Influence of a magnetic island on the edge impurity radiation in a heliotron

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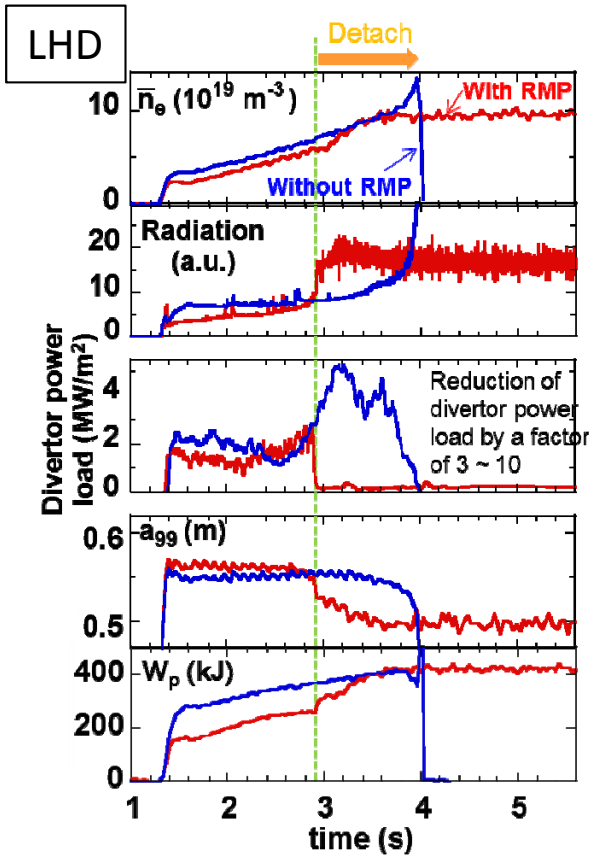
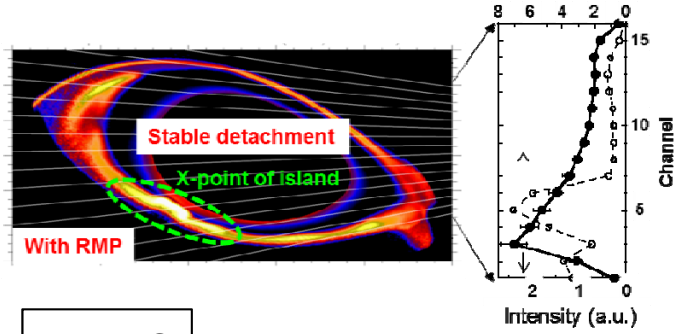
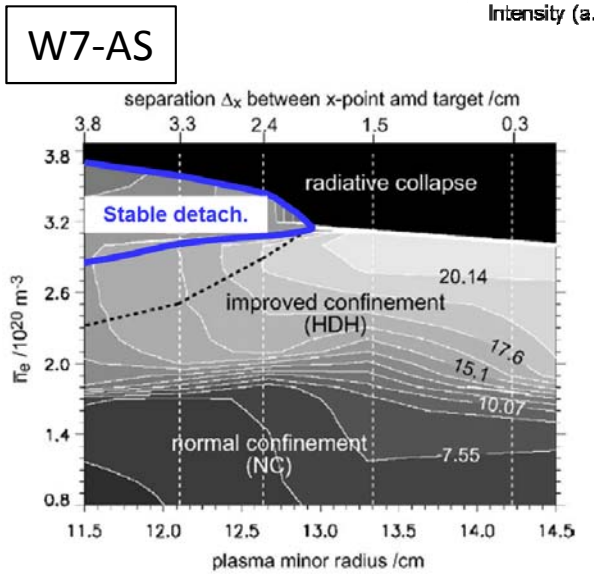
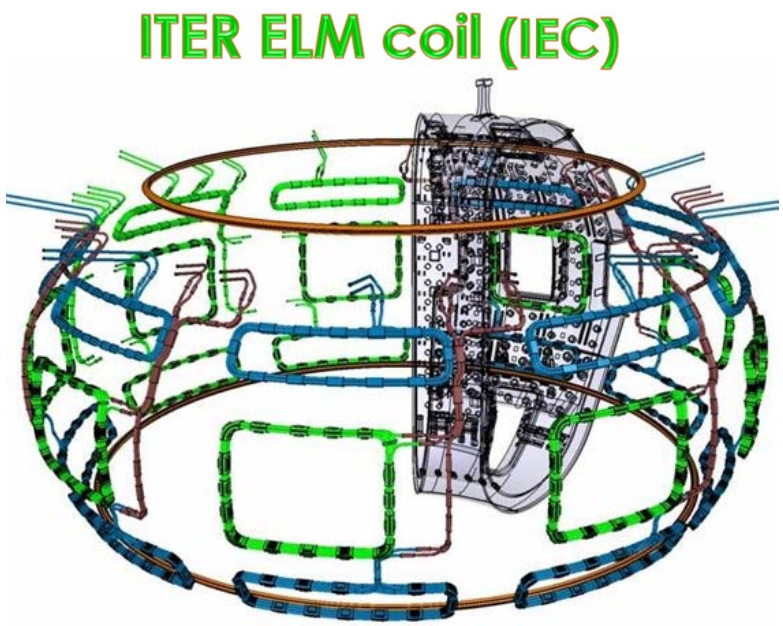
Understanding of effects of 3D field and RMP on detachment control is crucial issue for both stellarators and tokamaks

- Experimental evidence of edge island effects on detachment control in LHD & W-7AS
- ITER will operate with RMP to control ELM → Effects of RMP on detachment is currently investigated in AUG, DIII-D, EAST, KSTAR, NSTX etc.





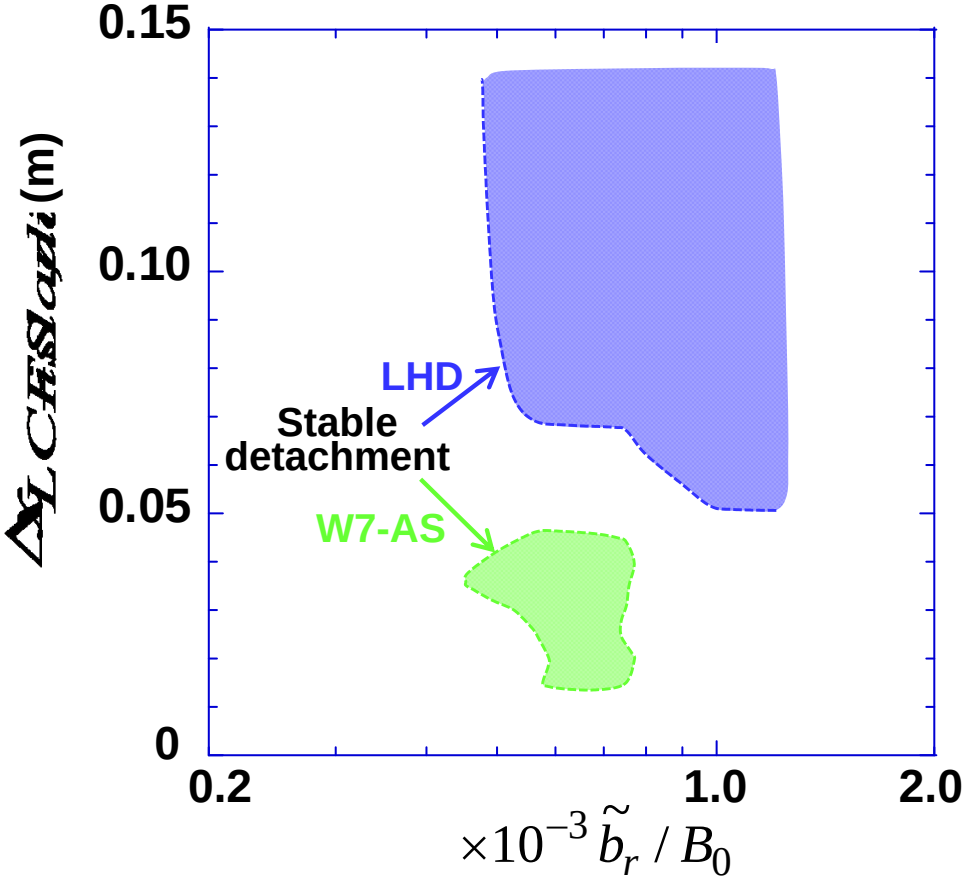


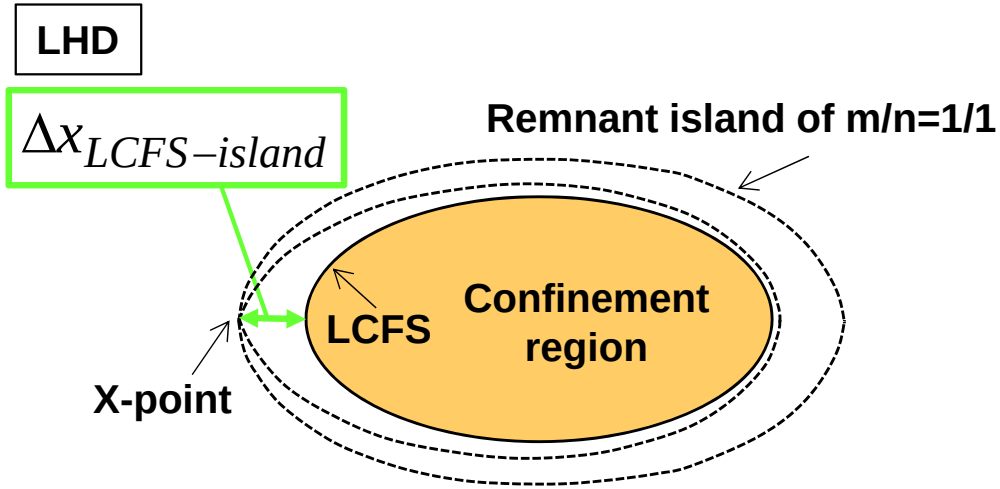


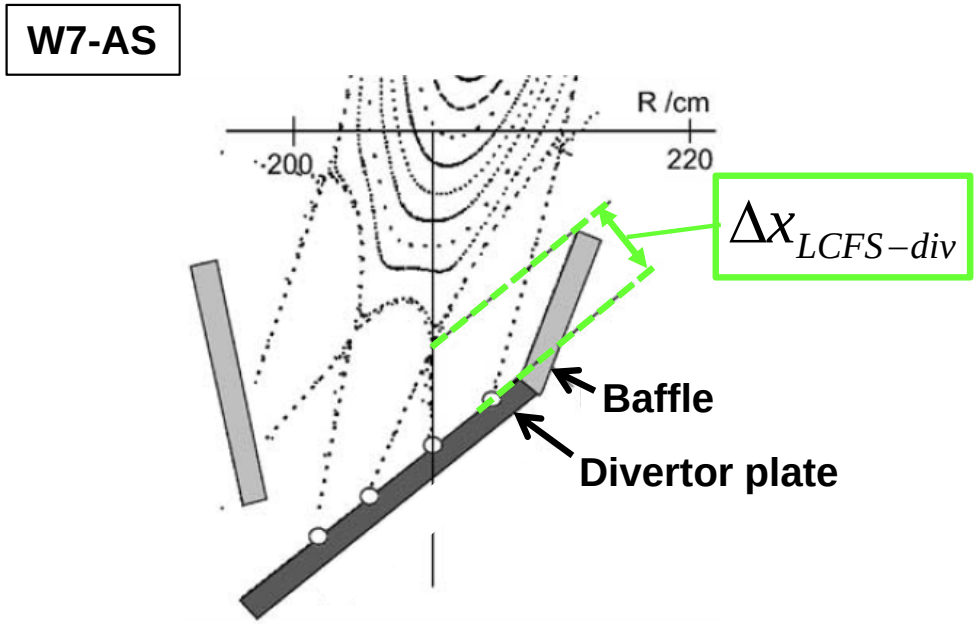
- In this contribution, impact of edge island on plasma transport and detachment scenario is analyzed by using reduced transport model.
  - → Understanding of dominant physics process
  - → Identify issues to be investigated further

Operation domain of stable detachment in LHD & W7-AS

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







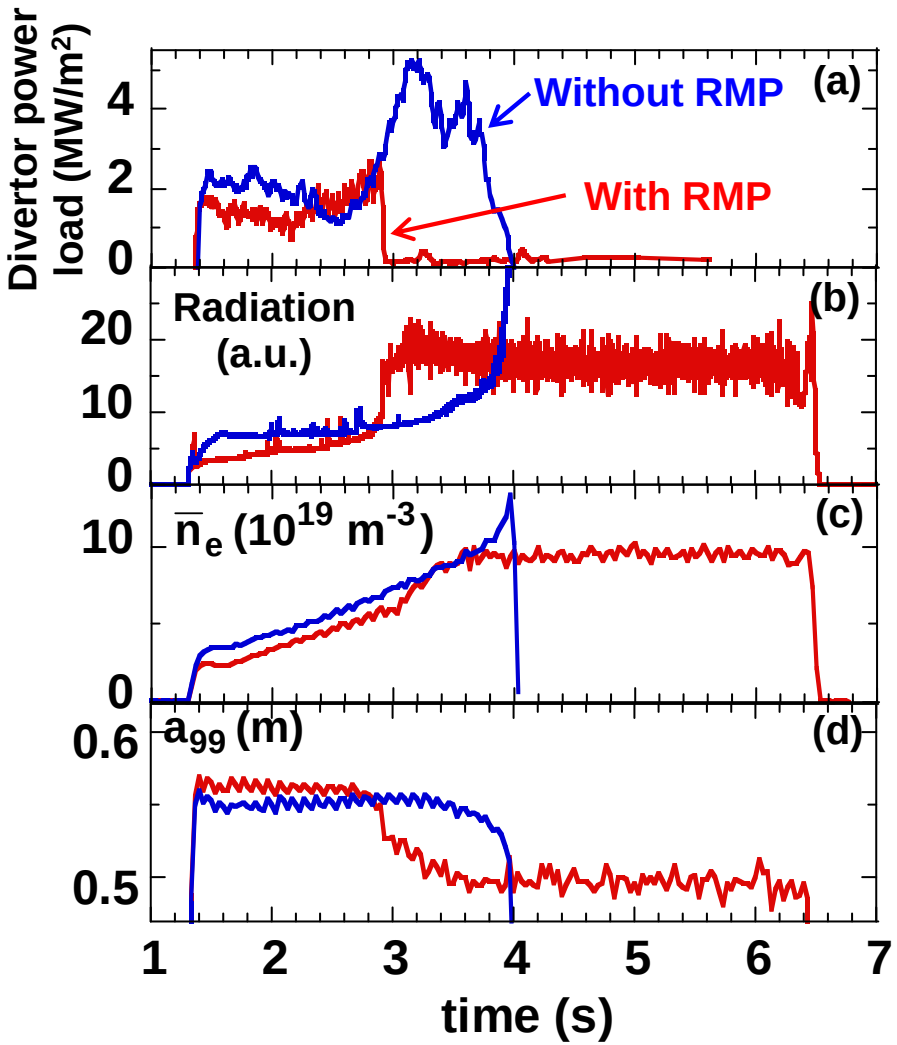
<u>Conditions for stable detachment</u>

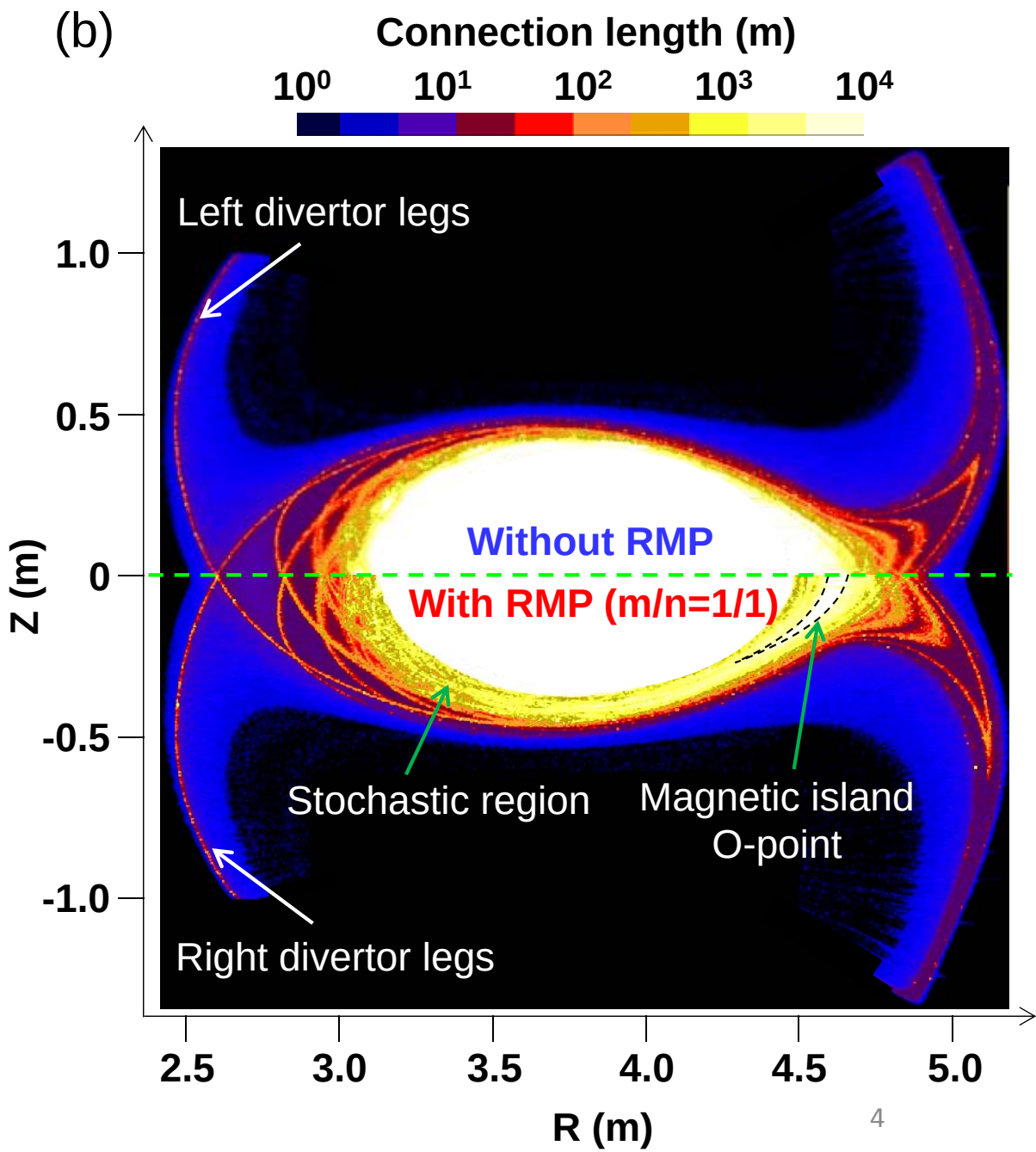
1) RMP field must be strong enough (intrinsic ones insufficient, additional MP needed).

2) the geometric SOL width ($\Delta x_{LCFS-island,div}$) must be sufficiently large.

Density ramp-up discharges with & without RMP

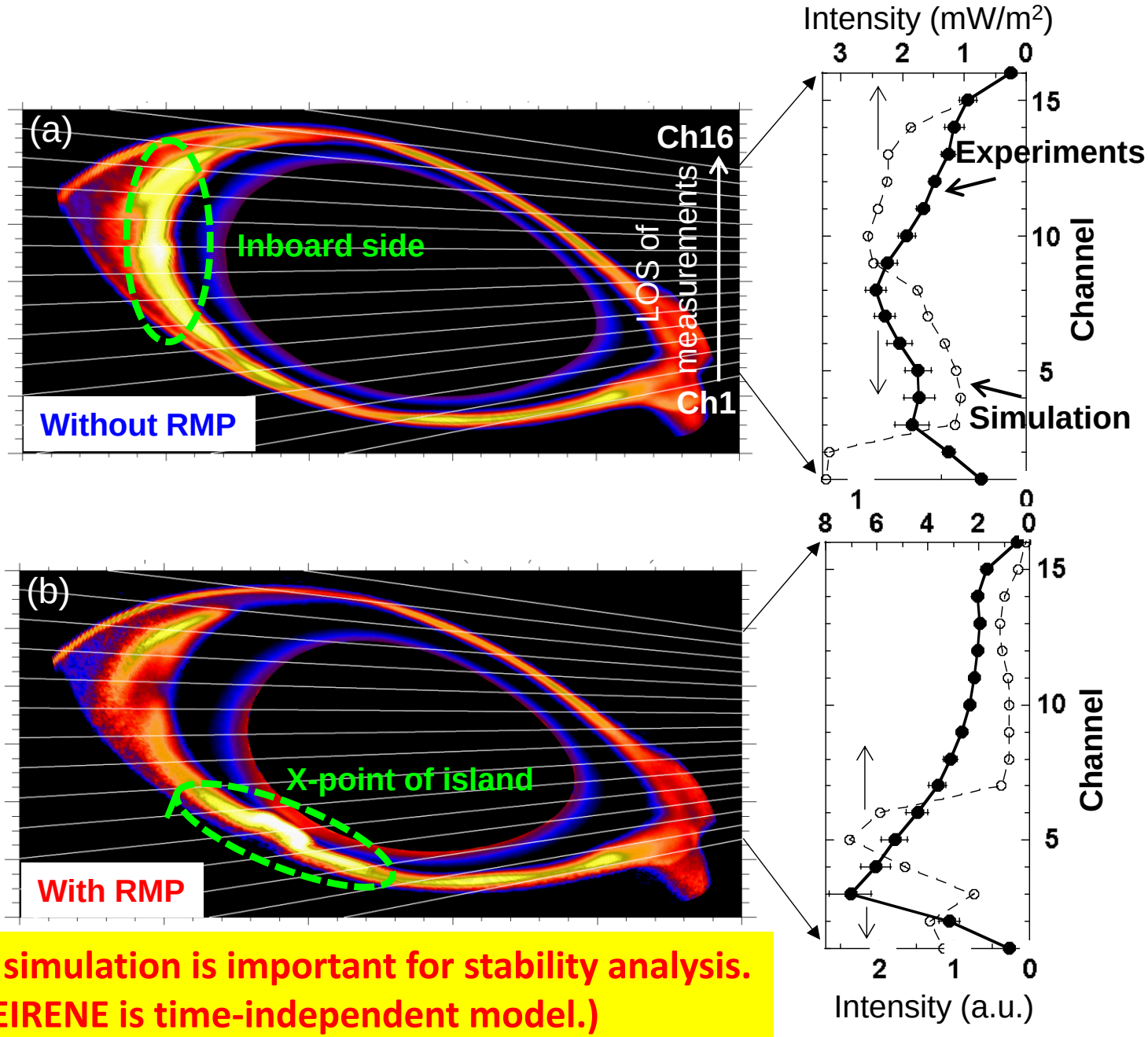
Why is detachment stabilized with edge magnetic island?
What happens in radiation distribution?





EMC3-EIRENE simulation and measurements of radiation.

Computation is time-consuming: ~10 months for one density scan.
Analysis of physical process is complicated in the big 3D code and in the stochastic layer.



Time-dependent simulation is important for stability analysis.
(EMC3-EIRENE is time-independent model.)

Model equations for time-dependent transport simulation

Bulk plasma

Particle
$$\frac{\partial n_i}{\partial t} = \nabla \cdot \left(-n_i V_{i\parallel}\mathbf{b} + D_\perp \mathbf{b}_\perp \mathbf{b}_\perp \cdot \nabla n_i\right) + S_p$$

//-Momentum
$$\frac{\partial m_i n_i V_{i\parallel}}{\partial t} = -\mathbf{b} \cdot \nabla \left(n(T_e + T_i)\right) + \nabla \cdot \left(m_i V_{i\parallel} D_\perp \mathbf{b}_\perp \mathbf{b}_\perp \cdot \nabla n_i + \eta_\perp \mathbf{b}_\perp \mathbf{b}_\perp \cdot \nabla V_{i\parallel}\right) - S_m$$

Energy (electron)
$$\frac{\partial n_e T_e}{\partial t} = \nabla \cdot \left(\kappa_e \mathbf{bb} \cdot \nabla T_e + n_e \chi_{\perp e} \mathbf{b}_\perp \mathbf{b}_\perp \cdot \nabla T_e\right) - C n_e^2 L(T_e) - S_e - K(T_e - T_i)$$

Energy (ion)
$$\frac{\partial n_i T_i}{\partial t} = \nabla \cdot \left(\kappa_i \mathbf{bb} \cdot \nabla T_i + n_i \chi_{\perp i} \mathbf{b}_\perp \mathbf{b}_\perp \cdot \nabla T_i\right) - S_i + K(T_e - T_i)$$

$$S_p = k_{ion} n_e (n_{at} + n_{CX})$$

$$S_m = k_{CX} n_{at} n_i V_{i\parallel} \qquad \eta_\perp = m_i n_i D_\perp$$

$$S_e = k_{ion} n_e (n_{at} + n_{CX}) E_{ion+exc} \quad (E_{ion+exc} = 31eV)$$

$$K = \frac{3 m_e n_e}{m_i \tau_{ei}}, \quad \tau_{ei} = 2.03 \times 10^{10}\, T_e^{1.5}/n_e$$

$$S_i = -k_{CX} n_i n_{at} (T_{at} - 1.5 T_i)$$

Model equations for time-dependent transport simulation

Neutrals (Fluid approximation)

Cold Atoms (Franck Condon atom)

$$n_{at}(r) = n_{at}(a)\,\exp\left(-\int_r^a \frac{k_{ion}+k_{cx}}{V_{at}} n_e(r)\,dr\right) \qquad V_{at} = \sqrt{\frac{2T_{at}}{3m_{at}}}$$

Charge exchange (CX) Atoms

$$0 = \nabla\cdot\left(D_{CX}\mathbf{b}_\perp\mathbf{b}_\perp\cdot\nabla n_{CX}\right) + k_{CX}n_e n_{at} - k_{ion}n_e n_{CX} \qquad D_{CX} = \frac{V_i^2}{n_e(k_{ion}+k_{CX})} \qquad V_i = \sqrt{\frac{T_i}{m_i}}$$

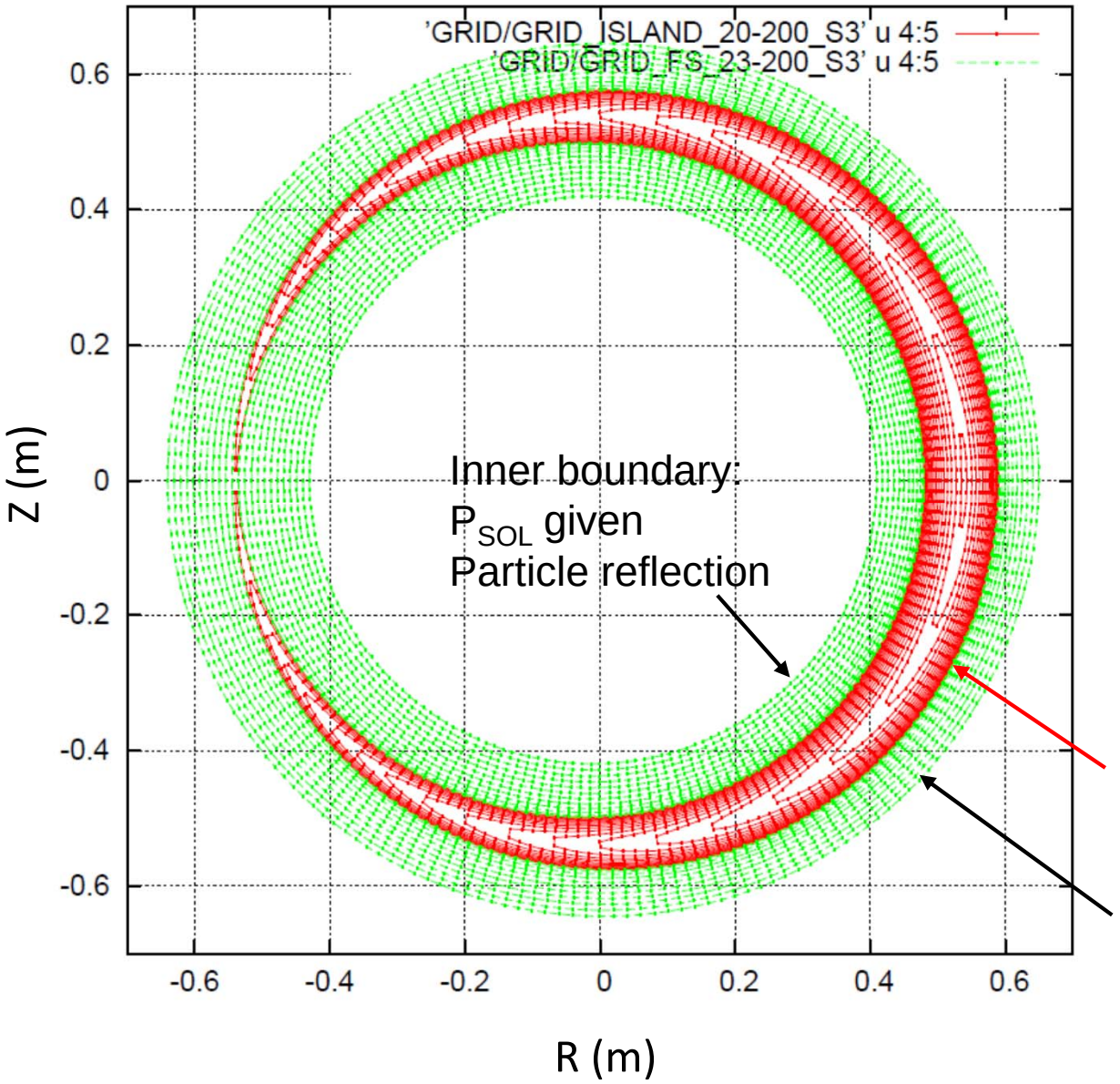
Impurity

$$\frac{\partial n_{imp}}{\partial t} = \nabla\cdot\left(-n_{imp}V_{imp\|}\mathbf{b} + D_\perp^{imp}\mathbf{b}_\perp\mathbf{b}_\perp\cdot\nabla n_{imp}\right) + S_p^{imp}$$

$$V_{imp\|} = V_{i\|} + \frac{\tau_s C_i}{m_{imp}}\mathbf{b}\cdot\nabla T_i$$ (Force balance between friction and ion thermal forces)

$$C_i = 2.6Z^2 \qquad \tau_s = 2.05\times10^{13}\frac{m_{imp}}{\ln\Lambda\, n_i Z_i^2 Z_{imp}^2\sqrt{m_i}}\frac{T_i^{1.5}}{\frac{m_i}{m_{imp}}+1},\ (\ln\Lambda = 17)$$

Geometry of numerical simulations with magnetic island



- The equations are solved with Implicit finite volume scheme.
- The edge region with m/n=1/1 magnetic island is modeled with cylindrical geometry.
- Information of magnetic field line pitch in toroidal direction is embedded in the grid points.
- Density is increased by increasing neutrals at the outer-most surface (mimicking gas puff).
- Neutral impurity is launched at the outer most surface according to divertor particle flux and sputtering coefficient.

Magnetic island (m/n = 1/1)

Outer boundary:
Bohm condition at outer-most surface

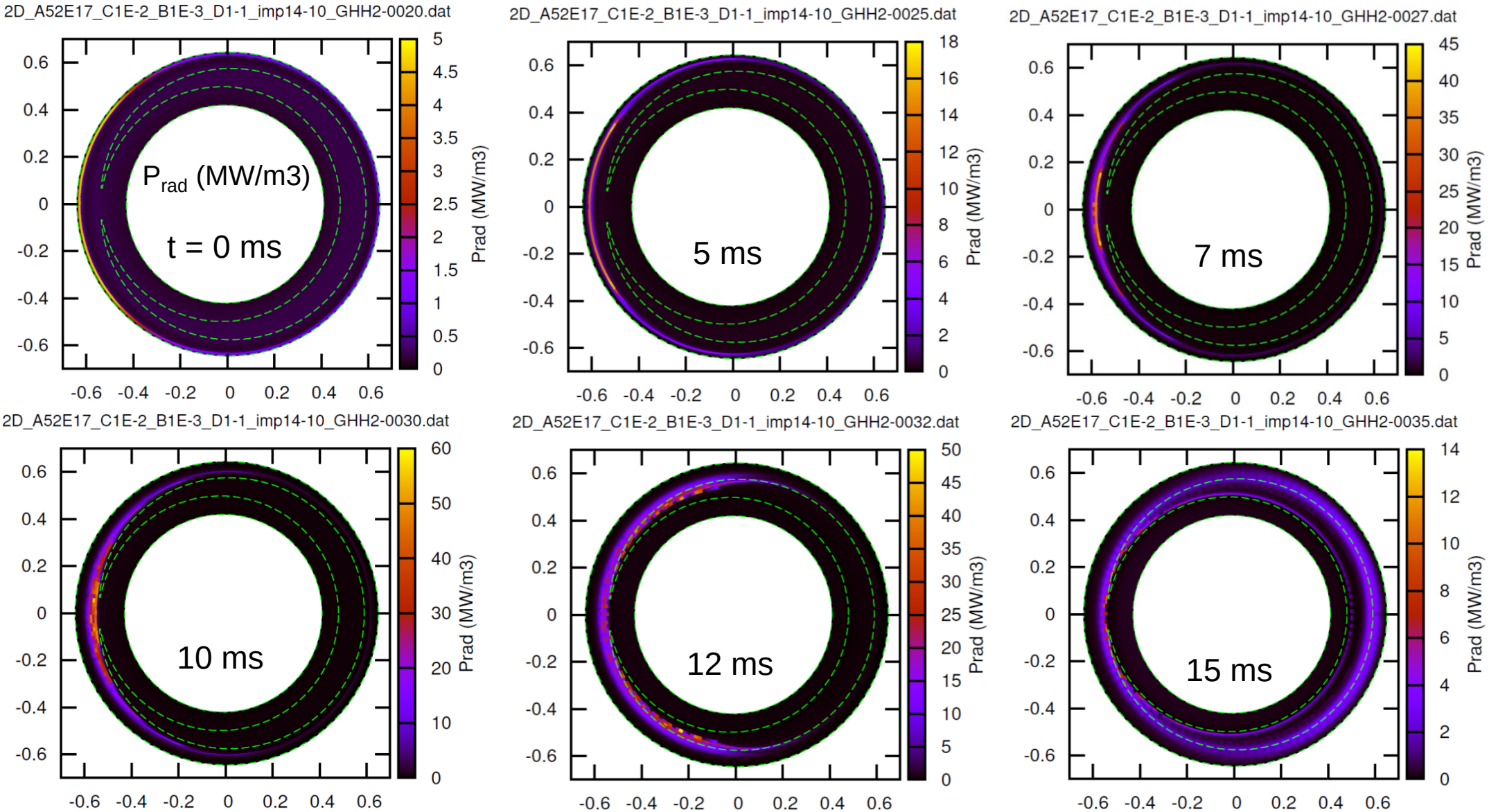
$$\Gamma_p = \beta n c_s$$

$$\Gamma_e = \beta (\gamma_e T_e + \gamma_i T_i + E_{ion+exc}) n c_s$$

$$\beta = \mathbf{r} \cdot \mathbf{b} = \frac{B_r}{B_\phi}$$

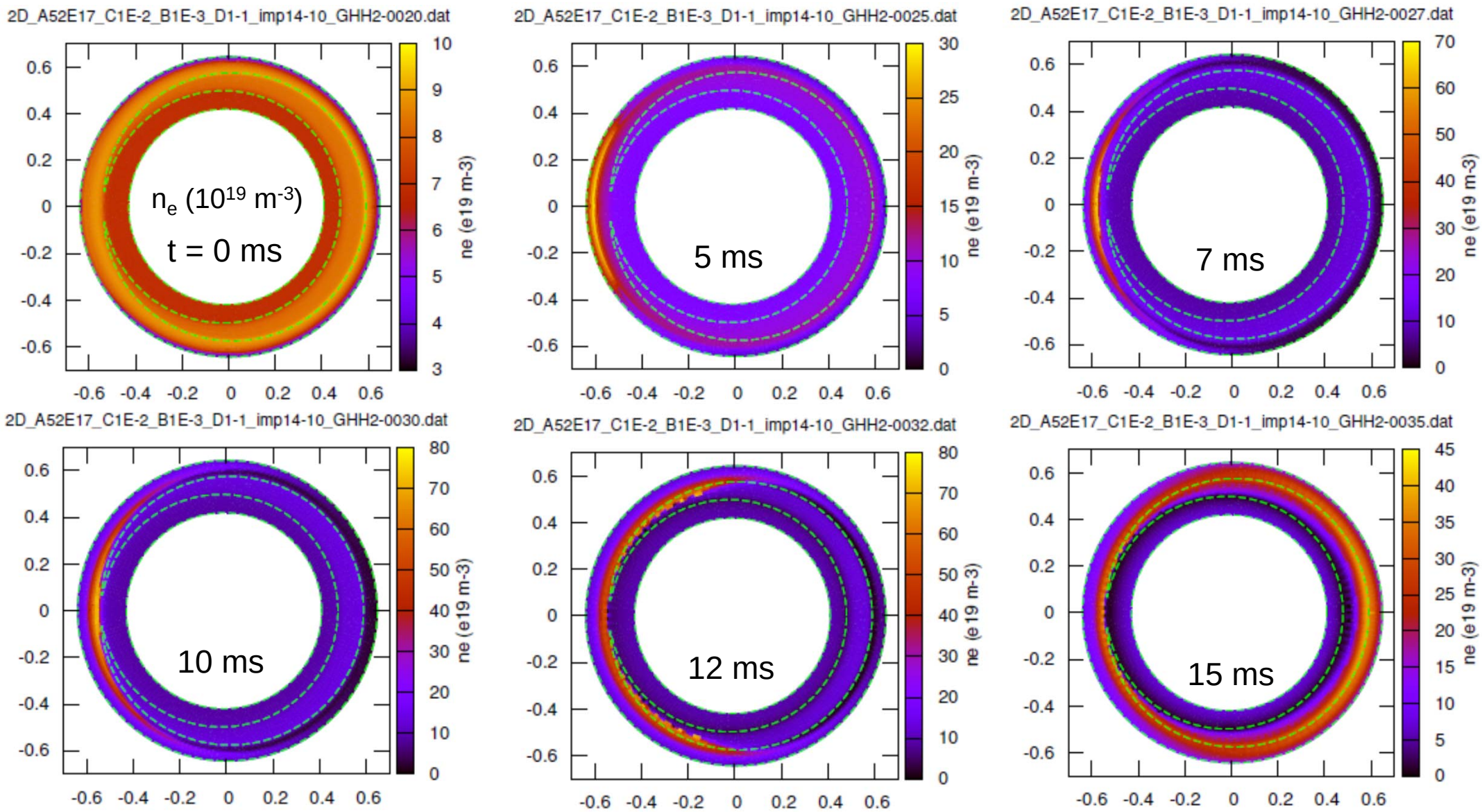
Dynamics of P_{rad} (radiation layer) during detachment transition

0 ms : Impurity radiation enhanced at the down-stream of X-point
5 ms : “Detaches” with poloidally localized radiation
10 ms : Reaches X-point
> 12 ms : Propagates toward O-point within



Dynamics of n_e during detachment transition

0 ms : Density (n_e) increases at outer periphery of island O-point in attached phase.
5 ms : n_e significantly peaked at the down stream of X-point at detachment transition
(due to pressure conservation along magnetic field.)
10 ms : Reaches, → propagates to O-point (15 ms)

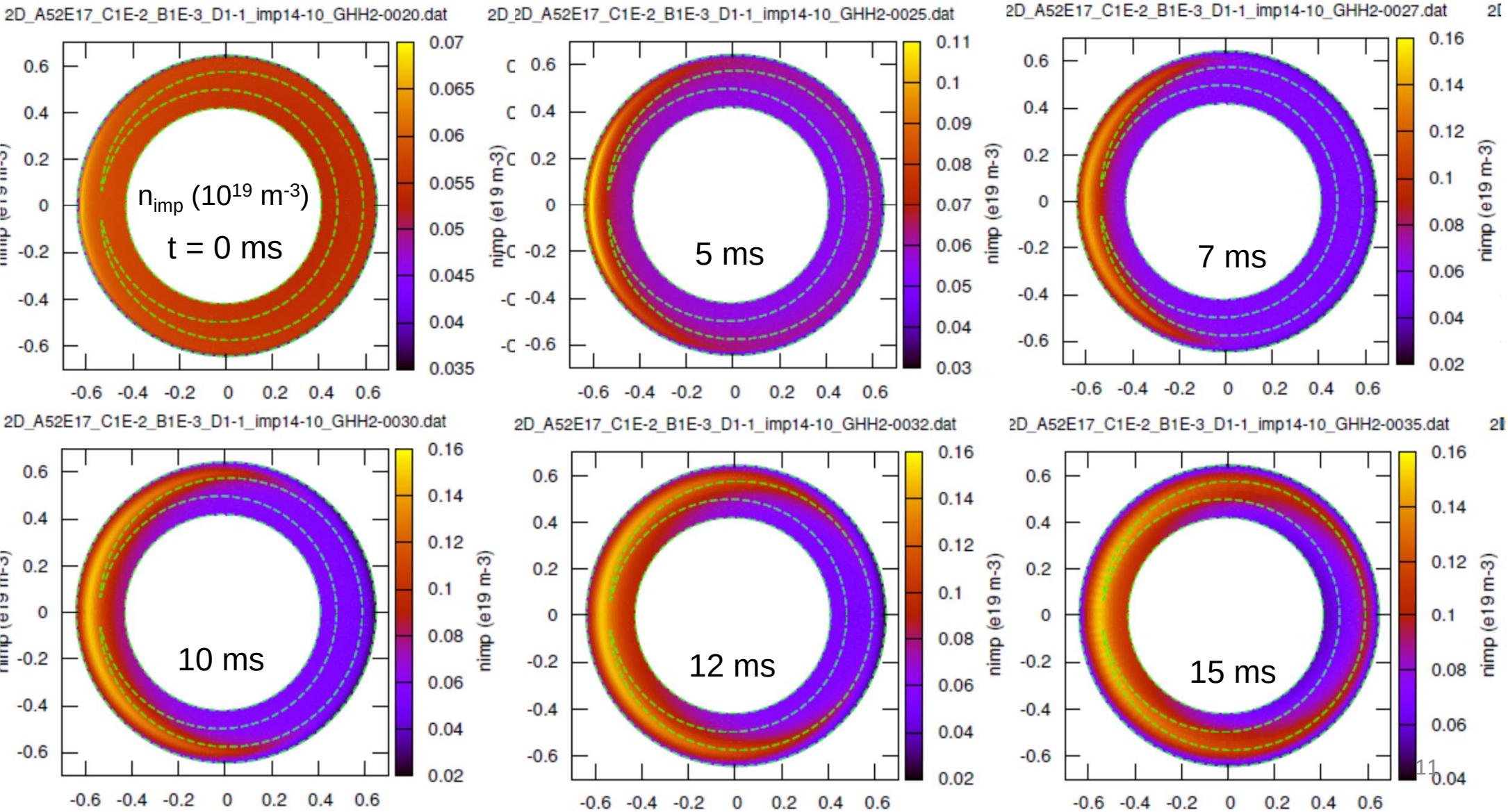


Dynamics of n_{imp} during detachment transition

0 ms : Impurity density (n_{imp}) slightly increases at down-stream of X-point in attached phase.

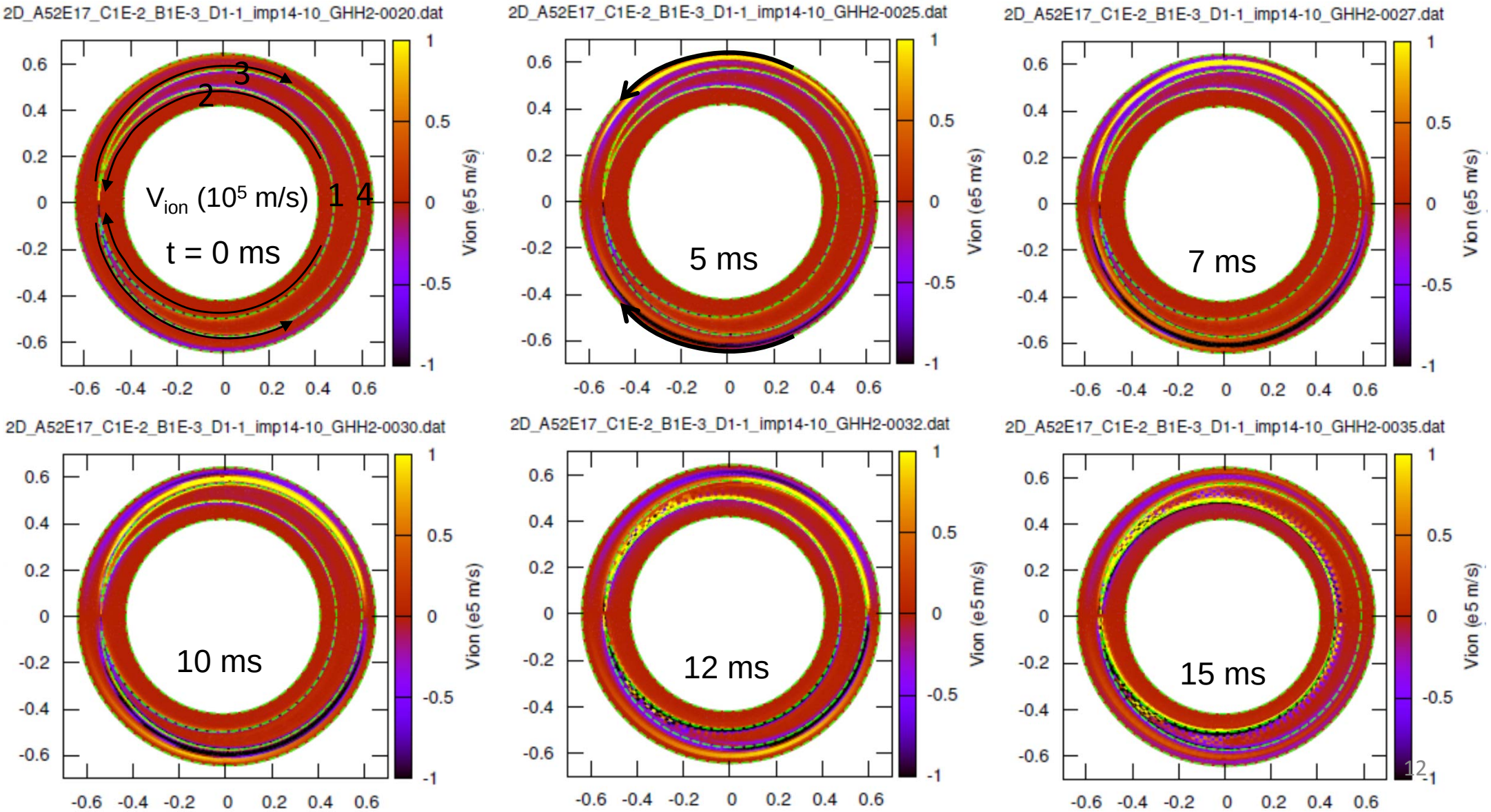
5 ms : n_{imp} significantly peaked at the down stream of X-point at detachment transition (due to friction force by plasma flow.)

7~10 ms : Gradual shift to X-point with peaked distribution → propagates toward O-point (12~15 ms)



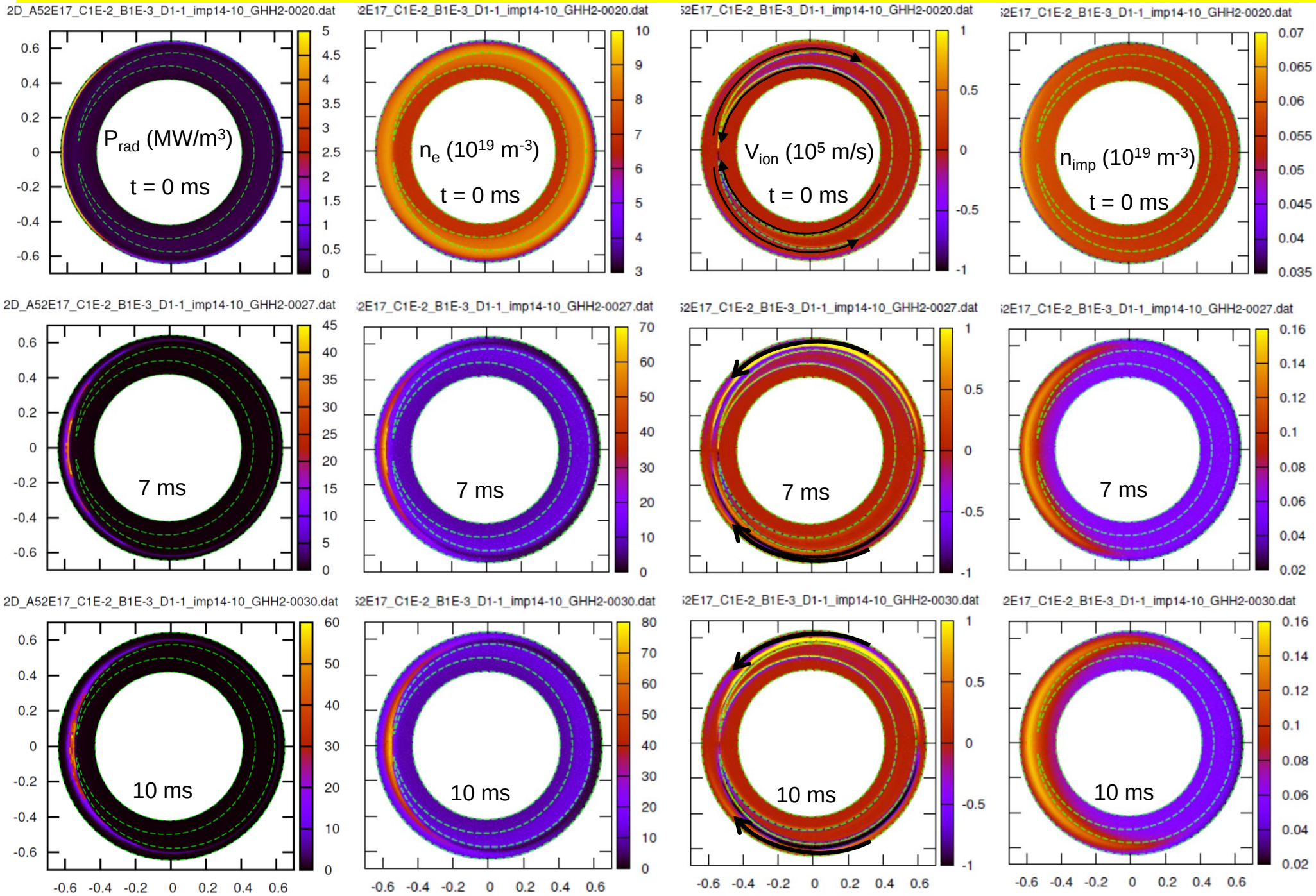
Dynamics of V_{ion} during detachment transition

0 ms : Plasma flow along separatrix is formed: 1 → 2 → 3 → 4 (through pressure conservation)
5 ms : Strong flow toward X-point is formed at detachment transition
7~15 ms : The global flow structure being kept with gradual inward shift



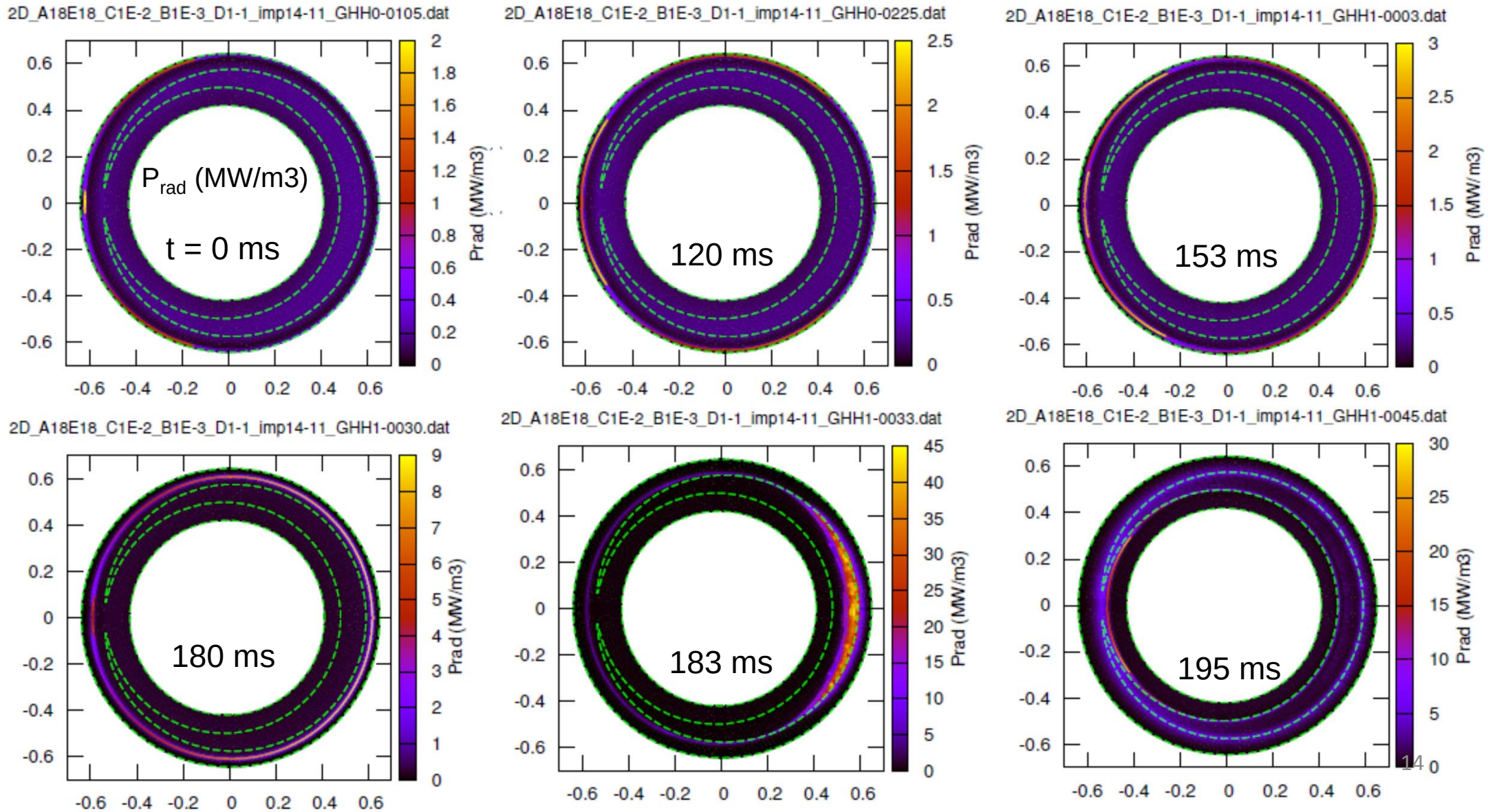
Dynamics of P_{rad} & plasma parameters during detachment transition

♦Radiation condensation around X-point. ♦P_{rad} inward shift ~ 5 ms. ♦Strong flow formation toward X-point.



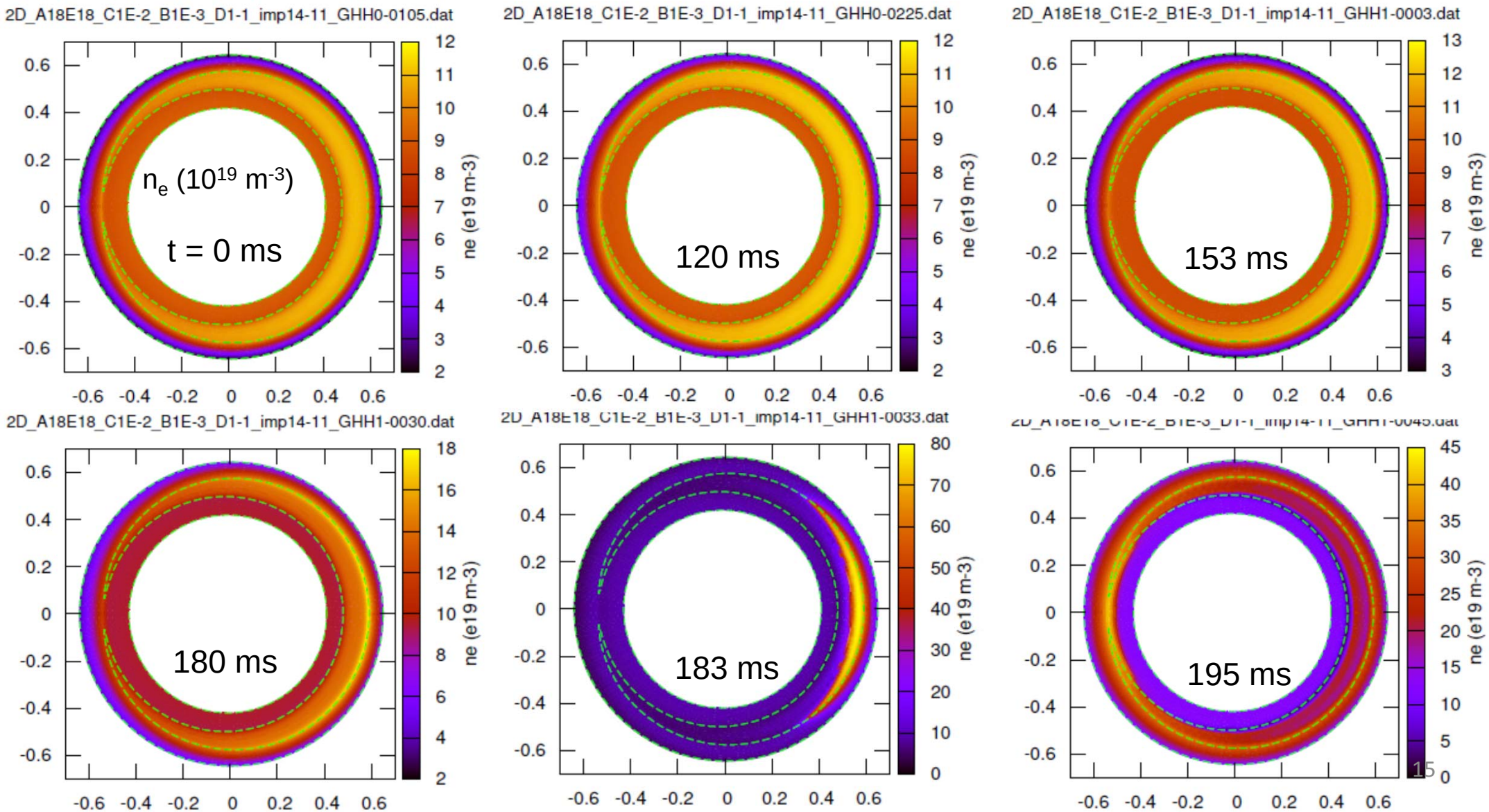
Dynamics of P_{rad} during detachment transition: No //-transport outside island

0 ms : Impurity radiation enhanced at the down-stream of X-point → Detach onset
< 180 ms : Inward shift very slowly, while widening in poloidal direction
183 ms : Change to O-point radiation
> 195 ms : Penetrates inside island from X-point



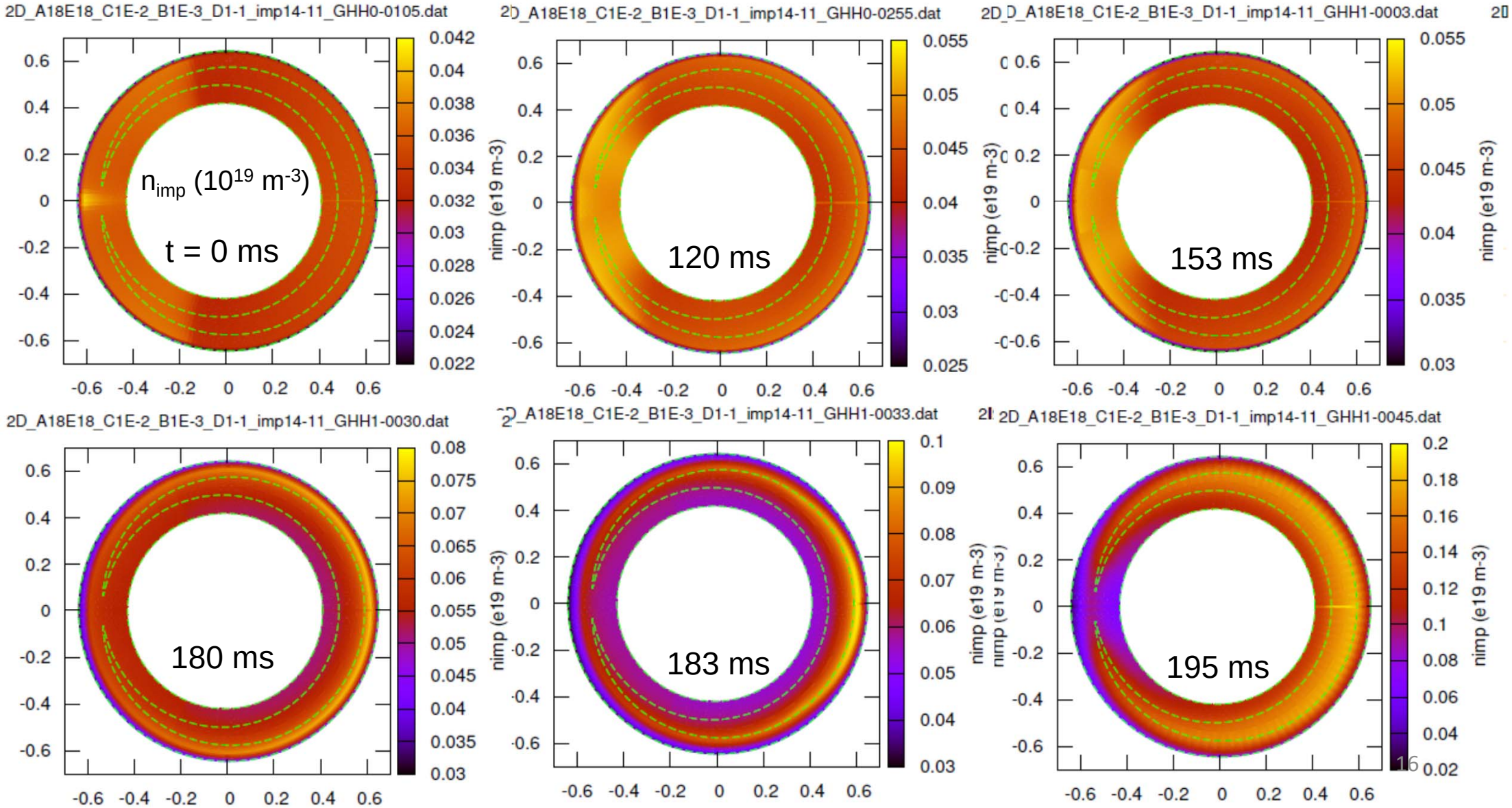
Dynamics of n_e during detachment transition: No //-transport outside island

0 – 153 ms : No n_e peaking at radiation region occurs ← Due to no //-pressure conservation
> 180 ms : n_e peaking appears at O-point (P_{rad} peaked there) due to //-pressure conservation
> 195 ms : n_e peaking moves to X-point, then penetrates inside island



Dynamics of n_{imp} during detachment transition: No //-transport outside island

0 ms : n_{imp} slightly peaked at down-stream of X-point at attached case (similar to with //-trans)
120 ms : n_{imp} peaking at X-point side remains, but modest than with //-trans.
→ Out of phase with n_e distribution
> 180 ms : n_{imp} peaking moves to O-point, in phase with n_e (←//-trans. Inside island)

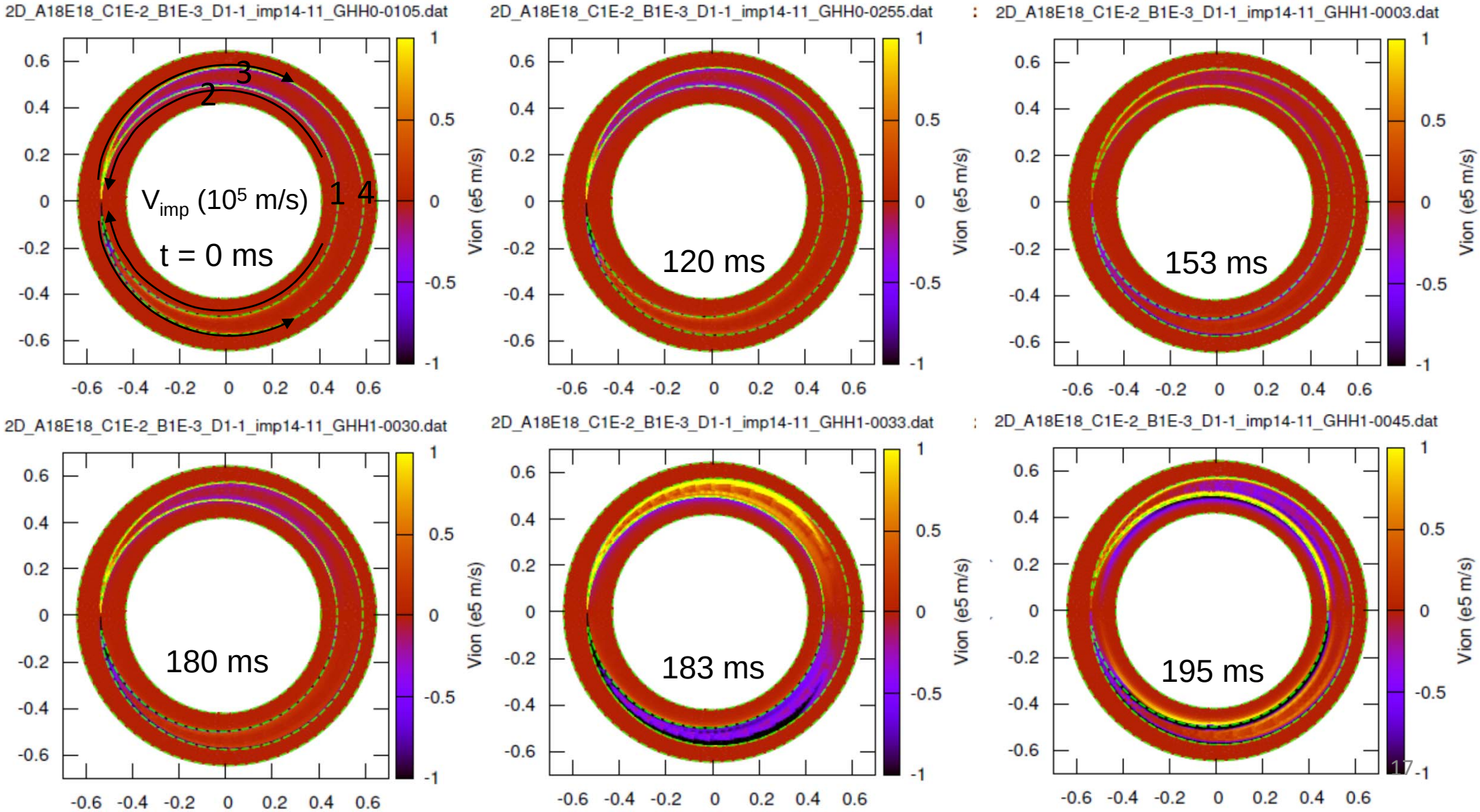


Dynamics of V_{ion} during detachment transition: No //-transport outside island

0 ms : Impurity flow along separatrix is formed: 1 → 2 → 3 → 4 (similar to with //-trans.)

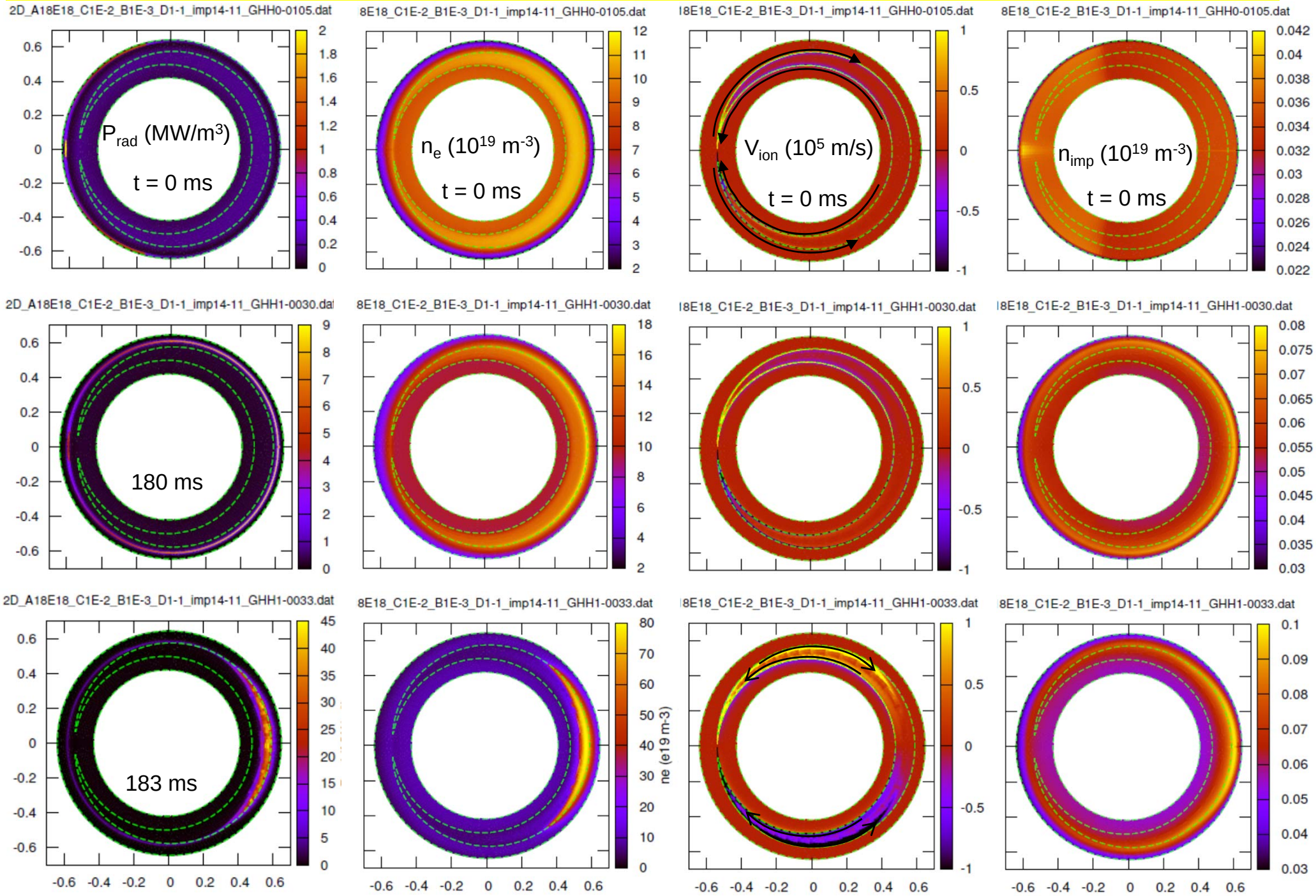
But No //-flow outside island → modest n_{imp} peaking

> 183 ms : Flow along separatrix enhanced when radiation enters island

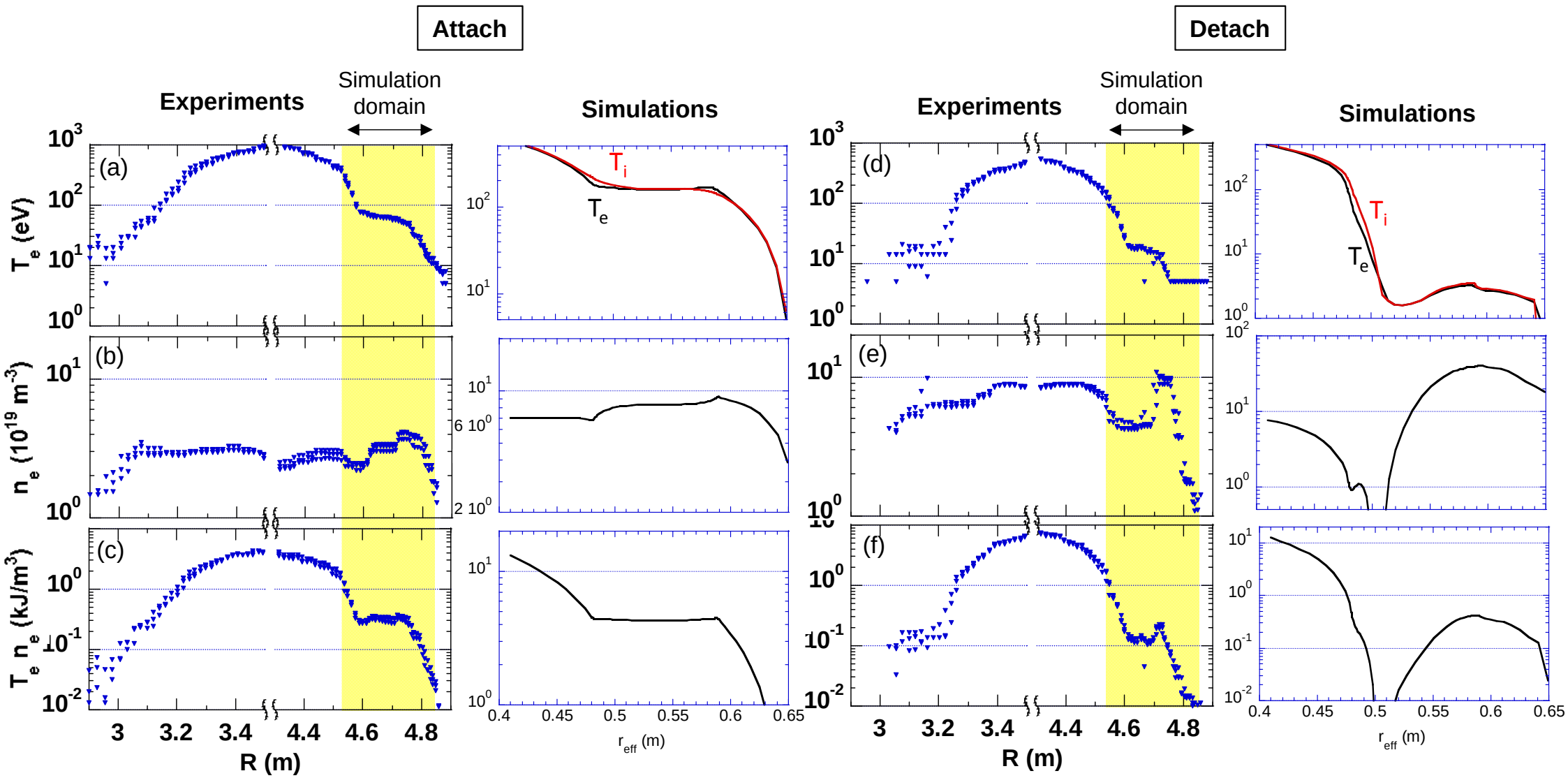


Dynamics of P_{rad} & plasma parameters during detachment transition No //-transport outside island

♦No radiation condensation around X-point. ♦P_{rad} inward shift ~ 180 ms. ♦No flow formation outside island.



Radial profiles modulation of plasma parameters due to island structure



Simulation qualitatively reproduce experimental profiles.
Attached : Flattening of T_e, Pressure. slight peaking of n_e at island outer edge.
Detached : Reduction of T_e, enhanced peaking of n_e & pressure at island outer edge.

Peaking of n_e at island outer edge ← //-pressure conservation + T gradient along separatrix

Qualitative agreement has to be explored by scanning transport coefficients etc.

Summary

1. Time-dependent transport simulation code is being developed to study detachment stability with edge magnetic island in LHD.

2. Radiation condensation is observed around X-point:

Caused by //-pressure conservation, flow formation + impurity transport toward X-point

3. Comparison between with & without //-transport outside island:

//-transport is more destabilizing for thermal condensation instability

~5 ms (with //-trans) vs. ~180 ms (without //-trans) for radiation front reaches island

→ **indicates enhanced perpendicular transport in stochastic layer acts as stabilizing detachment due to reduced //-coupling**

4. Radial profiles of T_e, n_e, pressure are qualitatively reproduced with simulation:

Flattening of T_e at island, n_e peaking of island edge etc.

5. The detachment stabilization is not reproduced in the present simulation.

Simulation: Radiation penetrates inside island

Experiment: Radiation stabilized outside island.

Next step:

1. Increase of perpendicular transport coefficients to mimic stochastic magnetic layer
2. Switch on perpendicular transport of momentum → //-pressure conservation is relaxed
3. Physics of low Te (< 1eV) plasma: Volume recombination, increased cross-field transport.