Max-Planck-Institut
für Plasmaphysik

Experimental Conditions for Suppressing Edge Localised Modes by Magnetic Perturbations in ASDEX Upgrade

Perturbation 5x magnified

Wolfgang Suttrop, A Kirk[2], V Bobkov, M Cavedon, M Dunne, N Leuthold, R M McDermott, H Meyer[2], R Nazikian[3], C Paz-Soldan[4], D A Ryan[2], E Viezzer[5], M Willensdorfer, and the ASDEX Upgrade[6] and MST1[7] teams

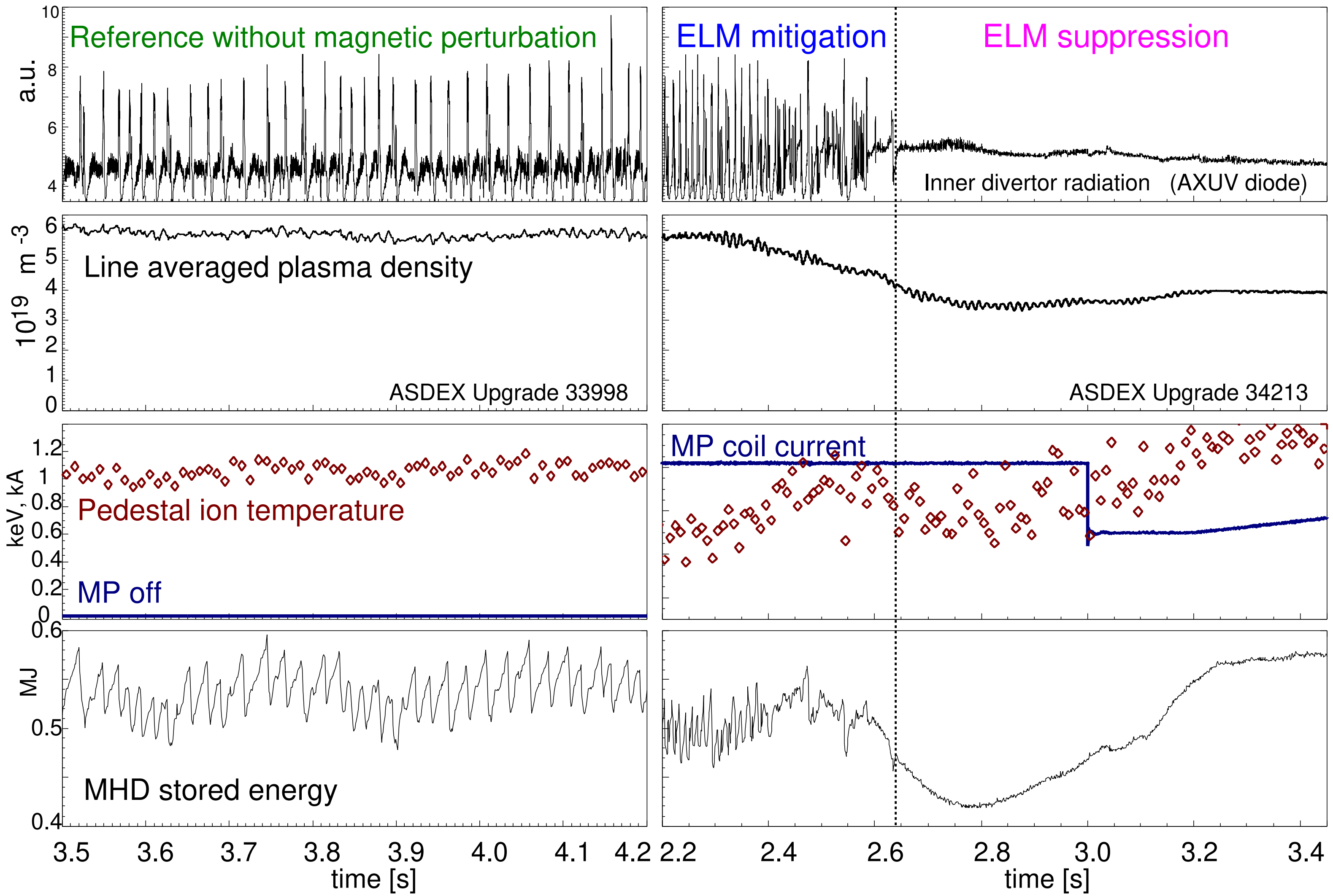
Max-Planck-Institut für Plasmaphysik D-85740 Garching, Germany
[2]CCFE, UK; [3]PPPL, USA; [4]General Atomics, USA; [5]U Sevilla, Spain
[6]see A Kallenbach et al, Nuclear Fusion **57** (2017) 102015
[7]see author list of H Meyer et al, Nuclear Fusion **57** (2017) 102014

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

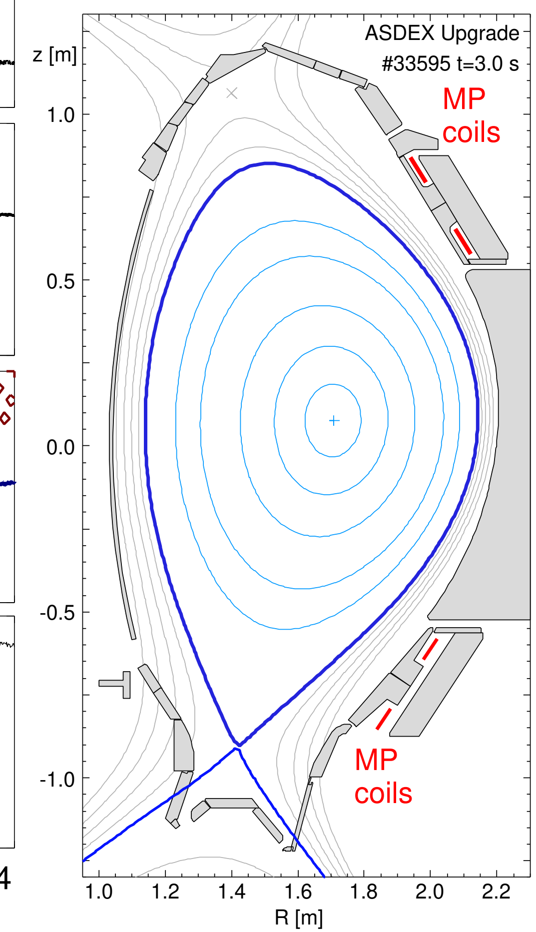
ELM mitigation and suppression in ASDEX Upgrade

Magnetic perturbation: **OFF** **ON** (toroidal mode# $n = 2$)



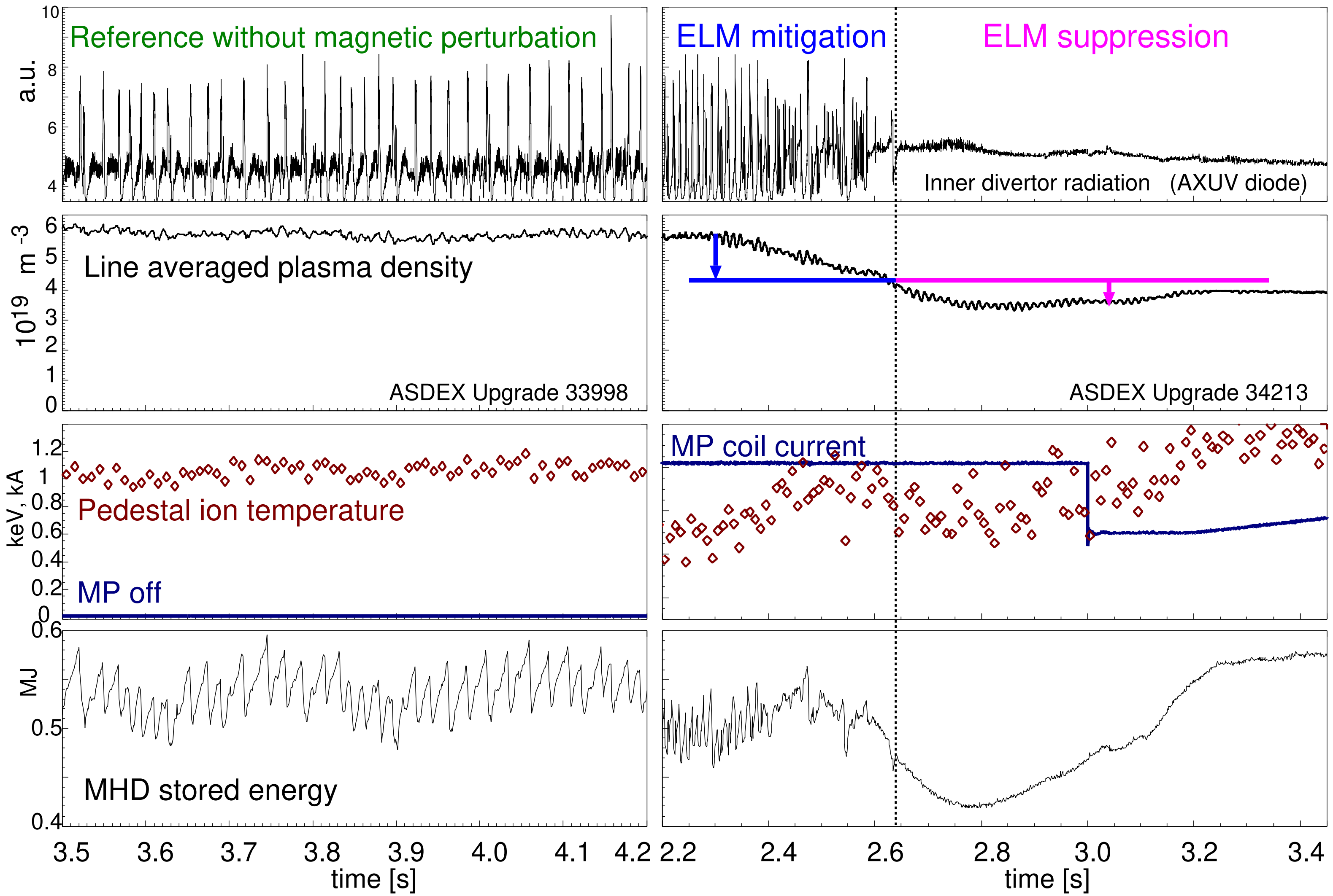
Moderately elevated triangularity required for ELM suppression

R Nazikian *et al*, IAEA FEC 2016



ELM suppression as observed in ASDEX Upgrade

Magnetic perturbation: **OFF** **ON** (toroidal mode# $n = 2$)



Effect on ELMs depends on plasma density.

ELM mitigation:

$\Delta W_{ELM}/W = 12\% \rightarrow \sim 2\%$

Density “pump-out”

Below a critical density:

ELM suppression:

More “pump-out”

T_i recovery at pedestal

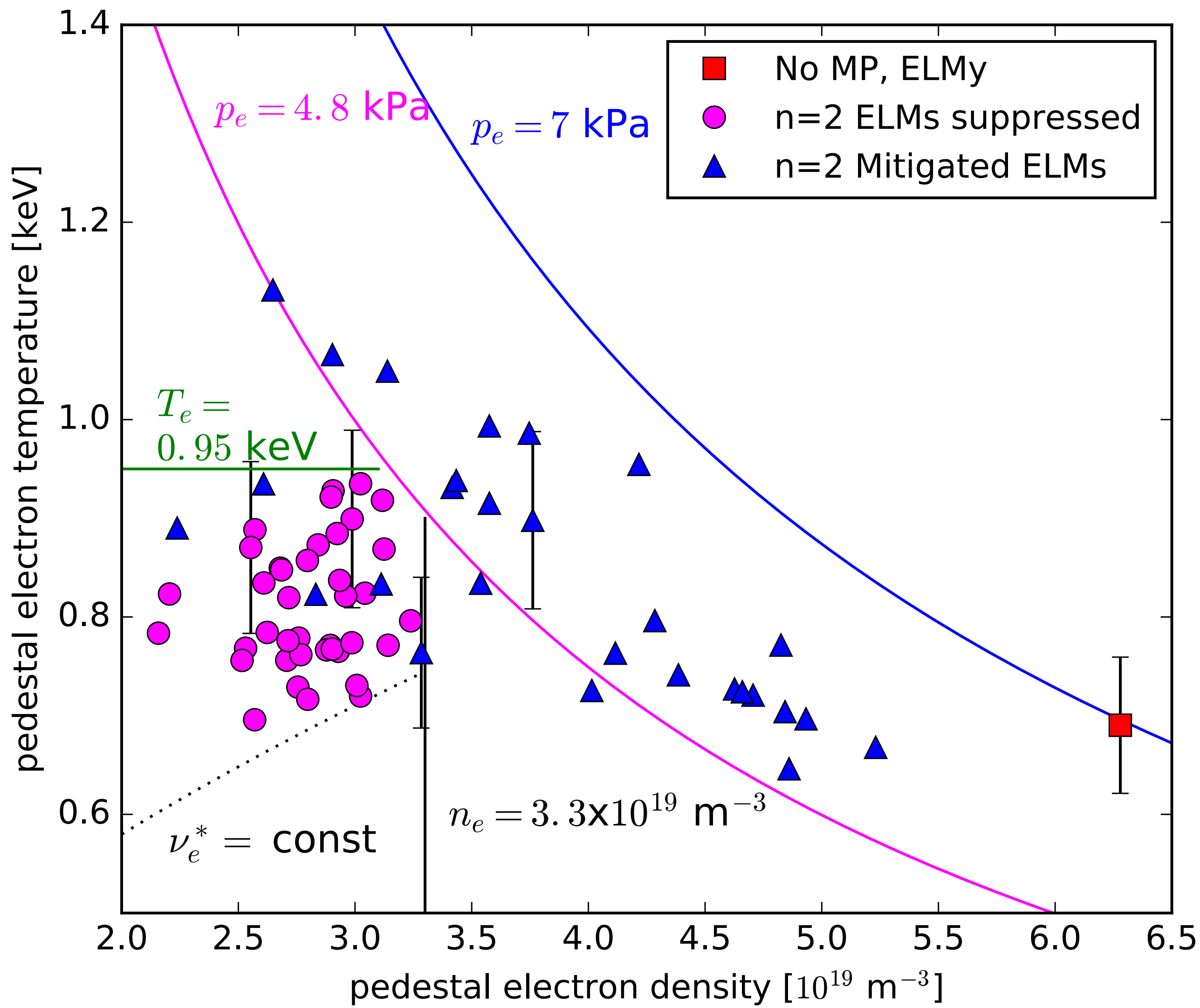
Conditions for ELM suppression in ASDEX Upgrade

- Is the density threshold a collisionality limit?
- Plasma response to the magnetic perturbation
- Safety factor constraints
- No rotation threshold observed
- Conclusions from transitions into and out of ELM suppression

see also: W Suttrop *et al*, Nucl. Fusion **58** (2018) 096031

Edge operational space of ELM suppression

Pedestal T_e - n_e diagram:



Maximum pedestal density:
$n_{e,ped} \leq 3.3 \times 10^{19}$

Collisionality limit: $T \propto \sqrt{n}$
However, no transitions $\perp$ ($\nu^* =$ const)

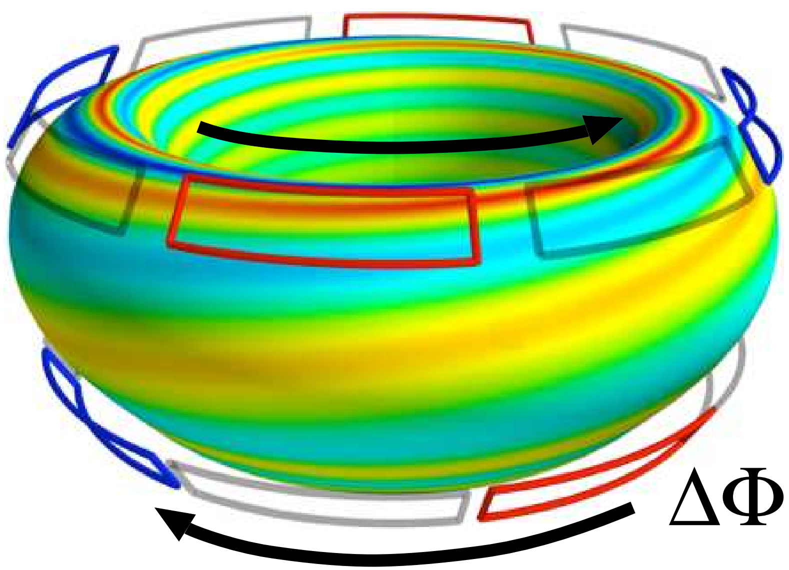
Small ELM pedestal pressure limit
(reduced with MP compared to axisymmetric case)

Conjecture:
Edge stability (shaping, B_t^2/q^2, j_{bs}) governs ELM suppression operational space.

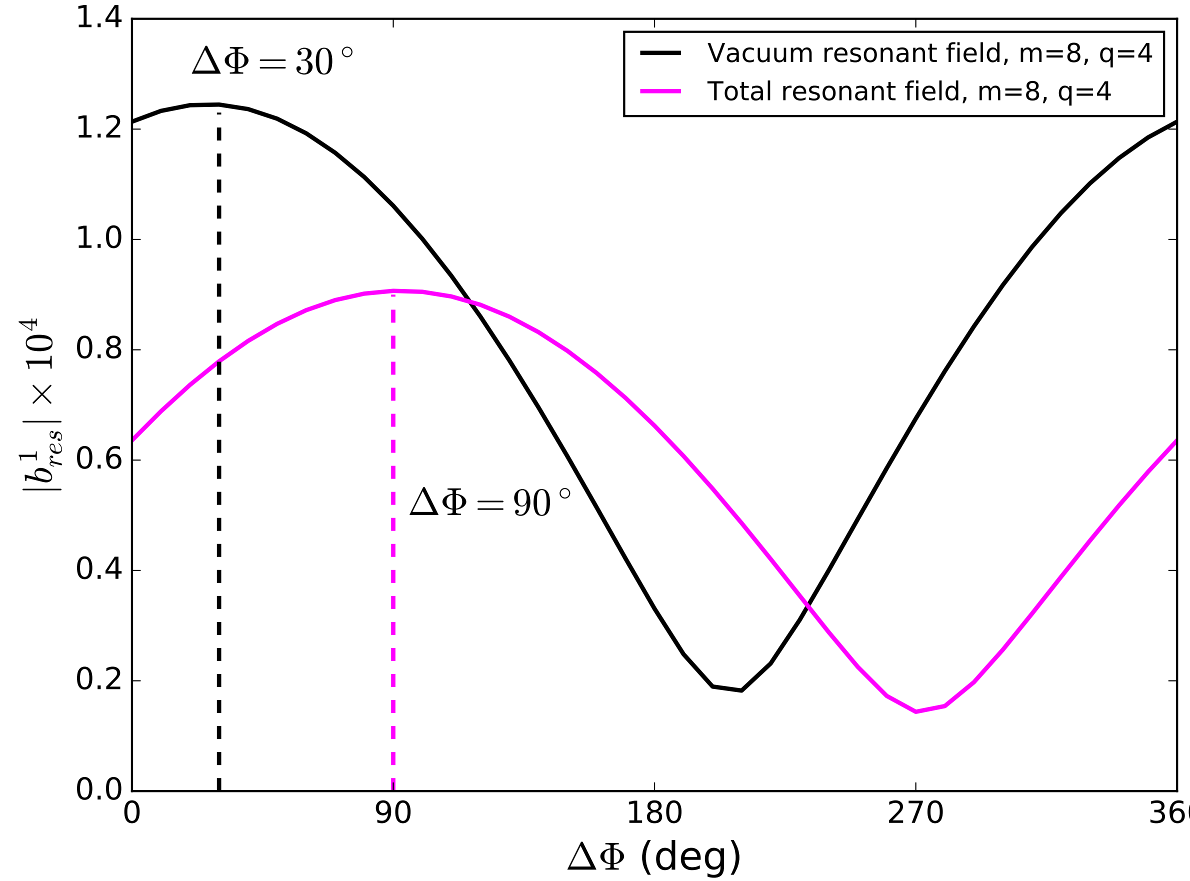
Poloidal spectrum variation to identify plasma response

Alignment of external MP with B can be varied by adjusting $\Delta\Phi$

(phase difference of upper vs. lower coil current patterns)



Predicted resonant perturbation field ($m = 8$, $n = 2$ at $q = 4$)



Resistive linear MHD response calculation (MARS-F): D A Ryan

Poloidal spectrum variation to identify plasma response

MP coil current threshold

for backtransition from ELM suppression

Measured ratio: 1.17

Expected for field-aligned MP: 1.7

kink-peeling: 1.0

→ **Kink-peeling response** important for maintaining ELM suppression

Ideal MHD response also describes:

— surface corrugation

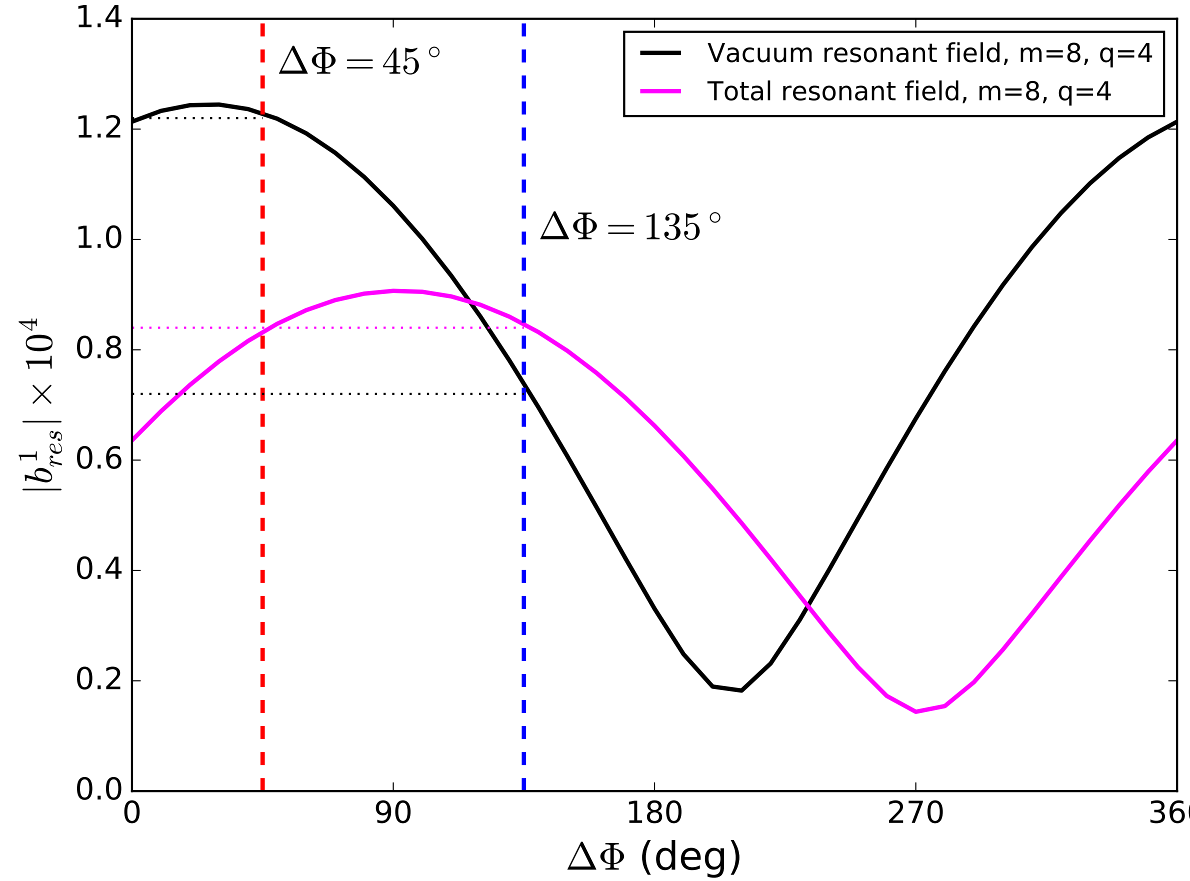
M Willensdorfer *et al*, **EX/P8-20**

Nucl. Fusion 57 (2017) 116047

— ELM mitigation, pump-out

D A Ryan *et al*, PPCF 60 (2018) 065005

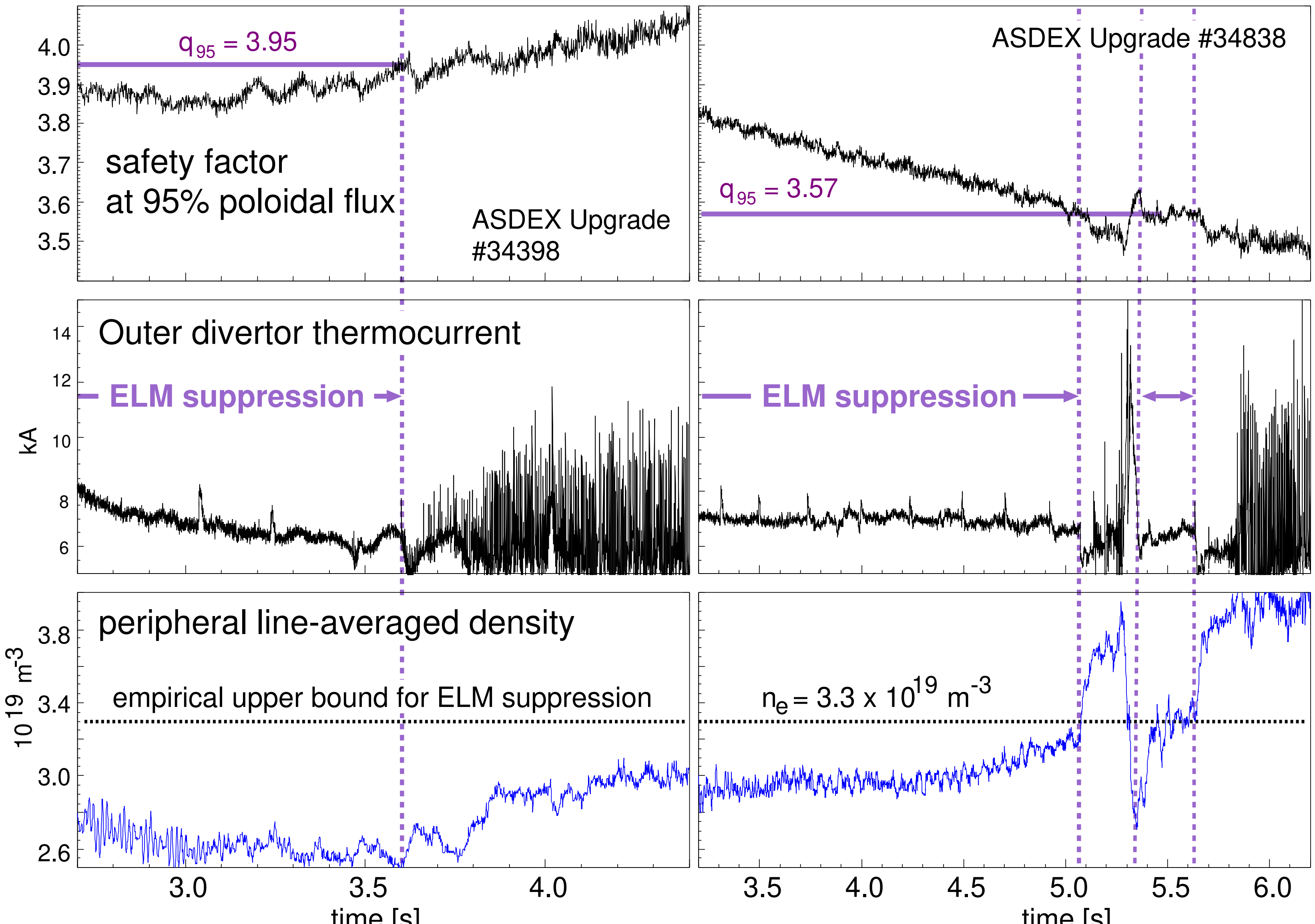
Predicted resonant perturbation field ($m = 8$, $n = 2$ at $q = 4$)



Resistive response (sideband to kink-peeling) **produced by toroidicity and poloidal plasma shaping**

Edge safety factor (q_{95}) constraints

ELM suppression occurs only in range $q_{95} = 3.57 - 3.95$

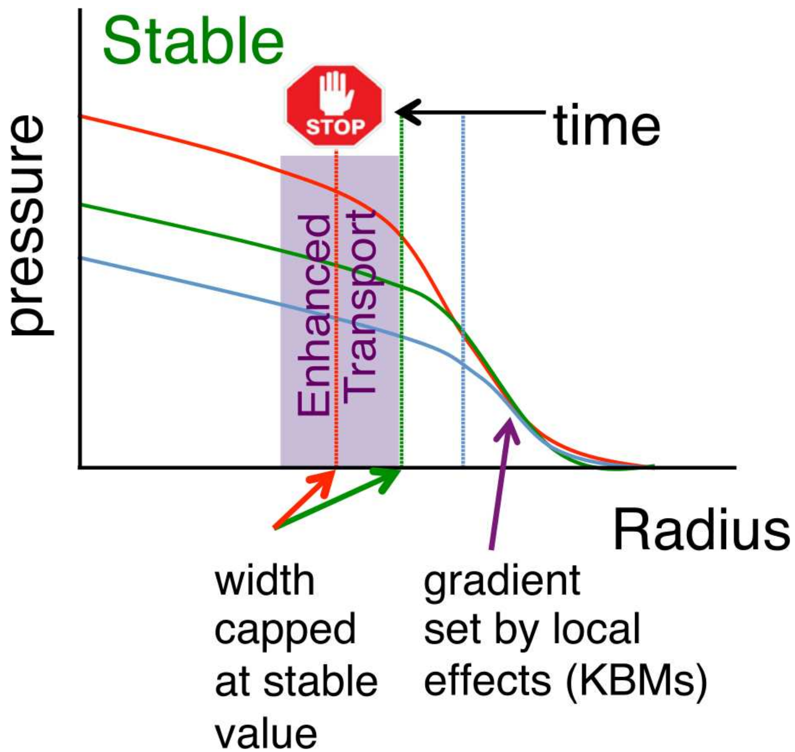


Repeats show q_{95} interval is reproducible.

During suppression:
Density remains small
$\rightarrow$ backtransition caused by q_{95} variation.

A Model for ELM suppression by RMP

Resonant response $q = m/n$ to magnetic perturbation stops expansion of H-mode edge transport barrier before ELMs are destabilised.



R Moyer *et al*, Phys. Plasmas **24** (2017) 102501

M Wade *et al*, Nucl. Fusion **55** (2015) 23002

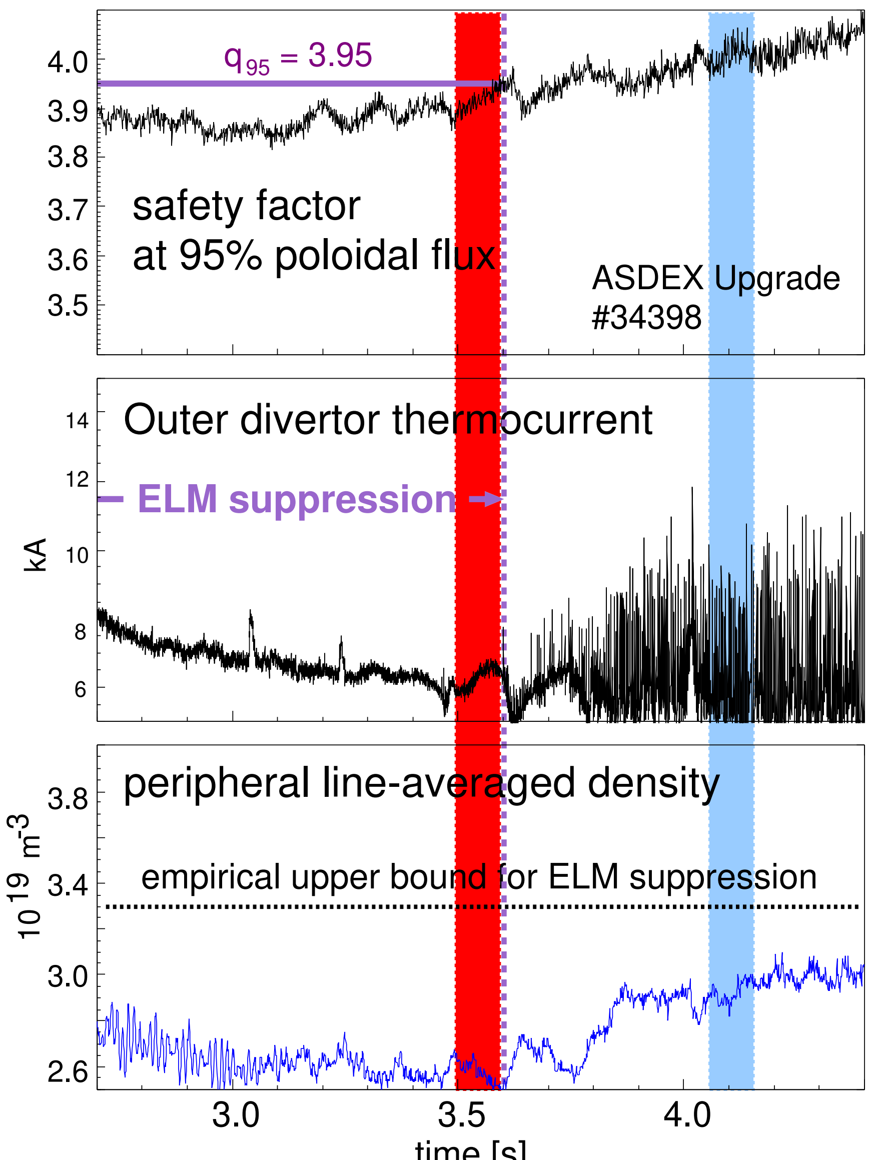
P Snyder *et al*, Phys. Plasmas **19** (2012) 56115

ASDEX Upgrade ELM suppression experiment:

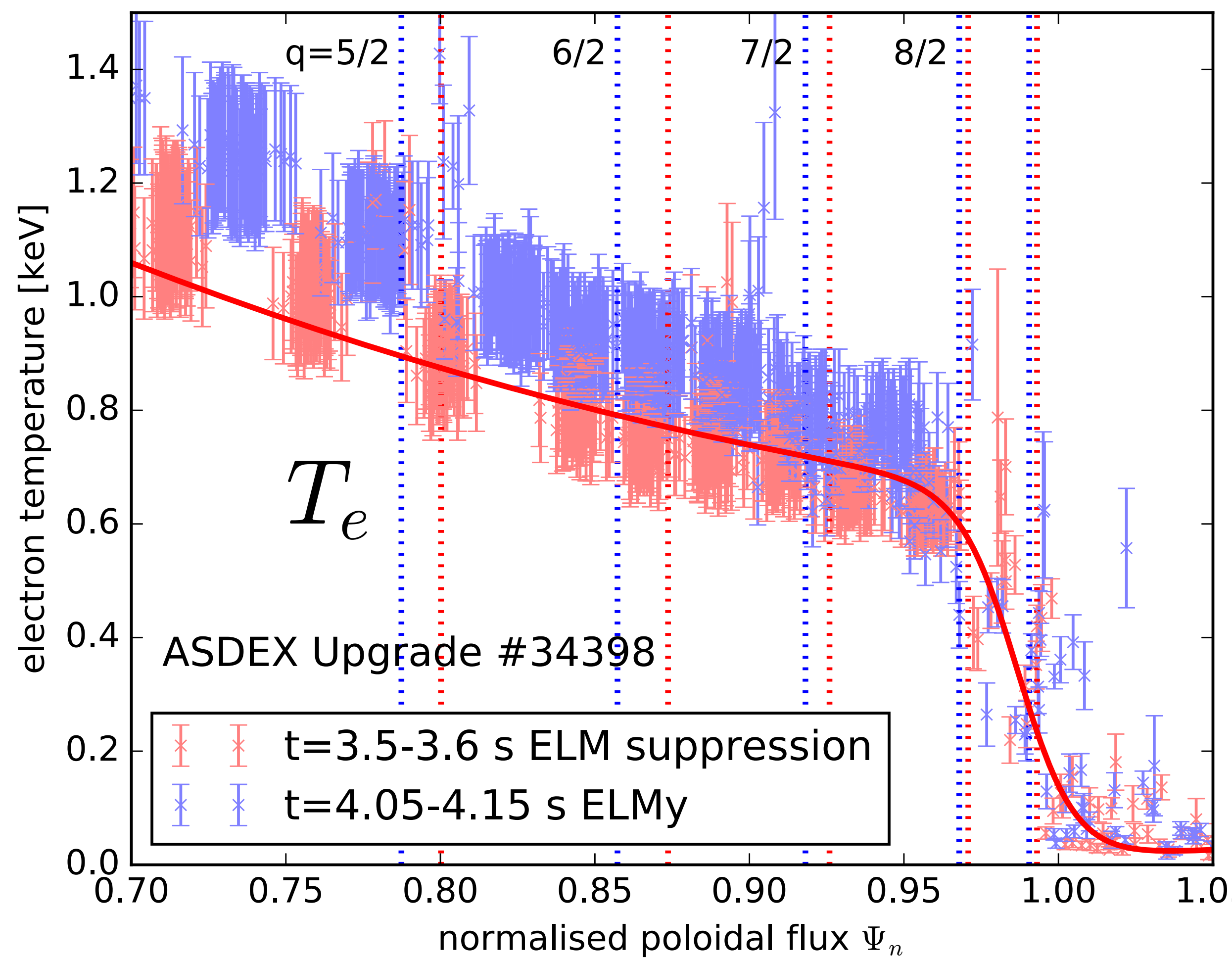
1. Alignment of resonant surfaces with barrier knee?

Is there a resonant surface at the barrier knee?

Profiles before/after back-transition



$q = 8/2$ surface is located near edge barrier top (✓).
Very small shift is sufficient to lose ELM suppression!

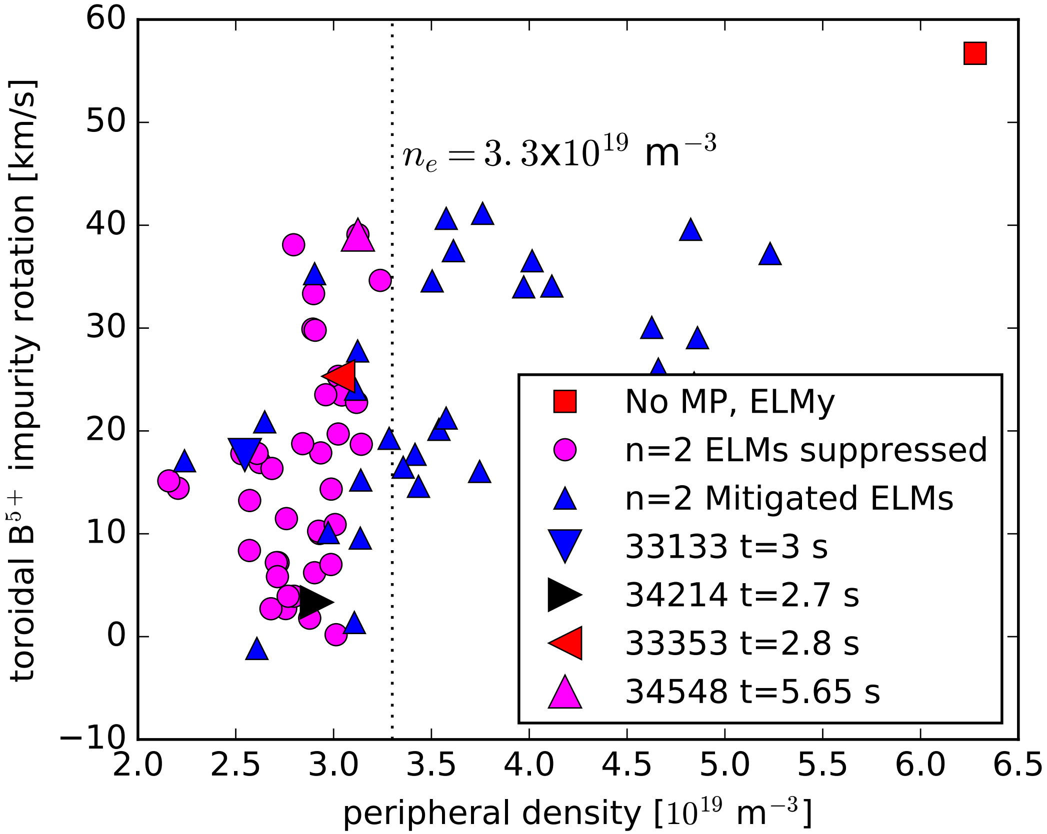


Is the resonant response shielded?

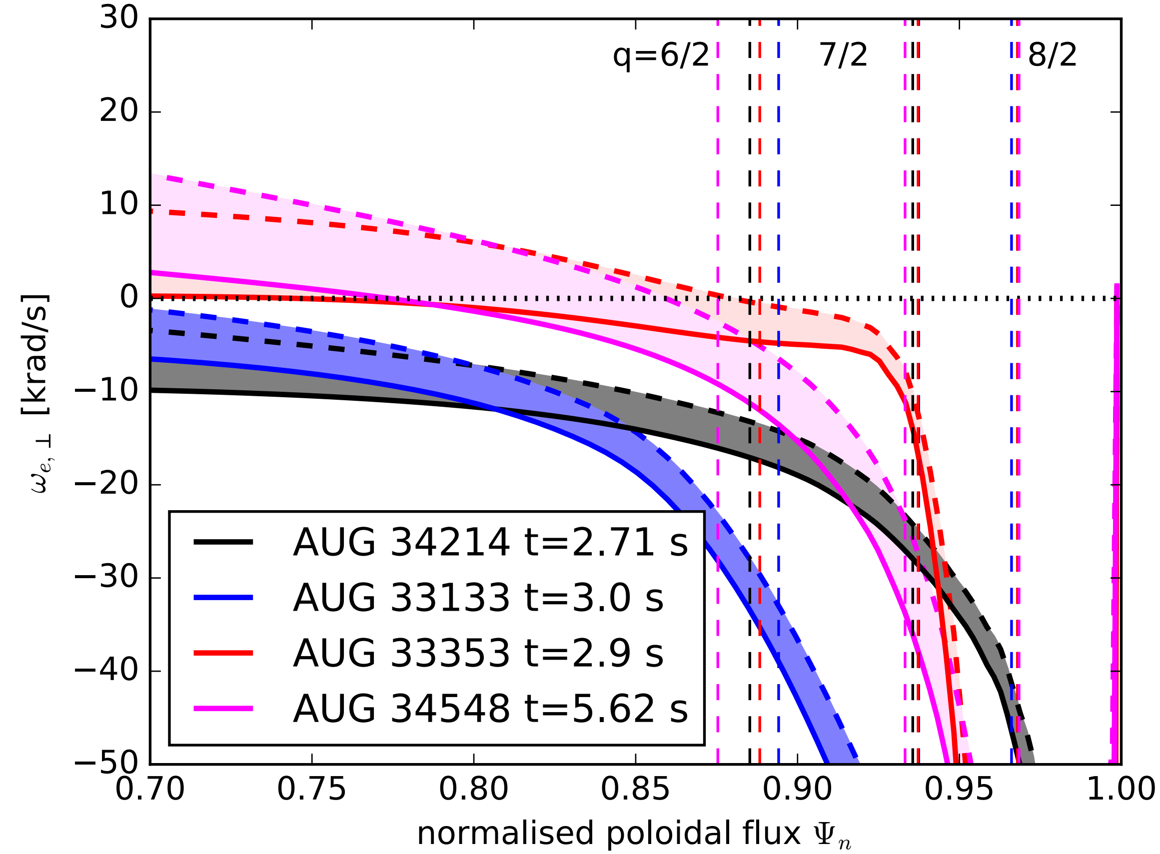
Resistive response can be reduced (shielded) by helical currents induced by cross-field flows

2-fluid MHD: $\omega_{e,\perp}$ governs field shielding   M Bécoulet *et al* Nucl. Fusion 52 (2012) 054003

So far no restrictions of plasma flow for ELM suppression in ASDEX Upgrade:



ELM suppression observed in cases where $\omega_{e,\perp}$ has no zero-crossing:



Is the resonant response shielded?

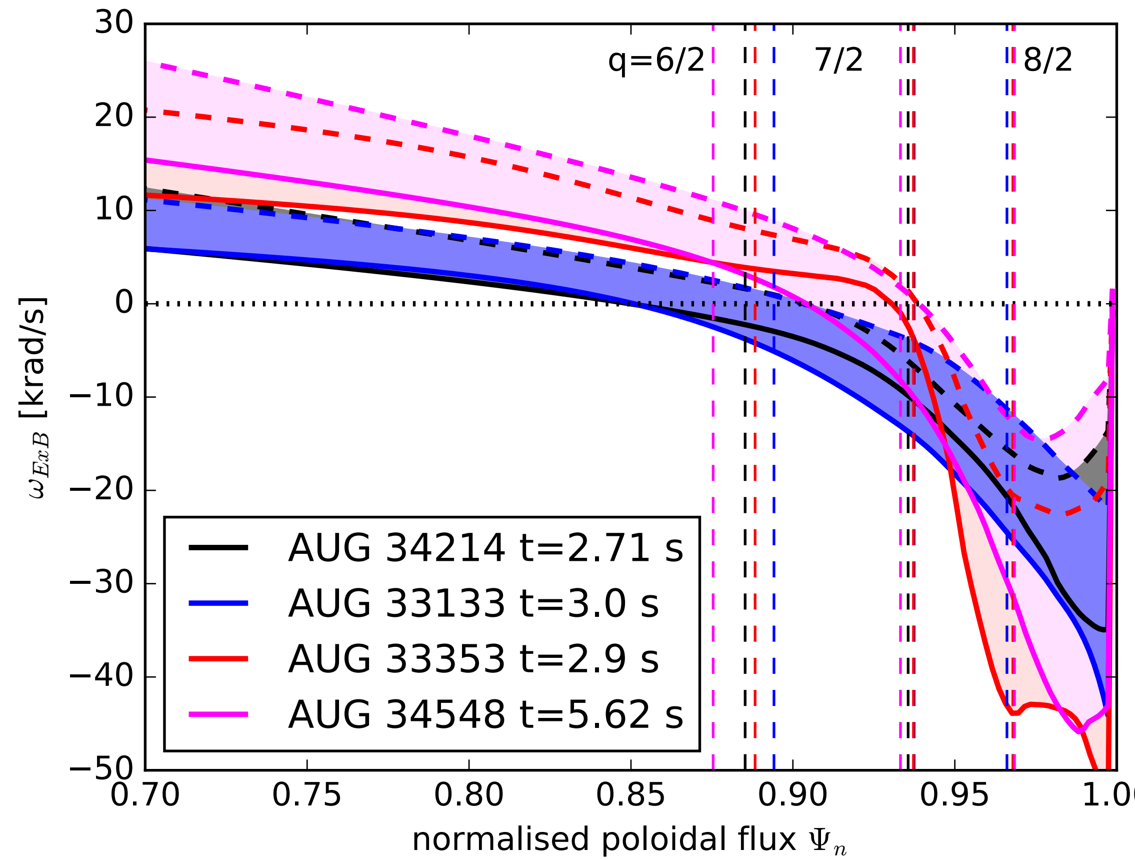
However, the $E \times B$ flow crosses zero in the pedestal region.

– With co-Ip NBI injection,
$E_r > 0$ in the plasma core

– H-mode edge barrier: $E_r < 0$

$\rightarrow$ particle orbits can resonate with the static MP field.

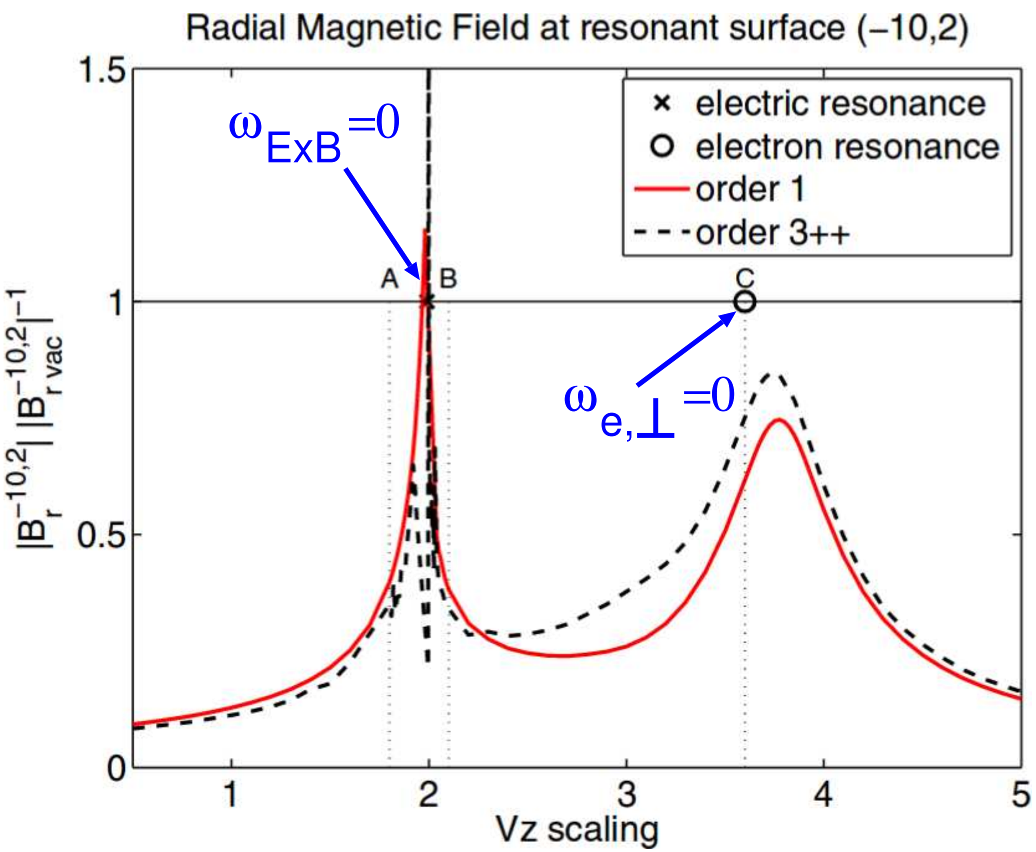
$\omega_{E\times B} = 0$ in the vicinity of some rational surface:



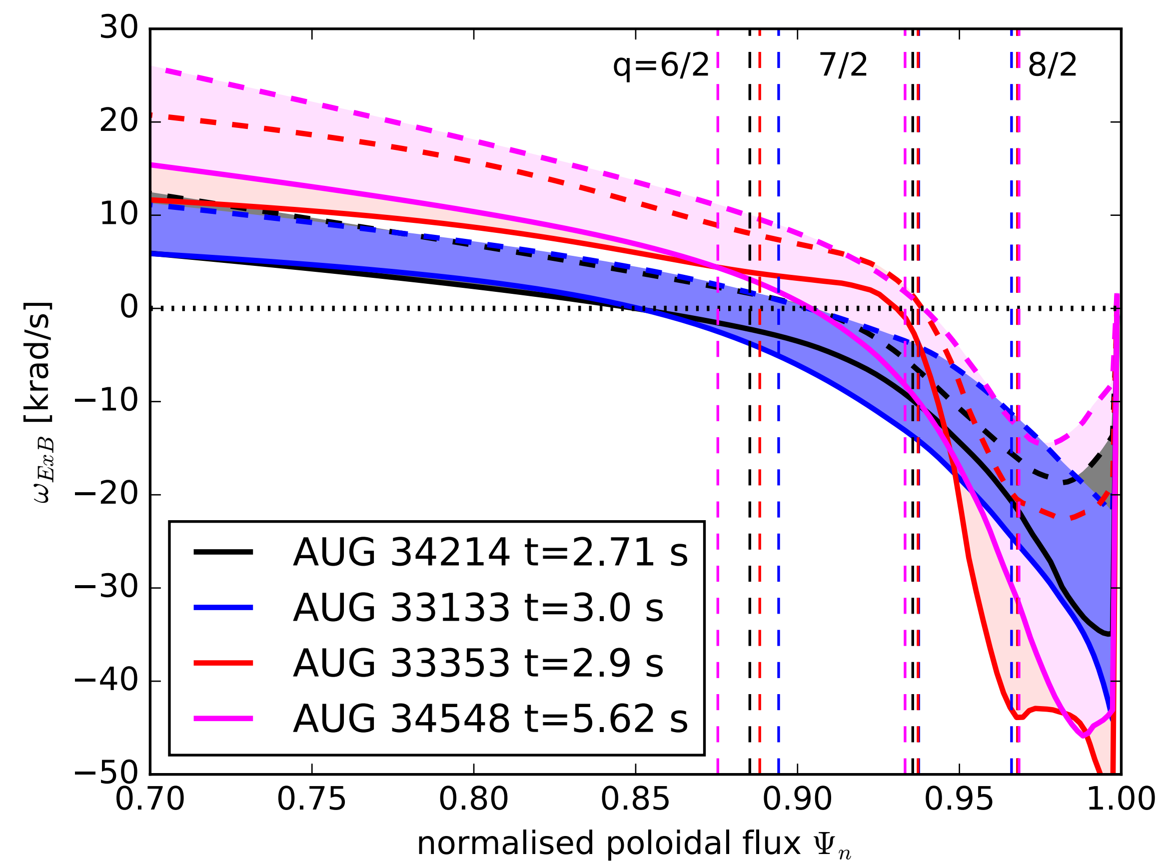
Kinetic model shows that a resonant response field B_r and enhanced radial transport can occur.

M Heyn *et al*, NF 54 (2014) 64005

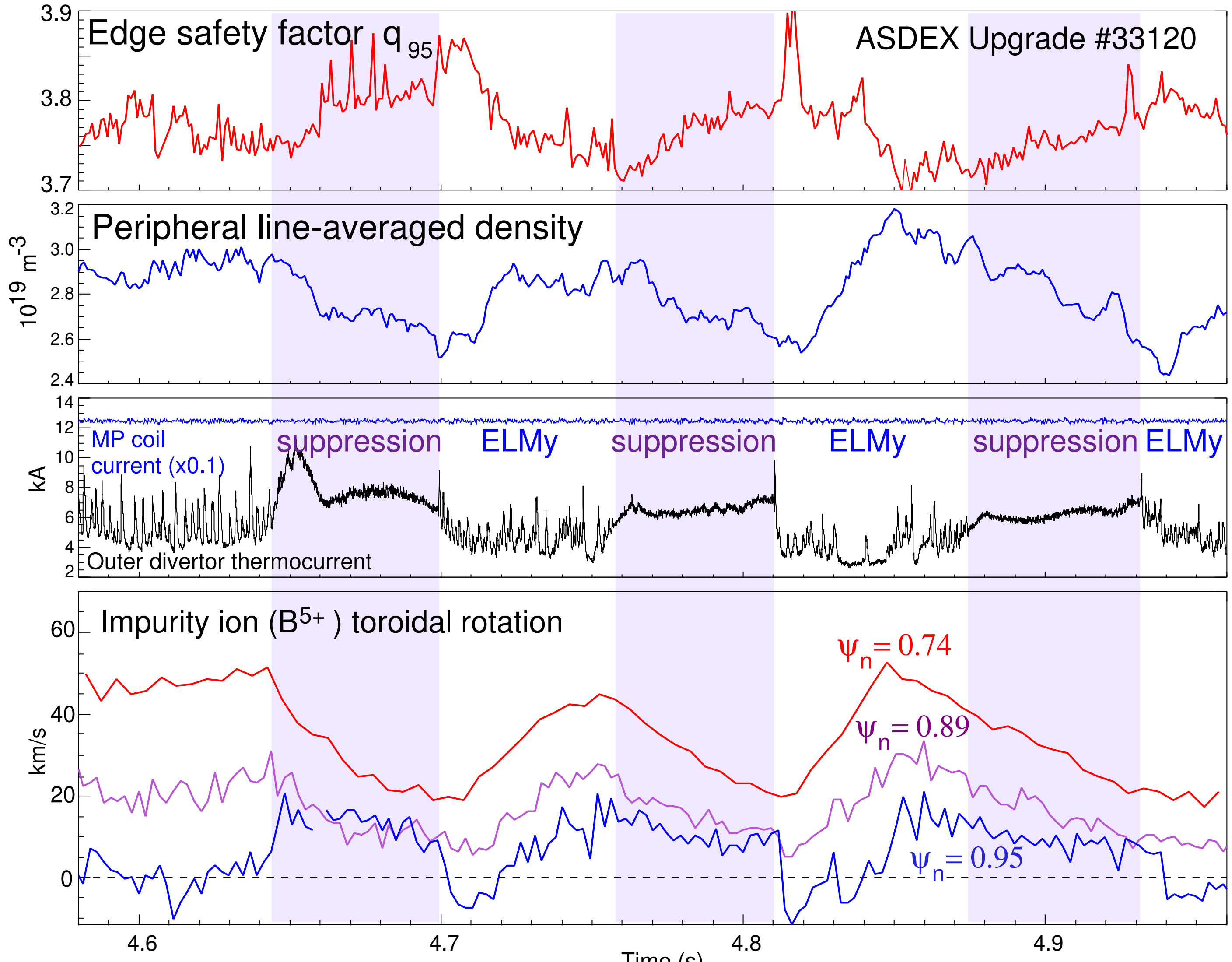
Additional “kinetic” resonance at $\omega_{E\times B} = \omega_{MP}$



$\omega_{E\times B} = 0$ in the vicinity of *some* rational surface:



Occasionally, repetitive transitions are observed:

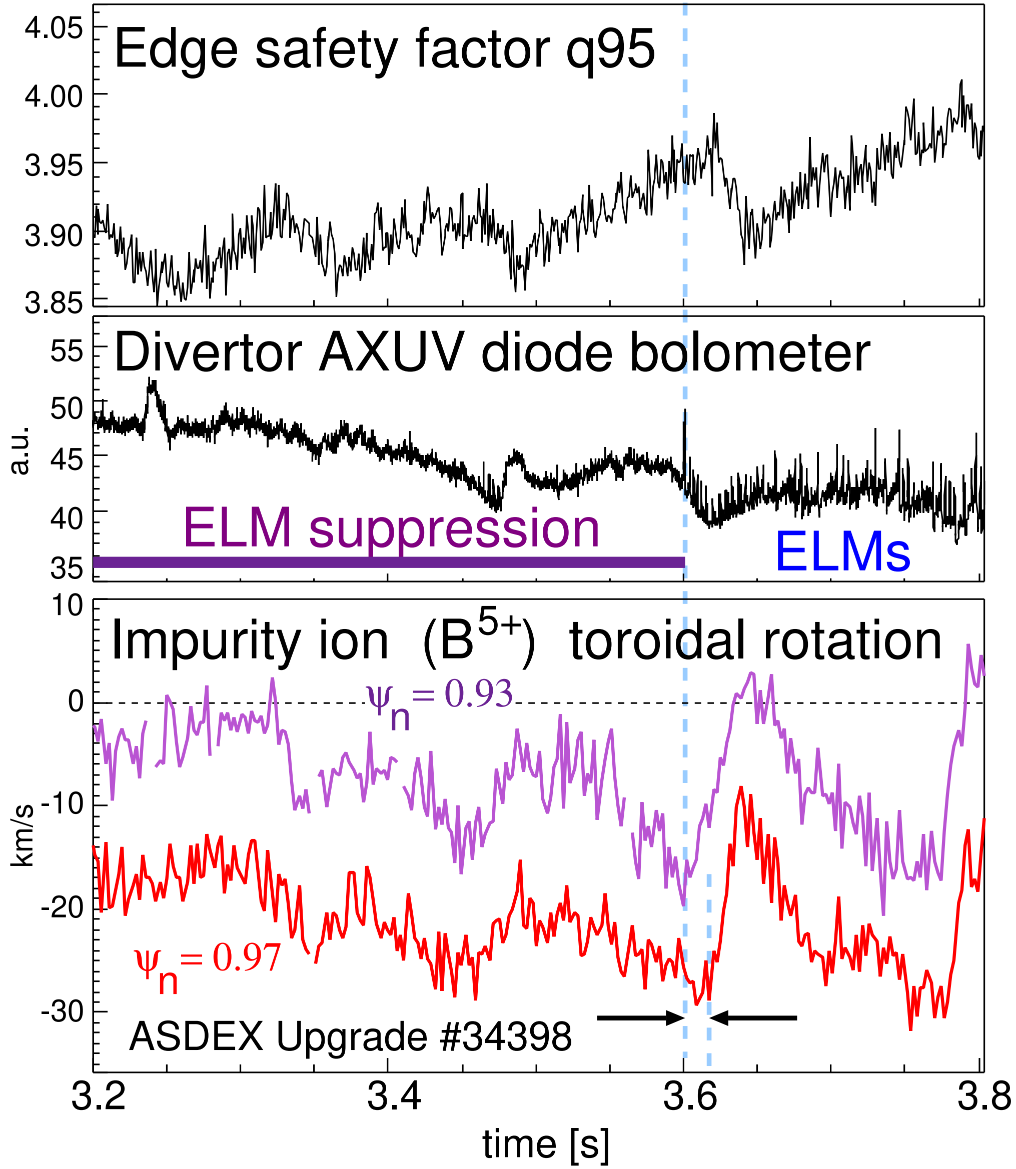


"Limit cycle" oscillations (possibly controlled by q_{95})

During suppression:
Strong rotation braking towards zero flow
$\rightarrow$ Resonant torque

ELMing phases:
Initial negative (ctr-NBI) rotation
$\rightarrow$ Dominant NTV torque (?)

Backtransition from ELM suppression:



Sharp change of toroidal rotation is observed:

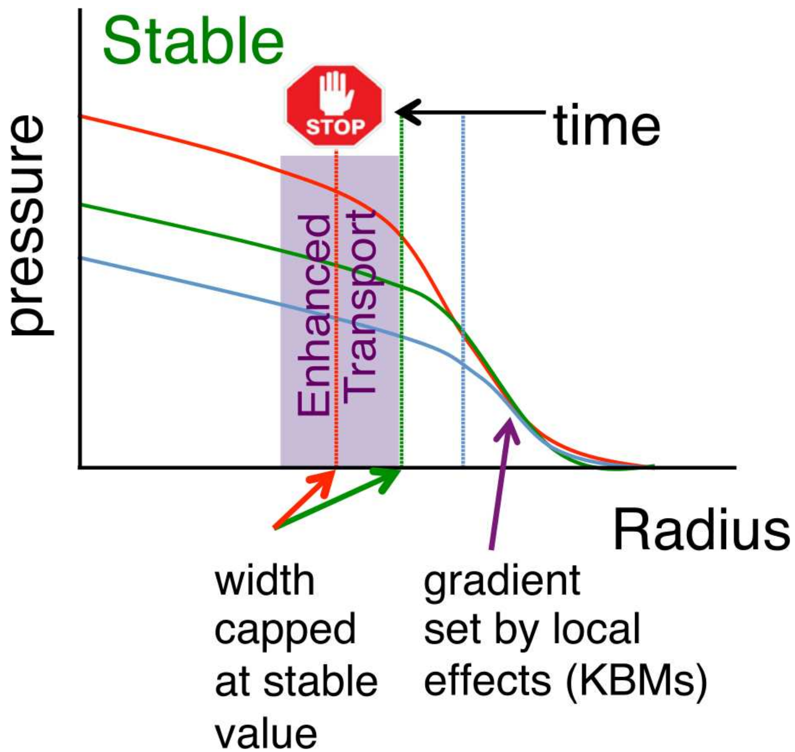
first on pedestal top ($\psi_n = 0.93$, $q = 7/2$)

ms later at the pedestal knee ($\psi_n = 0.97$, $q = 4$)

suggests torque is exerted well inside pedestal top and momentum is transported outward.

A Model for ELM suppression by RMP

Resonant response $q = m/n$ to magnetic perturbation stops expansion of H-mode edge transport barrier before ELMs are destabilised.



ASDEX Upgrade ELM suppression experiment:

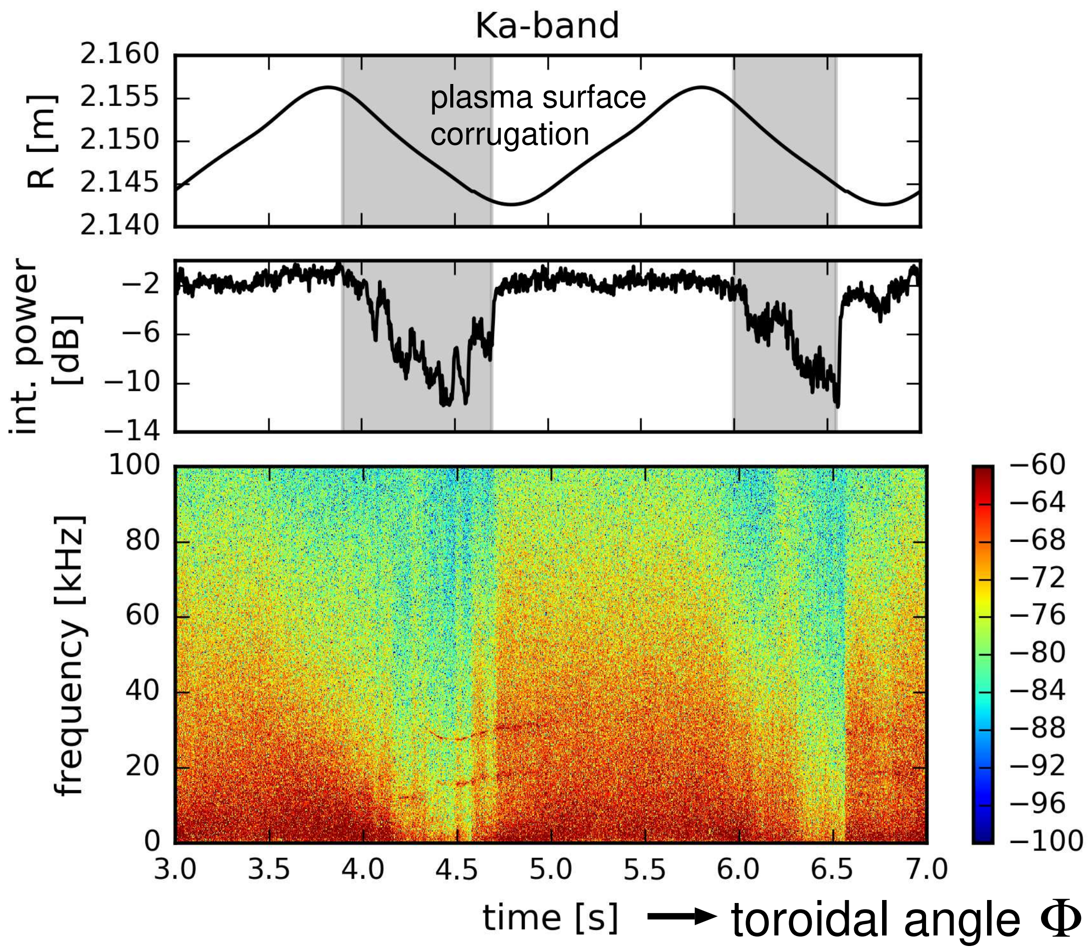
1. Alignment of resonant surfaces with barrier knee? Yes. (✓)
2. Resistive response at resonant surfaces?
   — Not expected in all cases from 2-fluid MHD (✗)
   — Requires particle resonance:
   $\omega_{E\times B} = \omega_{MP} = 0$ surface exists (✓)
   — Strong rotation braking during suppression (✓)
3. Alignment of *resistive response* with barrier knee? In some cases torque is exerted further inside (✗)

But — what else can cause the additional transport that keeps the plasma edge stable against ELMs?

Broadband turbulence causes transport across edge barrier

Broadband mode, intensity non-axisymmetric

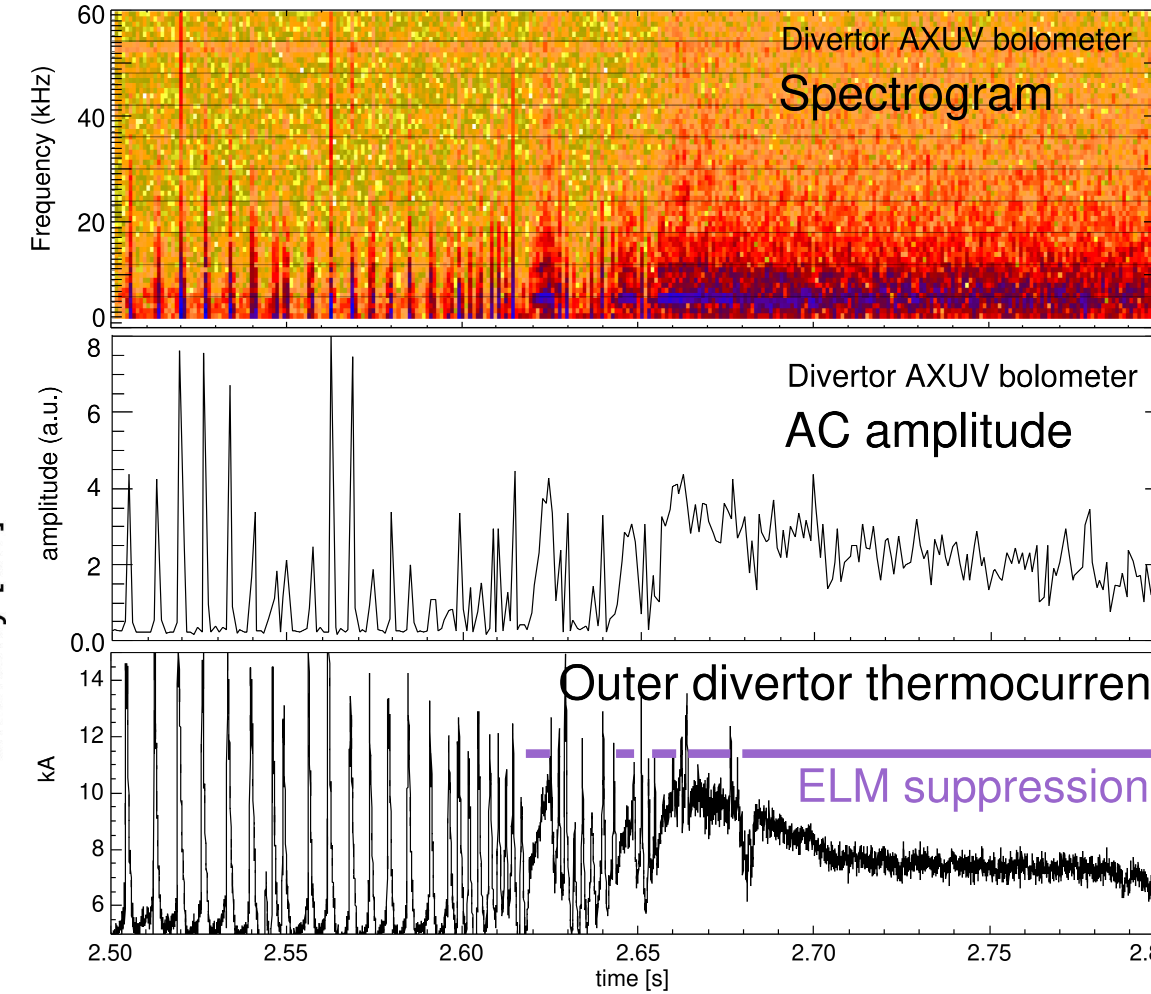
Fixed frequency reflectometry, rotating MP



N Leuthold, L Gil, J Vicente *et al*, EPS Conf. 2018, P1.1109

Fluctuating transport into divertor replaces ELMs

AXUV bolometer view onto inner divertor



Summary

- **Robust ELM suppression by Magnetic Perturbations in ASDEX Upgrade**
- **Main features:**
  - ▷ Amplification of MP by ideal plasma response
  - ▷ Resistive reponse at various surfaces (locations), role unclear
  - ▷ Pedestal pressure below ELM stability limit
  - ▷ Broadband turbulence causes additional transport across barrier