Ion temperature profile measurements in ITER using the Radial Neutron Camera

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Introduction

The ITER Radial Neutron Camera (RNC) is a multi-channel neutron diagnostic with 45 collimated lines of sight (LOS) spanning a full poloidal plasma section [1, 2] (Fig.1): its main function is to provide the plasma neutron emissivity (S, n s^{-1} m^{-3}), by means of spatial inversion of the line-integrated neutron fluxes measured at the end of the collimators. In the present work, two different approaches are investigated to analyze the potential of using the RNC also as an ion temperature (T) profile monitor in the ITER DT standard H-mode scenario (scenario 2) at full power. Since simulations performed for this scenario suggest that the non thermal components of the neutron emission due to the NBI and RF are small (typically <3%) and, moreover, should not introduce substantial poloidal asymmetry in S [4], our analysis has been carried out in the thermal plasma approximation (i.e.: Gaussian-shaped neutron emission spectra with full width half maximum (FWHM) $\propto\sqrt{T}$ and constant neutron emission on the magnetic flux surfaces (ψ)). The first approach (*Method 1*) relies on the exploitation of the capability of liquid scintillator detectors of working as neutron spectrometers. These detectors are used in most of present-day neutron cameras, such as in JET [3], and are under consideration for the RNC. The second approach (*Method 2*) is based on the combined use of neutron emissivity and other plasma parameters' measurements.

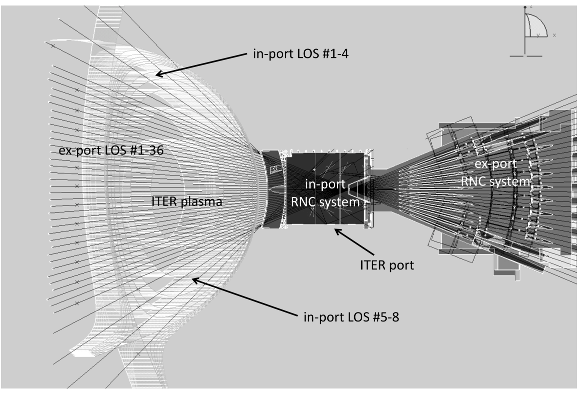

Fig. 1: RNC layout showing the 45 LOS distributed in an ex-port collimating structure (36 LOS for core plasma coverage) and two in-port collimating structures (9 LOS for plasma edge coverage).

Method 1

A neutron camera equipped with liquid scintillators (e.g. NE213) can provide a set of line-integrated pulse height spectra (PHS) each one representing the convolution of a line-integrated neutron spectrum with the detector response function (DRF) [5]. Unfolding techniques can be used to recover the line-integrated spectra, which, in turn, can just provide a *line-averaged* ion temperature profile. By combining energy unfolding with spatial inversion methods the *local* neutron emission spectrum (and hence a *local* ion temperature profile) can be derived instead. To test this new measurement technique a neutron source $g(\psi,E)$, consisting of Gaussian neutron spectra distributed on the poloidal plasma section, has been set up for ITER scenario 2, based on simulated T and S profiles [6] (Fig. 2a):

$$g(E,\psi) = \frac{S(\psi)}{w(\psi)\sqrt{\pi}} e^{-\left(\frac{E-E_{DT}}{w(\psi)}\right)^2} ; w(\psi) = \frac{177}{2\sqrt{\ln 2}} \sqrt{T(\psi)(keV)} ; E_{DT} = 14\,MeV \quad (1)$$

Integration of the neutron source along the RNC LOS has provided 45 line-integrated spectra. The temperatures values derived from these spectra indicate that line-integration introduces a non-negligible averaging effect: local and line-averaged temperatures differ by ~23% in the plasma core (Fig. 2a). The line-integrated spectra have been convoluted with the NE213 DRF (kindly provided by the *Physikalisch-Technische Bundesanstalt (Braunschweig-Germany)*); Poisson statistical errors depending on the detector's integration time (Δt) have been added to the energy bins of the PHS in order to simulate actual RNC measurements (synthetic measurements, SM) (Fig. 2b).

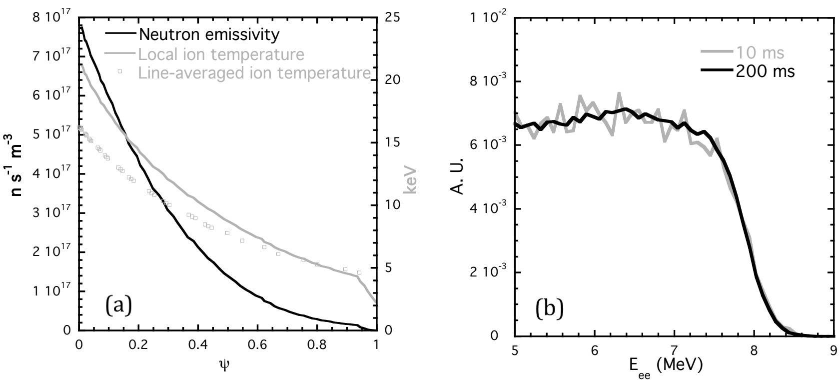

Fig. 2: (a) ITER scenario 2 S (black) and T (gray-solid) profiles together with the line-averaged T values viewed by the RNC LOS' (grey-dotted; ψ values correspond in this case to the intercepts of the LOS with a vertical axis passing through the magnetic axis); (b) Typical SM results for a central LOS at two different Δt values.

In order restrict the analysis to a region of expected low background a threshold corresponding to ~10 MeV neutron energy (equivalent electron energy (E_{ee}) ~ 5.2 MeV) has been set on the PHS'. The collimator diameters have been selected so that the neutron count rate for E_n>10 MeV in all RNC channels is ~1 MHz; this corresponds to a maximum total count rate, including scattered neutrons and gamma rays produced by neutron interactions, of ~3.9 MHz for E_n>1 MeV. The SM have been energy-unfolded using a forward convolution approach: a Gaussian spectrum has been folded with the DRF and its parameters varied until the difference between the resulting PHS and the SM is minimized [7]. A spatial inversion algorithm based on Thikonov regularization [8] has been applied separately to each energy bin of the 45 unfolded spectra, providing local neutron spectra and hence local temperature profiles. The whole procedure has been repeated several times at various Δt values to quantify the precision and the accuracy of the reconstruction and to compare them with the ITER requirements for the core ion temperature profile ($\rho<0.9$, 100 ms time resolution, 10% accuracy) [1]. The accuracy has been calculated as the absolute value of the difference between the average reconstructed and the original T values, while the precision as the standard deviation of the reconstructed T values around their mean. Results obtained after 40 runs performed at Δt= 100 ms indicate that both accuracy and precision can be kept below 10% up to $\psi\sim0.9$ suggesting that, under the mentioned assumptions and approximations, ITER measurement requirements can be met by the RNC (Fig. 3).

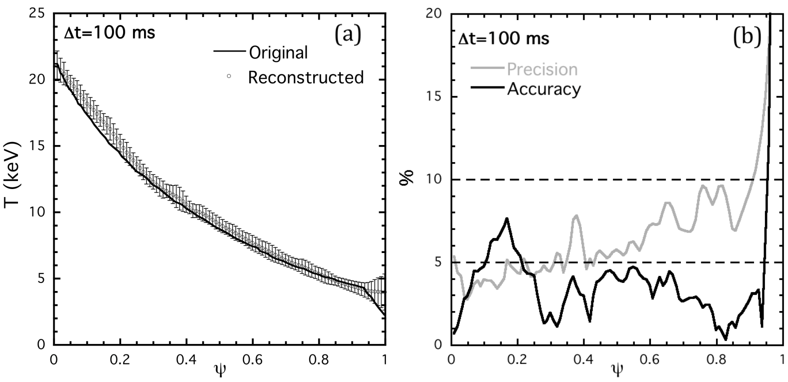

Fig. 3: (a) ITER Scenario 2 T profile (original) and average reconstructed T profile with standard deviation (reconstructed); (b) accuracy and precision of the reconstruction.

Work is on-going to assess the effects of the additional low-intensity spectral components due scattered neutrons (background) and neutral beam injection (NBI). Preliminary results suggest that the above results hold up to a background level (above 10 MeV) equal to ~ 1/500 of the thermal peak and to a NBI component having an integral equal to ~ 1% of the thermal component. If higher, these components should be included in the model with a consequent reduction in the achievable time resolution. Effects due to the high detector count rate (e.g. pile-up) are under investigation as well.

Method 2

In a thermal plasma with 50% deuterium and 50% tritium, S and T profiles are linked through:

$$S(\psi)=1/4 \times n^2(\psi) \times \langle\sigma v\rangle_T \qquad (2).$$

$n(\psi)$= ion density profile
$\langle\sigma v\rangle_T$= DT neutron reactivity (function of T)

An estimate of the ion temperature profile could be obtained in ITER from (2) using an analytical expression for $\langle\sigma v\rangle_T$ (e.g.: as given in [10]), S profiles from spatial inversion of RNC line-integrated flux measurements and n profiles from the combination of measured electron density (n_e), effective nuclear charge (Z_{eff}) and impurity density (n_k) profiles:

$$n(\psi)=c(\psi)\times n_e(\psi);\quad c(\psi)=\frac{Z_{eff}(\psi)-\sum_k z_k^2 n_k(\psi)\big/ z_k n_k(\psi)}{1-\sum_k z_k^2 n_k(\psi)\big/ z_k n_k(\psi)} \qquad (3).$$

k denotes the impurity species

To test this measurement approach synthetic measurements for S and n profiles have been set up based on ITER scenario 2 simulations [7] (providing S, Z_{eff}, n_e, n_{He}, n_{Be} (2%×n_e) and n_{Ar} (0.12%×n_e) profiles) and on ITER measurables ([1], Tab. 1); equation (2) has then been solved for T by means of a recursive algorithm. The synthetic measurements have been obtained by adding to the parameters in Tab. 1 a Gaussian noise with standard deviation equal the corresponding ITER requested accuracy. The achievable time resolution for this combined measurement is 100 ms (set by requirements on Z_{eff} and n_{He}/n_e).

Measurement	Parameter	condition	Range of coverage	Time resolution	Spatial resolution	Accuracy
Neutron emissivity	Neutron/α source		$1e^{14}$ - $4e^{18}$ $m^{-3}s^{-1}$	1ms	a/10	10%
n_e profile	Core n_e	r/a<0.9	$3e^{19}$ - $3e^{20}$ m^{-3}	10 ms	a/30	5%
Core He density	n_{He}/n_e	r/a< 0.9	1 - 20%	100 ms	a/10	10%
Impurity species monitoring	Be and Ar Rel concentrations:		$1e^{-4}$ - $5e^{-2}$	10 ms	Integral	10% (rel)
Zeff profile	Zeff	Default	1 - 5	100 ms	a/10	10%

Tab. 1: ITER measurement requirements for the quantities involved in the determination of T.

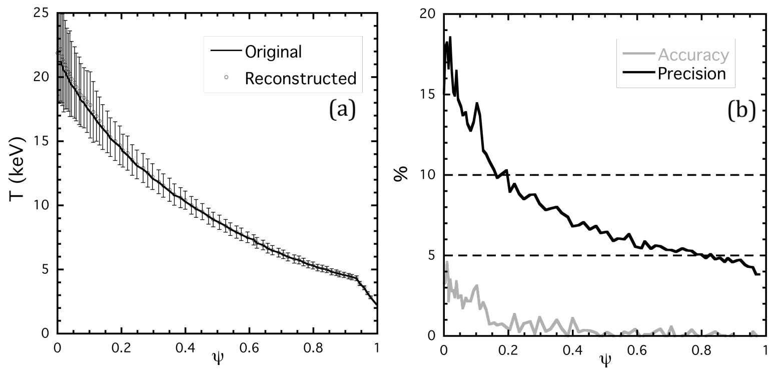

Fig. 4: (a) ITER Scenario 2 T profile (original) and average reconstructed T profile with standard deviation (reconstructed); (b) accuracy and precision of the reconstruction.

The results obtained after 500 runs (Fig. 4) indicate that, given the present target accuracy for n_e, Z_{eff} and impurity density profiles, and due to the strong variability of the neutron reactivity with temperature, the ITER requirements on T measurement cannot be fully matched using just the RNC line-integrated neutron flux information (precision above 10% for ψ<0.2 and reaching ~ 18% in the plasma core).

References

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