Tokamak Stability and Confinement

Do we have enough plasma performance?

- Tokamak plasma operation scenarios for fusion reactor system

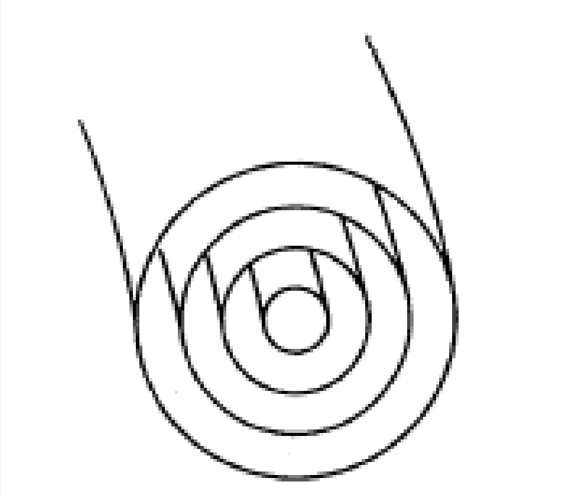
Stability → Operational limit
Transport → Confinement quality
Improved performance scenario → Feasible and sustainable solution

Tokamak Equilibrium

Tokamak equilibrium

- **Free-boundary equilibrium → plasma position and shape**
- **Fixed-boundary equilibrium with plasma pressure profiles**

Ideal MHD $\nabla p = \vec{J} \times \vec{B}$ **Force balance**



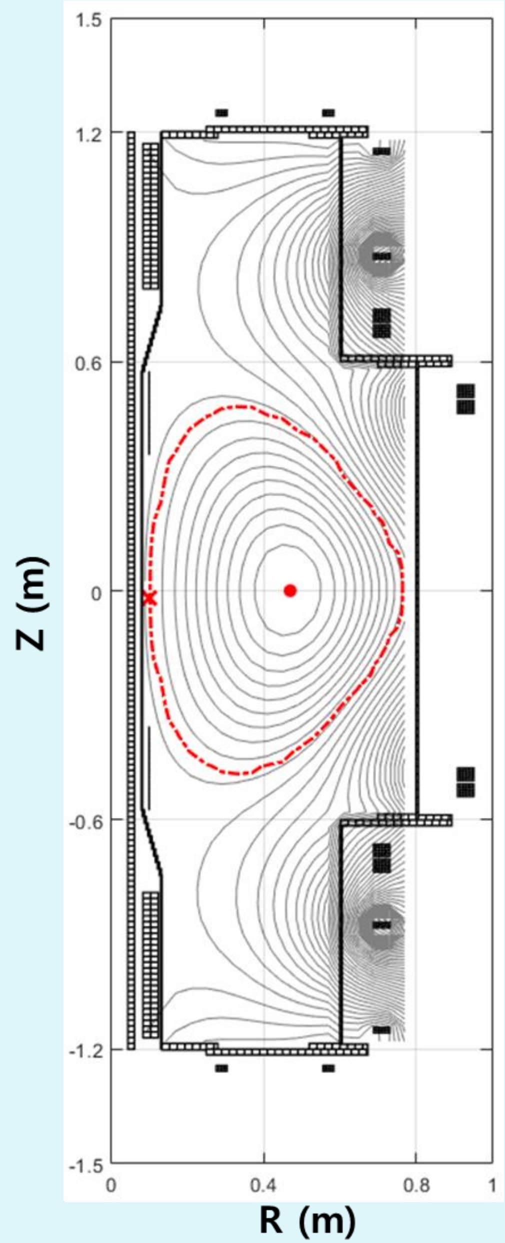
Flux tubes

$$\vec{j} \cdot \nabla p = 0 \qquad \vec{B} \cdot \nabla p = 0 \qquad \mu_o \vec{j} = \nabla \times \vec{B}$$

Grad-Shafranov equation becomes

$$-\mu_o R j_\phi = R \frac{\partial}{\partial R} \frac{1}{R} \frac{\partial \psi}{\partial R} + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_o R^2 \left(\frac{dp}{d\psi} + \frac{\mu_o f}{R} \frac{df}{d\psi} \right)$$

$$j_\phi = j_p + j_{ext} \qquad j_{ext} = \sum_i \delta(\vec{r} - \vec{r}_i)$$

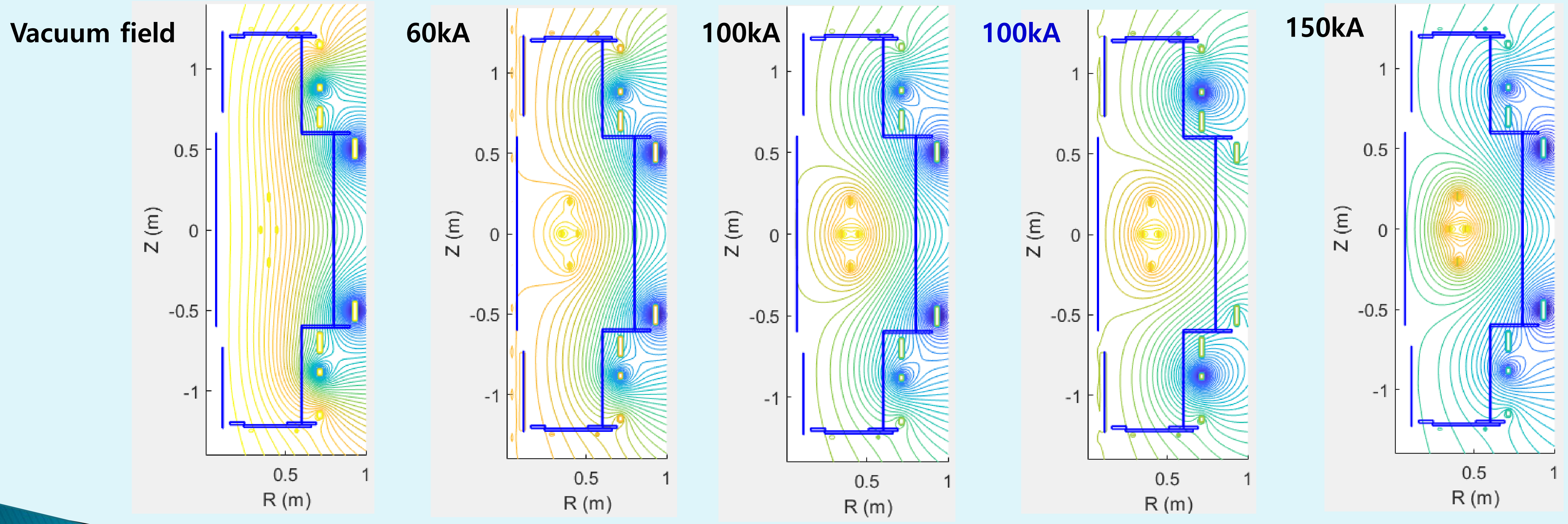


Free-boundary Equilibrium and Stability

Free-boundary equilibrium → plasma position and shape

Force balance

$$j_\phi = j_p + j_{ext} \qquad j_{ext} = \sum_i I_i \delta(\vec{r} - \vec{r}_i)$$



Radial and vertical instabilities (axisymmetric modes)

$0 < n < 3/2$

Fixed-boundary Equilibrium and Stability

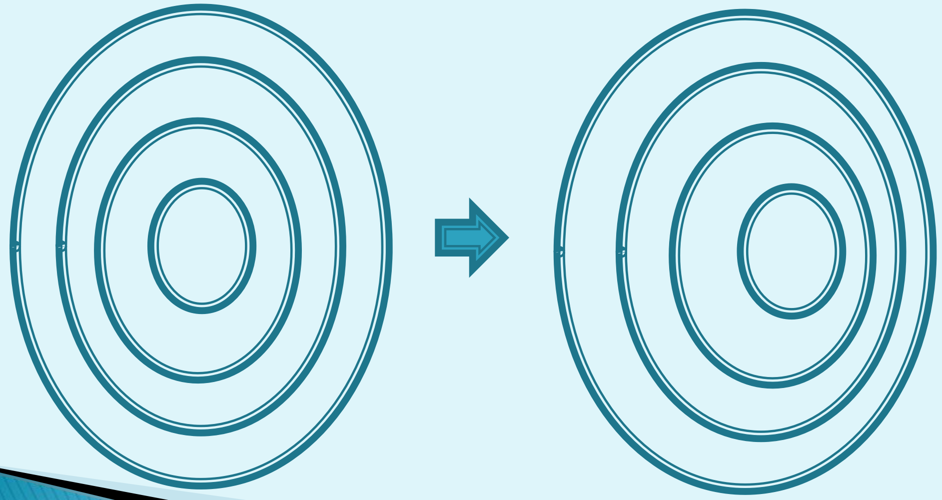
Fixed-boundary equilibrium with plasma pressure and current density profiles

Grad-Shafranov equation becomes

$$-\mu_o R j_\phi = R\frac{\partial}{\partial R}\frac{1}{R}\frac{\partial \psi}{\partial R} + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_o R^2 \left(\frac{dp}{d\psi} + \frac{\mu_o f}{R}\frac{df}{d\psi}\right)$$

Shafranov shift with plasma pressure force

Force balance with compressed magnetic pressure



Ideal MHD instabilities

$$\delta W_p = \frac{1}{2}\int d^3x \left\{ \varepsilon_o c^2 \delta B^2 + \varepsilon_o c^2 (\nabla \times \mathbf{B})\cdot(\xi \times \delta\mathbf{B}) + (\nabla\cdot\xi)(\xi\cdot\nabla p_o) + \gamma p_o (\nabla\cdot\xi)^2 \right\}$$

perturbed magnetic energy

current driven - destabilizing

pressure driven - destabilizing

plasma compression

Pressure-driven Instability

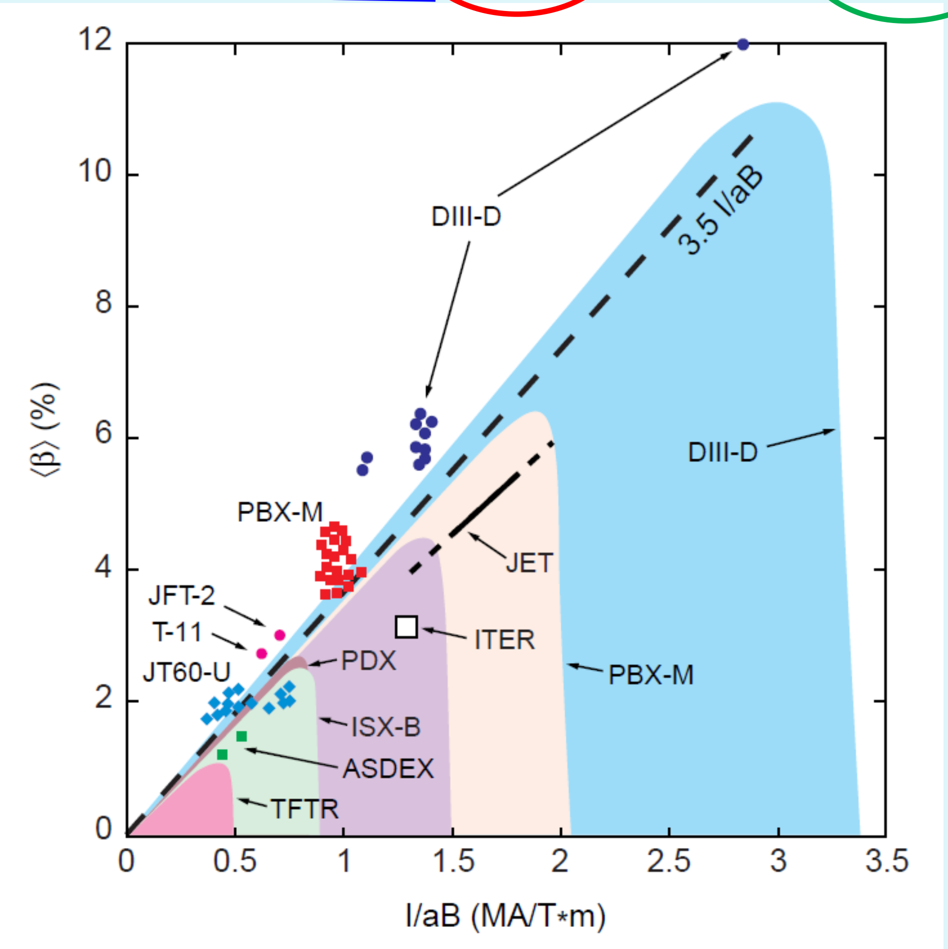
Fixed-boundary equilibrium with plasma pressure and current density profiles

Tryon beta limit

$$\beta[\%] = \beta_N l_i I_P[MA]/a[\mathrm{m}]B_{TF}[T]$$

Ballooning modes

NTM, RWM, etc.

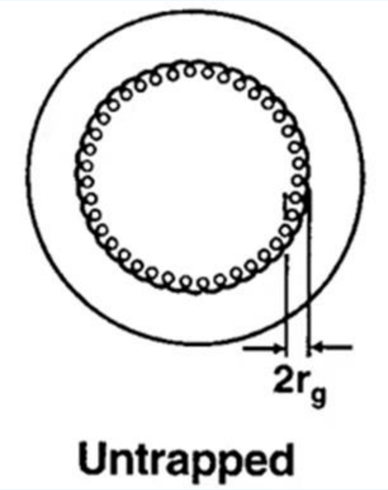


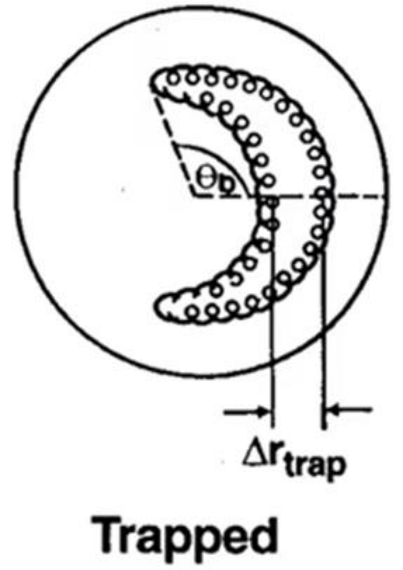
자장 가둠 성능

$$\beta \equiv \langle p \rangle / (B_{TF}^2 / 2\mu_o)$$

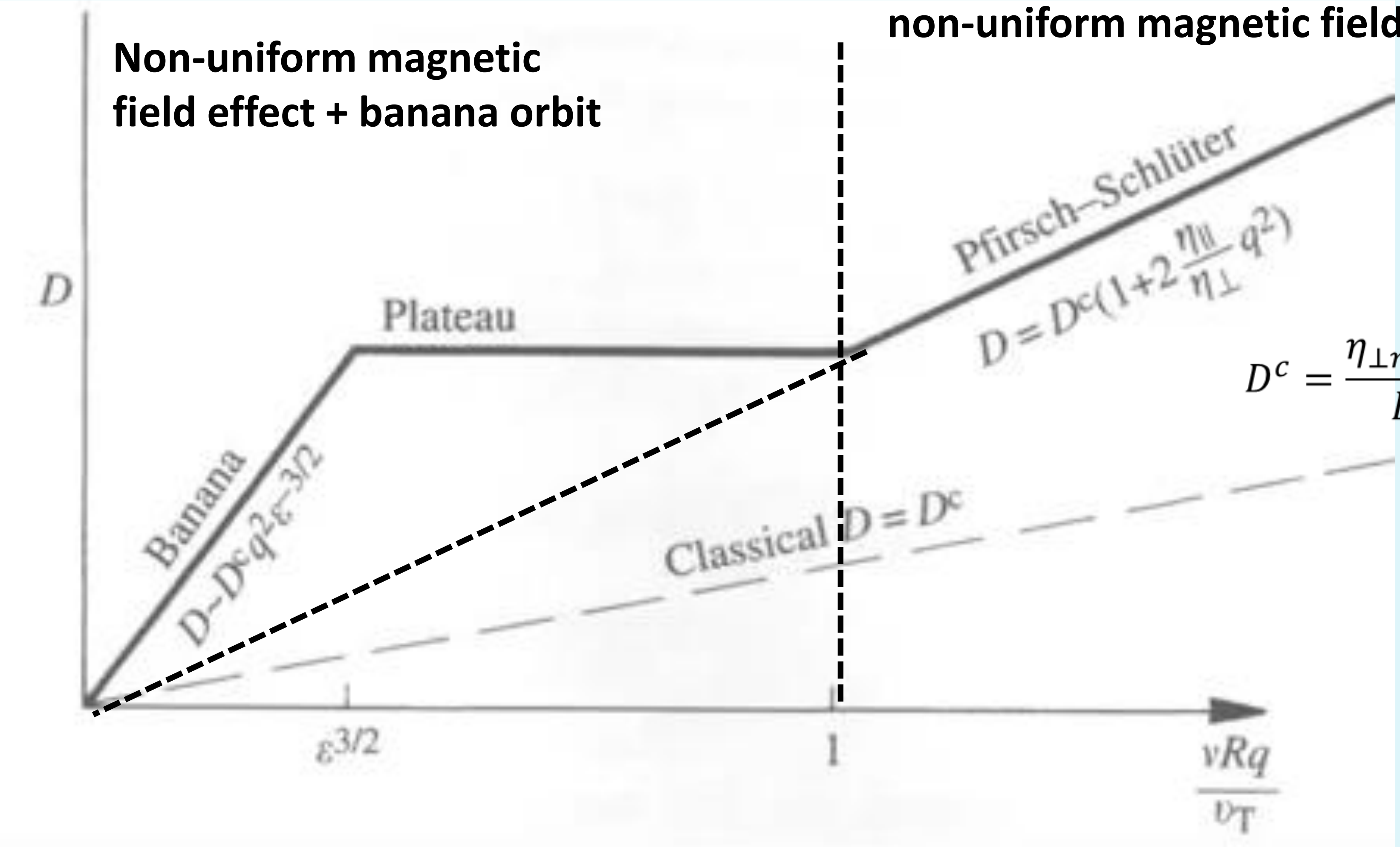
Tokamak Neoclassical Transport

Neoclassical transport





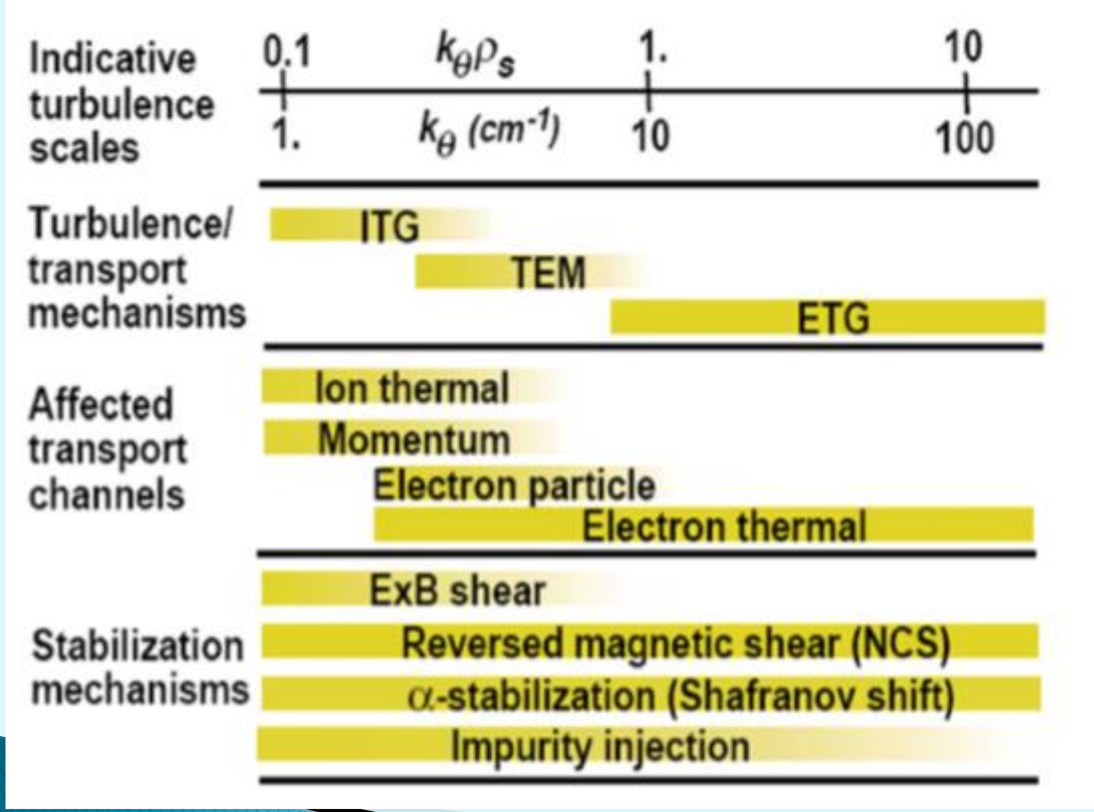
Modified classical diffusion duo to non-uniform magnetic field

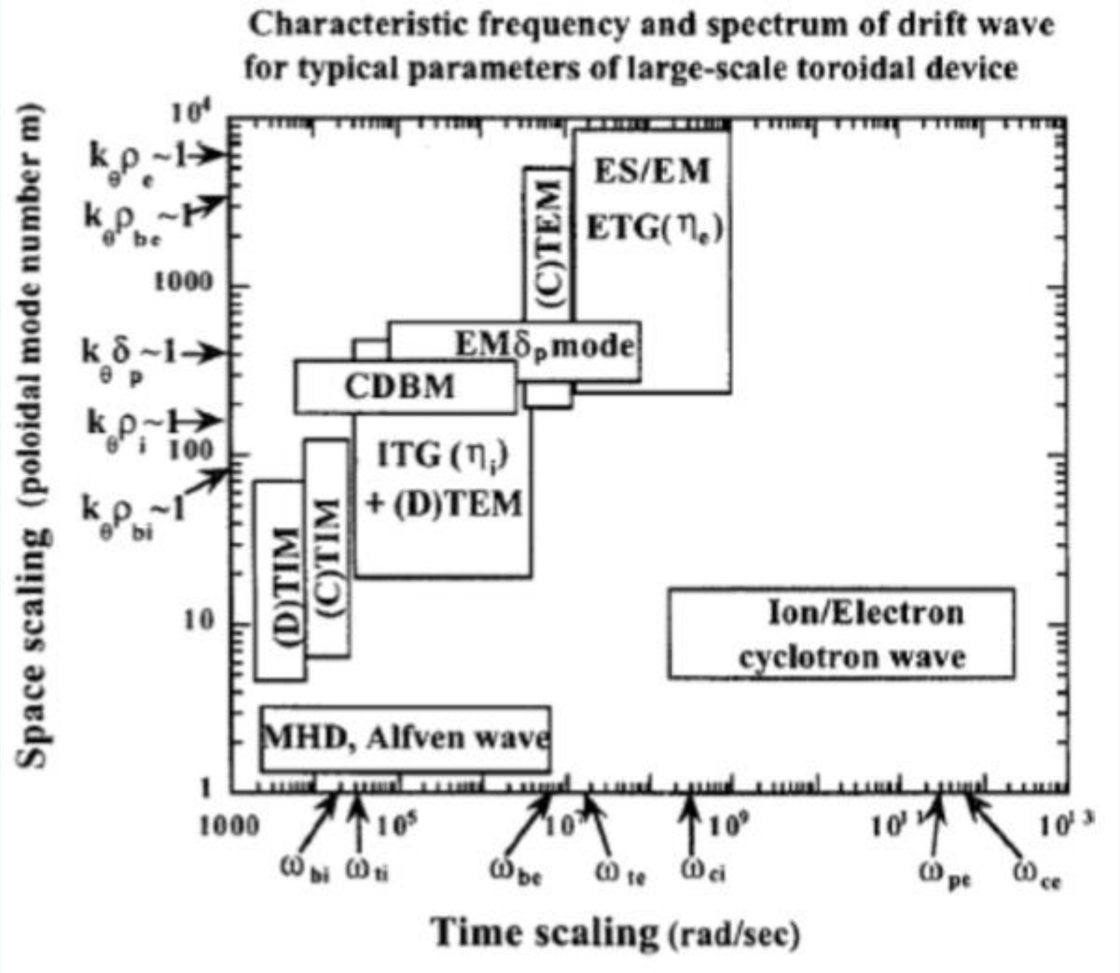


$$D^c = \frac{\eta_\perp n \sum kT}{B^2}$$

Tokamak Anomalous Transport

Outline summary of drift wave turbulence scales, with corresponding turbulence mechanisms, affected transport channels and stabilization mechanisms.





E.J. Doyle (Chair Transport Physics) et al 2007 Nucl. Fusion 47 S18

Transport and Confinement

Local and global transport, global confinement

Three primary predictive techniques

- global scaling,
- transport modelling, and
- non-dimensional scaling

Predictive capabilities for transport and confinement have been improved. Multi-machine experimental databases for constructing global confinement scaling and local transport modelling have been expanded and are applied to the ITER design and projection under the auspices of the ITPA.