Correlation between near scrape-off layer power fall-off length and confinement properties in JET operated with carbon and ITER-like wall

M Faitsch, T Eich, B Sieglin and JET Contributors

1 Max-Planck-Institute for Plasma Physics, Boltzmannstr. 2, D-85748 Garching, Germany
2 See author list of E. Joffrin et al 2019 Nucl. Fusion 59 112021

E-mail: Michael.Faitsch@ipp.mpg.de

Received 16 December 2019, revised 21 April 2020
Accepted for publication 5 May 2020
Published 22 June 2020

Abstract
Combining high plasma core performance with a suitable power exhaust solution is one of the major challenges in magnetic confinement fusion research. One of the most important power exhaust parameters is the power fall-off length in the scrape-off layer. Two infrared thermography based power fall-off length data sets from JET operated with carbon and ITER-like wall are revisited and compared to recently published scaling laws as well as to confinement and pedestal top parameters. It is shown that the power fall-off length is correlated to confinement, with the highest correlation among the tested parameters being the pedestal top density. The power fall-off length decreases with increasing pedestal top density in variance to the multi-machine scaling law. A similar trend is observed for the pedestal top pressure. This is in agreement with findings at C-Mod showing a scaling of the power fall-off length in various confinement regimes with the volume averaged pressure. Further, it is shown that a variation of the safety factor at constant pedestal top density is not changing the power fall-off length significantly in the two JET data sets.

Keywords: divertor, scrape-off layer, power exhaust, fall-off length, JET

1. Introduction

In recent years the focus of fusion research narrowed onto power exhaust reflecting that the power load onto the wall components is one of the major challenges in realising a power plant. Unmitigated divertor power loads in next step fusion devices like ITER are extrapolated to be close to or to exceed material limits [1, 2] making significant impurity seeding necessary. The amount of required injected impurities depends strongly on the scrape-off layer width [3, 4]. Though scaling laws for inter-ELM transport are well accepted, an agreed physics picture of near scrape-off layer transport is yet to be found. Further, any power exhaust solution has to be compatible with high plasma core performance.

A multi-machine scaling law [5] suggests that the poloidal magnetic field is the leading parameter setting the power fall-off length, \( \lambda_q \), and, thus, is inherently linked to confinement properties, e.g. the energy confinement time as seen in the confinement time scaling depending on the poloidal magnetic field [6]. A correlation between near scrape-off layer quantities with properties in the confined region was reported for various tokamaks [7–11]. Comparing \( \lambda_q \) with plasma parameters in the confined region was reported in L-mode with a correlation between \( \lambda_q \) and the edge electron density and stored energy at ASDEX Upgrade [12, 13], the edge electron temperature
at TCV [14] and in combined L, I and H-mode the volume-averaged plasma pressure at Alcator C-Mod [15] and pedestal top pressure at ASDEX Upgrade [16].

Here, we report on experimental studies investigating a correlation between near scrape-off layer power fall-off length and confinement properties at JET to highlight the coexistence between a narrow scrape-off layer and high confinement operation and a widening for reduced confinement factors.

The paper is organised as follows: The analysed data sets are described in section 2. There we discuss also key correlations between various confinement properties which were used in several published scaling laws. Section 3 presents a study of the correlation between the power fall-off length and pedestal top properties. In section 4 the influences of toroidal and poloidal magnetic field on $\lambda_q$ are compared. A summary and conclusions are presented in section 5.

2. JET data sets from operation with CFC and ILW divertor

In this work data sets originally generated for divertor target heat load studies are further analysed. As we aim to compare these divertor heat loads to upstream measurements, only data with suitable upstream Thomson scattering (TS) data can finally be taken, largely reducing the number of available discharges. The pedestal top data is obtained using a modified hyperbolic tangent ($\tanh$) function of the TS profiles [17] with typical uncertainties in the order of 10%, e.g. [18].

The data set for JET operated with a carbon fibre composite (CFC) divertor (named JET-CFC) is the same as in Eich et al [5]. The restriction of finding data where also pedestal top data from TS are available reduces the data set to 41 discharges. Furthermore a sub-set is identified having both TS pedestal top and near scrape-off layer measurements (named JET-CFC-SOL) that consists of 10 discharges. The separatrix is localised using the two point model to obtain $T_{e,sep}$ from the IR based power fall-off length $\lambda_p$. The electron fall-off length is calculated using the two neighbouring channels. From this $T_{e,sep}$ is self-consistently re-calculated using $\lambda_T$. The separatrix density is then taken at the same position. With this procedure no mapping with the equilibrium is needed. Error-bars will be shown in figures containing values derived from the separatrix TS values accounting for the larger uncertainties compared to all other used quantities.

The data set for JET operated with the ITER-like wall (ILW) divertor (named JET-ILW) is the same as in Sieglin et al [19, 20] (59 discharges) with all discharges having TS pedestal top data. Again a sub-set where both TS pedestal top and near scrape-off layer measurements are available (named JET-ILW-SOL) is taken in the same way as for the CFC data set (26 discharges).

The fall-off lengths are typically mapped to the outer mid-plane (OMP) and represent a local quantity. A different approach is to use the poloidally averaged value $\langle \lambda \rangle$ which can be translated by using [21]

$$\langle \lambda \rangle = \lambda_\text{geo} \frac{\beta_\text{pol}}{\beta_\text{geo}}$$

with the average poloidal magnetic field $B_\text{pol} = \frac{\mu_0 I_p}{2 \pi a (1+\epsilon)}$, and the local value at the outer mid-plane $B_\text{OMP}^\text{pol}$, minor radius $a$, plasma current $I_p$, elongation $\epsilon$, vacuum permeability $\mu_0$ and geometrical major radius $R_\text{geo}$ as well as that of the outer mid-plane $R_\text{OMP}$.

This allows to compare measured values to theoretical predictions typically using poloidal flux averaging. However, it was shown that the divertor power fall-off length measured at the inner and outer divertor targets are not the same, e.g. in ASDEX Upgrade [12, 22] and TCV [14, 23]. Thus, assuming the heat flux width to be constant along flux surfaces might not be valid for high and low field sides. Here, only measurements of $\lambda_q$ at the outer divertor target are presented.

For JET $f_{geo} \approx 0.55$ [21], however, being dependent on e.g. plasma pressure and shaping. For the presented JET data sets, where the plasma shape does not vary greatly, the main contribution to changes in $f_{geo}$ is the normalised plasma pressure $\beta_\text{pol}$. Figure 1 shows the correlation between $f_{geo}$ and $\beta_\text{pol}$. Here $\beta_\text{pol}$ is used defined as

$$\beta_\text{pol} = \frac{4 W_{\text{MHD}}}{3 V B_\text{pol}^2} = 2 \mu_0 \cdot \hat{p} \cdot B_\text{pol}^{-2}$$

with plasma stored energy $W_{\text{MHD}}$, plasma volume $V$ and volume-averaged plasma pressure $\hat{p}$. The difference between CFC and ILW data can partially be attributed to a variation in plasma volume with $V_{\text{CFC}} = 80 \pm 2 \text{ m}^3$ and $V_{\text{ILW}} = 75 \pm 1 \text{ m}^3$ combined with a reduced $W_{\text{MHD}}$ in ILW compared to CFC at similar heating powers [24, 25].

It is noted, that for the presented data sets the variation of $f_{geo}$ is not significant enough to distinguish between flux averaged or local mapping. The local mapping to the outer mid-plane will be used in the following if not stated otherwise. However, especially when attempting to combine data sets with larger variation in shaping, volume and $\beta_\text{pol}$, e.g. combining L and H-mode discharges, the mapping might be of importance.

![Figure 1. Correlation between $f_{geo}$ and $\beta_\text{pol}$.](image)
2.1. Correlations in the data sets

The two data sets consist mainly of dedicated experiments in order to assure good measurements with the infrared (IR) cameras. This assures that the uncertainty of \( \lambda_q \) is in the order of 15% from statistical variation as well as from signal to noise considerations [20]. However, this leads to limitations in the operational space as well as correlations, both being discussed in this section. The main limitation is the restriction to good confinement (\( H_{98}^{CFC} \approx 0.9 – 1.1 \) and \( H_{98}^{ILW} \approx 0.8 – 1.0 \)), type-I ELM My H-modes under attached divertor conditions.

With this restriction the main parameter for increasing the plasma stored energy \( W_{\text{MHD}} \) is the poloidal magnetic field \( B_{\text{pol}} \). This is also reflected in the ITER energy confinement scaling [6]. Figure 2 shows the linear increase of \( W_{\text{MHD}} \) with \( B_{\text{pol}} \). The variation of \( W_{\text{MHD}} \) at fixed \( B_{\text{pol}} \) is mainly due to changes in heating power, as shown in figure 3. This follows closely the expected trend assuming a scaling of the energy confinement time \( \tau_E \) as [6]

\[
\tau_E \propto B_{\text{pol}}^{1.5} P^{-0.7}
\]  

with \( P \) being the heating power. It can be seen that for operation with the ILW higher heating power is needed to achieve the same ratio between \( W_{\text{MHD}} \) and \( B_{\text{pol}} \). This reflects in a slightly reduced confinement factor. Further details for the pedestal composition are presented in section 3. Note here, that power balance analyses at JET showed a mismatch between input and output power. It remains unclear to which extent this is due to an overestimation of the input and/or underestimation of the output power [26]. This can potentially decrease the calculated \( P_{\text{SOL}} \) values and accordingly increase the confinement factor.

Figure 4 shows a linear correlation between \( W_{\text{MHD}} \) and the pedestal top electron pressure \( P_{e,\text{ped}} \). This confirms that the overall plasma performance in terms of \( W_{\text{MHD}} \) is set by \( P_{e,\text{ped}} \). Furthermore, it was shown that the ELM energy fluence linearly increases with \( P_{e,\text{ped}} \) in these data sets [19, 27, 28], pointing out the increasing challenge to exhaust transient power loads with higher core performance.

It is expected that \( P_{e,\text{ped}} \) increases with \( \beta_{\text{pol}} \) [29, 30]. However, no clear correlation is found between \( \beta_{\text{pol}} \), as defined in (2), and either \( P_{e,\text{ped}} \) or \( P_{\text{SOL}} \) in the analysed data sets. This is probably due to the selection of discharges in these data sets, which are characterised by a correlation of higher \( P_{\text{SOL}} \) and \( n_{e,\text{ped}} \) at higher \( B_{\text{pol}} \). This might cover the relation between \( P_{e,\text{ped}} \) and \( \beta_{\text{pol}} \) observed in dedicated data sets.

2.2. Correlation between divertor power and upstream electron temperature fall-off lengths

It was shown for ASDEX Upgrade that the power fall-off length, \( \lambda_q \), and electron temperature fall-off length, \( \lambda_T \), are in agreement with the assumption of Spitzer-Härm electron conduction to be the dominating parallel heat transport mechanism (\( \lambda_T / \lambda_q = 3.5 \)) in L-mode using simultaneous measurements of \( \lambda_q \) from IR at the divertor and upstream \( \lambda_T \) from TS [22]. Further, it was shown that \( \lambda_T \) and \( \lambda_q \) parameter dependencies are consistent in both L and H-mode with Spitzer-Härm electron conduction [10, 31].

Upstream scrape-off layer TS profiles are available in a sub-set of the data for JET. Figure 5 (left) shows a comparison between \( \lambda_T \) and \( \lambda_q \) from TS and divertor IR diagnostics, respectively, operated with both CFC and ILW.

The ratio of the two fall-off lengths is in the same order as the expected Spitzer-Härm electron conduction prediction indicated by the line. However, in both data sets a large scatter is observed.

A comparison between the separatrix and pedestal top electron pressure is shown in figure 5 (right). The lines are a linear regression, showing that JET with the ILW exhibits a larger separatrix pressure at similar pedestal top pressure. This is attributed to the higher fuelling used to prevent tungsten impurity accumulation in the metal device [19] as well as the
An available scaling law for $\lambda_q$ in H-mode based on multi-machine data sets indicate that the poloidal magnetic field at the outer mid-plane $B_{pol}^{\text{OMP}}$ is the main quantity determining $\lambda_q$ [5]:

$$\lambda_q^{\text{Multi}} (\text{mm}) = 0.63 \cdot B_{pol}^{\text{OMP}} (T)^{-1.19} .$$

(4)

Figure 6 shows the power fall-off length dependence on $B_{pol}^{\text{OMP}}$. A general trend of larger values for $\lambda_q$ with lower $B_{pol}^{\text{OMP}}$ can be seen. However, the data scatter is large, especially for the ILW data set. Both data sets exhibit a scatter towards larger $\lambda_q$ values compared to the scaling law. This is reflected in figure 3 of [5] where for each single device a vertical scatter is present.

Figure 7 shows a comparison between $\lambda_q$ and $\tau_E$. Because of (3) and all presented data being within a narrow $H_{q\delta}$ range the correlation between $\lambda_q$ and $\tau_E$ is closely linked to the correlation between $\lambda_q$ and $B_{pol}$. The energy confinement time is increasing with machine size [6], whereas it was shown that $\lambda_q$ is independent on machine size [5]. For this reason a scaling on e.g. confinement time needs to consider machines separately. A recent study by Brunner et al. [15] uses the volume-averaged plasma pressure $\tilde{p}$ to scale $\lambda_q$ combining L, I and H-mode in Alcator C-Mod:

$$\lambda_{q,Brunner}^{\text{mm}} = 8.9 \cdot \tilde{p}(\text{kPa})^{-0.5},$$

(5)

with

$$\tilde{p} = \frac{2 \cdot W_{\text{MHD}}}{3 \cdot V}. \quad (6)$$

Figure 8 shows a comparison between $\lambda_q$ and $\tilde{p}$. The line represents $\lambda_{q,Brunner}$, as shown in (5). The scaling law predicts values in the same range as measured. As previously mentioned $W_{\text{MHD}}$ and $B_{pol}$ are linked in the presented data sets for JET. Further, $W_{\text{MHD}}$ is closely correlated to $p_{e,\text{ped}}$.

The correlation between pedestal top values, $T_{e,\text{ped}}, n_{e,\text{ped}}$ and $p_{e,\text{ped}}$ with $\lambda_q$ is examined in the following. Figure 9 shows the measured pedestal top temperature and density in the data sets. It was previously shown that for achieving similar pedestal composition ($n_{e,\text{ped}}$ and $T_{e,\text{ped}}$) more heating power is needed for operating in ILW compared to CFC for the presented data sets [19] as a common feature of the ILW operation at JET [24]. At similar heating power ILW operation exhibits a higher $n_{e,\text{ped}}$ and lower $T_{e,\text{ped}}$ compared to CFC at comparable $p_{e,\text{ped}}$.  

3. Correlation between the power fall-off length and pedestal top properties

higher reflection coefficient and energy of ions on the metal first wall [32, 33]. This leads to a higher scrape-off layer density and with this to a higher pressure at the separatrix while the separatrix electron temperature in H-mode is observed to be about constant.
two data sets. The black lines are lines of constant pressure. The volume-averaged plasma pressure, $\hat{p}$, the reduced by the three data points at $T_{e,\text{ped}}$ in L-mode, not present in the H-mode data sets from JET. combined with TCV from sole ASDEX Upgrade $R$ crosses) and a distinguish between a $\lambda_q$ Correlation between power fall-off length, $\lambda_q$, and pedestal top density, $n_{e,\text{ped}}$. The data sets are divided into a temperature dominated (crosses, $T_e$) and a density dominated (dots, $n_e$) pedestal pressure as shown in figure 9. The data sets are divided into two branches, so that each has approximately the same number of data points. This allows to distinguish between a temperature dominated (above the line, crosses) and a density dominated (below the line, dots) pedestal. This distinction is used to identify temperature and density effects. For the ILW data set the confinement factor $H_{98}^{\text{ILW}}$ for the density dominated pedestal pressure is significantly lower than for the temperature dominated one. This is a consequence of the pedestal composition difference between CFC and ILW at similar heating powers and the reduced $W_{MHD}$ under these conditions [24, 25]. The correlations between $\lambda_q$ and pedestal top parameters ($T_{e,\text{ped}}, n_{e,\text{ped}}, p_{e,\text{ped}}$), as well as $B_{\text{pol}}^{\text{OMP}}, \hat{p}$ and $T_e$ are shown in table 1. It can be seen that the highest correlation, expressed by $R^2$, is between $\lambda_q$ and $n_{e,\text{ped}}$ for both data sets. Scaling laws from sole ASDEX Upgrade [12, 13] and ASDEX Upgrade combined with TCV [14] showed a correlation with $T_{e,\text{edge}}$ in L-mode, not present in the H-mode data sets from JET. The correlation with $p_{e,\text{ped}}$ in the CFC data set is significantly reduced by the three data points at $T_{e,\text{ped}} > 2$ keV. Excluding these points would result in a correlation of -0.55 instead of -0.34. This might explain the larger correlation in the ILW due to the absence of such high $T_{e,\text{ped}}$ values. ASDEX Upgrade results combining L, I and H-mode show an anti-correlation of $\lambda_q$ with $p_{e,\text{edge}}$ [16]. This is in line with the reported trend with $p_{e,\text{ped}}$. Thanks to the larger variation in $T_{e,\text{edge}}$ in the ASDEX Upgrade study using multiple confinement regimes it was concluded that neither $T_{e,\text{edge}}$ nor $n_{e,\text{edge}}$ correlate as well as $p_{e,\text{edge}}$. Figure 10 shows the correlation between $\lambda_q$ and $n_{e,\text{ped}}$. It can be seen that $\lambda_q$ decreases for increasing $n_{e,\text{ped}}$. The two branches, shown with different symbol types, do not exhibit a notable difference in the trend. However, the discharges with a density dominated pedestal have on average a narrower $\lambda_q$. Figure 11 shows the correlation between $\lambda_q$ and $T_{e,\text{ped}}$. It can be seen that the variation in $T_{e,\text{ped}}$ especially for the ILW, is smaller compared to the variation of $n_{e,\text{ped}}$. No clear correlation between $\lambda_q$ and $T_{e,\text{ped}}$ is seen, as also shown in the poor correlation value in table 1. The two branches of the pedestal composition show a slight variation. While having similar $T_{e,\text{ped}}, \lambda_q$ is larger for the temperature dominated branch. These data points are following the same trend as the density dominated branch when comparing $\lambda_q$ and $n_{e,\text{ped}}$, with smaller $n_{e,\text{ped}}$ values at similar $T_{e,\text{ped}}$. Finally, figure 12 shows the correlation between $\lambda_q$ and $p_{e,\text{ped}}$. The variation of $\lambda_q$ shows the same decreasing trend with increasing pressure as with increasing density. However, the two branches of the pedestal composition show a slight variation. While they separate in density, the two branches overlap for most of the range of achieved $p_{e,\text{ped}}$. It can be seen that the $\lambda_q$ is larger for the temperature dominated branch while having comparable $p_{e,\text{ped}}$. With $p_{e,\text{ped}}$ being closely correlated to $W_{MHD}$, and due to the small variation in volume also to $\hat{p}$, no distinction between a $\lambda_q$ dependence on either $\hat{p}$ or $p_{e,\text{ped}}$ is possible. The close connection between $\lambda_q$ and pedestal top values, as reported also in other studies, e.g. [11–14, 31, 34], is

**Figure 8.** Correlation between power fall-off length, $\lambda_q$, and the volume-averaged plasma pressure, $\hat{p}$. The solid line represents $\lambda_q^{\text{Brunner}} = 8.9 \cdot \hat{p}^{(0.5)}$. $\hat{p}$

**Figure 9.** Pedestal top temperature, $T_{e,\text{ped}}$, and density, $n_{e,\text{ped}}$, of the two data sets. The black lines are lines of constant pressure. The blue line is separating about half of the data sets into a temperature (above the line, crosses, $T_e$) and a density (below the line, dots, $n_e$) dominated pedestal top pressure with slope $\frac{1}{3}$ keV.$m^{-3}$. $\hat{p}$

**Figure 10.** Correlation between power fall-off length, $\lambda_q$, and pedestal top density, $n_{e,\text{ped}}$. The two data sets are divided into a temperature dominated (crosses, $T_e$) and a density dominated (dots, $n_e$) pedestal pressure as shown in figure 9.

**Table 1.** Correlation coefficients between power fall-off length $\lambda_q$ and various plasma parameters for JET operated with CFC and ILW.

|        | CFC   | ILW   |
|--------|-------|-------|
| $B_{\text{pol}}^{\text{OMP}}$ | -0.51 | -0.52 |
| $\hat{p}$ | -0.47 | -0.27 |
| $\tau_e$ | -0.40 | -0.49 |
| $T_{e,\text{ped}}$ | -0.18 | 0.02 |
| $n_{e,\text{ped}}$ | -0.64 | -0.60 |
| $p_{e,\text{ped}}$ | -0.34 | -0.51 |
This scaling law has a slightly negative exponent for $P_{\text{SOL}}$ in contrast to the IR based scaling laws by Eich et al [21] and Sieglin et al [20] where it is slightly positive. The second major difference is that this scaling law depends on $q_{95}$ without simultaneously $B_{\text{tor}}$ dependence. It is, thus, not being dominated by $B_{\text{pol}}$ in contrast to the above mentioned IR based scaling laws. Since (7) is a single machine scaling law no regression with major radius is available [11], thus, this can be interpreted as connection length, favourable for larger machines. When assuming that the dependence on $q_{95}$ is a dependence on the connection length, the scaling law predictions for JET are a factor $\left( \frac{R_{\text{tor}}}{R_{\text{pol}}^0} \right)^{0.08} \approx 1.6$ larger. Figure 13 shows a comparison between $\lambda_q$ and $\lambda_{q,\text{sun,H}}$. Although the absolute value is in the same range, especially for the smallest values, this scaling is not describing the JET data sets. Assuming the aforementioned dependence on the connection length from (7)—with a factor 1.6 larger predicted values at JET—would lead to an over-prediction compared to the measured values.

To study further the correlation between $\lambda_q$ and $q_{95}$ a triplet of $B_{\text{pol}}, B_{\text{tor}}$ and $q_{95}$ for the ILW data set is used. For each combination of $B_{\text{pol}}$ and $B_{\text{tor}}$ two (or three) values of $P_{\text{SOL}}$ are available. The corresponding values are presented in table 2. It can be seen that for high and low $q_{95}$ at fixed $B_{\text{pol}}$ (Ia,Ib vs Ia,IIb) similar values for $n_{\epsilon,\text{ped}}$ and $T_{e,\text{ped}}$ and consequently $P_{\text{ped}}$ are achieved. Further, also similar values for $\lambda_q$ are measured despite the variation in $q_{95}$ of about a factor of 2. At low $q_{95}$, high $B_{\text{pol}}$ and similar heating power (IIa,IIb) a larger $n_{e,\text{ped}}$ is achieved at similar $T_{e,\text{ped}}$ and consequently a higher $P_{\text{ped}}$. This correlates with a smaller $\lambda_q$. Increasing $P_{\text{SOL}}$ (IIIc) leads to a higher $T_{e,\text{ped}}$ and a similar $n_{e,\text{ped}}$ than (Ia-IIb). However, $P_{\text{ped}}$ is similar to (IIa,IIb) and higher than for (Ia-IIb). The same behaviour is observed for $\lambda_q$, with a similar value to (Ia-IIb) and a larger value than (IIa,IIb). This is in line with the correlation between $n_{e,\text{ped}}$ and $\lambda_q$. Figure 14 shows $\lambda_q$ depending on $n_{e,\text{ped}}$ for the ILW data set and in colour the discharges of table 2. The colours represent the different combinations of $I_p$ and $B_{\text{tor}}$ (I, II, III in table 2). The marker style represents the heating power level (a,b,c in table 2). The data points follow the trend of smaller $\lambda_q$ with increased $n_{e,\text{ped}}$. This is visible despite the variation of $q_{95}$ of a factor of two that does not lead to an additional variation of $\lambda_q$. It is concluded that in the presented ILW data set the variation of $\lambda_q$ cannot be explained by either $q_{95}$ or $B_{\text{pol}}$ alone. The CFC data set does not have distinctive in the presented JET data sets. Whether this is a causality with the absolute values, with the gradients in the confined region or a co-dependence on a third quantity, e.g. $B_{\text{pol}}$, cannot be examined in the presented JET data sets. Nevertheless, it shows that in the high confinement, attached conditions of these data sets, it is not possible to have high pedestal top - and with this core - performance and simultaneously a broad scrape-off layer. In the next section a sub-set of the JET-ILW data is used to have a closer look into the origin of the correlation between $\lambda_q$ and $n_{e,\text{ped}}$ by studying the variation of $\lambda_q$ with safety factor.

**4. Variation of the power fall-off length with safety factor**

In a recent work by Sun et al at ASDEX Upgrade using TS electron temperature fall-off length and assuming Spitzer-Härm electron conduction yields for H-mode [11]

$$\lambda_{q,\text{sun,H}}(\text{mm}) = \frac{2}{7} \cdot \lambda_{q,\text{sun,H}}^0(\text{mm}) = \frac{2}{7} \cdot 2.6 \cdot q_{95}^{0.82} \cdot P_{\text{SOL}}(\text{MW})^{-0.14}. \quad (7)$$

![Figure 11. Correlation between power fall-off length, $\lambda_q$, and pedestal top temperature, $T_{e,\text{ped}}$. The two data sets are divided into a temperature dominated (crosses, $T_e$) and a density dominated (dots, $n_e$) pedestal pressure as shown in figure 9.](image1)

![Figure 12. Correlation between power fall-off length, $\lambda_q$, and pedestal top pressure, $P_{e,\text{ped}}$. The two data sets are divided into a temperature dominated (crosses, $T_e$) and a density dominated (dots, $n_e$) pedestal pressure as shown in figure 9.](image2)

![Figure 13. Comparison between power fall-off length, $\lambda_q$, and scaling law prediction, $\lambda_{q,\text{sun,H}}(\text{mm}) = \frac{2}{7} \cdot 2.6 \cdot q_{95}^{0.82} \cdot P_{\text{SOL}}(\text{MW})^{-0.14}$.](image3)
discharges with a similar range of $q_{95}$ and, thus, are not shown due to the insignificant variation.

Interestingly, the positive dependence on $P_{\text{SOL}}$ of $\lambda_q^{\text{JET-ILW}}$ as seen in [20] might be explained by the reduction of $n_{\text{e,ped}}$ with increasing $P_{\text{SOL}}$ at otherwise similar parameters. It can be speculated that the reduced $n_{\text{e,ped}}$ is caused by an increased radial transport which in the same way could also be the cause for the broadening of $\lambda_q$.

Recent work at ASDEX Upgrade proposes a mechanism to broaden $\lambda_q$ w.r.t. the established scaling laws driven by turbulence [35]. A turbulence control parameter is defined as [35]:

$$\alpha_t = 3 \cdot 10^{-18} \frac{q_{95}^2}{\rho_{\text{sep}} T_{\text{e,sep}}^2} Z_{\text{eff}}.$$  

(8)

Figure 15 presents the poloidal averaged $\langle \lambda_q \rangle$ of the JET data sets normalised to $\rho_{\text{sep}}$ against $\alpha_t$ using

$$\rho_{\text{sep}} = \frac{\sqrt{m_p T_{\text{e,sep}}}}{e B_{\text{pol}}}$$  

(9)

with $m_p$ the ion mass and $e$ the elementary charge. We used here $Z_{\text{eff}} = 2$ for CFC and $Z_{\text{eff}} = 1.4$ for ILW. The solid line represents

$$\frac{\langle \lambda_q \rangle}{\rho_{\text{sep}}} = 2 \left( \frac{\lambda_T}{7 \rho_{\text{sep}}} \right) = 0.6 \cdot (1 + 2.1 \alpha_t^{1.7}).$$  

(10)

It can be seen that the $\alpha_t$ values are close to zero. This is a consequence of the data selection of having IR measurements and a low ELM frequency. A significant broadening is reported for ASDEX Upgrade when $\alpha_t$ approaches one [35]. It is of great interest to establish a JET data set with $\alpha_t$ approaching unity.

5. Summary and conclusions

This paper reports on the correlation between the near scrape-off layer power fall-off length $\lambda_q$ and confinement properties in JET operated with carbon and tungsten first wall. Previously this data was compared to global machine parameters, finding a scaling of $\lambda_q$ with safety factor and toroidal magnetic field strength and a weak positive dependence on power crossing the separatrix. Here, we show that $\lambda_q$ is correlated to the energy confinement time that is dominated by the poloidal magnetic field.

The data sets from tungsten and carbon wall are showing the same trends. Notably, two prominent differences are present between the data for the operation in tungsten and carbon. First, a reduced stored energy at similar poloidal magnetic field and heating power in tungsten compared to the carbon divertor operation. Second, a higher separatrix pressure at similar pedestal top pressure is present in tungsten compared to the carbon operation, a consequence of the higher gas puff needed for the tungsten first wall. Both differences do not lead to a significant variation of $\lambda_q$.

The highest correlation of $\lambda_q$ among the tested parameters is the pedestal top electron density $n_{\text{e,ped}}$. The correlation with confinement properties is in agreement with findings at C-Mod showing a scaling of the power fall-off length combining various confinement regimes with the volume-averaged plasma pressure $\rho$ [15]. A correlation with the pedestal top pressure $p_{\text{e,ped}}$ was reported for ASDEX Upgrade combining various confinement regimes [16].

Triplets of $B_{\text{pol}}$, $B_{\text{int}}$ and $q_{95}$ combinations are examined for the ILW data set. These data points follow the trend of smaller $\lambda_q$ with increased $n_{\text{e,ped}}$. It is concluded that a variation of $q_{95}$ cannot explain the variation of $\lambda_q$ in the presented JET data sets. Interestingly, the correlation with $B_{\text{pol}}$
is only present when \( n_{e,\text{ped}} \) is increasing, whereas at similar density a larger \( B_{\text{pol}} \) not necessarily correlates with a narrower \( \lambda_q \).

Various heuristic and theory based models predict a dependence of \( \lambda_q \) on \( B_{\text{pol}} \) in plasma discharges having JET like parameters [36–38], in line with the ITPA multi-machine scaling using \( B_{\text{pol}}^{\text{OMP}} \) as single regression parameter [5]. However, these models find the \( B_{\text{pol}} \) dependence due to different reasons.

In the presented empirical work it is shown that the \( B_{\text{pol}}^{\text{OMP}} \) scaling can be substituted with parameters that are associated with the energy confinement, namely \( p, p_{e,\text{ped}} \) or \( n_{e,\text{ped}} \). Plasma stored energy and poloidal magnetic field are closely correlated in the presented JET data sets, consisting of high confinement and low gas puff H-mode plasmas, making it impossible to identify the causality. A correlation between pedestal top parameters and \( \lambda_q \) due to edge transport setting the gradients just inside and outside the separatrix in a similar way by e.g. critical gradient induced turbulence is hence of great interest for future work. Here, clearly, global discharge parameters will not serve for further understanding and need to be substituted by a local description.

Direct conclusions for ITER will stay speculative and are, thus, not envisaged here. The reason is that the conditions at ITER, much larger P/R ratio, high scrape-off layer density and low pedestal top collisionalities are not realised at JET with simultaneous upstream \( T_{e,\text{sep}} \) and downstream poloidal power load profiles. However, a step towards such conditions are highly desired to improve empirical efforts and support the development of physics understanding. In practise, from the content of our paper as much as based on other recent work [15, 16, 35], it becomes clear that for JET gas fuelling experiments are highly desirable which combine high heating power, high current and high shaping such that the interplay between pedestal top conditions at lowest feasible collisionality and the scrape-off layer width can be studied in such ITER approaching conditions.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ORCID iDs

M Faitisch @ https://orcid.org/0000-0002-9809-7490
T Eich @ https://orcid.org/0000-0003-3065-8420
B Sieglin @ https://orcid.org/0000-0002-9480-4434

References

[1] Loarte A et al 2007 Nucl. Fusion 47 S203
[2] Pitts R et al 2013 J. Nucl. Mater. 438 S48
[3] Kukushkin A et al 2013 J. Nucl. Mater. 438 S203
[4] Goldston R et al 2017 Plasma Phys. Control. Fusion 59 055015
[5] Eich T et al 2013 Nucl. Fusion 53 093031
[6] ITER Physics Expert Group on Confinement and Transport et al 1999 Nucl. Fusion 39 2175
[7] Loarte A et al 1999 J. Nucl. Mater. 266 587
[8] Labombard B et al 2011 Phys. Plasmas 18 056104
[9] Neuhauser J et al 2002 Plasma Phys. Control. Fusion 44 855
[10] Sun H J et al 2015 Plasma Phys. Control. Fusion 57 125011
[11] Sun H J et al 2018 Plasma Phys. Control. Fusion 61 014005
[12] Sieglin B et al 2016 Plasma Phys. Control. Fusion 58 055015
[13] Sieglin B et al 2016 Nuclear Materials and Energy 12 216
[14] Faitisch M et al 2018 Plasma Phys. Control. Fusion 60 045010
[15] Brunner D et al 2018 Nucl. Fusion 58 094002
[16] Silvagni D et al 2020 Plasma Phys. Control. Fusion 62 045015
[17] Groebner R J et al 2002 Plasma Phys. Control. Fusion 44 A265
[18] Maggi C et al 2017 Nucl. Fusion 57 116012
[19] Sieglin B et al 2013 Plasma Phys. Control. Fusion 55 124039
[20] Sieglin B 2014 Divertor power load studies in all metal ASDEX upgrade and JET PhD thesis TU München
[21] Eich T et al 2011 Phys. Rev. Lett. 107 215001
[22] Faitisch M et al 2015 Plasma Phys. Control. Fusion 57 075005
[23] Maurizio R et al 2018 Nucl. Fusion 58 016052
[24] Beurskens M N A et al 2013 Plasma Phys. Control. Fusion 55 124043
[25] Maggi C et al 2015 Nucl. Fusion 55 113031
[26] Matthews G et al 2017 Nuclear Materials and Energy 12 227
[27] Eich T et al 2017 Nuclear Materials and Energy 12 84
[28] Sieglin B et al 2017 Nucl. Fusion 57 066045
[29] Dunne M G et al 2016 Plasma Phys. Control. Fusion 59 025010
[30] Saarelma S et al 2017 Plasma Phys. Control. Fusion 60 014042
[31] Sun H J et al 2017 Plasma Phys. Control. Fusion 59 105010
[32] Schneider P A et al 2014 Plasma Phys. Control. Fusion 57 014029
[33] Lunt T et al 2017 Plasma Phys. Control. Fusion 59 055016
[34] Leonard A et al 2017 Nucl. Fusion 57 086033
[35] Eich T et al 2020 Nucl. Fusion 60 056016
[36] Goldston R J 2012 Nucl. Fusion 52 013009
[37] Chang C et al 2017 Nucl. Fusion 57 116023
[38] Fedorczak N et al 2019 Nuclear Materials and Energy 19 433