



FORMATION OF COUNTER-FLOWS BY MAGNETIC PERTURBATIONS IN COMPUTER SIMULATIONS OF THE PLASMA BOUNDARY OF TOKAMAKS

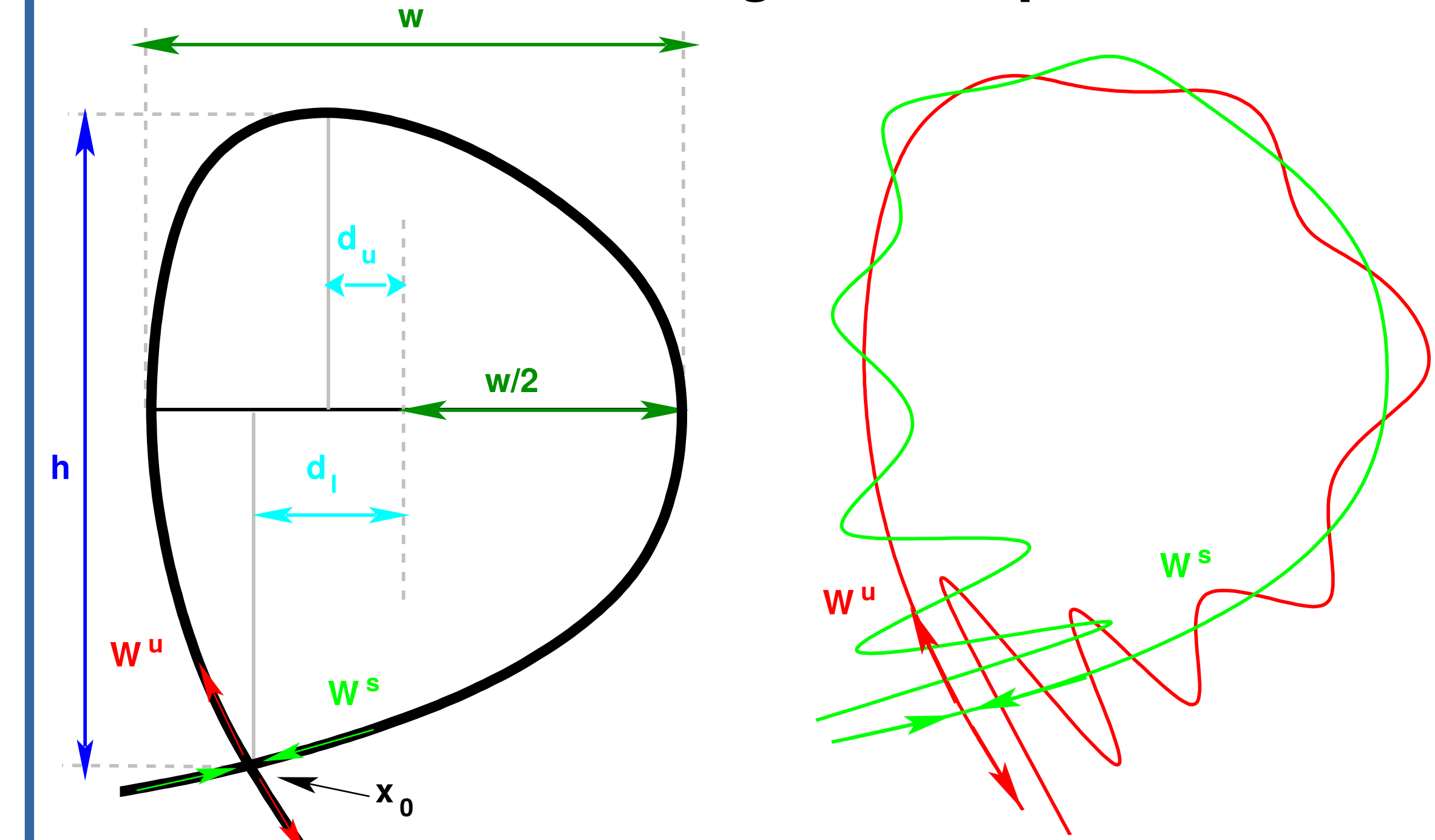
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Motivation

- Resonant Magnetic perturbations (RMPs) are presently considered the most promising method for ELM control in ITER.
- However, their application results in **non-axisymmetric** configurations, and consequently require that dedicated (computational) models are **three-dimensional**!
- Our present focus is on the **flow pattern introduced by RMPs** and its relation to the magnetic field configuration, which can be addressed with the EMC3-EIRENE code in very detail.
- A **detailed understanding of the flow structure** can facilitate further analysis related to cross-field momentum losses which may affect recycling characteristics (as suggested by observations at the W7-AS stellarator).

Perturbation of the magnetic separatrix



- Stable and unstable invariant manifolds associated with the X-point split and intersect transversely.
- This so called *homoclinic tangle* determines where fieldlines may connect from inside of the original separatrix to plasma facing components.

Plasma and neutral gas transport (EMC3-EIRENE)

- A fluid model is applied for the edge plasma:

Particle balance:

$$\nabla \cdot [m n u_{\parallel} \mathbf{e}_{\parallel} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla n] = S_p$$

Momentum balance:

$$\nabla \cdot [m n u_{\parallel}^2 \mathbf{e}_{\parallel} - \eta_{\parallel} \mathbf{e}_{\parallel} \mathbf{e}_{\parallel} \cdot \nabla u_{\parallel} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla (m n u_{\parallel})] = -\mathbf{e}_{\parallel} \cdot \nabla n (T_e + T_i) + S_m$$

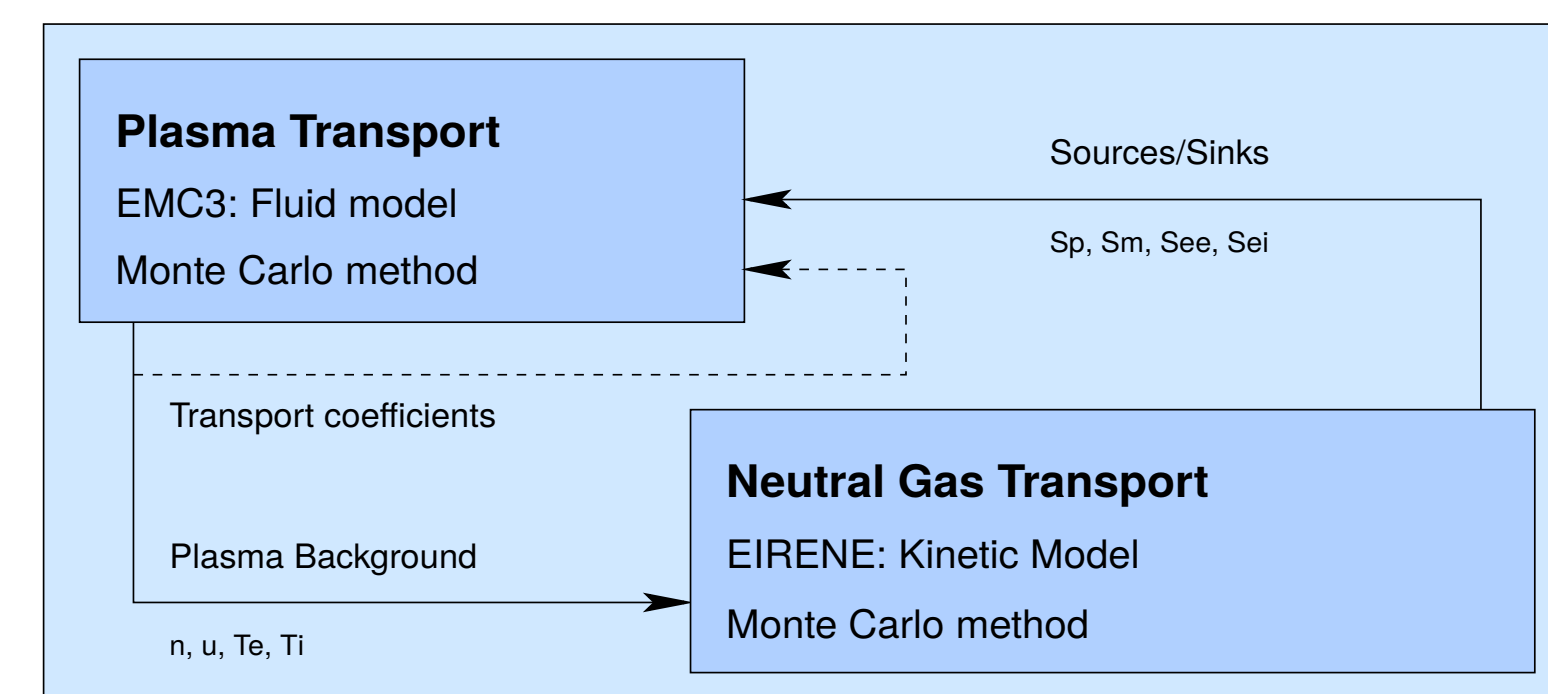
Energy balance:

$$\nabla \cdot \left[\frac{5}{2} T_e (n u_{\parallel} \mathbf{e}_{\parallel} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla n) - (\kappa_e \mathbf{e}_{\parallel} \mathbf{e}_{\parallel} + \chi_e n \mathbf{e}_{\perp} \mathbf{e}_{\perp}) \cdot \nabla T_e \right] = +k (T_i - T_e) + S_{ee}$$

$$\nabla \cdot \left[\frac{5}{2} T_i (n u_{\parallel} \mathbf{e}_{\parallel} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla n) - (\kappa_i \mathbf{e}_{\parallel} \mathbf{e}_{\parallel} + \chi_i n \mathbf{e}_{\perp} \mathbf{e}_{\perp}) \cdot \nabla T_i \right] = -k (T_i - T_e) + S_{ei}$$

- Monte Carlo method for fluid transport based on generic Fokker-Planck form and its relation to a stochastic process:

$$\frac{\partial}{\partial t} \mathcal{F} + \nabla \cdot [\mathcal{V}_{\mathcal{F}} \mathcal{F} - \nabla \cdot \mathcal{D}_{\mathcal{F}} \mathcal{F}] = S_{\mathcal{F}} \quad (\mathcal{F} = n, m n u_{\parallel}, \dots)$$

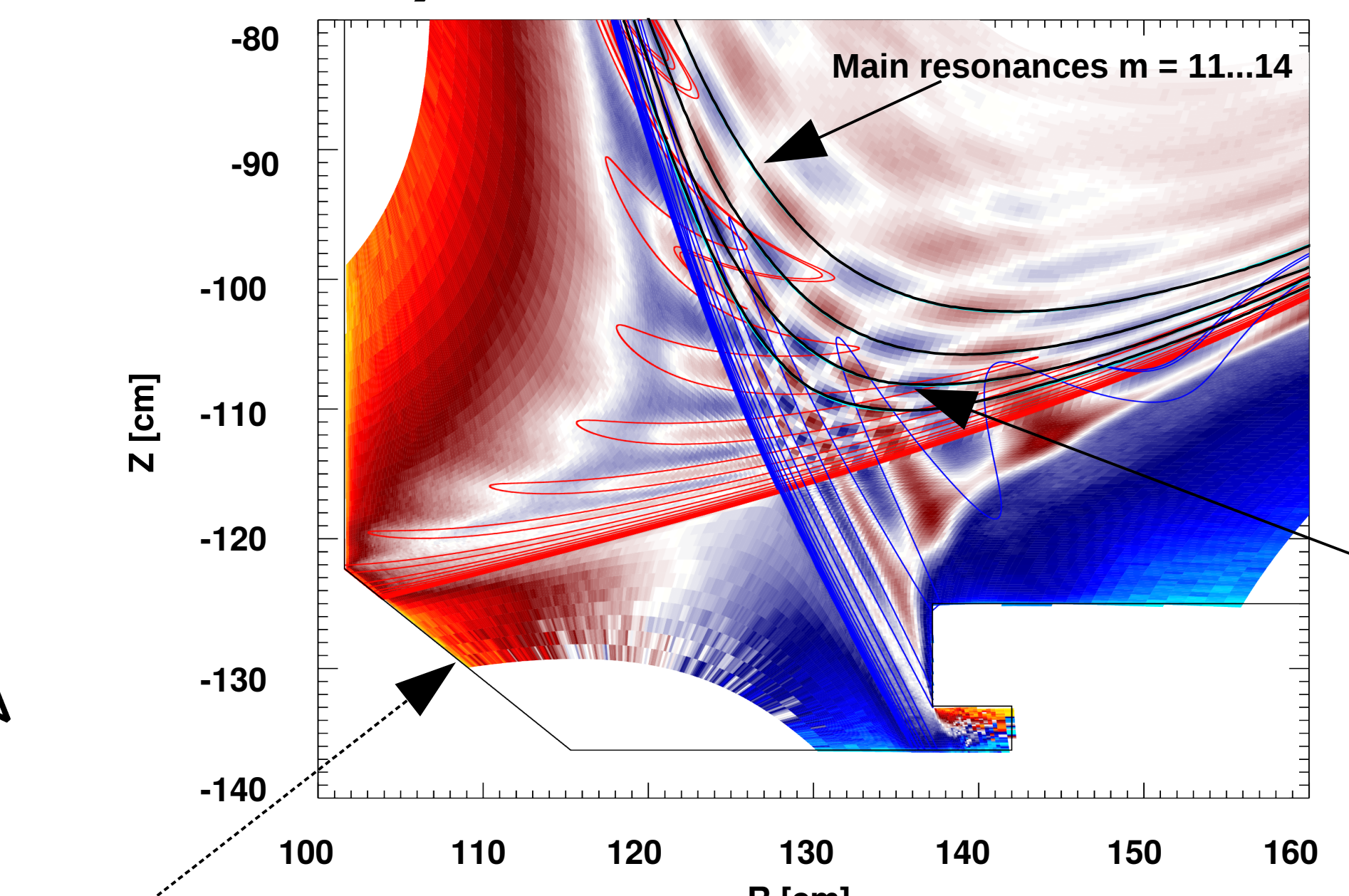
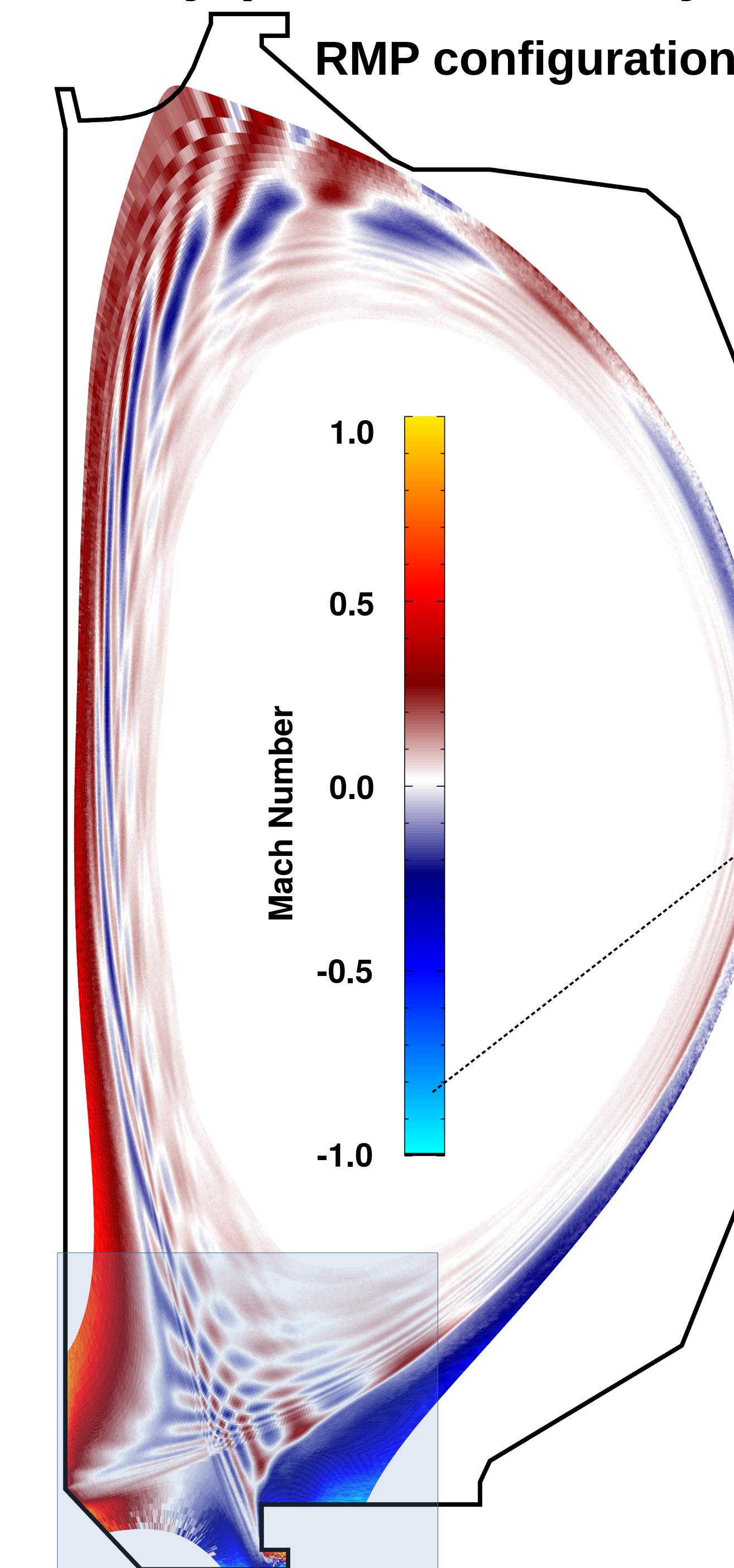
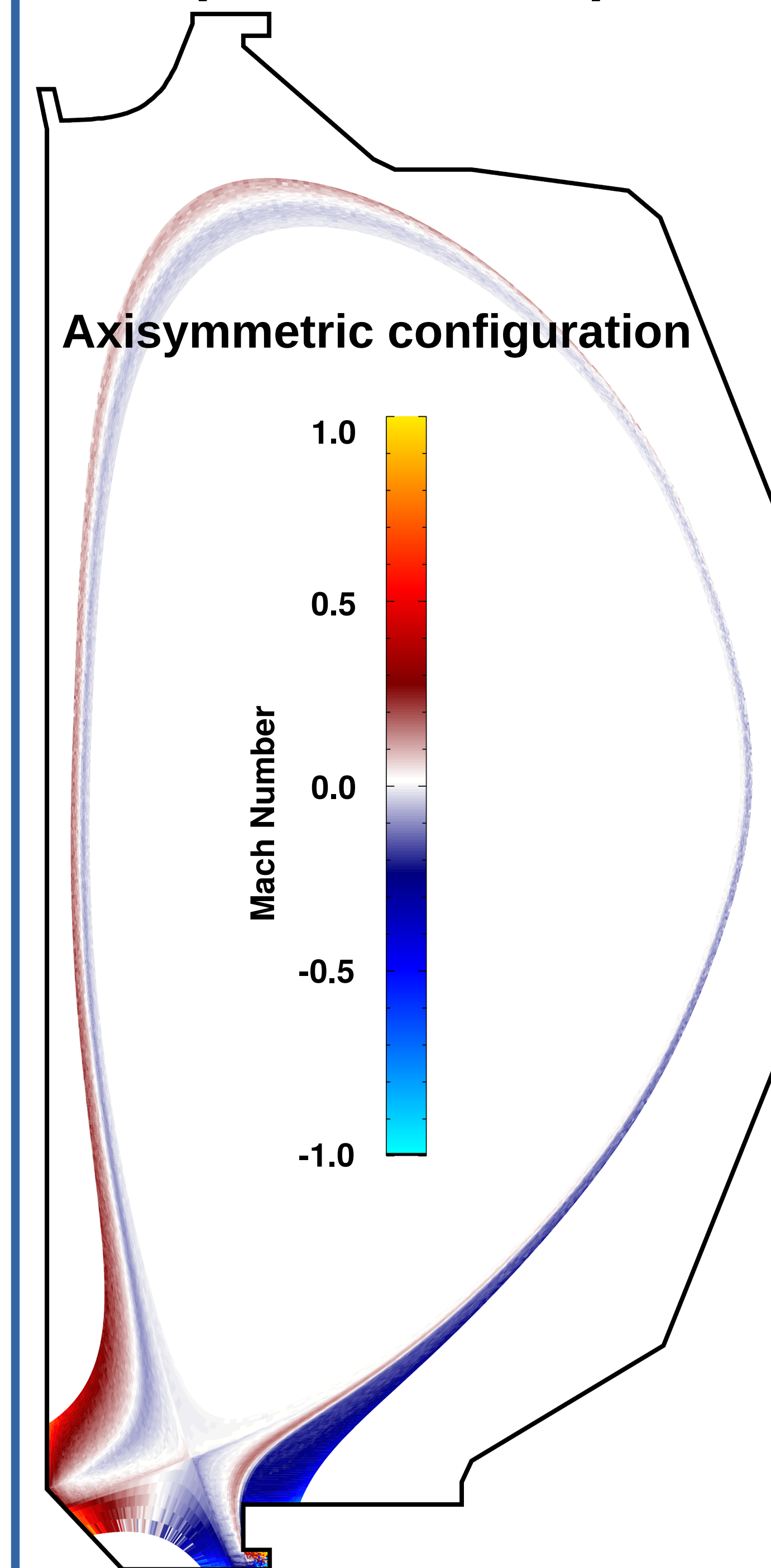


$$\eta_{\parallel} \propto T_i^{5/2}, \quad \kappa_{e,i} \propto T_{e,i}^{5/2}, \quad k \propto n^2 T_e^{-3/2}, \quad \frac{\kappa_e}{n \chi_e} \sim 10^6$$

Simplified pressure balance:

$$P_{\text{stat}} + m n u_{\parallel}^2 = \text{const}$$

Flow pattern in the plasma boundary (as calculated by EMC3-EIRENE)

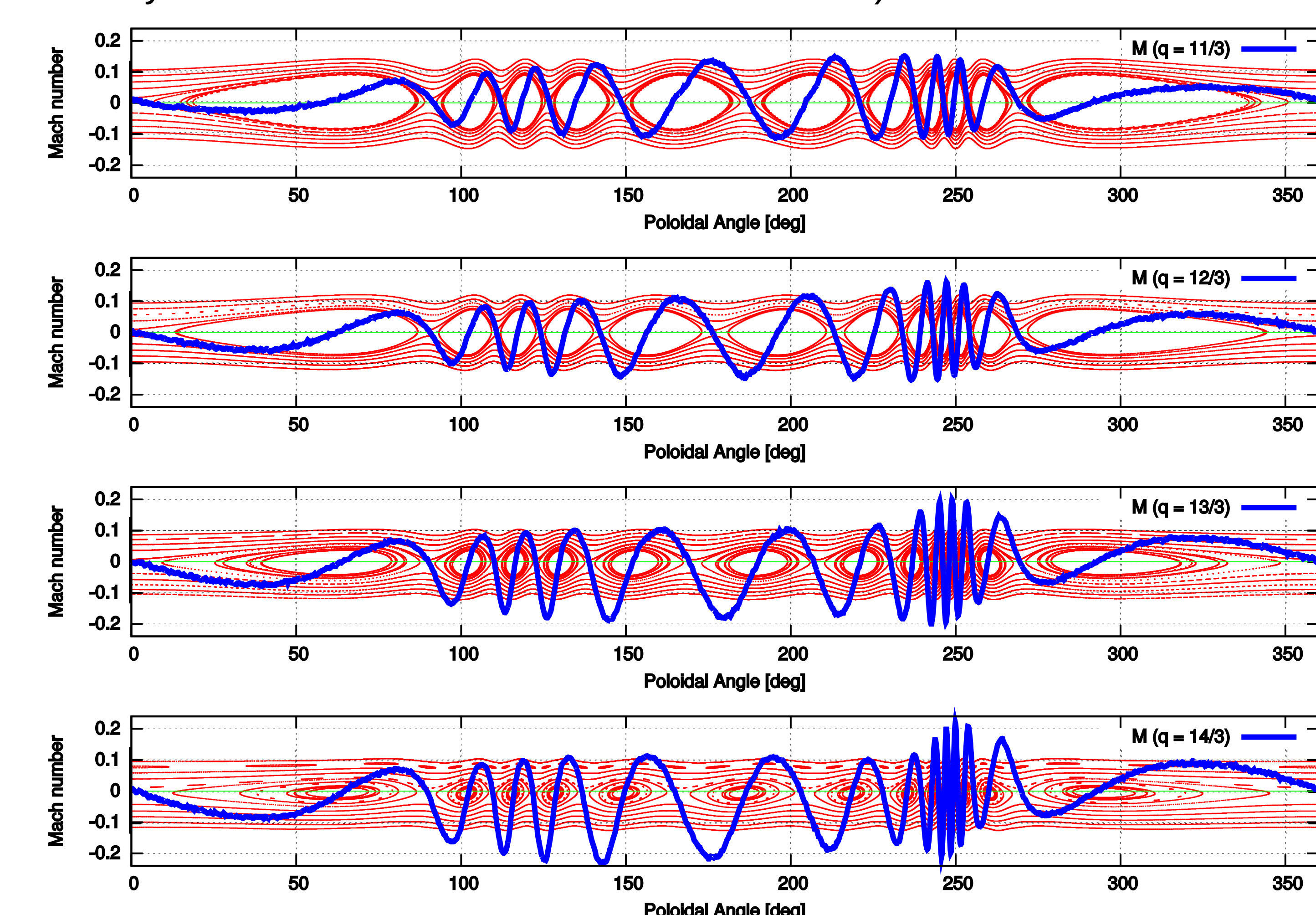


- Mach number:

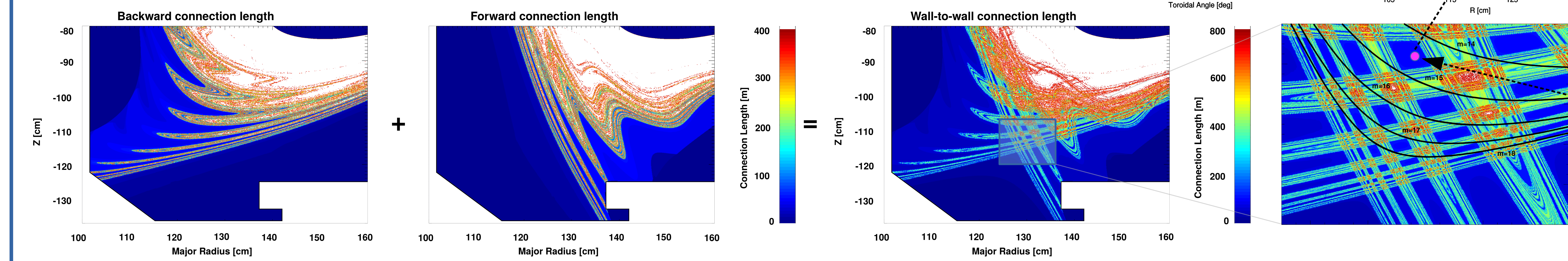
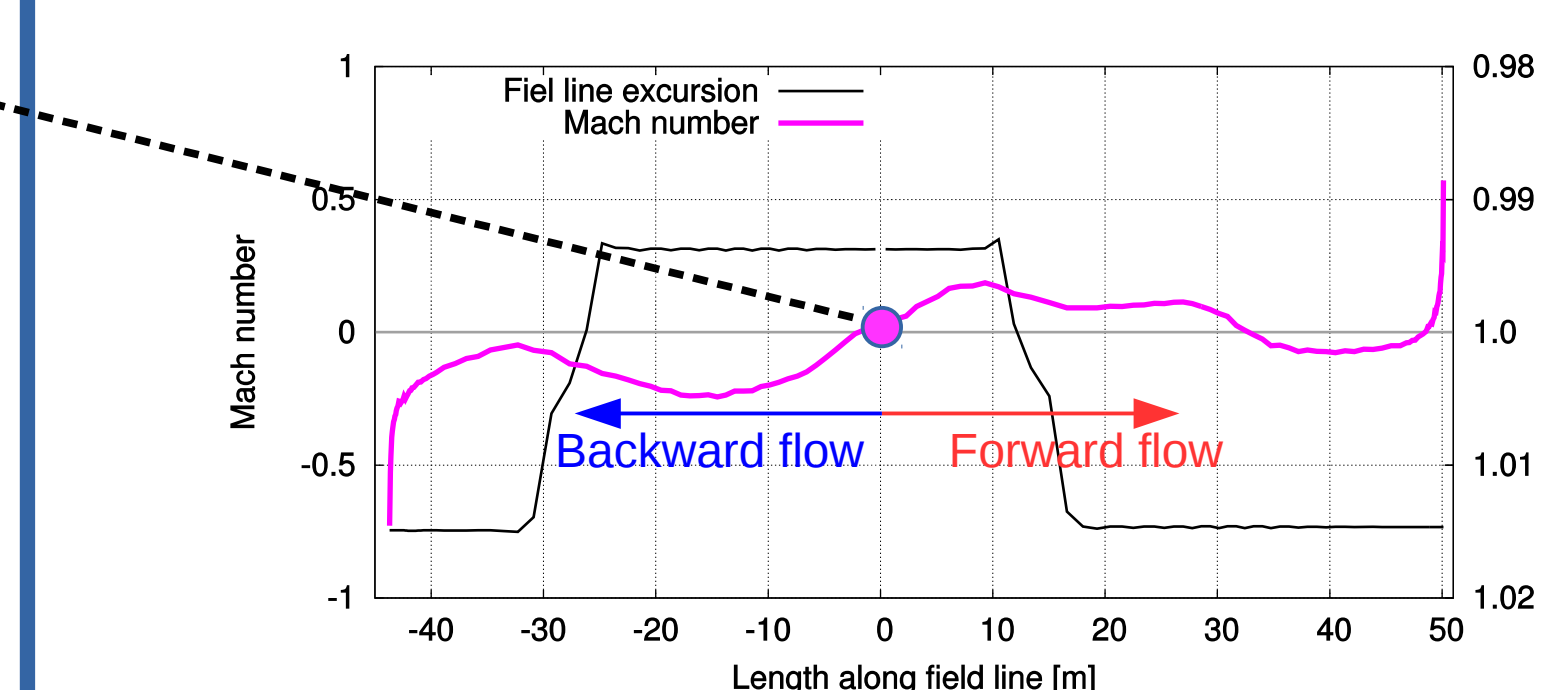
$$M = v_{\text{para}} / c_s, \quad c_s = \sqrt{\frac{T_e + T_i}{m}}, \quad (M_{\text{target}} = \pm 1)$$

- A flow reversal can be found in the scrape-off layer (SOL). Note that the regular SOL in the RMP configuration is between the helical lobes formed by the separatrix manifolds.
- The flow within the lobes is basically directed towards the target (except for the very peak of the lobes).
- A checkerboard pattern of flows with alternating direction is found to be related to the position of the **main resonances** $q = m/n$.

- The former O- and X- points of the resonances correspond to stagnation points (indicated by the island chains for 1% of the RMP field)

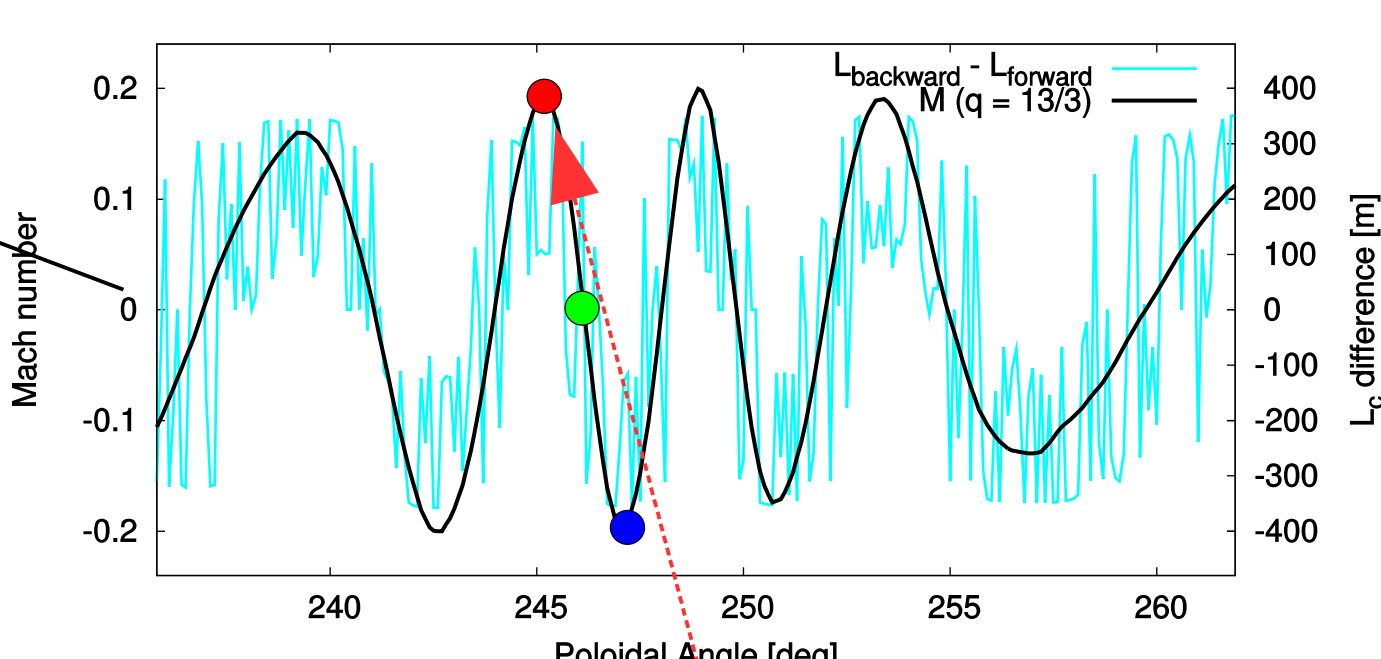


- The separatrix manifolds generate a mesh of short flux tubes, which are located between the main resonances in the vicinity of the X-point.
- These flux tubes connect the X-point region with the targets within 1 poloidal turn in each direction.
- Consequently, these position can be regarded as "upstream", and indeed stagnation is found there.

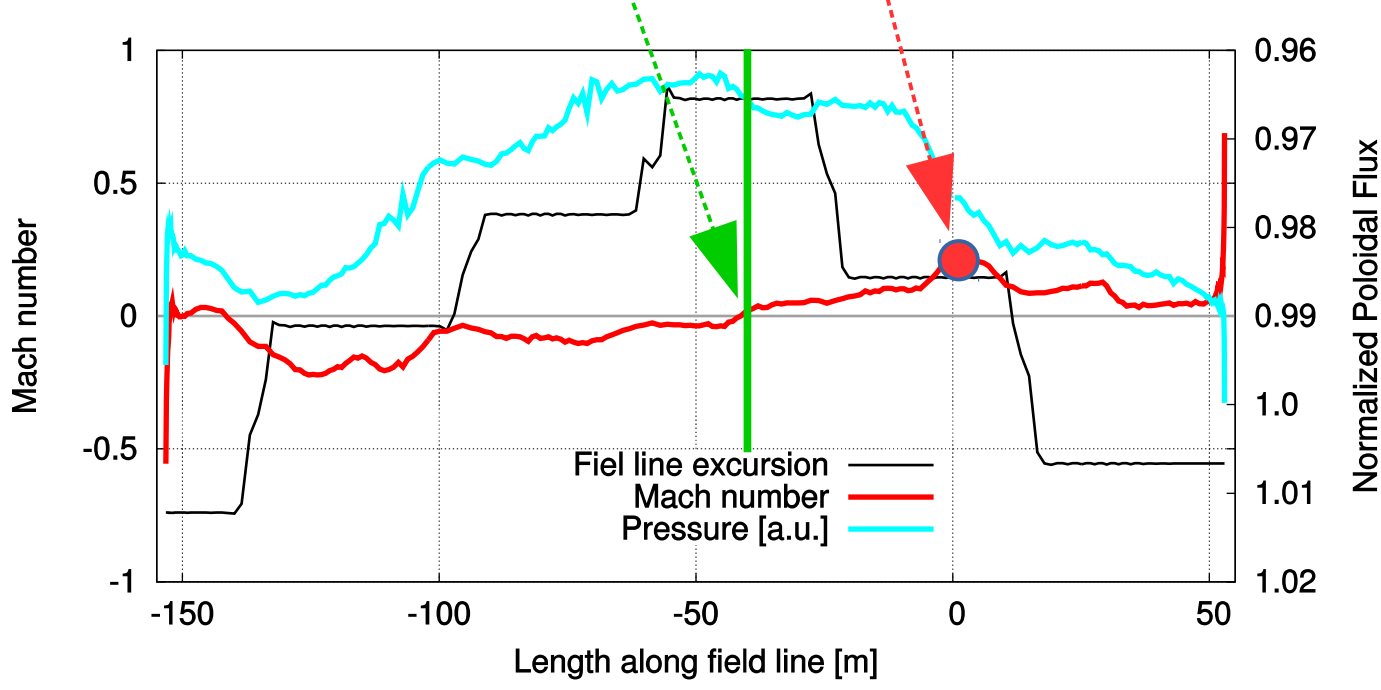


- The flow is related to a short one-sided connection length to the divertor target

Forward flow: $L_{\text{forward}} \ll L_{\text{backward}}$
Stagnation: $L_{\text{forward}} \sim L_{\text{backward}}$
Backward flow: $L_{\text{forward}} \gg L_{\text{backward}}$



- On a selected field line, the flow is directed outwards from the plasma interior (basically following the pressure gradient), with a **stagnation point** at the innermost position.



Conclusions

- The checkerboard pattern of forward and backward flow channels is aligned to the position of the resonant surfaces.
- Poloidally, the position of the stagnation points correspond to the position of the O- and X-points of the resonances.
- Plasma flow is basically directed from the interior to the target, and its qualitative behavior can be understood in terms of a simple pressure balance.
- Because of this direct link to the field structure, measurements of the flow pattern could provide useful information about the "openness" of the plasma edge (e.g. regarding plasma response effects and confinement quality).
- The present analysis has been performed for the DIII-D tokamak, but a similar flow pattern can be observed in simulations for ITER as well (see J11.0006).