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Characterisation of divertor detachment onset in JET-ILW hydrogen, deuterium, tritium and deuterium–tritium low-confinement mode plasmas


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ABSTRACT

Measurements of the ion currents to and plasma conditions at the low-field side (LFS) divertor target plate in low-confinement mode plasmas in the JET ITER-like wall materials configuration show that the core plasma density required to detach the LFS divertor plasma is independent of the hydrogenic species protium, deuterium and tritium, and a 40%/60% deuterium–tritium mixture. This observation applies to a divertor plasma configuration with the LFS strike line connected to the horizontal part of the LFS divertor chosen because of its superior diagnostic coverage. The finding is independent of the operational status of the JET cryogenic pump. The electron temperature ($T_e$) at the LFS strike line was markedly reduced from 25 eV to 5 eV over a narrow range of increasing core plasma density, and observed to be between 2 eV and 3 eV at the onset of detachment. The electron density ($n_e$) peaks across the LFS plasma when $T_e$ at the target plate is 1 eV, and spatially moves to the X-point for higher core densities. The density limit was found approximately 20% higher in protium than in tritium and deuterium–tritium plasmas.

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1 See the author list of ‘Overview of JET results for optimising ITER operation’ by J. Mailloux et al. Nucl. Fusion 62 (2022) 042026.

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1. Introduction

Detachment of the divertor plasma in ITER and in future fusion power plants is a prerequisite for safe operation at high duty cycle ([1,2] and therein). The onset of detachment, i.e., the formation of a cold (electron temperature, $T_e < 3$ eV) and dense (electron density, $n_e > 1 \times 10^{20}$ m$^{-3}$) plasma region adjacent to the divertor target plates, is characterized by the reduction of the fuel ion fluxes to the divertor target plates compared to the high-recycling, attached regime. In tokamaks, detached regimes are typically achieved when operating at high core plasma density, thus main scrape-off layer (SOL) densities, close to the density limit, often assisted by impurity injection to further cool the divertor plasma. The required degree of detachment in ITER and in future power plants is set by the remaining heat flux to the divertor surface, including plasma surface recombination. E.g., a residual fuel ion flux of $1 \times 10^{24}$ m$^{-2}$ s$^{-1}$ at 2 eV results in 5 MW/m$^2$, one third of the present upper limit of the heat flux [3], allowing for significant reduction of the fuel ion fluxes beyond what is achieved with radiative cooling only. Understanding and being able to predict the onset and formation of divertor plasma detachment is one of the most critical tasks in magnetic confinement fusion.

Conceptually, the usage of the different hydrogenic isotopes protium (here, H), deuterium (D) and tritium (T), and the homonuclear isotope mass ratios. E.g., the ionization mean free path of D and T atoms is 0.71 and 0.58 times shorter than that of H atoms, respectively. Furthermore, the sticking probability of hydrogenic molecules on a cryogenic panel is higher for D$_2$ and T$_2$ than for H$_2$ (for the JET divertor cryogenic pump, [4]). In addition, the fuel ion interaction with hydrogenic molecules is anticipated to be isotopomer-dependent as their reaction rates are impacted by the isotopomer mass ([5] and therein). Given these physics models, the plasma-neutral gas is anticipated to rearrange itself for each hydrogen isotope potentially offsetting or amplifying the impact of the isotope species.

Previous experiments in JET with the carbon wall (JET-C) showed for low-confinement mode ($\eta$-mode) H, D and T plasmas that the density required for the onset of detachment and the density limit scaled inversely with the fuel ion mass in a vertical divertor plasma configuration (20 % lower for T versus H), while no isotope effect was observed in a horizontal divertor plasma configuration [6]. Measurements in ohmic plasmas the JET ITER-like wall (JET-ILW) indicated a 10 % higher detachment onset density of the low-field side (LFS) divertor plasma for H versus D in a divertor plasma configuration with the high-field side (HFS) strike line on the vertical face of the HFS divertor and the LFS strike line on the horizontal face of the LFS divertor [7]. In contrast, and consistent with the JET-C measurements, a 30 % higher density for the onset of detachment of the LFS divertor plasma for H versus D plasmas was measured in a configuration with the HFS and LFS strike lines on the vertical faces of the HFS and LFS divertor, respectively.

Since JET operation in tritiated plasmas during the 2020–21 tritium and deuterium–tritium experimental campaigns was limited to a daily tritium consumption of 44 bar L of T per run day [8], the T and D-T experiments reported here were carried out with the divertor cryogenic pump panels operated at liquid nitrogen temperature (LN$_2$, 77 K), at which hydrogenic gases are not pumped. In contrast, in pumped operation the cryogenic pump panels are cooled to super-critical helium temperature (sc-He, 5.2 K, [9]). The cryogenic pump is toroidally symmetric and located in the sub-divertor attached to the radially inner side of divertor coil 4 (see Fig. 1a and Fig. 2 in [9]). The sub-divertor connects to the divertor via toroidally symmetric pump ducts of height 10 cm, including radiation shields (louvres), which determine the vacuum conductance and thus the effective pumping speed of the cryogenic system on the JET vacuum vessel.

2. General plasma description

The fuel ion fluxes to and the plasma conditions at the HFS and LFS target plates, and Lyman and Balmer emission across the LFS divertor were measured in H, D, T and D-T $\eta$-mode plasmas with the LFS strike line on the horizontal part of the JET divertor at the LFS (Fig. 1). The HFS strike line was placed onto the vertical face of the HFS divertor.
The decision for this divertor plasma configuration was made because of the superior spectroscopic coverage of the horizontal LFS target over the vertical LFS target, despite the indication of a stronger isotope effect in the latter configuration. For all considered plasmas the plasma current ($I_p$) was 2.5 MA and the toroidal magnetic field ($B_T$) at the magnetic axis 2.5 T, with the ion $\text{BxVB}$ drift pointing into the divertor. Besides ohmic heating (with increasing plasma density 1.6 to 1.9 MW) neutral beam heating of 1.0 to 1.1 MW was applied. Over the course of several campaigns, hydrogen (C37, 2016), deuterium (C28, 2011 and C38, 2019), tritium (C40, 2021) and deuterium–tritium (C41, 2021) plasmas were executed by way of hydrogenic gas only fuelling ramps from low-recycling conditions to the density limit with constant strike line positions. The characterization of the deuterium plasmas was previously reported in [10,11,12]. For the D-T plasmas, a tritium concentration of 55–60% was inferred spectroscopically across the LFS divertor plasma [13] and in the exhaust gas in the sub-divertor [14]. The absence of significant impurity concentration and radiation, in particular in detached conditions, resulted in plasmas of effective charge state 1.0–1.2 measured in all plasmas, independent of the isotope species. Radiation from beryllium was inferred to be one order of magnitude lower than from the hydrogenic species (dominated by Lyman-α emission) and Bremsstrahlung, and thus negligible [10]. In high-recycling and detached conditions in these plasmas, tungsten sputtering is suppressed [15] and tungsten radiation does not play a role in the power balance of the SOL [10]. Increasing the temperature of the cryogenic pump panels from sc-He to LN$_2$ for a subset of deuterium plasmas in these studies showed that for the same core plasma density and high-recycling conditions, the $D_2$ pressure in the sub-divertor increased by a factor of 5 (0.04 Pa to 0.2 Pa). Typically, gas injection rates of 1–2x10$^{21}$ tritons/s—a factor of 100 lower than the recycling ion currents at the target plates—were sufficient in unpumped plasmas to raise the core plasma density from low-recycling conditions to the density limit.

The profiles of ion saturation current densities ($I_{sat}$) to the LFS plate as measured by Langmuir probes (Fig. 1) are integrated for the total plate-integrated currents ($I_{div}$); for attached plasma conditions with $T_e \gtrsim 5$ eV, the Langmuir probes also provided reliable measurements for $T_e$ and $n_e$. Within the uncertainties of individual Langmuir probes contributing to $I_{div}$, $I_{div}$ is the least affected target plasma parameter affected by small ($\lesssim 5$ mm) deviations of the strike line position. Below 5 eV the Langmuir probe measurements for $T_e$ and $n_e$, thus electron pressure ($p_e$), at the sheath entrance are found to be unreliable and omitted from the analyses. Spectroscopic measurements of the Balmer series were made with several low and high-resolution instruments [16–18] (Fig. 1), and the line-averaged $T_e$ and $n_e$ across the LFS divertor leg, $<T_e>_{\text{LFS-div}}$ and $<n_e>_{\text{LFS-div}}$, respectively, were inferred using the fitted continuum emission of the Balmer series and Stark broadening of the Balmer-δ line, respectively [16,17]. These measurements critically extended the $T_e$ and $n_e$ measurements in the divertor to as low as 0.5 eV and 1x10$^{21}$ m$^{-3}$. The Balmer series emission is spatially resolved by tangentially viewing cameras, which peaked at the LFS strike line region for the high-recycling conditions investigated in these plasmas [11], hence locating the line-averaged $T_e$ and $n_e$ to the vicinity of the LFS strike line region. Note that the Langmuir probe and the spectroscopically inferred electron pressures are complementary, but cannot be assumed the same due to the different plasma regions and plasma conditions for which the methods are valid. Due to the absence of reliable measurements the separatrix location upstream of the divertor X-point, e.g., at the LFS midplane, and thus the plasma conditions at the separatrix, in this publication the line-averaged density in the LFS edge of the main plasma ($<n_e>_{\text{edge},LFS}$, see Fig. 1) is used as the primary independent plasma parameter. Previous studies in identical JET-ILW 1-mode deuterium plasmas indicated a 2:1 correlation of $n_e$ on the separatrix at the LFS midplane ($n_{e,sep,LFS-mp}$) with $<n_e>_{\text{edges}}$, and $T_{e,sep,LFS-mp}$ of approximately 60 eV for all $<n_e>_{\text{edge},LFS}$ considered [19]. Given the brevity of report, potential differences in the main SOL profiles due to the isotope mass are deferred to future publications. The suitability of

Fig. 2. Total ion current to the LFS target plate (a), electron temperature (b) and electron density (c) as a function of line-averaged density at the outer edge of the core plasma in deuterium plasmas. $T_e$ was measured with Langmuir probes (circles, probe S19A) and inferred spectroscopically (KT3A, squares, channel 10). The JET pulse with applied pumping by the cryogenic pump is shown as solid symbol (JPN 94579) and without by the open symbols (JPN 97699). The black dashed vertical line indicates the assumed detachment onset density based on the saturation of $I_{div,LFS-plate}$. 

The profiles of ion saturation current densities ($I_{sat}$) to the LFS plate as measured by Langmuir probes (Fig. 1) are integrated for the total plate-integrated currents ($I_{div}$); for attached plasma conditions with $T_e \gtrsim 5$ eV, the Langmuir probes also provided reliable measurements for $T_e$ and $n_e$. Within the uncertainties of individual Langmuir probes contributing to $I_{div}$, $I_{div}$ is the least affected target plasma parameter affected by small ($\lesssim 5$ mm) deviations of the strike line position. Below 5 eV the Langmuir probe measurements for $T_e$ and $n_e$, thus electron pressure ($p_e$), at the sheath entrance are found to be unreliable and omitted from the analyses. Spectroscopic measurements of the Balmer series were made with several low and high-resolution instruments [16–18] (Fig. 1), and the line-averaged $T_e$ and $n_e$ across the LFS divertor leg, $<T_e>_{\text{LFS-div}}$ and $<n_e>_{\text{LFS-div}}$, respectively, were inferred using the fitted continuum emission of the Balmer series and Stark broadening of the Balmer-δ line, respectively [16,17]. These measurements critically extended the $T_e$ and $n_e$ measurements in the divertor to as low as 0.5 eV and 1x10$^{21}$ m$^{-3}$. The Balmer series emission is spatially resolved by tangentially viewing cameras, which peaked at the LFS strike line region for the high-recycling conditions investigated in these plasmas [11], hence locating the line-averaged $T_e$ and $n_e$ to the vicinity of the LFS strike line region. Note that the Langmuir probe and the spectroscopically inferred electron pressures are complementary, but cannot be assumed the same due to the different plasma regions and plasma conditions for which the methods are valid. Due to the absence of reliable measurements the separatrix location upstream of the divertor X-point, e.g., at the LFS midplane, and thus the plasma conditions at the separatrix, in this publication the line-averaged density in the LFS edge of the main plasma ($<n_e>_{\text{edge},LFS}$, see Fig. 1) is used as the primary independent plasma parameter. Previous studies in identical JET-ILW 1-mode deuterium plasmas indicated a 2:1 correlation of $n_e$ on the separatrix at the LFS midplane ($n_{e,sep,LFS-mp}$) with $<n_e>_{\text{edges}}$, and $T_{e,sep,LFS-mp}$ of approximately 60 eV for all $<n_e>_{\text{edge},LFS}$ considered [19]. Given the brevity of report, potential differences in the main SOL profiles due to the isotope mass are deferred to future publications. The suitability of
below the detachment onset density which is consistent with recent
is challenging for T
\(< \\text{M. Groth et al.}\) [20], and resembles a similar T
\(< \text{LFS}-\text{div}} \text{-mode plasmas (Fig. 4 b and c), while j\text{edge}\text{–LFS-plate}
\text{of approximately 2.6 x10}^{21} \text{m}^{-3} \text{(Fig. 3a)}, and at which <\text{T}_e\text{–LFS}-\text{div}
\text{LFS-div} \text{-mode plasmas in unpumped D, T and D-T l-mode plasmas.
For <\text{n}_\text{edge}> larger than the detachment onset density, the LFS diverter
plasma transitions from partial detachment to the density limit over a
range of 3x10^{19} \text{m}^{-3} of <\text{n}_\text{edge}>. Similar radial shifts of the high-density regions across the spectrometer chords, interpreted as poloidal
movement of the high-density region from the LFS strike line to the LFS
X-point region, were observed in the D, T and D-T plasmas. Within the
uncertainties of how the density limit is established and determined,
the limit for the T and D-T plasmas was observed at <\text{n}_\text{edge}> \approx 5.4x10^{19}
\text{m}^{-3}.
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4. Detachment onset of the LFS diverter plasma in unpumped D,
T and D-T l-mode plasmas

The upstream density (<\text{n}_\text{edge}>) required to detach the LFS diverter plasma in unpumped D, T and D-T l-mode plasmas was found to be identical for \text{I}_{\text{div,LSF-plate}} <\text{T}_e\text{–LFS-div} and <\text{n}_\text{edge}> within the
uncertainties of the measurement (Fig. 3). Like in pumped and unpumped
due to the 20 % difference in the Balmer-
emission across the LFS divertor are 20
\% higher <\text{n}_\text{edge}> than the detachment onset density, and decreases for higher <\text{n}_\text{edge}> when <\text{T}_e\text{–LFS-plate}> is 1 \text{ eV}, or less (Fig. 3c).
While \text{I}_{\text{div,LSF-plate}} and \text{I}_{\text{Sat,LSF-plate}} (Fig. 4a) at the detachment onset were identical for the T
and D-T plasmas, both parameters were 20 \% higher for the D plasma.
For <\text{n}_\text{edge}> larger than the detachment onset density, the LFS diverter
plasma density control. Since the gas injection rates in unpumped
(10^{-2} \text{D/s}) and pumped (10^{-2} \text{D/s}) plasmas are factors of 100 and 10
lower than the recycling rates at the divertor plates (10^{-2}
and H-mode plasmas. In many of the discharges the JET machine protection system
terminated neutral beam heating prior to the physical density limit.
Thus, for both the pumped and unpumped deuterium discharges, the
physical density limit could not yet be determined.
3. Detachment onset of the LFS divertor plasma in deuterium
pumped and unpumped conditions

For both states of the cryogenic pump, <\text{n}_\text{edge}> at detachment onset
was the same density as indicated by the saturation of \text{I}_{\text{div,LSF-plate}} and subsequent reduction with <\text{n}_\text{edge}> in Fig. 2a. Both \text{T}_e
measured by a Langmuir probe radially outward of the LFS strike line, \text{T}_e\text{–LSF-plate}
(Fig. 1), and spectroscopically inferred, <\text{T}_e\text{–LFS-div} from a line-of-sight
which strikes the target plate at the same probe position (Fig. 1), showed a
marked reduction from 25 eV to 5 eV over the range of <\text{n}_\text{edge}> from
2.0x10^{19} \text{ m}^{-3} to 2.6x10^{19} \text{ m}^{-3}. Typically, the fitting of the current–voltage characteristics of Langmuir probes for \text{T}_e, and thus \text{n}_e,
becomes unreliable for \text{T}_e < 5 eV, while the spectroscopic analysis for \text{T}_e
is challenging for \text{T}_e > 30 eV. However, for the range of 20 eV < \text{T}_e < 5 eV the probe and spectroscopic measurements agree remarkably,
including the sharp, almost bifurcated reduction of \text{T}_e for <\text{n}_\text{edge}>
below the detachment onset density which is consistent with recent
observations in JET l-mode and high-confinement mode (H-mode)
plasmas [20], and resembles a similar \text{T}_e dependence on <\text{n}_\text{edge}> in
DIII-D (H-mode) plasmas observed with Divertor Thomson scattering
[21].

The saturation of \text{I}_{\text{div,LSF-plate}}, which is associated with the onset of
detachment, coincided with a <\text{T}_e\text{–LSF-plate} of 2–3 eV (Fig. 2b). The lower
bound of <\text{T}_e\text{–LFS-div} decreased to 0.5–0.7 eV at the highest <\text{n}_\text{edge}>
indicating strongly recombining plasmas. (The upper bound of <\text{T}_e\text{–LFS-div}
is centered at approximately 1.2 eV, which is inherent to the spec-
troscopic analyses as described in [17]). For <\text{n}_\text{edge}> larger than
detachment onset density, the spectroscopically inferred \text{n}_e across the
LFS divertor, <\text{n}_\text{edge}>, increased with increasing <\text{n}_\text{edge}> up to 6–8x10^{20} \text{ m}^{-3} and then decreased when <\text{T}_e\text{–LFS-div} reached 1 eV, or less,
indicating the shift of the high-density region from the strike zone to the
LFS divertor X-point (Fig. 2c, also Fig. 4 in [16] and Fig. 4 in [11]).
The movement of the high-density region was observed by a radial inward
shift across the spectrometer chords, which is interpreted as a poloidal
shift from the LFS strike line toward the LFS X-point region, and is
consistent with plasma imaging using tangential cameras and Balmer
emission line ratios [11,22]. While <\text{n}_\text{edge}> in the pumped and unpumped plasmas at their peak values, <\text{n}_\text{edge}> in the
unpumped plasma peaked at 10 \% lower <\text{n}_\text{edge}> than the pumped
plasma. Furthermore, the unpumped plasma exhibited an approxi-
mately 20 \% lower <\text{n}_\text{edge}> than the pumped plasma in partially
detached conditions. This small discrepancy can be explained by a <5
\text{mm} radial offset of the strike line at the LFS plate between the
two plasmas.

The line-average electron pressures across the LFS divertor, <\text{P}_\text{e}\text{–LFS-div}>
derived from <\text{T}_e\text{–LFS-div} and <\text{n}_\text{edge}> in the same man-
ner as <\text{n}_\text{edge}> is shown (not shown). Since <\text{n}_\text{edge}> and <\text{P}_\text{e}\text{–LFS-div} are line-integrated measurements, and \text{I}_{\text{Sat,LSF-plate}} and \text{I}_{\text{div,LSF-plate}} deter-
mined at the sheath entrance, it is also conceivable that plasma pressure
is lost at the surface at lower <\text{n}_\text{edge}> than in the region adjacent to the
plate. These observations are independent of the status of the divertor
cryogenic pump.
Spectroscopic measurements of the Balmer-α emission across the
outer divertor show that the intensities are indistinguishably the same
for the pumped and unpumped cases indicating that the D atomic dens-
ities at the strike zone, and potentially also in the LFS divertor corner
are the same despite the 5 times higher D₂ pressure in the sub-divertor
(not shown). These results suggest that the plasma conditions in the
LFS divertor are independent from the sub-divertor molecular pressure,
and that pumping raises the fuel throughput only thereby allowing
better plasma density control. Since the gas injection rates in unpumped
(10^{-2} \text{D/s}) and pumped (10^{-2} \text{D/s}) plasmas are factors of 100 and 10
lower than the recycling rates at the divertor plates (10^{-2}
and H-mode plasmas. In many of the discharges the JET machine protection system
terminated neutral beam heating prior to the physical density limit.
Thus, for both the pumped and unpumped deuterium discharges, the
physical density limit could not yet be determined.
5. HFS and LFS detachment in H, D, T and D-T pumped and
unpumped configurations

Langmuir probe measurements of \text{I}_{\text{LFS-div}} in fuelling ramps from low-
current density. The gas injection rates in unpumped (10^{-2} \text{D/s}) and pumped (10^{-2} \text{D/s}) plasmas are factors of 100 and 10
lower than the recycling rates at the divertor plates (10^{-2}
and H-mode plasmas. In many of the discharges the JET machine protection system
terminated neutral beam heating prior to the physical density limit.
Thus, for both the pumped and unpumped deuterium discharges, the
physical density limit could not yet be determined.
Fig. 3. Total ion current to the LFS target plate (a), electron temperature (b) and electron density (c) as a function of line-averaged density at the outer edge of the core plasma in unpumped plasmas. Deuterium plasmas are shown in blue (JPN 97699), tritium in magenta (JPN 100166) and deuterium–tritium in gold (JPN 99433). $T_e$ (b) was measured with Langmuir probes (circles, probe S19A) and inferred spectroscopically (KT3A, squares, channel 12), while $n_e$ was inferred spectroscopically only (KT3A, squares, channel 10). The black dashed vertical line indicates the assumed detachment onset density based on the saturation of $I_{div,LFS-plate}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
characterize the JET vacuum system and EDGE2D-EIRENE to isolate the physics described in section I are required. Secondly, the studies in both the ohmic and $L$-mode plasmas rely on the line-averaged density in the edge of the core plasma, $\langle n_e^{\text{edge}} \rangle$, being sufficiently representative for the plasma density, pressure and collisionality at the LFS midplane SOL, including at the separatrix. Despite the high-quality data obtained in these plasmas, the uncertainty in the separatrix location and the general inability to accurately determine the plasma conditions at the separatrix potentially prevent the experimental resolution of the isotope effect on the detachment onset density in these plasmas.

For the subset of the unpumped deuterium, tritium and deuterium–tritium plasmas, the electron temperature spectroscopically inferred across the plasma adjacent to the LFS strike line decreased from 25 eV to 5 eV over a narrow range of increasing core plasma density, and the ion currents saturated when the electron temperature reached 2–3 eV. For core plasma densities higher than the detachment onset density the line-averaged electron density spectroscopically inferred in front of the LFS target increased and then decreased, when the electron temperature reached 1 eV, or less. In this density range, the (spectroscopically inferred) electron pressure followed the trend of the electron density. For currently unknown reasons, but within the uncertainties of the assumed core plasma density, at the onset of detachment the ion saturation current density and the Balmer-$\alpha$ emission are 20–30 % lower for tritium and deuterium–tritium plasmas. The non-linearity of the divertor plasma conditions on the core plasma conditions at the onset of detachment when selecting the time representing the detachment onset in a fuelling ramp is one source of uncertainty that could explain the difference in ion saturation current density and Balmer-$\alpha$ emission without invoking a physics model.

These datasets provide one of the most stringent tests for SOL codes, such as SOLPS-ITER and EDGE2D-EIRENE, not only to elucidate the isotope effect in JET and other tokamaks, but also to validate the plasma and neutral distributions in the divertor SOL, the gas flow through the pump ducts, and the pumping efficiency of the cryogenic pump. As shown in previous publications for deuterium plasmas [7,10,12], both SOLPS-ITER and EDGE2D-EIRENE underpredict the measured electron density at the LFS target plate at the onset of detachment by a factor of 2 to 3 for both H and D plasmas. The resolution of this particular issue precedes the more complete understanding of the isotope effect on the onset of detachment. These studies, however, aid elucidating the impact of the different hydrogenic isotopomers on the onset of detachment, by improving the atomic and molecular input databases to SOLPS-ITER and EDGE2D-EIRENE [5].

These databases currently utilise dissociation, ionisation and recombination rates inferred from hydrogen only, which are scaled by the isotope mass for the main ion–molecule reactions.

Fig. 4. Radial profiles of the ion saturation current to the LFS plate as a function of distance from the separatrix (a), Balmer-$\alpha$ intensity across the LFS divertor plasma as a function of detector angle (b), and line-averaged $\langle T_e^{\text{LFS-div}} \rangle$ (c) and $\langle n_e^{\text{LFS-div}} \rangle$ (d) across the LFS divertor plasmas as a function of radial location of the intersection point of the line-of-sight with the LFS divertor plate at the detachment onset density ($\langle n_e^{\text{LFS-mp}} \rangle \approx 2.6 \times 10^{19} \text{ m}^{-3}$). Deuterium plasmas are shown in blue (JPN 97699 at 17.2 s), tritium in magenta (JPN 100166 at 13.5 s) and deuterium–tritium in gold (JPN 99433 at 8.4 s). In (b)-(d), the separatrix location is indicated by the thicker dashed black line, while the thinner black dashed lines indicate the radial locations of the innermost and outermost edges of the LFS horizontal plate, and innermost edge of the LFS vertical plate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Mathias Groth reports financial support was provided by European Consortium for the Development of Fusion Energy.].

Data availability

Data will be made available on request.
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