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Three-dimensional Plasma Boundary Physics Aspects for the Development of Next Generation Divertor Concepts with Resonant Magnetic Perturbations

Third IAEA Technical Meeting on Divertors, 11/06-09 2019

ITPA-DSOL task DSOL-37

Effects of 3-D fields on divertor conditions and plasma material interaction as compatibility issue of RMP ELM control in tokamaks

M. Jakubowski , O. Schmitz

Device representatives: J.-W. Ahn (NSTX-U), D. Orlov (DIII-D), R. Dejarnac (Compass), D. Harting (JET), S.-H. Hong (KSTAR), M. Jakubowski (W7-X), A. Kirk (MAST), M. Kobayashi (LHD), R. Pitts (ITER), M. Jia (EAST)

Modeling representatives: H. Frerichs (EMC3-EIRENE), A. Kirschner (ERO), P. Stangeby (DIVIMP), T. Evans (MCI), N. Ferraro (M3D-C1), F. Orain (JOREK)

ITPA DSOL meeting, Madison, USA, 12/11-12/14 2018

Outline

- Introduction: how is the 3D boundary formed and brief experimental survey for its existence
- Principles and experimental evidence for the relation to plasma response
- Present understanding of the scaling to high density
- Open challenges for ITER and beyond

Outline – specific aspects covered in next talk

- **Introduction: how is the 3D boundary formed and brief experimental survey for its existence**
- **Principles and experimental evidence for the relation to plasma response**
- **Present understanding of the scaling to high density into detachment**
- **Open challenges for ITER and beyond**

Talk by H. Frerichs

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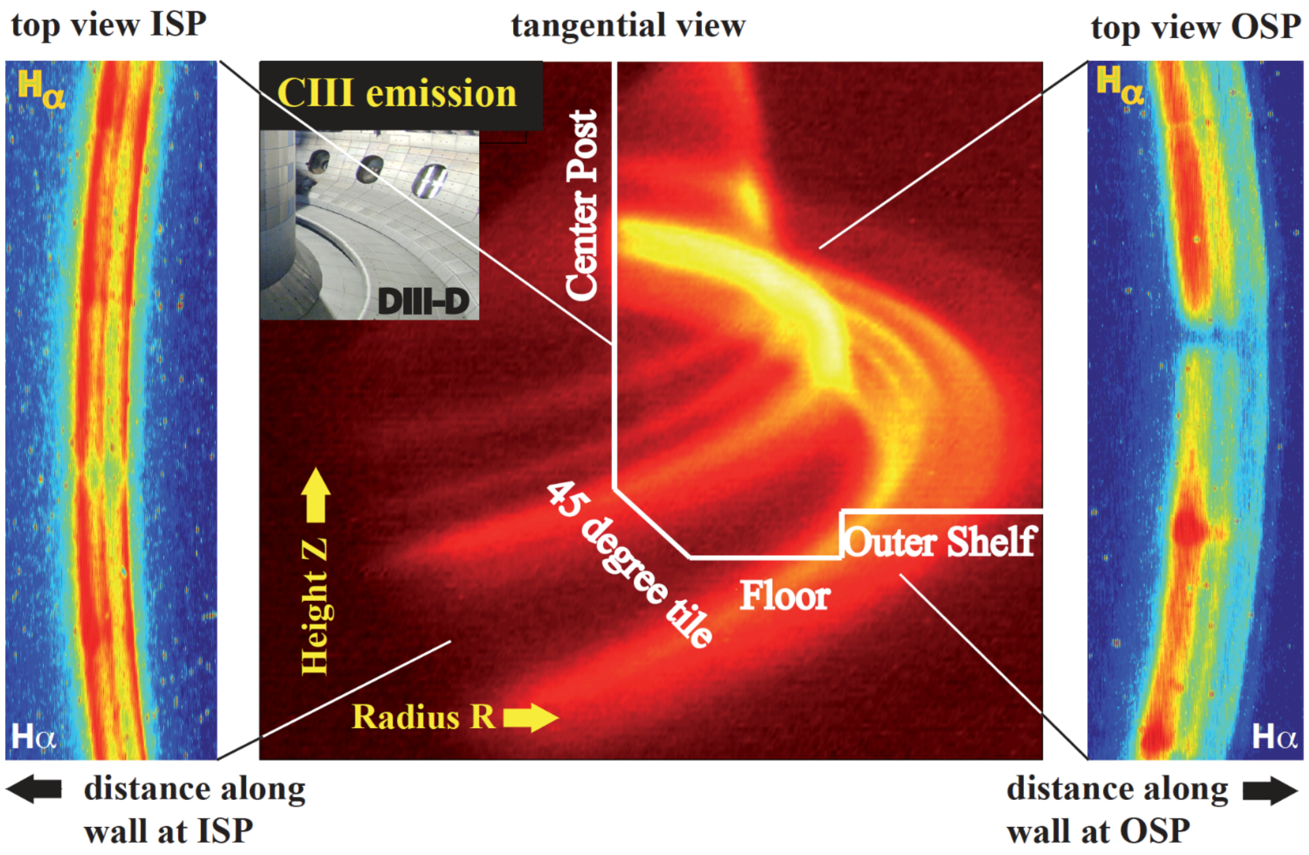
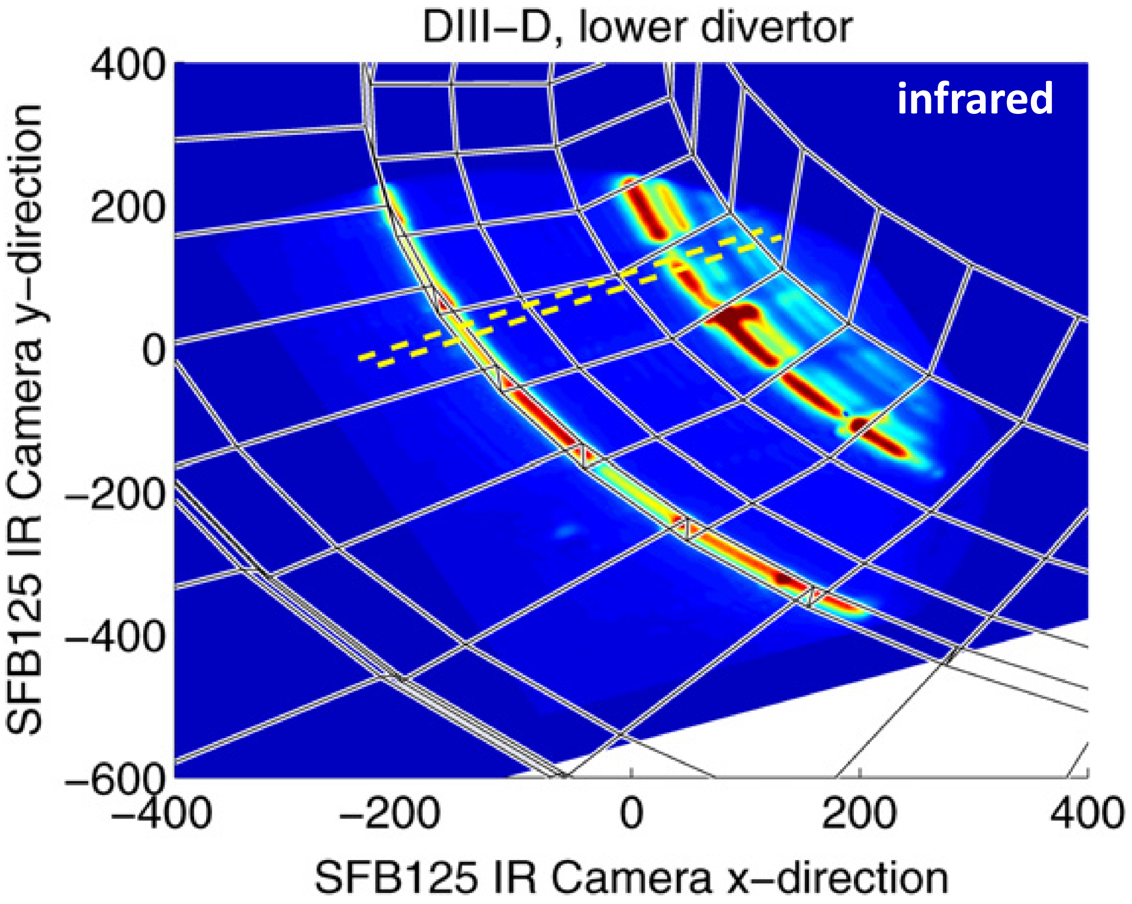
- **Introduction: how is the 3D boundary formed and brief experimental survey for its existence**
- **Principles and experimental evidence for the relation to plasma response**
- **Present understanding of the scaling to high density**
- **Open challenges for ITER and beyond**

Striated divertor heat fluxes are a commonly observed feature during RMP application and RMP ELM suppression



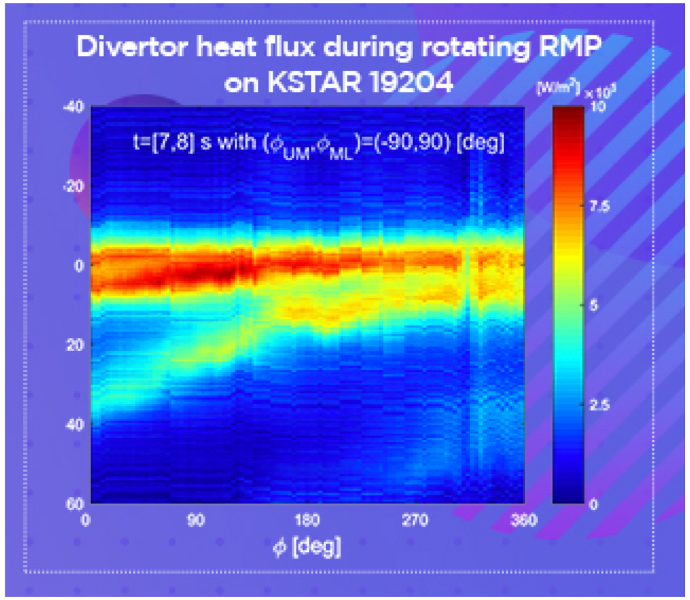


[O. Schmitz et al., Nuclear Fusion **56** (2016) 066008]

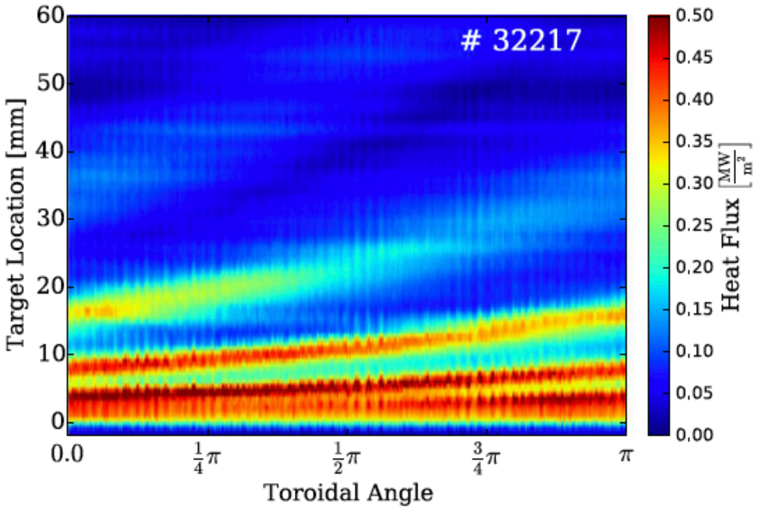
M. Jakubowski et al., Nuclear Fusion **49** (2009) 095013]

Striated divertor heat fluxes are a commonly observed feature during RMP application and RMP ELM suppression

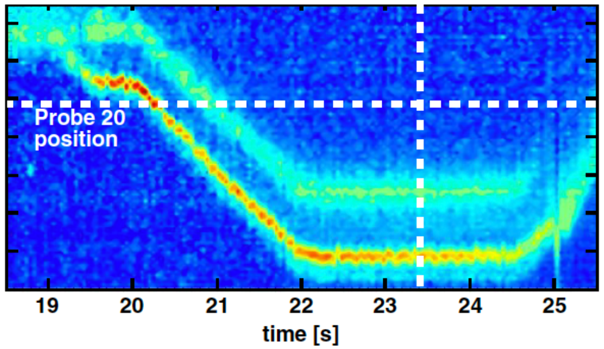
KSTAR



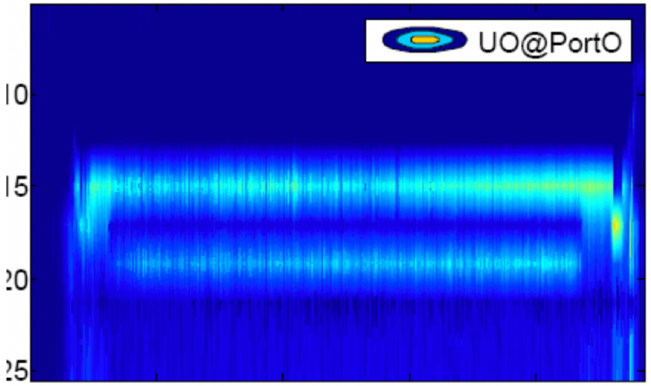
ASDEX-Upgrade



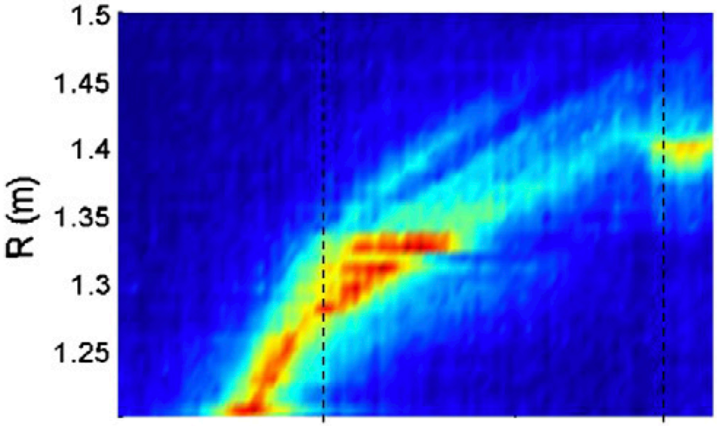
JET



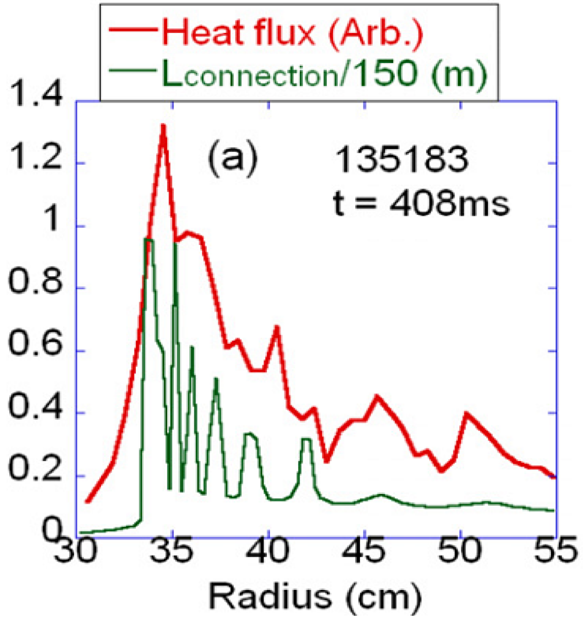
EAST



MAST



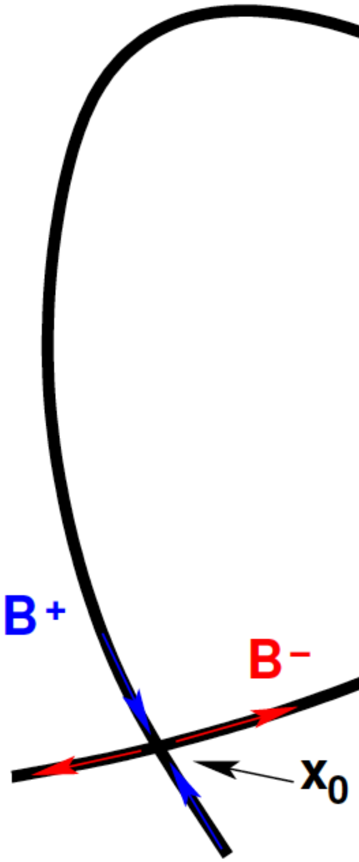
NSTX



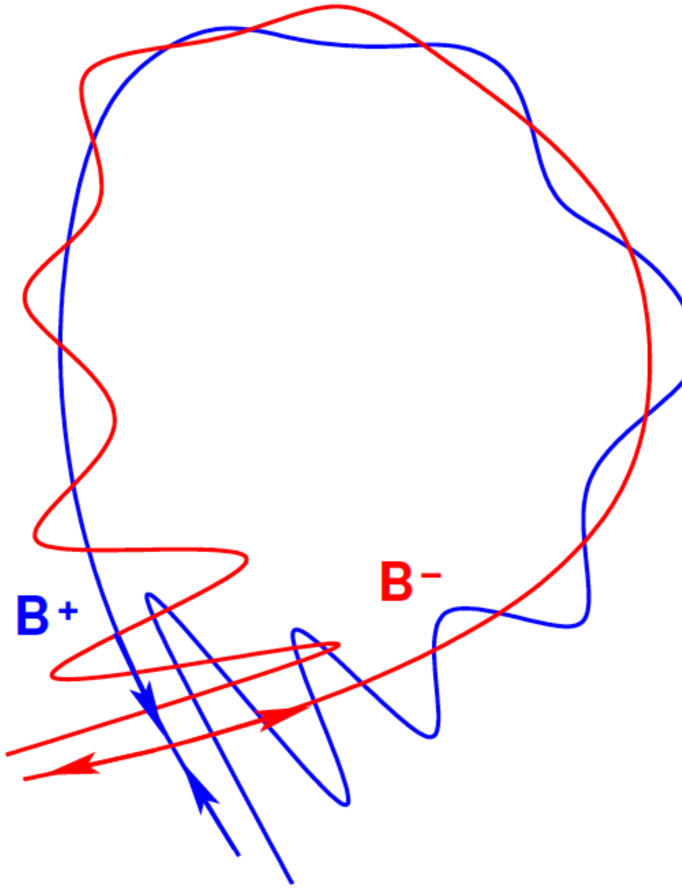
The manifolds are decomposed through radial magnetic field perturbation and form helical lobes

- The separatrix is the boundary between the confined plasma and the plasma boundary
- This generic perturbation mechanism defines the structure of the heat and particle fluxes in the divertor
- **Non-resonant separatrix tangles**, associated with **axisymmetric X-points**, determine in diverted plasmas, which **plasma facing surfaces intercept the magnetic flux** lost from the resonant stochastic region.

[T.E. Evans et al., J. Phys.: Conf. Ser. **7** (2005) 174]
[M. Jakubowski, et al, J. Nuclear Mat. 363-365 (2007) 371]

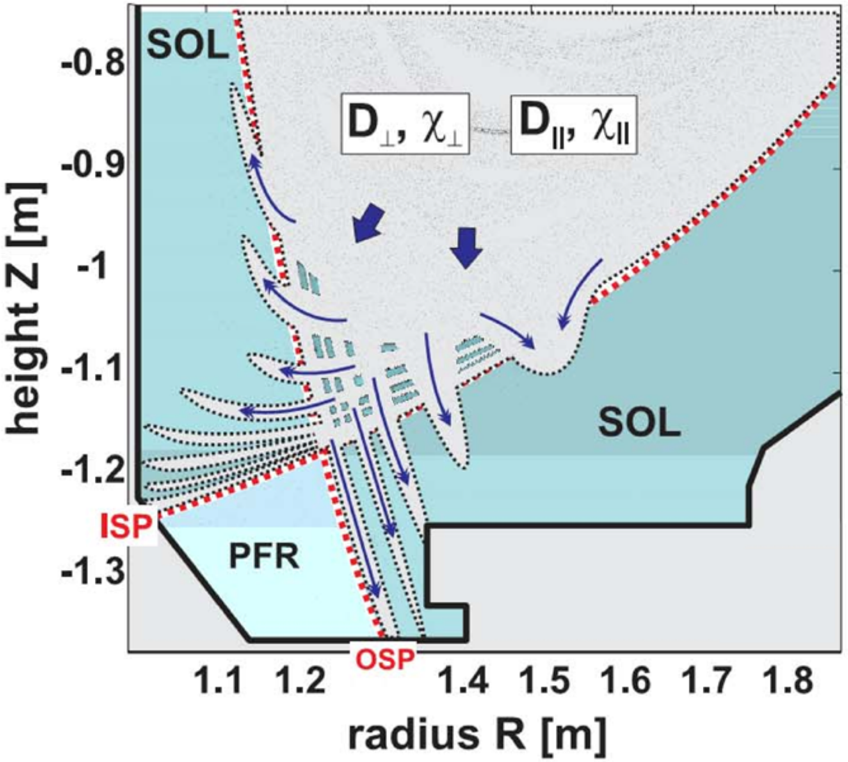


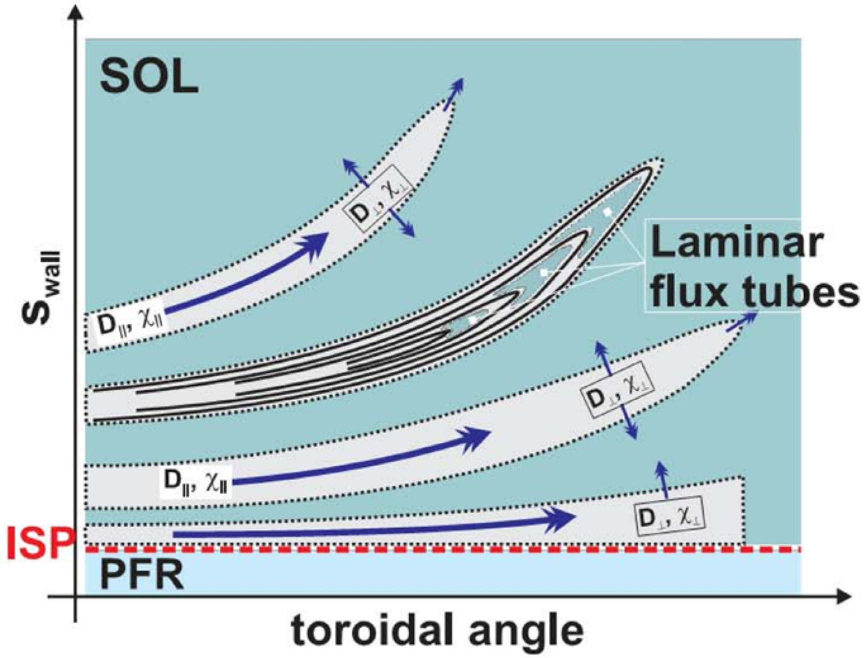
The manifolds are prone to strong oscillations under small perturbation fields



The helical separatrix lobes form a helical magnetic footprint on the divertor target – a strong deviation from axisymmetry

- RMPs break flux surfaces at the edge and connect field lines from the bulk plasma to the divertor targets
- **Deformation of the separatrix is always associated with stochastic layer near the perturbed separatrix** (analogy to stochasticity due to 3D equilibrium in stellarators)



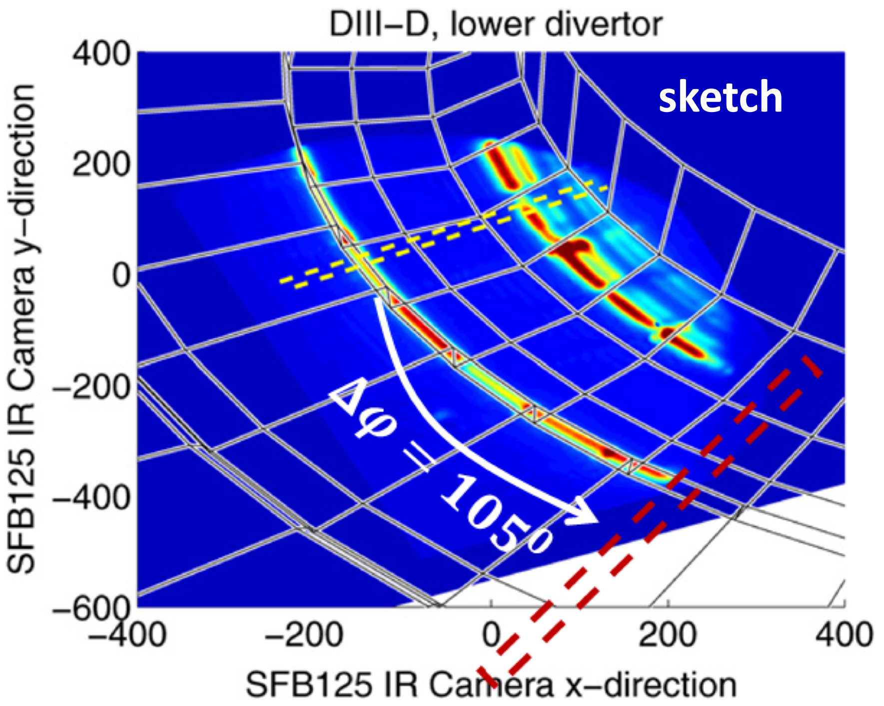


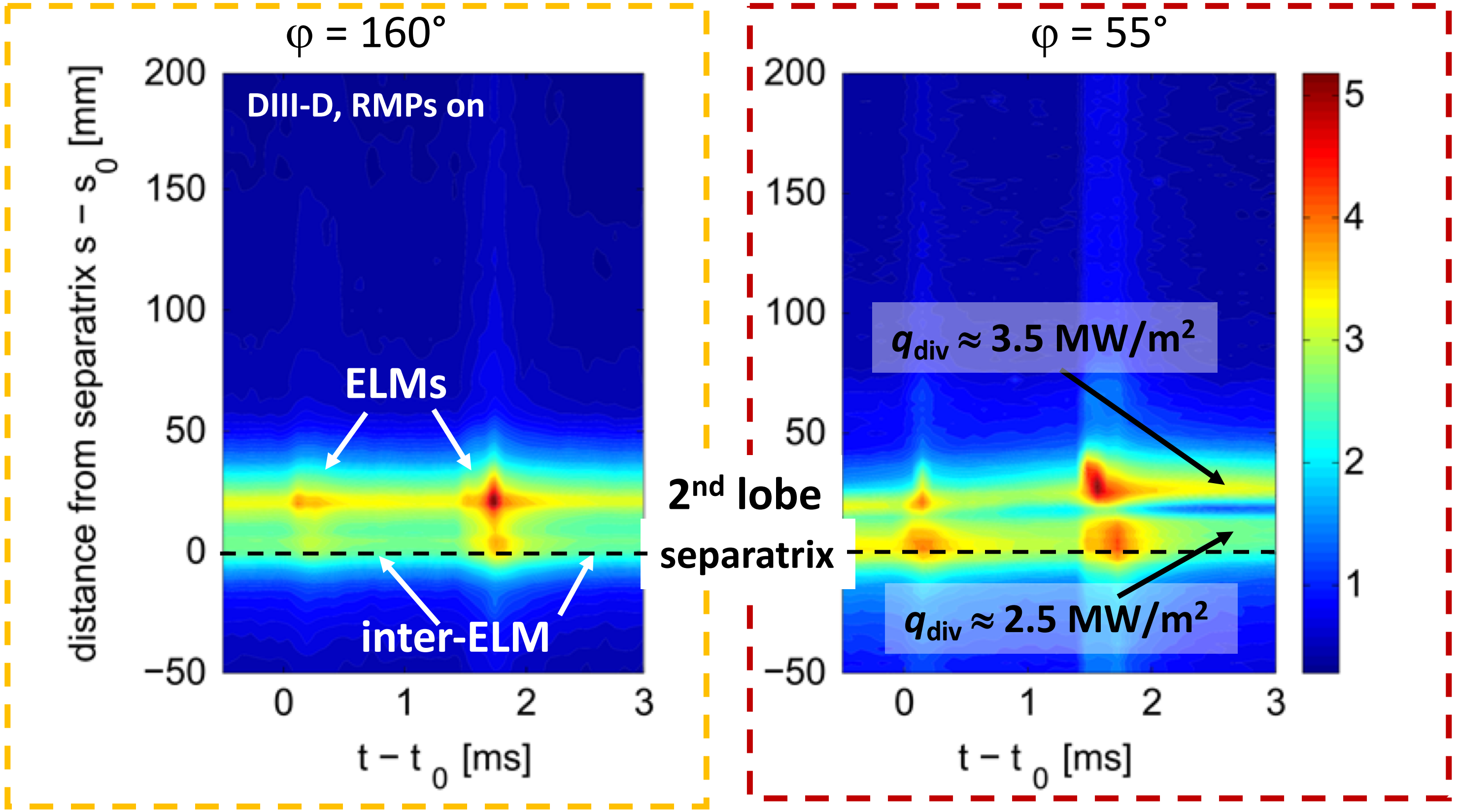
- **Energy and particle exhaust** is guided through the lobes if the **radial transport is strong enough** in order to "fill" the lobes.
- The scrape-off layer flux tube structure has a complex shape but its still a corelated flux tube. **Is two-point model still valid?** Modified for 3D divertor created by Y. Feng for W7-X

Talk R. König

Both inter-ELM and mitigated ELM loads follow striated footprints.

- At DIII-D scenarios, where secondary lobe gets more than the original separatrix have been identified.
- Toroidally resolved measurements, two fast cameras separated by 105°, showed that mitigated ELMs follow the same pattern. This may be important for scenarios with RMPs mitigating and not suppressing type-I ELMs.
- Both types of loads are not toroidally symmetric



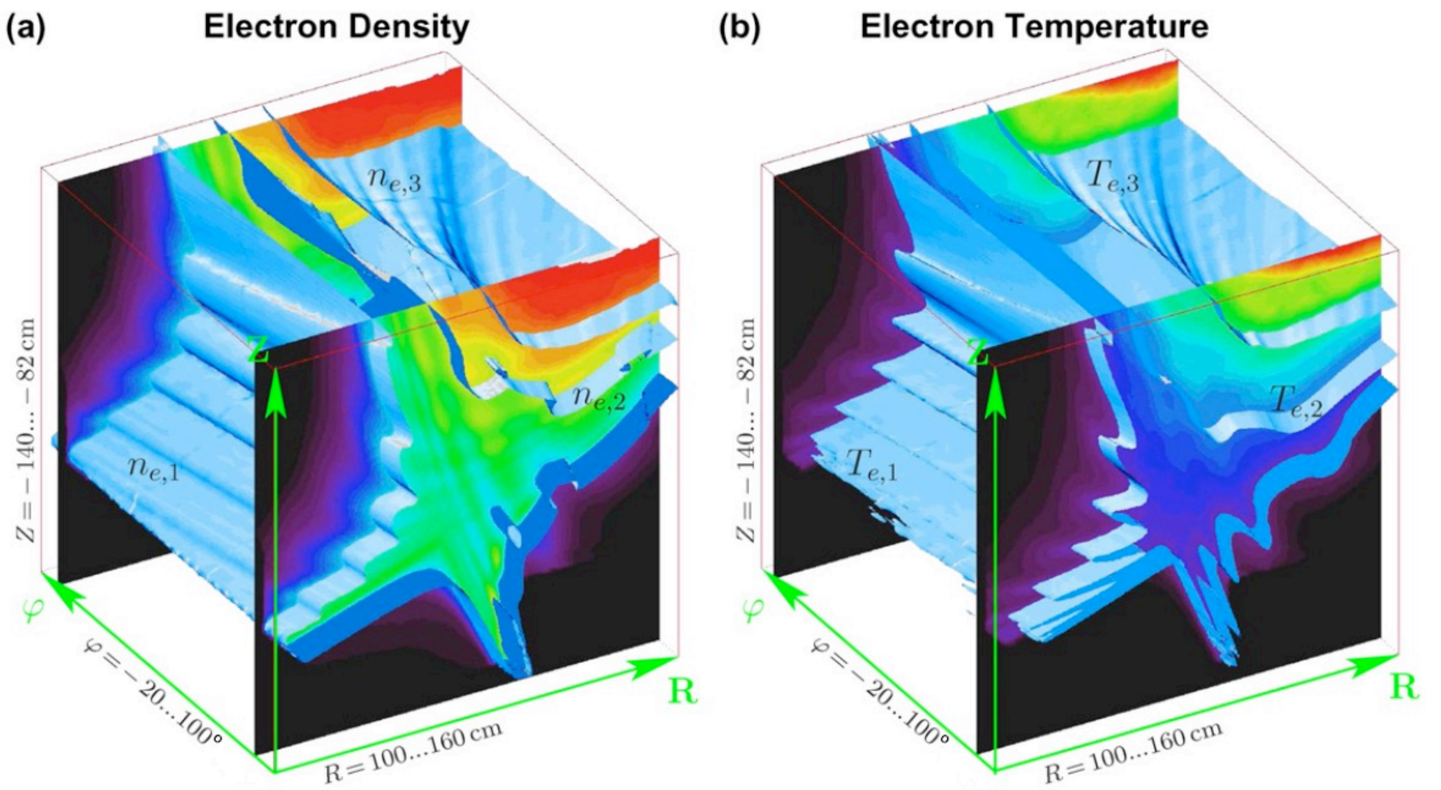


[M.W. Jakubowski et al.,Journal of Nuclear Materials 415 (2011) S901]

The helical lobes as a result of RMP fields have been visualized and modelled in 3D

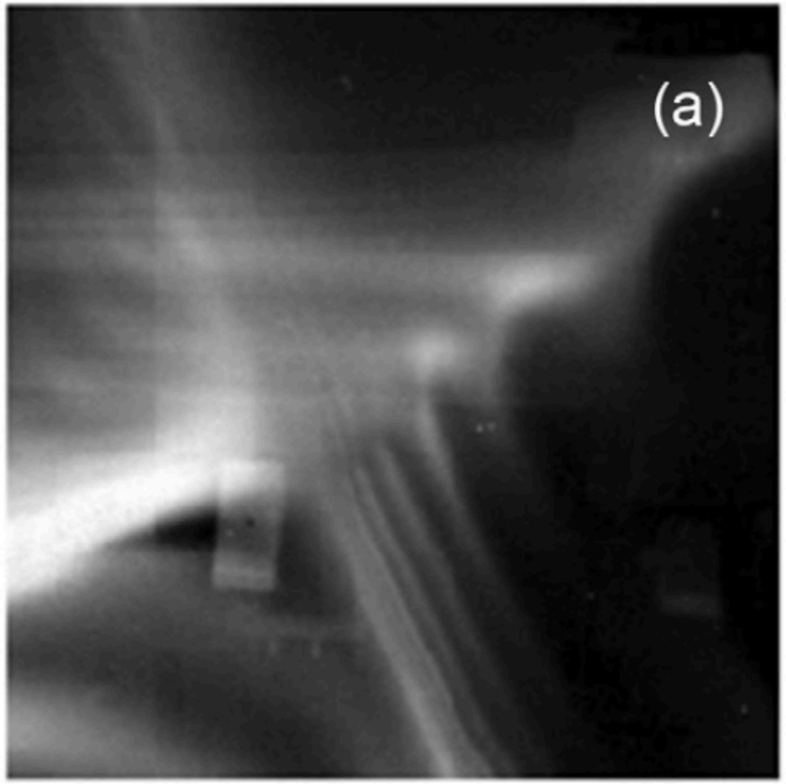
There is strong evidence for the existence of the lobes and their impact on the divertor

EMC3-EIRENE 3D plasma edge fluid and kinetic neutral modeling at DIII-D



H. Frerichs et al. Nuclear Fusion **50** (2010) 034004]

Direct visualization of lobes at MAST



A. Kirk et al. PRL **108** (2012) 255003

A. Kirk et al. PPCF **55** (2013) 124003

Talk H. Frerichs

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- Introduction: how is the 3D boundary formed and brief experimental survey for its existence
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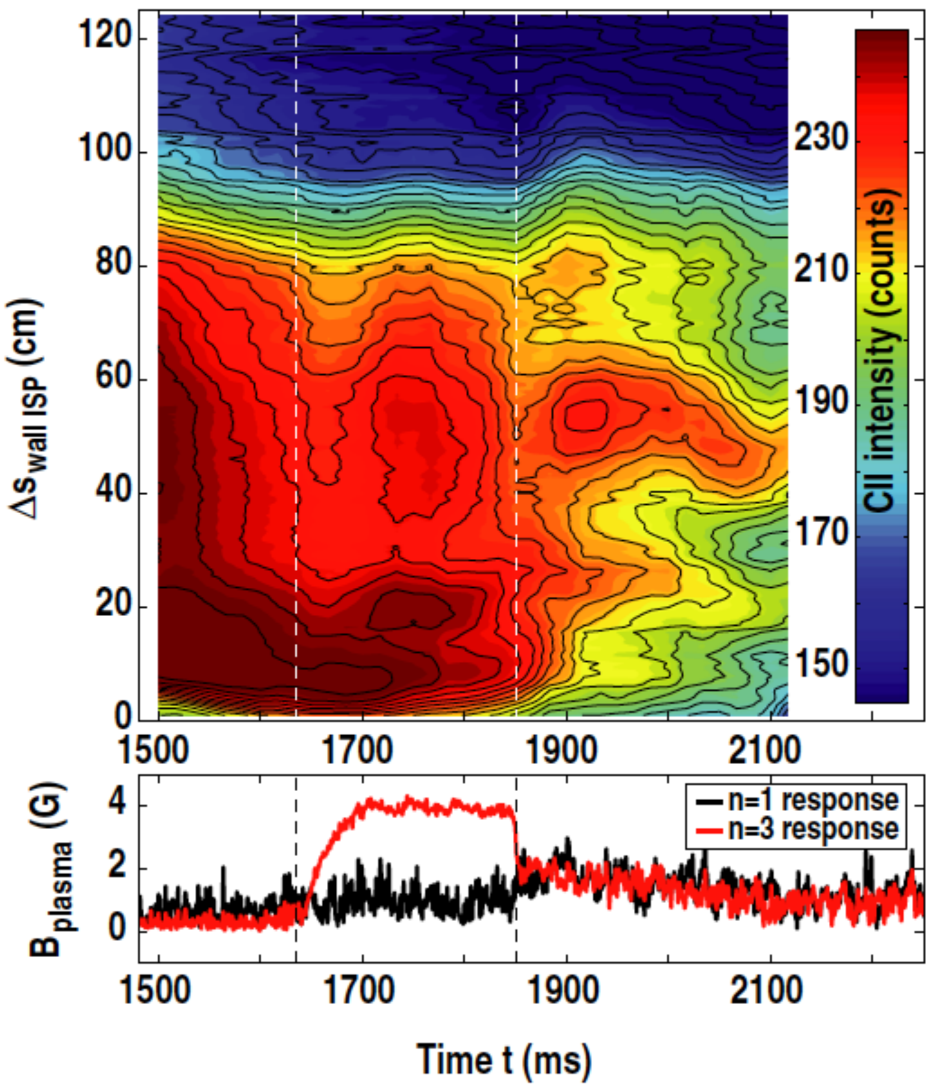
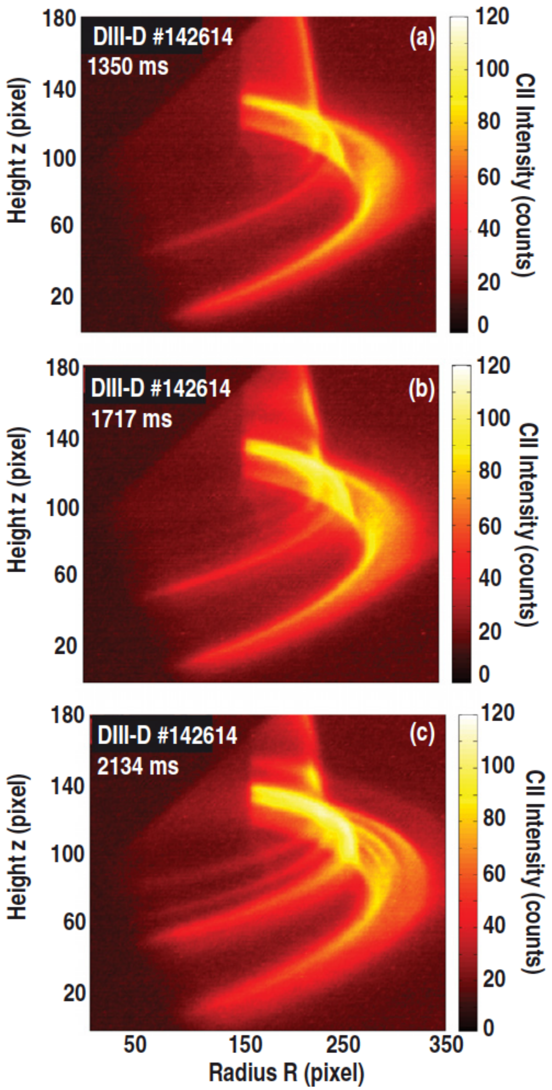
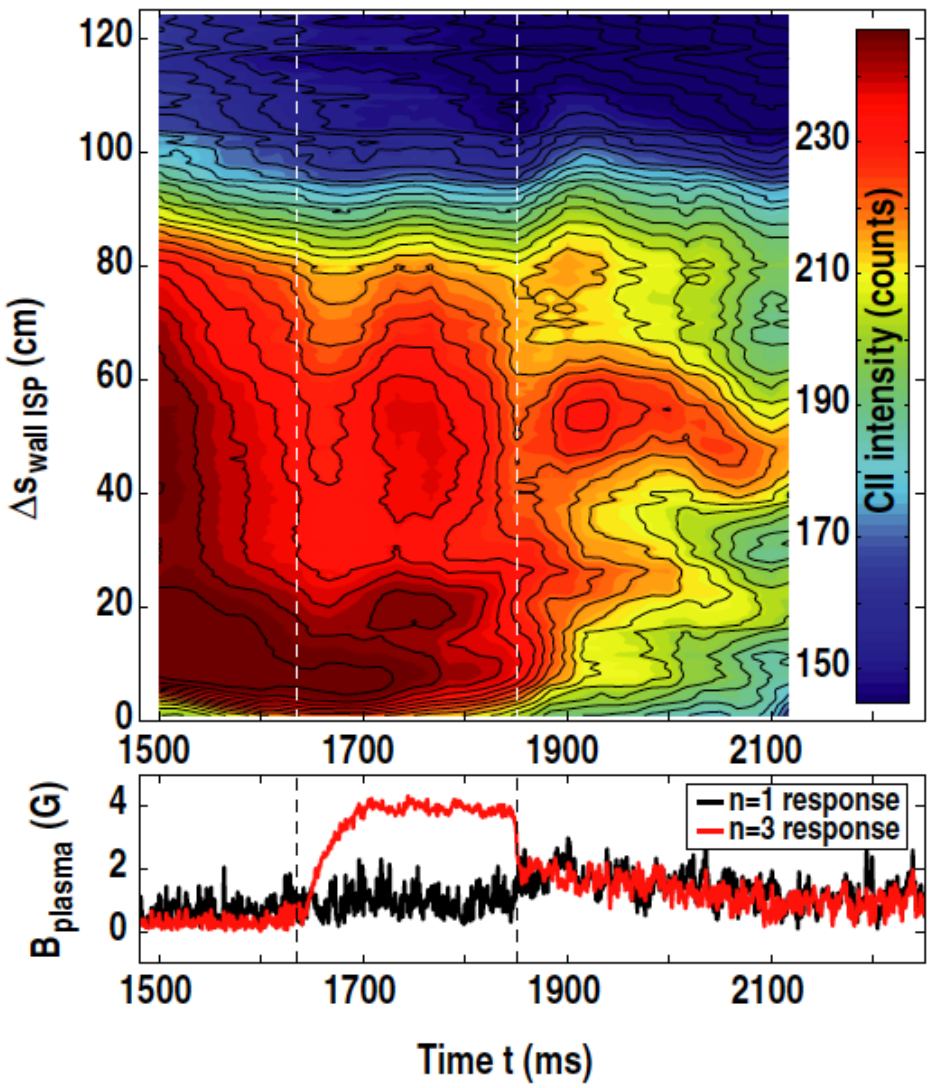
The internal plasma response to the applied RMP field impacts on the shape and extension of the divertor lobes

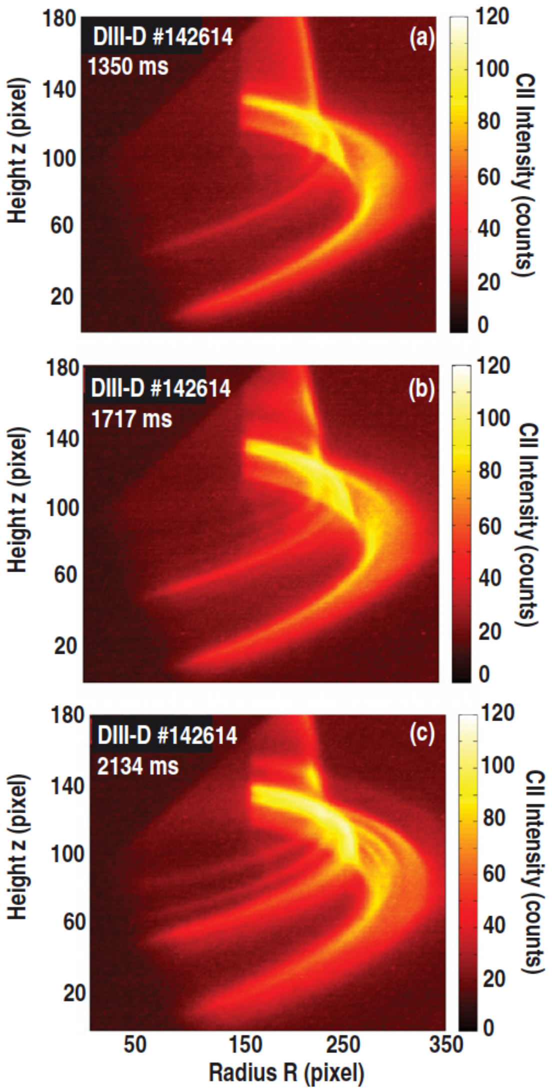




[O. Schmitz et al., Nuclear Fusion, **54** (2014) 012001]

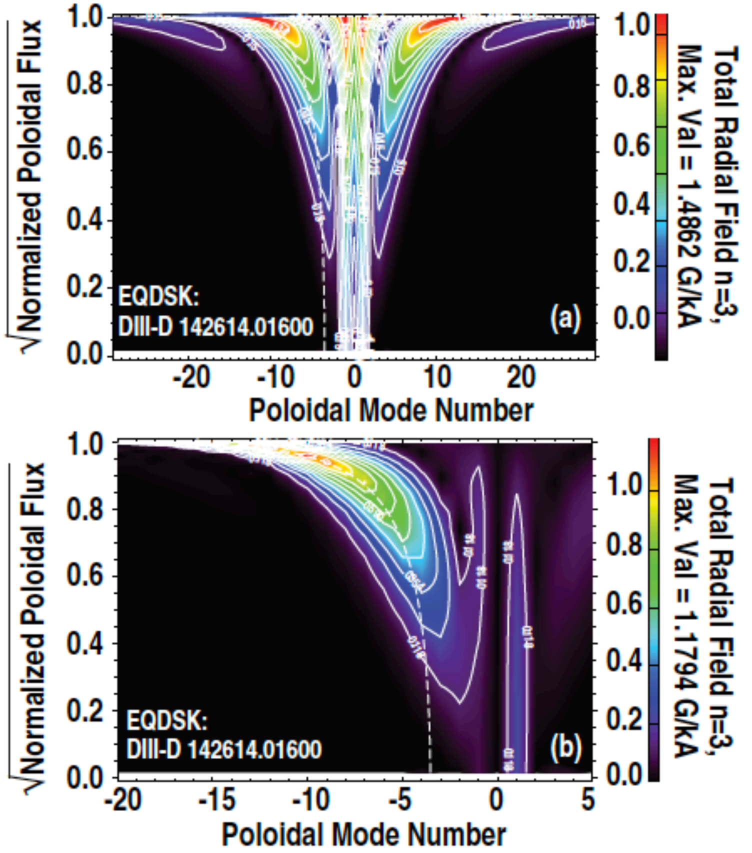
The internal plasma response to the applied RMP field impacts on the shape and extension of the divertor lobes





[O. Schmitz et al., Nuclear Fusion, **54** (2014) 012001]

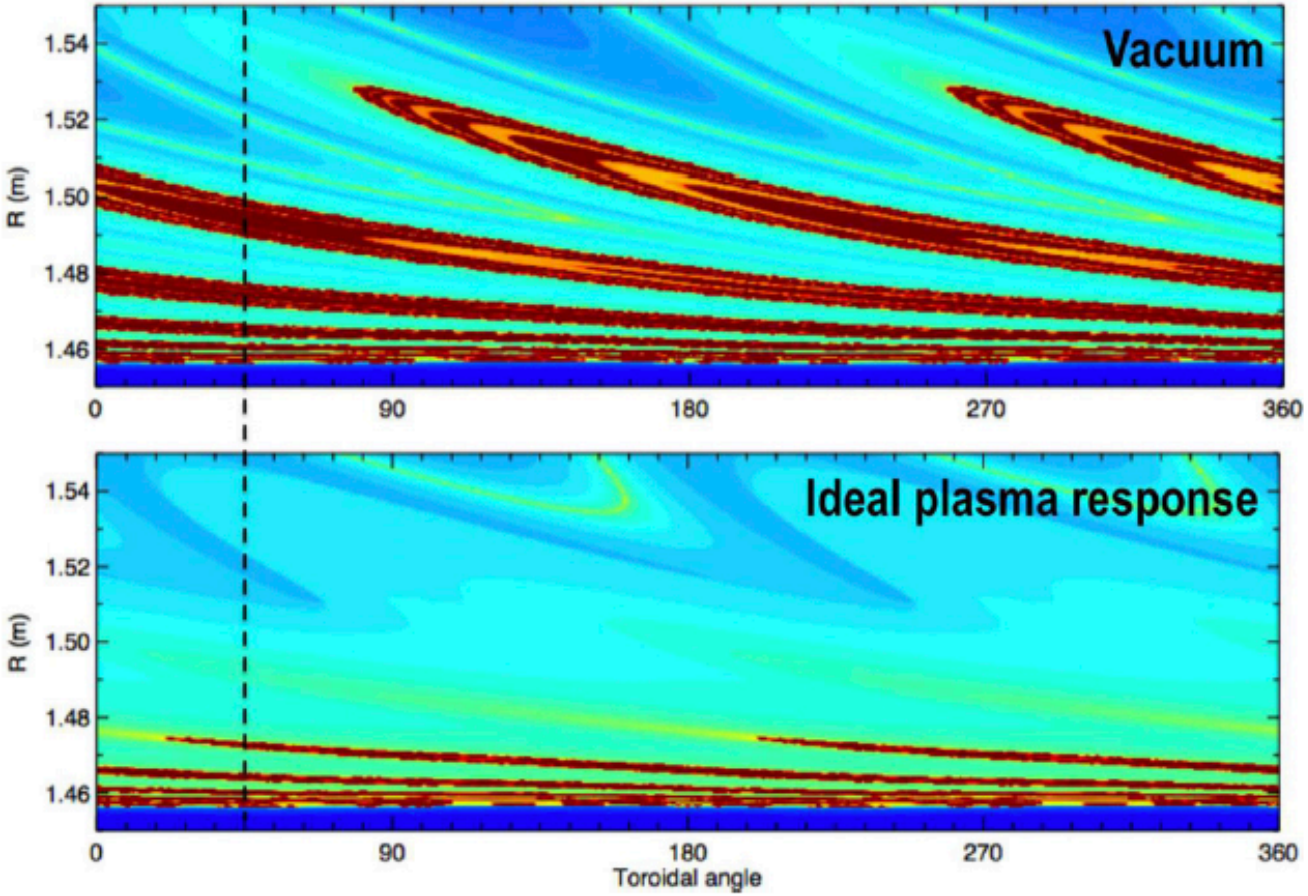
What does the "plasma response" do?



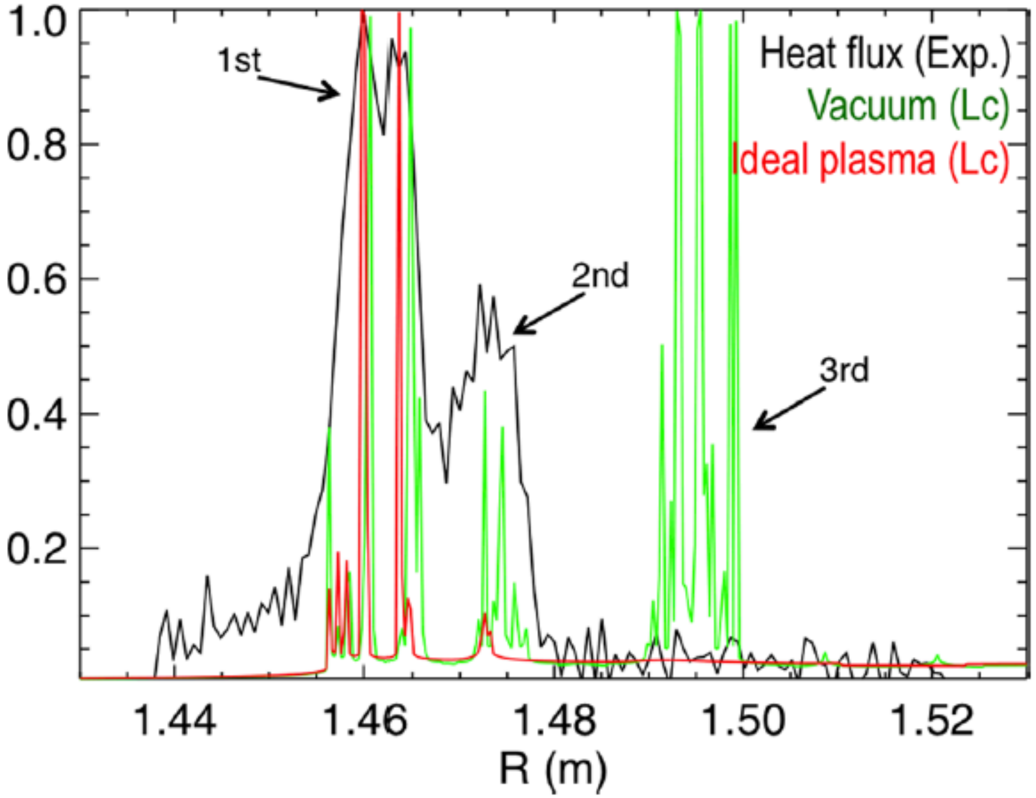
Phase shift of 90 degrees was measured suggesting destructive interference

At KSTAR, alteration of the magnetic footprint due to the plasma response is seen in heat flux measurements

Compression of helical lobes due to ideal response explains missing lobe in heat flux



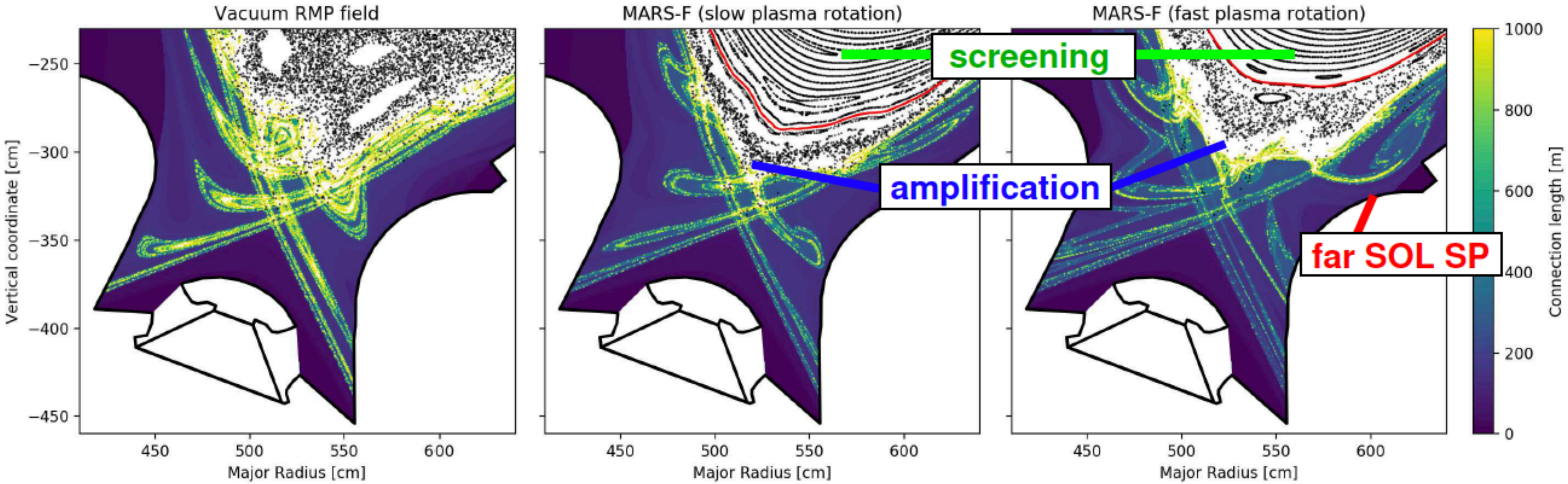
[K. Kim et al., PoP, **24** (2017) 052506]



Plasma response needs to be considered for heat flux analysis with RMP

Diamagnetic terms (high pressure gradient) yield amplification, which can increase lobe extension – talk H. Frerichs

Exact shape of the 3D separatrix lobes is sensitive to internal plasma response



MARS-F: linear, ideal MHD solution with resistivity and plasma rotation

[H. Frerichs et al. APS-DPP 2018, Contributed Oral]

[H. Frerichs et al. Nuclear Material And Energy (2019) accepted]

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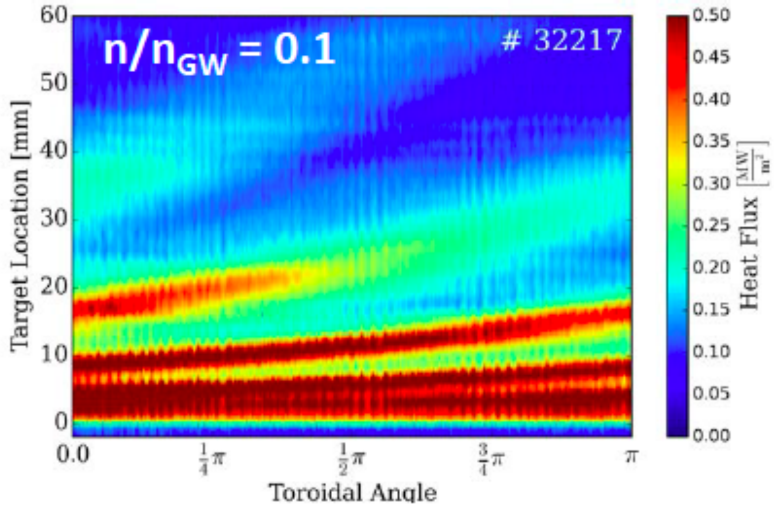
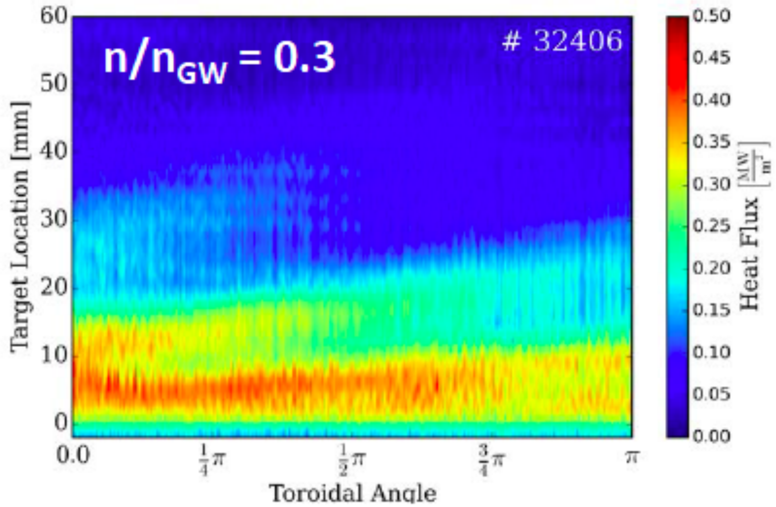
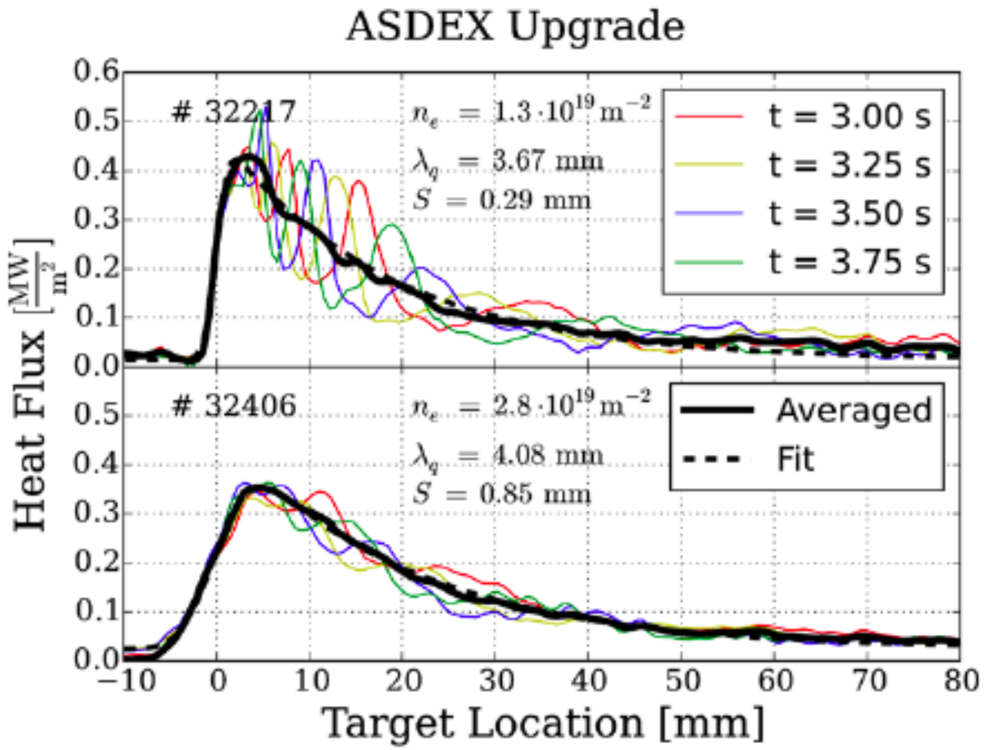
ASDEX-Upgrade L-mode results indicate that rotated heat flux pattern will be comparable axisymmetric situation

Density dependence suggest vanishing striation in L-mode







[M. Faitsch et al., PPCF **59** (2017) 095006]

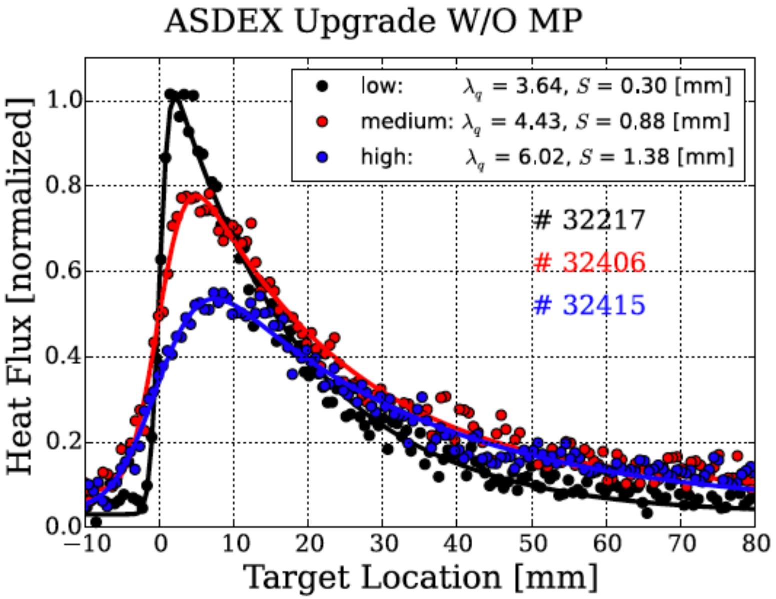
Can this profile be described by the same shape and decay parameter?

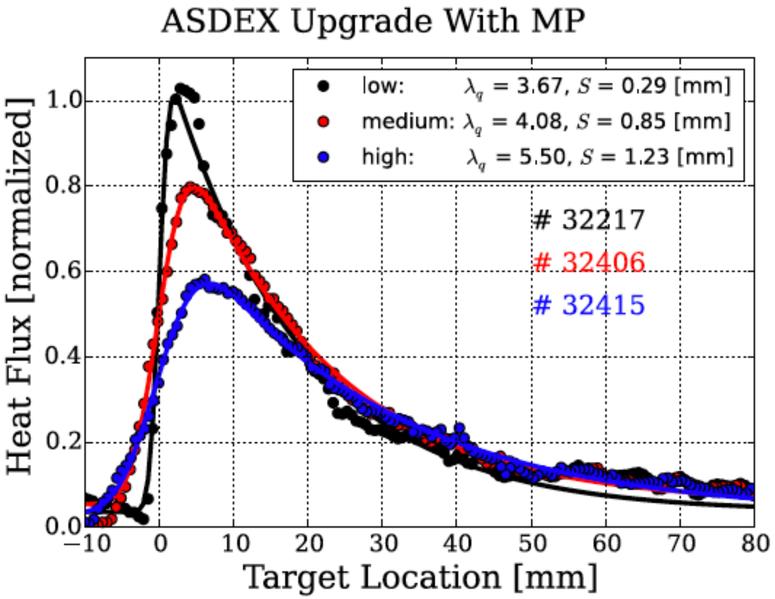
$$q(s) = \frac{q_0}{2} \exp\left(\left(\frac{S}{2\lambda_q}\right)^2 - \frac{s}{\lambda_q f_x}\right) \cdot \mathrm{erfc}\left(\frac{S}{2\lambda_q} - \frac{s}{S f_x}\right) + q_{BG} \quad \left[\frac{\mathrm{MW}}{\mathrm{m}^2}\right]$$

[T. Eich et al., Phys. Rev. Letter **107** (2011) 215001]

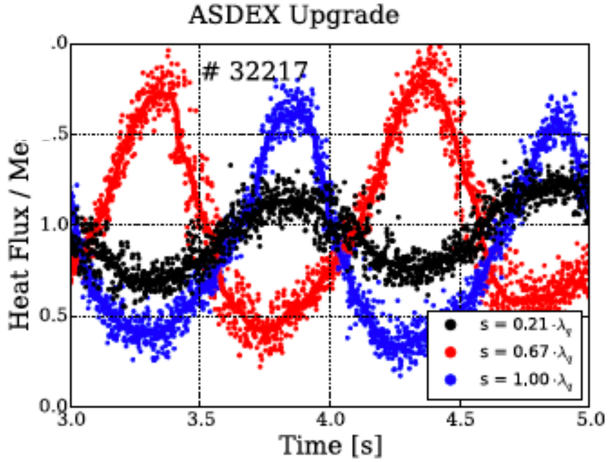
Will the striated heat flux be seen for high density divertor conditions – is it relevant after all?

The toroidally averaged heat flux profile collapses to diffusion governed situation with only moderate oscillation left



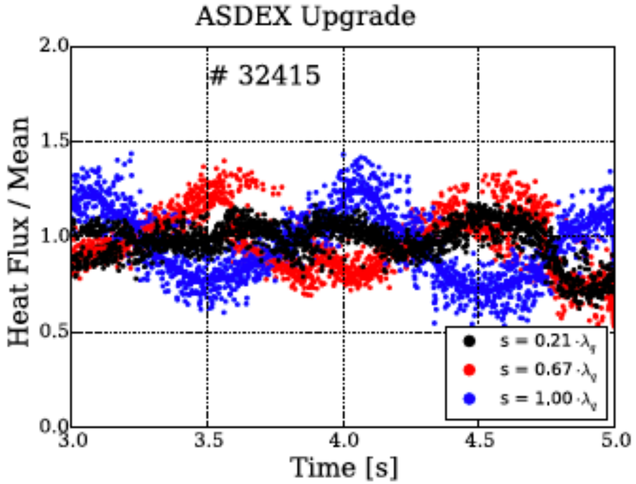


[M. Faitsch et al., PPCF **59** (2017) 095006]



reduced oscillations in *q*

Increasing plasma density



No access to RMP ELM suppression in detached H-mode → Need to rely on modeling → ITPA-DSOL 37 task formed

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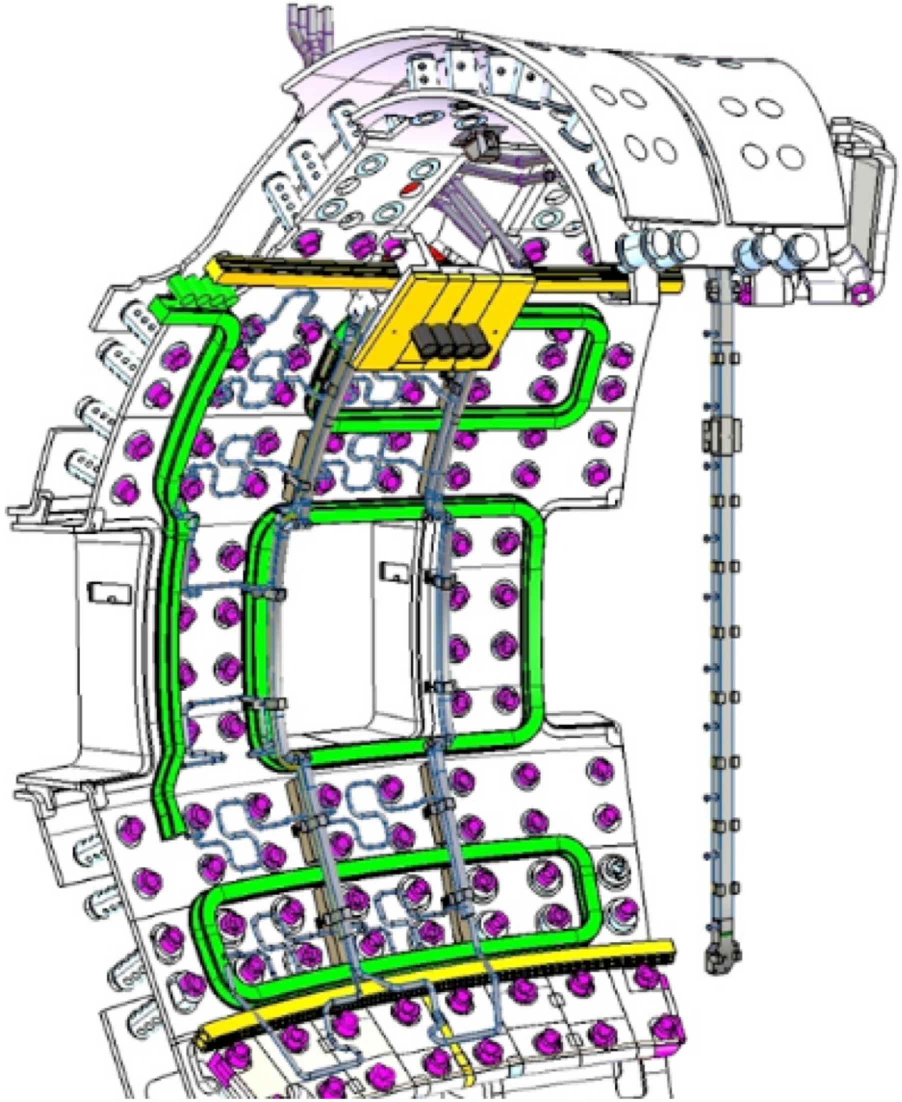
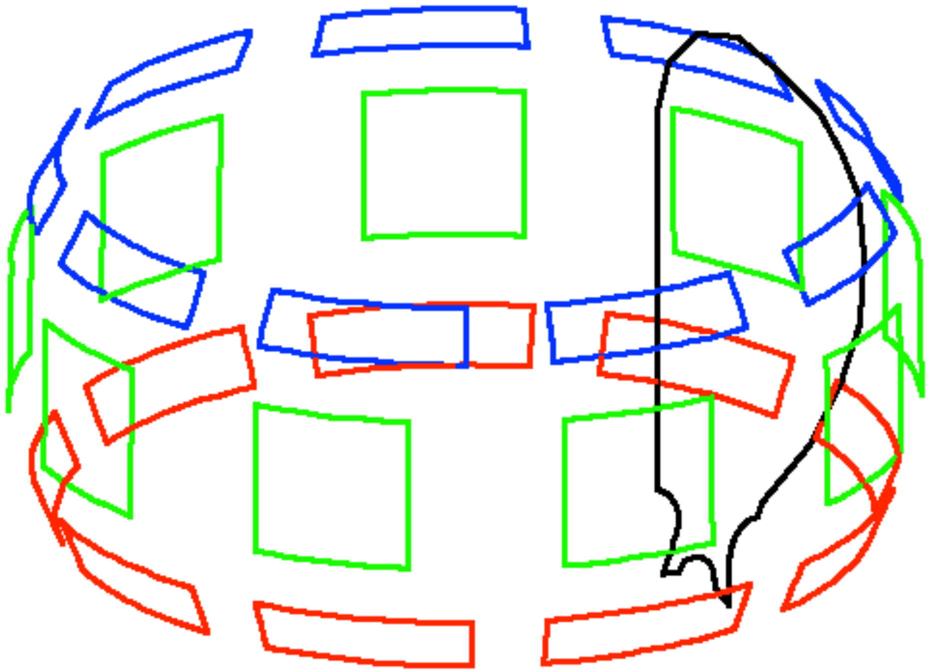
The ITER RMP coil set is a versatile tool for plasma edge control

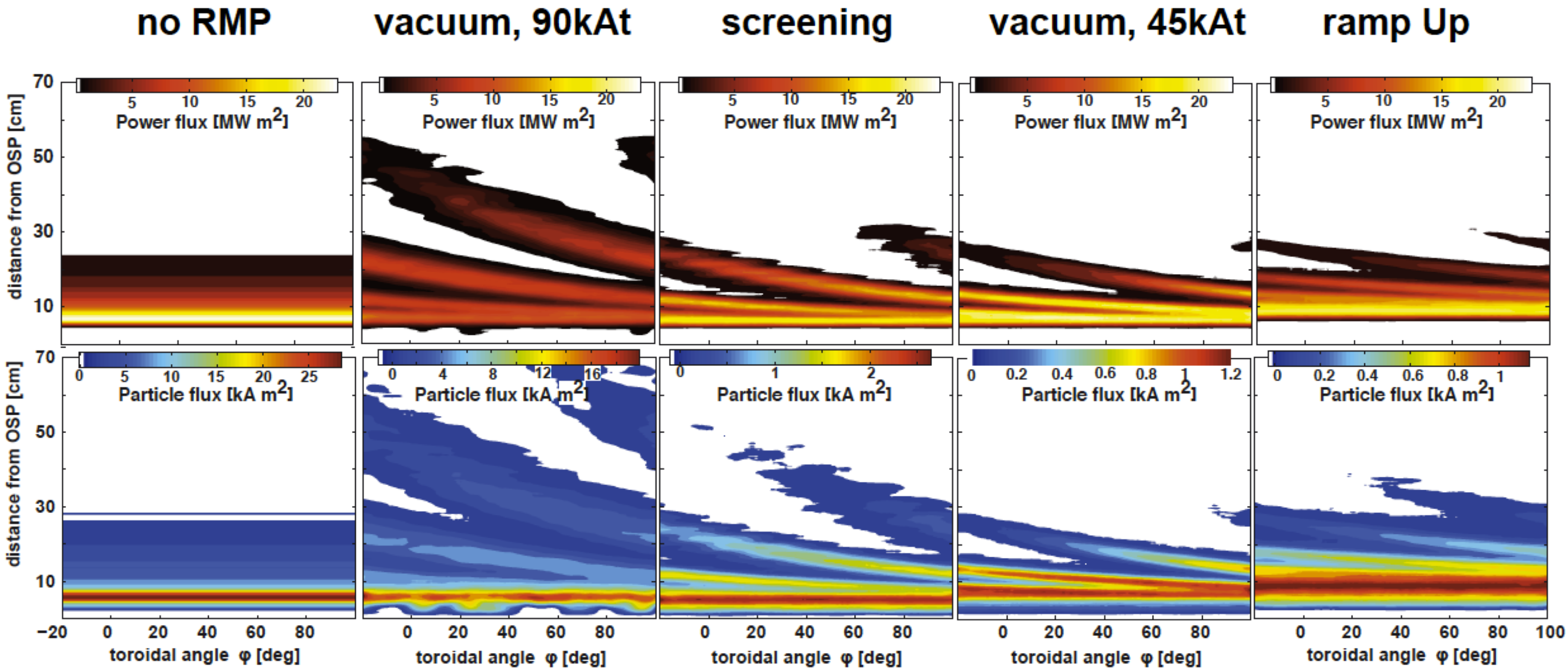




- In vessel coils mounted behind blanket
- 9x3 coils with single power supplies

Coil set with wide spectral flexibility

Helical heat and particle flux patterns are predicted (attached)

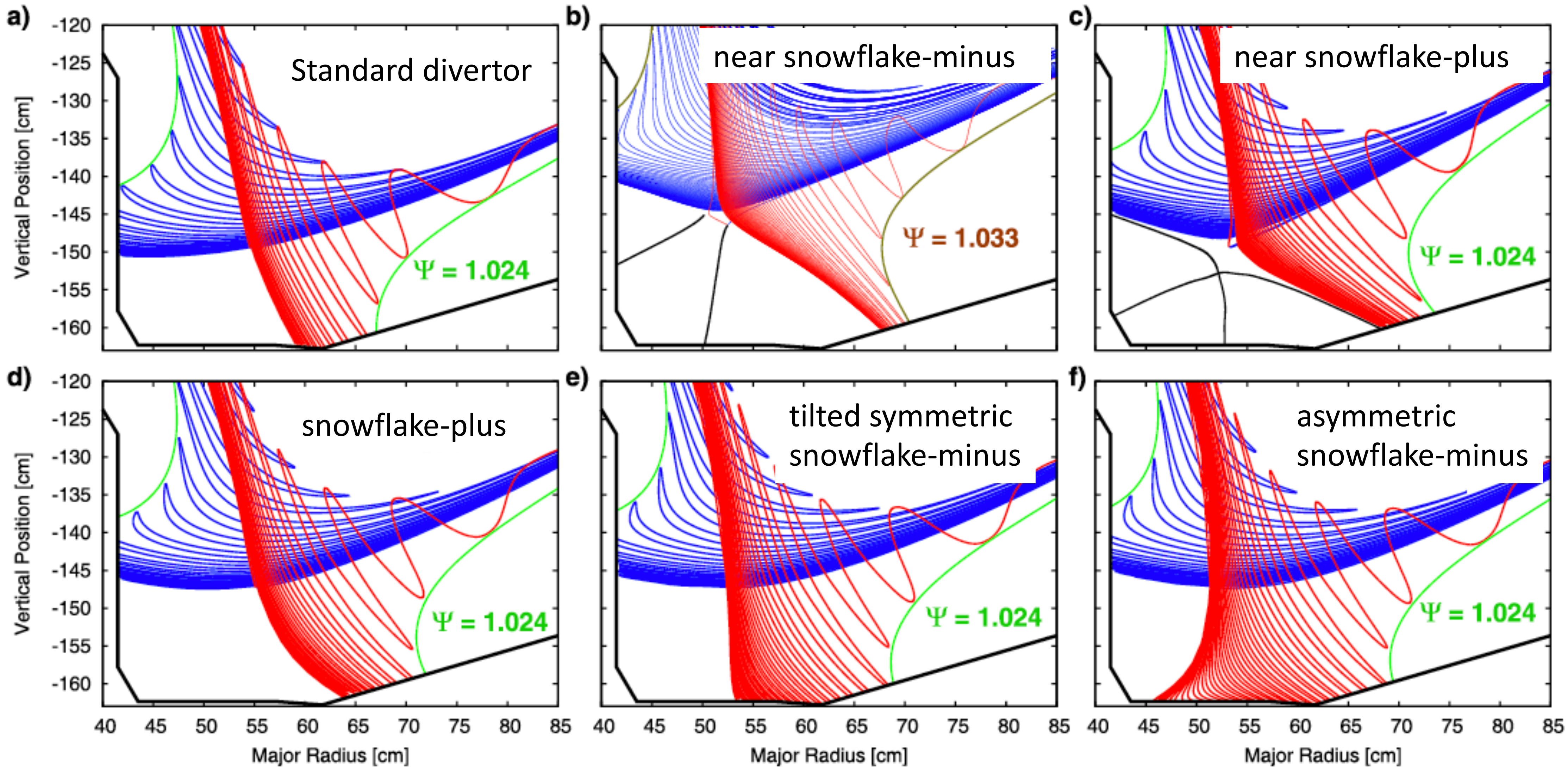


How does this propagate into the ITER divertor baseline?

Talk H. Frerichs

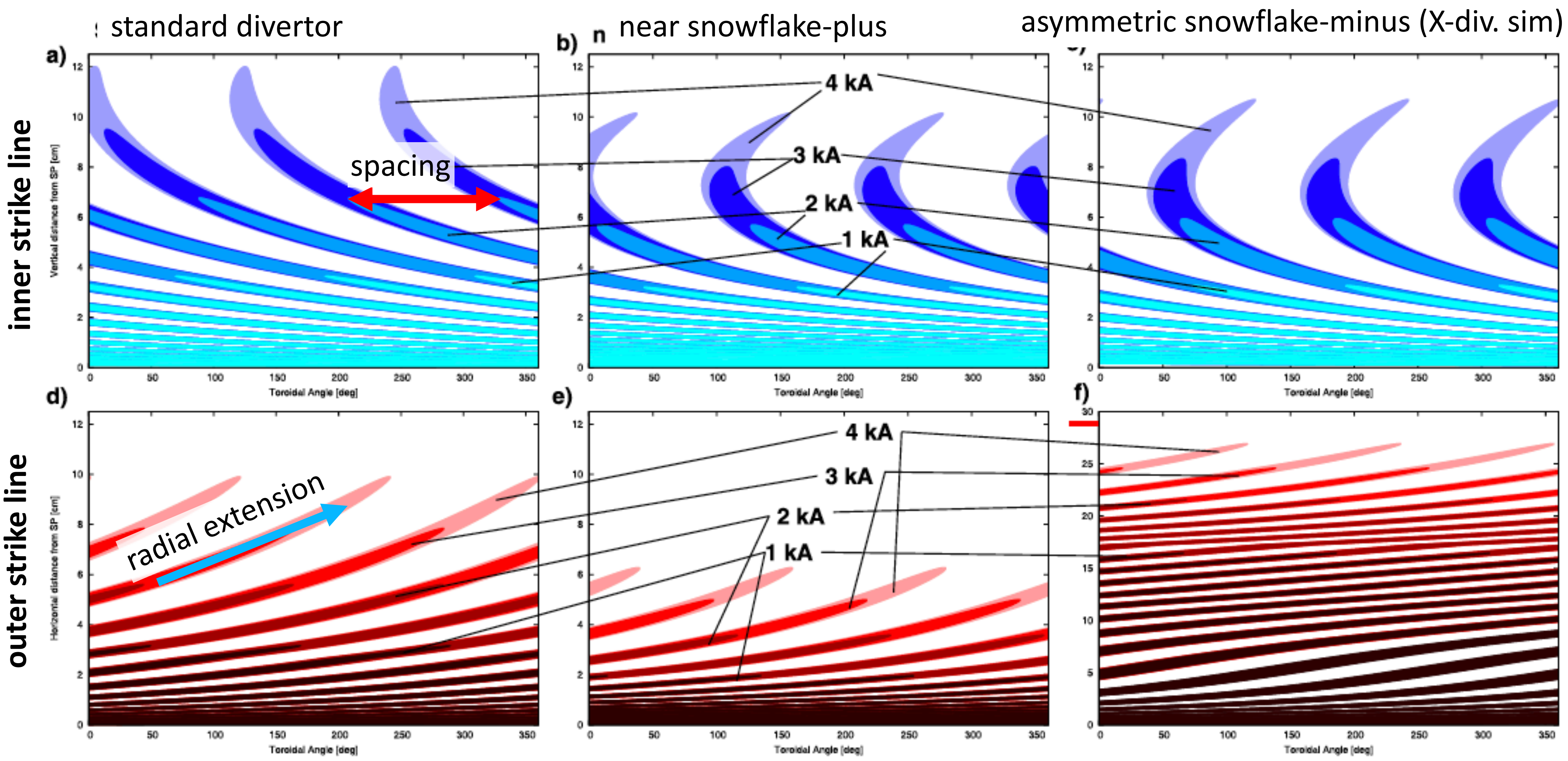
[O. Schmitz et al. NF **56** (2016) 002149]

Survey of impact in advanced divertor concepts shows dense mesh of helical lobes in high flux expansion conditions



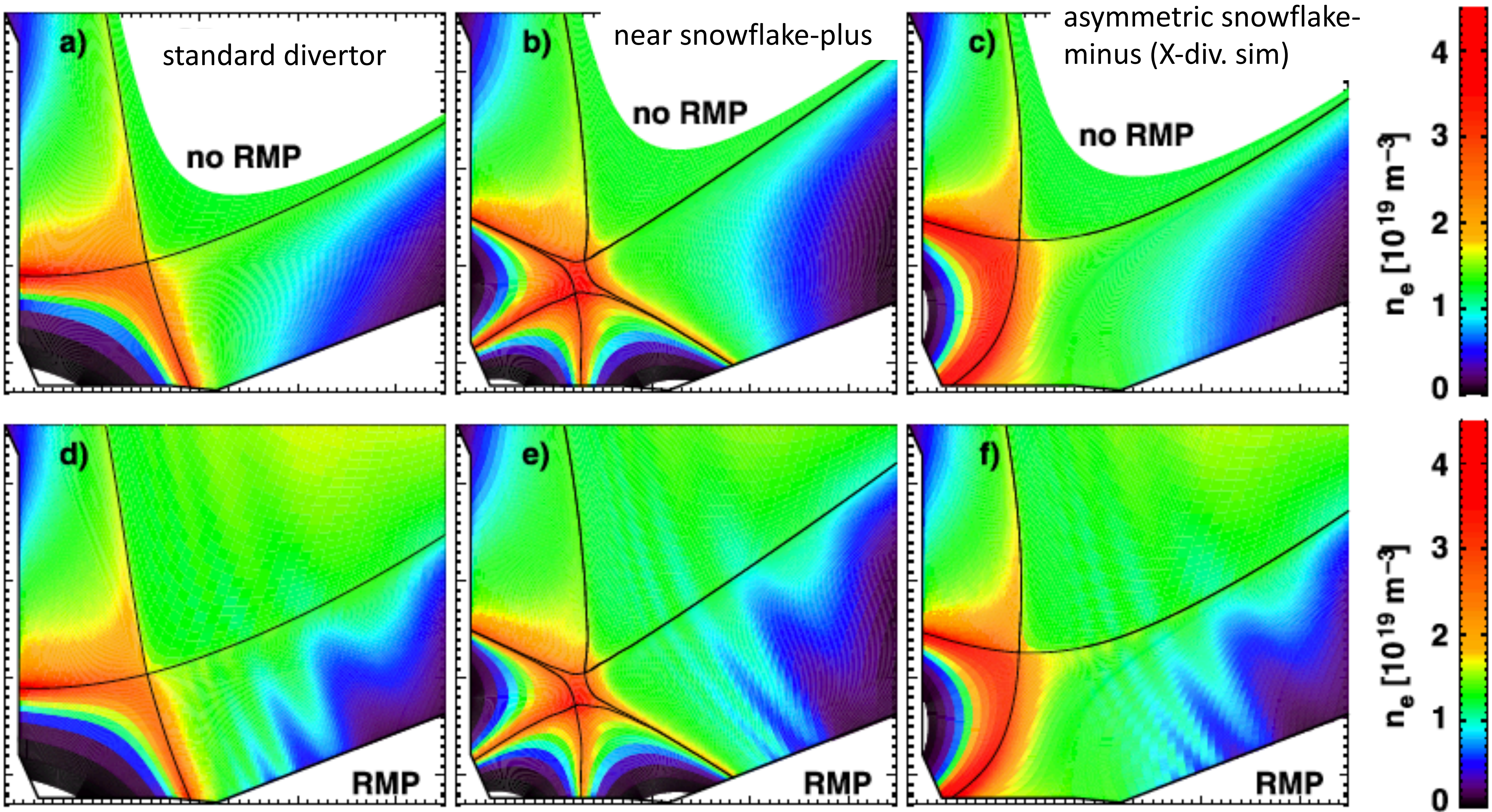
[H. Frerichs et al. PoP **23** (2016) 062517]

A dense mesh of thin lobes evolves for ASF- at outer strike point

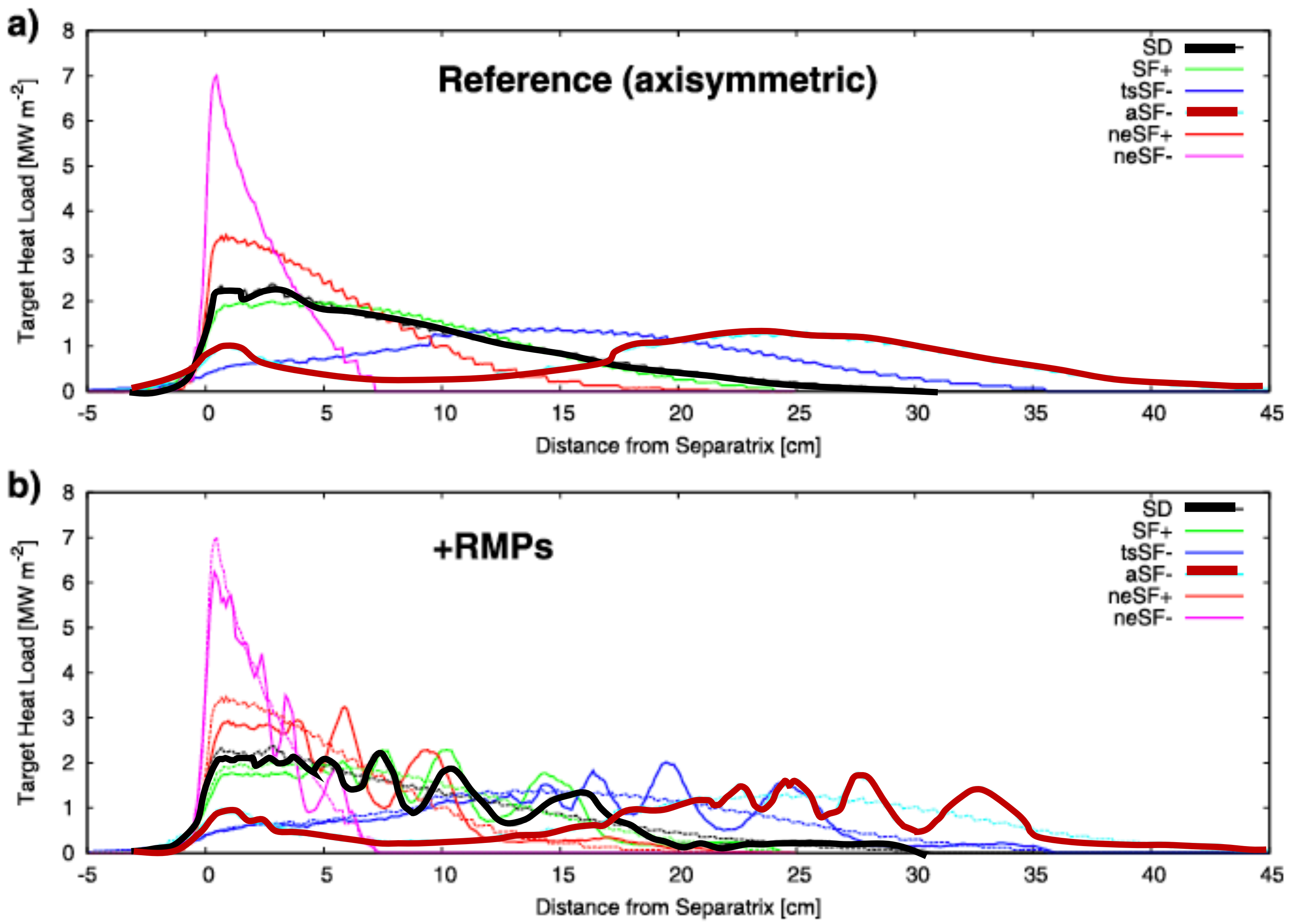


[H. Frerichs et al. PoP **23** (2016) 062517]

Typical plasma diffusive transport can smear out lobe structure



Perturbed heat flux oscillates around axisymmetric flux profile – rotating fields will most likely average towards 2D condition



The **X-divertor** like configurations have more flux expansion on the divertor target than the **standard divertor** configuration, and the heat loads are modified accordingly. **Peak heat loads are reduced by 40%, and their location is shifted ca. 20 cm away from the separatrix strike point** depending on the local flux expansion.

[H. Frerichs et al. PoP **23** (2016) 062517]

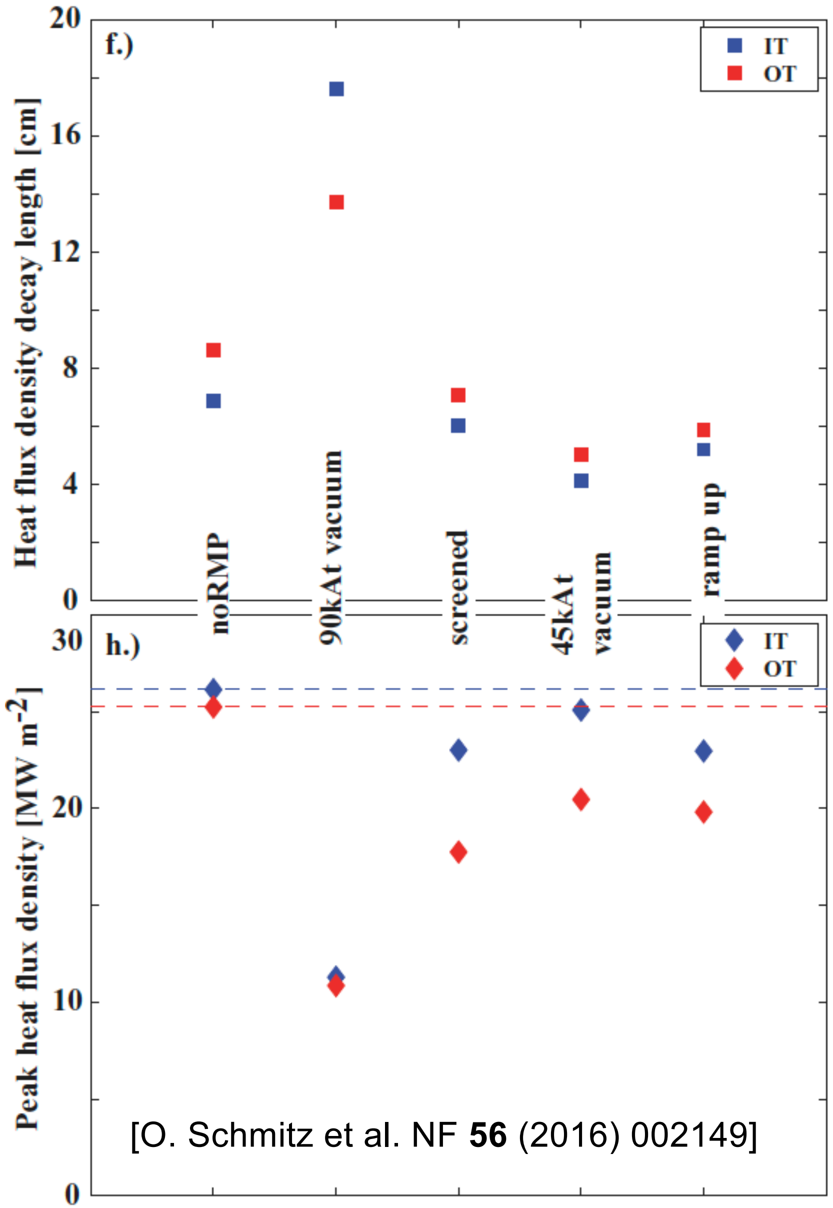
Summary in view of divertor concepts beyond ITER

- If Resonant Magnetic Perturbation fields will be applied beyond ITER, 3D boundary effects need to be considered.
- DIII-D and ASDEX Upgrade show different reaction of heat flux to magnetic perturbations. → Detailed survey of devices needed
- The RMP ELM suppressed ITER baseline will show us the impact in partially detached vertical target situation – at the moment it is almost impossible to achieve ITER-like detached scenarios with RMP ELM suppression. A task at ITPA-DSOL formed to address this question.
- Advanced divertor concepts were not studied so far in RMP ELM suppressed regimes experimentally, hence firm extrapolation is difficult
- Initial assessment with field line tracing and EMC3-EIRENE modeling shows higher fidelity effects – flux expansion "cures" some 3D effects
- Plasma response was not considered and no experimental basis exists to align with reality – that's a glaring gap for research on divertor concepts beyond ITER

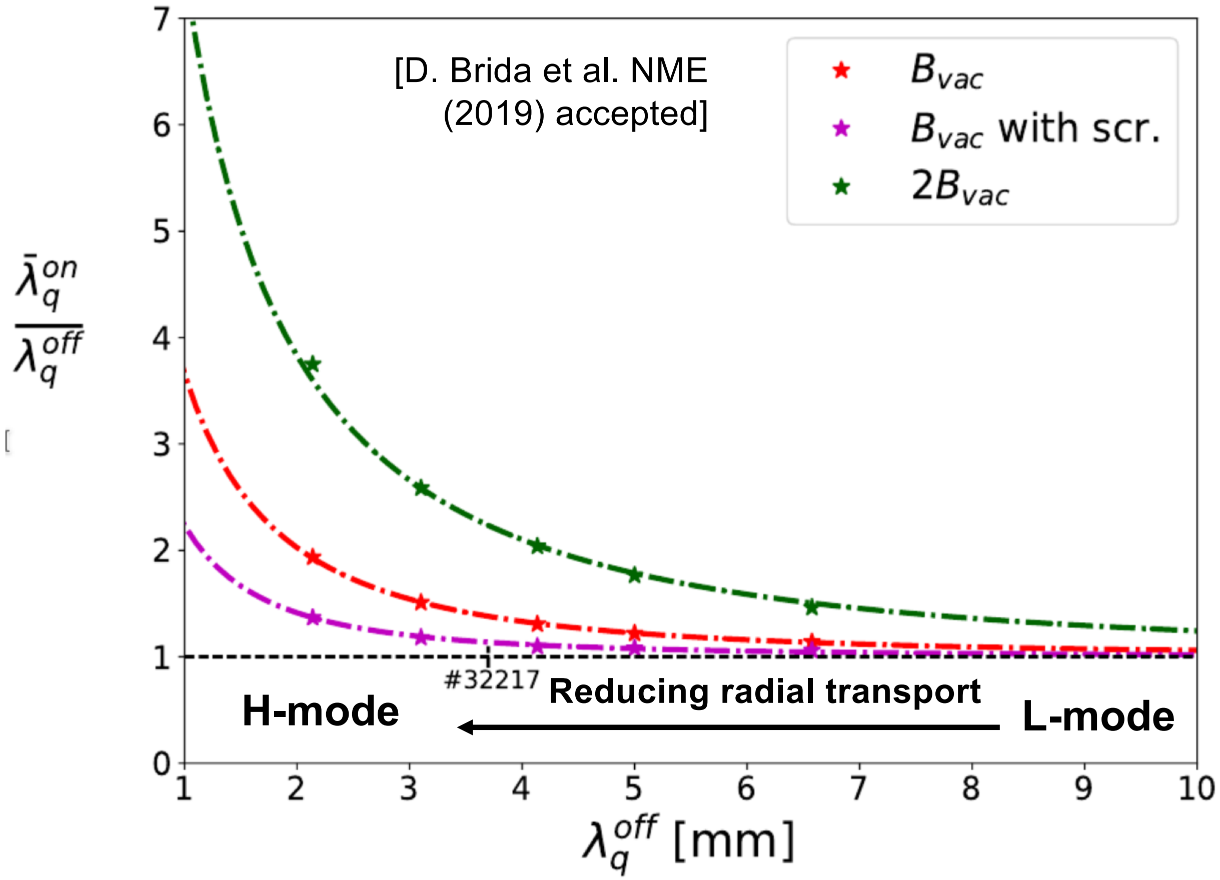
Questions

- **Questions, which needs to be answered for ITER:**
  - Do we need rotation of RMP fields to protect divertor or is detachment and RMPs compatible with each other?
  - How to approach detached discharges with RMPs? Are the results from DIII-D and ASDEX Upgrade concerning plasma response different?
  - What about mitigated ELMs scenarios?
  - How to determine the plasma response fields?
    - Does this change between attached and detached states?
    - Does this change from ELMy to ELM mitigates/suppressed states?
- **Questions beyond ITER**
  - How to approach RMP scenarios for DEMO?
    - Plasma equilibrium defined by fully non-inductive plasma current?
    - How to test RMP scenarios with X-divertor
    - Plasma response

Toroidally averaged λ_q increases with reduced transport



[O. Schmitz et al. NF **56** (2016) 002149]

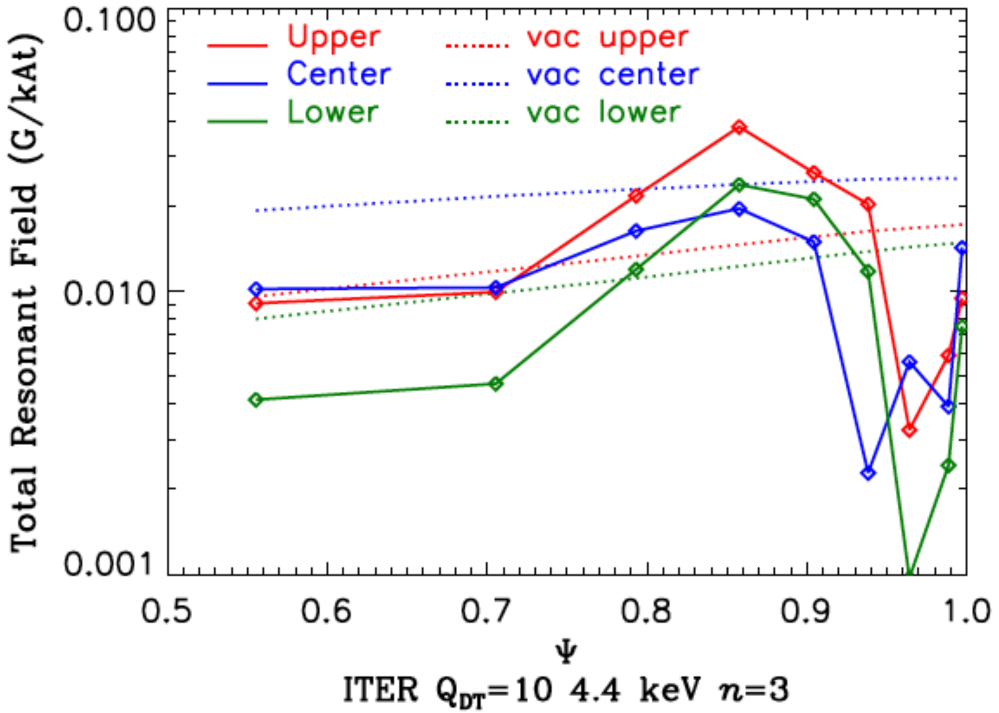


In H-mode a significant (benefical) impact is expected on toroidal averaged λ_q

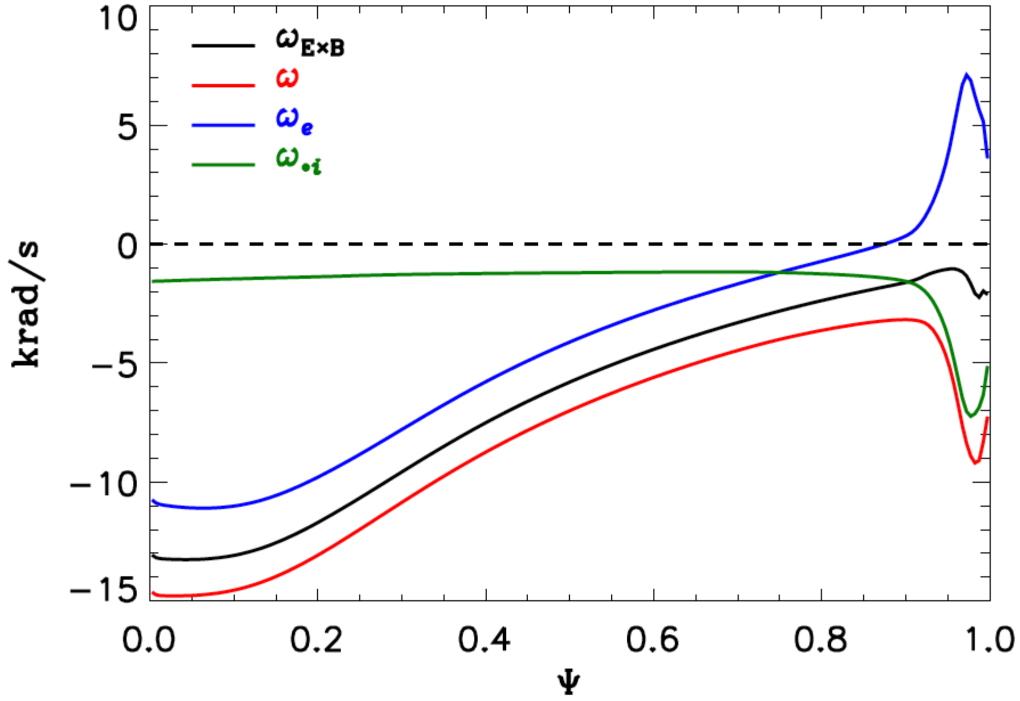
Very brief: what does the plasma response do to the resonant magnetic field amplitudes?

Courtesy of N. Ferraro, from final report of IO task IO/CT/11/4300000497

Linear, two-fluid modeling M3D-C1

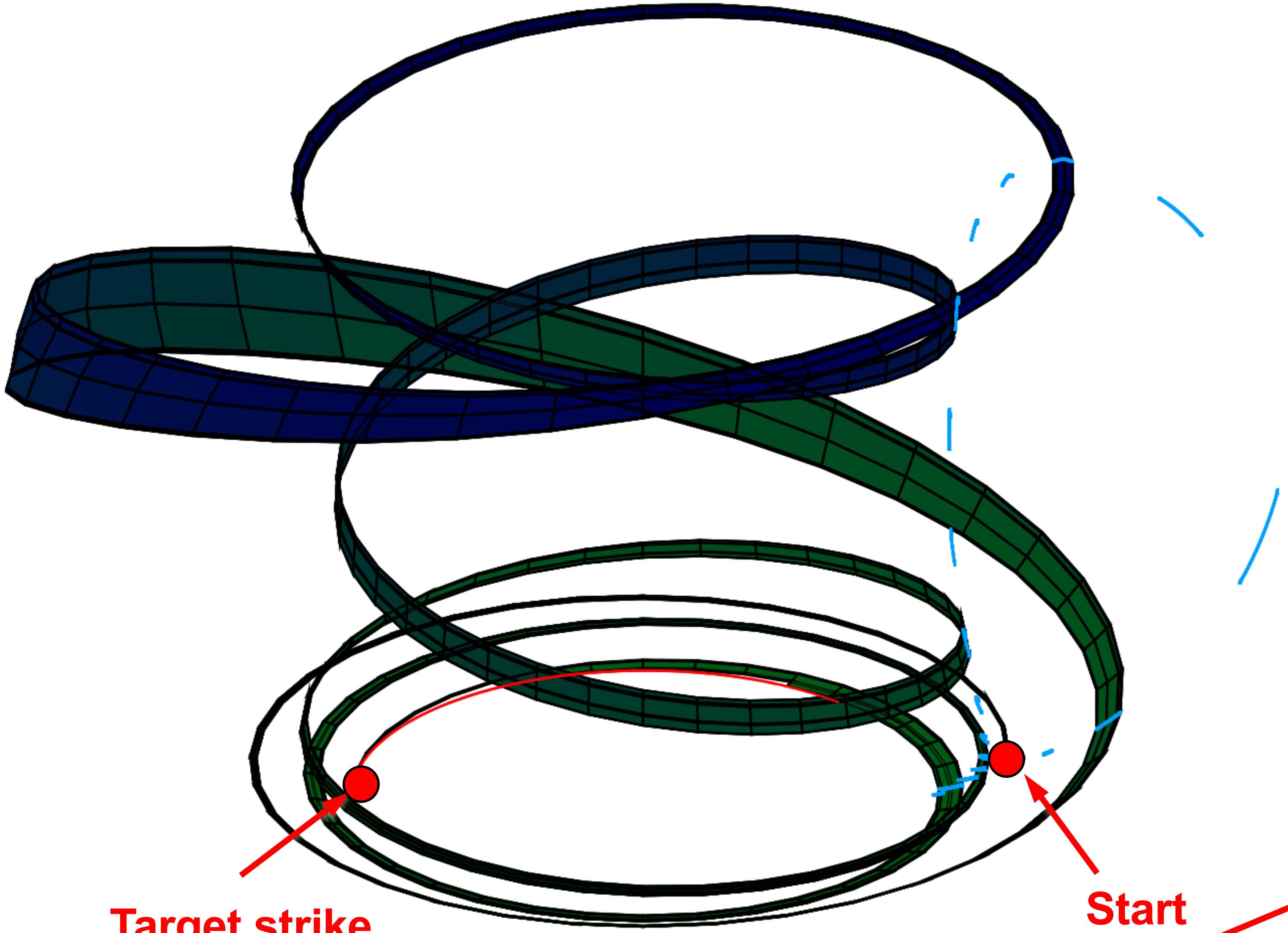


Underlying rotation profiles



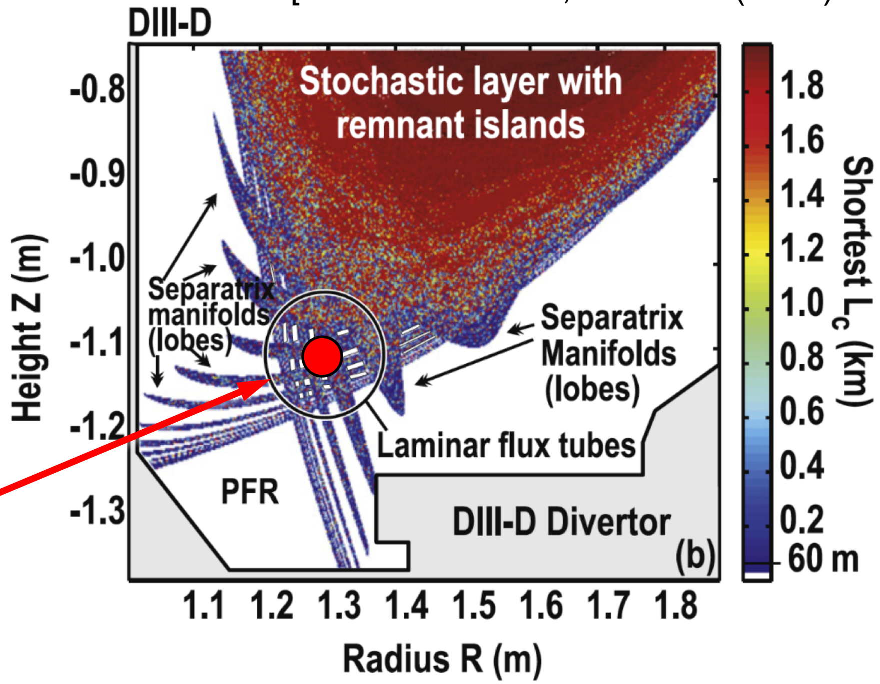
- **Linear response shows strong screening close to separatrix**
- **Resonant field amplification in plasma edge**
- **Moderate screening radially deeper inside**

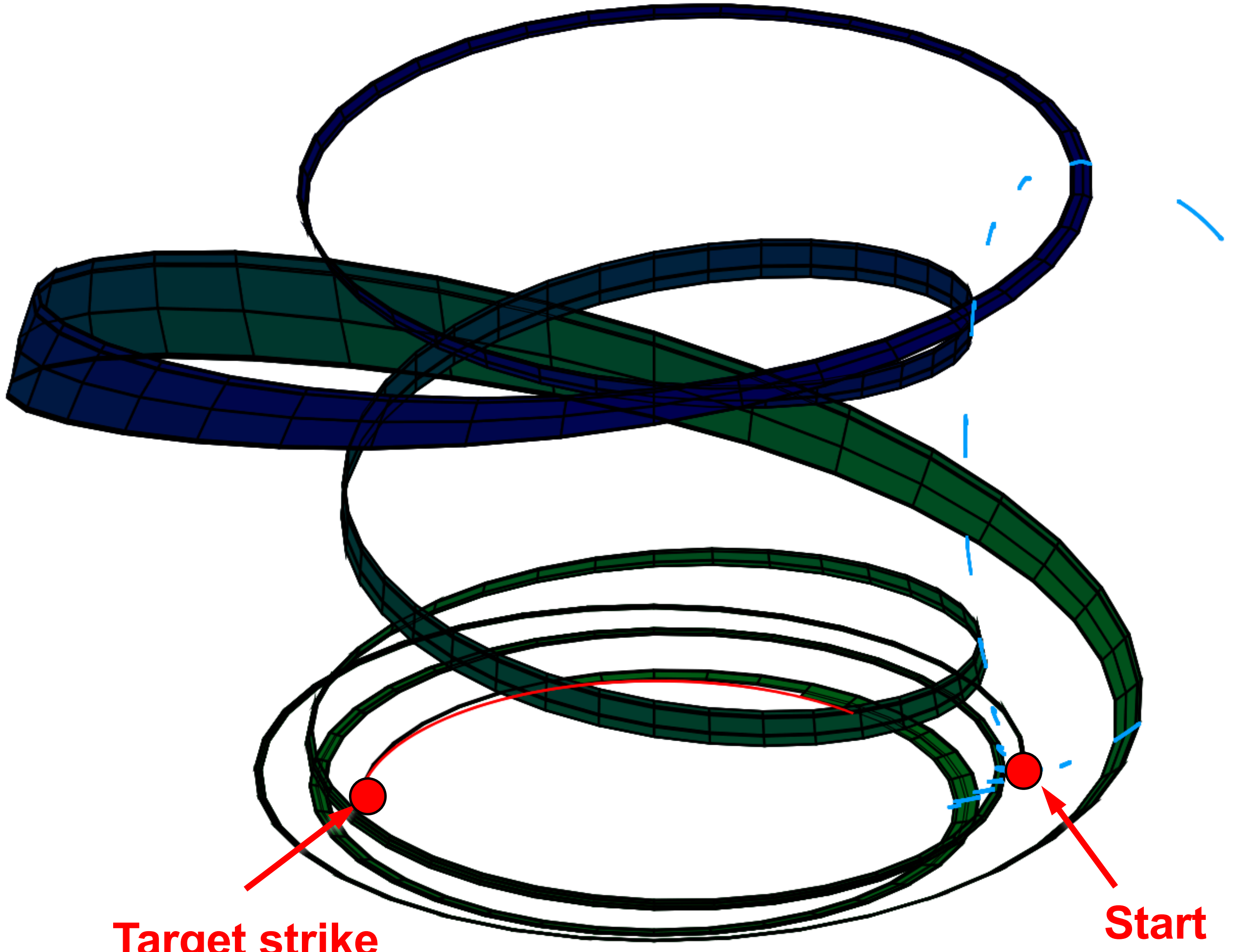
The scrape-off layer flux tube structure has a complex shape but its still a corelated flux tube



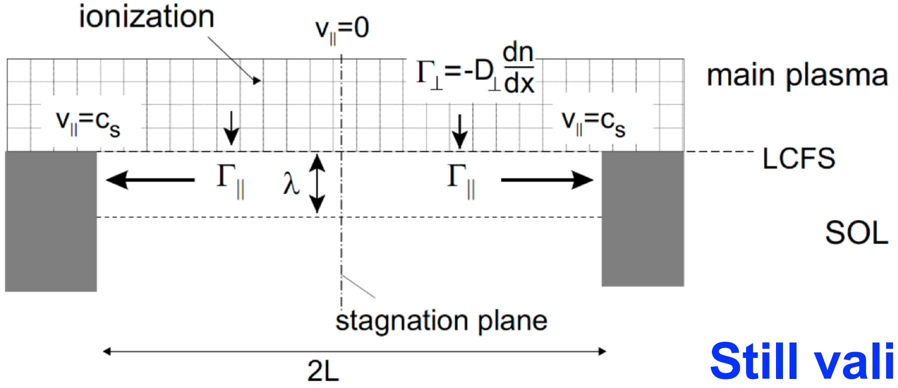
[H. Frerichs et al., PoP **22** (2014) 072508]

[O. Schmitz et al., JNM **415** (2011) S886]





[H. Frerichs et al., PoP **22** (2014) 072508]



Still valid?

[O. Schmitz et al., JNM **415** (2011) S886]