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## Observation of enhanced ion particle transport in mixed H/D isotopes plasma on JET

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### Abstract.

Particle transport is of a great importance for understanding physics of tokamak plasmas and planning future experiments on larger machines such as ITER. The subject was intensively studied in the past, particularly in relation to density peaking and presence of anomalous inward particle convection in L- and H-mode. While in the L-mode case presence of the anomalous inward pinch was unambiguously demonstrated, particle transport in H-mode was long unclear. Main difficulty of these studies is that particle diffusion and convection could not be measured independently in steady-state condition in 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 NBI heating.

In this work we describe experiments done on JET with mixtures of two hydrogenic isotopes: H and D. It is demonstrated that in case of several ion species, convection and diffusion can be separated in a steady plasma without implementation of perturbative technique such as gas puff modulation. Previous H-mode density peaking studies suggested that for this relatively high electron collisionality plasmas, observed density gradient is mostly driven by particle source and low particle diffusivity  $D < 0.5 * \chi_{eff}$ . But the transport coefficients derived from observation of the isotope profiles far exceed that value - ion particle diffusion found to be as high as  $D \geq 2 * \chi_{eff}$ , 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 specie plasma. This conclusion is confirmed by quasilinear gyrokinetic simulations.

### 1. Introduction

Particle transport in tokamaks was a subject of studies over the past two decades [2-20]. Special interest was given to the density behaviour in H-mode plasmas – main scenario for 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 the neoclassical theory. Quantitatively particle transport is usually described by a combination of diffusion  $D$  and convection  $V$  as following:

$$\Gamma = -D * \nabla n + V * n \quad (1)$$

where  $n$  is particle density and  $\Gamma$  is particle flux. It was shown in number of experiments that in L-mode plasmas non-negligible inward convection often exists and causes plasma core density to

significantly exceed the edge density, in other words makes plasmas with peaked density profile  $n_e(\text{core})/n_e(\text{edge}) > 1$  even in absence of a particle source in the core [3,10,11,16,17].

But presence of the anomalous inward convection in H-mode plasmas was long 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 plasma core is present, usually introduced by 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 somewhat faster diffusion. Different interpretations of the observed density peaking lead to different extrapolations to 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 reproduced by first principle modelling [9] and confirmed experimentally on C-MOD where H-mode plasma with peaked density profile was achieved with negligible core particle source [18]

In this work the effect of NBI source on density peaking was studied but with an approach which was never used in the past. Experiments were done with plasmas composed of 2 hydrogenic isotopes: protium and deuterium. NBI heating and therefore the core particle source was deuterium, while the background thermal plasma was hydrogen majority, with  $n_D/(n_D+n_H)$  reaching as low as 0.15. These plasmas have a strong density peaking, although unlike in the usual single isotope case, we could now separate beam fuelling effect from transport by observing how D/H isotope radial profile is changing from the edge to the core. We find that particle diffusivity calculated this way is significantly larger than the values derived from the previous density peaking studies, and significant inward convection is present which makes hydrogen isotope profile peaked even in absence of the core 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 transport and  $D/V$  ratio.

This paper organized as following: in section 2 experimental results will be shown together with explanation how isotope profiles can indicate the presence of inward particle convection; section 3 contains more accurate TRANSP analysis and derivation of particle transport coefficients; in section 4 the results will be 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 will be focussed mainly on the JET pulses #91232 and #91227. Both pulses have  $I_p=1.4\text{MA}$ ,  $B_T= 1.7\text{T}$  and  $8\text{MW}$  of additional NBI heating in deuterium (see figure 1). Both pulses had a stationary H-mode phase of at least several energy confinement times, i.e. all the plasma parameters described below can be considered as steady state. Difference between 91232 and 91227 is in the H/D isotope composition. #91232 was done with gas dosing of  $1.3e22 \text{ electrons/s}$  of pure hydrogen and #91227 was done 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  $\sim 9.3e20$  electrons/s.

Plasma isotope composition is measured routinely by comparing the relative amplitude of Balmer  $H\alpha/D\alpha$  spectral lines with two spectroscopy diagnostics: one looking at the plasma edge, and another one is measuring composition of the subdivertor neutral gas by analysing spectrum of a penning gauge glow discharge. Both measurements agree very well in these two pulses, indicating isotope composition of  $n_H/(n_D+n_H) = 0.86$  for the maximum hydrogen dosing (#91232) and  $n_D/(n_D+n_H) = 0.33$  for the mixed H/D dosing pulse (#91227).

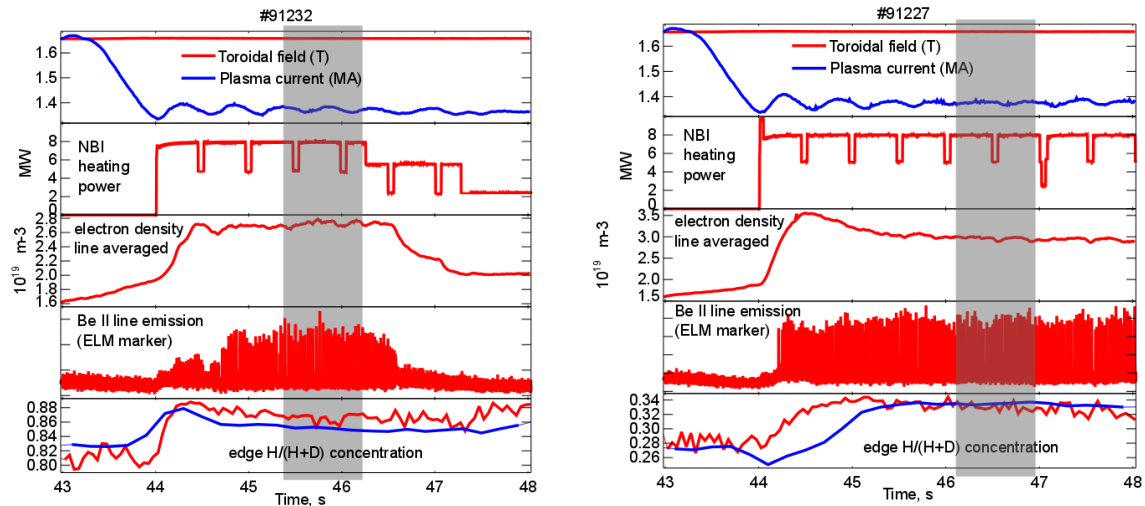


Figure 1. Overview of #91232 and #91227 with edge isotope compositions as measured by 2 different methods

There is no direct measurement of the core isotope composition available, so it had to be derived from the measured neutron rate. Neutrons are produced dominantly by the D-D beam-thermal reactions and the source is concentrated in the plasma core, therefore the number of neutrons generated is roughly proportional to concentration of deuterium in the core region.

Let's first discuss how dilution of hydrogenic isotopes in the core can be an indicator of the transport processes in such a plasma. NBI heating deposits electrons and deuterons in the plasma core at equal rates (see next section for more detailed analysis of particle sources), therefore in a steady state there is a constant outward flow of deuterons and electrons ( $\Gamma_D = \Gamma_e$ ), and zero net particle flux of hydrogen ( $\Gamma_H = 0$ ). In the absence of the convection term in the equation (1), i.e. in case of purely diffusive particle transport, it means that  $\nabla n_H = 0$  and  $\nabla n_D = \nabla n_e$ . In plasmas with strong density peaking i.e. strong density gradient, that leads to significant increase of D concentration in the core compared to the edge, i.e. core accumulation of the deuterium ions deposited by NBI heating.

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

$$\frac{\nabla n}{n} = \frac{V}{D} - \frac{\Gamma}{nD} \approx \frac{V}{D}, \quad \text{if } D \gg \Gamma/n \quad (2)$$

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

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

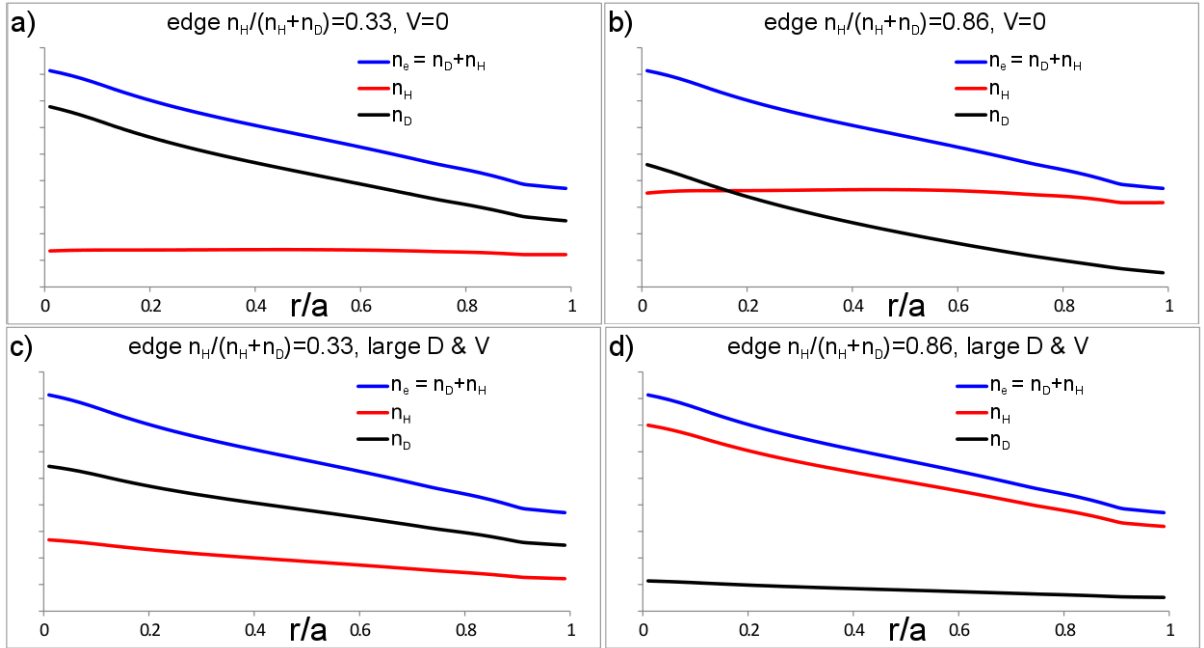


Figure 2. Illustration of possible H/D isotope profiles with two different edge values of  $n_H/(n_D+n_H)$  and two opposite transport behaviours: purely diffusive (a,b) and with large  $D$  &  $V$  (c,d).

Now returning to the comparison of pulses 91227 and 91232. Thanks to the weak dependence of confinement on the effective isotope mass observed in these H/D mixture plasmas (reported in [12]), parameters of both pulses are very similar (figure 3) despite a significant difference in the isotope ratio as measured at the plasma edge (figure 4). 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 difference in electron/ion heating ratio produced by NBI: ion drag force and therefore  $P_{\text{ion}}$  in hydrogen plasma is stronger.

Despite the similarity between the pulses, there is a factor of  $\sim 3.5$  difference in the neutron rate,  $\sim 6.17 \times 10^{14}$  versus  $\sim 1.77 \times 10^{14}$  neutrons/s. Now to properly estimate the difference in the core  $D$  concentration between the two pulses, one needs to take into account the reactions between NBI fast ions deposited in the plasma core, so-called beam-beam neutrons. Due to low concentration of



the slowing down ions, these reactions usually constitute only a small fraction of the total, beam-target dominated fusion reaction, but in the case of #91232 where majority of 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. TRANSP calculation gives a number of  $0.45 \times 10^{14}$  n/s for beam-beam reactions in 91232 (see section 3), therefore the difference in  $n_D/(n_D+n_H)$  in the core between the two pulses should be of the order of  $(6.17-0.45)/(1.77-0.45)=4.3$ . Difference in the edge  $n_D/(n_D+n_H)$  between these two pulses is measured as  $0.67/0.14 \sim 4.8$  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 on figure 2(c,d), i.e. must be dominantly transport driven. Note that the difference in  $T_i$  between the two pulses does not change the conclusion but strengthens it, since high  $T_i$  and consequently higher potential for beam-target fusion is observed in the pulse with *lower* neutron rate.

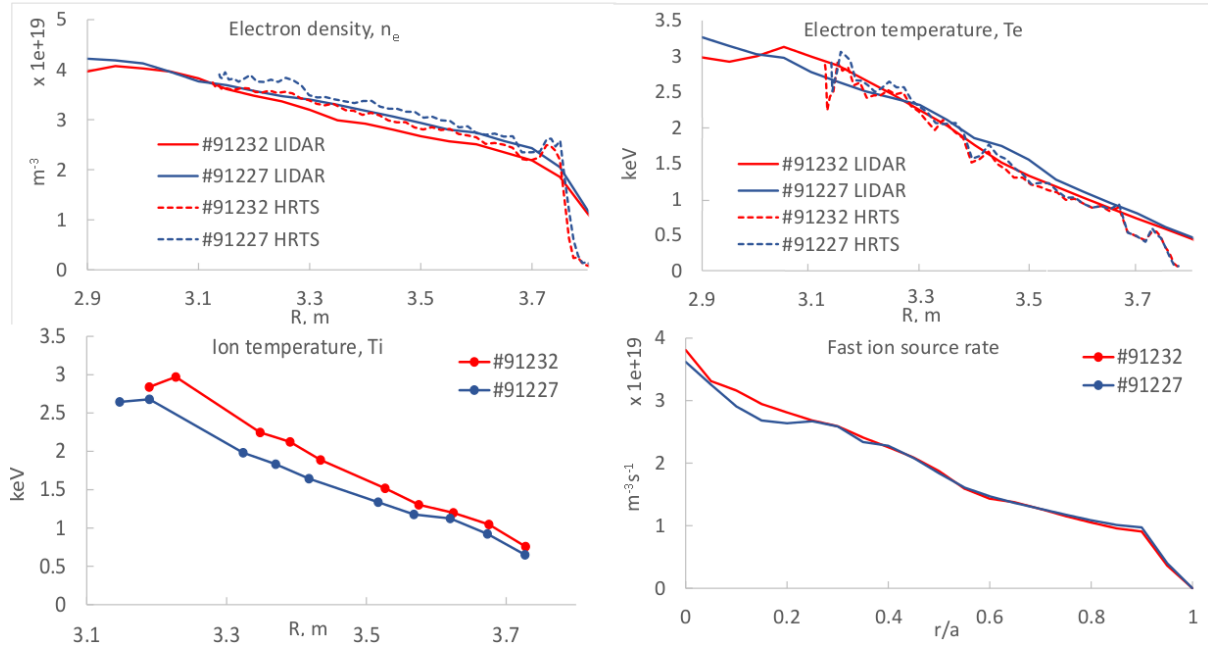


Figure 3: #91232 ( $t=45.2\text{s}-46.2\text{s}$ ) vs #91227 ( $t=46.2\text{s}-46.9\text{s}$ ) radial profiles overlapped, integrated over their respective time windows of interest. Electron density and temperature measured by two different Thomson Scattering diagnostics,  $T_i$  by charge exchange and fast ion source rate calculated by PENCIL[23] code using HRTS profiles as input for  $n_e$  and  $T_e$ .

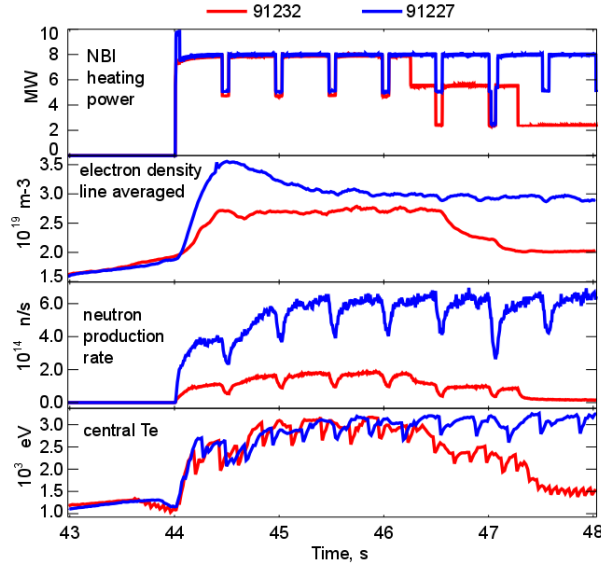


Figure 4. 91232 vs 91227 time traces overlapped: same Te, 10% different ne and large difference in the neutron rate.

If we assume that hydrogen 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 solving the following simple equations:

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

$$\frac{n_D(\text{core})^{91227}}{n_D(\text{core})^{91232}} = \frac{(1 - n_H(\text{core})^{91227})}{(1 - n_H(\text{core})^{91232})} = 4.3$$

The answer is given in table 2. 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 often observed in JET plasma simulations [13]

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	0.158	0.677
$n_H/(n_D+n_H)$ core – derived	0.842	0.323

Table 2: measured and calculated edge and core D/H isotope concentrations.

### 3. TRANSP analysis and particle transport coefficient

To back up the above approximate calculations with more accurate numbers, a TRANSP analysis was done for the 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. Ions composition was divided between hydrogen, thermal deuterium, fast deuterium and Be impurity. Thermal D profile

was prescribed as  $n_D/n_e = (1 + (1 - r/a) * \alpha) * (n_D/n_e)_{\text{edge}}$  where  $\alpha$  was a free parameter varied between different runs until modelled neutron rate was matched to the measurements. Be impurity profile was set assuming constant  $Z_{\text{eff}} = 1.05$  which was measured by Bremsstrahlung intensity. Fast D population is the NBI slowing down ions with density calculated by TRANSP/NUBEAM [21]. The rest of the ions are assumed to be thermal hydrogen.

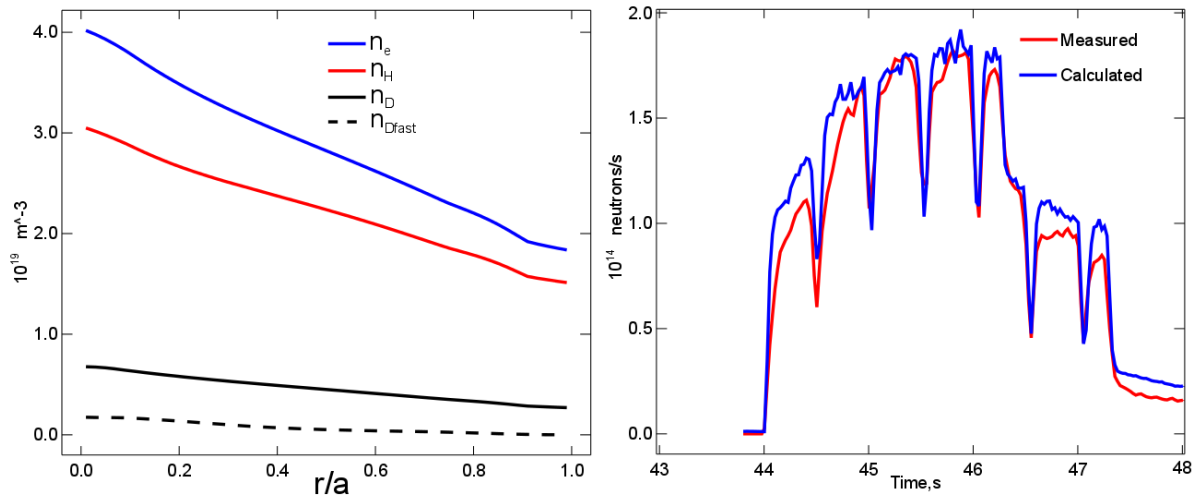


Figure 5: #91232 ( $t=45.3\text{s}$ - $46.2\text{s}$ ) density profiles of plasma components as reconstructed by TRANSP (left) except Be impurity, and neutron production rate, measured vs calculated (right).

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  $n_{D\text{fast}}/n_e=0.045$ ,  $n_{D\text{thermal}}/n_e=0.16$ . Neutron production is divided between beam-thermal and beam-beam reactions as  $1.3\text{e}14 / 0.45\text{e}14\text{n/s}$ . Thermal-thermal fusion reactions in these relatively low temperature plasmas with diluted deuterium can be ignored ( $<0.03\text{e}14\text{n/s}$ ). 80% of all the neutron production is from inside the  $r/a=0.5$  surface and 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 2

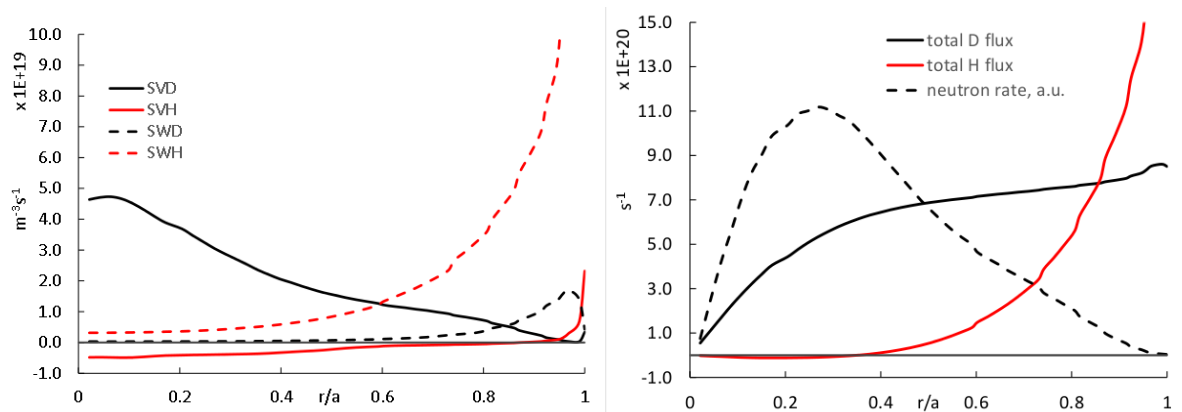


Figure 6: left: D and H particle source calculated by TRANSP for #91232, divided as volume source – produced by NBI (SVD and SVH) and wall sources produced by edge gas fuelling (SWD and SWH); right: total flux of D and H ions, and neutron production rate at different coordinate.

To find particle transport coefficients we need to solve equation (1) written for both isotopes:

$$\begin{cases} \Gamma_D = -D * \nabla n_D + V * n_D \\ \Gamma_H = -D * \nabla n_H + V * n_H \end{cases} \quad (3)$$

Here  $V$  and  $D$  are two unknowns,  $n_D$  and  $n_H$  are isotope densities and  $\Gamma$  are fluxes of respective isotopes through a given flux surface:  $\Gamma = \frac{1}{AREA} \int S dV$ , where AREA is the 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 4 different terms: sources of hydrogen/deuterium due to edge gas dosing, also called “wall source”, and the sources for both isotopes due to NBI deposition directly into the plasma volume. Source profiles for the #91232 case are shown on figure 6. In addition, total D and H flux for each radial coordinate is plotted. Notably, SVH value goes negative in the core indicating a loss of hydrogen ions which is caused by halo neutrals effect. This is happening 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 with thermal velocity is travelling elsewhere until another charge exchange or complete ionization.

Below on Figure 7 profiles of  $V$  and  $D$  plotted, together with  $D_{eff}$  and  $\chi_{eff}$  – effective thermal conductivity of a single fluid plasma as calculated by TRANSP. This is done for TRANSP ID K08 with closest neutron match of 91232. Transport coefficients are drawn as functions of coordinate 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,  $D \sim 3 * \chi_{eff}$  and combined with a strong inward pinch.

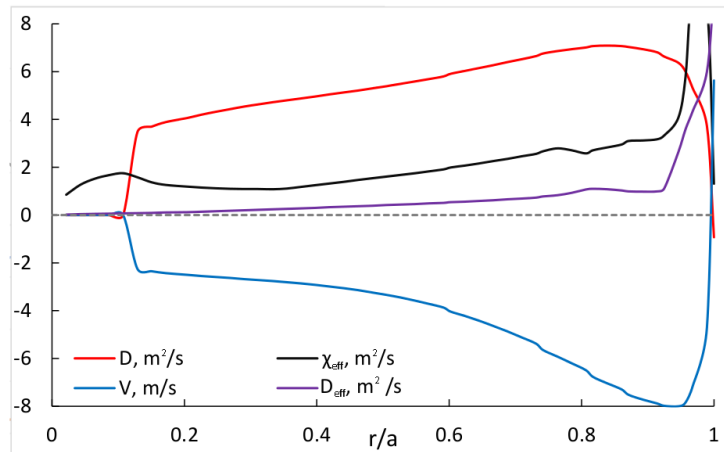


Figure 7: ion particle transport coefficients calculated with (3), and effective heat diffusivity  $\chi_{eff}$  calculated within TRANSP

Note that the equation (3) assumed the same particle transport coefficients for H and D isotopes, although a priori this is not the case. Nonetheless, as it will be shown in section 4, transport

coefficients found in quasilinear gyrokinetic simulations are very similar. This is also supported by the similarity of the two pulses compared in this work with very different hydrogenic isotopes content. Therefore, replacement of  $V_D, V_H$  and  $D_D, D_H$  by their average values  $\langle V \rangle$  and  $\langle D \rangle$  is justified and will not affect the main conclusion of this work.

To test how different core isotope composition affects the results of the calculation, more TRANSP run were done with different peaking of deuterium profile. Results are outlined in table 3. As expected, higher core D concentration causes overestimation in the neutron rate and reduction in the predicted ion transport. If  $\sim 40\%$  more neutrons are predicted by TRANSP, then particle diffusivity drops down to  $\sim 0.7 \cdot \chi_{\text{eff}}$  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 predicted neutron rate [13], but in these plasmas it is unlikely to be the case since TRANSP results with none or at least very modest neutron overestimate for #91232 are very well aligned with comparative analysis of 91232 vs 91227 which relies on relative change of neutron rate rather than on absolute value and therefore should not be affected by ability to predict the number of neutrons generated.

	Neutron rate, n/s *1e14 averaged over 45.3-45.9s	$(n_D/n_e)_{\text{core}}$ predicted	Particle diffusion $r/a=0.4-0.6$ averaged	Particle convection $r/a=0.4-0.6$ averaged
Measured	1.57			
TRANSP ID K08	1.64	0.166	5.55 m <sup>2</sup> /s	-3.57m/s
TRANSP ID K09	1.73	0.18	3.57 m <sup>2</sup> /s	-2.18m/s
TRANSP ID K10	1.98	0.217	1.83 m <sup>2</sup> /s	-0.97m/s
TRANSP ID K11	2.22	0.25	1.20 m <sup>2</sup> /s	-0.53m/s

Table 3: Results of different TRANSP calculations for #91232 with different  $D_{\text{thermal}}$  profile peaking, therefore different neutron rate and V&D coefficients derived.

One thing to note from table 3 is that transport coefficients derived from the equation (3) change strongly with the core  $n_D/n_e$  for smaller deuterium concentration. 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 transport, equation (3) become 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 exact solution in presence of even small errors in  $n_D/n_e(\text{core})$  is problematic. Hence, as the outcome of this analysis, we take a more conservative approach and conclude that the isotope density peaking is certainly dominated by pinch with  $D \geq 2 \cdot \chi_{\text{eff}}$ , which corresponds to  $\sim +10\%$  error in neutron rate as in TRANSP run K09.

#### 4. Discussion of the results

Core particle transport in H-mode plasmas, particular the magnitude of the inward anomalous pinch, has been a debated topic for years. In a most 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,  $D/\chi_{\text{eff}}$ . Statistical analysis done on the density peaking database on JET and AUG [4,8] suggested that  $D \sim 0.66 \cdot \chi_{\text{eff}}$ . Transport models used to describe anomalous particle transport in [6,7] used somewhat lower values  $D \sim 0.2-0.5 \cdot \chi_{\text{eff}}$ . Recent gas puff modulation experiments on JET [25-28] have shown that  $D \sim 0.2 \chi_{\text{eff}}$  and observed peaking in the analysed pulses dominantly comes from the source, except in the lowest collisionality case where transport and source contribution to the peaking is about equal.

Pulse 91232 has a moderate effective electron collisionality  $\nu_{\text{eff}} \sim 0.1$ , ( $\nu_{\text{eff}} = 0.2 \cdot \langle n_e \rangle R_{\text{geo}} / \langle T_e \rangle^2$  as defined in [4]) which is in the middle of the  $\log(\nu_{\text{eff}})$  range of the JET density peaking databases studied in [4,5,8]. Effective diffusivity at  $r/a=0.4-0.6$  is  $D_{\text{eff}} \sim 0.25 \chi_{\text{eff}}$  which is in line with the previous results. Therefore, based on all the density peaking studies cited above, 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 [14]  $D \sim \chi_i$  and on JET [15]  $D \leq 2 \cdot \chi_{\text{eff}}$ . In helium transport studies on DIII-D [24] it was found that  $D_{\text{He}} \sim \chi_{\text{eff}}$ . These results are in a much better agreement with the observation of the isotope profiles behaviour described here, with  $D \geq 2 \cdot \chi_{\text{eff}}$  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 following: *particle transport of electrons is not necessarily the same as of the main ions*. In fact, they can be very different with the ion particle transport significantly exceeding the one for the electrons.

Different electron versus ion particle transport may seem to be a paradox statement since particle fluxes do have to obey the ambipolarity constraint, i.e. equal charge flows for ions and electrons. This indeed would be the case if particle transport was purely diffusive, since the only way to satisfy the quasineutrality would be to impose  $\nabla n_e = \nabla n_i$  and  $D_e = D_i$ . But, since in a general case the particle flux is a combination of diffusive and convective processes, the corresponding  $D$  and  $V$  coefficients for ions and electrons don't have to be the same to still satisfy the quasineutrality. 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 as for the electrons.

This effect would not be possible to observe in case of a single main ion component, as there would be no way to disentangle diffusion and convection. But in case of isotope mixtures, especially if location of the sources of different isotopes are very different, enhanced ion particle transport becomes apparent. Although 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*.

To support this statement a series of quasilinear gyrokinetic simulations with stand-alone QualiKiz code [22,23] were performed for plasma parameters close to #91232 with deuterium (15%) and hydrogen (85%) as two main ion species. 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. No impurities were included,

therefore  $Z_{\text{eff}}=1$ .  $k_{\theta}^*$  values were in the range of 0.1 – 45 with a finer grid in 0.1-1.0 (19 values) and 9 more values at  $k_{\theta}^*>1.0$  to probe the ETG range.

Two different scans were performed with different ion isotope density gradients: with the same gradient for all the components  $R/L_{nD}=R/L_{nH}=R/L_{ne}=2.3$ , and with a disparity between D and H:  $R/L_{nH}=2.2$   $R/L_{nD}=2.88$ . In dimensional values it corresponds to  $\nabla n_e=2.14\text{m}^{-4}$ ,  $\nabla n_H=1.816\text{m}^{-4}$  and  $\nabla n_D=0.32\text{m}^{-4}$  in the first case;  $\nabla n_H=1.736\text{m}^{-4}$  and  $\nabla n_D=0.40\text{m}^{-4}$  in the second case.

For any  $R/L_{Ti}$  in the scan, all unstable modes within  $k_{\theta}^*<1.0$  had negative frequency, which corresponds to ITG-dominant mode in QuaLiKiz convention. ETG mode was found unstable at  $k_{\theta}^*=15$ , 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.

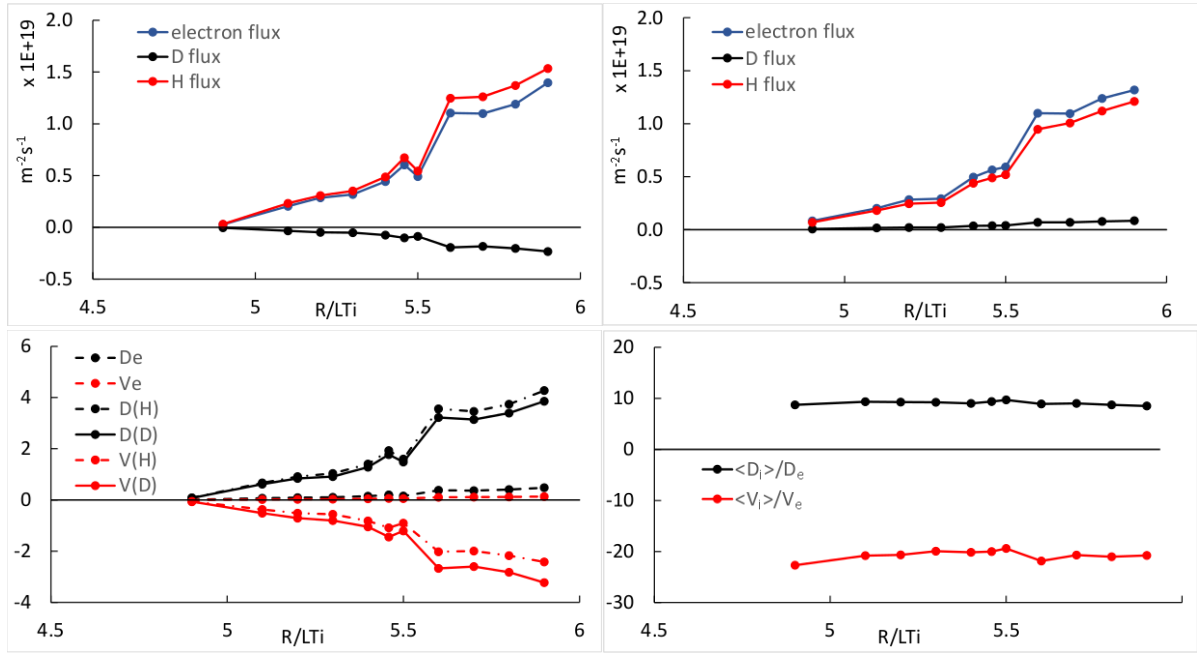


Figure 8: QuaLiKiz results a) ion and electron fluxes in the  $\nabla n_D=\nabla n_H$  case, b) ion and electron fluxes in the  $\nabla n_D>\nabla n_H$  case, c) transport coefficients, similar for both cases, d) ratios of transport coefficients for ions and electrons.

Results of the calculations are summarized on figure 8. Particle diffusion coefficient for electrons is order of  $0.1 \cdot \chi_{\text{eff}}$  and small outwards convection is present. It means that the observed density peaking in such 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,  $D \sim \chi_{\text{eff}}$ , and a large inward convection is present. That 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 ( $R/L_{ne}$  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 and this is outside of the scope of this paper. A lot more detailed theoretical study of ion versus electron particle transport including non-linear gyrokinetic simulations and integrated modelling will be published separately [1].

## 5. Conclusions

Core particle transport of hydrogenic isotopes H and D was studied in this work, based on experimental results obtained on 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. Both pulses were H-modes 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, neutron production rate in these pulses changes proportionally to the deuterium concentration at the edge, if beam-beam reactions are accounted correctly. It means that the peaking factor of isotope density profiles is similar to the electron density peaking. Notably, 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 coefficient for particle diffusion and convection were calculated based on the TRANSP run for #91232 giving  $D \geq 2 \chi_{eff}$  with a conservative approach if 10% error in the modelled neutron rate is assumed.

Apparent disagreement with a large variety of previous studies was explained by difference in particle transport properties of electrons and the main ion components. Indeed, to satisfy the ambipolarity of fluxes constraint,  $D$  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 particle sources. Local quasilinear gyrokinetic simulations were performed using stand-alone QuaLiKiz code, which confirmed that statement for plasma conditions similar to 91232 with dominant ITG turbulence. Much more detailed theoretical study of the effect of microturbulence on the ion and electron particles transport will be published separately [1]

While applicability of these results to different plasma conditions still to be studied, enhanced ion transport should be beneficial for a fusion reactor. Fast isotope mixing provides better control of the D/T fuel composition in the core which can only be changed by adjusting the D/T edge fuelling balance. If He4 transport exhibits similar behaviour to that of the main D/T fuel mixture, then the helium ash accumulation in the core will not be encountered and the total helium content shall only depend on recycling and pumping efficiency.

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