Comparative Divertor-Transport Study for W7-AS and LHD

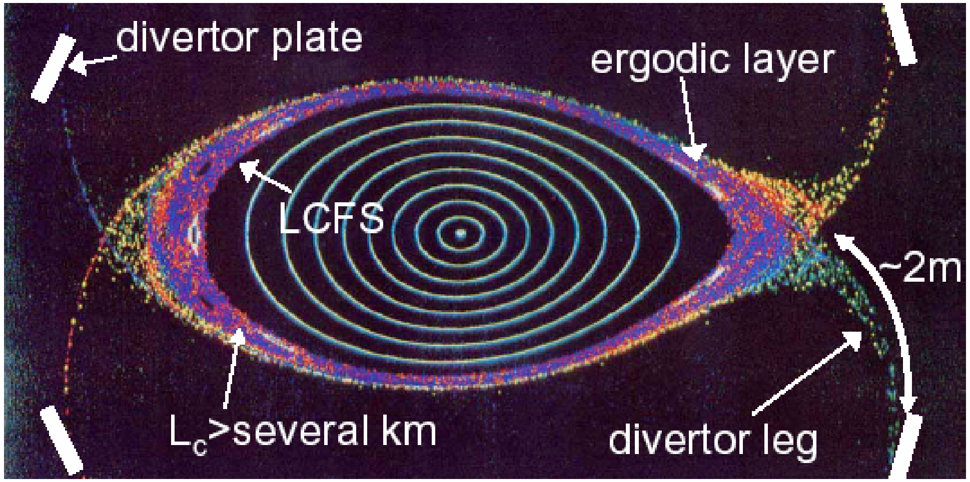
Y. Feng, M. Kobayashi, N. Ashikawa, L. Giannone, P. Grigull, K. Ida, J. Kisslinger, A. Komori, R. König, LHD experimental group, S. Masuzaki, K. McCormick, J. Miyazawa, T. Morisaki, S. Morita, O. Motojima, Y. Nakamura, K. Narihara, N. Ohyabu, B.J. Peterson, F. Sardei, K. Sato, M. Shoji, N. Tamura, H. Thomsen, M. Tokitani, F. Wagner, U. Wenzel, H. Yamada, I. Yamada

- Max-Planck-Institut für Plasmaphysik, Euratom Association, Germany
- National Institute for Fusion Science, Toki, Japan

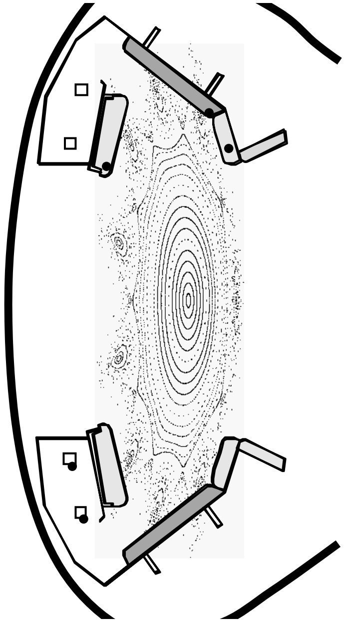
- Common SOL-transport features
- Impurity and neutral screening
- Stability of detached plasmas
- On the way to W7-X

W7-AS island divertor vs LHD helical divertor

LHD



W7-AS

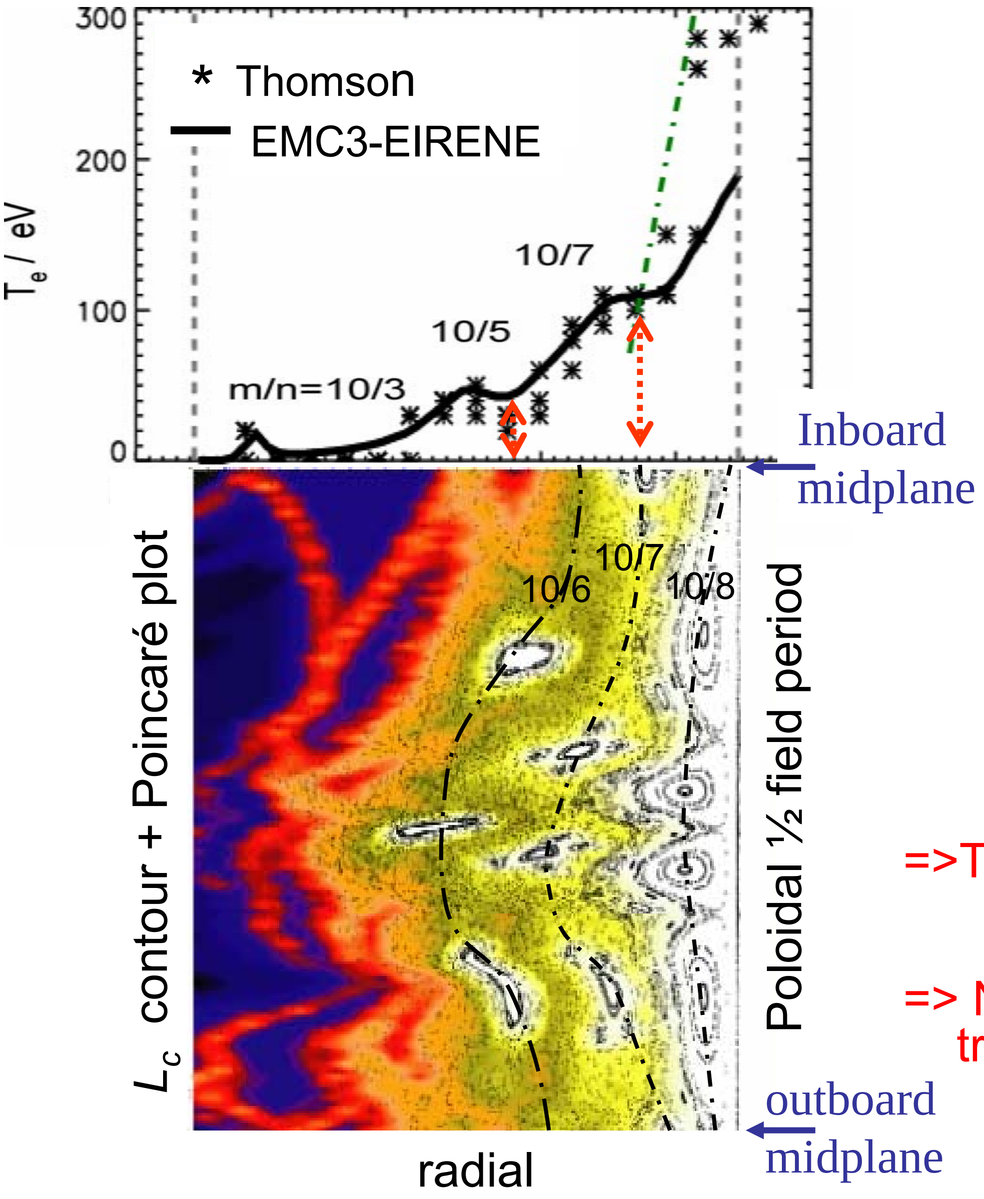


	Helical divertor (**HD**)	Island divertor (**ID**)
Shear:	large	low
Field structure:	stochastic (multi-island chain)	single island chain
SOL thickness:	~10 cm	~4 cm
L_c:	several m -> several km	~100 m
Targets:	4 continuous plates	10 discontinuous modules
Divertor structure:	open	open

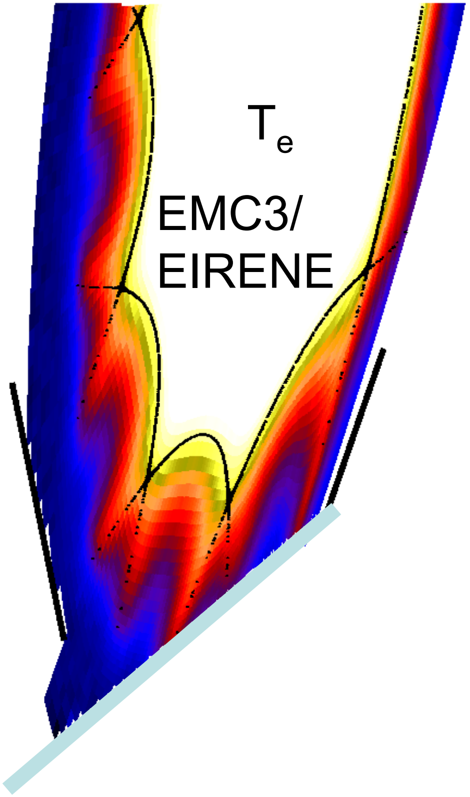
Θ=dr/dl 10^{-4}-10^{-3} (0.1 in tokamak) → Significant contribution of ⊥-transport

SOL-transport guided by low-order islands

LHD HD



W7-AS ID



=>Transport governed by low-order islands (W7-AS: 5/*m*, LHD: 10/*m*)

=> No remarkable stochastic effects on SOL transport even in LHD

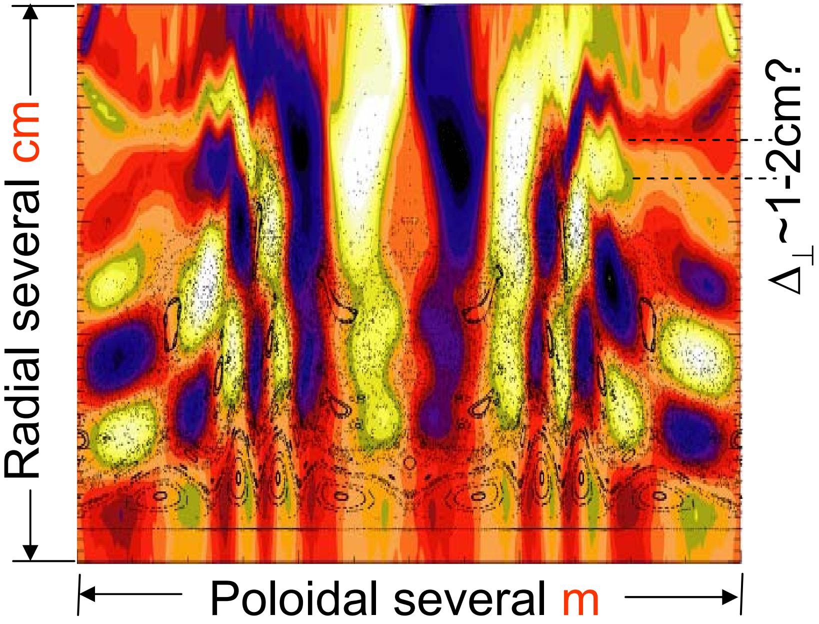
Viscous momentum loss between opposite flows

Parallel momentum balance:

$$p\left(1+M^2\right)=2p_{up}-D\int\frac{mnV_{\parallel}}{\Delta_{\perp}^{2}}dl=2p_{up}-D\left(\overline{\frac{mnV_{\parallel}}{\Delta_{\perp}^{2}}}\right)L_c$$

Small $\Delta_{\perp}$ and large L_c → large momentum loss

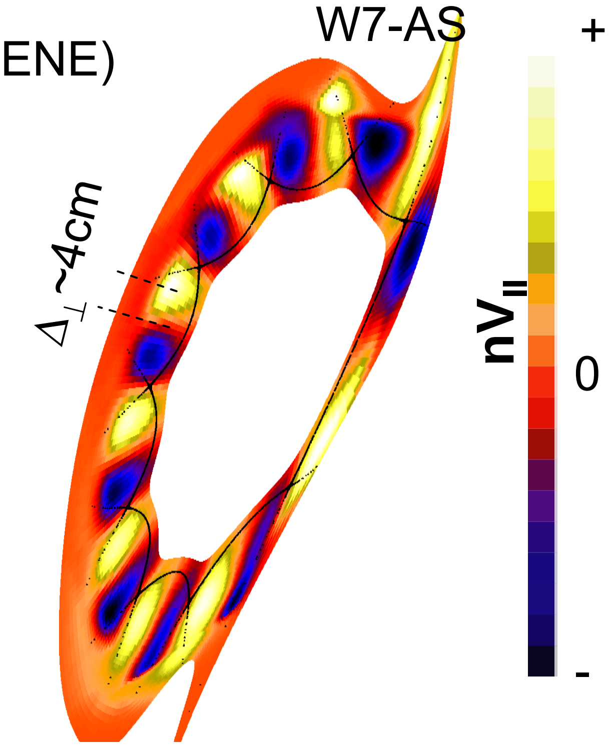
LHD



radial friction

(EMC3/EIRENE)

W7-AS

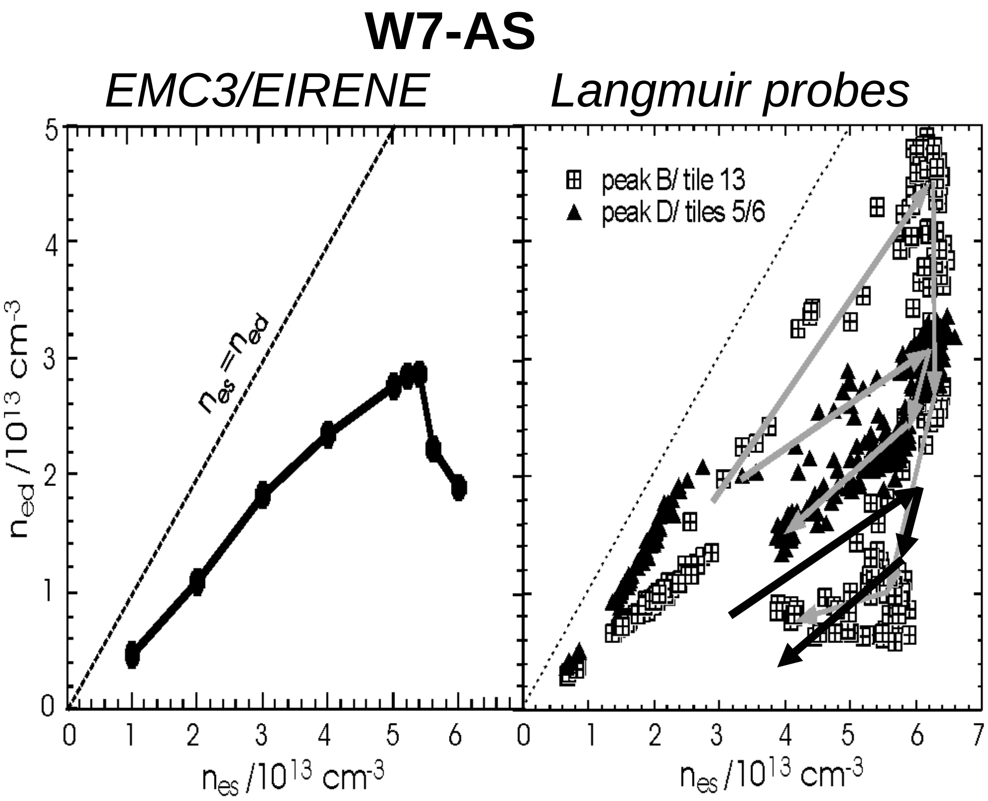


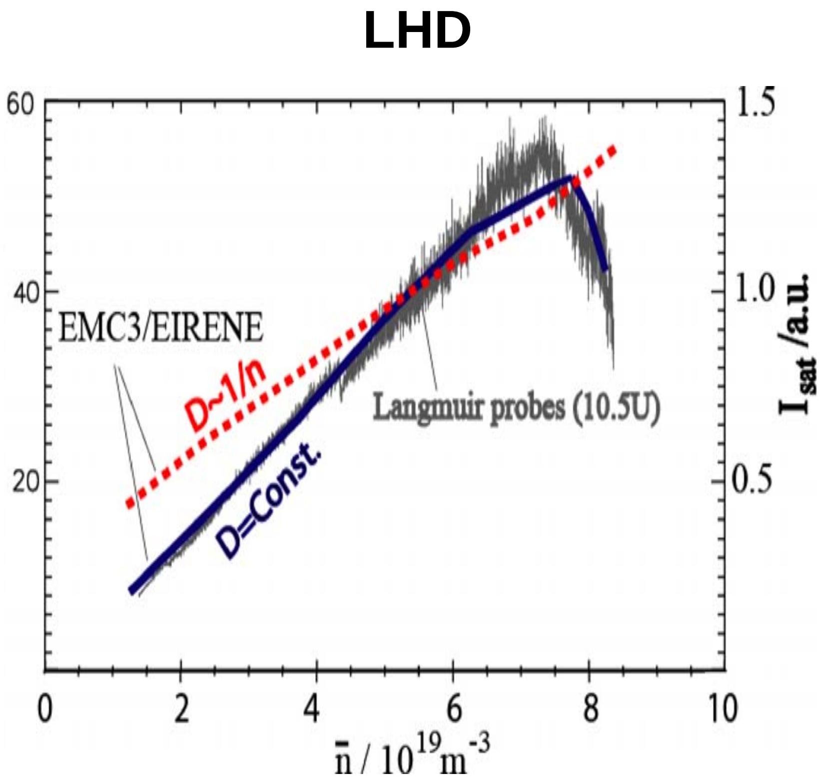
poloidal friction

=> break up parallel pressure conservation

No high recycling regime

(tokamak high recycling regime: $n_{ed} \sim n_{es}^3$, $\Gamma_{rec} \sim n_{es}^2$)





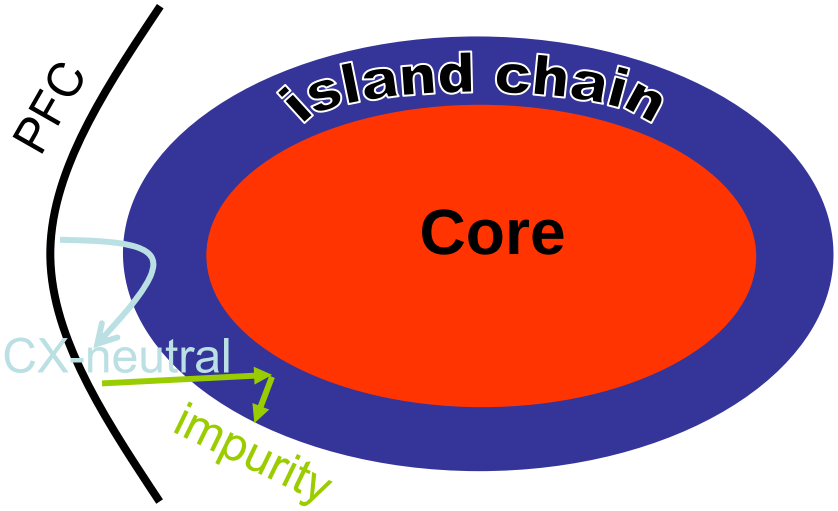
- No evidence for high recycling: n_{ed}, $I_{sat} \propto n_{es}$, n_e up to rollover

- Rollover of recycling flux:

$n_{es} \uparrow \;\Rightarrow\; T_{ed} \downarrow$ and $P_{rad} \uparrow \;\Rightarrow$ inward shift of ionization zone when $T_{ed} < E_{ion}$
$\Rightarrow$ larger recycling zone $\Rightarrow$ momentum loss $\uparrow \;\Rightarrow\; \Gamma_{recy}$, $n_{ed} \downarrow$

Island screening effects on intrinsic impurities

- Core plasma in both W7-AS and LHD surrounded by island chains of several cm thickness



$$\lambda_{SOL} \propto \sqrt{L_c}$$

Large L_c → thick SOL

- Reduction of physical sputtering yield (impurity source)

$$q_{SOL} = \gamma T \Gamma_{recyc} : \quad \uparrow \Gamma_{recyc} \rightarrow \downarrow T$$

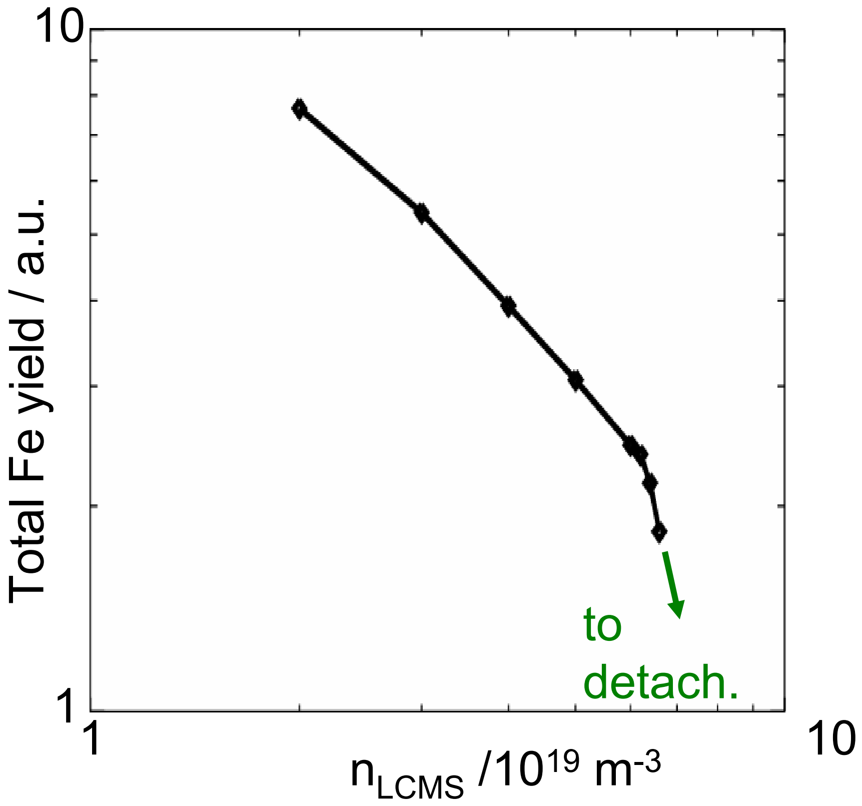
- Impurity retention (impurity transport)

→ high SOL density needed!

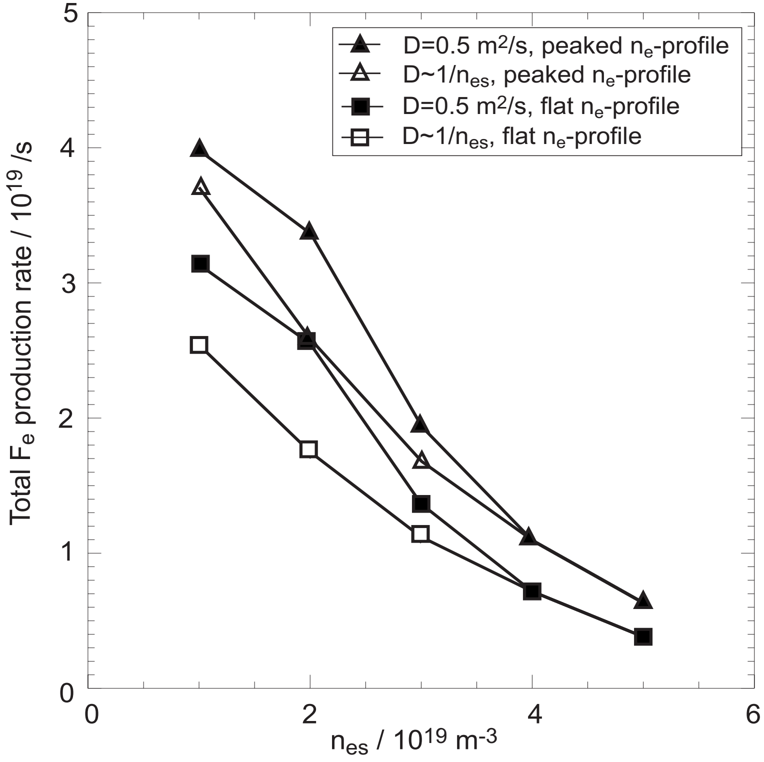
Island screening effect on CX-neutrals

(EMC3/EIRENE)

LHD



W7-AS



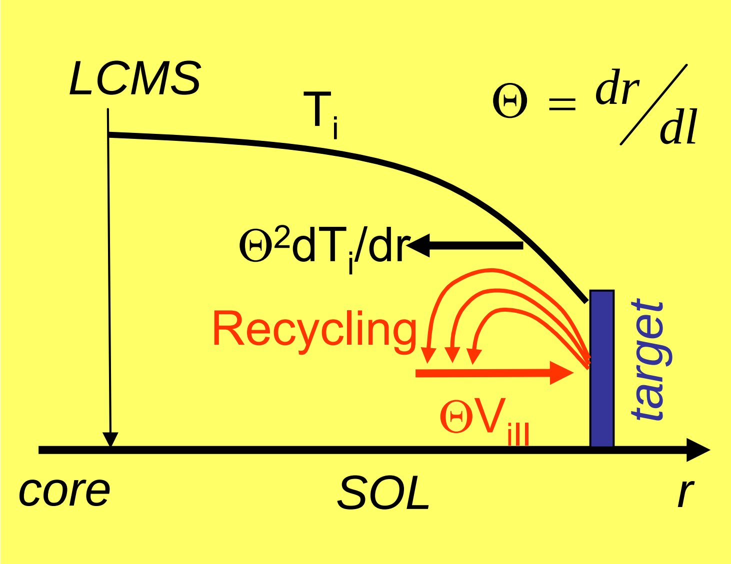
High densities shift CX-neutrals to low energy range in two ways:

1) by lowering the SOL temperature
2) by reducing the neutral penetration length

SOL impurity transport

Simplified force balance between friction and ion thermal force

$$V_{Z\,//} = V_{i\,//} + C_i \frac{\tau_{Zi}}{m_Z} Z^2 \nabla_{//} T_i$$



From 1D radial continuity for target-released impurities:

$$n_{Is} / n_{Id} = exp\left(- \int_{\mathrm{LCMS}}^{\mathrm{target}} \frac{\Theta V_{Z\,//}}{D_{Z\perp}} dr \right)$$

Impurity retention if $V_{z//}>0$ *i.e.* $V_{i\,//} > C_i \frac{\tau_{Zi}}{m_Z} Z^2 \nabla_{//} T_i$

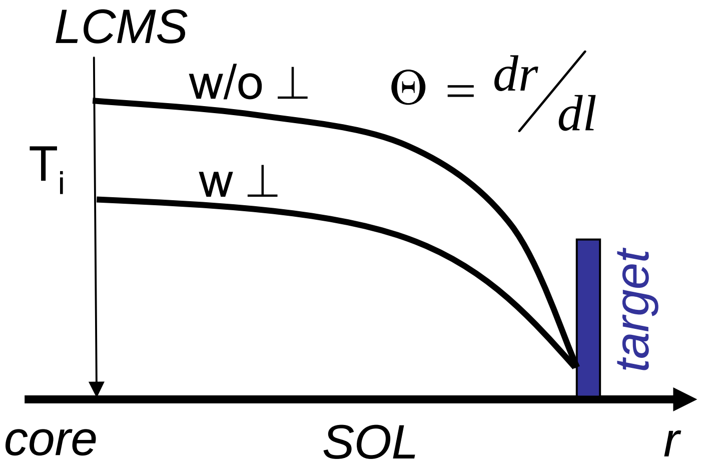
$$\frac{friction}{thermal\ \ force} \sim \frac{5/2 n_i T_i V_{i\|}}{\kappa_i T_i^{5/2} \nabla_{\|} T_i} > 1$$

→ reducing II-conductive heat flux is the key to reduce thermal forces

Reduction of II-conductive heat flux by ⊥-transport

1D radial energy transport for ions:

$$5/2\,\Theta n T_i V_{i\parallel} - \underset{\perp}{n\chi_i \frac{dT_i}{dr}} - \underset{\parallel}{\Theta^2 \kappa_i T_i^{5/2} \frac{dT_i}{dr}} = q_i$$



If Θ is small (long connection length), ⊥-heat conduction makes significant contributions.

Condition for significant reduction of parallel ion heat conduction:

$$\frac{n}{T_i^{5/2}} > \frac{\Theta^2 \kappa_i}{\chi_i}$$

Note that $\Theta \sim 10^{-4}$–10^{-3} in W7-AS and LHD and ~ 0.1 in tokamaks!

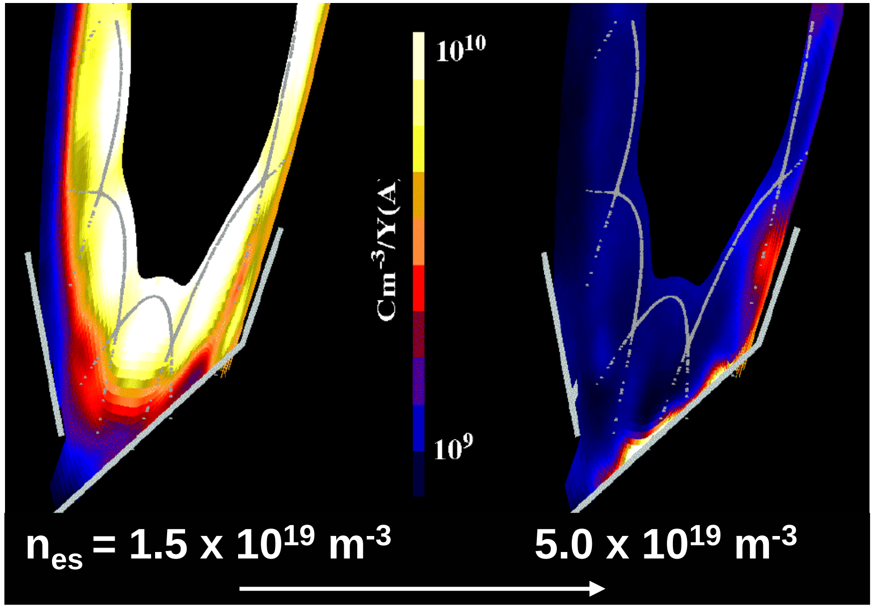
Use Bohm-condition $nT_i^{3/2} \sim q_i$: (only representative)

$$\frac{n^{8/3}}{q_i^{5/3}} > Const \cdot \frac{\Theta^2 \kappa_i}{\chi_i}$$

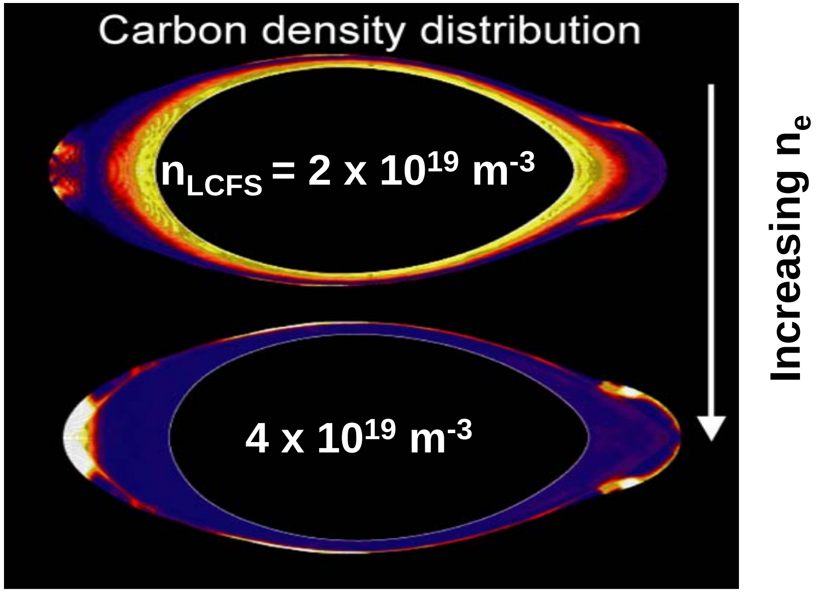
→ For a given power q_i, there is threshold density to switch off the thermal force

Impurity retention: 3D code predictions

W7-AS

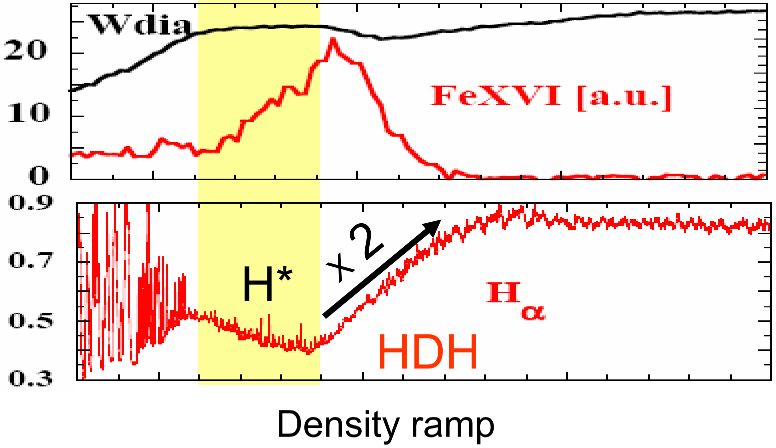


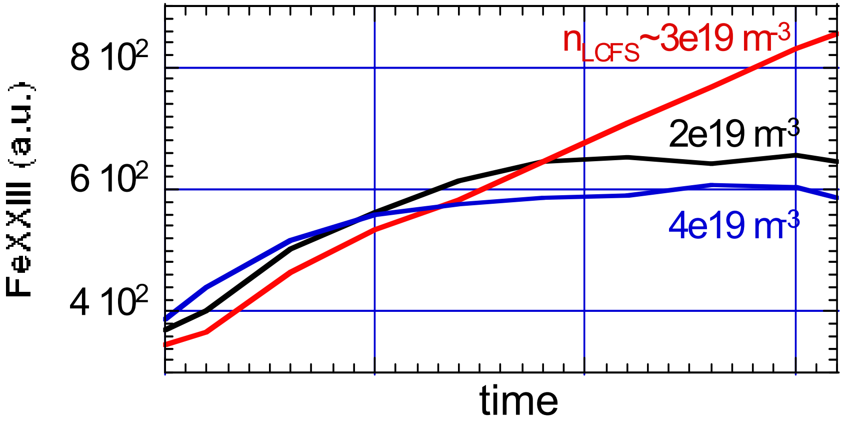
LHD



Relevance to experiments:

K. McCormick 15th ISWS



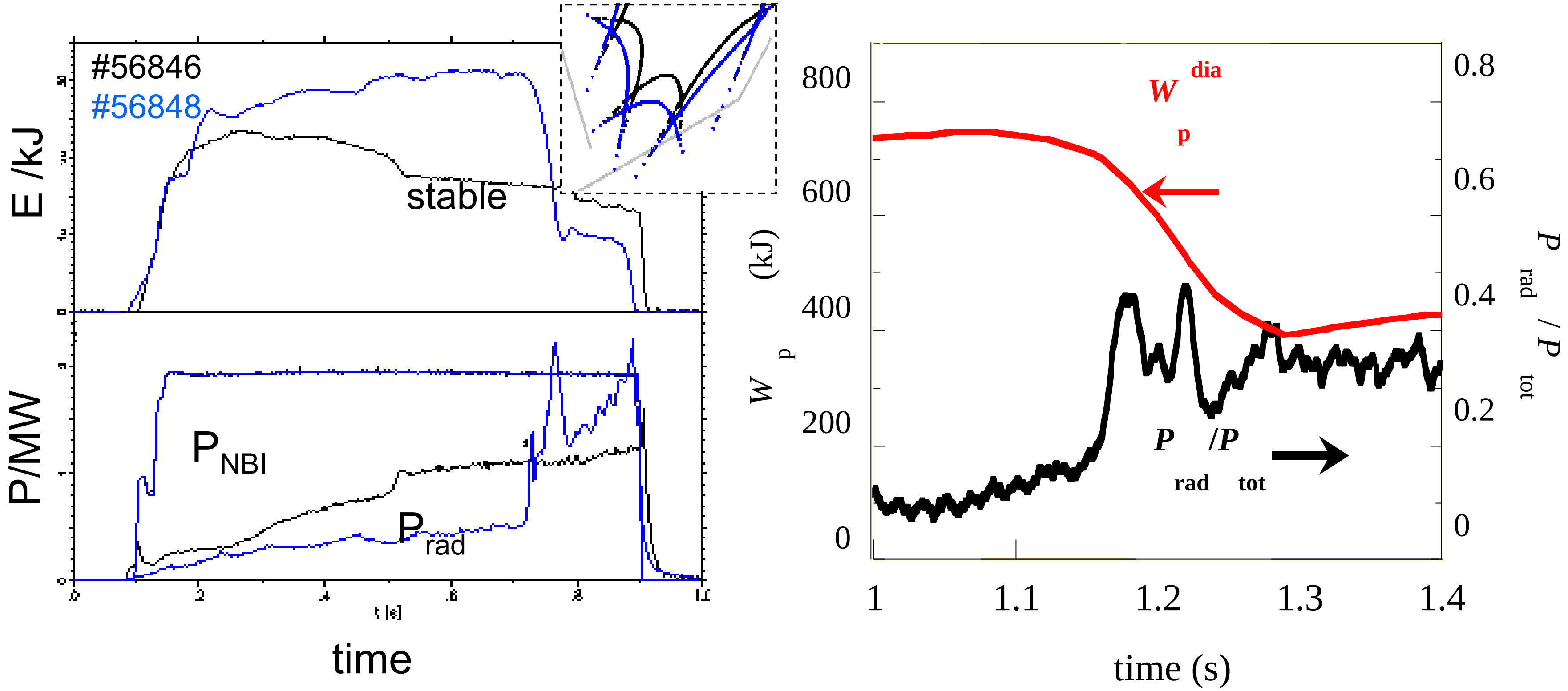


- *Low τ_{imp} measured for HDH (R. Burhenn) mechanism not yet understood*

Details -> I-07 Kobayashi

Detachment stability

W7-AS (experiments) LHD



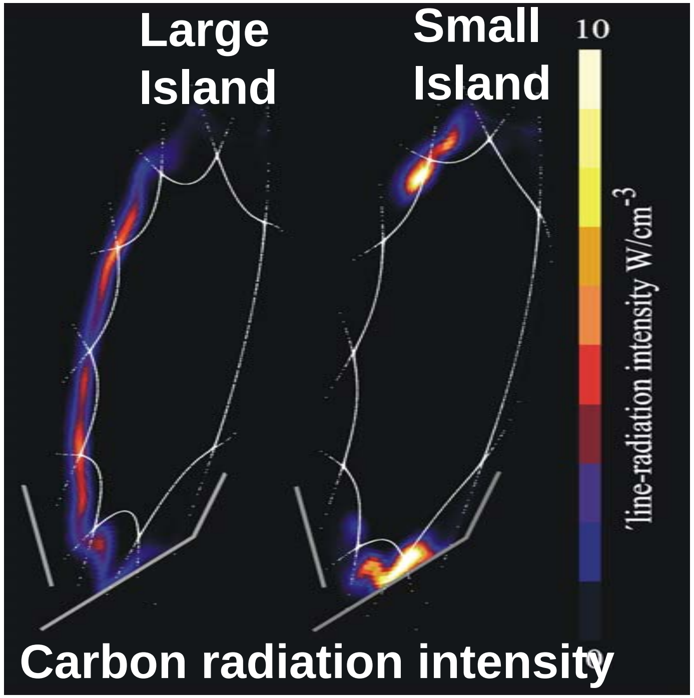
Geometry-related detachment stability:

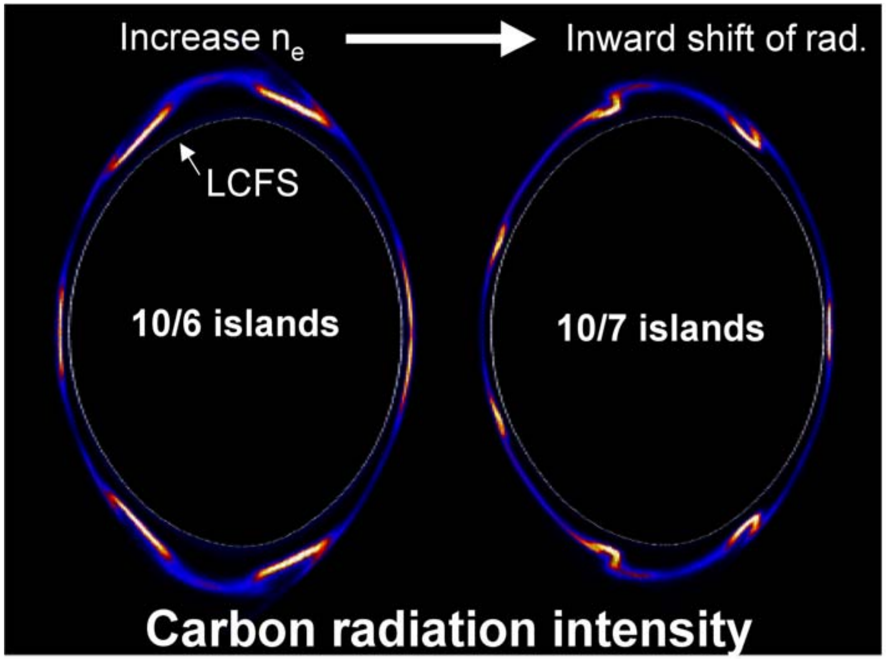
- large islands and field-line pitch → stable partial detachment
- small islands or field-line pitch → unstable complete detachment
- Sharp transition to detachment

- no stable partial detachment found
- quasi-stable complete detachment (Serpens mode) with a rotating radiation belt inside LCFS
- Sharp transition to detachment

Radiation distributions of detached plasmas

W7-AS (code results) **LHD**





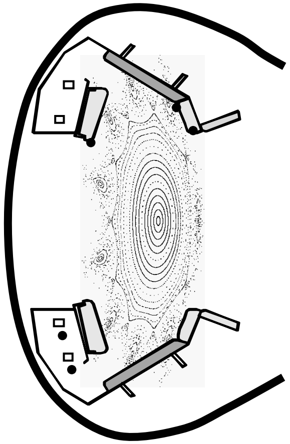
- X-point radiation
- radiation belt outside LCFS
- large island (stable partial detach.)
  - -inboard side radiation
  - -good neutral screening
- small island (unstable complete detach.)
  - -divertor radiation
  - -week neutral screening

- O-points of remnant islands
- solutions found with radiation belt outside LCFS
- no significant in/out asymmetry, neither among the islands
- week neutral screening
- experimentally not yet accessible as the divertor radiation case in W7-AS

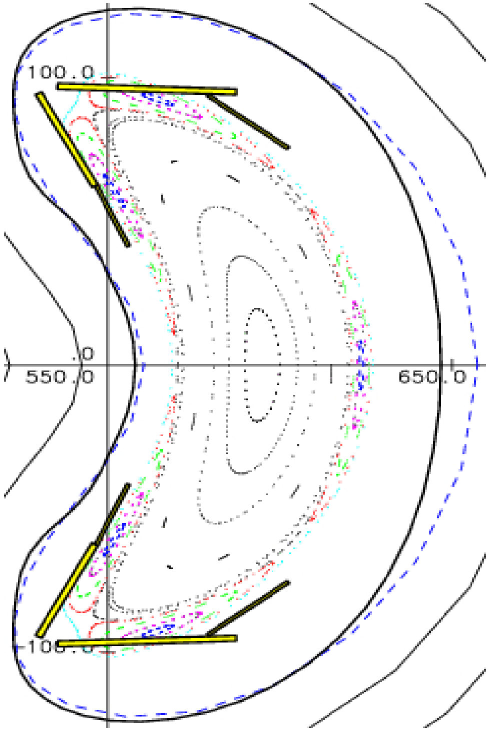
- due to loss of neutral screening?

From W7-AS to W7-X

W7-AS



W7-X



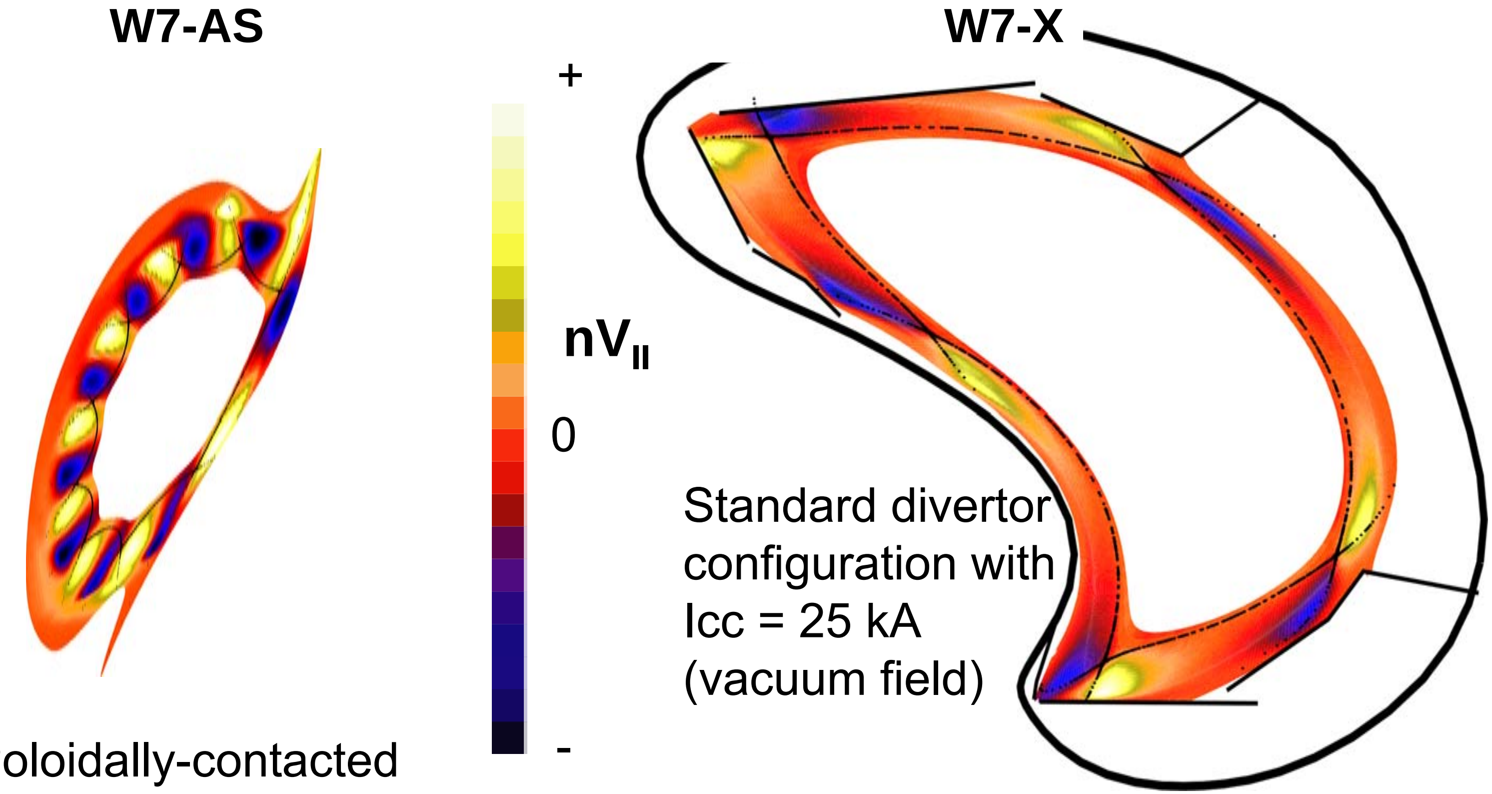
Similarities:

- SOL transport governed by low-order islands
- Large L_c, small Θ
- 10 open divertor modules
- Neutral baffling

Differences:

- lower poloidal mode number (4,5,6), larger a → larger poloidal distance
- larger islands

Moderate poloidal viscous transport

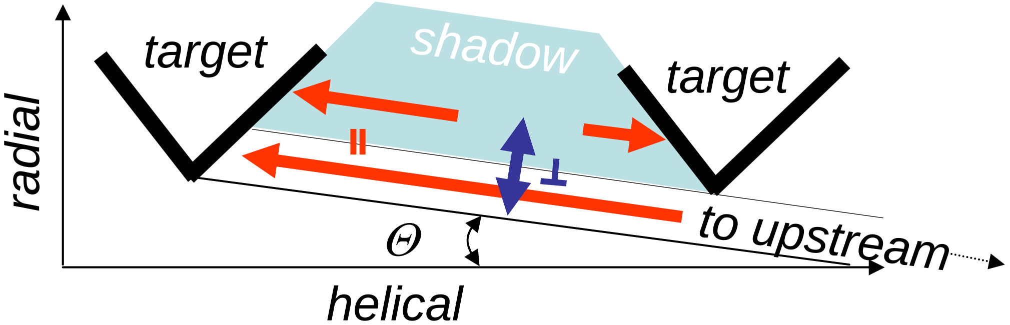


Standard divertor configuration with Icc = 25 kA (vacuum field)

Poloidally-contacted

Poloidally-isolated

divertor shadow trapping remains

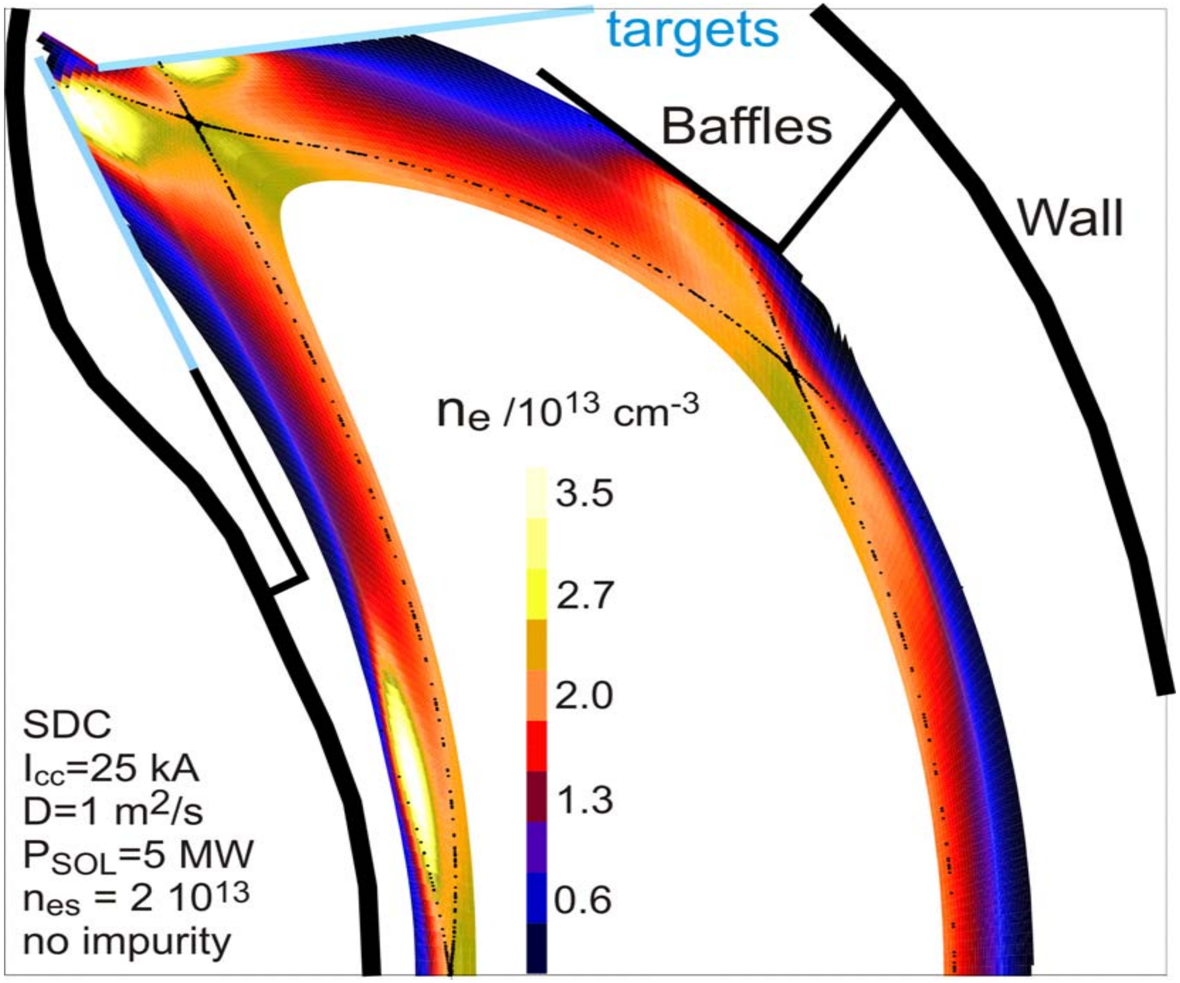


→ more ‘localized’ flows

→ impurity screening?

Density rise along island fans expected

Preliminary EMC3/EIRENE results

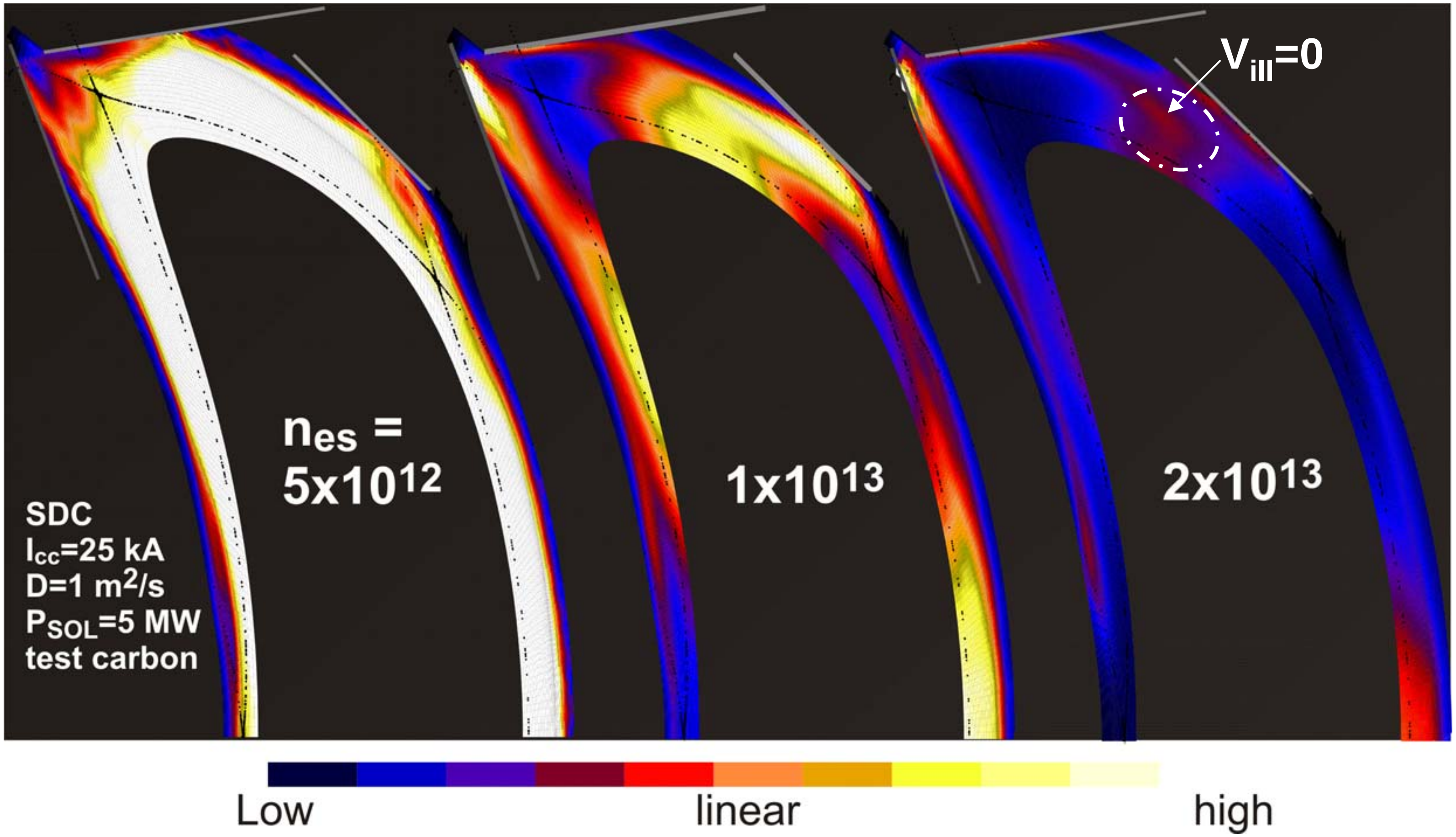


→ improved neutral screening ?
→ detachment shifted to lower densities ?

Transition to friction-dominated impurity transport

(preliminary EMC3/EIRENE results)

Carbon (test impurity) density distributions as function of n_{es}



Existence of large stagnation region → impurity leakage?
(especially for wall-released impurities)

Summary

Despite the large differences in divertor configuration and concept between W7-AS and LHD, there are common features in terms of SOL transport and divertor function:

- Transport governed by low-order islands
- Large L_c (small Θ) increases significantly the $\perp/\parallel$-transport ratio
- Viscous transport causes significant momentum loss
- No high recycling regime as found in tokamaks
- High n_{es} for detachment transition
- Dense, cold islands reduce influx of intrinsic impurities:
  - reduce impurity yield from CX-neutrals
  - reduce thermal forces so that frictional plasma flow drives impurities outwards (friction-dominated impurity transport regime)

  (These code results need further experimental confirmations)

Differences in detached plasmas:

W7-AS

- Stable partial detachment for large islands and field line pitch
  - inboard side radiation outside LCFS
- Unstable complete detachment for small islands and field line pitch
  - Marfe-like radiation inside LCFS

LHD

- Quasi-stable complete detachment (Serpens mode)
  - Rotating radiation belt inside LCFS

W7-X : Systematic numerical parameter pre-studies under way

Physics model in EMC3/EIRENE

Background plasma (fluid, EMC3**: Y. Feng et al., J. Nucl. Mater. 1999**):

$$\nabla\cdot\left(n_i V_{i\parallel}\boldsymbol{b}-D\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla n_i\right)=S_p$$

$$\nabla\cdot\left(m_i n_i V_{i\parallel}V_{i\parallel}\boldsymbol{b}-\eta_\parallel\boldsymbol{bb}\cdot\nabla V_{i\parallel}-m_i V_{i\parallel}D\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla n_i-\eta_\perp\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla V_{i\parallel}\right)=-\boldsymbol{b}\cdot\nabla p+S_m$$

$$\nabla\cdot\left(\tfrac{5}{2}n_e T_e V_{i\parallel}\boldsymbol{b}-\kappa_e\boldsymbol{bb}\cdot\nabla T_e-\tfrac{5}{2}T_e D\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla n_e-\chi_e n_e\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla T_e\right)=-k\left(T_e-T_i\right)+S_{ee}+S_{imp}$$

$$\nabla\cdot\left(\tfrac{5}{2}n_i T_i V_{i\parallel}\boldsymbol{b}-\kappa_i\boldsymbol{bb}\cdot\nabla T_i-\tfrac{5}{2}T_i D\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla n_i-\chi_i n_i\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla T_i\right)=+k\left(T_e-T_i\right)+S_{ei}$$

Impurities (fluid, EMC3:**Y. Feng et al., Plasma Phys. Control. Fusion 2002**):

$$\nabla\cdot\left(n_I^z V_{I\parallel}^z\boldsymbol{b}-D_I^z\boldsymbol{b}_\perp\boldsymbol{b}_\perp\cdot\nabla n_I^z\right)=S_{z-1\to z}-S_{z\to z+1}+R_{z+1\to z}-R_{z\to z-1}$$

$$U_{Ii}^z\left(V_{I\parallel}^z-V_{i\parallel}\right)=-\boldsymbol{b}\cdot\nabla n_I^z T_I^z+n_I^z ZeE_\parallel+n_I^z Z^2 C_e\boldsymbol{b}\cdot\nabla T_e+n_I^z C_i\boldsymbol{b}\cdot\nabla T_i$$

$$\boldsymbol{b}\cdot\nabla n_e T_e+n_e eE_\parallel+n_e C_e\boldsymbol{b}\cdot\nabla T_e=0$$

$$T_I^z=T_i$$

Neutrals (kinetic, EIRENE**: D. Reiter et al., Fusion Sci. Technol. 2005**):

Boltzmann equation

Plasma-surface and neutral-surface interaction:

Particle and energy reflection and sputtering models integrated in Eirene code