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Improved Modes and the Evaluation of Confinement Improvement

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Tokamak, Improved confinement, Evaluation of improvement, Fusion product, τ_E and fuel purity, Dilution and Radiation

Abstract:

Various improved confinement modes in tokamak are surveyed and their characteristics are reviewed. To search for the potentiality as a fusion core plasma in reactor, an examination to evaluate the core performance has been made. The fusion product near the ignition condition, where Q is large, is used for the evaluation. The dilution of the fuel ion and the profile effect are simultaneously examined together with the obtained τ_E.

Because of the fuel dilution and of the bulk radiation, the good performance does not always correspond to the mode with long τ_E. If their time evolution is taken into account the problem becomes more serious. Further extensive research to control the fuel purity is surely needed to ensure the long pulse operation.

1. Introduction

Recently various "Improved confinement modes" have been reported in tokamak plasmas. The H-mode, which is associated with the steep gradient and the pedestal formation of the density or the pressure near the edge, has been found.[1] The supershot[2] is another improved mode which has the peaked density/ion-temperature profile in the central region. Initiated by these experimental findings, improved modes which have various types of pressure profiles have been revealed. At present, the combined structure of peaked profile and pedestal formation has been realized and a case is called hot-ion-H mode.[3]

The H-mode studies on the threshold power and on the density have explored the importance of edge parameters. The various experiments with the aim of controlling the mode has led us to study the technique to change the plasma boundary conditions. The supershot has revealed the importance of the particle recycling near the edge on the plasma confinement. These knowledge have enabled us to make various improved modes with different pressure profiles.[4-12] Other than H-modes in various machines, peaked profiles modes like, high-T_i-mode, high-T_e mode, hot-ion-H mode are obtained in JET.[3] The Improved-L mode, which has been found in JFT-2M has also a peaked profile.[9]

In this paper, we survey various kinds of improved modes and examine their enhancement factor as well as the degraded factor. Using the database, we show an example for the evaluation of the confinement as a whole. As an enhancement factor, τ_E/τ_{EL} has been widely used, where τ_{EL} is the confinement time in L-mode.

One of the degraded elements is the decrease of the purity ratio, either due to high-Z impurities or due to low-Z impurities. The former affects the duration(life) time of the discharge, and the latter influences on the dilution of the fuel ions even if the radiation collapse can be avoided. Strong dilution has been found in almost all peaked profile modes. The true enhancement factor of the mode can be evaluated by an inclusive analysis.

In the following, we adopt the evaluation factor(s) for the fusion core performance in Sec.2. In Sec.3, several discharges of improved modes are examined based on the present database. Perspective of various modes are discussed, where the consideration for the consistency with external apparatus is included. In the final section, we note some future issues.

2. Evaluation of Confinement Performance

One well-known figure of merit is the energy confinement time, τ_E, which is defined by the ratio of an internal plasma energy, W_{in}, to an input power, P_{in}. The ratio of improved confinement time to that in L mode, $H \equiv t_E/\tau_{EL}$, is often called "the enhancement factor" of the mode. In a burning state, the core performance is dictated by the balance between a fusion input, P_f, and the power loss, P_{loss}. Namely, P_f dominates over P_{in} ($Q >> 1$) in the power balance equation, $P_{loss}=P_f + P_{in}$. The fusion product, $n_i(0)T_i(0)\tau_E$, is a figure of merit in this condition.

If we assume that the scaling law of τ_E can be used for an extrapolation and that the fuel dilution is small, the ratio of P_f

to P_{loss} corresponds to this value. Let the ion temperature to be from 7 keV to 25 keV, and the peakedness of the pressure profile to be γ_p, then the rough estimation gives

$$P_\alpha\ (\sim P_f\ )\ :\ P_{loss} = C\gamma_p n_i(0)T_i(0)\bar{n}_i\bar{T}\ :\ \bar{n}\bar{T}/\tau_E \qquad (1)$$

This ratio is a measure of a good confinement as a fusion core performance. When the effect of the fuel dilution is explicitly extracted, the ratio becomes

$$P_\alpha/P_{loss} \propto \gamma_p n_e(0)T_i(0)\tau_E f_{DT}^2 \qquad (2)$$

where $f_{DT}(\ <1\ )$ is the effective fuel ratio given by $1-\Sigma Z f_z$, and f_z is the impurity contamination ratio of the charge Z.

To compare various improved modes, the figure of merit can be adopted,

$$H\cdot f_{DT}^2 \quad (\ \ \gamma_p\cdot\tau_E\cdot f_{DT}^2\ \ ) \qquad (3)$$

as a point model approach. Inside the ( ) above is for including a profile effect for the given central performance of the plasma.

We see that the enhancement of the confinement time is necessary but is not sufficient for the improvement of the mode. In addition to it, the purity of the fuel which should be centered to the core, and the adequate peakedness of the profile are needed. Simultaneous fulfillment of these conditions is required for the true improvement. Adopting these guidelines, we examine various improved modes, which have been obtained so far.

3. Improved modes and An evaluation

There have been found kinds of operation modes, each of which has a longer energy confinement time than L-mode. We use the database published in literatures. The evaluation here may not be an universal but be an example. We list various modes in Table 1 as typical examples[4,7-14]. The mode classification, machine (with a shot number or on many shots), the change of the mode, the input scheme, information with respect to the density (averaged density, peakedness, pedestal formation), Z_{eff} and the main impurities, τ_p(the diffusion coefficient D, the inward pinch velocity V_{in}), the dilution rate, the impurity accumulation rate dZ_{eff}/dt, electron and ion temperatures and their peakedness, pressure peakedness, the plasma rotation and the profile, the enhancement factor of energy confinement time, the improved quantity and the location, the changes in fluctuation and in the heat transport coefficients, the information of the global modes, radiation power, the radiation increasing rate dP_{rad}/dt, surrounding neutrals, the plasma configuration, wall materials, working gas, wall conditioning method, and the width of the heat channel at the divertor plate are listed. Adopted operation modes are the H-modes, the high-$T_{i,e}$ mode,[12] the pellet mode, the Improved L-mode,[9] the IOC mode,[4] the Improve Divertor confinement mode[10] and the NBI Counter-injection mode[8].

Almost all improved modes are associated with the enhanced confinement of particles. A good confinement of particle usually leads to an impurity contamination. In the following, we study the data with respect to the impurity contamination. There have been reports on impurity study in ASDEX[15] and JET[16]. We use these data as our database.

ASDEX

Impurity contaminations in various type of discharges have been measured and reported[15]. From these data we shall obtain the global performance of the core plasma. In table 2, we show the main impurities and and their contamination rates, Z_{eff} values both from the spectroscopy measurement and from the bremsstrahlung, the energy confinement time, the diffusion coefficients and the particle confinement times, those of which are taken from ref.(15). Also shown are the purity ratios, f_{DT}, deduced from the data, and the enhancement factor of the energy confinement time, H, which is normalized to the confinement time in L-mode for additional heating cases, or to the value at the turn over to saturated confinement, τ_{ESOC}, for ohmic cases. The typical peaking factors of the density, γ_n($\gamma_n \equiv n_e(0)/\langle n_e\rangle$; the ratio of the central value to the line averaged one) , of the temperature, γ_T ($\gamma_T \equiv T_{e,i}(0)/\langle T_{e,i}\rangle$), and of the pressure, γ_p ($\gamma_p \equiv \gamma_n \cdot \gamma_T$) are taken from reported data[4,7,8,11,17].

Combining the data, we calculate the figure of merit presented in Sec. 2 and show the values of $H \cdot f_{DT}^2$ and $H \cdot f_{DT}^2 \cdot \gamma_p^N$, where γ_p^N is defined as $\gamma_p/\gamma_{p,L}$. These data are analysed from the view point of the snap shot, therefore a guiding principle for the sustenance of the modes can not be obtained.

Ohmic discharges in table 2 show that the so called improved ohmic modes suffer from dilution and/or radiation collapse. The peaked profile modes are seen to have more impurity contaminations than other ohmic discharges. The pellet mode has a little increase of the dilution but the concentration of the heavy ions in the plasma center causes the radiation collapse. The performance with respect to the dilution is out of the question.

The IOC mode has the stronger dilution than the standard case has. The IOC apparently has the good core performance, however, the H value in ohmic discharges is normalized to the saturated value. If we normalize it to the value of Alcator scaling which is applicable in linear regime, the figure of merit of IOC is the similar value to the standard case's. The peakedness, τ_n, of the IOC regime has been found to be proportional to the line averaged density as $\tau_n \simeq 1.2+4\langle n_e\rangle_{19}/30$[17], where $\langle n_e\rangle_{19}$ is measured in $10^{19}/m^3$. Many experimental observations have shown that the mode with a larger peakedness has the stronger dilution , $1- f_{DT}$, and the dilution rate, $-df_{DT}/dt$. The question about the optimum peakedness and its realization is left open.

In auxiliary heated plasmas, the analogous tendency to the ohmic discharges can be seen in the relation between the peakedness and the dilution. The most peaking case of NBI counter injection has the largest enhancement factor H , however, the dilution is also strong and the total figure of merit stays to be small. Furthermore, this shot has been terminated by the radiation collapse in the later phase of the discharge. This is due to the contamination of the heavy impurities.

With respect to the H-mode, the dilution overcomes the enhancement of τ_E. The total evaluation of this discharge is lower than the standard L-mode.

Modes associated with the long particle confinement times suffer from the dilution or the radiation collapse. Among these data, we can not obtain an conclusion for the best improved mode. The L-mode with a good wall condition has a better evaluation. These data sorely depend on the timing of the measurement during the discharges.

The impurity contamination, at present, is an unresolved problem. We do not observe the large difference between the different wall materials in ohmic discharges. Nevertheless, we observe the less impurity contamination for carbonized wall condition in a ICH heating discharge. From the data here, we are not able to judge the difference. Further systematic as well as the statistical analyses are necessary to make a conclusion.

JET

The analysis is applied to the recent JET data. For various kinds of improved modes, the values of Z_{eff} and the dilution rates are reported in ref(16). With respect to these data, the discharge traces, in which the temporal evolutions of the plasma parameters are drawn, have been reported in the annual progress report and so on.[3,12] Table 3 shows the present results of our analysis for the modes evaluation, where the data from the trace are used. Shown are the case studies for various modes. The typical plasma parameter, the discharge conditions, the dilution rate from Z_{eff} and from the neutron measurement, the enhancement factor H, the peakedness of the mode and the figure of merit are listed. This result is also from the snap shot analysis of the mode and the temporal evolution of the figure of merit is not known.

Even in ohmic discharges the dilution rate is larger by factor of around 3 than that in ASDEX. The reasons for the enhanced dilution can be speculated to be due to the larger energy content of the plasma, due to the open divertor configuration and the good conductance between the plasma edge and the divertor. Regardless of the modes of types, this difference should be kept in mind.

Among various modes of auxiliary heated plasmas, high-T_e and high-T_i modes, which are associated with the peaked profiles of the temperature and/or the density, have lower evaluations. The pellet mode in auxiliary heated discharge has also the peaked profile, and the evaluation of the mode may change according to the timing of the measurement. ·In table 3, this mode has a higher point, however, the mode is suffered from the internal disruption of the ion temperature even during the heating phase. The peaked profile mode with pellet and heating has the highest but the transient record of the core performance. There remains the serious problem with respect to the sustenance of the mode.

In table 3, we have two types of H-mode, one is obtained via L-mode on the medium density target plasma, and the other is obtained via the hot-ion mode on the low density target plasma.

Both have the better points and we may say that the H-mode is the better improved confinement than those of peaked profile's on JET. From the view point of number of neutrons, the H-mode is better than L-mode, i.e., $Q_{DD}(H) >> Q_{DD}(L)$. On the other hand, the presently obtained H-mode in ASDEX has the lower point than the L-mode, provided that wall conditioning plays the similar performance. The H-mode has the good particle confinement and hence has been suffered from the impurity contamination. The total performance can not judged from this present database. Further systematic analysis is surely necessary to obtain the guiding principle for the choice of the operation mode.

Perspectives

The evaluation of the confinement performance includes the capabilities for the extrapolation of the mode as well as for the duration time of the good performance. With respect to the former case, an applicability of the extension of the mode to the parameter region of interest is one issue. If the mode appears in a special parameter regime which is not extendible to the operation regime in future, the mode should be discarded even if the performance is excellent. The conventional H-mode, which finally goes to the radiation collapse due to the heavy ion concentration, has a problem with respect to the duration time. This limits the extension of the duration time of the discharge and conflicts to the steady-state operation.

The ELM_y H-mode may be a next candidate because of its capability of the particle exhaust and its consistency with the divertor performance.[18)] However, the parameter dependence of the working region available to ELM_y H-mode is not known. Some data show that the region of the appearance is restricted, and the narrow parameter space[13,19)] is determined by the edge parameters. The perspective of this mode to a quasi-steady state operation depends on the realization of the edge controlling method, which must be insensitive to the external/internal power supplies. Otherwise, a small amount of the perturbation in the fusion output may terminate the desired operation. The experiment of the external controlling system using Ergodic Magnetic Limiter (EML) is under way, however, the conclusive result, at present, is not known.[19)]

Another important factor is the duration of the improvement. The duration times of various improved discharges are limited, partially by the radiation collapse, the unknown internal disruption and/or disruptions caused by some blooms from the outside. Others are said to be restricted by the external circuit like a pulse length of the input power. Even if the discharge is apparently limited by the pulse lengths, the expected life of the good confinement can be obtained by the extrapolation from the temporal evolution of the discharge. The rough guidelines for the duration may be 1) the time until the occurrence of the radiation collapse or the density limit disruption, and 2) the time till the tolerable dilution rate is violated.

The rough time until the radiation collapse, τ_{rad}, may be estimated from,

$$(dP_{rad}/dt)|_{t0}\cdot\tau_{rad} = P_{in} - P_{rad}(t_0) \qquad (4)$$

The radiation power, P_{rad} is usually measured and this rate is inferred to discuss the core performance of energy confinement. The time derivative of this rate, (dP_{rad}/dt) at $t=t_0$, or the averaged value for some period, t_1-t_0, can predict the remaining time of the discharge life.

The H-mode shot in JET (#15894)[12] shows that $P_{rad}(t_0)/P_{in}$ = 1MW/8MW at the time when the H-mode starts, $t=t_0$. Even if the input power lasts as desired, about 8 seconds later the discharge might be terminated by the radiation collapse, provided that this radiation rate does not change.

The time derivative of the dilution rate also gives another time scale. This is given via df_{DT}/dt. If we estimate the time scale in which the dilution rate becomes a half of the initial stage, the time τ_{dil} is evaluated by

$$(df_{DT}/dt)\cdot\tau_{dil} = -1/2. \qquad (5)$$

If the main impurity is assumed to be carbon, then the dilution rate f_{DT} has the relation between Z_{eff} as $f_{DT} \simeq 1-(Z_{eff}-1)/5$. The effect of the heavier impurity can be counted by the introduction of the relation as, $\delta f_{DT}/f_{DT} = \delta Z_{eff}/Z_{eff}/(6/Z_{eff}-1)$. If we neglect this correction, we have τ_{dil} in terms of Z_{eff} as

$$(dZ_{eff}/dt)\cdot\tau_{dil}/5 = 1/2. \qquad (5')$$

For the case of ELM free H-mode in JT-60 (E11483),[14] the increasing rate of Z_{eff} during the Lower Hybrid wave input has been reported to be 0.3 per second. This means that even if the LH pulse will be prolonged, the dilution rate becomes a half of the initial state after 8.3 sec. In this case, we assume that the worse situations like C-bloom[12]/Be-Bloom and/or hot spot at the divertor plate[12,13] do not occur.

These two cases are typical examples to understand the life time of the discharges. Obtained values may not be universal. The systematic measurements and analyses will provide us the guiding principles for future problems and are surely necessary.

Aside from τ_{rad} and τ_{dil} we may have the other typical time scales which impose the constraints to the survival of the mode. In order to realize the long pulse operation of the improved confinements, further research to find out and to define the other time scales is needed.

4. Summary and Discussions

The case studies on the evaluation of the various improved modes, which have been obtained so far are done. To evaluate the performance of the mode, we use the fusion product as a figure of merit. From the view point of the long pulse operation(steady-state operation) we also show two time scales which may limit the good performance of the core.

In this report we compare the improved modes with the L-mode and/or with the SOC mode by using the evaluation function(s), $H \cdot f_{DT}^2$ ($\tau_p \cdot \tau_E \cdot f_{DT}^2$). As the case studies, we analyse the various modes in ASDEX and in JET, respectively. The results of two machines predict the different mode as the best. The peaked profile modes are found, tentatively, not to be a candidate for the core plasma of long pulse operation. This is because that these modes tend to be contaminated by impurities faster than the other modes. The combination to the other mode is out of scope.

We find that the long confinement time of the energy, τ_E, is only a necessary condition and the dilution dictates the evaluation of the mode. The purity of the fuel, sometime, has the stronger effect than the confinement time. Systematic analyses on the present database will reveal a choice of the operation modes which can be used in future. However, we as yet have not sufficient database to judge the core performance. The research to pursue the true improved confinement is still strongly needed.

An approach from the neoclassical theory shows us that the influx of the impurity to the plasma core is proportional to the peakedness of the profile and the contamination of the impurity at the initial stage, provided that the impurity fraction is small. If we consider the situation that the impurity invades from the outside, the dilution becomes serious faster for the peaked profile modes. The fuel purity decreases with the time and the rate is proportional τ_p. The evaluation factor, $\tau_p \cdot \tau_E \cdot f_{DT}^2$, has a maximum with respect to the peakedness. The experimental check should be done. Furthermore, it is also predicted that the impurity influx changes according to the changes of the plasma rotations. The realization of an active control by using the rotation may alter the results of the present analysis.

To examine the potentiality for the long pulse operation, the modes are checked by the introduction of two evaluation factors of the time scale, τ_{rad} and τ_{dil}. The former is the measure of the life time till the radiation collapse takes place and the latter is the one in which the sufficient purity holds. The present case study shows us the duration times would be less than 10 seconds for certain H-modes in JET and in JT-60.

To support the longer duration time of the mode, constraints on the time scale from the other components should be minimized. If the divertor function does not work well, impurities are to be produced and are not shielded, then their back flow to the core occurs. Usually the improved modes impose the harder condition to the divertor plate. The back up operation schemes other than the separatrix swing[20,21] and/or the plasma swing[22] are to be considered.

This evaluation factor can be used as one of the guidelines to compare different heating and current-drive schemes. For instance, according to the present database of τ_E scaling, the current-drive is necessary to increase τ_E. However, the efficient current-drive is realized only when the increase of τ_E prevails the dilution as the opposite effect. (i.e., If $\tau_E \propto I_p^{\alpha}$, $\alpha\Delta I_p/I_p + 2\Delta f_{DT}/f_{DT} > 0$ is necessary.)

The analysis here is a case study and is far from complete. In order to realize the better confinement of the core this kind of total analysis may help to explore some guidelines for the future scientific strategy.

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Table Captions

Table 1 Characteristic discharge and plasma parameters of various improved modes in JET, JT-60, ASDEX and JFT-2M. (cited from listed refs.)

Table 2 Impurity concentration in various ASDEX discharges and the particle(including the diffusion coefficient, D) and energy confinement times measured by laser blow-off experiments are cited from ref.(15). The purity ratio deduced from the data are shown. Using the characteristic parameters of the mode (cited from listed refs.) we examine the mode improvement factor at the measured time (a snap shot analysis).

Table 3 The purity ratio, deduced from the data of Z_{eff} and neutron measurements, and typical discharge and the plasma parameters of various modes in JET are cited from ref.(16). Using the characteristic parameters of the mode (cited from listed refs.) we evaluate the mode improvement at the measured time. This is a snap shot analysis and the remark is noted with respect to the mode duration.

Table 1a

Types of Mode	H	H	Pellet +ICH	high $T_i(T_e)$	high T_i (super-like)	IL (peak T_i)
Machine shot no.	JET 15894	JET 18757	JET 16211	JET 16066	JET 18379	JFT-2M statistical
Mode change	L – H	hig T_i – H	Pellet mode – Int. Disruption			H – high T_i – H
Heating / I_p	NBI 7.5MW/3MA	NBI 10.2MW/3MA	ICRF 7.1MW/3MA	NBI/ICRF 7.4/7.9MW/3MA	NBI/ICRF 19.9/2.7MW/3MA	NBI 0.3~0.4MW/0.3MA
ave. $\langle n_e \rangle$	3×10^{19}~5.5×10^{19}	2.8×10^{19}~5×10^{19}	3.5×10^{19}~5×10^{19}	~2×10^{19}	1~2×10^{19}	6.5~7×10^{19}
Density peaking γ_n, (P: Peaked, Ⓟ: pedestal)	γ_n~1.2 (n_{eo}~5.6) Ⓟ	γ_n~1.0 (n_{eo}~3) P, Ⓟ	γ_n~1.4 (n_{eo}~5.8)	γ_n~1.7 (n_{eo}~3)	γ_n~1.5 (n_{eo}~2)	γ_n~1.5
Z_{eff}, main impurities	~3, N_i 10^{-4} C/O (1-3%)	~3.5 C/O	$Z_{eff}(0)$~2.3~3.5, 2.~4 C/O	($Z_{eff}(0)$~5.0~5.2) 3.2~3.5 C/O	$Z_{eff}(0)$~5.5~6.5, 3.6~4.5 C/O	C/T_i
τ_p/D. V_{in}	D~0.3-0.6m^2/s	D~0.3-0.6m^2/s				
Purity / Z_{eff} estimation	0.6/0.6	0.6/0.55	0.85/0.85	0.45/0.3	0.35/0.2	
d Z_{eff}/dt	0.35/S			↗, C Influx	↗, C Influx	↗
Te, γ_{Te}	T_{eo}~5.5keV, γ_T~1.5	T_{eo}~6.8 γ_{Te}~1.7	T_{eo}~7.8keV, $\gamma_T < \gamma_n$	T_{eo}~10keV γ_{Te}~1.7	T_{eo}~8.1keV, γ_{Te}~1.7	T_{eo}~0.7keV γ_{Te}~2
Ti, γ_{Ti}	T_{io}~5.3keV, γ_T~1.5	T_{io}~13.1 γ_{Ti}~2.2	T_{io}~7.9keV,	T_{io}~13.3keV γ_{Ti}~2	T_{io}~15.3keV, γ_{Ti}~2.2	T_{io}~1.2keV, γ_{Ti}~3
T(r), γ_p	γ_p~1.8	T_i peak, γ_p~1.95	T_{io} Collapse, γ_p~1.9	T_e, T_i peak (~V_ϕ), γ_p~3.3	T_i peak~(~V_ϕ) γ_p~2.9	T_i peak~(V_ϕ) γ_p~3.75
$\nabla\phi(r)$, profile	change in edge	$\nabla\phi(r)$ ~$T_i(r)$		$T_i(r)$ ~ $\nabla\phi(r)$	$T_i(r)$ ~ $V_\phi(r)$	$T_i(r)$ ~ $V_\phi(r)$
τ_E/τ_{EL} (τ_E/τ_{E}^{ITER89})	~2	~2	1.2	1	1~1.2	~2
Improved quantities/place	$\bar{n}$ / pedestal	T_i, n /center, pedestal	P /center	no	T_i, n/ peak /center	T_i, n / center
$\tilde{\Phi}$, $\tilde{B}$, $\chi_{e,i}$ change	χ_i ↘	χ_i↘, χ_e, $\chi_i(r)$ crossing	χ_e, χ_i↗ profiles crossing			
global, change	Sawtooth ↘	T_i Collapses	Internal Crash T_i, T_e.			Internal Crash
$P_{rad}(0)/P_{in}$	1MW/8MW					0.5~0.6
d P_{rad}/dt	0.9MW/S					~0
neutrals		predegassing, low n starts		low n starts	low n starts	
Configuration, Lim/Div. SN/DN open/closed	D, SN, X-point, open	D, DN, x-point, open	D, x-point, open	D, DN, x-point, open	D, SN, x-point, open	D, SN, x-point, open
Wall/Gas / conditioning	C/D	C/D/He Cleaning	C/D	C/D/He Cleaning	/He Cleaning	
Div Heat flux · δ_T/δ_{TL}				hot spot	hot spot	

Ⓟ

Table 1b

Types of Mode	H	Pellet + Heatings	Limiter - H	IDC	IOC	Counter Injection
Machine shot no.	JT-60	JT-60 statistical	JT-60	JT-60	ASDEX	ASDEX
Mode change	L – H		$\bar{n}_e$ dictates L, ELMy, H		SOC – IOC	L
Heating / I_p	NBI <20MW	NB, IC LH 1-25MW	LHCD 1.2~2MW	NBI 10MW	OH 0.38MA	H^0–D 0.9MW/0.42MA Impurity puff (1.5MW)
ave. $\langle n_e \rangle$	2×10^{19}~7×10^{19}	4×10^{19}~1.5×10^{20}	2.5×10^{19}~3.5×10^{19}	2×10^{19}~4×10^{19}	3×10^{19}~6×10^{19}	3×10^{19}~6×10^{19}
Density peaking γ_n,	γ_n ↗	$\gamma_n < 5$ ($n_{e0} = 3\times10^{20}$; P	γ_n~1.6-1.7	γ_n~1.7-2.3	γ_n~$(1.2+0.133 n_e)$~1.7 ((5))	γ_n~1.7-2.4 n_{e0}~1.2×10^{20}
Z_{eff}, main impurities	2~2.6 C/O	1.5~2.5 C/O	4~5 C(12%)/O(0.5%)	3 C/O	2.4-2.7 C/O	3.3 C/O/Cu
τ_p/D, V_{in}	τ_p up ↗	0.2m²/sec (r~a/2)			$\tau_{Ti}\tau_p$ ~125msec D_{Ti}~0.05m²/s	D_{Ti}~0.05m²/s
Purity / Z_{eff} estimation	/0.7	/0.8	0.36/0.3	/0.5	0.81/0.7	0.4/0.54
dZ_{eff}/dt	0.3/sec	0.5/sec, 2.5/sec (initial)	0.3/sec		0.8/s dZ(0)dt ~1.6/S	1.4/s
Te, γ_{Te}	T_e(0.7)~1.1keV	T_{e0}~2.5keV γ_{Te}^{max}~3	γ_{Te}~2.6-2.9	γ_{Te}~1.9-2.2	T_{e0}~1keV, γ_{Te}~2	(1) γ_{Te}~1.8
Ti, γ_{Ti}		γ_{Ti}~γ_{Te}	γ_{Ti} ?	γ_{Ti}~2.6-3.2	T_{i0}~0.8keV, γ_{Ti}~2	γ_{Ti}~2.2
T(r), γ_p	pedestal.	peak (center), γ_p~5	γ_p~4.5	peaked', γ_p~4.5	peaked.., γ_p~3.4	peaked, γ_p~3.5~
$V_\phi(r)$, profile		q<1 region, $V_\phi(r)$ peaked	little			$T_i(r)$ ~ $V_\phi(r)$
τ_E/τ_{EL} (τ_E/τ_{SOC})	1.1~1.3	1.1~1.3	1.3	1.2	$\tau_E/\tau_{E\,SOC}$ ~130/80~1.6	2.7
Improved quantities/place	$\bar{n}$(particle)/pedestal	Particle (τ_p)/center	Particle(τ_p)/center	Particle (τ_p)	n, $T_i(T_e)$/center	n, T_i, (T_e)
$\tilde{\Phi}$, $\tilde{B}$, $\chi_{e,i}$ change	$\tilde{B}$ ↘ 1/6 of L mode				D ↘ χ_i ↘	χ_i ↘ χ_p ↘
global, change		Internal Crash, Sawtooth	No change	No change		Sawtooth Radiation Collapse
$P_{rad}(0)/P_{in}$	~ 2MW/20MW					/0.9MW
dP_{rad}/dt	2MW/sec<			remote colling increases		1.4MW/S
neutrals	T_i gettering	↘	↘		Gas puff-off, n_0 ↘	Gas puff-off, n_0 ↘
Configuration, Lim/Div. SN/DN open/closed	D, SN, X-(T) open	L/D, SN, X, open	Limiter	D, SN, x-(T), open	D, SN, closed	
Wall/Gas /	C/H, H_e/T_i gettering	C/H, H_e	C/H		C+Cu/D/CD_4	C+Cu/D
Div Heat flux · $\tilde{\delta}_T/\delta_{TL}$	$0.3\times P_{in}$			0.3~$0.4\times P_{in}$, 3-4cm		erosion rate 1/4

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Table 2

	Ohmic heating				NBI(D^0), 1.5MW			ICRH ($2\Omega_{CH}$), 1.5MW	
	Standard		IOC (5×10^{13} cm^{-3})	Pellet injection (carbonized wall)	L-mode	H-mode (carbonized wall)	Counter-injection	+NBI (D^0)	Carbonized wall
	SS Wall	Carbonized wall							
n_e(%)	0.5	1	1.5		2	5	2	3	2
n_0(%)	0.5	0.5	1		0.9	2		1.1	0.5
n_{Fe}(%)	0.015	0.003	0.01	0.02	0.06	0.3		0.2	0.04
n_{Cu}(%)	0.02	0.008	0.015	0.5	0.05	0.15	0.8	0.08	0.02
Z_{eff}^{a} (spectr.)	2.2	1.8	2.4		3	5	Radiation Collapse	4	2.3
Z_{eff} (Bremsstr.)	2.0	1.8	2.7	Radiation Collapse	3	3	3.3	3.9	2.5
f_{DT}	0.91	0.89	0.81		0.77	0.4	0.4	0.64	0.82
$f_{DT}^{Z_{eff}(c)}$	0.78	0.84	0.7		0.6	0.4	0.54	0.4	0.72
τ_E(ms)	80	85	130		37	65	80	36	50
$\tau_{p,D}$(ms)	50	30			21	50		32	
$\tau_{P,Ti}$(ms)	9	9			4			11	11
$\tau_{I,Ti}$(ms)	50		185		22	45		27	30
D_{Ti}(cm^2/s)		5,000	600		10,000	4,000	500	10,000	9,000
$H f_{DT}^2$	0.83	0.85	1.09		0.6	0.28	0.35	0.4	0.9
γ_n	1.45	1.45	1.7		1.45	1.4	1.7	1.45	1.5
γ_T	1.7	1.7	2.0		2.0	1.8	2.2	2.0	2.0
H	1	1.05	1.6		1	1.76	2.16	~0.97	1.35
$H f_{DT}^2 \gamma^N_P$	0.83	0.85	1.5		0.6	0.24	0.45	0.39	0.92

$H = \tau_E/\tau_L$, (τ_E/τ_E^S for ohmic), $\gamma_p = \gamma_n \cdot \gamma_T$, $\gamma_P^N = \gamma_n\gamma_T/(\gamma_n\gamma_T)^L$ ($\gamma_n\gamma_T/(\gamma_n\gamma_T)^s$ for Ohmic)

Table 3

Discharge		P_{RF}	P_{NBI}	$n_e(0)$	$T_e(0)$	$T_i(0)$	neutrons	n_H/n_e	n_D/n_e	τ_E/τ_{EL}		$\gamma_{PL} * 2.0$		Remark
Class	No.	(MW)	(MW)	$(10^{19} m^{-3})$	(keV)	(keV)	$(10^{15} s^{-1})$	(Z_{eff})	(neutron)	H	$H \cdot I_{OT}^2$	γ_P (γ_n, γ_T)	$\gamma^H_P : H \cdot I_{OT}^2$	
6 and 7 MA	17793	—	—	4.1	3.0	3.5	0.03	0.35	0.35					
Ohmic	17796	—	—	3.9	3.2	2.9	0.02	0.3	0.3					
^{4}He prefill	17797	—	—	4.1	4.0	4.2	0.04	0.35	0.35					
3 MA	17836	9.6	2.7	3.4	8.8	6.6	0.6	0.3	0.3	1.2	0.09	2.2(1.3,1.7)	0.1	
High T_e	17838	11.8	2.6	4.0	8.8	6.4	0.6	0.2	0.3	1.2	0.09	2.6(1.3,2.0)	0.12	
5 MA	16370	1.1	8.6	5.7	5.2	7.2	1.3	0.6	0.4					
Combined htg.	16382	6.8	12.0	5.5	7.3	7.4	2.7	0.3	0.3					
3 MA	16041	0.5	8.0	3.4	5.9	10.9	1.9	0.55	0.4					
High T_i	16066	7.9	7.4	3.0	10.0	13.3	3.8	0.30	0.45	1	0.16	3.4(1.7,2.0)	0.27	hot spot
	18379	2.7	19.9	3.1	8.1	15.3	8.3	0.20	0.35	1	0.09	3.0(1.5,2.0)	0.14	hot spot
	18589	1.4	15.2	5.2	5.7	11.0	3.1	0.20	0.4					
3 MA	15894	—	7.5	5.6	5.5	5.3	2.2	0.85*	0.6	2	0.85	1.8(1.2,1.5)	0.76	Prad~0.9MW/S
H-mode	16259	—	11.5	4.2	6.0	6.7	3.3	0.85*	0.6					
	16268	—	13.4	7.3	6.6	7.0	3.7	0.75*	0.53					
	18757	—	10.2	2.8	6.8	13.1	3.6	0.55*	0.6	2	0.72	2.2(1.1,2)	0.79	Ti Collapse
3 MA	16211	7.1	—	5.8	7.8	7.9	1.2	0.85	0.85	1.2	0.87	2.0(1.4,1.4)	0.87	Int. Disruption
Pellets	16228	10.0	—	5.2	7.7	7.3	1.8	0.85	1.0					
	16235	10.1	6.6	5.6	7.9	8.2	4.3	0.85	0.65					
	17279	7.2	2.8	5.2	8.2	7.4	1.8	0.65	0.7					
5 MA	15182	—	—	4.0	3.7	2.2	3.6	0.8	0.8					
Conditioned	15190	10.2	—	6.6	5.8	5.8	0.8	0.8	0.65					
Vessel	15196	12.1	—	7.1	5.3	5.0	0.8	0.85	0.65					