Role of thermal instabilities and anomalous transport in the density limit

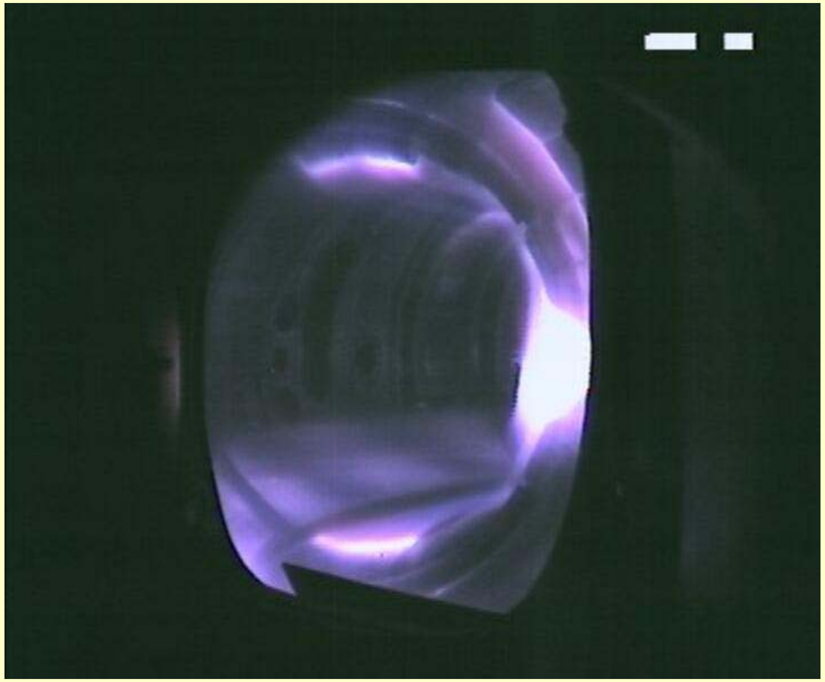
M.Z.Tokar, F.A.Kelly, Y.Liang , X.Loozen

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Association FZJ-Euratom, 52425, Jülich, Germany

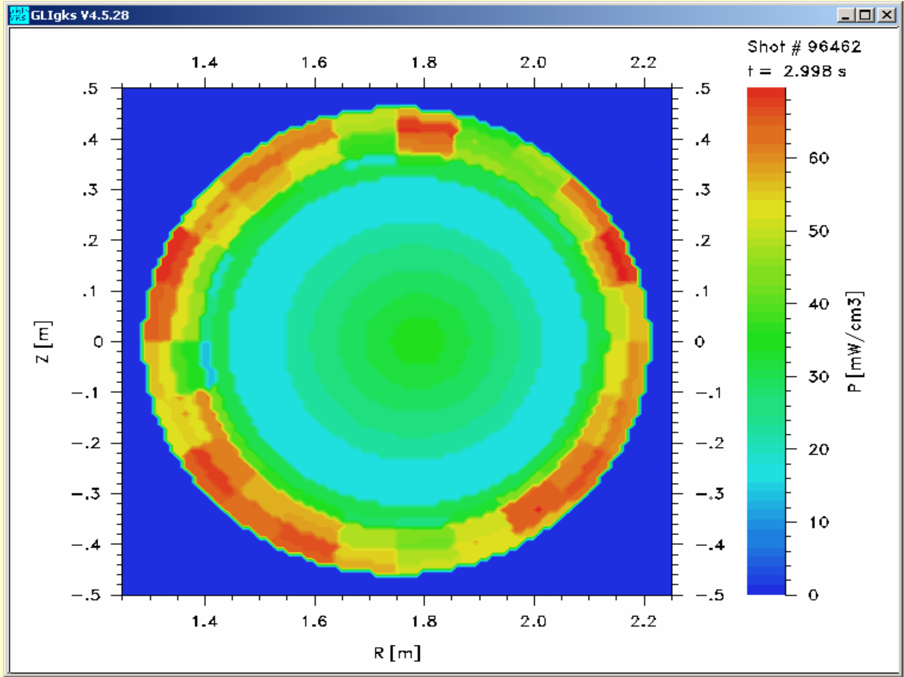
- Motivation
- Standard explanation of Density Limit
- New experimental observations
- Interpretation and results of modelling
- Discussion and conclusion

Two scenario for density limit (in TEXTOR)

Development of structures at the edge by critical density



MARFE in additionally heated plasmas



Detachment in ohmic plasmas

- What are the triggers and mechanisms of these events?
- What determines which kind of event will develop?

Thermal Instabilities at the Edge due to Impurity Radiation

Standard explanation:

Impurity radiation density:

$$Q_{rad} = n\, n_I\, L_I \Rightarrow$$

Poloidally symmetric detachment:

densities $n, n_I \approx const$, temperature $T \downarrow$:

$$T = T_0 + \tilde{T}, \tilde{T} < 0 \Rightarrow \quad \tilde{Q}_{rad} = Q_{rad} \frac{d \ln L_I}{d \ln T} \frac{\tilde{T}}{T}$$

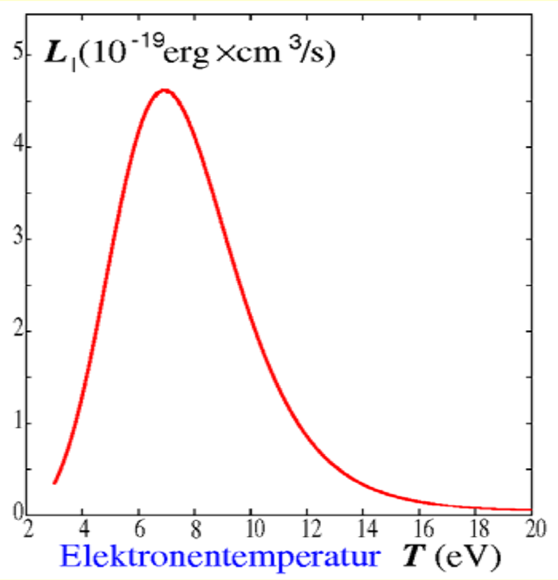
impurity radiation $\uparrow$ if cooling rate $\uparrow$ with $\downarrow$ temperature

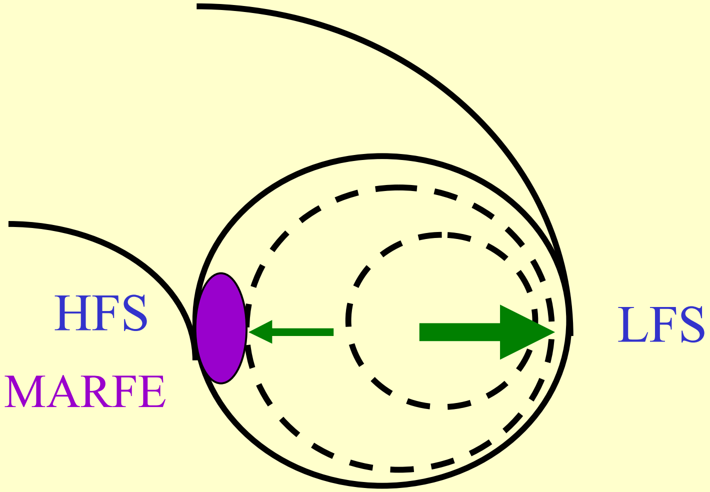
MARFE due to poloidally localized perturbations: pressures $nT, n_I T \approx const, T\downarrow \Rightarrow n, n_I \uparrow$

$$\tilde{Q}_{rad} = Q_{rad} \left(\frac{d \ln L_I}{d \ln T} - 2 \right) \frac{\tilde{T}}{T}$$

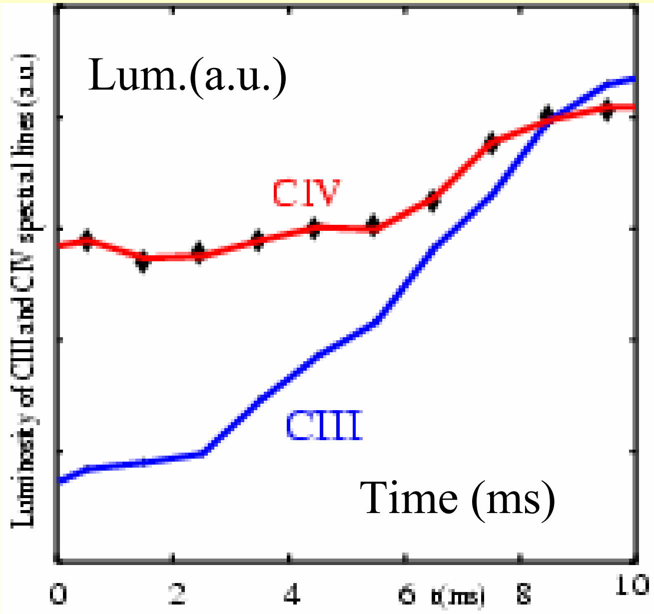
MARFE position : heat supply from core, counteracting radiation, is the smallest at HFS due to shift of magnetic surfaces

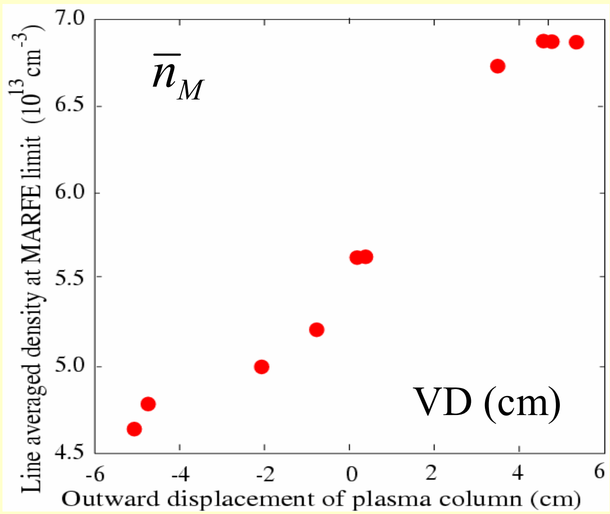
Carbon cooling rate in corona model





Spectroscopic measurements on TEXTOR during MARFE formation





Contradicts to “$dL_I/dT < 0$” concept: CIV radiation should grow first due to CV recombination

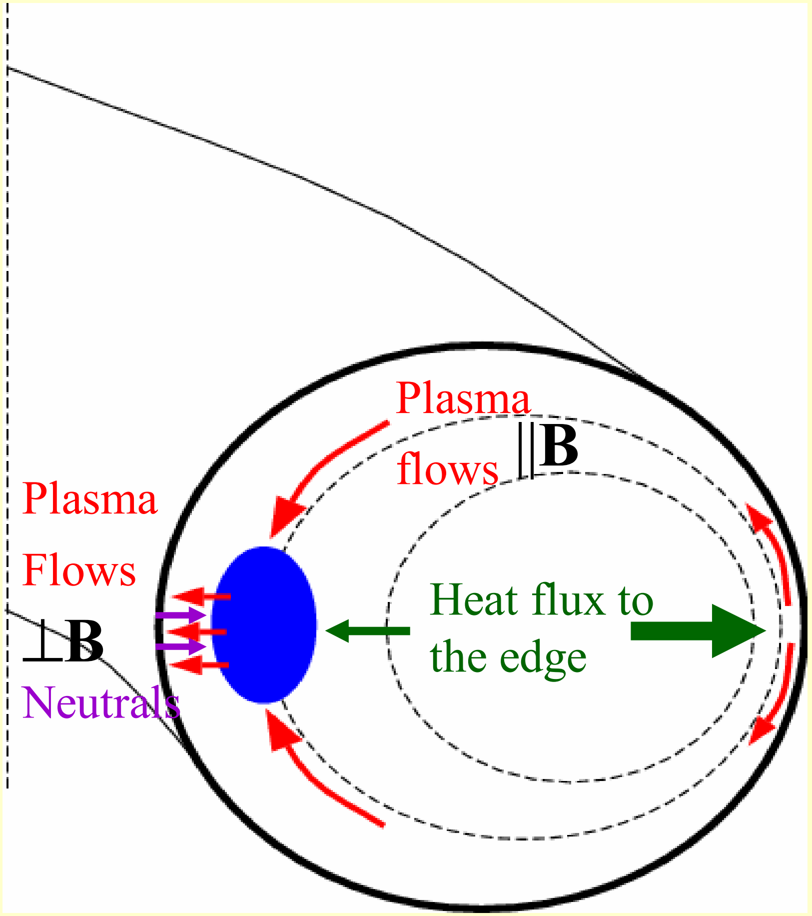
Why “$dL_I/dT < 0$” does not work: effect of impurity transport

$$\frac{d\ln L_I}{d\ln T} = \left(\frac{d\ln L_I}{d\ln T}\right)_{cor} \frac{1}{1 + D_\perp k_\perp^2 / \nu_{rec}}$$

Observed time development: local release of impurity by a sudden increase of plasma-wall interaction at HFS

Important role of plasma-wall interaction: MARFE threshold ↑ with plasma-wall clearance ↑ at HFS

Alternative Mechanism for MARFE Formation:
instability of plasma recycling on inner wall



Charged particle losses to wall:

$$\Gamma_{\perp} = -D_{\perp} \nabla_{\perp} n \approx D_{\perp} \frac{n}{l_a} \propto D_{\perp} n^2$$

Energy losses with particles:

$$q_{conv/rec} = \Gamma_{\perp} (\alpha T + E_i) \approx \propto D_{\perp} n^2 (\alpha T + E_i)$$

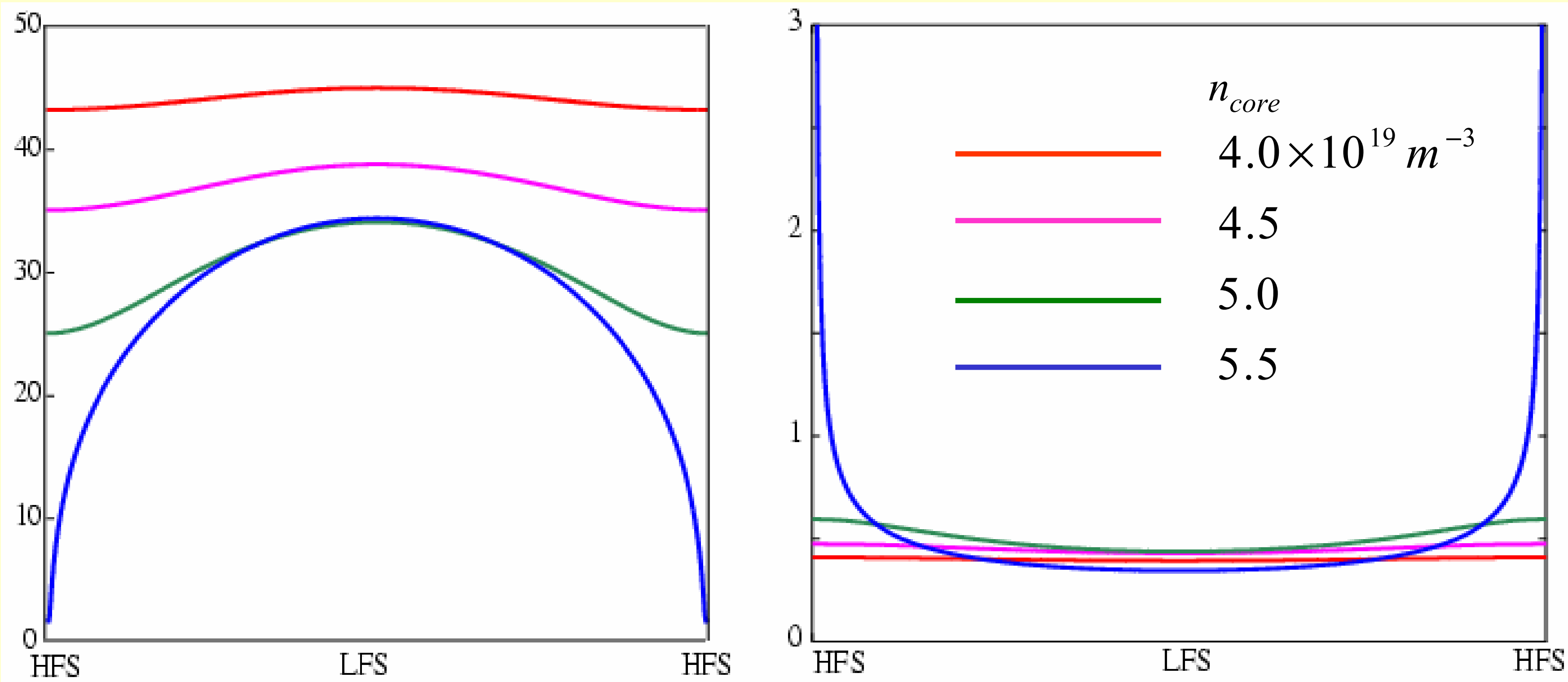
Numerical modelling of MARFE onset in TEXTOR

particle, momentum and heat transport equations are solved

P_{heat}(MW)=0.3(OH)+1.3(NBI), Λ= 0.8, $D_\perp = 1 m^2/s$, $\kappa_\perp = 3nD_\perp$

Convective, recycling and radiation losses are included

Edge temperature (eV): Edge density ($10^{20}\,m^{-3}$):



Some preliminary conclusions:

Behavior and role of impurity radiation

- Radiation of locally released impurities increases dramatically in MARFE
- MARFE threshold is influenced only weakly by impurity radiation
- MARFE is triggered mostly by “recycling” instability, radiation growth is a consequence

Density limit with fixed transport coefficients: $D_{\perp} = 1 m^2/s$

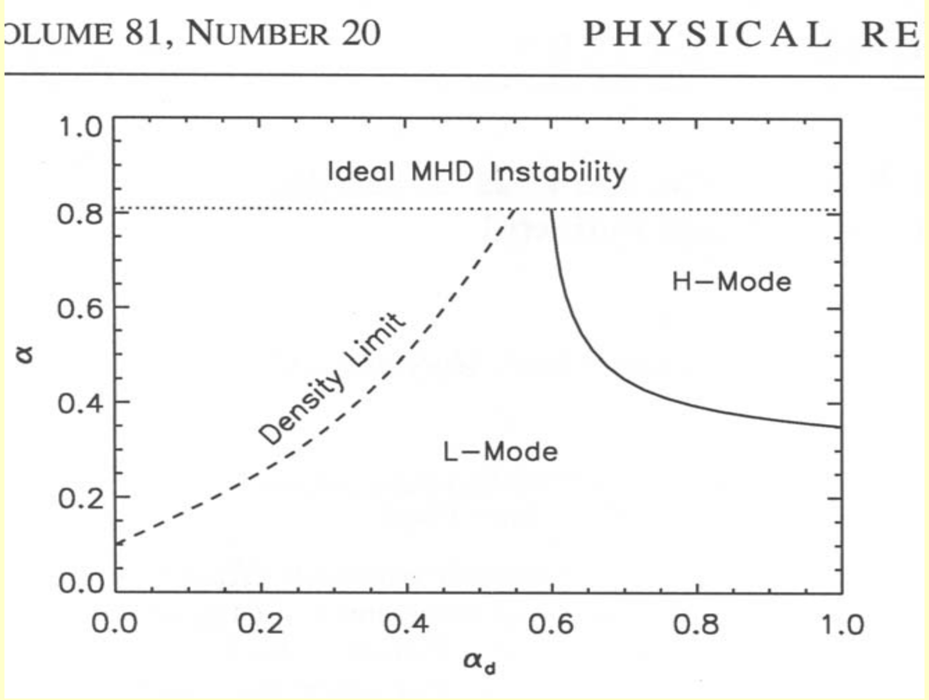
- For any level of heating and Shafranov shift, density limit is due to MARFE
- Simulations do not reproduce detachment at ohmic conditions with low heating and shift

Role of anomalous transport nature

Change in the nature of edge turbulence can also lead to density limit

"Phase Space of Tokamak Edge Turbulence..."
B.N.Rogers et al., PRL 81(1998) 4396

Ballooning parameter



Diamagnetic parameter

"Overview of Recent Alcator C-Mod Research", *E.S.Marmar et al*

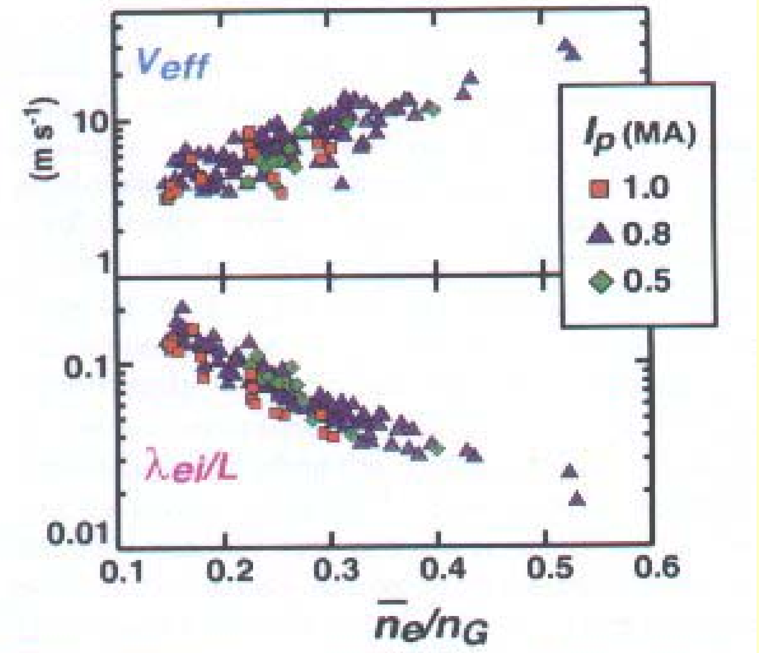


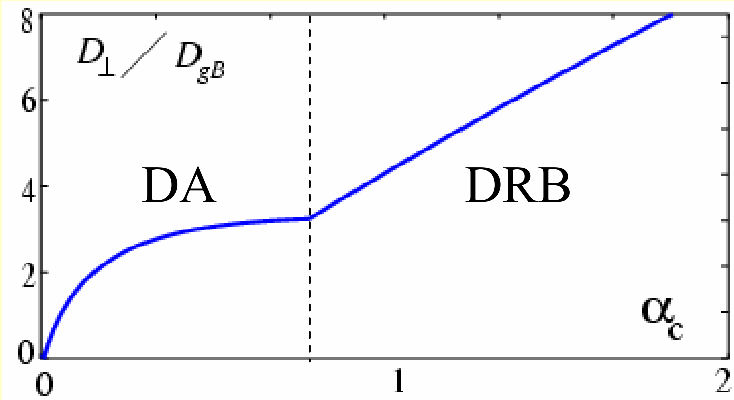
FIG. 12. Effective cross-field convection velocity and parallel collisionality as functions of the normalized plasma density.

Model for edge anomalous transport

Linearized parallel Ohm's, Faraday's and Ampere's law, ion momentum balance, quasi-neutrality, ion continuity equation ⇒ Eigen function equation for electric potential perturbation of Mathieu's type:

$$\frac{\partial^2 \tilde{\varphi}}{\partial \vartheta^2} + \left[A(\omega, k_\perp, \alpha, \alpha_c, \varepsilon_n) - 2Q(\omega, k_\perp, \alpha, \alpha_c, \varepsilon_n)\cos\vartheta\right]\tilde{\varphi} = 0$$

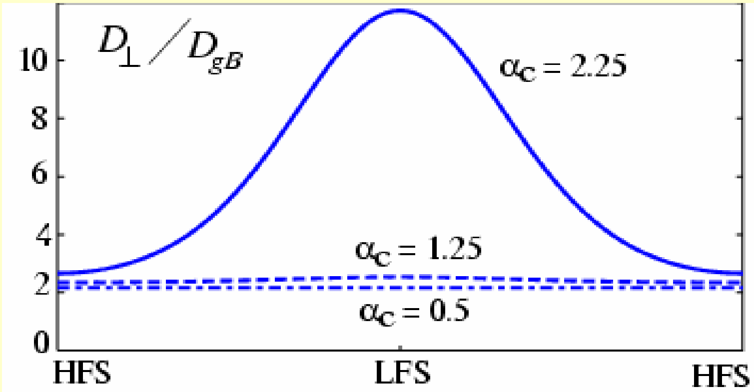
$$\alpha = q^2 R \left|\frac{d\beta}{dr}\right|, \alpha_c = \frac{2q^2 R}{\lambda_e}\sqrt{\frac{m_e}{m_i}} \propto \frac{1}{\alpha_d}, \varepsilon_n = \frac{2L_n}{R}$$



Importance of different modes:

Moderate collisionality, $\alpha_c \leq 1$ drift-Alfven mode described by ce_2 w/o localization on magnetic surface

High collisionality, $\alpha_c \geq 1$: drift-resistive ballooning mode described by ce_0 with maximum on LFS

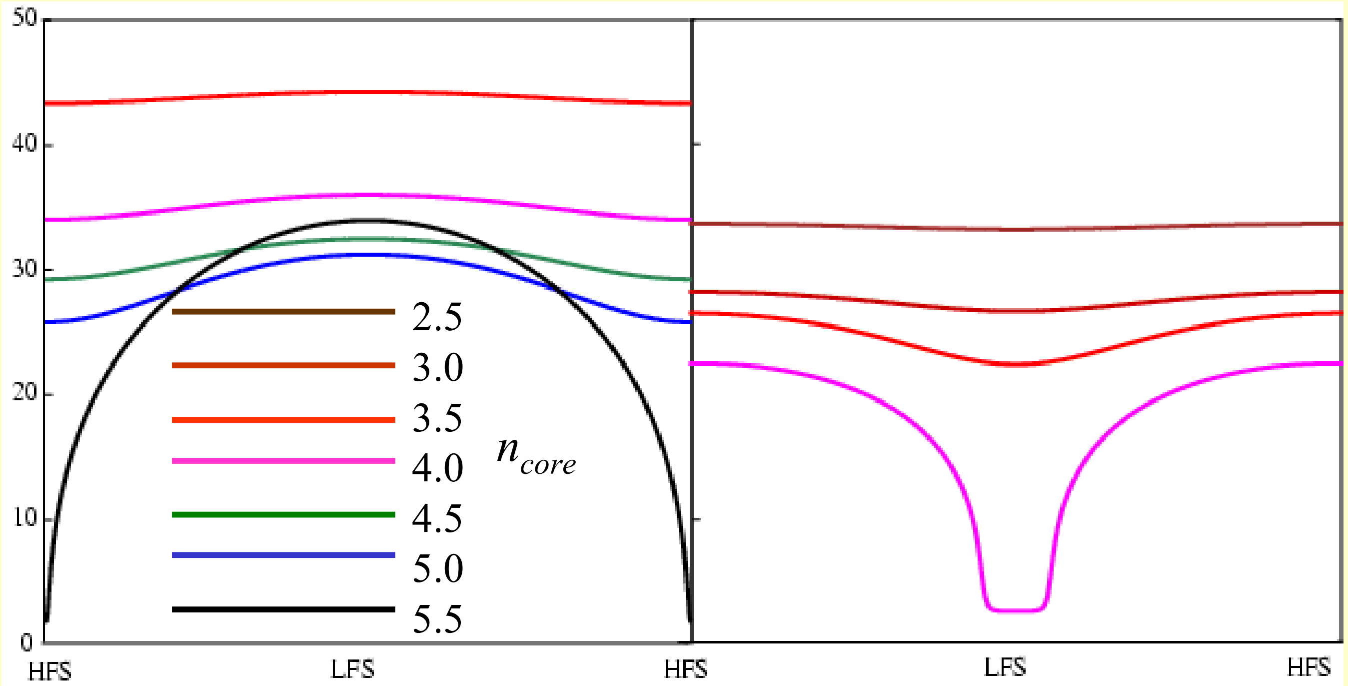


Edge temperature poloidal profiles computed with theory-based transport model

NBI heated plasma with P_{heat} = 1.6 MW, Λ= 0.8

Ohmic heated plasma with P_{heat} = 0.3 MW, Λ= 0.4

Temperature (eV):



Recycling instability leads to MARFE at HFS

Transition to DRB-driven transport results in detachment at LFS

What determines scenario of density limit?

MARFE: stimulated by ϑ-variation of heat influx from the core due to Shafranov shift Δ:

$$\propto 1 + 2\left|\Delta'\right| \cos\vartheta$$

Detachment: promoted by ballooning nature of anomalous transport losses:

$$\propto \exp\left(4\sqrt{\alpha_c}\cos\vartheta\right)$$

MARFE develops if: at the threshold shift asymmetry > ballooning asymmetry:

$$\frac{1+2\Delta'}{1-2\Delta'} > \exp\left(8\sqrt{\alpha_c}\right)$$

Impact of heating power on asymmetries:

$$W_{heat}\uparrow \Rightarrow \quad \Delta'\uparrow \Rightarrow \frac{1+2\Delta'}{1-2\Delta'}\uparrow$$

$$\alpha_c \propto \frac{1}{\lambda_c} \propto \frac{n}{T^2}\downarrow \Rightarrow \exp\left(8\sqrt{\alpha_c}\right)\downarrow$$

Density limit scenario abruptly changes at a critical heating power

Peculiarities of divertor geometry

Differences:

• Recycling is localized in divertor

• Presence of X-points leads to new drift modes

Similarities:

• Most favorite mechanism for MARFE (*Borrass*, ...): is due to recycling, but charged particles hit divertor plates || ***B***

• Transport ⊥ ***B*** starts to play important role close to the density limit (*Xu et al*.: BOUT code)

• New drift modes are of DRB nature (*Xu et al*.: BOUT code)

A self-consistent picture does not exist yet

Conclusion

Synergy of several mechanisms for DL have been analyzed:

- radiative instability
- recycling instability
- transition to ballooning anomalous transport

MARFE at HFS: result of recycling instability at high heating power when Shafranov shift dominates poloidal asymmetry

Detachment at LFS: develops at lower heating power because of transition to anomalous transport due to DRB-modes

Plans

Present model is very approximate in many respects
Further development is needed in all directions First: include divertor geometry