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ABSTRACT.

Two dimensional (2D) spatial profile and the temporal evolution of the 14MeV and 2.5MeV neutron emissivities from D-D and D-T fusion reactions were studied using the measurements of the upgraded neutron profile monitor during the last Trace Tritium experiments in JET. The JET neutron profile monitor provides unique capability for 2.5MeV and 14MeV neutrons line-integrated measurements simultaneously. A systematic comparison of D-D and D-T neutron emissivity was performed. The tritium concentration or fuel ratio \( n_T/n_D \) for a set of 30 ELMy-H mode discharges with Tritium puff was analyzed. Tritium concentration is deduced with a method based on the ratio of D-T 14MeV and D-D 2.5MeV neutron emissivities in order to exploit the maximum information available from neutron data. With the help of a tomographic algorithm, two dimensional (2D) spatial profiles of the tritium concentration in the plasma were obtained together with an estimate on the error bars. These profiles can be used to perform transport studies. Tritium core confinement clearly increases with plasma density for the set of discharges studied. Differences in the shape of these profiles are also found between low and high density plasmas. Close to the time of injection of the Tritium, two dimensional (2D) spatial profiles of the tritium concentration exhibit typical hollow profiles and in some cases, transient poloidal asymmetric features have been observed in 2D-images.

1. INTRODUCTION

In Trace tritium experiments, conditions are favorable to measure simultaneously 14MeV D-T neutrons and 2.5 MeV D-D neutrons emission. While it is easy to distinguish D-T neutrons from D-D neutrons, it is not possible to prevent the D-D neutron detection channel from responding to D-T neutrons. However, when the D-T neutron flux is the same order of magnitude than the D-D neutron flux [6], D-D neutrons may be satisfactorily distinguished. Therefore, recent Trace tritium experiments at JET offered a good opportunity to study simultaneously emission of 14MeV D-T neutrons and 2.5MeV D-D neutrons with the upgraded neutron profile monitor. It is demonstrated in this paper that it is possible to process the neutron measurements in such a way to derive direct information on important quantities such as the fuel ratio \( n_T/n_D \), i.e the tritium concentration. Tritium concentration profiles were obtained for a set of 30 ELMy-H mode discharges with Tritium puff. With the help of a tomographic algorithm, two dimensional (2D) spatial profiles of the tritium concentration together with the temporal evolution were achieved as well. Error bars are estimated which is an advantage of this approach. These profiles can be used to support or perform trace tritium transport studies.

Transport studies are the central point of focus and interest in Trace-Tritium diffusion experiments. This paper does not address transport issues which are well covered by several authors [23, 24]. The goal of this paper is to demonstrate the capability of the neutron profile monitor, combined with a specific method which will be described in the paper, to provide measurements of reasonably good accuracy of the tritium concentration with two dimensional (2D) spatial profiles and including the temporal evolution.
As will be demonstrated later in the paper, main advantages of this method are:

- no assumptions about tritium fluxes and sources are made
- it is rather insensitive to plasma profiles (temperature, rotation, $Z_{\text{eff}},...$)
- it is not sensitive to the beam deposition profile, beam slowing-down and beam power calibration

It is also worth mentioning that, the fuel ratio or tritium concentration is an important measurement for ITER and fusion reactor control. It is presently not clear and research is on-going to determine to what extent this information can be delivered in ITER with neutron measurements. Therefore it is an important research topic on the route to the reactor in the field of neutron diagnostics.

The paper is organized as follows. Section two describes the current neutron measuring device, i.e the neutron profile monitor which is used at JET to measure both spatial profiles and the temporal evolution of the 14MeV and 2.5MeV neutron emissivity respectively from D-T and D-D fusion reactions. Section 3 deals with experimental observations and with measurements of 14MeV neutron emissivity from D-T fusion reactions. Section 4 describes the procedure to combine neutron measurements and deduce Tritium concentrations. A key ingredient of the method, which is the D-D over D-T ratio of reactivities for beam-plasma fusion reactions, is calculated with several methods: numerical and analytical approximations. A sensitivity study of this ratio with respect to important plasma parameters is presented. In section 5, the tomographic algorithm is introduced. In section 6, a systematic comparison of spatial profiles of the 14MeV and 2.5MeV neutron emissivity from D-D and D-T fusion reactions is presented. In section 7, the results on the measurements of tritium concentration are shown. The accuracy is discussed and the procedure to estimate the error bars is outlined. A comparison case with a tritium profile obtained from other simulations is shown. Section 8 discusses the main features and properties of tritium concentration profiles, in particular the increase of tritium core confinement with density. Before a paper summary in section 10, images of two dimensional(2D) spatial profiles of tritium concentration are presented in section 9.

2. NEUTRON EMISSION PROFILE MONITOR

The neutron profile monitor (figure 1) is a unique instrument among neutron diagnostics available at large fusion research facilities. The instrument was well described before in several papers [4, 5]. In short, the system consists of 2 concrete shields of which each includes a fan-shaped array of collimators. These collimators define a total of 19 lines of sight, grouped in two cameras. The larger one contains 10 collimated channels with a horizontal view through the plasma while the smaller one has 9 channels with a vertical view. The collimation can be adjusted by the use of 2 pairs of rotatable steel cylinders. The size of the collimation can modify the count rates in the detectors by a factor 20 [7]. The plasma coverage is adequate for neutron tomography, although the spatial resolution is rough. Neighbour channels are 15-20cm apart and have a 7cm width as they pass near the plasma centre (see figure). Each line of sight is equipped with a set of three different detectors:
• a NE213 liquid organic scintillator with Pulse Shape Discrimination (PSD) electronics for simultaneous measurements of the 2.5MeV D-D neutrons, 14MeV D-T neutrons and \( \gamma \)-rays
• a BC418 plastic scintillator, rather insensitive to \( \gamma \)-rays with \( E\gamma < 10\text{MeV} \) for the measurements of 14 MeV D-T neutrons
• a CsI(Tl) scintillation detector for measuring the Hard X rays and \( \gamma \) emission in the range between 0.2 and 6MeV.

Each NE213 detector-photomultiplier unit sends output pulses to pairs of Pulse Shape Discriminators (PSD), one tuned for D-D neutrons and the other one for D-T neutrons, to distinguish neutrons from \( \gamma \)-ray induced events. These Pulse Shape Discriminators (PSD) have upper and lower energy detection biases set to detect preferentially unscattered neutrons and to reject scattered neutrons. The Bicron scintillators are located in front of the NE213 scintillators and are coupled to photomultiplier tubes via a light guide. They are sufficiently small that energetic gamma rays cannot deposit sufficient energy to produce a pulse greater than that produced by a neutron of 10MeV. Each Bicron detector has several lower energy detection thresholds to be set for the proton recoil energy providing different sensitivity to the scattered neutrons. The detector efficiencies depend on the scintillator geometry and the energy bias setting of the Pulse Shape Discrimination (PSD) electronics. The setting is controlled by recording the count-rates from a \(^{22}\text{Na} \) \( \gamma \) ray source which is mounted with the scintillator.

2.1. DYNAMIC RANGE, ACCURACY AND CALIBRATION OF NEUTRON EMISSION PROFILE MONITOR:

With electronic discrimination, it is possible to distinguish between neutrons and gamma rays if the count rates are not too high (typically \(< 200\text{kHz}\)). This sets a limit to the maximum count rate in the NE213 detectors. In a typical discharge with a Tritium puff (with a peak 14MeV D-T neutron emission of order \( 10^{16} \text{n/s} \)), the typical maximum count rate for NE213-D-T reached in a central channel is around 100kHz and only a few kHz in an edge channel [7]. This sets the limit for the time-resolution in the range of milliseconds. The intrinsic efficiency for D-D neutron detection was measured to an accuracy of about 5%. Further source of uncertainties include[7].

• solid angle: collimators were surveyed and do not introduce error larger than 5%
• Detector dead time: is typically \(< 15\% \) for NE213
• D-T contamination in D-D channel. The D-D channel has a detection efficiency for D-T neutrons of 0.49 times that of the D-T channel. The D-T contamination of the D-D channel is the largest correction and can be as large as 50%.
• Neutron backscattering (typically \( 2.10^{-4} \) times the total neutron yield for D-D and ten time less for D-T) and in-scattering in collimators
• Attenuation of magnetic shielding
The total uncertainty resulting from all these factors were calculated for the 10 horizontal channels and for a typical 50 ms time bin in reference [7]. With the exception of two bad channels (8 and 10), all channels have an error in neutron brightness less than 7%. For the bicron detectors, efficiency errors are estimated between 3% (for the best channels) up to 10% (for the worse channels) for both horizontal and vertical neutron camera. In section 5.2 of the paper, these factors will be used in the error analysis. The total neutron yield is measured at JET with a set of 3 fission chambers. The fission chambers are calibrated with activation foils. In turn, neutron emission profile is calibrated against the fission chambers[6]. More details on the performance and the calibration of the different neutron measuring instruments at JET during these experiments can be found in [28, 29]

2.1.1. Separation of 14 MeV D-T and 2.5 MeV D-D neutrons
As was mentionned in the above paragraph, D-T contamination of the D-D channel is the largest correction in 2.5MeV D-D neutron line-integrated measurements. A fraction of 14MeV D-T neutrons (both scattered and unscattered) is mis-counted as 2.5MeV D-D neutrons due to inherent detection principle of NE213 detector. In the case of NE213 detector, detection of neutrons is based on recoil protons. Recoil protons due to the 14MeV source span the whole energy range (0-14MeV) and recoil protons falling in the 2.5MeV energy window cannot be distinguished from recoil protons produced by 2.5MeV neutrons. In order to correct 2.5MeV D-D neutron line-integrated measurements, the contribution of 14MeV D-T neutrons is subtracted from the total number of neutron events recorded in the D-D window taking into account the spectrum of incident neutrons at the detector and the response function of the scintillator. In the case of a trace tritium experiment, this contribution is significant but not too large, thus enabling a correct separation of 14MeV D-T and 2.5MeV D-D neutrons. An accurate evaluation of this correction requires a measurement of the neutron spectrum, if available, or lengthy calculations involving the response function of each detector and calculation of neutron spectra at each detector-channel using Monte Carlo simulations of neutron transport. The latter was done for the 10 channels of the horizontal camera in above given reference [7]. A second approach, more practical and simpler, was preferred, for this paper, which is based on the property that these experiments are essentially perturbative experiments. As will be explained later in the paper, a small amount of Tritium is puffed in the plasma at a given time with no significant modifications of plasma parameters. In the phase preceding the tritium puff, the effect of residual amount of tritium on the 2.5MeV D-D neutron profiles can be neglected. In our procedure, last profiles of 2.5MeV D-D neutrons just before the tritium puff are used as reference profiles. In the case of significant contribution of 14MeV D-T neutrons into the D-D window, use of non-corrected 2.5MeV D-D neutron line-integrated data leads to somewhat lower tritium concentration with respect to the case of the use of the reference profile. In that case, use of the ‘reference profile’ is therefore recommended. As part of the future developments of the neutron profile monitor, improvements in processing detector events are foreseen, including the use of fast digitizing techniques[35]. This should allow a better separation of 14MeV D-T and 2.5MeV D-D neutrons.
3. LINE-INTEGRATED MEASUREMENTS: EXPERIMENTAL OBSERVATIONS

A set of 30 Elmy H-mode plasma discharges from the Trace Tritium experiments is investigated in the paper. The total neutron yield reached in these discharges and measured with fission chambers is in the range of $1.0 \times 10^{15} \text{s}^{-1}$ up to $5.0 \times 10^{16} \text{s}^{-1}$. The 14MeV D-T neutron yield is in the range from $1.0 \times 10^{15} \text{s}^{-1}$ up to $4.5 \times 10^{16} \text{s}^{-1}$ in the Tritium puff phase with a maximum of $4.4 \times 10^{16} \text{s}^{-1}$ for the Pulse No: 61110. The neutron yield domain explored for these discharges is illustrated in figure 2. For reasons that will be clear later in the paper, the discharges have been subdivided within 3 groups of different plasma density:

- low density $n_{e0} < 3.0 \times 10^{19} \text{m}^{-3}$
- medium density $3.0 \times 10^{19} < n_{e0} < 4.0 \times 10^{19} \text{m}^{-3}$
- high density $n_{e0} > 4.0 \times 10^{19} \text{m}^{-3}$.

All plasma discharges considered in this set are heated up with deuterium neutral beam injection with power ranging from a few up to 16 Megawatts of heating beam power. A subgroup of plasma discharges has additional auxiliary heating with Ion Cyclotron Resonance Heating (ICRH). The power is up to 6 Megawatts of ICRF power, with some of the discharges having a moderate fraction of ICRF power (less than 20%) and 2 discharges having a dominant fraction of ICRH power: Pulse No’s: 61110 and 61112.

3.1. TIME BEHAVIOUR OF 14 MEV D-T NEUTRON LINE-INTEGRATED MEASUREMENTS

When trace amount of Tritium is puffed into deuterium plasmas, only a relatively small fraction of tritium penetrates into the plasma core. About 10% of the Tritium goes inside the plasma while the rest of the Tritium goes into the wall or vessel tiles [11]. The 14MeV D-T neutron emission begins when reactions between fast deuterons and thermal tritium ions occur as tritium progressively diffuse towards the plasma core. The effect of a tritium puff on the 14MeV D-T neutron line-integrated measurements is well illustrated in figures (3) and (4). Normalized channel intensity of 5 channels of the 19 channels neutron profile monitor is shown versus time for the 3 pulses: Pulse No’s: 61118, 61372, 61374. In both figures, the delay between edge channels and central channels is seen. In figure 2, channels intensities are compared for Pulse No’s: 61118 and 61372. The delay before the effect of tritium puff is seen in the core of the plasma is about the same for both pulses. In contrast, figure 3 shows a comparison between Pulse No’s: 61372 and 61374 where delays are significantly different. In these two figures, horizontal camera channels 1 to 5 have been taken to illustrate the observations. Similar behaviour is found vertical camera channels.

3.2. POSITION OF MAXIMUM OF 14 MEV D-T NEUTRON EMISSIVITY

The figure 5 shows as function of time and near after the tritium puff injection, the position of the maximum of 14MeV D-T neutron emissivity as observed from the vertical camera. The full set of
discharges is shown in the plot. After Tritium injection, a shift of the maximum emissivity occurs from a central position (usually channel 15 or 14) towards channels located at the low field side: channels 16 to 18. After several hundred milliseconds the peak value of the profile returns to a central position. This shift is larger for some discharges and the higher the plasma density the higher the shift.

The figure 6 shows as function of time and near after the tritium puff injection time, the position of the maximum of 14MeV D-T neutron emissivity as observed from the horizontal camera and for the same set of discharges. After Tritium injection, a shift of the maximum emissivity occurs from a central position (usually channel 4 or 5) towards channels located at the upper side: channels 1 to 3. Although for 2 pulses this occurs towards channel 7 (bottom part). After several hundred milliseconds the emissivity profile returns to a central position of the maximum of emissivity. This shift is larger for some discharges and the higher the plasma density the higher the shift. Due to the profile ’hollow’ shape, two peaks are in fact observed. However, the maximum on the upper side comes higher more often. The average channel observed with horizontal camera similarly shows a shift during the puff.

3.3. WIDTH (FWHM) OF 14 MEV D-T NEUTRON EMISSIVITY PROFILE
Figure 7 shows as function of time and near after the tritium puff injection, the width (in fact the full width at half maximum) of 14MeV D-T neutron emissivity profile observed from the horizontal camera. The full set of discharges is shown in the plot. After Tritium injection, 14MeV D-T neutron emissivity profiles full width at half maximum starts to increase by 1 to 3 channels. After several hundred milliseconds the emissivity profile narrows down to return to or close to its initial width. The higher the plasma density is the broader the profile. Pulse No’s: 61110 and 61112 with low density and the highest fraction of RF heating have the highest peaking of neutron emission profile in the set of data examined.

3.4. SUMMARY OF OBSERVATIONS
Before proceeding to further analysis, the above observations on the 14MeV D-T neutron emission profiles can be summarized as follows:

- Time behavior of neutron channels: A delay of up to several hundred milliseconds is observed between edge and core channel reaching their maximum values. This delay varies from discharge to discharge and shows different behaviour of the Tritium diffusion towards the plasma core.
- Maximum of 14MeV D-T neutron emissivity: It is shifted towards low field side and upper vessel short time after the puff and returns later to a central position. The magnitude of the shift increase with density.
- Width of 14MeV D-T neutron emissivity profile: The full width at half maximum (FWHM) increases shortly after the puff an decreases later. The magnitude of the effect increases with density.
4. RATIO METHOD
This paragraph is intended to expose briefly the principles of the ratio method which will be used to
derive the tritium concentration or fuel ratio \(n_T/n_D\). The ratio method was first discussed in [12] and
subsequently refined for the interpretation of the first Tritium experiments at JET [3].

4.1. NEUTRON YIELD AND FUSION REACTIVITIES
The local neutron yield can be expressed as:

\[
Y(r) = \frac{n_A(r) n_B(r)}{1 + \delta_{AB}} \langle \sigma v \rangle_{AB}
\]

This is for a plasma containing ion species of types A and B where \(n_A\) and \(n_B\) are the particle densities
and \(\delta_{AB}\) is the Kronecker symbol. The reactivity \(\langle \sigma v \rangle\) is given by the six-dimensionnal integral:

\[
\langle \sigma v \rangle_{AB} = \int \int f_A (v_A) f_B (v_B) \sigma (|v_A - v_B|) (|v_A - v_B|) d\nu_A d\nu_B
\]

where \(f_A, f_B\) are the normalized velocity distributions of the reacting particles, \(\sigma\) is the cross section
of the fusion reaction considered and \((v_A - v_B)\) is the relative velocity.

4.2. DECOMPOSITION OF NEUTRON YIELD AND FUSION REACTIVITIES
The thermal particles in a plasma are considered to be in a thermodynamical equilibrium at a given
temperature. The use of injection of energetic neutral particles or ICRF heating or in general any
heating method in a Tokamak creates a population of energetic ions in the plasma. Given the energy
dependence of the cross-section, a fast deuteron will make a fusion reaction in a deuterium plasma
with a higher probability than a slow deuteron. It is customary[6], although arbitrary, to classify
fusion reactions into thermal-thermal \(Y_{th}\), beam-thermal \(Y_{bt}\) and beam-beam reactions \(Y_{bb}\).
The total neutron yield is a combination of these three components:

\[
Y (r) = Y_{bt} (r) + Y_{th} (r) + Y_{bb} (r) \tag{1}
\]

The emitted neutron spectrum is a combination of these three components as well. Experimentally,
neutron spectroscopy can help in measuring the amount of each component but this information is
not generally available except in few cases [27]. When experimental information from neutron
spectroscopy is not available, the contribution of each component must be calculated using complex
codes, TRANSP for example, or derived from approximate scaling laws [13].

<table>
<thead>
<tr>
<th>Pulse number</th>
<th>Beam-thermal (%)</th>
<th>Thermal (%)</th>
<th>Beam-beam (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61138</td>
<td>67</td>
<td>32.2</td>
<td>0.8</td>
</tr>
<tr>
<td>61372</td>
<td>74</td>
<td>24.8</td>
<td>1.2</td>
</tr>
<tr>
<td>61174</td>
<td>74</td>
<td>23.2</td>
<td>2.8</td>
</tr>
<tr>
<td>61132</td>
<td>88.6</td>
<td>7.6</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Break-up of D-D fusion-reaction contributions is given in the table below for a few pulses representative for the set of investigated discharges. The reported values are the result of TRANSP simulations.

Beam-thermal reactions $Y_{bt}$ are clearly the dominant contribution ranging from 60% up to 90% of the fusion reactions, thermal reaction account for 10% up to 30% of the reactions and beambeam reactions account for less than 5% of the reactions.

4.2.1. Thermal reactivity

The thermal reactivity $Y_{th}$ can be expressed in the following functional form [1, 2]:

$$<\sigma v> = C_1 \frac{\xi}{m_c^2 T^3} \exp(-3\xi)$$

$$\theta = \frac{T}{1 - \frac{T(C2 + T(C4 + TC6))}{1 + T(C3 + T(C5 + TC7))}}$$

where $T$ is the ion temperature in keV, the reactivity $<\sigma v>$ is given in $cm^3/s$, $B_G$ is the Gamov constant ($D-T$: $B_G = 34.3827 \sqrt{keV}$, $D-D$: $B_G = 31.3970 \sqrt{keV}$) and $m_c$ is the reduced mass of the particles in keV and $C_i$ are the fit parameters given in reference [2]. These fits are valid for ion temperatures $0.2 < T_i < 100keV$. The absolute uncertainties for the reactivities calculated from the best available cross sections are 3% for the D-T reaction and 6% for the D-D reaction.

In figure 8, the thermal reactivity as function of ion temperature in the range of interest for the $D(d, n)^3He$ reaction, the $D(t, n)\alpha$ are plotted together with the ratio of both of these reactions, i.e $D(d, n)^3He$ reactivity divided with $D(t, n)\alpha$. The values have been normalized to the last point at $T_i = 10keV$ for the purpose of a better illustration. The solid lines are reactivities obtained with the parametrization given in the formulas above. The data points (diamond) are obtained with numerical monte carlo calculations from the FPS code [15]. Both results differ by less than 5%. Both reactivity span a huge variation (8 orders of magnitude) when the temperature is increased from 0.2 to 10keV. Note that $D(d, n)^3He$ thermal reactivity grows faster at lower temperature. By contrast, the ratio of both reactivities varies much less in comparison with the variation in the individual D-D and D-T reactivities. It drops by a factor 5 and most of the decrease occurs below 1keV.

For modelling the neutron emission from relatively cold and dense plasmas, i.e High density Elmy- Hmode plasmas that we are studying in this paper, for large fraction of the plasma volume if not the whole volume the ion temperature is below ~3-4 keV, i.e. right in the middle of the fast varying zone of the thermal reactivity. To illustrate this, thermal reactivities in the ion temperature domain from 1 to 3keV are plotted in figure 9. An error of $\pm 10\%$ on the ion temperature propagates into a large error in the reactivity. For both $D(d, n)^3He$ and $D(t, n)\alpha$ reactions, thermal reactivity is changed by a factor 3. By contrast, the reactivity ratio is changes less than 5%.
To predict the absolute emission of thermal neutrons with a reasonable error bar in this temperature domain requires an accurate determination of the local ion temperature which is, in practice, difficult to get. In fact, it is easier to use the number of thermal neutrons emitted as a powerful constraint to check whether the ion temperature is consistent with the neutron emission.

4.2.2. Beam-thermal reactivity

Computation of fusion reaction rates have been discussed extensively in the literature by many authors. We can provide the reader for the following references [2], [19], [16], [17], [20], [18], [1], [15].

4.2.3. Analytical approximation to Beam-thermal reactivity

Several authors have elaborated useful analytical expressions for the calculation of beam-thermal reactivities. We will described briefly one analytical approximation to the beam-thermal reactivity[20] in this section. As we will show later, we will further develop this work into useful analytical expressions for the ratio method. The beam-thermal reactivity for a monoenergetic beam at a speed \( \sqrt{\gamma v_b} = 2E_b/m_b \) reacting with a Maxwellian plasma with a thermal speed \( \sqrt{\gamma v_{th}} = 2T/m_i \) is [20]:

\[
<\sigma v>_{bt} = \frac{2}{\mu v_b v_{th} \sqrt{\gamma}} \int_0^\infty S(E_{cm}) \exp \left\{ - \left( \frac{B_G}{v} + \left( \frac{v-v_{th}}{v_{th}} \right)^2 \right) \right\} dv
\]

where \( \mu \) is the reduced mass, \( B_G \) is the Gamov constant and \( S(E_{cm}) \) is defined as the slowly varying part of the cross section, see for example in [2]:

\[
\sigma(E_{cm}) = \frac{S(E_{cm})}{E_{cm} \exp \left( \frac{B_G}{E_{cm}} \right)}
\]

where \( E_{cm} \) is the energy in the center of mass frame. Integration above is performed with the Saddle-point approximation. The argument of the exponential is maximized at a speed \( v_* \) such that \( v_* \) satisfies the following cubic equation:

\[
v_*^2 (v_* - v_b) = v_{th}^2 B_G / 2
\]

Expanding the integrand in Taylor series about \( v_* \), neglecting higher order derivative of \( S \) and performing the integration, one obtains:

\[
<\sigma v>_{bt} \approx \sigma(E_*) v_* \exp \left\{ - \left( \frac{v_* - v_{th}}{v_{th}} \right)^2 \left( \frac{v_{th}}{v_{th}} \right) \right\} \left( 1 + \frac{\mu v_*^2 S'(E_*)}{4\gamma S(E_*)} + \frac{3(v_*^2 - v_{th}^2)}{2v_* v_{th}^2} \left( \frac{\mu v_*^2 S'(E_*)}{S(E_*)} - \left( \frac{v_{th}}{v_*} \right)^2 \right) \right)
\]

where \( E_* = \mu v_*^2 / 2 \) and \( \gamma = 1 + 2(v_* - v_{th})/v_* \).

4.2.4. Numerical calculation of Beam-thermal reactivity

Numerical calculation of Beam-thermal reactivity is usually performed with a Monte Carlo method. We refer the reader to [21] for an introduction to Monte Carlo Methods. One advantage of these methods is that it allows the computation of beam thermal reactivities with almost any sophisticated
models of fast ion velocity distribution functions. One disadvantage is the rather lengthy computational time involved.

Beam-plasma reactivities were calculated numerically with the FPS code [15] using different models of fast ion velocity distribution function for both D-D and D-T reactions. We then calculated the ratio of beam-plasma reactivity and we investigated the impact of the choice of the model for the fast ion velocity distribution on the reactivities and on the reactivity ratio. The results are summarized in the figure 10. Calculations have been done for the following model-types of ion velocity distribution function:

- Mono-energetic mono-directional pencil beam: a highly anisotropic distribution function representing a mono-energetic beam injected into the plasma under a well-defined angle with respect to the direction of the total magnetic field. The ions from the pencil orbit around the total magnetic field vector, resulting in rotational invariance in the distribution function of the reactant. However, the distribution function for this reactant varies with pitch-angle. The only parameters important for the distribution are the energy of the beam species, pitch angle of injected species, but the effect of plasma rotation can be optionally included by specifying a rotation velocity along the total direction of the magnetic field.

- Beam slowing down: An anisotropic distribution of initially mono-energetic beam-ions, injected at a pitch-angle theta, slowing down in a background plasma with a global electron temperature. No pitch angle scattering is introduced in this slowing-down distribution function. A reasonable assumption for as long as the beam ions have an energy close to the original injection energy and when the ions are probably most reactive. The following quantities need to be specified: initial injection energy, pitch angle of injection, electron temperature, effects of plasma rotation can be optionally included by specifying a rotation velocity.

- Beam slowing down with pitch-angle scattering: the following quantities need to be specified: initial injection energy, pitch angle of injection, electron temperature, $Z_{eff}$ and a rotation velocity.

The results are plotted in the figure 10 as function of the ion temperature. The reactivity ratio, i.e the D-D beam thermal reactivity over the D-T beam-thermal reactivity is shown in absolute value whereas individual D-T and D-D beam-thermal reactivities are multiplied by a constant factor for the convenience of illustration. To calculate correctly the D-T and D-D beam-thermal reactivities requires to take properly into account the slowing down of fast ions. Up to a factor of 4 to 5 difference appears between the case with and without slowing down. The values obtained with the analytical approximation are also shown on the figure. The figure shows that the reactivity ratio is much less sensitive to the detail modelling of the fast ion distribution function which is an advantage of the ratio method. Values for the reactivity ratio using analytical approximation deviate less than 3% with respect to the most sophisticated slowing down distribution case. The remarkable result here is that the ratio method does not depend on the slowing down properties of beam-ions and a rather simple analytical approximation is good enough to solve our problem.
4.2.5. Effect other parameters
We have investigated the effect of other parameters on the reactivity ratio. The effect of plasma rotation is illustrated in figure 11. Again the effect of plasma rotation, while influencing significantly both D-D and D-T beam-thermal reactivities, does not change significantly the reactivity ratio.

4.3. RATIO METHOD
In this section the formula used to calculate the tritium concentration or fuel ratio $n_T/n_D$ are described. We write equation 1 both for D-D 2.5MeV neutrons and for D-T 14MeV neutrons:

$$
Y(r)_{DD, bt} = Y_{DD}(r) - Y_{DD, th}(r) - Y_{DD, bb}(r)
$$

$$
Y(r)_{DT, bt} = Y_{DT}(r) - Y_{DT, th}(r)
$$

where $Y_{DT}(r)$ and $Y_{DD}(r)$ are the local neutron emissivities for D-D and D-T neutron respectively, which are measured with the neutron profile monitor. $Y_{DD, th}$, $Y_{DD, bb}$, $Y_{DT, th}$ are thermal and beam-beam corrections. Beam-beam corrections do not apply for D-T neutrons as the plasma pulses studied in this paper do not have injection of tritium beam or acceleration of tritons in the ion cyclotron range of frequency. The tritium concentration or fuel ratio is:

$$
n_T/n_D = \frac{Y(r)_{DD, bt} <\sigma_v>_{DT, bt}(r)}{Y(r)_{DD, bt} <\sigma_v>_{DT, bt}(r)} (1 + k(r))
$$

where $<\sigma_v>_{DD, bt}$ and $<\sigma_v>_{DT, bt}$ are the main components of the beam-thermal reactivities. They can be computed with the expression of the previous section. $k(r)$ is a correction function to take account of the various beam energies of the injector and half and third beam ions energies, and the deposition profile of fast ions.

5. TOMOGRAPHIC ANALYSIS
The neutron profile monitor system provides for a set of chord-integrated measurements from which 2-D images can in principle be obtained using standard tomographic methods and much less dependence on modelling. The general properties of tomographic inversion methods applied in plasma physics are reviewed in [8, 9]and [22]. Tomographic reconstruction of various neutron and gamma ray profiles have been presented[6, 30]. In this paper, we present 2-D images obtained from running a Minimum Fisher regularization algorithm. We have adapted for the neutron profile monitor a rapid version of this algorithm developed at TCV for inter-shot analysis. More information can be found in [10]. The comparison of the Minimum Fischer regularization method with other tomographic methods is beyond the scope of this paper and will be the subject of separate studies within the framework of fusion neutron profile measurements.

5.1. MINIMUM FISCHER REGULARIZATION METHOD
The Minimum Fisher Regularisation (MFR) is calculated within a simple but robust framework, suitable for sparse projections given by the neutron profile monitor: the emitting region is divided
into a number of finite picture elements or pixels within which the emissivity is assumed to be constant [8]. Each detector views a number of pixels and the signal \( P_i \) from the i-th detector is a linear combination of emissivities in the pixels \( g_j \):

\[
P_i = \sum_{j}^{N} A_{ij} g_j + \delta_i
\]  

(2)

where \( N \) is the total number of pixels, the matrix elements \( A_{ij} \) describe the contribution of the j-th pixel emissivity to the signal level in the i-th detector, and \( \delta_i \) represent data errors (both systematic and noise). The matrix \( A_{ij} \) is defined purely by the geometrical properties of the tomography setup and may be precalculated (notice that the plasma is transparent to neutrons). For the algorithm used in this work, the geometrical matrix \( A_{ij} \) was pre-calculated on a grid of \( 20 \times 40 \) pixels (size of grid element \( 90 \text{mm} \times 90 \text{mm} \)) and for negligible widths of viewing lines in the chord-integrated measurements.

The inversion of eq. 2 is an ill-posed problem, i.e. even small values of \( \delta_i \) can cause substantial distortions (artifacts) in the reconstructed emissivity pattern. Therefore, a regularisation is required. MFR belongs to so-called Philips-Tikhonov regularisation methods that constrain a norm of the solution, thus favouring a smooth reconstruction result. In the case of MFR, the smoothness is determined by minimising

\[
\Lambda_{\text{MinFisher}} = \frac{1}{2} \chi^2 + \lambda I_F
\]

where \( \lambda \) is a regularisation (smoothing) parameter and \( I_F \) the Fisher information of the emissivity distribution \( g_j \) [8]. The \( \chi^2 \) test includes, in case of the rapid version of the MFR algorithm, time averaging in addition to averaging over viewing lines:

\[
\chi^2 = \frac{1}{S} \frac{1}{M} \sum_{\tau} \sum_{j} \left( \frac{P_{i\tau} - \sum_{j} A_{ij} g_{j\tau}}{\sigma_i} \right)^2
\]

(3)

where \( M \) is the total number of detector chord-integrated measurements, \( \tau \) indexes the timeslices and \( S \) stands for the total number of timeslices. The regularisation parameter \( \lambda \) is determined so that residual misfit of the reconstructed emissivity does not exceed experimental data error bars \( \sigma_i \), i.e., \( \lambda \) is iterated until \( |\chi^2 - 1| < \lambda \epsilon \) is reached. Note that individual terms of the sum in eq. 3 can subsequently help to determine erroneous viewing lines and/or timeslices.

A considerable advantage of MFR is that the algorithm actually finds a single “inversion” matrix \( D_{ij} \). In case of the rapid version of MFR, this matrix is consequently applied to all timeslices within the analysed time interval which results in a speed gain:

\[
g_{j\tau} = \sum_{i}^{M} D_{ij} P_{i\tau}
\]

(4)

The inversion matrix \( D_{ij} \) is given by equation (26) in [8]:

\[
\mathbf{D} = \mathbf{U} \Lambda
\]

(5)
where \( \backslash \) means matrix left division that stands for a numerically advantageous equivalent of \( \mathbf{U}^{-1} \mathbf{A} \). The square matrix \( \mathbf{U} \) reads

\[
U_{ij} = \sum_{l} A_{il} A_{lj} + \lambda \sum_{k} B_{ik} w_{k} B_{kj}
\]

where \( B_{jk} \) is a smoothing matrix describing the influence of the \( j \)-th pixel on the \( k \)-th pixel, \( \lambda \) is the regularisation parameter and \( w_{k} \) are weighting factors, which describe the global and local smoothing levels, respectively. In MFR, the matrix \( B_{jk} \) corresponds to the first-order derivation operator imposed on a pixels grid so that it is, like the matrix \( A_{ij} \), constant for the given setup. Only parameters \( \lambda \) and \( w_{k} \) actually control the regularisation process and, in case of the rapid version, are time averaged. The weighting factors \( w_{k} \) serve to implement the constraint of Minimum Fisher information as shown in [8].

In practical terms, the effect of \( w_{k} \) is then to increase smoothing in low emissivity regions. This is particularly convenient for neutron emissivity studies, where signal to noise ratio is poor in the low emissivity regions.

On the other hand, the introduction of \( w_{k} \) limits accuracy of the rapid time-averaging approach in time intervals where sudden changes in the emissivity pattern appear. Therefore, whenever the results of rapid tomography indicate significant time dependence, a more careful step-by-step tomography reconstruction should be executed. On the other hand, renouncing to the time averaging process causes substantial increase in run-time and also apparent noise in the evolution of reconstructed emissivity [10].

5.2. ACCURACY OF THE TOMOGRAPHIC ANALYSIS

An advantage of 2-D tomography is that emissivity profile shapes do not require an initial profile specification and do not have to be constant along a flux surface. Hollow profiles and departures from constant emission on a flux surface have been observed with the profile monitor in the past [25], [6]. Some caution is needed in the interpretation of tomographic solutions. A solution \( n(r) \) which is found with the tomographic method is nearly always smoother than the actual emission profile. In other words, due to the finite spatial resolution of the profile monitor small scale spatial variations do not appear in the solution \( n(r) \) but major features are present.

Tests using model profiles, including 10% random errors, showed that peaked, flat, hollow, outwardly shifted, when reconstructed with 2-D tomography algorithm, reproduced the model profiles to an accuracy of 10%. In practice, to study the impact of the neutron measurements uncertainties described in section 2 of the paper, we proceed as follows: we apply a first variation to the input data such that central channel measurements are increased by 3 times their standard deviation (\( \sigma \)) and edge channels measurements are decreased by 3(\( \sigma \)). Then, we apply the opposite variation to the input data such that central channel measurements are decreased by 3 times their standard deviation (\( \sigma \)) and edge channels measurements are increased by 3(\( \sigma \)). This procedure is illustrated in figure 12. The resulting change...
in the tomographic reconstruction is shown in figure 13. The uncertainty in the neutron measurements has an impact mostly on the profile centre, the maximum of the profile is changed by $\pm 20\%$, keeping in mind that a 3 sigma variation is far too pessimistic. The profile edge is rather insensitive to measurement errors. The greater sensitivity of central region of the reconstruction to perturbations in the data is a typical feature of the Minimum Fischer algorithm.

6. COMPARISON OF D-T 14 MEV AND D-D 2.5 MEV NEUTRON EMISSION PROFILES

In figure 14, several neutron inverted profiles for discharges 61138 are shown; the D-D 2.5MeV and D-T 14MeV neutron profiles resulting from inversion of measured neutron emissivity profiles are plotted for a given time slice (t = 20.1s). 'Perturbed profiles' (see previous section) taking into account measurement errors are also plotted. The profile maximum heights have been normalized for the purpose of an easier comparison. D-D 2.5MeV and D-T 14MeV neutron emission profiles have identical position of the profile maximum, their widths are also equal within uncertainty, therefore in this typical case D-D 2.5MeV and D-T 14MeV neutron emission profiles are nearly identical. This result does not come as a surprise. The neutron emission is dominated by beamthermal neutrons and therefore both D-D 2.5MeV and D-T 14MeV neutron emission profile depend on the same beam deposition profile. The time slice (t= 20.1s) is not too close to the puff injection time (t = 19s) such that inward tritium diffusion has already taken place and the D-T 14MeV neutron emission profile has relaxed. In this typical example, the tritium concentration profile or fuel ratio $n_T/n_D$ is then expected to be rather flat.

6.1. SYSTEMATIC COMPARISON

As explained in the previous paragraph, if D-D 2.5MeV and D-T 14MeV neutron emission profiles are nearly identical in shape , the tritium concentration profile or fuel ratio $n_T/n_D$ is rather flat and on the contrary, if large departures exist between D-D 2.5MeV and D-T 14MeV neutron emission profiles, the tritium concentration profile or fuel ratio $n_T/n_D$ is not flat but is peaked, hollow or have an other shape. This motivated a systematic comparison study of D-D 2.5MeV and D-T 14MeV neutron emission profiles. The set of data is restricted only to pulses where 2.5MeV D-D neutron profile data are of outstanding quality at all time during the Tritium puff phase, i.e about 20% of the original data set. For this comparison, experimental raw data may be used as well as inverted data.

In figure 15, Full Width at Half Maximum (FWHM) of D-D 2.5MeV and D-T 14MeV neutron emission measured by the horizontal neutron camera are compared. The figure shows that D-T 14MeV neutron emission profiles have a Full Width at Half Maximum (FWHM) larger or equal than corresponding FWHM of D-D 2.5MeV neutron emission profiles. The points where full width at half maximum (FWHM) of D-T 14MeV neutron emission profiles are correspond in time slices close to the Tritium injection. If time slices near the Tritium injection are rejected, FWHM of both profiles are similar.
7. $N_T/N_D$ PROFILES
Two examples of tritium concentration or fuel ratio $n_T/n_D$ profiles are presented in order to illustrate a high density case and a low density case. Pulse No: 61161 illustrates a low density case. The tritium concentration or fuel ratio $n_T/n_D$ profile for Pulse No: 61161 is shown in figure 16. The tritium penetrates into the plasma core after the puff and reaches a peak concentration of tritium with respect to deuterium of 1.5%. This concentration in the plasma core is higher than the edge concentration. The high density case is illustrated with Pulse No: 61372. As shown in figure 17, the edge concentration of Tritium is higher and the core concentration reaches a maximum of about 0.7% with a flat profile.

7.1. ACCURACY OF $N_T/N_D$ FUEL RATIO PROFILE MEASUREMENTS
The correction due to thermal neutrons is shown in figure 18 for pulse # 61138. The impact of this correction is rather weak. In the core region and below $r < 0.15$ m the tritium density is reduced in the plasma core by 10 to 15% in the case of a fraction of 40% thermal neutrons which is an overestimation to the value given by TRANSP for this pulse (see Section 4.2). The fact that the thermal correction does not change significantly the Tritium profile comes as no surprise: the correction applies symmetrically on both D-T 14 MeV and D-D 2.5 MeV neutron profiles and is of the same order of magnitude. $S_{thDD} \sim n_D^2 <\sigma v>_{DD} \sim n_T^2 <\sigma v>_{DT}$ because $n_T$ is of the order of the percent of $n_D$ and the D-T thermal reactivity is two orders of magnitude larger than D-D thermal reactivity. The correction due to beam-beam neutrons has an impact only on the D-D 2.5MeV neutrons in the case of the discharges with Tritium puff. The impact of beam-beam neutron correction is larger than the impact of the thermal correction. From the plasma core up to about mid-radius the tritium concentration is increased by 10 to 15% for a beam-beam fraction of 20%. Beyond mid-radius the correction becomes very large, up to a factor of 2, at about $r = 0.7$ m, because the fraction of beam-beam neutrons becomes larger and larger towards the plasma edge. In practice, this is a large overestimation of the beam-beam neutron fraction. Discharges analyzed in this paper have beam-beam neutron fraction typically less than 5% (see Section 4.2) and therefore beam-beam corrections are not so important. To summarize the procedure to estimate the error bar: standard uncertainties from plasma parameters are included, neutron thermal, beam-beam and beam-thermal fraction are given from TRANSP simulation within 20% uncertainty and the perturbative procedure to the tomographic reconstruction is applied as described in the section 5.2. The total error bar resulting from these conditions were then computed.

7.2. COMPARISON WITH TRANSP/UTC PROFILES
Following the estimation procedure and the calculation of the error bars described before, the $n_T/n_D$ profile fully corrected is shown in figure 19, in the case of discharge 61138 at time $t = 20.1$s. It is in good agreement with the value obtained from a simulation of TRANPS/SANCO codes. Error bars are larger in the plasma core due to the fact that the tomographic reconstruction algorithm is more sensitive to perturbation in the core region. The deviation between the uncorrected ratio
and value corrected for thermal neutrons and beam-beam neutrons is respectively maximum 25% in the core region and maximum 30% in the outer region.

8. DISCUSSION

In this analysis, D-D 2.5MeV and D-T 14 MeV neutron emission profiles were combined simultaneously in order to exploit the maximum information available from neutron measurements. Best results are obtained when good quality 2.5 MeV neutron data are available, i.e D-D 2.5 MeV neutron emission profiles are left unperturbed by the Tritium puff. Pulses with strong heating in Ion Cyclotron Frequency Range (ICRF) were excluded from this study because the ICRF modification of deuteron velocity distribution function is important. Dedicated study have to be performed for those pulses.

8.1. DECAY OF TRITIUM PROFILES

In figure 20 the decay time of the core tritium concentration \( \frac{n_T}{n_D} \) versus the core electron density \( n_e \) is plotted. The plot shows that tritium core confinement time increases linearly with density. At higher density the scatter of points is larger. Pulses with pure beam heating are well aligned whereas pulses which have some fraction of ICRH heating (ICRH fraction lower than 20%) have a faster Tritium decay with the exception of 2 pulses (Pulse No’s: 61121, 61161) which do not behave as the others and do not give the same faster decay effect. Pulses with strong ICRH heating have been excluded from the density scan. For thoses pulses, ICRF modification of deuteron velocity distribution function is important. Transport of tritium gets slower when the plasma density increases. Possible explanations for the density effect are being reviewed in separate studies. To explain the inverse correlation of the tritium transport with density, one hypothesis[24] which has been proposed describes the tritium transport on the basis of test particle behaviour in a stochastic magnetic field.

8.2. SHIFT OF D-T 14MEV NEUTRON EMISSION PROFILES DURING TRITIUM PUFF

In section 3 of this paper, observations were presented about shift of the position of the maximum of D-T 14MeV neutron emission profiles. In reference[23], an interpretation is proposed for the horizontal shift towards the low field side during the tritium puff of the position of the maximum of D-T 14MeV neutron emission profiles. These profiles are characterized by a large number of trapped fast particles localized on orbits sitting on the outboard side. This source of D-T 14MeV neutrons is the initial source for the D-T 14MeV neutrons emission as the Tritium progressively penetrates into the plasma core. The magnitude of this shift increases with plasma density. With higher density, the fast particle density at the edge will be increased, therefore enhancing the effect. The vertical shift of the position of the maximum of D-T 14MeV neutron emission profiles which is observed with the horizontal camera is not understood so far. This reinforces the interest of performing tomographic analysis and obtaining 2-D images. It will be the subject of further detailed studies.
9. TWO DIMENSIONAL (2D) SPATIAL PROFILES OF THE TRITIUM CONCENTRATION

A 2D-image of the tritium concentration \( n_T/n_D \) profile is shown in figure 21. This 2-D image of a high density Elmy-H mode was obtained 270ms after the tritium puff. Reconstructed magnetic surfaces from EFIT are shown on the same plot. A significant departure of \( n_T/n_D \) contours from magnetic surfaces is visible at low field side and more pronounced at the upper part. Experimental data of this pulse are shown in figure 22 and figure 23. Backfitted data of tomographic reconstructions plotted on the same figures demonstrate the performance of our tomographic algorithm. However, caution is needed when interpreting this picture before more evidence can be collected. During the Trace Tritium experiments in JET, discharges which include a Tritium gas puff into sawtooth-unstable H-mode plasmas heated by deuterium beam were performed. 2D-images of the fuel ratio \( n_T/n_D \) profile would be valuable to study the effect of sawtooth activity on the transport of Tritium. Using the method presented in the paper would allow to clearly separate the effect on thermal Tritium and fast particles. In the set of 30 Elmy-H mode plasmas with Tritium puff some sawtooth-unstable discharges were identified but the quality of D-D 2.5 MeV neutron emission profiles for these discharges is not outstanding. Therefore, further preparatory work on these data is needed before they can be processed further. Effect of sawtooth activity on Tritium and fast deuterium evolution in trace tritium experiments on JET is discussed in [26].

SUMMARY

Using simultaneously D-D 2.5MeV and D-T 14MeV neutron emission, 30 Elmy-H mode discharges with Tritium puff from the last Trace Tritium experiments at JET were studied. Both D-D 2.5MeV and D-T 14MeV neutron emission profiles were examined with the goal to exploit the maximum information available from neutron measurements. Trace Tritium experiments gave favorable conditions for which D-D 2.5MeV neutrons are satisfactorily distinguished from D-T 14MeV neutrons. A coherent and original analysis method based on reactivity ratios was implemented in order to deduce the tritium concentration or fuel ratio \( n_T/n_D \). We presented the usefulness and advantages of the method. In particular for the reactivity ratio, the insensitivity of the method to the slowing down properties of beam ions was demonstrated and a simple analytical expression to solve the problem was proposed. Two dimensional (2D) spatial profile and the temporal evolution of the 14MeV and 2.5MeV neutron emissivities respectively from D-T and D-D fusion reactions were obtained from tomography. An horizontal shift towards the low field side of the position of the maximum of D-T 14MeV neutron emission profiles occurs during the tritium puff which can be explained by orbit effects of fast particles. A vertical shift of the position of the maximum of D-T 14MeV neutron emission profiles is seen by the horizontal camera as well for which the origin is unclear. Within experimental errors, D-D 2.5MeV and D-T 14MeV neutron emission profiles were observed to be similar in position and shape (FWHM), except for time close to Tritium puff. This is expected because the neutron emission is dominated by beamthermal neutrons and both D-D
2.5MeV and D-T 14MeV neutron emission profile depend on the same beam deposition profile. For time slices shortly after the Tritium puff, large departures between D-D 2.5MeV and D-T 14 MeV neutron emission profiles are observed due to Tritium diffusion.

Two dimensional(2D) spatial profiles of the tritium concentration were obtained giving good pictures of Tritium puffing. These profiles are useful for various purposes, including the support to transport analysis. We found that tritium core confinement time increases with density. For discharges having a small fraction of heating in the (ICRF) ion cyclotron frequency range, the confinement seems decreased. Clear differences between H-mode plasmas of different densities on the two dimensional(2D) spatial profiles of the tritium concentration are observed, in line with the results obtained from other simulations. A satisfactory comparison case during the decay phase of the tritium concentration profile between different approaches, our analysis method and TRANSP CODE, has been obtained, showing that the tritium behaviour in the plasma is described consistently by simulations and measurements. 2-D images during the penetration phase of Tritium show typical hollow profiles. In High density Elm-y H modes and for time close to Tritium puff, 2-D images exhibit significant departures of nt/nd contours from magnetic surfaces, being grounds for some more investigation in this direction.

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Figure 1: The JET neutron profile monitor. Channel numbers are indicated. The vertical (viewing) camera records the horizontal emissivity profile and vice versa.

Figure 2: Neutron yields: D-T 14MeV neutrons versus total for the set of 30 Elmy-H mode discharges studied. High density plasmas \( n_e > 4 \times 10^{19} \text{ m}^{-3} \) (blue data), medium density plasmas \( 3 \times 10^{19} < n_e < 4 \times 10^{19} \text{ m}^{-3} \) (green data) and low density plasmas \( n_e < 3 \times 10^{19} \text{ m}^{-3} \) (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars).

Figure 3: Normalized channel intensities (channels 1 to 5) of D-T 14MeV neutrons shown for Pulses No’s: 61118 and 61372
Figure 4: Normalized channel intensities (channels 1 to 5) of D-T 14 MeV neutrons shown for Pulse No’s: 61374 and 61372

Figure 5: Maximum of D-T 14 MeV neutrons channel intensity measured with neutron vertical camera (channels 11-19). 30 pulses database including high density plasmas $n_{e0} > 4.10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3.10^{19} < n_{e0} < 4.10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3.10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars). The right axis shows the corresponding approximate radial position in m.

Figure 6: Maximum of D-T 14 MeV neutrons channel intensity measured with neutron horizontal camera (channels 1-10). 30 pulses database including high density plasmas $n_{e0} > 4.10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3.10^{19} < n_{e0} < 4.10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3.10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars). The right axis shows the corresponding approximate vertical position in m.

Figure 7: Full width at half maximum (fwhm) of D-T 14 MeV neutrons emissivity profile measured with neutron horizontal camera (channels 1-10). 30 pulses database including high density plasmas $n_{e0} > 4.10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3.10^{19} < n_{e0} < 4.10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3.10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars). The right axis shows the corresponding approximate neutron source width in m.
Figure 7: Full width at half maximum (FWHM) of D-T 14MeV neutrons emissivity profile measured with neutron horizontal camera (channels 1-10). 30 pulses database including high density plasmas $n_{e0} > 4.10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3.10^{19} < n_{e0} < 4.10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3.10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars). The right axis shows the corresponding approximate neutron source width in m.

Figure 8: Thermal neutron reactivity as a function of ion temperature in the range of interest for the $D(d, n)\alpha$ reaction, the $D(t, n)\alpha$, and the ratio of both of these reactions, i.e. $D(d, n)\alpha$ reactivity divided with $D(t, n)\alpha$. The values have been normalized to the last point at $T_i = 10$keV. The solid lines are reactivities obtained with the parametrization given in [2]. The data points (diamond) are obtained with numerical monte carlo calculations from the FPS code [15].

Figure 9: Regions of uncertainty for thermal neutron reactivity corresponding to an error of 10% of the local ion temperature, for the $D(d, n)\alpha$ reaction, the $D(t, n)\alpha$, and the ratio of both of these reactions, i.e. $D(d, n)\alpha$ reactivity divided with $D(t, n)\alpha$.

Figure 10: Beam thermal reactivity at beam energy $E_{beam} = 80$keV plotted as function of ion temperature and for various models of fast deuterons distribution functions: 1) monoenergetic distribution, 2) anisotropic slowing down distribution, 3) anisotropic slowing down distribution with pitch angle scattering. Reactivities are computed with the FPS Monte-Carlo Code. An analytical formula for distribution (1) using Saddle-point approximation is also shown for comparison. True values are shown for the reactivity ratio. Normalized values are shown for D-T and D-D beam thermal reactivities for the purpose of better illustration. Values for the reactivity ratio using analytical approximation deviate less than 3% compared with the most sophisticated slowing down distribution case (3).
Figure 11: Effect of $v_{\text{rot}}$ on the Beam thermal reactivity at beam energy $E_{\text{beam}} = 80\text{keV}$ plotted as function of ion temperature for the $D(d, n)^{3}\text{He}$ reaction, the $D(t, n)^{4}\alpha$, and the ratio of both of these reactions, i.e $D(d, n)^{3}\text{He}$ reactivity divided with $D(t, n)^{4}\alpha$.

Figure 12: $D-T 14\text{MeV}$ neutron monitor profile data used for the tomography algorithm. 1) Dashed line is the actual measured profile. 2) More peaked profile: central channel measurements are increased by 3 times their standard deviation ($\sigma$) and edge channels measurements are decreased by $3(\sigma)$. 3) Less peaked profile: central channel measurements are decreased by 3 times their standard deviation ($\sigma$) and edge channels measurements are increased by $3(\sigma)$.

Figure 13: Tomographic reconstructions of $D-T 14\text{MeV}$ neutron profiles showing the sensitivity of the method to input data. Input data are shown in figure 12.

Figure 14: Plot of several neutron inverted profiles for Pulse No: 61138; D-D 2.5MeV and D-T 14MeV neutron profiles resulting from inversion of measured data and 'perturbed profiles' taking into account measurement errors (see previous section 5.2) for a given time slice (at $t = 20.1\text{s}$). The profile maximum heights are normalized for the purpose of an easier comparison.
Figure 15: Full width at half maximum (FWHM) of D-D 2.5MeV and D-T 14MeV neutron emission profiles given with the horizontal neutron camera. We use experimental data in this plot and not inverted data. High density plasmas $n_{e0} > 4.10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3.10^{19} < n_{e0} < 4.10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3.10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars).

Figure 16: Tritium concentration or fuel ratio $n_T/n_D$ profile for Pulse No: 61161. Mid-plane cut of 2-D spatial profile and temporal evolution during Tritium puff are shown.

Figure 17: Tritium concentration or fuel ratio $n_T/n_D$ profile for Pulse No: 61372. Mid-plane cut of 2-D spatial profile and temporal evolution during Tritium puff are shown.

Figure 18: Correction of $n_T/n_D$ profile due to thermal neutron fraction.
Figure 19: Fully corrected $nT/n_D$ profile obtained with our method with error bar estimation. It is compared with 1) the uncorrected $nT/n_D$ profile, 2) the TRANSP simulation of the same profile.

Figure 20: Characteristic decay time of the central value of the $nT/n_D$ versus the central value of the electron density $n_{e0}$. High density plasmas $n_{e0} > 4 \times 10^{19}$ m$^{-3}$ (blue data), medium density plasmas $3 \times 10^{19} < n_{e0} < 4 \times 10^{19}$ m$^{-3}$ (green data) and low density plasmas $n_{e0} < 3 \times 10^{19}$ m$^{-3}$ (red data). Heating scenarios are pure NBI (circles), ICRH dominant (diamond) and ICRH fraction lower than 20% (stars).

Figure 21: Two dimensional (2-D) spatial profile of the $nT/n_D$ profile at time = 14.27s obtained with the ration method combined with a 2-D tomography algorithm.
Figure 22: Measured and calculated (backfit of tomographic reconstruction) D-T 14MeV neutron profiles during beginning of Tritium diffusion phase for Pulse No: 61103.

Figure 23: Measured and calculated (backfit of tomographic reconstruction) D-D 2.5MeV neutron profiles for Pulse No: 61103.