

# In-situ gamma irradiation testing of radiation hardened chips till 1 MGy

David Geys<sup>1</sup>, Ying Cao<sup>1</sup>, Marco Van Uffelen<sup>2</sup>, Laura Mont Casellas<sup>2</sup>, Ludo Vermeeren<sup>3</sup>, and Andrei Gusarov<sup>3</sup>

<sup>1</sup>Magics Instruments, Belgium

<sup>2</sup>Fusion for Energy, Spain

<sup>3</sup>SCK CEN, Belgium

David.geys@magics.tech

**Abstract**—Ten samples of a custom tailored Mega-Gray hardened resolver/LVDT-to-digital converter, a resistive base sensor-to-digital converter and a RS485 communication application specific integrated circuit (ASIC) were combined in 1 irradiation campaign for Fusion for Energy (Barcelona, Spain). Radiation resistance of these ASICs, developed by Magics Instruments (Geel, Belgium) for Fusion for Energy, was assessed for a total ionizing dose (TID) above 1 MGy using the Co-60 gamma underwater irradiation test facility at SCK CEN (Mol, Belgium).

The 3 different ASICs were irradiated at an average dose rate of 484 Gy/h and their performance was continuously measured (in-situ) during 97 irradiation days. A fully autonomous and modular test setup was developed to perform these measurements and ensure continuous operation by implementing a recovery and warning system in case of failure to restrict measurement data loss to minimum.

An in-situ post-irradiation assessment was performed afterwards to observe recovery from the irradiation in a so-called annealing phase. Annealing was done for seven days at room temperature followed by another 7 days of high temperature annealing at 100 °C to accelerate the recovery effect.

During the full test campaign all data was saved in a database, post-processed with Python into readable plots to deduct possible performance shifts due to the irradiation and afterwards during recovery.

During the complete testing campaign of these ASICs the ESCC22900 (Total Dose Steady-State Irradiation Test Method) standard was followed.

**Keywords** —Rad hard ASIC, 1MGy TID, In-situ measurements

## I. INTRODUCTION

Most of today's commercial off-the-shelf (COTS) electronics are not specified to meet the demanding requirements of advanced nuclear applications requiring MGy-level Total Ionizing Dose (TID) tolerance. Examples are maintenance and diagnostics tasks in future burning plasma fusion reactors, for example the International Thermonuclear Experimental Reactor (ITER). Applications such as interventions during nuclear accidents, dismantling of old nuclear power plants and disposal of radioactive waste also call for rad-hard electronics. Therefore, first, the development and,

secondly, the testing of custom tailored MGy hardened integrated solutions become necessary for use in these environments. It will not only reduce the shielding requirements but will make it possible to place electronics closer to front-end sensor transducers and actuators in a radiation environment.

Three ASIC designs of such custom tailored MGy hardened integrated solutions, developed by Magics Instruments (Geel, Belgium) for Fusion for Energy, were tested in-situ to monitor their performance during irradiation and prove their MGy radiation hardness. Of each ASIC design, 10 samples were measured. Average dose rate during the irradiation experiment was 484 Gy/h to reach at least a TID-level of 1 MGy after 97 days of irradiation for all 30 samples in the test. During these 97 days of irradiation, specifications of all samples were measured continuously in a repeated fashion. Therefore, a fully automated modular test setup was developed to perform these measurements.

The irradiation assessment was performed at the Co-60 gamma underwater facility (RITA) at SCK CEN (Mol, Belgium). The irradiation assessment was followed by a post-irradiation assessment split up in an annealing at room temperature for 7 days followed by high temperature annealing at 100 °C for another 7 days. This post-irradiation assessment was performed in the temperature chamber (CLARA) also located at SCK CEN.

## II. BACKGROUND

The 3 ASIC designs tested in this test campaign are called: ASIC1, ASIC2 and ASIC5 and are part of a set of 5 radiation hardened ASICs developed by Magics Instruments:

- ASIC1: resolver/LVDT-to-digital converter ASIC
- ASIC2: resistive bridge sensor signal conditioner ASIC
- ASIC3: 10-channel limit switch readout ASIC
- ASIC4: 10-channel relay driver ASIC
- ASIC5: BiSS (RS-485) interface communication ASIC

With these 5 ASICs it is possible to build an actuator and sensor read-out network in a harsh environment up to 1 MGy TID. Such networks could be used for maintenance and diagnostic tasks in fusion reactors (like the ITER). A typical sensor/actuator network is depicted in Fig. 1. The presented network exists out of 3 RS-485 slave nodes. In each of these slave nodes a combination of up to 3 ASICs is used to read out different kind of sensors or drive relays. The first 4 ASICs out of the set of 5 listed above can be used for this purpose. The

measured sensor data are combined into packages and sent over the long bus cable via instances of ASIC5 in the bus. Communication in the bus to/from the RS-485 master of sensor/actuator data from/to the RS-485 slave nodes is possible over a long CAT7 cable of up to 215 meters long. All ASICs in this network need to be supplied by the rad-hard DC-DC power module. This module is outside the scope of this work presented here.

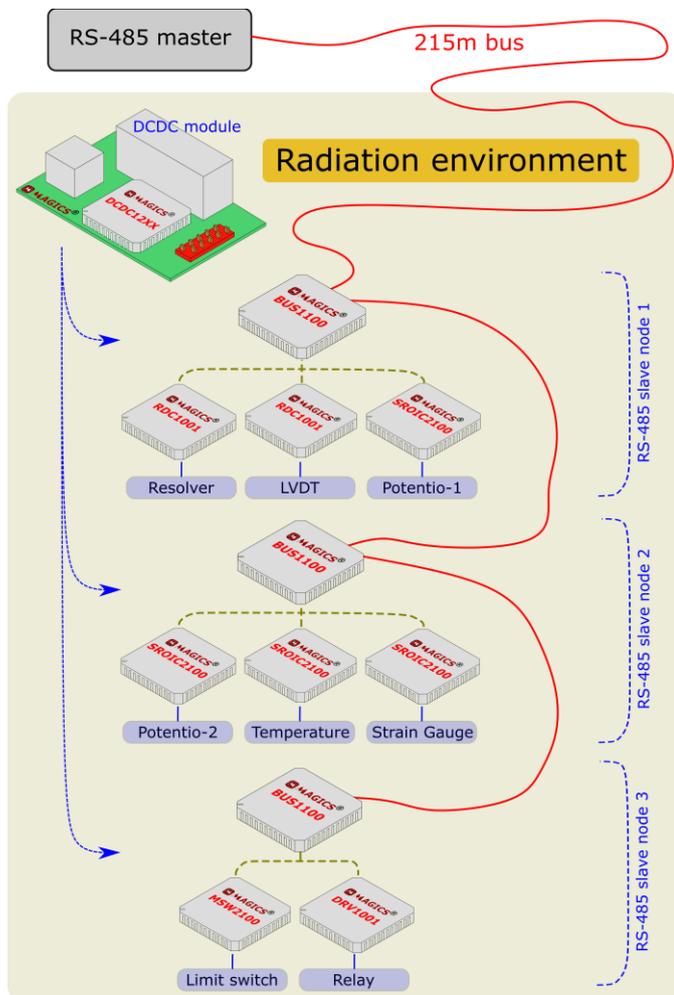


Fig. 1. Schematic representation of a network inside a radiation environment built up by custom tailored MGy hardened ASICs to read out sensors and drive actuators.

With the network presented in Fig. 1 it is possible to build closed loop motor control networks as they are needed for remote handling.

The big advantage for placing these electronics in the radiation environment itself is dual. (a) Only a standard single data communication cable is needed from the radiation environment to the safe zone and therefore significant cost savings could be achieved on multiple expensive cables in case these electronics were placed in the safe zone. (b) Additionally, the need for thick shielding is not stringent anymore. Consequently, also here a significant cost saving exists and furthermore, the system could be built smaller.

### III. GAMMA IRRADIATION TESTING

The goal of gamma irradiation testing in this project is to prove the functionality and measure specifications of the ASIC designs when irradiated up to an accumulated dose of at least 1 MGy.

The characteristics of the ASICs change with the received TID. This shift occurs in 2 directions, as a result of the well-known recovery effect, typically observed at 1-10 kGy. Therefore, it is important to monitor characteristics of the DUTs *in-situ*, during irradiation.

In-situ measurements can only be performed when the ASICs are accessible during irradiation. Therefore, numerous interconnection cables are needed between ASICs and lab equipment measuring the specifications.

During this gamma irradiation assessment samples of ASIC1, ASIC2 and ASIC5 were irradiated in the Co-60 test facility at SCK CEN at an average dose of 484 Gy/h. To reach a TID of 1 MGy the ASICs were exposed for 97 days. The applied dose rate is in-line with the dose rate of 300 Gy/h expected in the ITER during maintenance mode.

The irradiation was interrupted twice to investigate the dynamic balance between radiation-induced changes and recovery. These interruptions were held at an average TID of 10 kGy and 100 kGy each time for a duration of 1 hour.

### IV. POST-IRRADIATION TESTING

More measurements were performed after irradiation in the so-called annealing phase. Goal of these measurements is to monitor possible recovery effects of the performance of all ASICs after irradiation.

Following the standard ESCC22900 [1] the post-irradiation testing was split up into 2 main parts. (a) 7 days annealing at room temperature. This room temperature value may not differ more than 5 °C compared to the temperature during irradiation with a maximum of 30 °C. (b) 7 days annealing at high temperature. This accelerated ageing phase is carried out at a temperature of 100 °C ± 5 °C.

The post-irradiation testing has been performed in the CLARA temperature chamber at SCK CEN. This temperature chamber is located in another building than the RITA irradiation facility on the same site of SCK CEN. The first 24h of room temperature annealing have been performed in the RITA facility. In this period the largest recovery is expected. When moving the setup immediately after stopping of the irradiation from the RITA facility to the CLARA facility, precious time would be lost in disconnecting all cables, perform contamination checks, moving the full setup, re-connect all cables and perform a test run. After 24h the test setup was moved to the CLARA facility for 6 more days of room temperature annealing and 7 days at 100°C.

In-situ measurements were performed during the full post-irradiation assessment.

### V. TEST SETUP

During the full irradiation and post-irradiation assessment in-situ measurements were required to monitor current

consumption, accuracy and resolution of readout chains, verify communication and many more. In total more than 30 specifications of the ASICs were continuously measured during the 97 days of irradiation and 14 days of annealing. To ensure a long-term stable measurement setup a modular automated test setup was developed by Magics Instruments. With this setup it is possible to perform fully automated parallel measurements repeated in a sequential fashion of many ASICs placed close to each other in a remotely controlled setup with a minimum set of lab equipment. Furthermore, a data storage redundancy and failure warning mechanism with the possibility to self-restore was built in. A schematic representation of this setup is depicted in Fig. 2.

All ASICs in the test setup are mounted individually on a small substrate PCB which is plugged in, together with 3 other substrate PCBs holding other DUTs, on a test tower PCB slice. These PCB slices are stacked on top of each other constructing a test tower. This test tower, containing all DUTs in the setup, is placed in the RITA container for irradiation or in the CLARA temperature chamber for annealing.

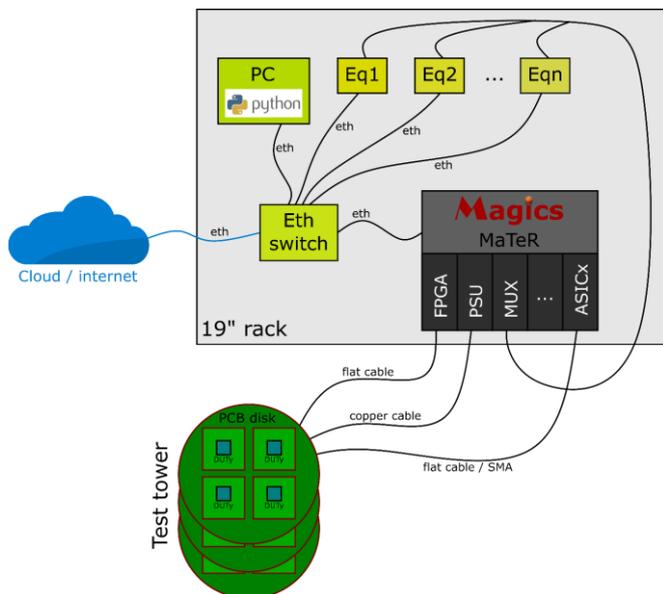


Fig. 2. Schematic representation of the developed in-situ automated test setup for (post-)irradiation testing.

Measurements are performed in-situ and therefore many connection cables are needed to route all signals and power from/to the test tower to/from the lab equipment in the safe test zone. Different types of interconnection cables are used depending on the signals they carry: flat cables for digital signaling, copper cables for power routing and SMA cables for highly sensitive analog signals. All these cables are routed from the test tower in 4 flexible tubes to the 19 inch rack. These cables have a length of 10 meters making it challenging to ensure high speed connections.

All equipment in this setup is mounted in a 19 inch rack placed in a safe zone. A rack PC is used to run all scripts and to drive the lab equipment and read from it. Multiple custom test rack computers (MaTeR) are also included householding multiple functionalities like there are FPGA, MUX, PSU and

others. An ethernet switch connects all devices in this 19 inch rack and ensure a connection towards the cloud.

#### A. MaTeR

The MaTeR (Magics' Test Rack) is an in-house development of a 19 inch test rack PC that can be used to include many DUTs in a test setup with a minimal set of lab equipment. A photo of 1 such a MaTeR is depicted in Fig. 3.



Fig. 3. Modular Magics' Test Rack (MaTeR) filled with 1 test card.

It is a modular design that can be adapted depending on the amount and type of DUTs in the test. Each MaTeR contains a back panel PCB in which up to 10 slide-in PCBs with different functionalities can be slit in. Currently the following types of slide-in PCBs are available:

- FPGA for digital signaling via flat cable and/or UTP
- PSU for power routing towards DUTs
- MUX for multiplexing SMA and flat cables
- CLK for generating different kinds of clock signals
- TC for reading out type-T class 1 thermocouples
- ASICx as ASIC specific test cards like f.e. a resolver simulator card to test ASIC1

In this project 4 FPGA cards were used to route in total 170 digital signals and 6 UTP cables. Six different PSU cards routed 80 supply lines towards the DUTs. Eighty four analog sensitive signals were multiplexed via 11 MUX cards to the limited set of lab equipment in the 19 inch rack. One resolver simulator card was integrated to test the LVDT and resolver functionality of all samples of ASIC1 in the test. Besides this also 20 clock signals were needed generated by the 2 CLK cards in the test. To monitor the temperature dependency of the measured specifications 1 TC card was used.

These MaTeRs are mounted in a 19 inch rack of which 2 of them exist in this project. Fig. 4 shows the smallest rack in which 3 of the 4 MaTeRs are located in. All cables needed to make connection to the DUTs are plugged/screwed in.

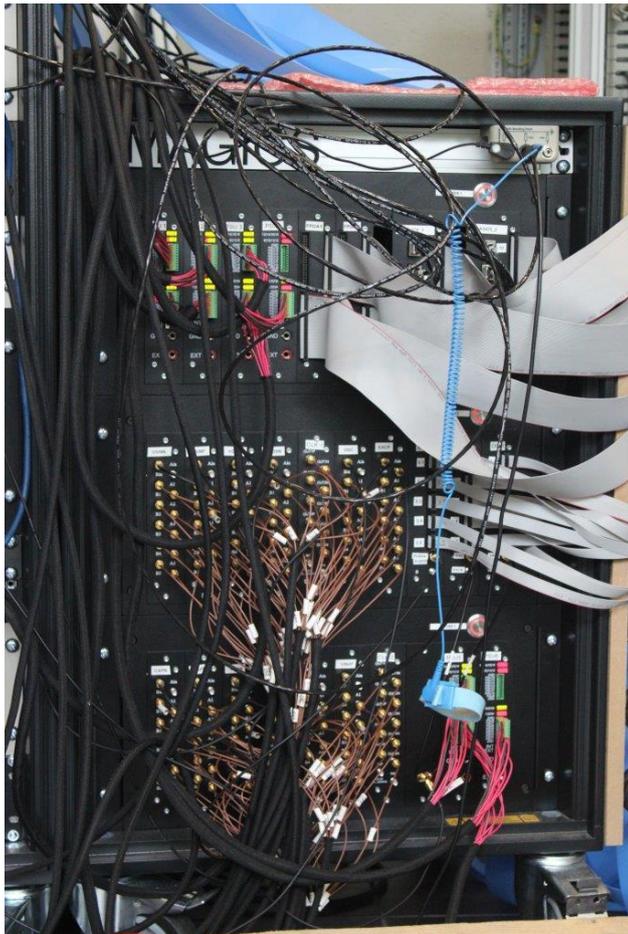


Fig. 4. Front view of a 19 inch rack with 3 MaTeRs fully connected.

### B. Test Tower

The test tower is specifically designed to fit in the container of the irradiation facility. DUTs are arranged in a way it is possible to allow many interconnection cables to each DUT in the test tower and include many DUTs very close to each other. In this project the following DUTs are included:

- ASIC1:  
6 (in-situ) + 2 (in-situ @ worst-case bias) + 2 (0 V bias)
- ASIC2:  
6 (in-situ) + 2 (in-situ @ worst-case bias) + 2 (0 V bias)
- ASIC5:  
6 (in-situ) + 2 (in-situ @ worst-case bias) + 2 (0 V bias)

Fig. 5 shows the test tower fully connected before the start of the irradiation experiment.

It is very important to locate all the DUTs close to each other because the dose rate varies along the vertical axis of the container. Before the actual start of the irradiation experiment the dose rate (dosimetry) was determined by SCK CEN. The dose rate was determined at specific heights (250, 300, 350, 400 and 450 mm). These data were used to determine the dose rate experienced at each level of the DUTs in the test tower by defining a 4<sup>th</sup> order polynomial fit through the data from the dosimetry. An average dose rate for all DUTs in the test was calculated at 484 Gy/h. Along the height of the test tower, the dose rate varied from 438 Gy/h (-9.5%) at the lowest located DUT to 516 Gy/h (+6.6%) at the highest located DUT in the

test tower. After 97 days of irradiation all samples received at least 1.014 MGy of TID. DUTs located at the top of the test tower almost received 1.2 MGy. The height of each DUT in the test tower with the corresponding dose rate and TID at the end of the irradiation experiment are depicted in Fig. 6.

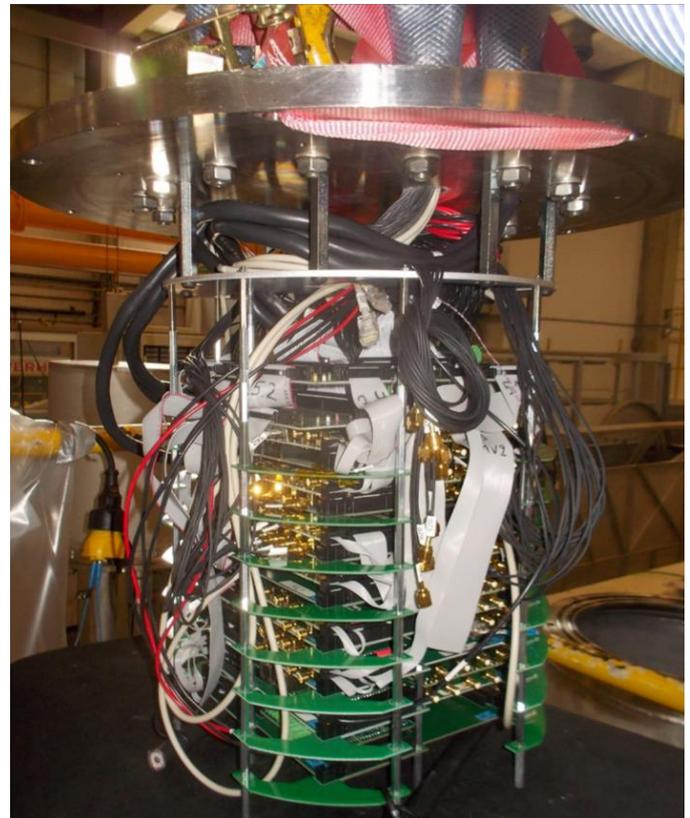


Fig. 5. Fully connected test tower before the start of the irradiation experiment.

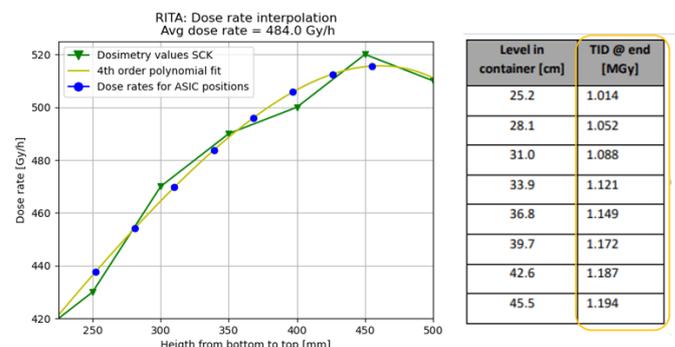


Fig. 6. Dose rate versus height in the test tower and TID at the end of the irradiation experiment.

### C. Software

The rack PC integrated in the 19 inch test rack of the setup (see Fig. 2) runs several scripts, all written in Python, in parallel:

- 3 measurement scripts: 1 script for each ASIC design in the test was running. This script is a combination of writing to or reading from the lab equipment in the test to measure all specifications of the DUTs. This script also handles the saving of the measured data in a database.
- 1 temperature script: This script monitors the

temperature via the 3 type-T class 1 thermocouples in the test tower. Temperature is measured each minute.

- 1 data replica script: Data locally stored on the hard disk of the rack PC is continuously copied to an on-line database at a cloud server for reasons of redundancy.
- 1 warning script: In case the setup comes to a halt a warning email and test message is sent to the engineers of Magics.

The above described scripts run all in parallel in different Python processes. This lowers the risk for the full setup to stop due to a failure in a single script. Each of the scripts runs sequentially for the duration of the experiment. This has the advantage that the test cycle time of 1 ASIC design could be kept small enough to observe shifts in performance of the DUTs due to irradiation. The test cycle time is defined as the total time needed to measure all specifications of all samples of 1 ASIC design in the test setup. Because dose rates are high in this test, each DUT must be measured fast enough to measure it again after the other 9 samples are measured to capture possible shifts in the performance due to irradiation. Target value for the test cycle time is to be smaller than 30 minutes.

If 1 or multiple scripts crash, the event is logged in a text file on the test rack PC. Thereafter, the warning script will send out a warning email and a text message to communicate to the engineers of Magics Instruments that the setup needs to be checked. Sending a text message was added to the methodology of this warning mechanism to cover the event the internet connection is down at the irradiation facility. Some possibility is built in the test setup to self-restore in the event of a script crashing. If that action is not successful, the setup could still be controlled remotely via the secured connection to restart scripts or power cycle lab equipment before going to the facility itself.

## VI. FACILITIES

Facilities used in this project were all located at the Research Centre for Nuclear Energy (SCK CEN) in Mol, Belgium. RITA is the irradiation facility and CLARA is the temperature chamber used for the annealing.

### A. RITA – Radio Isotope Test Arrangement

RITA is the Co-60 underwater irradiation facility of SCK CEN located at their site in Mol, Belgium. This facility allows in-situ measurements. An overview photo of this facility together with the test setup of this project is shown in Fig. 7. At the top, the RITA container is visible. In this container the test tower can be loaded. After sealing of the container with its lid, it can be lowered in the pool where the Co-60 sources are located at the bottom. From the moment the container is in between these sources, the irradiation is ongoing. The scheduled interruptions were performed by lifting the container out of the irradiation flux. It was chosen to not lift the container fully to the top of the 6 meter deep water basin to lower the risk of failure of cables, connecting the test setup to the test tower. With the TID accumulation the risk of the failure increases because cable insulation material becomes brittle and short-circuiting may occur during displacement of the container.



Fig. 7. RITA – Co-60 irradiation facility at SCK CEN (Mol, Belgium) with the test setup of this project before the start of the irradiation experiment.

The photo in Fig. 7 is taken just before the start of the irradiation experiment. The test tower was still located on a small stand next to the open RITA container to connect all interconnection cables. This is a very delicate job as a single wrong connection could damage the DUTs in the setup. All cables were connected wearing proper ESD protection to limit possible ESD event damaging the DUTs.

The test tower is connected at the bottom side of the lid of the RITA container. Four flexible tubes guide all interconnection cables from the lid-test tower combination to both 19 inch racks of the setup located next to the water basin. These 19 inch racks give place to the rack PC, MaTeRs and all lab equipment needed to perform the testing of all ASICs in the test.

The parameter control panel of the RITA facility itself is visible at the top left of the photo. Besides temperature monitoring by Magics, another temperature monitoring was performed by SCK CEN via thermocouples fixed in the RITA container.

Fig. 8 shows the RITA container during irradiation. The container is located at the bottom of the 6 meter deep water basin in between the Co-60 radio-active sources. The sources can be identified by the well-known blue Cherenkov light. The 4 flexible tubes make it possible to perform in-situ measurements.

One day after the irradiation was finished, the test tower was disconnected from all its cables, contamination check was performed, and it was moved together with the test racks to the CLARA facility.

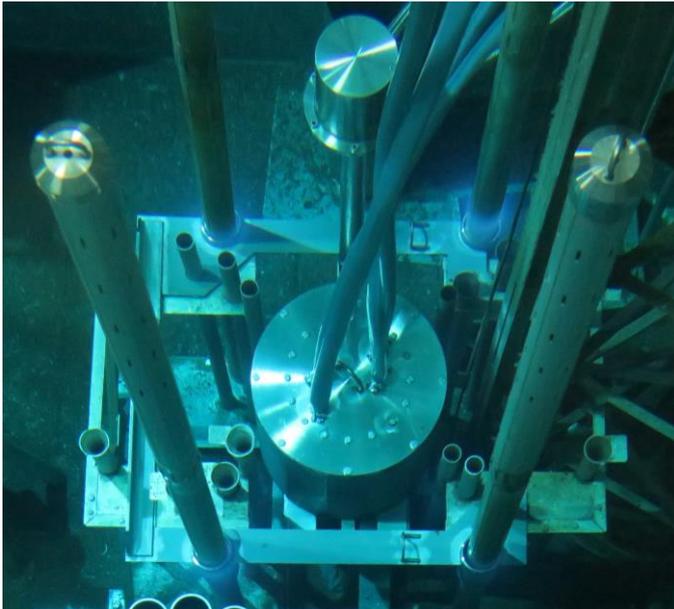


Fig. 8. RITA at SCK CEN (Mol, Belgium) when the container is in between the Co-60 sources.

### B. CLARA – CLimate chamber for Automated temperature and humidity Resistance Assessment

The post irradiation assessment was performed in the temperature chamber CLARA at SCK CEN in Mol, Belgium. This climate chamber offers a useful capacity of 2 m<sup>3</sup>. Holes are present to make the DUTs inside the chamber accessible for in-situ measurements.

An overview photo of the setup during annealing is shown in Fig. 9. All interconnection cables were routed through the hole at the side of the temperature chamber. Both 19 inch racks were placed, face-to-face, next to the temperature chamber to keep interconnection cable length low. Another set of cables than the ones used for the irradiation experiment was used. Re-use of the cables of the irradiation experiment is not possible because unscrewing these resulted in irreparable damage as they were brittle due to the outgassing by the irradiation. Cables used for post-irradiation are also shorter in length. An interconnection cable of 3 meters long is sufficient to make connection between the 19 inch test racks and the DUTs in the temperature chamber.

For the annealing, the test tower of the irradiation assessment was split up into 2 parts for ease of accessibility during connecting the cables. Before the start of the measurements during this annealing everything was verified for correctness and the photo in Fig. 10 was taken.



Fig. 9. CLARA at SCK CEN (Mol, Belgium).

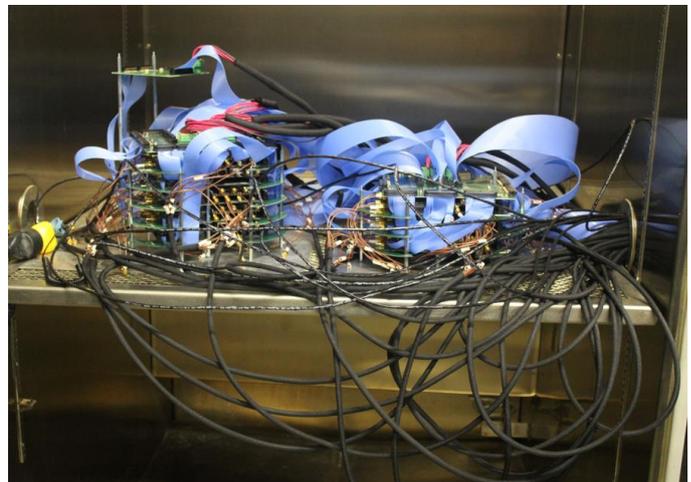


Fig. 10. Setup fully connected in CLARA before start of in-situ measurements during annealing.

## VII. OUTCOMES

All data measured during the irradiation and post-irradiation assessment was saved in a MySQL database locally stored on the test rack PC. Continuously a replica of this database was saved on the cloud database server for reasons of redundancy. A lot of measurement data was generated during this more than 100 days lasting experiment. Python was used to perform post-processing on this data. In total more than 48k lines of code were written divided over 262 Python files to generate more

then 10k of graphs. These graphs were all studied to detect possible shifts in performance due to the irradiation and possible recovery during annealing to prove functionality of all ASICs in the test during irradiation up to 1 MGy TID and beyond.

Thanks to the designed automated setup of Magics some drifts of the more than 30 measured specifications along the received TID could be observed. Radiation induced drifts up to 10% are monitored but all were still acceptable. All ASICs in the test were always fully functional and therefore can be concluded that ASIC1, ASIC2 and ASIC5 are 1 MGy radiation tolerant.

## VIII. CONCLUSIONS

The project to prove the 1 Mega-Gray TID radiation tolerance of 3 ASICs types, earlier developed by Magics Instruments for Fusion for Energy, was performed in co-operation with SCK CEN.

In total, 30 ASICs were measured in-situ during an irradiation campaign for almost 100 days to reach a TID of at least 1 MGy for all samples under the test. Additionally, samples were in-situ measured during a 14 day post-irradiation assessment split up in 7 days annealing at room temperature and another 7 days accelerated ageing at 100 °C. To perform these measurements non-stop in an automated fashion, Magics Instruments developed a modular test setup to measure the performance of all ASICs in the test.

After almost four months of continuous online measurements, less than 3 hours of cumulative down-time of the automated test setup were reported. Thanks to automatic detection of down-time and notifications to the team members, multiple issues were quickly identified and all of them, except one, were fixed in less than 15 minutes.

Magics test platform has proven to be a very stable and robust solution for automated bench test and long term irradiation measurements. This test platform supported to successfully confirm the 1 MGy radiation tolerance of all three ASICs under test.

The full assessment followed the total dose steady-state irradiation test method described in the ESCC22900 standard.

## IX. DISCLAIMER

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## REFERENCES

- [1] ESCC22900, Total Dose Steady-State Irradiation test, Version: Issue 5 June 2016 [Online]. Available: <http://escies.org/escs-specs/published/22900.pdf>