Overview of edge modeling efforts for advanced divertor configurations in NSTX-U with magnetic perturbation fields

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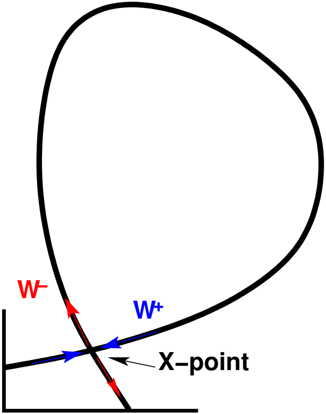
Motivation: control of divertor head loads

- Control of divertor **heat loads** (both steady state and transient) remains one of the key challenges for a fusion based reactor and for a compact **fusion nuclear science development facility (FSNF)**
- **Resonant magnetic perturbations (RMPs)** are a promising method for ELM control $\rightarrow$ breaking of axisymmetry
- **Advanced divertors** (specialized divertor geometry): Snowflake, X-divertor) for steady state heat flux reduction
- Likely, both concepts will have to work together, and NSTX-U is a well suited device to study this: What is the impact on **neutral fueling and exhaust** (density control), and how does this affect high recycling and transition to detachment?

Perturbation of the magnetic separatrix → lobes



(arrows indicate field direction)

- The separatrix associated with **X** has 2 branches (set of field line trajectories):

$$W^+ = \left\{ \mathbf{p} | \lim_{l \to \infty} F_{\mathbf{p}}(l) \to \mathbf{X} \right\}$$

$$W^- = \left\{ \mathbf{p} | \lim_{l \to -\infty} F_{\mathbf{p}}(l) \to \mathbf{X} \right\}$$

$F_{\mathbf{p}}(l)$: field line through **p**

- Both branches overlap in the unperturbed configuration

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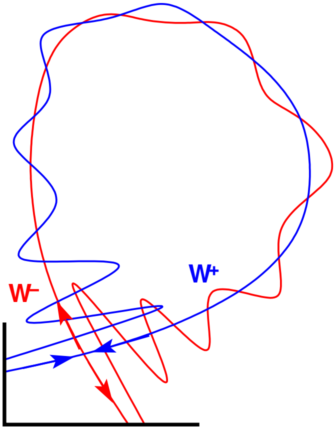

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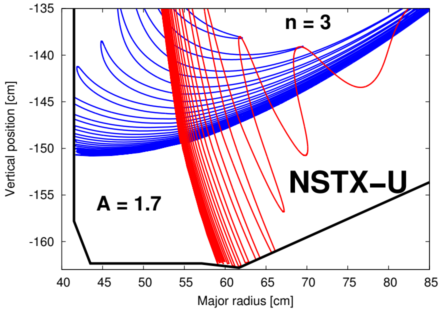
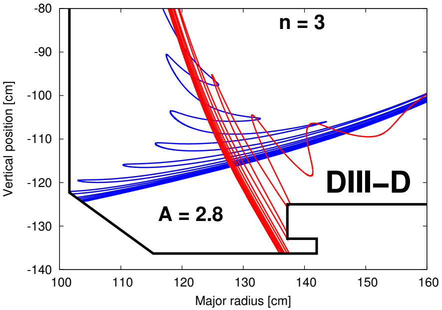
$F_{\mathbf{p}}(l)$: field line through **p**

- Both branches overlap in the unperturbed configuration
- Magnetic perturbations result in a splitting, and both branches may intersect each other transversely
- This opens up a **connection between the plasma interior and the divertor targets**

Lobe density increases with lower aspect ratio



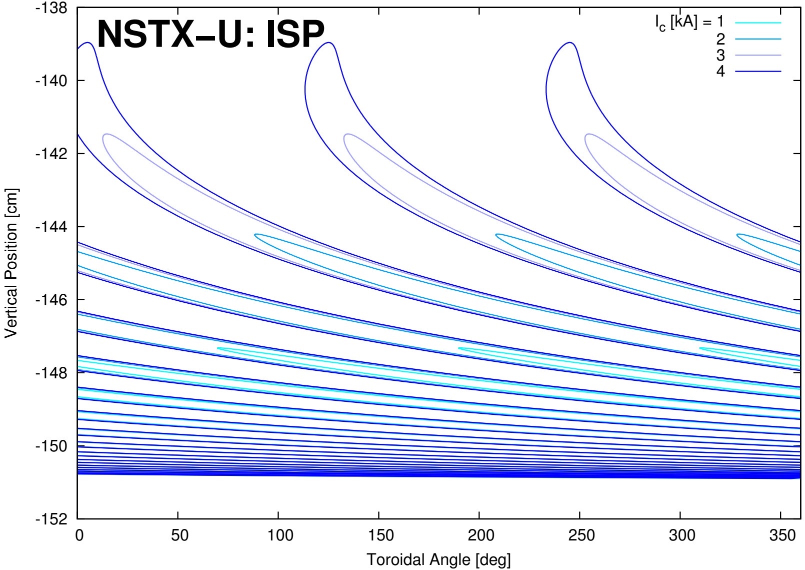


- Lobes become smaller and more frequent towards the X-point

lobe density: $$\frac{1}{L} \approx \frac{n\,B_{\mathrm{tor}}}{2\pi\,R\,B_{\mathrm{pol}}} \approx \frac{n\,B_0}{2\pi\,R_0\,B_{\mathrm{pol}}}\left(1-\frac{\delta_X}{A}\right)^{-2}$$

- Higher density may facilitate heat flux spreading between lobes
- Radial extension of lobes depends on perturbation strength

Radial size of lobes defines poloidal extend of the magnetic footprint, lobe density not affected by I_c



The snowflake divertor configuration

- Second order null of the poloidal magnetic field $\Rightarrow$ the separatrix acquires a characteristic hexagonal form
- This results in a flux expansion near the null-point, and

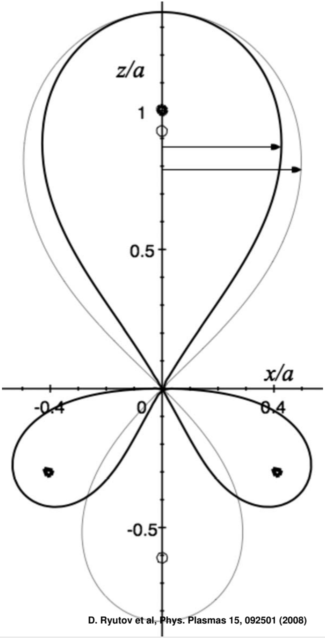
$$B_{\mathrm{pol}}^{(\mathrm{snowflake})} \sim r^2$$

while

$$B_{\mathrm{pol}}^{(\mathrm{standard\ divertor})} \sim r$$

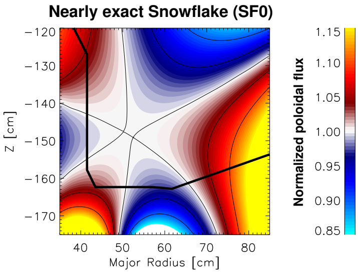
r: distance from the null-point

- SF facilitates longer connection lengths and two additional strike points
- Generalization: two first order nulls in (close) proximity



D. Ryutov et al, Phys. Plasmas 15, 092501 (2008)

The ’snowflake’ configuration allows for a variety of magnetic topologies at NSTX-U



- ’Nearly exact snowflake’: approximation to ’classical’ snowflake

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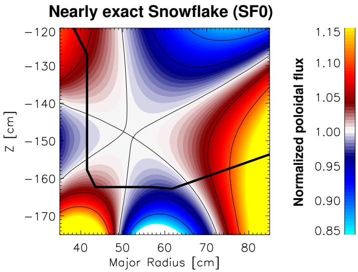

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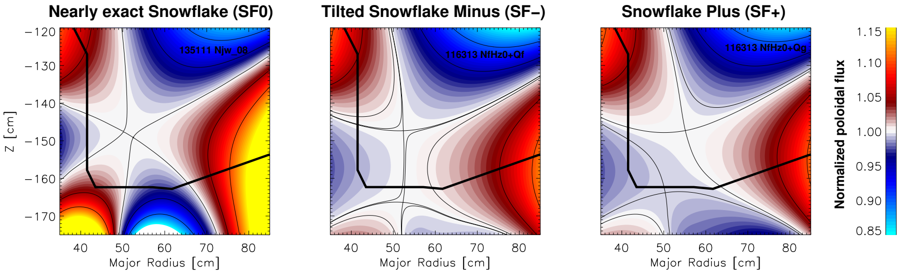
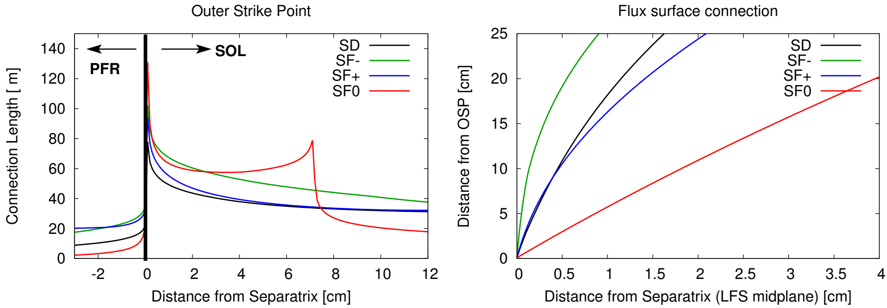


- ’Nearly exact snowflake’: approximation to ’classical’ snowflake
- Here SF0 is actually ’snowflake minus’, which is topologically equivalent to ’connected double null’ (CDN)
- The secondary X-points in the (tilted) SF- and SF+ configurations here are outside the divertor targets $\rightarrow$ topology is ’lower single null’ (LSN)

SF0 has increased connection length, but flux compression on target (with respect to SD)



- Both SF0 and SF- feature longer connection lengths then SD at the outer strike point: may result in lower divertor temperatures
- SF0 features flux compression while SF- features flux expansion with respect to standard divertor (SD) configuration: can impact heat flux spreading

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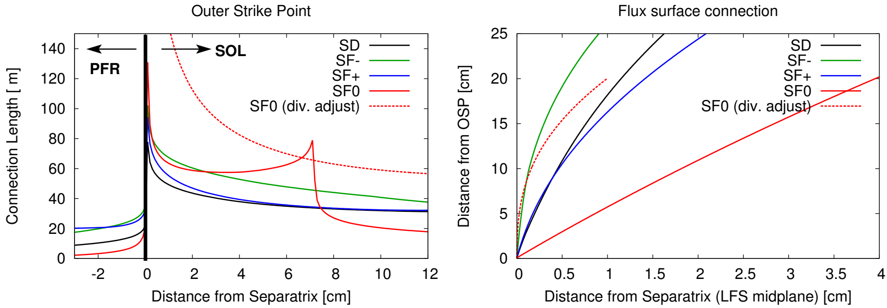

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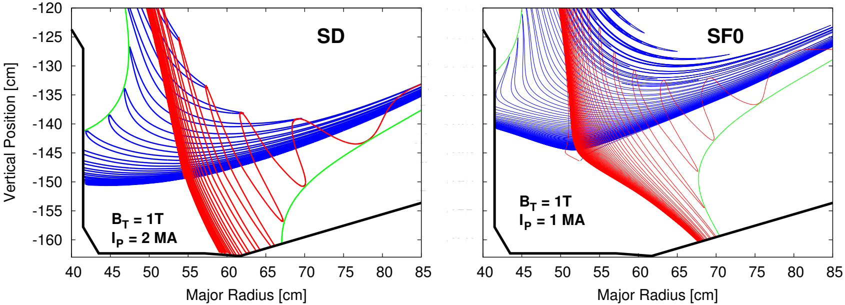
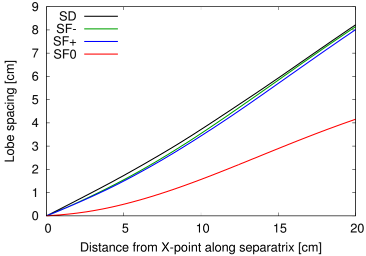
Lobe size and extension depends on equilibrium



- Lobe density is much higher in SF0, i.e. lobe size is smaller ($I_p = 1\,\mathrm{MA}$)
- Lobe size scales with r^2 near the X-point in SF0, because B_{pol} does
  $\rightarrow$ very small change in size between neighboring lobes

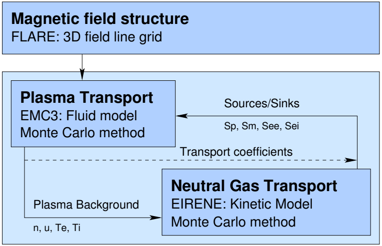


A 3D steady state transport model for the edge plasma

- Field lines are reconstructed from a 3D block-structured grid which can be adapted to the topology at hand

  H. Frerichs et al., Comp. Phys. Commun. 181 (2010) 61

- Classical transport (Braginskii) along field lines
- Self-consistent solution by iterative application

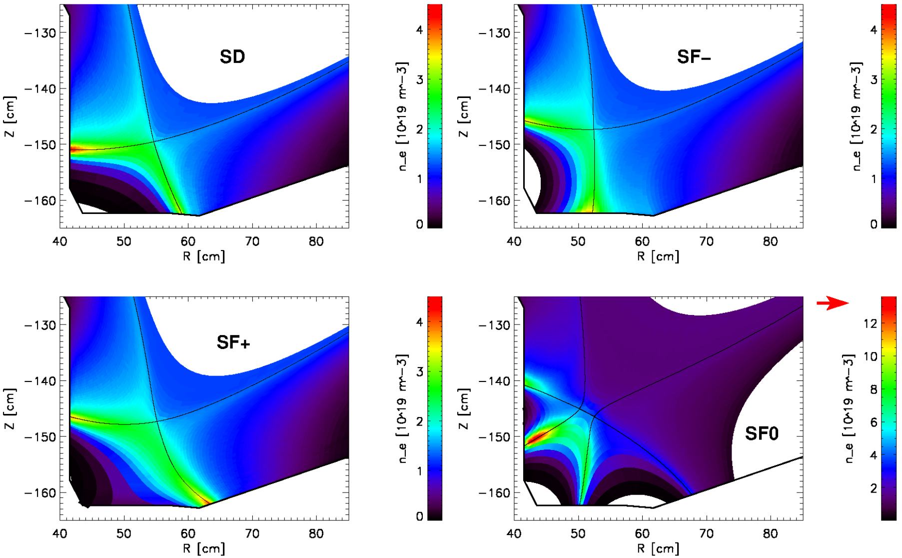


- The following simulations are based on:

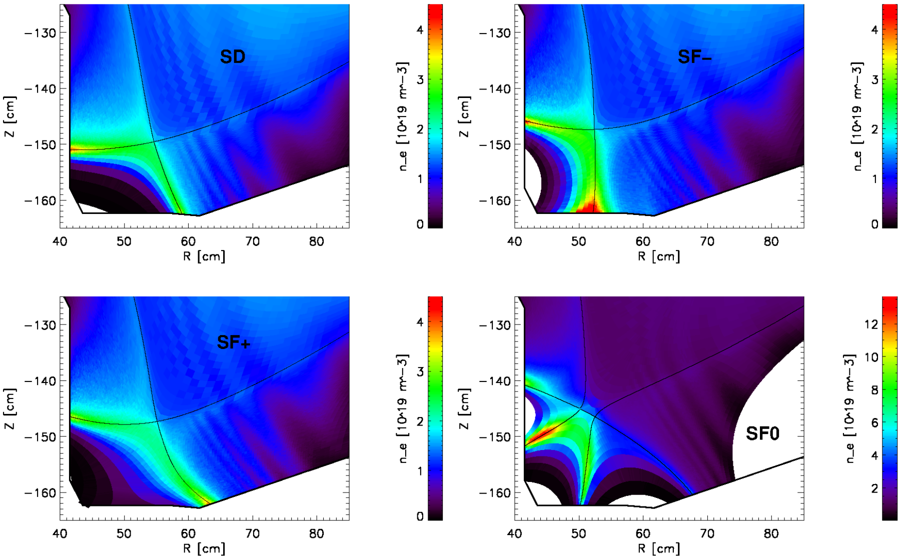
Particle in-flux	Γ_{in}	=	$3.12 \cdot 10^{20}\,\mathrm{s}^{-1}(50\,\mathrm{A})$
Recycling coefficient	c_{rec}	=	0.99
Edge input power	P_{in}	=	$2\,\mathrm{MW}$
Anomalous cross-field transport:			
(particles)	$D_\perp$	=	$0.3\,\mathrm{m}^2\,\mathrm{s}^{-1}$
(energy)	$\chi_{e\perp}$	=	$\chi_{i\perp} = 2.0\,\mathrm{m}^2\,\mathrm{s}^{-1}$

- Impurity transport and radiation is neglected at this point

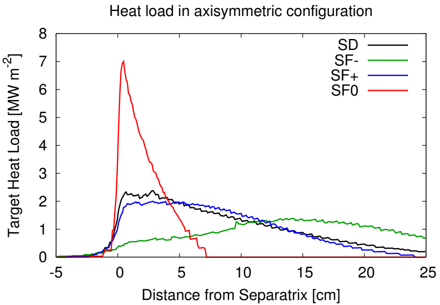
No RMPs: SF0 operates at higher divertor density



RMPs: Lobes at the LFS, diffusion to strong at HFS



Heat load analysis favours SF- configuration



- Small reduction of peak heat load in SF+
- Moderate reduction of peak heat load in SF-, peak is found at $10 - 20\,\mathrm{cm}$ distance from the separatrix
- Significant increase of peak heat load in SF0 due to compression of flux surfaces at the divertor target.

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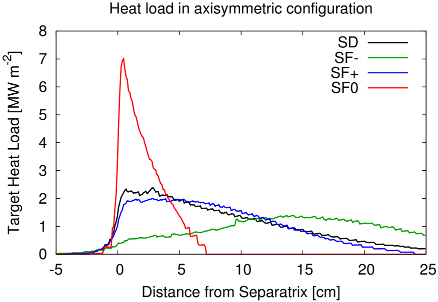

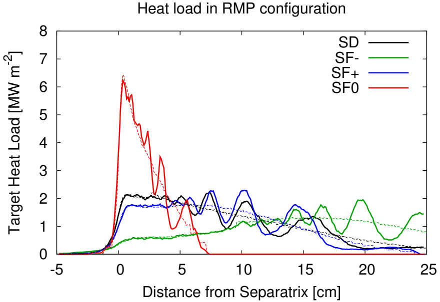

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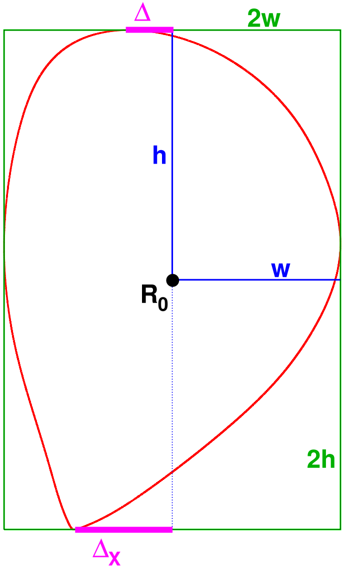
- Moderate reduction of peak heat load in SF-, peak is found at $10 - 20\,\mathrm{cm}$ distance from the separatrix
- Significant increase of peak heat load in SF0 due to compression of flux surfaces at the divertor target.
- No significant impact of RMPs on toroidally averaged heat loads

Summary and conclusions

- Application of RMPs results in the formation of helical lobes which have a higher frequency at lower aspect ratio
- The ’snowflake’ family of divertor configurations allows a variety of magnetic topologies ranging from flux compression to flux expansion at the divertor targets
- First transport simulations favour the SF- configuration for heat load reduction

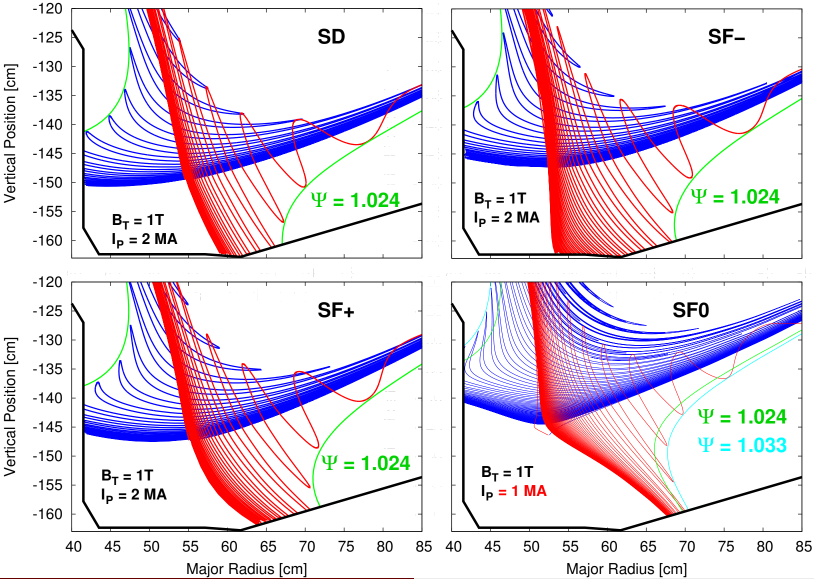
Outlook:

- How do RMPs and advanced divertor configurations impact neutral fueling and exhaust, and how does this affect high recycling and transition to detachment?
- What is the impact of plasma response effects (use NIMROD, M3D-C1)

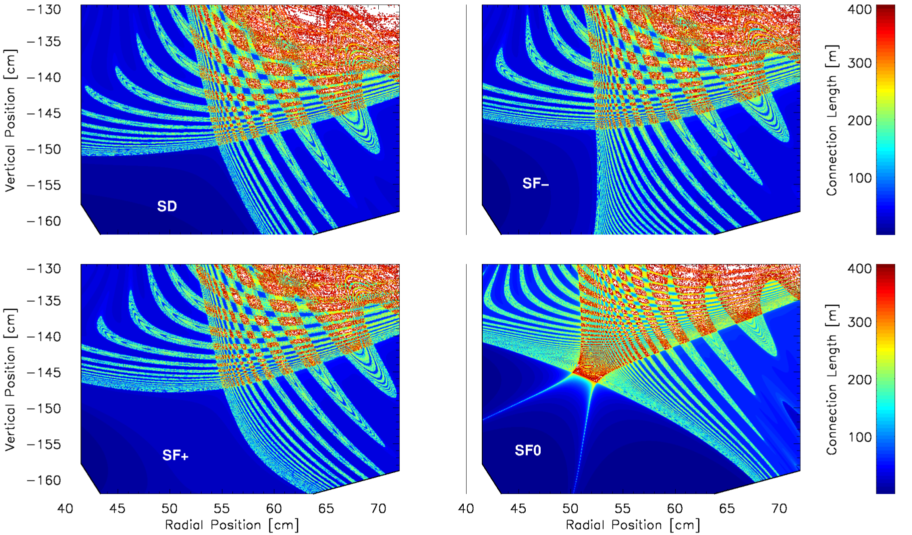


$$
\begin{aligned}
&\text{aspect ratio:} \quad && A = R_0/w \\
&\text{elongation:} \quad && \kappa = h/w \\
&\text{triangularity:} \quad && \delta = \Delta/w
\end{aligned}
$$

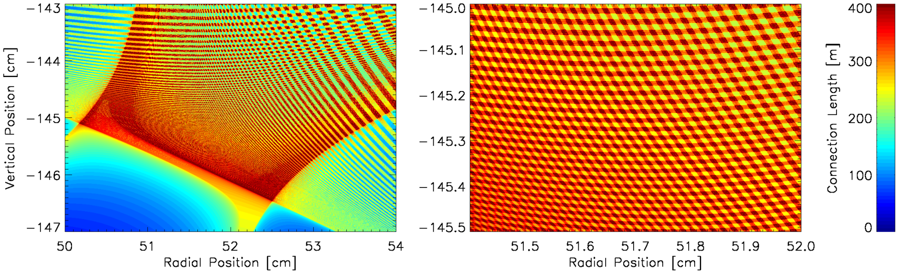
Radial lobe size depends on perturbation strength in relation to equilibrium field



Field lines can connect through the lobes from inside the separatrix to the divertor targets



Moiré pattern caused by small, similar sized lobes



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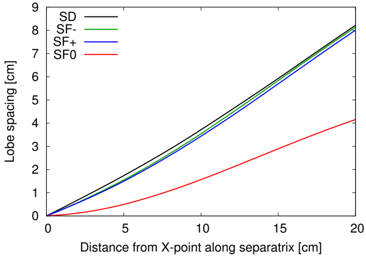


A 3D steady state fluid model for the edge plasma

Particle balance (n: plasma density)

$$\nabla \cdot \left[n u_{\|} \mathbf{e}_{\|} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla n \right] = S_p$$

$D_{\perp}$: anomalous cross-field diffusion, S_p: ionization of neutral particles

Momentum balance ($u_{\|}$: fluid velocity parallel to magnetic field lines)

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

$\eta_{\|} \propto {T_i}^{5/2}$: parallel viscosity, $\eta_{\perp} = m_i n D_{\perp}$: cross-field viscosity,
S_m: interaction (CX) with neutral particles

Energy balance (T_e, T_i: electron and ion temperature)

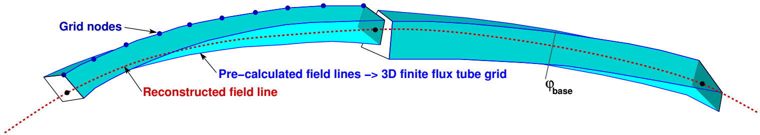
$$\nabla \cdot \left[\frac{5}{2} T_e \left(n u_{\|} \mathbf{e}_{\|} - D_{\perp} \mathbf{e}_{\perp} \mathbf{e}_{\perp} \cdot \nabla n \right) - \left(\kappa_e \mathbf{e}_{\|} \mathbf{e}_{\|} + \chi_e n \mathbf{e}_{\perp} \mathbf{e}_{\perp} \right) \cdot \nabla T_e \right] = +k \left(T_i - T_e \right)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

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

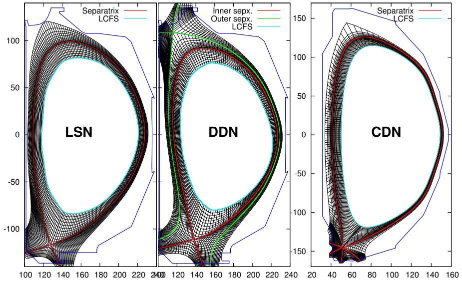
$\kappa_{e,i} \propto {T_{e,i}}^{5/2}$: classical parallel heat conductivity, χ_e, χ_i: anomalous cross-field transport,
$k \propto n^2 {T_e}^{-3/2}$: energy exchange between el. and ions,
S_{ee}, S_{ei}: interaction with neutral particles and impurities (radiation)

Field lines are reconstructed from a finite flux-tube grid

- The 3D grid is generated by field lines tracing starting from 2D base grids



- EMC3: bilinear interpolation within flux-tubes (4 pre-calculated field lines)



- Discretization in the 'cross-field' direction can be adapted to the magnetic configuration at hand.
- Unlike grids for 2D transport modeling, the actual information about the magnetic configuration is not stored in the 2D base grid(s) but in the 3D grid.