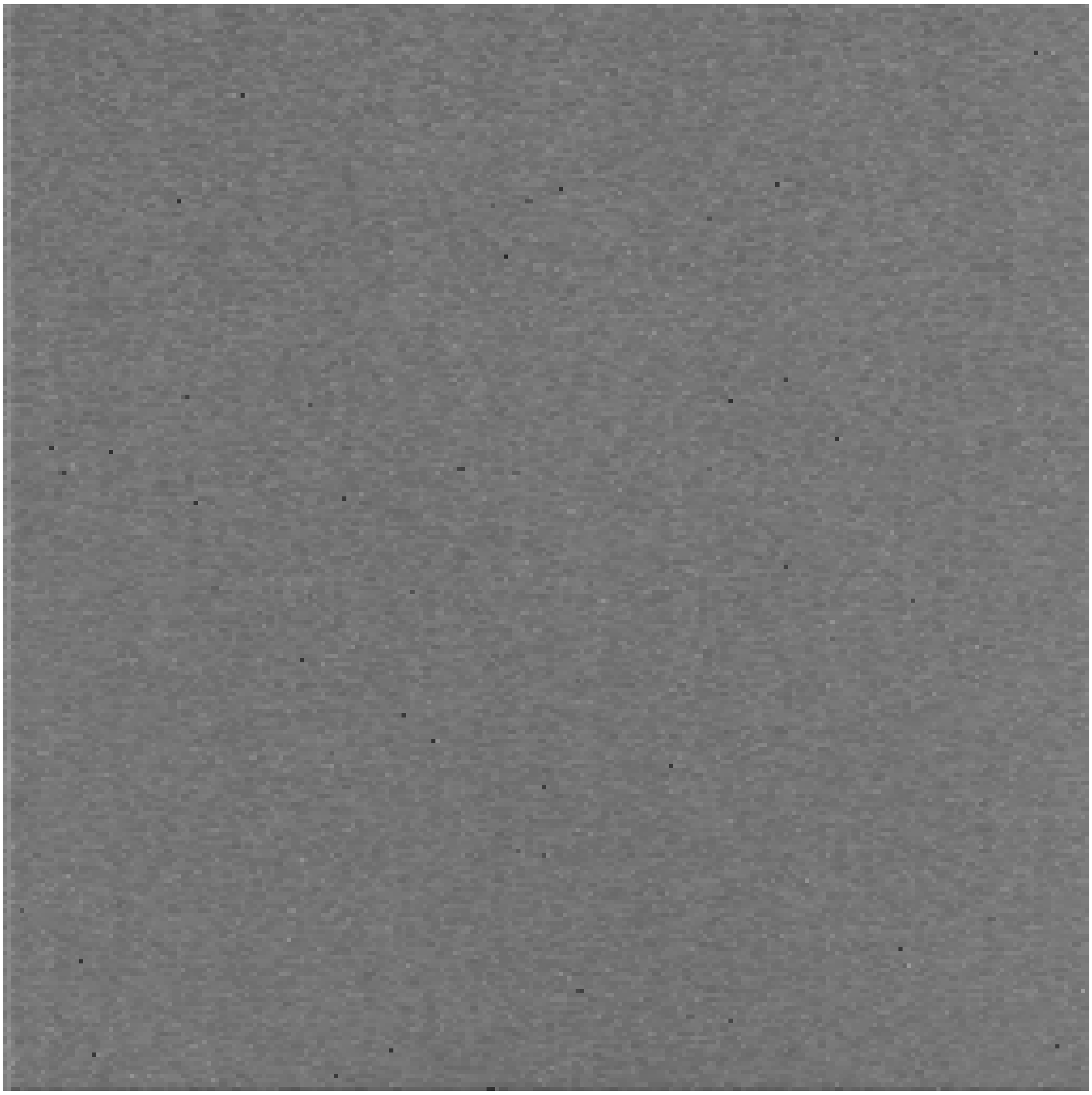
4.6 Dark current test results

The following dark currents were measured before and after radiation (lab environment, room temperature ca. 23 deg C):

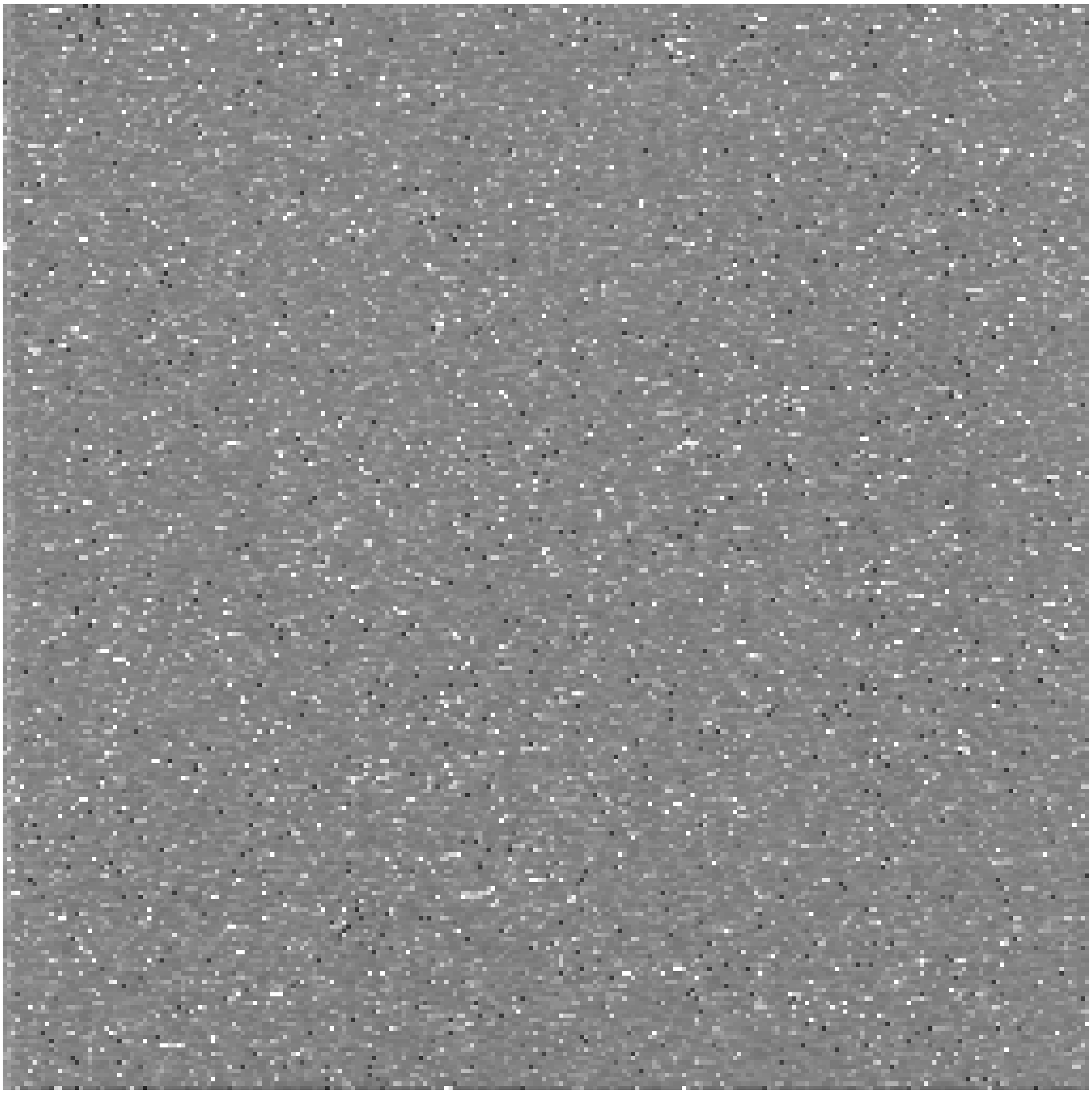
Sample	*Fluence [ions/cm²]*	*Dark current [mV/s]*
1B before radiation	0	13.1
1B after radiation	2.29E+07	21.8
5G before radiation	0	13.1
5G after radiation	1.45E+06	13.1

Sample 5G shows the same dark current after as before radiation. However, the dark current for sample 1B has increased by 66%. This can be explained by the fact that sample 1B has received more than 15 times as much heavy ions than sample 5G.

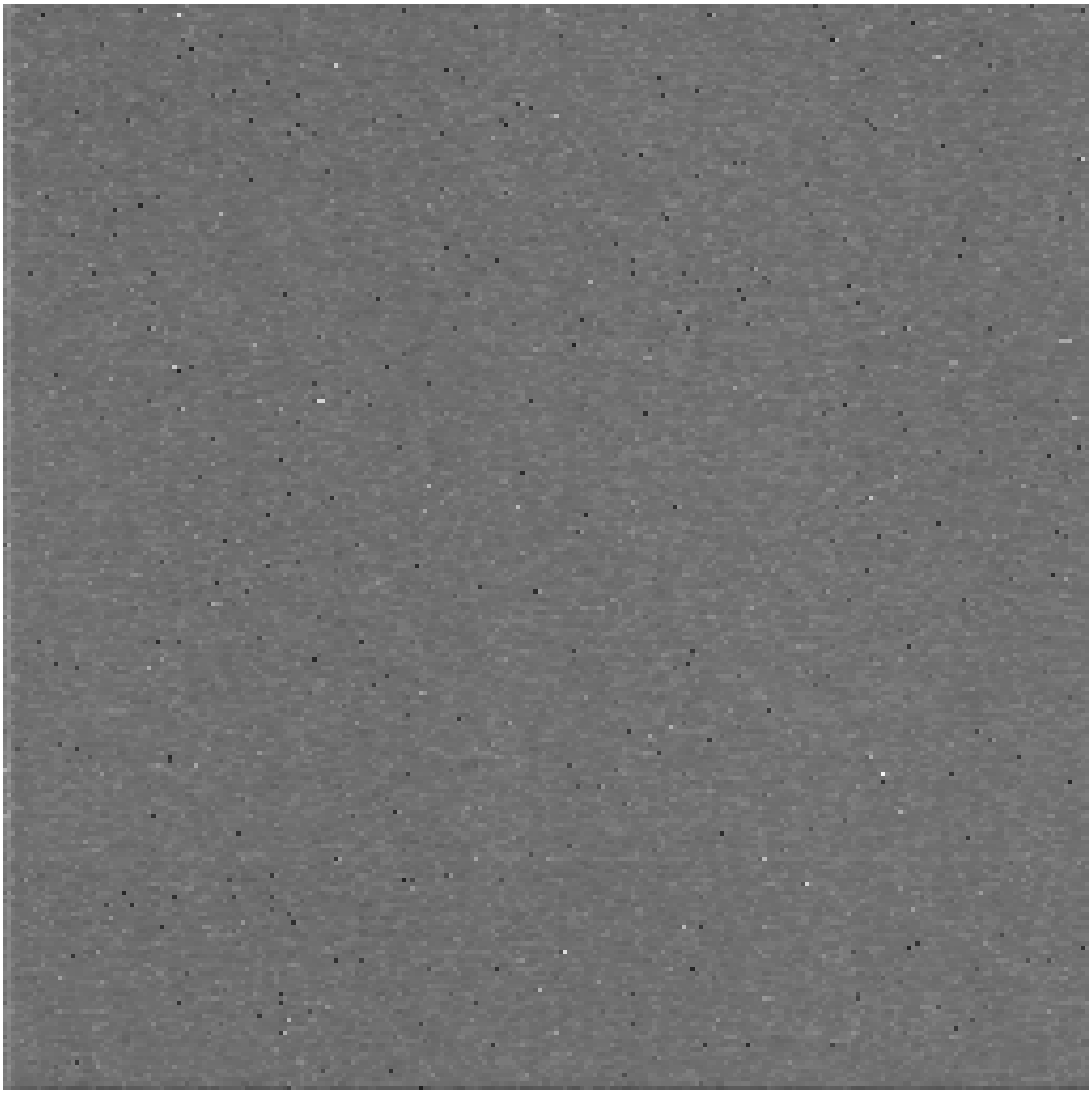
Sample dark images:



Typical dark image (256x256, exposure 255 lines) before radiation



Dark image (256x256, exposure 200 lines) from sample 1B after radiation



Dark image (256x256, exposure 200 lines) from sample 5G after radiation

The speckle (dark and bright pixels) in sample 5G have increased slightly compared to before radiation. However, in sample 1B this effect is much more clearly visible, together with an overall brighter image (because of increased dark current).