Principle Perpetrators of H-mode Energy Losses Identified by Their Transport Fingerprints: Drift Modes

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Introduction

The ability to map instabilities to their induced transport channels, constitutes a very powerful tool; when applied to a wide variety of pedestals, it can give a compelling identification of the instabilities responsible for transport for experimental pedestals. When observed through the lens of the "fingerprint" concept, patterns of observations on several devices take on far greater significance. Both analytical and numerical methods are used to establish the (multichannel) diffusivity ratios for electromagnetic modes: KBM and MTM. Results are compared to experimental data in multiple ways.

Thought experiments and overall patterns of experimental data

In the EPED model, KBM transport enforces inter-ELM marginal stability; in principle this can happen by modifying *any* combination of the n and T profiles. Suppose velocity shear is strong, so *only* modes resistant to suppression, MHD, MTM, and ETG (and neoclassical transport) are operative in a pedestal (as simulations often find). Analysis finds 1) MHD-like modes cause comparable levels of diffusivities, χ (thermal) and D (particle) in all channels (*and no pinches*) 2) ETG and MTM modes cause, almost exclusively, only χ_e, and neoclassical only χ_i, (with negligible D_e, but well known impurity transport with a pinch).

We further take the density source (due to ionization) to be much weaker than the energy sources. This has been estimated to be so in the published literature on DIII-D[1,2], ASDEX[3,4], and JET[5] (i.e, inferred $D_e << \chi$ for estimated n_e sources). Furthermore, suppose that the inter-ELM profiles roughly saturate between ELMs, as typically happens.

As the pedestal recovers from an ELM, and the pressure gradients increase, suppose an MHD-like mode (e.g. KBM) becomes active, *causing comparable diffusivity in all channels*. Since the density profile is much more weakly driven, it is much more strongly affected. So it is, primarily, the evolution of the density profile that is expected to enforce marginal stability of the MHD-like mode. Due to the small density source, the D to enforce near-marginal stability is commensurately small. Hence, the corresponding level *of* χ_e *and* χ_i *(~D for MHD modes) will not be sufficient per the requirements of power balance to saturate T profiles since the energy channel is much more strongly driven*. The χ_e and χ_i, needed to saturate the evolution of T_e and T_i profiles, must, therefore, arise when other mechanisms, e.g., MTM, ETG and neoclassical transport, saturate T.

Viewed through the fingerprint concept, overall patterns of experimental findings, below, take on entirely new significance, strongly reinforcing the scenario described above.

Ion heat transport: Transport analysis of pedestals on ASDEX-U and DIII-D shows that the total χ_i is close to neoclassical, χ_{neo} while, *often*[1,6], $\chi_e >> \chi_{i\ anom} = \chi_i - \chi_{neo}$ But if $\chi_e >> \chi_{i\ anom}$, most anomalous energy transport must come from modes that, preferentially and predominantly, act on the T_e channel, producing only $\chi_{e\ anom}$. This is impossible if MHD-like modes dominated anomalous χ_e. In some other cases on ASDEX-U[6], $\chi_e << \chi_i \sim \chi_{neo}$, so that *total* heat conduction is *nearly* neoclassical. In this case, if KBM modes are enforcing marginal stability of the pressure profile, they *must* do so by affecting transport in the density channel. Transport consistent with observation is only possible for weak n_e source.

Impurity transport: The inter-ELM impurity transport is estimated in the literature to be neoclassical[7], with an impurity pinch. ELMs are widely inferred to be primarily responsible for preventing a consequent secular rise in impurity content. ELMs are an MHD instability. Even though they *expel a minority of the plasma heating power*- (estimated as ~ 30% on time average[8]) they are apparently *much more effective at expelling impurities* than the inter-ELM transport; the latter is responsible for considerably more energy loss. If inter-ELM energy transport were dominated by MTM and ETG, *neither of which expels impurities*, then ELMs would, indeed, be needed. But, if another MHD-like mode (such as KBM)were responsible for most energy transport, then the induced inter ELM *impurity* diffusivity D_Z would be large as well. If true, then ELMs would not be needed, at all, to prevent secular impurity increases. But inter-ELM impurities *do* evolve neoclassically; so KBM cannot dominate inter-ELM energy transport since D_Z is weak. (Implying weak D_e.)

Analytical and simulation results

To compute the quasilinear fluxes in different channels, one subtracts out the "purely convective" part of the perturbed distribution δf_s. Simple algebra gives, for the deviation from that convective response, $\delta f_{dev\,s} = \delta f_s - \delta f_{conv\,s}$, the fully kinetic equation

$$-i\omega_{pl}\, \delta f_{dev\,s} + (\mathbf{v_d} + v_{||}\, \mathbf{b}) \cdot\nabla\delta f_{dev\,s} + C(\delta f_{dev\,s}) = (1 - \omega_s^*/\omega_{pl})\, (q_s\, \delta E_{||}/T_s) v_{||}\, f_{Ms} + (q_s\, \mathbf{v_d} \cdot\nabla\, \delta\phi/T_s)\, (\omega^*/\omega_{pl})\, f_{Ms}$$

in standard notation: ω^* is the diamagnetic frequency, δ refers to fluctuations, $v_{||}$ and $\mathbf{v_d}$ are the parallel and drift velocity, ω_{pl} is frequency ω in the local plasma frame (including $\mathbf{v_{0ExB}}$ Doppler shift), $\omega_{pl} = \omega - \omega_{ExB}$, and $\delta E_{||} = -\mathbf{b} \cdot\nabla\delta\phi - i\, \omega_{pl}\, \delta A_{||}$.

The deviations from purely convective response are, thus, driven by terms ~ $\delta E_{||}$ and ~ $(1/\omega_{pl})\, \mathbf{v_d}$. For steep gradients, and modes with $\omega \sim \omega^*$, the latter term is very small (~ L/R). *So in the pedestal, if $\delta E_{||} \sim 0$, as in MHD-like modes,* δf_s is mainly $\delta f_{conv.}$

If the primary behavior is ExB convection of all species, we expect that all channels have similar transport diffusivities; computing quasi-linear fluxes confirms this expectation. (And, when $\delta f_{conv\,s}$ dominates, there is no pinch). These general arguments are not strongly dependent on details of the mode structure or type. Further analysis in the steep gradient ordering shows there is a connection between frequency in the plasma frame ω_{pl} and the magnitude of $\delta E_{||}$. These analytic predictions are borne out by simulations with GENE[9]:

Discharge	Simulat-ion Type	Mode Type	$\lvert\delta E_{||}\rvert$	D_e/χ_e	D_Z/χ_e	χ_i/χ_e	$\langle\omega_{pl}\rangle/\langle\omega^*\rangle$	Q_{ES}/Q_{EM}	n
JET-C 78697	Gl. Lin.	MHD	0.03	0.89	0.43	0.44	5.21	1.3	4
	Gl. Lin.	MTM	0.41	0.01	0.01	0.01	-0.65	.06	8
JET-ILW 82585	Gl. Lin.	MTM	0.43	0.01	NA	0.01	-0.92	0.2	14
C-mod 1120815027	Gl. Lin.	MHD	0.18	0.80	0.74	1.05	0.57	8.4	11
	Gl. NL	MHD		0.67	0.50	0.86		22.	11
	Gl. Lin.	MTM	0.43	0.04	0.05	0.07	-1.65	0.13	10
DIII-D 153764	CG Lin.	MTM	0.51	0.01	0.01	0.01	-0.94	0.01	14
	CG NL	MTM		0.01	0.01	0.01		0.01	14
	Gl. Lin.	MHD	0.11	0.78	0.77	1.29	0.35	5.8	26
	Loc. Lin.	MHD	0.18	0.70	0.71	1.00	0.01	340	26
DIII-D 98889	Gl. Lin.	MTM	0.56	0.04	0.06	0.08	-0.71	0.41	18
	Gl. NL	MTM		0.02	0.03	0.03		0.18	18
	Gl. Lin.	MHD	0.06	0.54	0.65	0.71	0.51	14.8	12

Table 1: A summary of simulation results for several experimental pedestals. MHD modes are shaded. Simulation type is either 1) Global 2) constant gradients over the pedestal using values at mid-pedestal or 3) local linear (Loc. Lin). Simulations are either linear or nonlinear. MTM have electron heat flux strongly dominated by the magnetic contribution ($Q_{ES}/Q_{EM} \ll 1$) distinguishing them from modes where the ExB convection dominates ($Q_{ES}/Q_{EM} > 1$). Also MTM have $\langle\omega_{pl}\rangle/\langle\omega^*\rangle \sim -1$ (electron direction), whereas MHD modes have $\langle\omega_{pl}\rangle/\langle\omega^*\rangle > 0$ (ion direction).

Application to DIII-D discharges in detail

These concepts were applied to conduct a detailed examination of two DIII-D pedestals. On shot 153674, measurements[10] show a Quasi-Coherent Fluctuation (QCF) in the electron diamagnetic direction in lab frame, of order ω_e*. For the measured E_r and k, the Doppler shift, throughout the pedestal, is calculated to be small, implying that the frequency in the plasma frame is also ~ω_e*, typical frequency of an MTM. Inter-ELM profile evolution shows a strong correlation of the fluctuations with T_e gradients, *but with no effects on the evolution of Ti or impurity (Carbon) density*. This pattern is impossible to fit with a KBM. Nonlinear simulations of the MTM (with contributions from ETG) can match power balance at mid-pedestal with small gradient adjustments (<20%). Analysis of a different shot DIII-D 98889 is facilitated by an invaluable multi-channel transport analysis already available in the literature[1]. The pattern of and transport channel behavior is impossible to fit if energy transport is mainly from KBM, but is consistent with MTM and ETG. Observed high frequency magnetic fluctuation bands are only consistent with MTM, not KBM.

Consider JET experimental experience. Almost all JET type I ELMy H-modes have magnetic Mirnov signals termed washboard modes[11]. These strongly correlate with pedestal T_e evolution and transport, but they cause no apparent density transport. Furthermore, their frequency is likely in the electron diamagnetic direction in the plasma. Hence, these modes are not KBM, but rather, MTM. This is yet another indication that MTM are a substantial energy loss channel in pedestals, and is under detailed examination for JET discharges.

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