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RAMI analysis of ITER diagnostic radial neutron camera

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ABSTRACT

RAMI (Reliability, Availability, Maintainability and Inspectability) assessments are mandatory part of the design process for all ITER systems to anticipate possible risks in terms of reliability and availability and support reliability growth program. A RAMI assessment performed on the ITER Radial Neutron Camera (RNC) diagnostic system is presented. The assessment is aimed at evaluating the RNC design capability to provide the neutron emissivity radial profile measurement with required reliability and availability. The RNC is composed by two collimating structures equipped with neutron flux detectors, the In-Port RNC sub-system and the Ex-Port RNC sub-system respectively. Such systems radially view different plasma locations thus enabling the emissivity profile reconstruction. Both In-Port and Ex-Port detection systems (sensors, collimators, shielding) and full acquisition system chain (front-end and back-end electronics) are considered in the analysis.

The RAMI performance was assessed by means of reliability block diagrams (RBDs) with respect to required mean inherent availability for 2 years of operations fixed at 99.5% for the Ex-Port system and at 88.3 % for the In-Port system. A set of failure events for each RNC component was defined by means of a failure mode and effect analysis. The resulting unavailability conditions of the systems were then identified. Hence identified groups of events were used to feed the RBDs model definition according to reliability-wise integration of the considered components. The integrated RAMI performance of RNC systems was finally estimated. Considering the current level of design development, In-Port RNC system appears able to meet stated requirement thanks to design redundancy. Ex-Port RNC, which includes Back End Electronics for data acquisition, is still below the RAMI target and requires further design improvement.

1. Introduction

RAMI (Reliability, Availability, Maintainability and Inspectability) analyses are an essential part of design process for complex systems required to continuously perform an expected mission over a minimal given period of time (reliability) and to guarantee an average availability including maintenance and repair operations in a long-term perspective. Especially for first-of- a-kind systems, the role of RAMI assessment during design phase, is to increase system robustness through measures such as redundancy, diversity, built-in testing, advanced diagnostics, and modularity to enable rapid physical replacement. The present paper is focused on the RAMI assessment performed for the International Thermonuclear Experimental Reactor (ITER) Radial Neutron Camera (RNC) diagnostic system. ITER [1] is the largest world experiment aimed at demonstrating a burning plasma able to provide an energy gain from nuclear fusion reactions. ITER is designed to yield in its plasma a ten-fold return on power ($Q = 10$), or 500 MW of fusion power from 50 MW of input heating power. RNC is a key ITER diagnostic for the real-time monitoring of burning plasma fusion power density profile.

RAMI performance is currently recognized among the main challenges for nuclear fusion economic viability as a power plant [2,3]. Several factors contribute to such challenge such as the technological complexity of fusion devices, the presence of several components with little or no operating experience and the high level of integration across systems expected to simultaneously function with small redundancy

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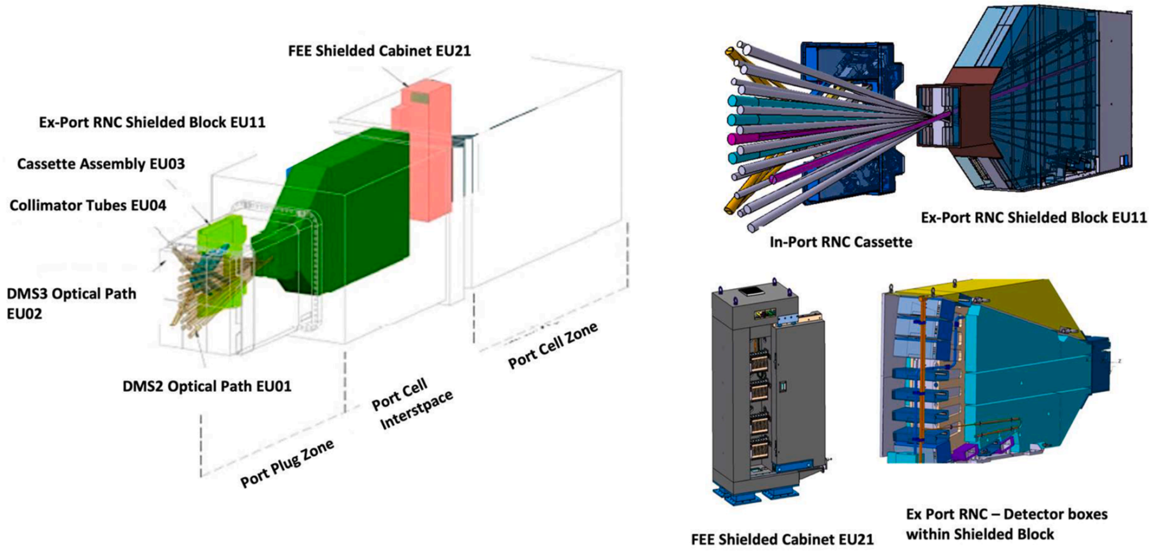

Fig. 1. Layout of RNC embarked units containing system equipment (left figure). Rendering of In-Port RNC cassette and Ex-port shielding block (right figure top), rendering of front-end electronics shielded cabinet (right figure bottom).

margin. To anticipate possible risks in terms of reliability and availability of the system and timely address them, RAMI assessments are mandatory parts of the design review steps for all ITER systems [4].

The specific assessment here presented is aimed at evaluating the RNC design capability to provide the neutron emissivity radial profile measurement with the required mean inherent availability fixed at 99.5% and 88.3 % for the Ex-Port and In-Port RNC sub-systems, respectively, for 2 years of operations. Note that In-Port RNC system design is more mature and currently at the final design review stage, while Ex-Port RNC sub-systems design, including the data acquisition and processing system, is still at a preliminary design stage. Therefore, the purpose of RAMI analysis is to verify compliance with requirement for the former system while identifying possible criticalities for the latter system.

2. Description of RNC system

The RNC [5] diagnostic is located in the Equatorial Port 1. The RNC diagnostic mission is to provide a real-time measurement of plasma neutron emissivity profile on a poloidal cross section of the plasma and spatially ranging from plasma core to plasma edge along tokamak minor radius dimension. The RNC system exploits a set of collimated Lines of Sight (LoS) along which uncollided 14 MeV and 2.5 MeV line-integrated neutron fluxes from deuterium–tritium (DT) and deuterium-deuterium (DD) fusion reactions are measured. The neutron emissivity profile is derived by processing through reconstruction techniques such measurements.

The RNC is composed by two collimating structures equipped with neutron flux detectors: the In-Port RNC sub-system and the Ex-port RNC sub-system (Fig. 1). Such systems radially view different plasma locations by LoS respectively probing the edge and the core zone of the plasma over the selected poloidal cross section. Note that to view plasma edge (towards higher values of plasma minor radius a), the In-Port RNC system is located inside the Vacuum Vessel (VV) port plug. Conversely, the Ex-Port RNC detection sub-system focusing on plasma core region is placed outside the Vacuum Vessel in the ITER port cell interspace.

The In-Port system has 6 LoS, with detectors located in a cassette assembly (3 detector modules in the upper part of the cassette and 3 detector modules in the lower part of the cassette). Each LoS allows for uncollided neutrons from a specific plasma region to reach a detector module equipped with two types of detectors: a fission chambers (FC) and a single crystal diamond (sCD) matrix detector. The In-Port RNC is equipped with thermocouple and signal cabling routed within the cassette up to electrical feedthroughs on the cassette. A section of electrical cables is then routed within the port plug up to specific vacuum and electrical feedthrough interface on the closure plate of the port (out of RNC system scope). An additional section of signal cables routed from electrical feedthrough interface on VV up to front-end electronics (FEE) cabinet in the port cell a shielded cabinet (SC) (Fig. 1) located on the Port Cell (PC) Supporting Structure (PCSS) in port cell#01 hosting the RNC front-end electronics (preamplifiers).

The In-Port RNC cassette is under secondary vacuum condition which is monitored by means of an interface to Service Vacuum System (SVS) because of the presence of the FC pressurized chambers constituting a trapped in-vessel volume. The following equipment for such sub-system are considered in scope: electrical and vacuum pipes feedthroughs on the cassette, vacuum pipes within the port plug.

The Ex-port RNC system foresees 16 LoS collimating uncollided neutrons from plasma core up to detector modules hosting three types of detectors: a single crystal diamond (sCD) detector, a 4He gas scintillator and a plastic scintillator. The detector modules are placed within a shielding structure in the port cell interspace and their temperature is monitored by means of thermocouples.

The cabling from/to detectors carrying both power supply and detector signals are routed through the port-cell up to the FEE-SC. Depending on the environmental loads and carried signal, different cable types are used: thermocouples cables, tri-axial and co-axial cables, fiber-optics. Also, connectors at routing interface points and marshalling board are considered in the analysis.

The FEE includes preamplifier boards for In-Port RNC and Ex-Port RNC. The cabinet is also equipped with a fan for cooling the front-end electronics. The In-Port SVS system located in the Port Cell is not considered in present scope, because still under design.

A power supply system, shared between Ex-port and In-Port RNC sub-systems, is located in the North-East Shielded Corner (NESC) area of the tokamak building and includes: remote chassis units hosting power supply boards; 400VAC /48 V DC converters; one mainframe controller with the related branch controller.

The Back-End Electronics (BEE) system for the RNC signal acquisition and processing is located in the diagnostic building. BEE includes components for fast signals (ADCs including Field Programmable Gate Array (FPGA) with PCIe connection to dedicated host computers, high performance computer) and slow signals (PLC including I/O boards).

The following auxiliary sub-systems are also included in the Ex-port

Table 1
Identified Unavailability conditions for In-Port RNC.

UC In Port RNC	Description
U_In1LOS	Unavailability of detectors in one line of sight
U_InRNC	Unavailability of all detectors inside the cassette
U_InRNC_FEE-PS	Unavailability of FEE within Port Cell or power supply in NorthEast-Shielded Corner.
U_SVS	Unavailability of SVS pumping/monitoring and loss of secondary vacuum within cassette

Table 2
Identified Unavailability conditions for In-Port RNC.

UC Ex Port RNC	Description
U_ExLOS	Unavailability of detectors in one line of sight
U_ExRNC_DAQ	Unavailability of acquisition system, data processing and transfer to CODAC of Ex-Port RNC within PC or NESC areas.
U_ExRNC_DB_DAQ	Unavailability of acquisition system of Ex-Port RNC data processing and transfer to CODAC within Diagnostic Building
U_Auxiliary	Unavailability of TSS or Unavailability of PMS or Unavailability of Calibration system.

RNC system: (i) a Temperature Stabilization System (TSS) to keep detectors within a known stable range of temperatures; (ii) a calibration system exploiting embedded reference signal sources (alfa-sources, light emitting diodes) to periodically calculate a calibration factor for detector response; (iii) a Position Monitoring System (PMS) [6] to monitor the alignment between Ex-Port RNC systems' LoS and port plug penetrations.

3. Methodology of analysis and models

The RAMI analysis of the RNC diagnostic has been performed according to ITER RAMI programme and established methodology common practices in fusion facilities [7,8]. First the identification of system unavailability conditions by means of Failure Mode and Effect Analysis (FMEA) methodology is performed. The FMEA step identifies plant and function breakdown structure (PBS and FBS respectively). PBS and FBS are then mutually associated to evaluate possible events occurring on the plant components resulting in the loss of operating functions. These events are then investigated by systematically considering for each component: operating mode, possible failure and related likelihood of occurrence, related causes and consequences of the failure. Final output of FMEA are the unavailability conditions (UCs) resulting from the grouping of similar consequences.

Moving from FMEA outcome, a Reliability and Availability simulation is performed for identified UCs on the basis of component reliability and availability parameters taking into account the maintainability and inspectability aspects by means of Reliability Block Diagrams (RBD). RBDs represent the system as reliability-wise aggregated components boxes including related failure and repair models. Such diagrams are implemented into software (Reliasoft – Blocksim [9] software is exploited in present analysis) enabling the simulation of reliability and availability performance.

3.1. *Identified unavailability conditions*

As outcome of the performed component FMEA, several system unavailability conditions were respectively identified for the In-Port RNC (Table 1) and the Ex-Port RNC (Table 2) systems.

Note that, depending on design redundancy and repairability policy, only part of the identified UCs directly impacts on the achievement of RNC system mission to provide the neutron emissivity measurement. In fact, despite all described systems are needed to provide measurement at the best accuracy level or to monitor system stability over time, the RNC mission can be nonetheless accomplished with a reduced set of LoS signals. For In-Port RNC system the minimal set requires at least 2 LoS in the upper part of the cassette and 2 LoS in the lower part of the cassette each with at least 1 detector available per LoS. Also, for Ex-Port RNC the redundancy in the number of detectors can be exploited to relax availability requirements impact. Similarly, auxiliary systems (TSS; PMS and calibration system) are used to keep diagnostics within optimal measurement conditions, but their failure does not result into immediate loss of RNC diagnostic.

Table 3
Extract example of FR models implemented. Either exponential distribution (λ) or lognormal distribution (μ,σ) parameters are reported.

Component	Failure Mode	Failure Model Parameters
Cable signal	Short to ground/circuit	(μ,σ) = (13.86, 0.58)
Detector-sCD	All failure modes	(μ,σ) = (11.16, 0.08)
4He scintillator	Loss of leak tightness	λ = 6,36E-08 /h
Preamplifier [11]	Channel failure	λ = 5.71E-07 /h
Photomultiplier	tube failure	λ = 5.00E-07 /h
HV Power Supply	All failure	(μ,σ) = (15.02,7.33)
Power cable	Short to ground	(μ,σ) = (14.51, 1.44)

As part of the ITER RAMI program a Failure Mode Effects and Criticality Analysis (FMECA) was also performed for both In-Port and Ex-Port systems. Risks associated to component failures identified in the FMEA step were therefore quantified by means of a criticality index (CI). Such criticality index is obtained by multiplying a failure likelihood of occurrence index (ranging from **1**- MTBF > 2000 yrs; to **6-** MTBF < 10 weeks) and a consequence severity index in terms of resulting machine downtime until recovery (ranging from **1**- <1 h; to **6-** > 1 year). Risks are then classified according to hence obtained criticality index magnitude as minor (CI<7), medium (7<CI<13) or major risks (CI>13).

In-Port RNC system major risks derived from:

- Cassette electric feedthrough loss of signal resulting from electrical contacts failure or loss of insulation across different channels.
- Cassette Feedthrough loss of leak tightness.
- Detector units failure.

Actions were then considered to reduce the initial criticality risks. In particular, the occurrence probability was reduced by means of design redundancy or defining specific tests at assembly and/or commissioning stage. The remaining major risk is related to cable signal loss where multiple signal cables converge in a single point at cassette F/T. Qualification/commissioning tests are expected to reduce the occurrence frequency and particular attention shall be paid in the construction and assembly of such components. It should be noted though that RAMI RBD simulation has nonetheless confirmed system ability to achieve reliability targets.

Concerning the Ex-Port RNC system, no major risks and no Ex-port RNC failure requiring immediate ITER machine stop were identified. The medium level risks identified resulted from:

- Rupture or misalignment in Shielding block or collimator.
- Sensor defects in PMS requiring maintenance in PC-IS.
- sCD detector failure.
- Failure in TSS equipment.

These risks can be reduced by QA control and test during assembling and exploitation of redundancy in design. On the other hand, the availability of spares for PC equipment has been considered in reducing severity impact.

3.2. *Reliability block diagrams*

RBD diagrams were implemented by reliability-wise connecting all components leading to considered UC (Tables 1 and 2). Each component failure mode was represented by a different block including the failure

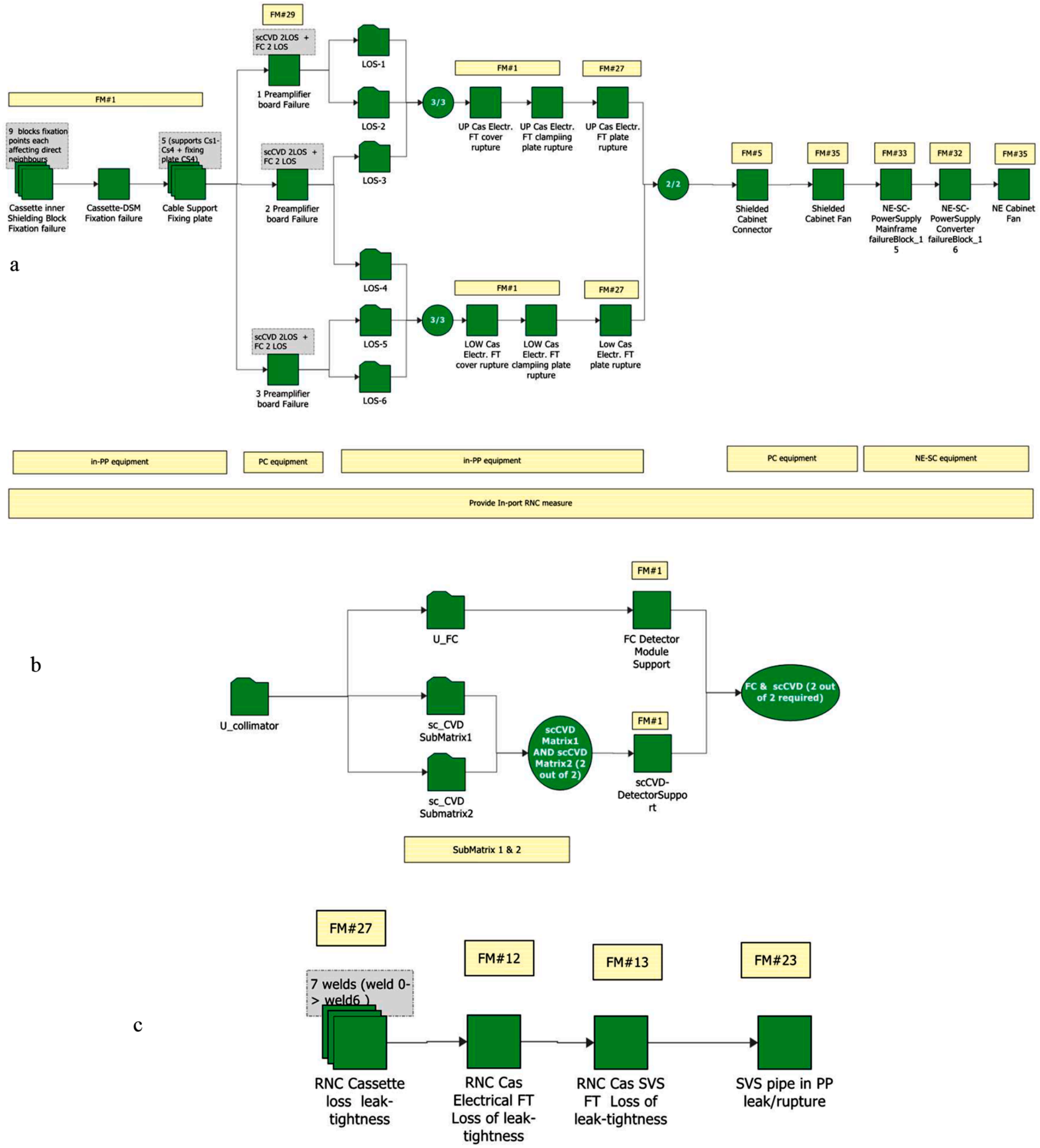

Fig. 2. RBDs for In-Port RNC overall system (a), Line Of Sight RBD sub-diagram expanded (b), SVS interface system RBD sub-diagram expanded (c).

rate (FR). An extract of FR models [10] exploited in the analysis is reported in Table 3.

Note that for sCD detectors for which no reliability data were available, the failure model has been calculated assuming an expected life of 1.E15 neutrons/cm^2 per detector, as experimentally derived in [12]. To translate neutron fluence into the expected operational life of the detectors in terms of ITER full operational years, the ITER operational reference scenario specifying the number of pulses, their duration, and the associated power (reference sequence of DD and DT experimental campaigns) was used. This way the cumulated fluence of uncollided neutrons on each detector location per ITER operational year was extrapolated. sCD failure time was then defined equal to the number of ITER full operational years needed to reach the cumulated neutron fluence of 1.E15 neutrons/cm^2. An average value over all LoS has then been adopted as Mean Time To Failure (MTTF) model for the sCD.

Also Mean Time To Repair (MTTR) data were defined in the RBD to reflect the defined maintenance models for RNC system. In particular, in order to avoid the stop of the ITER machine and the port plug opening for operations triggered by the In-Port RNC system, no preventive maintenance has been foreseen. Corrective maintenance operations are instead foreseen for equipment within the PC or the NESC, which can only take place at first available Short-Term Maintenance (STM). Such components failure events will then trigger a STM phase (2–4 days). Diagnostic building can be immediately accessed, so in case of failure for therein located BEE equipment two different maintenance tasks duration are foreseen: (i) <1 h maintenance for hot-swappable equipment with spare parts available (ii) <1day maintenance for not hot-swappable equipment with spare parts available. A preventive replacement maintenance every other Long Term Maintenance (LTM) has been foreseen for the data processing PC host computer.

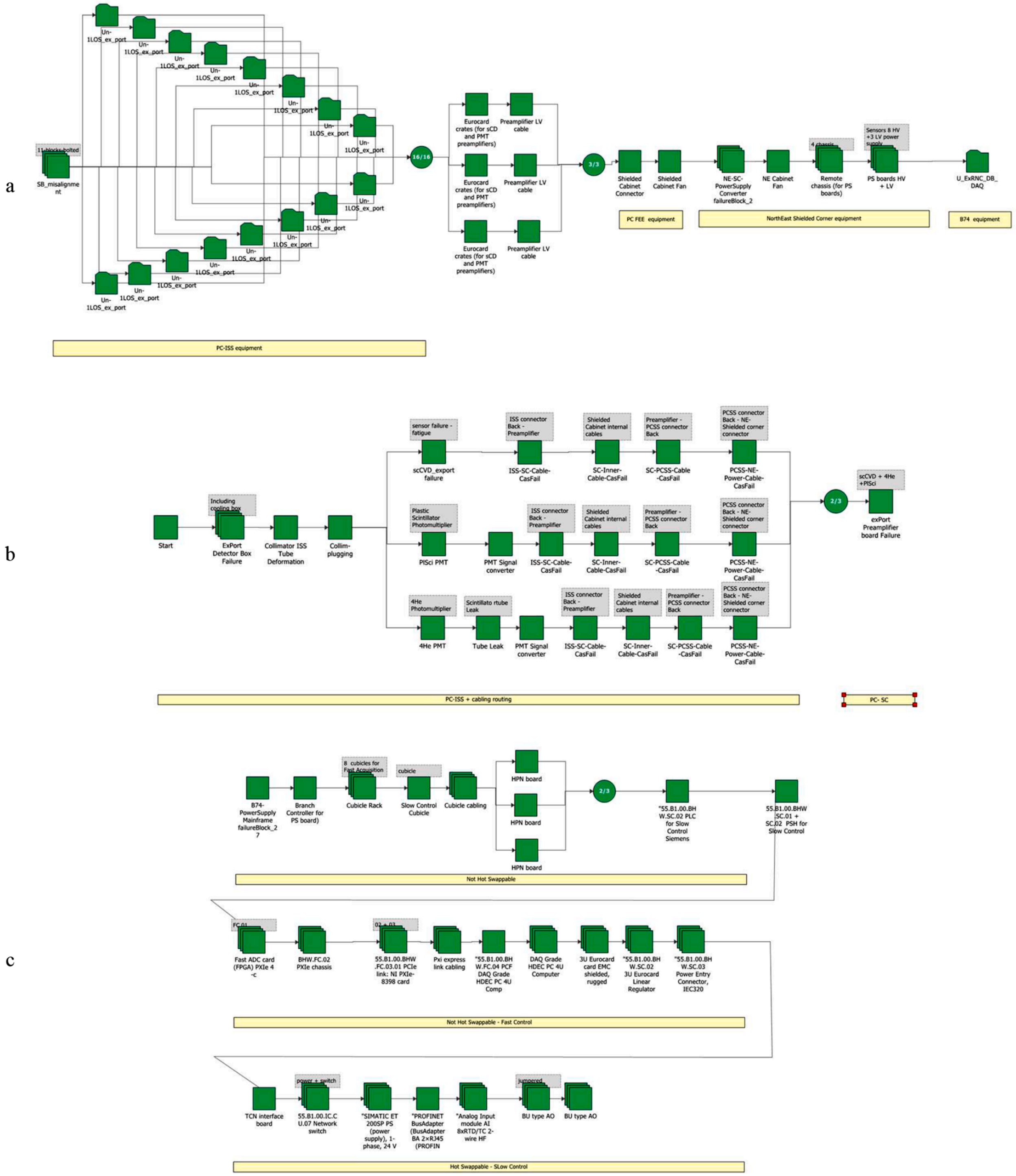

Fig. 3. RBDs for Ex Port RNC overall system (a), LOS RBD sub-diagram expanded (b), data acquisition equipment in diagnostic building B74 RBD sub-diagram expanded (c).

Fig. 2 reports an extract of RBD diagrams implemented to study the mean inherent availability performance of the In-port RNC sub-system, including related FEE and power supply in NESC area. It also reports the interface of In-port RNC subsystem with SVS.

Fig. 3 reports an extract of RBD diagrams implemented to study the mean inherent availability performance of the Ex-Port RNC sub-system. In this case, other than the Ex-Port RNC related FEE and power supply in NESC area, the RBDs include the BEE equipment for data acquisition and processing located in diagnostic building. Note that such equipment is shared between In-Port RNC and Ex-Port RNC sub-systems.

4. Results

The system mission time over which to provide neutron emissivity profile was assumed in 2 calendar years of continuous operations as stated from RAMI requirements. In particular, the equivalent continuous operation time with ITER machine in Plasma Operation State and RNC subsystems in acquisition mode was considered. So, assuming the average operational hours per year$= 4608\ \text{h}/y + 156\ \text{h}/\text{y}^{1} = 4764$ h, the total operational hours up to first LTM (16-month operation and 8 of LTM) to reach 2 years' target availability will sum up to $2\text{y}{*}4764\ \text{h}/y =$ 9528 h.

The In-Port RNC system mean inherent availability performance for above-mentioned 9528 h mission time simulated by means of RBDs in Fig. 2 (upper box) resulted to be 99.99 %. Note that this performance refers to the ability of the system to provide measurement considering the design redundancy, and according to the measurement loss definition described in Section 3.1.

The SVS interface Mean Inherent Availability was also studied by means of RBDs in Fig. 2 (lower right box), resulting into a 100 % performance at 9528 h, because of a MTTFF (h): 1.24×10^7, much higher than considered mission time.

A sensitivity analysis was performed on Ex-Port RNC system mean inherent availability performance at 9528 h, by means of RBDs in Fig. 3 (upper box). An 89.72 % Mean Inherent Availability performance was achieved when requiring all 3 detectors in all LOS functioning (CASE1). This performance is below the stated 99.5 % target requirement. So, a simulation was performed relaxing measurement accuracy constraint by requiring only 2 out of 3 detectors to function across all LOS (CASE2). In this case Mean Inherent Availability performance increased up to 97.66 %.

Note that the RBD model implemented for the Ex-Port RNC system (Fig. 3 lower box) includes the BEE Data AcQuisition (DAQ) equipment for the whole system (both In-Port and Ex-Port RNC). Such BEE DAQ system is still at preliminary design stage and neither a possible decoupling between In-Port and Ex-Port RNC DAQ processing equipment nor the feasibility of redundant architecture has been investigated. So, to estimate the potentiality of Ex-Port RNC to achieve the stated 99.5 % target, a simulation considering (CASE2) configuration and excluding BEE DAQ equipment contribution was performed. In this case Mean In. *Av*. performance accomplished a 99.66 %.

5. Conclusion

The In-Port RNC system, now at the final design stage, is compliant with the required mean inherent availability of 88.3 %, achieving 99.99 % mean inherent availability at 2-years thanks to design redundancy. For the Ex-Port RNC system, presently at the preliminary design stage, RAMI driven design optimization is still ongoing. The 89.72 % full configuration performance is below the required 99.5 % mean inherent availability at 2-years. Though when exploiting design redundancy in the number of LOS or available detectors per LOS RAMI, the Mean Inherent Availability performance gets close to the required target, achieving a 97.66 %. Note that an estimation of the impact of such degraded configuration operation on measurement accuracy is focus for future work. Moreover, the analysis has quantified the contribution of the BEE DAQ sub-system on Ex-Port RNC system. BEE DAQ system is in fact characterized by a high number of components with relatively low Mean Time Between Failure (MTBF). Future work will focus on possible design improvements in such sub-system by possibly: i) decoupling In-Port and Ex-Port RNC DAQ systems and ii) introducing a redundant configuration minimizing the risk of losing all data from a given LoS in case of failure of a single detector signal chain; iii) distribute onto different ADC board signal from same LoS. This way the redundancy existing in the In-Port and Ex-Port RNC systems for the detector sensors will also be reflected in the DAQ sub-system.

CRediT authorship contribution statement

Danilo Nicola Dongiovanni: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Francesco Belli:** Data curation. **Giorgio Brolatti:** Visualization. **Cristina Centioli:** Data curation, Writing – review & editing. **Silvia Cesaroni:** Data curation. **Basilio Esposito:** Funding acquisition, Project administration, Writing – review & editing. **Ryszard Kantor:** Data curation. **Jerzy Kotula:** Visualization. **Waldemar Maciocha:** Data curation. **Daniele Marocco:** Funding acquisition, Project administration, Validation, Writing – review & editing. **Domenico Marzullo:** Data curation. **Chiara Monti:** Data curation. **Fabio Moro:** Data curation. **Tonio Pinna:** Conceptualization, Data curation, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Basilio Esposito reports financial support was provided by Fusion for Energy. If there are other authors, they 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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fusengdes.2024.114209.

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