III. Investigation of the cause of the High-to-Low mode confinement transition following MARFE formation in DIII-D

(DoE Grant ER54538) W. M. Stacey, Z. W. Friis, T. W. Petrie and A. W. Leonard

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Abstract

The common observation that the onset of a core MARFE (Multifaceted Asymmetric Radiation From Edge) is followed immediately by a H-L (High-to-Low) confinement mode transition in DIII-D [J. Luxon, Nucl. Fusion, 42, 614 (2002)] was investigated by comparing a theoretical prediction of the threshold non-radiative power across the separatrix needed to maintain H-mode with an experimental determination of the non-radiative power flowing across the separatrix. It was found that in three shots with continuous gas fueling the increased neutral influx associated with the MARFE formation caused a sharp increase in the predicted threshold non-radiative power crossing the separatrix that was required for the plasma to remain in H-mode to a value comparable to the experimental power crossing the separatrix.

Introduction

A variety of thermal instability phenomena are observed when tokamak discharges are continuously gas-fueled to build up the density, ultimately leading to one or more density limiting phenomena. A typical sequence of events that is observed when the density is increased by continuous gas fueling in a diverted, H-mode plasma has been well documented for DIII-D [e.g. Refs 1-5]: 1) the plasma 'partially detaches' (complete detachment near the separatrix strike point on the divertor target and significantly reduced power and particle fluxes to the remainder of the divertor target) and a dense, radiating region forms just in front of the target; 2) with continued fueling the density in front of the divertor target is suddenly reduced, and a dense, cool radiating region (a "divertor MARFE") is formed upstream in the vicinity of the x-point but outside the separatrix, or LCFS (last closed flux surface), on open field lines; 3) with continued fueling the divertor MARFE appears to gradually move inward across the separatrix to trigger the formation of a radiating region of high density and low termperature on closed field lines in the vicinity of the x-point (an "x-point MARFE"); and immediately thereafter 4) the plasma makes a back transition from H-mode to L-mode confinement. A similar sequence of events has been documented for other experiments[6-10]. The H-L transition constitutes an effective density limit for an H-mode plasma. The proximity of the H-L transition following immediately after the formation of the core MARFE is suggestive of a causative relationship, an investigation of which is the purpose of this paper.

The lines of this investigation are suggested by the well-known existence of a power threshold for the transition from L-mode into H-mode and for another, usually lower, power threshold for remaining in H-mode. The 'power' in question is the non-radiative power that flows across the separatrix or last closed flux surface. It seems likely that the formation of a core MARFE may increase the radiative power from inside the separatrix and thus reduce the non-radiative power flowing outward across the separatrix below the threshold value for remaining in H-mode. It is also plausible that events associated with the MARFE may affect the power threshold for remaining in H-mode.

An international database of measured L-H and H-L power thresholds in tokamaks has been compiled and various correlations have been suggested (e.g. Ref. 11). In general, these correlations tend to be based on machine parameters (major and minor radii, magnetic field, etc.) and the line average density. The parameters used in such power threshold predictions do not vary significantly with the formation of a MARFE and thus are not useful for attempting to explain the effect of MARFE formation in producing a H-L transition.

Instead, we will use a recently developed theoretical model for the H-L power threshold[12] which has the advantage for our purposes of being based on edge physics parameters which do vary significantly over the course of MARFE formation. The model is based on the predicted existence of electron and ion temperature radial gradient scale length thresholds for the destabilization of the respective power balances with respect to thermal instabilities with short radial wavelengths which increase the transport in the edge transport barrier. This model, which is described in Ref. 12, has been found to predict both the H-L[13] and L-H[14] power thresholds in several DIII-D discharges.

II. Effect of Core MARFE Formation on Proximity to H-L Power Threshold

The H-L (and L-H) power threshold model[12] used in this paper has the following elements: 1) a model[15] for the growth rate of thermal instabilities with short radial wavelengths in the edge pedestal region, or 'transport barrier'; 2) an enhancement of transport in the pedestal when thermal instabilities are growing; and 3) the conventional transport heat conduction closure relation among heat fluxes, temperature gradients and transport coefficients. A linear analysis of the stability of the plasma particle, momentum and energy

balance equations in the edge pedestal against two-dimensional (r-⊥) coupled density, velocity and temperature perturbations with radial wavelength k_r^{-1} leads to a dispersion relation from which the growth rates (real parts of ω) of such modes can be calculated. This dispersion relation can be solved for a threshold value of the temperature gradient scale length for stabilizing instabilities by setting ω = 0, and from this threshold temperature gradient scale length and the heat conduction relation an expression for a separatrix power threshold, P_{thresh}, can be determined[12].

We have evaluated the theoretical expression for the power threshold for remaining in H-mode, P_{thresh}, at several times during three continuously gas fueled DIII-D discharges (Table 1), including well before, just before and just after core MARFE formation. We have also evaluated the non-radiative power, $P_{sep}^{\exp}$, flowing across the separatrix at the same times.

A. Evaluation of P_{thresh}

The theoretical prediction of the threshold power for remaining in H-mode is evaluated as the sum of the threshold powers for stabilizing thermal instabilities with radial wavelength k_r^{-1} in both the ion and electron temperature balances, $P_{thresh} = P_{thresh,i} + P_{thresh,e}$, where[12]

$$P_{thresh} = \frac{5}{4}\Gamma_{\perp}T\,A_{sep}\left[\sqrt{1 + \frac{\left(\chi^0\left(\alpha - \chi^0 k_r^2\right)/\nu\right)}{\left(\frac{5}{4}\frac{\Gamma_{\perp}}{n}\right)^2}} + 1\right] \tag{1}$$

is the generic form for $P_{thresh,i}$ or $P_{thresh,e}$. The quantity α refers to terms arising from the atomic physics cooling terms in the ion and electron power balance equations and are given in Ref. 12. The respective ion or electron particle flux across the separatrix ($\Gamma_{\perp}$), density and temperature in the edge transport barrier, H-mode thermal conductivity (χ^0) in the edge transport barrier, and radiation and atomic physics cooling terms must be used to evaluate $P_{thresh,i}$ and $P_{thresh,e}$. A_{sep} is the separatrix area, and ν represents the temperature dependence of $\chi^0 \sim T^{\nu}$. We use an average magnitude $\chi^0 = 0.1\left(T/T_0\right)^{\nu}$ m^2/s, k_r^{-1} = 1 cm and ν = 2.5 (an average value for anomalous transport theories[16]), but the results are relatively insensitive to variations in these parameters. The average density and temperature in the edge transport barrier were taken from experiment, as was the average carbon impurity concentration needed to evaluate the radiation term in the electron α. The neutral densities needed to evaluate the atomic physics cooling terms in the α's were calculated as described next.

The ion particle flux across the separatrix, $\Gamma_{\perp}$, was determined from particle balance on the plasma core inside the separatrix

$$\Gamma_{\perp} = (S + \Gamma_o^{in} A_{sep} - Vol \times \frac{\partial n^{\exp}}{\partial t}) \Big/ A_{sep} \tag{2}$$

where S represents the neutral beam heating particle source and Γ_o^{in} represents the net influx of fueling and recycling neutrals across the separatrix. The outward ion flux was input to a "2-point" divertor model[17] (with radiation and recycling neutrals), which predicted an ion flux to the divertor plate that was used to calculate the recycling source of neutrals at the divertor plate from recycling plasma ions. This recycling neutral source and the neutral fueling sources were then used in a 2D neutral transport calculation[17] to determine Γ_o^{in} and the neutral concentrations in the edge transport barrier needed to evaluate the atomic physics contributions to the α's. Experimental values of density and temperature in the edge plasma and values calculated from the "2-point" model for the divertor plasma were used in the neutral attenuation calculation. The total neutral fueling source was adjusted empirically to take into account wall outgassing sources by requiring the calculation to match the experimental value of the line averaged density, using a pulsed measurement[5] of the particle confinement time (i.e. to calculate the neutral fueling correctly). This procedure has been found to predict local neutral densities in the edge plasma in reasonable agreement with measured values[18].

B. Evaluation of $P_{sep}^{\exp}$

The non-radiative power crossing the separatrix was determined experimentally from

$$P_{sep}^{\exp} = P_{nb} + P_{OH} - P_{rad}^{core} - \partial W_{\exp} / \partial t \tag{3}$$

where the subscripts "nb" and "OH" refer to "neutral beam" and "ohmic", respectively, and W_{exp} is the measured thermal energy. P_{rad}^{core} is the radiated power from within the separatrix determined from the bolometer system[19].

C. Analysis of DIII-D Discharges

The pedestal values of electron densities, ion and electron temperatures and their gradients needed to evaluate Eqs. (1) and (2) were taken directly from experiment, and the neutral beam particle source was calculated directly from the known beam power. The neutral influx term needed to calculate the outward ion flux across the separatrix, $\Gamma_{\perp}$, was calculated as described above. The value of the power flux crossing the separatrix was determined experimentally, as discussed above. Three times in each shot were examined: 1) early in the shot (2500 ms) near the time that the divertor MARFE took place; 2) later in the shot somewhat before the core MARFE formed; and 3) after the core MARFE had formed and immediately before the H-L transition took place. The values of $P_{sep}^{\exp}$, of the various contributing terms given in Eq. (3), and of $P_{thresh} = P_{thresh,i} + P_{thresh,e}$ calculated from Eq. (1) are given for the 3 times in each shot in Table 2.

It is clear that $P_{sep}^{\exp}$ □ P_{thresh} early in the shot and up to just before the onset of the core MARFE (the first 2 times) and that $P_{sep}^{\exp} \approx P_{thresh}$ following core MARFE formation and immediately prior to the H-L transition (third time) for all 3 shots. The interesting result is that this pattern is caused more by a sharp increase in P_{thresh} after core MARFE formation more than by any sharp decrease in $P_{sep}^{\exp}$ accompanying core MARFE formation (the anticipated cause). In fact, $P_{sep}^{\exp}$ did decrease strongly with core MARFE formation due to the anticipated increase in P_{rad} for shot 92976, but the increase in P_{rad} was partially compensated by an increase in P_{OH} in shot 92972 and more than offset by the combination of a large increase in P_{OH} and a decrease in $-dW^{\exp}/dt$ in shot 96887. It should be noted that because of the spatial resolution and finite grid size of the bolometer system there is an uncertainty in the determination of the amount of radiation from the vicinity of the X-point that is actually inside the separatrix, so that an error bar in P_{rad} of about 0.1 MW is associated with the later times in the first two shots and of about 0.5 MW is associated with the later times in shot 96887.

The quantities in Eq. (1) for P_{thresh} which change with time during the shots are tabulated in Table 3. It is clear from the table that the neutral influx $\left(S_{recycle} = \Gamma_o^{in} A_{sep}\right)$, hence the neutral concentration in the edge (f_o), increases with time in general and increases sharply at the time of core MARFE formation. The increase in neutral influx produces an increase in the ion outflux across the separatrix, as given by Eq. (2), and causes an increase in both the neutral and electron densities in the pedestal. The increased neutral density in the pedestal increases the ionization, charge-exchange and scattering rates in the pedestal, $\nu_{ion} \equiv n_o \langle \sigma \upsilon \rangle_{ion}$ and $\nu_{at} \equiv n_o^{cold} (\langle \sigma \upsilon \rangle_{cx} + \langle \sigma \upsilon \rangle_{elast})$, which generally causes an increase in the atomic physics terms α_e and α_i. An increase in neutral concentration in the edge also causes an increase in the carbon radiation emissivity, which causes an increase in α_e.

We conclude from these results that the increased neutral influx associated with the MARFE formation causing a sharp increase in the threshold non-radiative power crossing the separatrix that is required for the plasma to remain in H-mode is a principal mechanism triggering the back H-L transitions that are observed to follow MARFE formation in DIII-D. The onset of MARFE formation is also predicted to be strongly influenced by the penetration of recycling and fueling neutrals into the plasma edge in DIII-D[20]and other tokamaks (e.g. TEXTOR[21]). The extent to which this increase in neutral influx is caused by core MARFE formation, as distinguished from merely associated with it, remains an open question.

Appendix: Thermal Instability Modeling

As discussed previously, an important aspect of this analysis is the modeling of the divertor plasma properties and of the related transport of fueling and recycling neutrals in the divertor and into the plasma edge, because the prediction of the threshold power for staying in the H-mode depends on the neutral influx across the separatrix and on the neutral density in the edge transport barrier. In addition to the edge thermal instability on which the power threshold analysis used in this paper was based, there are (at least) two other thermal instabilities that also depend on the modeling of the divertor (divertor MARFE) and of the neutral transport inward across the separatrix into the edge transport barrier (core MARFE).

We have previously carried out thermal instability analyses leading to predictive algorithms for the onset of divertor and core MARFEs, the comparison of which with observed experimental manifestation of the instabilities in DIII-D are summarized in Ref. 20. For the divertor MARFE, a prediction of the growth rate of parallel density and temperature perturbations along the field lines in the divertor channel, ω_{DIV}, was developed which is sensitive to the divertor densities, temperatures and geometry. For the core MARFE, a prediction of the maximum density for which the plasma in the edge transport barrier is stable against poloidal perturbations in density and temperature was developed in terms of the temperature, atomic and impurity cooling rates, and cross-field heat fluxes into the scrape-off layer. This core MARFE prediction is sensitive to the neutral influx into the edge transport barrier. Both of these predictions have previously been found to be in agreement with observation of the respective thermal instability onset[20].

Thus, an indirect check of the modeling procedure used in evaluating the power threshold for the H-L transition is a comparison of the prediction of thermal instability onset, $\omega_{DIV} > 0$ and $MI \equiv n_{edge}^{\exp} \big/ n_{edge}^{MARFE} > 1$, with experimental observation of divertor and core, respectively, MARFE onset. These quantities are predicted as part of the overall calculation for each time in each shot, as shown in Table 4. Clearly the onset conditions (times) for divertor and core MARFEs are predicted for these shots. The onset conditions for the core MARFEs in these discharges were strongly influenced by the penetration of recycling and fueling neutrals into the edge plasma.

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Table 1. Parameters of gas fueled D-IIID shots that underwent a H-L transition immediately following core MARFE formation. (The ion $B \times \nabla B$ drift is towards the X-point in all shots.)

Shot #	*Times (ms)*	I_p *(MA)*	*B(T)*	q95	P_{NBI} *(MW)*	n_{eped} *(e19/m³)*	T_{eped} *(eV)*	*nebar (e19/m³)*
92976	2500 to 3212	1.0	2.1	6.2	5.2	4.1 to 4.4	218 to 187	5.0 to 6.1
92972	2500 to 3325	1.0	1.1	3.2	5.0	5.5 to 6.2	414 to 168	6.3 to 8.4
96887	2500 to 3650	1.7	2.1	3.2	8.5	9.6 to 11.3	440 to 231	10.1 to 12.7

Table 2. P_{thresh}^{theory} and $P_{sep}^{\exp}$ evolution during three DIII-D shots that underwent H-L transitions following core MARFEs (units MW).

92976 *TIME(ms)*	P_{rad}	P_{NBI}	$\frac{dW}{dt}$	P_{OH}	$\mathbf{P_{sep}^{exp}}$	$\mathbf{P_{thresh}}$
2500	.54	5	0	.30	**4.8**	**2.5**
2962-3000	DIVERTOR MARFE					
3000	.39	5	0	.58	**5.2**	**3.0**
3050-3100	CORE MARFE					
3212	1.4	5	0	.63	**4.2**	**4.1**
3230	H-to-L TRANSITION					

92972 *TIME(ms)*	P_{rad}	P_{nbi}	$\frac{dW}{dt}$	P_{OH}	$\mathbf{P_{sep}^{exp}}$	$\mathbf{P_{thresh}}$
2500	.62	5.2	0	.35	**4.9**	**3.5**
2750-2790	DIVERTOR MARFE					
3000	.87	5.2	0	.45	**4.8**	**3.7**
3190	CORE MARFE					
3325	1.29	5.2	0	.55	**4.5**	**4.6**
3323	H-to-L TRANSITION					

96887 *TIME(ms)*	P_{rad}	P_{nbi}	$\frac{dW}{dt}$	P_{OH}	$\mathbf{P_{sep}^{exp}}$	$\mathbf{P_{thresh}}$
2390	DIVERTOR MARFE					
2500	.8	8.5	0	.21	**7.9**	**6.1**
3200	1.09	8.5	-.46	.37	**8.2**	**6.8**
3240	CORE MARFE					
3650	1.2	8.5	-.23	.95	**8.5**	**8.8**
3653	H-to-L TRANSITION					

Table 3. Evolution of edge pedestal parameters during three DIII-D shots that underwent H-L transitions following a core MARFE.

	92976 *TIME(ms)*	$S_{recyc}(10^{20}/s)$	$n_{ped}(10^{20}m^{-3})$	$T_{eped}(eV)$	F_0 (%)	$\alpha_i(10^3s^{-1})$	$\alpha_e(10^3s^{-1})$	$\Gamma_\perp(10^{20}/m^2s)$
TIME ↓↓↓	2500	.64	.41	218	.84	.37	.40	1.6
	2962-3000	DIVERTOR MARFE						
	3000	1.4	.43	212	1.7	.88	1.3	3.0
	3050-3100	CORE MARFE						
	3212	3.9	.44	187	3.7	2.3	2.4	6.9
	3230	H-to-L TRANSITION						

	92972 *TIME(ms)*	$S_{recyc}(10^{20}/s)$	$n_{ped}(10^{20}m^{-3})$	$T_{eped}(eV)$	F_0 (%)	$\alpha_i(10^3s^{-1})$	$\alpha_e(10^3s^{-1})$	$\Gamma_\perp(10^{20}/m^2s)$
TIME ↓↓↓	2500	.40	.59	414	.48	.26	.29	1.1
	2750-2790	DIVERTOR MARFE						
	3000	1.1	.62	212	.91	.48	1.0	2.7
	3190	CORE MARFE						
	3325	7.2	.55	168	2.3	1.6	1.6	12
	3323	H-to-L TRANSITION						

	96887 *TIME(ms)*	$S_{recyc}(10^{20}/s)$	$n_{ped}(10^{20}m^{-3})$	$T_{eped}(eV)$	F_0 (%)	$\alpha_i(10^3s^{-1})$	$\alpha_e(10^3s^{-1})$	$\Gamma_\perp(10^{20}/m^2s)$
TIME ↓↓↓	2390	DIVERTOR MARFE						
	2500	2.1	.99	440	.46	.45	.46	5.3
	3200	2.5	.96	450	.56	.54	.55	6.1
	3240	CORE MARFE						
	3650	6.7	1.13	231	.70	.90	1.1	13
	3653	H-to-L TRANSITION						

Table 4. Divertor and core MARFE prediction and observation in three DIII-D shots that underwent H-L transitions following core MARFE formation.

	92976	$\omega_{DIV}(10^5/s)$	$MI=n_{exp}/n_{marfe}$
	TIME(ms)		
TIME ↓↓↓	2500	-93	.23
	2962-3000	DIVERTOR MARFE	
	3000	25	.65
	3050-3100	CORE MARFE	
	3212	46	1.8
	3230	H-to-L TRANSITION	

	92972	$\omega_{DIV}(10^5/s)$	$MI=n_{exp}/n_{marfe}$
	TIME(ms)		
TIME ↓↓↓	2500	-36	.39
	2750-2790	DIVERTOR MARFE	
	3000	-4.8	.80
	3190	CORE MARFE	
	3325	27	1.5
	3323	H-to-L TRANSITION	

	96887	$\omega_{DIV}(10^5/s)$	$MI=n_{exp}/n_{marfe}$
	TIME(ms)		
TIME ↓↓↓	2390	DIVERTOR MARFE	
	2500	14	.43
	3200	22	.53
	3240	CORE MARFE	
	3650	65	2.2
	3653	H-to-L TRANSITION	