THERMAL INSTABILITY ANALYSIS OF DIFFERENT TYPES OF DENSITY LIMITS IN DIII-D GAS FUELED, H-MODE DISCHARGES

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Summary

We examined high density, gas fueled, high confinement mode, DIII-D shots that were limited in density buildup by: 1) a H-L transition apparently triggered by a core X-point MARFE, following the thermal instability sequence of detachment—divertor MARFE—core X-point MARFE; 2) a density limit apparently triggered by large scale core MHD activity; and 3) a H-L transition apparently triggered by excessive radiated power from the plasma core. The presence or absence of a MARFE was correctly predicted by thermal instability theory. A sharp edge temperature gradient was identified as an important factor inhibiting the usual detachment—MARFE sequence in DIII-D and thus leading to the achievement of higher density.

THERMAL INSTABILITIES IN EDGE PLASMA PRODUCE ENHANCED TRANSPORT

Short radial wavelength thermal instabilities localized in the plasma edge, driven primarily by radiative and atomic physics cooling, are predicted (PoP,6,2452,1999). Instabilities associated with both the ion and electron energy balances are predicted, with growth rates of the general form

$$\omega_{i,e} \approx -\left[\chi_r\left(L_T^{-2}+\lambda^{-2}\right)-\left(f_z h_z\left(L_z\left(T, f_0\right)\right)+f_0 h_0(T)\right)\right]$$

These instabilities may enhance edge transport as $\Delta\chi \approx \omega\lambda^2$ where λ is the radial wavelength of the instability. Taking $\lambda \approx$ O(pedestal width) $\approx$ 1 cm as a characteristic radial distance for a localized instability in the edge pedestal, growth rates $\omega \geq \approx 10^3$/s would produce a level of transport enhancement ($\Delta\chi \geq \approx 10^3$ cm^2/s) that is comparable to the estimated (PoP,5,4311,1998) transport rate $\chi \approx$ 1-5 x 10^3 cm^2/s in the edge of a DIII-D H-mode plasma.

THERMAL INSTABILITIES IN EDGE PLASMA (INSIDE LCFS) PRODUCE MARFES

The edge density limit for the formation of **MARFEs** is of the form (Fusion Tech., 36, 38, 1999)

$$n_{MARFE} \approx \frac{\left(\frac{Q_{\perp}}{T}\right) L_T^{-1}}{f_z h_z\left(L_z\left(T, f_o\right)\right) + f_o h_o\left(L_o\left(T\right)\right)}$$

where $Q_{\perp}$ is the radial heat flux flowing outward through the plasma edge, L_T is the temperature gradient scale length, f_z and f_0 are the concentrations of impurities and neutrals in the plasma edge, L_z and L_0 are the emissivity of impurity radiation and an equivalent term describing atomic physics cooling, and h_z and h_0 are functions involving L_z and L_0, respectively, and their temperature derivatives.

Define MARFE Index

$$MI = n_{exp}/n_{MARFE}$$

When MI > 1 a MARFE is predicted.

AN EXAMPLE OF DENSITY LIMITED BY LARGE-SCALE MHD

OBSERVATION: NO DETACHMENT, NO MARFE FORMATION, LARGE SCALE @ 4500 ms

Shot 98893[a]

Time (ms)	3000	4000	4500
Experimental parameters			
n_{aver} (10^{20} m^{-3})	1.07	1.36	1.51
T_{edge} (eV)[b]	50	55	70
τ_E (s)	0.22	0.24	0.25
L_n (cm)	1.7	1.5	1.4
L_T (cm)	1.8	1.7	1.8
f_{carbon} (%)	1.5	1.0	1.0
Calculated parameters			
f_0 (%)	0.08	0.11	0.09
MI	0.7	0.9	0.9
ω_i (10^4/s)	-0.24	0.00	-0.04
ω_e (10^4/s)	0.05	0.08	0.09

ANALYSIS OF DATA

- ***NEUTRAL CONCENTRATION REMAINS LOW AND EDGE GRADIENT SCALE LENGTHS REMAIN SMALL OVER DISCHARGE***

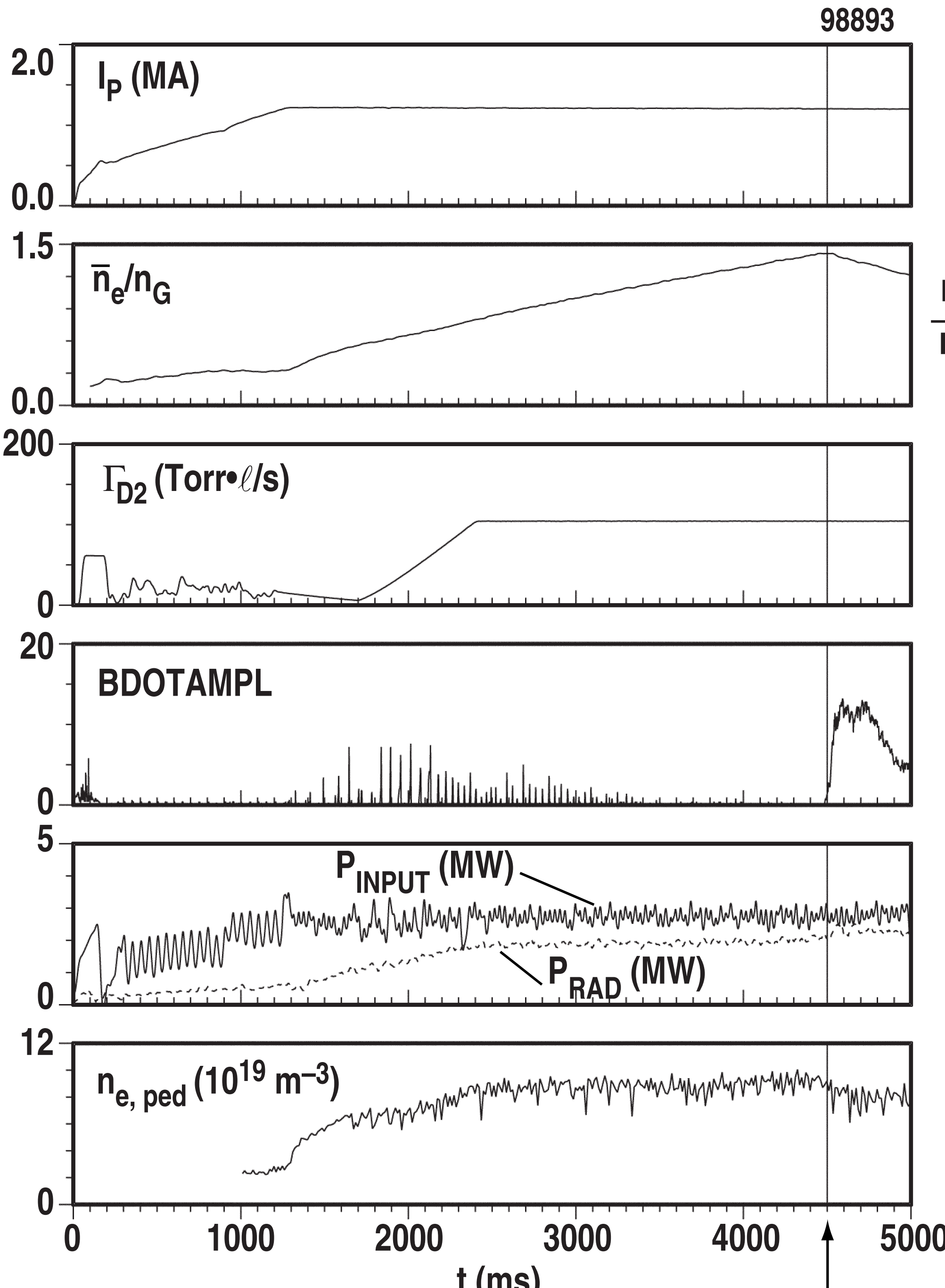
- ***CALCULATED $\omega_{i,e}$ REMAINS TOO SMALL TO ENHANCE TRANSPORT AND MEASURED τ_E DOES NOT DECREASE***

- ***MARFE FORMATION IS NOT PREDICTED NOR OBSERVED, AND A MUCH HIGHER DENSITY (n/n_G = 1.4) IS ACHIEVED BEFORE MHD LIMIT***

[a] P_{INPUT}= 2.9 MW, B_T= 1.6 T, I_P= 1.2 MA, n/n_G =1.4, , LSN, δ_{bo} = 0.14

[b] average of pedestal and separatrix temperatures

DENSITY RISE WAS TERMINATED BY LARGE-SCALE MHD ACTIVITY



Lower SN
B_T = 1.6 T

$\left.\frac{n_e}{n_G}\right|_{max} \simeq 1.4$

Steady D_2 Gas Fueling

Density Rise Halted by Strong MHD Activity

PRAD ≃ 2.1 MW
PINPUT ≃ 2.9 MW

Steady Pedestal Density During $\bar{n}_e$ Rise

MHD TERMINATED DENSITY RISE

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ONE EXAMPLE OF A SHOT WITH THE DENSITY LIMITED BY MARFE FORMATION FOLLOWED BY H-L TRANSITION

OBSERVATIONS: DETACHMENT (2700 ms), "DIVERTOR MARFE" (2900-3000 ms), CORE X-POINT MARFE (3050-3100 ms), H-L TRANSITION (3230 ms).

SHOT 92976[a]

Time (ms)	2000	2500	3000	3200
Exp. parameters				
n_{aver} (10^{20} m^{-3})	0.40	0.49	0.55	0.59
T_{edge} (eV)[b]	292	277	158	118
τ_E (s)	0.12	0.11	0.09	0.07
L_n (cm)	3.9	3.9	4.6	6.2
L_T (cm)	2.6	3.0	4.1	4.3
f_{carbon} (%)	2.8	2.7	1.0	1.0
Calculated parameters				
f_0 (%)	0.04	0.11	0.12	0.18
MI	0.3	0.5	0.6	1.7
ω_i (10^4/s)	0.07	0.13	0.23	0.42
ω_e (10^4/s)	-0.16	0.09	0.13	0.32

ANALYSIS OF THE DATA

- ***NEUTRAL CONCENTRATION (f_0) AND EDGE GRADIENT SCALE LENGTHS INCREASE OVER DISCHARGE***

- ***CORRELATION BETWEEN INCREASING CALCULATED $\omega_{i,e}$ AND DECREASING MEASURED τ_E***

- ***PREDICTION OF MARFE ONSET (MI > 1) BETWEEN 3000-3200 ms, IN AGREEMENT WITH EXPERIMENTAL OBSERVATION***

[a]**PARAMETERS: P_{INPUT}= 5 MW, B_T= 2.1 T, I_P = 1.0 MA, n/n_G = 0.7, LSN, δ_{bot} = 0.22**

[b] **average of pedestal and separatrix temperatures**

DENSITY LIMITED AT HIGH RADIATION ($P_{RAD}/P_{INPUT} \approx 0.9$)

OBSERVATIONS:

- **SHOT 102461: AN H-L TRANSITION AT $n/n_G = 1.0$ (3332 ms) WITHOUT PREVIOUS MARFE FORMATION/DETACHMENT OR DISRUPTIVE MHD ACTIVITY.**
- **SHOT 102456: AT A HIGHER TOROIDAL FIELD, DETACHMENT AND MARFE FORMATION PRECEDED AN H-L TRANSITION AT $n/n_G = 0.8$ (3510 ms).**

SHOT 102456 & 61[a]

B (T)	2.0	1.5
Time (ms)	3510	3332
Exerimental Parameters		
n_{aver} (10^{20} m^{-3})	0.94	1.13
T_{edge} (eV)[b]	112	87
L_n (cm)	4.8	3.7
L_T (cm)	4.4	3.5
f_{carbon} (%)	1.2	2.0
Calculated parameters		
f_0 (%)	0.076	0.078
MI	1.07	0.89

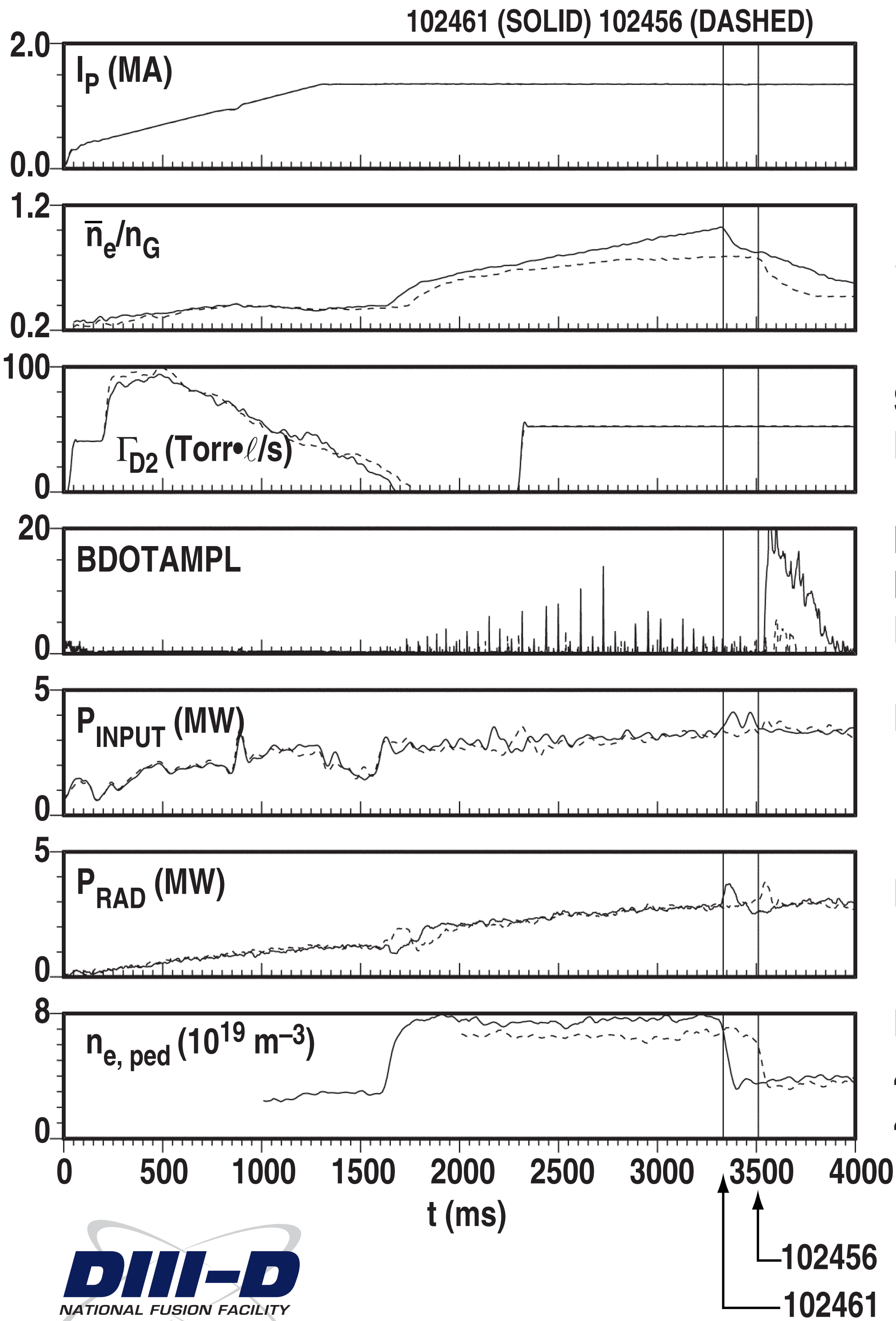
ANALYSIS OF DATA

- ***THE EDGE GRADIENT SCALE LENGTHS AND TEMPERATURE WERE SOMEWHAT LARGER IN THE HIGH-FIELD SHOT, LEADING TO A PREDICTION OF MARFE ONSET (MI > 1) FOR THE HIGH-FIELD SHOT BUT NOT FOR THE LOW-FIELD SHOT, CONSISTENT WITH OBSERVATION.***

[a] P_{INPUT} = 3.1 MW, B_T = 1.5T & 2.0 T, I_P = 1.35 MA, LSN, δ_{bot} =0.74

[b] average of pedestal and separatrix temperatures

- DROP IN DENSITY PRECEDED JUMP IN MHD ACTIVITY IN THE CORE PLASMA
- HIGH RADIATED POWER FRACTIONS (PRAD/PINPUT ≈ 0.9) FOR BOTH ATTACHED DIVERTOR (461) AND DETACHED DIVERTOR (456) CASES WERE LIKELY IMPORTANT FACTORS IN THEIR H–L DENSITY LIMIT



B_T (T) = { 1.5 (461) ; 2.0 (456) }

$\frac{n_e}{n_G} \simeq$ { 1.0 (461) ; 0.8 (456) }

Similar Gas Puff Programs for Both Shots

MHD Activity Played No Role in Halting Density Rises

P_{INPUT} (MW) = { 3.3 (461) ; 3.4 (456) }

P_{RAD} (MW) = { 2.8 (461) ; 3.1 (456) }

Behavior of $n_{e,\,ped}$:

461 ⇒ Not Detached

456 ⇒ Detached

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SUMMARY

- **THERMAL INSTABILITY THEORY PREDICTED MARFES IN THOSE SHOTS IN WHICH THEY WERE OBSERVED AND DID NOT PREDICT MARFES WHEN THEY WERE NOT OBSERVED.**

- **HIGHER DENSITIES WERE ACHIEVED IN SHOTS IN WHICH MARFES DID NOT OCCUR THAN IN SHOTS LIMITED BY MARFES.**

- **SHORT EDGE TEMPERATURE GRADIENT SCALE LENGTHS THAT SUPPRESS THE GROWTH OF EDGE THERMAL INSTABILITIES WERE IDENTIFIED AS AN IMPORTANT FACTOR IN AVOIDING MARFES AND ACHIEVING HIGHER DENSITY.**