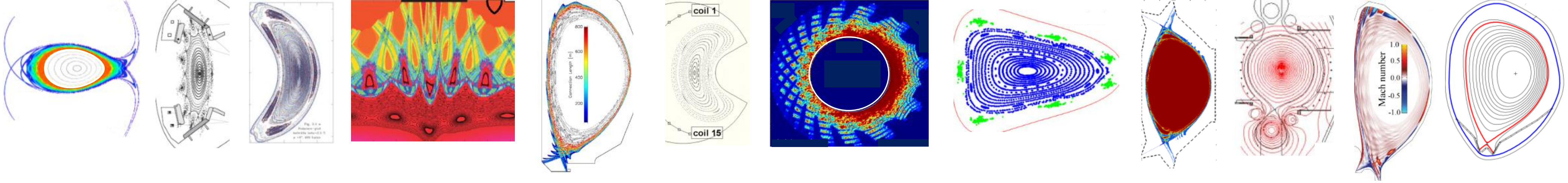

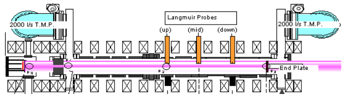

OV/4-4

3D effects of edge magnetic field configuration on divertor/SOL transport and optimization possibilities for a future reactor

M. Kobayashi[1], Y. Feng[2], O. Schmitz[3], K. Ida[1], T.E. Evans[4], H. Frerichs[3], F.L. Tabares[5], Y. Liang[6], Y. Corre[7], Ph. Ghendrih[7], G. Ciraolo[7], A. Bader[3], Y. Xu[8], H.Y. Guo[4,9], J.W. Coenen[6], D. Reiter[6], Z.Y. Cui[8], U. Wenzel[2], N. Asakura[10], N. Ohno[11], D. Tafalla[5], S. Morita[1], S. Masuzaki[1], B.J. Peterson[1], K. Itoh[1] and H. Yamada[1]

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Introduction: background, motivation & goal

- **Tokamak devices:** 2D axi-symmetric configuration + symmetry breaking perturbation
  → 3D configuration

  For edge transport control (Tore Supra, TEXTOR-DED), ELM mitigation/suppression (DIII-D, JET, AUG, MAST, NSTX…, ITER)

- **Helical devices:** Divertor optimization in 3D magnetic configuration is inevitable

- Recent progress of 3D numerical transport codes, systematic experiments, accumulation of experimental data

- **Identification of 3D effects** on SOL/divertor transport, **physical interpretation** & **key parameters** that control the effects, will be useful for divertor optimization in future reactors, taking full advantage of 3D configurations.

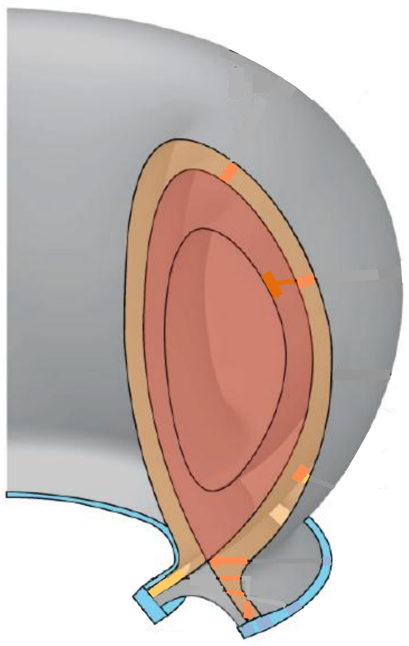
↓

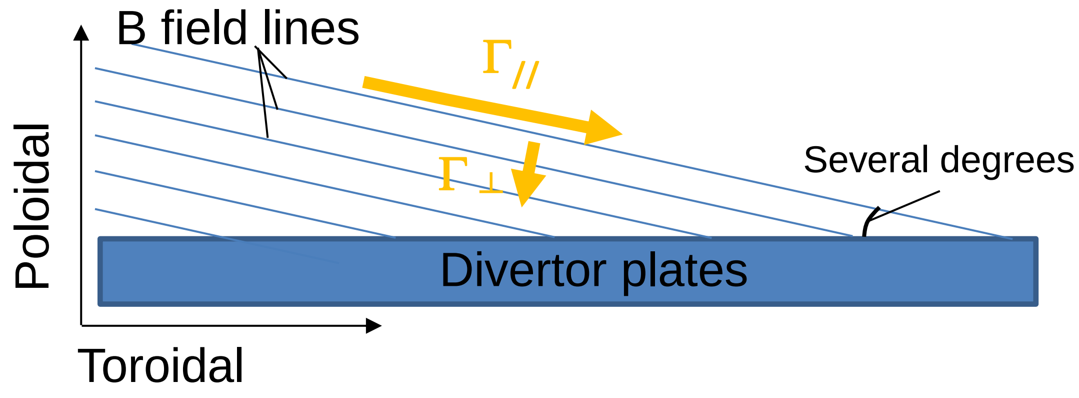
Multi-machine comparison between tokamak and helical devices.
Impacts of 3D configuration on the divertor functions.

Outline of the talk

1. Introduction
2. Definition of 3D effects
3. Impact on divertor density regime
4. Impact on impurity transport
5. Impact on detachment control
6. Summary

Transport in 2D axi-symmetric configuration





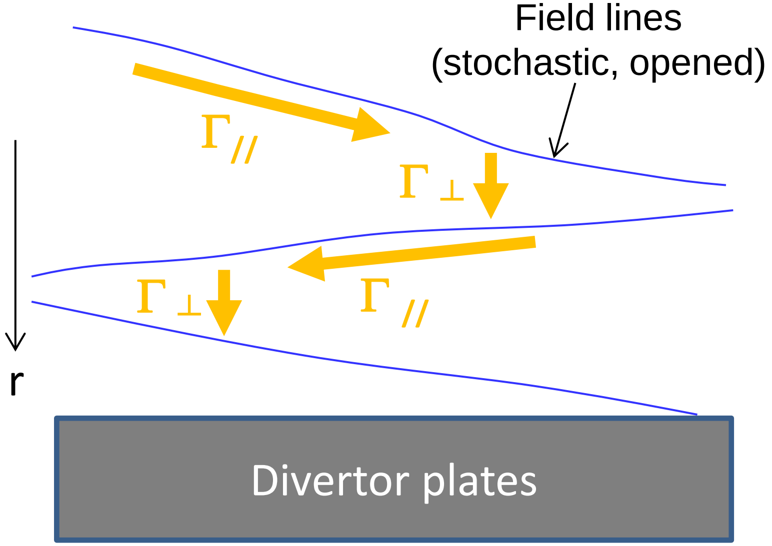
$$\frac{B_\theta}{B_t} \sim 0.1 \qquad \frac{\Gamma_{//}}{\Gamma_\perp} = 10^5 \sim 10^8$$

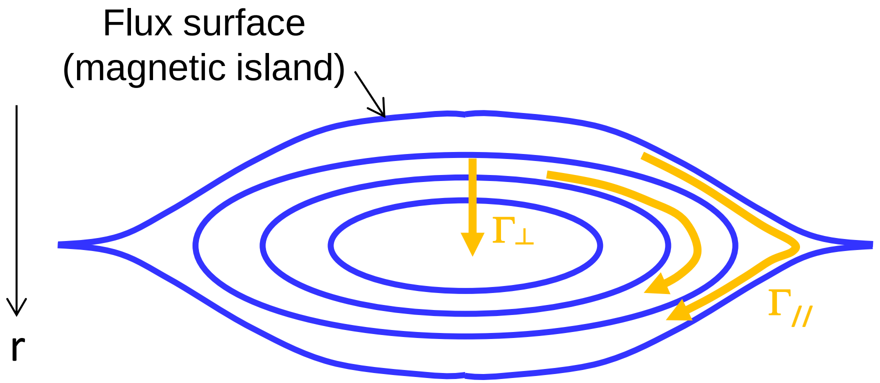
$$\Gamma_{//}\left(\frac{B_\theta}{B_t}\right)^2 >> \Gamma_\perp$$

//-transport is dominant to deliver plasma quantity from upstream to divertor plates.

Magnetic field structure & "3D effects"

3D effects: Competition between // and ⊥ transport, which originates from structural/topological change of magnetic field lines, such as **openness of stochastic field lines**, or formation of **magnetic island**.





$$\frac{B_r}{B_t} = 10^{-4} \sim 10^{-3} \quad \frac{\Gamma_{//}}{\Gamma_{\perp}} = 10^{5} \sim 10^{8}$$

3D effect emerges

$$\Gamma_{//}\left(\frac{B_r}{B_t}\right)^2 \sim \Gamma_{\perp}$$

B field is prescribed for present analysis.
→ Self-consistent inclusion of dynamics of B field change due to plasma response is future work.

OV/2-3 K.Ida et al. (Monday) **EX/1-3 T. Evans et al. (Tuesday)**

Impact on divertor density regime

Absence of high recycling regime prior to detachment in the 3D configurations

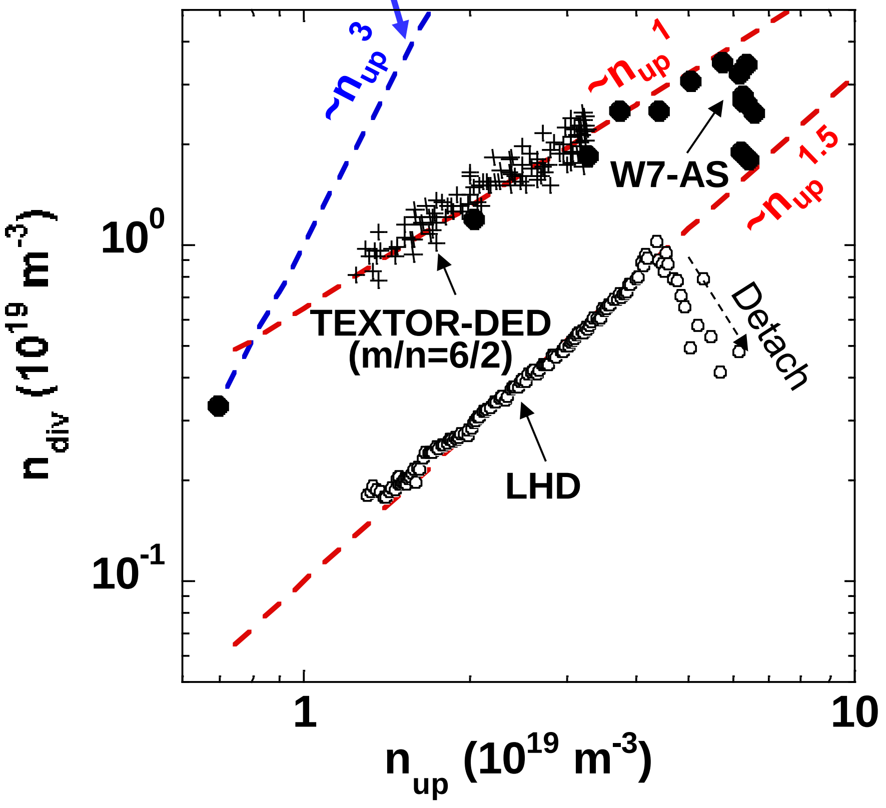
In helical devices as well as tokamaks with RMP, the modest density dependence is often observed.

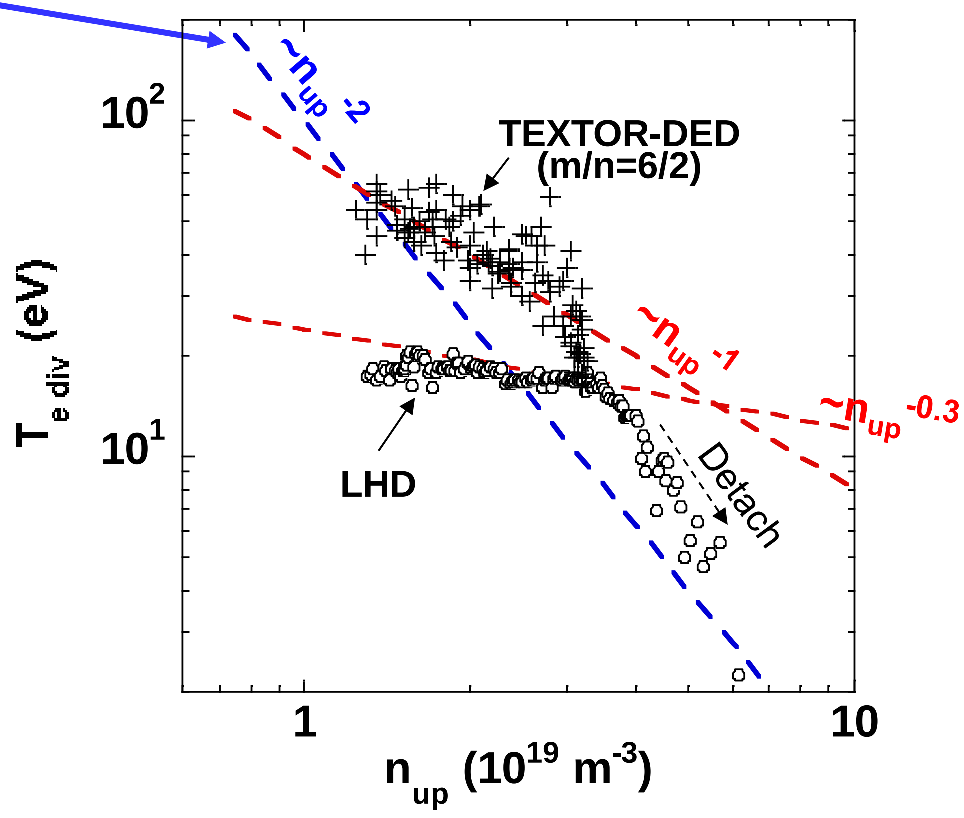
High recycling in 2D tokamaks

$n_{div} \propto n_{up}^{3} \quad T_{div} \propto n_{up}^{-2}$

The modest dependence in 3D configuration

$n_{div} \propto n_{up}^{\sim 1} \quad T_{div} \propto n_{up}^{\sim -1}$



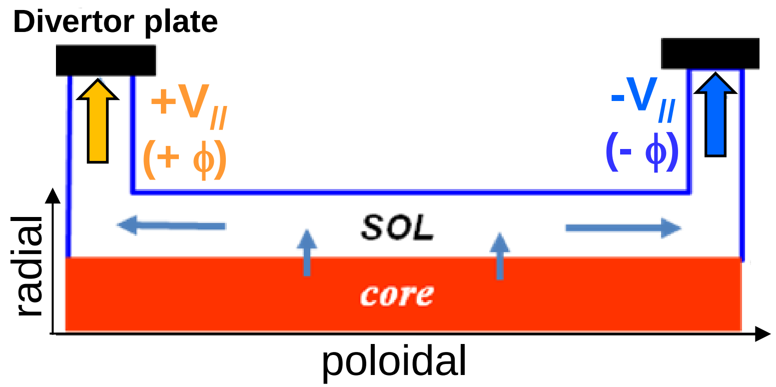


Y. Feng et al., PPCF **44** (2002) 611.
M. Clever et al., Nucl. Fusion **52** (2012) 054005.
S. Masuzaki et al., JNM **313-316** (2003) 852.

Effects of enhanced ⊥ interaction of momentum transport on divertor regime

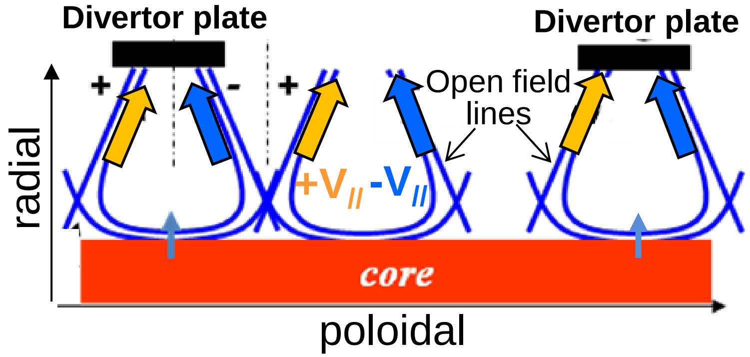
2D axi-symmetric divertor

Pressure conservation along flux tube



3D configuration (e.g. stochastic layer, ID)

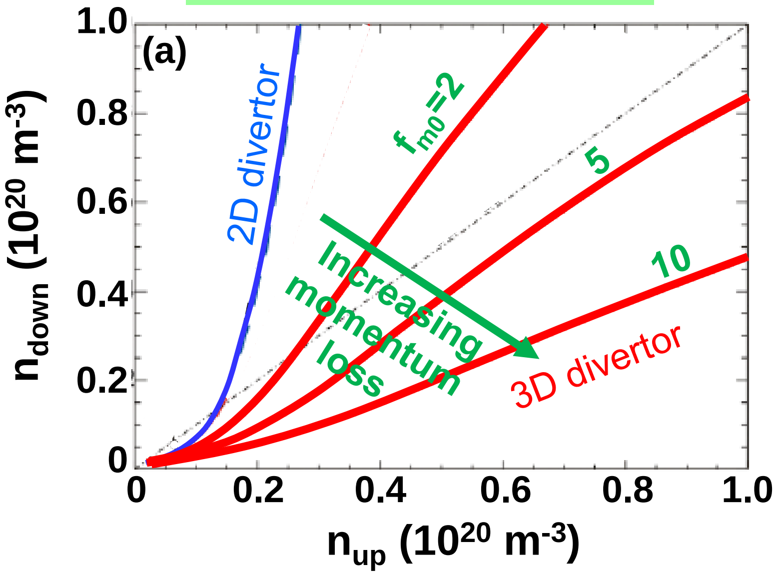
//-Momentum loss due to counter flows



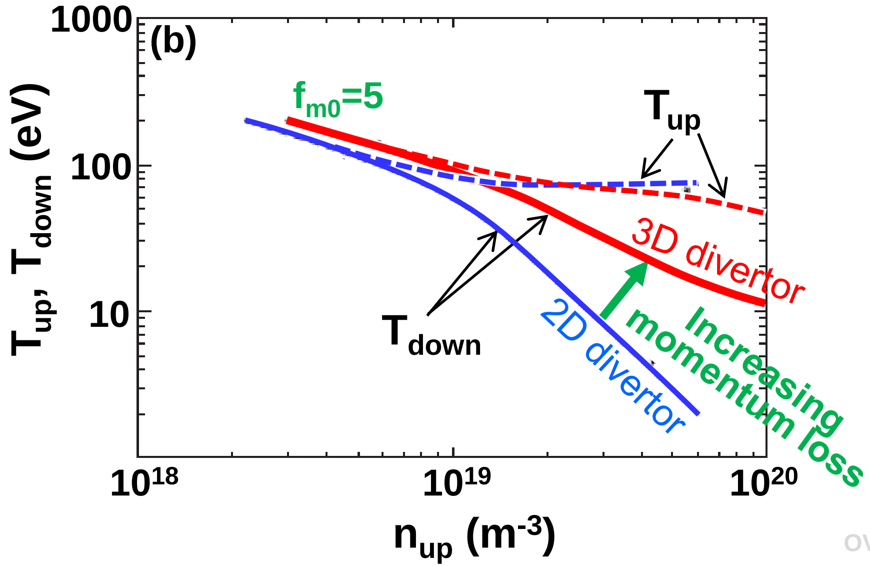
➢ ⊥ loss of //-Momentum $\frac{\tau_{m//}}{\tau_{m\perp}} = \frac{D_\perp L_{//}}{V_{//}\lambda_m^{2}} \propto f_{m0}$

Y. Feng et al., Nucl. Fusion **46** (2006) 807.

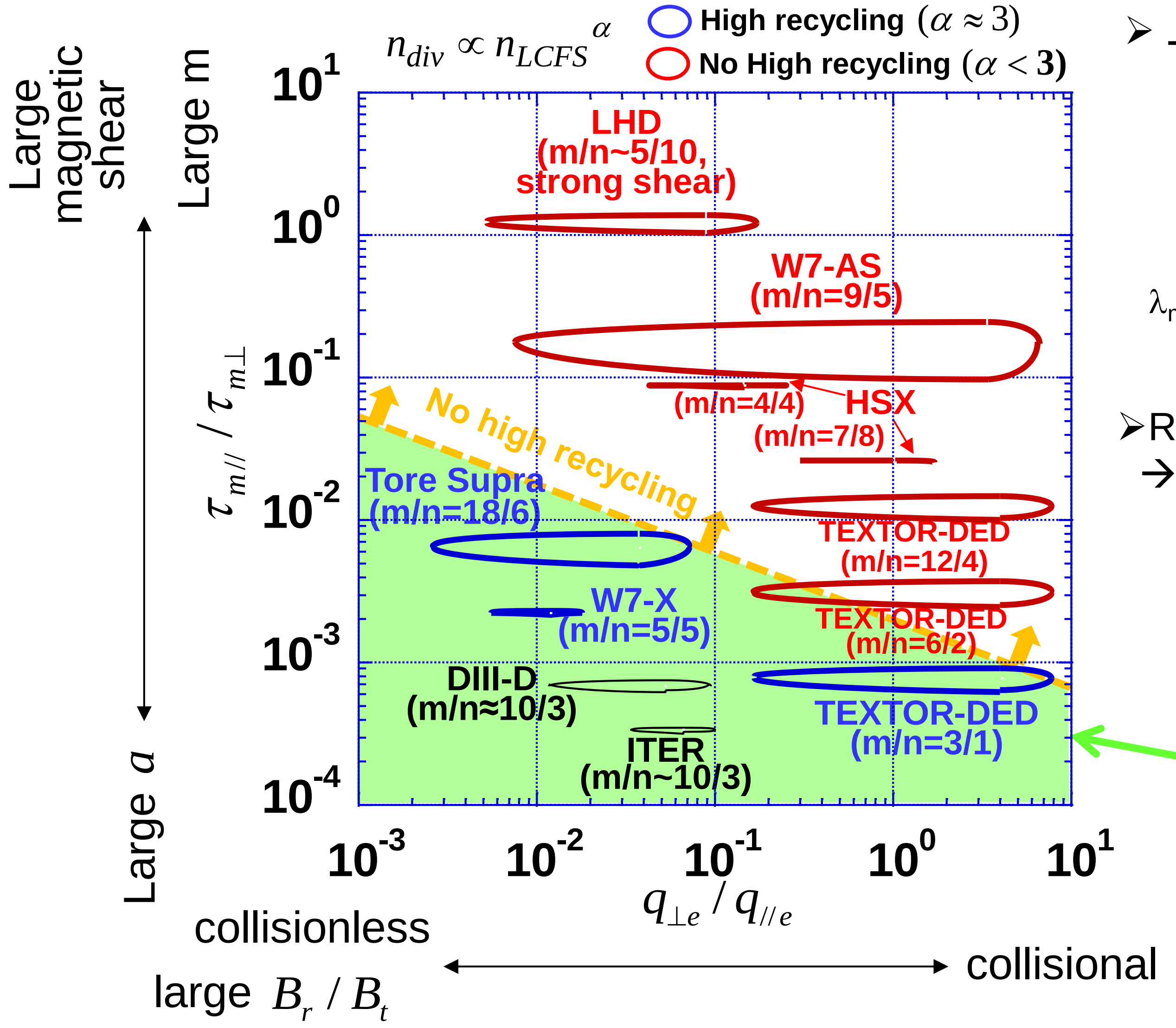
n_{down} is suppressed



//-Temperature drop T_{up}/T_{down} becomes small



Multi-machine comparison for divertor density regime



- ⊥ loss of //-Momentum
  → //-pressure drop $p_{LCFS} > p_{div}$

$$\frac{\tau_{m//}}{\tau_{m\perp}} = \frac{D_{\perp} L_{//}}{V_{//} \lambda_m^2}$$

λ_m: ⊥ characteristic scale length for momentum loss (e.g. ~2πa/m)

- Replacement of //-energy flux with ⊥ -flux
  → reduction of //-conduction energy

$$\frac{q_{\perp e}}{q_{//e}} = \frac{n \chi_{\perp e}}{(B_r / B_t)^2 \kappa_{0e} T_e^{2.5}}$$

Operation domain for high recycling regime

$$\left(\frac{\tau_{m//}}{\tau_{m\perp}}\right)^2 \left(\frac{q_{\perp e}}{q_{//e}}\right) < 4 \times 10^{-6}$$

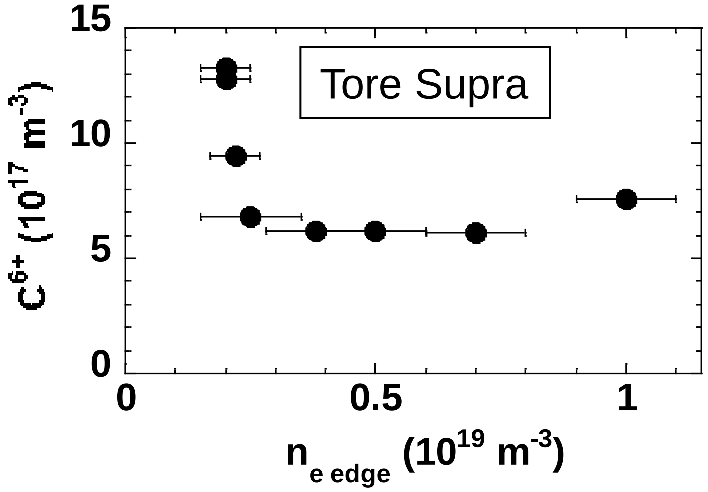
Possible Impacts on divertor functions due to the absence of high recycling regime:
Pumping efficiency ↓, physical sputtering ↑, detach. onset density ↑ (!?)

Can be avoided in detached phase | **Preferable for core performance**

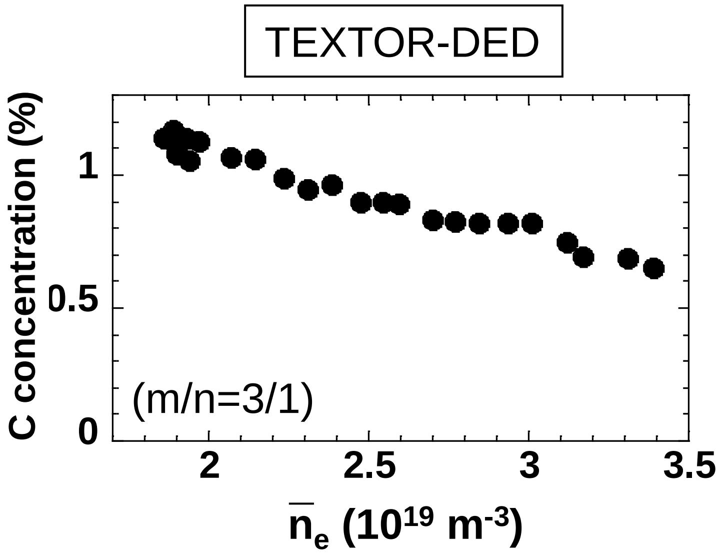
Impact on Impurity screening

Impurity screening has been observed in many devices with edge stochastic layer

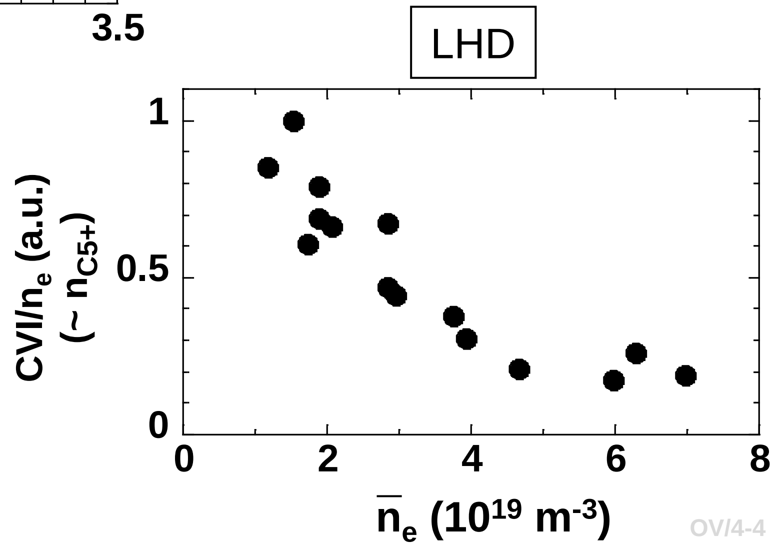
Experiments with density scan shows better screening at high density (low Te)



Y. Corre et al., Nucl. Fusion **47** (2007) 119.



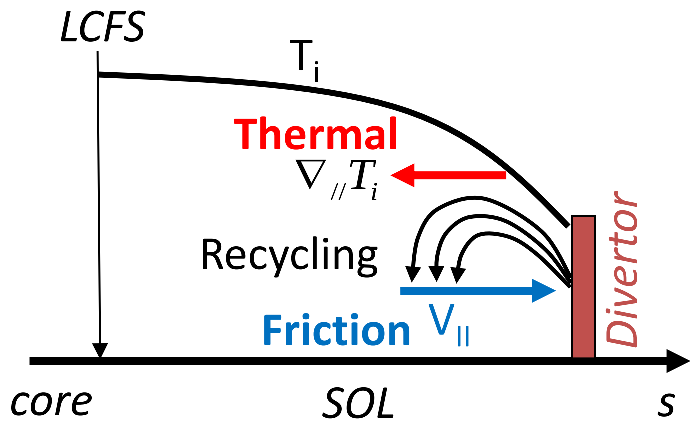
M. Lehnen et al., PPCF **47** (2005) B237.



Interpretation of the impurity screenings: key parameters

//-transport model for impurity momentum

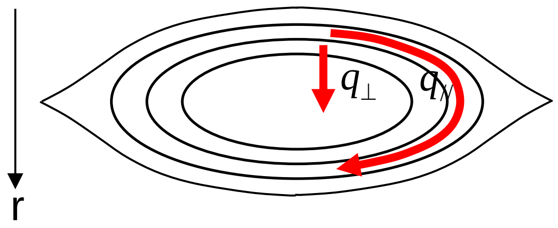
$$m_z \frac{\partial V_{z//}}{\partial t} = \underbrace{m_z \frac{V_{i//} - V_{z//}}{\tau_s}}_{\text{Friction force}} + \underbrace{2.6 Z^2 \nabla_{//} T_i}_{\text{Ion thermal force}} + \dots$$



- ➢With B_r, outward plasma flow ($V_{//}$) is enhanced
  - → particle confinement time ↓
  - → recycling ↑ → **friction force** ↑

$$\frac{D_{st}}{D_\perp} = \frac{(B_r / B_t)^2 V_{//} L_{//}}{D_\perp}$$

- ➢Replacement of //-energy flux ($q_{//}$) with ⊥-flux ($q_\perp$) for ion
  - → $q_{//i} = \kappa_{0i} T_i^{2.5} \nabla_{//} T_i$ ↓ → **thermal force** ↓



$$\frac{q_{\perp i}}{q_{//i}} = \frac{n \chi_{\perp i}}{(B_r / B_t)^2 \kappa_{0i} T_i^{2.5}}$$

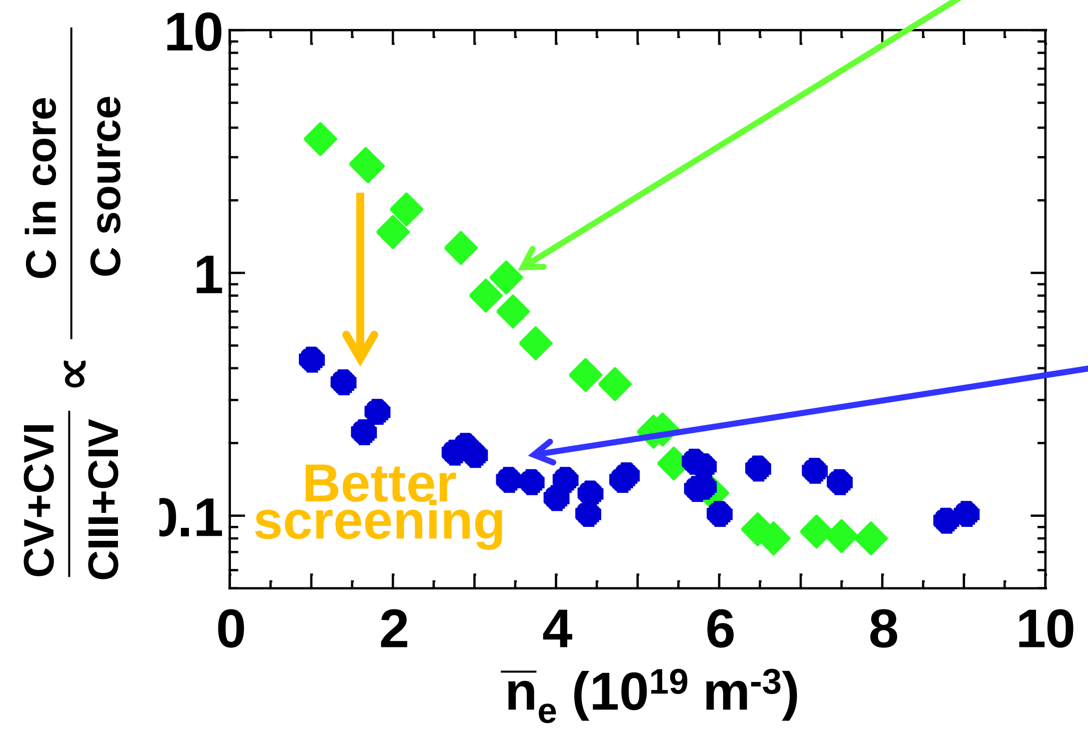
Y. Feng et al., NF **46** (2006) 807.

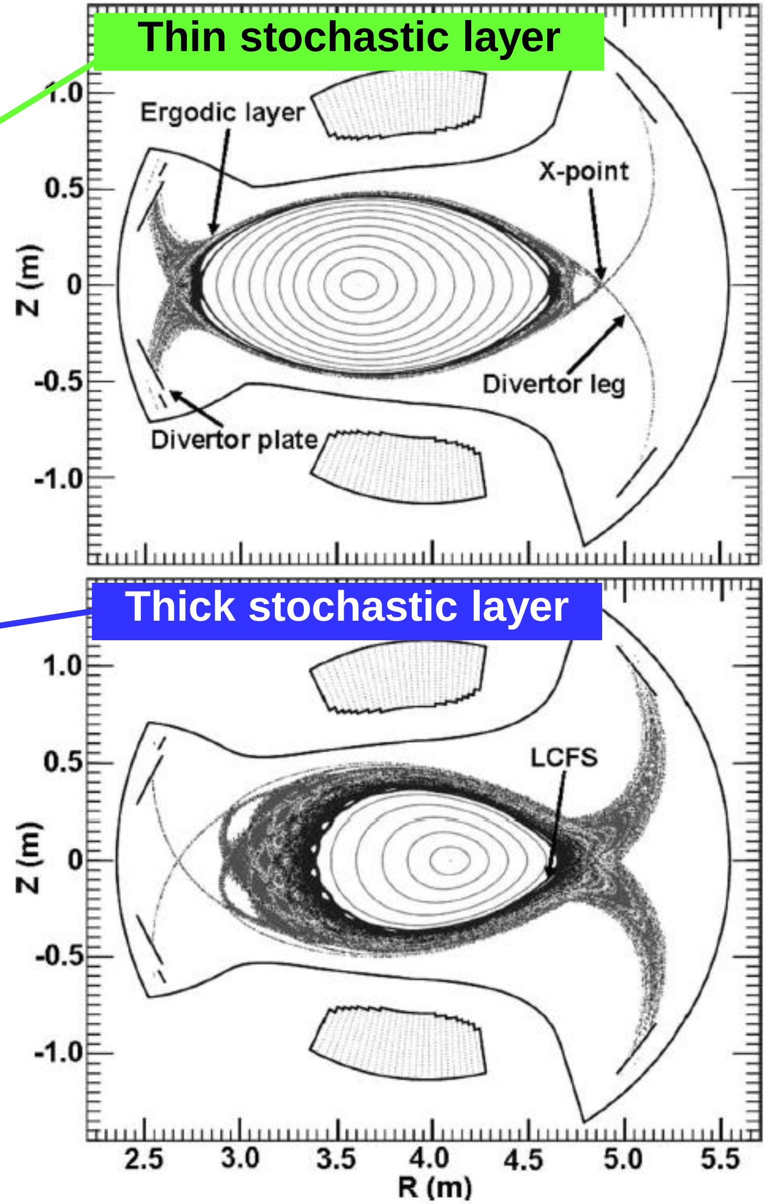
SOL thickness dependence of impurity screening: thicker stochastic SOL → better screening already at low density

- Thicker stochastic layer/SOL (λ_{st-SOL}) relative to neutral impurity penetration (λ_{imp})

  $\lambda_{st-SOL} / \lambda_{imp}$ ↑→ better screening

LHD

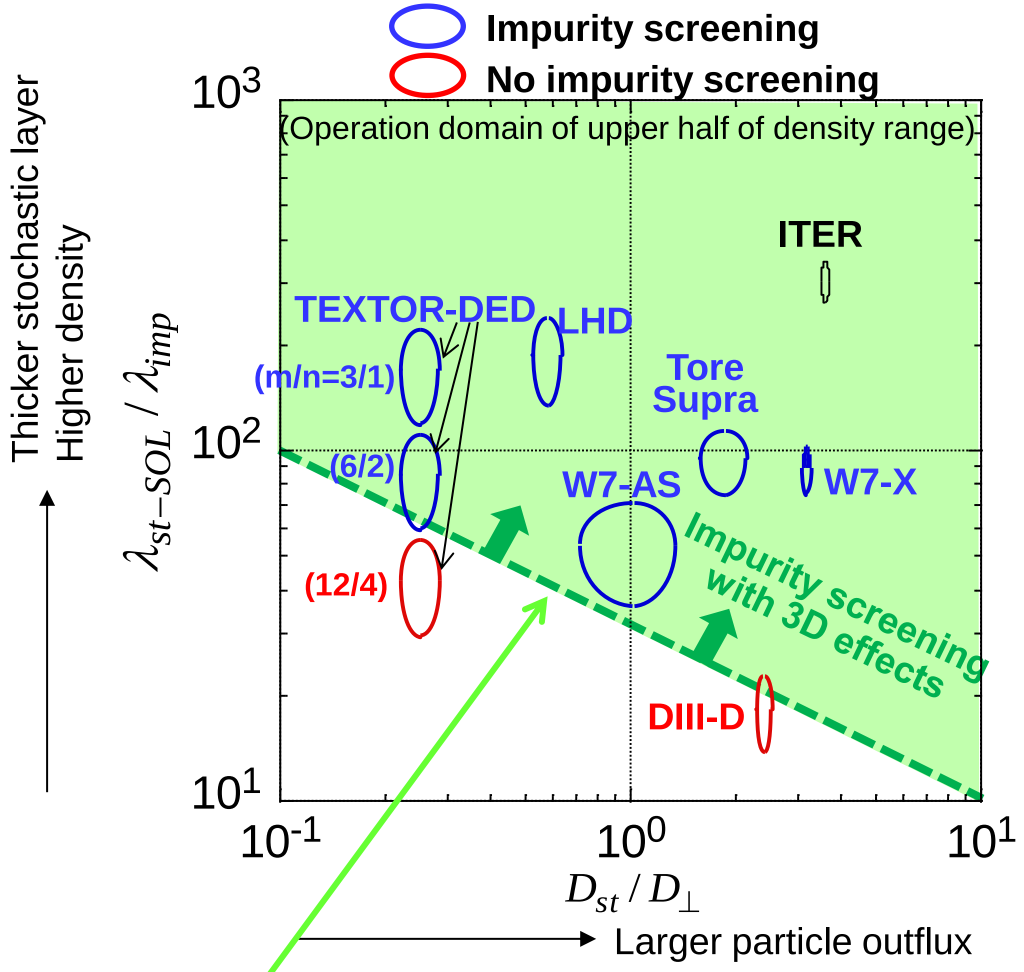




M.B. Chowdhuri et al., Phys. Plasmas **16** (2009) 062502.

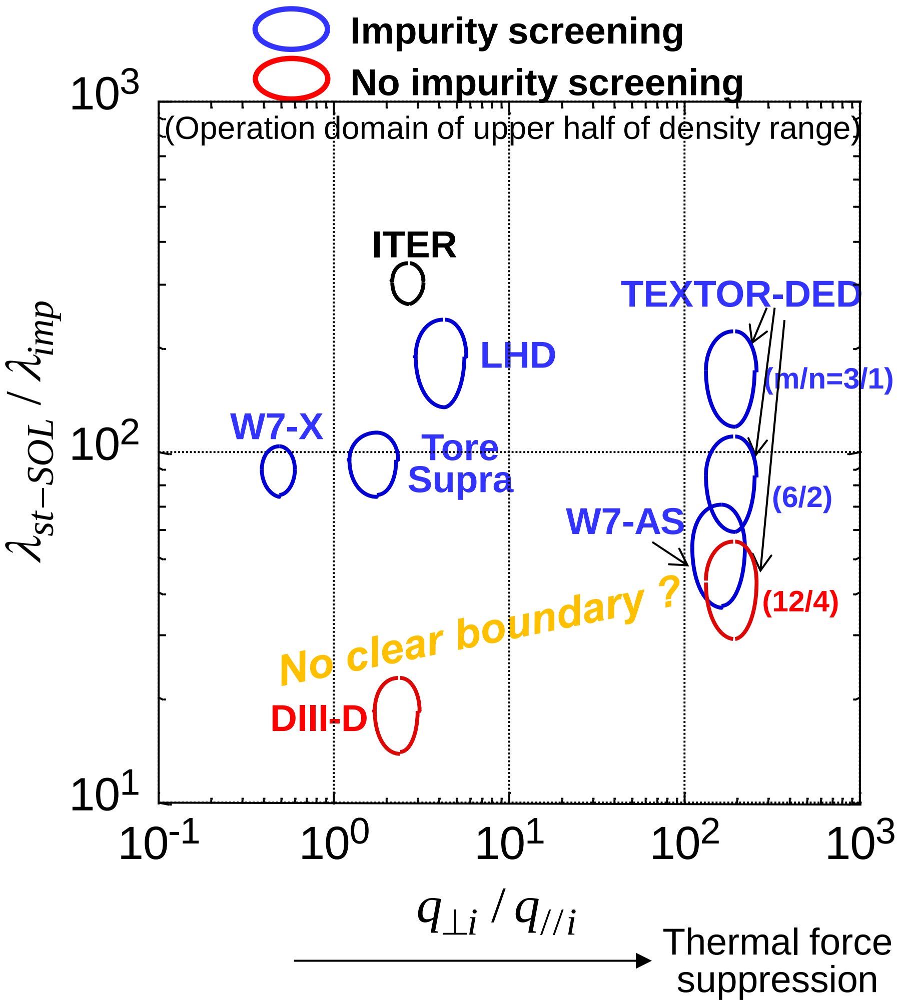
Multi-machine comparison for impurity screening at high density range

Operation domain of upper half of density range ← impurity screening is usually observed at high density



Operation domain for Impurity screening

$$\left(\frac{\lambda_{st-SOL}}{\lambda_{imp}}\right)^2\left(\frac{D_{st}}{D_\perp}\right) > 10^3$$



- ➢ **Thicker stochastic layer/SOL & enhanced particle transport seem to provide screening effects.**
- ➢ No clear boundary identified in the parameterization with thermal force suppression.

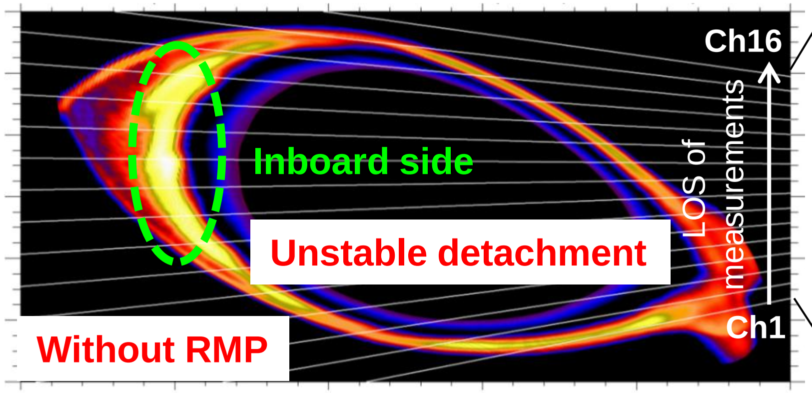
Further study: Quantification of screening, impurity injection energy, source location, drift, E field, turbulent transport

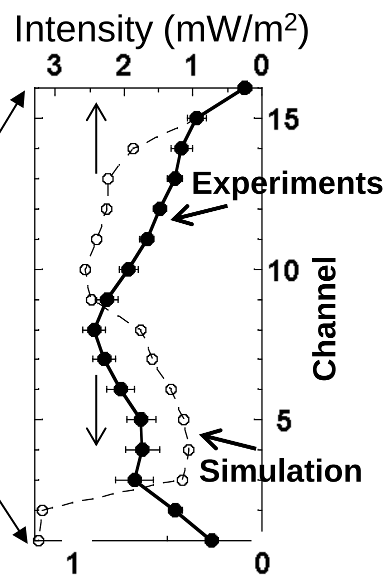
Impact on detachment control

Detachment stabilization with RMP application (LHD, W7-AS)

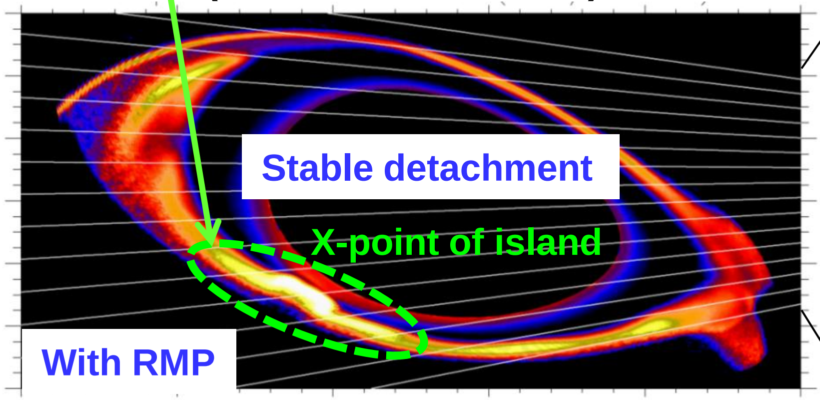
LHD

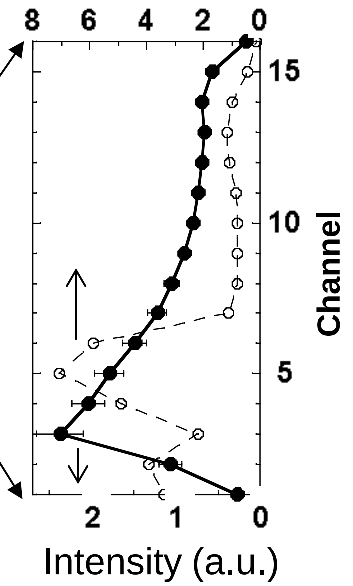
Carbon radiation distribution by EMC3-EIRENE





Radiation condensation at X-point (MARFE like behavior)

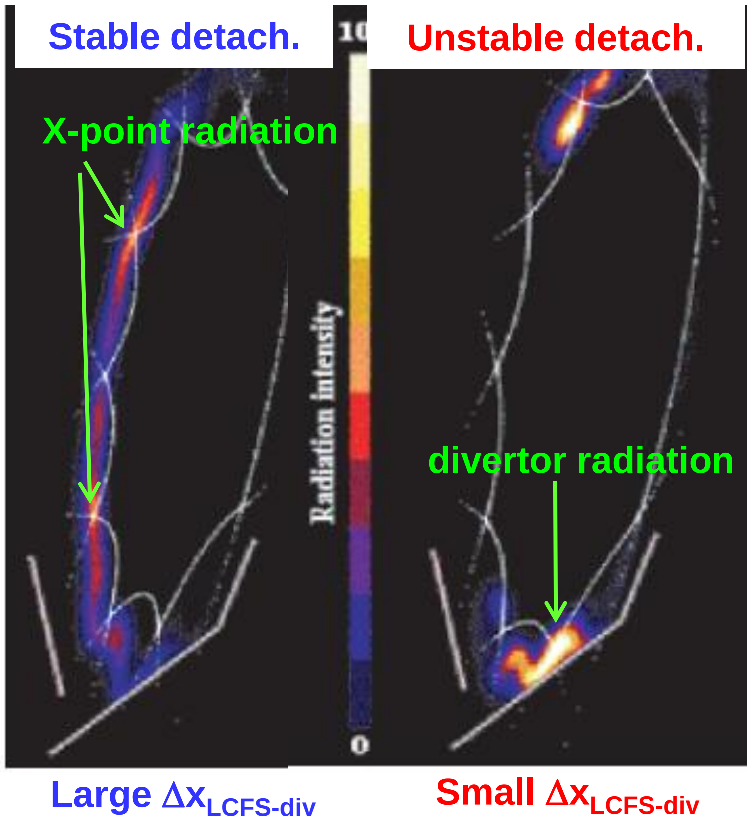




EX/P6-26 N. Ohno et al. (Thursday)

W7-AS

Carbon radiation distribution by EMC3-EIRENE



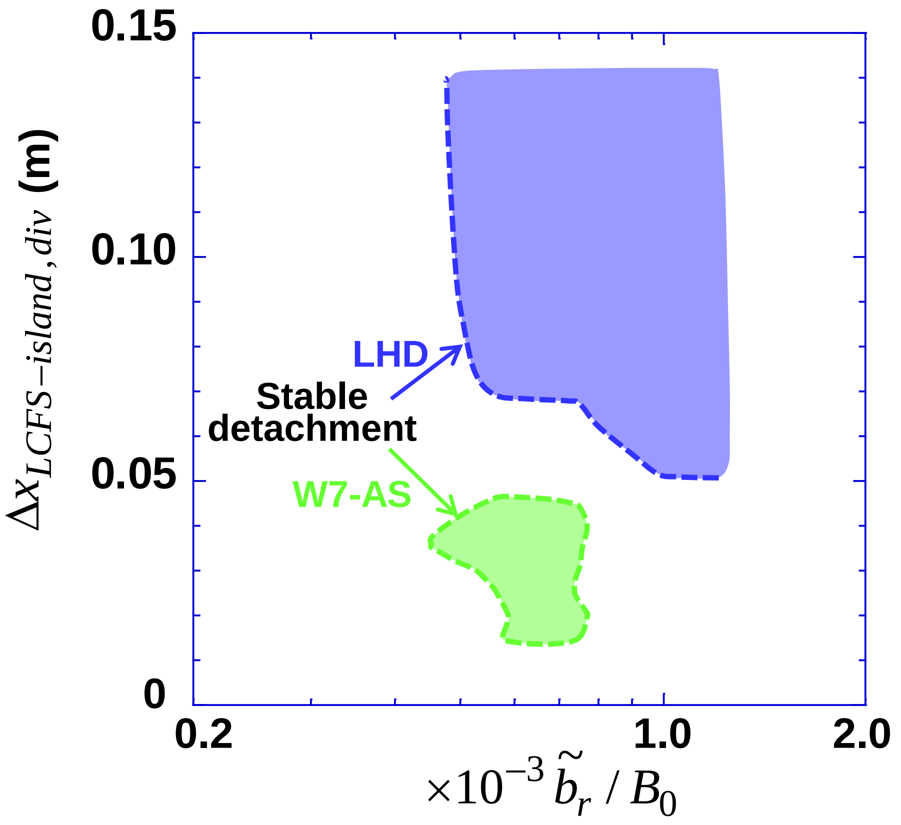
Y. Feng et al., NF **45** (2005) 89.

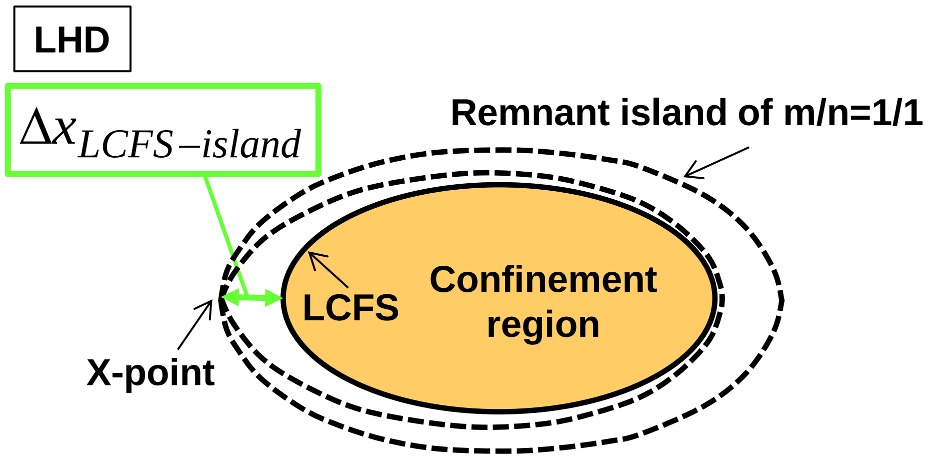
- **Modification of 3D edge radiation structure with RMP application → stable detachment**
- **Separation between radiation region & confinement region is important factor for stable detachment**

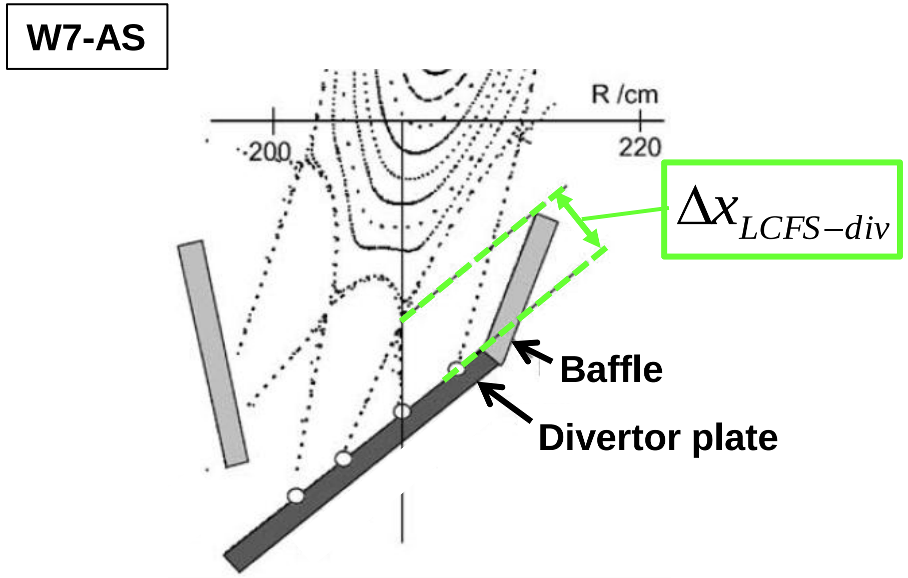
M. Kobayashi et al., Nucl. Fusion **53** (2013) 093032.

Operation domain of stable detachment in LHD & W7-AS

Key geometric parameters: $\Delta x_{LCFS-island,div}$, $\tilde{b}_r / B_0$



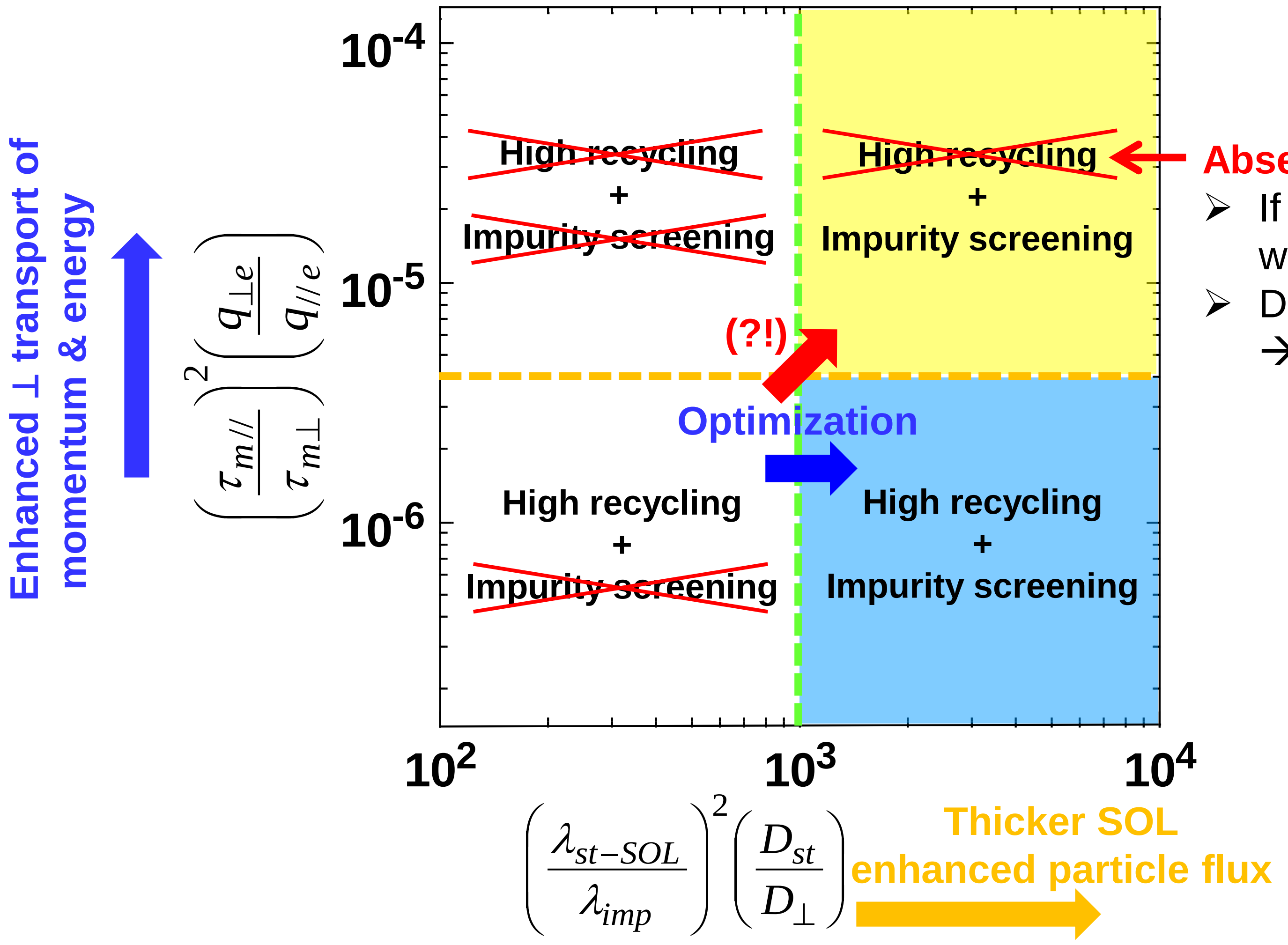




<u>Conditions for stable detachment</u>
1) RMP field must be strong enough (intrinsic ones insufficient, additional MP needed).
2) the geometric SOL width ($\Delta x_{LCFS-island,div}$) must be sufficiently large.

Recently the effects of RMP on detachment are being investigated in NSTX, DIII-D, too.

Optimization possibility for a future reactor



Absence of high recycling regime:

- If pumping efficiency is sufficient with proper baffle/divertor design
- Detached phase
  → physical sputtering is suppressed

Candidate for optimization

Summary

➢**The 3D effects** : competition between transports parallel (//) and perpendicular (⊥) to magnetic field, in open stochastic field lines or magnetic islands.

➢**The competition process affects energy, particle and momentum transport in divertor/SOL region**

♦ **Density regime** → absence of high recycling regime

Momentum loss via ⊥-transport, enhanced ⊥-energy transport, //-convection energy flux

Operation domain for high recycling: $\left(\frac{\tau_{m//}}{\tau_{m\perp}}\right)^2 \left(\frac{q_{\perp e}}{q_{//e}}\right) < 4\times10^{-6}$

♦ **Impurity screening**

Friction force enhancement, ion thermal force suppression, thicker SOL with stochastization & ID

Operation domain for impurity screening: $\left(\frac{\lambda_{st-SOL}}{\lambda_{imp}}\right)^2 \left(\frac{D_{st}}{D_{\perp}}\right) > 10^3$

→Need further study on quantification of screening efficiency, source characteristics, E-field, turbulence

♦ **Detachment stability**

Radiation modification by RMP, sufficiently large $\tilde{b}_r / B_0$, separation between radiation region & confinement region $\Delta x_{LCFS-island,div}$

→ Detachment stabilization

Further study: Edge E-field/turbulence, plasma response to MP, Divertor heat load (strike-line splitting), ELM mitigation/suppression, control of high-Z impurity

Systematic understandings of the impact of 3D divertor configurations will open new perspective on divertor optimization for future reactors.

Absence of high recycling regime prior to detachment in the 3D configurations

In helical devices as well as tokamaks with RMP, the modest density dependence is often observed.

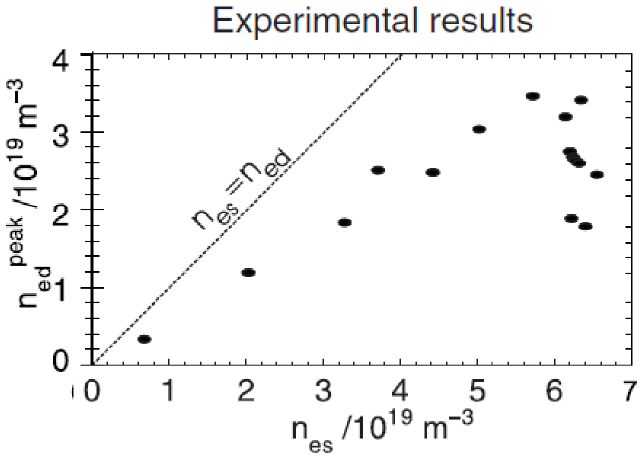
High recycling in 2D tokamaks

$$n_{div} \propto n_{up}^{3} \quad T_{div} \propto n_{up}^{-2}$$

The modest dependence in 3D configuration

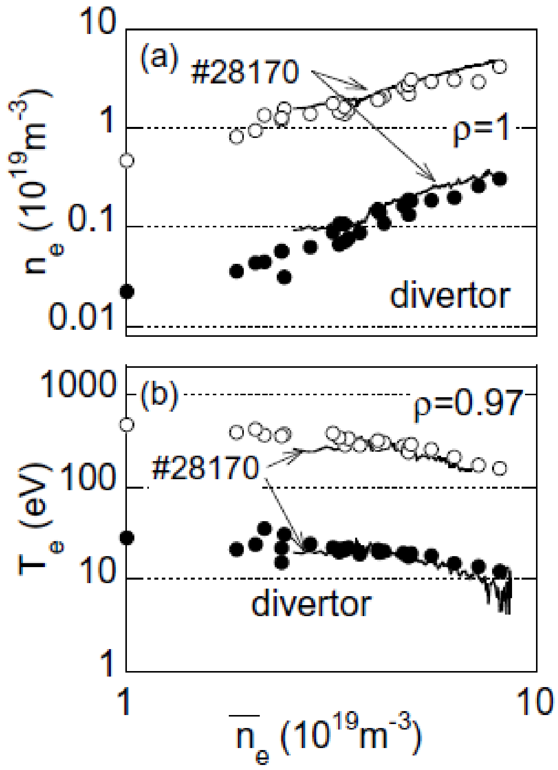
$$n_{div} \propto n_{up}^{\sim 1} \quad T_{div} \propto n_{up}^{\sim -1}$$

W7-AS

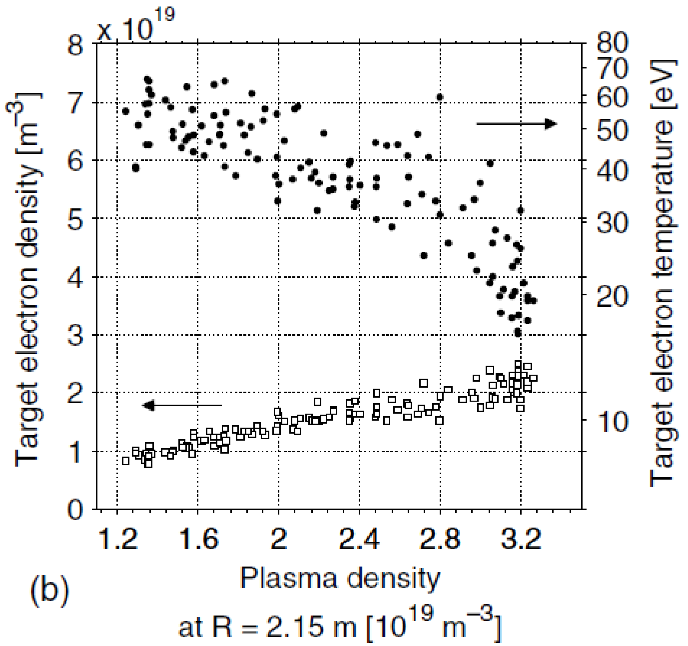


Y. Feng et al., PPCF **44** (2002) 611.

LHD



TEXTOR-DED (m/n=6/2)



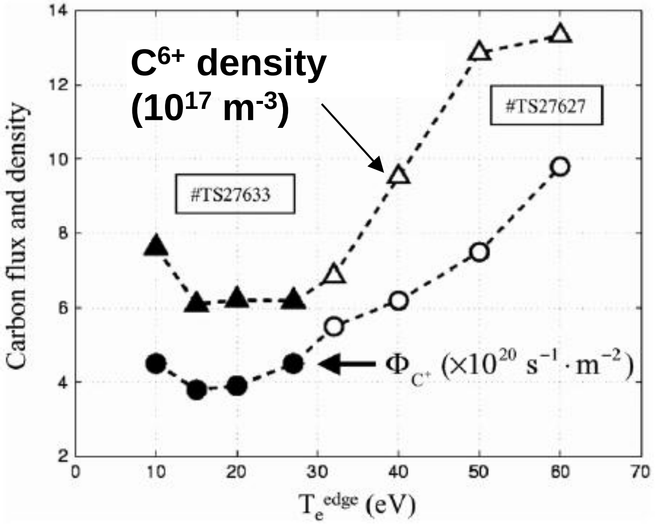
M. Clever et al., Nucl. Fusion **52** (2012) 054005.

S. Masuzaki et al., JNM **313-316** (2003) 852.

Impurity screening has been observed in many devices with edge stochastic layer

Experiments with density scan shows better screening at high density (low Te)

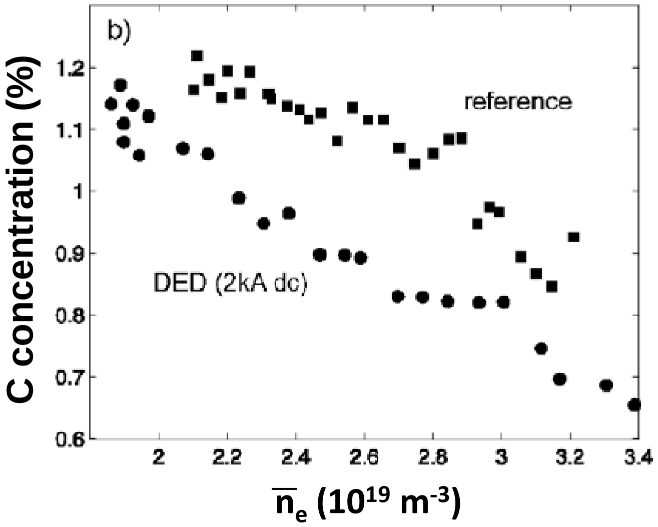
Tore Supra



Higher n

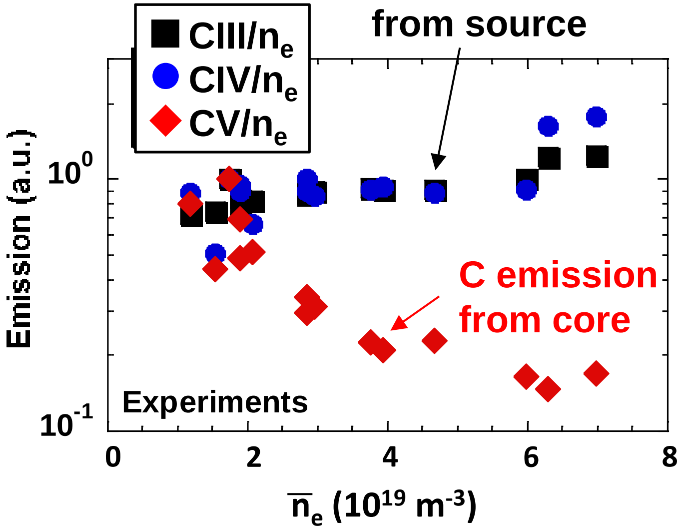
Y. Corre et al., Nucl. Fusion **47** (2007) 119.

TEXTOR-DED



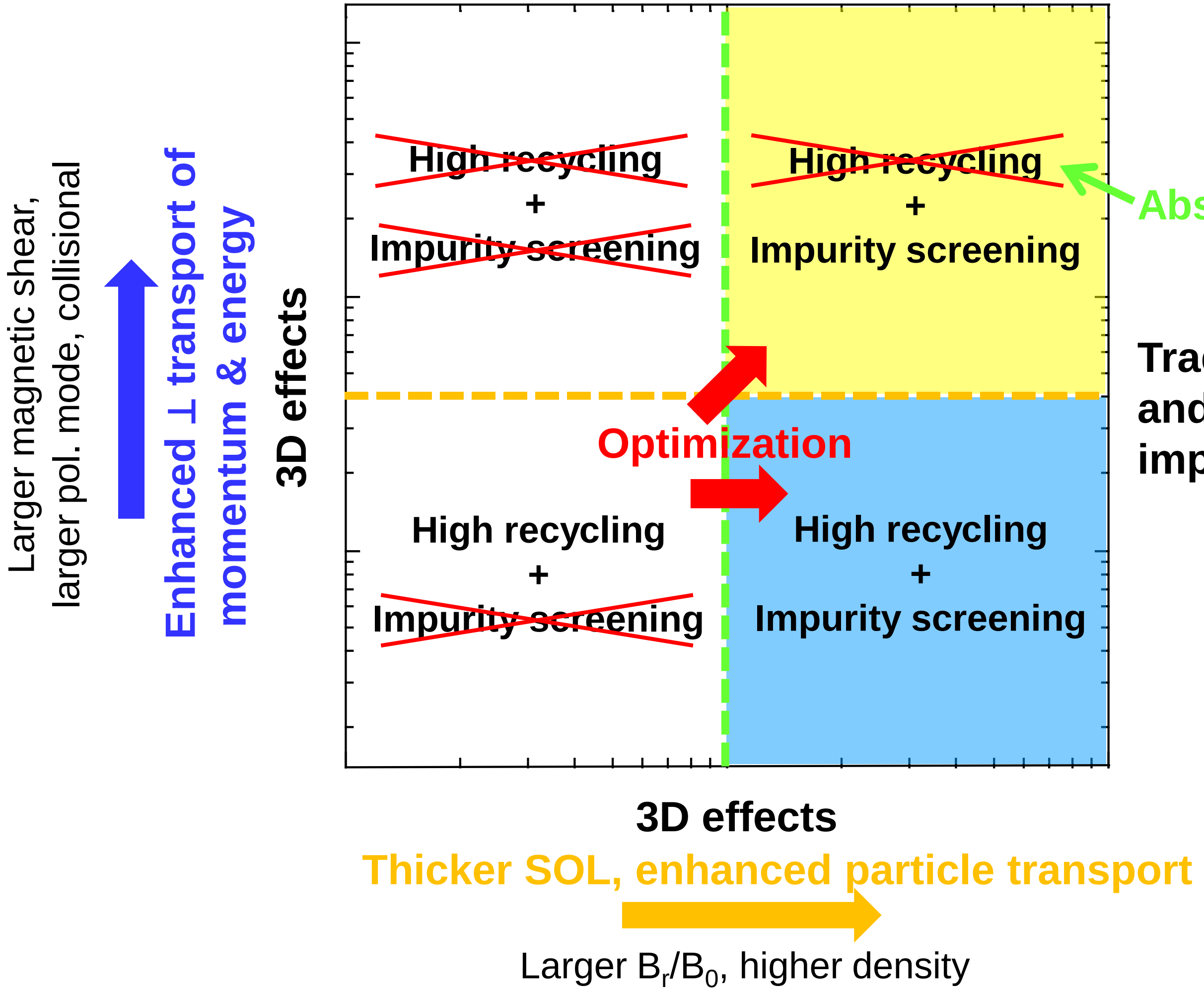
M. Lehnen et al., PPCF **47** (2005) B237.

LHD



M. Kobayashi et al., Nucl. Fusion **53** (2013) 033011.

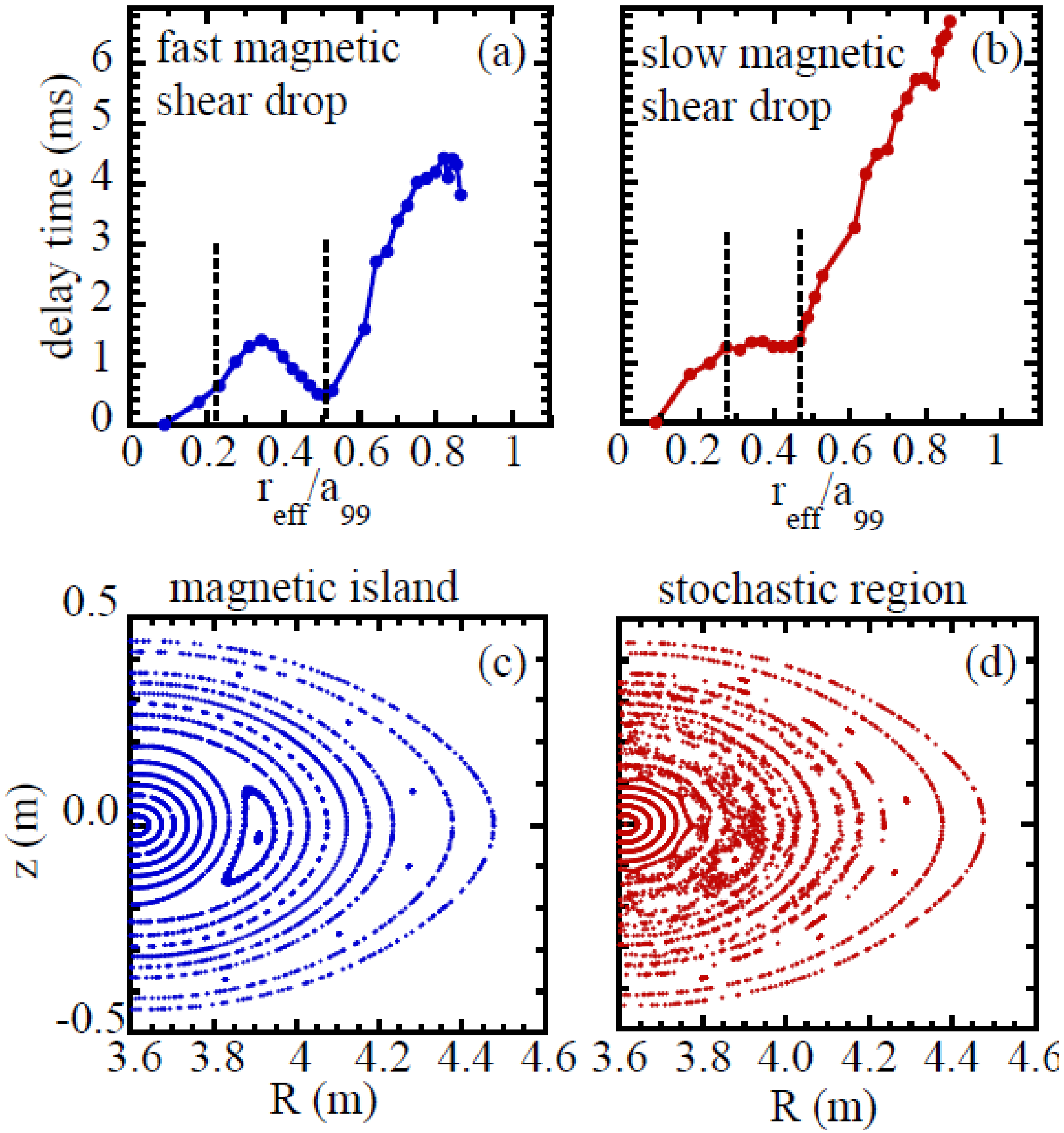
Which direction to go for 3D divertor optimization of a future reactor?



Absence of high recycling regime:

Trade-off between pumping efficiency and controllability of detachment & impurity transport with 3D B field.

Magnetic field structure (stochastic or island) can be investigated with heat propagation experiments



K. Ida et al., New Journal of Physics **15** (2013) 013061.

The time delay of heat propagation changes depending on the magnetic topology:

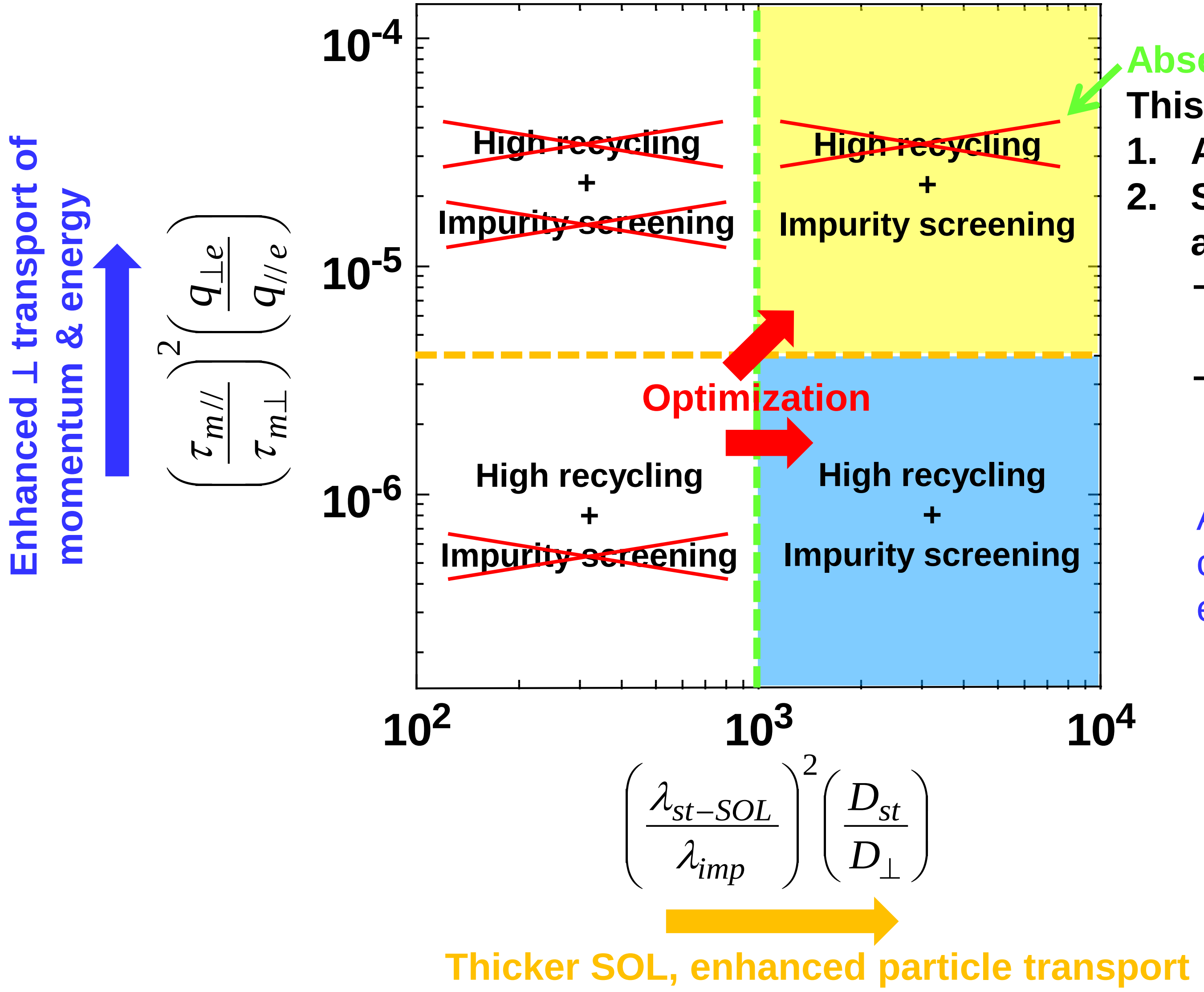
Magnetic island → time delay at O-point

Stochastic field → no time delay

OV/2-3 K.Ida et al. (Monday)

EX/1-3 T. Evans et al. (Tuesday)

Indication for 3D divertor optimization of a future reactor



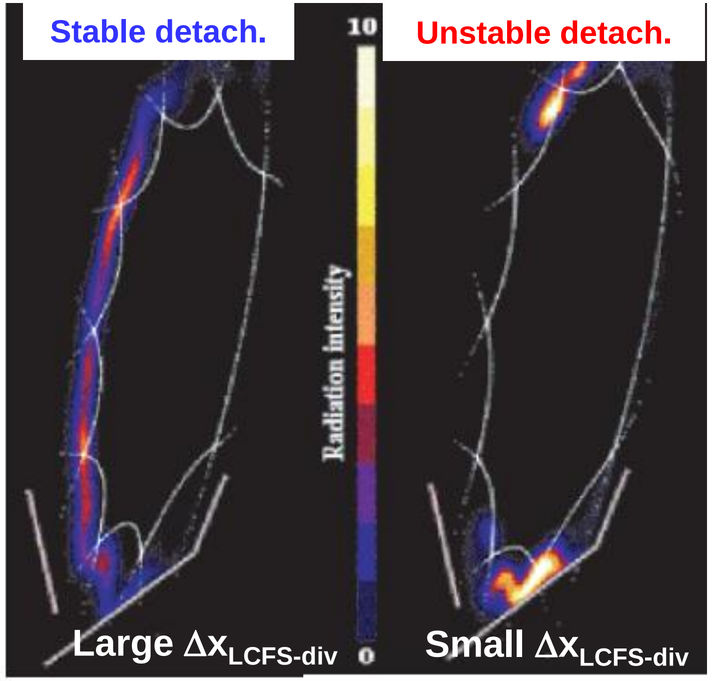
Absence of high recycling regime:
This might not be drawback

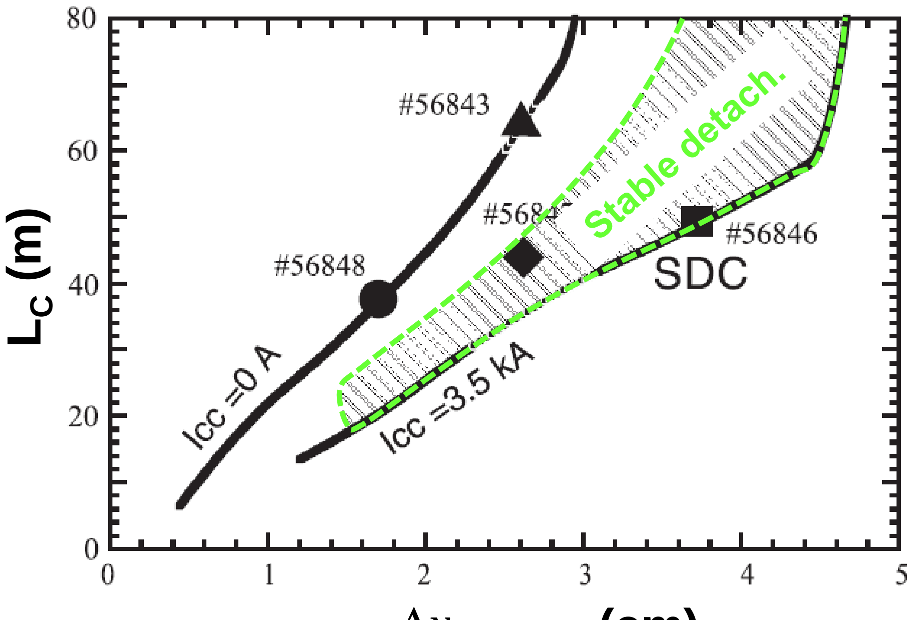
1. **After detached phase is achieved.**
2. **Since relatively high n_{up} can be achieved due to slow T_{div} decrease**
   → better impurity screening via thermal force suppression
   → better core plasma performance

A divertor should be optimized considering balance with pumping efficiency.

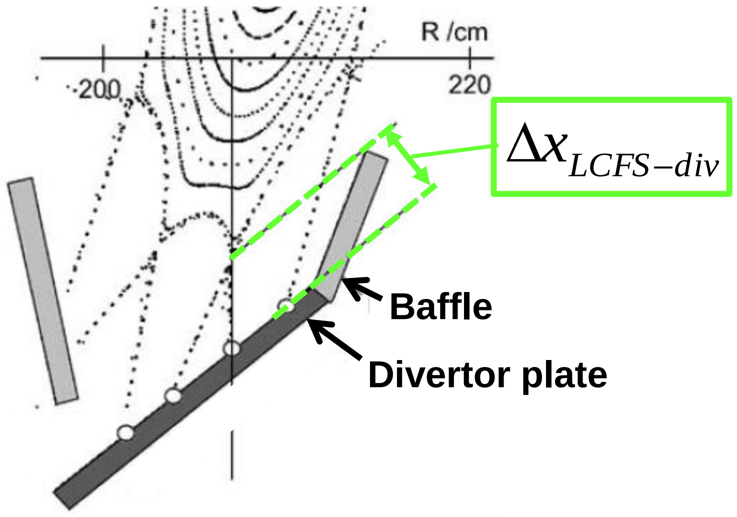
Possibility of 3D edge radiation structure control and radiation stabilization

W7-AS





W7-AS



Large $\Delta x_{LCFS-div}$ and short L_C

→ Radiation region moves to inboard side

→ Hot island

→ Better neutral screening

→ Stable detachment

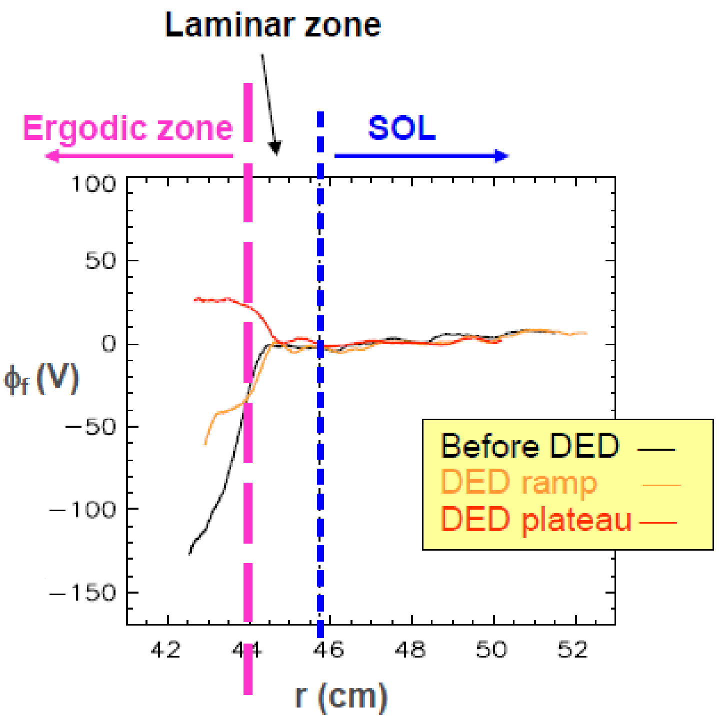
Decoupling between core and recycling region in terms of neutral fueling plays a key role.

[22] P. Grigull et al. JNM **313-316** (2003) 1287.
[23] Y. Feng et al., NF **45** (2005) 89.

Impact of RMP on edge electric field

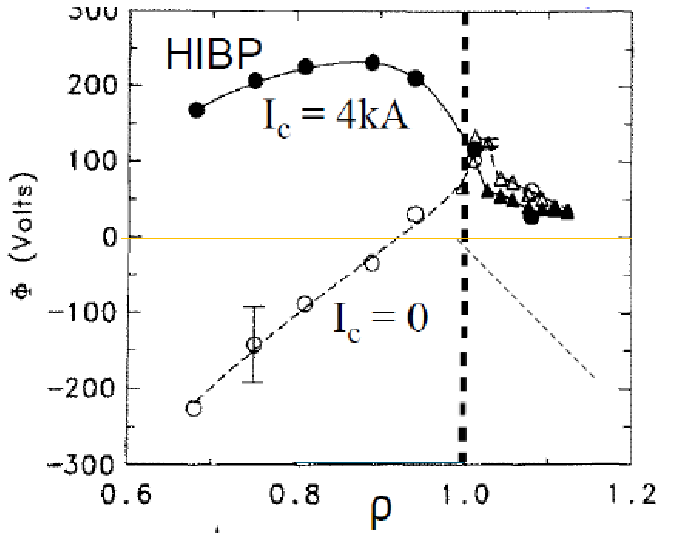
In many devices, the change of edge electric field (potential profile) has been observed
→ Effects on edge turbulence, drift …. → impurity transport

TEXTOR-DED



Y. Xu, EPS(2008), O4-6

TEXT

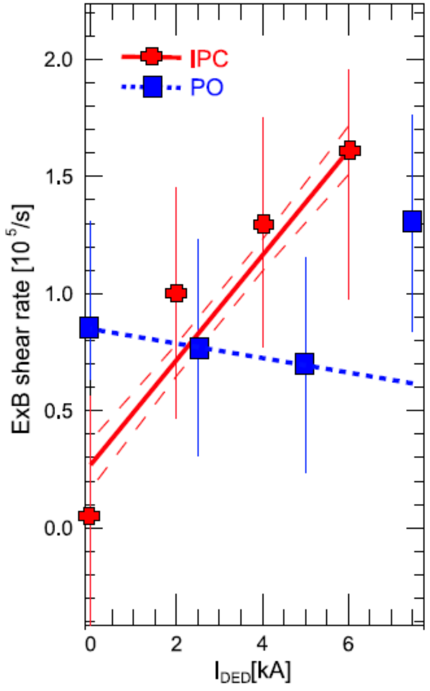


V_f profile affected by RMP in TEXT

(Limiter)

A. Wootton, JNM **176-177** (1987)

TEXTOR-DED



O. Schmitz et al., JNM **390-391** (2009) 330.

These results suggest that the stochastic layer induced by RMP application can impact on edge turbulence transport, and hence on plasma-wall interaction, impurity transport and also plasma confinement.