Mitigation of Edge Localized Modes with non-axisymmetric magnetic perturbations in ASDEX Upgrade

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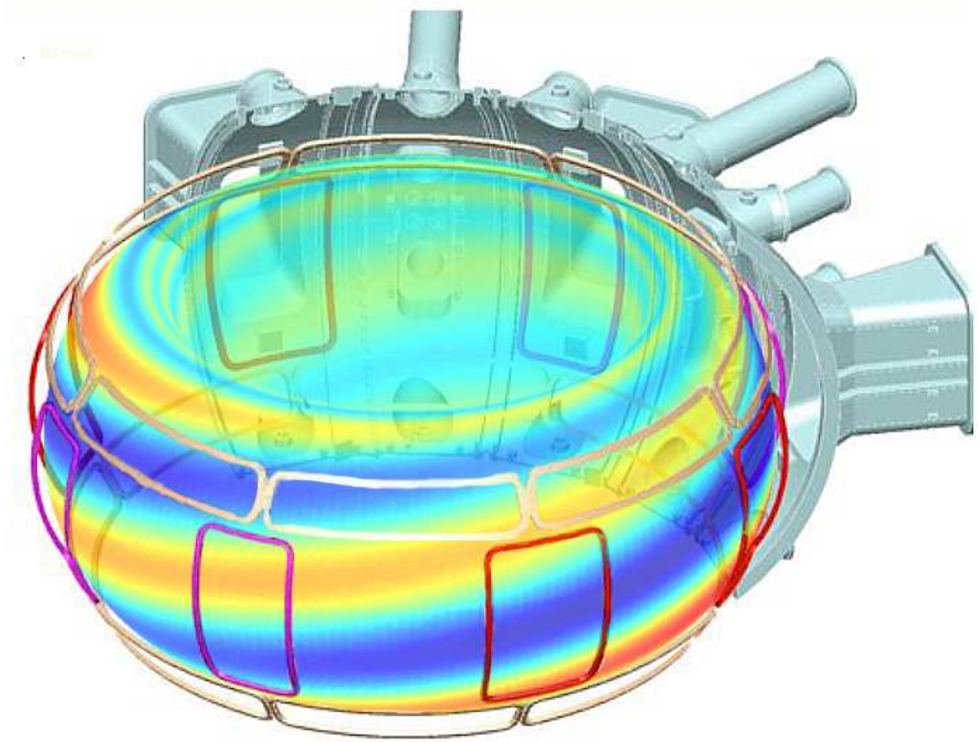
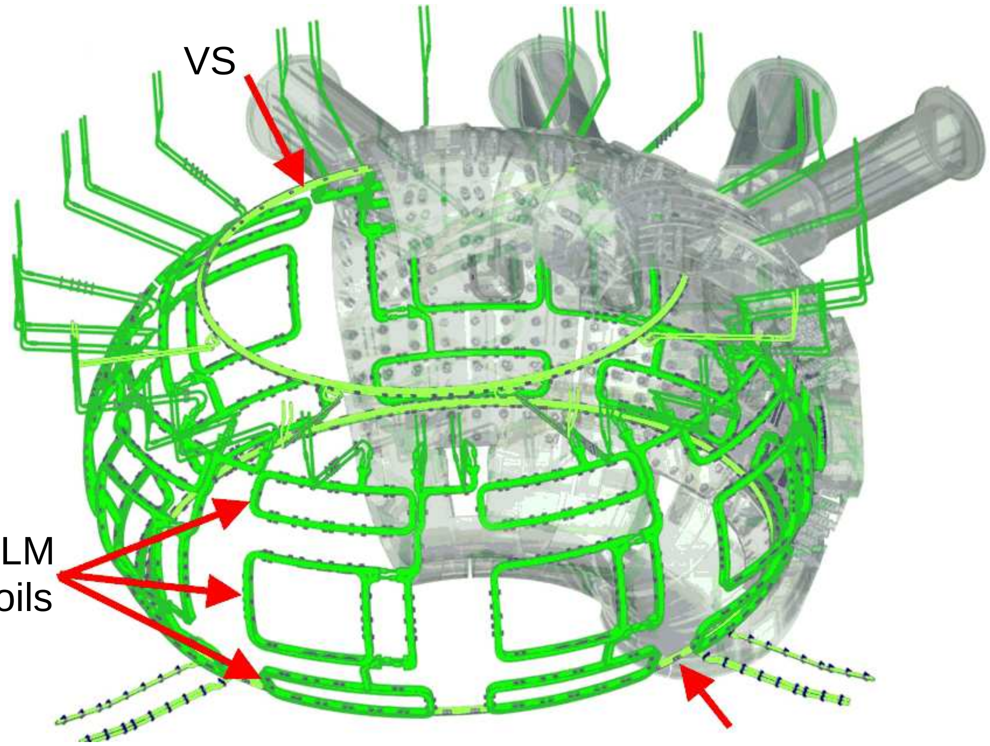
ASDEX Upgrade enhancement to study ITER "ELM-coils" physics

ASDEX Upgrade



ITER



Mitigation of Edge Localised Modes (ELMs)

Locking of MHD modes to error fields

Control of the Resistive Wall Mode (RWM) — with conducting wall and feedback system

W Suttrop *et al*, Fus. Eng. Des. 84 (2009) 209

ELM mitigation with magnetic perturbations

First enhancement stage is in operation:

4 (8) upper and 4 (8) lower coils

DC power supplies (2 circuits)

Any (anti-) series connection of coils

Plasma surface: $B_{r,\max} \sim 10^{-3} \times B_t$

Outline of presentation

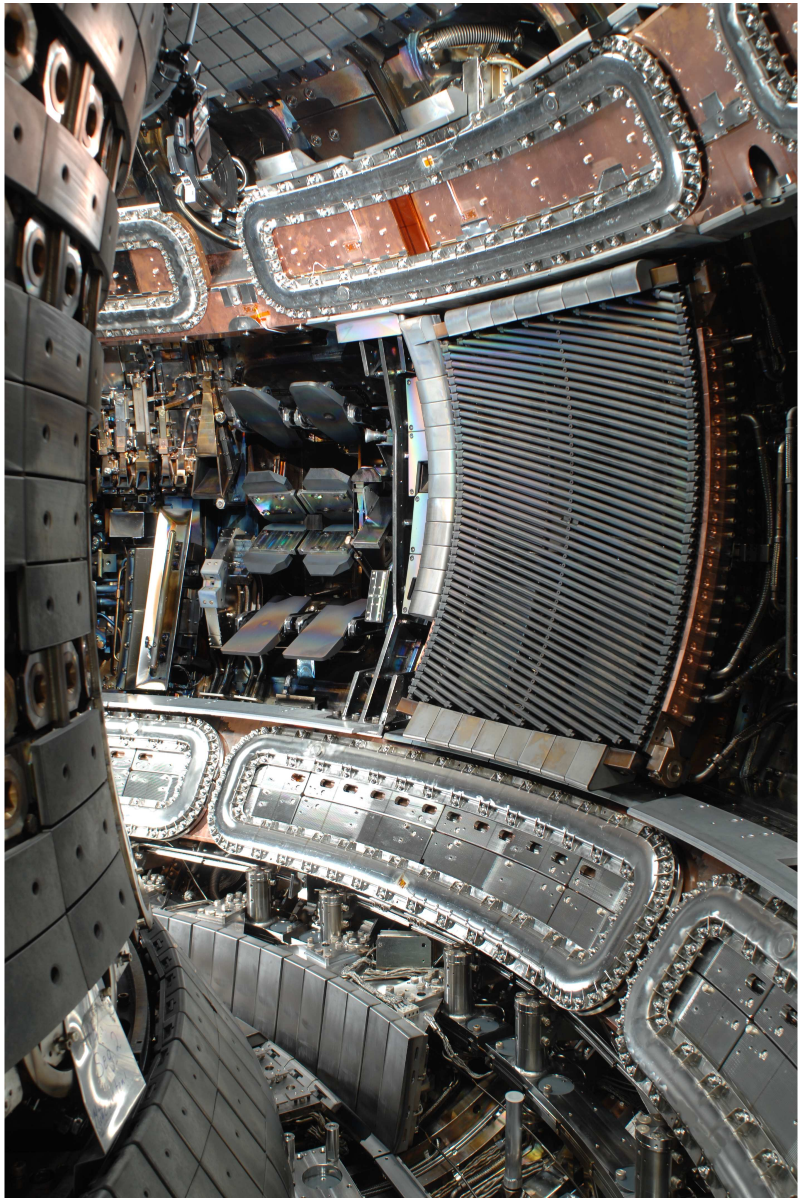
Phenomenology of ELM mitigation

Access conditions

— Plasma density

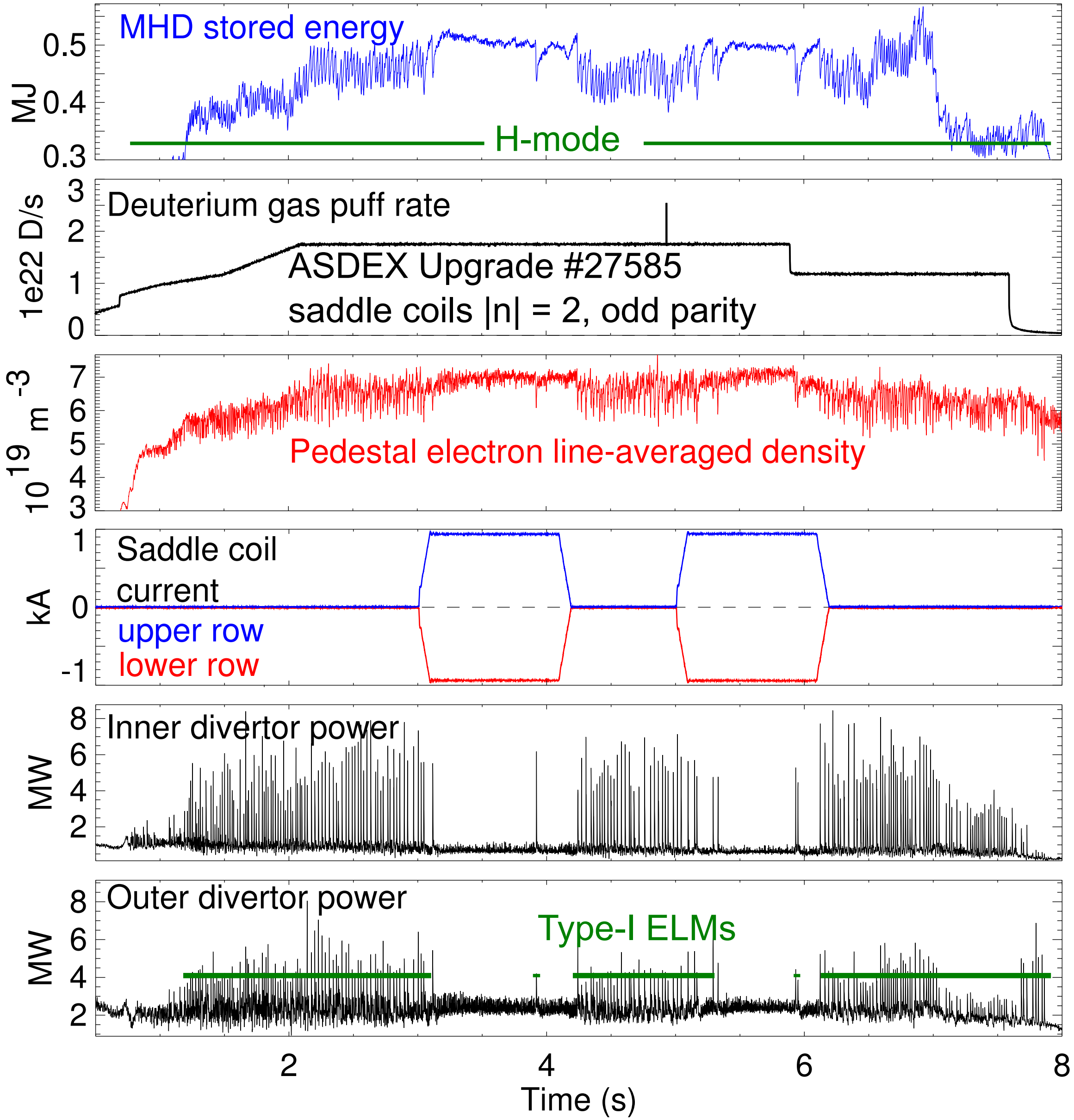
— Importance of resonance condition

— Extension to $n = 1, 2, 4$, He plasmas



Saddle coils mounted in ASDEX Upgrade
(view with PFCs removed)

Large ELMs disappear as saddle coil current applied



Deuterium divertor plasma

Lower single null, $B_t = -2.5$ T, $I_p = 0.8$ MA

$P_{\mathrm{NBI}} = 7.5$ MW

$\rightarrow$ ELMy High-confinement mode

Type-I ELMs disappear when $|n| = 2$ perturbation is applied

Peak power to divertor targets strongly reduced

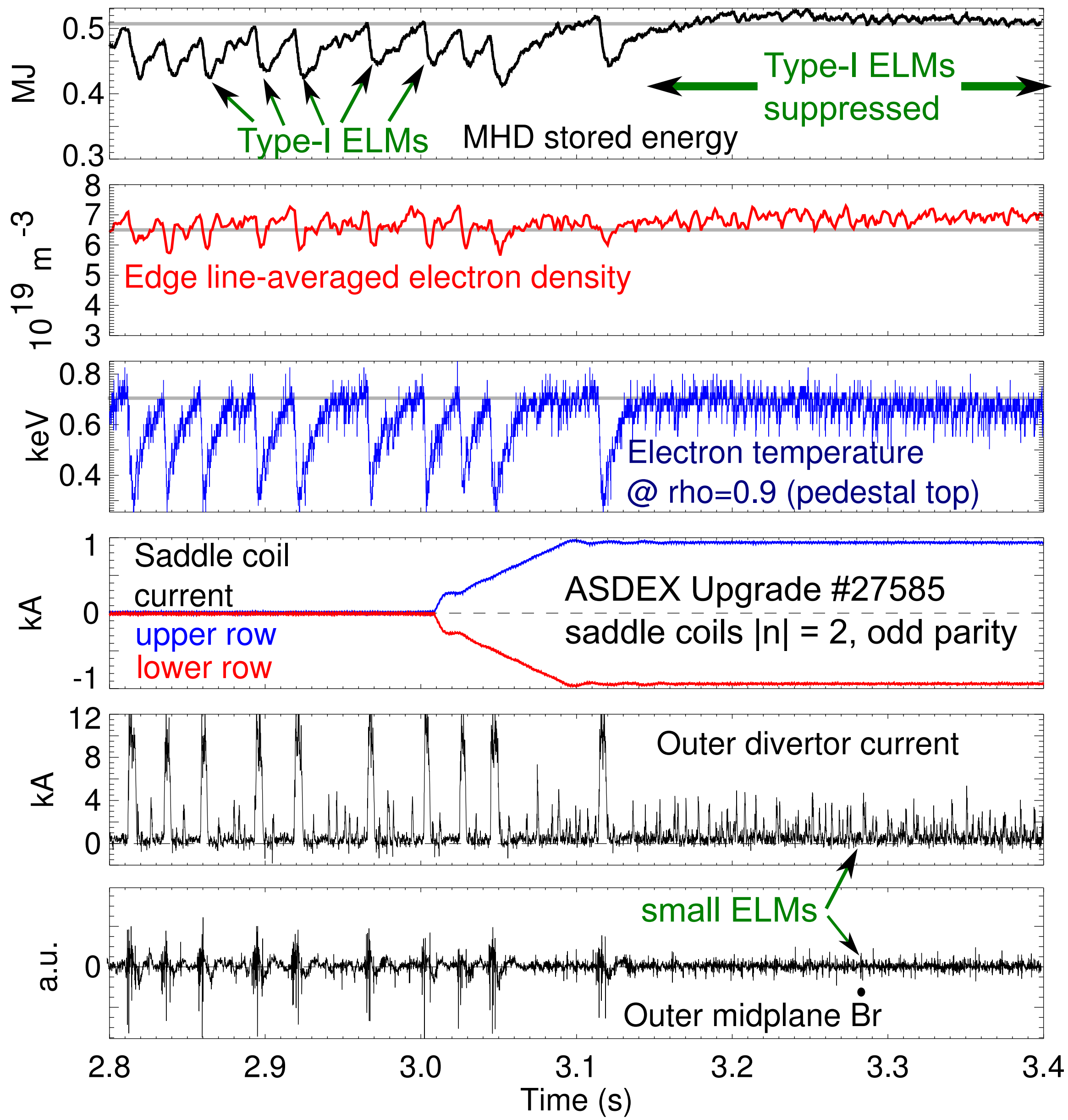
— Inner diverter remains continuously detached

— Steady heat flux to outer divertor

W Suttrop *et al*, PRL 106 (2011) 225004

W Suttrop *et al*, PPCF 53 (2011) 124014

Large ELMs are replaced by small ELMs



As large type-I ELMs disappear:

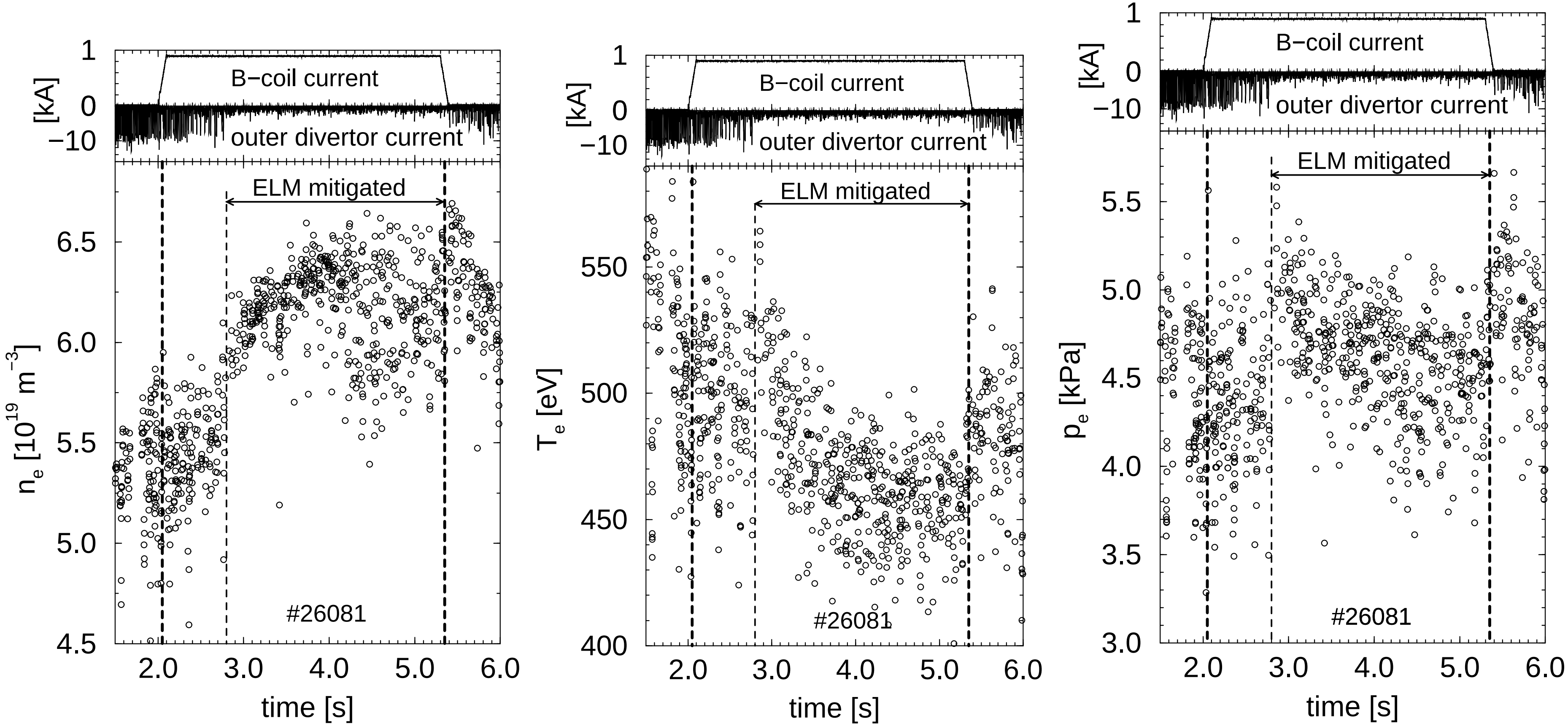
Stored energy,
plasma density and
temperature

at H-mode edge pedestal top remain at upper envelope of type-I ELM cycle

Magnetic activity shows that plasma edge is still limited by a localised MHD instability:
Frequent “small” ELMs

Edge collisionality increases as type-I ELMs are suppressed

Pedestal density increases, pedestal pressure is maintained



— Minimum density for type-I ELM suppression: $n_{\mathrm{ped}} = 65\%\ n_{\mathrm{GW}} \quad (|n| = 2)$

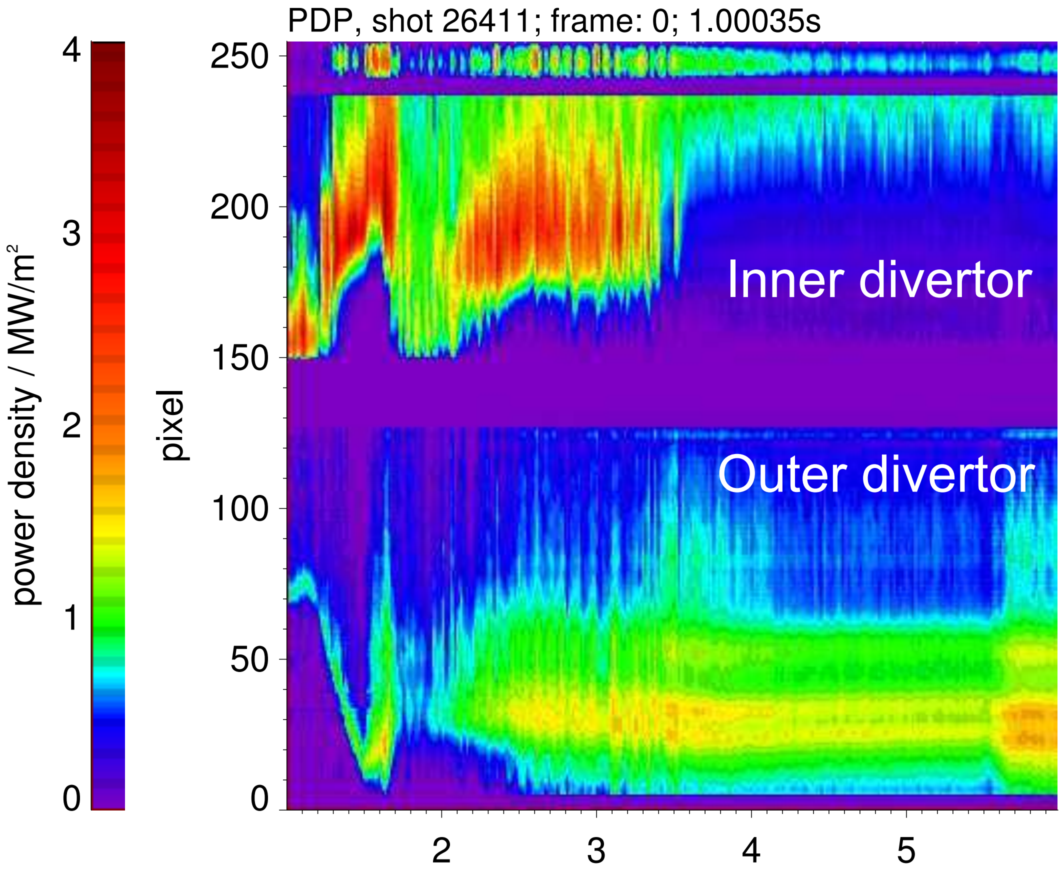
— Increased particle confinement as type-I ELMs disappear

— Gradients change little, light and heavy impurity contents comparable or reduced

R Fischer *et al*, accepted for PPCF, EPS 2011, P1.072

Strike line splitting consistent with (vacuum) perturbation field

Thermography view of divertor targets:

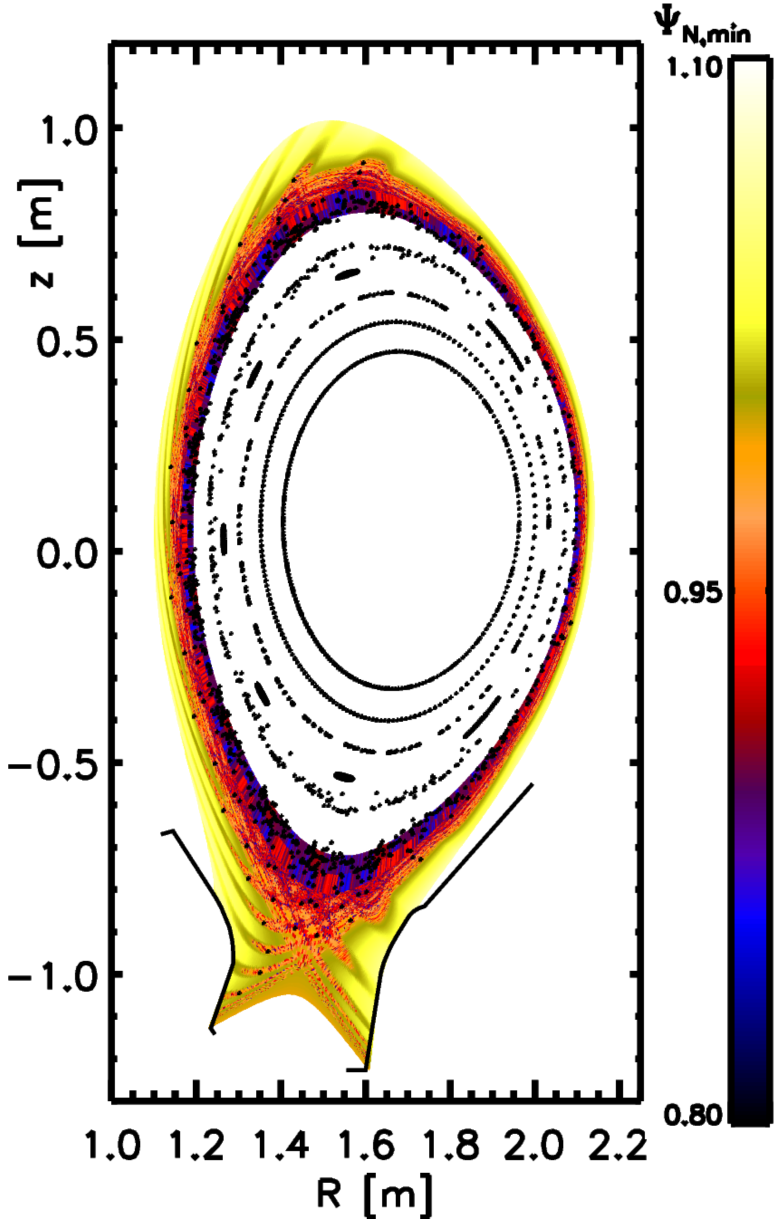


Comparison with magnetic field structure:

J C Fuchs *at al* EPS 2011, P1.090

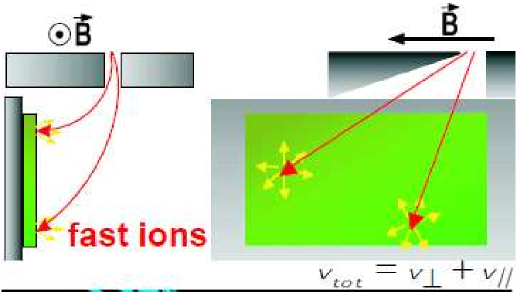
T Lunt *et al* Nucl. Fus. 52 (2012) 54013

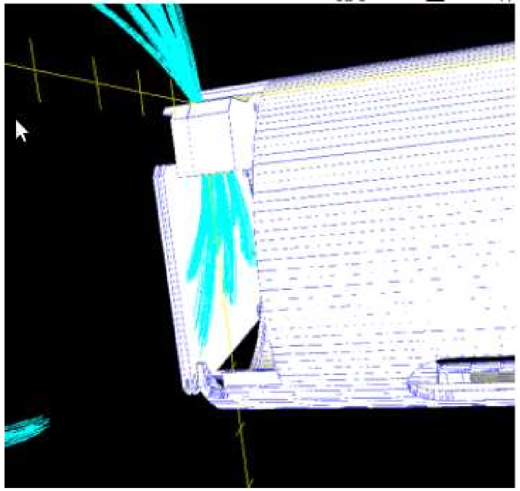
M Kočan EX/P7-23



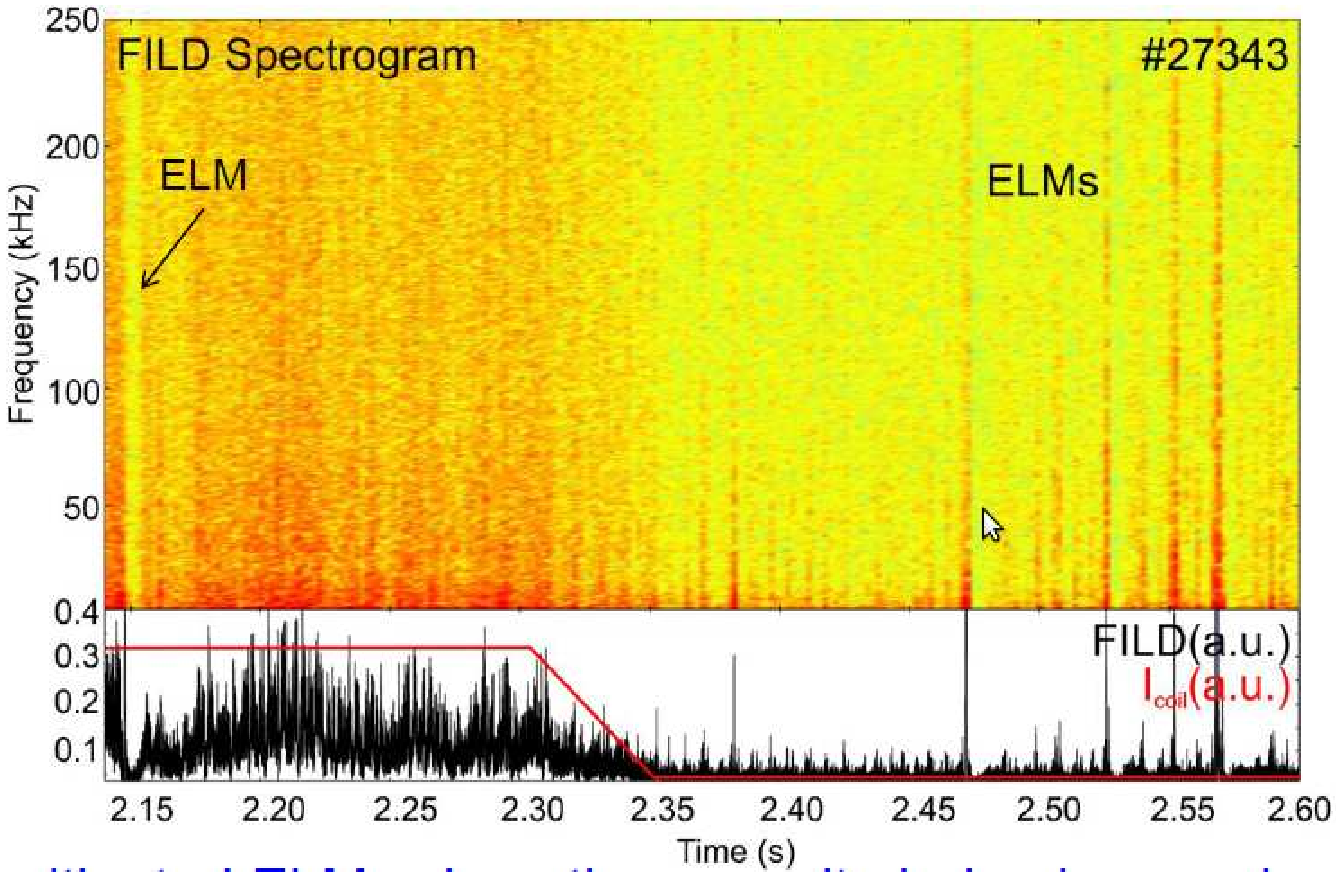
Fast Ion Loss due to edge MHD

Fast **I**on **L**oss **D**etector (FILD)
Ion energy and pitch angle resolution





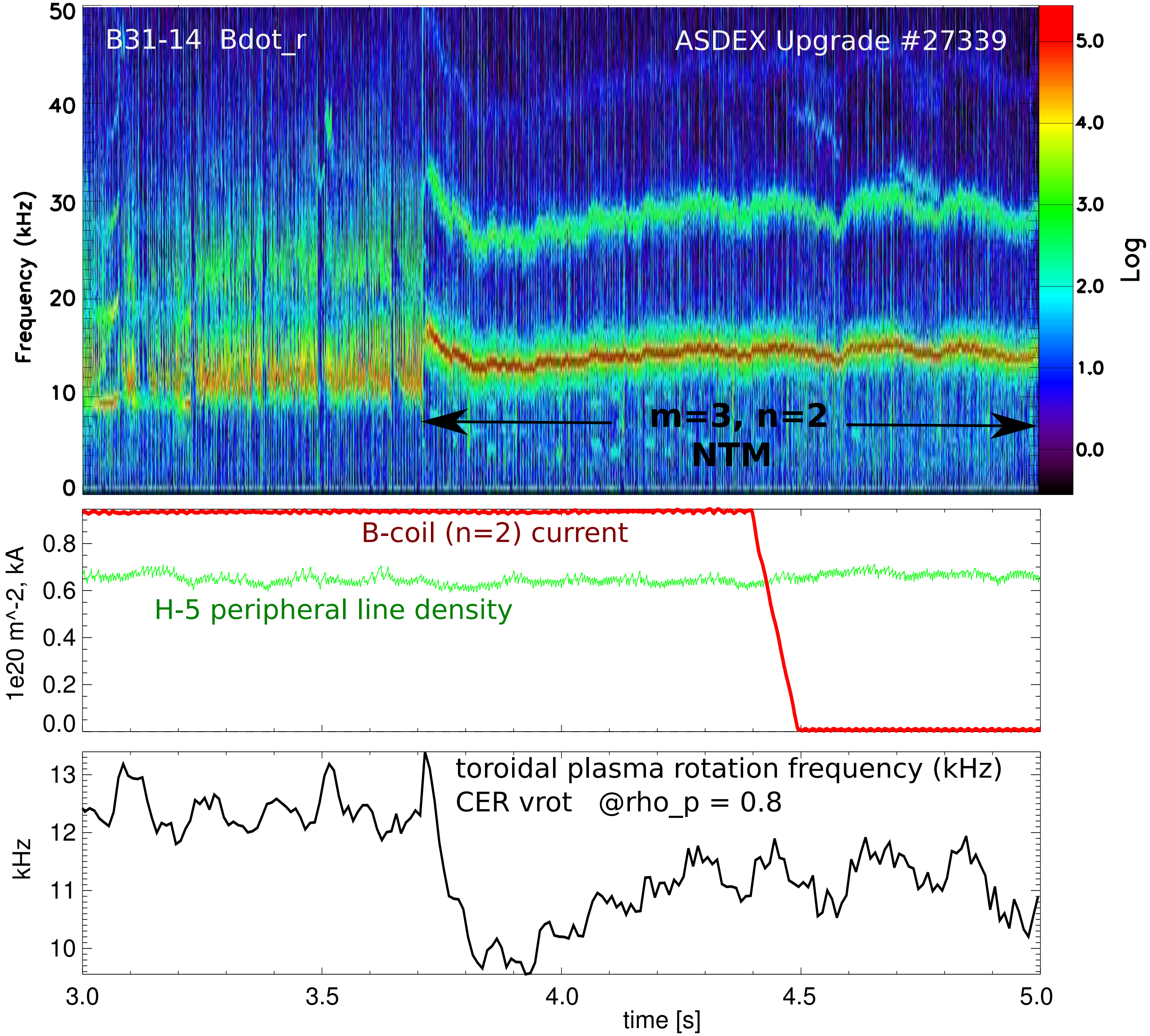
M García-Muñoz *et al*,
RSI 80 (2009) 053003



M García-Muñoz, EX/P6-03

Power load on wall by fast particles:
T Kurki-Suonio, ITR/P1-33

Strong shielding of field in plasma core



Neoclassical Tearing Mode (NTM) island does not lock to $n = 2$ error field

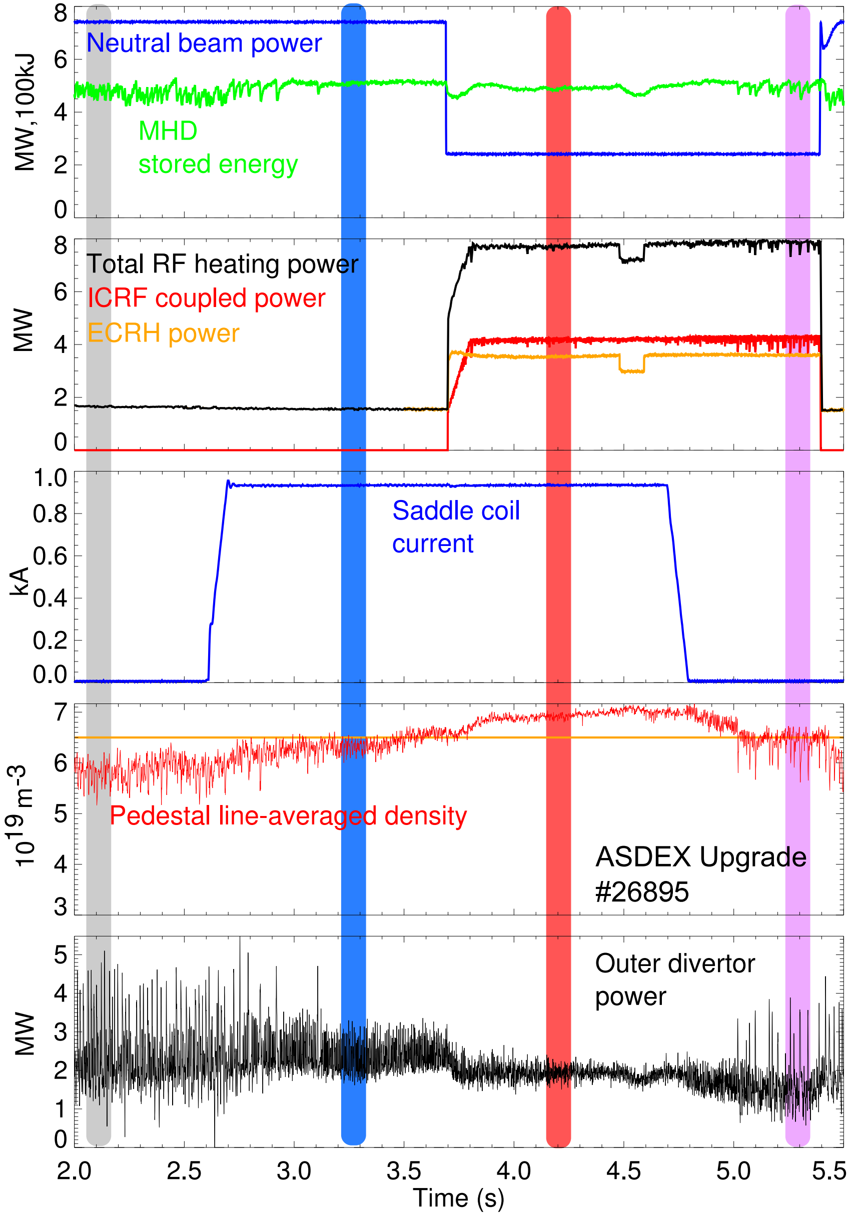
$m = 3$, $n = 2$, $\rho_p \approx 0.8$

$T_{J\times B}$(Vacuum) $\sim 100\ T_{\mathrm{NBI}}$

Local magnetic shear small at outer midplane

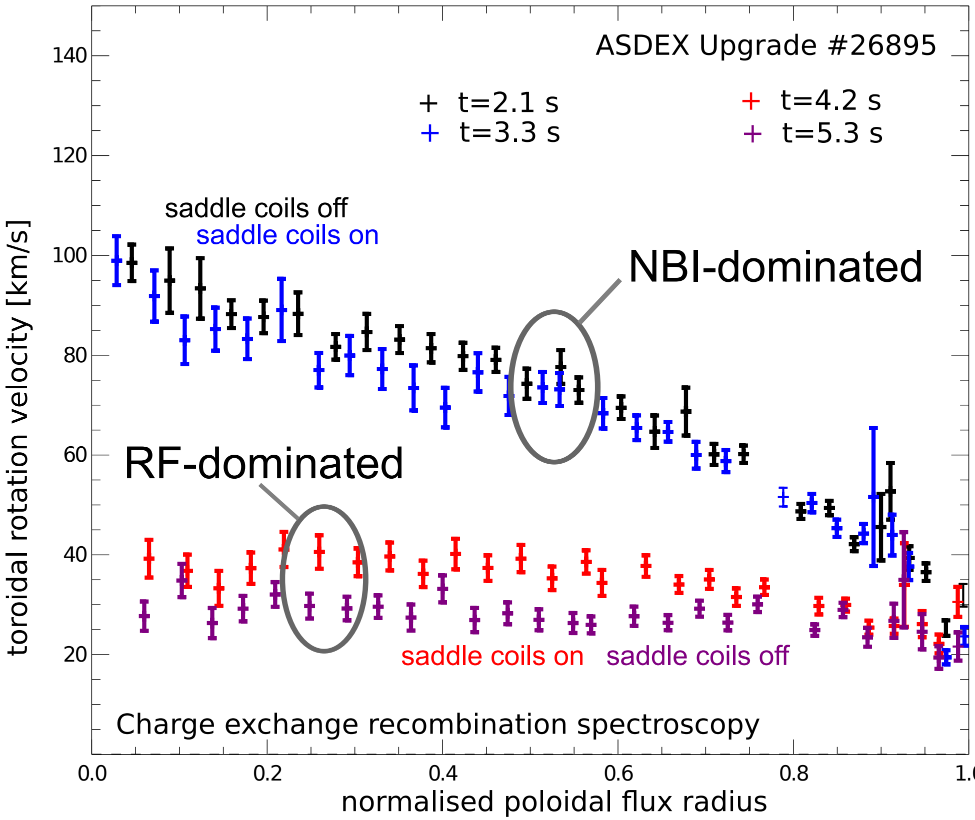
$\rightarrow$ multiple resonant surfaces can carry shielding currents

ELM mitigation independent of heating method ...



... and independent of plasma rotation

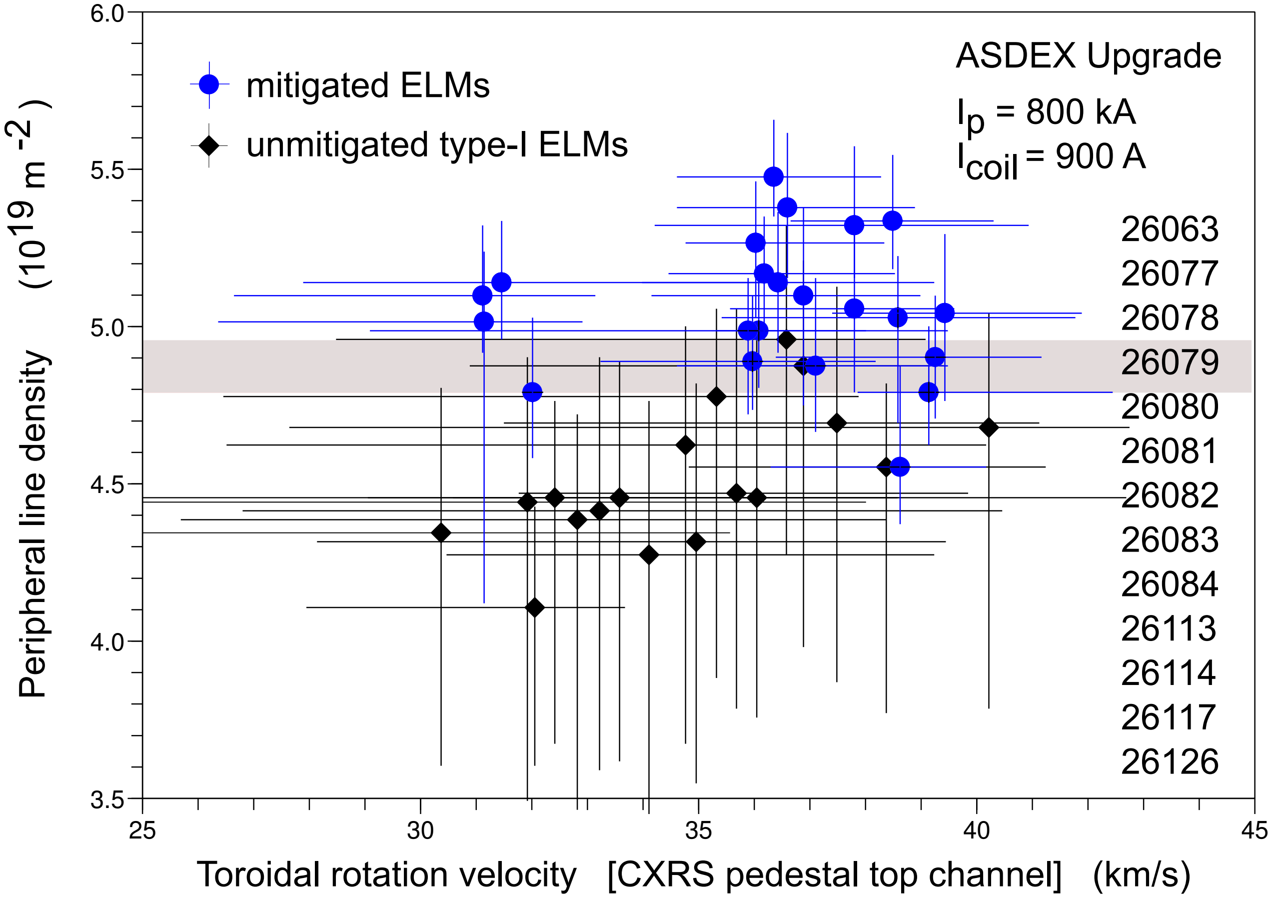
As yet no window in v_{rot} for plasma core islands/ergodisation observed



Connections between v_ϕ, density peaking and turbulence regimes: **R M McDermott EX/2-1**

Minimum density to access ELM mitigation

Data set of plasmas with identical shape, plasma parameters.
Variation of momentum input (heating type and power):
$P_{\mathrm{NBI}} = 2.5 - 12.5$ MW, $P_{\mathrm{ECRH}} = 0 - 1.6$ MW.



Minimum density
(best description so far)

$$n_{\mathrm{e,ped}} \geq 65\%\ n_{\mathrm{GW}}$$

for $n = 2$ perturbations.

No maximum density

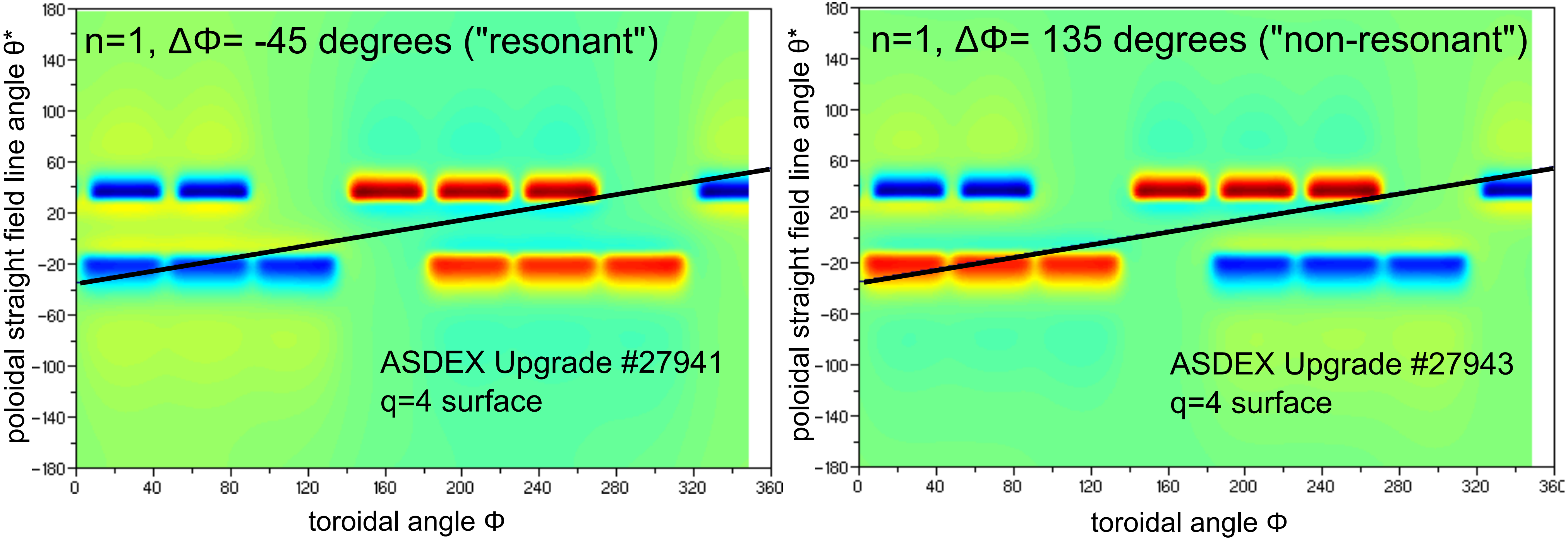
Cryogenic pellets:

— $\bar{n}_e = 1.5 n_{\mathrm{GW}}$
— no ELMs triggered
— good fueling effiency

P T Lang, EX/P4-01
Nucl. Fus. **52** (2012) 023017

Coil configuration varied to test importance of resonance

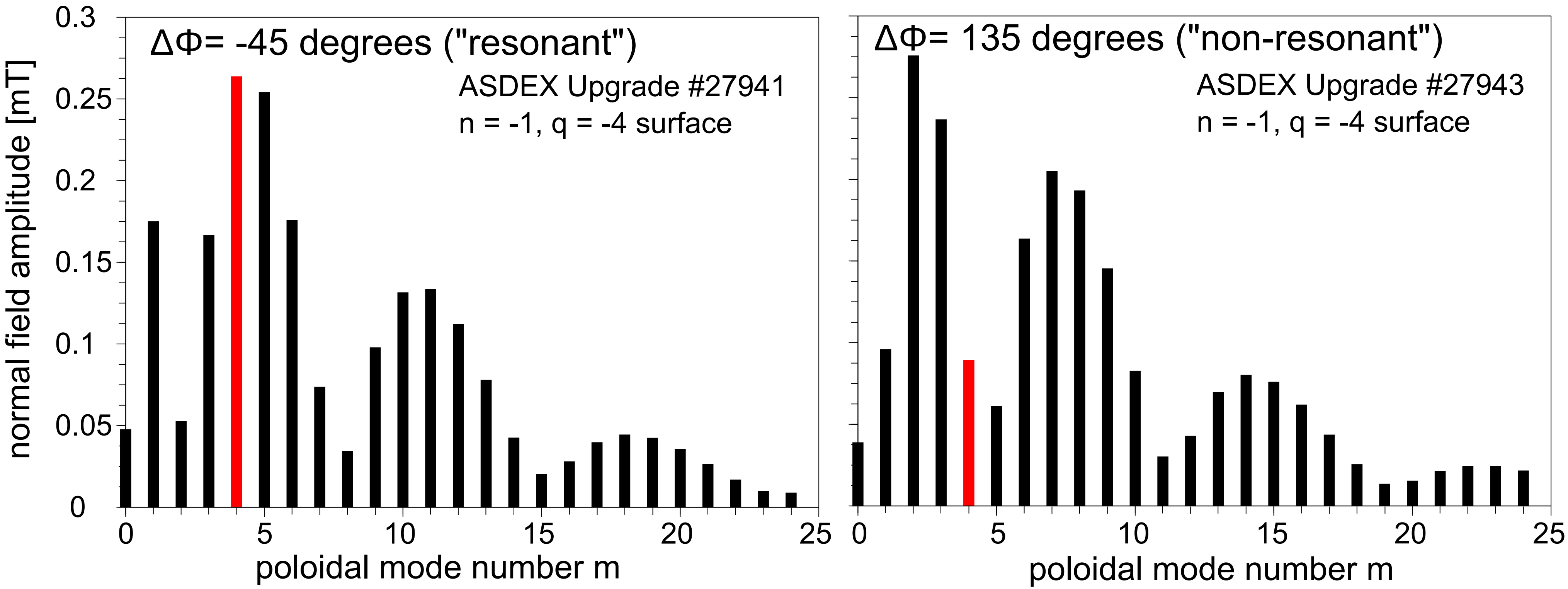
Example: $n = 1$ perturbation



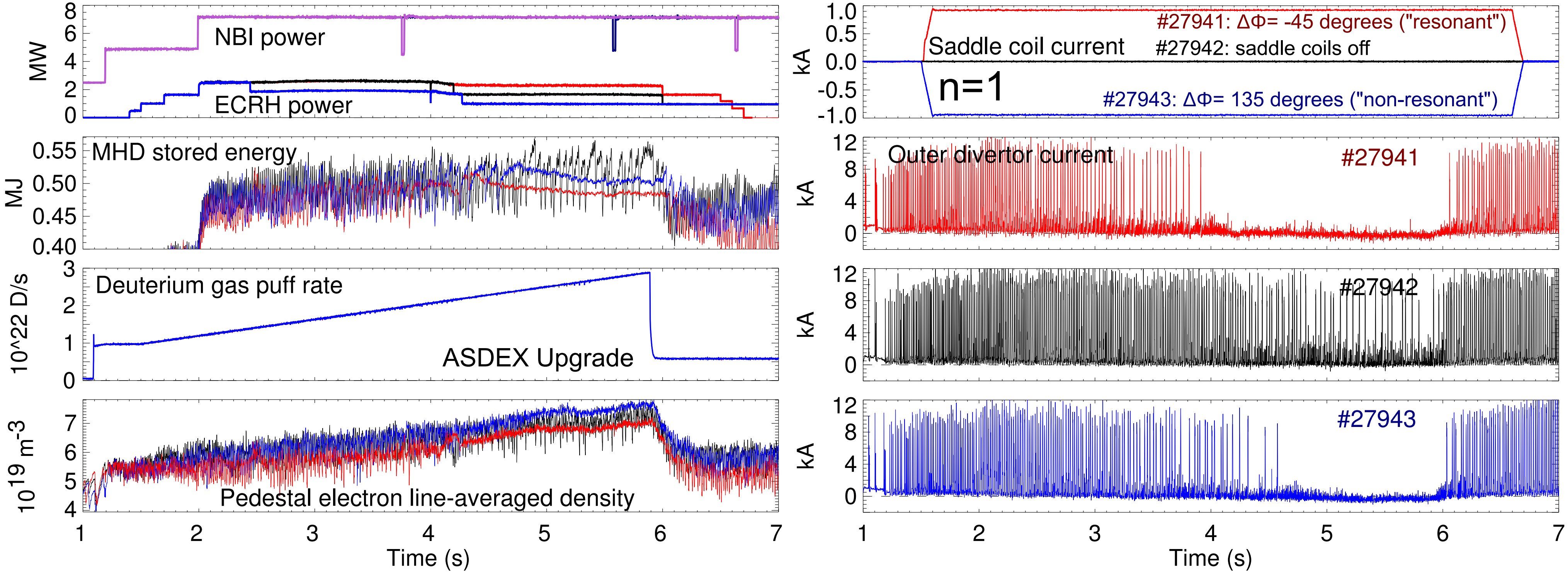
Alignment of perturbation field with field lines can be changed
by varying the toroidal phase $\Delta\Phi$ between upper and lower coil rings.

Resonant $n = 1$ field amplitude varied by configuration change

Poloidal mode number spectrum:



ELM mitigation with resonant and non-resonant perturbation



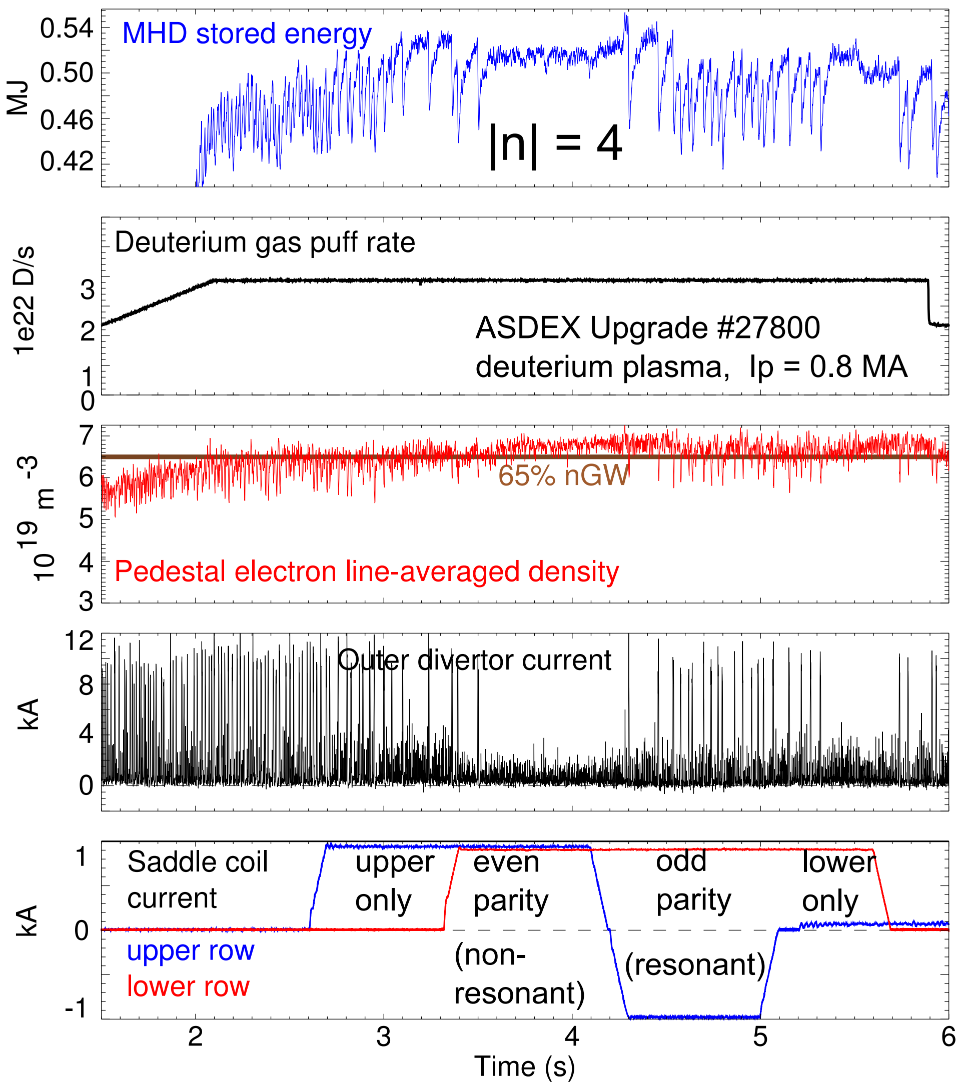
Resonant and non-resonant configurations work (Same coil current threshold, see poster)

Slightly lower threshold density for $n = 1$, resonant config.: $n_{\mathrm{e,ped}} = 60\%\ n_{\mathrm{GW}}$

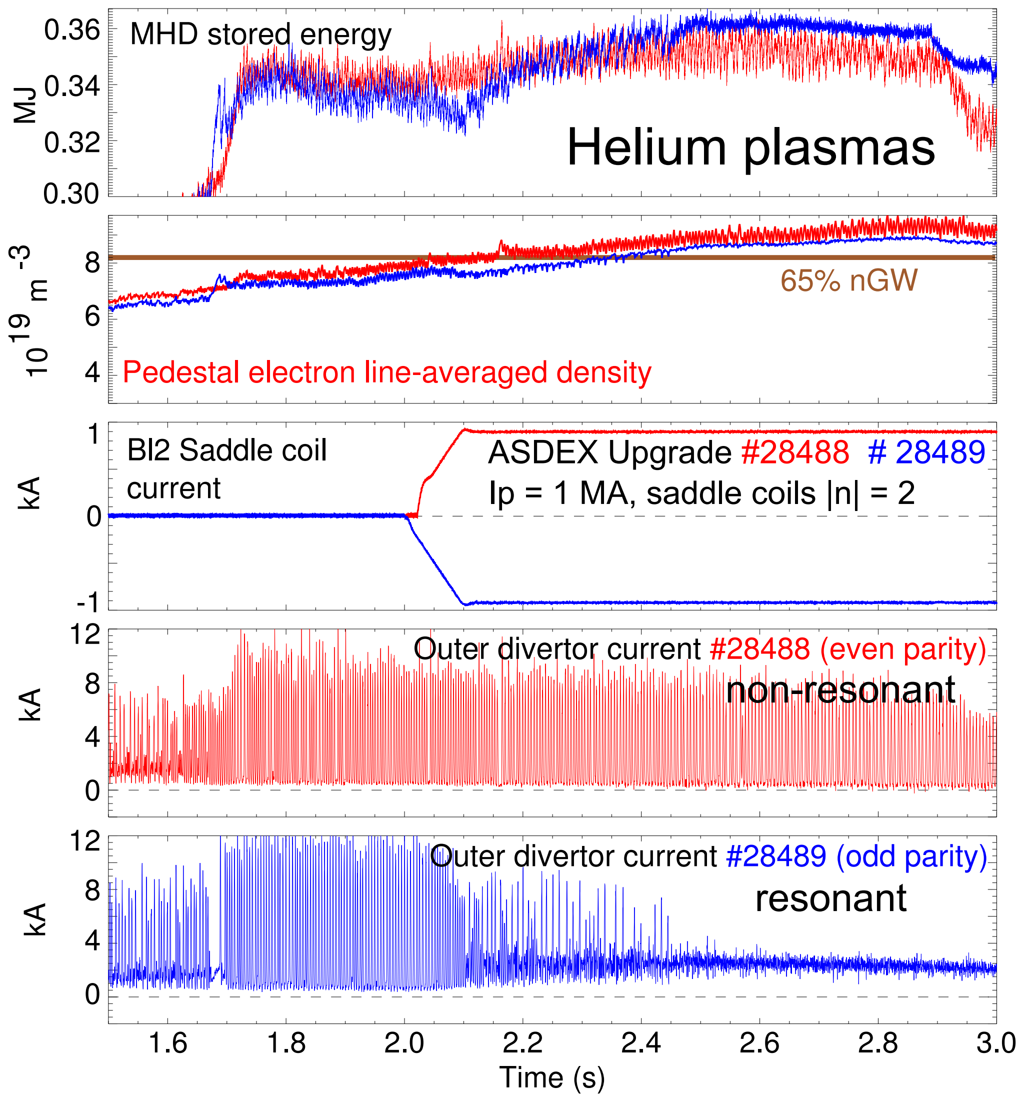
Control experiment (saddle coils off):
At highest gas puff, type-I ELM frequency decreases
because small ELMs appear spontaneously $\rightarrow$ upper end of ELM mitigation window.

Expanding the ELM mitigation operation range

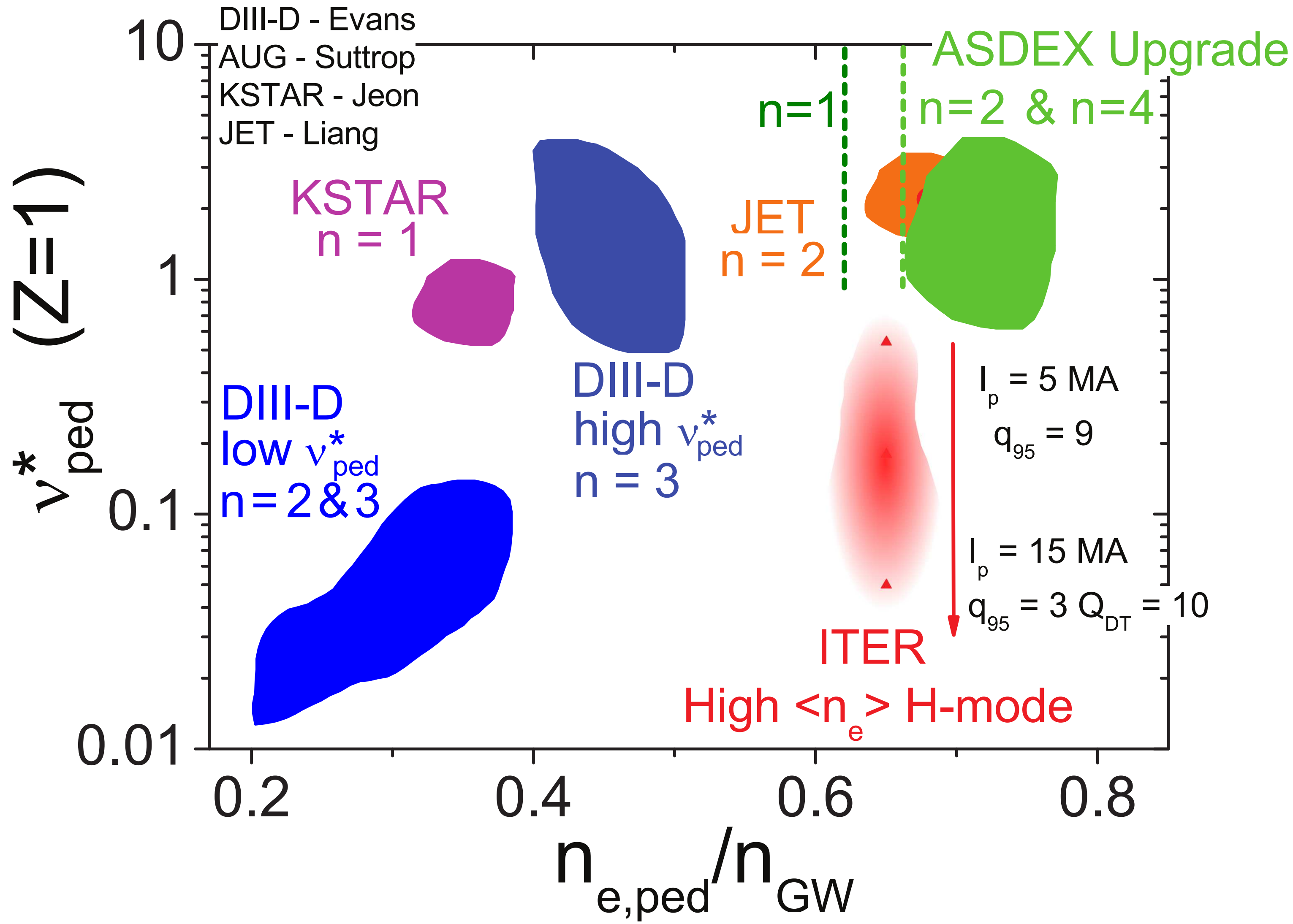
Deuterium plasma, $|n| = 4$, $I_p = 0.8$ MA



Helium plasma, $|n| = 2$, $I_p = 1.0$ MA

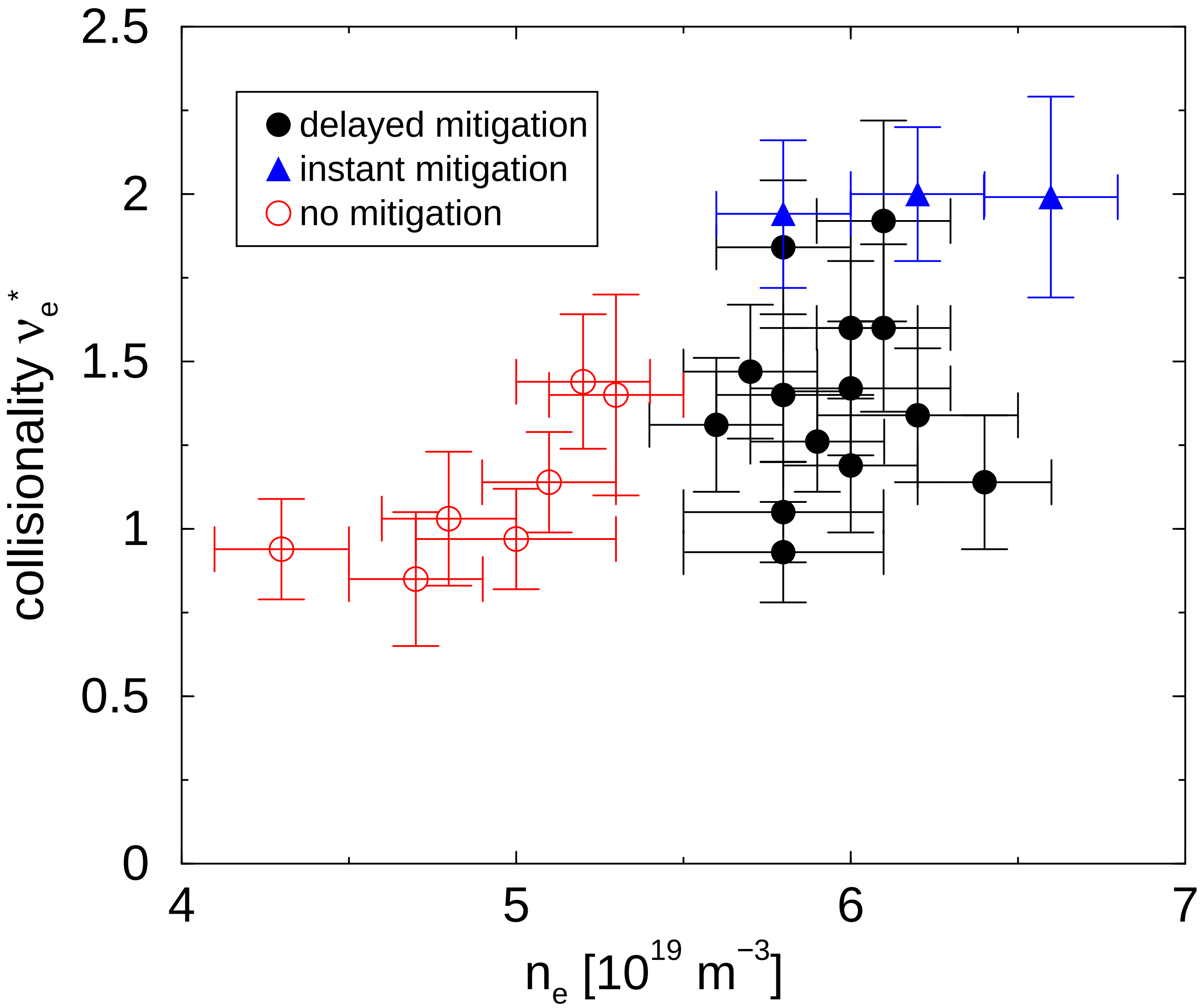


Parameters for Type-I ELM suppression in ITER?



A Loarte, ITR/1-2

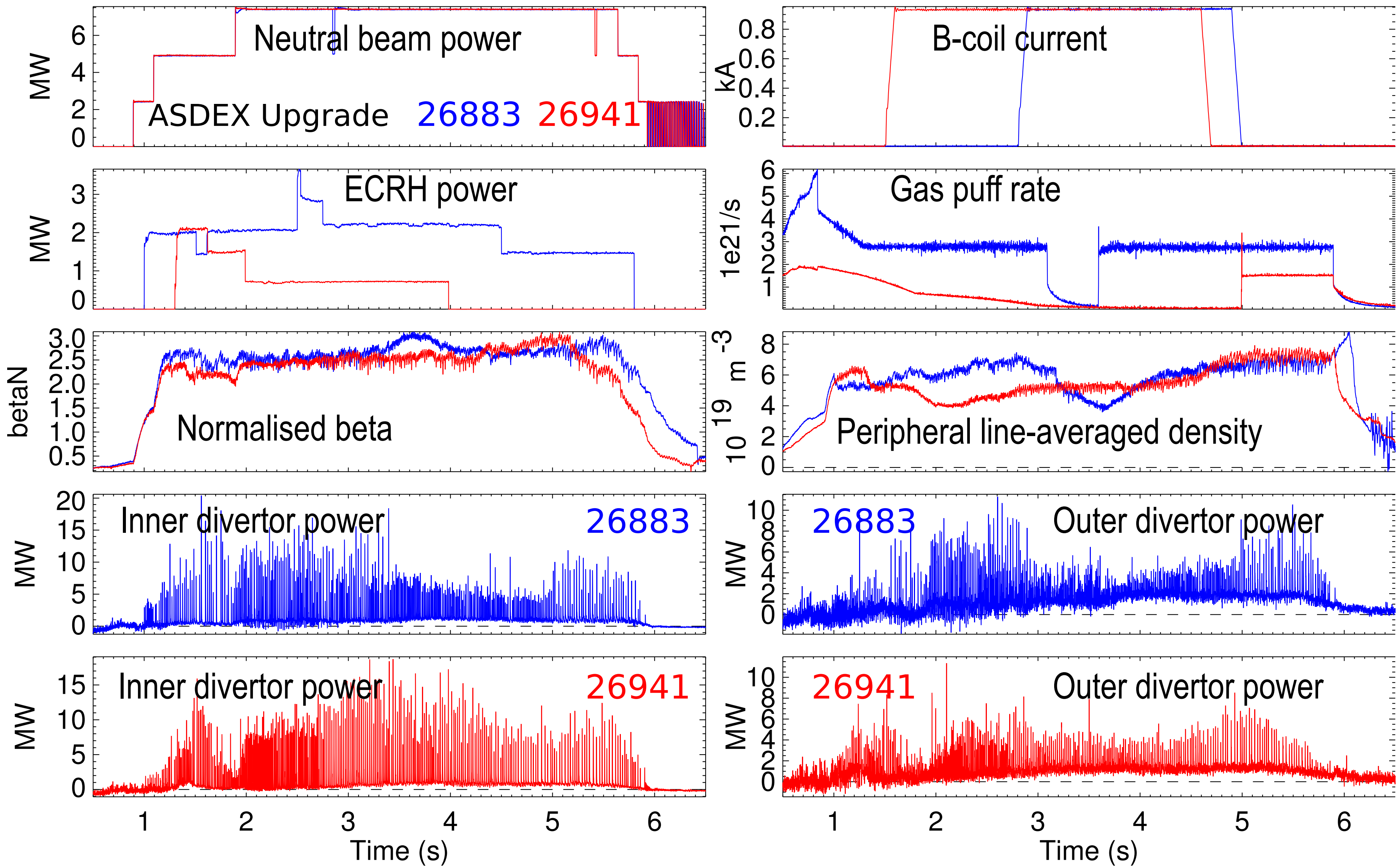
ASDEX Upgrade: Density threshold, not collisionality



R Fischer *et al*, accepted for Plasma Phys. Control. Fusion

At low plasma collisionality, ELM suppression so far not found

$q_{95} = 3.2$, $\nu^*_{i,neo} = 0.14 - 0.36$ (pedestal top)



Summary

Type-I ELMs suppressed with
$n = 1, 2, 4$ perturbations in ASDEX Upgrade

Frequent, small ELMs
— Benign energy loss and divertor power load,
— No penalty in energy confinement, impurity content

Minimum pedestal plasma density:
$f_{GW} = 0.65 \ \ (|n| = 2, 4)$
$f_{GW} = 0.6 \ \ \ (|n| = 1$, resonant)

Works with non-resonant perturbation

Not sensitive to
— q_{95} (tested $q_{95} = 3.7 \ldots 6.2$)
— heating power, β
— heating method, plasma rotation

Search for low density (collisionality) ELM suppression regime continues

See also:

Pellet injection with MP
No ELM triggered
High fueling efficiency
P T Lang EX/P4-01

L-H transition with MP
Suppression of first ELM
F Ryter EX/P4-03

Small ELM filaments
I Classen EX/P4-07

Fast ion redistribution
M García Muñoz EX/P6-03

SOL structure with MP
M Kočan EX/P7-23