EUROPEAN FUSION DEVELOPMENT AGREEMENT

Numerical modeling of plasmas with edge transport barrier

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Outlines:

- Introduction
- Transport model and possibilities for the barrier formation
- Evolution of major plasma parameters during ETB formation
- Interplay between the dominant mechanism for heat losses and barrier onset
- Comparison with inter-machine scaling for the H-mode threshold
- ETB formation trough the pulsed gas puffing
- Conclusions

Introduction

Formation of the ETB is the most outstanding feature of the H-mode performance

Parameters at the barrier region can determine both the local and, due to profile stiffness, the global plasma behavior

For the modeling of plasma parameters, it is important to have the ETB description in a transport code

Recently, 1-D transport code RITM was amended by introducing the model for the edge transport which allows for the modeling of the ETB formation

RITM code

RITM solves one-dimensional transport equations for the densities and temperatures of electrons, main and impurity ions and the current diffusion equation.

particle sources are due to ionization of neutrals recycling from limiters, from neutral beam injection and impurities eroded or puffed into the plasma

heat sources are due to Ohmic and auxiliary heating and energy exchange between different plasma components

particle fluxes include diffusive and convective components

heat fluxes are composed of conductive and convective contributions

all charged states of impurities as He, C, O, Ne, Si, Ar can be considered simultaneously

D.Kalupin et al, (2005) NF ***45*** *468*

Transport model

CORE TRANSPORT

$$-i\omega\tilde{n}+\tilde{V}_{i,r}\frac{dn}{dr}=0$$

$$\tilde{n}=\left(1+f_{tr}\frac{\omega_*-\omega+i\nu_{eff}\dfrac{\omega_{Te}}{\omega-\omega_D+i\nu_{eff}}}{\omega+i\nu_{eff}}\right)\frac{en\tilde{\varphi}}{T_e}$$

$$\left(\omega_{Ti}-\frac{2}{3}\omega_*\right)\frac{e\tilde{\varphi}}{T_e}+\frac{2}{3}\omega\frac{\tilde{n}}{n}=\left(\omega+\frac{5}{3}\tau\omega_D\right)\frac{\tilde{T}_i}{T_i}$$

quartic dispersion equation

γ^{ITG}, k^{ITG} $\quad$ γ^{TE}, k^{TE}

$if\ \mathrm{Re}\,\omega>0$ $\quad$ $if\ \mathrm{Re}\,\omega<0$

EDGE TRANSPORT

$$-i\omega\tilde{n}+\tilde{V}_{i,r}\frac{dn}{dr}=0$$

$$-i\omega m_i n\tilde{V}_{i,r}=\frac{\tilde{j}_y B}{c},\quad ik\left(T_e+T_i\right)\tilde{n}=-\frac{\tilde{j}_r B}{c}$$

$$\vec{\nabla}\cdot\vec{j}=\frac{\partial\tilde{j}_{\parallel}}{\partial l}+ik_y\tilde{j}_y+\frac{\partial\tilde{j}_r}{\partial r}=0$$

$$-i\omega m_e\tilde{V}_{e,\parallel}=-en\tilde{E}_{\parallel}-T_e\nabla_{\parallel}\tilde{n}-\frac{\partial\left(nT_e\right)}{\partial r}\frac{\tilde{B}_r}{B_0}+m_e\nu_{ei}\frac{\tilde{j}_{\parallel}}{e}$$

$$\tilde{E}_{\parallel}=i\frac{4\pi\omega}{k_y^2c^2}\tilde{j}_{\parallel}-\nabla_{\parallel}\tilde{\varphi},\qquad \tilde{B}_r=i\frac{4\pi}{k_y c}\tilde{j}_{\parallel}$$

dispersion equation of Mathieu type

γ^{edge}, k^{edge}

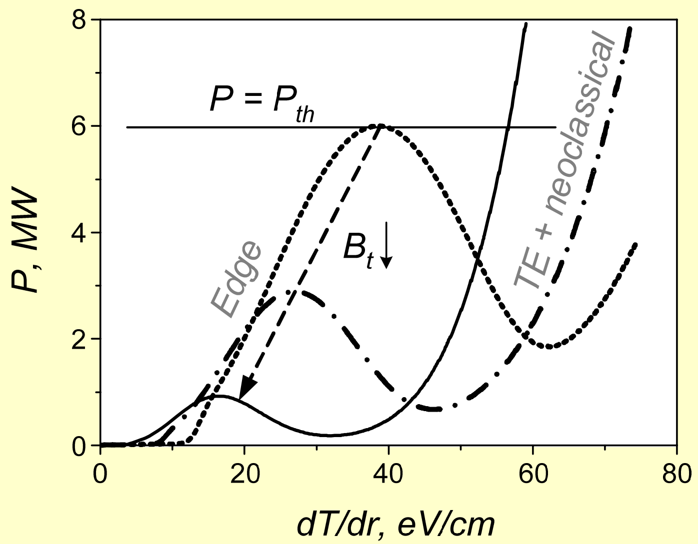
Bifurcation into improved confinement state

global power balance:

$$P_{heat} = P(n, T, \nabla n, \nabla T) \equiv S\langle \chi_\perp n \nabla T \rangle$$

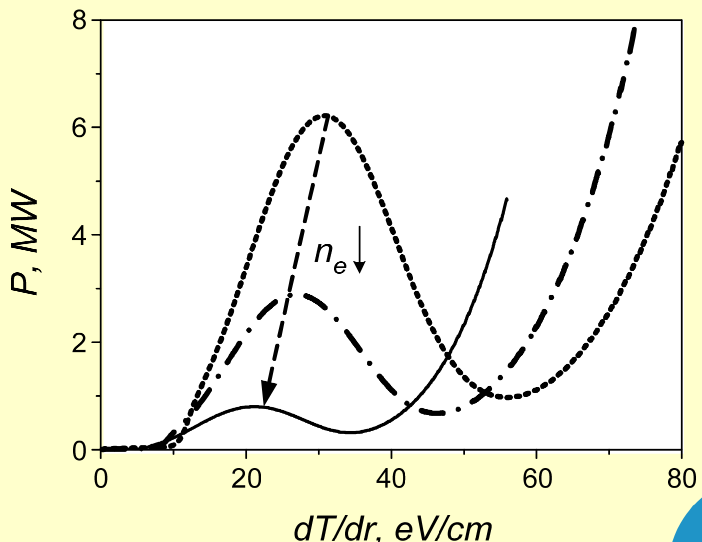
$$\langle \nabla n \rangle \approx \langle n \rangle / l, \quad \langle \nabla T \rangle \approx \langle T \rangle / l$$

$$l = 1 / \langle n \rangle \sigma_* \qquad \sigma_* = \sqrt{(k^{cx} + k^i) k^i} / V_{thi}$$



if the total heating power exceeds P_{th} the confinement improves

the critical power varies with n_e and B_t in the same way as it is predicted by multi-machine scaling for H-mode threshold



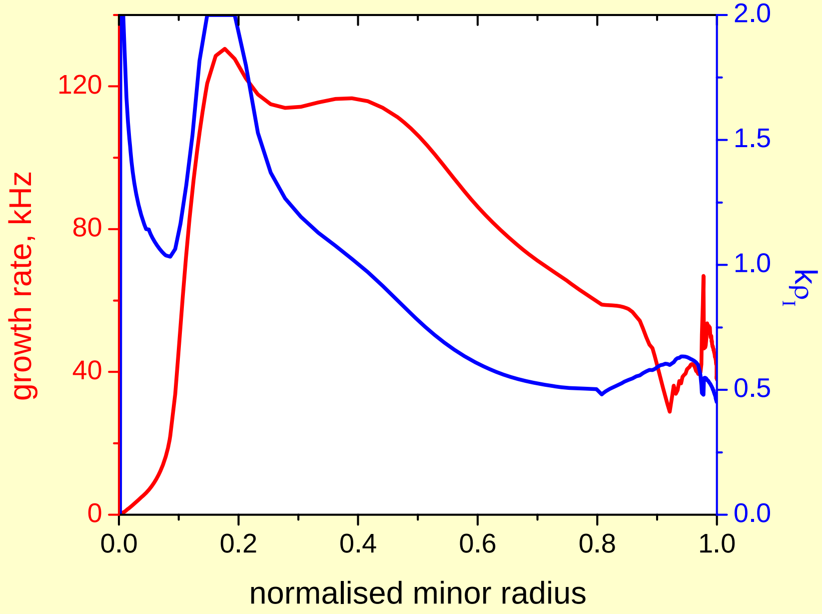
D.Kalupin et al, (2006) POP **13** 032504

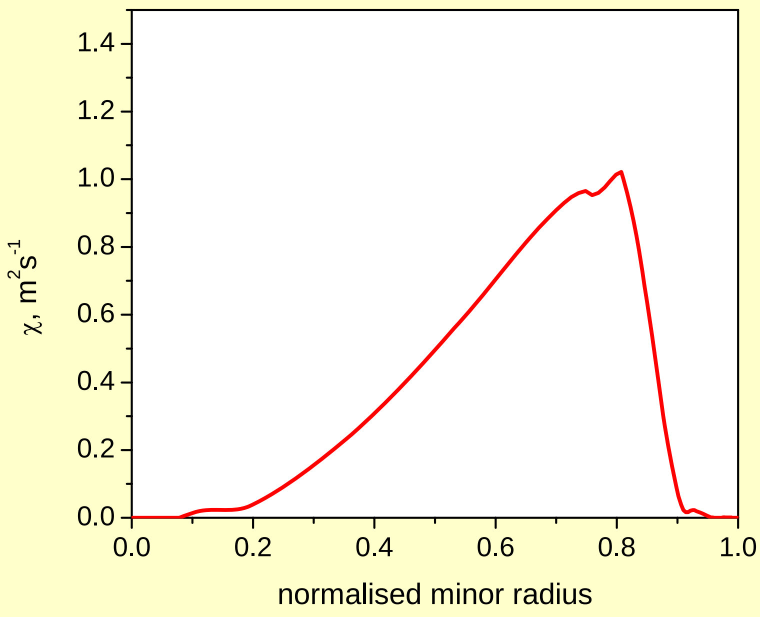
Transport coefficients

Improved mixing length approximation

$$D_\perp = \frac{\gamma}{k^2}\frac{\gamma^2}{\gamma^2 + (\mathrm{Re}\,\omega)^2}$$

ITG





Total transport coefficients

Electron transport

$$D_\perp^e = D^{ITG} f_{tr} R^{ITG} + D^{TE} R^{TE} + D^{edge} R^{edge} + D^{core}$$

$$V_\perp^e = \left[D^{ITG} f_{tr} (4r/3R) R^{ITG} + D^{TE} R^{TE} \right] (d \ln q / dr)$$

Ion transport

$$D_\perp^Z = D_\perp^e$$

$$V_\perp^Z = V_\perp^e + V_\perp^{Z,NEO}$$

Heat transport

$$\chi_\perp^e = 3/2 \left(D^{ITG} f_{tr} R^{ITG} + D^{TE} R^{TE} + D^{edge} R^{edge} + D^{core} \right)$$

$$\chi_\perp^i = \chi_\perp^{i,NEO} + 3/2 \left(D^{ITG} R^{ITG} + D^{TE} R^{TE} + D^{edge} R^{edge} + D^{core} \right)$$

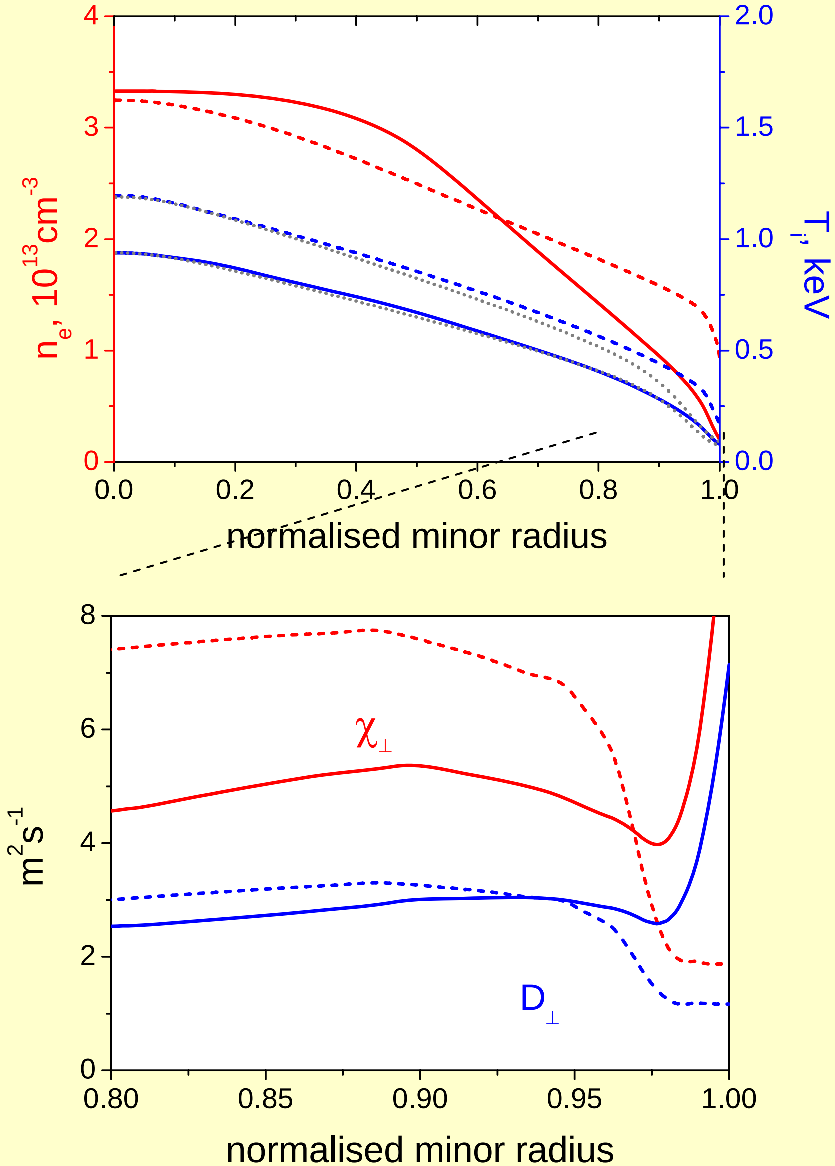
ExB and magnetic shear stabilization:

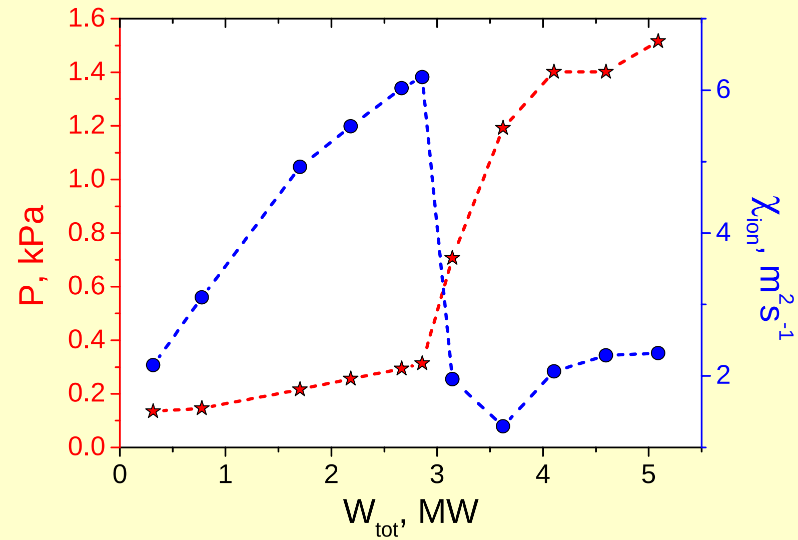
$$R^{ITG,TE,edge} = C^{ITG,TE,edge} \cdot \frac{1}{1 + (\omega_{ExB} / \varepsilon \gamma_{ITG,TE,edge})^2} \cdot \frac{1}{\max\left(1, (s - s_0)^2\right)}$$

Radial electric field:

$$E_r = \frac{V_\varphi B_\vartheta - V_\vartheta B_\varphi}{c} + \frac{1}{e n_i} \frac{\partial (n_i T_i)}{\partial r}$$

Preparatory modeling for H-mode experiment in TEXTOR

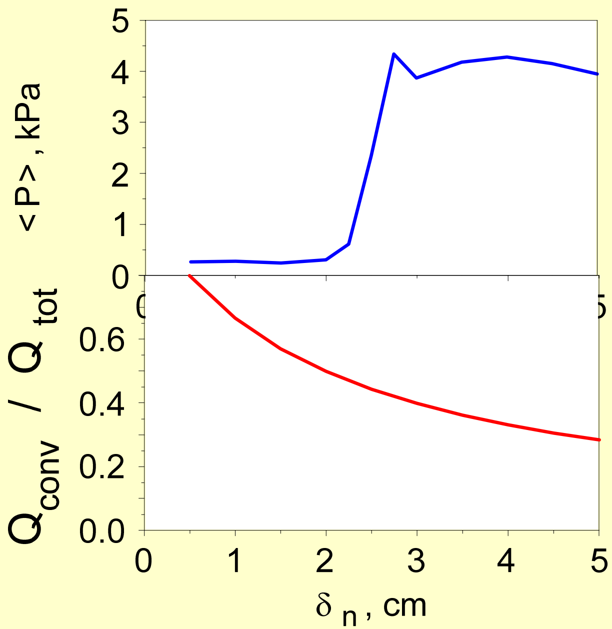


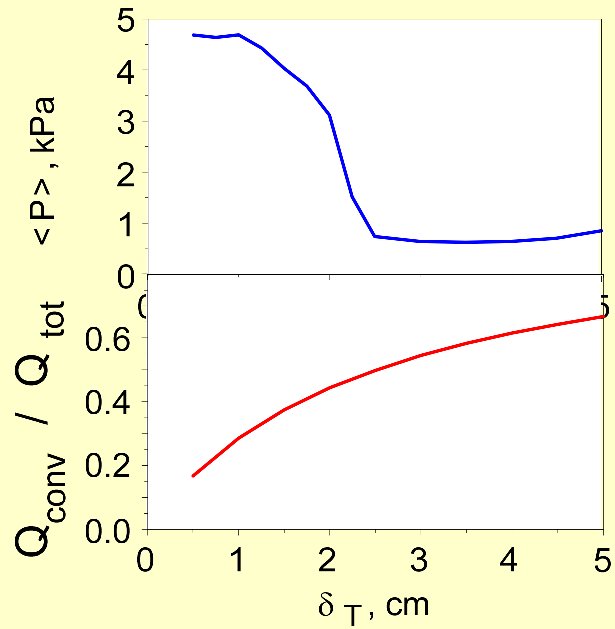


***P<P$_{th}$*, transport coefficients have the maximum at the LCMS, temperature profile reproduce the Ohmic shape**

***P>P$_{th}$*, transport coefficients at the edge reduce to the neoclassical level, pedestals are formed on density and temperature profiles**

Influence of the boundary conditions on the ETB formation





convective heat loss $-3TD_{\perp}\nabla n$

conductive heat loss $-\chi_{\perp}n\nabla T$

at the LCMS $\nabla n = -n/\delta_n \,, \nabla T = -T/\delta_T$

$$\frac{Q_{conv}}{Q_{tot}} = \left(1 + \frac{\chi_{\perp}}{3D_{\perp}}\frac{\delta_n}{\delta_T}\right)^{-1}$$

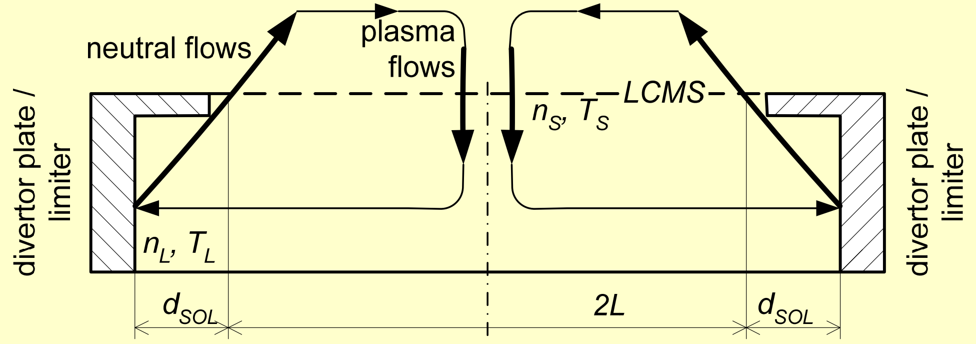
Sudden improvement of confinement occurs if the fraction of the convective heat losses reduces below 50 %

(*D.Kalupin et al, (2006) PPCF **48** accepted for publication*)

Improved two point model for the SOL

power balance in SOL:

$$P_{heat} = 4\pi R\delta(\gamma T_L + E_i) n_L V_s \sin\psi$$



particle balance in SOL:

$$\Gamma_{LCMS} = 4\pi R\delta n_L V_s \sin\psi \exp(-n_L \sigma_* d_{SOL})$$

pressure balance:

$$2n_L T_L = n_S T_S$$

parallel heat transport:

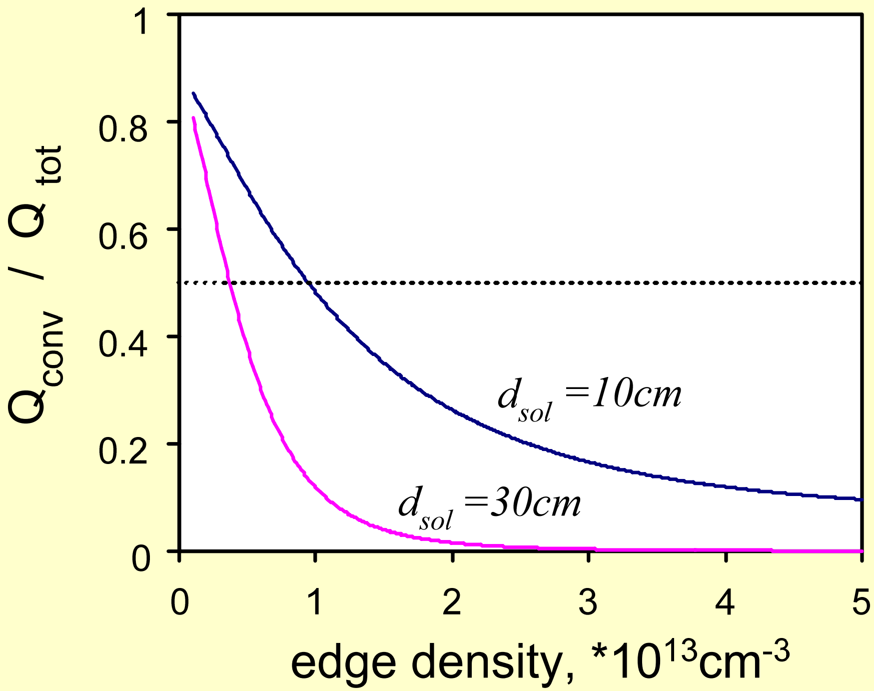
$$\frac{T_C^{5/2}}{2}\left[\ln\frac{\sqrt{T_C}+\sqrt{T_S}}{\sqrt{T_C}-\sqrt{T_S}} - \ln\frac{\sqrt{T_C}+\sqrt{T_L}}{\sqrt{T_C}-\sqrt{T_L}}\right] = \frac{T_S^{5/2}-T_L^{5/2}}{5} + T_C\frac{T_S^{3/2}-T_L^{3/2}}{3} + T_C^2\left(T_S^{1/2}-T_L^{1/2}\right) + \frac{5L^2}{A_k\delta}\frac{\Gamma_{LCMS}}{S}$$

$$T_C = 5P_{heat}/\Gamma_{LCMS}$$

particular assumption: $\delta = \delta_n \delta_T / (\delta_n + \delta_T)$

$$\frac{\Gamma_{LCMS}}{S} = \frac{D_\perp}{\delta_n} n_S \qquad \frac{P_{heat}}{S} = \left(\frac{3D_\perp}{\delta_n} + \frac{\chi_\perp}{\delta_T}\right) n_S T_S$$

Two point model for the SOL



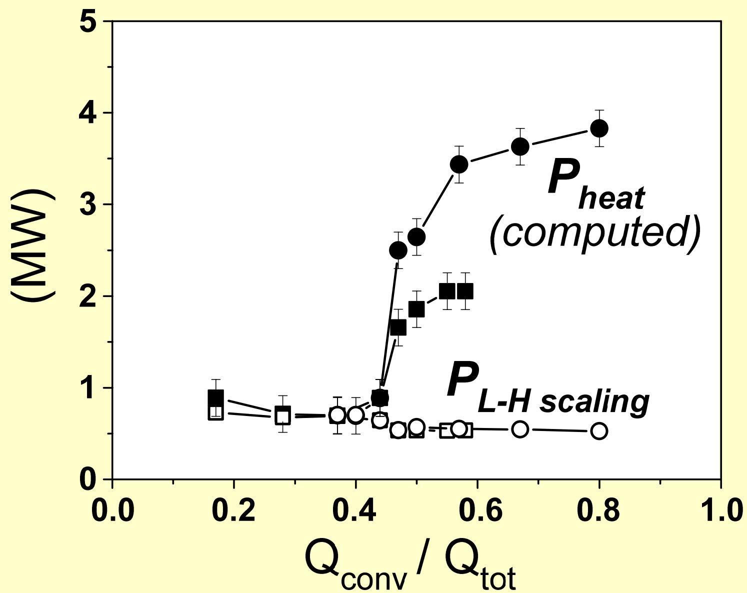
Both, decreasing density and decreasing d_{SOL} lead to the increase of convective losses

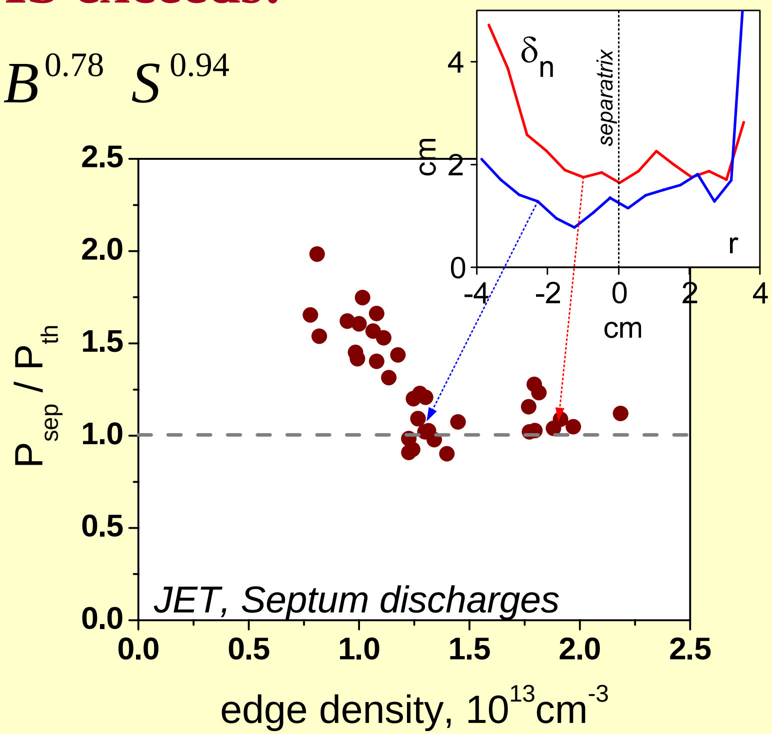
For a given heating power, a larger convection fraction results in lower temperature and its gradient, this hinders the ETB formation

Comparison with multi-machine scaling

- **The multi-machine scaling established from divertor machine data predicts that the transition to the H-mode takes place when the total power transported through the LCMS exceeds:**

$$P_{th} = 0.042\, \overline{n}_e^{\,0.64}\, B^{0.78}\, S^{0.94}$$





Computed threshold power coincides with the scaling predictions if the fraction of convective heat losses does not exceed 50%

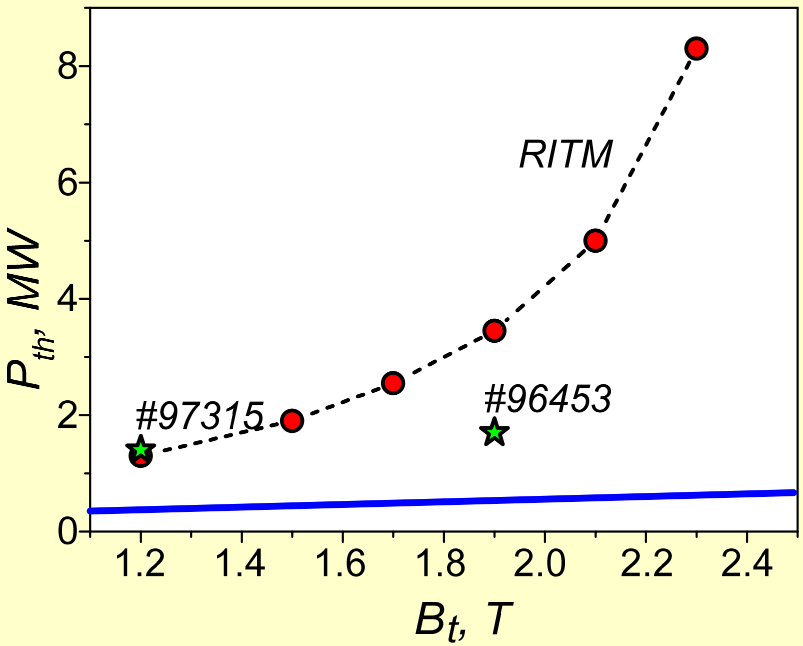
(**D.Kalupin et al, (2006) POP **13** 032504)***

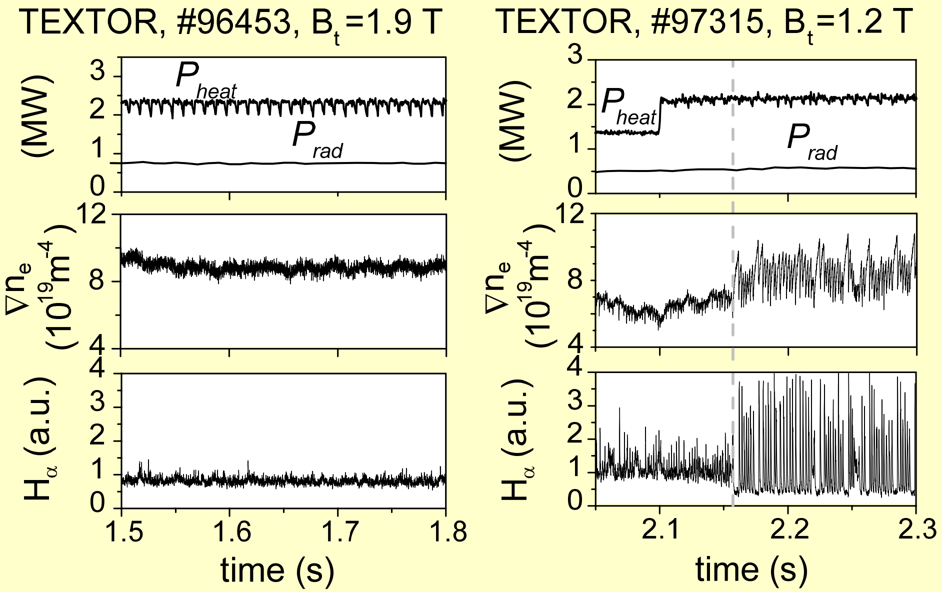
This can explain the deviation of the thresold power from the scaling at low densities (JET, *Y.Andrew et al, (2006) PPCF **48** 479****)***

Predictions for TEXTOR

Typical e-folding lengths for the edge density and temperature in TEXTOR L-mode:

$$\delta_n = 1cm \quad \delta_T = 1.5cm$$





(more details in the presentation by B.Unterberg at this meeting)

The first indication for the ETB formation is observed at the power just above the critical one computed with the RITM code prior to the experiment

Gas puff triggered ETB

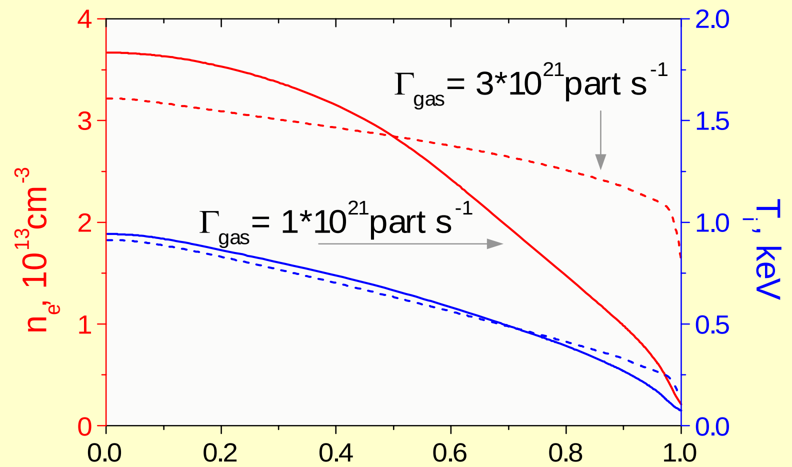
Is it possible to reduce the threshold power?

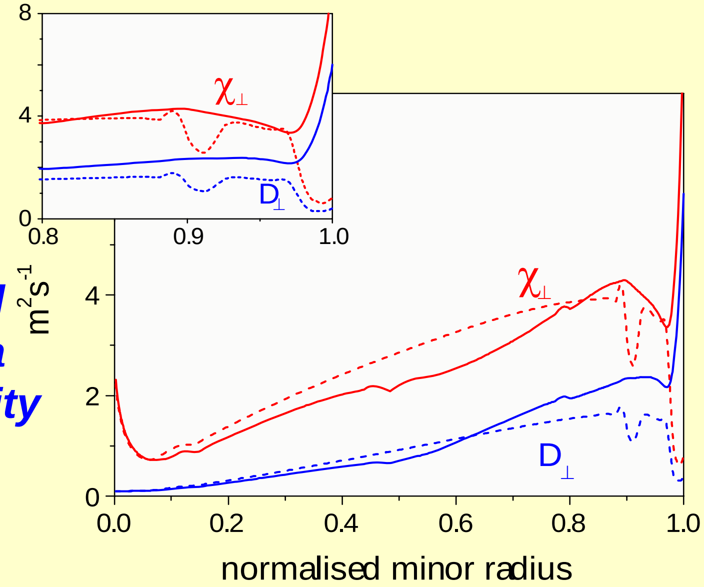
***Gas puffing can trigger the ETB (TUMAN tokamak,** Lebedev et al, (1996) PPCF **38** 1103)*

For the total heating power, substantially lower than a critical one, the stationary ETB forms after the short (~5ms) intense blip of deuterium gas.

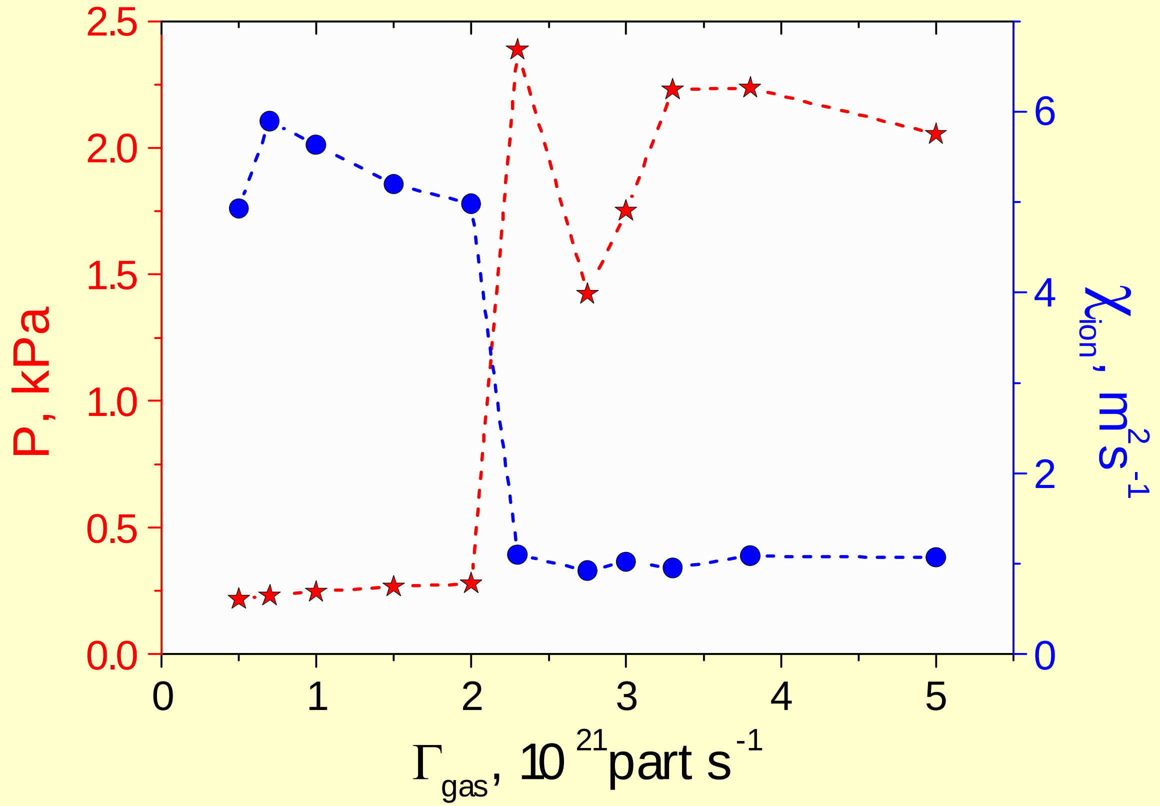
$$E_r = \frac{V_\varphi B_\vartheta - V_\vartheta B_\varphi}{c} + \frac{1}{en_i}\frac{\partial(n_i T_i)}{\partial r}$$

This occurs due to suppression of the turbulent transport by the shear of the radial electrical field, which emerges at the plasma edge due to the formation of the steep density gradient driven by the gas injection





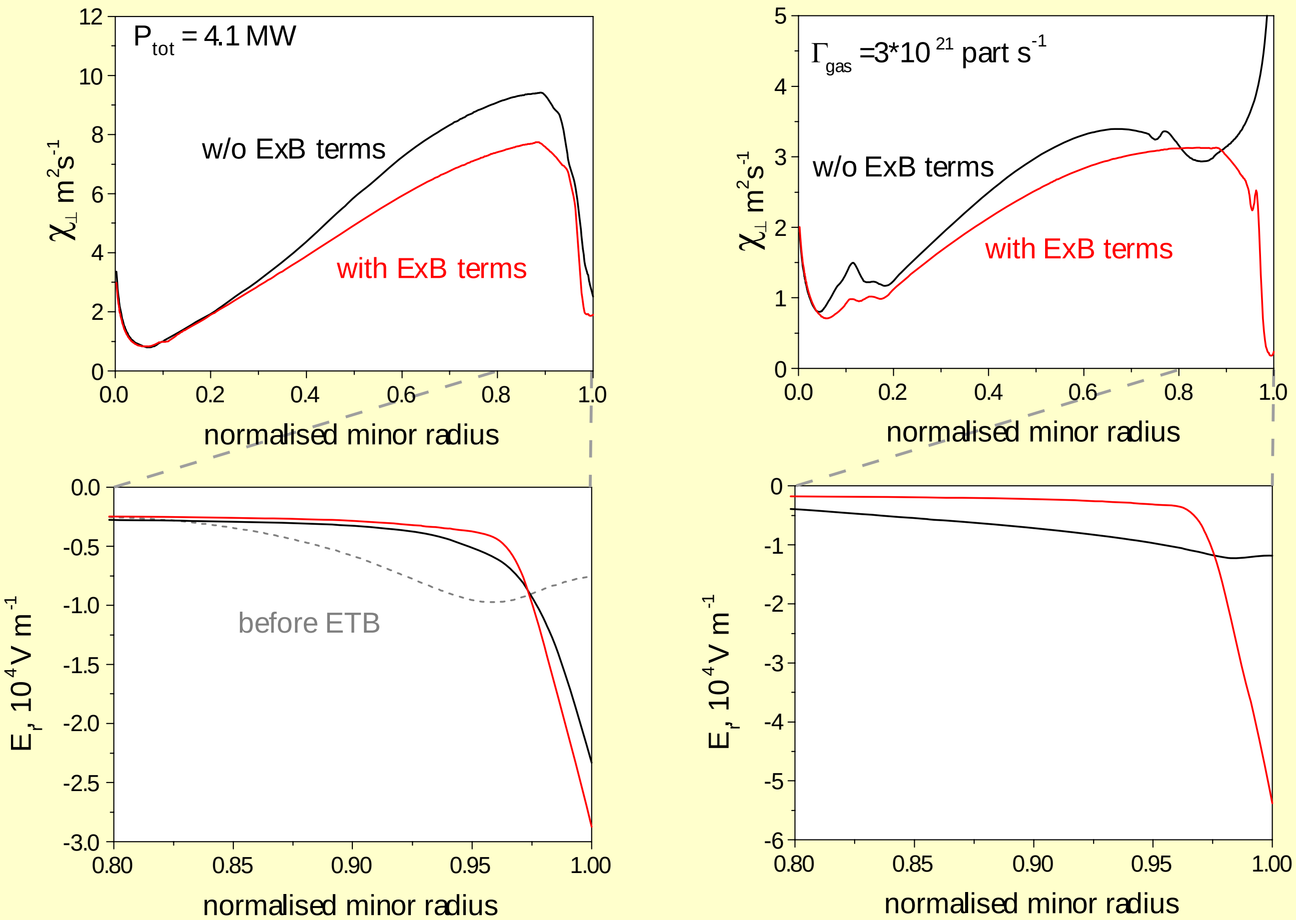
Critical gas puff intensity



Computations predict the critical intensity of the gas puffing allowing to trigger H-mode onset

Injection of the same amount of particles but with intensity lower than a critical one do not trigger the ETB formation, on contrary, it leads to the amplification of the edge transport due to increased collisionality

Role of the ExB shear in the barrier formation under different scenarios

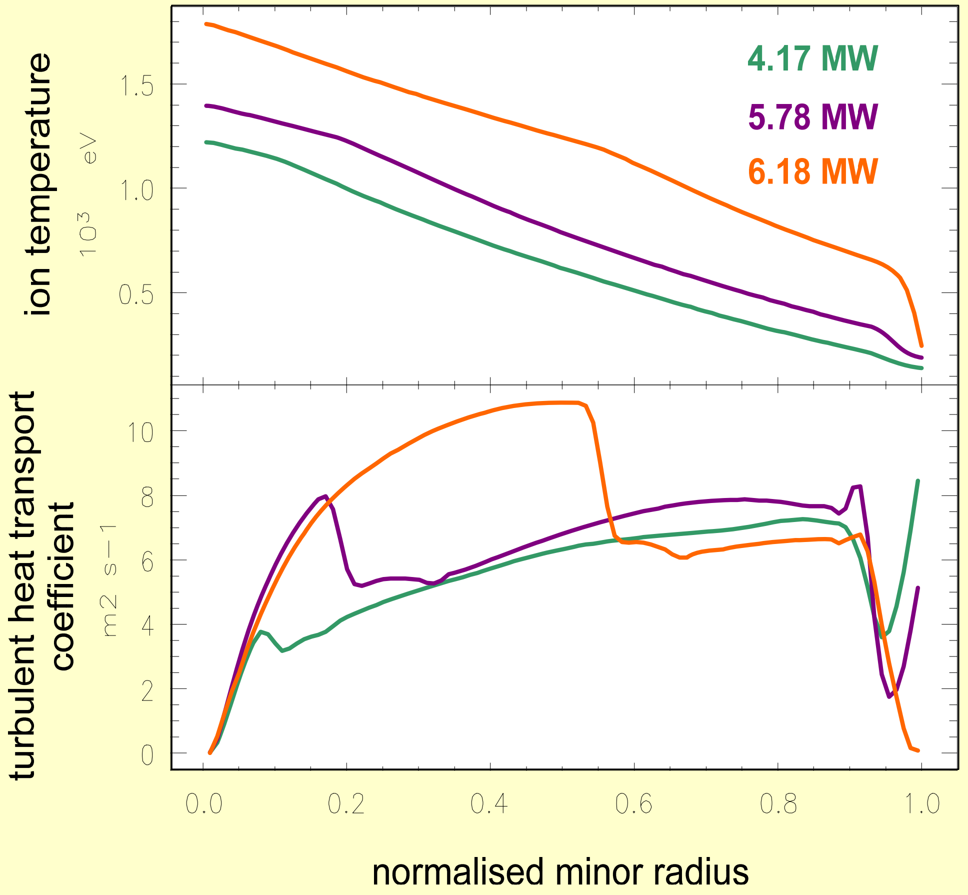


stabilization of the turbulence by the ExB shear is not the dominant mechanism in the ETB triggered by heating, in this case the stabilisation occurs due to decreasing collisionality and inceasing density gradient

on contrary, in case of the gaspuff, when collisionality do not decrease or even increases, stabilization can occur only due to ExB shear

Coupling to the JETTO code

The model can be used in other transport codes to provide a self-consistent description of the ETB



To set up the default settings of the model, the benchmarking against JET data should be done

Conclusions

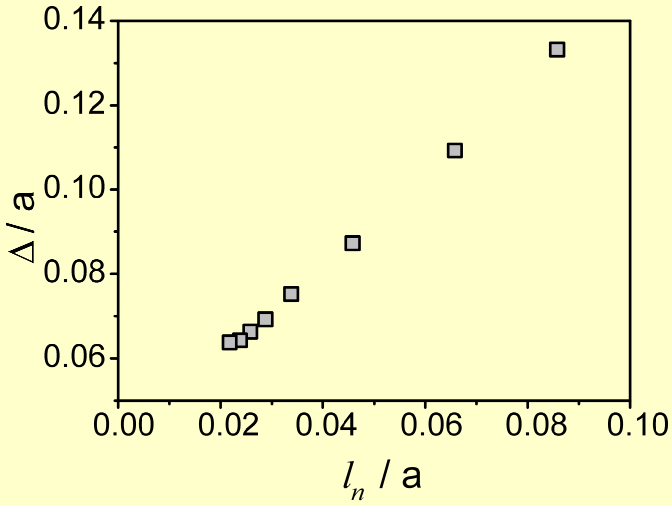
- *The transport model allows a self-consistent modeling of L and H-mode plasmas. The ETB forms if the total heating power exceeds the certain critical value which increases with density and magnetic field.*

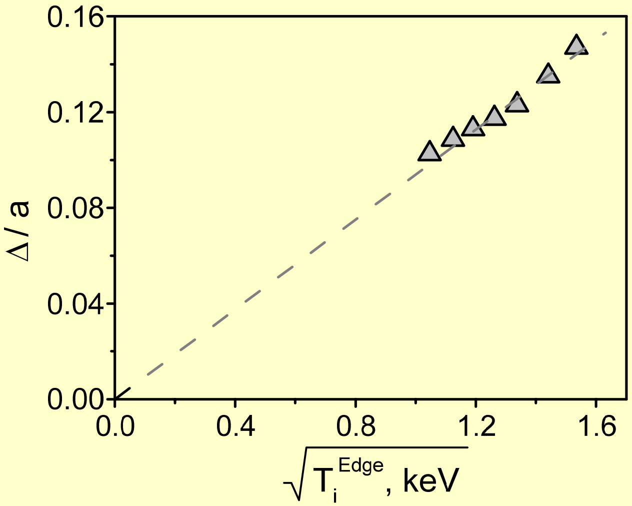
- *For the given heating power, the transition to improved confinement occurs if the e-folding length of density is increased and the temperature e-folding length is reduced. This can be explained by the change of the dominant mechanism for the heat losses at the plasma edge, where the strong convective heat losses hinder the H-mode onset*

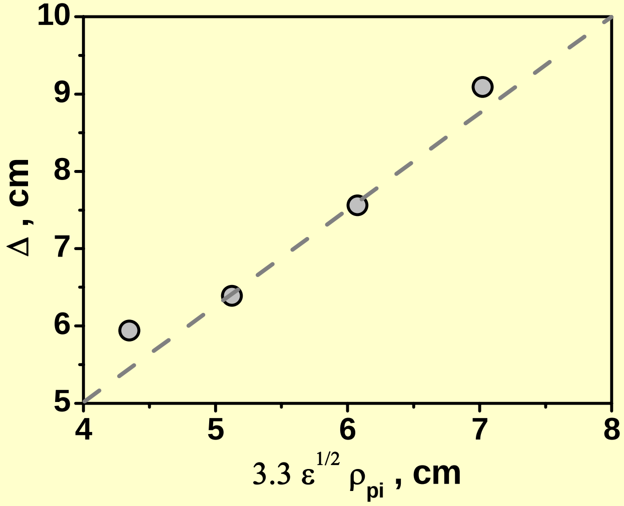
- *The pulsed gas puffing can be an effective tool to reduce the threshold power. In this case, the suppression of the turbulent transport by the radial electric field, increased due to increased pressure gradient, is the dominant mechanism for the ETB formation.*

- *The transport model was coupled with JETTO transport code, where the formation of ETB with increasing heating power was observed. The benchmarking of the coupled version is to be done.*

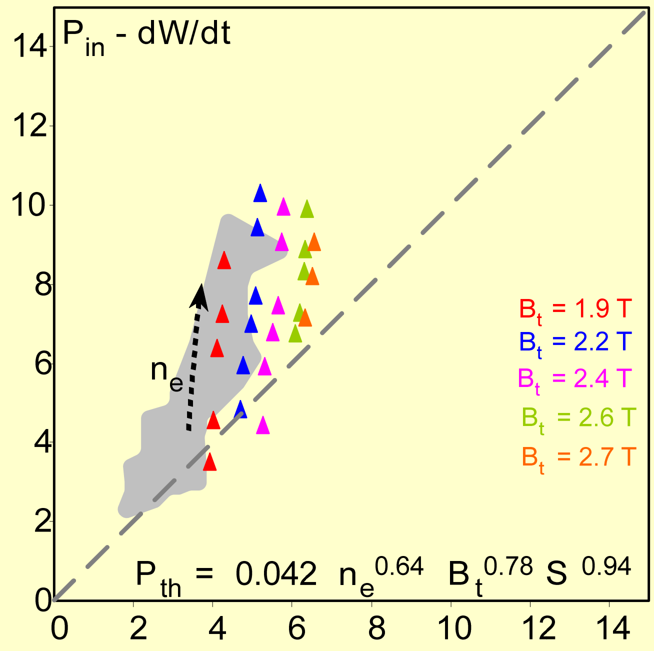
Discussions 1

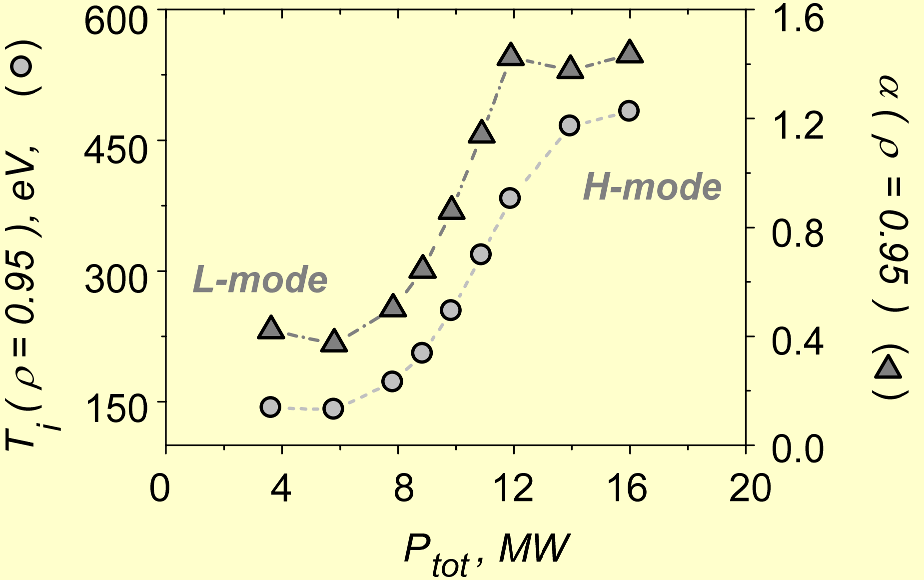






Discussions 2





Discussions 3