IAEA nuclear fusion

PAPER

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To cite this article: M. Maslov *et al* 2018 *Nucl. Fusion* **58** 076022

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IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **58** (2018) 076022 (10pp) https://doi.org/10.1088/1741-4326/aac342

Observation of enhanced ion particle transport in mixed H/D isotope plasmas on JET

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Received 19 February 2018, revised 20 April 2018
Accepted for publication 9 May 2018
Published 4 June 2018

Abstract

Particle transport in tokamak plasmas has been intensively studied in the past, particularly in relation to density peaking and the presence of anomalous inward particle convection in L- and H-modes. While in the L-mode case the presence of the anomalous inward pinch has previously been unambiguously demonstrated, particle transport in the H-mode was unclear. The main difficulty of such studies is that particle diffusion and convection could not be measured independently in steady-state conditions in the presence of a core particle flux. Therefore, it is usually not possible to separate the transport effect(inward convection), from the source effect (slow diffusion of particles introduced to the plasma core by neutral beam injection heating).

In this work we describe experiments done on JET with mixtures of two hydrogenic isotopes: H and D. It is demonstrated that in the case of several ion species, convection and diffusion can be separated in a steady plasma without implementation of perturbative techniques such as gas puff modulation. Previous H-mode density peaking studies suggested that for this relatively high electron collisionality plasma scenario, the observed density gradient is mostly driven by particle source and low particle diffusivity $D < 0.5 * \chi_{\text{eff}}$. Transport coefficients derived from observation of the isotope profiles in the new experiments far exceed that value—ion particle diffusion is found to be as high as $D \geqslant 2 * \chi_{\text{eff}}$, combined with a strong inward convection. Apparent disagreement with previous findings was explained by significantly faster transport of ion components with respect to the electrons, which could not be observed in a single main ion species plasma. This conclusion is confirmed by quasilinear gyrokinetic simulations.

Keywords: plasma, tokamak, particle transport

(Some figures may appear in colour only in the online journal)

[a] See X. Litaudon *et al* [35].

1. Introduction

Particle transport in tokamaks has been the subject of a number of studies over the past two decades [1–11, 14–22]. Special interest was given to the density behaviour in H-mode plasmas—the principal scenario foreseen to achieve the ITER $Q = 10$ DT fusion power target. It is commonly agreed that the transport process is anomalous in nature, i.e. driven by turbulence, and significantly exceeds the collisional transport magnitude predicted by neoclassical theory. Quantitatively, radial particle transport (where density is constant on a magnetic flux surface) is usually described by a combination of diffusion D and convection V as follows:

$$\Gamma = -D\frac{\mathrm{d}n}{\mathrm{d}r} + Vn \quad (1)$$

where n is the particle density and $\boldsymbol{\Gamma}$ is the particle flux for any given species. It has been shown in a number of experiments that in L-mode plasmas a non-negligible inward convection often exists and causes plasma core density to significantly exceed the edge density, in other words a peaking of the density profile $n_e(\mathrm{core})/n_e(\mathrm{edge}) > 1$ even in the absence of a particle source in the core [2, 10, 11, 18, 19].

However, presence of the anomalous inward convection in H-mode plasmas has long been doubted. The underlying transport coefficients D and V cannot be measured independently in a steady state condition and therefore, whenever a significant particle source in the plasma core is present, usually introduced by neutral beam injection (NBI) heating, peaking of the density profile can be explained by either slow outwards diffusion of the deposited particles or inwards convection which would partially compensate for somewhat faster diffusion. Different interpretations of the observed density peaking lead to different extrapolations for larger plasmas with no core particle source, such as ITER.

Eventually the H-mode studies converged to a conclusion that anomalous inward particle convection in H-mode plasmas does exist but manifests itself only at low electron collisionality. This was determined by first-principles modelling [8, 9] and confirmed experimentally on C-MOD where H-mode plasma with peaked density profile was achieved with negligible core particle source [20]

In this work the effect of the NBI particle source on density peaking was studied using a novel approach. Experiments were done with plasmas composed of two hydrogenic isotopes: protium (H) and deuterium (D). NBI heating and therefore the core particle source was deuterium, while the background thermal plasma was hydrogen majority, with $n_H/(n_D + n_H)$ reaching the value of 0.86. These plasmas have a strong density peaking, although unlike in the usual single isotope case, we could now separate the beam fuelling effect from transport by observing how the D/H isotope radial profile varied from the edge to the core. We find that particle diffusivity calculated this way is significantly larger than the values derived from previous density peaking studies and significant inward convection is present, which makes the hydrogen isotope profile peaked even in the absence of the core particle source. It was concluded that observation of isotope density profiles allows us to evaluate ion particle transport coefficients which can be significantly different from those of the electrons without breaking the quasineutrality constraint. One of the outcomes is that while peaking of H-mode plasma density at high collisionality is mainly determined by the core particle source, peaking of individual ion components can be relatively insensitive to the source, i.e. determined by the transport and D/V ratio.

This paper organized as follows: in section 2 experimental results are shown together with an explanation of how isotope profiles can indicate the presence of inward particle convection; section 3 contains more accurate TRANSP analysis and derivation of particle transport coefficients; and in section 4 the results are discussed and stand-alone quasilinear gyrokinetic simulations with QuaLiKiz are shown to support the main outcome of this work.

2. Experimental results

Experiments were done on JET as a part of the isotope studies campaign in 2016. This work is focussed mainly on the JET pulses #91232 and #91227. Both pulses have plasma current $I_p = 1.4$ MA, toroidal magnetic field Bt = 1.7 T and 8 MW of additional NBI heating in deuterium (see figure 1). Both pulses had a stable H-mode of at least several energy confinement times, i.e. during the windows of interest indicated by the shaded grey areas in figure 1, the plasma can be considered to be in a stationary state. The principal difference between 91232 and 91227 is in the H/D isotope composition. #91232 was fuelled with gas dosing of 1.3×10^{22} electrons s^{-1} of pure hydrogen and #91227 was fuelled with similar total gas dosing rate but split equally between hydrogen and deuterium. Neutral beam heating introduced deuterons and electrons into the plasma at a rate of ~9.3×10^{20} electrons s^{-1}.

Edge plasma isotope composition is measured routinely by comparing the relative amplitude of Balmer Hα/Dα spectral lines with two spectroscopy diagnostics. One observes the plasma edge directly, and the other measures the composition of the subdivertor neutral gas via spectral analysis of a penning gauge discharge. Both measurements agree very well in these two pulses, indicating the isotope composition of $n_H/(n_D + n_H) = 0.86$ for the maximum hydrogen dosing (#91232) and $n_H/(n_D + n_H) = 0.33$ for the mixed H/D dosing pulse (#91227).

There is no direct measurement of the core isotope composition available, so it was necessary to derive this from modelling of the total neutron emission rate and comparison of this quantity with measurements. Neutrons are produced dominantly by reactions between the fast NBI deuterons with the plasma thermal deuterons and the source is concentrated in the plasma core. Therefore, the neutron emission rate for particular input NBI power and total ion and electron density profiles is roughly proportional to concentration of deuterium in the core region.

In this study, the dilution of hydrogenic isotopes in the core is used as an indicator of the transport processes in the plasma and can be understood by consideration of the following arguments. NBI heating deposits electrons and deuterons in the plasma core at equal rates (see section 3 for a more detailed analysis of particle sources), therefore in a stationary state

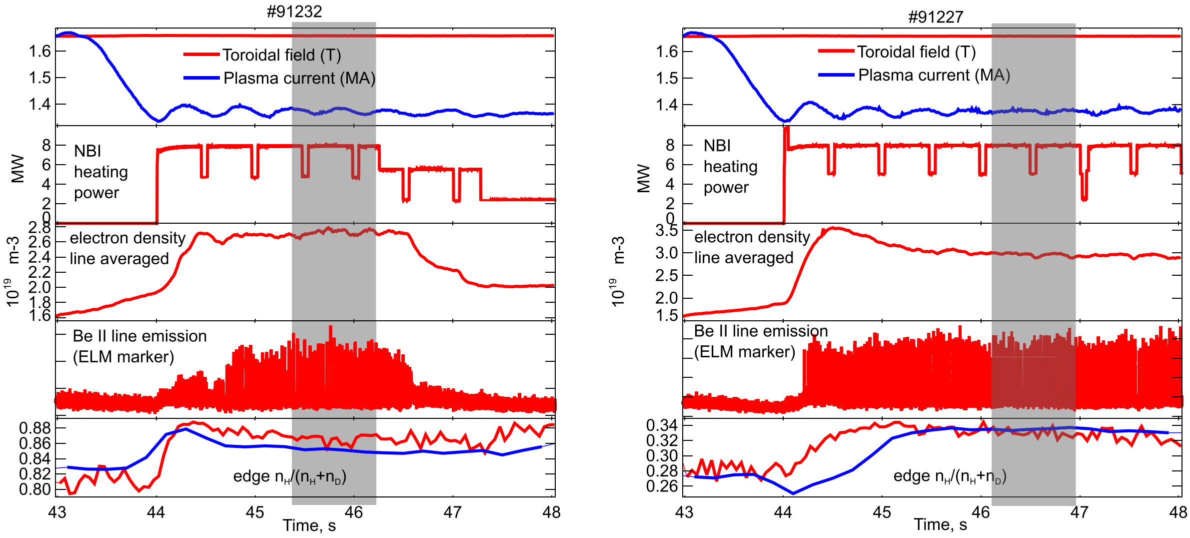

Figure 1. Overview of #91232 and #91227 with the edge isotope compositions as measured by two different methods.

there is a constant outward flow of deuterons and electrons ($\mathbf{\Gamma}_\mathrm{D} = \mathbf{\Gamma}_\mathrm{e}$), and zero net particle flux of hydrogen ($\mathbf{\Gamma}_\mathrm{H} = 0$). In the absence of the convection term in equation (1), i.e. in the case of purely diffusive particle transport, this means that $\nabla n_\mathrm{H} = 0$ and $\nabla n_\mathrm{D} = \nabla n_\mathrm{e}$. In plasmas with strong density peaking i.e. a large density gradient, this leads to a significant increase of deuterium concentration in the core compared to the edge, i.e. core accumulation of the deuterium ions deposited by NBI heating. Note that in this paper we define $\nabla \equiv \frac{\mathrm{d}}{\mathrm{d}r}$, to maintain clarity of exposition.

Introduction of an inward convection V into equation (1) requires an increase of the diffusion necessary to keep the net particle flux the same. There is an infinite number of combinations of D and V which would produce the same electron density profile and yield the same net outward particle flux that is equal to the total number of particles deposited by NBI, thus D and V cannot be determined separately. Ultimately, with very large V and D, the effect of the particle source becomes negligible and the observed density gradient length will be determined mainly by the V/D ratio

$$\frac{\mathrm{d}n/\mathrm{d}r}{n} = \frac{V}{D} - \frac{\Gamma}{nD} \approx \frac{V}{D}, \text{for} \quad D \gg \Gamma/n. \qquad (2)$$

This is the case of density gradient (peaking) purely driven by the transport.

As was already mentioned, by observing a steady state density profile and in the presence of a particle source, one cannot distinguish between source or transport driven density peaking cases or any combination of the two. Nonetheless, in the case of isotope mixtures with very different particle source profiles, different particle transport models will result in different steady state isotope profiles. Indeed, in the case of purely diffusive transport we will have $\nabla n_\mathrm{D} = \nabla n_\mathrm{e}$, $\nabla n_\mathrm{H} = 0$ and $n_\mathrm{D}/n_\mathrm{H}(\mathrm{core}) \gg n_\mathrm{D}/n_\mathrm{H}(\mathrm{edge})$, but in the presence of a strong convection $\nabla n_\mathrm{D}/n_\mathrm{D} = \nabla n_\mathrm{H}/n_\mathrm{H} = \nabla n_\mathrm{e}/n_\mathrm{e}$ and $n_\mathrm{D}/n_\mathrm{H}(\mathrm{core}) = n_\mathrm{D}/n_\mathrm{H}(\mathrm{edge})$, as shown in figure 2. Therefore, by observing how isotope concentration in the core differs from the edge, one can separate the source effect from the particle inward convection and derive the actual values of D and V.

Returning to the comparison of pulses 91227 and 91232 it is observed that the weak dependence of confinement on the effective isotope mass observed in these H/D mixture plasmas (reported in [12]) results in the kinetic profiles of both pulses being nearly identical (figure 3) despite a significant difference in the isotope content as measured at the plasma edge. Density of the D-rich pulse is about 10% higher, although the effect on flux surface averaged fast ion deposition is negligible. There is a measurable difference in T_i between the pulses, presumably due to the difference in the electron/ion heating ratio produced by NBI: ion drag force and therefore P_ion in hydrogen plasma is stronger.

Despite the similarity between the pulses, there is a factor of ~3.5 difference in the neutron rate, ~6.17×10^{14} versus ~1.77×10^{14} neutrons s^{-1} (see figure 4). To properly estimate the difference in the core D concentration between the two pulses, one needs to take into account the reactions between the NBI fast ions deposited in the plasma core, so-called beam–beam neutrons. Due to a low concentration of the NBI fast ions in the plasma, these reactions usually contribute only a small fraction (<10%) of the total with the dominant contribution being beam–target (>90%). In the case of the hydrogen-rich pulse #91232, where the majority of thermal plasma ions consist of non-fusing hydrogen, beam–beam reactions become non-negligible. These reactions happen at about the same rate even in the absence of thermal deuterium in plasma, i.e. they set a minimum neutron rate which will be measured in plasma with close to zero D concentration. Interpretive analysis using the TRANSP code [13] gives a number of 0.45×10^{14} n s^{-1} for beam–beam reactions in 91232 (see section 3), therefore the difference in $n_\mathrm{D}/(n_\mathrm{D} + n_\mathrm{H})$ in the core between the two pulses should be of the order of (6.17–0.45)/(1.77–0.45) = 4.3. The difference in the edge value of $n_\mathrm{D}/(n_\mathrm{D} + n_\mathrm{H})$ between these two pulses is measured as 0.67/0.14 ~4.8, i.e. a very similar number. It brings us to a conclusion that peaking of hydrogenic isotopes in these plasmas behaves close to what is shown in figures 2(*c*) and (*d*), i.e. must be dominantly transport driven. Note that the difference in T_i between the two pulses does not change the

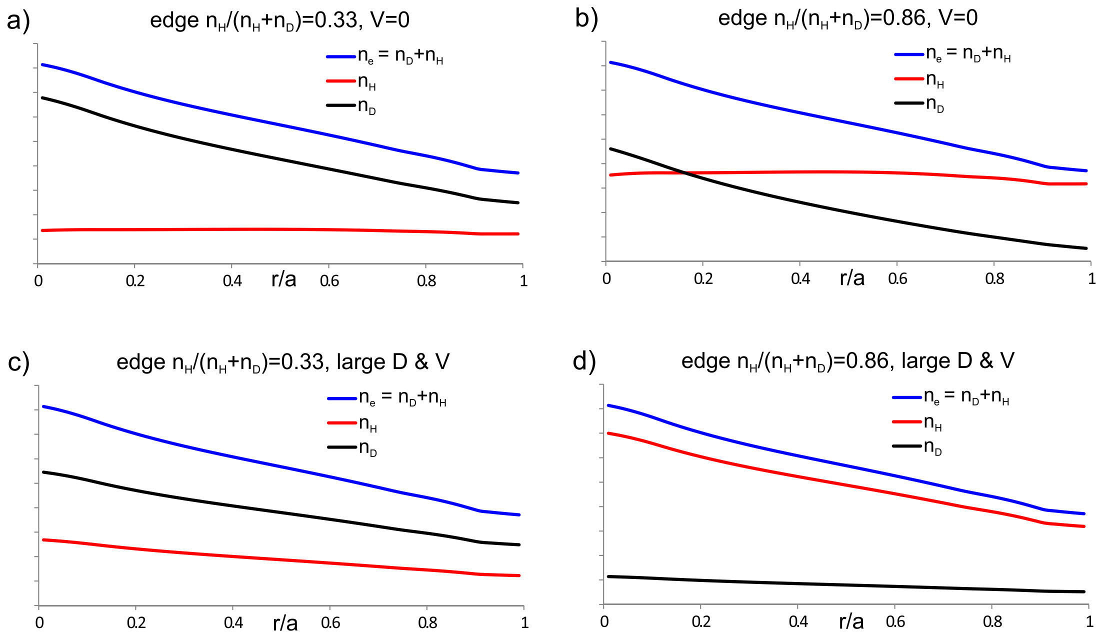

Figure 2. Illustration of possible H/D isotope profiles with two different edge values of $n_H/(n_D + n_H)$ and two opposite transport behaviours: purely diffusive (*a*) and (*b*) and with large *D*&*V* (*c*) and (*d*).

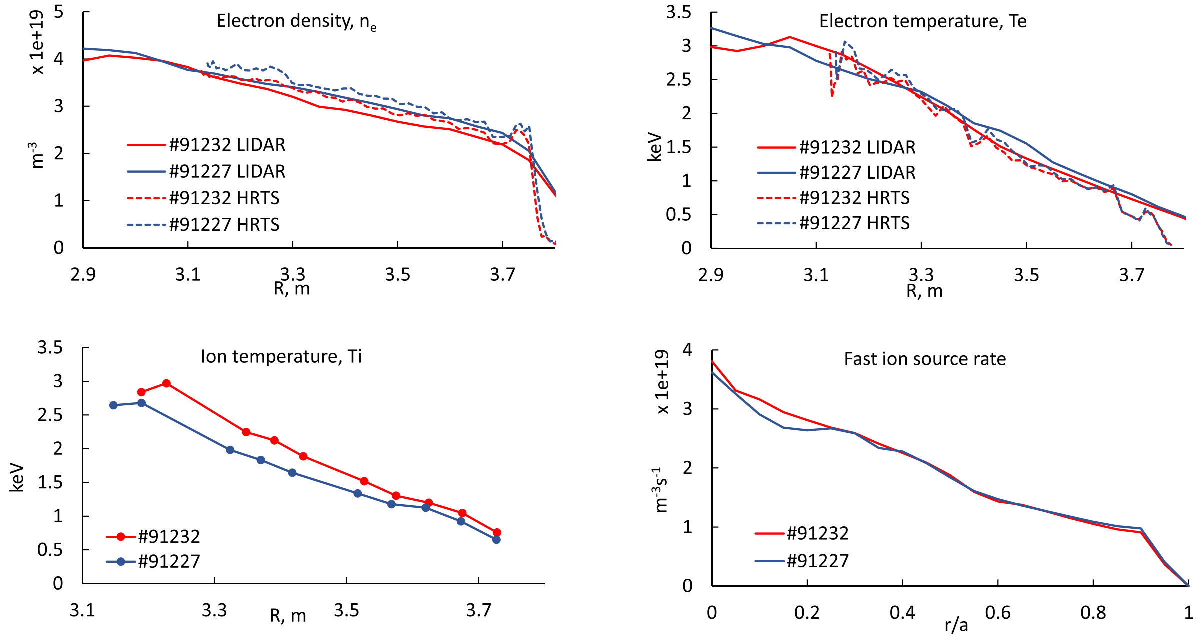

Figure 3. #91232 ($t = 45.2$ s–46.2 s) versus #91227 ($t = 46.2$ s–46.9 s) radial profiles overlapped, averaged over their respective time windows of interest. Electron density and temperature are measured by two different Thomson Scattering diagnostics, T_i by the charge exchange diagnostic and the fast ion source rate is calculated by PENCIL [33] code using HRTS profiles as input for n_e and T_e.

conclusion but strengthens it, since high T_i and consequently higher potential for beam–target fusion is observed in the pulse with the *lower* neutron rate.

If it is assumed that hydrogen particle transport coefficients only depend on plasma parameters and therefore are roughly the same in these two pulses, then peaking of the hydrogen isotope profile should also be the same due to the absence of hydrogen sources in the core, and therefore it shall only depend on V_H/D_H. Using that information together with the difference in the measured edge $n_H/(n_D + n_H)$ in these pulses we can find the actual core deuterium concentrations by solving the following simple equations:

$$n_H(\text{core})^{91227} \big/ n_H(\text{core})^{91232} = n_H(\text{edge})^{91227} \big/ n_H(\text{edge})^{91232} = \frac{0.33}{0.86} = 0.384$$

$$n_D(\text{core})^{91227} \big/ n_D(\text{core})^{91232} = \left(1-n_H(\text{core})^{91227}\right) \big/ \left(1-n_H(\text{core})^{91232}\right) = 4.3.$$

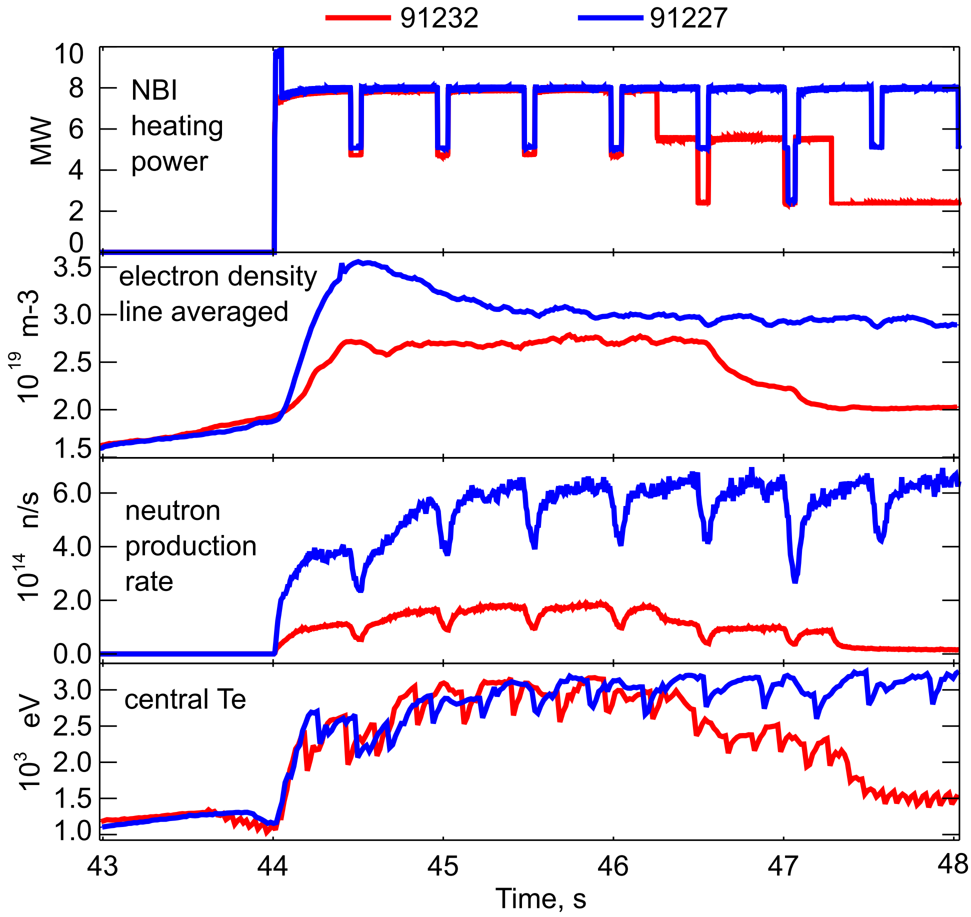

Figure 4. 91232 versus 91227 time traces overlapped: same T_e, 10% different n_e and large difference in the neutron rate.

The answer is given in table 1. Note that although this calculation is rough, it does not rely on the absolute neutron calibration and should be insensitive to the ‘neutron deficit’—mismatch between predicted by TRANSP and measured neutrons sometimes observed in JET plasma simulations [15].

Table 1. Measured and calculated edge and core D/H isotope concentrations.

Pulse number	91232	91227
$n_D/(n_D + n_H)$ edge—measured	0.14	0.67
$n_H/(n_D + n_H)$ edge—measured	0.86	0.33
$n_D/(n_D + n_H)$ core—derived	0.157	0.676
$n_H/(n_D + n_H)$ core—derived	0.843	0.324

3. TRANSP analysis and particle transport coefficient

To back up the above approximate calculations with more accurate numbers, a TRANSP analysis was performed for pulse 91232. TRANSP runs were in fully interpretive mode, with T_e, n_e and T_i taken from diagnostic measurements—Thomson scattering and beam charge exchange. Ion composition was divided between hydrogen, thermal deuterium, fast deuterium and Be as the impurity species. The thermal D profile was prescribed as $n_D(r)/n_e(r) = (1 + (1 - r/a) * \alpha) * (n_D/n_e)_{edge}$ where α was a free parameter varied between different runs until the modelled total neutron rate was matched to the measurement. The Be impurity profile was set assuming constant $Z_{eff} = 1.05$ which was measured by bremsstrahlung intensity. The NBI fast ion deposition and slowing down is calculated by TRANSP/NUBEAM [23]. The rest of the ions are assumed to be thermal hydrogen.

Figure 5 shows the results of the run with a good neutron match, achieved with $\alpha = 0.15$. Core ion isotope concentrations in this case are $n_H/n_e = 0.76$ and $n_D/n_e = 0.205$ which is split between fast and thermalized components as $n_{Dfast}/n_e = 0.045$, $n_{Dthermal}/n_e = 0.16$. Neutron production is divided between beam–thermal and beam–beam reactions as 1.3×10^{14} and 0.45×10^{14} n s^{-1}. Thermal–thermal fusion reactions in these relatively low temperature plasmas with diluted deuterium is negligible ($<0.03 \times 10^{14}$ n s^{-1}). 80% of all the neutron production is from inside the $r/a = 0.5$ surface and the maximum neutron rate is found at $r/a \sim 0.25$. Note that core concentration of thermal D found in the TRANSP calculations is a very close match to the value shown in table 1.

To find the particle transport coefficients it is necessary to solve equation (1) for both isotopes:

$$\begin{cases} \Gamma_D = -D\frac{dn_D}{dr} + Vn_D \\ \Gamma_H = -D\frac{dn_H}{dr} + Vn_H \end{cases}. \quad (3)$$

Here V and D are two unknowns, n_D and n_H are isotope densities and $\mathbf{\Gamma}$ are fluxes of the respective isotopes through a given flux surface: $\Gamma(r) = \frac{1}{\mathrm{AREA}(r)} \int S\mathrm{d}V$, where AREA($r$) is the

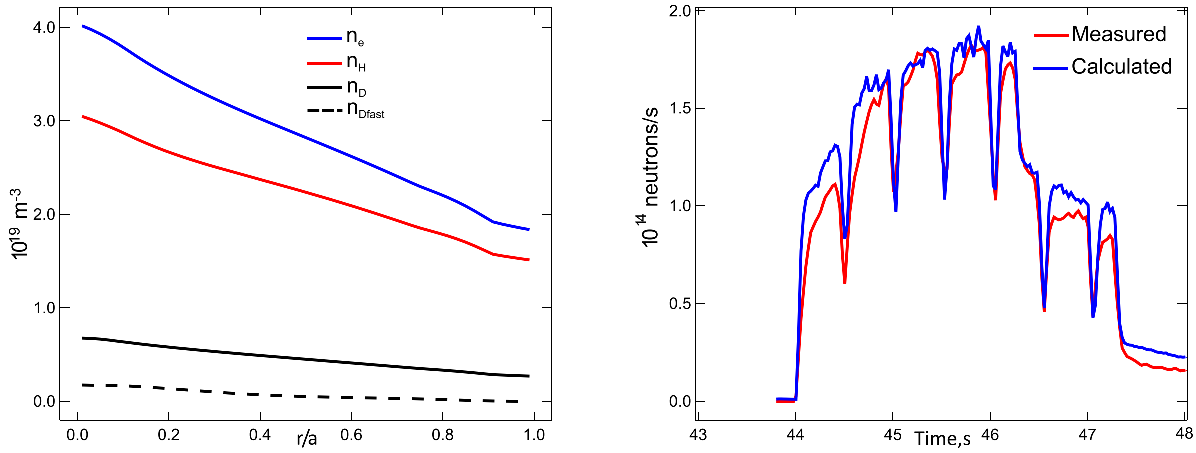

Figure 5. #91232 (t = 45.3 s–46.2 s) density profiles of plasma components as reconstructed by TRANSP (left) except Be impurity, and neutron production rate, measured versus calculated (right).

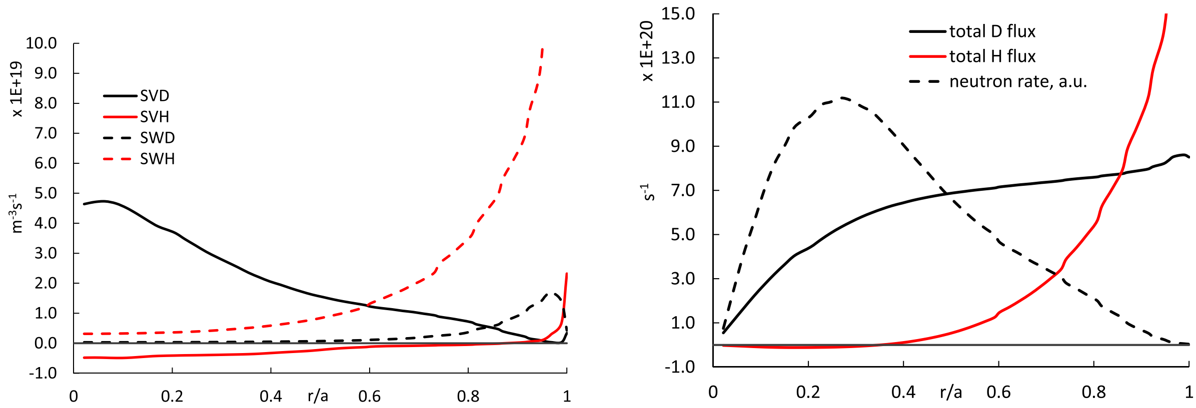

Figure 6. Left: D and H particle source calculated by TRANSP for #91232, divided as the volume source produced by the NBI (SVD and SVH) and the wall source produced by the edge gas fuelling (SWD and SWH); right: total flux of D and H ions, and neutron production rate at different radial coordinates.

area of the flux surface and the integral is the total source of a hydrogenic isotope inside that surface. Core particle sources are calculated by TRANSP and for ions it can be split into four different terms: sources of hydrogen/deuterium due to edge gas dosing, termed the 'wall source', and the sources for both isotopes due to NBI deposition directly into the plasma volume, termed the'volume source'. Source profiles for the #91232 case are shown in figure 6. They are divided into NBI-induced sources of D (SVD) and H (SVH), and the edge gas fuelling driven also for both isotopes, SWD and SWH. In addition, total D and H fluxes for each radial coordinate are plotted. Notably, the core particle source of hydrogen (SVH) is negative in the core indicating a loss of hydrogen ions which is caused by the halo neutrals effect. This happens due to charge exchange reactions between NBI fast D atoms and thermal H ions in plasma, where as a result fast D is deposited and neutral H travels to a larger radius in the plasma with thermal velocity until another charge exchange or complete ionization occurs.

Figure 7 shows profiles of V and D found by solving equation (3) at each radial coordinate, together with D_{eff} and χ_{eff}, effective particle diffusivity and thermal conductivity of a single fluid plasma as calculated by TRANSP. This is done for TRANSP ID K08 with the closest neutron match of 91232.

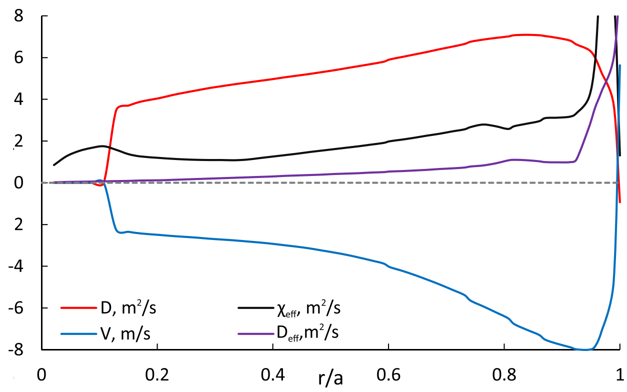

Figure 7. Ion particle transport coefficients calculated with (3), effective electron particle diffusivity D_{eff} and effective heat diffusivity χ_{eff} calculated within TRANSP.

Transport coefficients are drawn as functions of coordinates for illustration purpose only, of course the exact shapes of the isotope profiles are not known, therefore only the average value for V and D could realistically be estimated. We will consider values averaged over $r/a = 0.4$–0.6. As one can see, particle diffusivity is found to be very large, $D \sim 3 * \chi_{\text{eff}}$ and combined with a strong inward pinch.

Table 2. Results of different TRANSP calculations for #91232 with different $D_{thermal}$ profile peaking, therefore different neutron rate and *V*&*D* coefficients derived.

	Neutron rate, n $s^{-1} \times 1 \times 10^{14}$ averaged over 45.3–45.9 s	(n_D/n_e) core predicted	Particle diffusion $r/a = 0.4$–0.6 averaged (m s^{-1})	Particle convection $r/a = 0.4$–0.6 averaged (m s^{-1})
Measured	1.57			
TRANSP ID K08	1.64	0.166	5.55	−3.57
TRANSP ID K09	1.73	0.18	3.57	−2.18
TRANSP ID K10	1.98	0.217	1.83	−0.97
TRANSP ID K11	2.22	0.25	1.20	−0.53

Note that equation (3) assumed the same particle transport coefficients for H and D isotopes, although *a priori* this is not necessarily the case. Nonetheless, as will be shown in section 4, transport coefficients found in quasilinear gyrokinetic simulations are very similar, with deuterium exhibiting a slightly smaller diffusion coefficient and slightly larger inward convection. In [14] a similar behaviour was found in GYRO simulations for *D*/*T* mixture, where the heavier isotope appears to have larger peaking, although the disparity in the equilibrium normalized gradients was reported to be very small. Therefore, replacement of V_D, V_H and D_D, D_H by their average values $\langle V\rangle$ and $\langle D\rangle$ shall not affect the conclusions of this work.

To test how different core isotope composition affects the results of the calculation, more TRANSP simulations were carried out with different peaking of the deuterium profile. Results are outlined in table 2. As expected, higher core D concentration causes overestimation of the neutron rate and reduction of the predicted particle transport. If ~40% more neutrons are predicted by TRANSP, then particle diffusivity drops down to ~$0.7 \times \chi_{eff}$ which is close to previously reported particle diffusivities derived in density peaking studies (see section 4) although even in that case inward convection is still necessary. TRANSP simulation of JET plasmas is known to sometimes overestimate the predicted neutron rate [15], but in these plasmas it is unlikely to be the case since TRANSP results with no, or at least very modest, neutron overestimates for 91232 are very well aligned with comparative analysis of 91232 versus 91227. The comparative analysis relies on the relative change of neutron rate rather than on absolute values and therefore should not be affected by ability to predict the absolute number of neutrons generated.

A significant point to note from table 2 is that the transport coefficients derived from equation (3) change strongly with the core n_D/n_e for smaller deuterium concentrations. This is due to the fact that in the vicinity of $\nabla n_D/n_D \sim \nabla n_H/n_H$, i.e. fully transport (pinch) driven gradients, equation (3) becomes undetermined and the *D*, *V* solution grows to infinity. Therefore, once the transport coefficients are large enough to ensure the pinch dominated isotopes' density peaking, finding an exact solution in the presence of even small errors in n_D/n_e(core) is not possible. Hence, as the outcome of this analysis, we take a slightly conservative approach and conclude that the isotope density peaking is dominated by pinch, and $D \geqslant 2 \times \chi_{eff}$ which corresponds to ~+10% error in the modelled neutron rate as in TRANSP run K09.

4. Discussion of the results

Core particle transport in H-mode plasmas, in particular the magnitude of the inward anomalous pinch, has been a debated topic for many years. In a typical case an H-mode plasma was achieved by using significant NBI power and the observed density peaking could be attributed to both NBI core particle source and/or the inwards convection above the base neoclassical level (Ware pinch). Relative significance of the two mechanisms depends on the ratio of particle diffusivity to heat diffusivity, D/χ_{eff}. Statistical analysis performed on the density peaking database on JET and AUG [3, 7] suggested that $D \sim 0.66 \times \chi_{eff}$. Transport models used to describe anomalous particle transport in [5, 6] used somewhat lower values $D \sim 0.2$–$0.5 \times \chi_{eff}$. Recent gas puff modulation experiments on JET [29–32] have shown that $D \sim 0.2\ \chi_{eff}$ and observed peaking in the analysed pulses dominantly comes from the source, except in the lowest collisionality case where the transport and the source contributions to the peaking are approximately equal. Similar conclusions were drawn in [6].

Pulse 91232 has a moderate effective electron collisionality $\nu_{eff} \sim 0.1$, ($\nu_{eff} = 0.2 \times \langle n_e\rangle R_{geo}/\langle T_e\rangle^2$ as defined in [3]) which is in the middle of the log(ν_{eff}) range of the JET density peaking databases studied in [3, 4, 7]. Effective diffusivity at $r/a = 0.4$–0.6 is $D_{eff} \sim 0.25\ \chi_{eff}$ which is in line with the previous results. Therefore, based on all the density peaking studies cited above, density peaking in this pulse should be mostly source driven.

On the other hand, there are experimental studies that have showed larger numbers for particle diffusion, such as trace tritium experiments on TFTR [16] $D \sim \chi_i$ and on JET [17] $D \leqslant 2 \times \chi_{eff}$. In helium transport studies on DIII-D [28] it was found that $D_{He} \sim \chi_{eff}$. These results are in much better agreement with the observation of the isotope profiles behaviour described here, with $D \geqslant 2 \times \chi_{eff}$ and almost negligible source effect on the gradients.

Apparent inconsistency between the different particle transport studies including the results of this work can be interpreted as follows: *particle transport of the electrons is not necessarily the same as that of the main ions*. In fact, they can be very different with the ion particle transport significantly exceeding the transport of the electrons.

Different electron versus ion particle transport may seem to be a paradoxical statement since particle fluxes do have to obey the ambipolarity constraint, i.e. equal charge flows for ions and electrons. The transport would indeed be the same if it

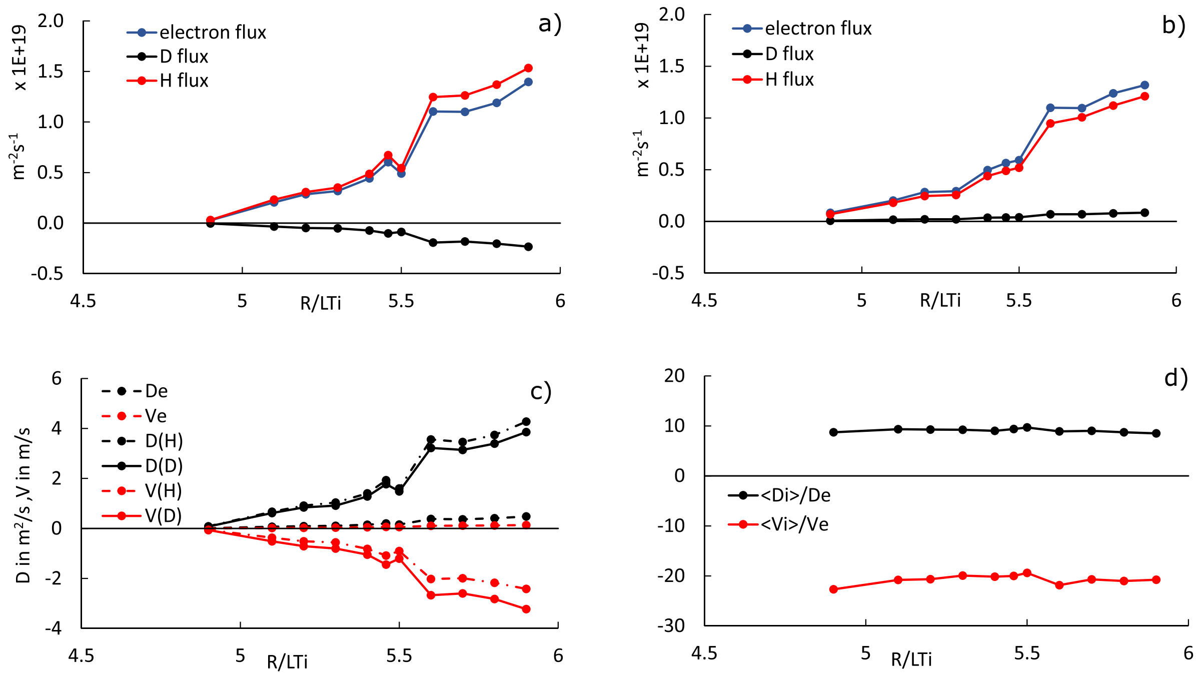

Figure 8. QuaLiKiz results (*a*) ion and electron fluxes in the $\nabla n_D/n_D = \nabla n_H/n_H$ case, (*b*) ion and electron fluxes in the $\nabla n_D/n_D > \nabla n_H/n_H$ case, (*c*) transport coefficients, similar for both cases, (*d*) ratios of transport coefficients for ions and electrons.

was purely diffusive, since the only way to satisfy the requirement of quasineutrality in that case is to impose $D_e = D_i$. But, since in a general case the particle flux is a combination of diffusion and convection, the corresponding D and V coefficients for ions and electrons do not have to be the same to satisfy the quasineutrality requirement. In the simplest exemplary case, if the electron particle transport is purely diffusive, ion diffusivity can still be much larger but will have to be accompanied by a sufficiently large inward convection to produce the same net particle flux.

This effect would not be possible to observe in the case of a single main ion component, as there would be no way to disentangle diffusion and convection. But in the case of isotope mixtures, especially if the location of the sources of different isotopes are very different, enhanced ion particle transport becomes apparent. Since the total ion particle flux is still constrained by the total electron flux, it would be more appropriate to call it *enhanced ion mixing*.

The difference in particle transport between ions and electrons has a very interesting and important consequence in the NBI heated plasmas such as the one described here. Electrons and ions are deposited into the plasma core at the same rate, and due to slow electron transport the plasma density profile will be mainly determined by the diffusion, i.e. the density gradient will be roughly proportional to the source. The same of course applies for the combined $n_D + n_H$ ion density profile to maintain the charge neutrality. However, due to fast ion particle transport, profiles of the individual isotopes will only weakly (if at all) depend on the corresponding sources, even if only one of the ion species is deposited in the core. Therefore, even if the core source of particles does have a direct effect on the core plasma density, it does not necessarily change the core ion composition.

It should be noted that fast ion particle transport can be reproduced in gyrokinetic modelling and this was indeed done in previous studies. For example, in [24] it was shown that deuterium particle diffusivity in certain conditions can reach value of $2 \times \chi_{eff}$. In [14] and [25] helium diffusivity was studied with conclusion that the He impurity profile follows the electron density profile and is insensitive to the source, which confirms the experimental observations described in [28]. To the authors' knowledge though, the problem of ion versus electron particle transport and consequences on the hydrogen isotope composition were not explicitly discussed before.

To demonstrate that the fast ion particle transport can be reproduced in modelling for the JET plasmas considered here, a series of quasilinear gyrokinetic simulations with the stand-alone QuaLiKiz code [26, 27] were performed for parameters close to those of #91232 with deuterium (15%) and hydrogen (85%) as the two main ion species. Simulation runs were performed at a single radial coordinate $r/a = 0.5$ with the following parameters: $R/LT_e = 4.909$, $T_e = 1.56\,\text{keV}$, $R/Ln_e = 2.3$, $n_e = 2.727 \times 10^{19}\ \text{m}^{-3}$, $T_i = 1.78\,\text{keV}$, R/LT_i changed between 4.9…5.9. Electron temperature and density gradients were adjusted from the experimental values to match experimental heat and particle fluxes as closely as possible. No impurities were included, therefore $Z_{eff} = 1$. $k_\theta \rho_i$ values were in the range of 0.1–45 with a finer grid in 0.1–1.0 (19 values) and nine more values at $k_\theta \rho_i > 1.0$ to probe the electron temperature gradient (ETG) mode range.

Two different scans were performed with different ion isotope density gradients: firstly with the same gradient for all the components $R/Ln_D = R/Ln_H = R/Ln_e = 2.3$, and secondly with a disparity between D and H, $R/Ln_H = 2.2$ $R/Ln_D = 2.88$. In dimensional values this corresponds to $\nabla n_e = 2.14\ \text{m}^{-4}$,

$\nabla n_H = 1.816\ m^{-4}$ and $\nabla n_D = 0.32\ m^{-4}$ in the first case, and $\nabla n_H = 1.736\ m^{-4}$ and $\nabla n_D = 0.40\ m^{-4}$ in the second case.

For any R/LT_i in the scan, all unstable modes within $k_\theta \rho_i < 1.0$ had negative frequency, which corresponds to the ITG-dominant regime in QuaLiKiz convention. ETG mode was found unstable at $k_\theta \rho_i = 15$, which was responsible for the majority of electron heat transport but did not affect the particle transport, so did not have any effect on the main purpose of this analysis.

Results of the calculations are summarized in figure 8. The particle diffusion coefficient for electrons is of the order of $0.1 \times \chi_{eff}$ and a small outwards convection is present. This means that the observed density peaking in such a plasma would come solely from the core fuelling which is consistent with the above density peaking discussion. Nonetheless the particle diffusion for the ions is much larger, $D \sim \chi_{eff}$, and a large inward convection is present. This can also be seen by how much the D and H fluxes change between the two cases with a small isotope density gradient variation. Note that these simulations do not fully reproduce the experimental observations (R/Ln_e is lower, net hydrogen flux is large rather than zero), the sole purpose of this modelling exercise is to support the point of different particle transport of the electron and ion components. To adequately reproduce experimental results a full self-consistent modelling over the whole r/a range is required which is outside of the scope of this paper. A much more detailed theoretical study of ion versus electron particle transport including non-linear gyrokinetic simulations and integrated modelling will be published separately [34].

5. Conclusions

Core particle transport of hydrogenic isotopes H and D was studied based on experimental results obtained on the JET tokamak. Two pulses with similar kinetic profiles (T_e, T_i, n_e) but different isotope compositions ($n_H/(n_H + n_D) \sim 0.85$ and 0.33) were analysed. The analysed periods in both pulses were in H-mode with D-NBI heating which produced strong core fuelling of pure deuterium. Isotope composition of the plasma was controlled by changing the H/D ratio of the additional gas dosing.

Despite strong core deuterium fuelling, the neutron production rate in these pulses changes proportionally to the deuterium concentration at the edge, assuming the relative contributions of beam–beam and beam–target reactions are accounted correctly. This means that the peaking factors of the isotope density profiles are similar to the electron density peaking. Notably, the hydrogen isotope profile remains peaked even without the core particle source. Such behaviour implies that the NBI source has little effect on the isotope profiles and the observed peaking is heavily determined by the transport. Corresponding transport coefficients for particle diffusion and convection were calculated based on the TRANSP run for #91232 giving $D \geqslant 2 \times \chi_{eff}$ with a conservative approach if 10% error in the modelled neutron rate is allowed.

Apparent disagreement with a large number of the previous density peaking studies can be attributed to the difference in particle transport properties of electrons and the main ion components. Indeed, to satisfy the ambipolarity of the fluxes, D and V of electrons and ions do not have to be the same, and $D_i \gg D_e$ would impose strong inward $V_i \ll 0$ to maintain the same net flux. Remarkably, it also means that in a plasma where density (i.e. electron) profile peaking is determined by the core particle source, profiles of the individual isotopes can be dominated by transport and be relatively insensitive to the sources of the corresponding ion components. Local quasilinear gyrokinetic simulations were performed using the stand-alone QuaLiKiz code, which confirmed this statement for plasma conditions similar to 91232 with dominant ITG turbulence. A much more detailed theoretical study of the effect of microturbulence on the ion and electron particles transport will be published separately [34].

Fast ion particle diffusivity was previously described in the literature [24], although mainly focussing on impurities and helium in the context of DT fusion ash accumulation. The fast isotope mixing property discussed in this work is also very relevant for reactor conditions as it allows easy control of the D/T fuel composition in the plasma core, where the majority of reactions will be taking place. This is also important for DT experiments in tokamaks such as JET, where the core particle source can be significant. Large ion diffusivity in JET DT plasmas potentially means that the core isotope composition is not sensitive to the type of species used for NBI heating and, for example, 100% D-NBI can be injected instead of the 50/50 DT-NBI without creating an unwanted bias in the core *D/T* ratio.

Acknowledgments

The authors are grateful to M. Valovic for his comments. This work was carried out within the framework of the EUROfusion Consortium and received funding from the Euratom research and training programme 2014–2018 under grant agreement No 633053 and from the RCUK Energy Programme (grant number EP/I501045). To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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