

Tests on the prototype of the Optical Hinge for the Wide Angle Viewing System to ITER gamma radiation conditions

R. Carrasco^{a,*}, F. Lapayese^a, A. de la Peña^a, M. Medrano^a, F. Mota^a, A. Soletto^a, A. Pereira^a, C. Pastor^a, C. Rodríguez^a, E. Rincón^a, S. Cabrera^a, A. Fernández^a, F. Ramos^a, V. Queral^a, L. Letellier^b, F. Le Guern^c, J.J. Piqueras^c

^a CIEMAT, Laboratorio Nacional de Fusión, Avda. Complutense 40, Madrid 28040, Spain

^b CEA, IRFM, Saint-Paul-Lez-Durance F-13108, France

^c F4E, Josep Pla 2, Torres Diagonal Litoral B3, Barcelona 08019, Spain

ARTICLE INFO

Keywords:

ITER
WAVS
Diagnostics
Piezo actuator

ABSTRACT

The Wide Angle Viewing System (WAVS) for ITER is a major diagnostic for machine protection, plasma control and physics analysis. The diagnostic will measure the surface temperature of the plasma facing components by infrared thermography being one of its main roles to protect them from damage. It will also image the plasma emission in the visible range. The full system is composed of 15 lines of sights located in four equatorial ports (3, 9, 12 and 17).

As part of the ex-vessel optics, the first element of the optical chain is the Optical Hinge (OH). It is constituted by two folding mirrors which face the port plug exit optical beam. The mission of this component is to compensate the differential motion between the vacuum vessel and the building, during normal operation and baking. This function will be performed by means of a piezo actuator coupled to the OH upper mirror (and a set of reference switches) to drive the vertical displacement of the mirror in order to get the desired alignment position of the optical beam. The piezo actuator has been identified as the main critical item of the OH what has motivated the fabrication of an OH prototype (for one line of sight) aimed at performing a set of tests to validate the piezo actuator under operation conditions. The tests have consisted in the characterization of the piezo actuator behavior with the nominal load after being irradiated to 272.40 kGy of total accumulated gamma dose, which is the dose expected in ITER. Moreover, additional tests have been conducted to find out the influence of the cable length from the piezo actuator to the controller in the performance. A description of these tests and the results obtained will be presented in the paper.

1. Introduction

The ITER Equatorial Port Visible/Infrared Wide Angle Viewing System (WAVS) comprises viewing systems in four equatorial ports #3, #9, #12 and #17. Three of these ports implement four views. Three views of, respectively, the upper target, and the tangentially left and right views, and a view of the divertor. Only the EP #12 does not implement the upper target view [1].

The ultimate aim of this diagnostic is to support the operation of the tokamak by providing visible and infrared viewing and temperature data from plasma facing components to protect them from damage.

This diagnostic is designed for carrying the infrared and visible light from the port plug to the cameras situated in the port cell through a long

optical path. Each of the optical components (mirrors, lenses...) will be mounted in the port plug, the interspace and the port cell areas, minimizing alignment errors, so that the camera receives adequate quality images.

It has been necessary the implementation of an optomechanical system to compensate for the relative movements between the Vacuum Vessel (VV) and the Interspace (IS) due to the thermal expansion produced during the plasma operation (the temperature of the VV will be up to 100 °C) and baking process (up to 200 °C). The angular displacement of the Vacuum Vessel is not considered to be compensated (disruptions, etc.)

Thus, the first element of the optical chain is the Optical Hinge (OH), formed by two folding mirrors, which face the port plug exit optical

* Corresponding author.

E-mail address: ricardo.carrasco@ciemat.es (R. Carrasco).

<https://doi.org/10.1016/j.fusengdes.2023.113680>

Received 28 October 2022; Received in revised form 16 February 2023; Accepted 17 March 2023

Available online 27 March 2023

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beam, to compensate these thermal displacements of the Port Plug (PP) with respect to the IS [2]. An active alignment control system associated to the Optical Hinge has been introduced to correct possible image defocusing and decentering caused by misalignments between the WAVS optical components through the long optical chain.

Three operation scenarios are considered for ITER (temperature of the VV at 20 °C during maintenance periods, 100 °C during plasma operation, and 200 °C during baking). According to each scenario, the upper mirror of the OH has to be moved to one of the three positions. This function will be performed by means of a piezo actuator coupled to the OH upper mirror and a set of reference rad-hard switches to drive the vertical displacement of the mirror in order to get the desired alignment position of the optical beam [3].

The piezo actuator has been identified as the main critical item of the Optical Hinge [4]. The piezoelectric technology has shown a good behavior in high magnetic fields [5] and nuclear radiation environment, both neutrons [6] and gamma [7]. However, the displacement mode in the piezo motor tested in [5,6] and [7] is different from the piezo actuator chosen for the WAVS, and it is not straightforward to conclude that the results can be extrapolated from one to another. For this reason, it was proposed to test the piezo actuator under operating conditions. Thus, in order to validate the piezo actuator and the mirror position precise control, a set of tests have been carried out on a 1:1 scale mock-up of the mechanical structure for the OH structure (corresponding to the Divertor LoS).

2. Piezo actuator

The chosen piezo actuator for the OH is based on the commercial high-load piezo actuator N-216 Nexline linear actuator from PI (Physik Instrumente), customized with rad-hard components and an increased travel range up to 40 mm (the expected range for OH is about 36 mm). This piezo actuator has an active force of 600 N and a holding force of 800N (see Fig. 1).

The working principle of the PI N-216 Linear actuator is explained in the PI manual E-712 Digital Piezo Controller System for PiezoWalk® Drives [8]:

“The N216 NEXLINE® linear actuator is a compact drive which consists of two piezo drive modules which are coupled to the same moving runner. The piezo drive modules themselves each consist of four piezo actuators. The feed is generated by coordinated shearing and clamping motion of strongly pre-loaded piezo elements that are coupled to a runner (PiezoWalk® principle). The feed of the runner results from coordinated lifting and clamping of the piezo actuators in conjunction with shearing motion. In other words, the piezo drive module performs a stepping motion along the runner.

Each PiezoWalk® drive thus requires four piezo voltage signals: two for

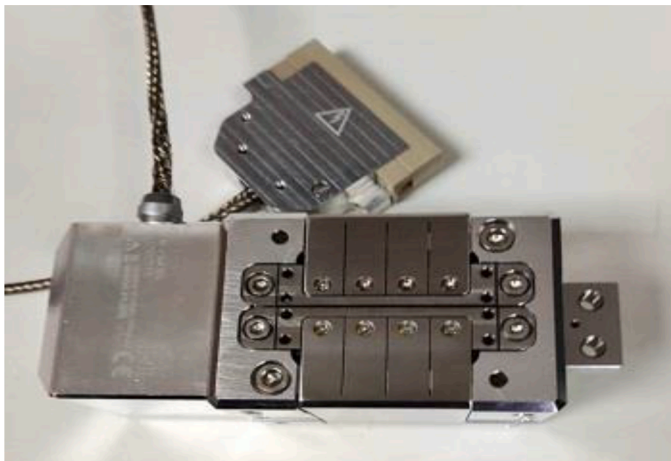


Fig. 1. Customized PI-N216 piezo actuator.

clamping components and two for shearing components. For stepping motion, a step cycle is defined as a complete piezo-voltage-changing sequence for shearing and clamping. At the end of the step cycle, the piezo voltages show the same values in the same relation as at the start of the step cycle.

The step size of a PiezoWalk® drive depends on the load and the resulting force. Depending on the direction of motion the drive acts against that force or in the direction of that force. Accordingly, the actual steps size varies.”

The working principle of the N216 NEXLINE® linear actuator is shown in Fig. 2.

Different driving modes are provided by the PiezoWalk® firmware of the E-712 system. The main modes are full-step mode, to get maximum velocity and maximum holding force, and nanostepping mode, to get steady motion with uniform velocity and a low vibration mode. In this mode, the velocity is about 60% of the velocity in full step mode. Figs. 3 and 4 show the shearing and clamping voltages applied to the piezo drives modules for both driving modes.

The tests for the N-216 piezo actuator aimed to find out the effects of the radiation as well as the cable length from the piezo actuator to its controller on its performance, observing the changes in the step size and the maximum velocity. The test for the cable length was also necessary because the controller will be placed about 100 m from the piezo actuator, much longer than the distance referred by the manufacturer in other applications for the correct operation, which is about 30 m.

3. Náyade Co-60 irradiation facility

For gamma-ray irradiation studies, CIEMAT possesses a Co-60 sources facility with unrestricted access. This permits extended temporal irradiation studies. The Náyade facility is a pool-type facility (1.2 m wide by 4.5 m deep) that uses water as the biological shield. This provides shielding for about 100,000 Ci of Co-60. Safety control is achieved through water level monitoring, radiation detectors and water purity control by pH and conductivity measurements. The use of water as a biological shield also allows direct vision for positioning the sources and extracting of samples in different chambers.

The test campaign in the Náyade Gamma irradiation facility was performed to evaluate the reliability and lifetime expectation after gamma radiation of the customized motor PI N-216. To be compliant with ITER requirements the target was to reach at least 272.40 kGy of total accumulated gamma dose [9], which corresponds to gamma dose in the Divertor view for Sapphire in the Vacuum Window Assembly up to 93 kGy, the delayed gamma dose from water activation up to 155 kGy and a 10% of safety factor. The Vacuum Window is the component closer to the piezo actuator for which reference data are available. The installation of the piezo actuator in Náyade is shown in Fig. 5. In the left, the sample holder where the piezo actuator has been introduced to receive the gamma dose, in the right an upper view of the pool where the gamma source irradiates the samples.

The gamma test campaign was performed in two phases: 50% and 100% according to the schedule shown in Table 1.

4. Optical Hinge mock-up

The OH mechanical mock-up is made up of the support structure, the two flat mirrors with mounts, and the set of the piezo actuator and the electrical switches coupled to the upper mirror to move it vertically. Specifications from the supplier in terms of maximum torques and forces that can affect potentially to the runner of the piezo actuator have to be implemented in the design. Therefore, as the coupling between the mirror and the actuator is quite complex, it was considered necessary to build a 1:1 mock-up (see Fig. 6). In this sense, the assembly of the actuator has to be perfectly aligned with the vertical axis of the mirror as the most critical force limited for the motor is the lateral one. This force can be induced in the motor from the lateral guiding system if inaccurate, as these elements guide the vertical movement of the mirror.

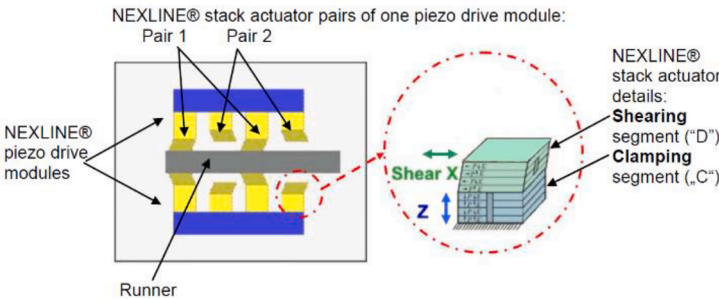


Fig. 2. NEXLINE® drive with 2 piezo drive modules, performing stepping motion.

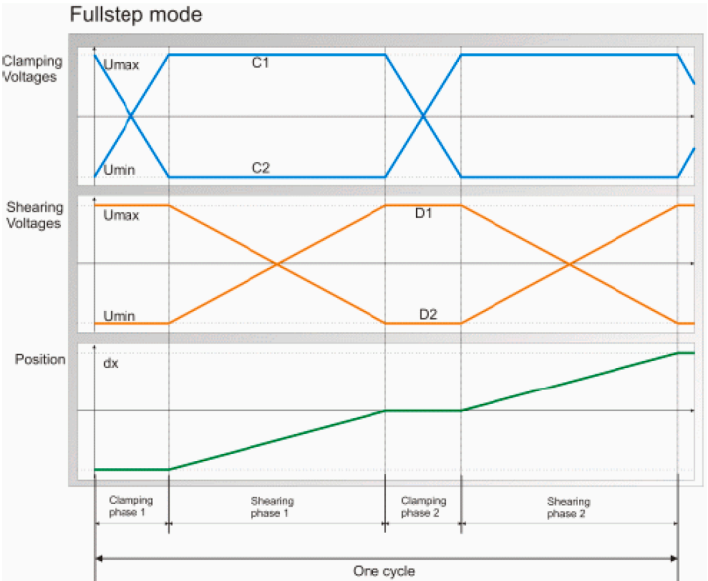


Fig. 3. Shearing and clamping voltages and motion over time for full-step driving mode.

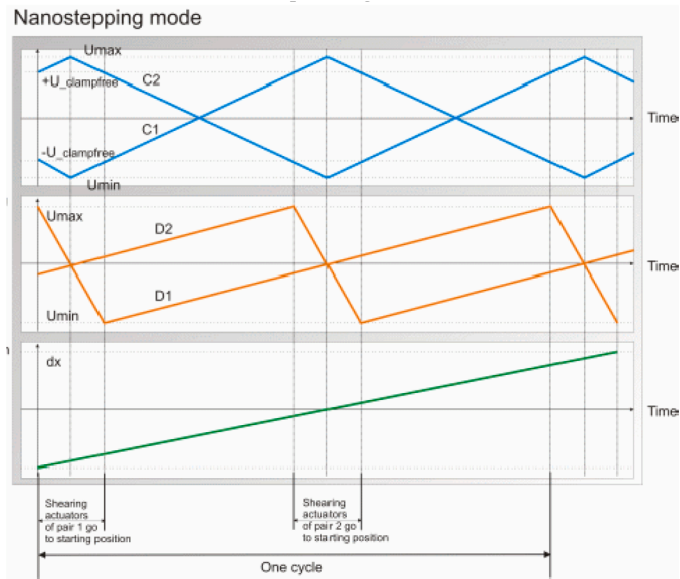


Fig. 4. Shearing and clamping voltages and motion over time for nanostepping driving mode.

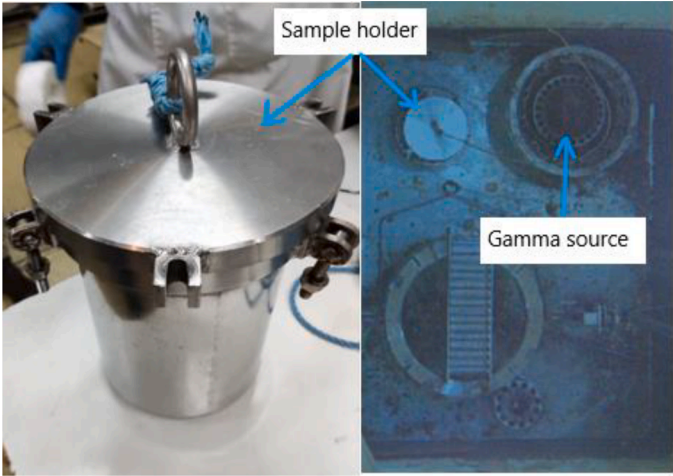


Fig. 5. Installation of piezo actuator in Náyade facility.

Table 1
Gamma irradiation phases.

Phase	kGy/h	kGy by phase	Accumulated Doses	Irradiation Time
1	4.3	136.20	136.20	1d 7 h 41m
2	4.3	136.20	272.40	1d 7 h 41m

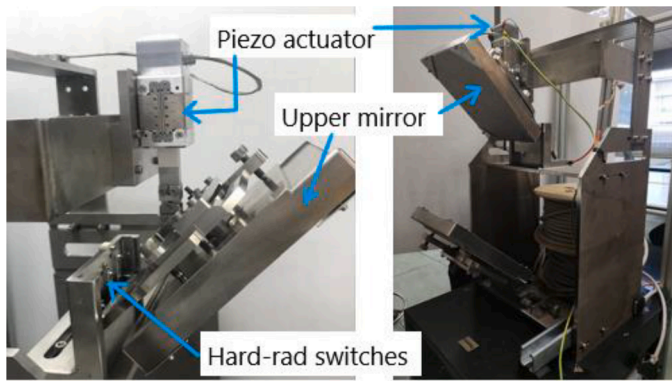


Fig. 6. Optical Hinge Mock-up, with the piezo actuator coupled to the upper mirror.

5. Test procedure

The parameter measured during the tests is the motion speed from switch to switch, which is related to the active force [10]. Moreover, the temperature on the surface of the actuator has been measured.

In the first phase, the performance of the PI N-216 piezo actuator coupled to the mechanical structure has been characterized considering a cable length between the piezo and the controller of 10 m.

Afterwards, at the end of every cycle of gamma irradiation (50% and 100% of the estimated dose that the piezo will receive at the end of the ITER life), the piezo actuator is reassembled in the mock-up and then the same characterization tests have been performed.

In addition, a test of the actuator performance has been carried out with a cable length up to 110 m. This cable length test has been performed before and after the irradiation process.

The average reached speed is measured after each gamma irradiation phase. The mirror is moved between each position switch with two programmed velocities: maximum speed (1 mm/s) and medium speed (0.5 mm/s), and using different loads (with and without the mirror weight) and different cable lengths between the motor and its controller (10 m, 60 m and 110 m).

6. Test results

6.1. Piezo actuator characterization

The initial characterization is performed with a cable of 10 m from the piezo actuator to the controller, the driving mode set to full-step and the programmed velocity is the maximum given by the supplier without load, 1 mm/s. A set of ten movements are performed from the switch indicating the lower position of the mirror to the switch indicating the upper position, and vice versa, to move the piezo actuator up and down, and with and without the mirror load, ten movements in each case. The OH control system calculates the speed of the piezo actuator by recording the time at which the mirror covers the distance between the two switches. Table 2 shows the results, calculated as the average of all

Table 2

Average velocities and step sizes with full-step driving mode and 10 m cable length.

	10 Kg (mirror)		7.38 Kg (without mirror)	
	Up	Down	Up	Down
Velocity (mm/s)	0.836	0.924	0.848	0.897
+/- Δ Velocity (mm/s)	0.0008	0.0017	0.0014	0.0013
N. Steps	4088	3736	4061	3839
Step Size (set) (μm)	8.40	9.25	8.65	9.10
Step Size (real) (μm)	8.49	9.28	8.54	9.03
Range (mm)	34.68	34.68	34.67	34.67

the tests performed.

The range shows the distance covered by the mirror displacement. The step sizes are different upwards and downwards, but this was expected, since the behavior of the piezo actuator causes the step size to be different when entering than when exiting the runner; the load to be moved affects to the step size too. The results show that the step size increases with the weight and when it goes down, and it decreases with the weight and when it goes up. Maximum speed is slower when the motor has to lift the mirror than when the mirror goes down.

The difference between upwards and downwards speeds is higher the heavier the load to be moved. The term +/-Δ Velocity shows the difference between the maximum and the minimum speeds in movements made with the same conditions.

The same characterization, with a set of five movements in each case, has been performed for nanosteping driving mode, with 0.4 mm/s programmed velocity. Table 3 shows the results calculated as the average of the tests performed.

The step size with nanosteping is smaller than with full-step driving mode. The programmed velocity is reached when going down (better results can be achieved as long as the step size is programmed more precisely).

When the actuator is moved with slower programmed speeds than the maximum that the piezo can reach, the speed can be maintained without any problem as long as the programmed step size is similar to the real one. This is true in both nanosteping and full-step driving modes.

6.2. Full-step driving mode after irradiation

The tests have been performed to evaluate the velocity of the piezo actuator with the nominal load of 100 N and a reduced load of 74 N, equivalent to removing the mirror from the mock-up. The average values of the velocity for full-step driving mode and programmed velocity of 1 mm/s are shown in Table 5, with the percentage of reduction with respect to the velocity without irradiation. The step size has been calculated after each period of irradiation, in order to program the controller with a more appropriate step size.

All the tests have been done with a 10 m cable length.

The step size after each irradiation period is different. It is shown in Table 6, with the percentage of reduction respect to the step size without irradiation.

The most direct effect of the irradiation on the behavior of the actuator is the reduction of the step size after each period of irradiation. This is associated with a lower maximum velocity. The reduction of the step size is bigger after the first period of irradiation at 50% of the gamma dose than after the second one at 100%.

Fig. 7 shows the maximum velocities measured in five different tests for each case, with and without gamma radiation. There is not important variation between tests performed under the same conditions, even after a complete gamma irradiation cycle. For 0% gamma the maximum variation is 0.0017 mm/s (see Table 2), and 0.008 mm/s for 100% gamma. Fig. 8 shows how the maximum velocity gets slower when gamma irradiation is applied to the piezo actuator.

A set of tests with a programmed speed lower than the maximum observed have also been performed. The results for a programmed speed

Table 3

Velocities and step sizes with nanosteping driving mode and 10 m cable length.

	10 Kg (mirror)		7.38 Kg (without mirror)	
	Up	Down	Up	Down
Velocity (mm/s)	0.349	0.396	0.357	0.390
+/- Δ Velocity (mm/s)	0.0000	0.0010	0.0032	0.0006
N. Steps	9856	6700	8220	7009
Step Size (set) (μm)	3.60	5.20	4.70	5.05
Step Size (real) (μm)	3.51	5.17	4.21	4.94
Range (mm)	34.62	34.61	34.60	34.61

Table 5

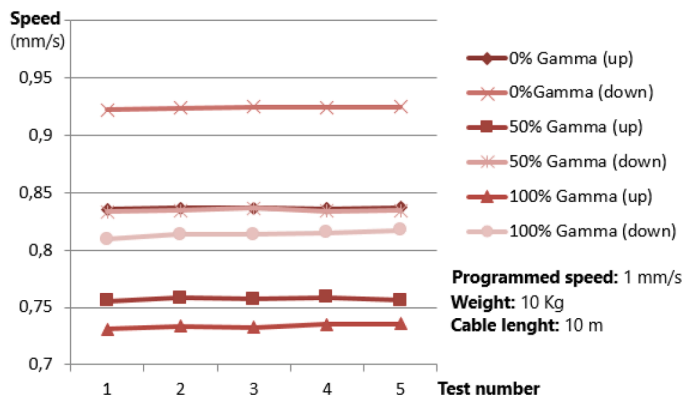
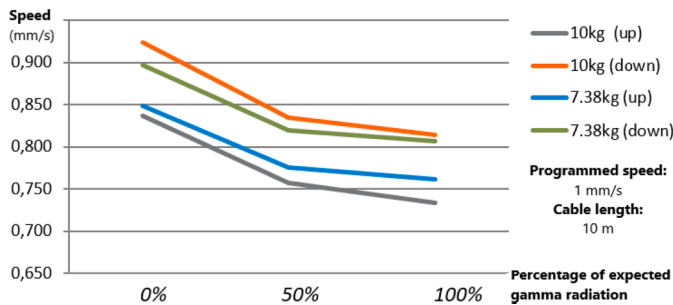
Maximum average velocity before and after the irradiation periods.

Gamma Dose	10 Kg		Down (mm/s)		7.38 Kg		Down (mm/s)	
	Up (mm/s)				Up (mm/s)			
none	0.836		0.924		0.848		0.897	
50%	0.757	−9.4%	0.834	−9.7%	0.776	−8.5%	0.819	−8.7%
100%	0.734	−12.2%	0.814	−11.9%	0.762	−10.1%	0.807	−10.0%

Table 6

Step sizes before and after irradiation.

Gamma Dose	10 Kg		Down (mm)		7.38 Kg		Down (mm)	
	Up (mm)				Up (mm)			
none	8.49		9.28		8.54		9.03	
50%	7.58	−10.7%	8.40	−9.5%	7.80	−8.7%	8.23	−8.9%
100%	7.37	−13.2%	8.21	−11.5%	7.67	−10.2%	8.09	−10.4%

**Fig. 7.** Velocities before and after radiation.**Fig. 8.** Variation of the maximum velocity with radiation.

of 0.5 mm/s show that the controller can maintain the programmed velocity when the controller is updated with an expected step size similar to the calculated after the irradiation.

6.3. Nanosteping driving mode

When the piezo actuator is driven in nanosteping driving mode, the step size is smaller and the maximum velocity is lower. The latter, when programmed at 0.4 mm/s, the piezo actuator can maintain this velocity when the load goes down, and it is slightly slower when it goes up, even after the complete irradiation cycle.

The step sizes in this driving mode are slightly smaller after each irradiation period and it seems that the effect of the irradiation is produced mainly in the first cycle of irradiation, as in full-step mode. Slower programmed velocities than the maximum can be achieved without any problem if the controller is properly adjusted.

6.4. Cable length tests

A set of tests have been performed with a 60 m and a 110 m cable after the complete irradiation period, in order to analyze the behavior of the piezo actuator in a scenario where the location of the controller is up to 110 m from the OH. Table 7 shows the behavior of the piezo actuator in full step driving mode. Using nanosteping mode the piezo actuator has shown to be more sensitive to the length of the cable when it has to lift the load.

The maximum speed with increasing cable length is very similar: the radiation effects are close to those obtained with the standard 10 m cable, i.e. a longer cable length does not make the piezo actuator more difficult to control than with a standard cable length.

The speeds calculated in these cable length tests are slightly higher than the presented in the Table 6, which are performed with a cable length of 10 m, but these small differences could be attributed to the fact that they were made on different days and the environmental conditions (mainly room temperature) were not exactly the same.

7. Performance analysis

The performed tests show that the expected gamma irradiation dose causes a reduction from 10% to 12% in the maximum speed that the piezo actuator can reach when assembled to the OH mock-up. However, this speed is fast enough not to compromise the proper operation of the system.

If the step size, i.e., the displacement in a voltage cycle, which is reduced after the irradiation, is calculated periodically and updated in the controller parameters, the piezo actuator could work without any problem at the programmed speed, for example with a programmed speed of 0.5 mm/s in full-step driving mode.

Thus, the piezo actuator will be working well (speed less than 0.7 mm/s) even with a 110 m cable to its controller after the complete irradiation period.

Respect to the temperature that the piezo actuator can reach during its working period, it has been observed that it increases slightly, up to 4 °C after forty up and down movements of the full range (about 34,5 mm), remaining stable that temperature after that.

Table 7

Cable length vs weight, with 100% gamma dose and maximum speed (1 mm/s).

Length	10 Kg		7.38 Kg	
	Up (mm/s)	Down (mm/s)	Up (mm/s)	Down (mm/s)
10 m	0.762	0.833	0.775	0.812
60 m	0.758	0.830	0.775	0.812
110 m	0.753	0.820	0.774	0.808

8. Summary and next test

The main conclusion is that the piezo actuator is working properly after being exposed to the expected gamma irradiation, even if it is located at 110 m (cable length) from the controller. Full step driving mode is preferable if the length of the cable is 110 m, because the piezo actuator is less sensitive to the effect of the length when working in this mode.

As a summary, although maximum speed and active force decrease, the piezo actuator can move properly the OH mirror to the prefixed position as well as keep the mirror fixed in that position.

The next step for the validation of the piezo is to test the same piezo actuator (already gamma irradiated) with the equivalent nuclear heating in Sapphire of 74.69 kGy [9] induced by neutrons. These tests are foreseen to be performed in TAPIRO reactor (ENEA Casaccia center) to verify compatibility with WAVS working conditions.

Disclaimer

The work leading to this publication has been partially funded by Fusion for Energy under Specific Grant Agreement F4E-FPA 407(DG)-SG04. This publication reflects the views only of the author, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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