# A model for L-H bifurcation, characteristics of ETB and ELM


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Pedestal Physics Working Session
03 - 05 April 2006
Cadarache, France

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# Motivation

on the same principles as in the code RITM (talk of D.Kalupin)

provide a simple model for edge transport barrier

for a better understanding and broad applications

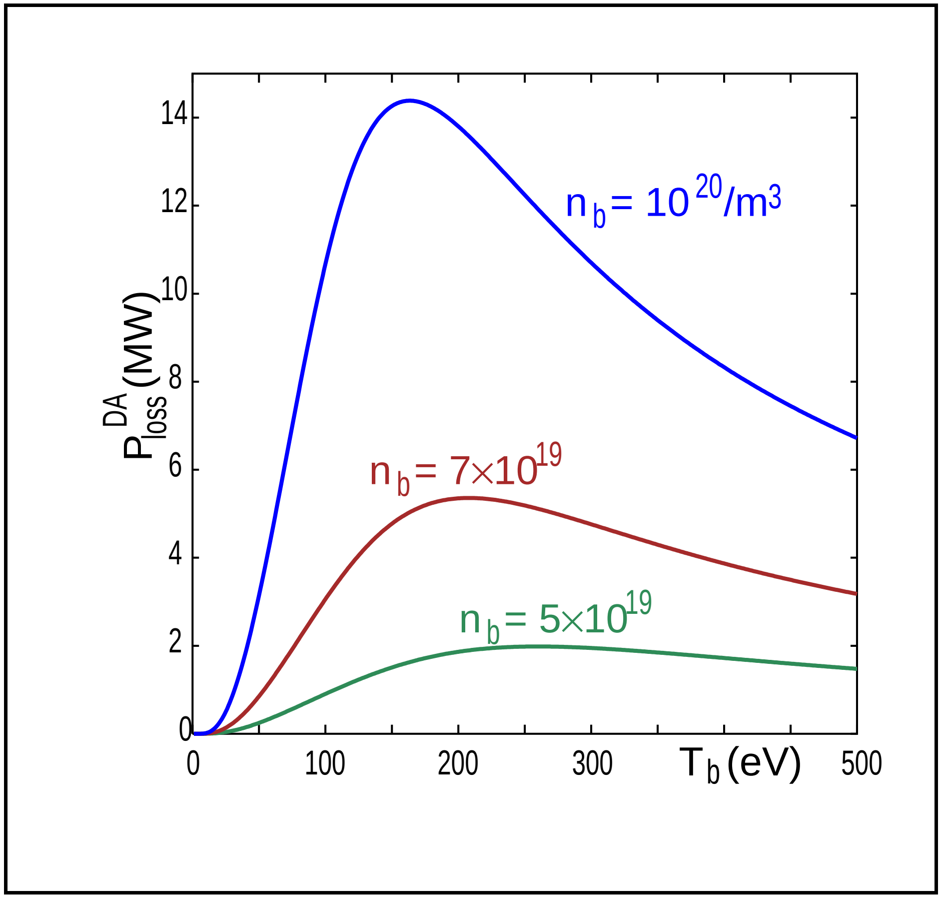
## Conditions for ETB formation: Drift-Alfven turbulence is stabilized by low collisionality and high pressure gradient

*Kerner-Pogutse model*:

$$\chi_{DA} \sim \chi_{gB} \sqrt{\frac{\nu_{cr}^2 + \nu_n^2}{\nu_{cr}^{-2/3} + \nu_n^{4/3}}}$$

$$\nu_n = \left(\frac{m_i}{m_e}\right)^{0.25} \frac{\sqrt{qRL_p}}{\lambda_c}$$

$$\nu_{cr} = \left[1 + \frac{m_i}{m_e}\left(\frac{\beta qR}{L_P}\right)^2\right]^{-3/2}$$



# ETB width: ITG turbulence is stabilized by density gradient and $\Omega_{E\times B}$

negative growth rate in edge transport barrier, $x \equiv a - r \leq \Delta_b$:

$$\gamma_{ITG} \approx \frac{c_s}{2R} \mathbf{Re} \sqrt{\frac{R}{L_T} - \frac{R^2}{8L_n^2}} - \frac{c_s \rho_s}{L_n L_T} \leq 0$$

$L_n = -dr/d\ln n$, $L_T = -dr/d\ln T$ - $e$-folding lengths;
$c_s = \sqrt{T/m_i}$ - ion sound velocity, $\rho_s = c_s/\Omega_{L,i}$ - ion Larmor radius;
radial electric field is determined mainly by pressure gradient

## $L_n$ : **particle balance (I)**

continuity equation for density of recycling neutrals:

$$\frac{d}{dx}\left(-D_a \frac{dn_a}{dx}\right) = -k_i n n_a$$

continuity equation for charged particle density:

$$\frac{d}{dx}\left(-D_\perp \frac{dn}{dx}\right) = k_i n n_a$$

with diffusivities:

$$D_a = \frac{T}{(k_i + k_{cx})\, n m_i},\ D_\perp\,(x \le \Delta_b) = D_b,\ D_\perp\,(x > \Delta_b) = D_c$$

# $L_n$ : **particle balance (II)**

$T,\ k_i,\ k_{cx}\ \Rightarrow$ averaged values, $n\left(x=0\right)=0\Rightarrow$
density profile:

$$n\left(x\right)=\frac{1}{\sigma_*\lambda_n}\tanh\left(\frac{x}{\lambda_n}\right),\ L_n\left(x\right)=\lambda_n\sinh\left(\frac{x}{\lambda_n}\right)$$

$$\sigma_*=\sqrt{\frac{k_i\left(k_i+k_{cx}\right)m_i}{T}},\ \lambda_n=\sqrt{\frac{D_b}{2\sigma_*\Gamma_s}}$$

# Equations for $\lambda_n$ and $\Delta_b$

linear temperature profile in the barrier with $T(x=0)=0 \Rightarrow$

$$L_T = x;$$

particle transport in plasma core is much stronger: $D_b \ll D_c \Rightarrow$

$$n(\Delta_b) \approx n_c \Rightarrow \lambda_n \approx \frac{1}{\sigma_* n_c} \tanh\left(\frac{\Delta_b}{2\lambda_n}\right)$$

$$\gamma_{ITG}(\Delta_b) = 0 \Rightarrow \Delta_b = \lambda_n \ln\left(\sqrt{\zeta} + \sqrt{\zeta + 1}\right)$$

with $\zeta = \frac{R}{\lambda_n^2}\left(\frac{\Delta_b}{8} + \frac{4\rho_s^2}{\Delta_b}\right)$; $D_b,\ \Gamma_s$ particular values are unimportant!

# Temperature $T_b$ at the barrier top: heat balance in the barrier

$$\kappa_\perp \frac{dT}{dx} = q_{core} \Longrightarrow T_b = \frac{q_{core}\Delta_b}{\kappa_\perp(T_b)}$$

heat conductivity: ion neoclassical heat conductivity in plateau and Pfirsch-Schlüter regimes

$$\kappa_{neo} = n\frac{\rho_s^2 c_s}{R}\frac{2q}{E^2}\left(\frac{1.18\nu_*^2}{1+0.74\nu_*} + 2.13\right), \ \nu_* = \frac{qR}{\lambda_i}$$

no banana regime in barrier: would lead to unrealistically high temperature and therefore is hindered by development of ELMs

# Examples for application (I): density scaling of barrier width

JET parameters:

$R = 3m$

$a = 0.9m$

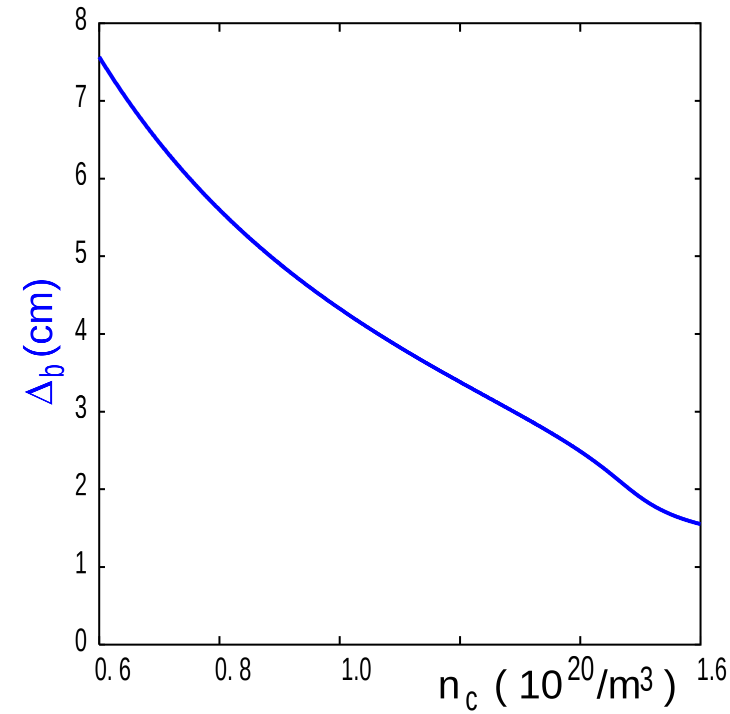
$E = 1.6$

$B_T = 2.5T$

$q_{0.95} = 4.5$

$W_{heat} = 15MW$

Barrier width decreases with density as neutral penetration depth



# Examples for applications (II): type I ELMs

## Non-stationary balances in ETB

### Charged particles:

$$\frac{d}{dt}\left(n_b \Delta_b \zeta_n\right) = j_n - \frac{D_\perp}{2\sigma_* \lambda_n^2}$$

### Energy:

$$\frac{d}{dt}\left(n_b T_b \Delta_b \zeta_E\right) = q_{core} - \kappa_\perp \frac{T_b}{\Delta_b}$$

$\zeta_{n,E}$ – profile factors

### Transport coefficients:

$$D_\perp = D_b + qRc_s \left(\frac{B_r}{B_\varphi}\right)^2$$

$$\kappa_\perp = \kappa_{neo} + \kappa_\perp \left(\frac{B_r}{B_\varphi}\right)^2$$

### Time evolution of $B_r$:

$$\frac{dB_r}{dt} \approx \left(\mathrm{Re}\,\gamma_{BP} - \frac{c^2}{4\pi\sigma\Delta_b^2}\right) B_r$$

With perturbations from external coils:

$$B_r \geq B_r^{ext}$$

# Linear growth rate of ballooning peeling MHD-mode:

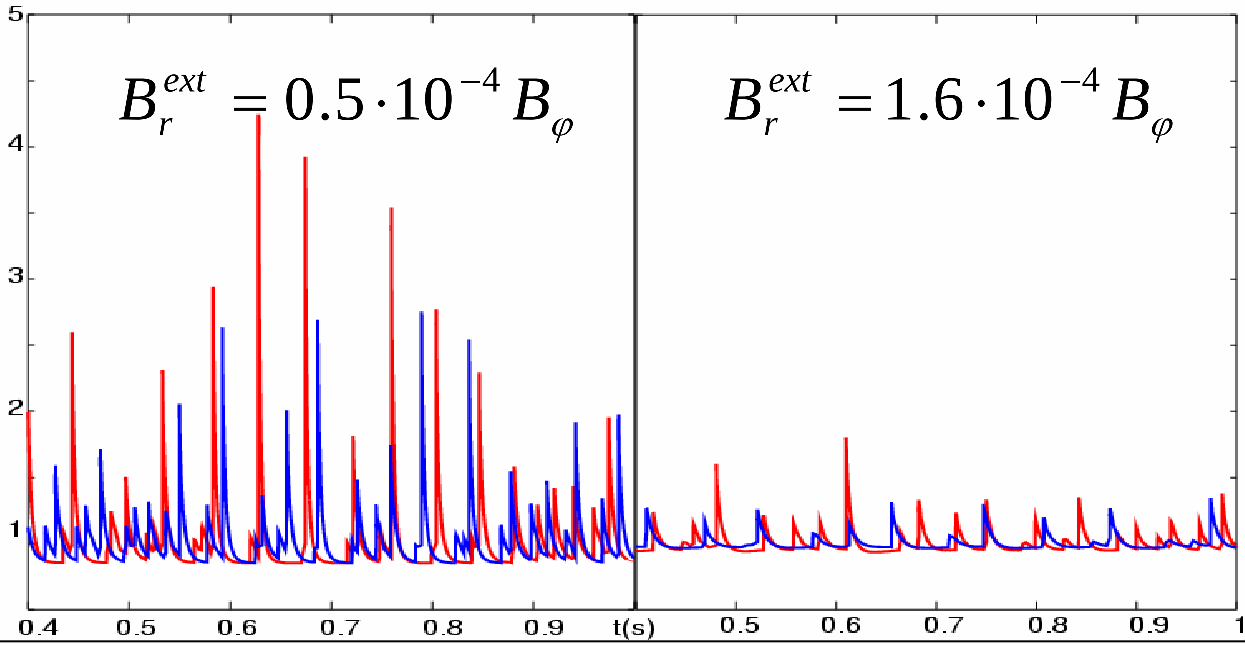
$$\gamma_{BP} = \frac{c_A}{qR}\sqrt{q^2 R\left|\frac{d\beta}{dr}\right|(1+p)-1-\left|\frac{qR}{\delta_R}\frac{\delta B_r^{ext}}{B}\right|^2}, \quad p = 1.22\,\frac{\delta_R}{\Delta_b}\sqrt{\frac{R}{a}}, \quad \delta_R = \left(\frac{\rho_s^2 R}{4}\right)^{1/3}$$

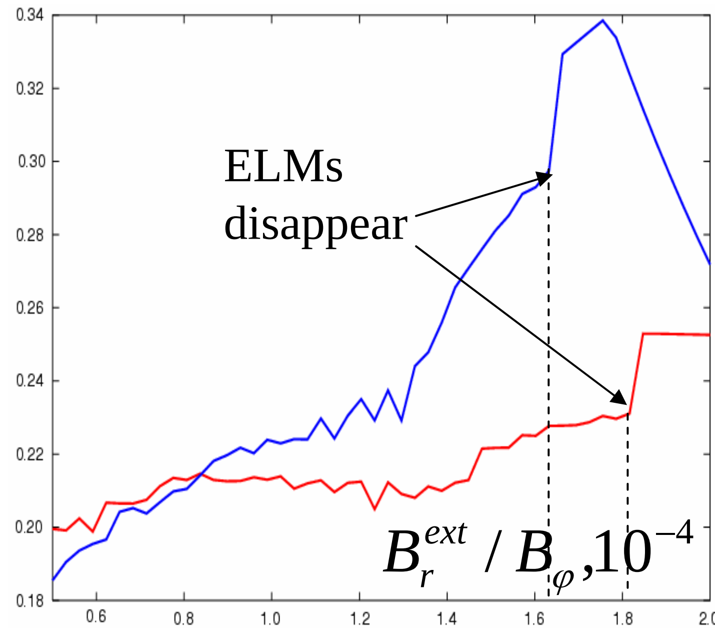
JET H-mode with $W_{heat}$=15 MW, $\langle n_b \rangle = 10^{20} m^{-3}$

Charged particle flux density through separatrix:

Time averaged pressure at barrier top:

(red line) $B_r \geq B_r^{ext}$ only (blue line) $B_r \geq B_r^{ext}$ + effect on $\gamma_{BP}$



# Examples for application (III):
# H-mode neoclassical density limit

Plateau regime $\nu_* < 1$:

$$\kappa_{neo} \sim n\frac{\rho_s^2 c_s}{R} \sim nT^{1.5}$$

$$\Rightarrow T_b \sim n_c^{0.8},\ P_b \sim n_c^{0.2}$$

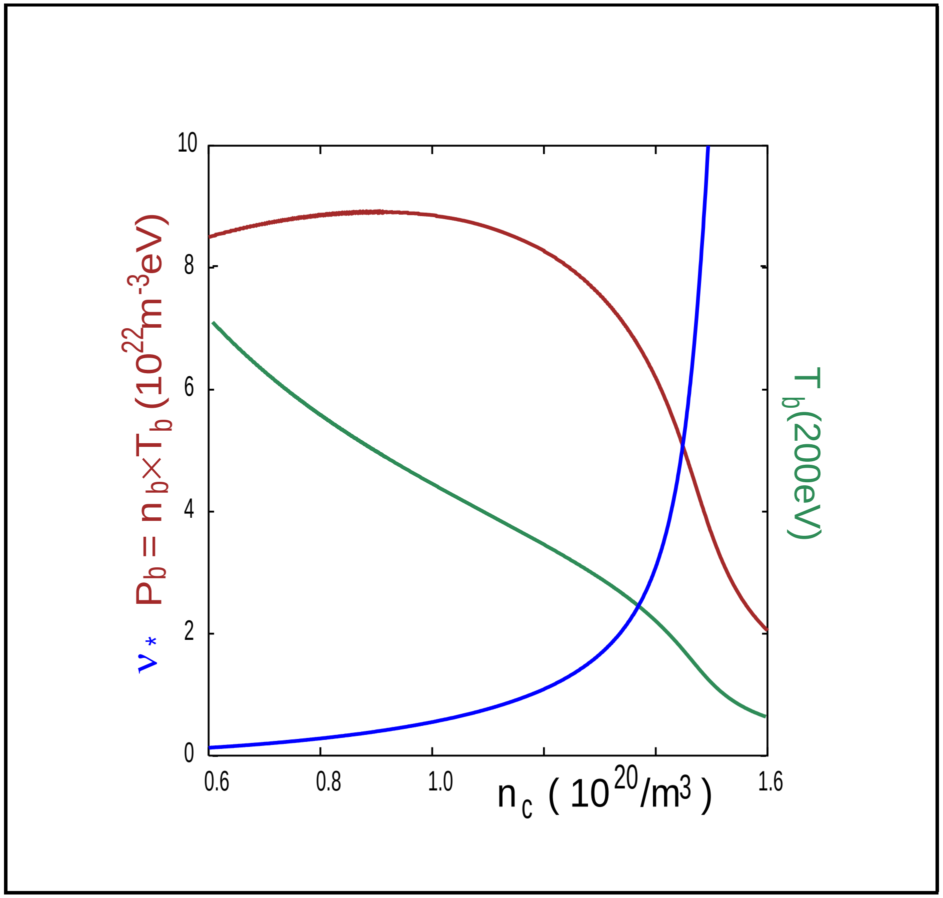
Pf.-Schl. regime $\nu_* > 1$:

$$\kappa_{neo} \sim n\frac{\rho_s^2 c_s}{\lambda_c} \sim \frac{n^2}{T^{0.5}}$$

$$\Rightarrow T_b \sim n_c^{-6},\ P_b \sim n_c^{-5}$$

H-mode DL $\nu_* \approx 1 \Rightarrow$

$$n_c^{cr} \sim P_{heat}^{0.3}\ B_T^{0.08}\ \frac{I_p^{0.7}}{a^2}$$



# Conclusions:

- ETB model based on requirement that ITG-turbulence is suppressed by density gradient and shear of radial electric field, is proposed
- Barrier width is determined by neutral penetration depth
- By including time variation of plasma parameters and transport along magnetic field lines perturbed by peeling ballooning MHD-mode, type I ELMs can be described
- Model provides a strong degradation in barrier confinement at a density limit where transition into Pfirsch-Schlüter neo-classical regime takes place