# Power (and particle) fluxes during ELM-controlled scenarios and extrapolation towards ITER

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**ITER School, KAIST, South Korea, 2019**

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College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

# Outline of lecture

- **Understand reason and relevance of non-axisymmetric tokamak divertor loads**

*You have been wondering about this picture?*

10th ITER International School 2019

The physics and technology of power flux handling in tokamaks

21st (MON)-25th (FRI) January 2019

Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
www.iterschool2019.kr

This lecture will address this!

- Why are these patterns this important?
- Fundamentals of these patterns – where do they come from?
- Implications on plasma edge and PMI – are they relevant?
- Consequences for ITER – how do we know?

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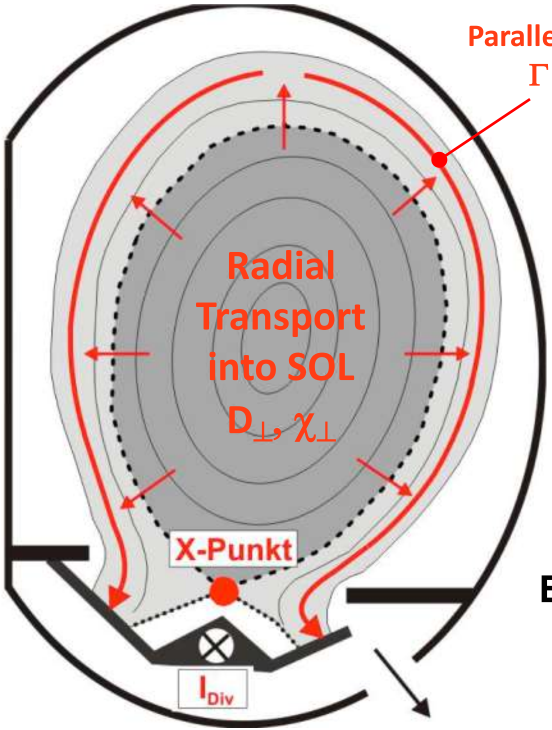
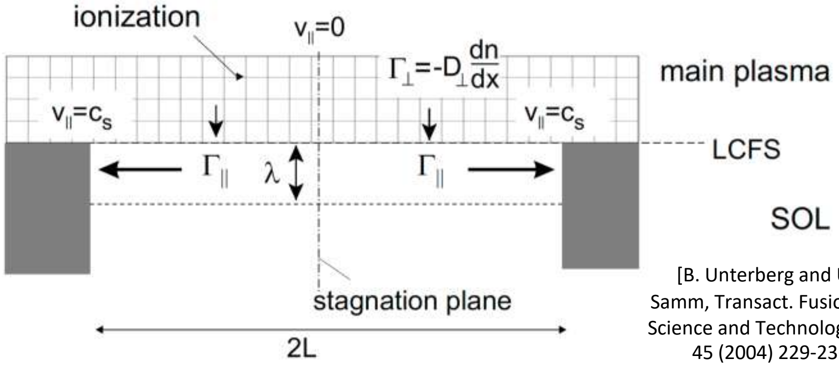
# Ideally we start with a toroidally axisymmetric divertor heat and particle flux structure

**Simplified Example for Calculation of Deposition Width: the Simple SOL model** (talk D. Reiter)



Parallel Heat $q_{||}$ and Particle $\Gamma_{||}$ Fluxes to Target



[B. Unterberg and U. Samm, Transact. Fusion Science and Technology 45 (2004) 229-236]

**Mass conservation in open field line region:**

$$\frac{\partial}{\partial x} D_\perp \frac{\partial n}{\partial x} = \frac{\partial}{\partial z}(n v_\parallel)$$

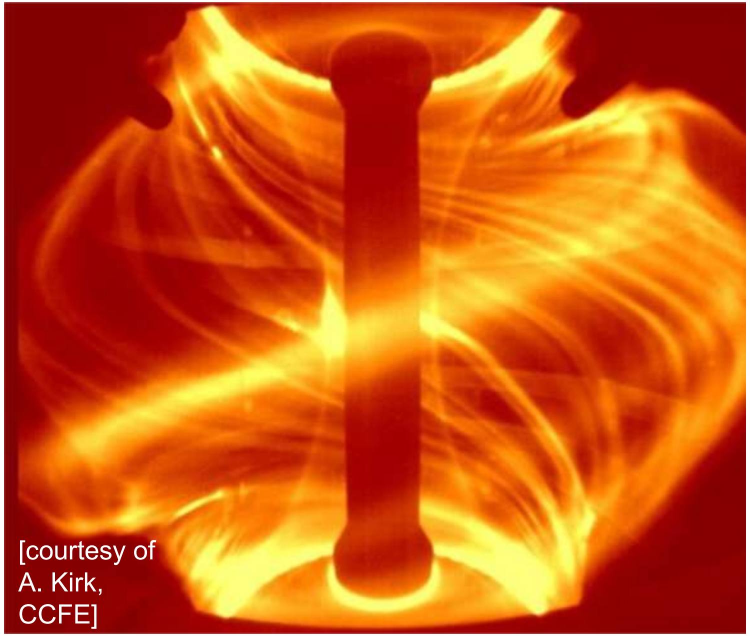
Radial constant diffusion, parallel flow with ion sound speed

**Exponential decay in SOL** → $n(x) = n(0)\exp(-x/\sqrt{D_\perp \tau_\parallel})$

**Thin deposition width (toroidal symmetry)** → $\lambda = \sqrt{D_\perp \tau_\parallel}$ → $\lambda = \sqrt{\frac{D_\perp L}{0.5\, c_s}}$

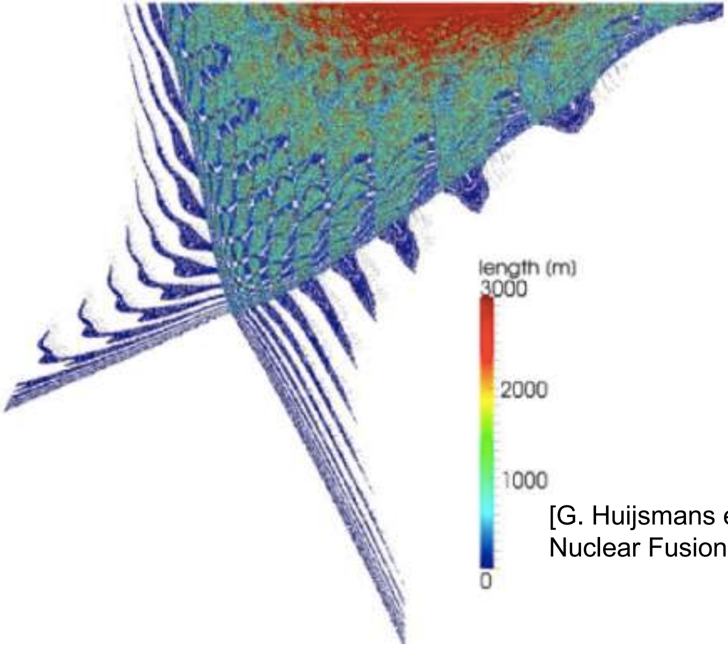
# Edge localized Modes (ELMs) cause self-organized, filamentary and fully 3D heat and particle fluxes

**Self-organized ELM filament structure**



[courtesy of A. Kirk, CCFE]

**Self-organized, chaotic magnetic field topology of ELM**



[G. Huijsmans et al., Nuclear Fusion 53 (2013) 12]

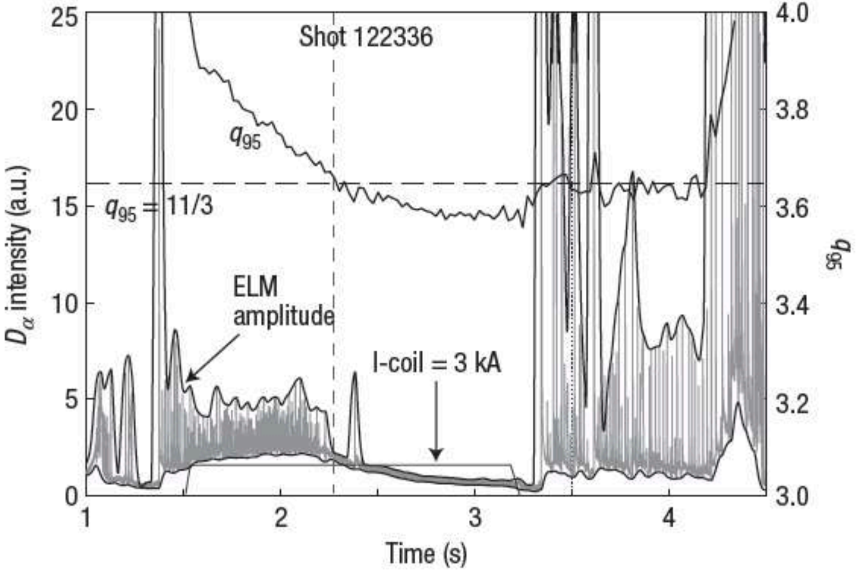
**High, impulsive divertor target loads due to ELMs establish need for ELM control**

See previous talks by R. Maingi, M. Fenstermacher, R. Pitts and others

# Application of Resonant Magnetic Perturbation fields is the most promising route for stable ELM control

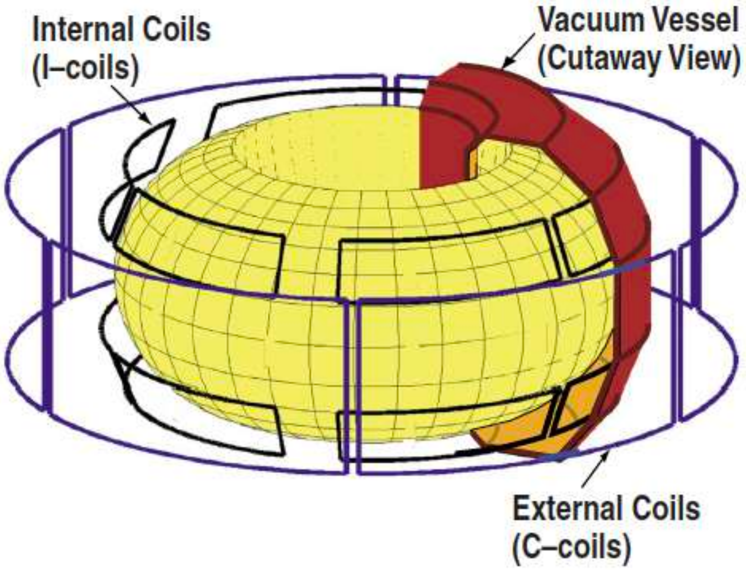
- Small amplitude ($10^{-4}$ $B_T$) RMPs are applied from in-vessel magnetic control coils

**The famous discovery**



[T.E. Evans et al., Nature 2 (2006) 419-423]

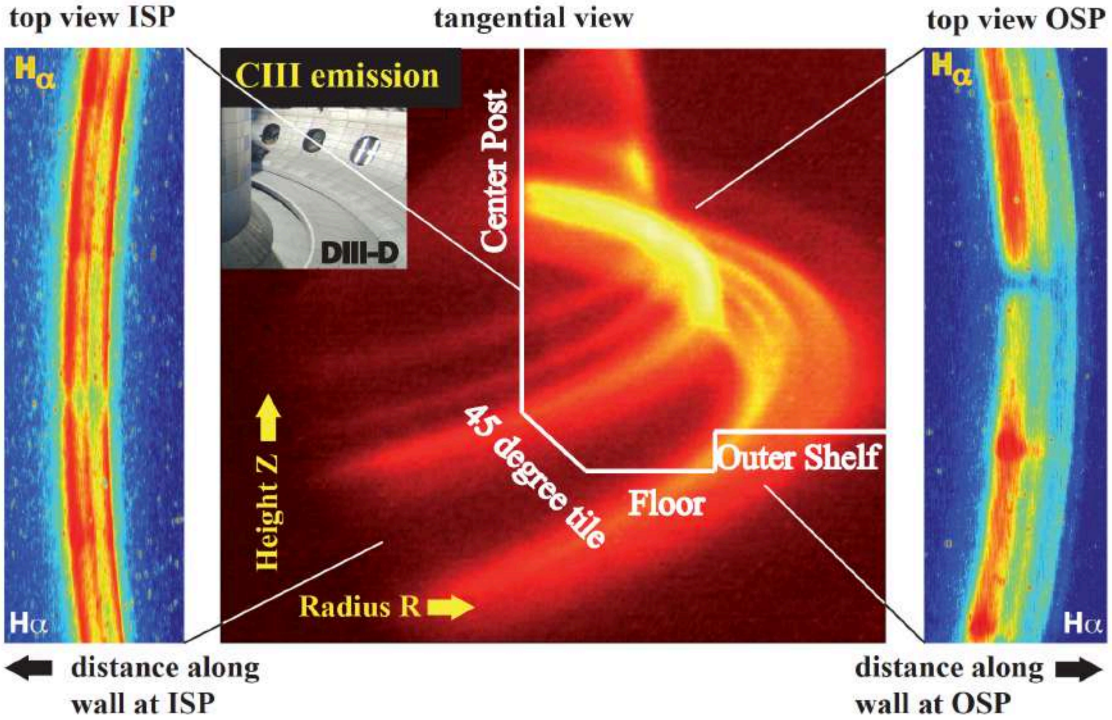
**Perturbation coil set at DIII-D**



[M.E. Fenstermacher et al., PoP **15** (2008) 056122]

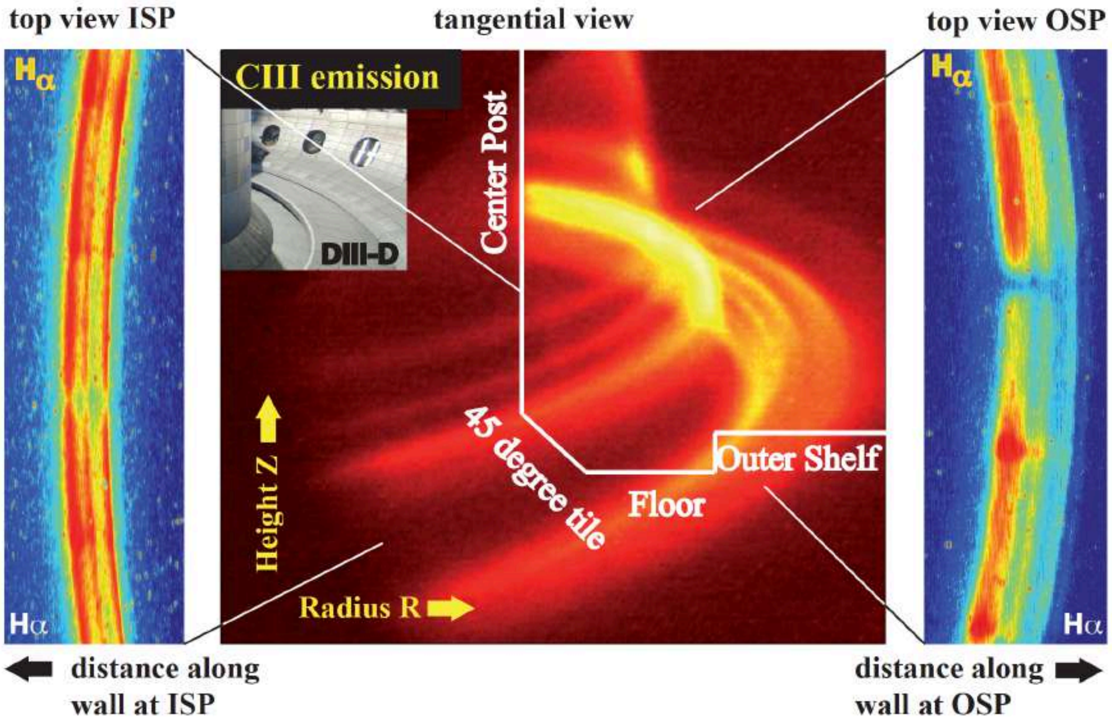
**Physics of RMP ELM control: see lectures by Y. In, M.E. Fenstermacher**

# RMPs make the plasma edge a fully 3D system



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

# RMPs make the plasma edge a fully 3D system



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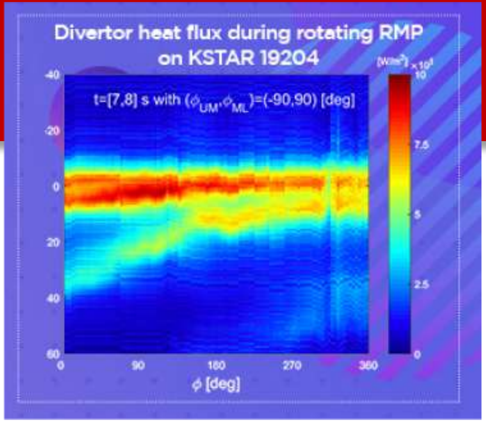

**RMP ELM suppressed H-mode plasmas show separatrix perturbation and strike line splitting**

**Plasma edge and material interface becomes a 3D system**

**We need to understand the system to judge impact on the divertor**

***Why and how does this happen?***

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Divertor heat flux during rotating RMP on KSTAR 19204

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# Small, resonant perturbations can have a huge impact

- Chaotic center of mass trajectories in a simple oscillator system

# Small, resonant perturbations can have a huge impact – you know it!

- Chaotic center of mass trajectories in a simple oscillator system

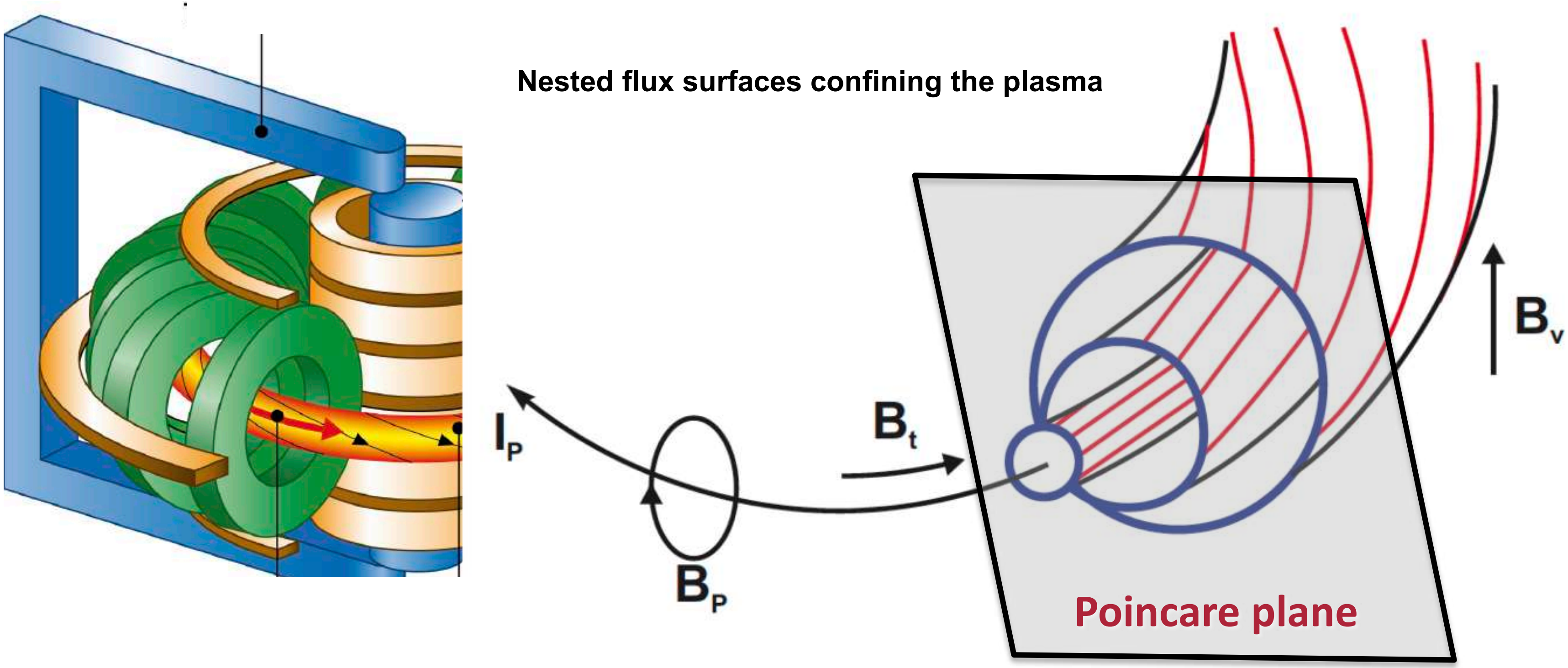
Chaotic trajectories

Resonant coupling

And how – please – does this matter in RMP ELM control?

# Along the trajectory of the field line we have a “swing-like” situation – resonant kicks

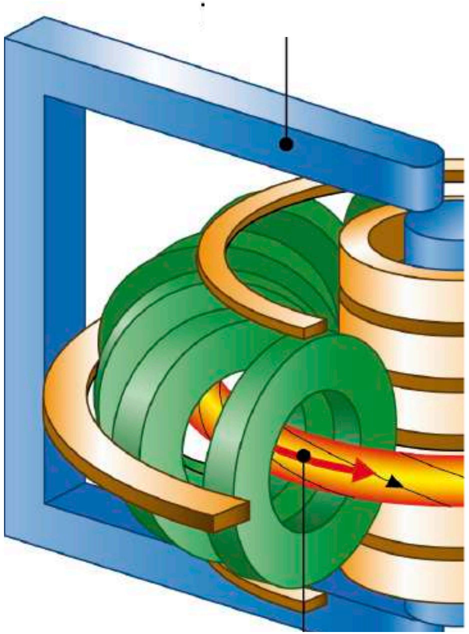
- **Consider a simple tokamak setup as introduction of the fundamentals**



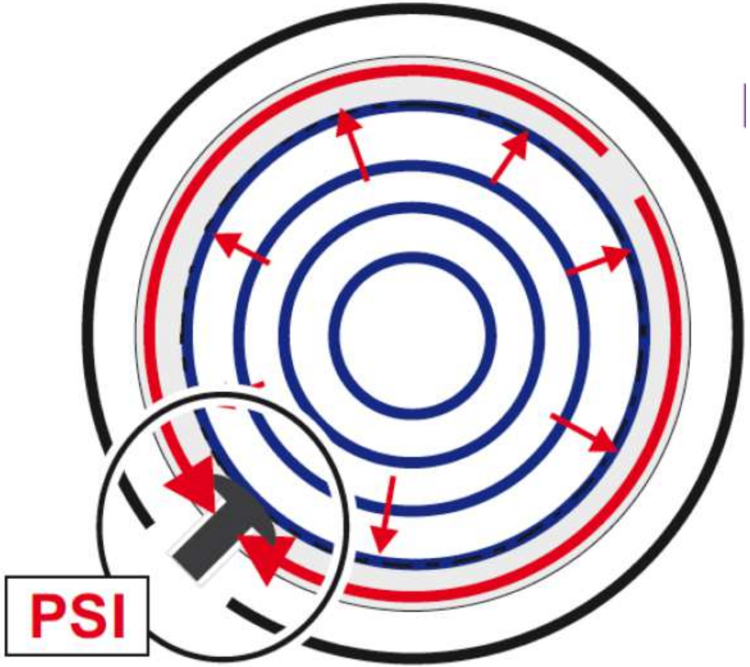
**Nested flux surfaces confining the plasma**

# Along the trajectory of the field line we have a "swing-like" situation – resonant kicks

- **Consider a simple tokamak setup as introduction of the fundamentals**



**Cut torus at one toroidal position:**
**the Poincare plane**



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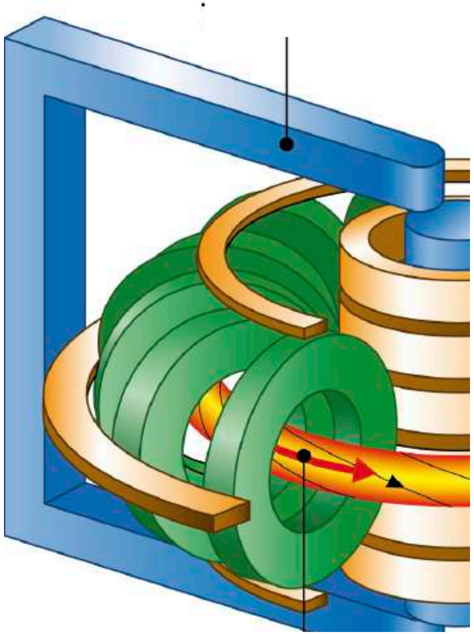
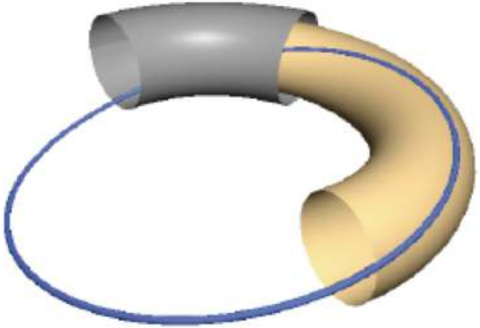
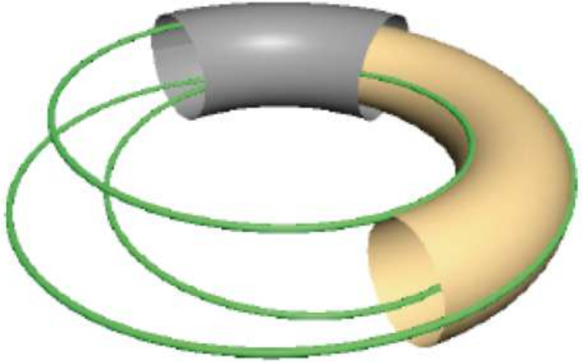


Resonant coupling to self-closing field lines



1 poloidal / 1 toroidal

1 poloidal / 3 toroidal



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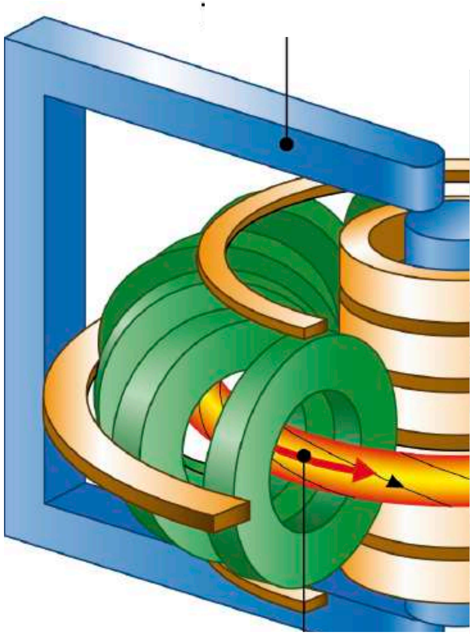
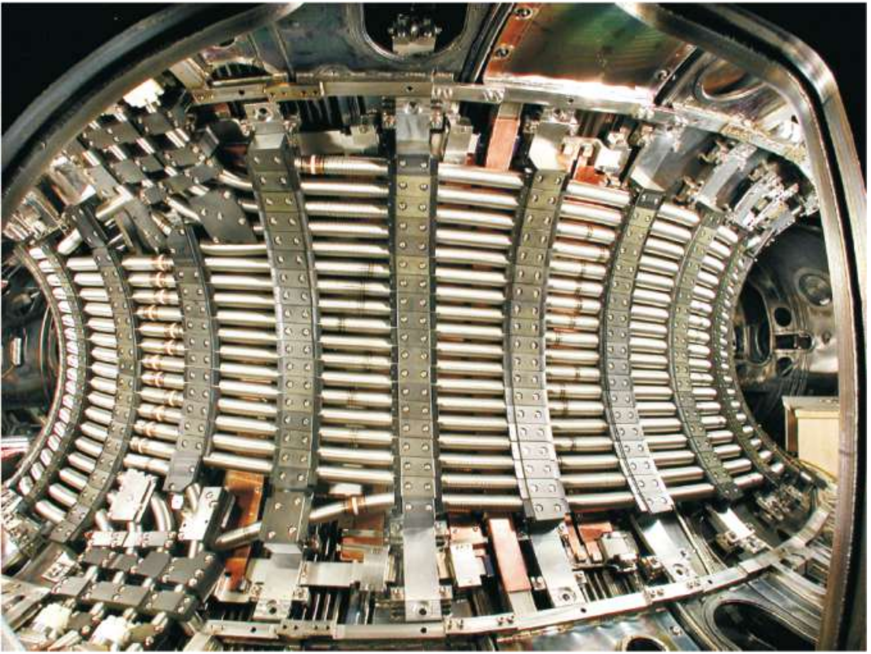


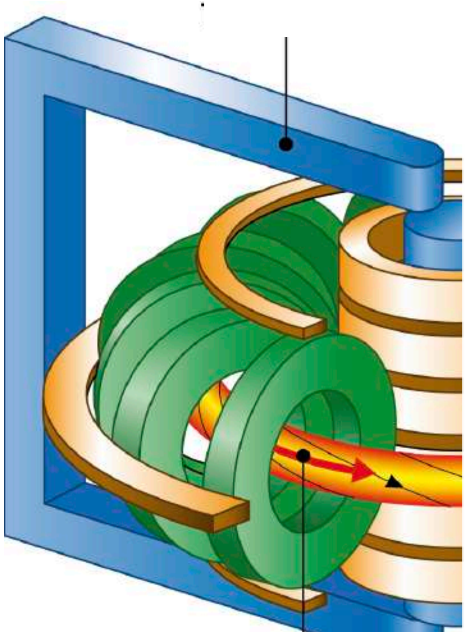


**Well aligned external field yields local resonant perturbation**

***Remember***

# Along the trajectory of the field line we have a “swing-like” situation – resonant kicks

- **Consider a simple tokamak setup as introduction of the fundamentals**



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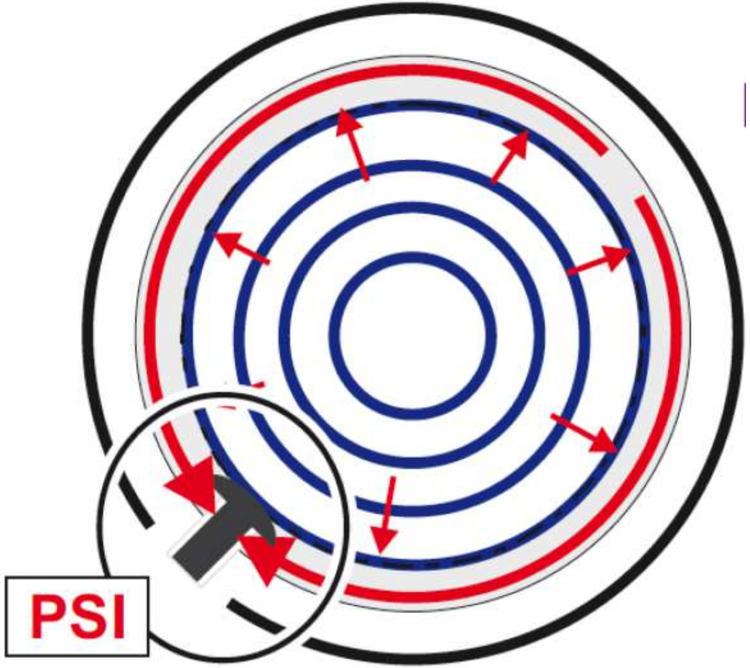

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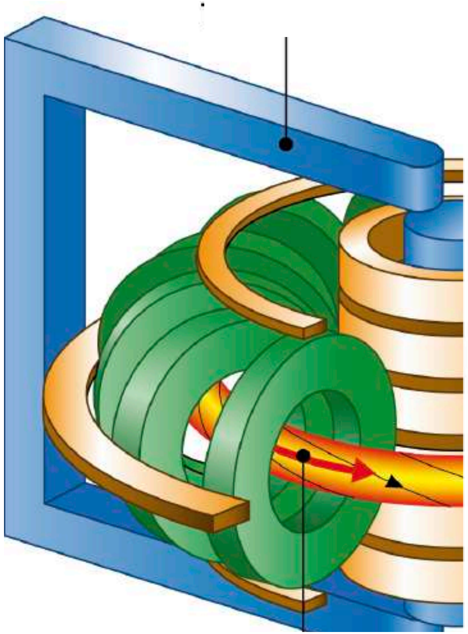
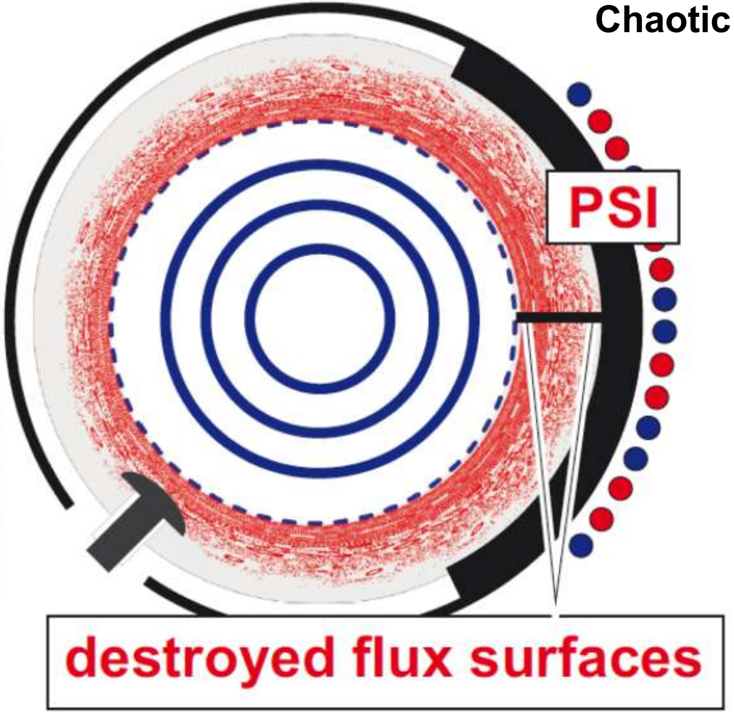
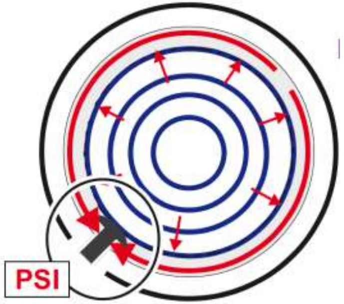
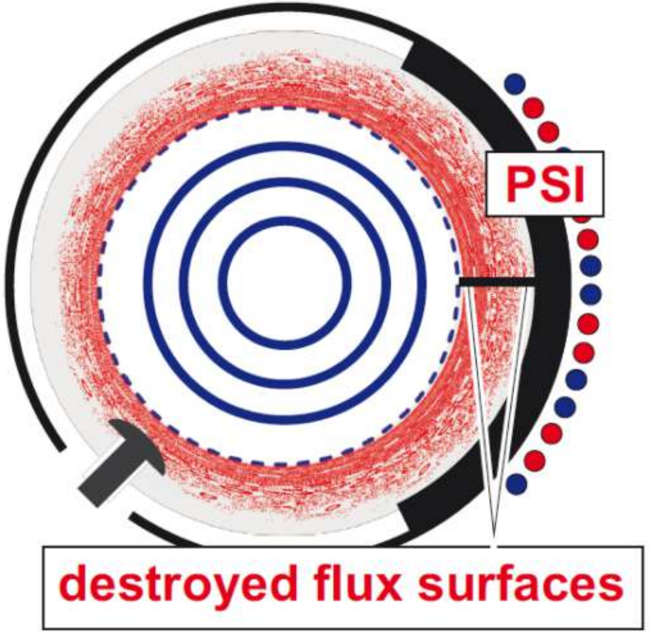




**Chaotic magnetic edge is formed**



# Description as perturbed conservative system shows resonant perturbation character



**Field line trajectory** $\frac{d\vec{x}}{ds} = \frac{\vec{B}}{|\vec{B}|}$

$$\vec{x}(s) = (r(s), \theta(s), \varphi(s))$$

**Tangency vector** at point **s** → $\vec{x}(s)$

**radius** → $r(s)$

**poloidal** and **toroidal** angle → $\theta(s)$, $\varphi(s)$

**Write guiding magnetic field in canonical coordinates**

$$\vec{B} = \nabla\psi \times \nabla\vartheta + \nabla\varphi \times \nabla H(\psi, \vartheta, \varphi)$$

**with** $\psi$ **as toroidal magnetic flux through Poincare plane**

$$\boxed{\frac{d\psi}{d\varphi} = -\frac{\partial H}{\partial \vartheta}, \qquad \frac{d\vartheta}{d\varphi} = \frac{\partial H}{\partial \psi}}$$

**Hamilton equation with Hamiltonian H representing the poloidal magnetic flux**

**Apply perturbation theory** $H = H_0(\psi) + \epsilon H_1(\psi, \vartheta, \varphi)$

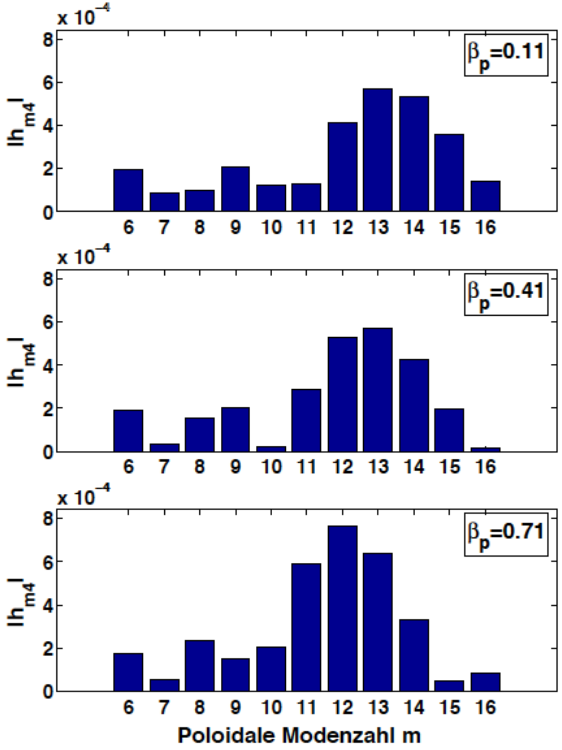
**With harmonic (resonant) field perturbation**

$$H_1(\psi, \vartheta, \varphi) = \sum_{m,n} H_{mn}(\psi) cos(m\vartheta - n\varphi)$$

[S.S. Abdullaev et al., PoP **8** (2001) 2739]

# Two typical representations of $H_1(\psi,\vartheta,\varphi) = \sum_{m,n} H_{mn}(\psi)\cos(m\vartheta - n\varphi)$

**TEXTOR n=4 spectrum**



[K.H. Finken et al., Nuclear Fusion **47** (2007) 522]

**DIII-D radial Fourier coefficients n=3**

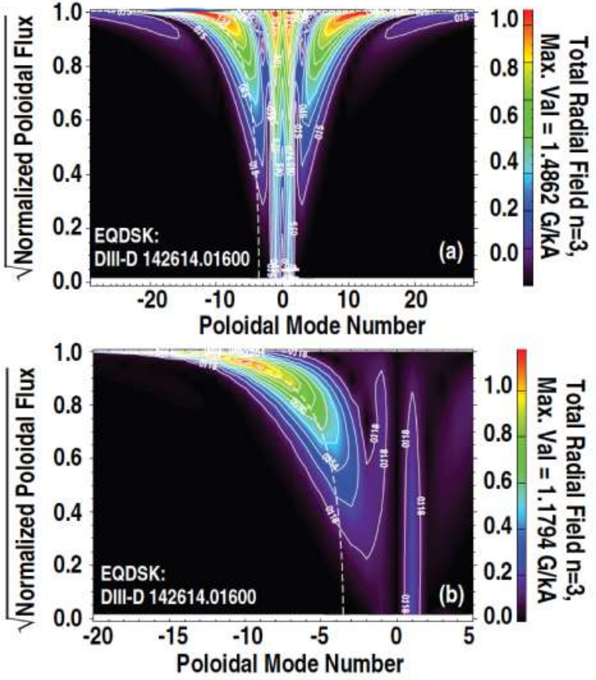


**Figure 2.** Vacuum spectral perturbation amplitudes of the $n = 3$ (*a*) components and (*b*) MARS-F plasma response modelling.

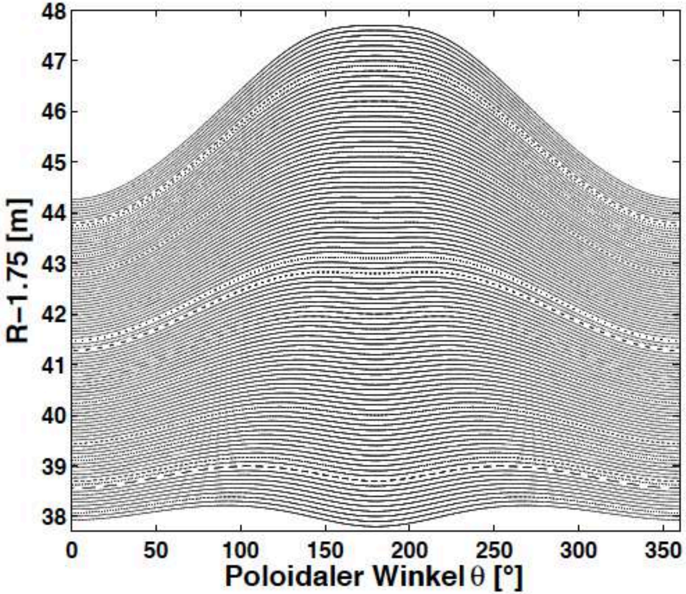
[M. Lanctot et al., Physics of Plasmas **18** (2012) 056121]

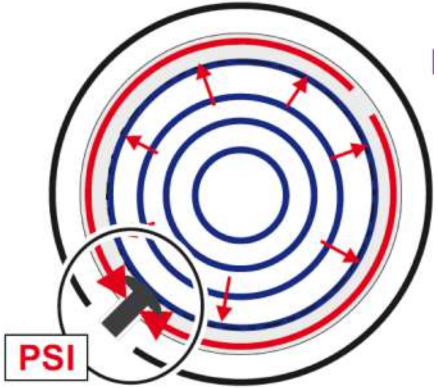
**Plasma response has to be taken into account!**

*Remember lecture by Y. In*

# Magnetic flux surfaces are broken and a chaotic magnetic field structure is formed

Good magnetic flux surfaces





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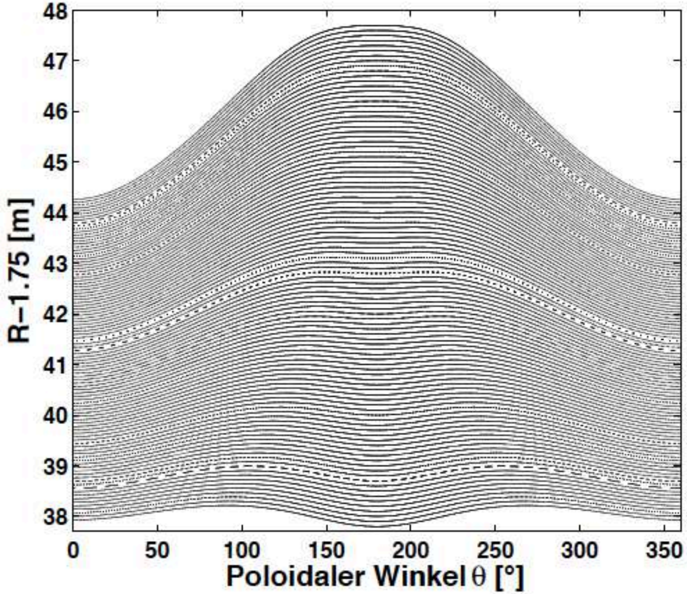
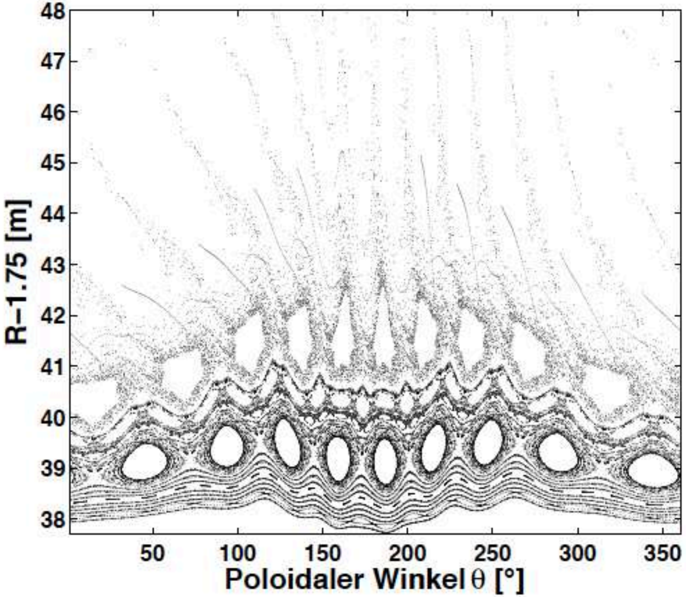
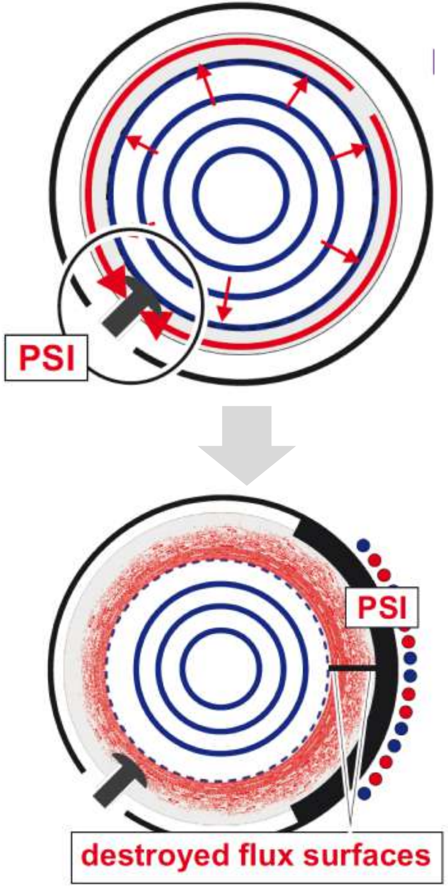


**Chaotic edge plasma**





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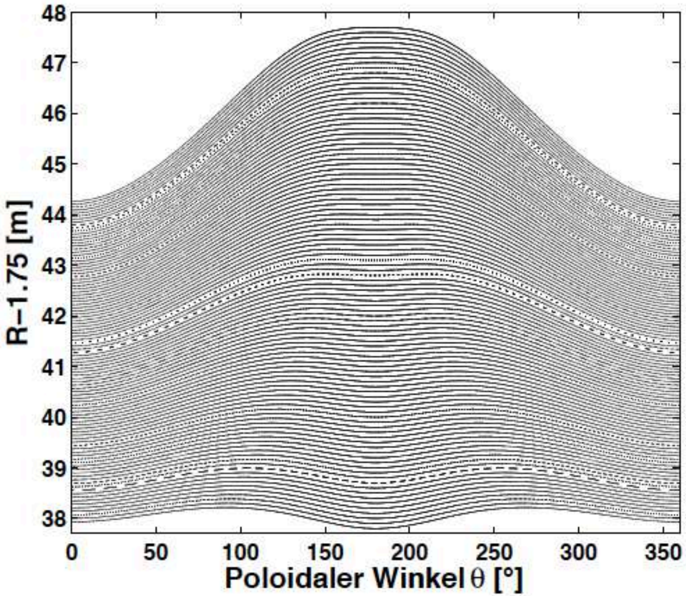

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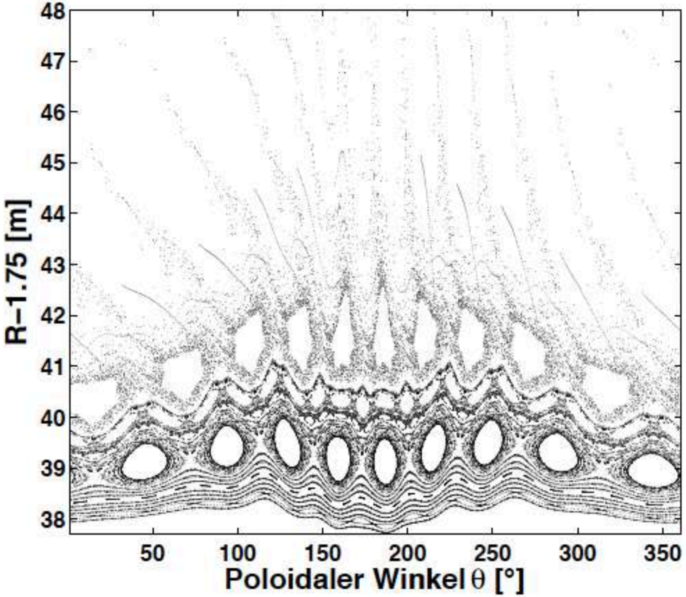

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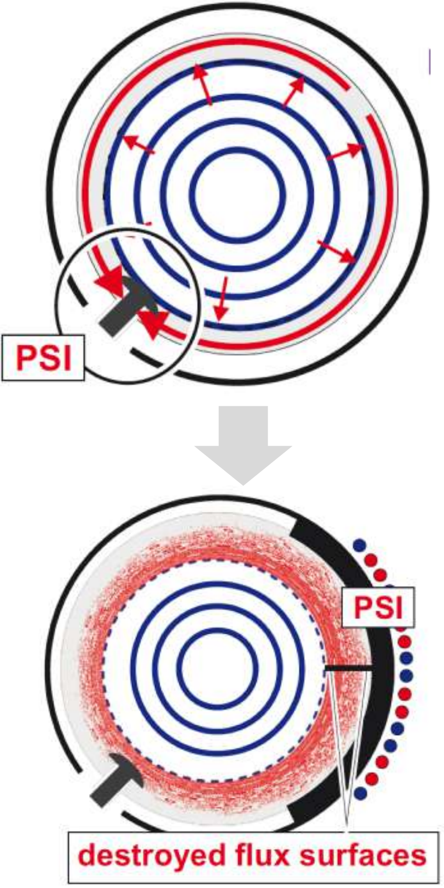
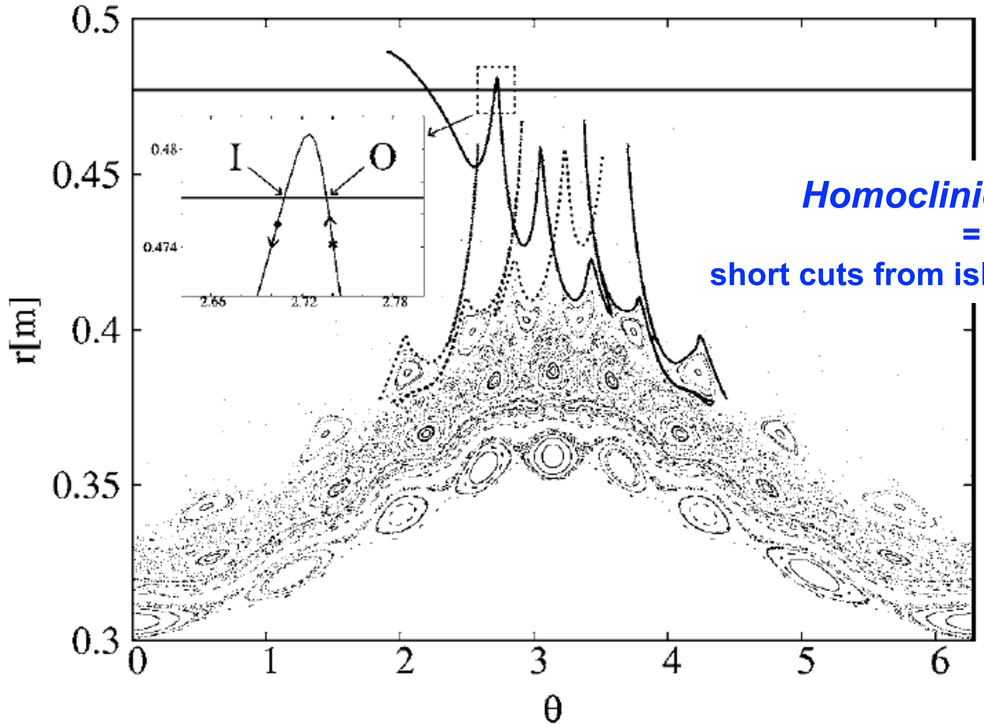


**But what about the heat and particle loads?**

[O. Schmitz et al., Nuclear Fusion **48** (2008) 024009]

# The invariant manifolds of the outermost magnetic island chain define the plasma surface interaction

**Field line tracing from outermost island chain**



***Homoclinic tangels***

**=**

**short cuts from island onto tartget**

[A. Wingen et al. PoP **993** (2007) 042502]

# The invariant manifolds of the outermost magnetic island chain define the plasma surface interaction

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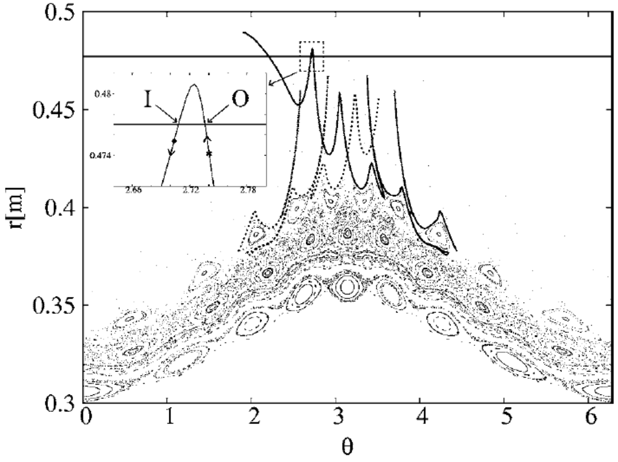
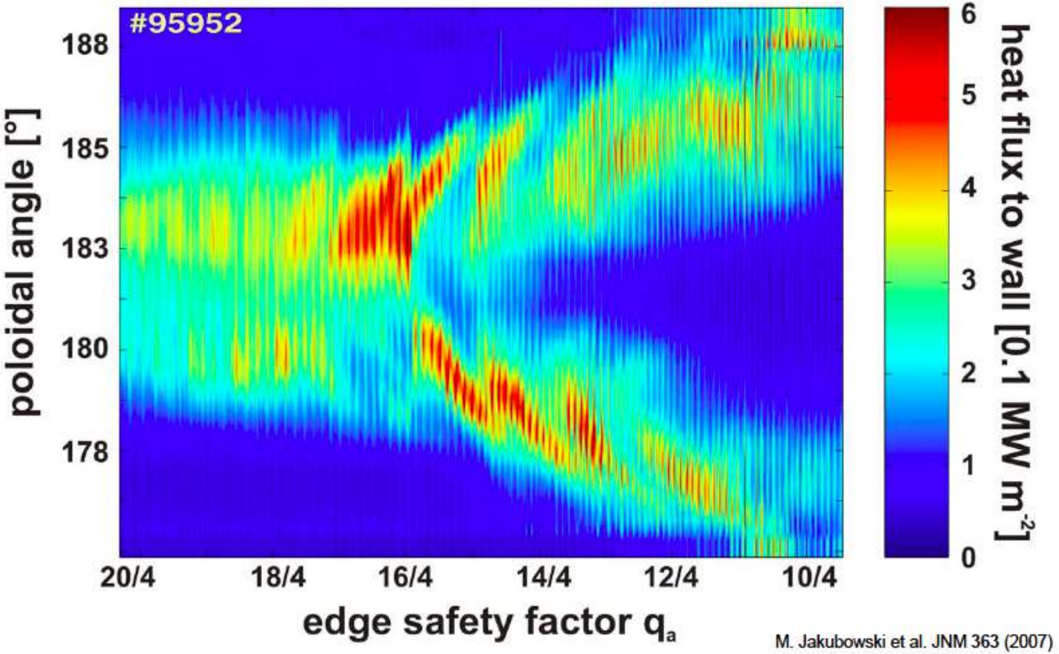


[A. Wingen et al. PoP **993** (2007) 042502]



M. Jakubowski et al. JNM 363 (2007)

**This measurement directly proves the existence of these structures!**

# The invariant manifolds of the outermost magnetic island chain define the plasma surface interaction

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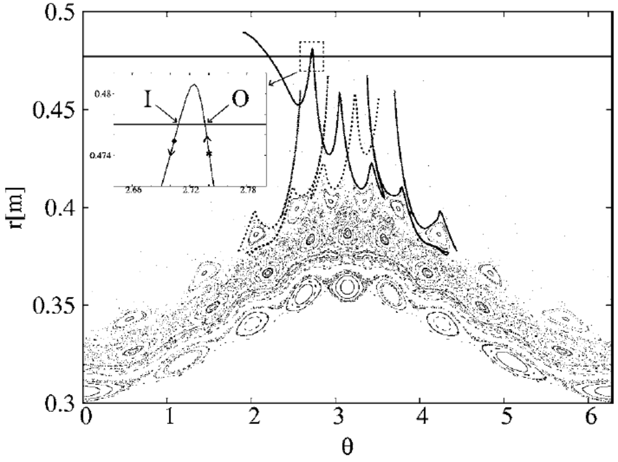

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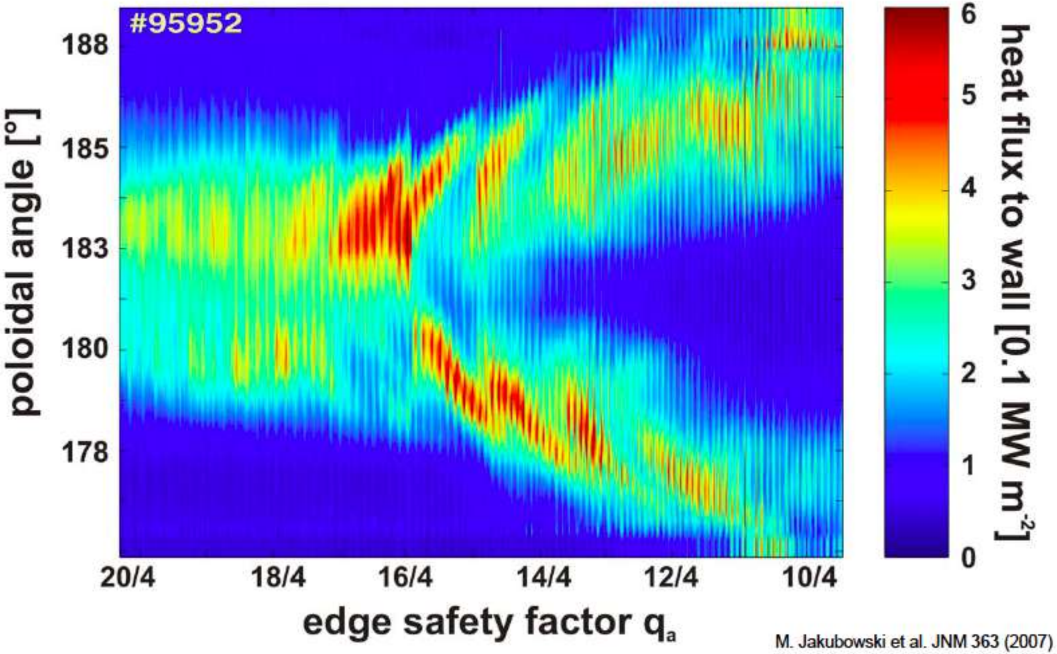


M. Jakubowski et al. JNM 363 (2007)

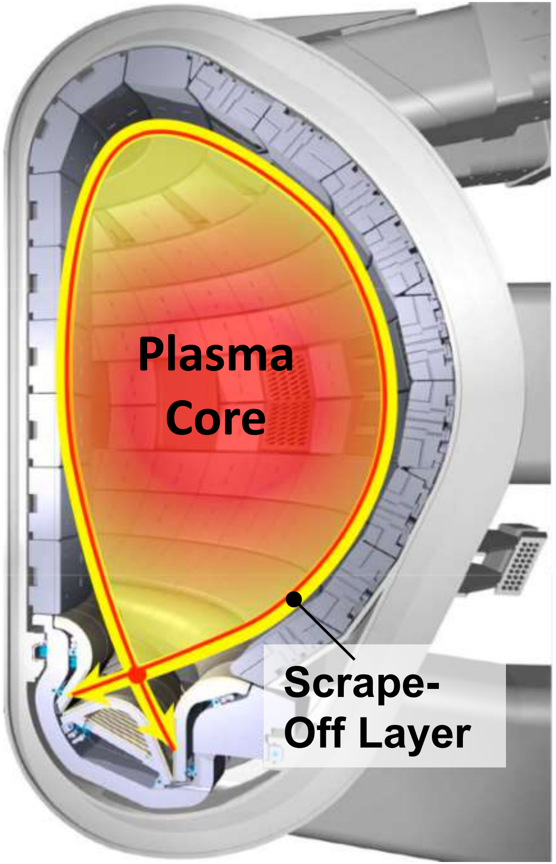
**This measurement directly proves the existence of these structures!**

**How about a separatrix?**

# The separatrix of a divertor tokamak comes with a robust hyperbolic fixed point – the X-point

**The separatrix is the boundary between the confined plasma and the plasma boundary**

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



# The separatrix consists out of stable and unstable manifolds

**The separatrix is the boundary between the confined plasma and the plasma boundary**

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

**Stable manifolds approaches X-point**

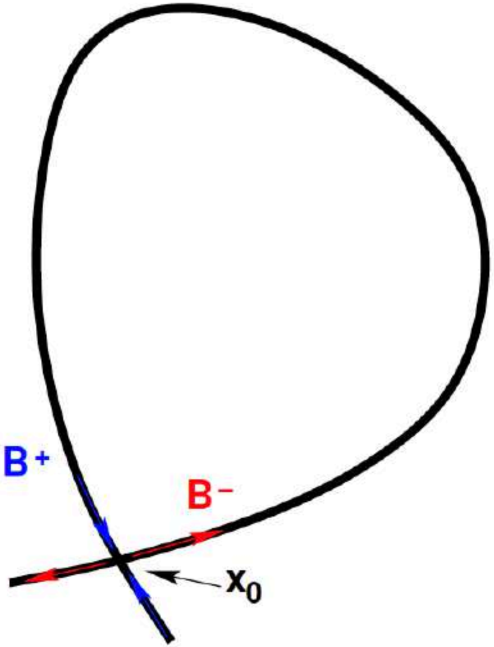
$$B^{+} = \{\mathbf{x} \in \mathbb{R}^3 | \lim_{\varphi \to \infty} F_{\mathbf{x}}(\varphi) \to \mathbf{X}\}$$

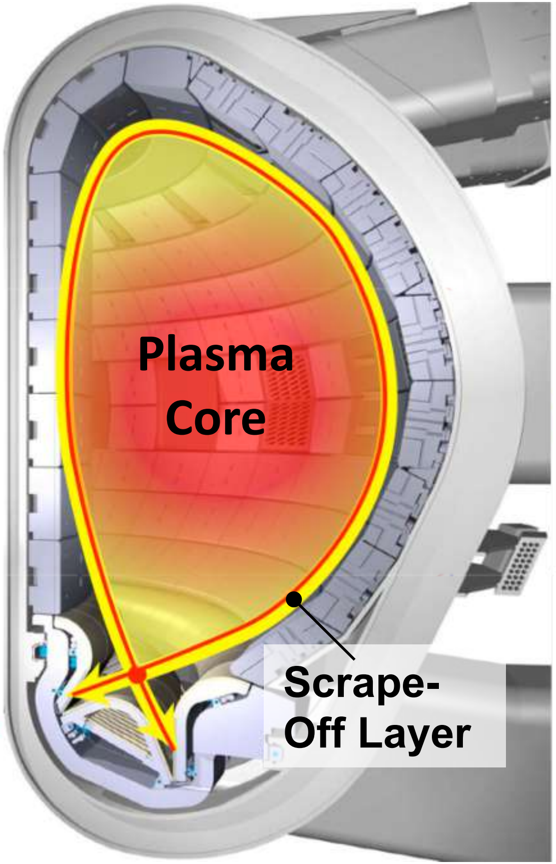
**Unstable manifolds diverges from X-point**

$$B^{-} = \{\mathbf{x} \in \mathbb{R}^3 | \lim_{\varphi \to -\infty} F_{\mathbf{x}}(\varphi) \to \mathbf{X}\}$$

**Here,** $F_x(\varphi)$ **is the field line trajectory along a magnetic field line**

**Consider again** $\varphi$ **as time variable.**



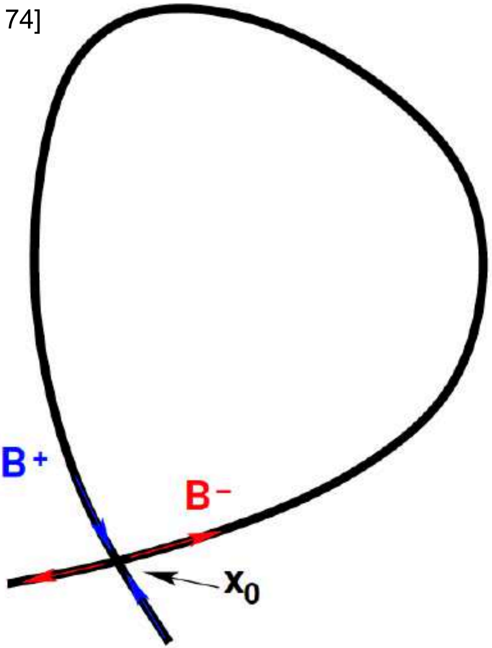


# The manifolds are decomposed through radial magnetic field perturbation and form helicon lobes

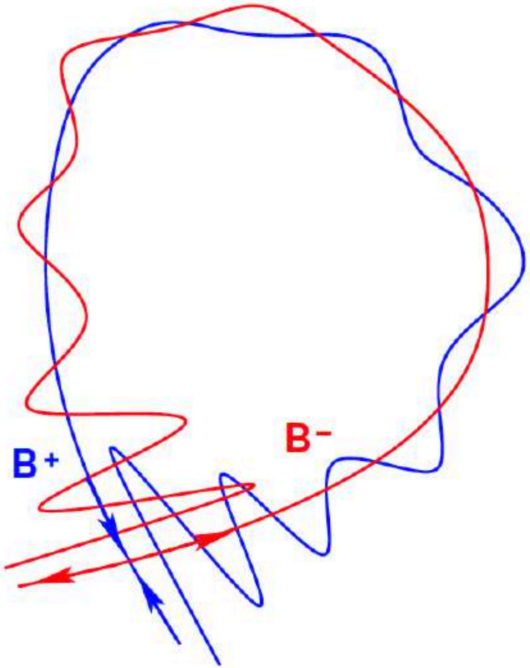
## The **separatrix** is the boundary between the confined plasma and the plasma boundary

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

[T.E. Evans et al., J. Phys.: Conf. Ser. **7** (2005) 174]



The **manifolds** are prone to strong oscillations under small perturbation fields



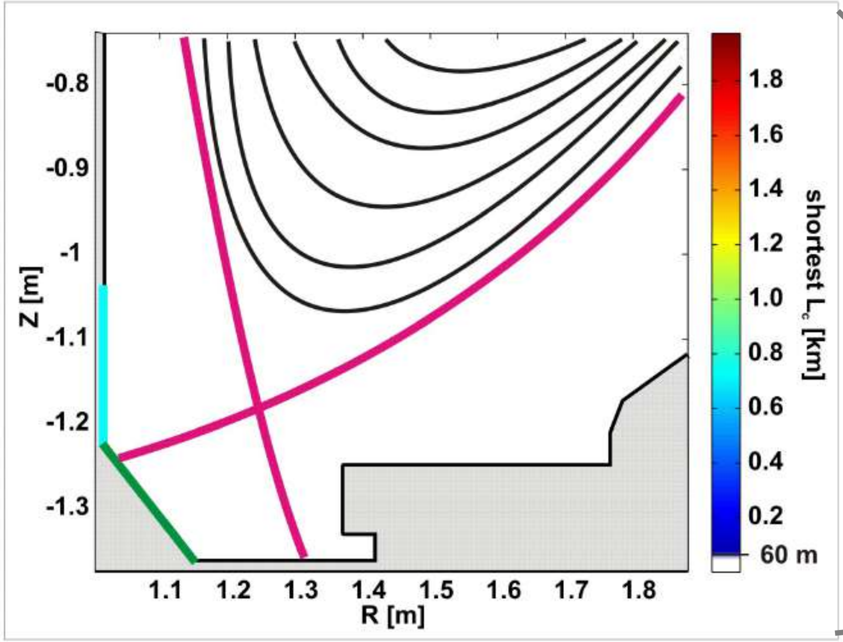
**This generic perturbation mechanism defines the structure of the heat and particle fluxes in the divertor**

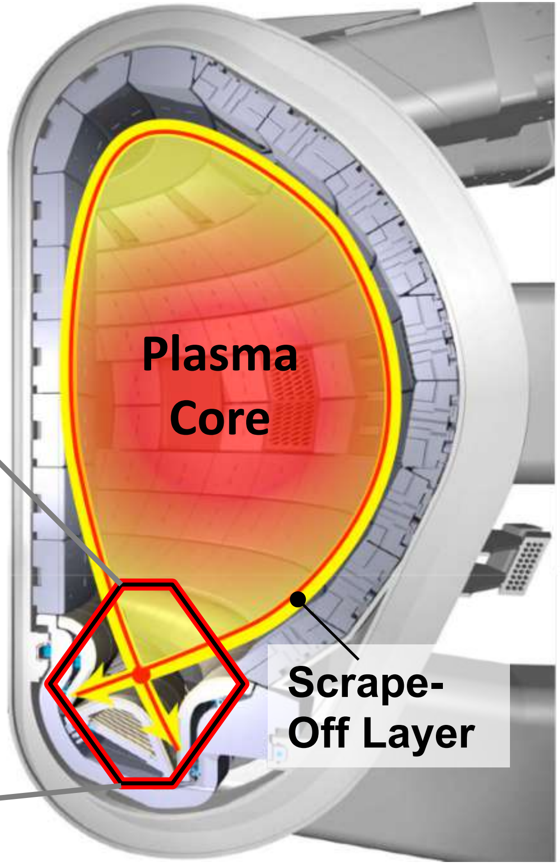
# The manifolds are decomposed through radial magnetic field perturbation and form helicon lobes

**The separatrix is the boundary between the confined plasma and the plasma boundary**

[O. Schmitz et al., PPCF **50** (2008) 124029]

**No RMP**





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

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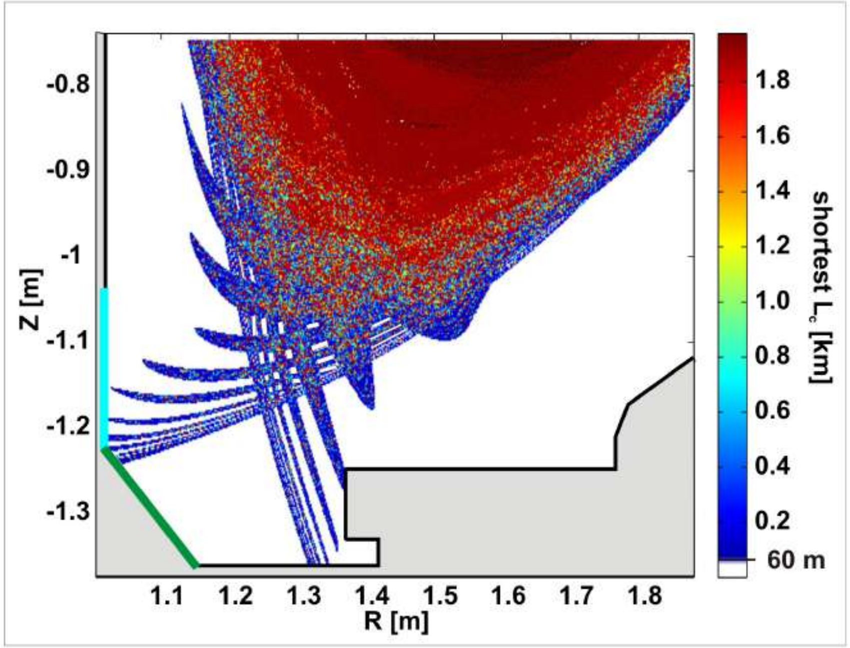
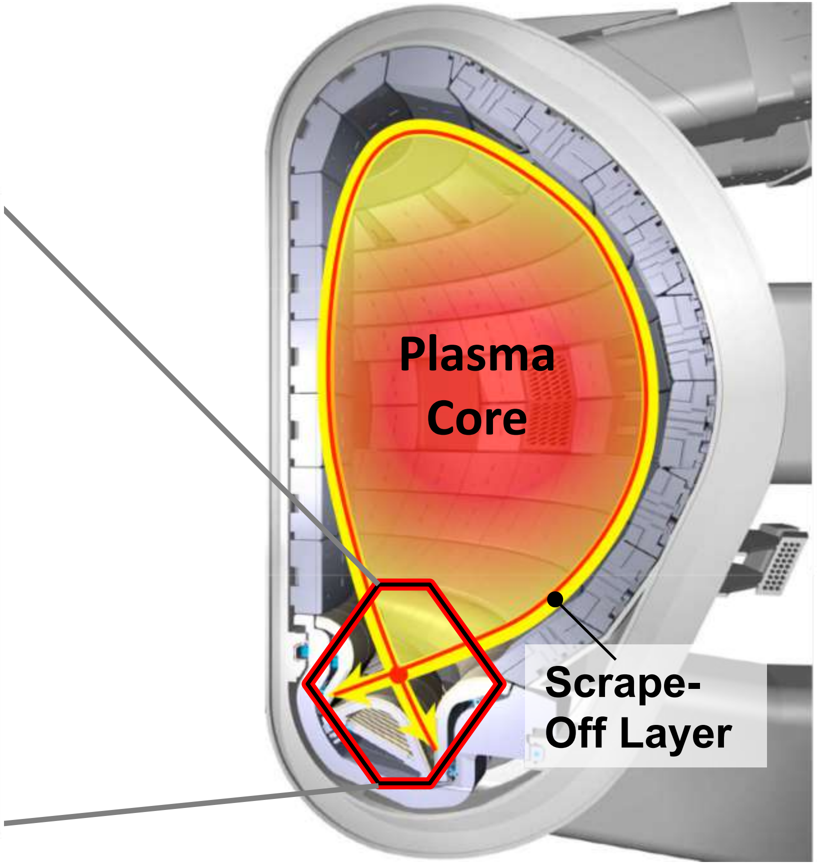
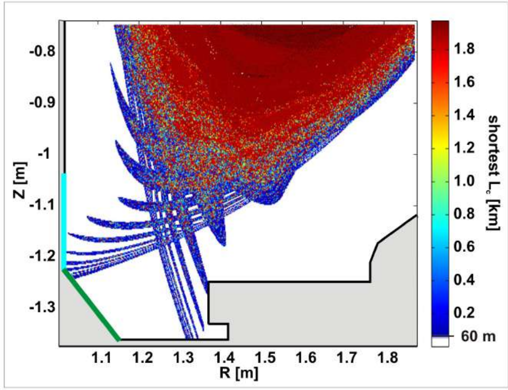
[O. Schmitz et al., PPCF **50** (2008) 124029]

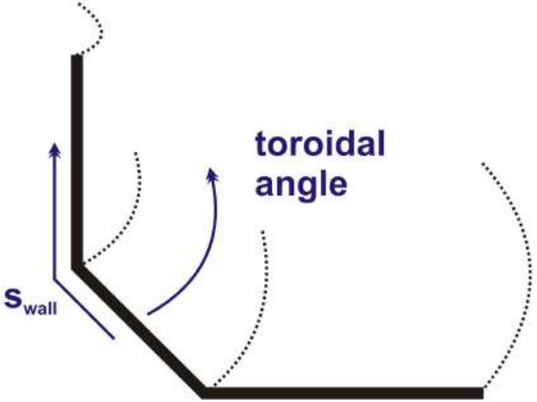
**With RMP**

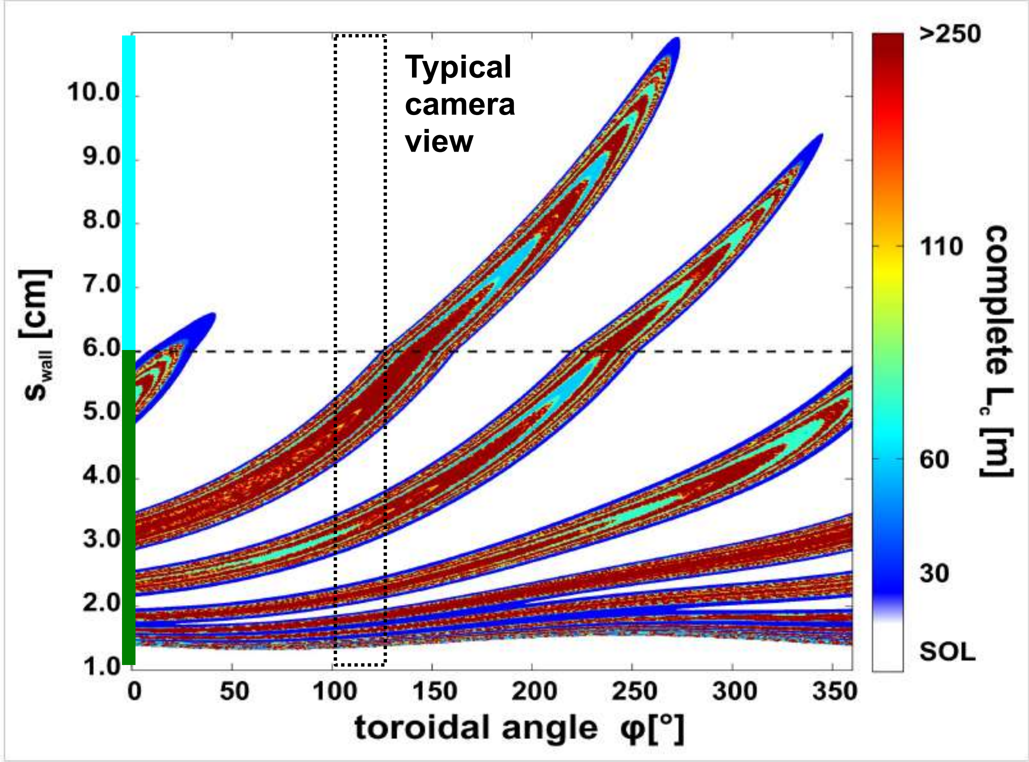




# The helical separatrix lobes form a helical magnetic footprint on the divertor target – a strong deviation from axisymmetry

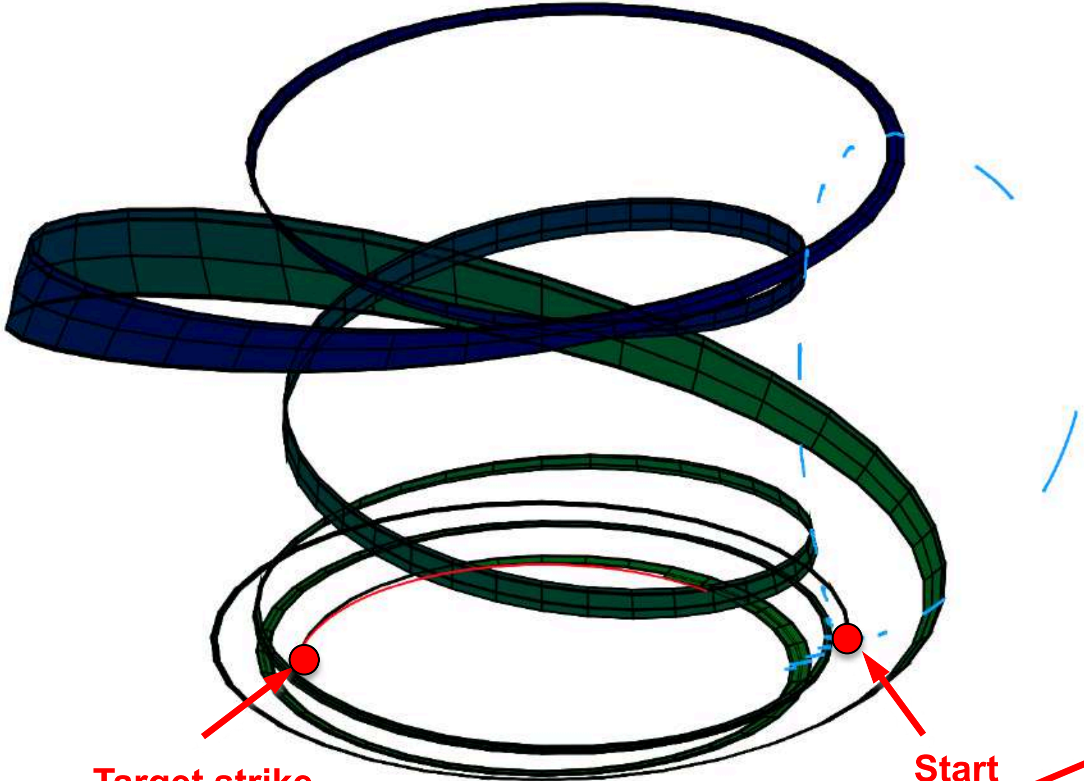






[O. Schmitz et al., PPCF **50** (2008) 124029]

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

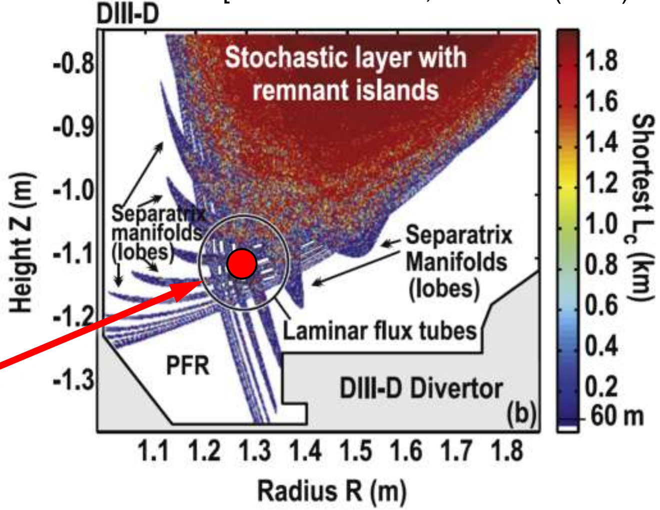


**Target strike point**

**Start Point**

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

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



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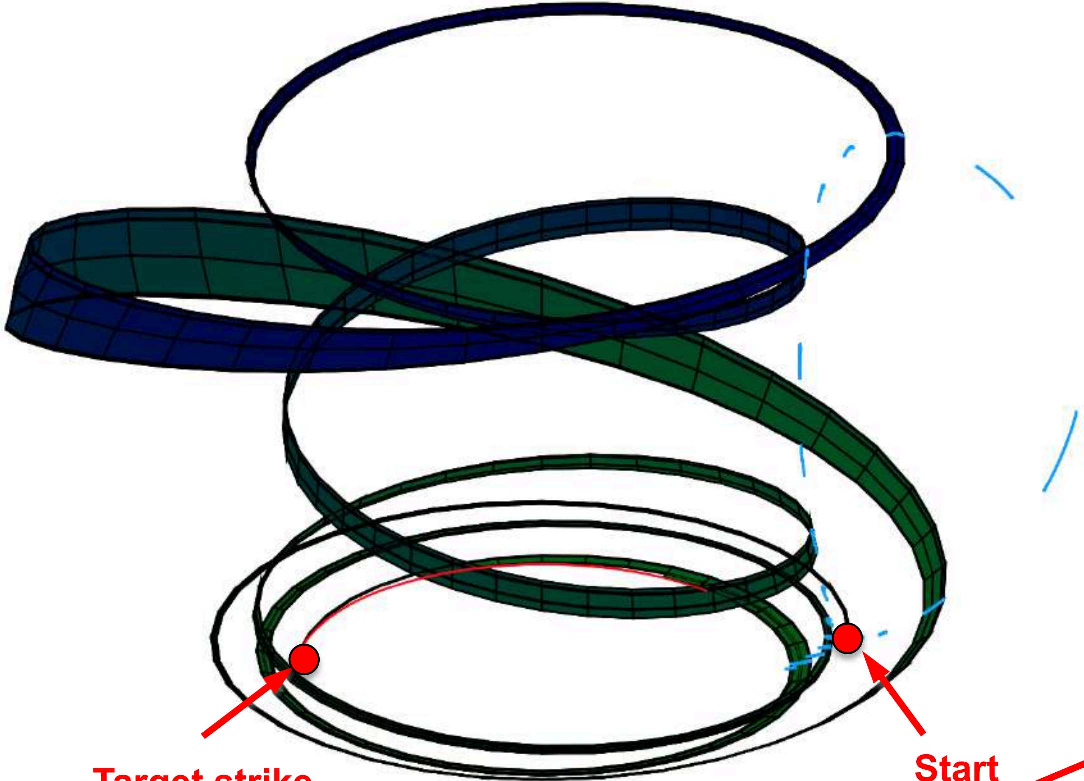

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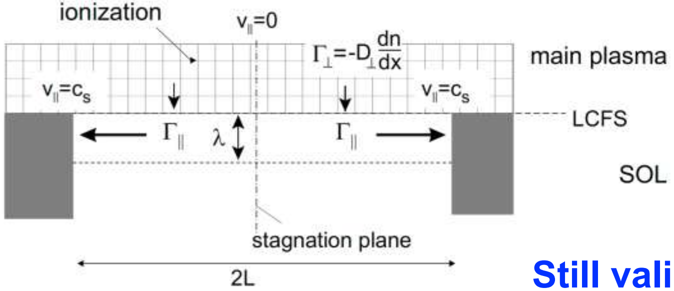
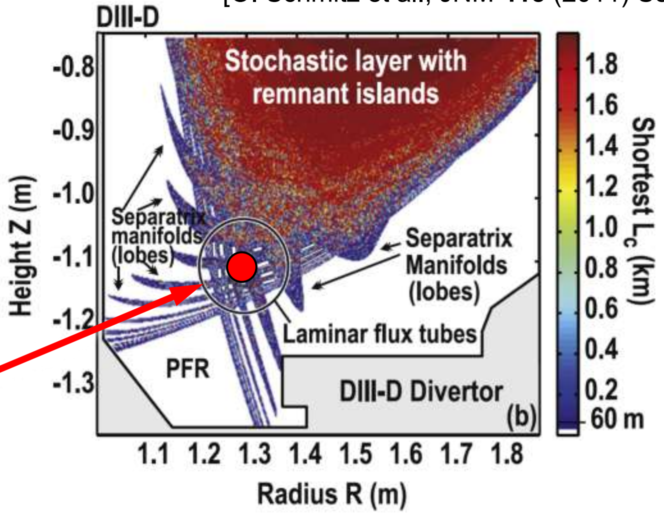


**Still valid?**

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



# Outline of lecture

- **Understand reason and relevance of non-axisymmetric tokamak divertor loads**

*You have been wondering about this picture?*

10th ITER International School 2019

**The physics and technology of power flux handling in tokamaks**

21st (MON)-25th (FRI) January 2019

Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
www.iterschool2019.kr

Divertor heat flux during rotating RMP on KSTAR 19204

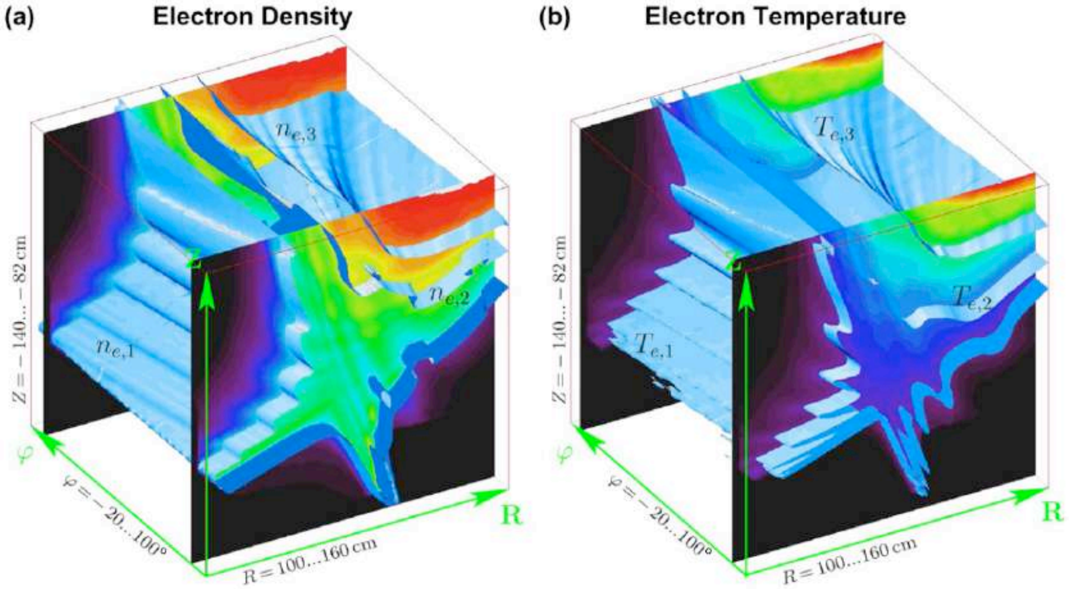
This lecture will address this!

- Why are these patterns this important?
- Fundamentals of these patterns – where do they come from?
- **Implications on plasma edge and PMI – are they relevant?**
- Consequences for ITER – how do we know?

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

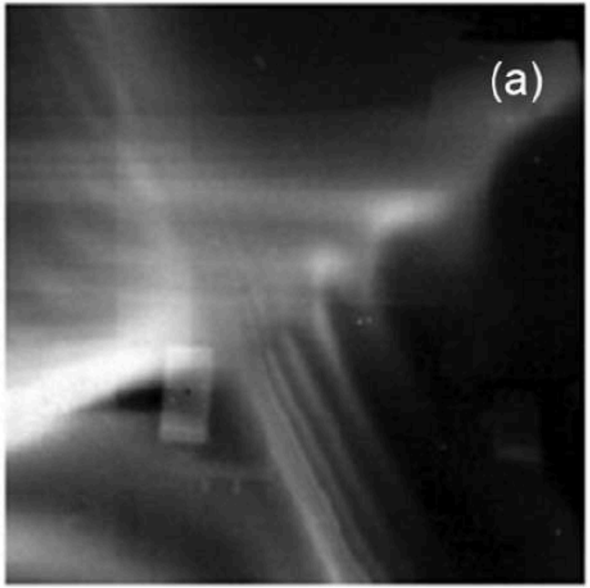
## There is strong evidence for the existence of the lobes and their impact on the divertor

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



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

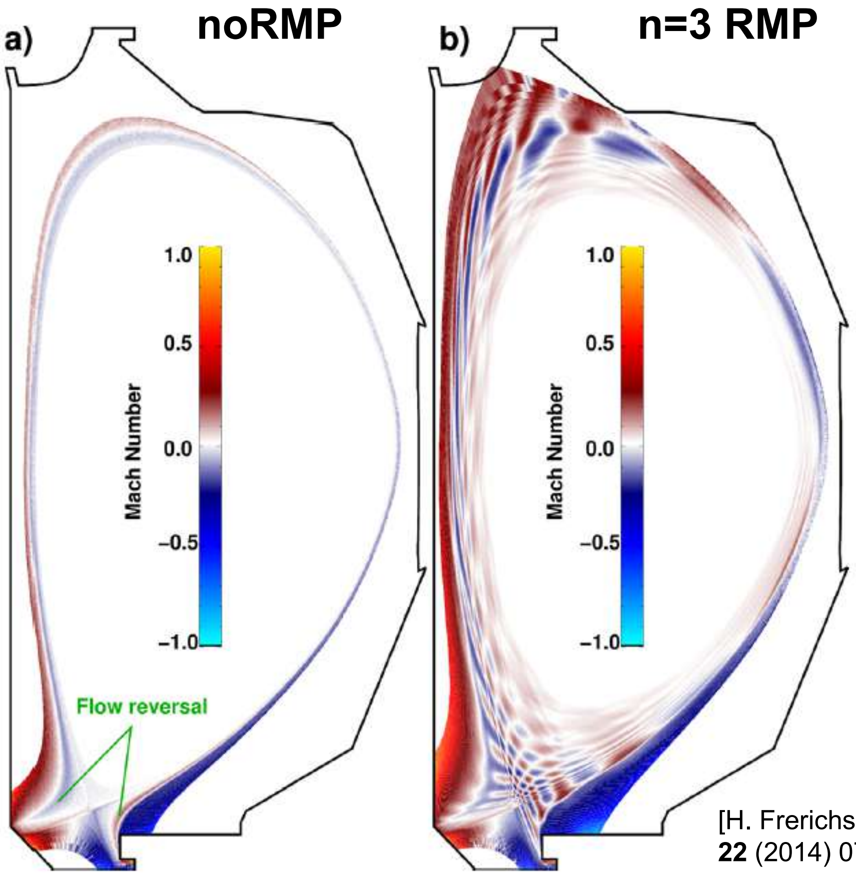
### Direct visualization of lobes at MAST



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

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

# A complex mesh of SOL flux tubes is generated by RMP and represents the interface to the divertor



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

- **These structures intertwine forward and backward streaming SOL flows**

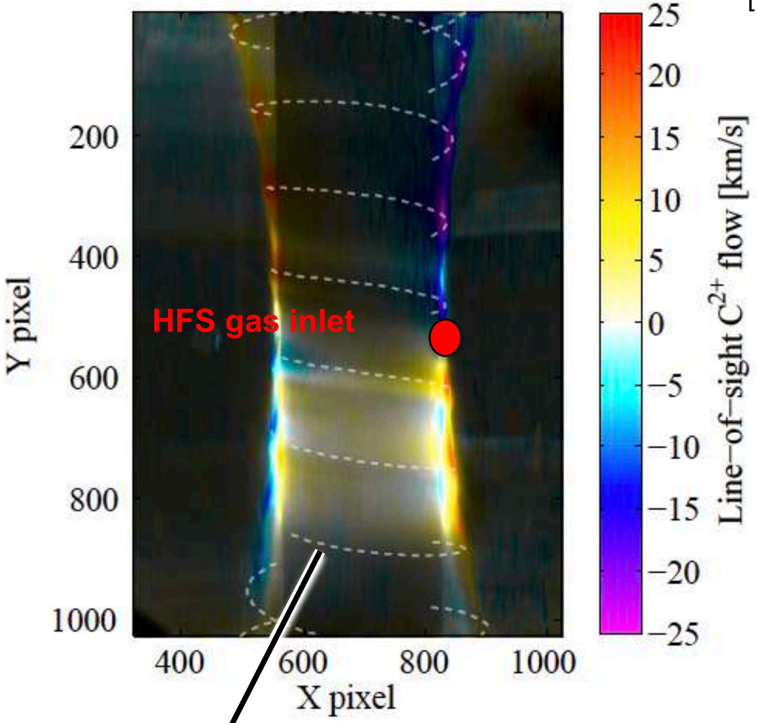
  **This is likely to change the momentum balance by enhanced friction losses (lecture D. Reiter)**

  **Predicted reason for expected high $T_e$ detachment in stellarators.**

  [Y. Feng et al., NF **46** (2006) 807-819]

- **The SOL radial extension is increased and reaches inside of separatrix**

# Flow drive along SOL flux tubes by local neutral injection were directly measured in MAST



Magnetic field line around center stack

[I. Waters et al., Nuclear Fusion **58** (2018) 066002]

**$C^{2+}$ flow measurement in the MAST spherical tokamak (CCFE, UK)**

**Launching a gas flux at the high field side (HFS), yields a flow along the field line where the gas puff is located.**

**This is an excellent test case for EMC3-EIRENE**

**In EMC3-EIRENE, parallel flows are driven by a pressure gradient along the field line – is this a reasonable assumption?**

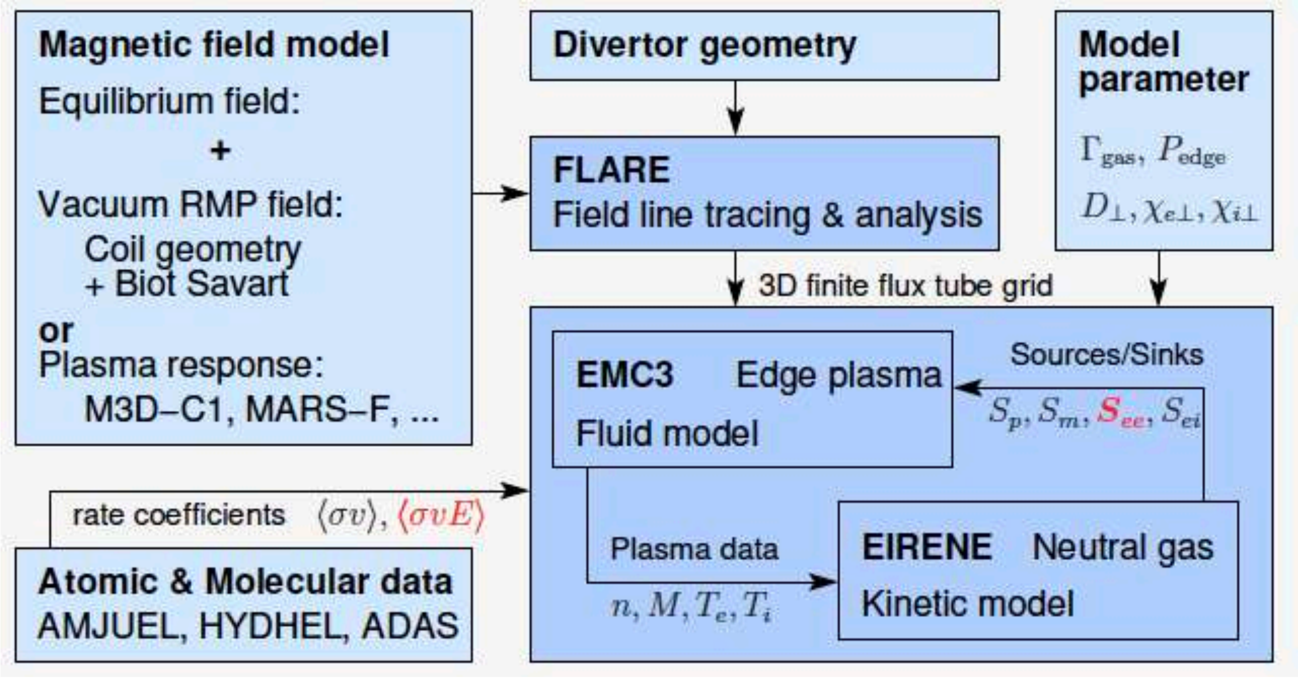
# Before we test EMC3-EIRENE we should know a bit about it

## EMC3-EIRENE is the only fully 3D plasma edge fluid and kinetic neutral transport code

[Y. Feng et al., NF **45** (2005) 89]

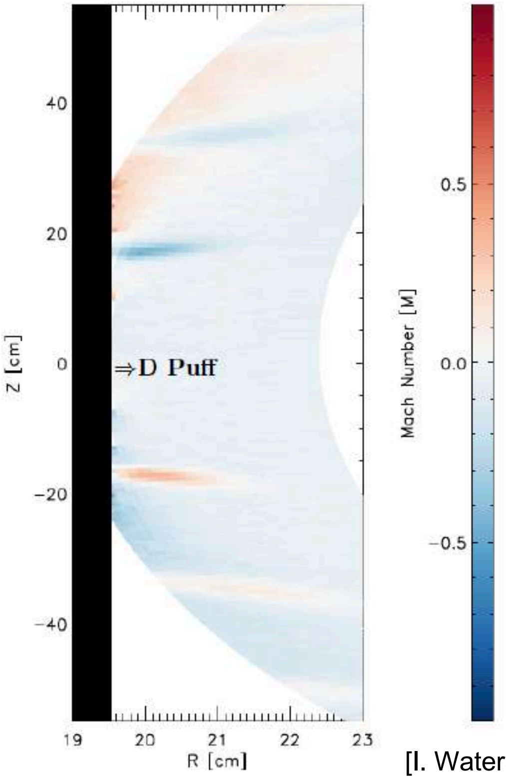
[D. Reiter et al., FST **47** (2005) 172-186]

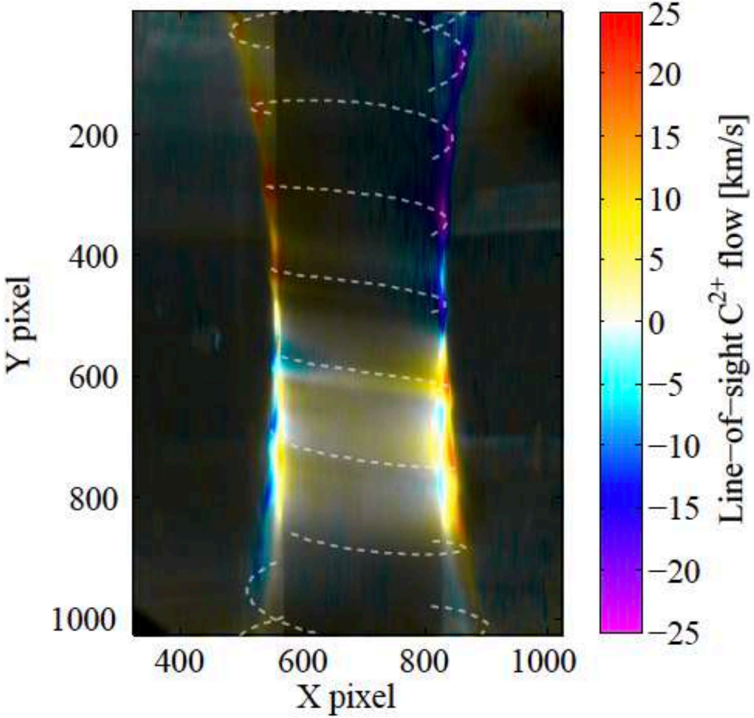
and references therein …



# Flow drive along SOL flux tubes by local neutral injection are also seen in EMC3-EIRENE prediction

**Poloidal cut of D Mach number along field lines from EMC3-EIRENE**





[I. Waters et al., Nuclear Fusion **58** (2018) 066002]

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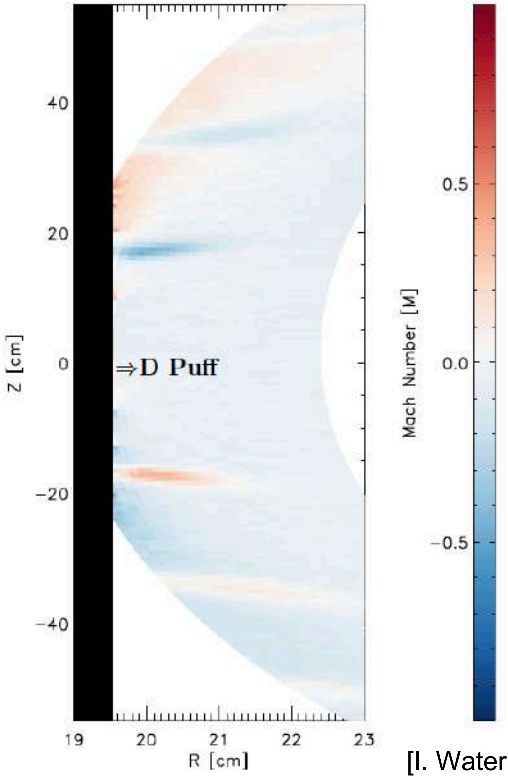
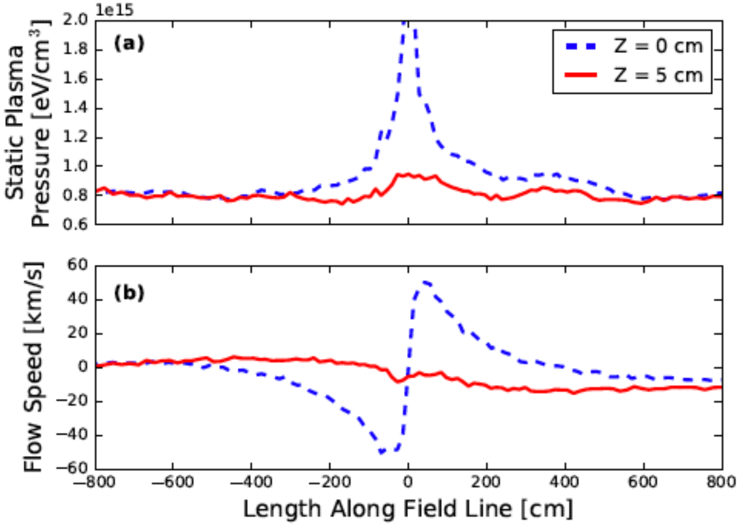


**Radial scale length for flow drive is small**



[I. Waters et al., Nuclear Fusion **58** (2018) 066002]

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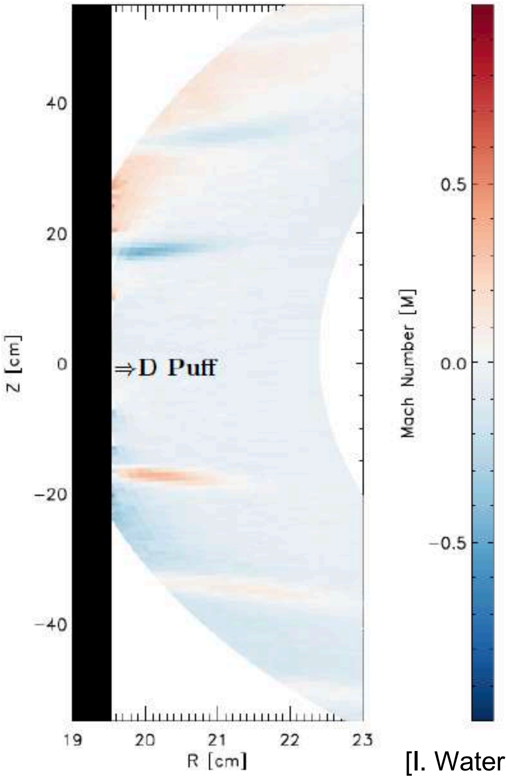
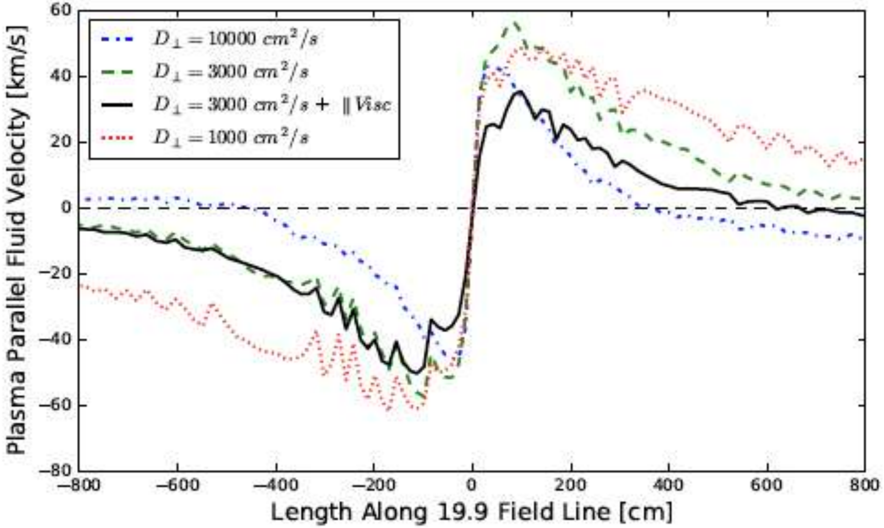


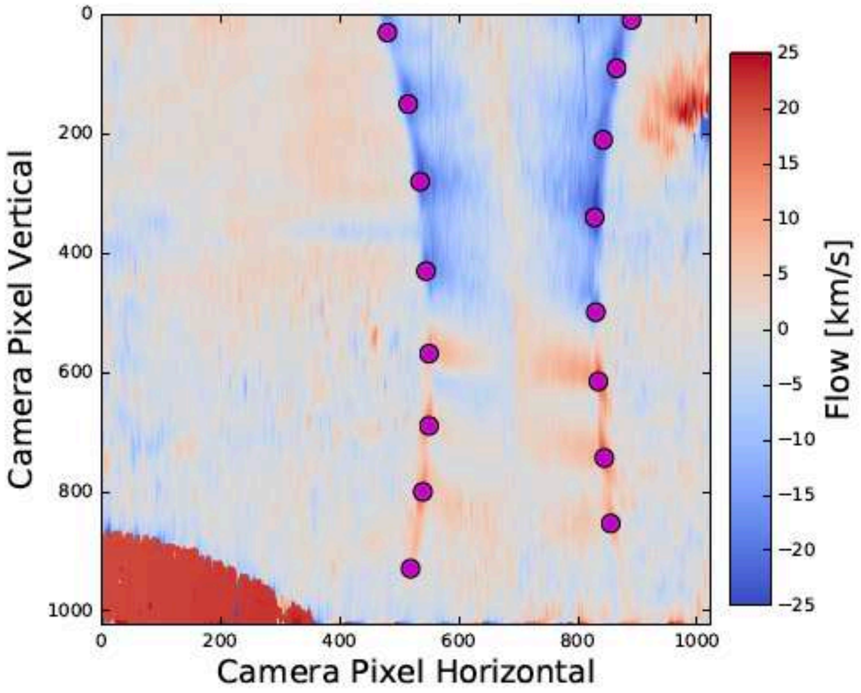
**Perpendicular diffusion and parallel viscosity dampens flow**



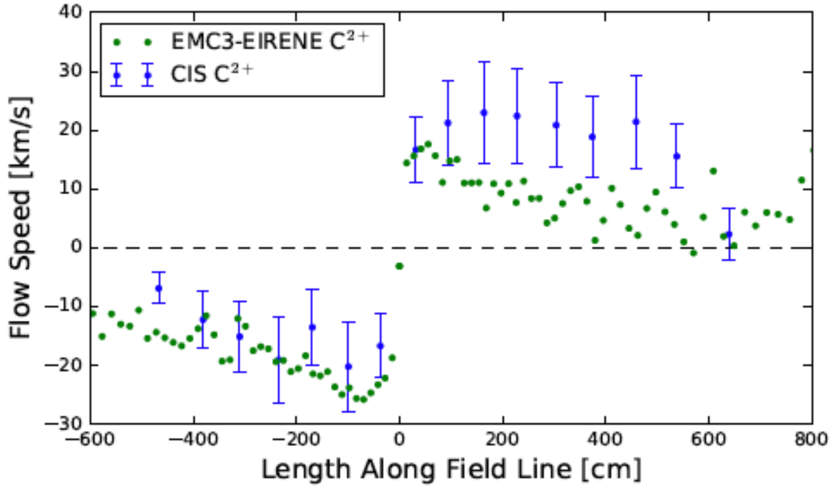
[I. Waters et al., Nuclear Fusion **58** (2018) 066002]

# Flow drive along SOL flux tubes by local neutral injection are in agreement with EMC3-EIRENE prediction

## Projected $C^{2+}$ flow measurement along field lines



## Parallel flow speed comparison

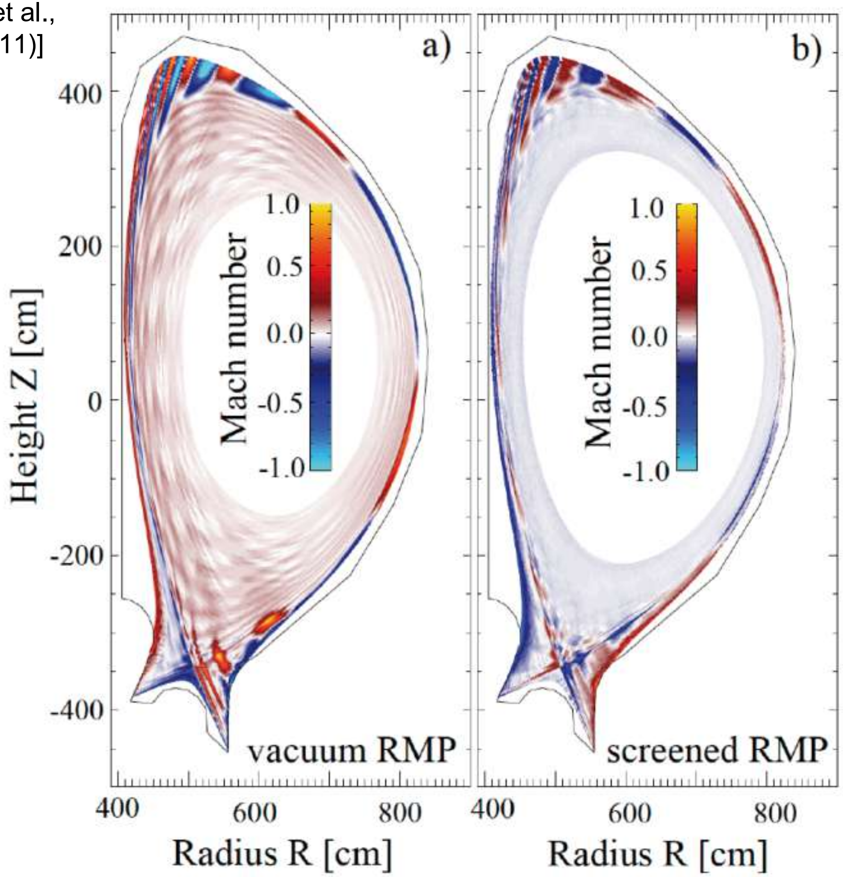


**This basic experiment demonstrates the generation of parallel particle flows along a flux bundle by a local particle source.**

[I. Waters et al., Nuclear Fusion **58** (2018) 066002]

# The inward extension of the SOL is a basic contributor to the particle pump-out

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



3D flow channels

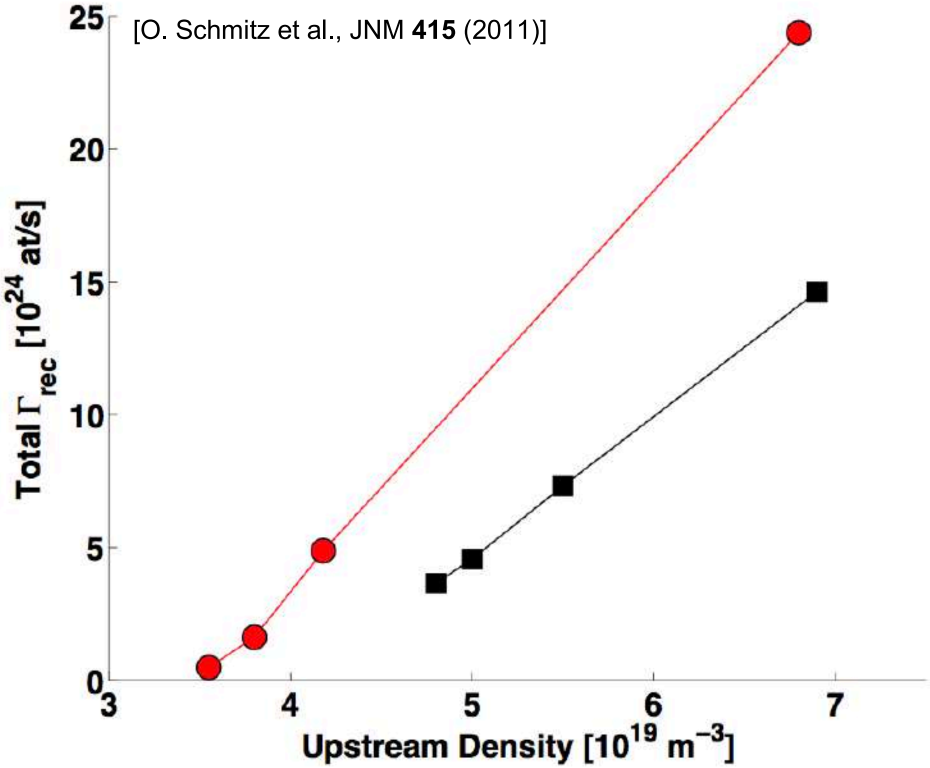
Flattening of density profile

Increase upstream pressure in 3D SOL

Downstream n up
Downstream T down

**Role in enhanced outward particle flux and convective part of heat flux**

# Particle source for sustainment of density needs to be increased with RMP – particle pump out



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

**Upstream density** vs. **divertor recycling flux** at constant external source level ($Q_n$=1.9 x $10^{22}$ at/s)

**Same density requires less recycling flux at fixed external source**

⇨ **Particle "pump out"**

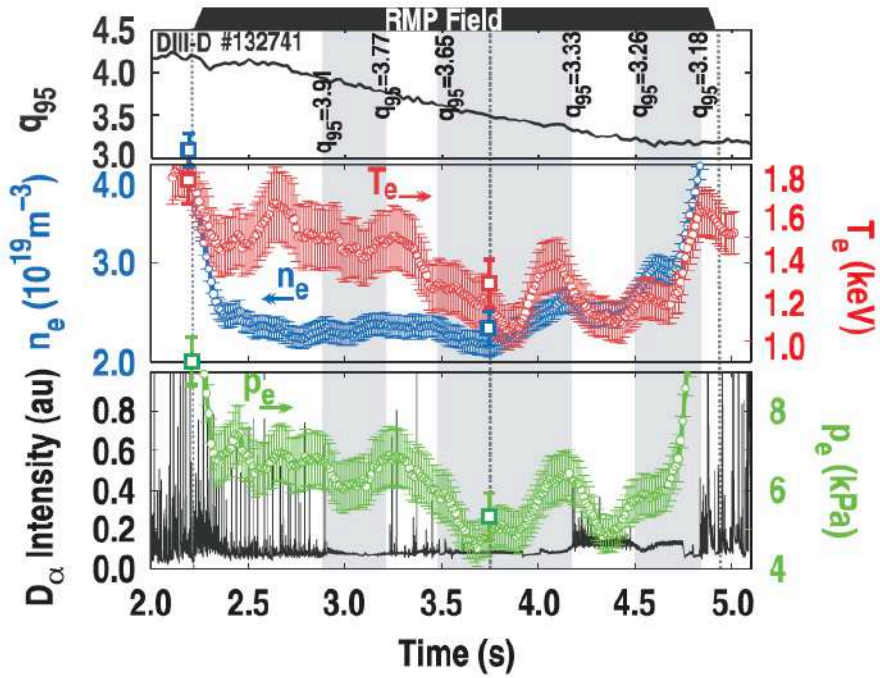
$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f \cdot \Phi_{rec} + f \cdot \Phi_{gas}$$

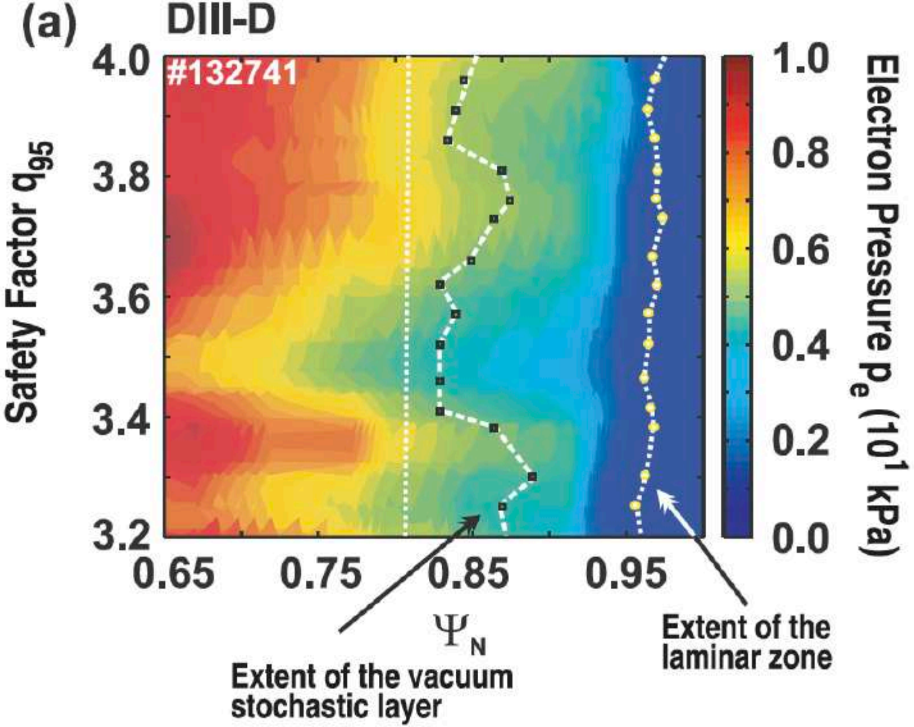
$$\tau_p = \frac{N_{tot}}{f \cdot \Phi_{rec} + f \cdot \Phi_{gas}}$$

| 90kAt vacuum case | screened case |
|---|---|
| $\Delta\tau_P = -35\%$ | $\Delta\tau_P = -15\%$ |

# A correlation has also been found between inward extension of SOL and pedestal pressure at DIII-D

[O. Schmitz et al., PRL **103** (2009) 165005]





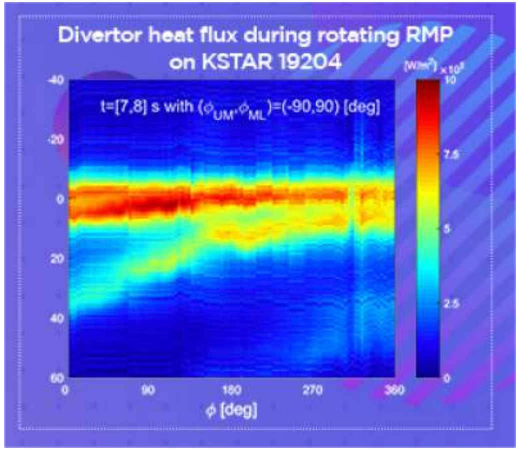
Extent of the vacuum stochastic layer

Extent of the laminar zone

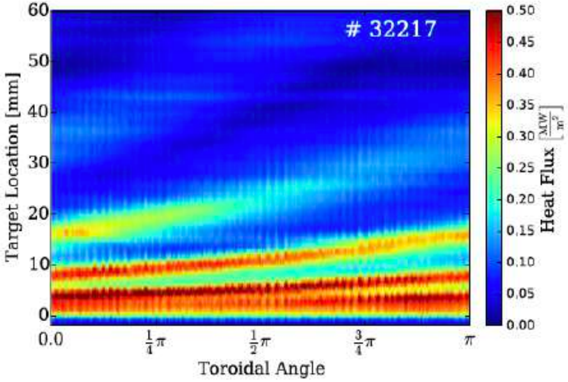
**The 3D magnetic edge structure governs the interface between plasma and wall**

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

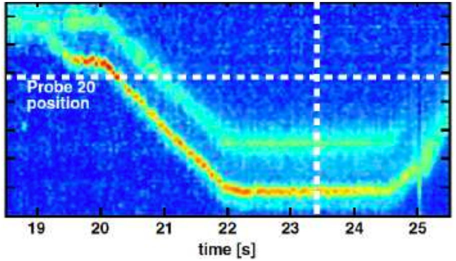
**KSTAR**



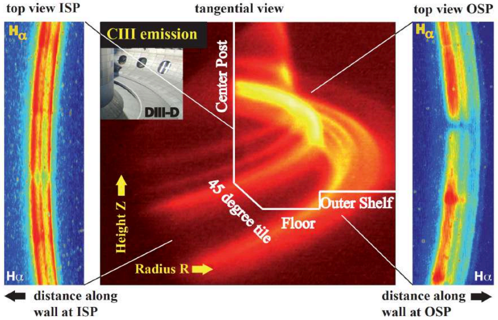
**ASDEX-Upgrade**



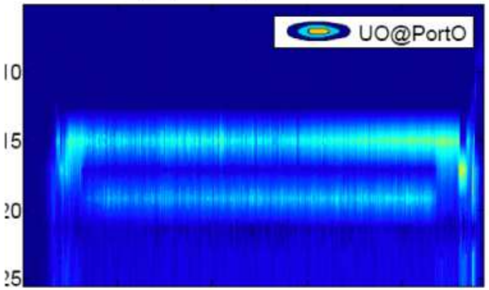
**JET**



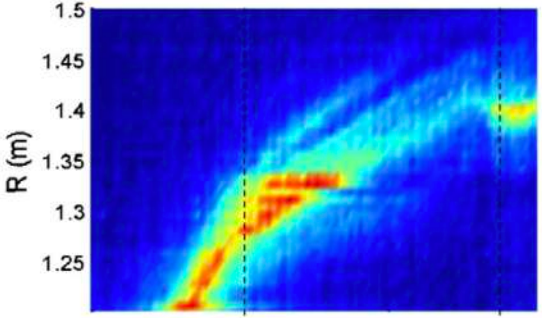
**DIII-D**



**EAST**



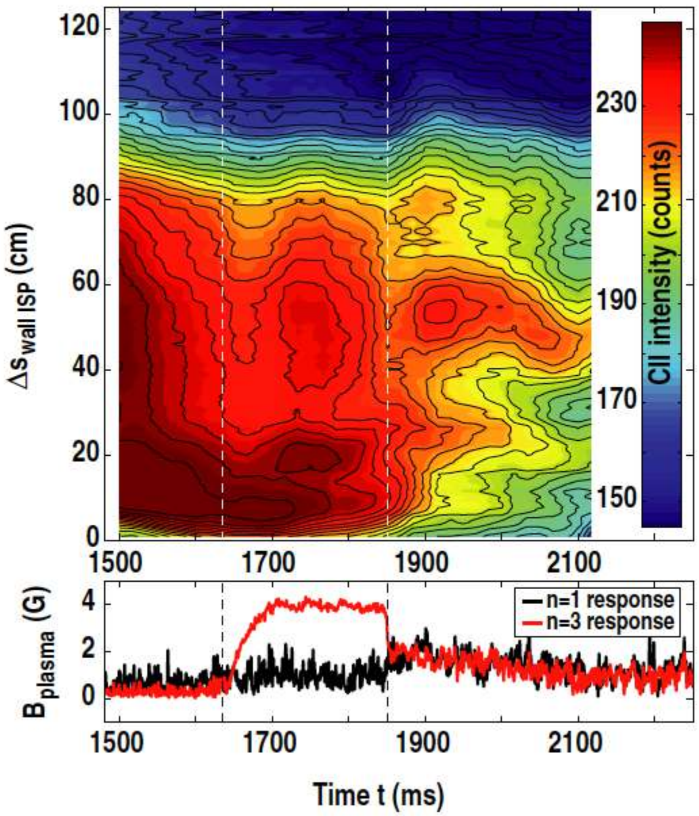
**MAST**

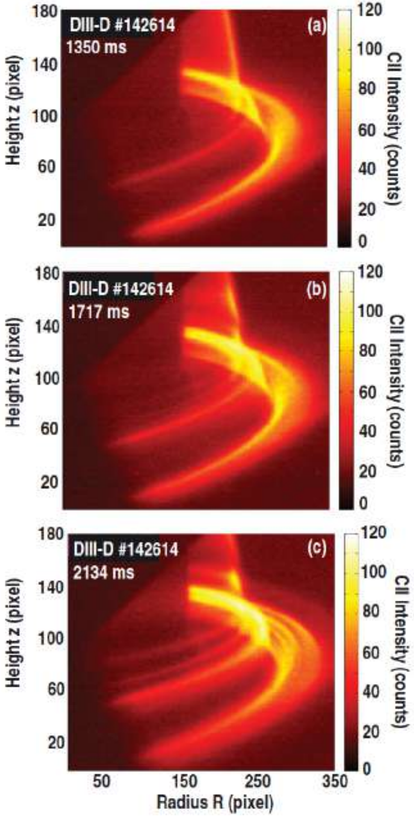


**Key questions:**

- Distribution of heat fluxes
- Impact of plasma response
- Impact on high density /detachment

# The internal plasma response impacts on the shape and extension of the divertor lobes





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

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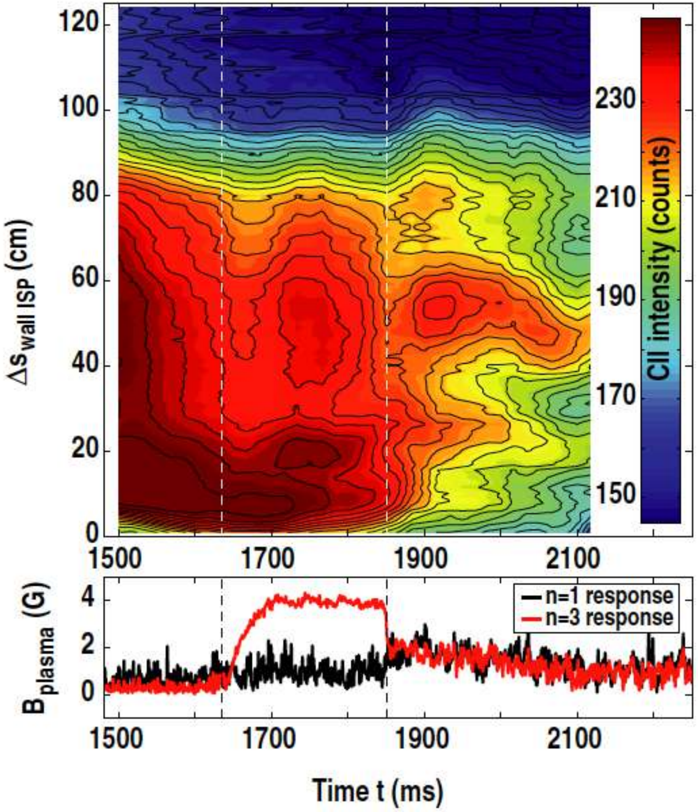
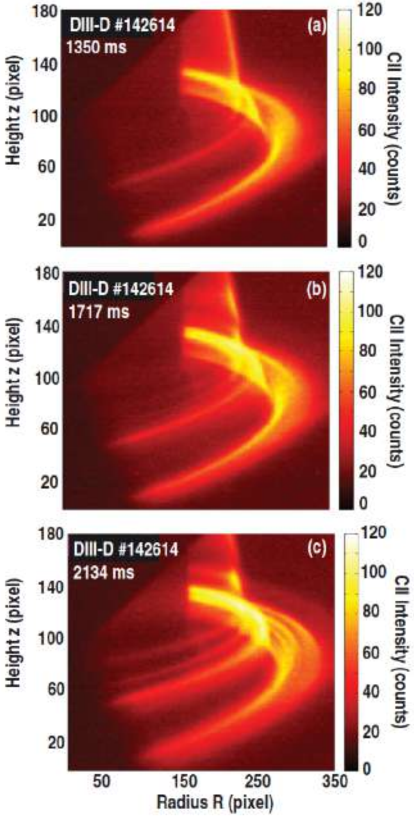
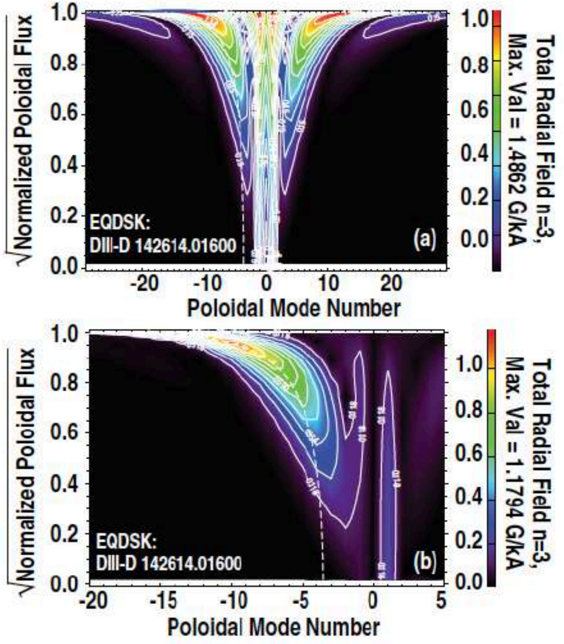




## What does the "Plasma Response" do?



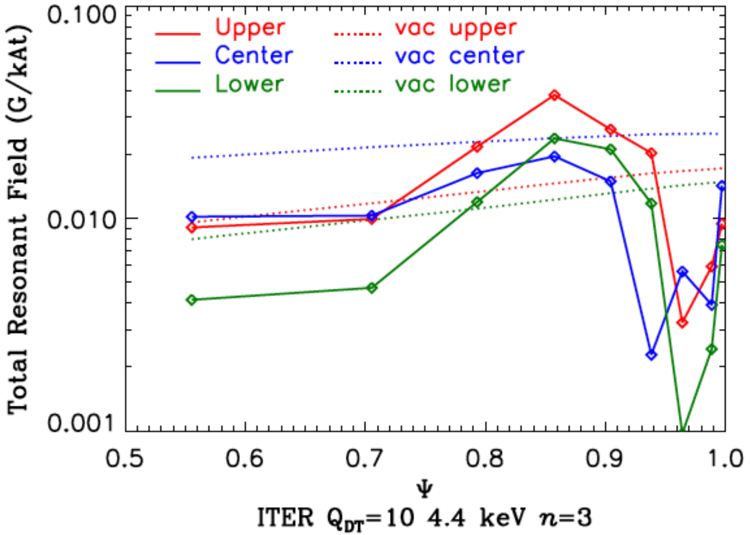
**Phase shift of 90 degrees was measured suggesting destructive interference**

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

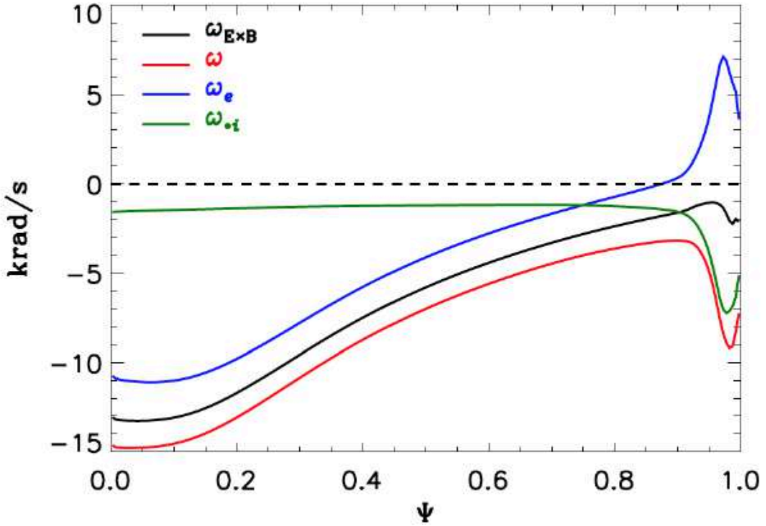
# Very brief: what does the plasma response do to the resonant magnetic field amplitudes?

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

**Linear, two-fluid modeling M3D-C1**



**Underlying rotation profiles**

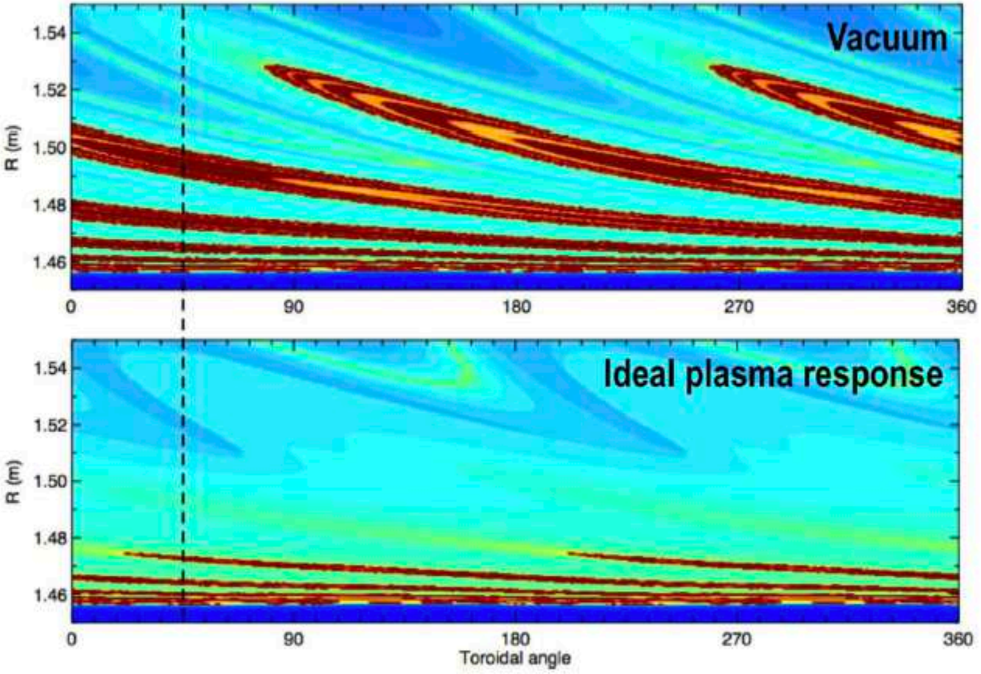


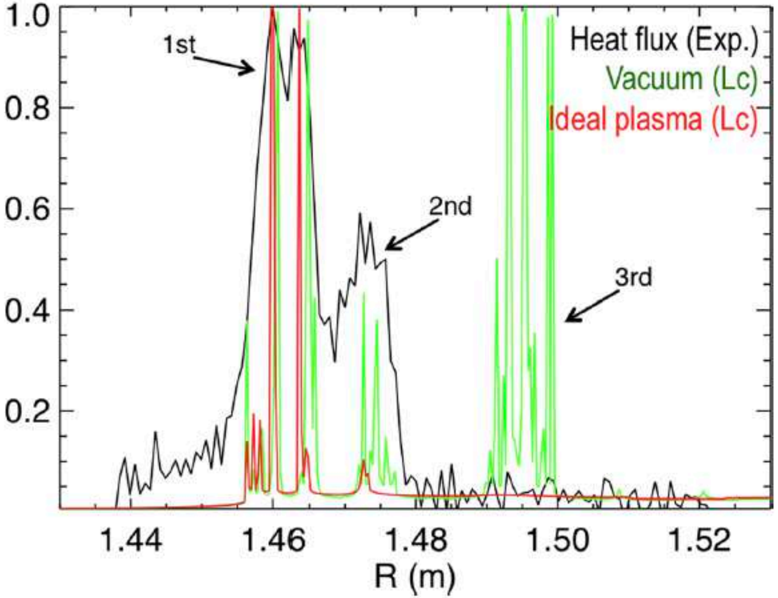
- **Linear response shows strong screening close to separatrix**
- **Resonant field amplification in plasma edge**
- **Moderate screening radially deeper inside**

**Congruent, yet not conclusive when compared to RMP tokamaks**

# 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



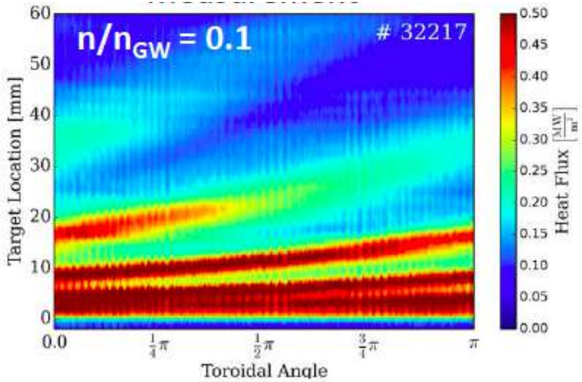


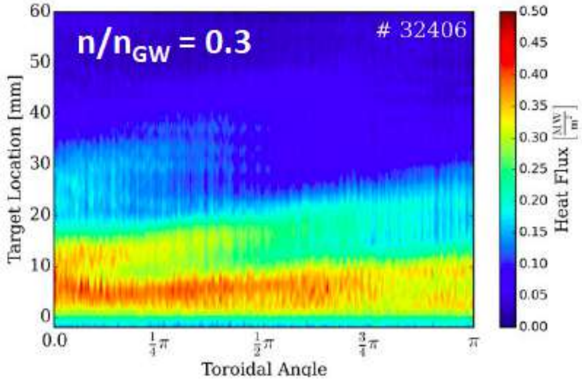
[K. Kim et al., PoP, **24** (2017) 052506]

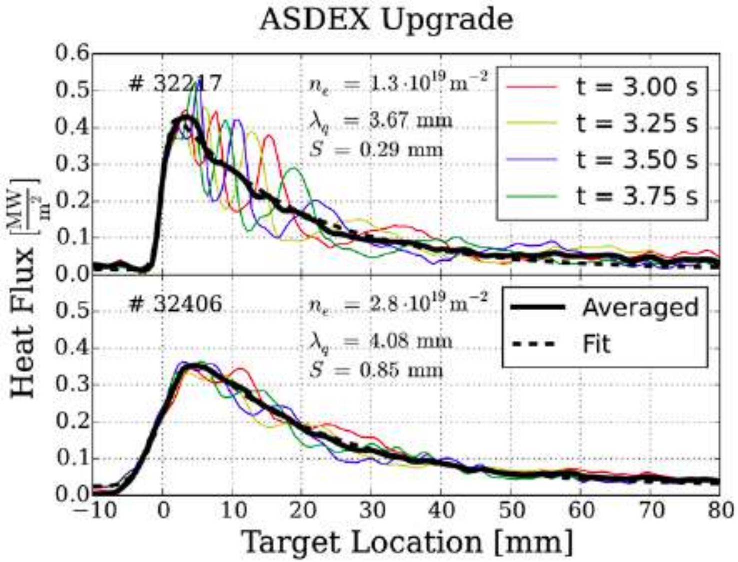
**Plasma response needs to be considered for heat flux analysis with RMP**

# 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?**

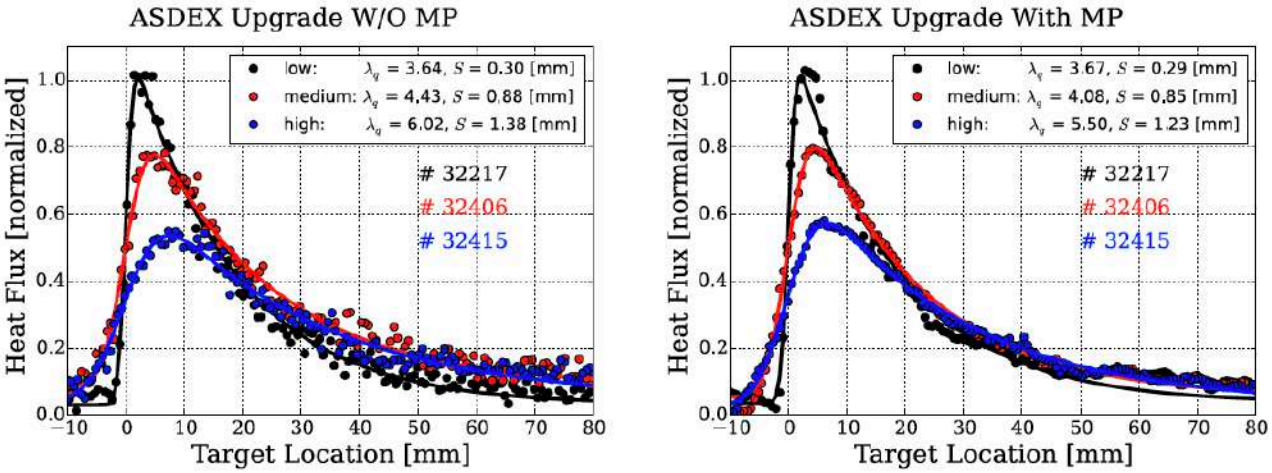
$$q(s) = \frac{q_0}{2}\exp\left(\left(\frac{S}{2\lambda_q}\right)^2 - \frac{s}{\lambda_q f_x}\right) \cdot \mathrm{erfc}\left(\frac{S}{2\lambda_q} - \frac{s}{S f_x}\right) + q_{BG} \quad \left[\frac{\mathrm{MW}}{\mathrm{m}^2}\right]$$

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

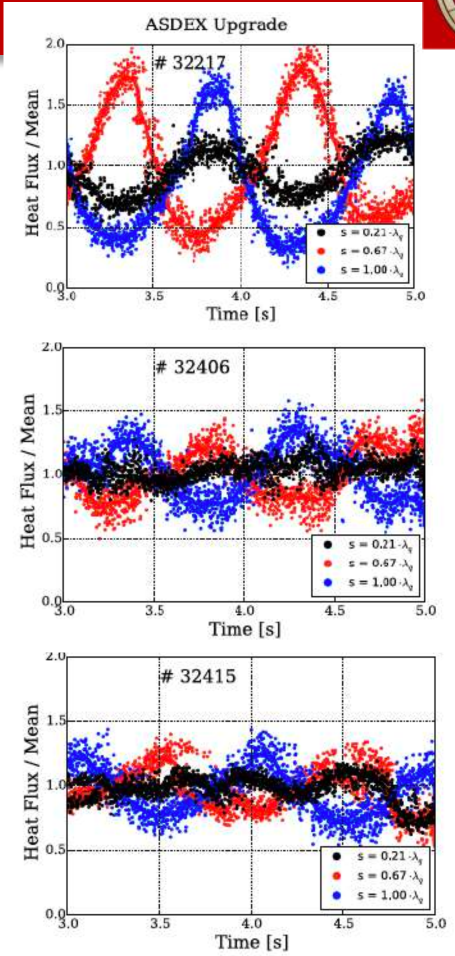
**Lecture by R. Pitts**

# 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]



**No access to RMP ELM suppression in detached H-mode**

**Need to rely on modeling**

# Outline of lecture

- **Understand reason and relevance of non-axisymmetric tokamak divertor loads**

*You have been wondering about this picture?*

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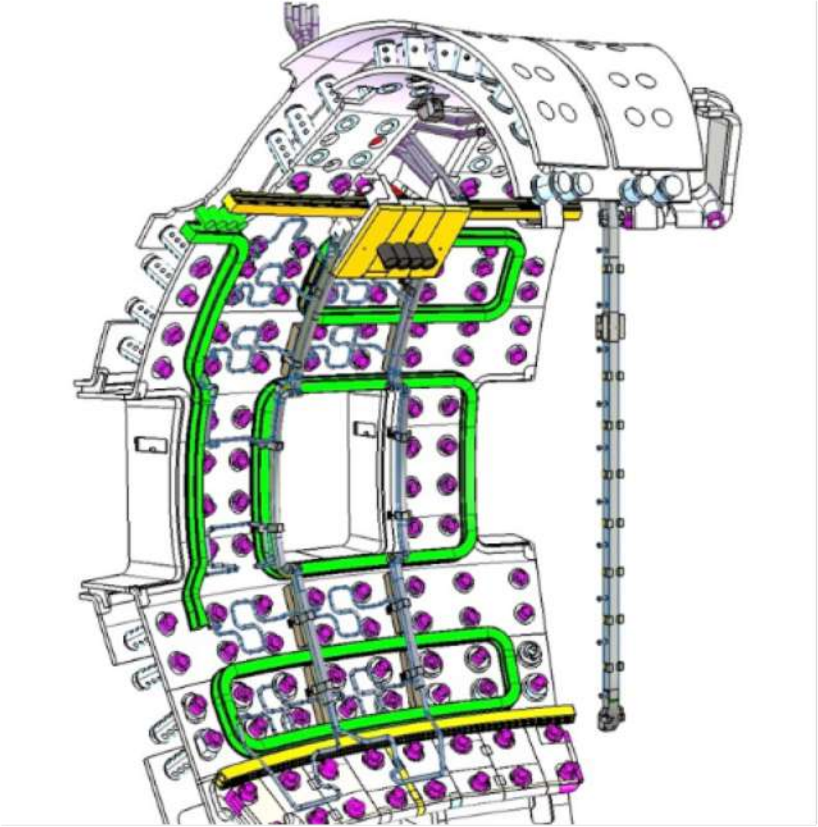
Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
www.iterschool2019.kr

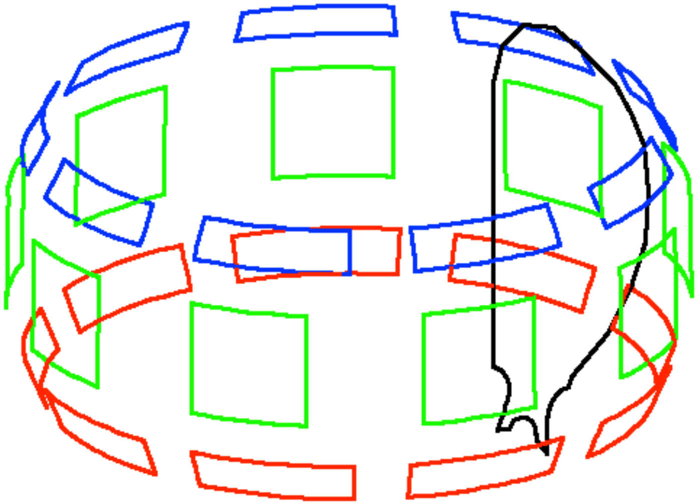
?

This lecture will address this!

- Why are these patterns this important?
- Fundamentals of these patterns – where do they come from?
- Implications on plasma edge and PMI – are they relevant?
- **Consequences for ITER – how do we know?**

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

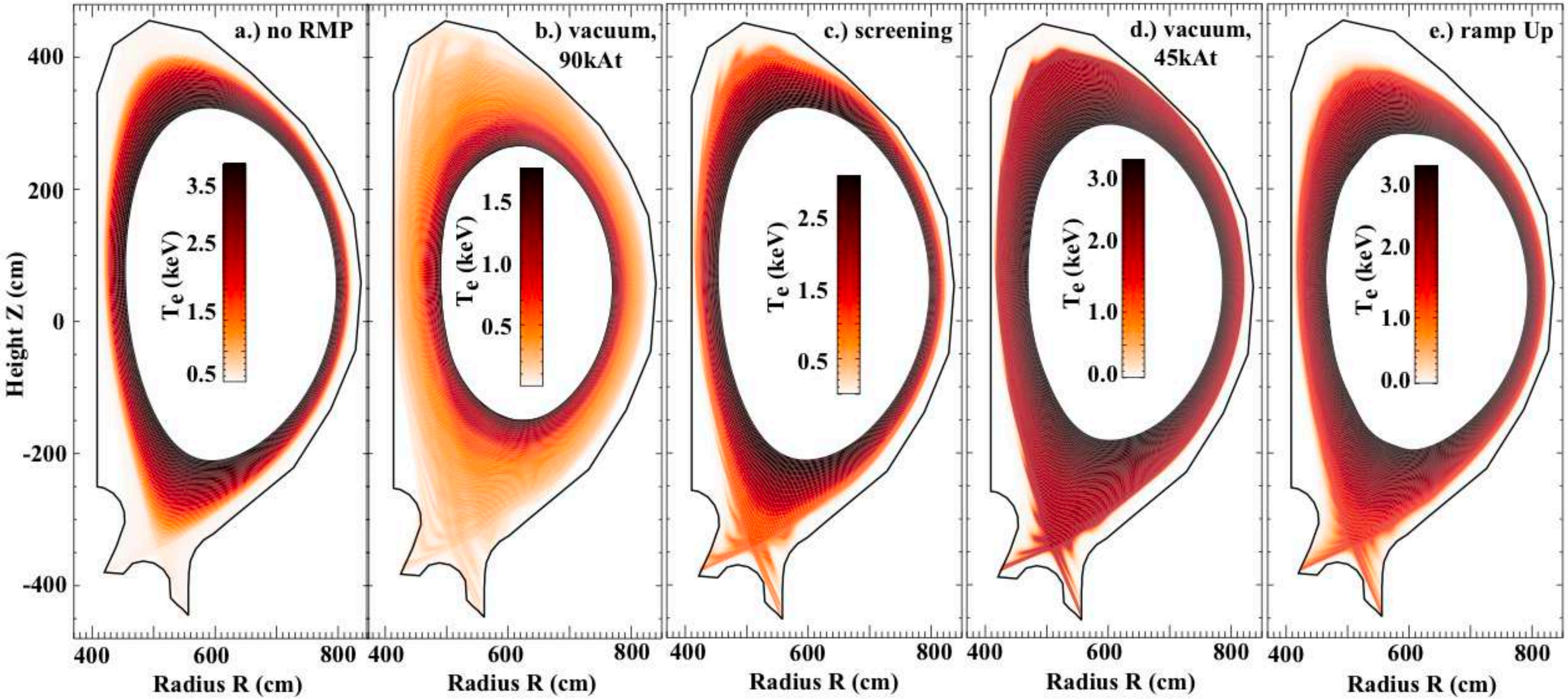




- In vessel coils mounted behind blanket
- 9x3 coils with single power supplies

Coil set with wide spectral flexibility

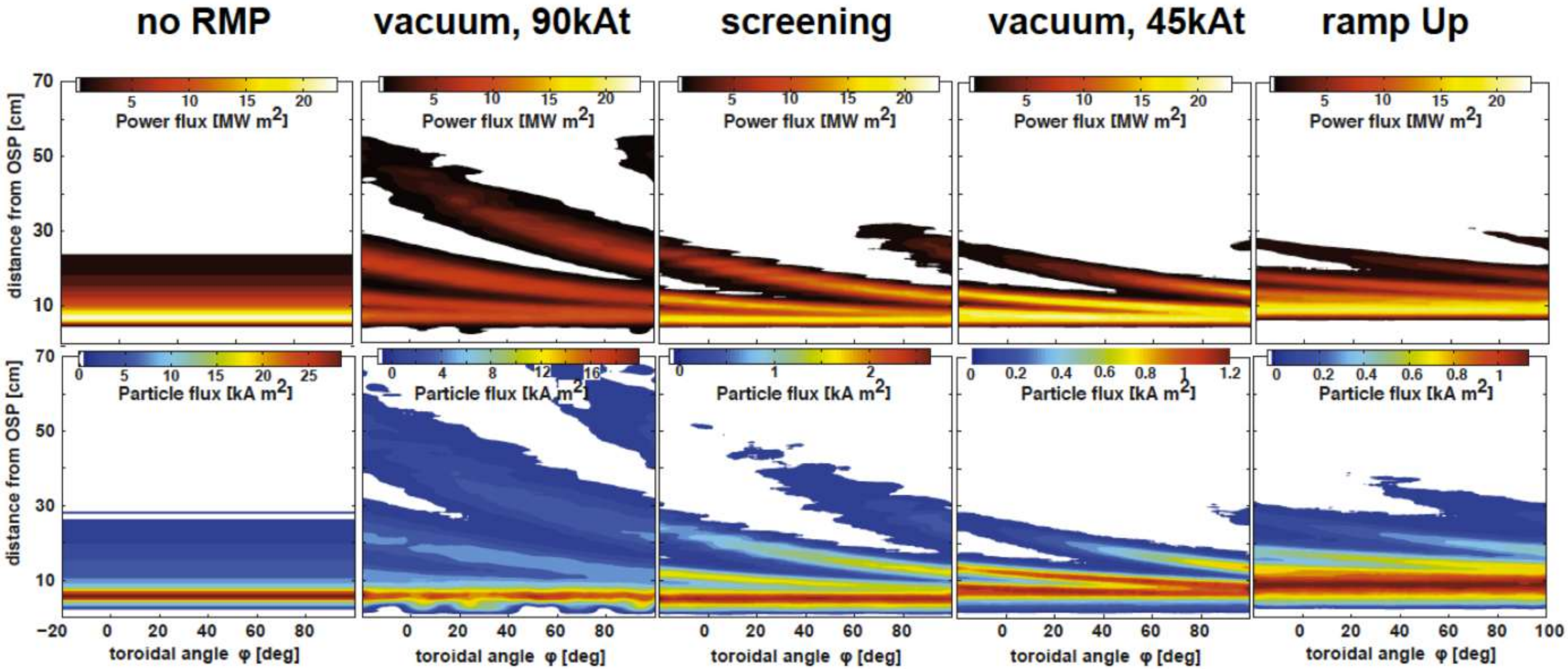
# Consistent lobe formation is seen in EMC3-EIRENE modeling



$I_P$=15MA, $B_T$=5.3T, $n_e$=2.0 $10^{19}m^{-3}$, $T_{e,ped}$=3.7keV, D=1.2$m^2$/s, $\chi$=3 x D

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

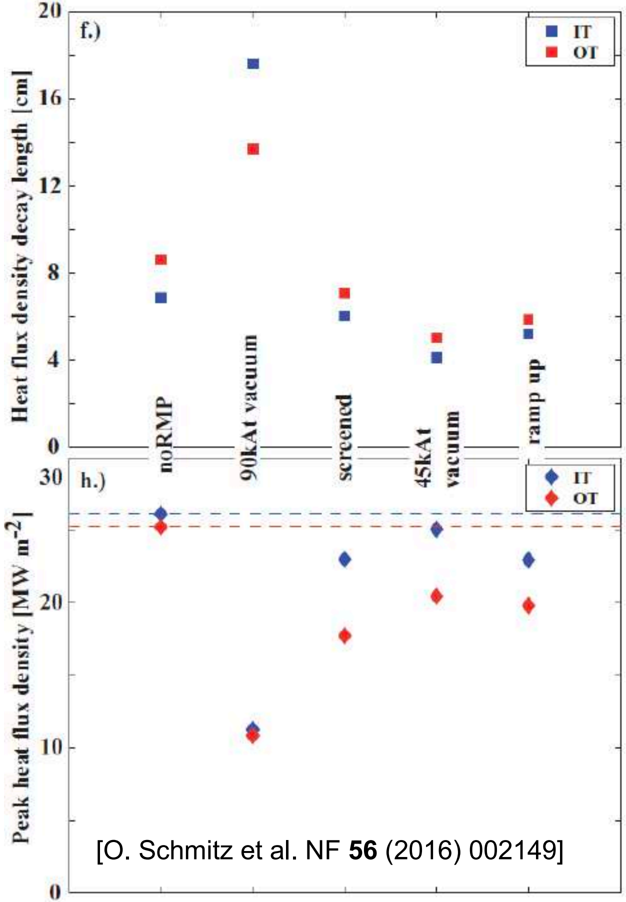
# Helical heat and particle flux patterns are predicted (attached)



*How does this propagate into the ITER divertor baseline?*

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

# Toroidal averaged $\lambda_q$ with increases for reduced transport



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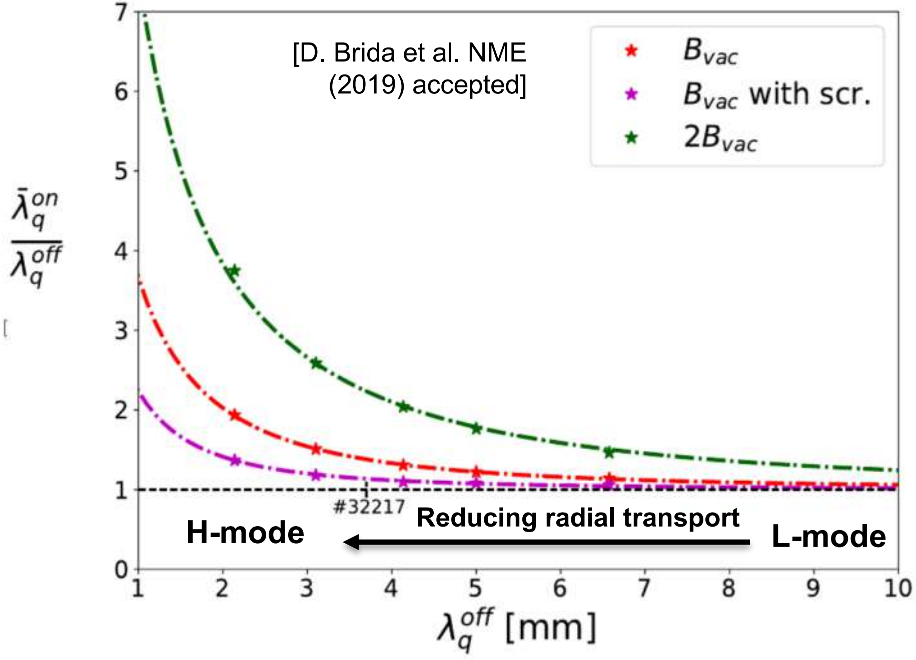


[D. Brida et al. NME (2019) accepted]

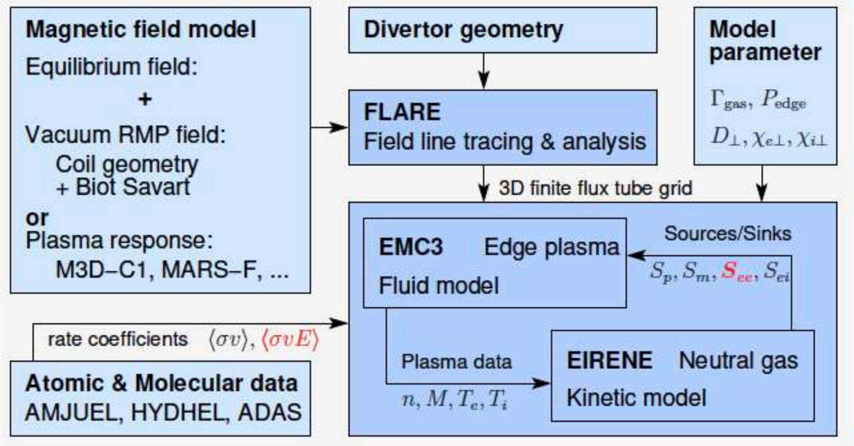
**In H-mode a significant (benefical) impact is expected on toroidal averaged $\lambda_q$**

# Access to detachment in 3D boundary?

- Flows affected – momentum balance?
- Relocation of fluxes/ different energy sources for divertor?
- Fueling/particle exhaust relation from particle pump out?

**Lets have a look!**

# Big issue: EMC3-EIRENE can't do this!!



**Magnetic field model**
Equilibrium field:
+
Vacuum RMP field:
Coil geometry
+ Biot Savart
or
Plasma response:
M3D–C1, MARS–F, ...

**Divertor geometry**

**FLARE**
Field line tracing & analysis

**Model parameter**
$\Gamma_{\text{gas}}, P_{\text{edge}}$
$D_{\perp}, \chi_{e\perp}, \chi_{i\perp}$

3D finite flux tube grid

**EMC3** Edge plasma
Fluid model

Sources/Sinks
$S_p, S_m, S_{ee}, S_{ei}$

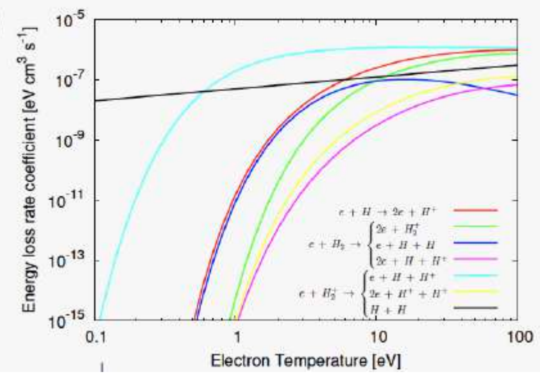
rate coefficients $\langle\sigma v\rangle, \langle\sigma v E\rangle$

Plasma data
$n, M, T_e, T_i$

**EIRENE** Neutral gas
Kinetic model

**Atomic & Molecular data**
AMJUEL, HYDHEL, ADAS

$$S_{ee} = -n_e \sum_{x=D,D_2,D_2^+} n_x \langle \sigma_x v E\rangle(T_e, n_e)$$



**Plasma neutral interaction is highly non linear at low temperatures**

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

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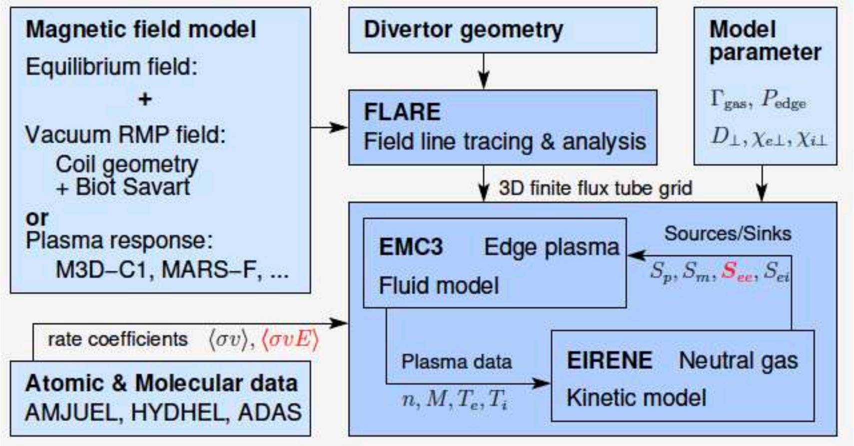

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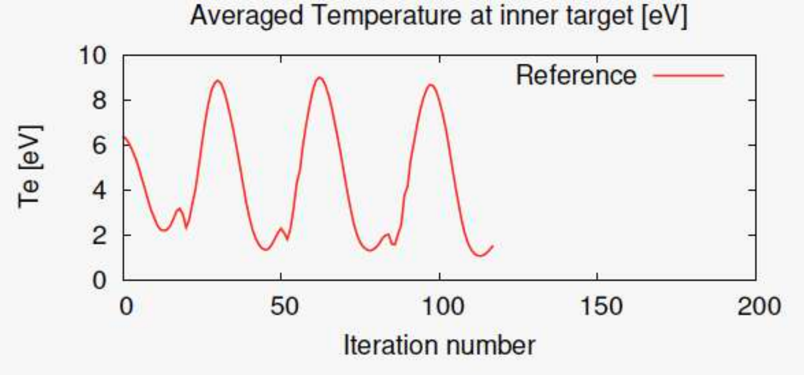
## Numerically unstable solution



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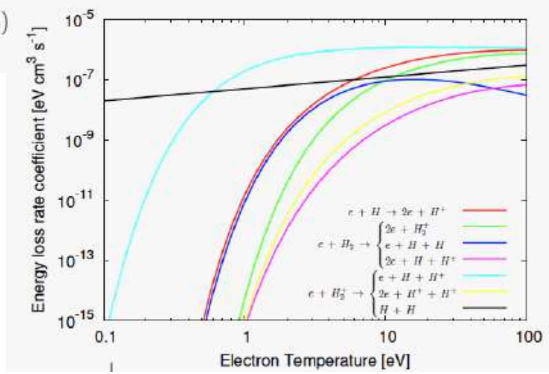
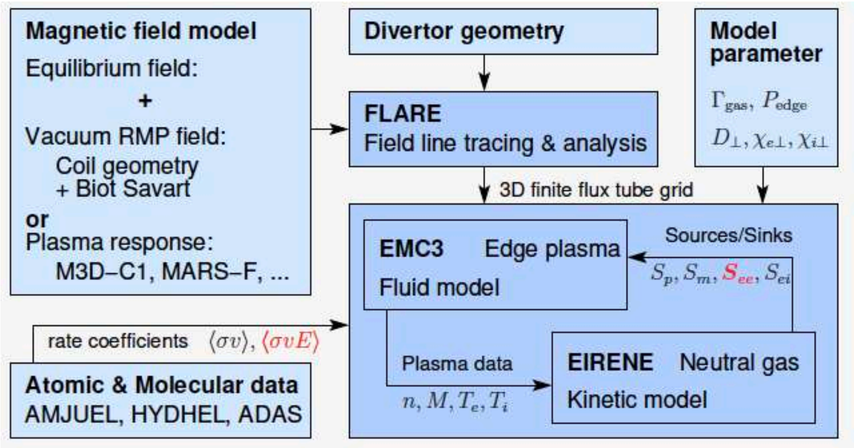


**Plasma neutral interaction is highly non linear at low temperatures**

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

# Big issue: EMC3-EIRENE can’t do this!! Hold on: now it can!



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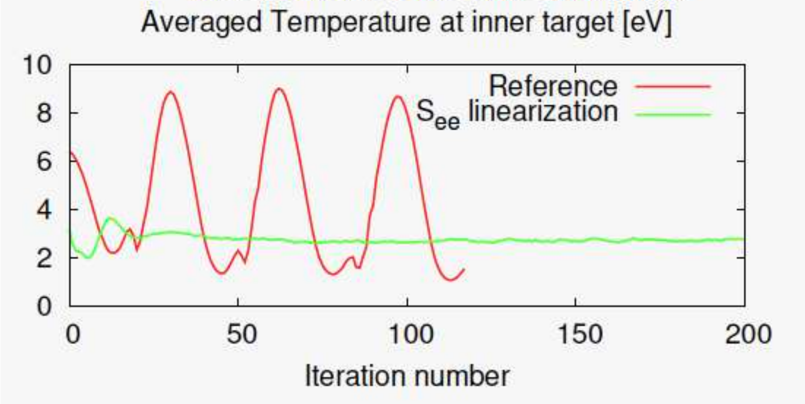

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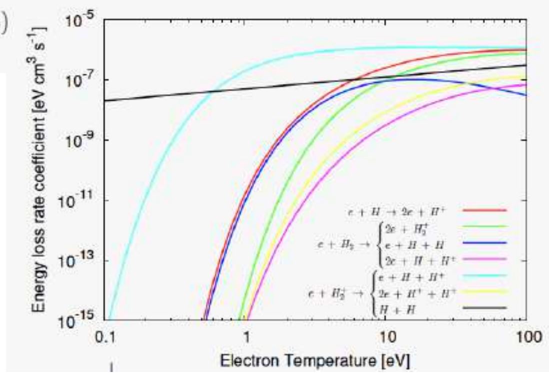


$$S_{ee}\left(T_e^{(j)}\right) \approx S_{ee}\left(T_e^{(j-1)}\right) + \left(T_e^{(j)} - T_e^{(j-1)}\right) \left.\frac{dS_{ee}}{dT_e}\right|_{T_e^{(j-1)}}$$

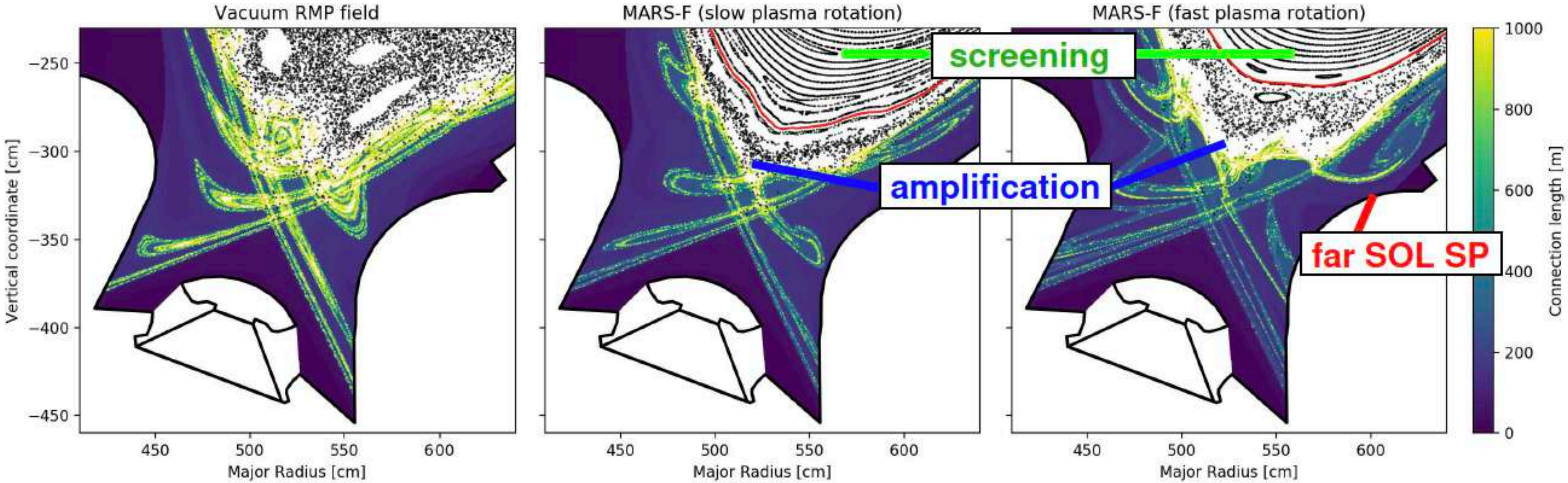
**Plasma neutral interaction is highly non linear at low temperatures**

**This enables to model for the first time detached RMP divertors**

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

# For ITER, the 3D edge solution is very sensitive to plasma response

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



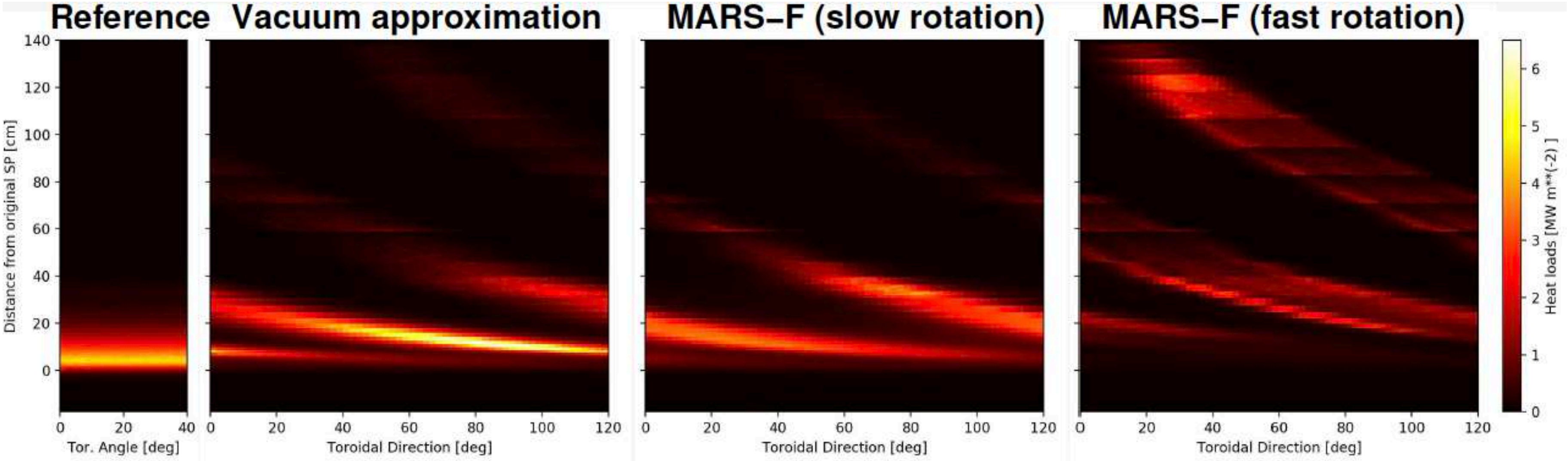
**MARS-F: linear, ideal MHD solution with resistivity and plasma rotation**

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

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

# Helical heat flux can be shifted outward substantially

## Attached solution at moderate density shows shift into helical lobes



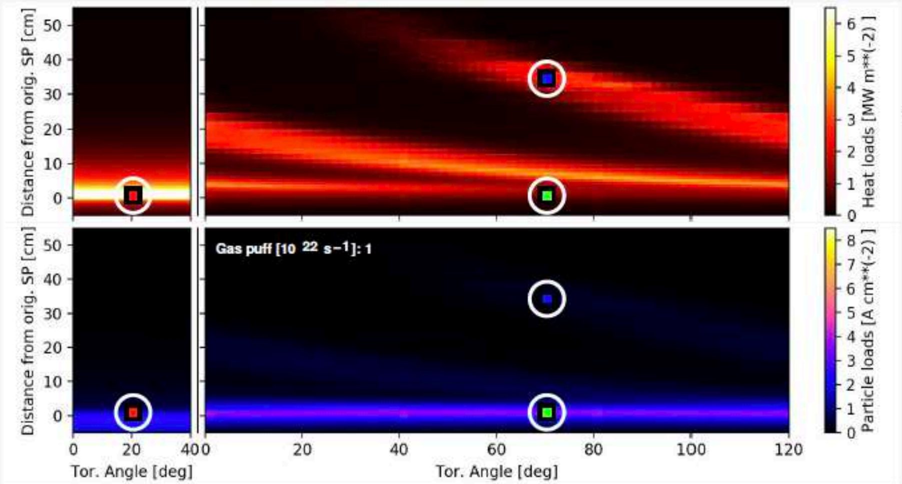
$$\Gamma_{\text{gas}} = 3 \cdot 10^{22}\,\mathrm{s}^{-1},\ P_{\text{edge}} = 30\,\mathrm{MW},\ D_{\perp} = 0.3\,\mathrm{m}^2\,\mathrm{s}^{-1},\ \chi_{\perp} = 1\,\mathrm{m}^2\,\mathrm{s}^{-1}$$

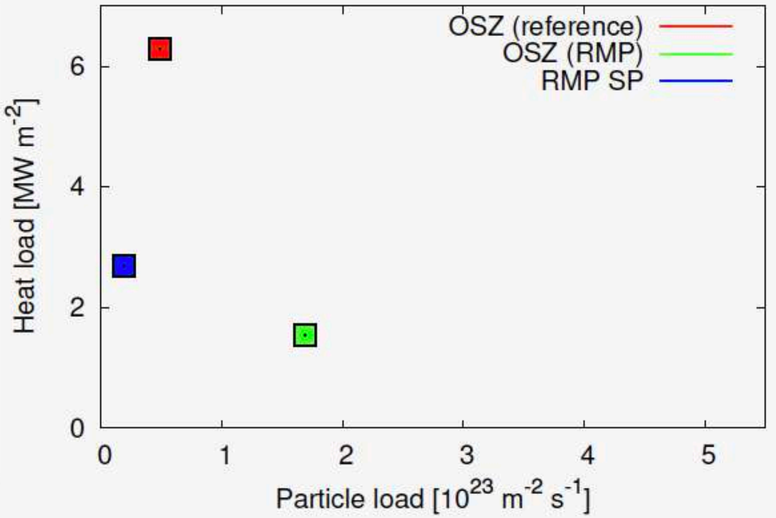
[H. Frerichs et al. APS-DPP 2018, Contributed Oral]

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

# Earlier detachment at unperturbed strike line combined with heat flux filling of outer lobes is seen during transition into detachment

## Comparison of heat flux at original outer strike zone and inside of outer lobe





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

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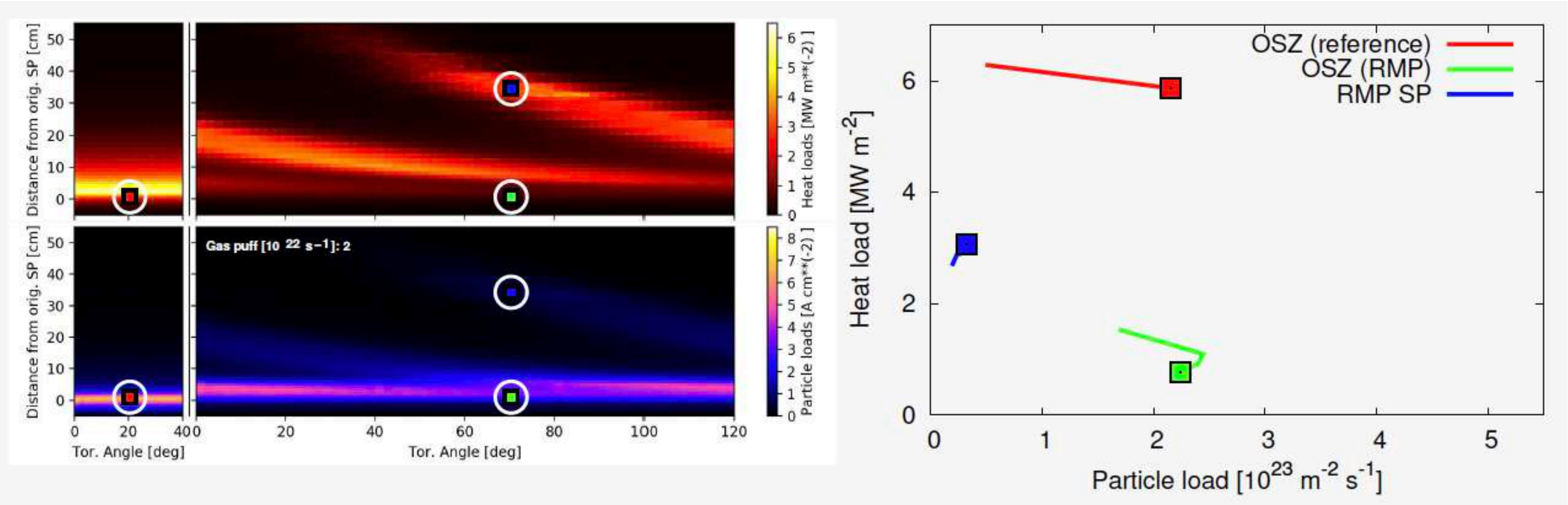

- **Roll over of heat flux inside of lobe**

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

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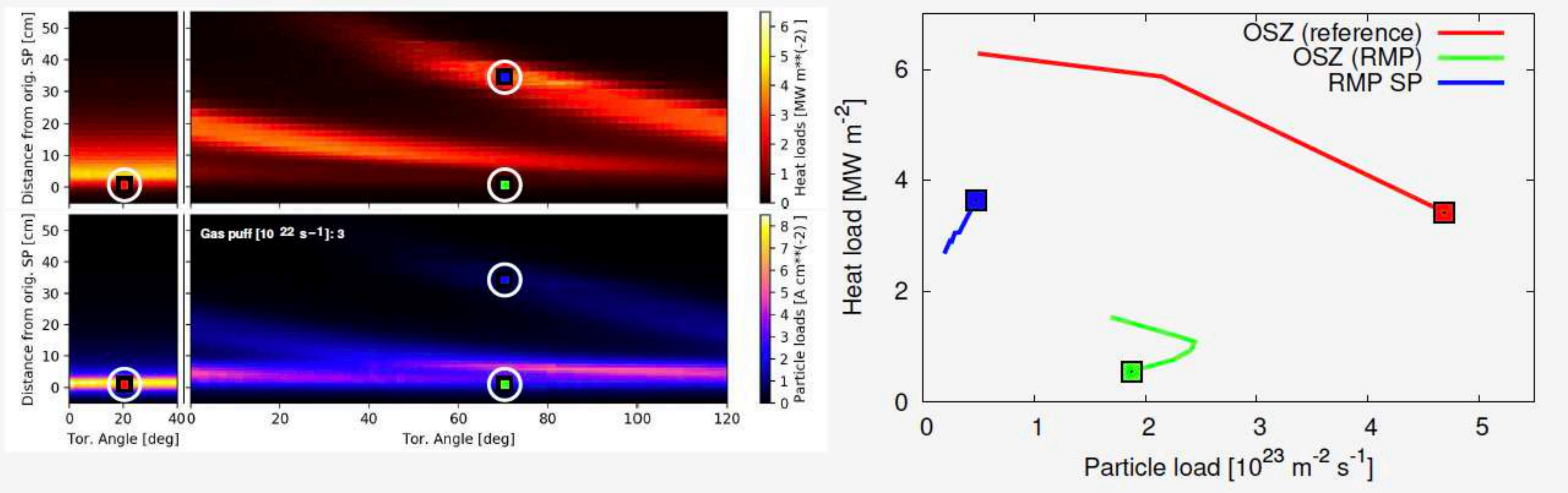

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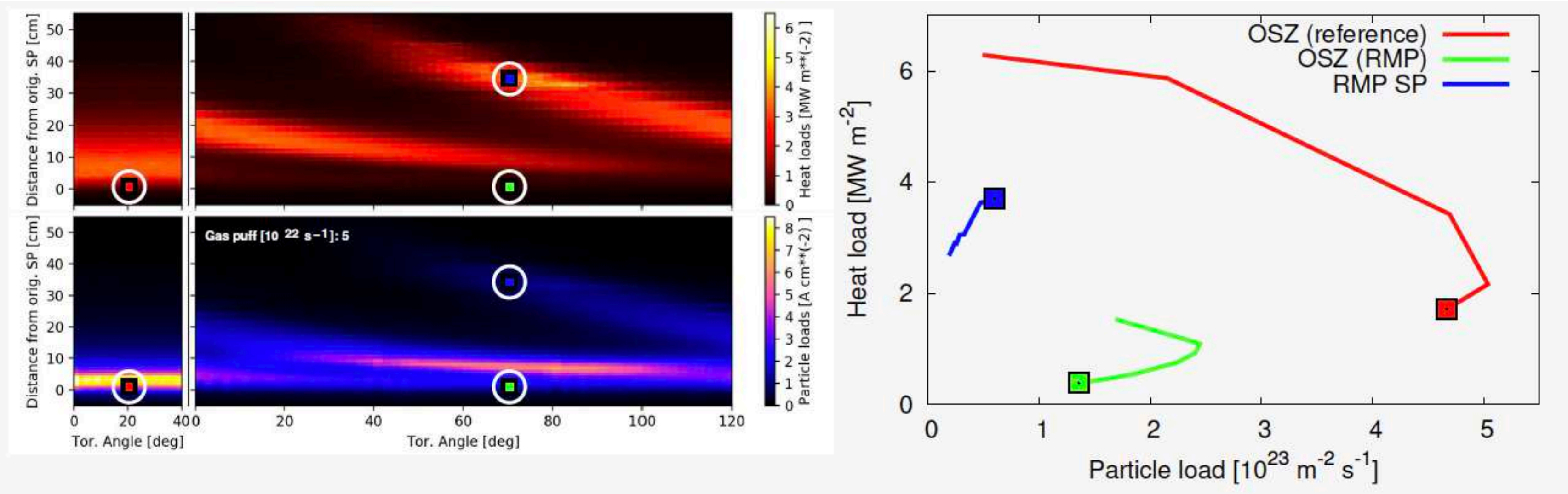

- **Roll over of heat flux inside of lobe**
- **Roll over at original strike line at higher particle flux (later)**

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

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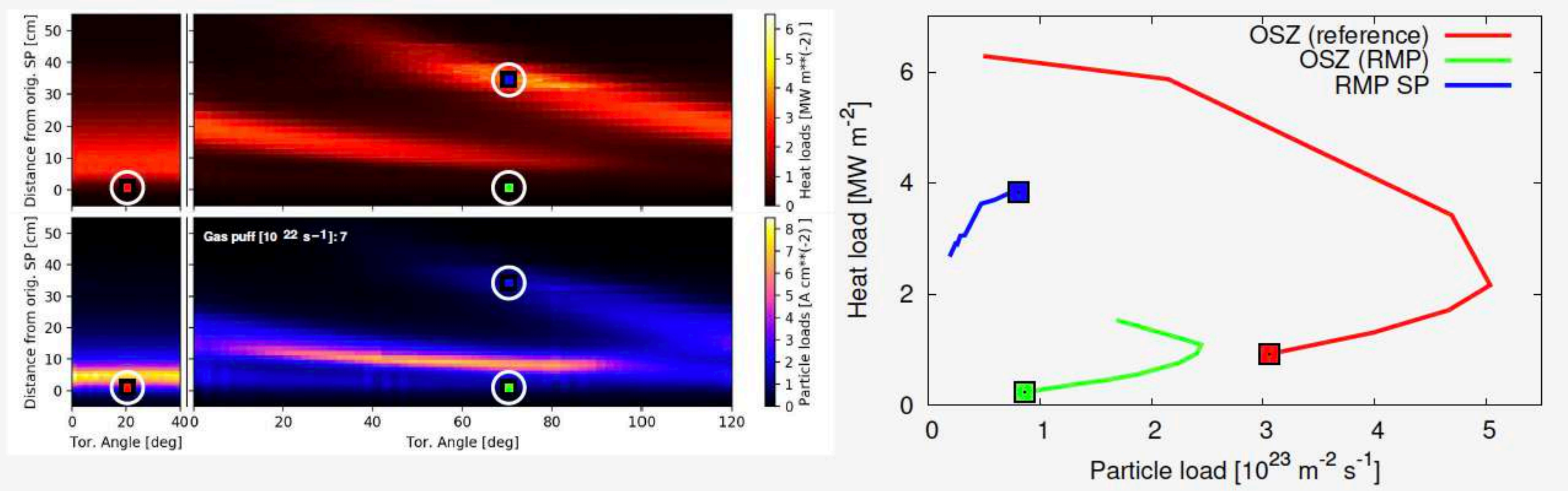

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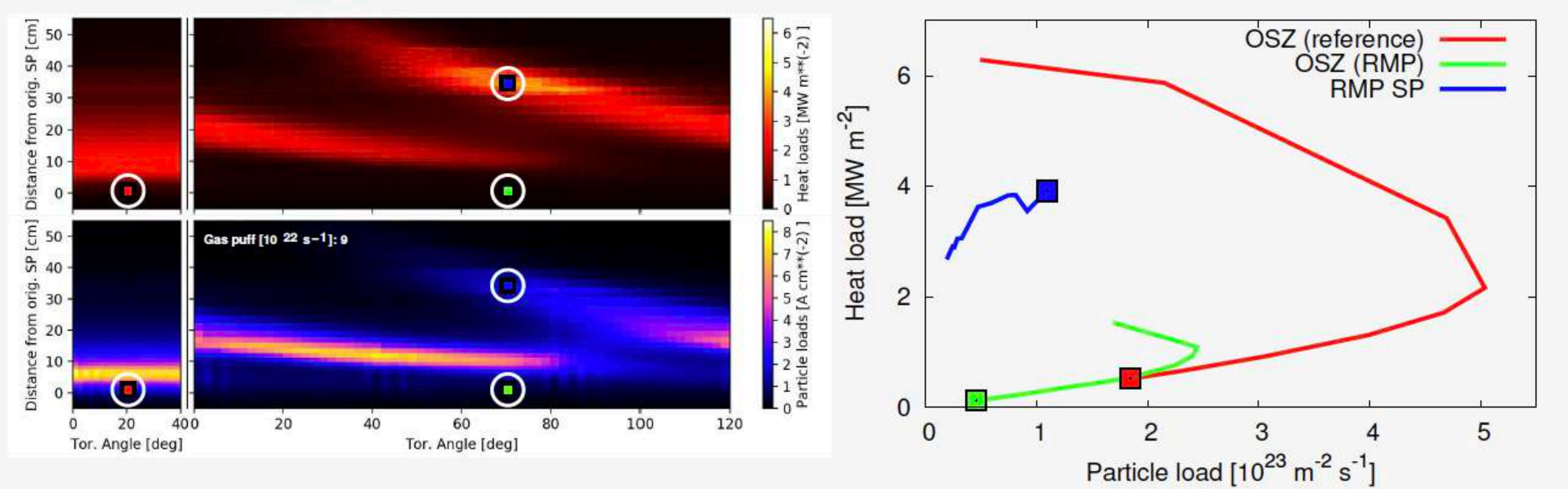

- **Roll over of heat flux inside of lobe**
- **Roll over at original strike line at higher particle flux (later)**
- **Similar level of detachment but outer lobe attached**

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

# Some take aways …

10th ITER International School 2019

The physics and technology of power flux handling in tokamaks

21st (MON)-25th (FRI) January 2019

Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
www.iterschool2019.kr

*Hope that became clear!*

- **Generic perturbation of separatrix by RMP field transforms the power exhaust challenge into a full 3D issue**
- **Heat fluxes reach unexpected divertor areas which might be designed for this loading and detachment features are affected**
- **Our capacity to extrapolate to ITER depends on advances in modeling and theory combined with experiments**

**3D fluid transport - Plasma Response - Location – Rotation – Divertor Cooling**