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Predictions of alpha heating in ITER L-mode and H-mode plasmas

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Predictions of alpha heating in L-mode and H-mode DT plasmas in ITER are generated using the PTRANSP code. The baseline toroidal field of 5.3 T, plasma current ramped to 15 MA and a flat electron density profile ramped to Greenwald fraction 0.85 are assumed. Various combinations of external heating by negative ion neutral beam injection, ion cyclotron resonance, and electron cyclotron resonance are assumed to start half-way up the density ramp. The time evolution of plasma temperatures and, for some cases, toroidal rotation are predicted assuming GLF23 and boundary parameters. Significant toroidal rotation and flow-shearing rates are predicted by GLF23 even in the L-mode phase with low boundary temperatures, and the alpha heating power is predicted to be significant if the power threshold for the transition to H-mode is higher than the planned total heating power. The alpha heating is predicted to be 8-76 MW in L-mode at full density. External heating mixes with higher beam injection power have higher alpha heating power. Alternatively if the toroidal rotation is predicted assuming that the ratio of the momentum to thermal ion energy conductivity is 0.5, the flow-shearing rate is predicted to have insignificant effects on the GLF23-predicted temperatures, and alpha heating is predicted to be 8-20 MW. In H-mode plasmas the alpha heating is predicted to depend sensitively on the assumed pedestal temperatures. Cases with fusion gain greater than 10 are predicted to have alpha heating greater than 80 MW.

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1. Introduction

One of the goals of ITER [1] experiments will be to produce H-mode plasmas with a fusion gain Q_{DT} (the ratio of the DT fusion and the external heating powers P_{DT}/P_{ext}) ≥ 10 . Enhanced confinement regimes such as in the H-mode appear necessary to achieve this, but the physics basis for the $L \rightarrow H$ transition as well as confinement enhancement remain unclear, and extrapolations of the database scaling might not be reliable for predicting the heating power needed for the transition. Thus having the capability of large amounts of external heating power would increase the chances of success. The planned heating and current drive systems for ITER are: Negative ion Neutral Beam Injection

(NNBI), Ion Cyclotron Resonance Frequency (ICRF), and Electron Cyclotron Resonance Frequency (ECRF) with maximum total power of 73 MW. Lower-hybrid current drive (LHCD) is planned as a possible later upgrade.

This paper uses the PTRANSP code [2–4] to generate time-dependent integrated predictions of ITER L-mode and H-mode plasmas. The time dependence is modeled to include long-term trends and to obtain predictions of both the L-mode and H-mode phases. Several expressions for the H-mode power threshold are coded into PTRANSP. The one used here is based on a database fit [5]

$$P_{\text{MW}} = 2.15\kappa^{\pm 0.107} n_{e20}^{0.782 \pm 0.037} B_{\text{tesla}}^{0.772 \pm 0.031} a_{\text{m}}^{0.975 \pm 0.08} R_{\text{m}}^{0.999 \pm 0.01} 2.0/M_{\text{AMU}} \quad (1)$$

Here κ is the elongation of the boundary. This expression is multiplied by either two or four for use in the L-mode studies. Note this scaling gives a low threshold at low density, so it could be beneficial for ITER to start NNBI injection early. Injection is started at half-density in this study. Full-power beam injection can not start too early since the beam shine-through could damage the first wall. In PTRANSP a power threshold for the back transition $P_{H \rightarrow L}$ is also modeled and the H-mode phase is terminated when $P = P_{\text{ext}} + P_{\alpha}$ decreases below some pre-set factor of $P_{L \rightarrow H}$. The default factor 75% is used here.

The full external power $P_{\text{ext}} = 73$ MW is sufficient to achieve the H-mode assuming Eq. 1. With that power only a brief transient L-mode phase is predicted. The alpha heating during the Ohmically-heated L-mode at half density is predicted to be relatively small ($\simeq 0.3$ MW).

In this paper the predictions for the L-mode assume pessimistic cases in which the power threshold is higher than the database scaling Eq.1 P_{Eq1} by a factor of two or four. Even with a factor of two $P_{\text{ext}} = 73$ MW would be insufficient alone and the additional alpha heating would be necessary to achieve the H-mode. Thus the power from alpha self-heating in the L-mode phase could play a crucial role in achieving the H-mode. In the factor-of-two case only half of the heating mixes considered are predicted to transition to H-mode.

ITER L-mode predictions are in Ref. [4]. Here a wider range of assumptions both more and less pessimistic are used to explore a range of possibly results in ITER. Predictions of ITER H-mode P_{DT} with a scan in boundary temperatures T_{ped} are in Ref. [2]. Here a wider scan in the equivalent $\beta_{n,ped}$ is studied and results for a wider range of plasma parameters are given.

2. Plasmas Studied

Six mixes of external heating are considered, as summarized in [Table I](#), with heating power waveforms plotted in [figure 1](#). The first five are similar to those considered in Ref. [\[4\]](#). Each NNBI beam line is specified to deliver up to $P_{\text{NB}}=16.5$ MW of 1 MeV D. The baseline design includes two beamlines, but a third beamline is still being considered for ITER. The case with only ECRF is not being considered for ITER, but has been discussed as an alternative in case the NNBI and ICRF developments do not succeed. Comparisons of the merits of four similar mixes of heating are discussed in [\[6\]](#).

The NUBEAM module [\[7\]](#) in PTRANSP is used to simulate the NNBI heating, torquing, and current-drive, and alpha heating. Below-axis beam NNBI steering is assumed, with the center of the beams displaced 25 cm below the vessel midplane at the “turning point” of minimum major radius, as described in Ref. [\[2\]](#). The ICRF is assumed to use He^3 minority heating at 52.5 MHz for central heating. The baseline design specifies capability of 20 MW injected power. The TORIC full-wave code [\[8\]](#), coupled into PTRANSP is used to simulate the ICRF heating. TORIC simulations for ITER have been benchmarked with other full-wave solvers [\[9\]](#). The planned ECRF heating and current drive frequency is 170 GHz, launched in O-mode. The baseline design specifies capability of 20 MW injected power. Three midplane launchers and two upper launchers (for NTM suppression) are planned. The assumed launcher positions and angles are those in Table 2 of Ref. [\[4\]](#). The TORAY-GA code [\[10–12\]](#) is used to model the heating and current drive.

Standard assumptions are used for the toroidal magnetic field $B_{\text{tor}} = 5.3$ T, plasma current I_p ramped to 15 MA, and Greenwald fraction $\bar{n}_e/\bar{n}_{\text{GW}}$ (with $\bar{n}_e$ the line-average, and $\bar{n}_{\text{GW}} \equiv I_p/(\pi a^2) \times 10^{20}/\text{m}^3$) ramped to 0.85. The assumed ramp-up of the central electron density and the computed ion densities are shown in [Fig. 2-a](#)). The plasma current and various components are shown in [Fig. 2-b](#)).

Previous PTRANSP papers [\[2–4\]](#) use physics-based models to predict profiles of the temperatures T_e and T_i , and in some cases, the toroidal rotation v_{tor} . The GLF23 model [\[13\]](#) is used here. An improved model TGLF [\[14\]](#) achieves more accurate predictions of temperatures measured in DIII-D, JET, and TFTR. The code requires parallel processing because it is a longer calculation per call than GLF2, and it has not yet been coupled into a comprehensive self-consistent transport code. GLF23 does achieve approximate agreement predicting temperatures. Examples of predictions are in [Ref. \[14\]](#).

There are various options and adjustable parameters for running GLF23. The most extensively tested options use measured toroidal rotation rates to compute flow-shearing rates and use these rates to predict ion and electron temperatures. Alternatively the toroidal rotation can be predicted and used to compute flow-shearing rates which can be used to predict self-consistently ion and electron temperatures. Both options are used here to compute the toroidal rotation: Option 1 where the toroidal rotation is predicted assuming that the ratio of the momentum transport χ_ϕ to the GLF23-predicted ion energy conductivity χ_i is 0.5, which is about midway between values measured in tokamaks with co-plasma-current neutral beam injection; Option 2 where the toroidal rotation is predicted by GLF23. Predictions for ITER using flow shear from Option 2 suggest the possibility of significant improvement of Q_{DT} in ITER H-mode plasmas [16]. The momentum predictions of GLF23 do not have a rigorous physics basis, Ref. [15], and are not well tested and so this option is more speculative. Nevertheless both options are used here for the L-mode predictions to illustrate ranges of uncertainties in ITER performance predictions. This option gives more pessimistic predictions for ITER L-mode plasmas.

The flow shearing rate in GLF23 is a constant times the gradient of the $E \times B$ velocity. The value of 1.35 for the constant is usually used in comparing with experiments. Here it is assumed to be unity, to be conservative. The toroidal rotation is computed using GLF23 and the torques predicted for the NNBI. The boundary values for the temperatures and toroidal rotation are taken at the flux surface with x defined as the square-root of the normalized toroidal flux at 0.85.

Sawteeth effects are modeled using a Kadomtsev-like mixing with a period assumed to be 10 s. Details are given in Section 3.2 of Ref. [2]. The impurities are assumed to be Be, Ar, and He ash. The Be and Ar density profiles are assumed to be 2% and 0.12% of the electron density n_e . Ash transport and recycling are also modeled following Ref. [2]. The ash recycling coefficient is assumed to be 0.7, and the ash diffusivity is assumed to be $1 \text{ m}^2/\text{s}$ with an inward pinch of $1 \text{ m} / \text{s}$. The poloidal field diffusion and Ohmic heating are calculated using neoclassical resistivity predicted by NCLASS [17], and the calculated T_e and Z_{eff} profiles. Radiation losses and effects of charge-exchange losses due to collisions with recycled neutrals are included. The total radiation loss is predicted to be about 30 MW. The total net charge-exchange loss is predicted to be confined to the edge region beyond $x = 0.9$ and to be relatively small. The atomic cross sections used are those from the ADAS project [18, 19].

3. Results for the L-mode phase

Profiles of the predicted rotation using Option 1 and assuming high $P_{L \rightarrow H}$ are shown in Fig. 3-a). These rotation rates are modest compared with rates often measured in tokamaks with neutral beam injection delivering net torque. The temperatures are assumed to be pessimistically low at the boundary for the L-mode, as shown in Fig. 4-a). GLF23-predicted temperature profiles are shown in Fig. 5). The thermal ion and electron heating integrated to the edge region is plotted in Fig. 6-a). The differences of the flows predicted for the different heating mixes is relatively small, indicating that P_α is not large, and that flow shear suppression effects are small. Plots of $P_\alpha(t)$ are shown in Fig. 7-a). The peak P_α is 20 MW (for the mix 3NB/IC) and decreases after 130s as P_{ext} is reduced. The values of P_α at the end of the high P_{ext} phase are listed in Table II. The peak P_{DT} is 90 MW and peak Q_{DT} is around 2 (for the mix 3NB/IC). Plots of $Q_{\text{DT}}(t)$ are shown in Fig. 8-a). It is below unity for mixes with two or fewer beam lines.

With Option 2 much higher toroidal rotation rates and fusion yields are predicted. First consider the case where $P_{L \rightarrow H}$ is higher than P_{ext} for all the heating mixes. Central rotation rates are shown in Fig. 3-b). The boundary temperatures are the same as those used for Option 1 and shown in Fig. 4-a). The peak temperatures are shown in Fig. 9. The ion temperatures are relatively high, especially for the heating mixes with large NNBI power (and relatively large toroidal rotation rates). Similar phenomena are observed in the supershot regime in TFTR and the hot ion H-mode in JET. This results from the stiffness of GLF23 and the flow shear suppression. The large minor radius and existence of a lower bound for the temperature gradients imply that even with the low boundary temperatures assumed, the central ion temperature is high. Profiles at one time near peak central temperatures are shown in Fig. 10.

The thermal ion and electron heating densities volume-integrated to the boundary region are plotted in Fig. 6-b). The external heating is relatively constant in the initial phase, but the alpha heating increases as the density and temperature increase. Plots of $P_\alpha(t)$ are shown in Fig. 7-b). The alpha heating reaches 74 MW in the heating mix with three beam lines. The alpha heating decrease in the next phase with reduced external power. Profiles of the alpha electron and thermal ion heating for two of the heating mixes are compared in Fig. 11 with the profiles of the DT power divided by five, the ratio of the energies carried by neutrons to alphas when the He^5 resonance decays. The P_{DT} and P_α profiles are predicted to have identical shapes except during transients. P_{DT} is the instantaneous fusion power whereas P_α depends on the slowing down of the alphas. No anomalous diffusion for the fast alpha particles

is assumed, and the classical slowing-down and pitch angle scattering have relatively small effects on their profiles. Results for the heating profiles for the six heating mixes near the peak temperatures are shown in [Fig. 12](#). The alpha heating profiles are included in the total electron and thermal ion heating profiles.

Next consider Option 2 with $P_{L \rightarrow H}$ scaled up a factor of two instead of four. Three of the heating mixes transition to H-mode and three do not. The thermal ion and electron heating densities volume-integrated to the boundary region are plotted in [Fig. 6-c](#)), and the total alpha heating in [Fig. 7-c](#)). When the plasma transitions to H-mode the PEDESTAL module [20] in PTRANSP is used to predict the pedestal width and the pressure at the top of the pedestal. Since the electron density is prescribed, the pressure determines the pedestal temperatures. These values can be scaled, and for these runs the flat top values of both the ion and electron temperatures are 4.6 keV.

The times of the $L \rightarrow H$ are listed in [Table II](#). The total alpha heating is also given in [Table II](#). Their values increase as the transition time increases, mainly due to the increase in density. Note that the alpha heating remains high after the $H \rightarrow L$ transition, $P_\alpha \simeq 80$ MW. This appears to be the maximum achievable in L-mode, so the maximum heating power for achieving the H-mode at flat top density is $73 + 80$ MW. The corresponding results for the total fusion power are shown in [Fig. 7-c](#)).

The values of Q_{DT} are shown in [Fig. 8-b](#)). The mix 3NB/IC achieves Q_{DT} of 7.0 with $P_{\text{ext}} = 73$ MW, and 3.0 when P_{ext} is lowered to 47 MW. The back transition is assumed to occur if the heat flow decreases below 75 % of $P_{L \rightarrow H}$. The times for the three mixes that obtain H-mode are listed in [Table I](#). Note that the mixes with more NNBI power achieve the H-mode earlier and have higher alpha heating. This shows a clear advantage of more beam power. In contrast this advantage is predicted to be more modest during the flat top phases and far from critical values [Ref. \[2\]](#).

4. Results for the H-mode phase

For the H-mode predictions GLF23 is used for the plasma temperatures, but not for the toroidal rotation to avoid the issue of how valid these predictions are. Instead, the momentum transport is assumed to be related to the ion energy conductivity by $\chi_\phi/\chi_i = 0.5$, as in Option 1 used for the L-mode study. With the PTRANSP-NUBEAM predictions of the NNBI torques, the toroidal rotation is predicted to be relatively low ($\simeq 6$ kRad/s) and the flow-shearing rate is predicted to have little effect on the GLF23-predicted temperatures.

The nominal database scaling [Eq. 1](#) for the $L \rightarrow H$ power threshold is assumed. Consequently the transition occurs immediately after the external heating is applied, precluding prediction of alpha heating in L-mode plasmas except

during the Ohmic phase.

After the transition to H-mode the pedestal temperatures is predicted by the PEDESTAL module in PTRANSP. Their values are used as boundary values for the GLF23 predictions. The resulting core temperatures depend sensitively on them. Since there is uncertainty about their values, scans were performed for the 2NB/IC/EC heating mix by scaling the pedestal values and predicting the temperatures and alpha heating powers.

The $P_{\alpha-e}$ profiles for the scans are shown in Fig. 13. The $P_{\alpha-e} + P_{\alpha-i}$ time evolutions for the scans are shown in Fig. 14. The Q_{DT} time evolutions for the scans are shown in Fig. 15-a). The scaling of Q_{DT} with P_{ext} shown in Fig. 15-b) is $(P_{ext})^{-1.5}$, contrasting the result $(P_{ext})^{-0.8}$ in Ref. [14] using TGLF when the heating profiles are held fixed and only T_{ped} is varied. The results here are predicted with the heating profiles calculates self-consistently for each T_{ped} .

The Q_{DT} values during the high P_{ext} phase (73 MW in the interval 80-130 s) are plotted versus the local normalized β at the top of the pedestal $\beta_{n,ped}$ (proportional to T_{ped} since the n_e profile is fixed) in Fig. 16-a). Note that Q_{DT} remains below 10 even with pedestal temperatures of 8.8 keV, which appears too high for practical use in ITER due to large transient loss of power from ELMs. The Q_{DT} when P_{ext} is lowered to 47 MW is shown in Fig. 16-b).

Scaling of Q_{DT} with $(T_{ped})^2$ and equivalently with $(\beta_{n,ped})^2$ was found using TGLF when the heating profiles are held fixed and only $\beta_{n,ped}$ and T_{ped} are varied [14]. The results here, with the heating profiles being calculates self-consistently at each $\beta_{n,ped}$ give a scaling closer to unity. Predictions for the central temperatures, β_n , and other variables are shown in Fig. 16. Note that in Fig. 16-b) β_n rises to values that might indicate instability as the pedestal temperature and Q_{DT} increase. Modeling of the peeling-ballooning stability of the edge [21] indicates that the value $\beta_{n,ped}$ will be limited to $\simeq 0.6-0.8$.

5. Summary

ITER L-mode plasma performance is studied assuming that the power threshold for the $L \rightarrow H$ transition is higher than the maximum heating power anticipated (73 MW). The GLF23 model is used to predict temperatures. Two alternative options are used to compute the flow-shearing rate for GLF23. One uses the conservative assumption that $\chi_\phi/\chi_i = 0.5$. The more speculative option uses GLF23 to predict the toroidal rotation, which predicts higher alpha heating in cases with neutral beam injection. Examples are given of conditions with $L \rightarrow H$ transitions when $P_{ext} + P_\alpha$ exceeds the threshold. Values of $P_\alpha = 8-76$ MW are predicted.

During the H-mode alpha heating as well as the total fusion power and Q_{DT} are predicted (with GLF23) to depend sensitively on the pedestal temperature. For pedestal pressures compatible with peeling-ballooning simulations P_α up to 80 MW are predicted.

These results suggest that having as much NNBI power available as possible is a good strategy for ITER. The predictions indicate that higher temperatures and P_{DT} would be expected. If the $L \rightarrow H$ power threshold is high and if the flow-shearing rate is high, as expected with the optimistic option, then more NNBI power could be crucial for the H-mode.

Improvements in theory and modeling that would strengthen the validity of the predictions are: 1) better models are needed for predicting plasma temperatures, rotation, and density. Density profiles are coupled with performance, so predictions of the transport, including pinches and non-diagonal terms such as thermo-electric diffusivities of the various plasma species are needed. Intrinsic rotation and neoclassical viscosity might be important in ITER. Having the TGLF model coupled to a time-dependent integrated predictive model would be an important improvement over the GLF23 model used here.. 2) better models of anomalous fast-ion transport are needed. These should include effects of MHD, NTM, and TAE modes. 3) improved predictions of the heating, torquing, and current-drive are needed for source terms in the transport calculations.

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Heating mix	80-130	130-300	300-400	400-500
	s	s	s	s
3NB/IC	50-23-0	33-13-0	33-0-0	0-0-4
2NB/EC	33-0-40	17-0-30	17-0-17	0-0-4
2NB/IC/EC	33-20-20	17-10-20	17-0-17	0-0-4
1NB/IC/EC	17-20-37	0-10-37	0-0-33	0-0-4
IC/EC	0-20-53	0-10-36	0-0-33	0-0-4
EC	0-0-73	0-0-46	0-0-33	0-0-4

TABLE I: Heating powers NNBI-ICRF-ECRF during four time periods and the transition times.

Heating mix	Option 1	Option 2	Option 2	Option 2
$P_{L \rightarrow H} / P_{Eq1}$	4	4	2	2
	P_α [MW]	P_α [MW]	H-mode time [s]	P_α [MW]
3NB/IC	20.0	76	87.5 - 400.0	32
2NB/EC	13.3	62	108.2 - 400.0	41
2NB/IC/EC	16.6	34	110.1 - 311.0	41
1NB/IC/EC	14.2	28	none	-
IC/EC	12.5	13	none	-
EC	8.4	8	none	-

TABLE II: Values for P_α [MW] computed at 130 s using Options 1 and 2 with $P_{L \rightarrow H}$ scaled by up a factor of four or two. The H-mode is predicted only three of the heating mixes with Option 2 with $P_{L \rightarrow H} / P_{Eq1} = 2$.

T_{ped}	$T_e(0)$	$T_i(0)$	Q_{DT}	PP_α
keV	keV	keV		MW
8.8	38.0	42.0	9.5	122
6.0	30.0	29.9	5.5	78
4.8	26.5	23.8	4.2	58
1.7	16.5	15.0	1.5	22
0.7	15.5	13.9	0.7	20

TABLE III: Results for the H-mode scan in the early phase with $P_{ext} = 73$ MW. Q_{DT} is less than 10 since P_{ext} is large.

T_{ped}	$T_e(0)$	$T_i(0)$	Q_{DT}	P_α
keV	keV	keV		MW
7.5	34.0	35.5	17.5	113
5.1	26.0	25.0	11.0	77
4.0	22.0	20.3	7.8	57
1.2	13.3	11.8	2.0	18

TABLE IV: Results for the H-mode scan in the flat top phase with $P_{ext} = 47$ MW.

FIG. 1: (Color) Powers for the heating mixes.

FIG. 2: (Color) a) Assumed central electron density ramped up to $f_{Greenwald} = 0.85$, and computed central ion densities; b) Current ramped up to 15 MA.

FIG. 3: (Color) Central toroidal rotation for different heating mixes predicted using a) Option 1 ($\chi_\phi = 0.5\chi_i$); b) Option 2 (GLF23 rotation) and $4 \times P_{L \rightarrow H}$. The peak rotation is much higher using Option 2, but is comparable to rates measured in some L-mode beam-heated plasmas.

FIG. 4: (Color) Ion temperatures a) assumed at the boundary, and b) computed at the magnetic axis for different heating mixes using Option 1 and high $P_{L \rightarrow H}$.

FIG. 5: (Color) a) Ion, and b) electron temperature profiles predicted using Option 1 near the time when they are largest.

FIG. 6: (Color) Energy flow near the boundary for the six heating mixes; a) Option 1 with the $L \rightarrow H$ power threshold is assumed to be scaled up by a factor of 4 to prevent the H-mode; b) Option 2 with the $L \rightarrow H$ power threshold is assumed to be scaled up by a factor of 4 to prevent the H-mode; c) Option 2 with the $L \rightarrow H$ power threshold is assumed to be scaled up by a factor of 2 allowing three heating mix cases to achieve H-mode; For these, the pedestal temperature is assumed to increase to a flat top value of 4.4 keV, causing the central temperatures and alpha heating to increase.

FIG. 7: (Color) Total alpha power to thermal electrons and ions. a) Option 1 with the $L \rightarrow H$ power threshold scaled up by a factor of 4 to prevent the H-mode. b) Option 2 with the $L \rightarrow H$ power threshold scaled up by a factor of 4; c) Option 2 with the $L \rightarrow H$ power threshold scaled up by a factor of 2. The total power is close to the DT fusion power divided by five except for a dwell in time of approximately two sec due to the slowing down of the alpha particles.

FIG. 8: (Color) Predictions of Q_{DT} using a) Option 1; b) Option 2 with $P_{L \rightarrow H}/P_{Eq1} = 4$; c) Option 2 with $P_{L \rightarrow H}/P_{Eq1} = 2$. The large oscillations in Q_{DT} predicted for the 3NB/IC mix are caused by large sawtooth inversion radii causing large oscillations of the central ion temperature.

FIG. 9: (Color) Predictions using Option 2 of a) Central ion and b) electron temperatures.

FIG. 10: (Color) a) Ion, and b) electron temperature profiles near the time when they are largest.

FIG. 11: (Color) Alpha power to thermal electrons and ions and their total compared to the profile of $P_{DT} / 5$ when the $L \rightarrow H$ power threshold is assumed to be scaled up by a factor of 2. a) Heating mix that does not achieve H-mode; b) Heating mix that does achieve H-mode. The $L \rightarrow H$ power threshold is assumed to be scaled up by a factor of 2. The total power is close to the DT fusion power divided by five except for a dwell in time of approximately two sec due to the slowing down of the alpha particles. If a non-classical radial shift of fast alphas occurs (due, say to MHD or TAE activity) then the the shapes of the P_{DT} and alpha density profiles would differ.

FIG. 12: (Color) Predictions of electron and ion heating using Option 2 late in the L-mode phase, two sec before the transition to H-mode. The alpha heating profiles are summed in the total ion and electron heating profiles.

FIG. 13: Profiles of $P_{\alpha-e}$ at the flattop with $P_{\text{ext}} = 73 \text{ MW}$.

FIG. 14: Evolution of the total alpha heating for different assumptions for the pedestal temperature.

FIG. 15: (Color) Evolution of Q_{DT} for different assumptions for the pedestal temperature.

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