Assessment of the Baseline Scenario at $q_{95}$~3 for ITER

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1. Introduction
The Integrated Operation Scenarios Topical Group (IOS-TG) of the ITPA has coordinated experiments in H-mode at $q_{95}$~3 in several tokamak devices (AUG, C-Mod, DIII-D, JET and JT-60U) that can be compared to simulations of ITER operation at Q=10 (baseline scenario). The principal aim of joint experiments was to demonstrate operation at $q_{95}$=3, $\beta_N$=1.8 and $n_e$≤0.85$n_{GW}$, matching the main plasma and performance parameters in the ITER simulations. The results of these joint experiments are combined with other data available from the five devices involved in this study to review and document the whole operating space at $q_{95}$~3.

2. Database for stationary discharges with $q_{95}$=2.7-3.3
During the last four years a database with global parameters has been assembled by the IOS-TG for 2.7<$q_{95}$<3.3 from AUG, C-Mod, DIII-D, JET and JT-60U using both carbon wall and (high-Z) metal walls. Note that for all experiments the data supplied are up to 2014, following publication of the results at the previous Fusion Energy Conference and papers thereafter. The data available from the experiments are summarised in Table I.

- For AUG, operation with some carbon plasma facing components ended in 2006, followed by operation with full tungsten walls from 2008 onwards. Data are available from both periods starting in 1998. ITER demonstration discharges at triangularity $\delta$~0.36 are included. With the W wall, careful programming of gas dosing and central heating with ICRH or electron cyclotron heating (ECH) are required to obtain stationary discharges at $q_{95}$~3. More stable discharges at $q_{95}$~3.6, reported in [1], are not included in the dataset.
- For Alcator C-Mod (C-Mod), operating with molybdenum walls, discharges with ion cyclotron resonance heating (ICRH) >1MW are selected for diverted plasmas with elongation ($\kappa$) >1.5. The discharges are from the period 2007-2012 and include H-mode and I-mode discharges. The C-Mod data contain ITER demonstration discharges at both

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$^a$ See the author list of “Overview of the JET results in support to ITER” by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

$^b$ See the Appendix of Zohm H. et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014 (OV/2-2), Saint Petersburg, Russia

$^c$ See the Appendix of Buttery R. et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014 (OV/1-4), Saint Petersburg, Russia

$^d$ See the Appendix of Marman E. et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014 (OV/2-5), Saint Petersburg, Russia

$^e$ See the Appendix of Isayama A. et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010 (OV/2-3), Daegjeon, Rep. of Korea
2.7T and 5.4T, matching the ITER shape [2]. An example of a discharge from C-Mod is given in Figure 1a, showing that radiation excursions limit the stationary period during the heating phase at low $q_{95}$ in C-Mod (plasma operation with molybdenum walls/divertor).

- Data from DIII-D with carbon plasma facing components are available for the period 1996-2014. The dataset contains a large number (1059) of discharges with different plasma shapes, including demonstration discharges matching the ITER shape and discharge evolution [3]. Moreover, DIII-D has data with co-neutral beam injection (NBI), counter-NBI, ICRF heating and ECRH, allowing variations of ion/electron heating and the applied torque to the plasma.

- JET operates routinely at $q_{95}$~3 with dominant NBI heating. Operation with carbon walls ended in 2009. H-mode data with an ITER-like beryllium wall and a tungsten divertor (ILW) are available from 2012 [4]. An example is given in Figure 1b. With a large amount of data available, only discharges with constant plasma density are selected for JET.

- For JT-60U, results with carbon walls are available. The data come from dedicated neutral beam power scans at $q_{95}$~3 performed in 1999, with several steps in NBI power (~1s) during the discharge [5]. With the energy confinement time ($\tau_E$) in the range 0.23s-0.46s, the data supplied are the parameters achieved at the end of these heating steps (several time windows per discharge).

### Table I. Overview of the entries in the database.

<table>
<thead>
<tr>
<th>Device*</th>
<th>Wall</th>
<th>Entries</th>
<th>Period [year]</th>
<th>$I_p$ [MA]</th>
<th>$B_r$ [T]</th>
<th>$P_{NB}$ [MW]</th>
<th>$P_{ICRF}$ [MW]</th>
<th>$P_{ECRH}$ [MW]</th>
<th>$n_e$ [10^{19}m^{-3}]</th>
<th>$H_{98y2}$</th>
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<tr>
<td>AUG CFC</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0.6</td>
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<td></td>
<td>1.2</td>
<td>2.3</td>
<td>12.5</td>
<td>6.4</td>
<td>1.1</td>
<td>12.4</td>
<td>1.5</td>
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<tr>
<td></td>
<td>Max 2014</td>
<td></td>
<td>1.2</td>
<td>2.0</td>
<td>7.3</td>
<td>2.6</td>
<td>2.6</td>
<td>14.3</td>
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<td></td>
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<tr>
<td>C-Mod H-mode</td>
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<td>Min 2009</td>
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<td>2.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10.4</td>
<td>0.5</td>
</tr>
<tr>
<td>(264)**</td>
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<td>3.6</td>
<td>59.1</td>
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<td>21.0</td>
<td>1.1</td>
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<tr>
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<td>Min 2009</td>
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<td>4.2</td>
<td>1.6</td>
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<td>0</td>
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<td>0.0</td>
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<td>0.6</td>
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<tr>
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<td>25.9</td>
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<td>33.9</td>
<td>11.7</td>
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<td>3.1</td>
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<td>0</td>
<td>0</td>
<td>2.4</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Max 1999</td>
<td></td>
<td>1.8</td>
<td>3.1</td>
<td>10.6</td>
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<td>4.5</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
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<td>Be/W</td>
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<td>Values 2015</td>
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<td>33</td>
<td>10</td>
<td>6.7</td>
<td>9.6</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table I. Overview of the entries in the database. *: Colour coding used in overview plots. **: C-Mod data are also available for duration/$\tau_E < 5$. For ITER, $P_a \sim 100$ MW.

For ITER, two simulations are available: (1) A DINA simulation from 2013 [6] aimed at achieving the longest possible burn phase within the limitations of the poloidal field coils. During the flat-top phase $q_{95}=2.86$, normalised beta $\beta_N=1.8$ are obtained with $H_{98y2}$ proscribed to be 1.0, giving a fusion gain $Q$ of 10.2. In these simulations carbon is the main impurity and $Z_{eff}=1.7$. (2) A CORSICA simulation from 2015 [7] using the reference plasma shape for ITER has $q_{95}=3.27$, $\beta_N=1.9$ and $H_{98y2}=1.03$, giving $Q=9.5$ and using Be/Ar to obtain $Z_{eff}=1.7$.

The data from the experiments and ITER simulations are averaged for the period when $\beta_N \geq 0.85$ of the maximum normalised beta during the pulse. The analyses focus on discharges that are stationary for duration $\geq 5\tau_E$ during the heating phase. Spanning >15 years of data, ~3300 entries of stationary discharges have been collected; the majority of the data (75%) is from discharges with carbon walls (AUG, DIII-D, JET-CFC and JT-60U) as summarised in
Table I. Data from C-Mod with a shorter duration (<5τE) are also available as well as I-mode data; these data can be used to confirm trends seen in the data.

FIG. 1a. C-Mod discharge in H-mode.

FIG. 1b. JET discharge with the ITER-like Wall.

3. Dimensionless parameter space

The dataset covers a wide range of plasma conditions in plasma current (0.6MA to 4MA), toroidal field (0.6T to 5.75T), line averaged electron density (1.3x10^{19} m^{-3} to 6.0x10^{20} m^{-3}) as well as a wide range of plasma shaping (κ=1.5 to 2.0, δ= -0.15 to 0.8). Normalised performance parameters achieved are H_{98y2}=0.55-1.55, β_N=0.55-3.8 and f_{GW}=0.15 to 1.15, which encompasses the plasma parameters for the ITER baseline with H_{98y2}=1, β_N=1.8 and f_{GW}=0.85. The data show a variation in the energy confinement normalized to standard H-mode confinement scaling, indicating possible deficiencies in the scaling coefficients used or influence of additional physics variables absent from the scaling used for projections to ITER.

Variations in the normalised confinement with the two dimensionless parameters that vary most from present-day experiments to ITER, gyroradius and collision frequency (as defined in [8]), are significant. Trends with collision frequency show a favourable scaling compared to the standard H-mode scaling (Figure 2); the maximum H_{98y2} obtained increases at lower collision frequency [9].

The definitions used here are [8]:

\[ \nu^* - \text{Luce} = \left( n V / W_\text{th} \right)^{1/2} \left( R^2 / a^3 \right)^{1/2} \]

and

\[ \rho^* - \text{Luce} = (W_\text{th} / n V)^{1/2} / B a \]

where n is the plasma density (in units of 10^{19} m^{-3}), V the volume (in m^3), W_{th} the thermal stored energy (in MJ), B the toroidal magnetic field (in Tesla) and R and a the plasma major and minor radius respectively (in m). The favourable scaling compared to IPB98 scaling towards lower collision frequency [9] is most evident within each device, similar to trends observed in the IOS-TG database for advanced inductive discharges [8]. The IOS-TG has defined specific joint experiments to firm-up the conclusions on the scaling with collision frequency.

The carbon wall data show differences comparing to H-mode data obtained with metal walls (AUG, JET-ILW, and C-Mod) as shown in Figure 2; metal devices have (so-far) not found a way to access the low collision frequencies obtained with carbon walls. Only I-mode discharges in C-Mod do access collision frequencies as low as 2x10^5 in stationary conditions.
(see Figure 3 below). No difference in performance is observed between carbon wall and metal wall discharges at high collision frequency and the trends towards lower collision frequency show a similar rate of increase in confinement enhancement, $H_{98y2}$.

Figure 3 shows a strong anti-correlation of $\rho^*$ and $v^*$ in the data and the ITER values for $\rho^*$ are significantly outside the existing dataset (>2x smaller in ITER). $H_{98y2}$ increases with $\rho^*$ and $H_{98y2}=1$ is obtained in each device. However, achieving the required $H_{98y2}=1$ in ITER depends on scaling to low $v^*$ and low $\rho^*$. This motivates understanding whether these trends reflect a true physical scaling as reviewed in [10]. The variation in confinement in this dataset may be consistent with Bohm scaling ($B_{TE} \propto \rho^*^{-3}$), as shown in Figure 3. This is a weaker dependence of $B_{TE}$ with $\rho^*$ than for the IPB98 scaling expression which is closer to gyroBohm scaling ($B_{TE} \propto \rho^*^{-3}$).

4. Plasma confinement

The maximum achievable $H_{98y2}$ increases with $\beta_N$ as shown in Figure 4 and is most apparent for high-Z metal devices. This trend with $\beta_N$ is also observed in the advanced inductive discharges [8] and is in line with observations of no change in normalised confinement with beta in dedicated experiments in DIII-D [10]; in contrast to IPB98 scaling, which has an unfavourable scaling. Stationary discharges at $q_{95}-3$ and $H_{98y2} \geq 1.0$ are obtained for a wide range of $\beta_N$ in experiments with carbon walls, using pre-dominantly co-current NBI heating (AUG, DIII-D and JET). At high $\beta_N>2.5$ discharges at $q_{95}-3$ in DIII-D and AUG with a carbon wall reach $H_{98y2}=1.4-1.5$, similar to hybrid regimes at higher $q_{95}-4$. In H-modes obtained with metal walls in AUG, C-Mod and JET, the confinement is significantly reduced ($H_{98y2} \approx 0.8-0.9$) at $\beta_N<1.8$ with only the best discharges obtaining $H_{98y2} \geq 1$ at the ITER beta of $\beta_N=1.8$. Stationary discharges at $q_{95}-3$ and $H_{98y2} \approx 1$ are typically obtained at $\beta_N>2$ or higher. The observed reduced confinement at low $\beta_N$ will affect the entry to burn in ITER, as simulations currently assume $H_{98y2}=1.0$ after transition to H-mode. The exception to these are I-mode discharges in C-Mod and dominant ICRF heated discharges with the carbon wall at JET (blue open diamonds at $\beta_N<1.8$ in Figure 4); they achieve good thermal confinement at low $\beta_N$. Both C-Mod and JET achieve these results at low Greenwald density fraction $f_{GW}<0.2$ (Figure 5) and relatively high plasma inductance values $l_0(3)-1.1-1.1$ (see Figure 10).

Fuelling studies of stationary H-modes at $q_{95}-3$ indicate that in some experiments it is not possible to reach $f_{GW}>0.8$ in H-mode. In C-Mod the density is limited to $f_{GW}<0.80$ for $H_{98y2}>0.8$, operating in configurations matching the ITER shape. The carbon wall data show a drop in $H_{98y2}$ with increasing $f_{GW}$, as do metal wall results as shown in Figure 5. However, for any $f_{GW}$ value, the maximum $H_{98y2}$ achieved is lower in high-Z metal wall devices as indicated by the dashed red lines in Figure 5. The ITER requirement of $f_{GW}<0.85$ with $H_{98y2}=1$ is at the top of the data range available in experiments with metal walls.

![FIG. 3. Dimensionless parameter space of carbon wall and metal wall devices; Top: normalised collision frequency vs gyroradius [8]. Bottom: $B_{TE}$ vs gyroradius. Grey: carbon wall data, red: metal wall results, with ITER simulations in purple.](image-url)
FIG. 4. Comparing devices with a carbon wall (top) and metal wall (bottom); the normalised H-mode confinement ($H_{98y2}$) as a function of the normalised beta obtained ($\beta_n$).

FIG. 5. Comparing devices with a carbon wall (top) and metal wall (bottom); the normalised H-mode confinement ($H_{98y2}$) as a function of the Greenwald density fraction achieved ($f_{GW}$).

FIG. 6. Comparison of carbon wall and metal wall results; Greenwald density fraction ($f_{GW}$) vs triangularity ($\delta_{upper} + \delta_{lower}$)/2 for discharges with $H_{98y2}>0.95$. Grey: carbon wall data, red: metal wall results, with ITER simulations in purple.

FIG. 7. Comparison of carbon wall and metal wall results; normalised confinement ($H_{98y2}$) vs electron gas fuelling rate used. Grey: carbon wall data, red: metal wall results, with ITER simulations in purple.

For H-mode discharges that obtain $H_{98y2}>0.95$ the dataset for carbon wall and metal wall discharges shows an overall increase of $f_{GW}$ attainable with average triangularity as shown in Figure 6, although only a few discharges for JET-ILW are available at the operating point of ITER. There are no data at $f_{GW}>0.6$ for triangularity $>0.5$.

For AUG with the tungsten wall and JET with the ILW no data are available with gas fuelling rates below $1\times10^{21}$ electrons/s as shown in Figure 7; discharges with lower fuelling rates are not stable as gas fuelling is required to reduce the tungsten influxes and ensuring high enough ELM frequency to prevent tungsten accumulation [1,4]. Nevertheless, at fuelling
rates in the range 5x10^{21}/s to >1x10^{23}/s the plasma confinement is similar for H-mode operation with carbon walls and metal walls, especially for seeded plasmas in AUG [11]. Inter-machine comparisons of electron fuelling rates in H-modes is complicated by the fact that devices have different pumping speeds and divertor geometries; at the moment it is not clear how these results would scale to ITER.

5. Input power and radiation

Obtaining sufficient energy confinement is critical in ITER for entry into H-mode and starting the burn with the installed additional heating power. The total heating power P_{tot} available in ITER is at or below 2x the power required to enter H-mode (P_{LH}) at baseline operating conditions, with the majority of the power provided by alpha heating (P_\alpha \sim 100MW, P_{in} \sim 50MW). For the prediction of P_{LH} the expression given in [12] is used, although the measured L- to H-mode threshold power in the experiments may be different compared to the scaling predictions. This is especially the case for discharges in AUG and JET with metal walls where the measured P_{LH} values are 30-40% below the scaling [13, 14].

Figure 8 shows the variation of H_{98y2} with P_{loss}/P_{LH}, where P_{loss}=P_{tot}dW/dt (dW/dt is the change in stored energy; \~ zero for the stationary discharges in the database). For discharges with carbon walls, the plasma confinement enhancement factor can be ≥1 for any value of P_{loss}/P_{LH} ≥1. At low input power these discharges have low ELM frequency (in JET \~ 1Hz). In contrast, this is not possible with high-Z metal walls or divertors, as the high-Z impurities (Mo or W) accumulate in the plasma core, leading to a radiation collapse. These discharge only reach H_{98y2}~1 for P_{loss}/P_{LH}~2, when (with the help of gas dosing) the ELM frequency is high enough (e.g. 15-20Hz in JET) to provide stationary H-mode discharges. Also data from C-Mod with duration <5t_E (more transient) have confinement similar to stationary discharges with metal walls for P_{loss}/P_{LH} in the range 1 to 2. The requirement for ELM pacing for controlling the plasma radiation during the entry to burn in ITER is elucidated in [15].

In the ITER simulations the total bulk radiation is the sum of bremsstrahlung (P_{brem}), the cyclotron radiation (P_{cycl}) and line radiation (P_{line}) and ranges from 40MW to 48MW. DIII-D and JET have data for the bulk radiation of H-mode discharges in the database. The normalised radiation levels in ITER (P_{rad bulk}/P_{tot}=0.29-0.39) are within the data available from the experiments. H_{98y2} does not show a strong variation for P_{rad bulk}/P_{tot} values between 0.2 and 0.5, as shown in Figure 9. However, in contrast to computations of the normalised confinement in experiments, H_{98y2} in ITER is calculated by subtracting the core radiation from the heating power: P=P_{tot}-(P_{brem}+P_{cycl}+P_{line}/3). In simulations for ITER, the core radiation should not be subtracted in the computation of H_{98y2} to allow comparisons of the confinement with experimental data and to avoid overestimating core confinement in ITER.
In addition, for the total radiation of the plasmas ($P_{\text{rad\_bulk}} + P_{\text{rad\_SOL\_divertor}}$) no difference is observed between carbon wall data and metal wall data for radiation fractions of >50%. The best carbon wall discharges (from JET and DIII-D) reach values for $H_{98y2}$ from 1.18 down to 1.0 for radiation fractions increasing from 50% to 80%, while AUG (seeded, W wall) discharges obtain $H_{98y2}$ ~1.1 at radiation fraction >50%; similar to discharges from AUG reported in [11].

6. Plasma performance

The operating space covered in this dataset is shown in Figure 10, where the achieved $\beta_N$ in stationary discharges is plotted against the internal inductance $l_i(3)$. All four machines occupy roughly the same region of this parameter space and lie within the specified range for the ITER poloidal field coils for 15MA operation ($0.6 < l_i(3) < 1.2$). The lower values of $l_i(3)$ at higher beta reflect an increase in bootstrap current contribution due to the edge pedestal. The data from high-Z metal wall devices lie above the ITER flat top predictions of $l_i(3) \approx 0.73$, even discharges at the highest $\beta_N$ values achieved in AUG and JET only approach $l_i(3) = 0.75$. The data may indicate that it could be challenging to obtain the predicted (and required) edge pedestal pressure in ITER with a Be/W wall, but care should be taken comparing $l_i(3)$ values for different plasma shapes.
The figure of merit $G = H_{98y2} \beta_N/q_{95}^2$ should be 0.42 for $Q=10$ in ITER (note $H_{98}$ is used here). As shown in Figure 11, $G$ spans a range of 0.25 to 0.51 at the ITER reference beta of $\beta_N=1.8$ for carbon wall data, while for data obtained with metal walls $G$ varies from 0.23 to 0.36 (at $\beta_N=1.8$). More specifically, $G>0.4$ has only been obtained at $\beta_N>2.5$ for metal devices operating at $q_{95} \approx 3$, using dominant co-current NBI heating (AUG and JET). The figure of merit $G$ uses the total plasma energy, including the fast particle pressure $W_{\text{fast}}$. Only discharges with carbon walls can obtain $W_{\text{fast}}$ in excess of 20% of the total stored energy ($W$). However, analyses of the data show that the best performance is obtained for $W_{\text{fast}}/W$ in the range 5-20%, which is the predicted fast particle content of ITER plasmas.

7. Summary

A database with global parameters of stationary H-mode discharges at $q_{95}=2.7-3.3$ from AUG, C-Mod, DIII-D, JET and JT-60U, provides a unique overview of the operational range:

- Variations of $H_{98y2}$ with collision frequency and gyroradius are significant; the maximum $H_{98y2}$ obtained increases at lower collision frequency. The ITER values for $\rho^*$ are significantly outside the existing dataset. Devices with high-Z metal walls have (so far) not found a way to access the low collision frequencies obtained with carbon walls.

- For the dataset, $H_{98y2}$ increases with $\beta_N$, however for high-Z metal wall devices the confinement is significantly reduced ($H_{98y2} \approx 0.8-0.9$) at $\beta_N \leq 1.8$, with $H_{98y2} \approx 1$ typically obtained only for $\beta_N \approx 2$ or higher.

- For high gas fuelling levels in the range 5x$10^{21}$/s to $>1x10^{23}$/s, $H_{98y2}$ is similar for carbon walls and metal wall devices. However, the ITER requirement of $f_{GW}=0.85$ with $H_{98y2}=1$ is at the top of the data range available in experiments with metal walls.

- For discharges with carbon walls, $H_{98y2}$ can be 1 for $P_{\text{low}}/P_{\text{LH}}\approx 1$ at low ELM frequency. This is not possible with high-Z metal walls due to impurity accumulation and $H_{98y2} \approx 1$ is only obtained for $P_{\text{gas}}/P_{\text{LH}} \approx 2$. Bulk radiation fractions observed in both carbon and metal wall devices are similar to ITER simulations.

- $l_i(3)$ values are obtained lie within the specified range for the ITER poloidal field coils for 15MA operation (0.6 < $l_i(3)$ < 1.2). The figure of merit $G>0.4$ required for $Q=10$ in ITER has only been obtained at $\beta_N>2.5$ in metal wall devices.

These observations should be used in simulations for ITER, in particular the entry to burn.

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References