Physics and Modeling of the W7-AS Island Divertor

Y.Feng, F.Sardei, P.Grigull, K.McCormick, J.Kisslinger, L.Giannone,
Y.Igitkhanov, D.Reiter, T.Bindemannm H.Ehmler, R.König,
N.Ramasubramanian, E.Pasch, H.Thomsen

- **Status of the EMC3-EIRENE code**
- **W7-AS island divertor physics**

  -Major results and present understanding
  -Recent results
   * Geometry-related detachment stability
   * Dynamic behavior of edge radiation
   * Efficiency of neutral gas screening and its impact on detachment stability

- **First application on TEXTOR-DED**
- **Summary**

Status of the EMC3-EIRENE code

Physics

- standard fluid model for ions and electrons
- simplified fluid model for impurities
- kinetic model for neutral gas

} **Coupled self-consistently**

Geometry

- fully 3D for plasma, divertor plates, baffles and wall
- ergodic and non-ergodic B-field configurations

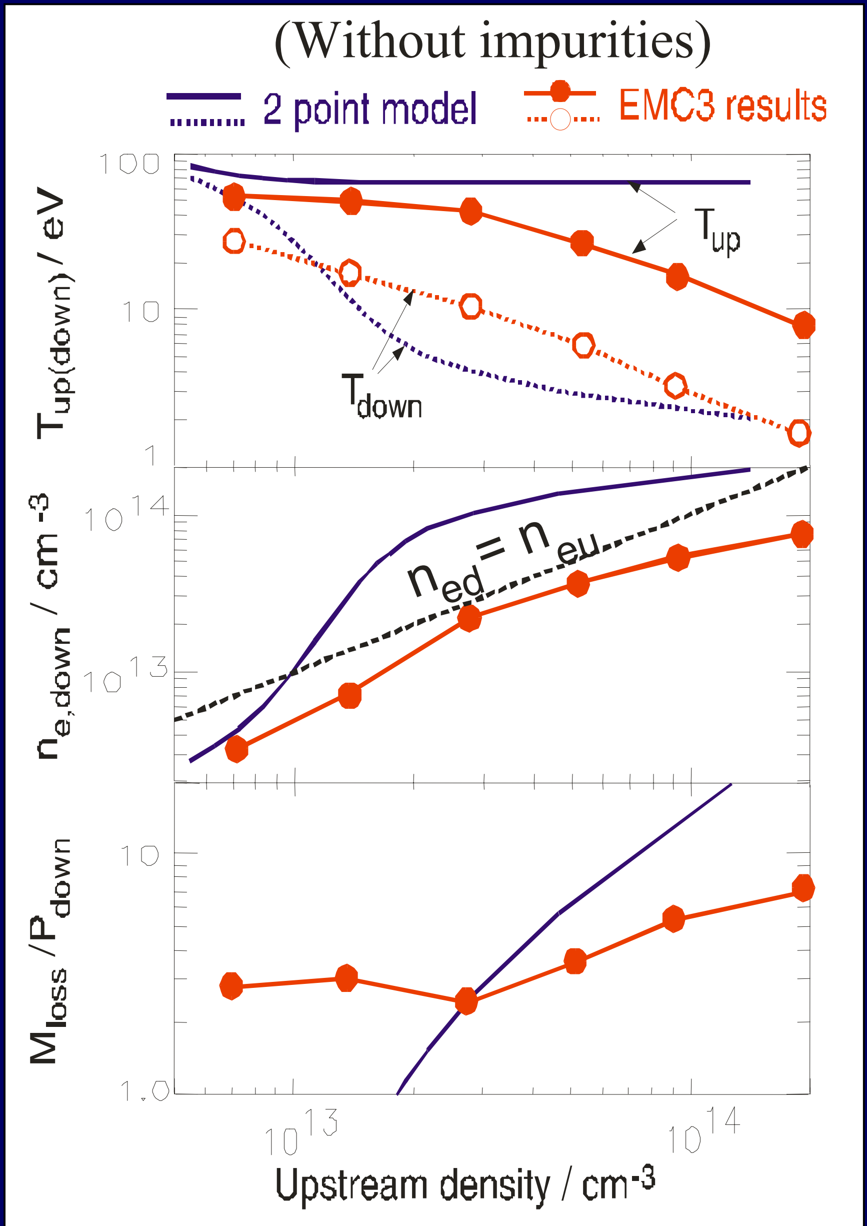
Numerics in EMC3

- Monte Carlo technique on local field-aligned vectors, piecewise parallel integration for separation of the small ⊥ from the large ll-transport ($\perp/\parallel \sim 10^{-8}$)
- new Reversible Field Line Mapping (RFLM) technique, Finite flux tube coordinates for B-field line interpolation

Applications

- W7-AS: weakly ergodic, routine
- W7-X: weakly ergodic (D. Sharma)
- TEXTOR-DED: strongly ergodic (M. Kobayashi)

Transport: island divertor vs. tokamak divertor



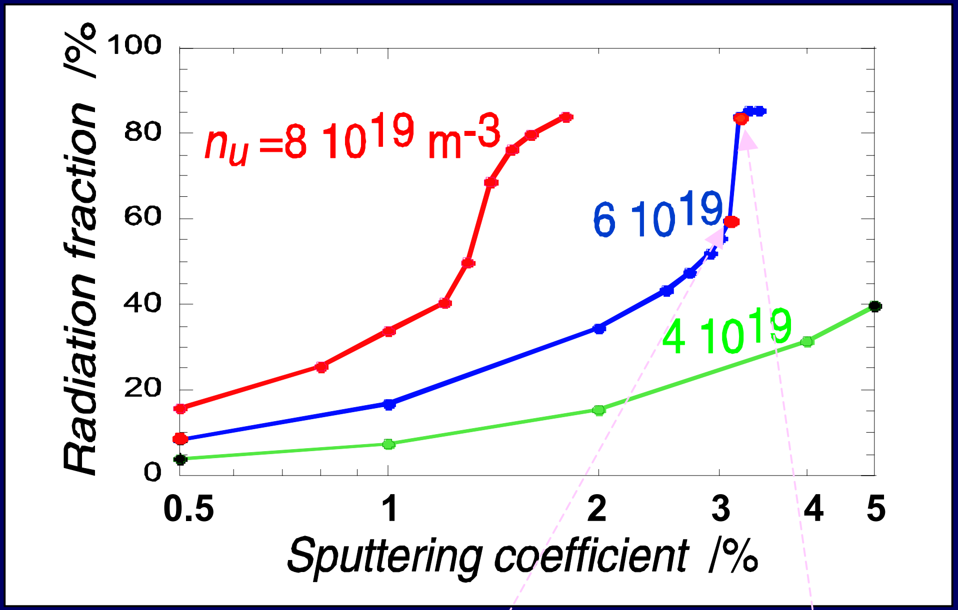
Code results

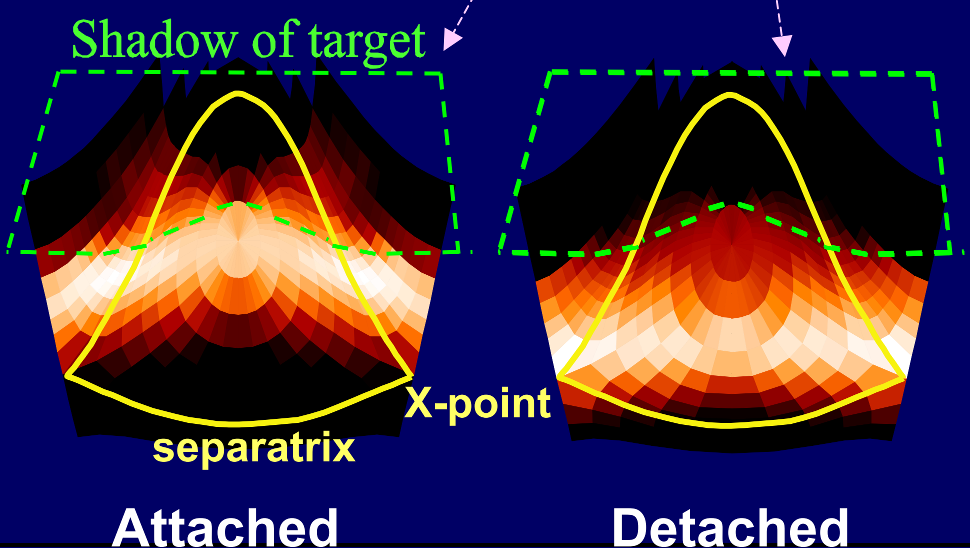
- Drop of T_{up}
  (cross-B heat conduction)
- Downstream density never exceeds upstream density, no high recycling
- Momentum loss at low densities, high temperatures
  (cross-B diffusion)

confirmed by experiment

Detachment transition

Looking for transition condition





Code results

- High density needed to achieve detachment (momentum loss)
- Jump of radiation level (thermal instability)
- Jump of radiation zone towards separatrix (X-points) (flat radiation capability profile)

confirmed by experiment

Stable detachment

Conditions for a stable detachment

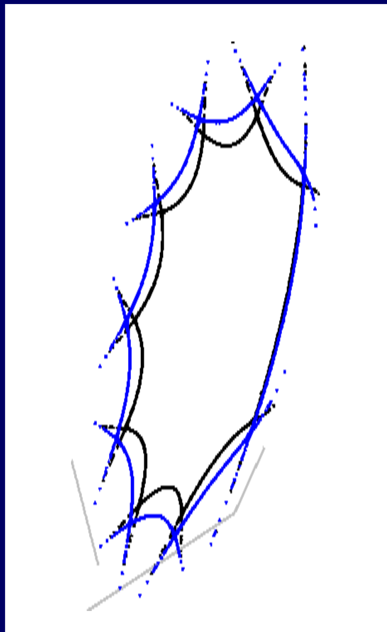
- no impurity accumulation under high density conditions (reached in HDH regime)

Experimental observations:

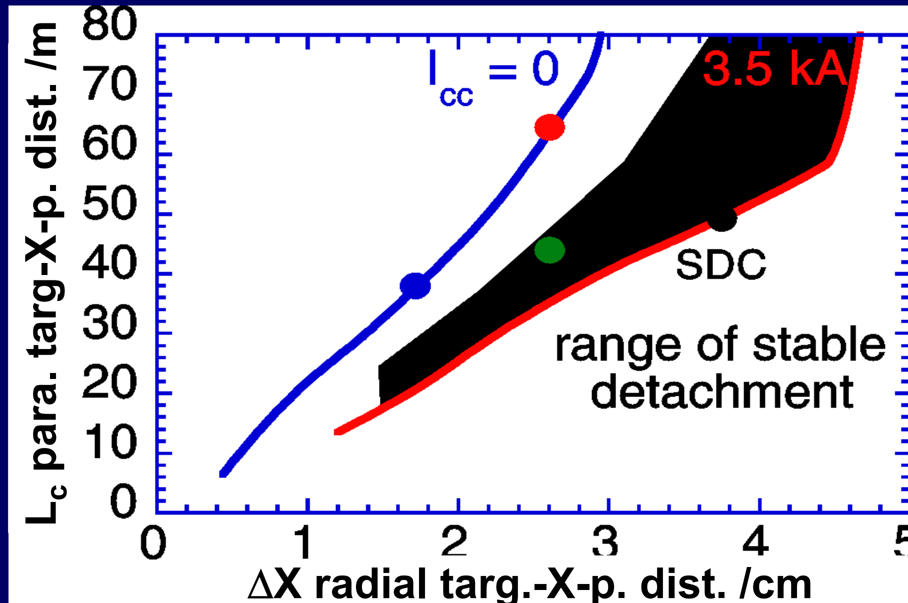
- stable detachment only for sufficiently large islands and field line pitch ?

Detachment stability depends on island geometry

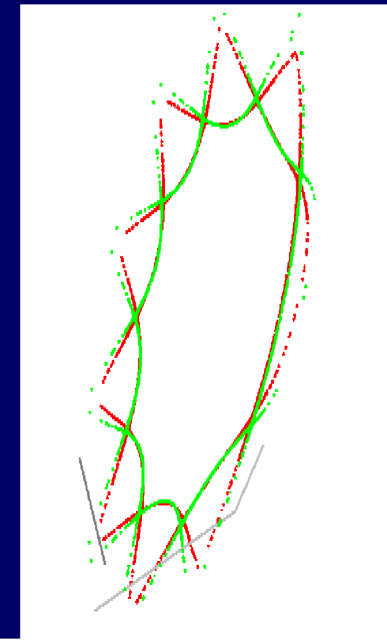
change of Δx

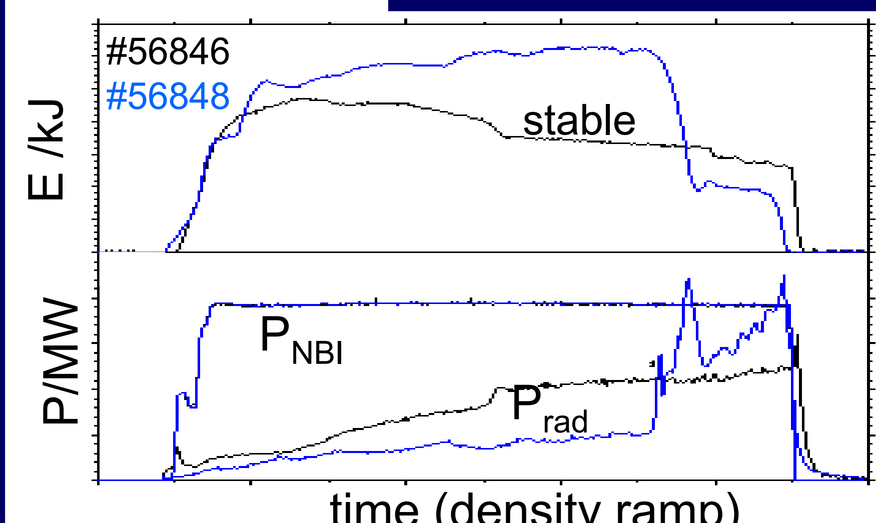


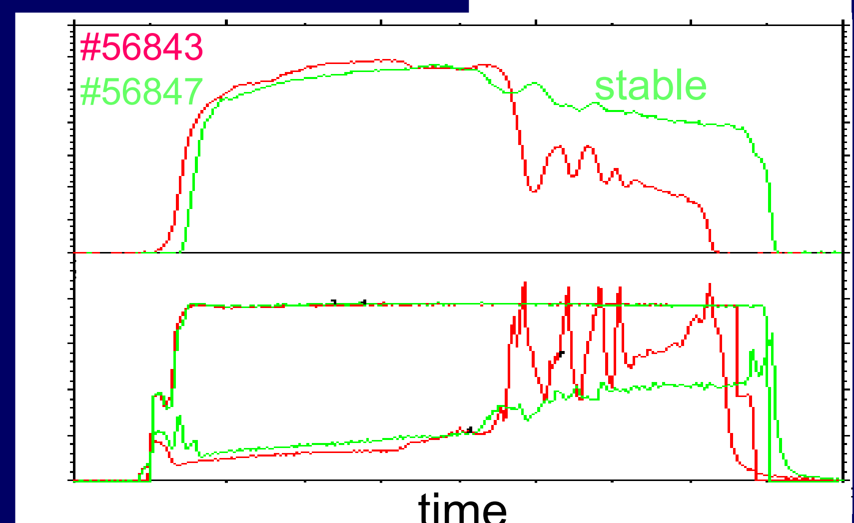
Experimental results



change of L_c

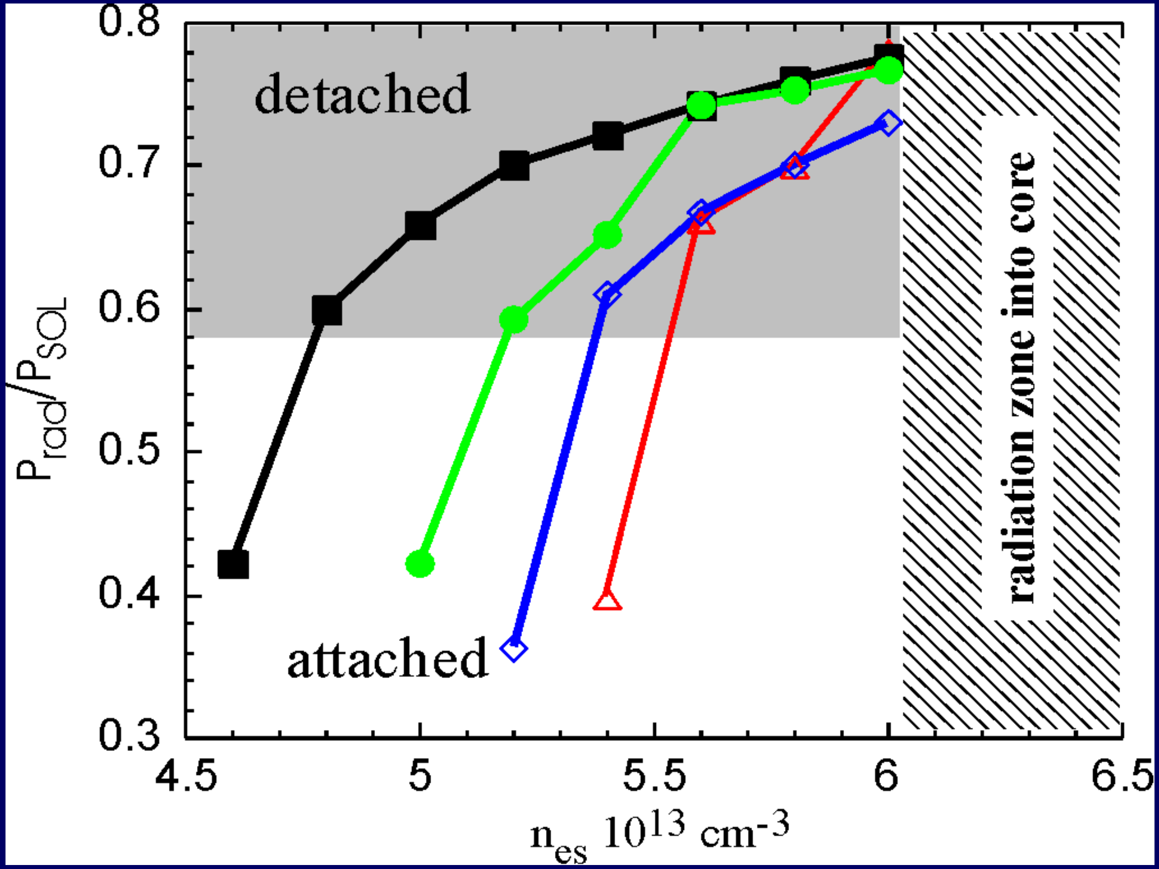


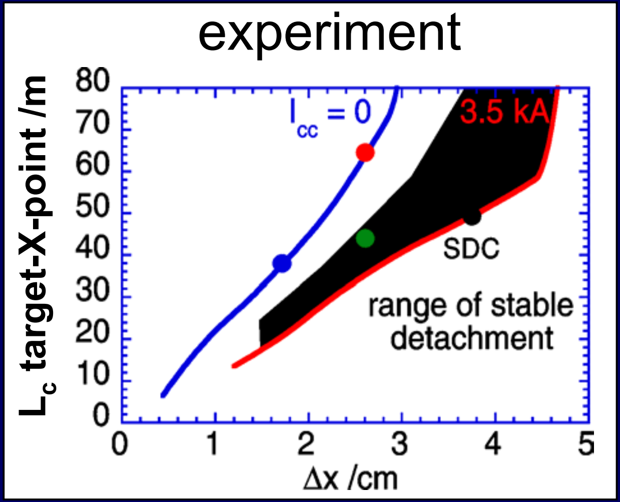


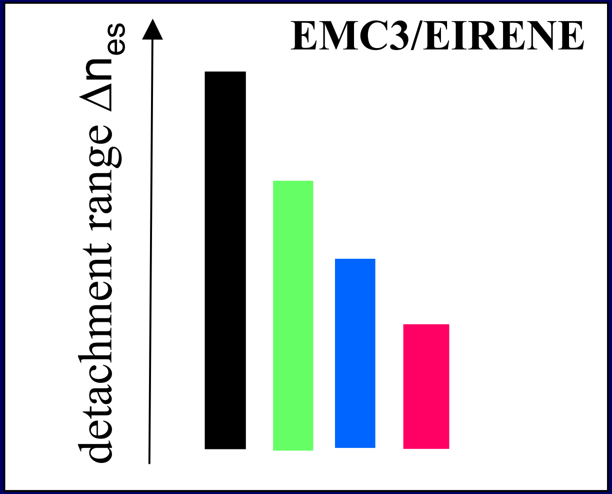


Numerical results

EMC3/EIRENE

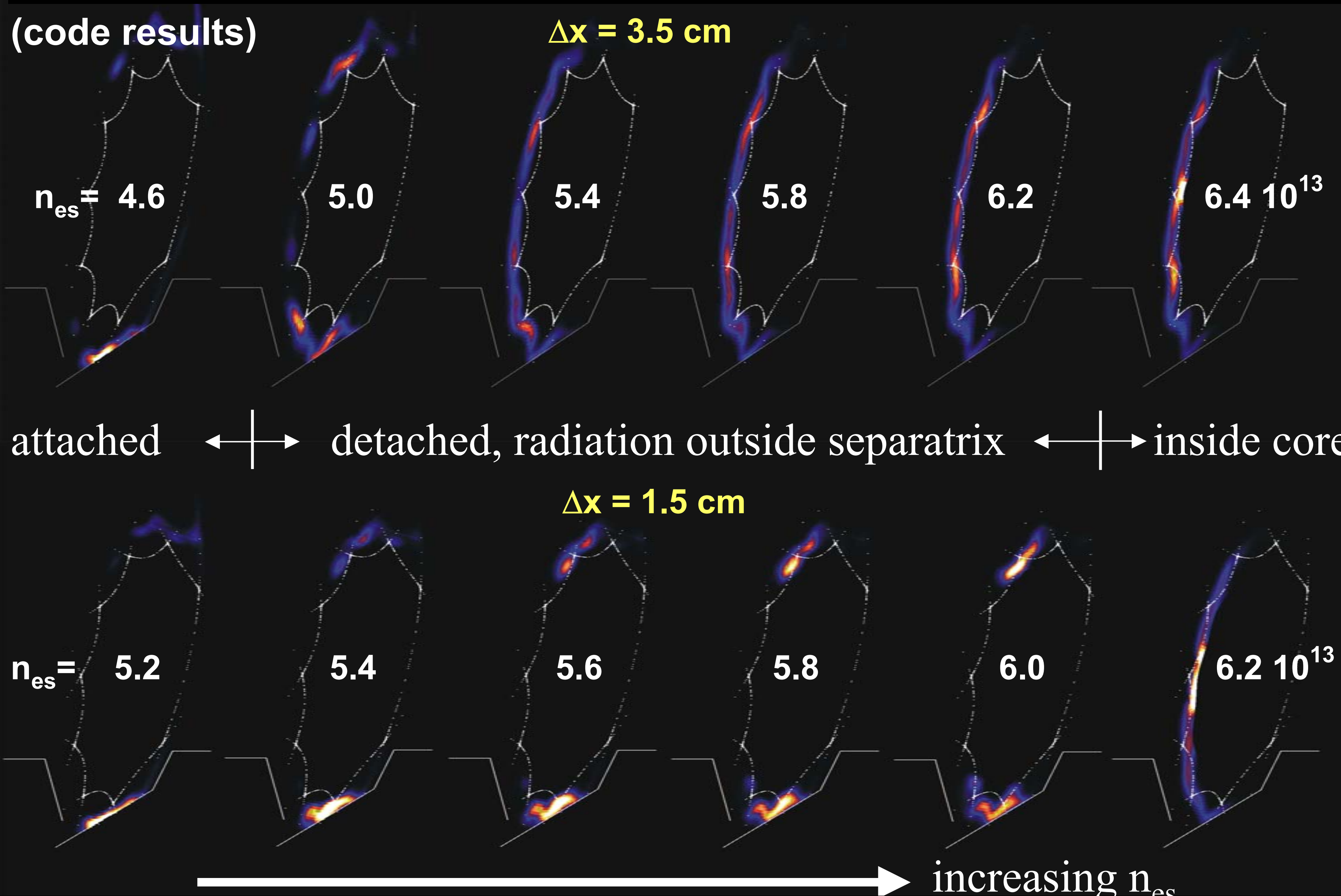






Detachment transition shifts to higher densities for smaller Δx or larger L_c so that the detachment range Δn_{es} becomes smaller

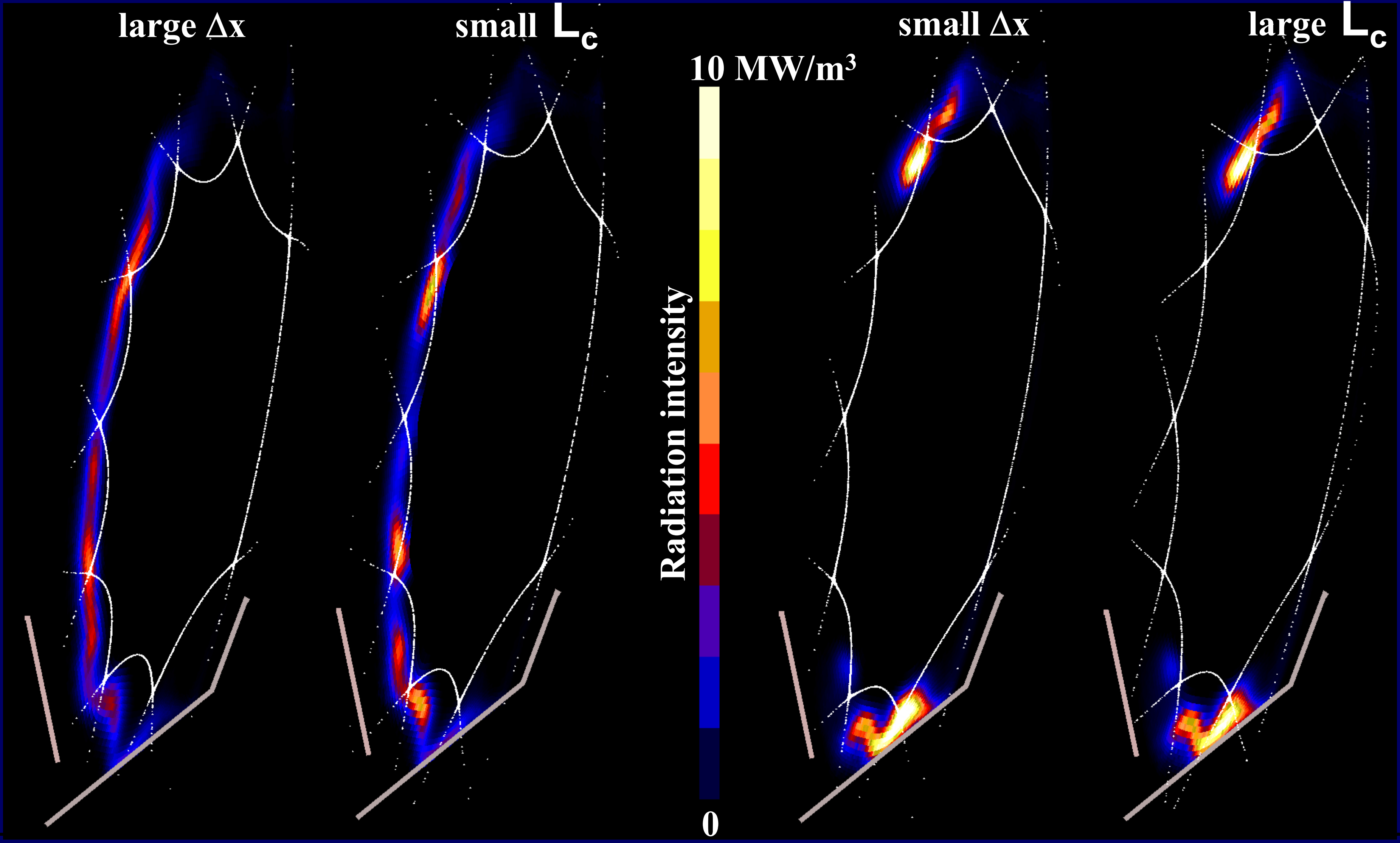
Evolution of radiation through detachment



Two different radiation patterns identified by EMC3

inboard side radiation (expt. stable detachment)

divertor radiation (unstable)



Comparison to tokamak Marfes

Tokamaks

toroidally symmetric poloidally asymmetric

W7AS

toroidally, poloidally and helically asymmetric

radiative condensation

increasing n_e

Tokamaks:

radiation zone moves to X-point to form Marfe

Marfe moves through X-point

Marfe moves to inboard side inside separatrix

radiative and MHD disruption

W7AS:

Radiation **Z**one (RZ) moves to the X-point close to the target

small islands or field line pitch — **unstable path**

RZ moves through the X-point

large islands and field line pitch — **stable path**

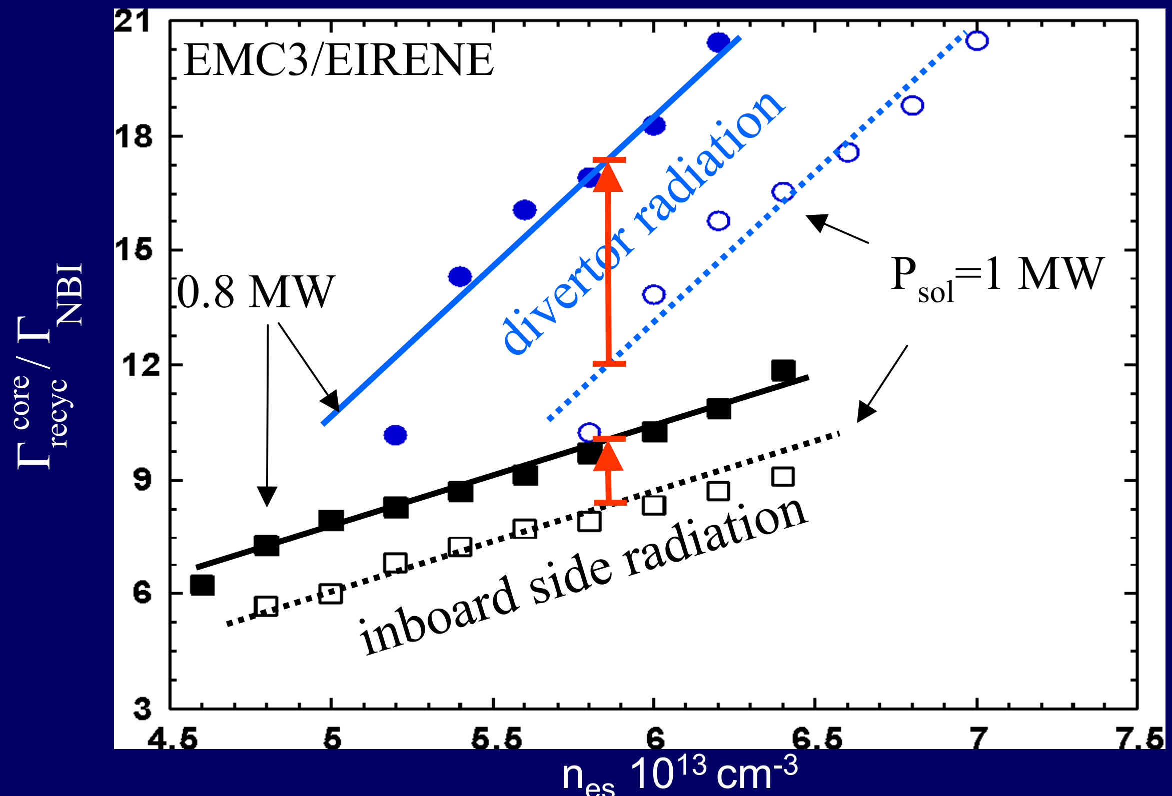
RZ moves to the X-points on the inboard side

RZ moves to inboard side inside separatrx

radiation oscillation or collapse

Impact of radiation location on neutral screening

sensitivity of neutral screening to configuration, n_{es} and P_{sol}



Divertor radiation → cold recycling zone → less efficient for neutral screening

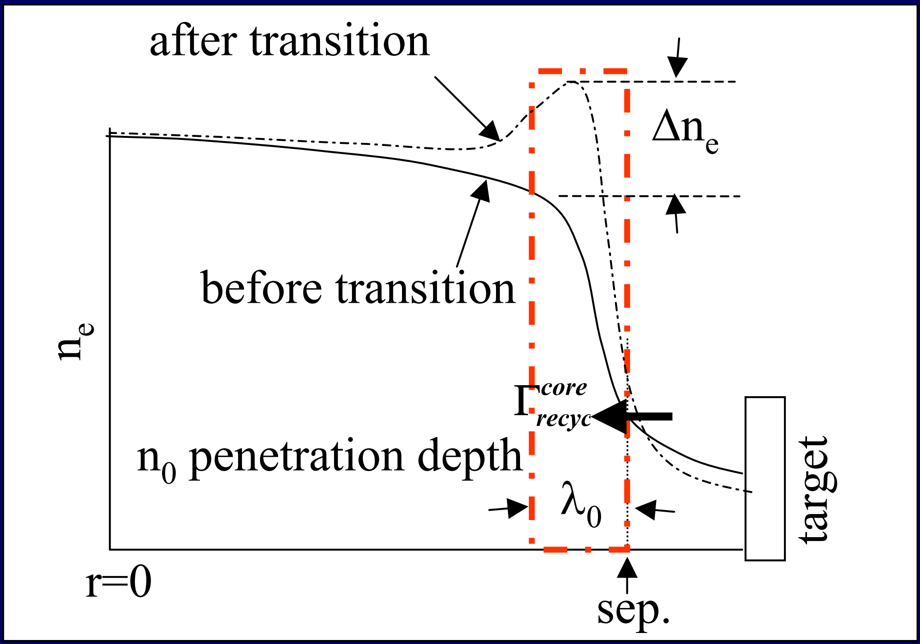
'less efficient' means: 1) higher Γ_{recyc} into core (smaller ΔX)

2) more sensitive to change of n_{es} or P_{sol} (radiation location),

i.e. larger $\frac{\partial \Gamma^{core}_{recyc}}{\partial P_{SOL}}$ and $\frac{\partial \Gamma^{core}_{recyc}}{\partial n_{es}}$

Instability driven by neutrals

A comprehensive stability study needs a core model coupled self-consistently!



↑ core energy loss due to n_0

$$\uparrow \Gamma^{core}_{recyc} \rightarrow \uparrow \Delta n_e \rightarrow \uparrow R_{core} \rightarrow \downarrow P_{sol}$$

positive feedback

growth rate of instability $\propto \dfrac{\partial \Gamma^{core}_{recyc}}{\partial P_{SOL}}$

a linear stability analysis

$$\frac{\partial \Delta n_e}{\partial t} = \frac{1}{A_s \lambda_0} \Delta \Gamma^{core}_{recyc} - D \frac{\Delta n_e}{\lambda_0^2}$$

(note that the change of Γ^{core}_{recyc} from the edge is much faster than core transport with the time scale λ_0^2 / D)

$$\frac{\partial \Delta n_e}{\partial t} \propto \Delta \Gamma^{core}_{recyc} = \frac{\partial \Gamma^{core}_{recyc}}{\partial n_{es}} \Delta n_{es} + \frac{\partial \Gamma^{core}_{recyc}}{\partial P_{SOL}} \Delta P_{SOL}$$

Second term is destabilizing as

$$\uparrow \Delta n_e \rightarrow \downarrow \Delta P_{SOL} \rightarrow$$

$$\partial\, \Delta n_e / \partial t \sim \left| \frac{\partial \Gamma^{core}_{recyc}}{\partial P_{SOL}} \right| \Delta n_e$$

- **divertor radiation less efficient for neutral screening → larger growth rate of instability**

Stabilization by decreasing edge density

Stabilization through $\downarrow \Delta n_{es}$ (edge parameter)

$$\downarrow n_{es} \rightarrow \downarrow R_{edge} \rightarrow \uparrow \mathbf{T_{e,island}} \rightarrow \uparrow \mathbf{n_0}\text{-}\mathbf{screening\ effic.} \rightarrow \downarrow \Gamma^{core}_{recyc}$$

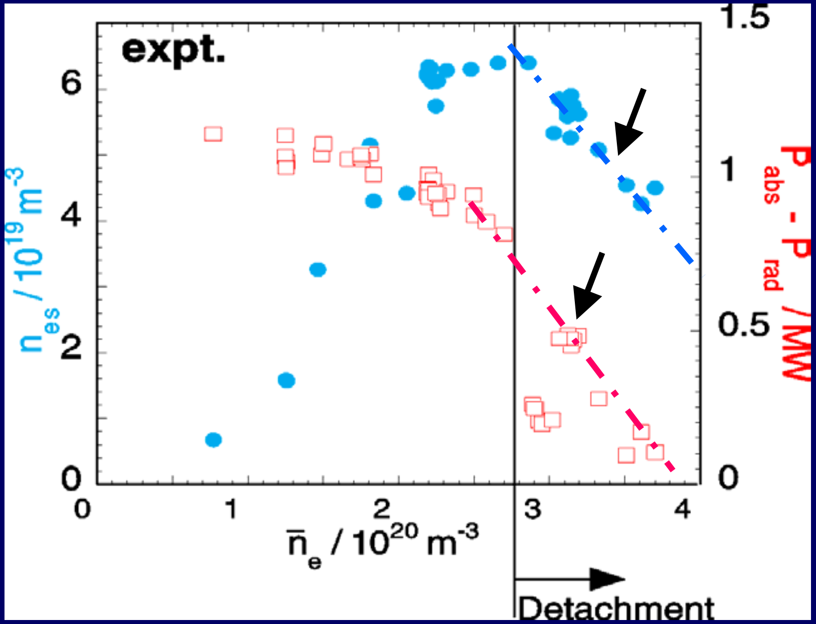
- Stable only for sufficiently quick and strong drop of n_{es}

Steady state (stable detachment):

$$\left|\frac{\partial \Gamma^{core}_{recyc}}{\partial n_{es}}\right| \Delta n_{es} = \left|\frac{\partial \Gamma^{core}_{recyc}}{\partial P_{SOL}}\right| \Delta P_{SOL}$$

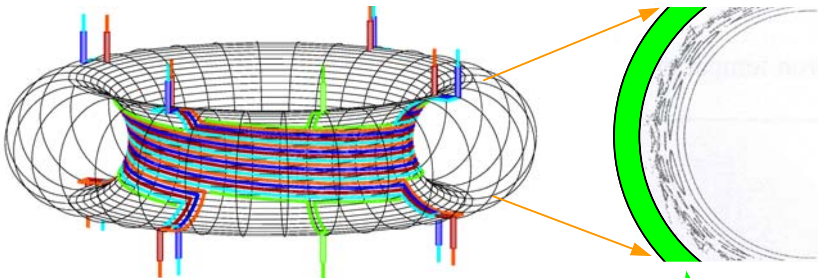
- if P_{sol} drops after the transition to detachment n_{es} has to be decreased correspondingly

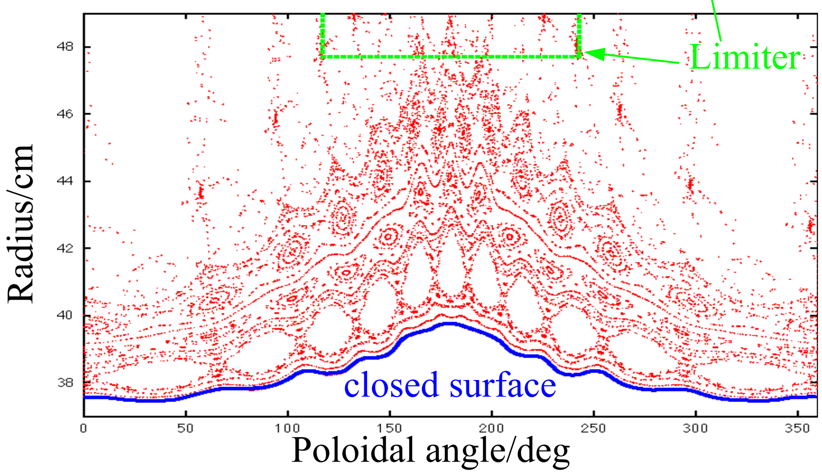
This is seen in experiments!



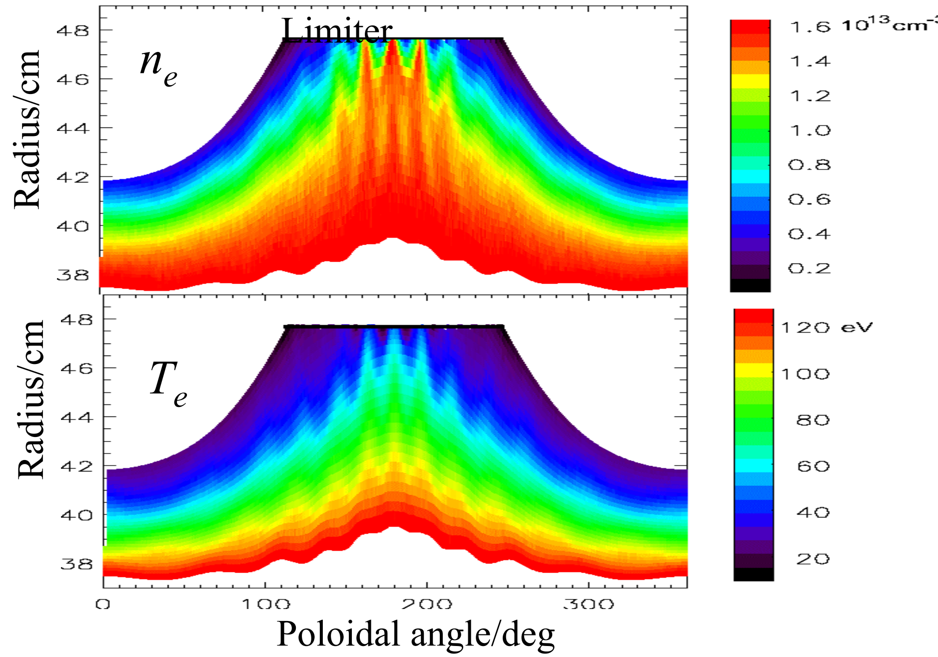
First application to TEXTOR-DED

M. Kobayashi, 30th EPS St. Petersburg 2003
9th PET San Diego 2003



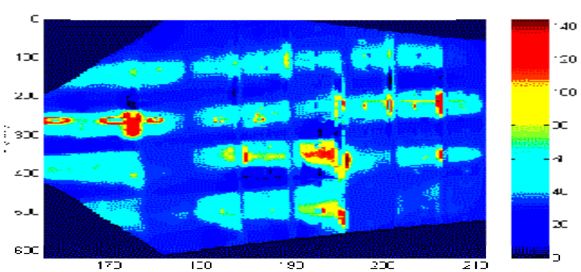


EMC3-EIRENE

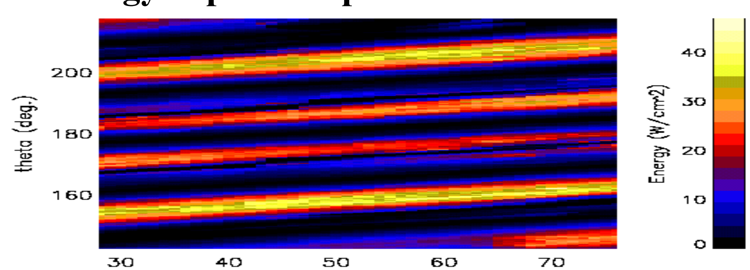


First experiment

IR measurement



Energy deposition pattern onto divertor



Conclusions

- EMC3-EIRENE treats self-consistently the plasma, impurities and neutral gas transports in 3D ergodic and non-ergodic edges including realistic divertor plates, baffles and wall. The code has been implemented on W7-X and TEXTOR-DED.
- The main differences in physics between the W7-AS island divertor and a tokamak divertor are the geometry-related momentum loss, the absence of the high-recycling regime, the high separatrix density required for detachment transition (and for an effective pumping) and the weak efficiency of neutral gas screening.
- Detachment stability depends on island geometry
  * Stable detachment only possible for sufficiently large island and field-line pitch

  Code results:

  * Only two typical radiation patterns
    - inboard side radiation (large islands and field-line pitch)
    - divertor radiation (small islands or field line pitch)
  * Evolution of radiation through detachment similar to that of MARFEs in tokamaks
  * Divertor radiation $\rightarrow$ cold islands $\rightarrow$ poor neutral screening
  * Loss of neutral screening responsible for detachment instability
  * Stabilization by decreasing n_{es}