JÜLICH FORSCHUNGSZENTRUM

Divertor Physics in Tokamaks with 3D Perturbation Fields

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7 - CEA/IRFM, Cadarache, 13108 St Paul-lez-Durance Cedex, France
8 – IPP AS CR, Za Slovankou 3, 18200 Prague 8, Czech Republik
9 – ITER Organization, 13115 St Paul-lez-Durance, France
10 – Fusion for Energy F4E, Barcelona, Spain

DIII-D NATIONAL FUSION FACILITY

TEC

Structure of talk

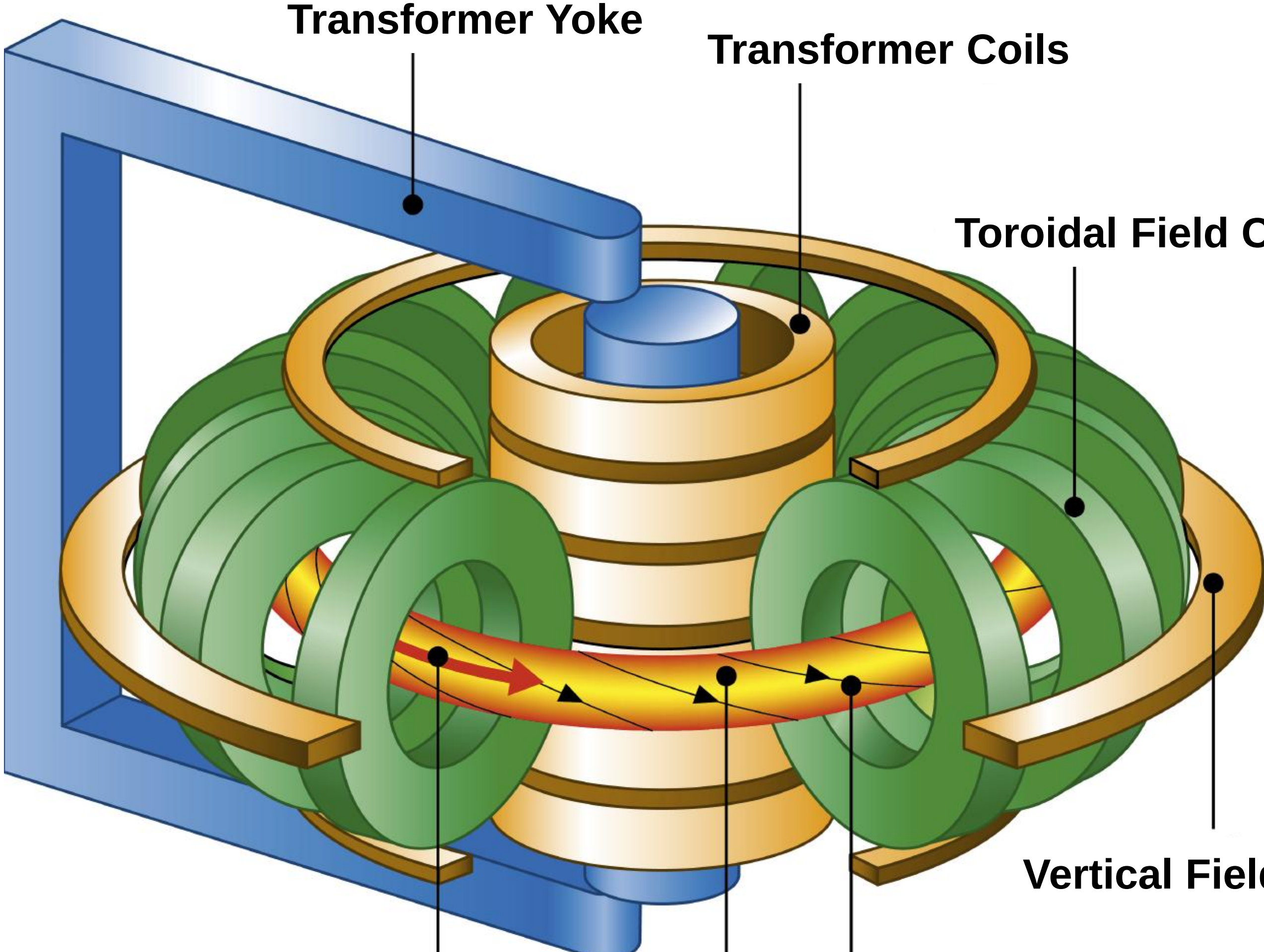
Motivation: why are 3D effects relevant in tokamaks?
ELM control with RMP

3D plasma boundary and plasma surface interaction
New state with new features

3D plasma boundary and transport hypothesis
Candidate mechanisms for RMP ELM control

3D plasma boundary @ ITER
Extrapolation with EMC3-Eirene

Introduction: Tokamak is usually treated as a toroidally axisymmetric system



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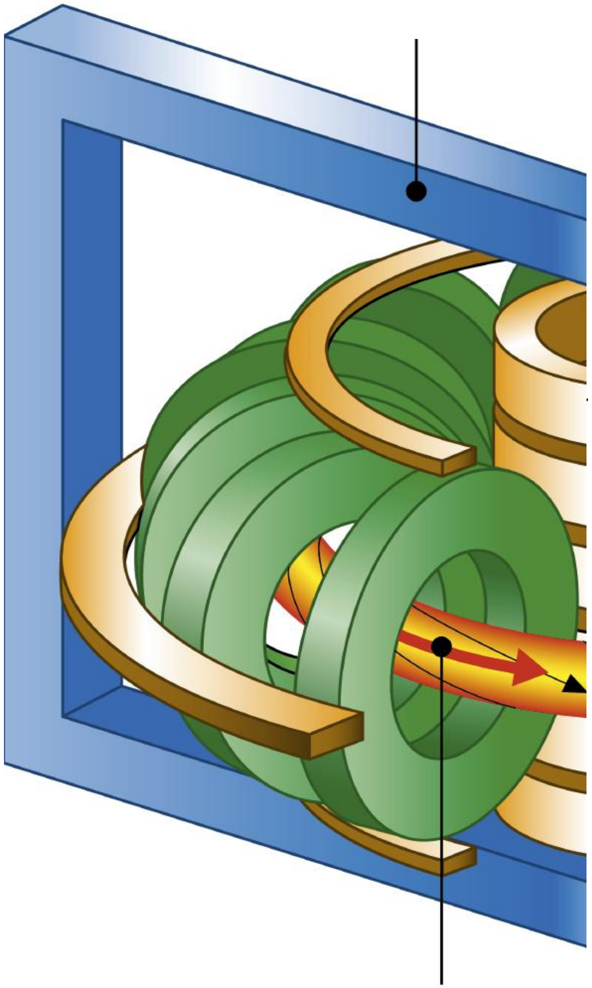
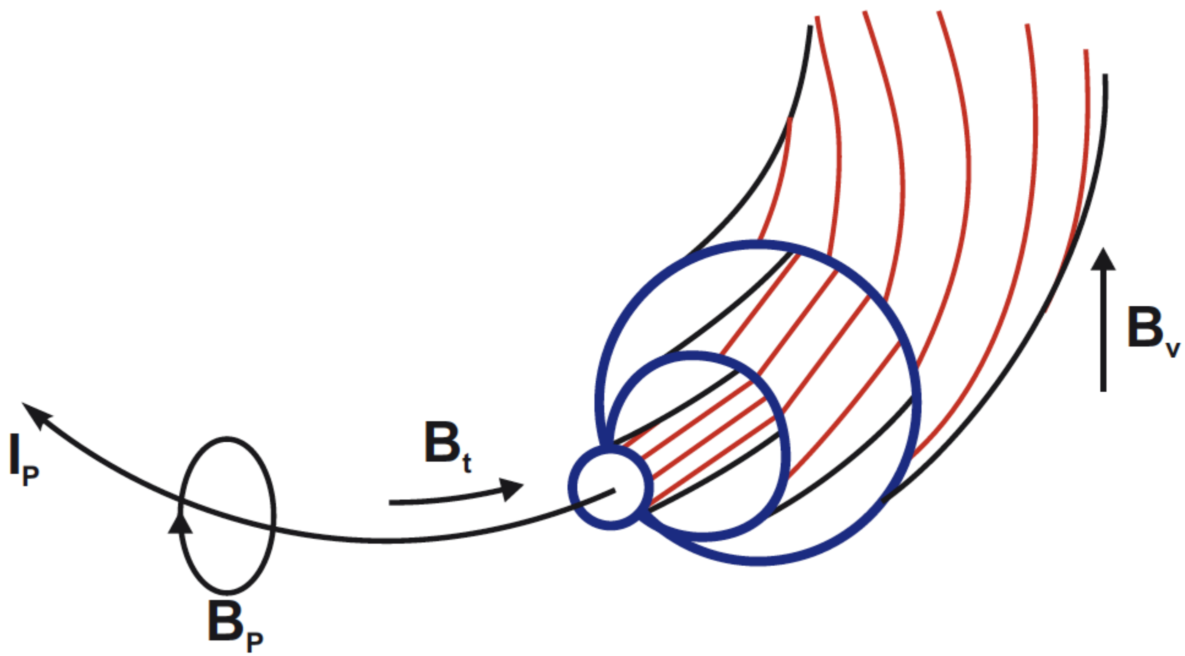


Nested flux surfaces confining the plasma



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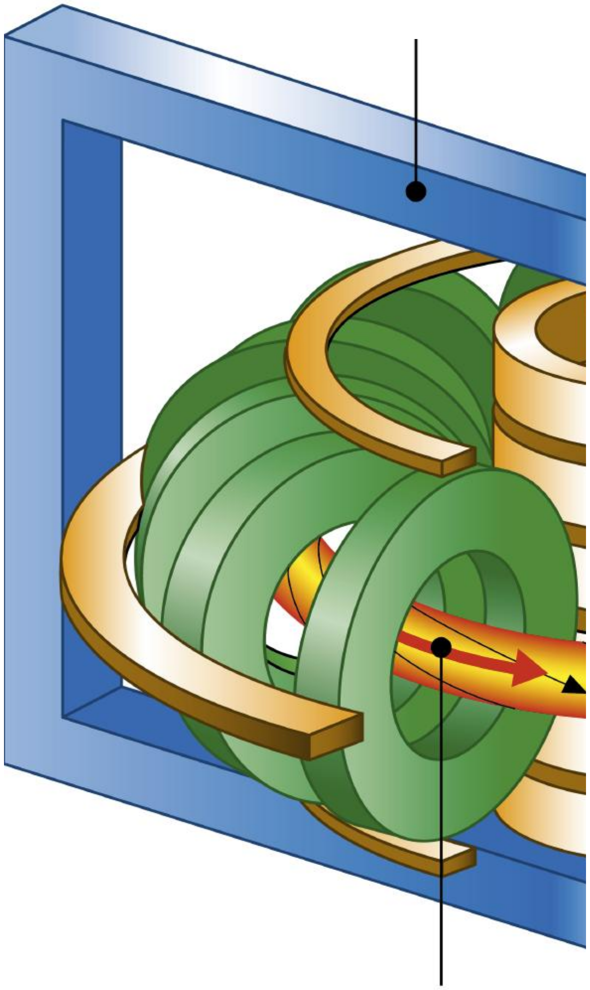
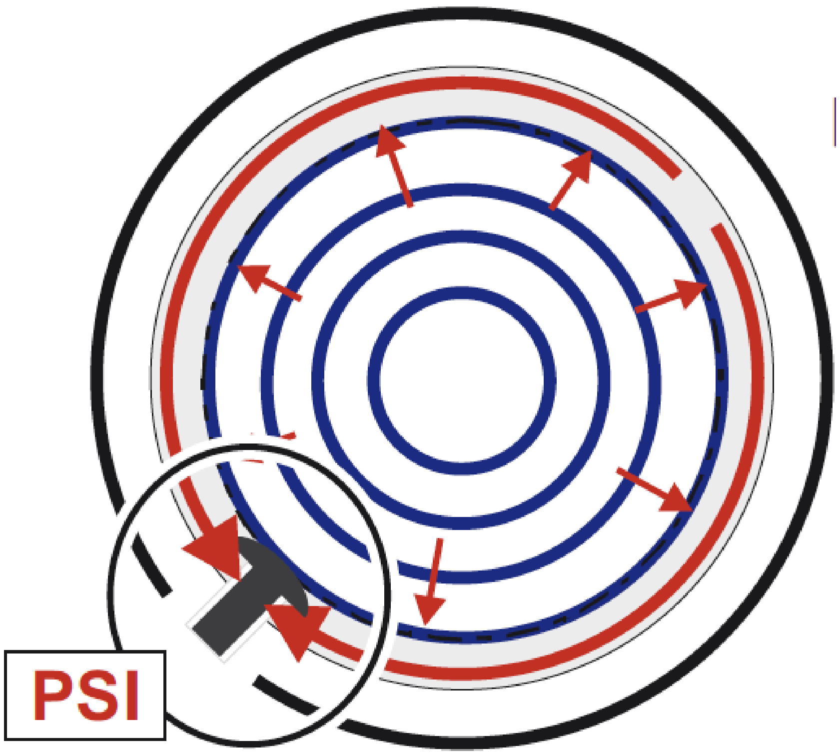


Challenge to exhaust particles and energy



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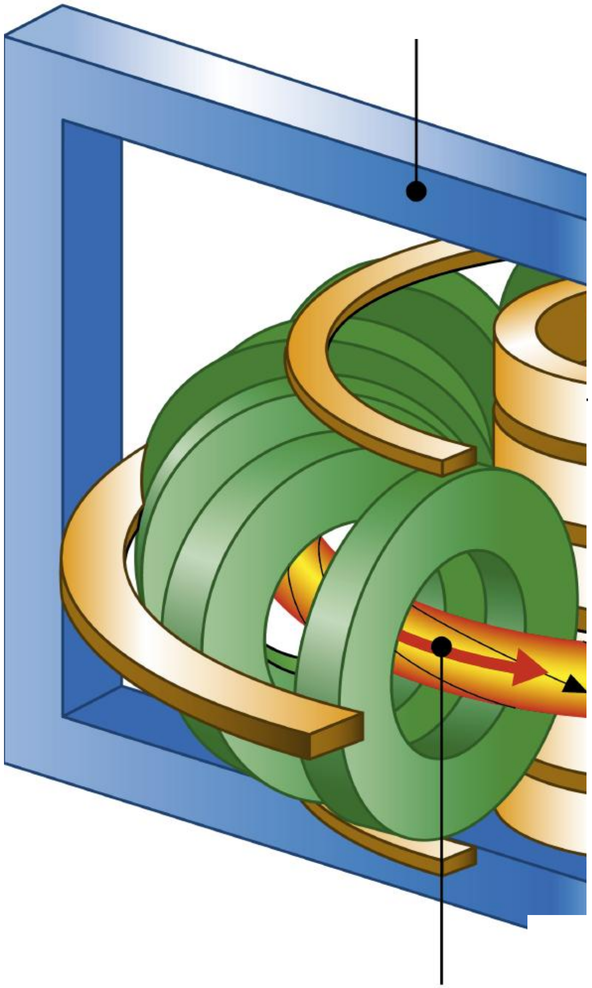

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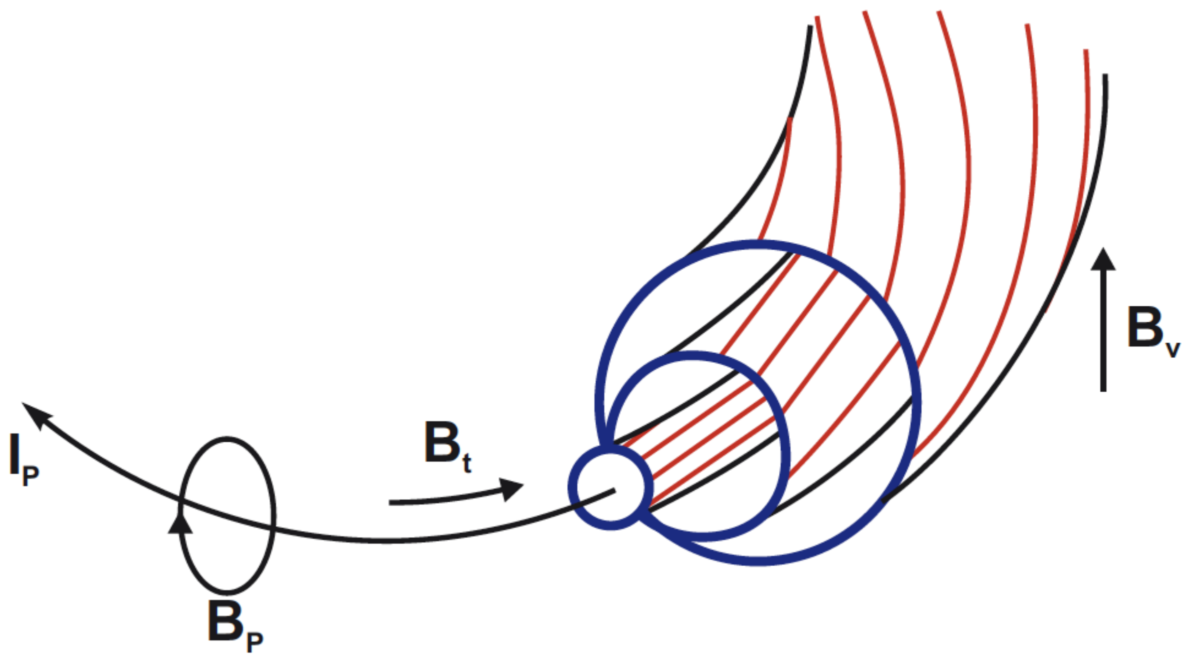

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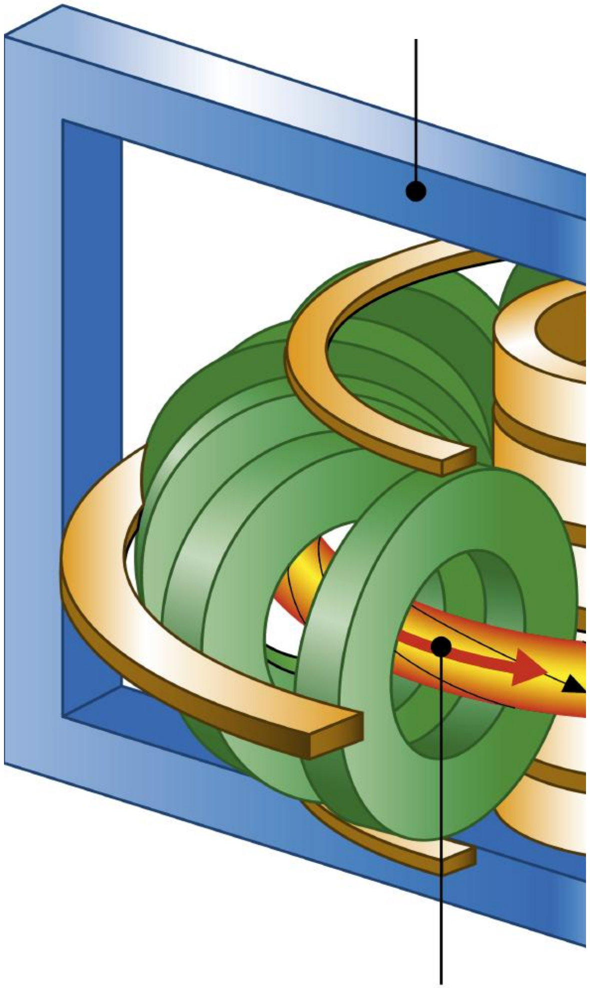
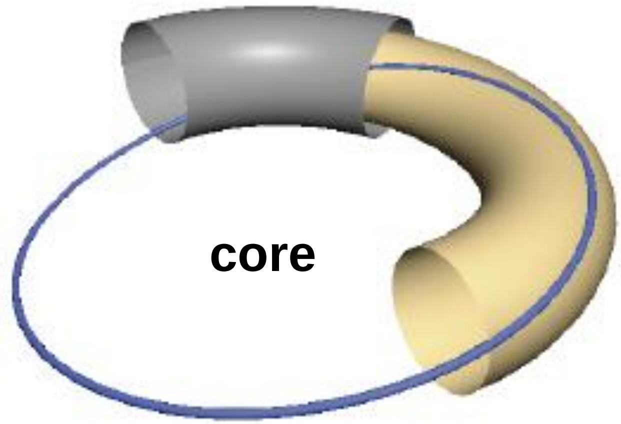
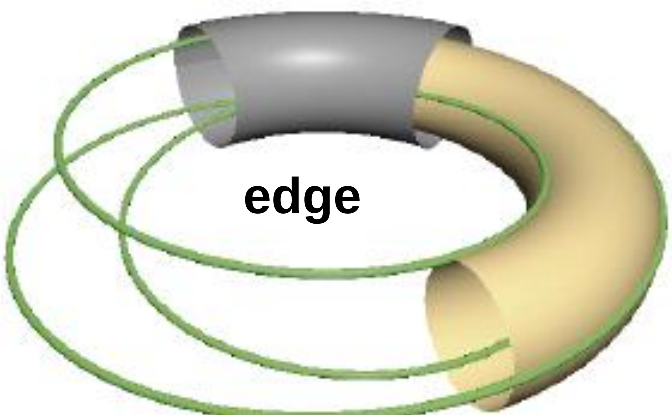


Resonant coupling to self-closing field lines





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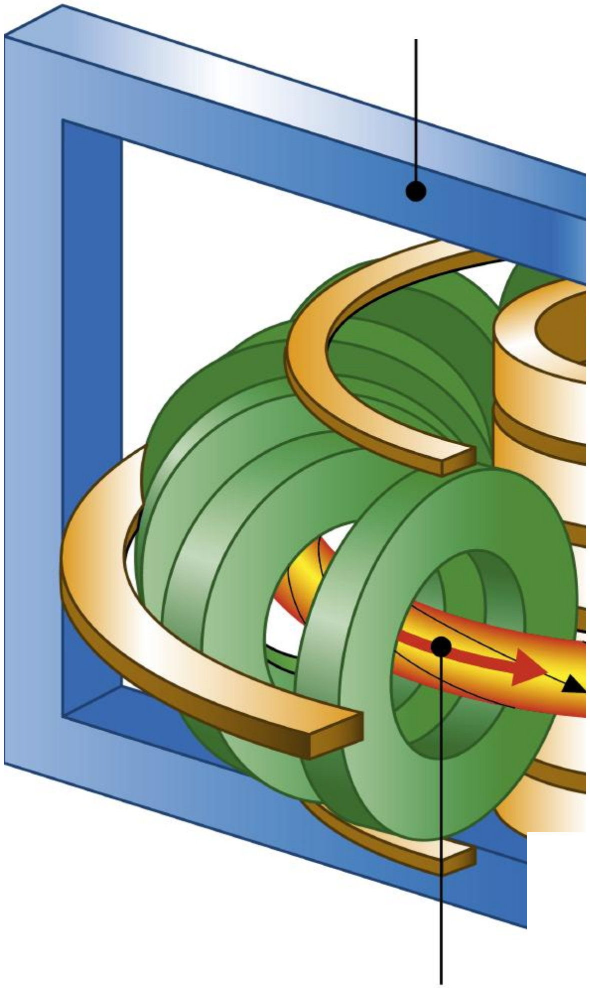
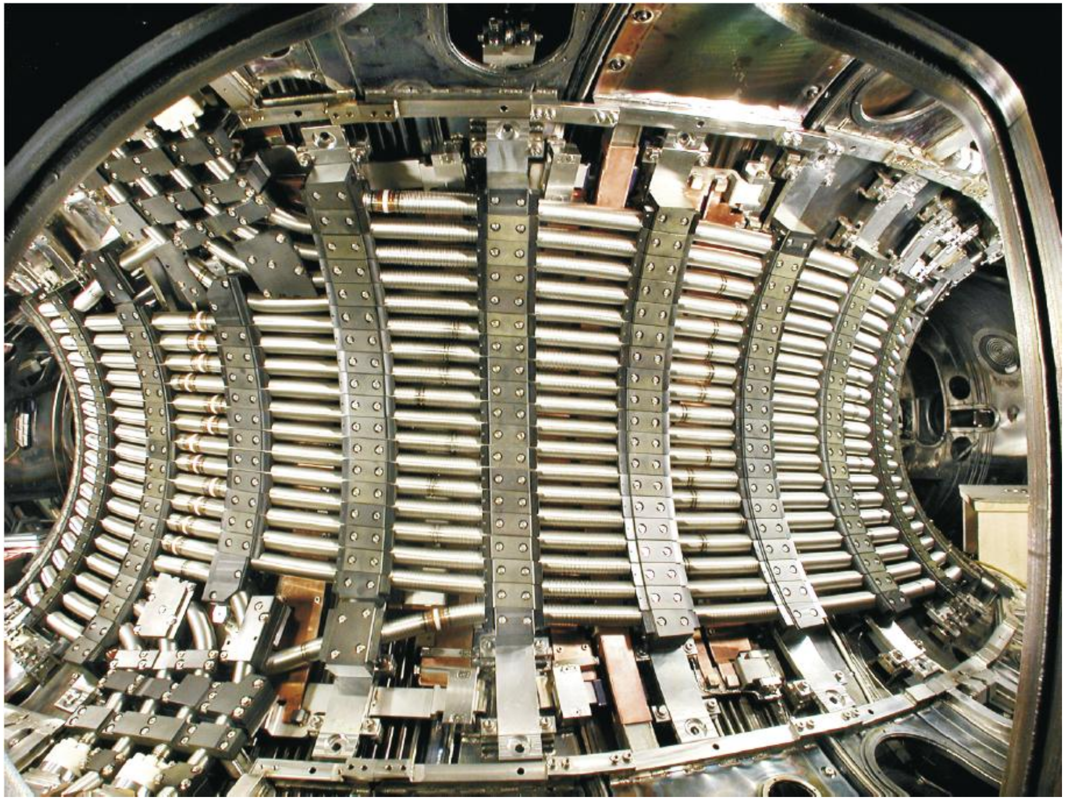


Well aligned external field yields local perturbation



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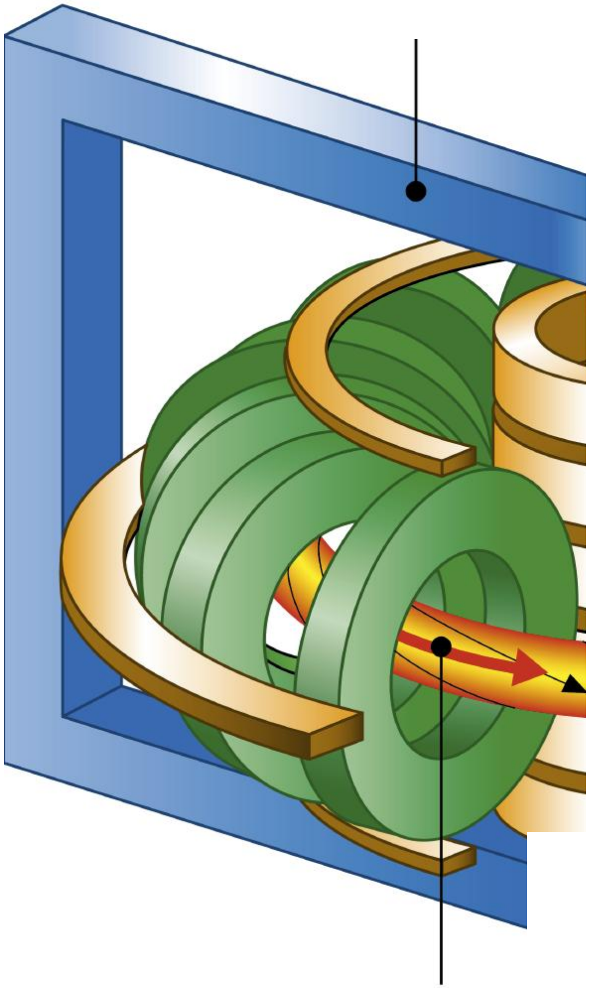
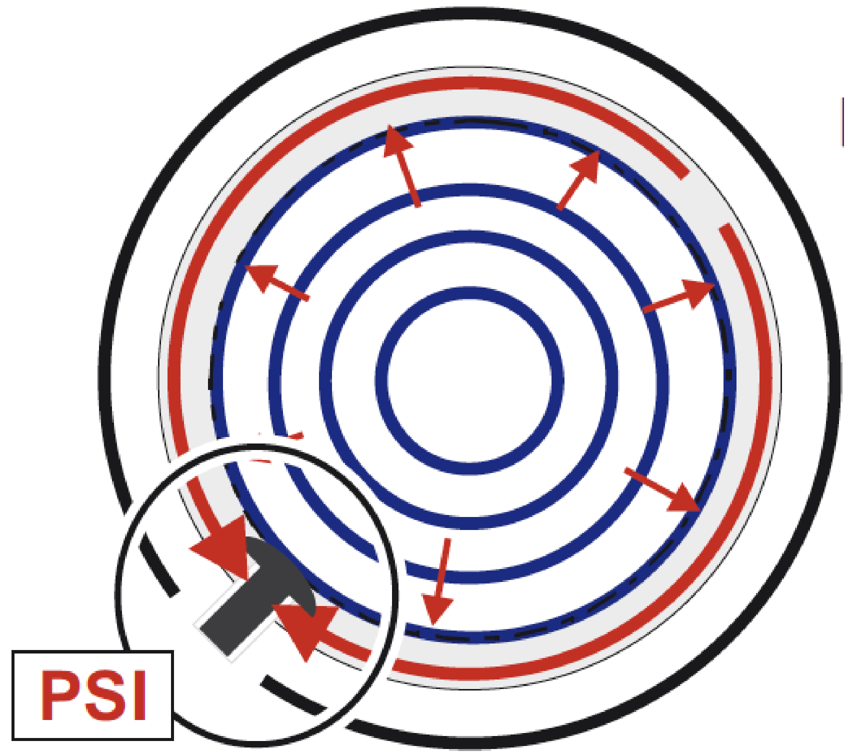


Stochastic magnetic edge is formed



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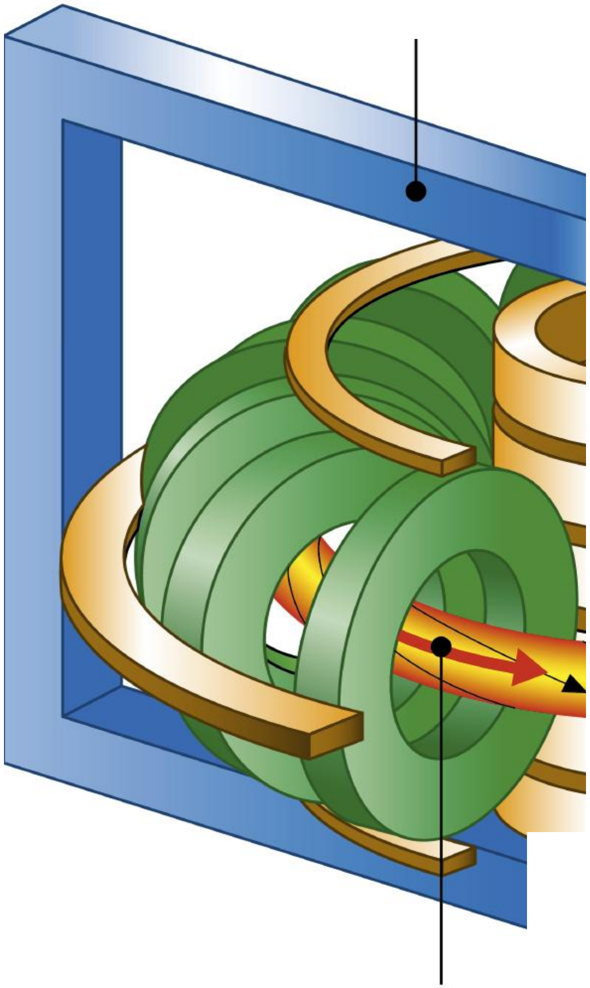

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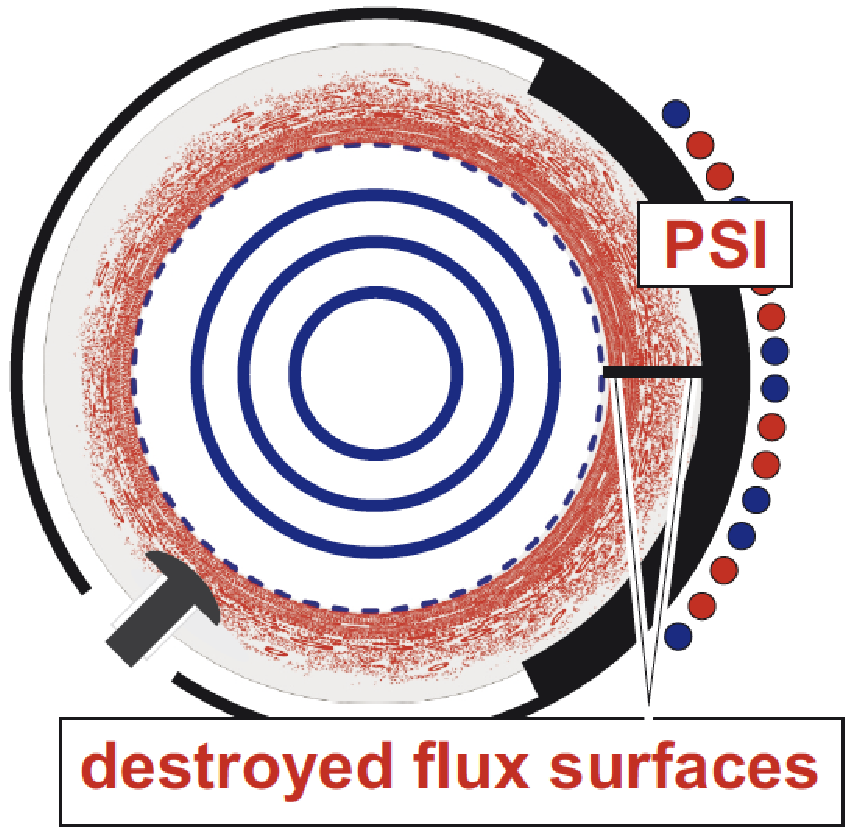
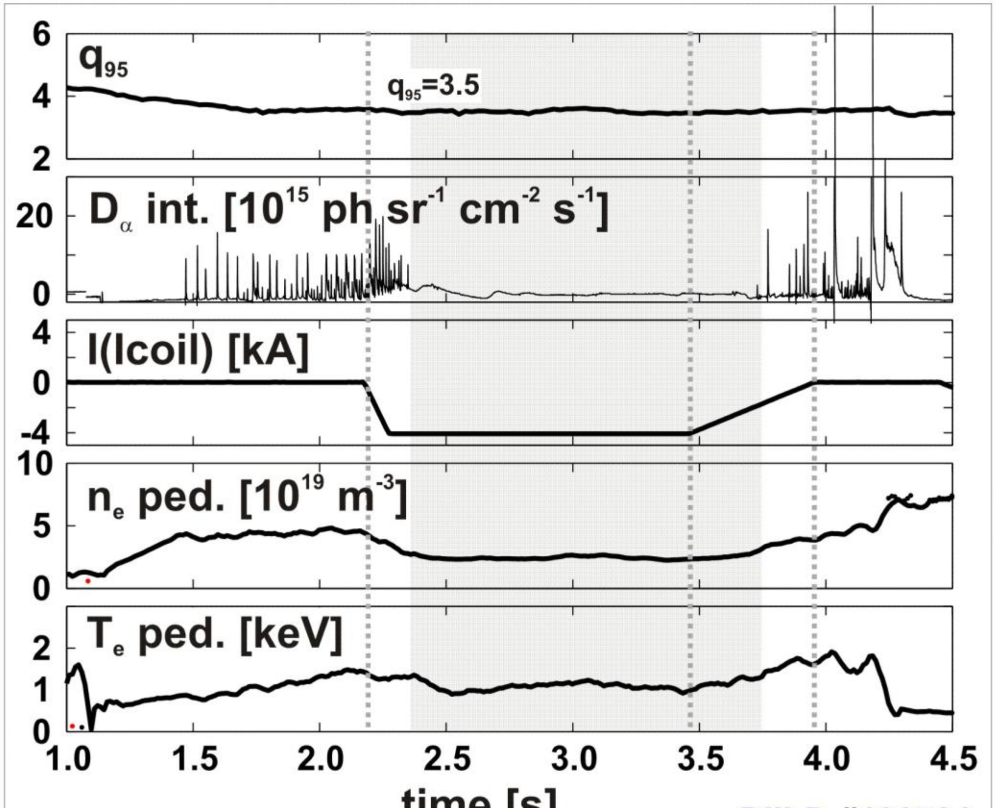
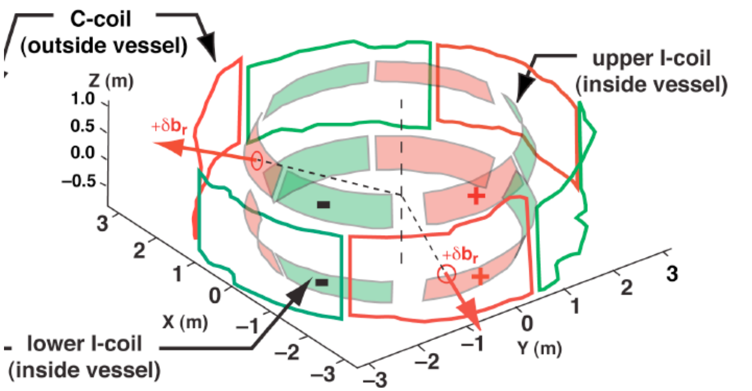


Motivation: ELM suppression by edge resonant magnetic perturbations was demonstrated at DIIID

[T.E.Evans et al. Nature of Physics 2 (2006) 419]



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

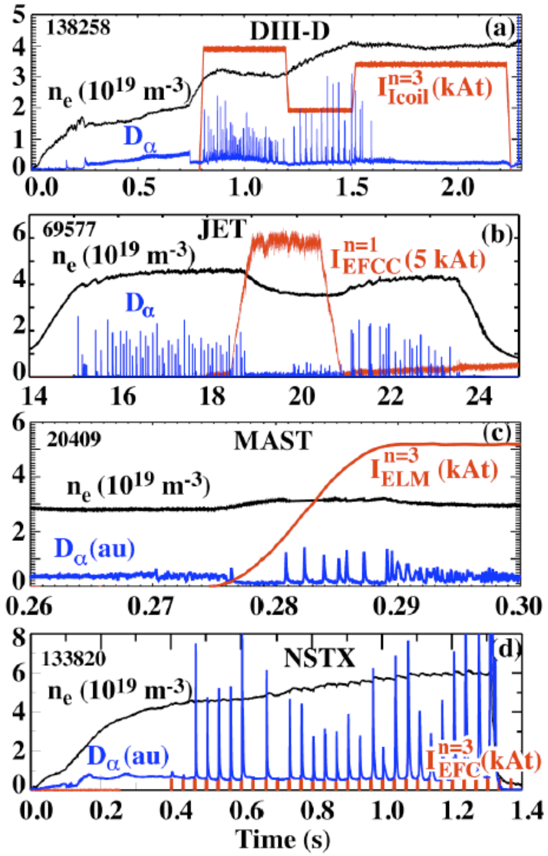


Ex-vessel, mid-plane centered coils (C-coil, EFC)

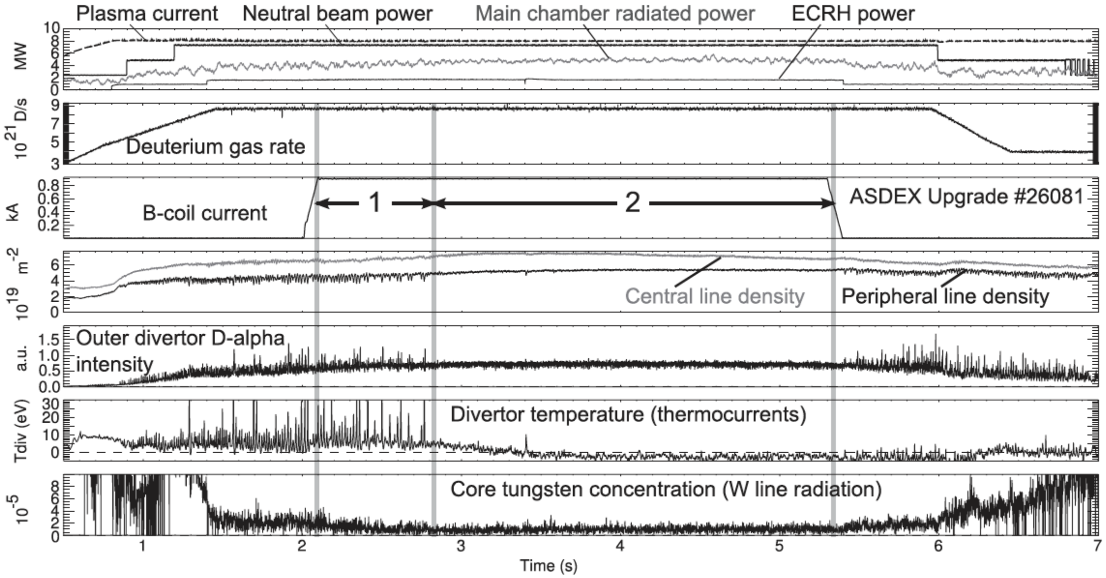
In-vessel, off mid-plane coils (I-coil, RMP + EFC)

ELMs were suppressed at DIII-D for different edge collisionalities ν_e* and shapes, in particular ITER similar shape (ISS) at ITER relevant ν_e*~0.1 [T.E.Evans NF 2008]

Motivation: ELM suppression by edge resonant magnetic perturbations is a worldwide effort



[M. Fenstermacher et al., IAEA FEC 2010, Daejon, Korea]



[W. Suttrop et al., Phys. Rev. Letters 106 (2011)225004]

Control of ELMs by RMP is envisaged as key functionality for protection of the wall integrity at ITER

Structure of talk

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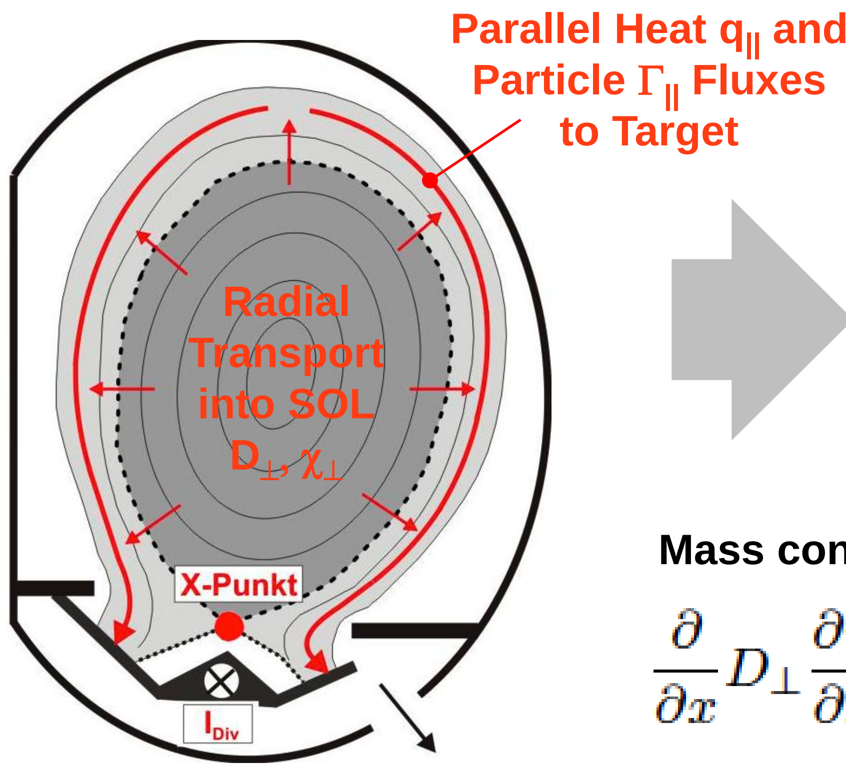
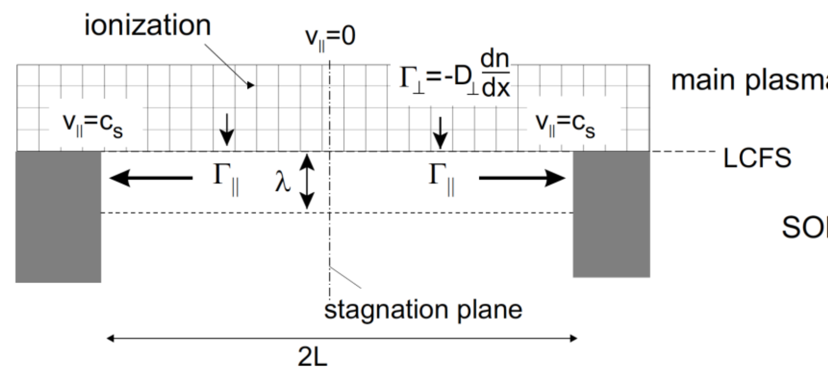
3D plasma boundary and plasma surface interaction
New state with new features

Introduction: Axisymmetry is Assumed to Design the Divertor Components

Simplified Example for Calculation of Deposition Width





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

Mass conservation in open field line region:

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

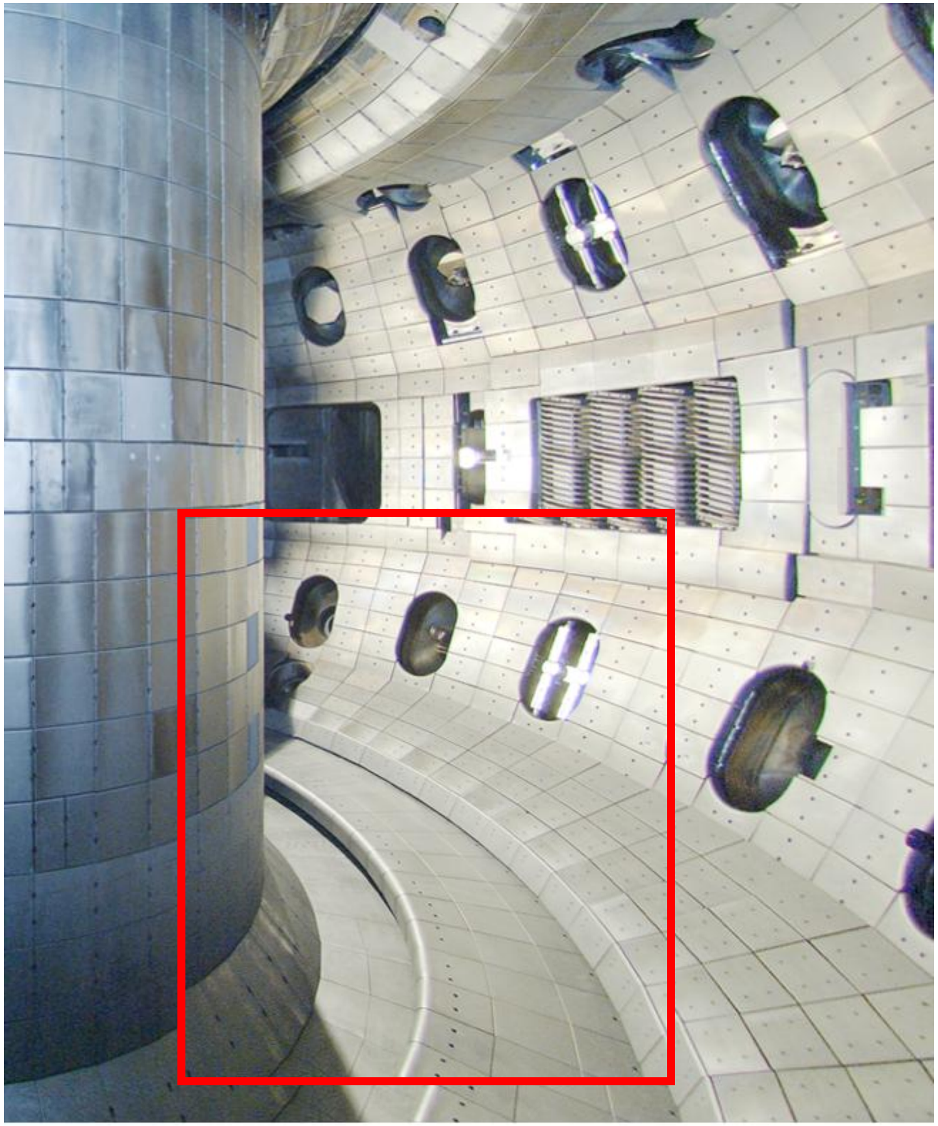
Radial constant diffusion, parallel flow with $n/\tau_{||}$

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

Thin deposition width ➡ $\lambda = \sqrt{D_\perp \tau_{||}}$ ➡ $\lambda = \sqrt{\frac{D_\perp L}{0.5\, c_s}}$

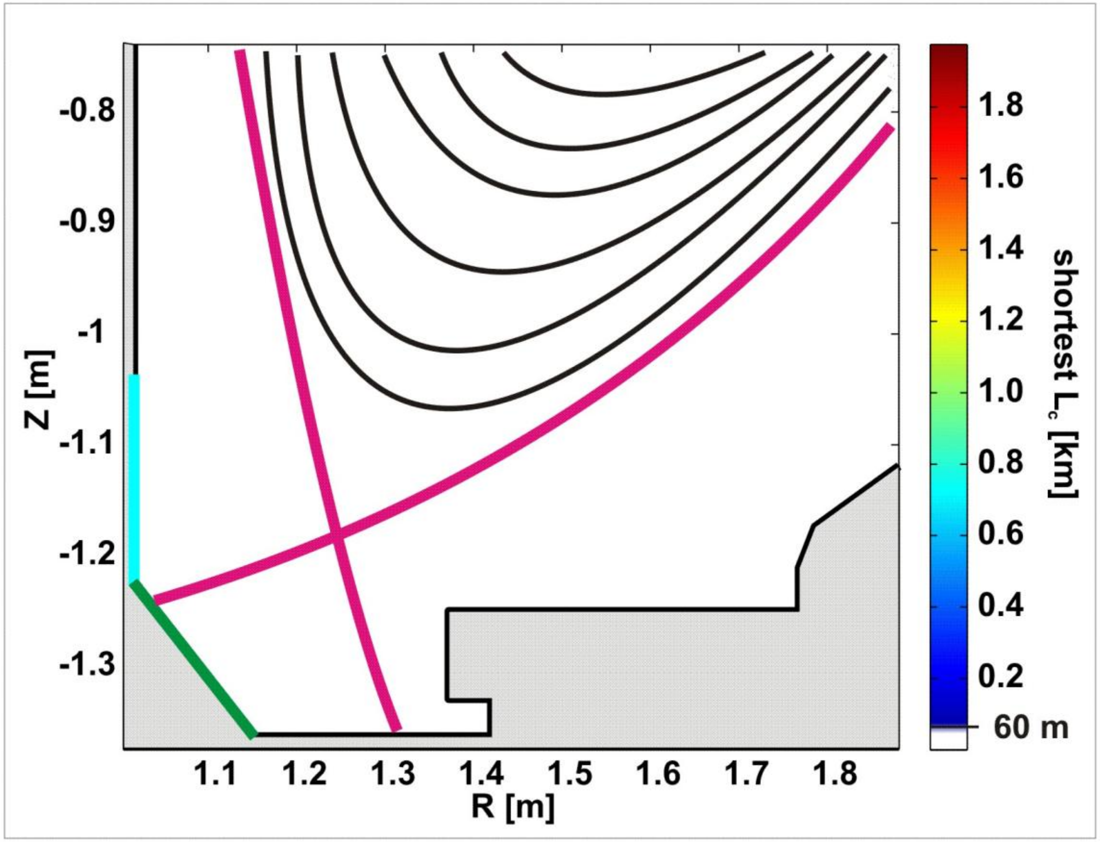
Strong symmetry assumptions

- **RMP fields applied for ELM control break the axisymmetry of the plasma boundary**



RMP fields applied for ELM control break the axisymmetry of the plasma boundary

- The separatrix is very sensitive to external and internal perturbation fields



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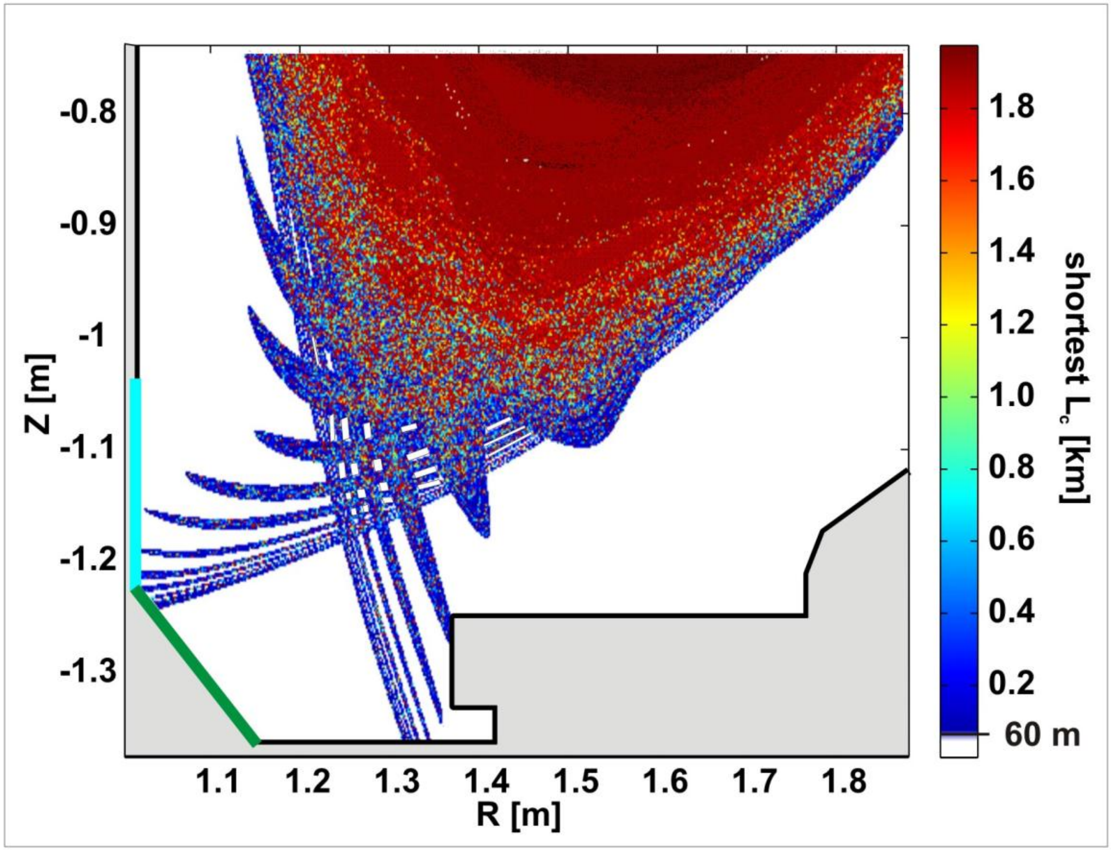

- **Typical magnetic perturbation field strengths B_r applied are $B_{r,\,n=3}$= 4G, i.e. $B_r/B_T = 0.5 \times 10^{-4}$**

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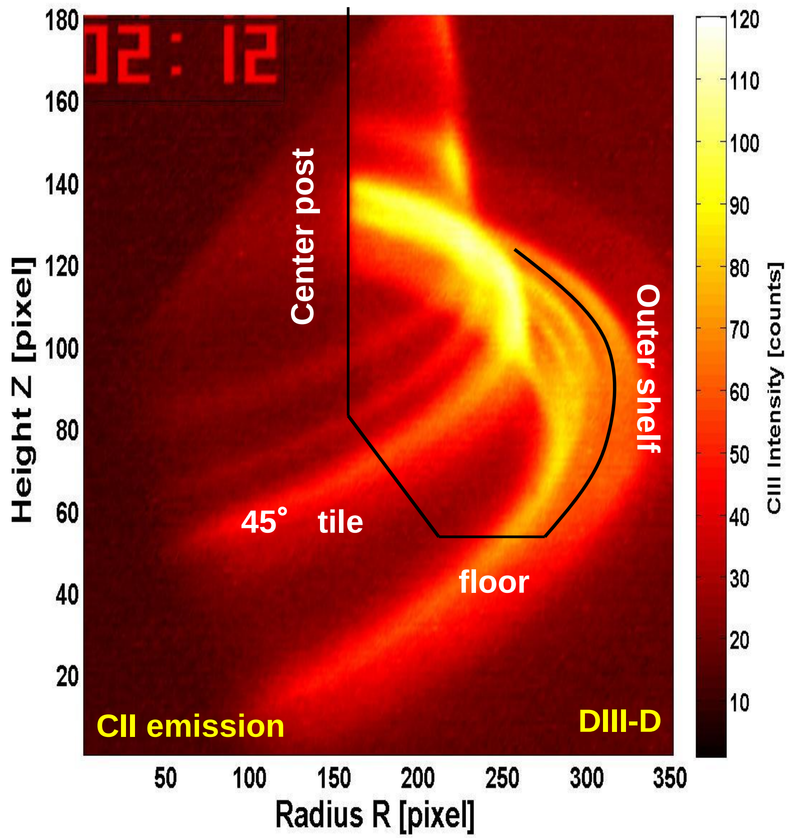

- **Typical magnetic perturbation field strengths B_r applied are $B_{r,\, n=3}$ = 4G, i.e. $B_r/B_T = 0.5 \times 10^{-4}$**

Striated, helical divertor fluxes are connected to application of RMP fields

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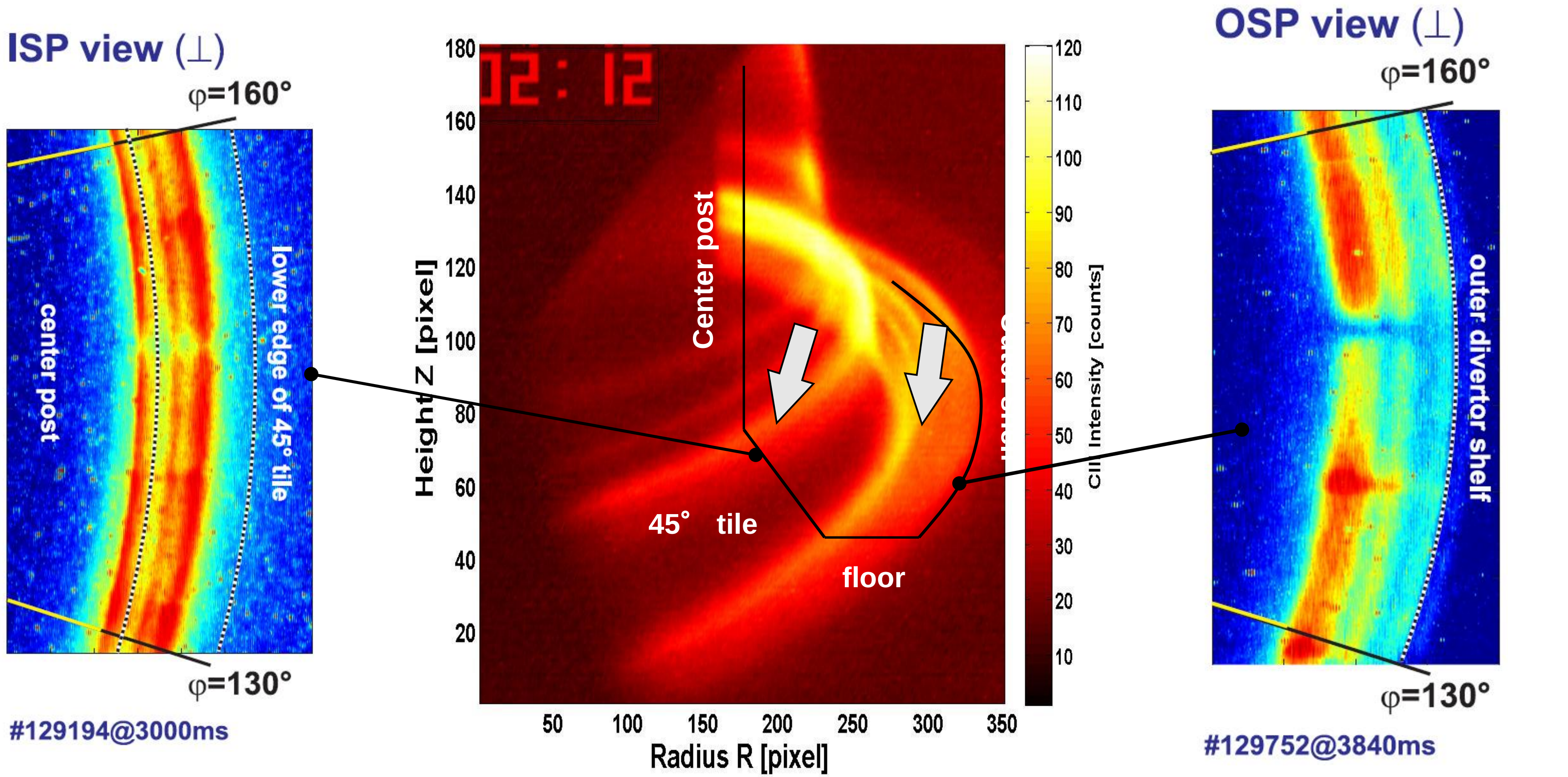
[T.E. Evans et al., Journ. Phys. **7**, 174 (2005)] [O. Schmitz et al., JNM **415** (2011) 886-893] [M. Jakubowski et al., Nucl. Fusion **49** (2009) 095013]



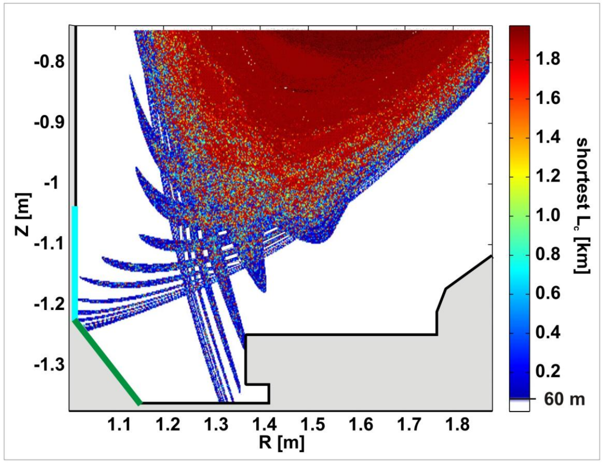
Striated heat and particle fluxes are connected to ELM suppression at DIII-D

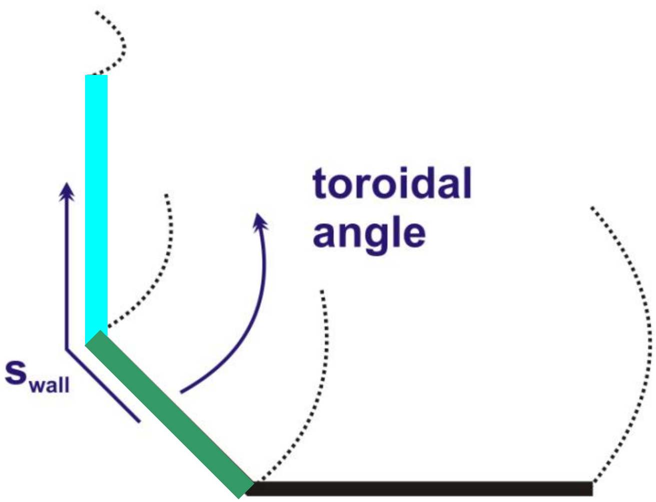
Weak heat flux filling of lobes

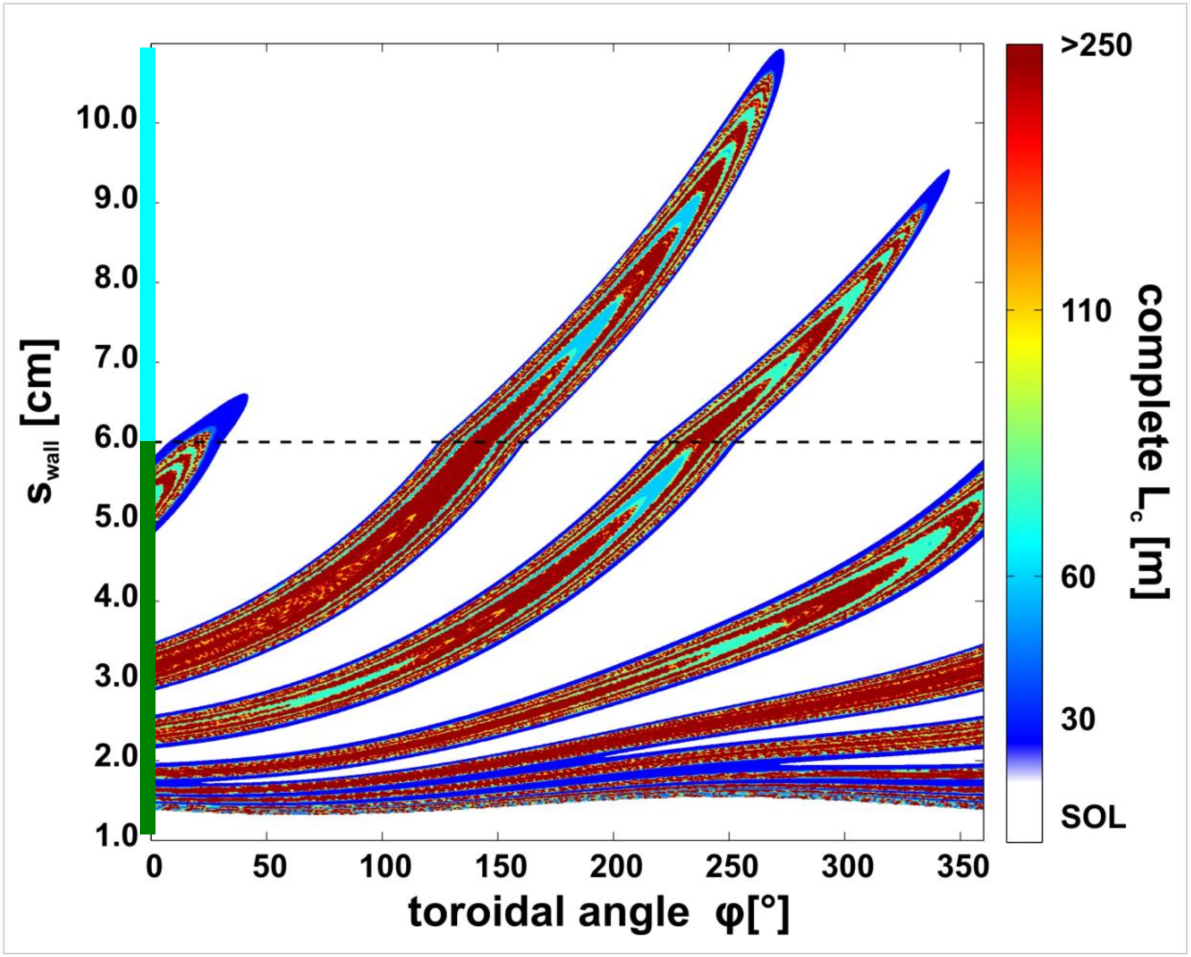
Always clearly seen in particle flux

Geometry: fair agreement with vacuum topology found

Poloidal divertor – formation of separatrix sets a boundary for the stochastic system



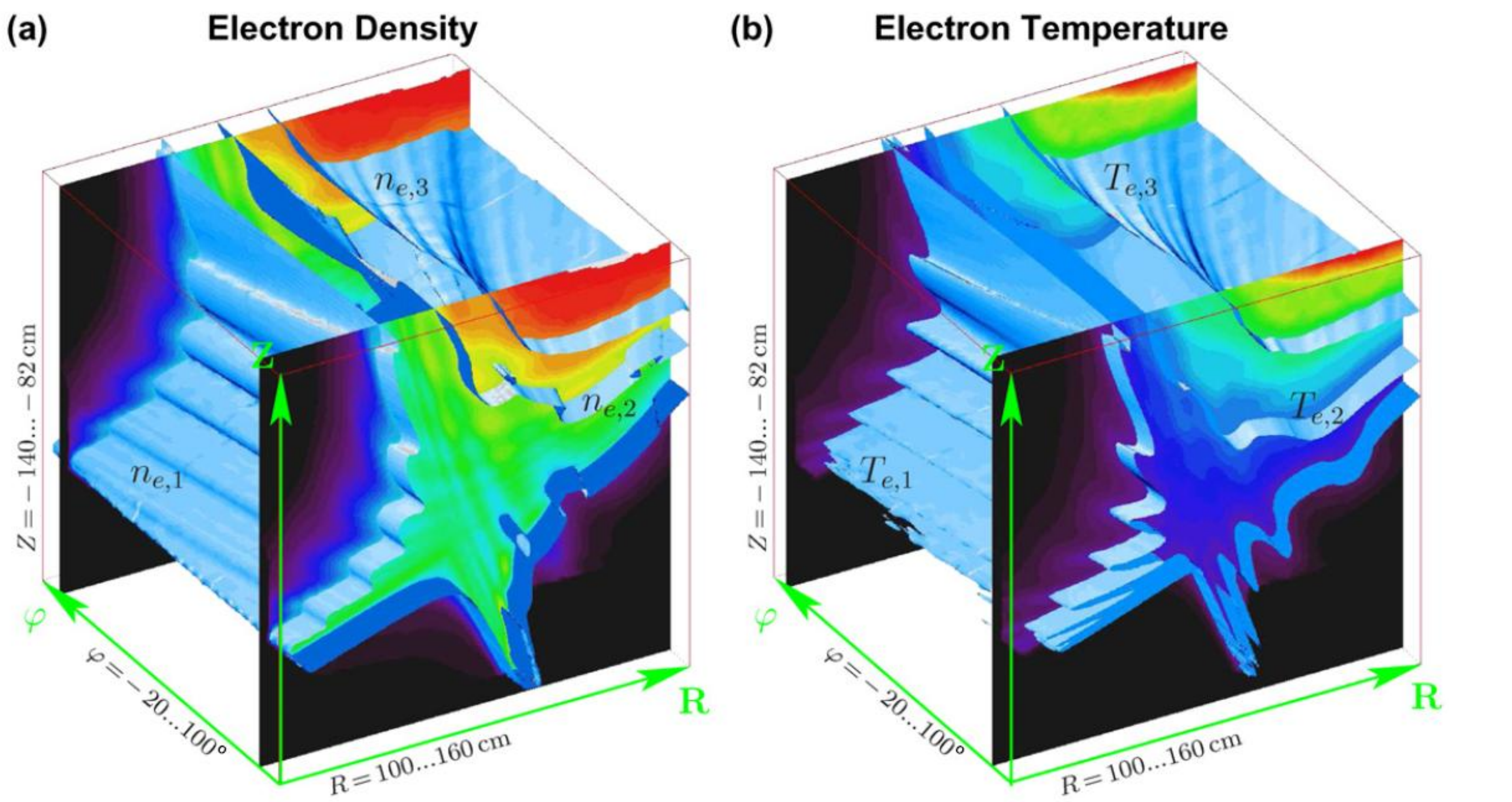




Perturbed separatrix represents envelope for stochastic interior

Perturbed separatrix defines 3D shape of the plasma boundary

EMC3/EIRENE modeling results

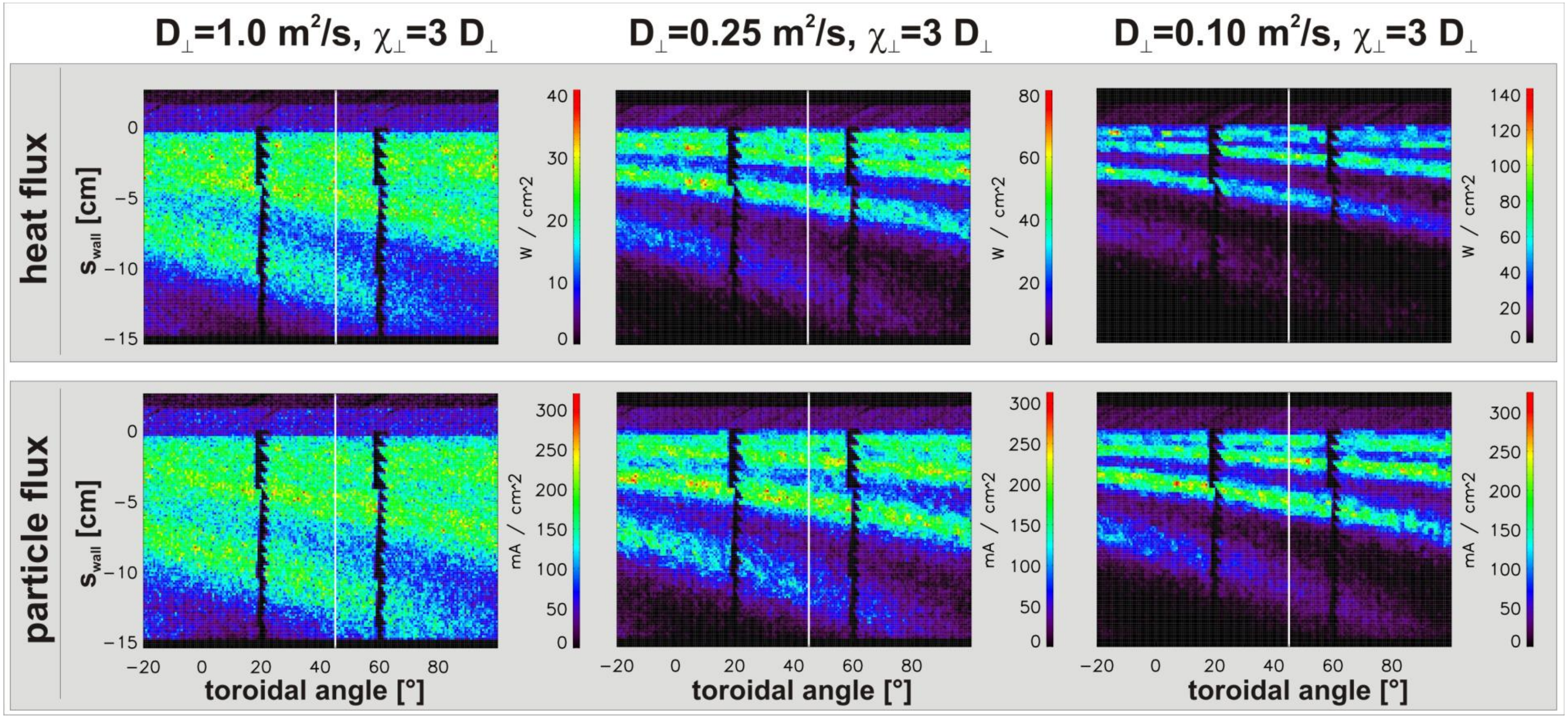


H. Frerichs et al. Nuclear Fusion **50** (2010) 034004

Plasma and neutral transport modeling predicts 3D boundary in electron and ion temperature and density fields

Modeled target particle and heat fluxes follow magnetic footprint pattern

EMC3/EIRENE modeling results



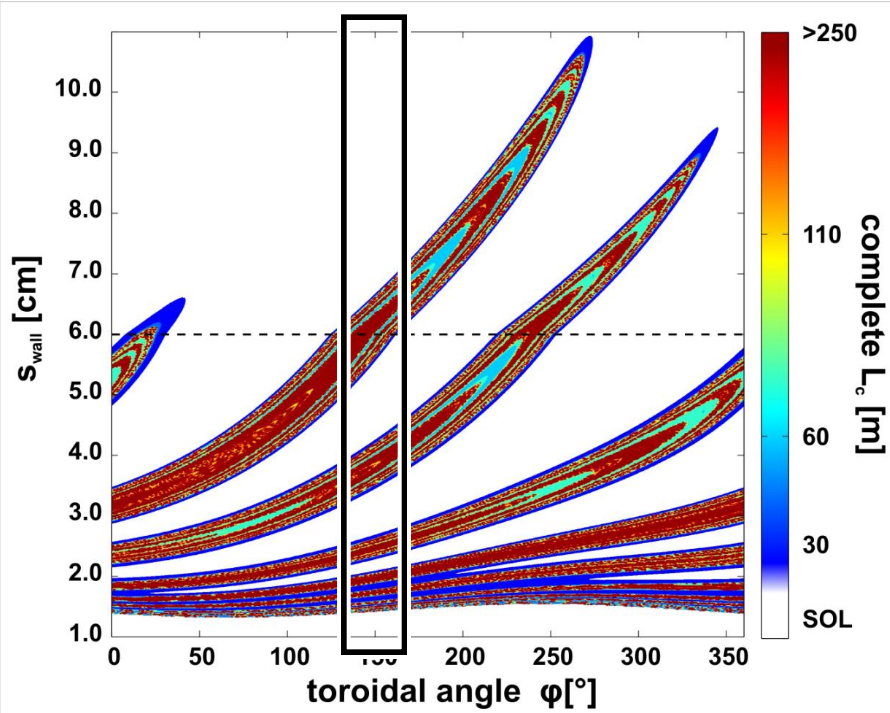
H. Frerichs et al. Nuclear Fusion **50** (2010) 034004

Low diffusive transport required to see striated magnetic footprints

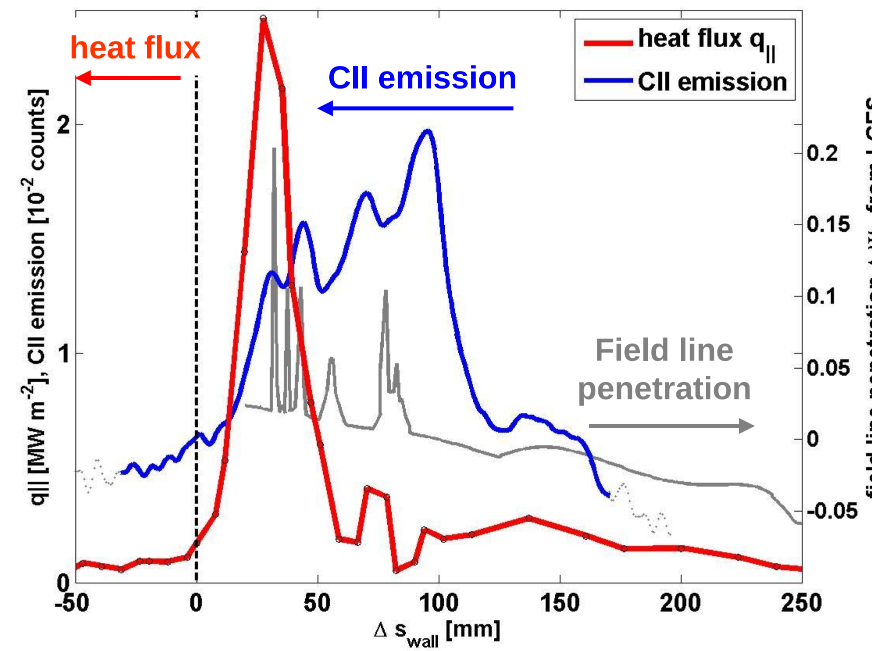
Lobes must be filled by dominant parallel transport along open field lines

In ELM controlled H-modes, vacuum modeled lobes define position of heat and particle fluxes onto target

O. Schmitz et al. PPCF **50** (2008) 124029 [O. Schmitz et al., JNM **415** (2011) 886-893]



H-mode plasma



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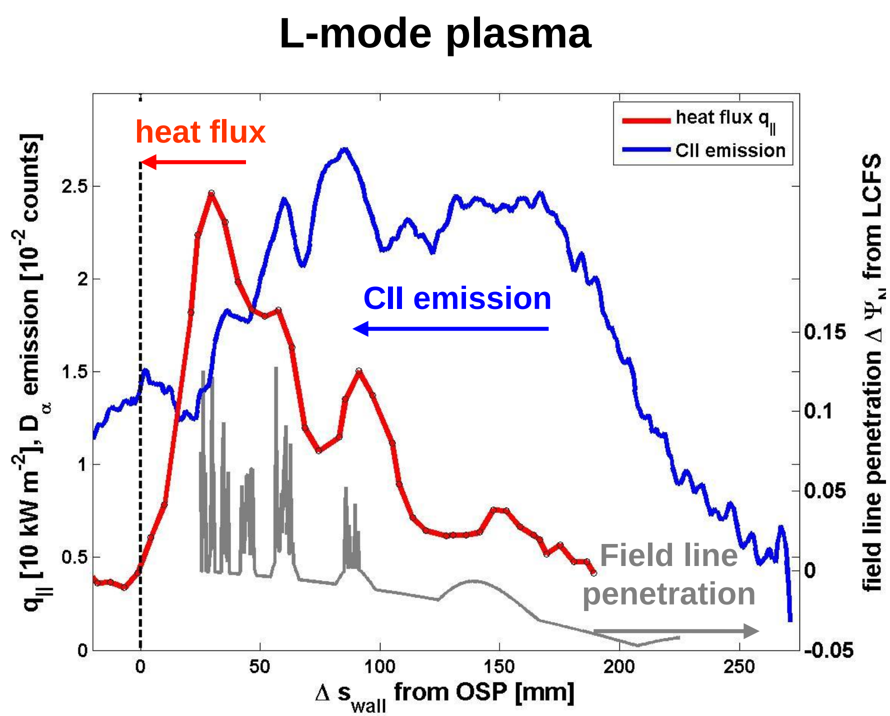
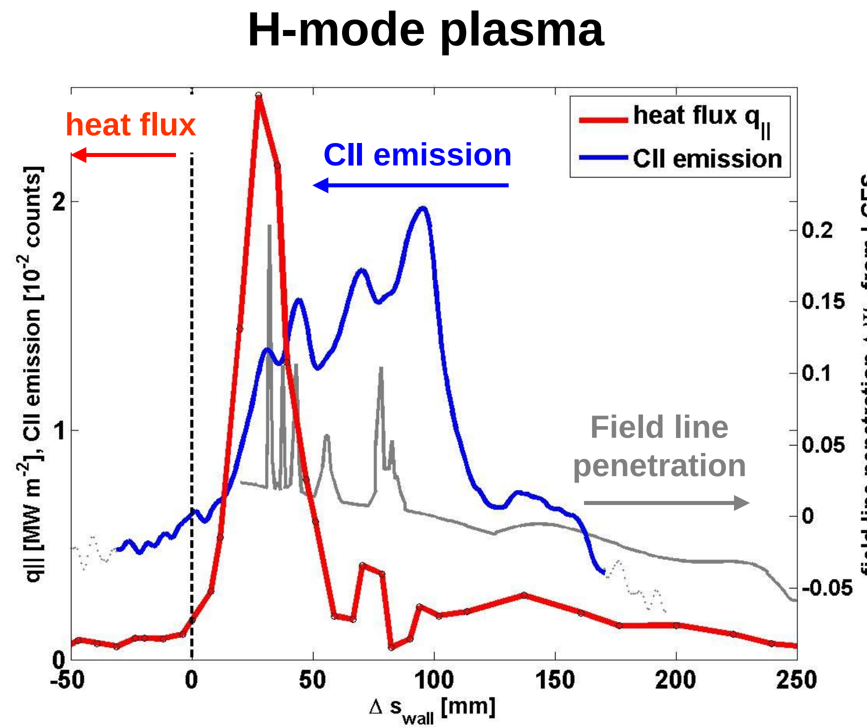




Proves existence of the separatrix lobes and a 3D plasma boundary

However, only indirect information about interior stochastic structure!

Exact shape is determine by sum of all radial perturbations at the separatrix

Structure of talk

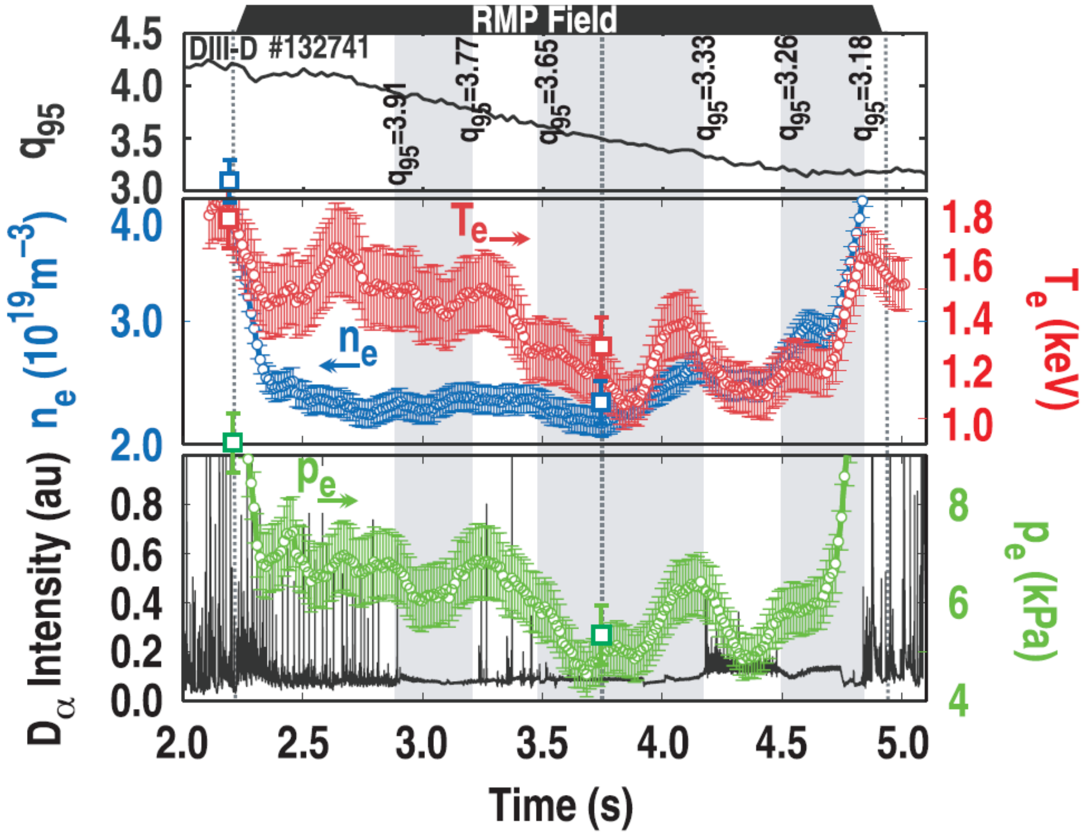
Motivation: why are 3D effects relevant in tokamaks?
ELM control with RMP

3D plasma boundary and plasma surface interaction
New state with new features

3D plasma boundary and transport hypothesis
Candidate mechanisms for RMP ELM control

Electron temperature resonance is a pre-requisite for q_{95} resonance of ELM suppression at low ν_e^*

O. Schmitz et al., Phys. Rev. Lett. **103** (2009) 165005 O. Schmitz et al., Nuclear Fusion **52** (2012) 043005



Global density pump out

+

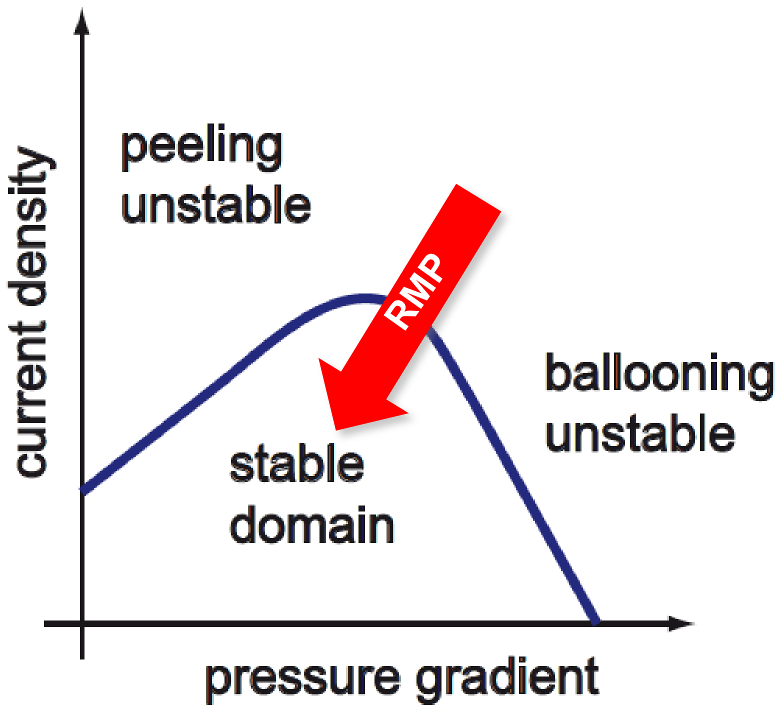
High T_e sensitivity on q_{95}

Highly q_{95} dependent pressure reduction at the pedestal

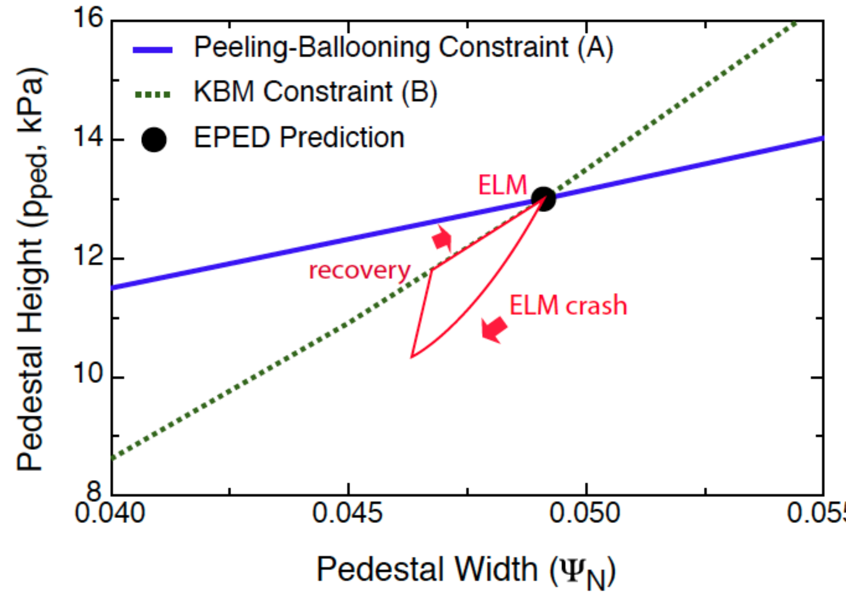
- ELM suppression is not linked to specific pedestal pressure value as peeling-ballooning stability is determined by complete plasma pressure profile shape
- Edge current density changes are not addressed yet at all (DIII-D)

Potential mechanism for ELM stabilization by RMP

ELM as MHD instability



EPED stability model of ELM cycle



[P. Snyder et al. Physics of Plasmas **19** (2012) 056115]

Pedestal height and width determine stability against peeling-ballooning modes and kinetic ballooning modes (local effects)

Local kinetic effects ("Kinetic Ballooning" modes KBM) interact with global modes (P-B modes) on pedestal width scale and determine stability

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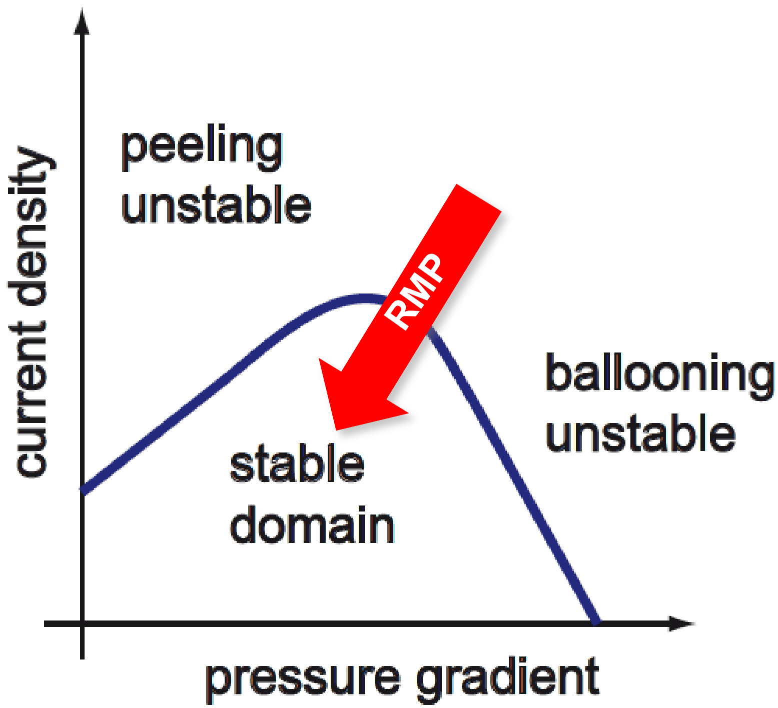

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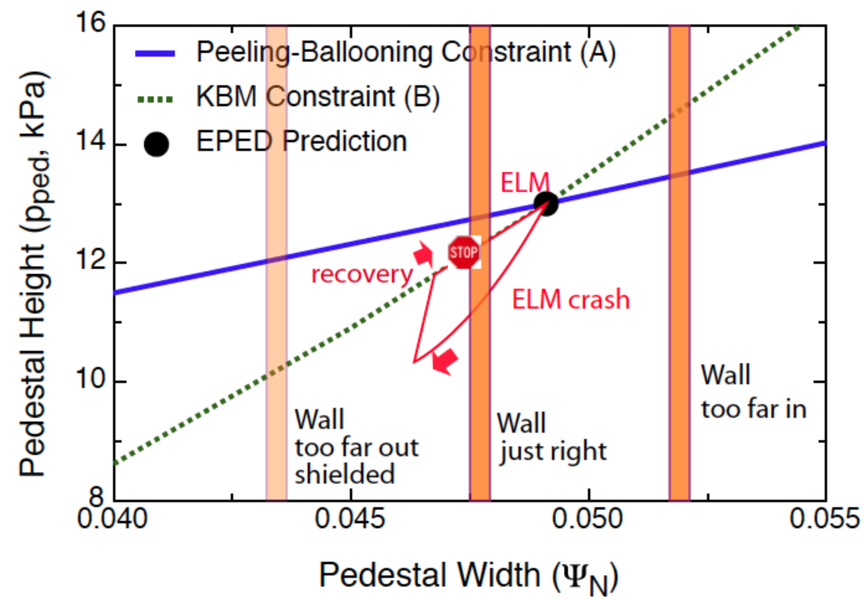


[P. Snyder et al. Physics of Plasmas **19** (2012) 056115]

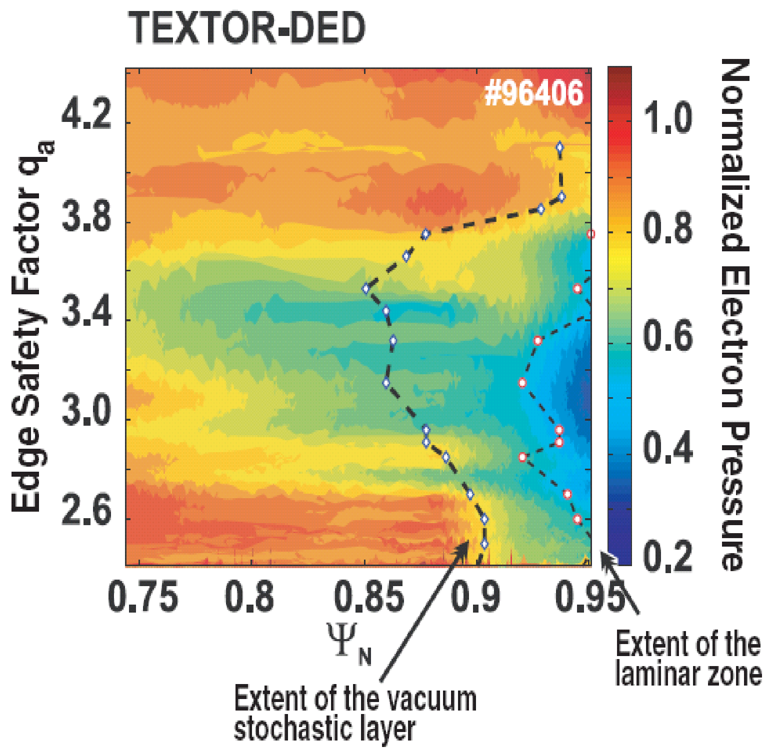
Candidates for stop mechanism?

-Open field line layer as new LCFS definition

-Magnetic island at right location within pedestal

Pedestal pressure profiles resemble stochastic layer width at DIII-D and TEXTOR

O. Schmitz et al., Phys. Rev. Lett. **103** (2009) 165005



➯ **Field line connection length L_c compared to**
(a) Kolmogorov Length L_K and
(b) electron mean free path λ_e

- **Laminar Zone: $L_c < L_K \sim \lambda_e$ (Y_N>0.95)**
- **Stochastic Layer: $L_c > L_K \sim \lambda_e$ (Y_N>0.8)**

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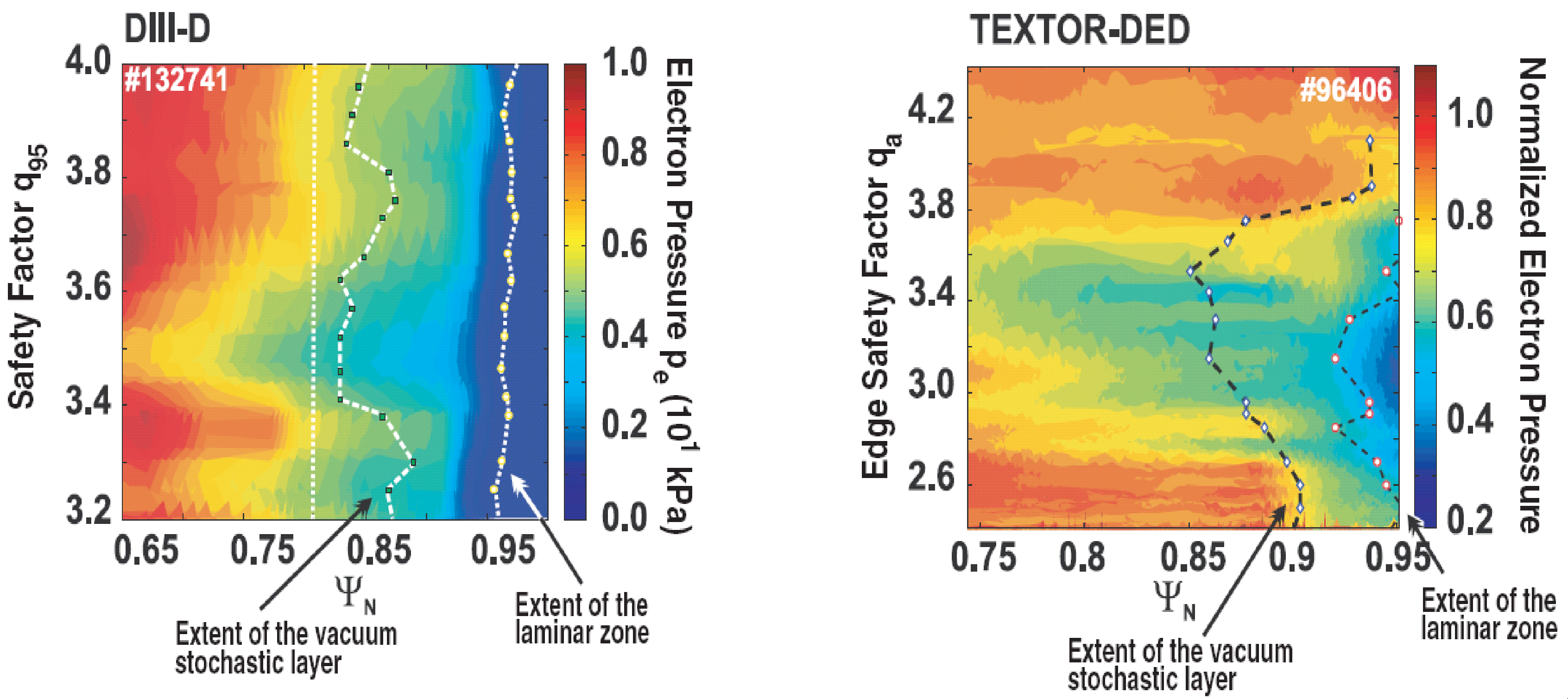
O. Schmitz et al., Phys. Rev. Lett. **103** (2009) 165005



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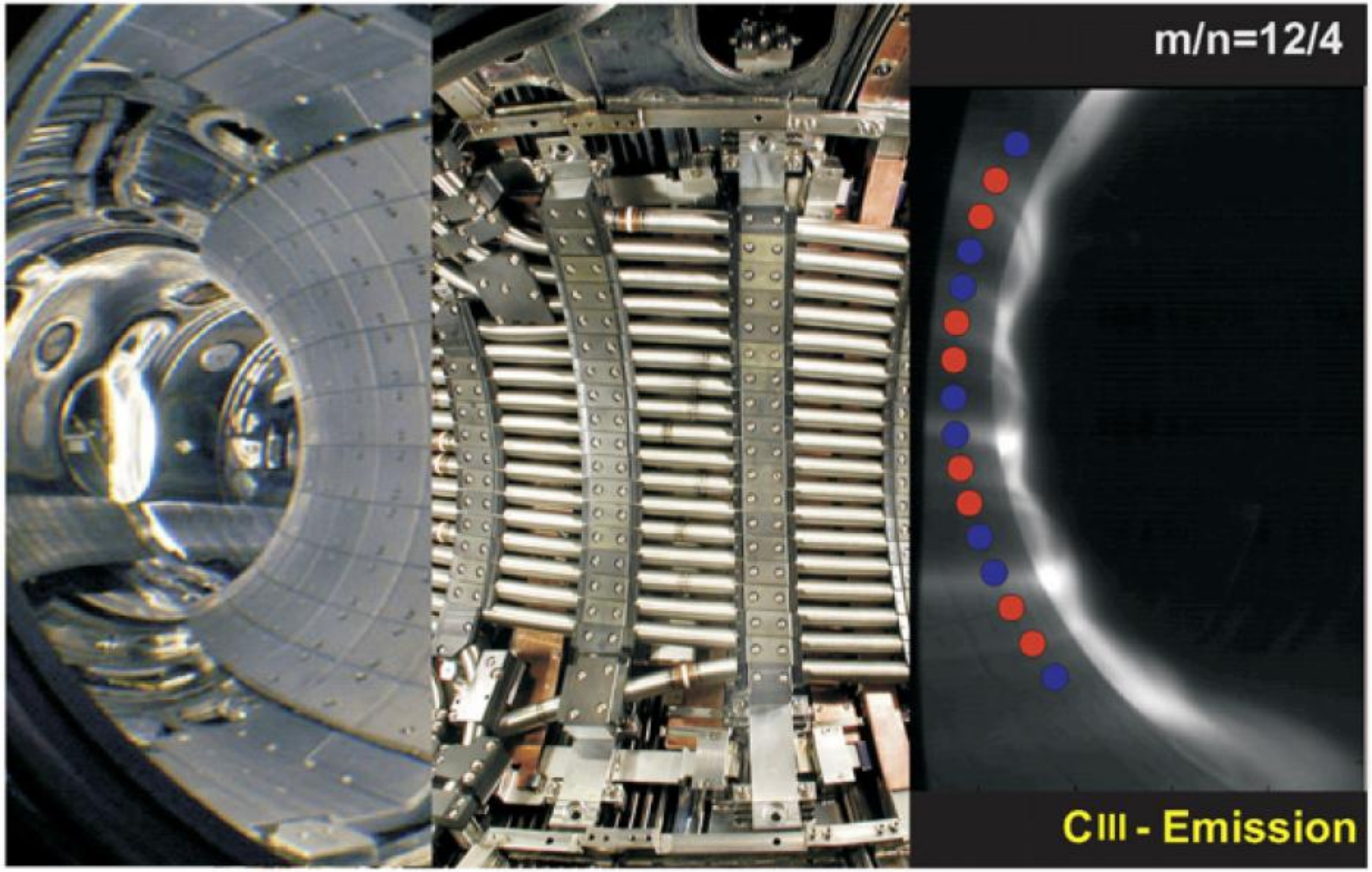
Link between exact profile shape and stochastic vs. laminar field line topology?

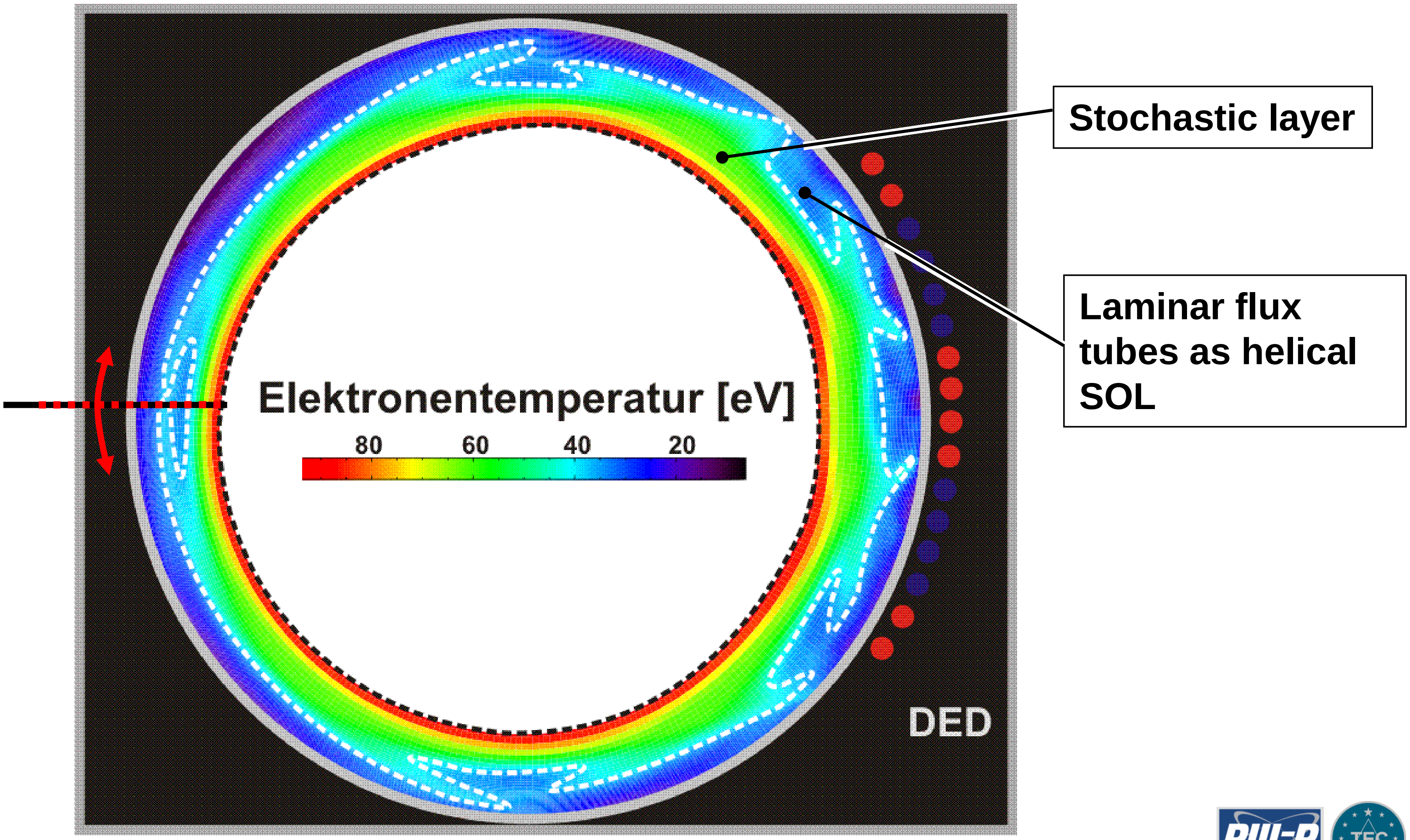
DED at TEXTOR as flexible tool to generate highly edge resonant perturbation fields



3 pitch resonant base mode spectra: m/n=12/4, 6/2, 3/1	AC operation: 1,2,5,10 kHz

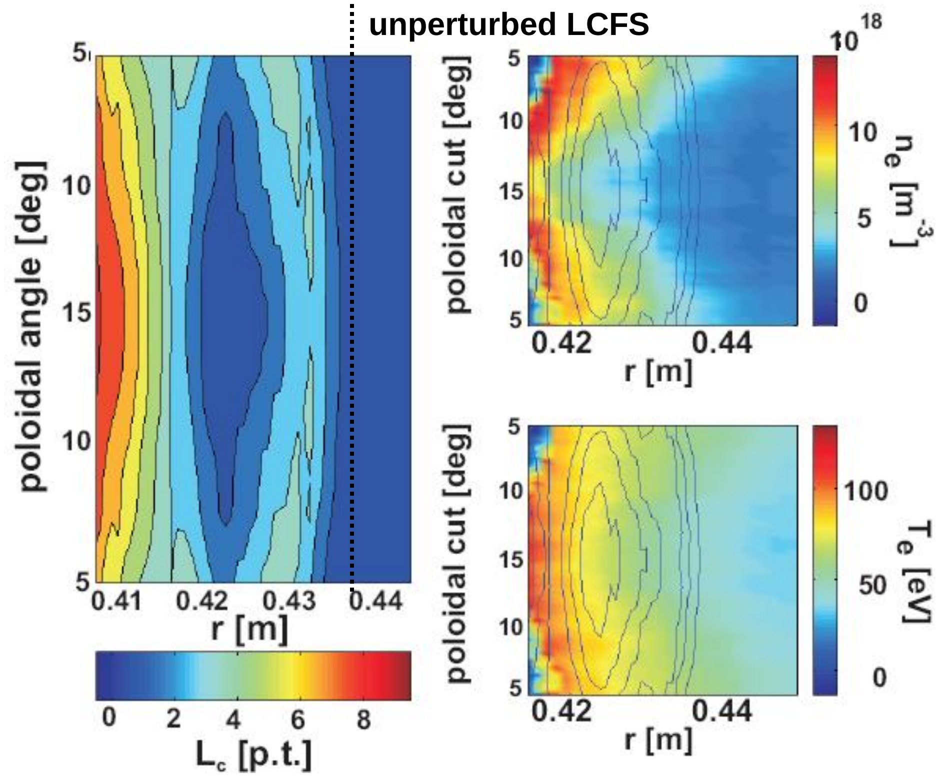
EMC3-Eirene neutral and plasma transport modeling predicts strong poloidal asymmetry

O. Schmitz et al. Nucl. Fusion **48** (2008) 025009 T. Eich et al. Nucl. Fusion **40** (2000) 1757



Plasma edge profiles are governed by new balance of radial vs. parallel transport

O. Schmitz et al. Nucl. Fusion **48** (2008) 025009



Short connection length, laminar flux tubes represent helical SOL

Plasma edge profiles are governed by new balance of radial vs. parallel transport

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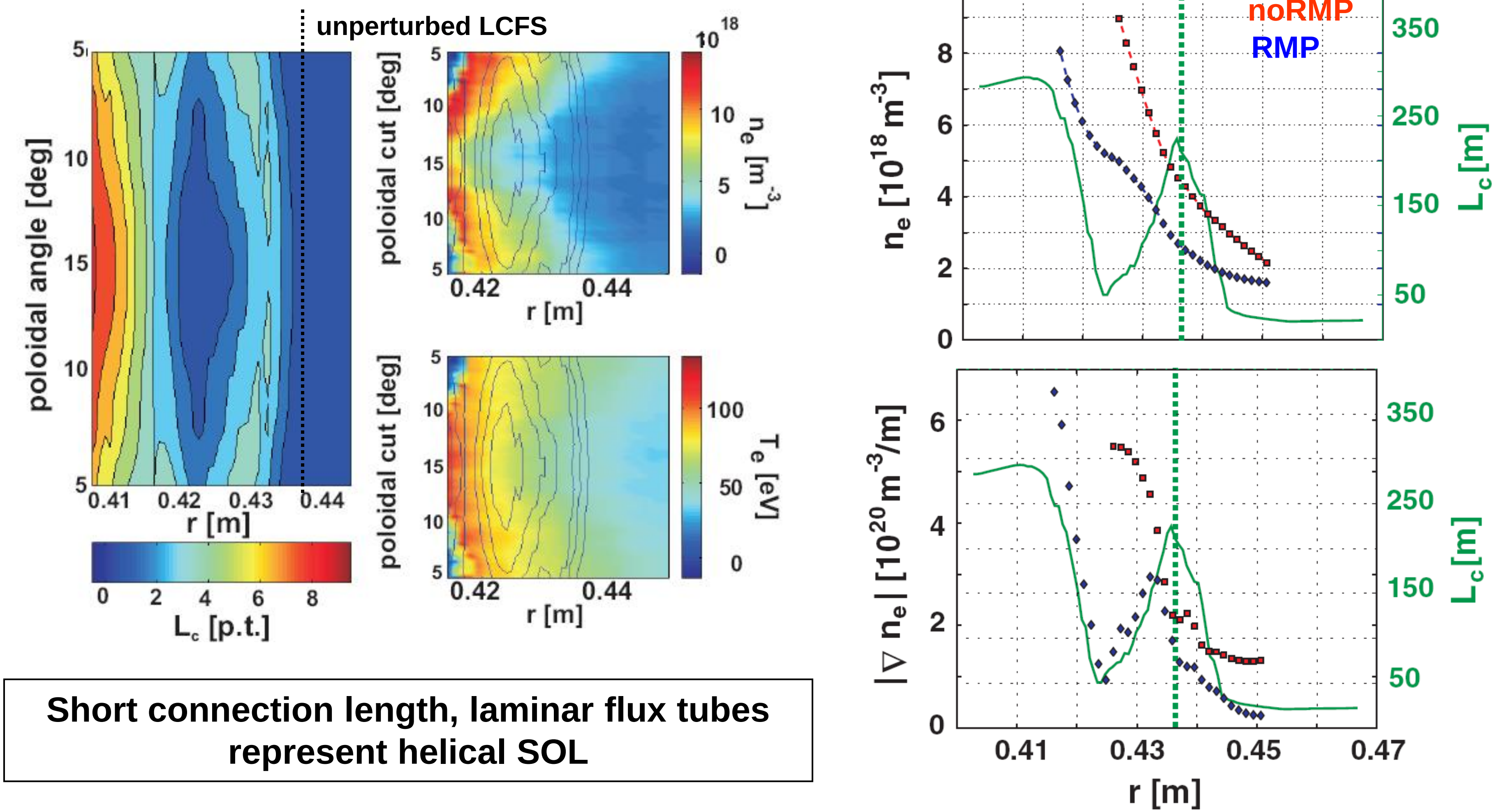
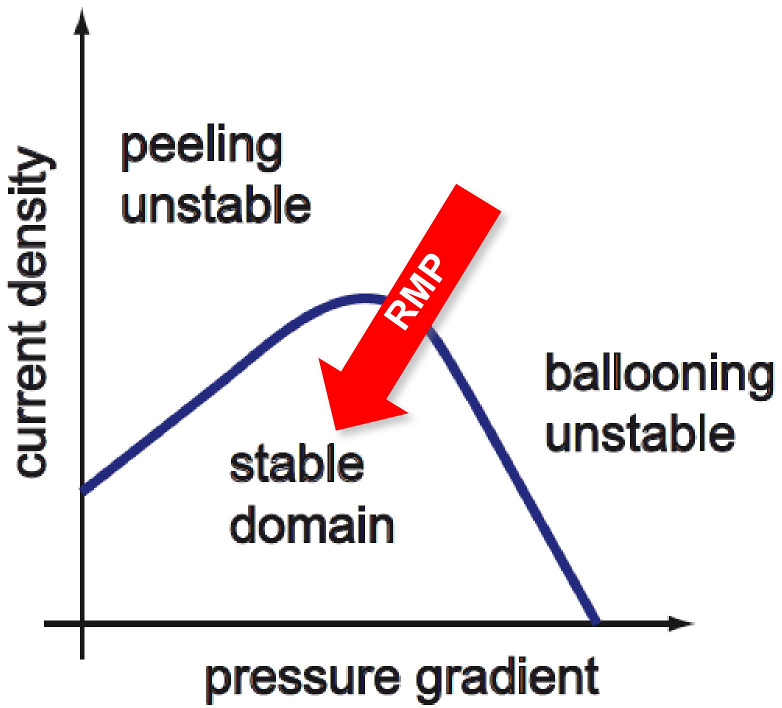


Short connection length, laminar flux tubes represent helical SOL

A thin, short connection length open field line layer can be an effective limitation of the pedestal width

Potential mechanism for ELM stabilization by RMP

ELM as MHD instability



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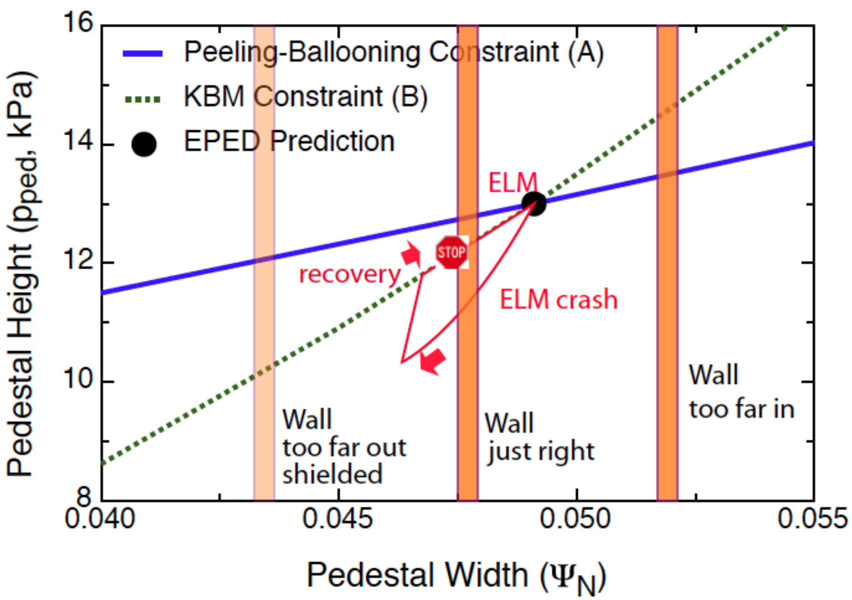

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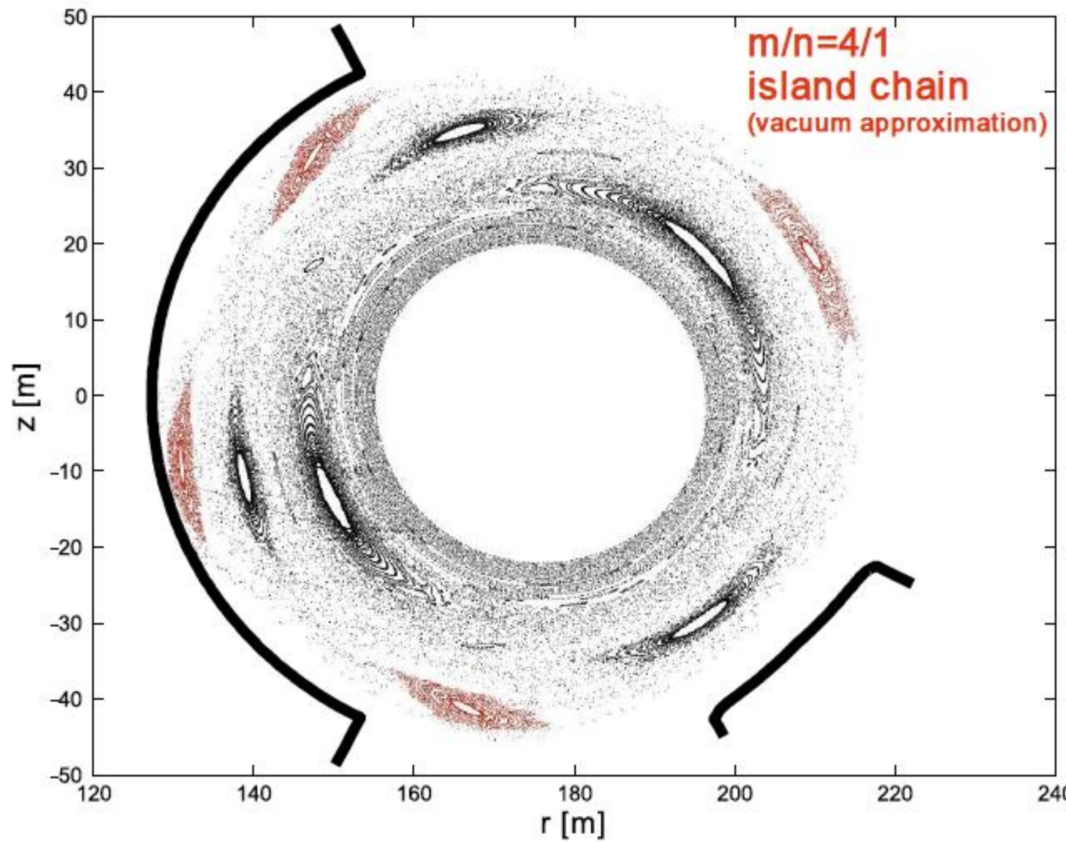
Candidates for stop mechanism?

-Open field line layer as new LCFS definition

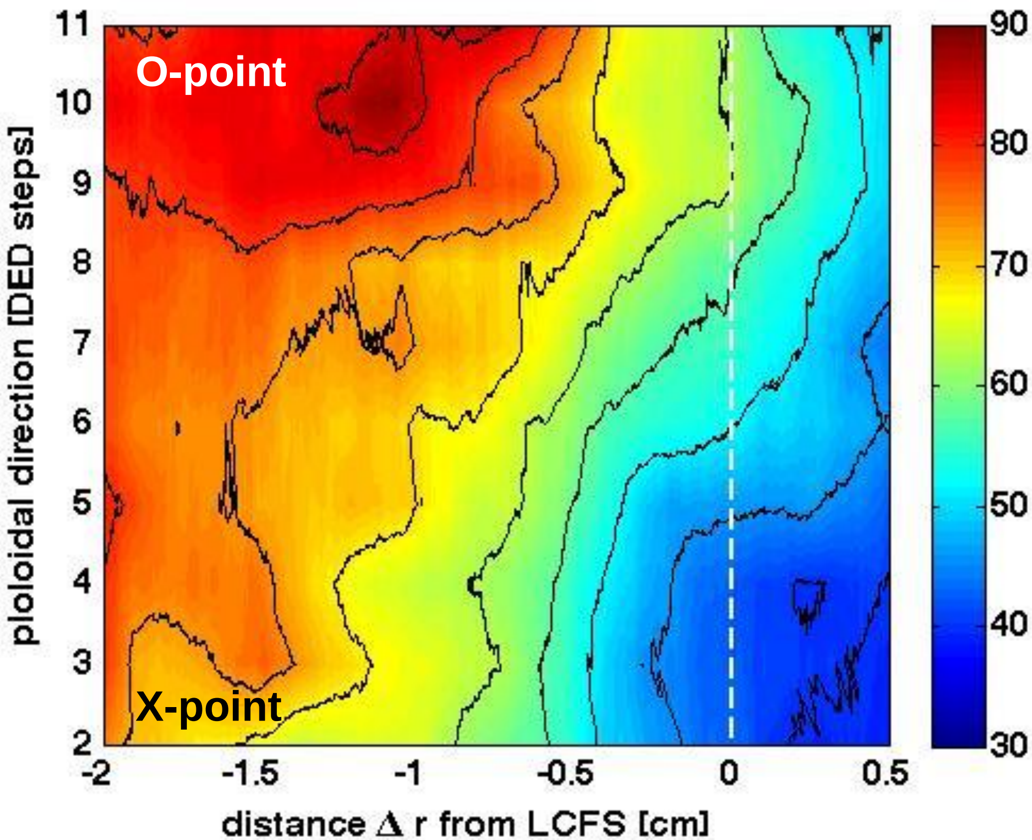
-Magnetic island at right location within pedestal

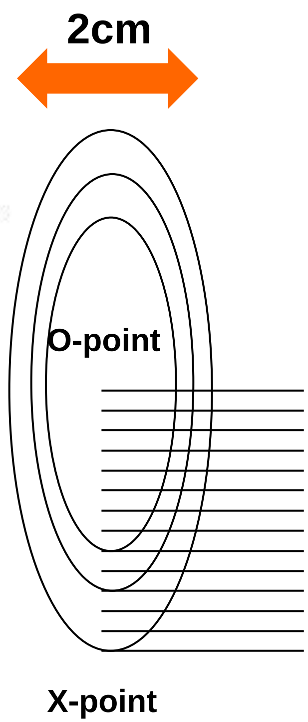
■ **Magnetic islands in the plasma edge were identified at TEXTOR in correlation to the vacuum field line tracing**



Role as an effective driver of transport during RMP application?

Experimental evidence for edge island inducing enhanced particle transport as a convective cell





- **Electric fields towards island center ~ 2-20 V/cm**
- **τ_p drops by 30% with island - no refuel possible**

$$v_{\wedge\_gc} = \vec{E}\times\vec{B}/B^2 = 4\times10^3 - 4\times10^2\ cm/s$$

$$D_\wedge = \Delta R_{isl}\, v_{\wedge\_gc} = 80 - 8\ m^2/s$$

Structure of talk

Motivation: why are 3D effects relevant in tokamaks?
ELM control with RMP

↙ ↘

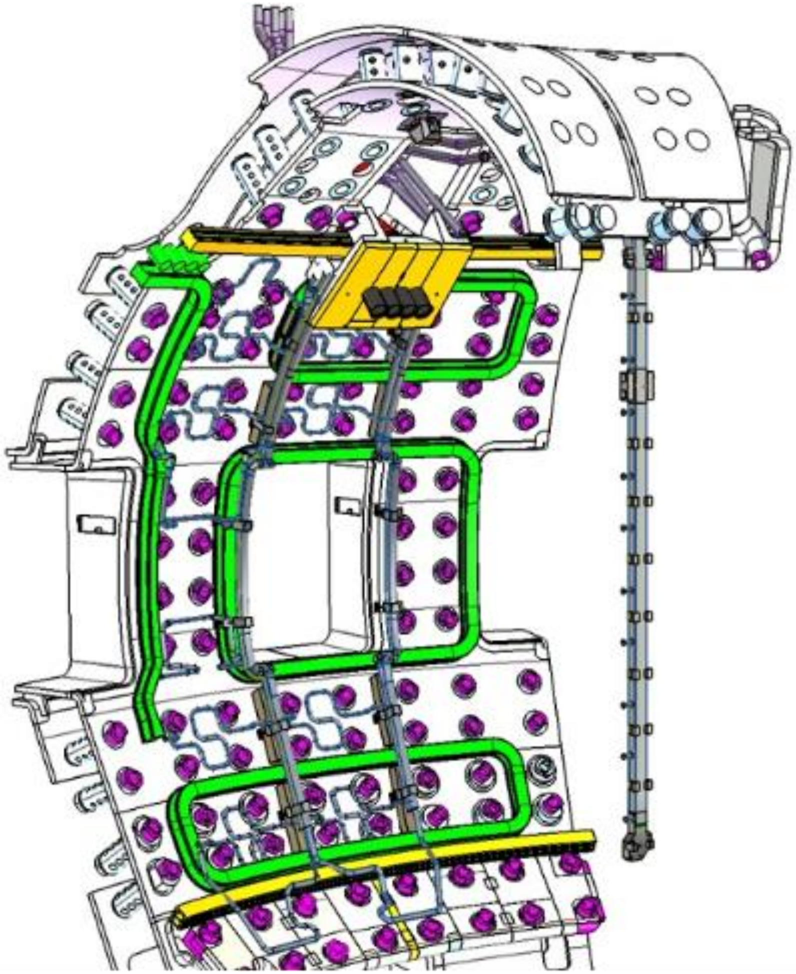
3D plasma boundary and plasma surface interaction
New state with new features

3D plasma boundary and transport hypothesis
Candidate mechanisms for RMP ELM control

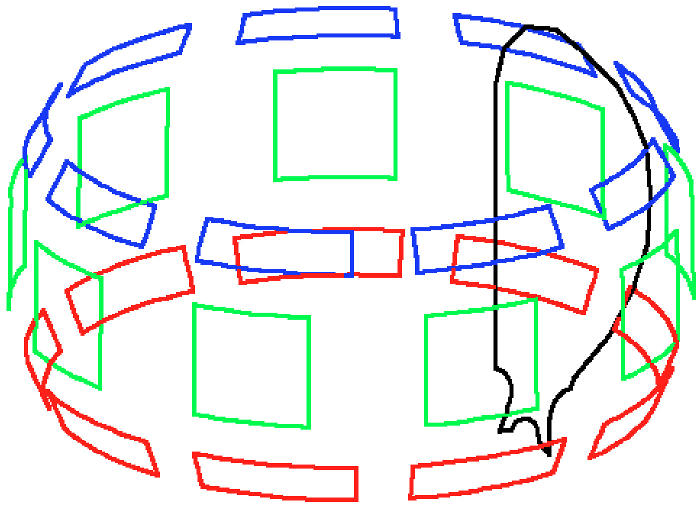
↘ ↙

3D plasma boundary @ ITER
Extrapolation with EMC3-Eirene

ELM control coil setup at ITER



In vessel coil set for ITER



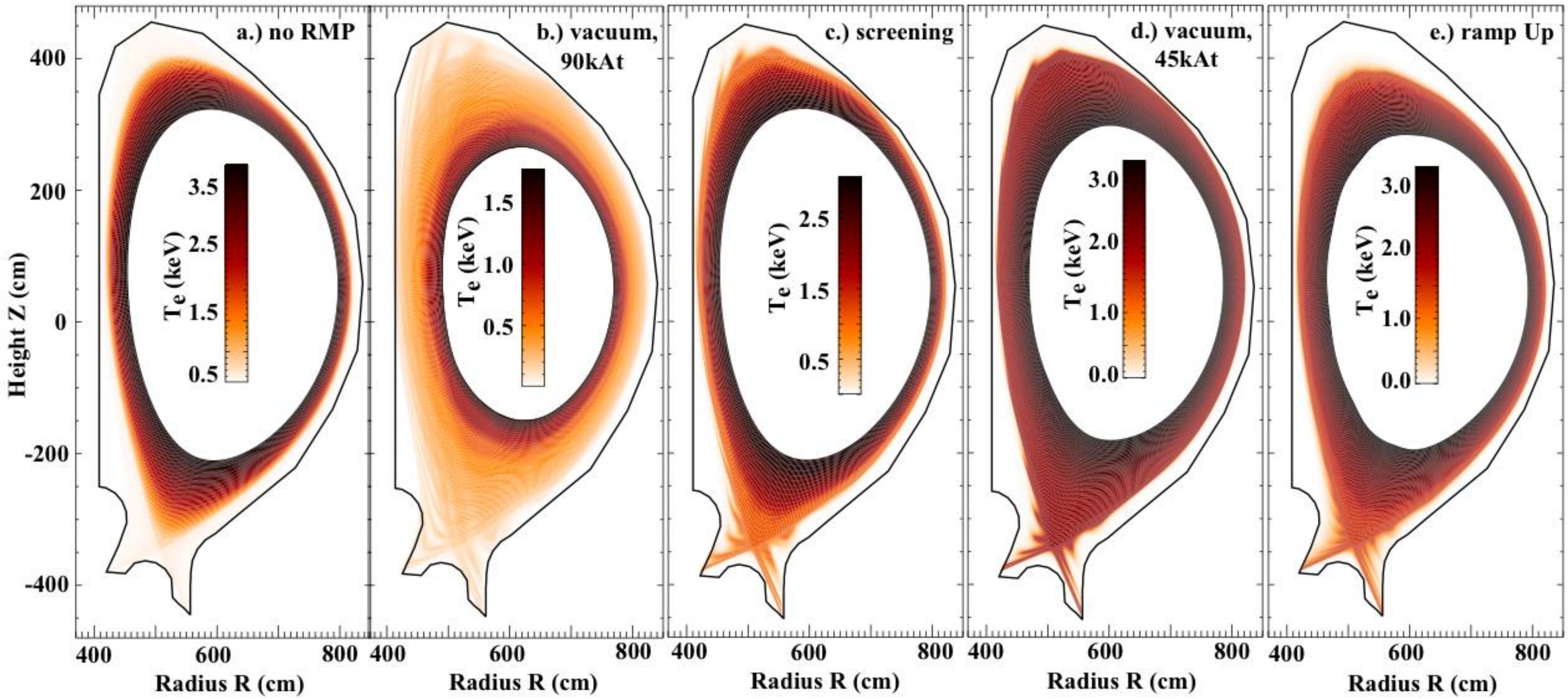
- In vessel coils mounted behind blanket
- 9x3 coils with single power supplies

Coil set with wide spectral flexibility

Toroidal mode number n=3 and n=4 fields seem to be advantageous at the moment

Formation of 3D boundary and level of thermal and particle transport is dependent on RMP amplitude

O. Schmitz et al., IAEA FEC 2012, San Diego, USA

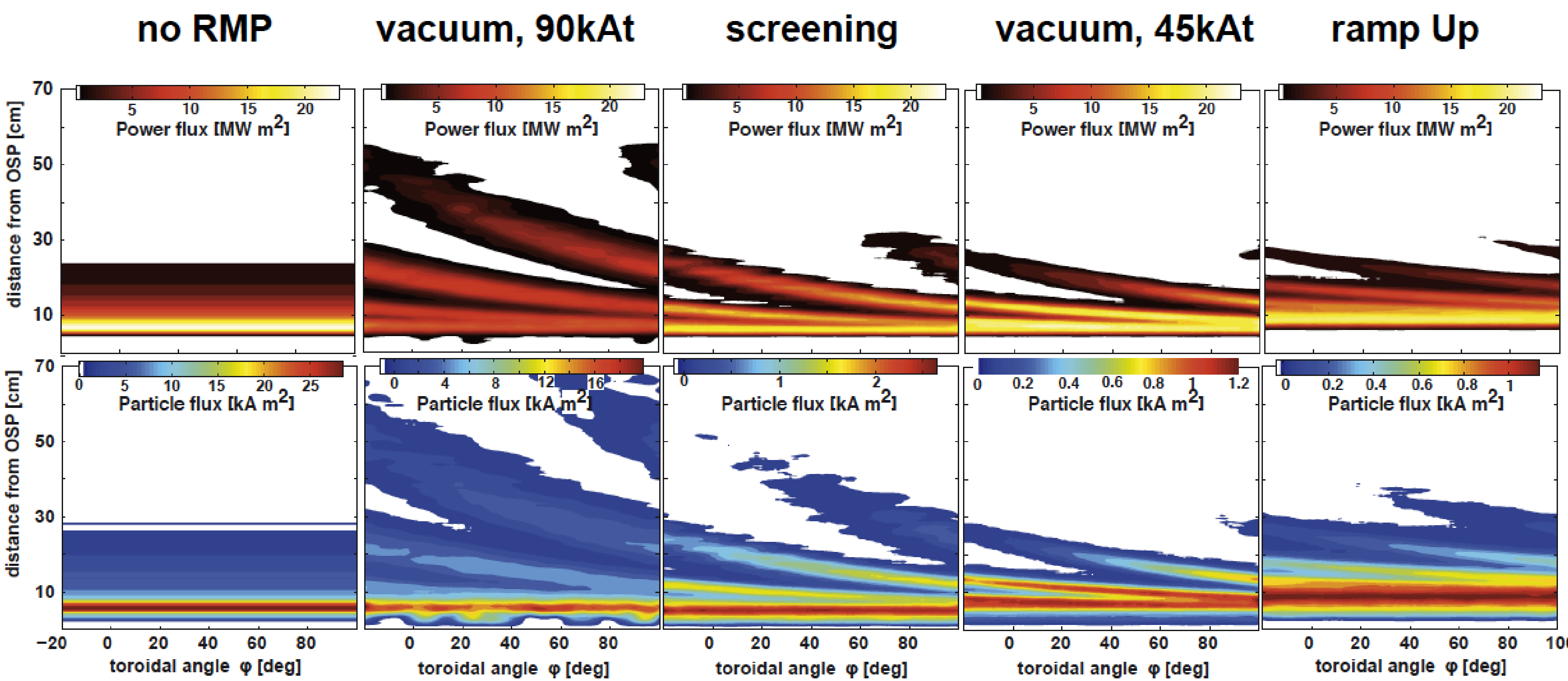


Implementation of screening and linear reduction of RMP amplitude have similar impact on plasma edge

High q_{95}=4.2 case shows compression of invariant manifolds

Heat and particle fluxes are deposited in helical pattern with extension depending on RMP amplitude

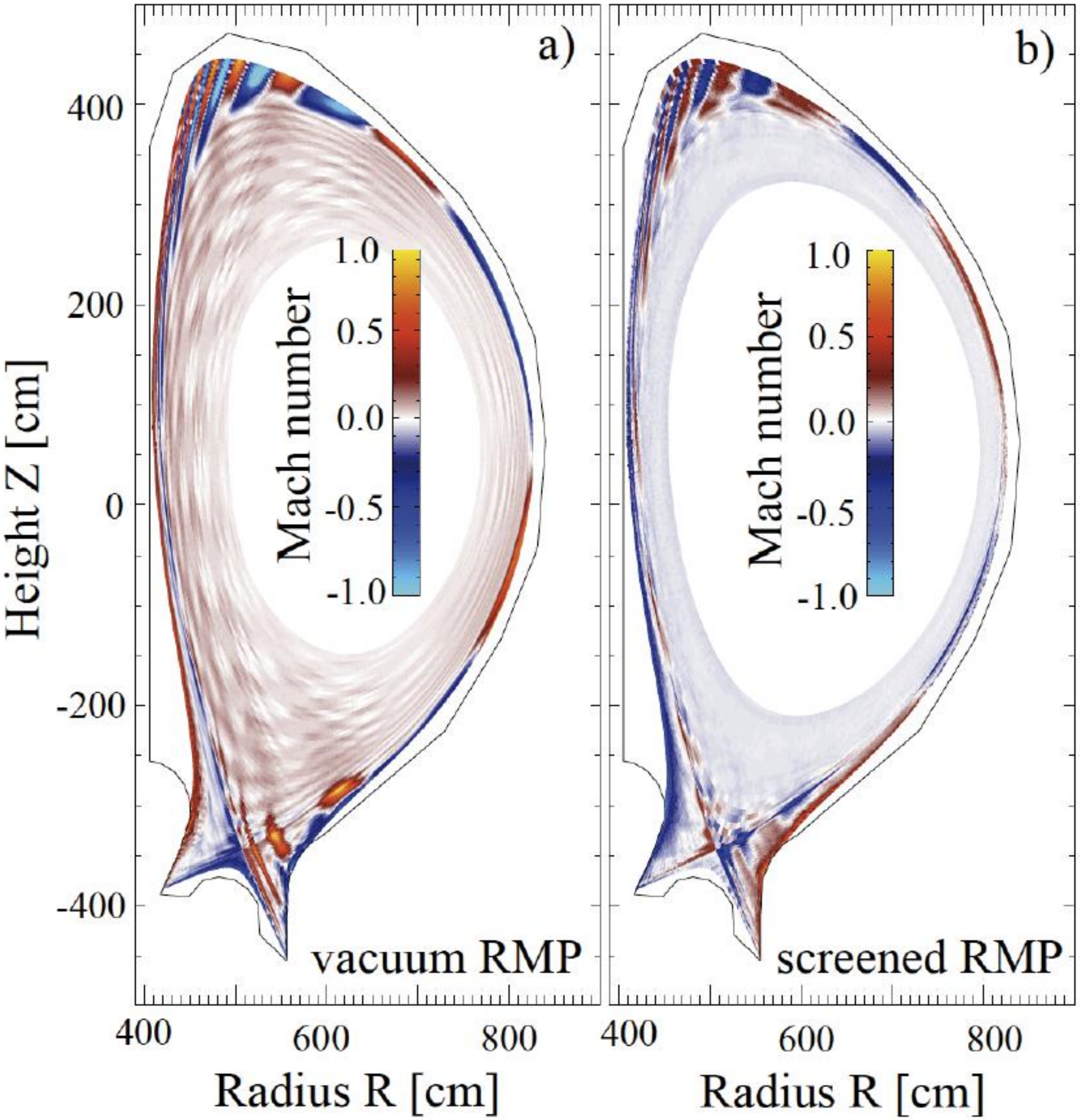
O. Schmitz et al., IAEA FEC 2012, San Diego, USA



Implementation of screening and linear reduction of RMP amplitude have similar impact on plasma edge

High q_{95}=4.2 case shows compression of invariant manifolds

- **Counter streaming flow channels with reduced edge gradients is potential explanation for pump out**



90kAt vacuum case

$$\Delta\tau_P = -35\%$$

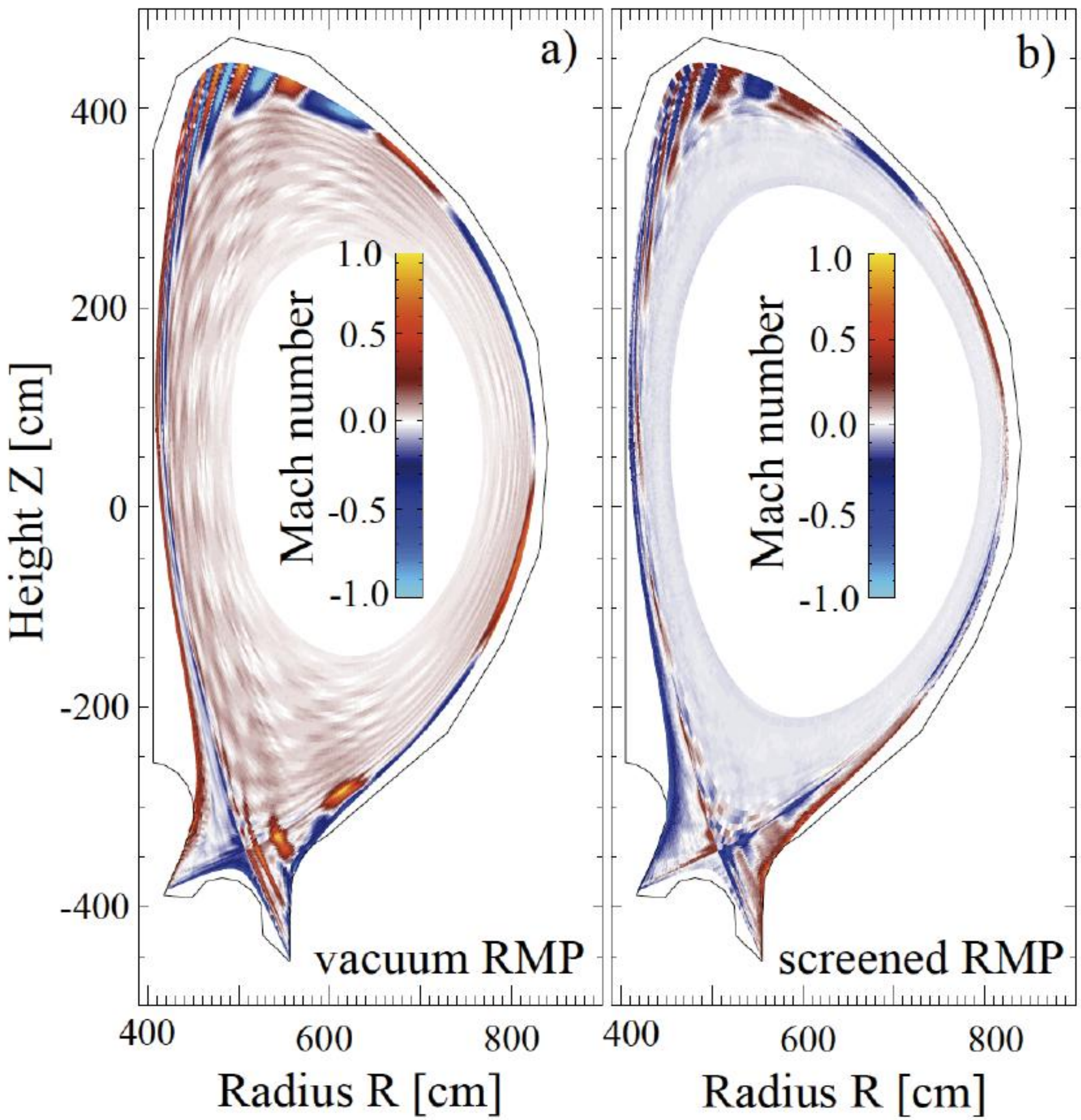
screened case

$$\Delta\tau_P = -15\%$$

Screened case: can be compensated with ITER pellet fueling capability

O. Schmitz et al., JNM (2013) at press

- **Counter streaming flow channels with reduced edge gradients is potential explanation for pump out**



3D flow channels

↓

Radial outflow with flattening of density profile

↓

Increase pressure in 3D SOL equivalent

↓

Downstream n up
Downstream T down

↓

3D flow channels as candidate for enhanced outward particle flux and reduced fueling

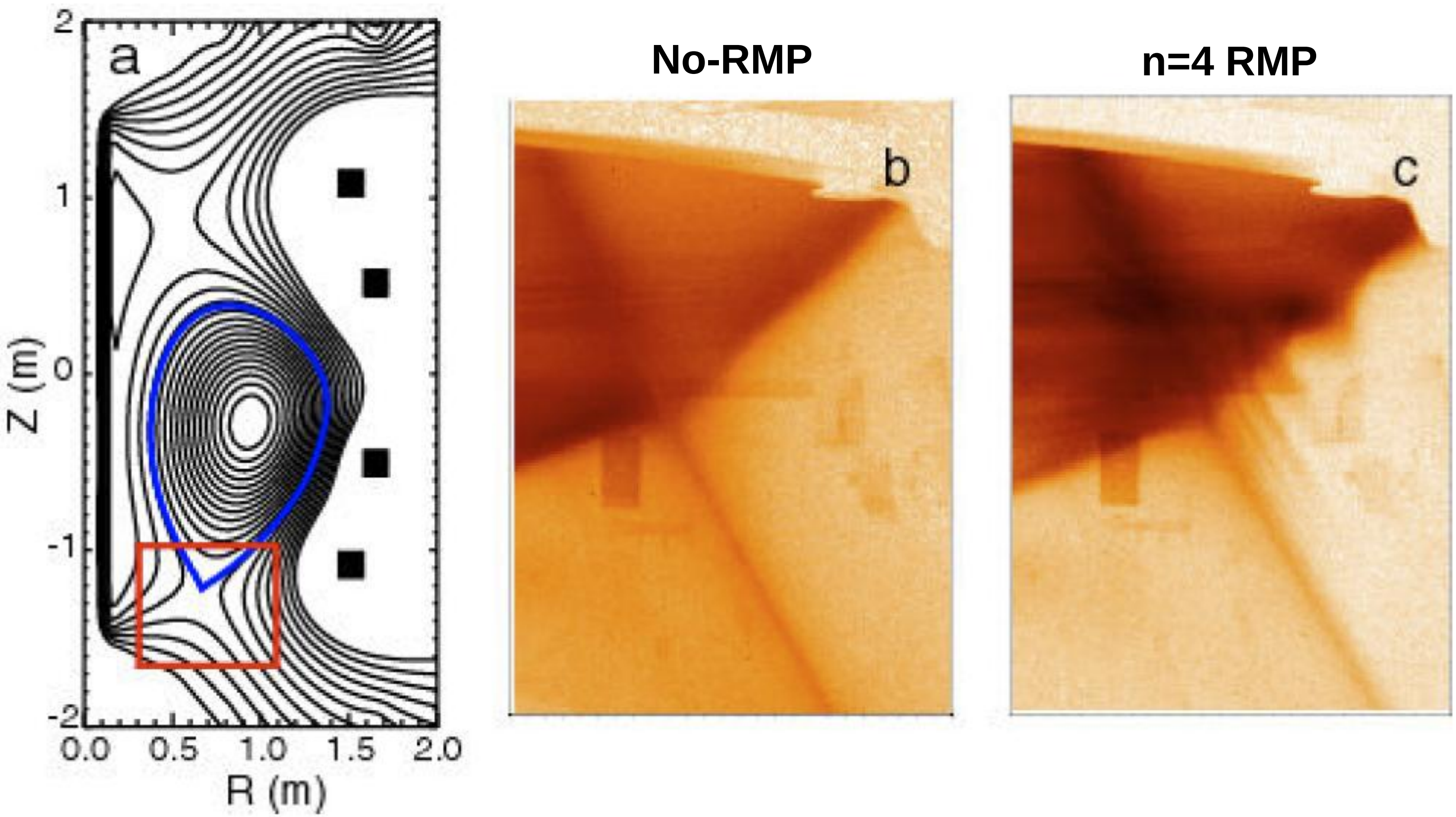
O. Schmitz et al., JNM (2013) at press

Summary and conclusion

- A tokamak is sensitive to internal and external (plasma edge control) sources yielding formation of a 3D plasma boundary
- Therefore 3D effects have to be taken into account at tokamaks
- The plasma profile shape is affected by the external fields allowing suppression of edge localized modes at DIII-D
- The change of the plasma profile shape induces new heat and particle flux patterns channeled into a helical 3D magnetic geometry
- Striation of heat and particle fluxes modeled provide evidence for 3D PSI as a generic topic at ITER during RMP ELM control
- Inclusion of plasma response into modeling ongoing and coupling to ERO as dedicated PSI code is our final goal

2D image of perturbed separatrix was obtained at MAST and DIII-D in visible light images

[A. Kirk et al., Phys. Rev. Letters 108 (2012) 255003] [E. Nardon et al., JNM **415** (2011) 914-917]

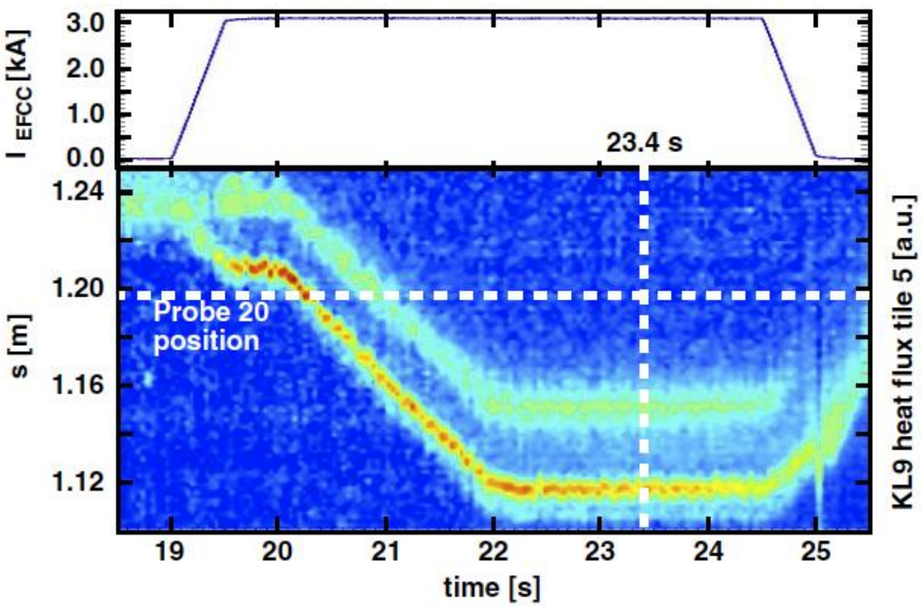


At MAST and NSTX, [J.-W. Ahn et al., NF **50** (2010)] **lobe structure was found in fair agreement with vacuum magnetic topology**

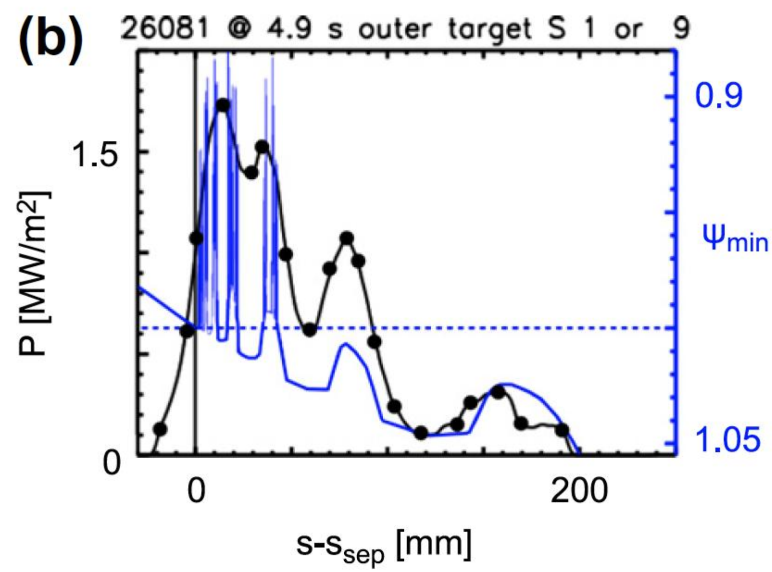
- **At JET, striation is seen in L-mode plasmas only -> indication for plasma screening response in H-mode**

[D. Harting et al., Nucl. Fusion **52** (2012) 054009] [H. W. Müller et al., JNM (2013) at press]

JET, n=2 fields, L-mode



Asdex-Upgrade, n=3 fields, L-mode



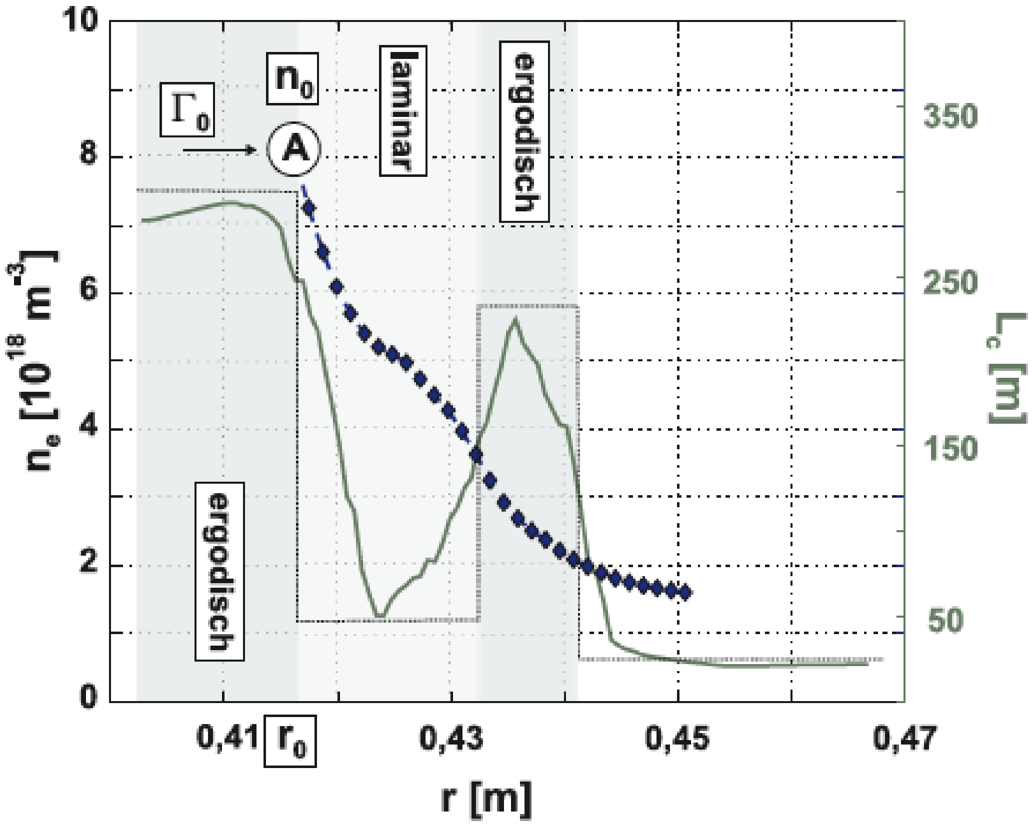
3D boundary formation, i.e. at least 3D shaped separatrix is present on all devices with external (and internal) RMP fields applied

Interaction with plasma response?

Radial transport in 3D boundary and resulting divertor fluxes?

Consequences for ITER with RMP ELM control?

- **Actual magnetic topology determines transport characteristic in stochastic edge layer**



Stochastic field lines:

$$\Gamma_\perp = -D_\perp \nabla n_e$$

$$\nabla n(r) = -\frac{\Gamma_\perp^0}{D_\perp}$$

Radial diffusion and gradient drive transport

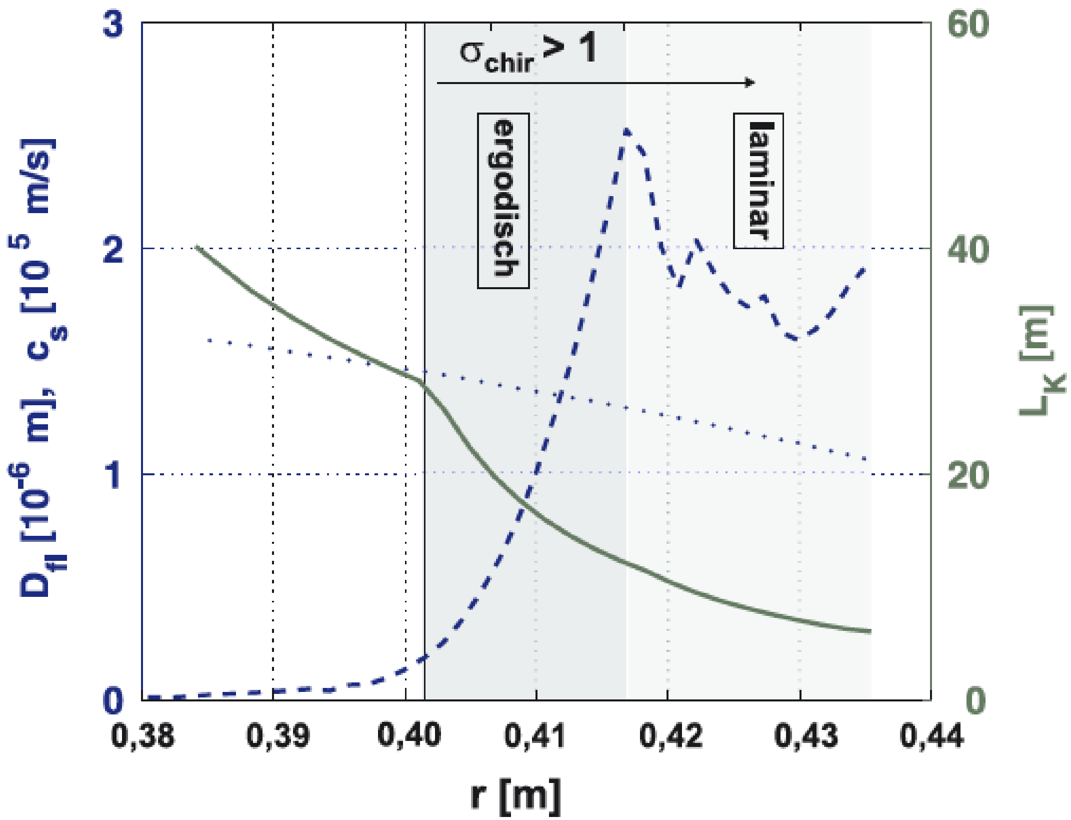
$$D_\perp = D_{\perp 0} + v_\parallel \, D_{fl}$$

$$D_{fl} = \frac{\langle (\Delta r)^2 \rangle}{2 \cdot \Delta l}$$

Enhanced radial transport by field line diffusion causes gradient to decrease

- **Actual magnetic topology determines transport characteristic in stochastic edge layer**

JÜLICH FORSCHUNGSZENTRUM



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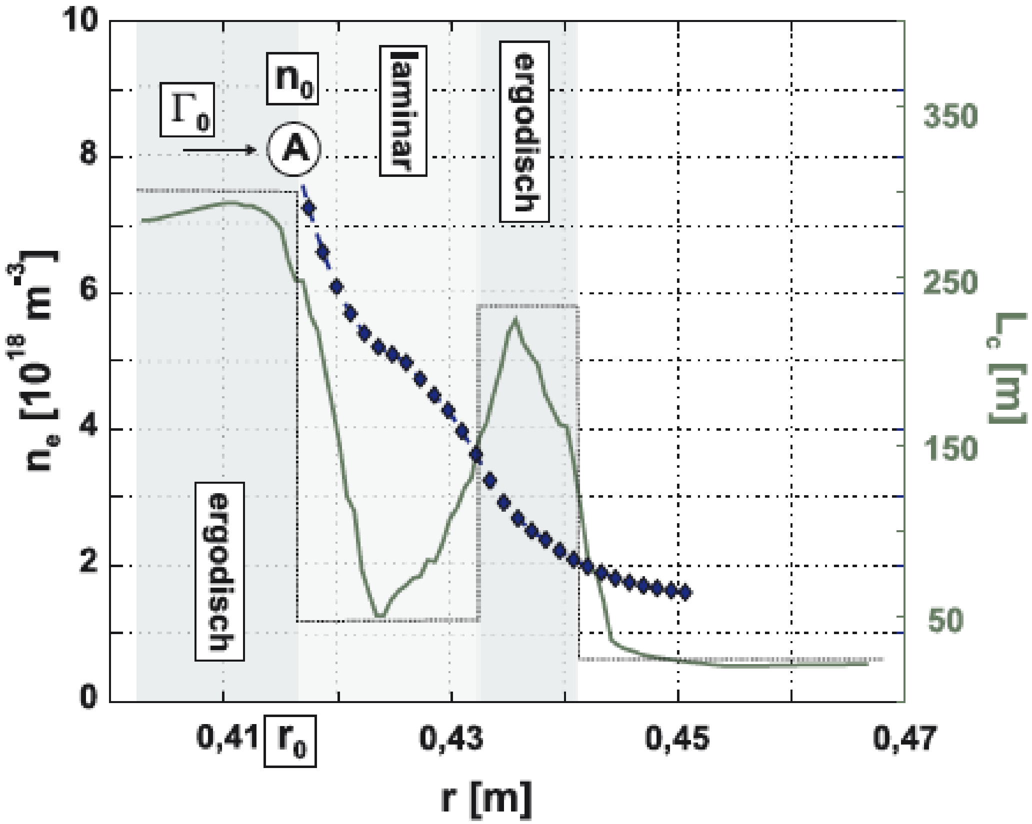
TEC

Actual magnetic topology determines transport characteristic in stochastic edge layer



"Laminar" field lines:

$$n_e(r) = n_0 \cdot exp\left(-(r - r_0)/\lambda_n\right)$$

SOL like field lines

$$\Gamma_\perp = -D_\perp \cdot \frac{dn_e}{dr}\Big|_{r=0} = \frac{D_\perp n_0}{\lambda_n}$$

$$\Rightarrow n_0 = \frac{\Gamma_\perp^0 \lambda_n}{D_\perp}$$

Gradient decay with λ_n

$$\nabla n(r) = -\frac{\Gamma_\perp^0}{D_\perp} \cdot exp\left(-(r - r_0)/\lambda_n\right)$$

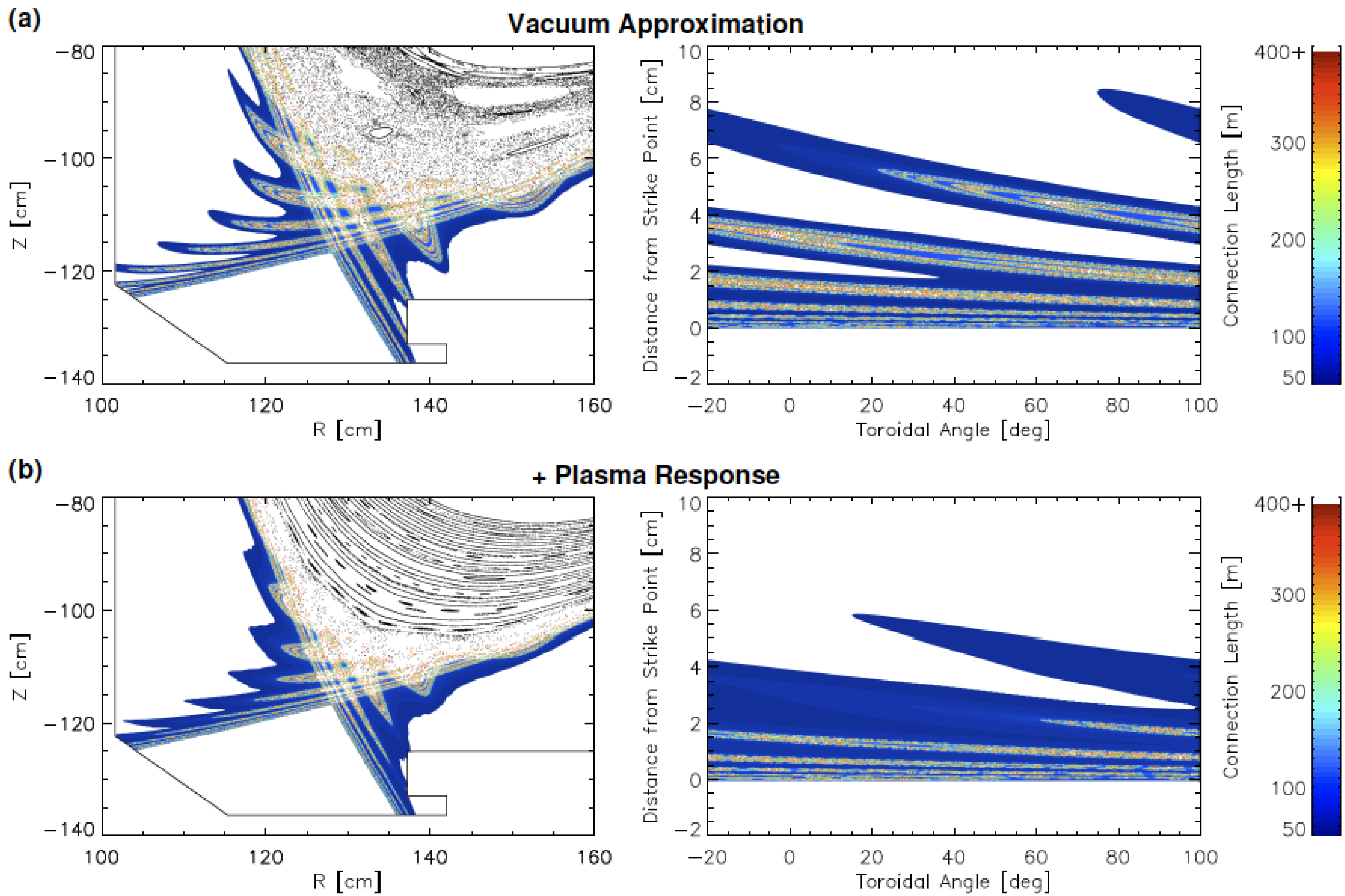
Enhanced parallel transport causes gradient increase

An open field line layer can be an effective limitation for pedestal width

Note: overlapping separatrix lobes in divertor shape cause small laminar layer and its inward extension is highly q_{95} resonant

Implementation of screening plasma response does not resolve deviations of EMC3-Eirene from experiment

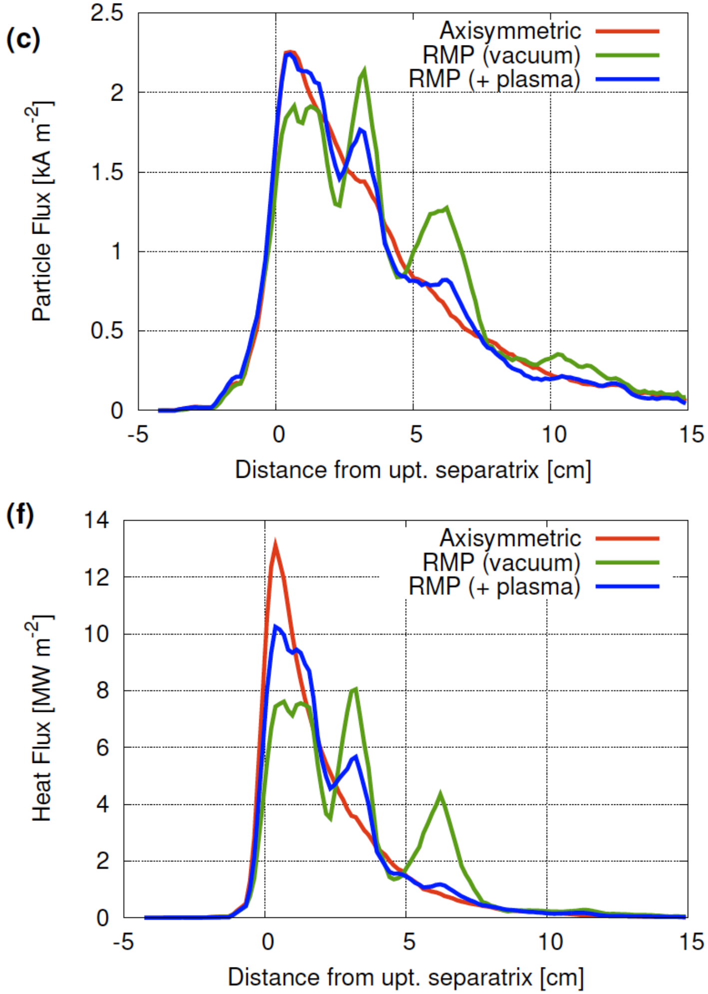
H. Frerichs et al. Phys. Of Plasmas **19** (2012) 052057

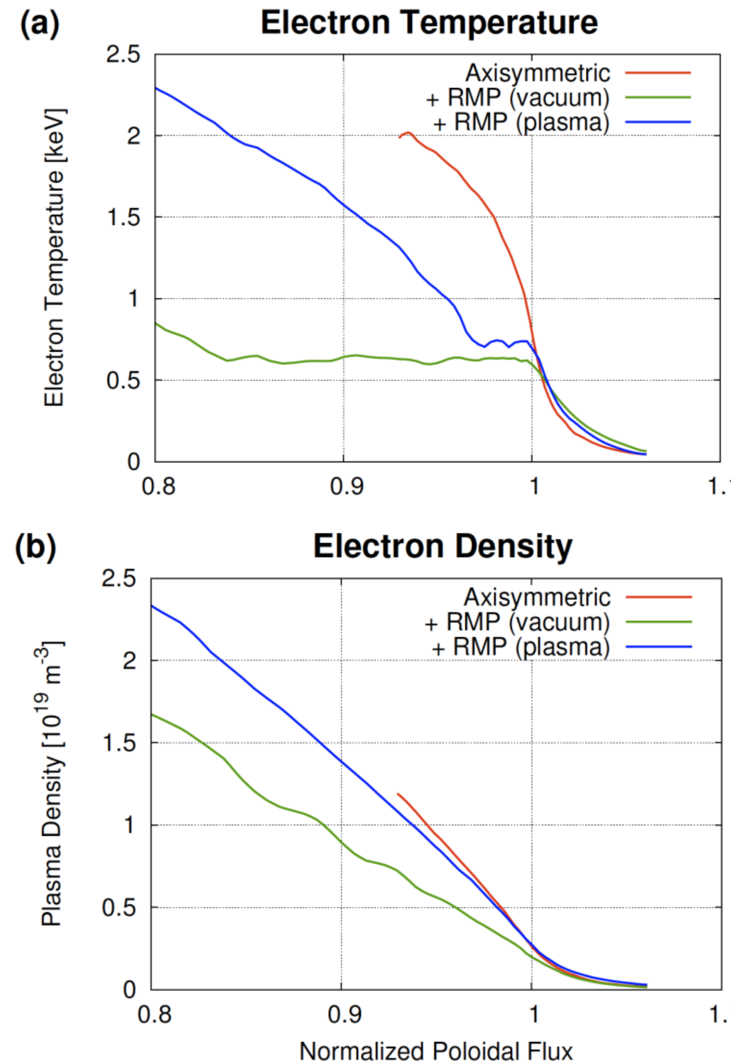


Excursion of helical lobes is reduced and lobes move back within helical footprint envelope of separatrix

Implementation of screening does not resolve deviations of EMC3-Eirene solution from experiment

H. Frerichs et al. Phys. Of Plasmas **19** (2012) 052057



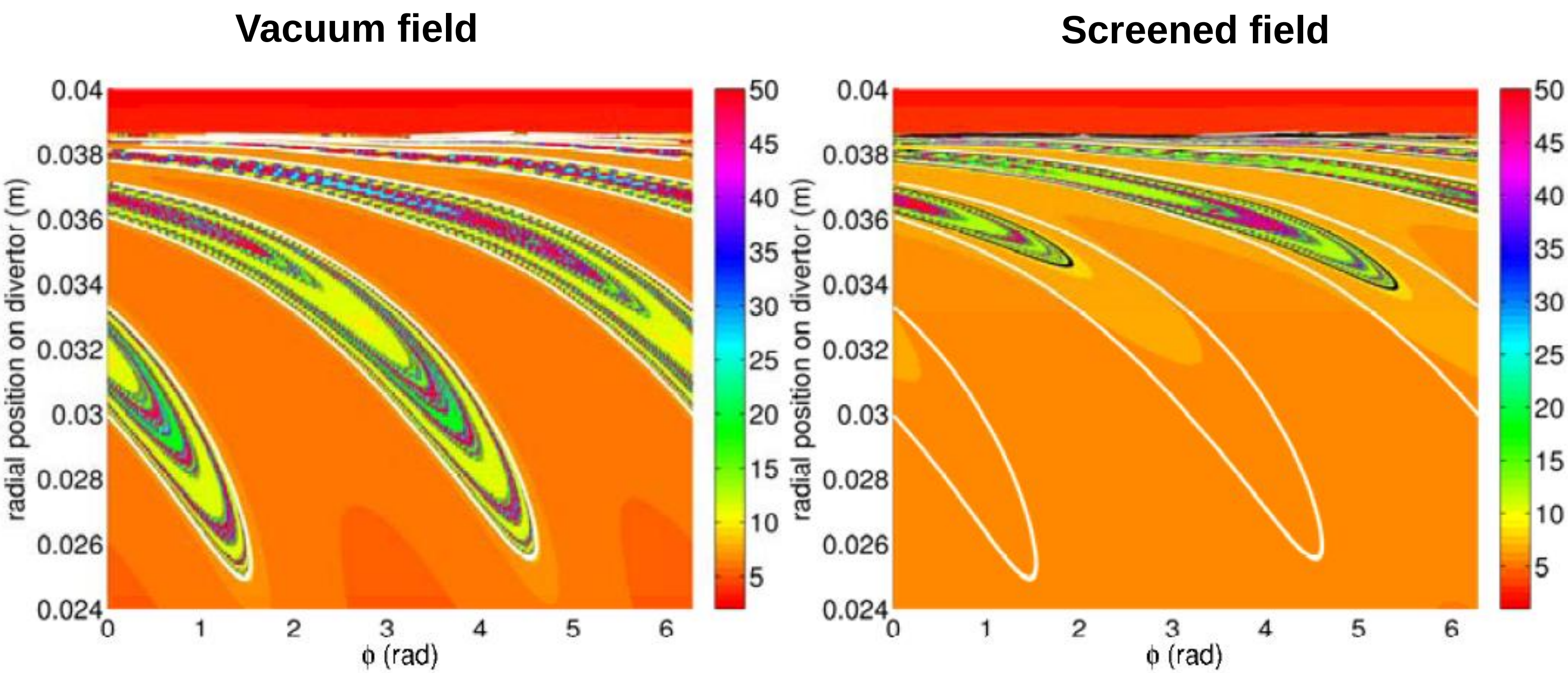


Target flux profiles trend better with screening response included

Temperature profiles trend better but density pump out is erased

Impact of screening on footprint

P. Cahyna et al. Journ. Of Nucl. Mater 415 (2011)

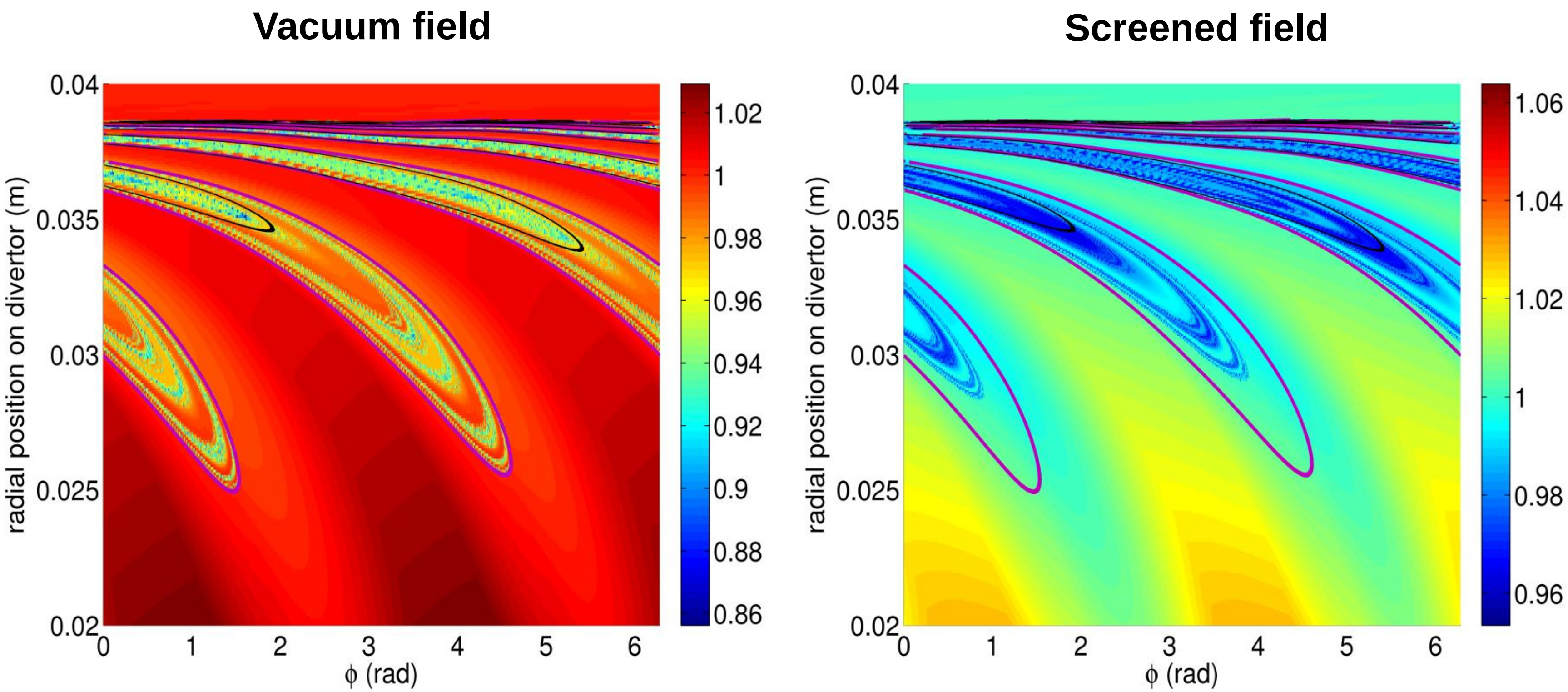


➡ **Separatrix structure maintained but interior of helical lobes moves back within separatrix envelope**

➡ **Radial displacement of field lines from inside separatrix is reduced**

Impact of screening on footprint

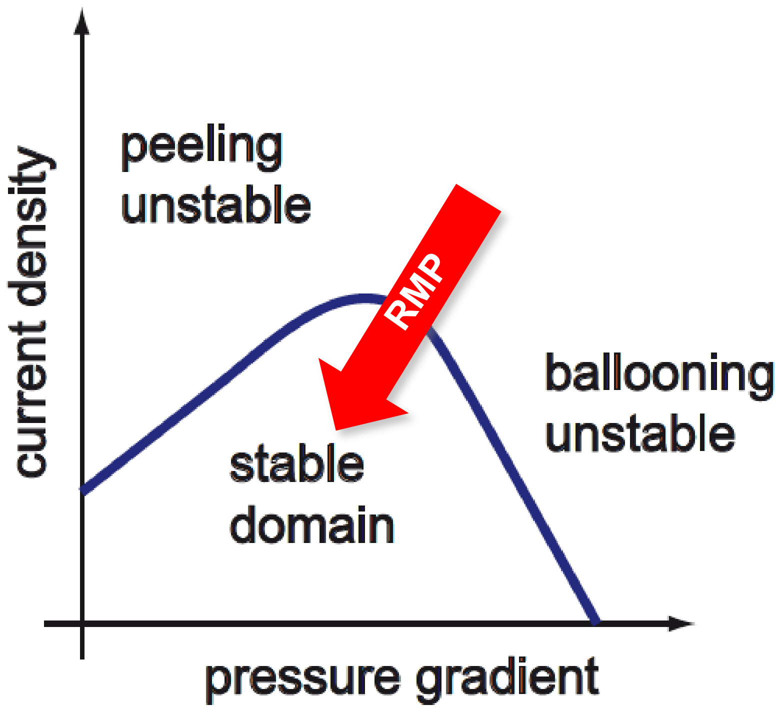
P. Cahyna et al. Journ. Of Nucl. Mater 415 (2011)



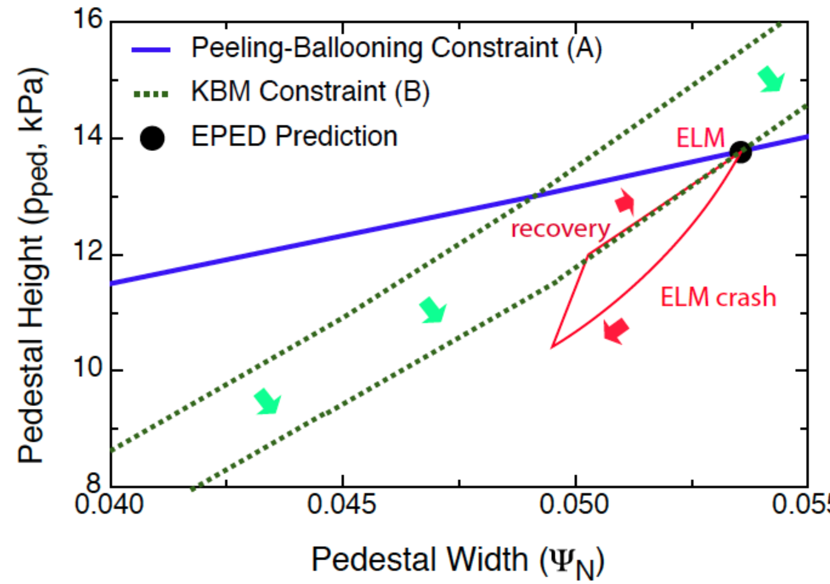
- **Field line connections to deeper radial positions are cut off by screening layers**
- **Potential to reduce thermal loss, particle pump out but might increase divertor flux magnitudes**

Potential mechanism for ELM stabilization by RMP

Simplified example of the ELM cycle



Stability model of ELM cycle



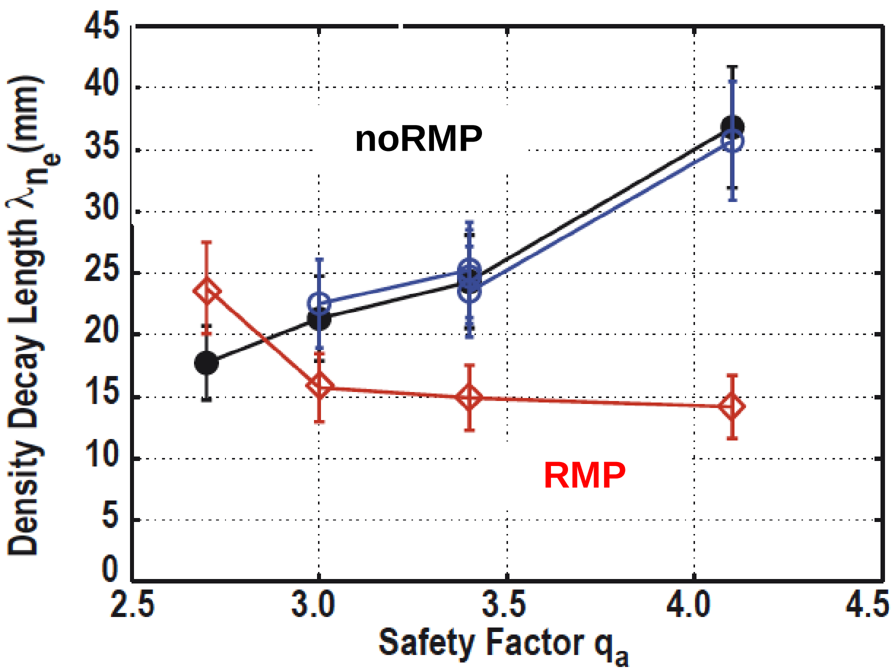
[P. Snyder et al. Physics of Plasmas (2012) submitted]

Reduction of pressure alone only reduces KBM stability, i.e. moves stability boundary to more non-local effects

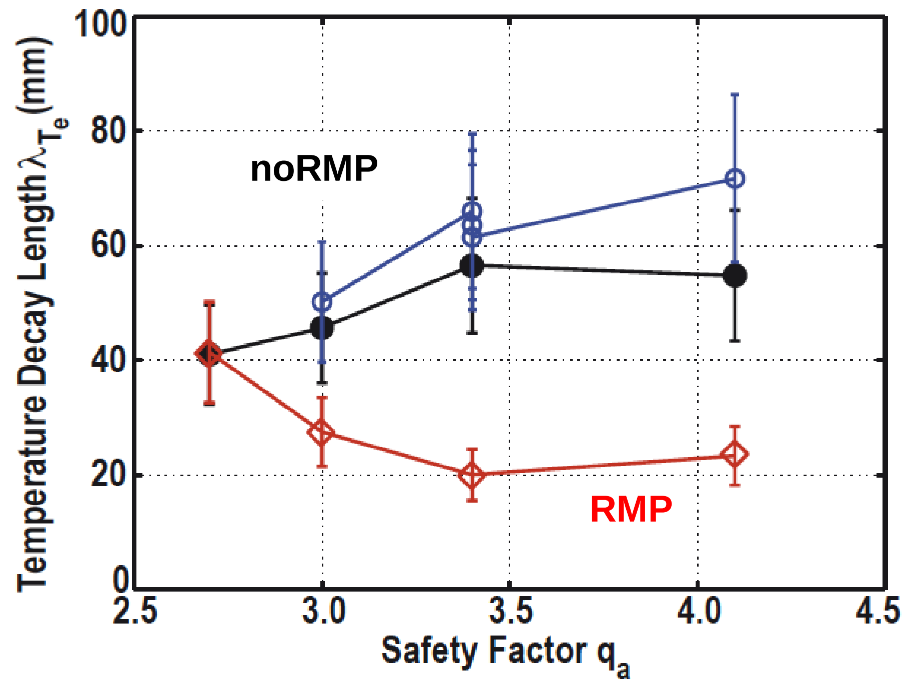
In crease in SOL profile decay length with q_a while decrease with RMP application and helical SOL formation

O. Schmitz et al. Nucl. Fusion **48** (2008) 025009 O. Schmitz et al. Journ. Of Nucl. Mater 415 (2011) 886

Electron density decay length in SOL



Electron temperature decay length in SOL

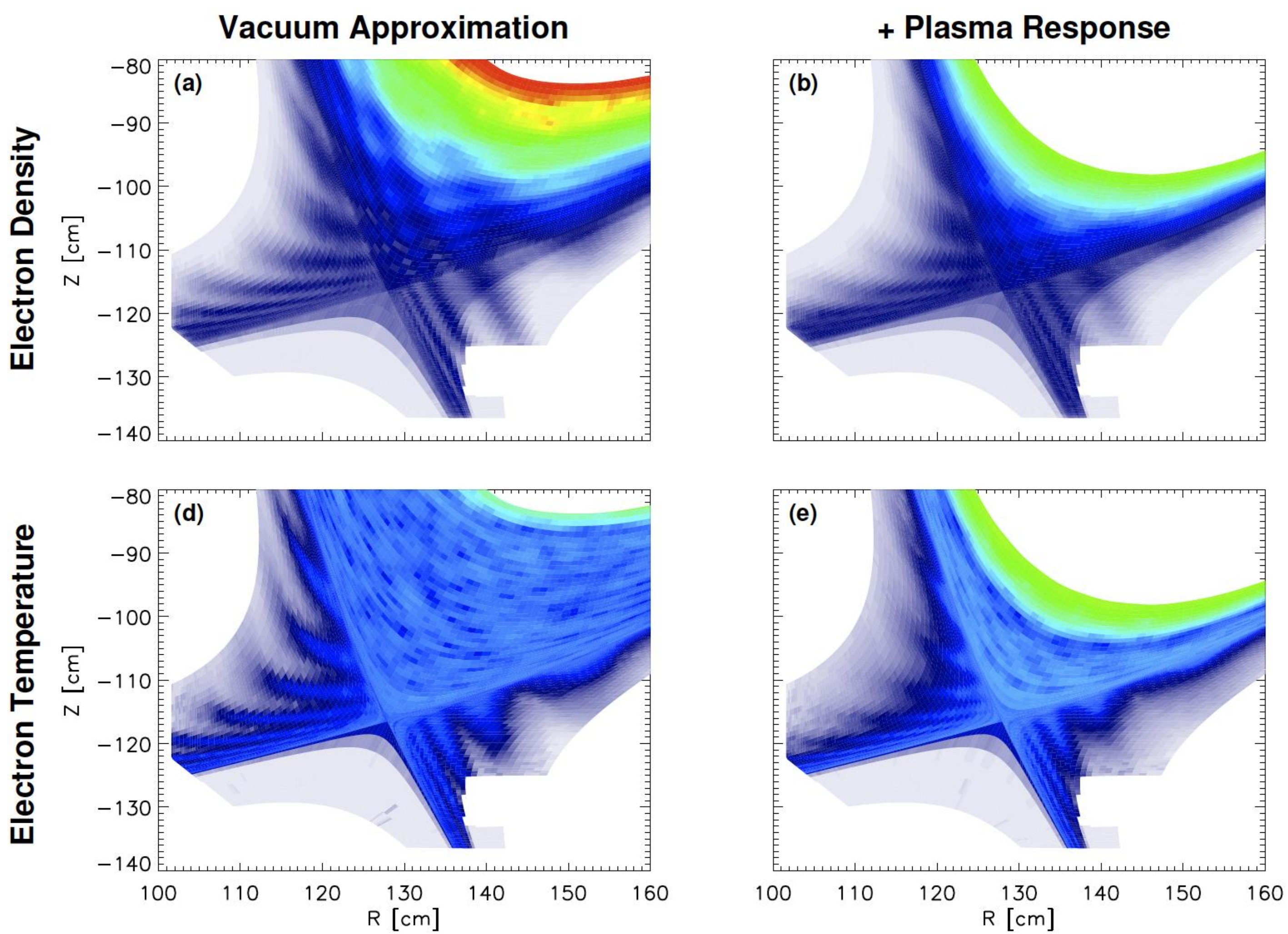


- Without RMP fields, a systematic trend for an increase in λ_{ne} and λ_{Te} decay length with increasing q_a is measured
- With RMP, λ_{ne} and λ_{Te} decrease with increasing q_a, suggesting a strong channeling of particle and heat fluxes in well developed helical flux tube

All RMP profiles taken in helical SOL of stochastic edge layer

Implementation of screening does not resolve deviations of EMC3-Eirene solution from experiment

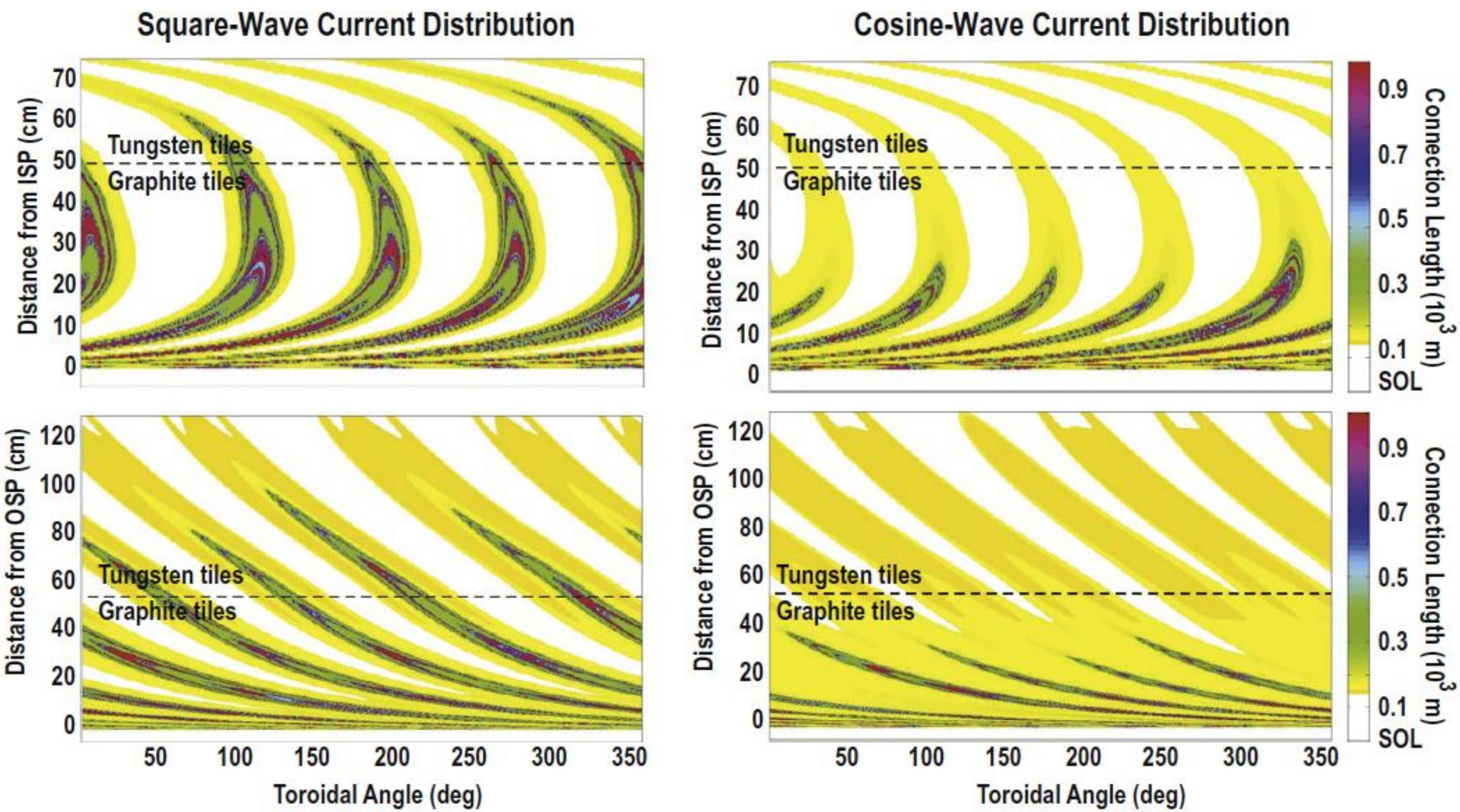
H. Frerichs et al. submitted to Phys. Of Plasmas (2011)



⇨ **Density and temperature fields follow**

- **3D magnetic footprint is induced in n=4 RMP ELM control setup**

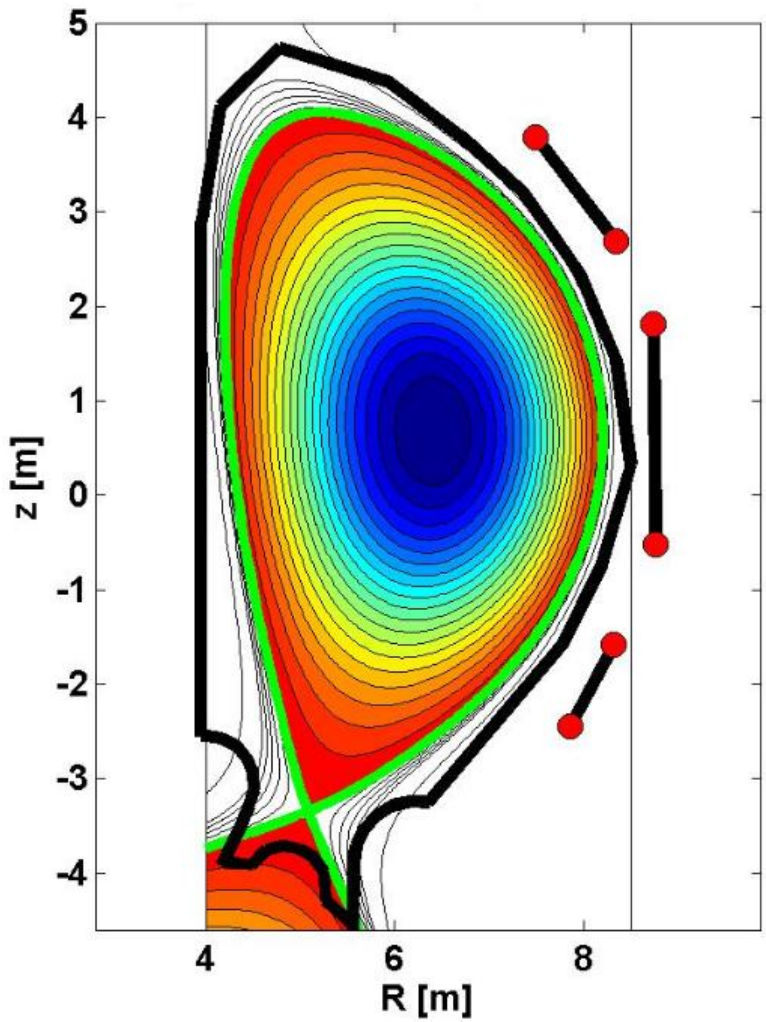
O. Schmitz et al. Journ. Of Nucl. Mater 415 (2011) 886



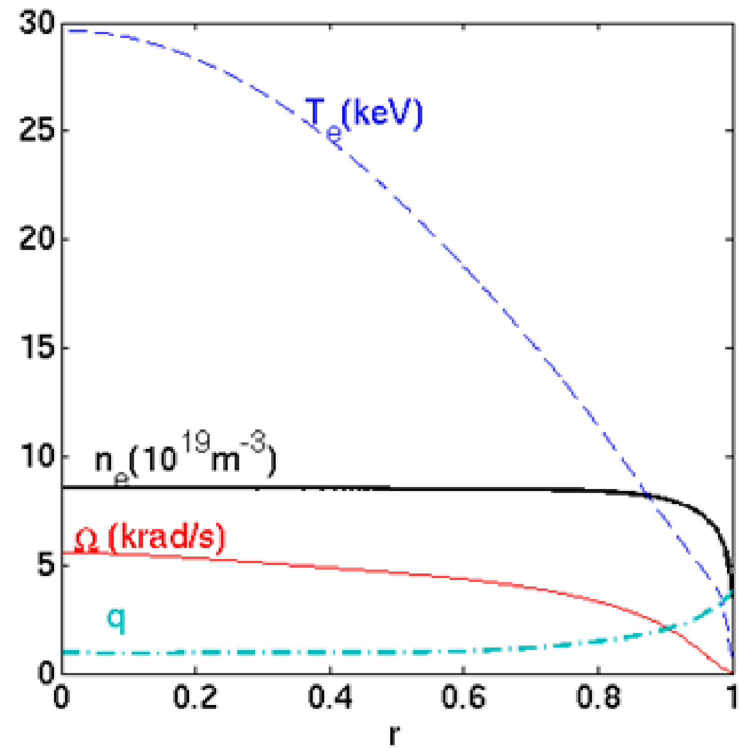
➡ **Assessment of 3D edge transport and resulting wall loads and relevance for the resulting erosion/deposition and material migration is important**

Main focus so far: standard Q=10 H-mode

- I_P=15 MA, B_T=5.3T with pedestal temperature constrain of 4.5keV

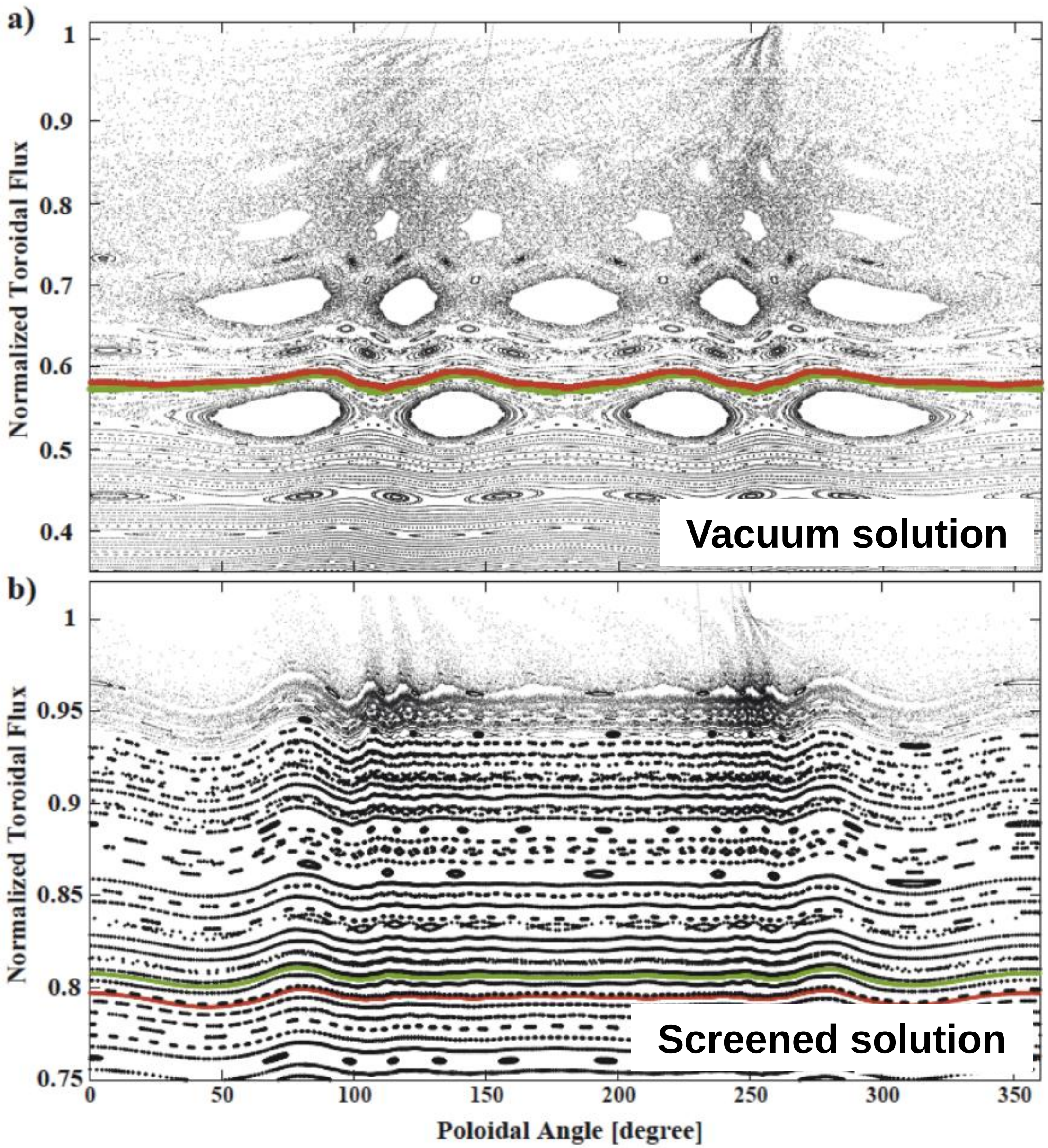


CORSICA data as constrain for the equilibrium



- B2-Eirene benchmark was performed to connect to 2D modeling predictions on which ITER design relies on so far (Y. Feng et al., EPS2011)

- Vacuum solution and solution with strong plasma screening was studied



Screening of all modes with n=3,6 and m<7 within Ψ_N<0.96 yields recovery of good flux surfaces

Open field line domain is restricted to plasma edge where field penetration happens including lobe structure

Radial extension of EMC3-Eirene modeling domain was reduced

■ **Non-linear cylindrical MHD modeling with RMHD (CEA) and drift-fluid modeling with ATTEMPT as basis**

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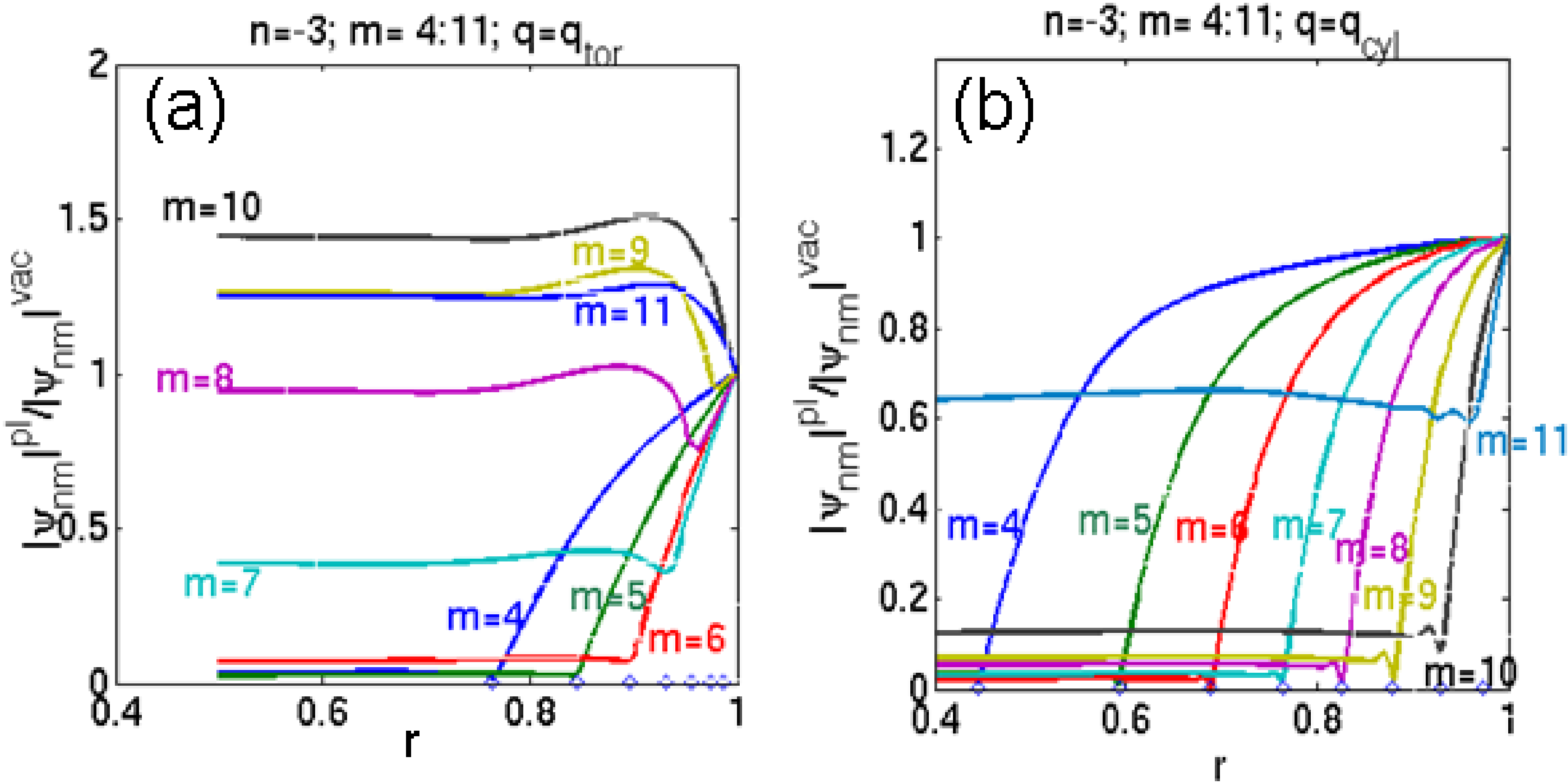
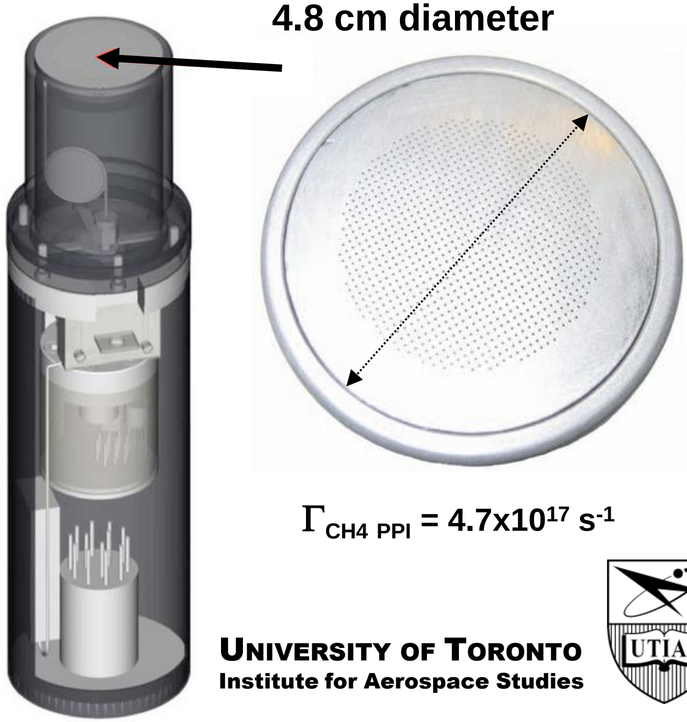


Cylindrical treatment induces consistency issues for direct implementation in toroidal geometry

Codes in needed which treat the problem in shaped, poloidally diverted geometry self-consistently (JOREK, M3D-C1, NIMROD …)

TEC

The DiMES Porous plug injector (PPI) was used to characterize erosion properties in the separatrix lobes

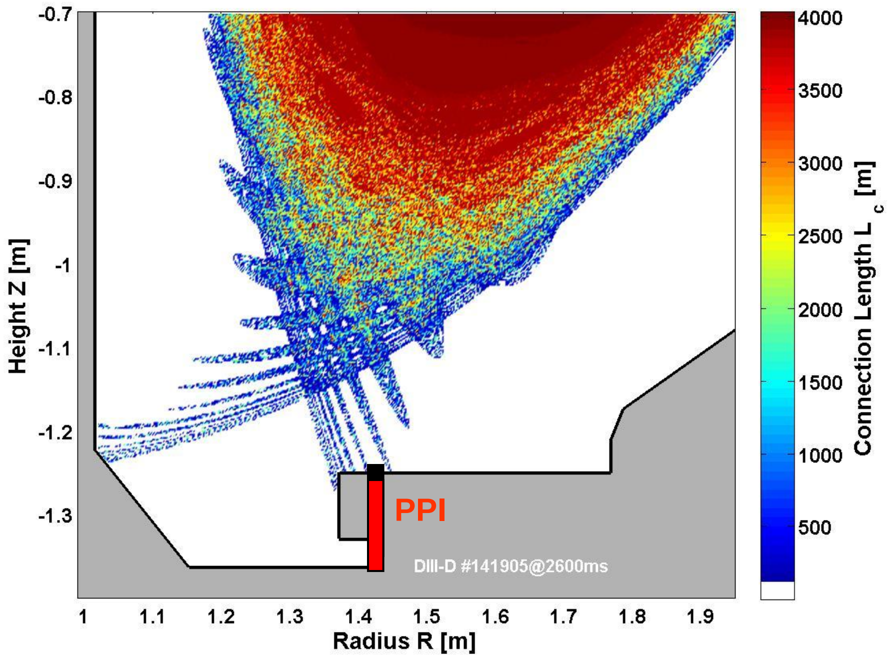


$\Gamma_{CH4\ PPI}$ = 4.7x10^{17} s^{-1}

University of Toronto
Institute for Aerospace Studies

A. McLean et al. Rev. Scientific Inst. **80** (2009) 043501 c

Talk of A. McLean et al., O-34, Friday



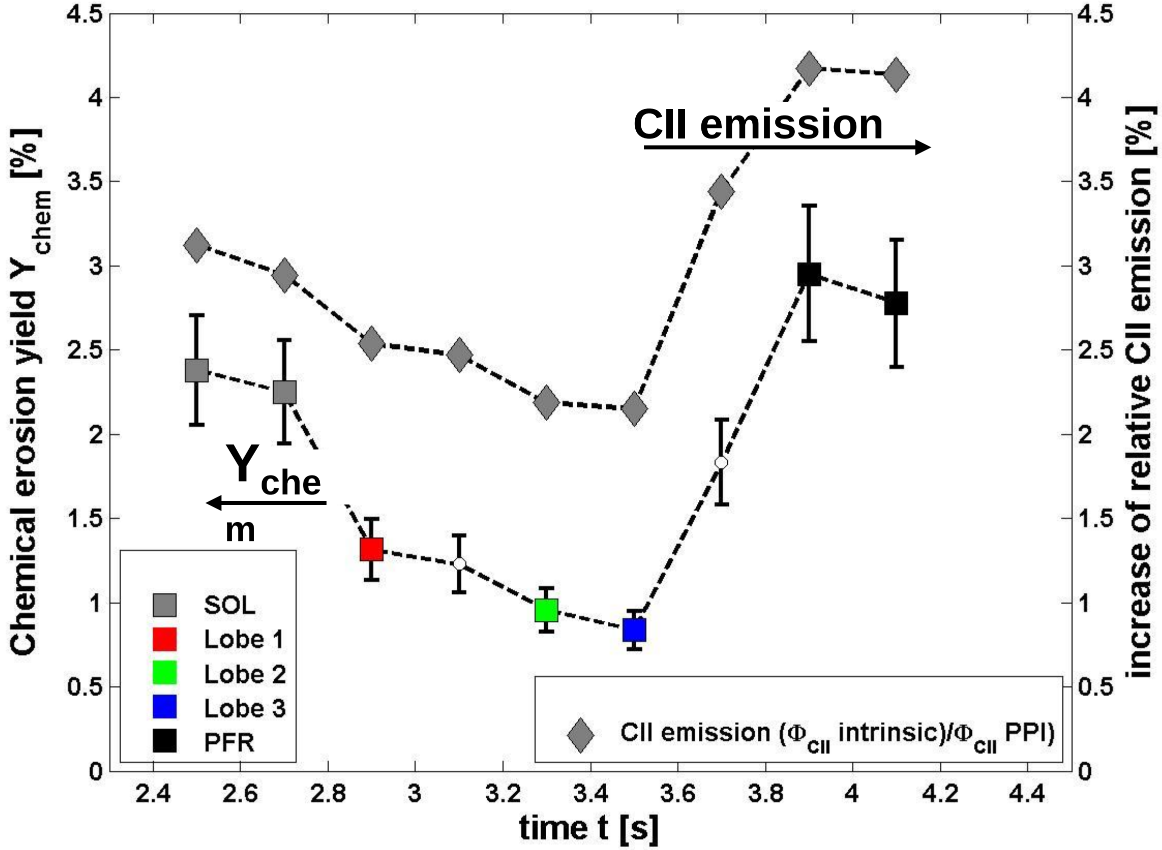
Measure chemical erosion within lobes by slow sweeping of the outer strike point

$$Y^{C}_{chem} = \frac{\Gamma_{CH_4,PPI}}{\Gamma_{D^+}} \cdot \frac{\phi^{Intrinsic}_{CD}}{\phi^{PPI\,puff}_{CH}}$$

Measure directly the chemical erosion properties within the 3D boundary

A. McLean et al. Journal Nucl. Mater. **390-391** (2009) 160-163

Local chemical erosion yield is reduced and local CII source decreases within separatrix lobes

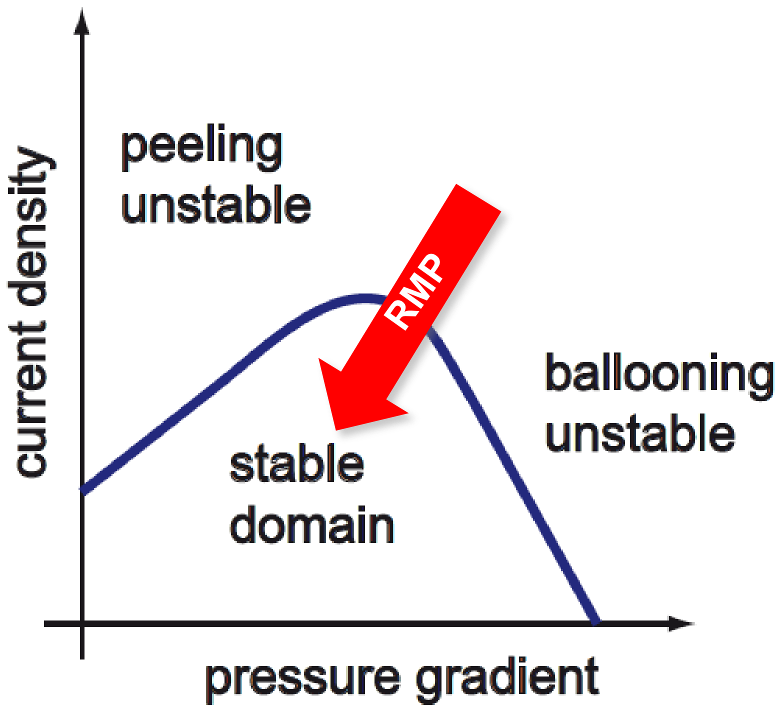


$$Y^{C}_{chem} = \frac{\Gamma_{CH_4,PPI}}{\Gamma_{D^+}} \cdot \frac{\phi^{Intrinsic}_{CD}}{\phi^{PPI\,puff}_{CH}}$$

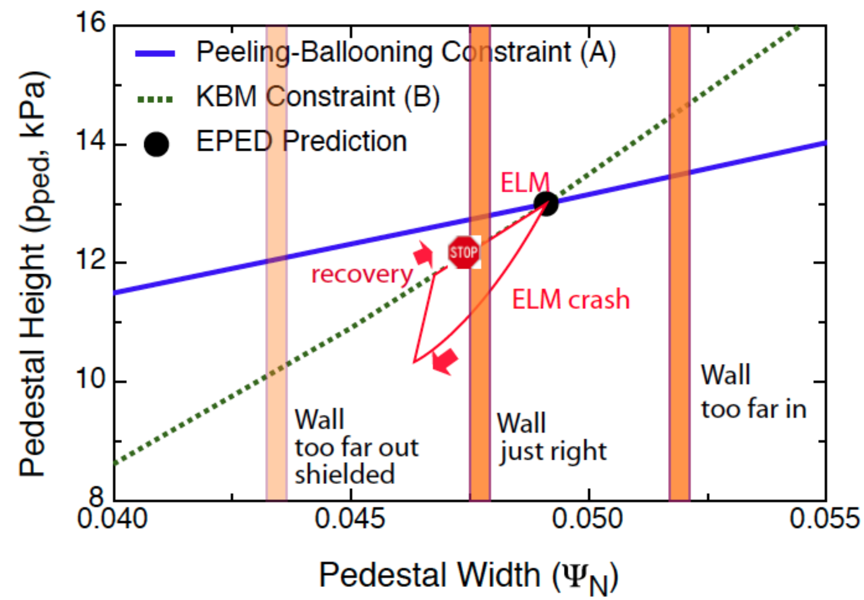
- Evidence for decrease of chemical and increase of physical sputtering with separatrix lobes as end point of open field lines from stochastic boundary
- Great data set for validation of combined 3D plasma fluid and surface layer code and investigation of relevance of effects for ITER

Potential mechanism for ELM stabilization by RMP

ELM as MHD instability



EPED stability model of ELM cycle



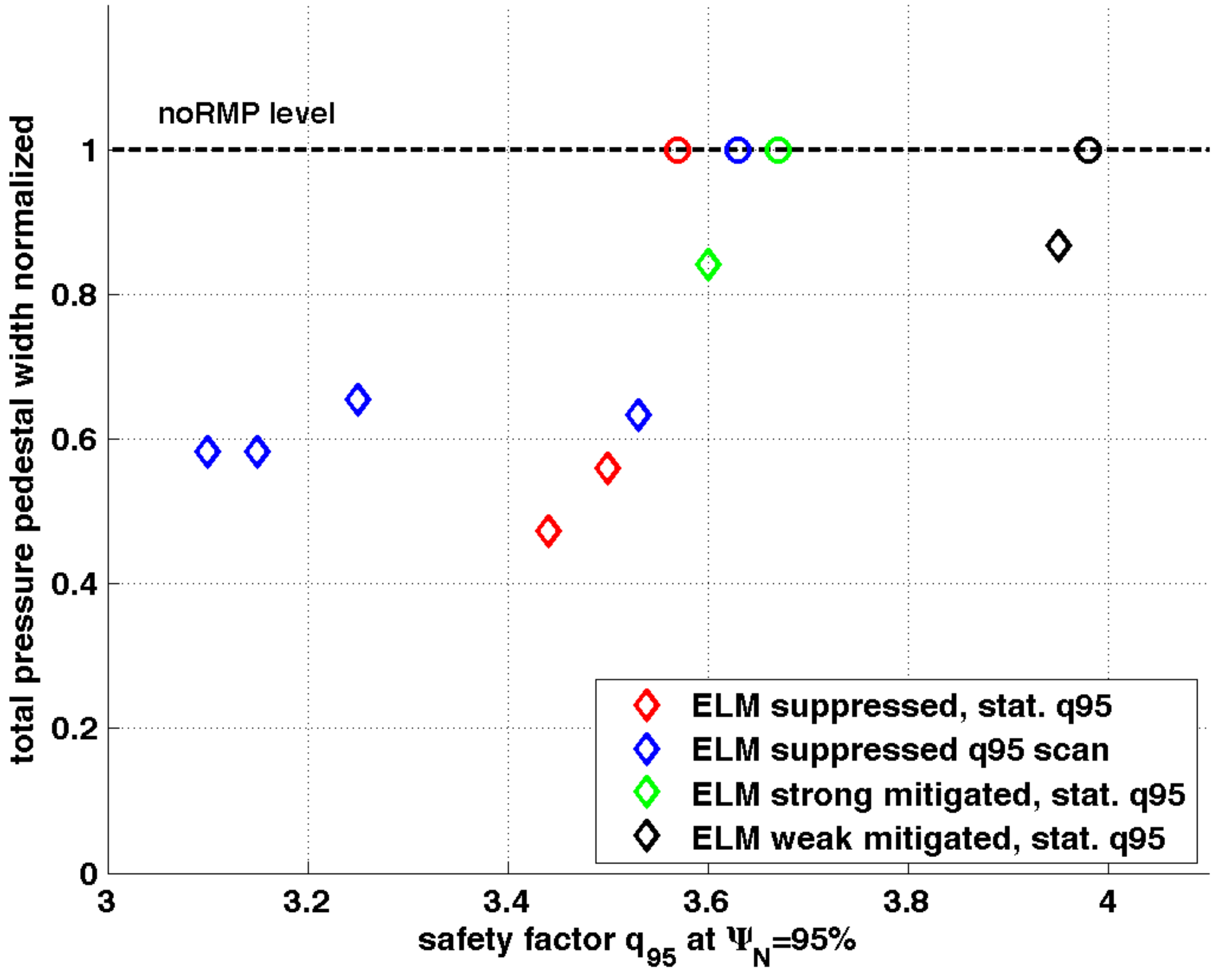
[P. Snyder et al. Physics of Plasmas **19** (2012) 056115]

Reduction of pressure alone only reduces KBM stability, i.e. moves stability boundary to more non-local effects

Mechanism to stop cycle from evolution is required with right location in P-B and KBM stability space in terms of pedestal height and width

First experimental evidence for stop of ELM cycle by RMP driven reduction of pedestal width

[P. Snyder, .. O. Schmitz,.. et al., Invited Talk, APS-DPP meeting, 2012, Salt Lake City, USA]

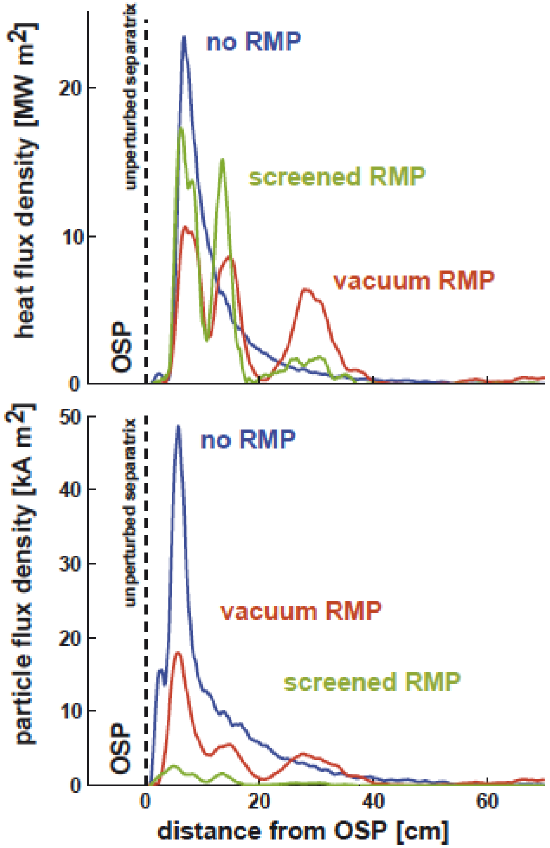


Strong q_{95} sensitivity of ELM suppression can be caused by resonant manipulation of edge transport and hence details of profile shape

- **Toroidal average shows significant effect for decay length only for vacuum case at full current level**

O. Schmitz et al., JNM (2013) at press

Toroidally localized profiles show striated heat flux with reduced peak heat loads



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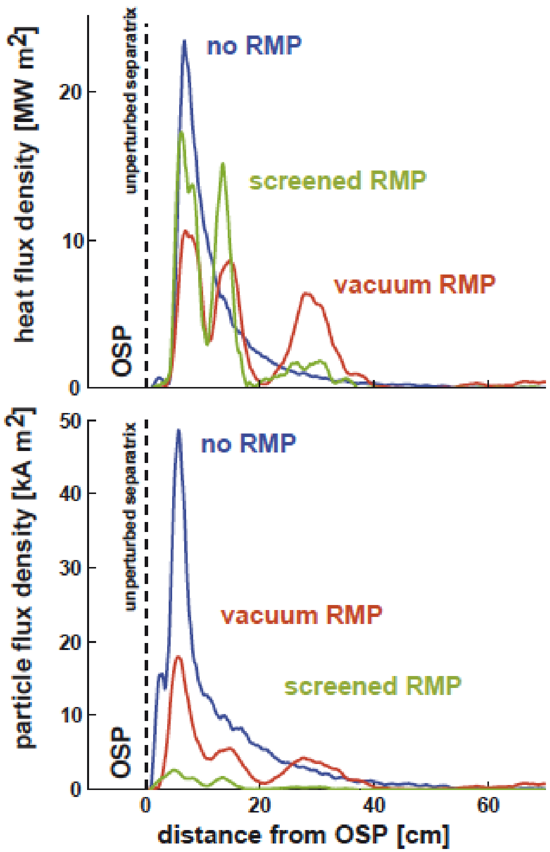

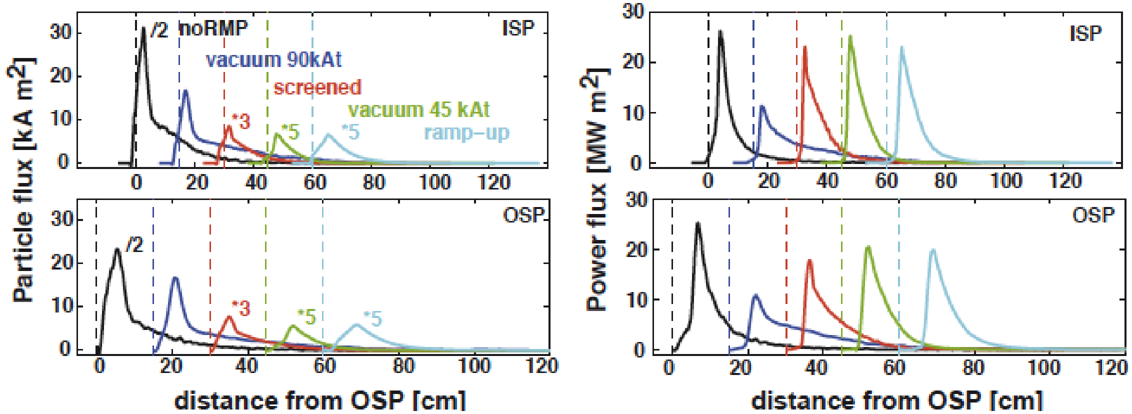

Toroidal averaging requires rotation of external RMP field

Toroidal average shows significant effect for decay length only for vacuum case at full current level

O. Schmitz et al., JNM (2013) at press

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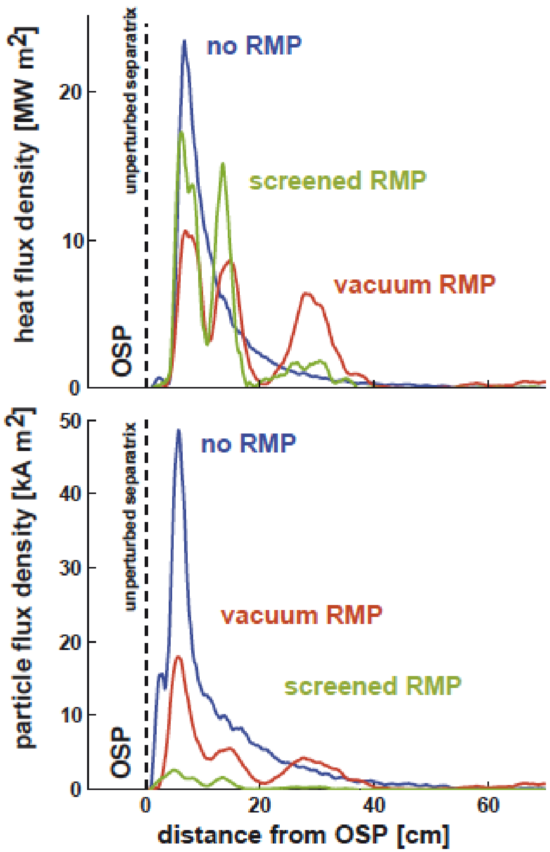

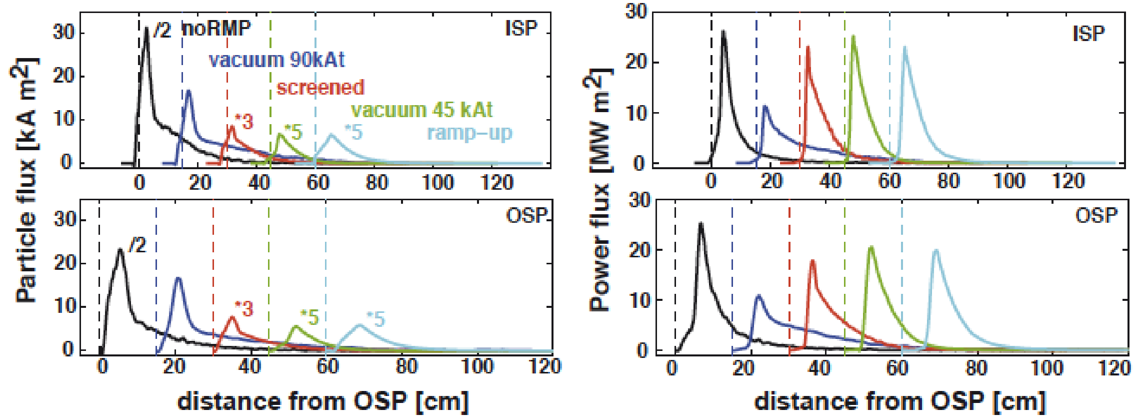

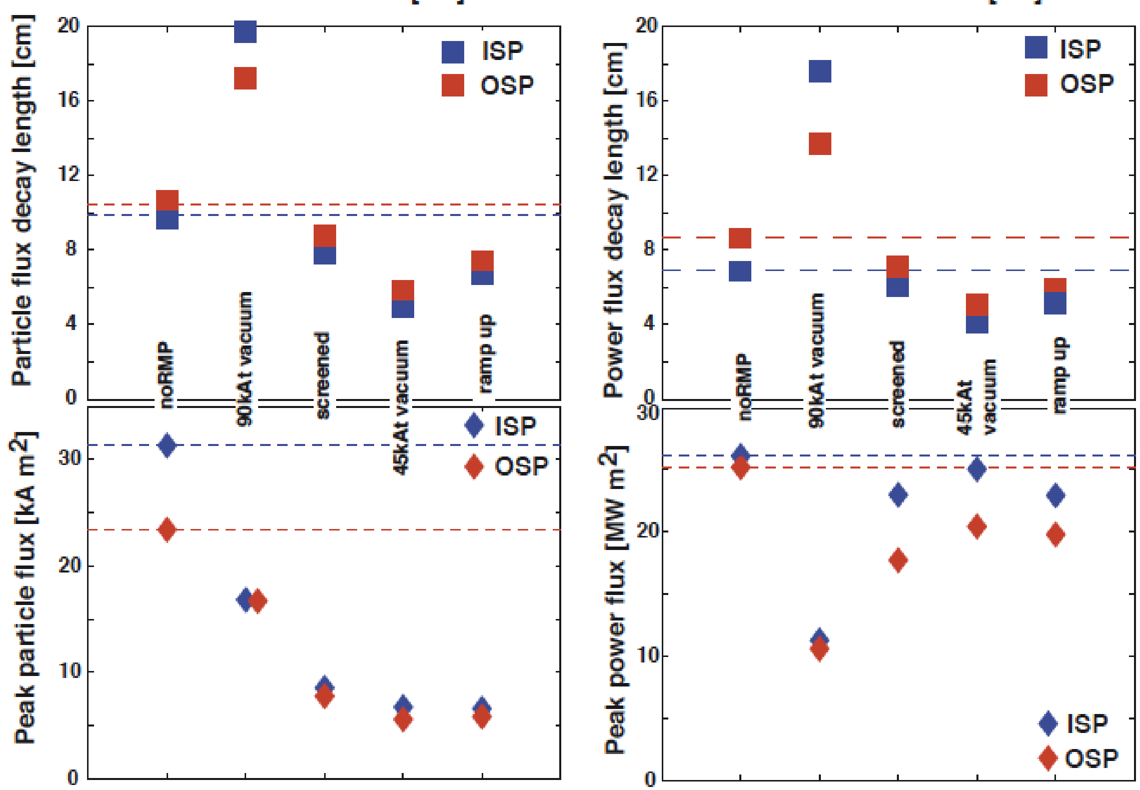

Toroidal averaging requires rotation of external RMP field