System Level Design and Performances of the ITER Radial Neutron Camera

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\textbf{Abstract.} The paper describes the work on the design of the ITER Radial Neutron Camera (RNC) performed by a consortium of European institutes within a framework contract placed by Fusion For Energy (F4E), the ITER European Domestic Agency. The RNC will measure the uncollided 14 MeV and 2.5 MeV neutrons from deuterium-tritium (DT) and deuterium-deuterium (DD) fusion reactions through an array of flux monitors/spectrometers located in collimated lines of sight (LOS) viewing the plasma through the ITER Equatorial Port Plug #1. The line-integrated neutron fluxes are used to evaluate, through reconstruction techniques, the radial profile of the neutrons emitted per unit time and volume (neutron emissivity) and therefore the neutron yield and the alpha particles birth profile. The RNC is presently at the System Level Design (SLD) stage, whose final scope is the definition of an Intermediate System Architecture (ISA) for the diagnostic to be put under configuration control. The goal is achieved through a System Engineering process in which different RNC architectural options are proposed and ultimately ranked according to selection criteria. The paper concentrates on the part of the process that, starting from the diagnostic functions, leads to the analysis of the RNC measurement performances during DD and DT operations. The analysis includes statistical and background errors only and is carried out using a set of DT and DD ITER plasma scenarios covering the required neutron emissivity measurement range.

\section{Introduction and background}

The main role of the ITER Radial Neutron Camera (RNC) is the measurement of the local profile of the plasma neutron emission (neutron emissivity, \textit{s}^{-1} \textit{m}^{-2}) for real-time plasma burn control; requirements for real-time neutron emissivity measurements ([1], [2]) are reported in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Neutron Emissivity Range & Time Resolution & Accuracy & Spatial Resolution & Role \\
(\textit{s}^{-1} \textit{m}^{-2}) & (\text{ms}) & & & \\
\hline
$10^{14} - 6 \times 10^{18}$ & 10 & 10\% & a/10 & Advanced control \\
\hline
\end{tabular}
\caption{Neutron emissivity measurement requirements.}
\end{table}

The RNC concept is based on collimated lines of sight (LOS) viewing a poloidal plasma section from ITER Equatorial Port Plug #1. Neutron flux monitors/spectrometers, located at the end of each LOS, provide line-integrated neutron flux measurements which, processed by means of inversion algorithms, enable the \textit{neutron emissivity} to be inferred. A well-defined volume (configuration model, CM) has been allocated to the RNC diagnostic to accommodate the LOS both in the port plug (In-port RNC sub-system) and in the port interspace (Ex-port RNC sub-system).

The System Level Design (SLD) of the RNC has been assigned in 2014 by Fusion For Energy (F4E), the ITER European Domestic Agency, to a consortium of European institutes coordinated by ENEA. The objective of the SLD activity is to identify a baseline RNC layout (Intermediate System Architecture, ISA) that will successively undergo detailed engineering
analysis for the definition of the diagnostic up Build-To-Print\(^1\) (BTP) level. A System Engineering approach has been adopted for the SLD assuming as RNC design driver the \textit{measurement of the neutron emissivity within the IO requirements assuring minimal shutdown dose rate in the interspace area}\(^2\) [3]; the main functions of the RNC are identified and based on such functions a set of RNC architectural options is chosen (Section 2); criteria are identified to score the capability of each option to reconstruct the \textit{neutron emissivity} in DD and DT ITER operation (Section 3); the measurement performances of the RNC options are evaluated by means of \textit{neutron emissivity} reconstruction algorithms and the best performing option is identified (Sections 3 and 4); RNC ISA is selected based on further refinements imposed by integration and cost constraints (Section 5).

2. Selection of RNC options

The process used for the selection of a set of RNC options foresees, as a first step, the identification of the top-level RNC functions, sub-functions and high-level components implementing the sub-functions (architectural elements). An initial set of RNC options is then defined by choosing different values for the architectural elements. A reduced set of RNC architectural options is finally selected by checking CM compatibility, signal to background (S/B) and additional external constraints.

Identification of RNC functions, sub functions and architectural elements: The top-level functions identified for the RNC are listed in Figure 1. The function “\textit{to perform measurement}” is chosen for the definition of the RNC options while the remaining functions act as design constraints. Its sub-functions and related architectural elements are also indicated in Figure 1; the list is ordered top-down, where the ranking reflects the impact of the sub-function on the definition of the RNC architectural options.

Definition of initial set of RNC options: The first three sub-functions of the top-level function “\textit{to perform measurement}” are used to define the initial set of RNC options. The space defined by the architectural elements of the first sub-function (\textit{To provide plasma coverage}) is scanned by varying the number and the distribution of the LOS within the two RNC subsystems (In-port and Ex-port) and the region of the plasma probed by the LOS. Four main plasma coverage configurations have been identified:

- \textit{MAXLOS}: maximum number of LOS compatible with CM. Two configurations have been considered: 20 Ex-port + 8 In-port as proposed in [4]; 20 Ex-port + 6 In-port.
- \textit{MINLOS}: minimum reasonable number of LOS: 8 Ex-port + 4 In-port.
- \textit{NO IN}: same plasma coverage as \textit{MAXLOS} but with no In-port RNC.

\(^1\) Drawings and/or manufacturing specifications for an item of sufficient detail to allow potential manufacturers to develop an accurate costing in response to a Call for Tenders for manufacture of the item.

\(^2\) Shutdown dose rate optimization is not discussed here since is the subject of an on-going integrated analysis, carried out in collaboration with the port integrator, that will include all port plug #1 diagnostics and penetrations.
• **CROSS**: options enabling neutron emissivity tomographic reconstruction within the RNC. In-port LOS are chosen so that all of them (MAXCROSS) or part of them (AVECROSS) cross Ex-port LOS. Ex-port plasma coverage is the same as MAXLOS.

All plasma coverage configurations have purely radial LOS with roughly uniform angular distribution (most natural choice to measure whatever emissivity profile). Ex-port LOS are divided in two fan-shaped sets located on two planes, toroidally separated by ~1.4° and poloidally interleaved. In-port LOS are divided in two fan-shaped sets located in the upper and lower part of a side drawer of the port plug.

The space defined by the architectural elements of the second (To provide field of view) and third (To detect particle/radiation) sub-functions is scanned by selecting various values of collimator diameter (d), length (L) and location along the LOS (i.e. focus to collimator distance, F) and by identifying a set of candidate detector types to be put in-line on each LOS. The detector choice is made on the basis of the experience on compact neutron flux monitors/spectrometers in present-day tokamaks: single unit scintillators with neutron/gamma discrimination capability (SC); matrix of single crystal diamond detectors (D) and parallel-plate multilayer 235U fission chambers (FC). The neutron efficiency is maximized for D (maximum thickness commercially available: 500 μm) and is chosen for the two other detector types (FC and SC) so that they, respectively, cover approximately one measurement decade above and below that of D (Table 2). FC is included as a back-up detector only, since it has higher S/B (no setting of energy threshold to reject scattered neutrons is possible) and no spectrometric capability; no performance analysis is carried out assuming the use of FC.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Code</th>
<th>Thickness</th>
<th>Energy (MeV)</th>
<th>Efficiency (counts/neutron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator</td>
<td>SC</td>
<td>1 μm</td>
<td>10 MeV (DT) - 1.8 MeV (DD)</td>
<td>(6 \times 10^8\times 10^6\times 10^6)</td>
</tr>
<tr>
<td>Diamond</td>
<td>D</td>
<td>2 mm (DT)</td>
<td>7.5 MeV (DT) - 0.3 MeV (DD) (deposited energy)</td>
<td>(5 \times 10^8\times 10^6\times 10^6)</td>
</tr>
<tr>
<td>U238 Fission Chamber</td>
<td>FC</td>
<td>2 mg/cm², 9 layers</td>
<td>-</td>
<td>(6 \times 10^8\times 9\times 10^6\times 10^6)</td>
</tr>
</tbody>
</table>

Table 2: RNC candidate detectors.

To scan the space of the Field of view architectural elements values of L compatible with the CM are selected while F and d are chosen so that the following conditions on plasma sampling and count-rate are met in all cases: the LOS sample the plasma uniformly as much as possible (i.e. fields of view of adjacent collimators are almost overlapping in the plasma center); the count rate in the detectors does not exceed approximately \(1 \times 10^6\) counts per second (1 MCPs) in ITER scenarios with highest emissivity (Section 3). This last figure guarantees a 1% statistical error on raw RNC measurements (assuming 10 ms time resolution), that is much lower than the required accuracy for neutron emissivity measurements (10%). Separate optimization of plasma sampling and count rate (C) is possible since, to a first approximation, C at the detector positions is independent of the location of the collimator along the LOS and only depends on d and L \((C \propto d/L^2)\).

In the case of Ex-port RNC, different values of L (2, 3 and 4 m) and options with collimators having the same or different diameters in the two Ex-port planes are considered; in the first case the collimator optimization is done for D while in the second case the optimization is done for D in one plane and for SC in the other. The MINLOS plasma coverage configuration is associated to the use of Ex-port adjustable collimators (rotating structures with 3 different diameters) given the larger space availability; in this case each collimator diameter has been optimized for a different detector (SC, D, FC). In the case of In-port RNC, due to space constraints imposed by the CM, a single set of optimized L, D and F values is considered for each plasma coverage configuration.

**Identification of final RNC architectural options:** the above analysis has led to the identification of 8 Ex-port and 5 In-port separate options. The consistency of such options with the CM has been checked through CAD analysis and possible integration issues arising
from interfaces with the Radial Gamma-Ray Spectrometer (RGRS, sharing some Ex-port LOS with the RNC) and High Resolution Neutron Spectrometer (HRNS, sharing the central Ex-port LOS with the RNC) diagnostics have been analyzed. The CAD optimization leads to modifications of $d$ and $L$ of Ex-Port edge LOS and to a significant reduction of the FC optimized $d$. As a final step of analysis, the $S/B$ for all CAD optimized options is evaluated using the following procedure: a) MCNP Calculation$^3$ of the spectra of uncollided (i.e. direct from the plasma through the collimators) and collided (i.e. scattered) neutrons at the detector positions in reference DD and DT scenarios (Figure 2); b) Folding of neutron spectra with the detector response functions to obtain the pulse height spectra (PHS) of uncollided/collided neutrons (Figure 2); c) Evaluation of $S/B$ as the ratio of uncollided to collided PHS counts above a fixed energy threshold: $S/B = \frac{PH_{uncoll}(E>E_{threshold})}{PH_{coll}(E>E_{threshold})}$.

![Figure 2. MCNP spectra (left), Scintillator PHS (center) and Diamond PHS (right) for a central RNC Ex-port LOS in ITER high power DT plasma. Vertical lines in PHS plots indicate energy thresholds used for $S/B$ calculations.](image)

Figure 3. Comparison between MCNP spectra of In-port options with 4 and 3 LOS viewing plasma edge.

The In-port option with 4 LOS probing the plasma edge has been discarded due to its lower $S/B$ compared to the 3 LOS case (Figure 3). The selection among the Ex-port options is made based on other criteria (no detectors in the bio-shield plug, easier manufacturing/assembly) since they are found roughly equivalent in terms of $S/B$. Details for the six final RNC architectural options are shown in Figure 4 (plasma coverage) and Table 3 (field of view).

![Figure 4. RNC architectural options (plasma coverage).](image)

<table>
<thead>
<tr>
<th>Option</th>
<th>Core to collimator distance (m)</th>
<th>Core to detector distance (m)</th>
<th>Detectors for (S/B)</th>
<th>Core to collimator distance (m)</th>
<th>Core to detector distance (m)</th>
<th>Detectors for (S/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINLOS</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>MAXLOS</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>MINX</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>MAXX</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>MINC</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>MAXC</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
<td>3.5</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. RNC architectural options (field of view).

$^3$ Calculations have been performed using F5 tally (point detector) and the following shielding materials: concrete (same type as in the ITER C-lite model for the Bioshield) in the Ex-port; B$_4$C (density: 2.52 g/cm$^3$) in the In-port. More details on MCNP calculations for RNC design can be found in [5].
3. RNC performance analysis tools, analysis procedure and scoring criteria

The neutron emissivity measurement performance of the 6 RNC options has been analyzed using a set of 4 ITER reference plasma scenarios (two DD and two DT) (Figure 5, [6]).

![Graph of measurement requirements.]

Figure 5. Reference neutron emissivity profiles used for performance analysis.

A 1D reconstruction code (constant emissivity on magnetic flux surfaces as from IO input emissivity profiles) developed in ENEA and based on Tikhonov regularization with first derivative objective functional (MSST, [7, 8]) is used as main tool for the analysis. Two additional codes are also used for crosscheck in a subset of cases: a 1D or 2D algorithm (rectangular mesh of pixels with preferential smoothness on magnetic surfaces) based on Tikhonov regularization with Minimum Fisher Information objective functional (MF, developed by the Institute of Plasma Physics of the Czech Academy of Sciences [9, 10]) and a 1D inversion algorithm based on neural networks (NN, developed in Uppsala University) whose results are summarized in [11].

The analysis follows a statistical approach. For each of the analyzed cases (plasma scenario/RNC option/time resolution):

- A large number of data sets (N=10^3), each representing a set of line-integrated RNC measurements (synthetic measurements) is created.
- The reconstruction algorithm is used to retrieve the corresponding set of N reconstructed emissivity profiles on M pre-defined magnetic surfaces (e_{ij}, i=(1, N), j=(1, M)). The maximum number of magnetic surfaces allowing real-time emissivity reconstruction within 1 ms (<<10ms ITER requirement) is used (M=20, i.e. spatial resolution a/20).
- Accuracy (A_j) and 1σ uncertainty (σ(A_j)) of the reconstruction at each radial position j are evaluated by comparison with the reference profile (e_{ref}) according to:

\[
A_j = \frac{\langle e_j \rangle - \langle e_{ref} \rangle}{\langle e_{ref} \rangle}, \quad \sigma(A_j) = \frac{\sigma(e)}{\langle e_{ref} \rangle}, \quad \text{with} \quad \sigma(e) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (e_i - \langle e \rangle)^2}
\]

(1)

The performance analysis is carried out including in the synthetic measurements only statistical errors and conservative S/B values from MCNP calculations (DT operations: 30 (In-port); 70 (Ex-port). DD operations: 5 (In-port); 20 (Ex-port)) and neglecting additional sources of noise such as those deriving from magnetic equilibrium reconstruction, solid angle evaluation, determination of detectors efficiency and LOS misalignment.

To quantitatively score the performance of each RNC option (O_k) a cost function is used:

\[
S(O_k) = \sum w_k f_k(FOM_k(O_k))
\]

(2)

where FOM_k(O_k) is a figure of merit (criterion) identified to score the option, f_k is the specific function of FOM_k used for the scoring (e.g. ratio of the FOM with respect to a reference value for FOMs to be maximized) and w_k is a weight assigned to the criterion. The most relevant FOMs used in the cost function are shown in Table 4, together with the associated weights assigned by consortium experts with the support of an Analytic Hierarchy Process.
4. RNC options performances

Figures 6-9 summarize the main results of the performance analysis. The top plots show the comparison between the reference emissivity profile and the average reconstructed profile with 1σ error, while the bottom plots report the accuracy of the reconstruction at each point along the profile with 1σ error. The detectors used for the reconstruction are also indicated.

![Figure 6. MSST Reconstruction results for DT HIGH scenario (10 ms time resolution). Light yellow shaded area in accuracy plots delimits 10% accuracy region.](image)

![Figure 7. MSST Reconstruction results for DT LOW scenario (10 ms time resolution).](image)

![Figure 8. MSST Reconstruction results for DD HIGH scenario (10 ms time resolution).](image)

![Figure 9. MSST Reconstruction results for DD LOW scenario (100 ms time resolution). Light blue shaded area delimits the region in which neutron emissivity is below measurement requirements.](image)

Some qualitative remarks arise from the analysis of the pictures:

- \( MAXLOSa \) and \( AVECROSS \) show best performances and behave similarly: the maximum \( r/a \) for reconstruction within requirements is \(~0.9\) in high power DT operations and \(~0.8\)
in low power DT operations; the high background of In-port detectors and the sharp emissivity peak in the plasma core restricts the reconstruction to r/a ∼ 0.1÷0.7 in high power DD while a relaxation of the time resolution down to at least 100 ms (considered acceptable by IO [2]) is needed to recover the 10% accuracy in low power DD.

- **MINLOS** accuracy results are similar to **MAXLOSa** but with much larger errors, suggesting that a factor ∼2 reduction of the number of LOS (11 vs. 26) should be avoided.
- **MAXLOSb** is outperformed by **MAXLOSa** in all scenarios except at high power DT operations: due to the choice of different diameters in the two **MAXLOSb** Ex-port planes (larger one optimized for D and smaller one optimized for SC) this option has one of the planes having less counts than **MAXLOSa**.
- **NO-IN** and **MAXCROSS** performances are equivalent and the worst of all options (r/a for reconstruction within requirements ∼ 0.75 in high power DT, progressively worsening at lower power), suggesting the need of In-port LOS viewing the plasma edge.

This analysis is confirmed quantitatively by the scoring obtained using the cost function: $s(\text{AVECROSS})=100$, $s(\text{MAXLOSa})=91$, $s(\text{MINLOS})=72$, $s(\text{MAXLOSb})=50$, $s(\text{MAXCROSS})=21$, $s(\text{NOIN})=6$.

Minimum Fisher 1D and 2D accuracy contours are depicted in **Figure 10** for **MAXLOSa** and the two crossing options in the **DT HIGH** scenario. Also MF 1D results indicate similar performances for **MAXLOSa** and **AVECROSS** (10% accuracy up to r/a ∼ 0.85) and worse performances for **MAXCROSS**. Moreover, comparison of MF 2D results reinforce the request for RNC LOS covering to the outer regions of the plasma (large worsening of accuracy in regions with missing LOS is indeed observed for **AVECROSS** and **MAXCROSS**). Note that 2D reconstructions, as expected, are worse than the corresponding 1D results since symmetry along magnetic surfaces is not imposed as a rigid constraint; on the other hand, 2D results are expected to be more robust against uncertainties on equilibrium reconstruction.

![Figure 10. 1D and 2D MF accuracy contours for a subset of RNC options (DT HIGH, 10 ms).](image)

**5. ISA selection**

Based on the 1D and 2D performance analysis, **MAXLOSa** has been initially considered as a suitable RNC ISA. However, further analysis has pointed out several problems: reduced performances due to a significant reduction of the diameters of the 3 lower and 3 upper collimators in the Ex-port right hand side plane (imposed by the most recent CM constraints); difficulty in alignment of Ex-port collimators with the corresponding port-plug optical paths, whose size is already the maximum allowed by the CM; high cost of D matrix detectors employed in all Ex-port LOS; integration/cost issues of SC employed in the In-port (e.g. complex cooling system needed during plasma operations and baking). As a consequence, to solve the above issues with no loss of performances, a modified **MAXLOSa**, with unchanged plasma coverage and different field of view/detector set has been adopted as RNC ISA (**Figure 11**):

- Ex-port: reduction of collimator diameters from 2 cm to 1.1 cm and use of 2 SC units (1 cm thick replacing the D detector matrix in high power DT operation and 10 cm thick replacing 1 cm thick SC in low power DT and DD operations). The new layout fits with the reduction of the diameters imposed by the CM, mitigates alignment issues and
reduces costs. Possible problems related to high count rate and radiation hardness of SC might be mitigated by the use of segmented detector units with separated read-outs.

- In-port: increase of collimator diameters from 2.5 cm to 3.2 cm and use of D to cover both DT and DD operation, with FC used as back-up detectors in high power DT operation. This solution enables In-port cooling only during baking and provides detector redundancy in high power DT operation. The drawback is the assumption of the feasibility of n/γ separation for D detectors, necessary in DD phase, and still to be fully demonstrated, as well as the increase in the expected count rate up to 6 MCps in high power DT operation (not a problem due to the pixelated nature of D).

![Diagram of detector system](image.png)

**Figure 11.** Details of Ex-port (left) and In-Port (right) RNC Intermediate System Architecture.

### 6. Conclusions

An intermediate system architecture for the ITER RNC is proposed. The choice is the result of a process in which the measurement performances of different RNC architectural options, defined according to a system engineering approach, are analyzed and scored against selection criteria. The analysis highlights the importance of In-port LOS viewing the plasma edge and the inadequacy of a number of LOS \( \leq 11 \). The proposed ISA, based on 26 LOS equipped with 2 detectors per LOS (scintillators in the Ex-port and diamonds/fission chambers in the In-port) has an Ex-port plasma coverage very close to that proposed in [4] and fulfills the ITER measurement requirements except in DD low power scenarios, where a reduction of the time resolution down to 100 ms appears necessary. The performance analysis, whose final aim is the selection of a best architecture, takes into account background and statistical errors only; more insight on actual RNC measurement capability shall be obtained by including additional sources of error.

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