Fusion Engineering and Design 203 (2024) 114439

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Design of a position monitoring system for the ITER radial neutron camera

S. Cesaroni [a,*], D. Marocco [a], D. Marzullo [b], F. Moro [a], F. Belli [a], G. Brolatti [a], C. Centioli [a], E. Occhiuto [b], M. Riva [a], G. Rocchi [a], B. Esposito [a]

[a] *ENEA, Fusion and Nuclear Safety department, via E. Fermi 45, 00044 Frascati, Roma, Italy*
[b] *Trieste University, Department of Engineering and Architecture, 34127, Trieste, Italy*

ARTICLE INFO

Keywords:
ITER
Radial neutron camera
Position monitoring system

The Radial Neutron Camera (RNC) is an ITER diagnostic system devoted to the radial measurement of the plasma neutron emissivity during ITER operation. In particular, plasma core measurements will be performed using 48 detectors located in the Ex-Port RNC subsystem and viewing the plasma through 16 lines-of-sight (LOS). Since discrepancies concerning the position of the LOS and the related optical path can occur during RNC installation and ITER operation, a Position Monitoring System (PMS) is foreseen to evaluate the misalignment and provide a correction tool for the neutrons count rate. During the design of the PMS for the RNC, optic fiber-based displacement sensors have been identified as the best solution to measure the displacements from reference positions along the radial, vertical and toroidal directions. Potential issues that could arise during the installation and operation of such sensors have been evaluated; MCNP calculations have been performed to determine the radiation level at the position of the PMS components. Finally, mechanical tests have been carried out at ENEA to evaluate the performance of the sensors: results indicate compliance with the specifications provided by the producer and the ITER RNC design requirements.

1. Introduction

The ITER Radial Neutron Camera (RNC) [1] is a diagnostic system located in the ITER Equatorial Port #1, dedicated to the evaluation of the plasma neutron emissivity. The RNC shall measure the uncollided neutrons from Deuterium-Tritium (DT) and Deuterium-Deuterium (DD) fusion reactions through an array of neutron flux detectors located in collimated lines of sight (LOS). The line-integrated neutron fluxes are used to evaluate, through reconstruction techniques, the neutron emissivity of plasma during ITER operation.

The RNC is composed by two independent collimating structures probing respectively the plasma edge (In-Port RNC subsystem) and the plasma core (Ex-Port RNC subsystem). The Ex-Port RNC Fig. 1 contains 16 line-of-sight (LOS), distributed in two radial planes and located inside a shielding block installed on the Interspace Supporting Structure (ISS); each LOS has an associated optical path which penetrates the Diagnostic Shielding Module (DSM) of the Port Plug (PP).

Since the PP and the ISS are mechanically disjointed, a Position Monitoring System (PMS) is foreseen in order to evaluate the misalignment between each LOS and the related DSM penetration, which can occur during the installation, baking and operation of the machine.

Displacements data measured by the PMS will be processed to correct for the following two effects induced by misalignment:

- Vignetting, i.e. partial/total loss of direct view of the plasma along a LOS
- Mismatch between the reference LOS positions used by the emissivity profile reconstruction code and the actual LOS positions.

Three different technologies to be implemented in RNC PMS have been investigated and compared, namely:

1) Radiation hardened camera imaging
2) Laser scanning system
3) Fiber optic-based sensors

The fiber optic-based displacement sensors have been selected because of their ease of integration and small interfacing impact on the RNC system. The design of the PMS is outlined in Section 2, with two emphases on the devices produced by the Smartec company (Section 2.1) and their integration on the PMS (Section 2.2). Studies on the suitability of such sensors to be installed on ITER RNC have been performed and are shown in Section 3. In Section 4 the current status of the

---

* Corresponding author.
E-mail address: silvia.cesaroni@enea.it (S. Cesaroni).

https://doi.org/10.1016/j.fusengdes.2024.114439
Received 13 October 2023; Received in revised form 5 April 2024; Accepted 8 April 2024

PMS design and future developments are reported.

2. The Ex-Port position monitoring system (PMS)

The PMS is a specific subsystem of Ex-Port RNC that must be able to identify the actual regions of plasma seen by the detectors and employ such information for the reconstruction of the neutron emissivity. The aim of the PMS is to provide a corrective factor to be used during data processing for a proper measurement of the neutrons count rate. It is important to point out that, at the current state of RNC design, a remote-controlled motorized system able to move the shielding block in order to obtain a realignment of LOS is not foreseen.

The main components of the PMS are:

- a measuring subsystem able to track in real-time the movements of the Port flange with a resolution of mm
- a control and processing subsystem able to compare the position of the Port flange with a reference position, measure the misalignment and produce in real-time the correction factors for the emissivity reconstruction code.

During machine operations, the measuring subsystem of the PMS should be able to determine a maximum displacement of:

- ± 10 mm in radial direction
- ± 9 mm in toroidal direction
- ± 6 mm in vertical direction

with a tolerance of ± 0.5 mm. The system integrity and operation must be guaranteed in ITER lifetime from installation to III-type loading event. In particular, the scenario BAK III.1 (i.e. machine BAKing operating conditions and Maximum Historically Probable Earthquake - SMHV as initiating event) is considered the worst case, during which the calculated maximum relative displacements of the PP closure plate are:

- 40.59 mm in radial direction
- 4.1 mm in toroidal direction
- 43.86 mm in vertical direction

2.1. Fiber optic-based sensors

The sensors considered for the measuring subsystem of RNC PMS are Fabry-Perot displacement sensors produced by Smartec company [2], as the ones adopted for the ITER superconducting magnets [3,4] and under development for the ITER Vacuum Vessel. The working principle of the Fabry-Perot displacement sensors is based on the U.S. Patent 5.202.939. A light signal travels along a fiber, bounces against a semi-transparent mirror located at the close end of the fiber, passes through a cavity and bounces on a second fully mirrored surface; this second mirror is attached to a movable wedge which modifies the dimensions of the cavity (Fig. 2a). The light travels then back to the recording instrument; the light is expanded and fed through a Fizeau interferometer, where the opening of the cavity is accurately reproduced and measured, and finally recorded on a Charge-Coupled Device (CCD) array. The proper use of calibration coefficients allows to obtain the displacement measured by the devices.

The sensors do not require power supply and are only equipped with an optical fiber able to withstand harsh environment, with a minimal impact on the design of the Ex-Port RNC. The sensors have been developed to work either in “push” or “pull” mode (as shown in Fig. 2b).

Sensors operated in “push” mode feature a mechanical probe at the end of the plunger, while those operated in “pull” mode are equipped with a pulley and a metal wire that allow the plunger traction.

The main characteristics of the sensors have been assessed by Smartec company with dedicated tests and are summarized in Table 1.

The accuracy of displacement measurement can be improved up to 0.1 mm, if a temperature measurement of the device is available. The sampling rate is 250 Hz if the acquisition unit (provided by the manufacturer) samples data of a single sensor, while it decreases to 125 Hz if the unit works per couple of sensors.

2.2. Sensors layout on the RNC

The application of the fiber optic displacement sensors for the RNC PMS requires the following set of devices:

- 3 sensors for radial displacement (i.e. one is for redundancy approach)
- 2 sensors for toroidal displacement

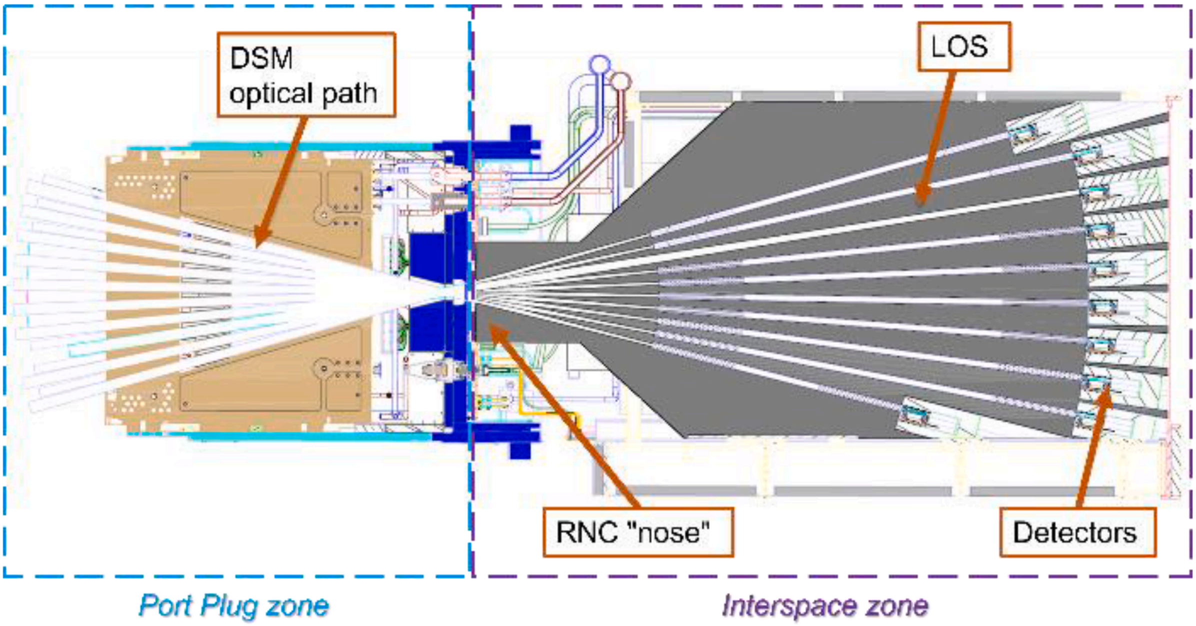

Fig. 1. View of Ex Port RNC components, with a focus on sections which may experience a misalignment.

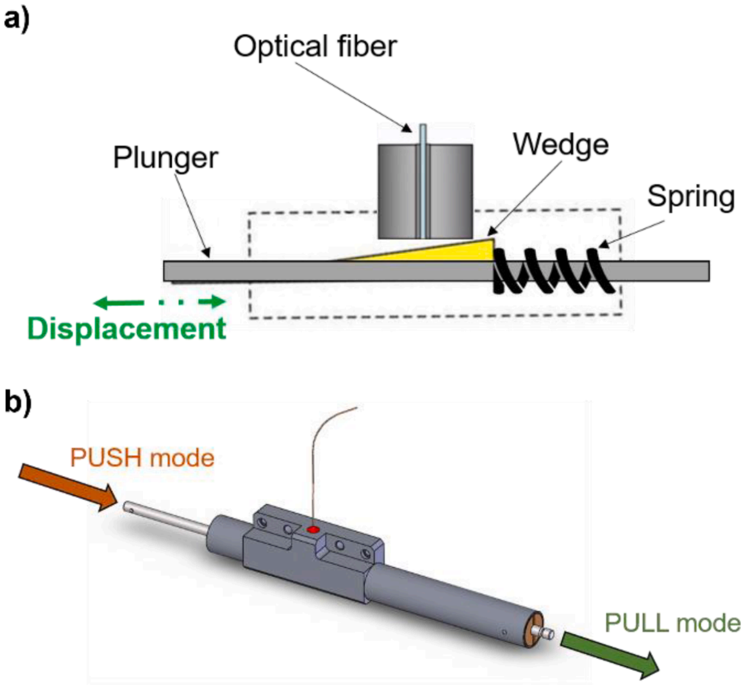

Fig. 2. The fiber optic based displacement sensor: a) main components and b) scheme of the two operational modes.

Table 1
Fiber optic-based sensors characteristics.

Parameter	Qualification results
Displacement range	0–40 mm in push-mode 0–80 mm in pull-mode (with a pulley 2x)
Accuracy	0.5 mm Deviation <1 %
Max sampling rate	250 Hz
Signal strength loss	<10 %
Operating temperature	−100 °C to 200 °C
Max gamma irradiation dose	6 MGy

- 2 sensors for vertical displacement.

The 7 sensors will be housed in the final part of the Ex-port shielding block (i.e. the Ex-port RNC “nose”) facing the port closure plate, as shown in Fig. 3. Each sensor is supplied on a base plate that must be fixed on the Ex-port RNC nose. The choice of the operational mode of the devices will impact their layout and location inside the port interspace.

In order to meet the measurement range requirements of the PMS and optimize sensors installation, a hybrid configuration (i.e. some sensors in “push” and some sensors “pull mode”) has been selected and a thermocouple is provided to each sensor in order to improve the measurement accuracy down to 0.1 mm. The sensors should be equipped

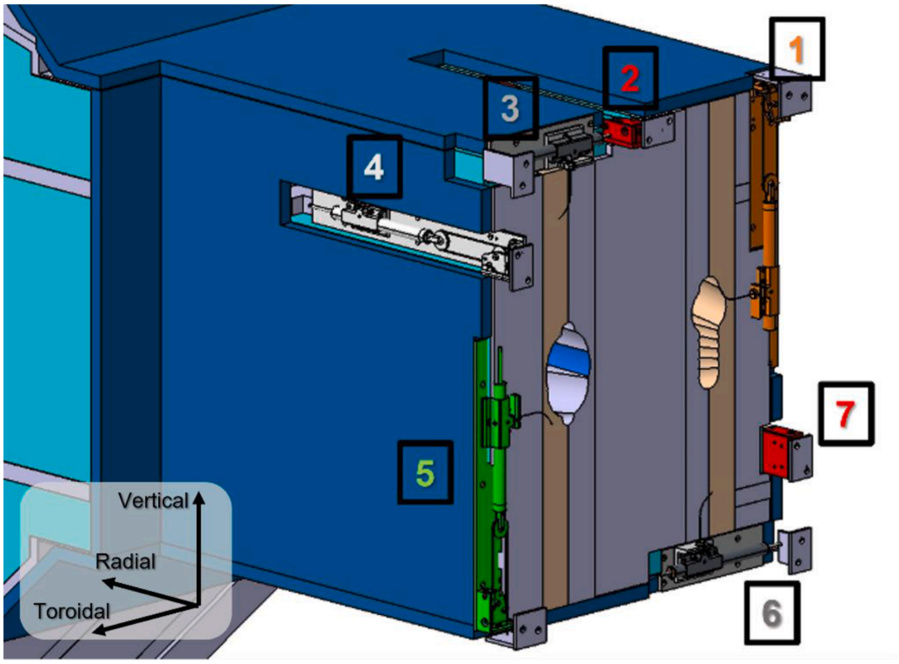

Fig. 3. Set of 7 PMS sensors installed on the Ex-port RNC nose.

with a 2x pulley and operated in pull mode for the radial and vertical displacement measurements, while sensors without pulley and operated in push mode can be used for toroidal displacement measurements.

Considering Fig. 3, the final sensors configuration is given below:

- sensors #3 e #6 in push mode for toroidal displacement measurements
- sensors #1, #2, #4, #5, #7 in pull mode for radial and vertical displacement measurements.

Reference plates and attachment points have been introduced on the closure plate, as fiducial interface points used for the attachment of the metal wire (for sensors in pull-mode) or contact surface (for sensors in push-mode). The optical fiber outgoing each device will be wrapped in a peek spiral tube and routed using clips to the RNC electrical interface cassette.

3. Assessment of PMS sensors operational features

As stated above, the fiber optic-based sensors are already in possession of the ITER qualification since they have been adopted on ITER magnets [3,4], and additional R&D activities are not required. However, a study was conducted at ENEA to verify the suitability of the selected devices in terms of radiation resistance and measurement capabilities within the context of the RNC Ex-Port design.

3.1. Radiation resistance

The irradiation tests performed in the past by the manufacturer have established that there is no significant degradation of the sensors after a gamma dose irradiation up to 6 MGy. In order to verify the sensors' suitability to the ITER RNC radiation environment, a calculation of neutron flux, gamma flux and dose absorbed by the PMS sensors has been performed using the MCNP code [5].

The MCNP model of the RNC Ex-port shielding block [6] has been modified introducing a cell to cover the area where the sensor should be installed. This updated model has then been integrated into the ITER MCNP C-model Fig. 4a. Moreover, additional calculations have been performed using as scoring areas 3 cm radius spheres located on the upper, lower, right and left side of the shielding block nose Fig. 4b. Based on the material specifications provided by the manufacturer, calculations have been performed considering a mixed material made of 50 % Aluminum (Al) and 50 % Stainless Steel (SS) to represent the PMS sensors' structure.

The above-mentioned geometry has been used to assess the following nuclear responses on the PMS:

- Neutron flux [n/cm^2/s]
- Gamma flux [γ/cm^2/s]
- Cumulative dose [Gy] integrated over the ITER lifetime (i.e. 1.7×10^7 s).

The PMS nuclear loads assessment, averaged over both the spherical volumes and the whole annulus around the nose, is summarized in Table 2. Fig. 5 shows the maps resulting from the calculation of the neutron flux Fig. 5a, the gamma flux Fig. 5b and the cumulative dose Fig. 5c. The computed values highlight that the worst positioning for the PMS sensor is on the left and right side of the shielding block nose (i.e. spheres #2 and #4) where the neutron and secondary gamma fluxes are significantly higher. No safety factor has been applied to the computed

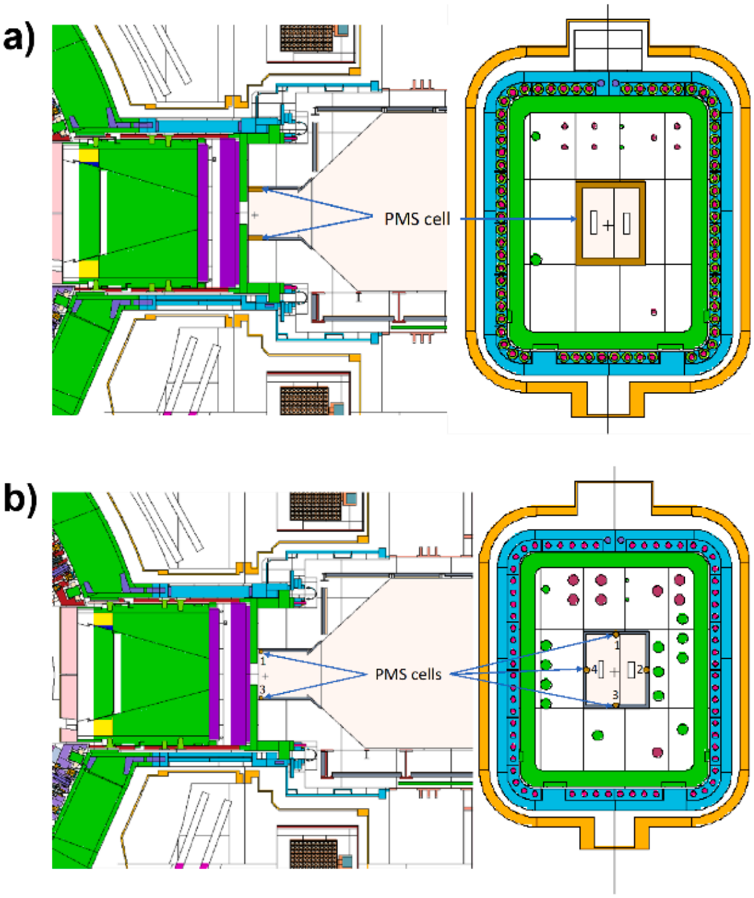

Fig. 4. ITER MCNP C-model integrating the RNC Ex-Port shielding block and a) the PMS schematized as an annulus around the nose or b) four PMS sensor positions represented as spherical cells.

Table 2
Nuclear loads assessed in the spherical cells (#1 to #4 from top to bottom) and in the annulus around the shielding block nose.

	PMS (computed inside the spheres, #1 to #4)	PMS (average value computed inside the annulus)
Neutron flux [n/cm^2/s]	1.43×10^9 8.18×10^9 1.39×10^9 4.56×10^9	1.52×10^9
Gamma flux [γ/cm^2/s]	3.79×10^8 3.75×10^9 3.72×10^8 1.99×10^9	4.54×10^8
Cumulative dose [MGy]	0.03 0.34 0.03 0.16	0.04

quantities.

Looking at Table 2, the maximum value of neutron flux results at the location of sphere #2, where the fluence calculated over the ITER lifetime is 1.4 × 1017 n/cm^2, which corresponds a damage of about 2 × 10−5 dpa for the Al/SS mixture used to represent the PMS sensors. Such value is well below limit above which significant effects on elastic properties of steel materials (i.e. Young module and Yield strength) are observed. The optical fiber is thus considered to be the only component of the PMS sensors that degrades under neutron irradiation. The decrease of the fibers performance is measurable in loss of the transmitted signal, whose upper acceptable limit has been fixed at 2.5 dB/50 m by Smartec. The analysis of experimental data available in literature [7] showed that the optical fiber selected by the manufacturer for the PMS sensors (i.e. pure silica core fiber with a fluorinated cladding) is expected to fulfil the signal loss requirements when exposed to a 14 MeV neutron irradiation up to 10^{18} n/cm^2, which is a value larger than that foreseen at RNC location.

3.2. *Measurement accuracy*

Two fiber optic-based sensors (hereafter called S1 and S2) have been tested in dedicated experiments at ENEA Frascati in order to highlight the differences in displacement measurements when each device is operated in "pull" or "push" mode. The two experimental setups for the mentioned sensor operational modes are shown in Fig. 6a ("push" mode) and Fig. 6b ("pull" mode). Sensors have been applied to a metal plate mounted on a track that allows movements in two directions, one along (i.e. Parallel Displacement) and the other perpendicular (i.e. Cross Tension) to the direction of measurement of the sensors, as shown in Fig. 6c. The actual displacement was controlled by a micrometer able to measure a maximum length of 3 cm, with a resolution of ±1 μm. A preloaded spring was also installed on the track to perform impulsive force tests and simulate the shake that can occur during ITER operation as a consequence, for example, of disruptions. The acquisition system, consisting in two FPI-HR-2 modules housed on the EVO-SD-2 unit (produced by FISO Evolution Life Sciences [8]), has been provided by the Smartec company together with the software to record data. All tests have been performed at room temperature and without the use of a thermocouple.

During the mechanical tests, the displacements have been measured along one direction at the time, maintaining the sensors fixed in one position and moving the metal plate. Measurements have been performed using one sensor at the time, as well as in parallel with a simultaneous data acquisition. In Fig. 7 data recorded during Parallel Displacement tests in "push" mode" (Fig. 7a) and "pull" mode Fig. 7b are given; the error bars provide the standard deviation of several measurements made at the same value of real displacement.

The sensor S2 exhibited a good linear response to different displacements of the metal plate, while the sensor S1 exhibited a non-linear behaviour. This discrepancy is probably due to the fact that the two sensors were not new but already used in previous mechanical and thermal tests which may have affected their response.

The accuracy (α) of each measurement has been calculated as the difference between the real displacement (R) and the average of the measured displacements ($\overline{m}$):

$$\alpha = |R - \overline{m}| \ [mm] \tag{1}$$

The accuracy calculated for the two operational modes of sensor S2 during some of the performed mechanical tests is shown in Table 3. Values found in "push" mode are always compatible with the accuracy declared by Smartec company in the device datasheet (i.e. 0.5 mm, shown in Table 1). Slightly higher values have been found in "pull" mode during the "Impulsive Force" tests, probably due to the higher complexity of the "pull" mode operation, where additional components (e.g. metal wires, pulley…) are required.

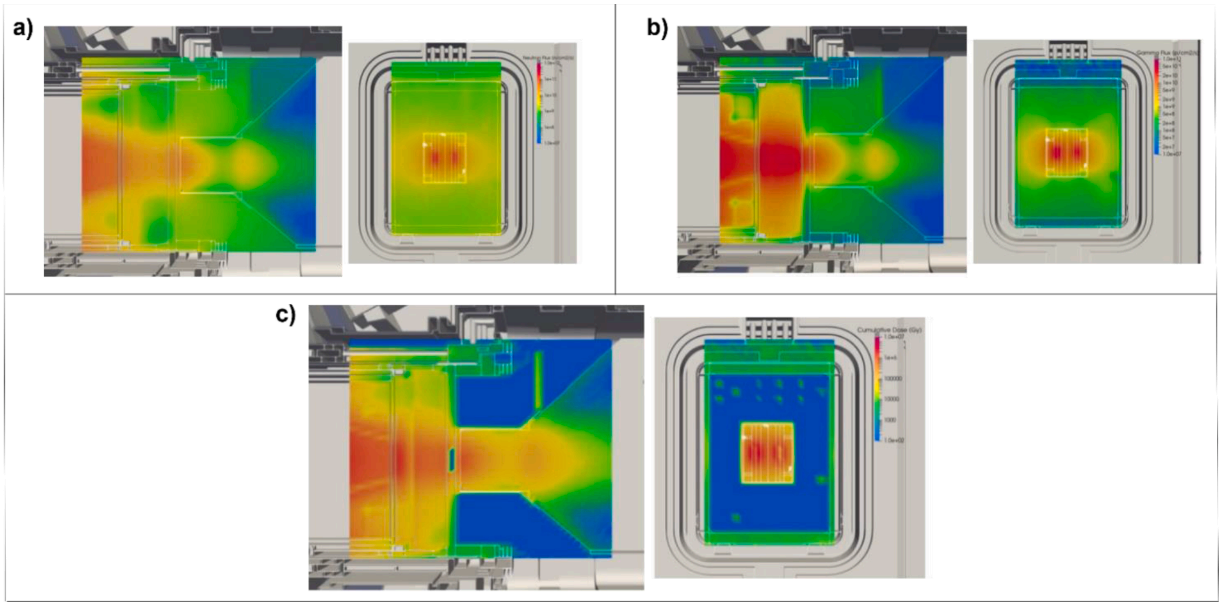

Fig. 5. 3D map of nuclear loads calculated around the Ex-port RNC nose: a) neutron flux, b) gamma flux and c) cumulative dose.

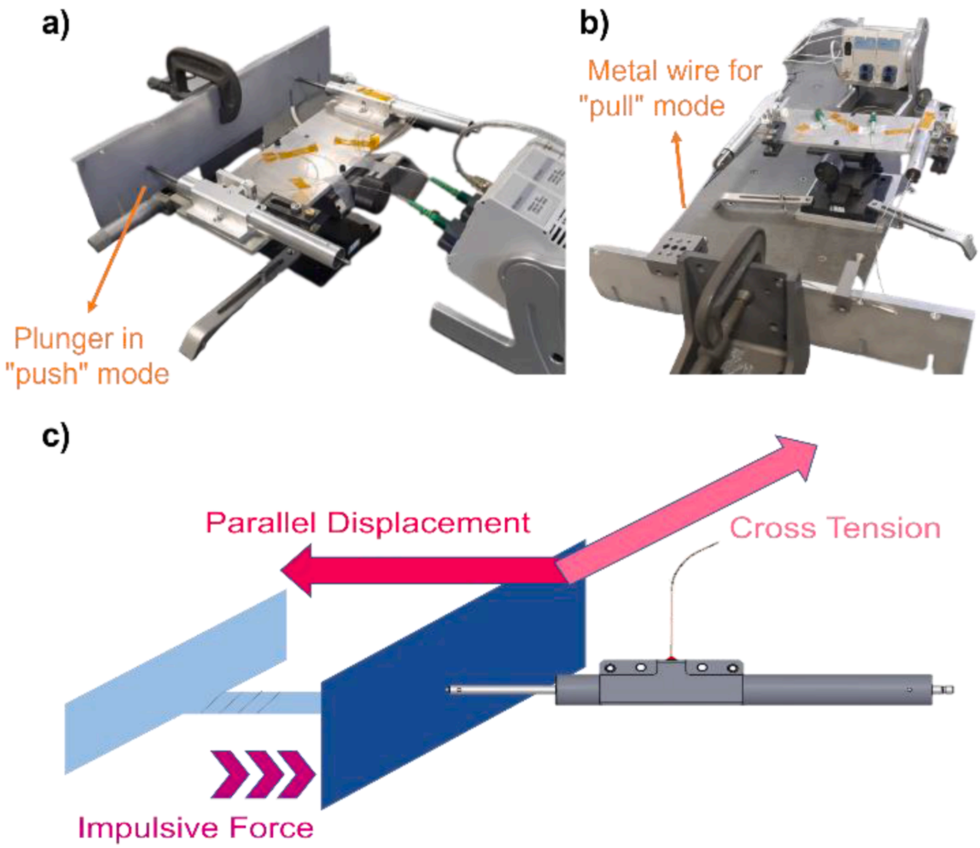

Fig. 6. Mechanical tests on the fiber optic based sensors: experimental setups in a) “push” mode and b) “pull” mode, and c) sketch of the stresses applied to the sensors.

In Fig. 8 data recorded during an Impulsive Force test of the sensor S2 in push mode is shown: after the sensor has been stressed with eleven shots of impulsive force, there is still a good agreement in displacement measurement, with a relative error less than 2 %.

Finally, Cross Tension tests have also been performed. No variation in the displacement measurement was observed when sensors were operated in “push” mode, while the presence of the metal wire during the “pull” mode operation produces output measurements even when the displacement occurs along a direction different from that of the sensor’s installation, as expected.

4. Conclusions

A Position Monitoring System (PMS) based on Fabry Perot displacement sensors is foreseen for the Ex-port RNC. Mechanical tests have been conducted on two sensors and the data acquired roughly confirmed the accuracy declared by the producer, which is deemed acceptable for the use of these devices on the PMS. According to the dimensions, layout and operational mode, a hybrid installation of the sensors on the Ex-port RNC “nose” has been selected, i.e. n. 5 sensors installed in pull-mode and n. 2 sensors installed in push-mode. Each sensor will be paired with a thermocouple aiming to further improve the measurement accuracy of displacement.

MCNP calculations were performed to investigate the dose and neutron fluence at the installation location of the displacement sensors. Taking into account the list of materials composing the devices provided by the producer, a maximum of 0.34 MGy of gamma dose absorbed over the ITER lifetime by the PMS components has been calculated. This value results far lower than the gamma dose value (6 MGy) achieved in the manufacturer qualification tests of these sensors. Regarding the effects on components due to neutron irradiation, no dedicated tests have been conducted, but a literature survey has provided information about optical fibers, which are the components most susceptible to damage under neutron irradiation. Considering the calculated 14 MeV neutron fluence foreseen at the RNC location, optical fibers with similar characteristics to those selected to be installed on the PMS sensors exhibit an induced loss below 2.5 dB/50 m, which is the maximum value accepted by the producer.

An algorithm able to process the displacement data recorded by each sensor is currently under development, as key part of a software able to perform the 3D-reconstruction of the RNC closure plate position and recalculate the LOS geometry during ITER operation.

Disclaimer

F4E: This publication reflects only the views of the authors, Fusion for Energy cannot be held responsible for any use of the information contained therein.

ITER: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

CRediT authorship contribution statement

S. Cesaroni: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **D. Marocco:** Project administration, Supervision, Validation, Visualization, Writing – review & editing. **D. Marzullo:** Conceptualization, Data curation, Resources. **F. Moro:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. **F. Belli:** Conceptualization, Data curation, Methodology, Resources, Validation. **G. Brolatti:** Conceptualization, Resources. **C. Centioli:** Validation. **E. Occhiuto:** Conceptualization, Resources. **M. Riva:** Software, Validation. **G. Rocchi:** Conceptualization, Methodology, Resources. **B. Esposito:** Funding acquisition, Project

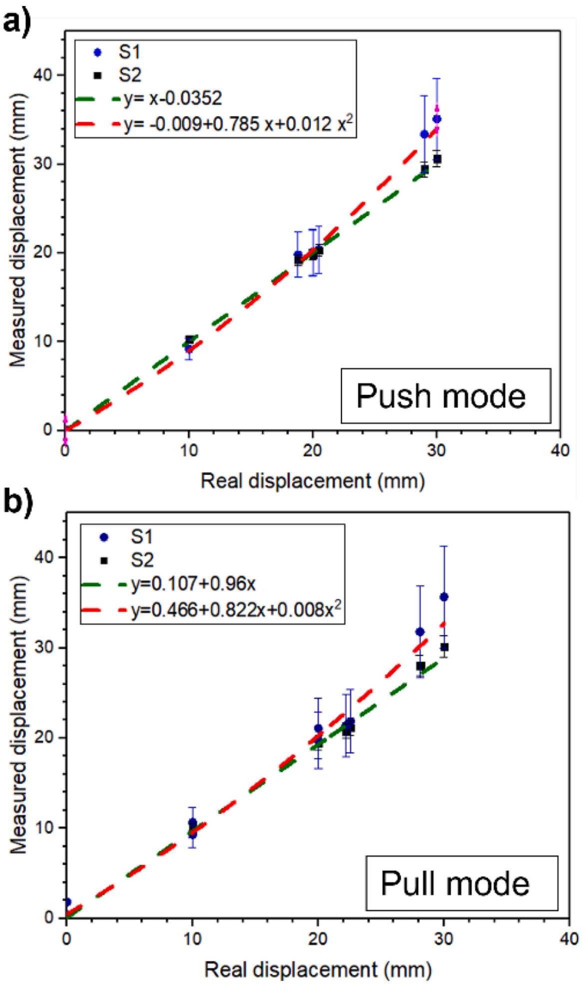

Fig. 7. Response of the sensors to different values of Parallel Displacement during tests in a) "push" mode and b) "pull" mode operation.

Table 3
Measurements accuracy of sensor S2 during "Parallel Displacement" and "Impulsive Force" tests.

Operational mode	Type of test	R [mm]	α [mm]
"Push" mode	Parallel Displacement	10	0.35
		30	0.54
	Impulsive Force	20	0.17
"Pull" mode	Parallel Displacement	10	0.1
		30	0.11
	Impulsive Force	20	0.88

administration, Supervision, Validation, Writing – review & editing.

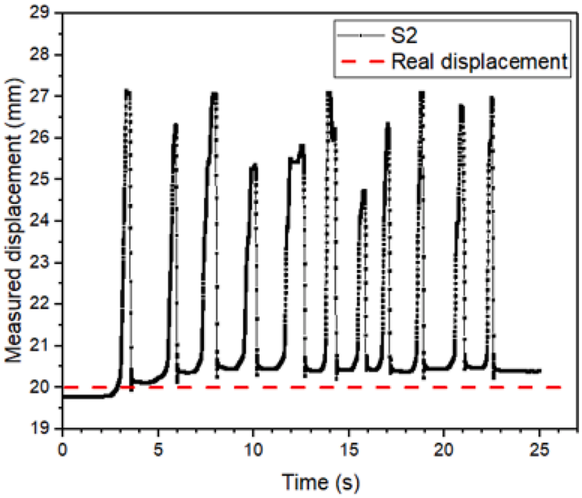

Fig. 8. Response of sensor S2 to eleven shot of Impulsive Force on the metal plate fixed at 20 mm of displacement.

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

Data will be made available on request.

References

[1] B. Esposito, et al., Progress of design and development for the ITER radial neutron camera, J. Fusion Energy 41 (2022) 22, https://doi.org/10.1007/s10894-022-00333-9.
[2] https://smartec.ch/en/.
[3] A. Poncet, et al., Thermo-mechanical instrumentation of the ITER magnet structures, IEEE Trans. Appl. Supercond. 22 (2012), https://doi.org/10.1109/TASC.2011.2178582, 9500604-9500604.
[4] A. Poncet, et al., Fiber optic sensors for the thermo-mechanical instrumentation of the ITER magnets, in: 5th European Conference on Structural Control, Genoa, Italy, 2012.
[5] Los Alamos National Laboratories, MCNP User's manual code version 6.2, 2017.
[6] F. Moro, et al., Nuclear analyses in support of ITER Ex-port radial neutron camera design, Fus. Eng. Des. 202 (2024) 114295, https://doi.org/10.1016/j.fusengdes.2024.114295.
[7] Kakuta, et al., Neutron irradiation effects on optical fibers, Sci. Rep. RITU A40 (1994) 153–157.
[8] https://fiso.com/en/.