

Performance Assessment of ITER-FEAT

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Abstract. A performance assessment for ELMy H-mode operation of ITER-FEAT mainly at the nominal plasma current of 15 MA is made by using 1.5D transport codes PRETOR and ASTRA. Operation domain analysis is performed for various transport assumptions. Sensitivities to density profile, the ratio of ion thermal diffusivity to electron thermal diffusivity χ_i/χ_e and the ion heating fraction are investigated. It is shown that, under rather conservative assumptions, 400 MW operation with fusion gain $Q = 10$ should be achievable. Operations with lower and higher fusion power are explored and an operation range of 200 ~ 600 MW is obtained. A probabilistic performance assessment is also done by using 0D modeling. The "maximized conditional probability (MCP)" to reach Q larger than a specified lower bound is estimated considering the beta limit $\beta_N \leq 2.5$, L-H transition threshold power and density limit $n_e/n_{GR} \leq 0.85$. The MCP of achieving $Q \geq 10$ is about 70%, and the MCP of $Q \geq 50$ is about 30% when the HH factor distribution is a Gaussian with $\sigma = 20\%$. By increasing the plasma current to 17 MA, the MCPs of achieving $Q \geq 10$ and $Q \geq 50$ increase to 85% and 50%, respectively.

1. Introduction

ITER-FEAT (ITER is used in the following) has been developed and the performance projection based on the reference physics rules [1] shows that 400 MW of fusion power is produced when the plasma parameters are; major radius $R = 6.2$ m, minor radius $a = 2.0$ m, elongation $\kappa_{95} = 1.7$, plasma current $I_p = 15$ MA, additional heating power $P_{ADD} = 40$ MW, the ratio n_e/n_{GR} of electron density to the Greenwald density limit is 0.85 and $HH(y,2) = 1.0$. Here, $HH(y,2)$ is the energy confinement time enhancement factor over IPB98(y,2) scaling [1]. In the present paper, the operation performance of ITER is assessed by using 1.5D transport codes PRETOR [2] and ASTRA [3]. Operation domain analysis on the HH factor and the fusion power plane is performed for various transport assumptions. Sensitivities to density profile, the ratio of ion thermal diffusivity to electron thermal diffusivity χ_i/χ_e and the ion heating fraction are investigated. Operations with lower and higher fusion power are explored. Probabilistic performance assessment is also done by using 0D modeling. In this paper, we concentrate only on ELMy H-mode operation in the inductive scenario.

2. Reference Plasma Parameters and Operation Domain Analysis

Figure 1 shows plasma profiles in a typical inductive operation scenario with the flat-top current of 15 MA. Here, electron density (n_e), helium density (n_{He}), electron temperature (T_e), ion temperature (T_i), safety factor (q_ψ), total toroidal plasma current density (j_T), ohmic current density (j_{OH}), bootstrap current density (j_{BS}), current density (j_{NB}) driven by neutral beam (NB) injection are shown as functions of normalized minor radius (r/a). In the simulation, transport coefficients given by the RLWB model [2] are normalized so that the global energy confinement time τ_E is equal to that given by the scaling IPB98(y,2) [1]. Therefore, the analyses are limited to ELMy H-mode operations. In this case, 33 MW of NB power and 7 MW of RF power are used. Here, RF power deposition in the core ($r/a < 0.3$) is assumed with 50% to ions and 50% to electrons. Helium accumulation is calculated for the pumping speed provided $\tau_{He^*}/\tau_E = 5$. Argon impurity ($\sim 0.12\%$) is seeded to limit the power to the divertor region to 30 MW, which roughly corresponds to 5 MW/m² of target heat load. To be conservative, a flat density profile is assumed for the reference plasma.

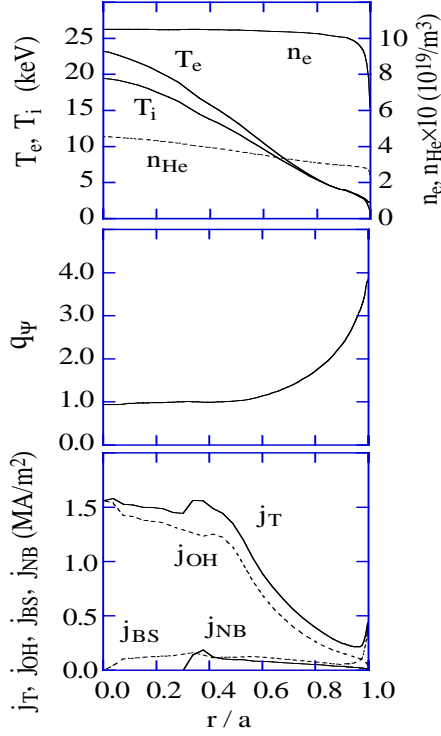


FIG.1: Typical plasma profiles of inductive mode operation. Notations are given in the text.

3. Sensitivity Analysis

(1) Density and temperature profiles

In general, peaked density profiles tend to produce larger fusion power for the same average density. Here, the density profile effect is examined by including the inward pinch effect, as an example. This kind of profile could be achieved also with deep fuelling by high field side (HFS) pellet injection. Figure 3-a shows the density profiles when a pinch term proportional to the thermal diffusivity χ and to the magnetic shear is included with a different pinch coefficient V_p . In this modeling, the pinch effect is not significant in the core region ($r/a < 0.5$) where the shear is small. Figure 3-b shows the fusion power for various pinch coefficients. Here, the volume-averaged density is fixed to $1.0 \times 10^{20}/\text{m}^3$, which corresponds to $n_e/n_{GR} = 0.85$ for the flat profile. It is seen that significantly higher fusion power is available in the nominal to high HH factor region, while the margin below 1.0 in HH factor is not increased in the lower fusion power region. Helium accumulation due to the pinch effect also degrades performance. If a peaked density profile is achieved by using HFS pellet injection, a more significant improvement is expected. This issue is under investigation.

Figure 3-c shows the relation between the edge density $n_{e,edge}$ and fusion power when $HH(y,2) = 1.0$ and $Q = 10$. If the maximum density is limited by the edge density, the requirement for the density limit is mitigated and the confinement degradation would be small or negligible (the lowest edge density would be limited by divertor requirements). In this case, operation with smaller plasma current (and high q_ψ) is possible and the type II ELM region would be attainable.

The operation domain plot in HH factor and fusion power space is a useful tool to analyze the performance of ITER. Figure 2 shows such a plot resulting from 1.5D simulations. Here, the fusion power as a function of $HH(y,2)$ for various operation conditions is presented. Each point of the domain corresponds to a fusion gain $Q = 10$. Here, β_N is the normalized beta, n_{GR} is the Greenwald density limit ($= 10^{20} \times I_p[\text{MA}] / \pi a[\text{m}]^2$), P_{LOSS} is the power across the H-mode edge pedestal and P_{LH} is the power required for the H-mode transition [1]. If the operation boundaries are given by $n_e/n_{GR} \leq 1.0$ and $P_{LOSS}/P_{LH} \geq 1.3$, the minimum and maximum fusion powers are 260 MW and 560 MW, respectively, when $HH(y,2) \leq 1.0$. It is also seen that about 7% of confinement margin (margin in HH factor to achieve operation with $Q = 10$) exists even if the density boundary is set to $n_e/n_{GR} \leq 0.85$. In the following section, we investigate the operation domain and confinement margin (or the achievable fusion power) for various transport assumptions.

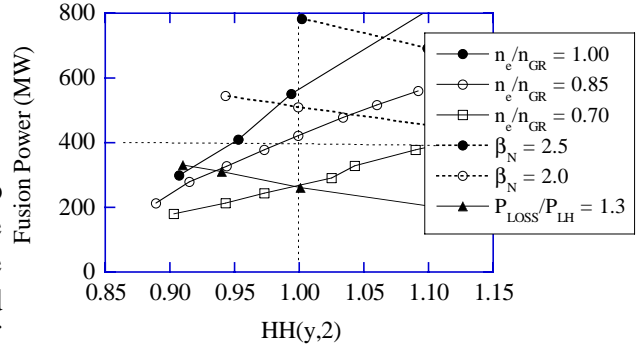


FIG.2. Operation domain in HH-factor and fusion power space when $I_p = 15$ MA.

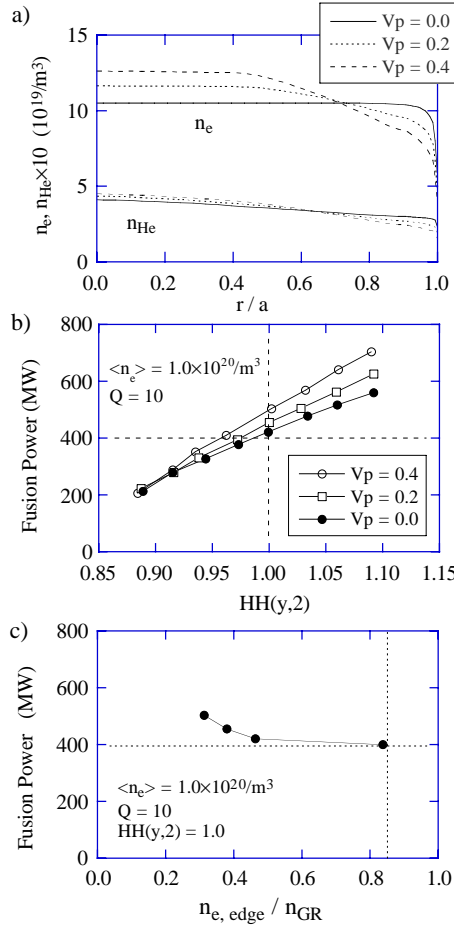


FIG.3. a) Density profiles for various pinch coefficients V_p , b) dependence of fusion power on HH factor for the pinch coefficients shown in a), c) relation between edge density $n_{e,edge}$ and fusion power when $HH(y,2) = 1.0$.

heating power is RF and the total heating power $P_{RF} = P_i + P_e$ is adjusted to $Q = 10$ with $n_e/n_{GR} = 0.85$. In the figure, the NB-heating-only case is also shown. It is seen that the fusion power increases with P_i/P_{RF} through the HH range, and the lower HH margin is also improved.

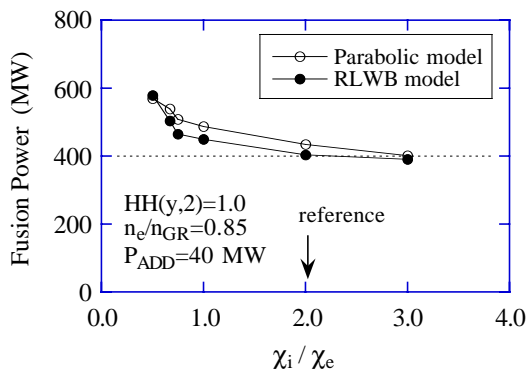


FIG.4. Dependence of fusion power on χ_i/χ_e when $HH(y,2) = 1.0$, $P_{ADD} = 40$ MW and $n_e/n_{GR} = 0.85$.

The height of the H-mode temperature pedestal has been shown to be an important factor for the prediction of fusion power, and high pedestal temperature is required for good confinement [1]. In the simulation, an H-mode pedestal is created by reducing χ in the edge region with the pedestal temperature 3 ~ 4 keV according to [4]. At constant energy confinement time, formal increase of the height of the edge pedestal requires a central temperature decrease (profile flattening). If a more peaked temperature profile with smaller pedestal temperature is assumed, larger fusion power is expected.

(2) Dependence on χ_i/χ_e ratio

The ratio of ion thermal diffusivity to electron thermal diffusivity χ_i/χ_e is assumed to be 2 for the reference case with additional physics dependencies such as $(T_e/T_i)^{0.5}$. This χ_i/χ_e value was chosen as a conservative assumption although $\chi_i/\chi_e < 1$ is obtained in many experiments. Figure 4 shows the relation between χ_i/χ_e and fusion power for two types of transport coefficients profiles, those are the RLWB model [2] and parabolic: $\chi_e = c_0(1+4(r/a)^2)$ both with normalization factor c_0 . It is seen that the fusion power increases with decreasing χ_i/χ_e for both models and the present assumption ($\chi_i/\chi_e = 2$) is conservative. Figure 5 shows the relation between the HH factor and fusion power for various χ_i/χ_e values in the RLWB model when $n_e/n_{GR} = 0.85$. It is seen that the fusion power increases significantly at the nominal HH factor and the confinement margin is increased with decreasing χ_i/χ_e .

(3) Effect of ion heating fraction

The increase of the ion heating fraction is also favorable for the improvement of operation performance. Figure 6 shows the relation between the HH factor and fusion power for different ion heating fractions P_i/P_{RF} . Here, all

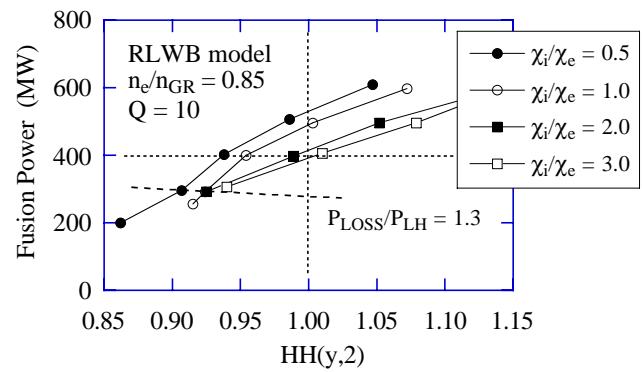


FIG.5. Dependence of fusion power on HH(y,2) for various χ_i/χ_e when $Q = 10$ and $n_e/n_{GR} = 0.85$.

(4) Operation with lower fusion power

Figure 7 shows the relation between fusion power and n_e/n_{GR} for various χ_i/χ_e and P_i/P_{RF} values. Here, $HH(y,2) = 1.0$ and $Q = 10$. Operation constraints by H-mode transition are also shown. For the reference assumptions ($\chi_i/\chi_e = 2$ and $P_i/P_{RF} = 0.5$), the minimum fusion power is about 260 MW and the minimum density $n_e/n_{GR} = 0.7$. By assuming higher P_i/P_{RF} and/or smaller χ_i/χ_e value, the operation region is extended to the small density and the small fusion power region. Operation with 200 MW is possible when $\chi_i/\chi_e = 0.5$ and $P_i/P_{RF} = 0.7$. This operation mode would be useful if the heat load of type I ELMs is too high and/or degradation of confinement is serious at high density.

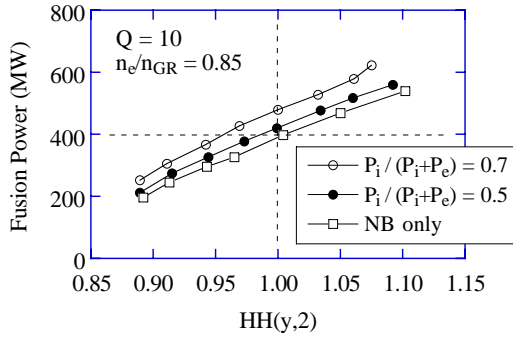


FIG.6. Dependence of fusion power on HH-factor for various ion heating fractions.

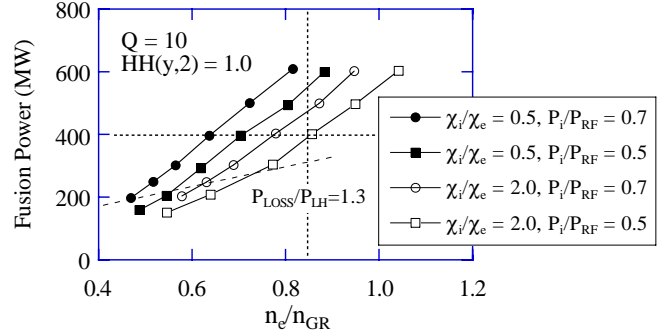


FIG.7. Dependence of fusion power on n_e/n_{GR} for various ion heating fractions and χ_i/χ_e .

4. Probabilistic Performance Assessment

If the distribution of the HH factor is known, the expectation of achieving the required performance in ITER can be estimated. In this section, we try to make such an estimation by assuming a distribution function of the HH factor. The distribution of HH factor is approximately characterized by a Gaussian function with standard deviation σ . The 2σ log-linear or 1σ log-non-linear interval for the predicted confinement time has been recommended to be 20% by the ITER Confinement Database and Modeling Expert Group [1, 5]. Here, we make calculations using 10% and 20%, respectively. The distribution range of HH factor in the database is smaller than 10% or 20% for similar discharge conditions. For example, 5% of distribution range is observed with $n_e/n_{GR} \geq 0.65$, $q_{95} \leq 3.5$, $P_{RAD}/P_{HEAT} \leq 0.5$ and elongation $\kappa \geq 1.5$ in the database for IPB98(y,2). Therefore, only a part of the deviation comes from the scattering of data for similar discharge conditions and the major deviation comes from the uncertainty of the scaling law. Here, we make a parameter survey for σ .

The expectation of achieving a Q value of at least a specified value Q_0 can be estimated by setting the beta limit $\beta_N \leq 2.5$, the L-H transition threshold power and the density $n_e/n_{GR} \leq 0.85$. If the additional heating power P_{ADD} is fixed to 40 MW, the expectation of achieving $Q \geq 10$ is 50% since the device parameters are chosen such that 400 MW is achieved when $P_{ADD} = 40$ MW, $HH(y,2) = 1.0$ and $n_e/n_{GR} = 0.85$. (Beta limit and L-H transition threshold power are not important in this case). By decreasing the heating power (and the fusion power), operation with $Q = 10$ can be achieved even with a smaller HH factor, as is shown in the previous sections. Therefore, a higher expectation can be achieved for operations with $Q = 10$. Here, we define the "maximized conditional probability (MCP)" by optimizing the heating power.

Figure 8-a shows the calculation results of MCPs when $\sigma = 10\%$ and 20% . The results for different boundary in L-H transition threshold P_{LOSS}/P_{LH} are also shown. The P_{LOSS}/P_{LH} value is important only in the high- Q_0 region. The MCP of achieving $Q \geq 10$ is about 70%, and the MCP of $Q \geq 50$ is about 30% when $\sigma = 20\%$. With smaller σ ($= 10\%$), higher MCPs of $Q \geq 10$ are expected, while MCPs of $Q \geq 50$ decrease.

The probability of achieving $Q \geq 10$ with standard ELMy H-mode plasma is relatively high. If $Q \geq 10$ is not obtained, there are several possible ways to increase the Q value. For example, increasing the plasma current to 17 MA (See Fig. 8-b) increases MCPs to 85% for $Q \geq 10$ and 50% for $Q \geq 50$ even when $\sigma = 20\%$. Furthermore, optimizing wall conditioning, deep fueling by HFS pellet injection and strong ion heating by ICH&CD can be considered to improve the performance as is discussed in the previous sections. These considerations lead to a conclusion that $Q \geq 10$ is achievable with a high confidence for the relationship of ITER predicted performance.

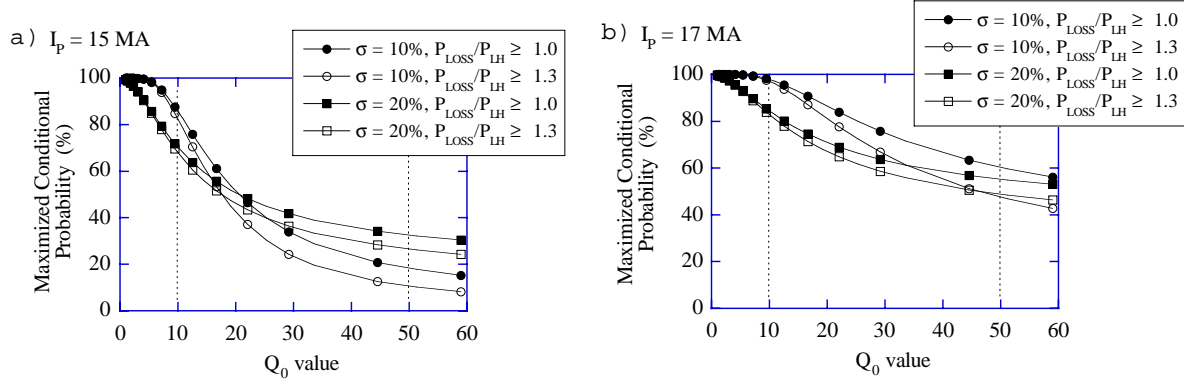


FIG. 8. Maximized conditional probability of achieving $Q \geq Q_0$ for various σ values. Here, $n_e/n_{GR} \leq 0.85$, $\beta_N \leq 2.5$ and $P_{LOSS} \geq 1.0 \times P_{LH}$ (or $P_{LOSS} \geq 1.3 \times P_{LH}$). a) $I_p = 15$ MA, b) $I_p = 17$ MA.

5. Conclusion

Performance of inductive ELMy H-mode operation in ITER is investigated by 1.5D transport simulations. Operation domain analysis is performed for various transport assumptions. Operation with $Q = 10$ is achievable with a certain amount ($> 7\%$) of confinement margin in ITER. It is also shown that the present assumptions for the performance prediction are conservative. Operations with lower and higher fusion power are explored and an operation range of 200 ~ 600 MW is obtained when $Q = 10$. Operation with lower fusion power (~ 200 MW) is also preferential from the point of view to mitigate ELM energy loss per ELM at the initial phase of experiments. A probabilistic performance assessment is made by using 0D modeling. The "maximized conditional probability (MCP)" to reach Q larger than a specified lower bound is estimated considering the beta limit $\beta_N \leq 2.5$, L-H transition threshold power and the density limit $n_e/n_{GR} \leq 0.85$. The MCP of achieving $Q \geq 10$ is about 70%, and the MCP of $Q \geq 50$ is about 30% when the HH factor distribution is a Gaussian with $\sigma = 20\%$. By increasing the plasma current to 17 MA, the MCPs of achieving $Q \geq 10$ and $Q \geq 50$ increase to 85% and 50%, respectively. The present assessment indicates fair and realistic chances for ITER to achieve predominant alpha heating with a consistent set of plasma parameters.

Acknowledgments:

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