IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 4, 2019, accepted November 20, 2019, date of publication December 23, 2019, date of current version December 30, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2959724

Gamma and Proton Irradiation Tests on a Piezoelectric Actuator

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This work was supported by the CERN Institution.

ABSTRACT Piezoelectric actuators are candidates for use in radioactive environments but specific radiation tests are necessary to understand the radiation effects on the whole actuator assembly. The results of three irradiation tests on a piezoelectric actuator used for Crystal Collimation are presented. The total ionising dose effects are studied with two Gamma (^{60}Co) Tests up to 10 MGy and 1 MGy, whereas the displacement damage effects are studied in a Proton Test up to 2 MGy and 1.14×10^{16} p/cm^2 fluence. The main results are summarised for each test, presenting a maximum impedance increase of less than 25% (Proton Test), a maximum free stroke reduction of less than 25% (Proton Test) and a variation in the shape of the hysteresis response of the actuator.

INDEX TERMS Gamma-ray effects, hysteresis, material testing, piezoelectric actuators, proton effects, radiation effects.

I. INTRODUCTION

Crystal collimation [1] constitutes one of the most promising techniques for high cleaning efficiency in particle accelerators. It requires a challenging positioning performance of a bent crystal with respect to the beam trajectory. The combination of high positioning performance with the harsh operational environment (ultra high vacuum (UHV) and radiation) limits dramatically the collimator construction materials.

For such applications, piezoelectric materials constitute a suitable solution due to their UHV compatibility (when specifically selected) and potential radiation resistance, in addition to their electromechanical properties. Among the various piezoelectric options, the lead zirconate titanate (PZT) material is the one studied in this work, and one of the most common in industry due to their large mechanical response to electric field.

The objective of this manuscript is to summarise the results of a gamma and proton irradiation tests performed on a piezoelectric actuator used for crystal positioning in Crystal Collimation at CERN. The results of the proton irradiation test were originally presented at RADECS 2019 [2]. The addition of two gamma irradiation test reinforce these initial results, providing a more complete understanding of the expected mixed field radiation effects on this and similar actuators, and enlarging the scope of the conclusions.

The associate editor coordinating the review of this manuscript and approving it for publication was Hui Xie.

The rest of the paper is organised as follows: the literature on radiation effects on piezoelectric materials is reviewed in section II, the Offline Gamma Test up to 10MGy is presented in section III, the Online Gamma Test up to 1MGy is presented in IV and the Online Proton Irradiation Test in section V. The general conclusions are summarised in section VI.

II. BACKGROUND

A. RADIATION ENVIRONMENT AT LHC

During normal operation of the Large Hadron Collider (LHC), a large variety of beam losses are produced generating a mixed and complex radiation environment. The origin and nature of this radiation differs significantly from point to point of the accelerator [3].

For example, in the vicinity of the interaction points (IR1 and IR5) the main source of losses is related to the particle collision debris (beam-to-beam interaction, usually proton-proton inelastic interactions which generate secondary particles). In addition, halo particles are caught in collimators close to the experiments and generate hadronic and electromagnetic showers that contribute to the radiation production. This particular effect is dominant in the beam cleaning insertions (IR3 and IR7) where the crystal collimators are located, whereas in the arcs, the predominant effect is the production of losses due to beam-gas interaction [4].

B. RADIATION EFFECTS ON PIEZOELECTRIC MATERIALS

Despite the large number of applications where the piezoelectric materials are used in industry, there are few cases where piezoactuators have to withstand harsh environmental conditions similar to particle accelerators (in terms of UHV compatibility and mixed field radiation).

For this reason, the literature about the radiation effects on piezoelectric materials is limited and the use of piezoelectric material in the studies that do exist not always coincide with the use in the considered application.

An example of a piezoelectric material application can be found in the ultrasonic transducers employed in nuclear plants, where substantial radiation fields are present. The literature survey presented in [5] summarises the different radiation endurance tests performed in recent years on this type of transducer under cumulative gamma dose and neutron fluence.

For the particular case of PZT materials, the results for gamma radiation in [6] show reliable operation after doses of 1.5 MGy and [7], [8] present an ionization damage threshold of approximately 400 MGy with low temperature and neutron fluence. In the case of neutron radiation, the results in [9] show minor degradation in thin films up to 1.5×10^{15} n/cm^2 or the drop in response amplitude presented in [6].

Another application of piezoactuators is when operating in an oscillating mode for adjusting and controlling the fundamental resonant mode in superconducting radio frequency (SRF) cavities. Initially in [10] and later in [11], piezoactuators from three different manufacturers were irradiated with fast neutrons at liquid helium temperature at the CERI cyclotron. The results of the test show no major damage in the piezo samples up to 7×10^{14} n/cm^2 but slight performance degradation in terms of loss factor increase ($5 - 10\%$).

A more recent radiation test for the same application was presented in [12] with accumulated dose levels up to 5 MGy with a gamma source ^{60}Co. The irradiated samples presented a stroke reduction of less than 10% which was considered acceptable for the requirements of that application.

In the field of non-volatile memories, piezoelectric materials (mainly PZT) are used as ferroelectric memories (FeRAMs). The results for the ionising radiation response are summarised in [13].

In [14], the authors study the irradiation effects on an acoustic sensor using a piezoelectric transducer. Two sensors were irradiated with a neutron fluence of 3.16×10^{19} n/cm^2 and a gamma dose up to 0.25 MGy.

Other studies focused on the radiation effects on bulk material, as in [15], [16], or [6], where the reliability of PZT piezoelectric cells was proven for gamma irradiation up to 1.5 MGy and thermal neutron irradiation up 1.6×10^{21} n/cm^2, with variations in the resonance frequency generally less than 1%.

Similarly, in [17] the authors study the effects on soft and hard PZT materials of neutron irradiation up to 1×10^{19} n/cm^2. These results show how the electromechanical coupling factor, the dielectric permittivity and the loss factor decreased by 30%, 70% and 50% respectively, with defects in the material produced mainly, but not exclusively, by oxygen vacancy creation.

Various summary tables can be found in [5], where the results for other piezoelectric materials apart from PZT are also reviewed. The general trend from these test is a change of properties but not a complete failure.

C. PROPOSED IRRADIATION TESTS

The previous literature review provides an overall picture of what to expect in terms of radiation effects on piezoelectric materials, but the actual performance degradation, or even complete failure, of a specific actuator assembly has to be individually studied under the conditions foreseen during its operation.

For this reason, three different tests are proposed for these piezoelectric actuators: an Offline Gamma irradiation test up to 10 MGy, an Online Gamma irradiation test up to 1 MGy and a Online Proton irradiation test up to 2 MGy.

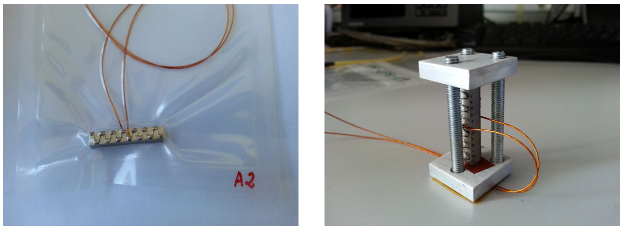
The targeted accumulated doses are selected as a trade-off between the desired dose levels and the total irradiation time in the Gamma tests. In addition, the final activation of the DUTs is also considered for the Proton test.

The objective of the gamma irradiation tests is to evaluate the Total Ionizing Dose (TID) effects on the actuator, whereas the proton irradiation test will allow the analysis of potential Displacement Damage (DD) effects. Although no SEE damage is initially expected due to the lack of particularly sensitive zones like silicon layers, the SEE possibility cannot be completely discarded since a failure in any insulating layer can lead to the total failure of the device for example, and therefore SEE could be detected during the three proposed tests.

It is important to remember that crystal collimators in IR7 of the LHC have an estimated total accumulated dose of 10 MGy mixed field during their lifetime of 10 years. The accumulated dose of the tests was selected as a trade-off between the expected total dose of the device in operation, the exposure time and cost. In the case of proton irradiation, the activation of the samples after the test was also considered.

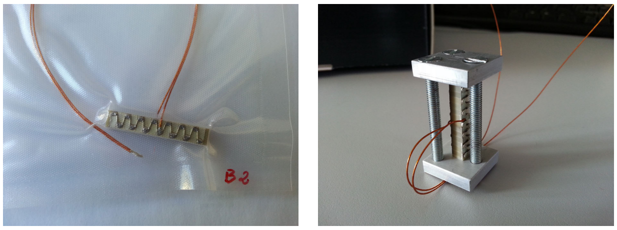
The devices under test (DUT) are stack actuators belonging to two different batches labelled as Type A and Type B. The main difference between both batches is the use of glue (Ceramabond 569) between the piezo actuator blocks in the Type B, whereas in the Type A the blocks are held only by the electrical bus wires and solder on the side of the stack, without additional glue. The general specifications of the DUTs are:

- Manufacturer: Noliac.
- Model: NAC2013-H30-C09 (NCE51F).
- Nominal stroke [Voltage range]: $42\mu m \quad [0 - 150V]$



(a) Piezo stack actuator without glue between the blocks. (b) Actuator mounted in the support with kapton pads for electrical insulation.

FIGURE 1. Type-A Piezo stack actuator.



(a) Piezo stack actuator with glue between the blocks. (b) Actuator mounted in the support (no need of kapton pads because it includes ceramic insulating tiles glued in each end).

FIGURE 2. Type-B Piezo stack actuator.

- Piezo stack volume: $5 \times 5 \times 28\ mm^3$.
- Kapton wiring (for radiation environments).
- The sensitive volume is the piezo stack ($5 \times 5 \times 28\ mm^3$ volume, not including cabling and solder).
- High melting point solder (Lead (Pb) 93.5%, Tin (Sn) 5%, Silver (Ag) 1.5% - Melting Point $296 - 301°C$).

The reason to evaluate two different batches is to understand if the presence of glue between blocks, which facilitates the handling of the stack during the mounting process of the actuator in the rotational stage, would present any additional advantage or problem when exposed to ionising radiation.

III. GAMMA IRRADIATION TESTS - OFFLINE - 10MGY ACCUMULATED DOSE

A. DESCRIPTION

This offline test consists of the irradiation of 24 piezo stack actuators up to 10 MGy accumulated dose at BGS Facility of Fraunhofer Institute, Germany, with gamma irradiation source Co-60L. The term "offline" of the test makes reference to the lack of measurements during the irradiation period, so all the characterisation of the devices under test (DUT) will be performed before and after the irradiation period or at the programmed stops.

The DUTs in this test are 26 piezo stack actuators (24 irradiated and 2 control samples) of which 13 of them are of Type A and 13 of them of Type B.

The DUTs were mounted in mechanical holders to maintain a constant pressure on them during the irradiation as can be seen in Figures 1(b) and 2(b).

TABLE 1. Gamma irradiation test at Fraunhofer Institute - Offline Test - Irradiation conditions.

Number of samples	26
Irradiated samples	24
Control samples	2
Radiation source	^{60}Co
Max. Accumulate dose	10 MGy (air)
Dose steps	1, 4, 10 MGy (air)
Dose rate	7.7 to 9.0 kGy(air)/h
Start of irradiation	02-03-2017
Stop of irradiation	22-06-2017
Irradiation temperature	$< 50°C$

This offline test was performed by Fraunhofer Institute of Technological Trend Analysis (INT) in March-June 2017 (113 days in total). The irradiation took place at Beta-Gamma-Service (BGS) in Whiehl, Germany, with a ^{60}Co gamma radiation source. The irradiation conditions are summarised in Table 1.

B. MEASUREMENTS AND SETUP

A full characterization of every DUT was performed at CERN before and after the irradiation test. This characterisation included the following tests (equipment specified in brackets):

1) Leakage current at 5V and 150V (Keithley 2410 Source Measurement Unit (SMU)).
2) Impedance analysis (Cypher Instruments C60 impedance analyser).
3) Stroke test (Piezoactuator Characterisation Testbench at CERN to measure mechanical stroke and hysteresis).

During this characterisation, the temperature of the laboratory was maintained at $25°C$ ($\pm 1°C$).

The irradiation test was stopped at the TID steps of 0, 1, 4 and 10 MGy. In each stop, the following measurements were performed in each DUT at the irradiation facility (equipment specified in brackets):

1) Picture.
2) Temperature of the piezo (Fraunhofer temperature sensor).
3) Leakage current Test (Keithley 2410 SMU).
4) Impedance analysis test (Cypher Instruments C60 impedance analyser from 1kHz to 1MHz).

After each irradiation stop and corresponding measurements, four samples of each batch were sent back to CERN for their final characterisation. The accumulated dose of each DUT is presented in Table 2.

For the setup of the test, the DUTs were fixed with aluminium tape onto two trays as shown in Figure 3(a). These trays were placed in one aluminium basket, shown in Figure 3(b), that was grouped with other samples onto a palette.

Care was taken to leave the DUTs exposed to fresh air to prevent the generation of ozone. In the final application, the actuators will operate under UHV conditions and

TABLE 2. Gamma irradiation test at Fraunhofer Institute - Offline Test - DUT accumulated dose distribution.

Offline Test		
	Type A	Type B
Accumulated dose (TID) [MGy]	Piezo stack ID	Piezo stack ID
1	A1	B1
	A2	B2
	A3	B3
	A5	B5
4	A6	B6
	A7	B7
	A9	B9
	A10	B10
10	A11	B11
	A12	B12
	A16 (15-074)	B16 (15-074)
	A17 (15-074)	B17 (15-074)
0 (Control samples)	A13	B13

(a) DUTs mounted onto the trays for irradiation. (b) Ventilated box with DUT trays.

FIGURE 3. Irradiation setup.

therefore no risk of ozone accumulation is expected. The final palette was mounted on a conveyor belt that circulates around the radioactive source until the desired accumulated dose is reached.

C. RESULTS

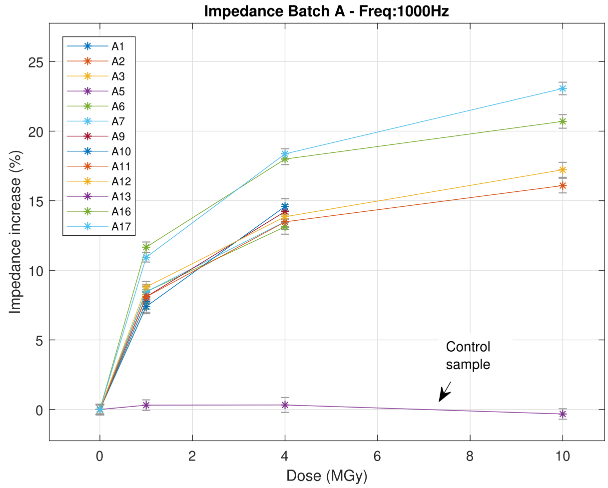
The impedance of each DUT was measured at every irradiation stop (0, 1, 4 and 10 MGy) with a Cypher Impedance Analyser that measures the impedance from 1kHz to 1MHz.

The impedance module results at 1kHz are presented in figures 4(a) and 4(b), with similar values to the results obtained at 2kHz.

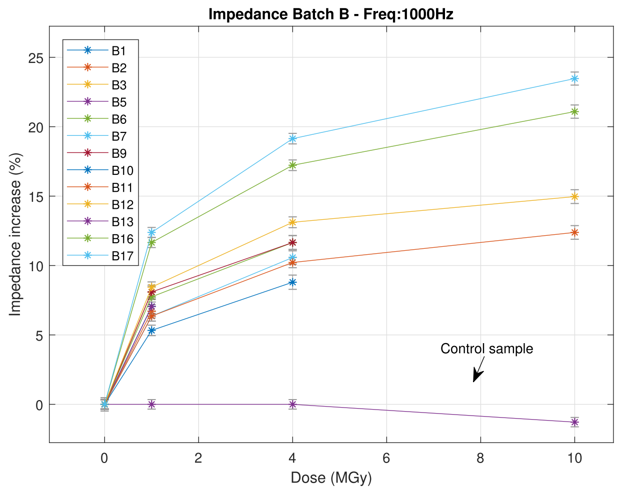
The total stroke of the DUT was measured before and after the irradiation period in the in-house piezoactuator characterisation testbench. The stroke differences are summarised in Figures 5 (Batch A) and 6 (Batch B) with the pre-irradiation range of all DUTs corrected according to the average variation of the corresponding control sample.

The results show how all the DUT were operational after the irradiation period. It is important to remark that the number of samples at each radiation dose is only four and, therefore, the statistical value of conclusions is limited. However, it is clear how all DUTs presented similar strokes after the irradiation period, with an averaged stroke reduction that never exceeded 20% even at 10MGy accumulated dose.

Besides the total stroke, it is also interesting to evaluate the radiation effect on the shape of the hysteresis loop, as is suggested by some literature.



(a) Batch A.



(b) Batch B.

FIGURE 4. Impedance results at 1kHz. A13 and B13 are the control samples.

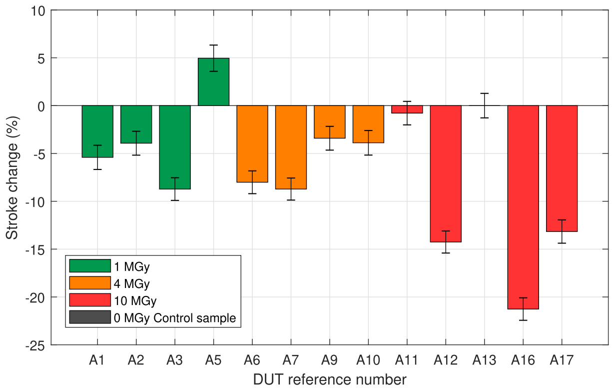
The obtained results present no clear trend in terms of maximum hysteresis value nor total area change. However, the increase in the voltage where the maximum hysteresis is achieved with respect to the accumulated dose is noticeable, as can be seen in Figures 7(a) and 7(b).

D. CONCLUSION

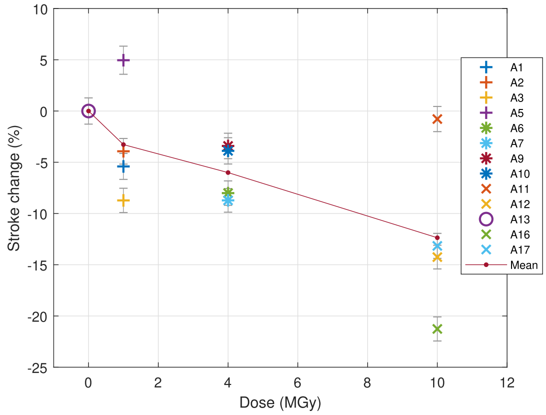
The irradiation test was performed on 13 piezo samples of each type (non-glued and glued stacks) with a ^{60}Co gamma source. In addition to the irradiated samples, 1 extra sample of each batch was placed in a radiation-free area for control purposes (in this case, sample number 13)

The samples were extracted from the irradiation zone at three different accumulated doses of 1, 4 and 10 MGy. According to the different tests and results presented in the previous sections, the main conclusions are:

- The impedance modulus clearly increased in the irradiated DUTs with respect to the control ones, with a maximum impedance increase of $< 25\%$ at 10MGy and similar results between batch A and B.

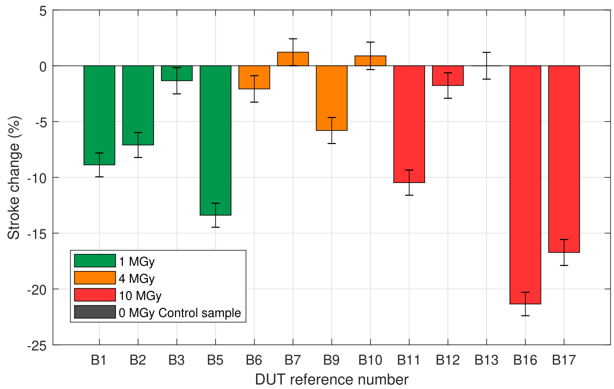


(a) Change of total stroke.

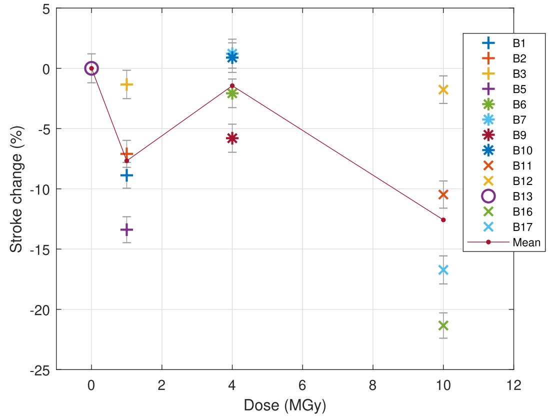


(b) Change of total stroke (in %) vs dose.

FIGURE 5. Batch A - Stroke test results comparing before and after the offline gamma irradiation.



(a) Change of total stroke.



(b) Change of total stroke (in %) vs dose.

FIGURE 6. Batch B - Stroke test results comparing before and after the offline gamma irradiation.

- All samples were fully operative after the irradiation period. However, the results showed reduction of the stroke with the accumulated dose. The maximum stroke loss was $<$ 22% in all cases and the results at 10MGy.
- Apart from the stroke reduction, the results suggest a radiation effect on the shape of the hysteresis loop. The most significant variation is in the voltage where the maximum hysteresis percentage is achieved, experiencing a shift towards higher values with a maximum averaged increase of 12.8 V at 10 MGy in Batch A and Batch B.

IV. GAMMA IRRADIATION TEST - ONLINE - 1MGY ACCUMULATED DOSE

A. DESCRIPTION

This online test consists of the gamma irradiation of 4 piezo stack actuators (2x Type A and 2x Type B) up to 1 MGy accumulated dose at Fraunhofer Institute for Technological Trend Analysis INT, Germany. The term "online" refers to the monitoring via online measurements performed during the irradiation period, in addition to the characterisation tests before and after the irradiation period.

The objective of the test is the study of the gamma radiation effect on the piezoactuators and, unlike the offline test presented in section III, the online measurements can provide a better understanding of the actuator evolution during and immediately after the irradiation period.

The DUTs have the same specifications as the ones presented in section II-C, with 8 piezo stack actuators belonging to batches A (4 samples) and B (4 samples). As mentioned before, the batches differ in the presence of glue between the piezoelectric blocks in batch B.

The DUTs were mounted in a similar mechanical holders as in the offline test as shown in Figure 1(b) or Figure 8(b) for the irradiated samples.

The irradiation conditions are summarised in Table 3.

TABLE 3. Gamma irradiation test at Fraunhofer Institute - Online Test - Irradiation conditions.

Number of samples	8
Irradiated samples	4
Control samples	2 + 2
Radiation source	^{60}Co
Max. Accumulate dose	1210 kGy (air)
Dose steps	One single step
Dose rate	0.4005 Gy(air)/h
Start of irradiation	14-12-2016 9:00
Stop of irradiation	18-01-2017 8:52
Irradiation temperature	$22° \pm 1.2°C$

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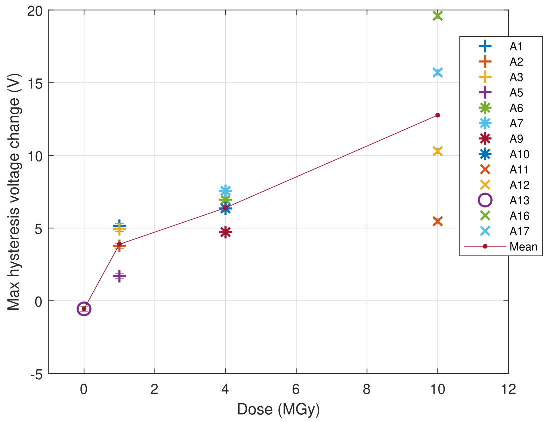
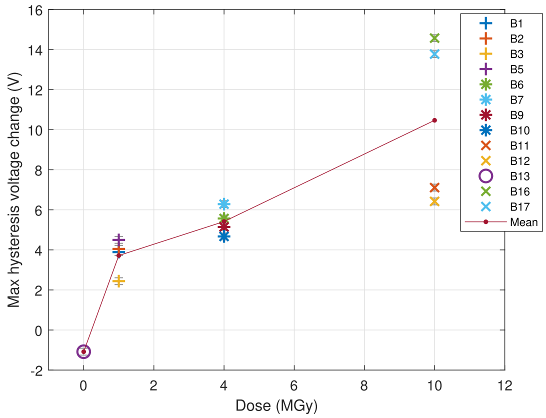


(a) Batch A - Change in voltage for maximum hysteresis vs dose.



(b) Batch B - Change in voltage for maximum hysteresis vs dose.

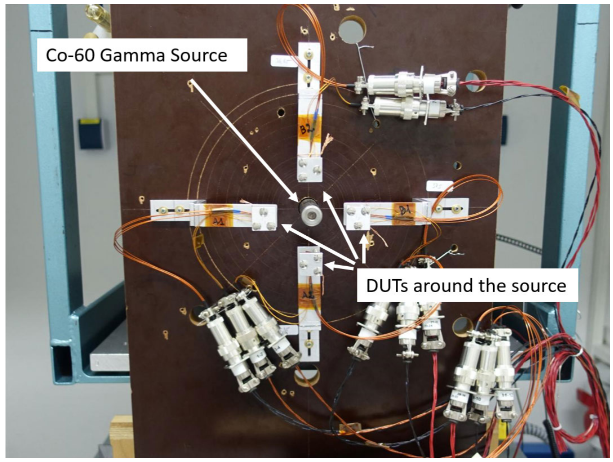
FIGURE 7. Hysteresis results comparing before and after the irradiation.

B. MEASUREMENTS AND SETUP

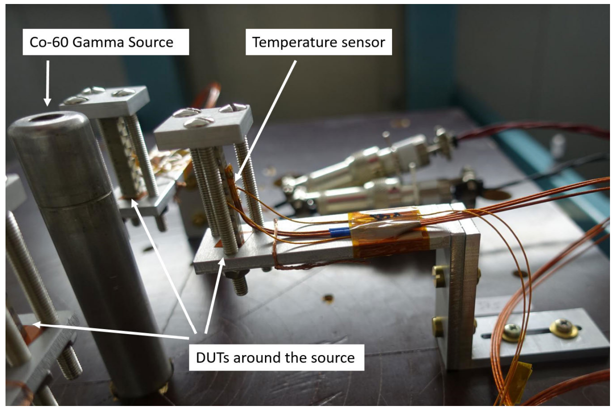
According to the radiation facility options, it was decided to distribute the DUTs in three different areas:

1) Radiation zone: The DUTs were arranged equidistantly and aligned around the radiation source, as shown in Figure 8. In this distribution, the piezo stacks were irradiated from one of their sides, maximizing the dose rate and homogeneity along the length. It is important to remark that the irradiated piezo stacks were maintained in the open air and not enclosed in a container.
2) Low-radiation zone: The control samples in this area were placed on a table in open air and not enclosed in a container, as can be seen in Figure 9(a).
3) No-radiation zone: The control samples in this area are shown in figure 9(b). They were under the same temperature conditions as the irradiated piezos, keeping them also in the open air and not enclosed in a container.

The no-radiation zone consisted of a separated climatic chamber following the temperature of radiation zone, but no humidity control was possible. For this reason, the low-radiation zone was included since it was in the same enclosure as the radiation zone.



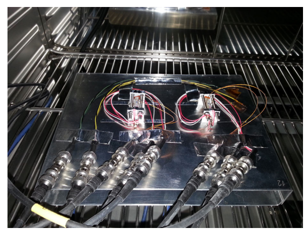
(a) Front view of the four DUTs around the source in the center.



(b) Zoom of the DUT holders.

FIGURE 8. DUTs mounted around ^{60}Co Gamma source in the radiation zone.

(a) Low-radiation zone.



(b) No-radiation zone.

FIGURE 9. Non irradiated DUTs in their respective zones.

The initial and final characterization of every DUT was performed similarly to the measurement description presented in section III-B.

In addition to the previous characterisation, three different measurements were performed online during the irradiation period on each sample:

1) The temperature, by means of a temperature sensor attached to the stack.
2) The leakage current test at 5V.
3) The impedance, by means of an impedance analyser.

For this purpose, the setup presented in Figure 10 was deployed in the irradiation facility.

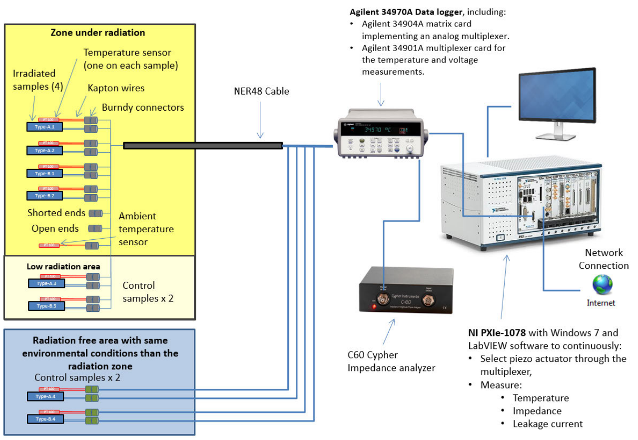


FIGURE 10. **Online Gamma test setup with the DUT distribution in the different zones.**

A custom LabVIEW program ran the measurements continuously and saved the data locally and on the network storage.

The use of long cables for the connection of the DUT in the different areas imply that the impedance test results include not only the DUT, but the effect of the cables. For this reason, additional ''open'' and ''shorted'' cables were included in each region with the purpose of compensating for the corresponding cable characteristics (using the Nominal T-Model).

C. RESULTS

The radiation period took place during 36 days to reach the targeted 1 MGy accumulated dose at Fraunhofer Institute for Technological Trend Analysis INT, Germany.

1) ONLINE MEASUREMENTS

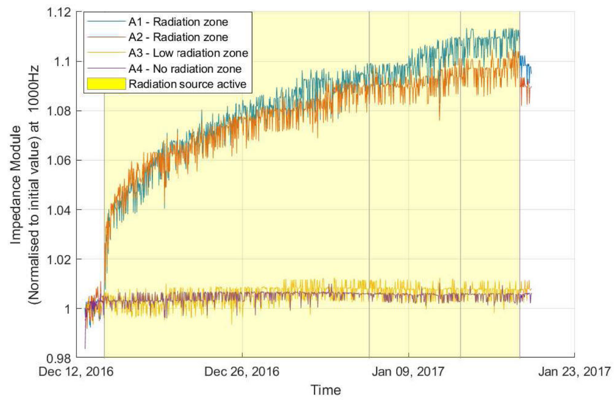
The temperature, which was monitored in every DUT over the full irradiation period, was maintained always within the range $[20, 22]°C$ with a maximum temperature variation of $\pm 1.2°C$ in each DUT.

The impedance results at 1 kHz are presented in Figures 11(a) and 11(b) for the Batch A and B respectively. It can be concluded that there is an initial step increase in the impedance modulus, which could be related not only to the radiation effect but to the internal temperature increase. After this step, the impedance continues increasing until the end of the irradiation period with maximum values of $< 12\%$ in all irradiated cases. At the end of the irradiation period there is a slight reduction of the impedance due to temperature decrease.

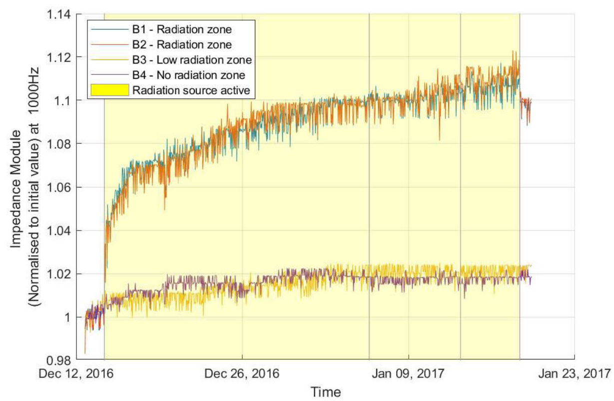
The results for the leakage current test showed nominal values ($< 50\mu A$) along the whole irradiation period, suggesting the correct operation of all DUTs.

2) OFFLINE MEASUREMENTS

The same DUT characterisation was performed before and after the irradiation period for comparison.



(a) Batch A - Impedance vs time.



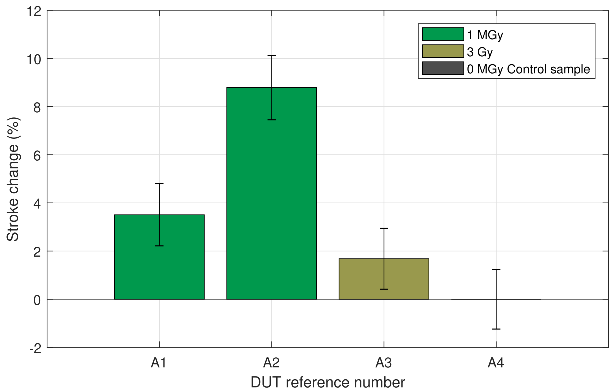
(b) Batch B - Impedance vs time.

FIGURE 11. **Impedance results at 1kHz. (a) Batch A - Impedance vs time. (b) Batch B - Impedance vs time.**

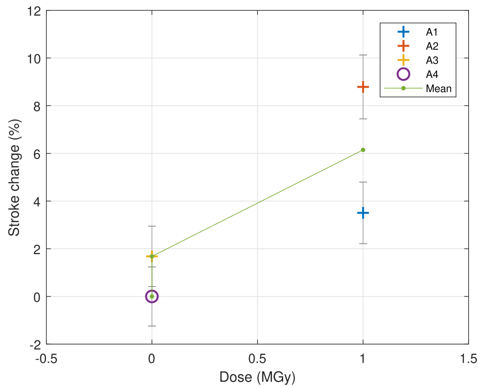
The results for the stroke test are presented in Figures 12 and 13, for batch A and B respectively, with the pre-irradiation range of all DUTs corrected according to the average variation of their corresponding control sample from the no radiation zone. Unlike the results of the 10MGy offline test where the stroke was slightly reduced, in this occasion the total displacement achieved after the irradiation period increased in both batches, with higher expansion in the batch B reaching the 19.7% in one of the DUTs. In all cases, the irradiated samples present a higher increase with respect to the control samples, which suggest that the stroke change is related to the radiation effect on the piezoactuator and not due to other external factors.

The shape of the hysteresis loop is analysed before and after the irradiation period. The maximum hysteresis value (maximum difference in the hysteresis loop) is summarised in Figures 14(a) (Batch A) and 14(b) (Batch B). The voltage at which this maximum difference occurs is shown in Figures 15(a) (Batch A) and 15(b) (Batch B). Finally, the results for the change in the total area of the hysteresis loop are presented in Figure 16(a) and 16(b) for Batch A and B respectively.

According to these results, it can be concluded that the radiation has a clear effect on the shape of the hysteresis loop,

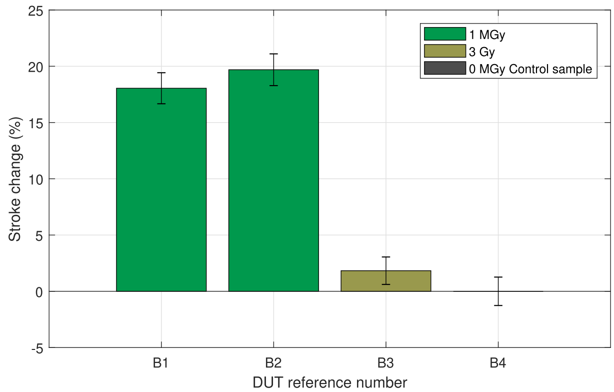


(a) Change of total stroke.

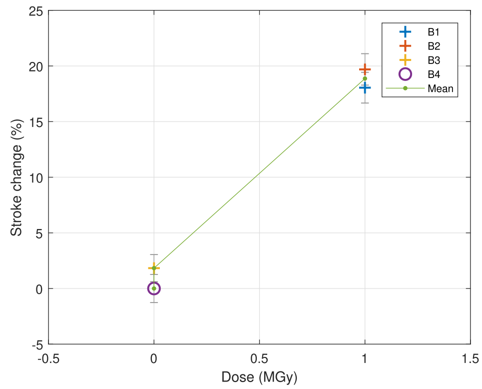


(b) Change of total stroke (in %) vs dose.

FIGURE 12. **Batch A - Stroke test results comparing before and after the online gamma irradiation.**



(a) Change of total stroke.



(b) Change of total stroke (in %) vs dose.

FIGURE 13. **Batch B - Stroke test results comparing before and after the online gamma irradiation.**

with an increase of the voltage where the maximum hysteresis occurs. On the contrary, the control samples presented nearly identical hysteresis shapes, as expected, before and after the irradiation period.

D. CONCLUSION

The online irradiation test was performed on 2 piezo samples of each type (non-glued and glued stacks) with a ^{60}Co gamma source. In addition to the irradiated samples, control samples of each batch were placed in a low-radiation area and a radiation-free area (4 control samples in total).

Apart from the initial and final characterisation of the DUT, the samples were measured remotely (temperature, leakage current and impedance) during the irradiation period.

The samples in the radiation zone show a clear general increase (10% approx.) in the whole impedance response with respect to the control samples in the low and no-radiation zone. At the end of the test (1.2 MGy accumulated dose) the maximum increase remained in all cases under 12% with respect to their initial value.

Furthermore, the stroke test after the irradiation period confirmed resistance of the DUTs to the 1MGy gamma accumulated dose, showing even an increase in the stroke of the irradiated DUTs, with a maximum of +19.7% in one of the samples.

The analysis of hysteresis loops suggest a slight increase in the maximum hysteresis percentage (with a maximum increase of +3.4% obtained in B2) as well as in the voltage where this maximum hysteresis occurs (with a maximum increase of +2.1V also in B2).

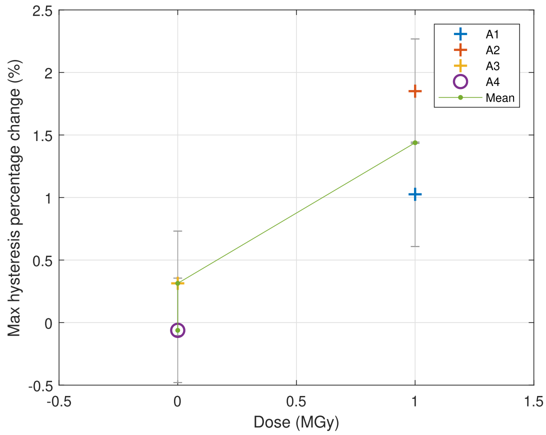
V. PROTON IRRADIATION TEST - ONLINE TEST - 2 MGY ACCUMULATED DOSE

A. DESCRIPTION

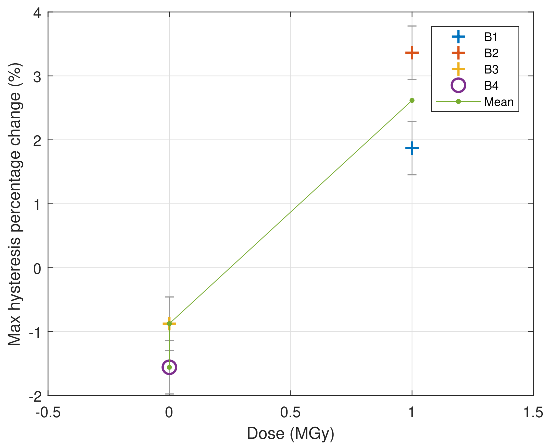
Before the installation of the first piezoactuated goniometers at CERN in 2012, a test with proton irradiation was performed in the PIF facility at PSI up to 150 kGy (PIF beam energy ranges from 74 MeV to 230 MeV). This low dose was not sufficient to correctly assess any potential displacement damage (DD).

For this reason a new irradiation test, up to 2 MGy accumulated dose and 1.14×10^{16} p/cm^2 fluence, was foreseen to run at the IRRAD Proton Facility [18] at CERN. The purpose of the test was to evaluate potential DD on the actuators under conditions similar to the accelerator environment. The test was originally presented at RADECS 2019 [2] and it is also included in this section as a part of the whole irradiation study.

The 2 MGy accumulated dose of this test was chosen as a trade-off between expected lifetime dose of 10 MGy, irradiation time constraints and post-irradiation activation limits.

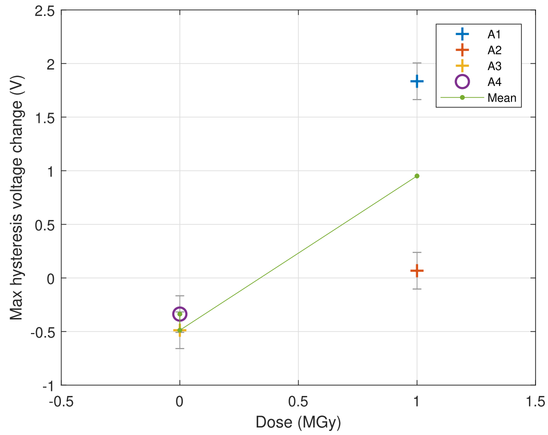


(a) Batch A - Change in the maximum hysteresis value vs dose.

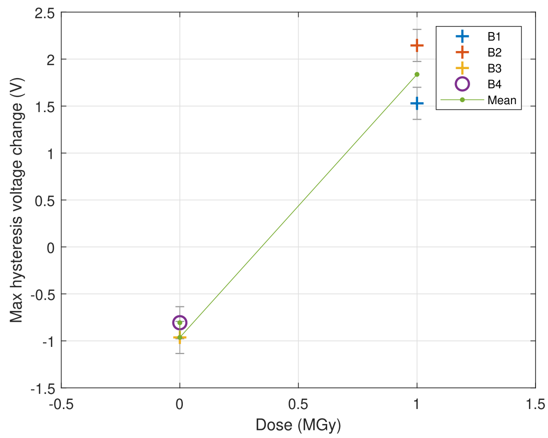


(b) Batch B - Change in the maximum hysteresis value vs dose.

FIGURE 14. Maximum hysteresis variation.



(a) Batch A - Change in voltage for maximum hysteresis vs dose.



(b) Batch B - Change in voltage for maximum hysteresis vs dose.

FIGURE 15. Voltage for maximum hysteresis variation.

The devices under test are 8 piezo stack actuators, 6 of them in the radiation area and 2 control samples. The specifications of the DUT are the same as in section II-C, but in this case only non-glued DUTs are studied.

Figures 17(b) and 17(c) show an example of the DUT mounted in a custom-designed support that holds and positions the actuator in the beam axis. The blocks holding the DUT are made of polycarbonate (PC) in order to avoid any metallic parts in the beam path, which would be highly activated after the test and would cause additional downstream beam distortion.

The IRRAD proton beam has a section of 12 mm diameter and therefore the DUTs are positioned with a 75.17° angle with respect to the beam axis as shown in Figure 17(a). In this orientation, the dose is spread along the whole DUT volume and the effective "thickness" seen by the protons crossing the material will be minimised.

Unlike gamma irradiation, which is generally produced by an isotropic source that irradiates continuously (like the ^{60}Co source), the proton irradiation is generated by accelerated protons. In the case of the IRRAD Facility, this acceleration is achieved at the Proton-Synchrotron (PS) accelerator at CERN achieving a momentum of 24 GeV/c. The primary proton beam at the PS is extracted from its ring and driven to the IRRAD facility (located on the T8 beam-line in the CERN PS East Hall).

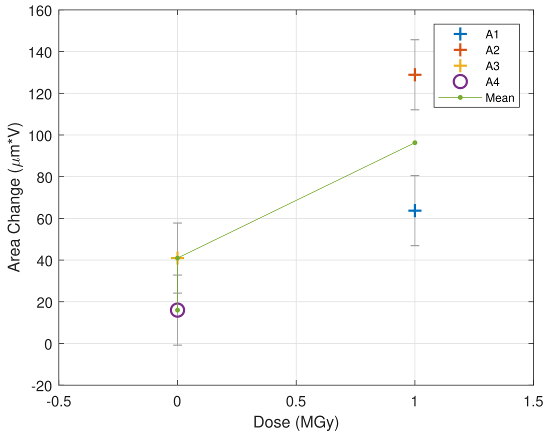
The proton beam arrives at the IRRAD facility in spills, whose frequency depends on the PS operation. For the weeks of operation of this test, the facility received an average of 1 spill of protons every 14 seconds.

The beam parameters used in this test are summarised as:

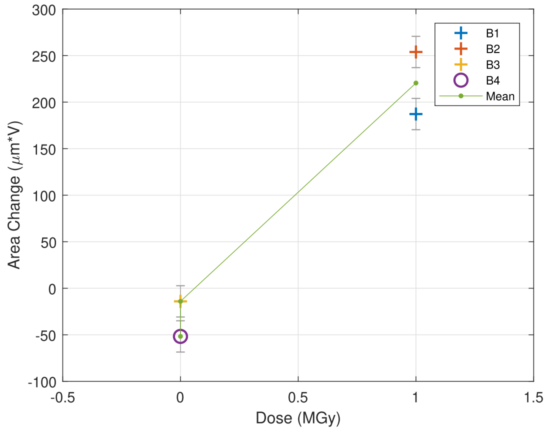
- Momentum of 24 GeV/c.
- Beam spot of $\sim$ 12 mm diameter with Gaussian profile (with optics FWHM and beam standard deviation of $\sigma =\sim 5$ mm).
- Protons delivered in spills of $\sim 5 \times 10^{11}$ p/spill at $\sim$ 14 s/spill.

The test started the 25th October 2018 and finished the 5th November 2018 (11 days duration) reaching an accumulated dose of 2 MGy and 1.14×10^{16} p/cm^2 fluence.

After the irradiation period, the DUTs were stored for a cool-down period of 3 months until their radioactivity was safe for the post-irradiation characterisation.

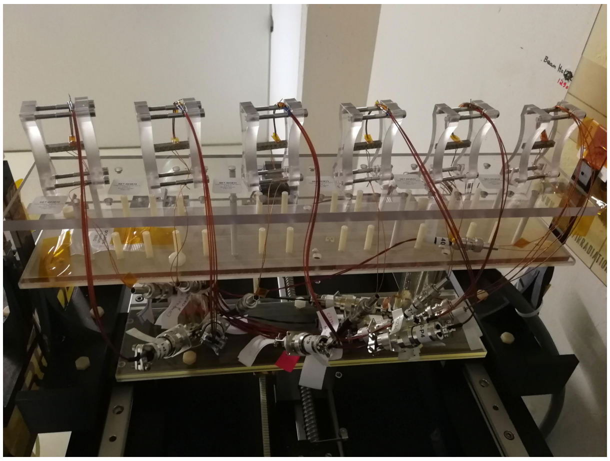


(a) Batch A - Change of hysteresis area vs dose.

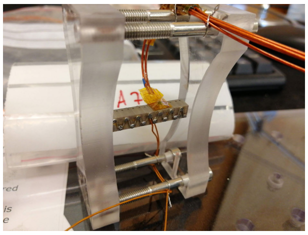


(b) Batch B - Change of hysteresis area vs dose.

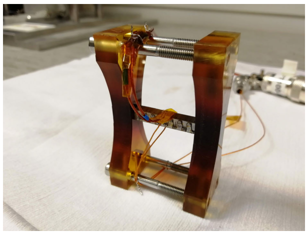
FIGURE 16. **Hysteresis area variation.**



(a) Table with DUTs pre-aligned and installed the beam line.



(b) DUT A7 - Before irradiation test. The temperature sensor is positioned at the surface of the DUT.



(c) DUT A7 - After irradiation test. Please note that PE material changes colour with radiation.

FIGURE 17. **DUT mounted in its support for the proton irradiation.**

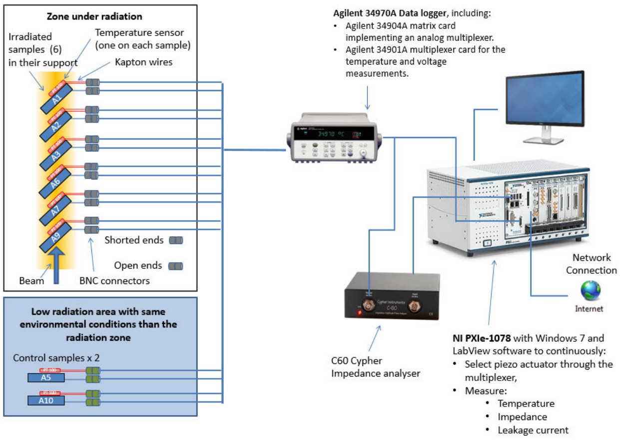


FIGURE 18. **Online Proton test setup.**

B. MEASUREMENTS AND SETUP

The measurements performed on the DUT during the different stages of the irradiation test can be divided into three groups according to the moment when the measurement takes place:

1) PRE-IRRADIATION CHARACTERISATION TESTS

A full characterization of the samples was performed in the laboratory before mounting them in their support for the radiation test. This characterisation included the following tests:

1) Leakage current at 5V and 150V (Keithley 2410 Source Measurement Unit (SMU)).
2) Impedance analysis (Cypher Instruments C60 impedance analyser).
3) Stroke test (CERN Piezoactuator Characterisation Testbench)

During this characterisation, the temperature of the laboratory was maintained at $25° \pm 1°$ C.

2) MEASUREMENTS DURING THE IRRADIATION TEST (ONLINE MEASUREMENT)

Figure 18 presents the test setup diagram for the irradiation test. It shows the electronic equipment involved in the measurements and the distribution of the DUT in the different zones. It is important to note that every DUT had a temperature sensor (PT100) and extra shorted and opened ends were included in the radiation zone for cable length compensation.

A custom program ran the measurements continuously and saved the data locally and on the network storage.

3) POST-IRRADIATION CHARACTERISATION TESTS

After the cool-down period, all DUTs were characterised with the same tests as at the initial characterisation described in V-B.1.

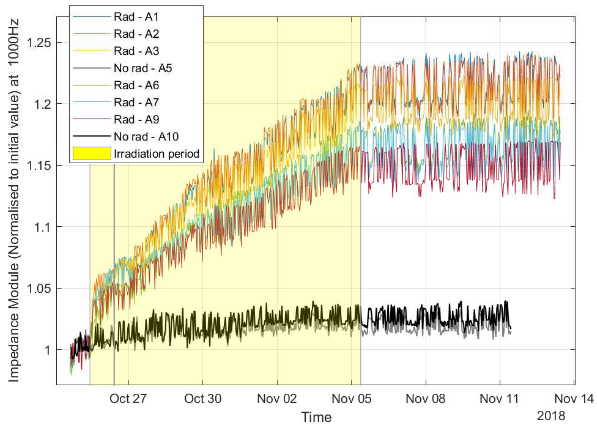


FIGURE 19. **Impedance response variation at 1kHz.**

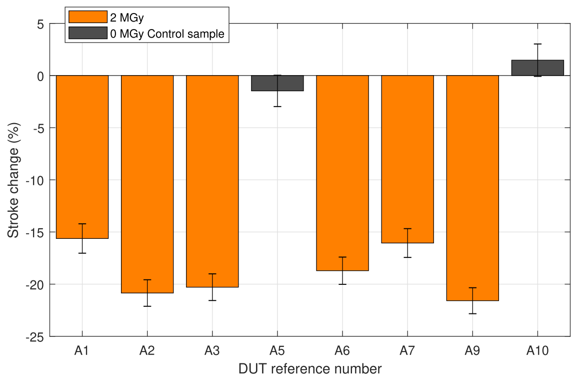


FIGURE 20. **Stroke variation.**

The testbench was transported to the IRRAD buffer area and the DUT characterisation was performed using lead-glass for personal radio-protection.

C. RESULTS

1) ONLINE MEASUREMENTS

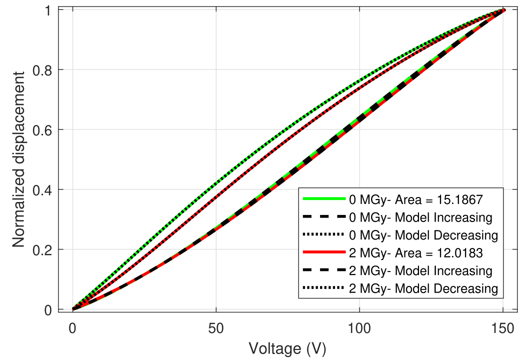
The temperature measured in each DUT remained always within 22.5° ± 2.5° C. The leakage current tests showed normal values during the whole irradiation period, with currents below 1 mA.

For case of the impedance analysis test, Fig 19 presents the 1kHz response evolution during the irradiation period. The impedance increased only on the irradiated samples, remaining under 25% in all cases for the final 2 MGy accumulated dose.

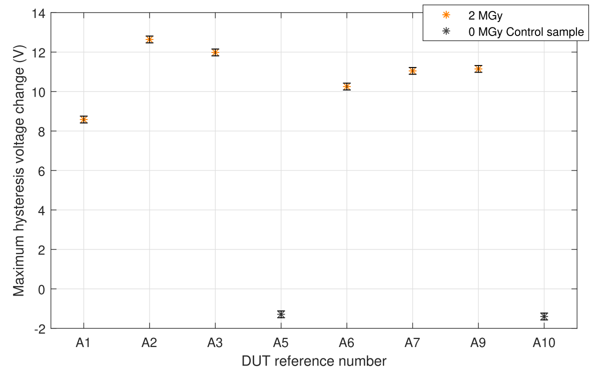
2) OFFLINE MEASUREMENTS

After the cool-down period, the activation level of the irradiated DUTs was 350 μSv/h at contact. The DUTs were dismounted from their holders and characterised. As shown in Fig 20, all DUTs presented a correct operation and the irradiated samples experienced a stroke reduction of $< 25\%$, with the pre-irradiation range of all DUTs corrected according to the average variation of the control samples.

The shape variation of the actuator hysteresis response, illustrated in Fig 21. This variation implies an increase of the voltage value at which the maximum hysteresis takes place as shown in Fig 21(b).



(a) DUT A9 - Example of hysteresis response.



(b) Maximum hysteresis voltage variation.

FIGURE 21. **Hysteresis shape variation.**

D. CONCLUSION

A total of 6 DUTs have been irradiated with protons up to 2 MGy with 1.14×10^{16} p/cm^2 fluence, with 2 control samples placed in a radiation free zone.

The online results have shown a continuous impedance increased along the irradiation exposure, with $< 25\%$ increase at the end of the test. The post-irradiation characterisation confirmed the operation of all DUTs, concluded in a stroke reduction of $< 25\%$ and a hysteresis shape change with an averaged maximum hysteresis voltage increase of 10.9V.

VI. GENERAL CONCLUSION

The state of the art of radiation effects on piezoelectric materials was reviewed. Despite the many studies, the specific material composition of the DUT, the irradiation specifications and the test conditions are, in most of the cases, very specific to the application under study, and therefore it is difficult to make a direct comparison between studies. For this reason, a custom irradiation test is necessary in order to take into account the specific material and irradiation conditions of the application at hand.

Three different irradiation tests were proposed and performed on piezoactuators used in the CERN Crystal collimators. The key objective was to study the resistance of the actuator to the mixed field radiation present in the LHC

TABLE 4. Summary of the results of the various test performed in the piezoactuator. The figures in brackets "()" correspond to the averaged values and the lines in correspond to the results for the Batch B (glued stack).

Test	Dose (MGy)	Max. Impedance variation (at 1kHz)	Max. Stroke variation	Max. Hysteresis Voltage variation
Gamma (Offline)	10	<+25% <+25%	-21.2% (-12.4%) -21.3% (-12.6%)	+19.6V (+12.8V) +14.6V (+10.5V)
Gamma (Online)	1	<+12% <+12%	+8.8% (+6.1%) +19.7% (+18.9%)	+1.8V (+1.0V) +2.1V (+1.8V)
Proton (Online)	2	<+25%	-21.6% (-18.8%)	+12.6V (+10.9V)

tunnel, where they are expected to receive 10 MGy accumulated dose in 10 years of operation, the desired lifetime.

The proposed tests were: Gamma irradiation test up to 10 MGy (Offline Test), Gamma irradiation test up to 1 MGy (Online Test) and Proton Irradiation test up to 2 MGy (Online Test). The purpose of the gamma irradiation tests was the evaluation of TID effects on the actuator, whereas the proton irradiation test allowed the analysis of potential DD damage.

The Table 4 summarises the results for the three tests at their final accumulated dose. The results for the impedance and maximum hysteresis voltage variation are consistent between them, with maximum increases of less than 25% and 19.6V respectively in all cases.

The positive sign of the stroke variation in the Gamma Online Test (1MGy) contrasts with the results for the Gamma Offline Test (10 MGy) and Proton Online Test (2 MGy), where the stroke is reduced. Although a stroke increase is not harmful for this application, this result is clearly unexpected and it could be produced due to untracked changes in the DUT (different humidity with respect to the control samples) or mechanical changes in the testbench. Further investigation should be performed to motivate this stroke increase. From the final application point of view, the stroke reduction is the key effect threatening the correct operation of the device and therefore, the worst case scenario is represented by the results of the Gamma Offline Test (10 MGy) and Proton Online Test (2 MGy).

Considering the presented results, it can be concluded that the studied piezoelectric actuator is acceptable for use in mixed field environments up to 10 MGy such as the CERN crystal collimators. All irradiated samples were operational after their corresponding tests and the radiation-induced effects, in terms of impedance increase and stroke variation, can be acceptable. Closed loop control of the final application can compensate for the impedance increase or hysteresis variation, and the consequences of a potential stroke reduction can be mitigated by considering this reduction in the system design process.

Future lines of research include the structural analysis of the DUTs to identify radiation-induced effects in the material that can motivate the observed stroke reduction and the modelling of these radiation induced effects.

ACKNOWLEDGMENT

The authors would like to thank Dr. F. Ravotti and Mr. G. Pezzullo from IRRAD Team for their help with the setup, and Mr. Í. Lamas and Mr. J. Maestre for their temperature simulation.

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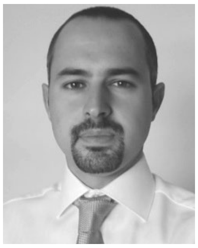

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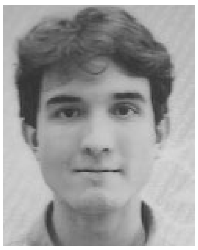

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