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JÜLICH
FORSCHUNGSZENTRUM

531st Wilhelm and Else Heraeus Seminar

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Active Control of Tokamak Edge Instabilities by 3D Fields

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Outline

- Introduction to ELMs and 3D fields on tokamak
- Summary of ELM control with 3D fields
  - ELM suppression
  - ELM mitigation
- What are the possible physical mechanisms of ELM control with 3D fields?
  - Resistive Plasma Responses
    - Field Penetration / Mode Excitation
    - Edge Ergodisation
  - Ideal Plasma Responses
    - Rotation Screening Effect
    - Resonant Field Amplification (RFA)
- ELM control through the magnetic topology control by another methods
- Summary

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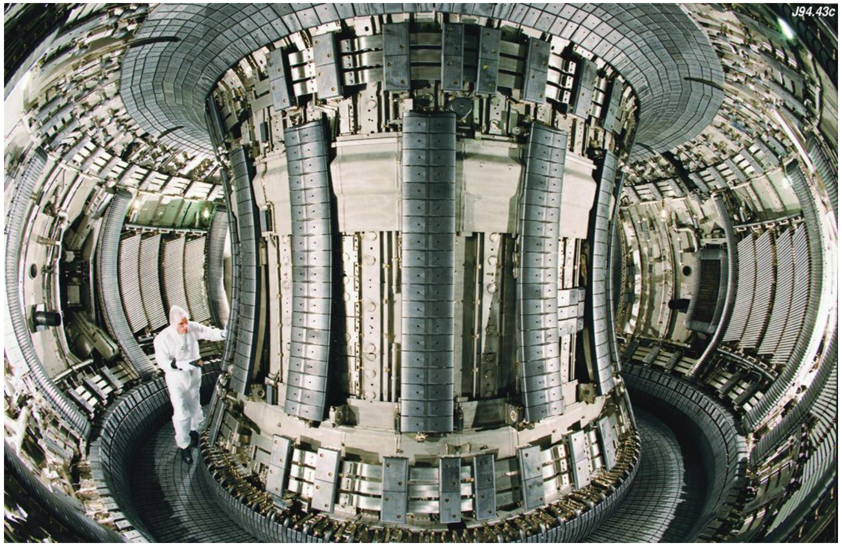
Problem of Edge MHD Instabilities

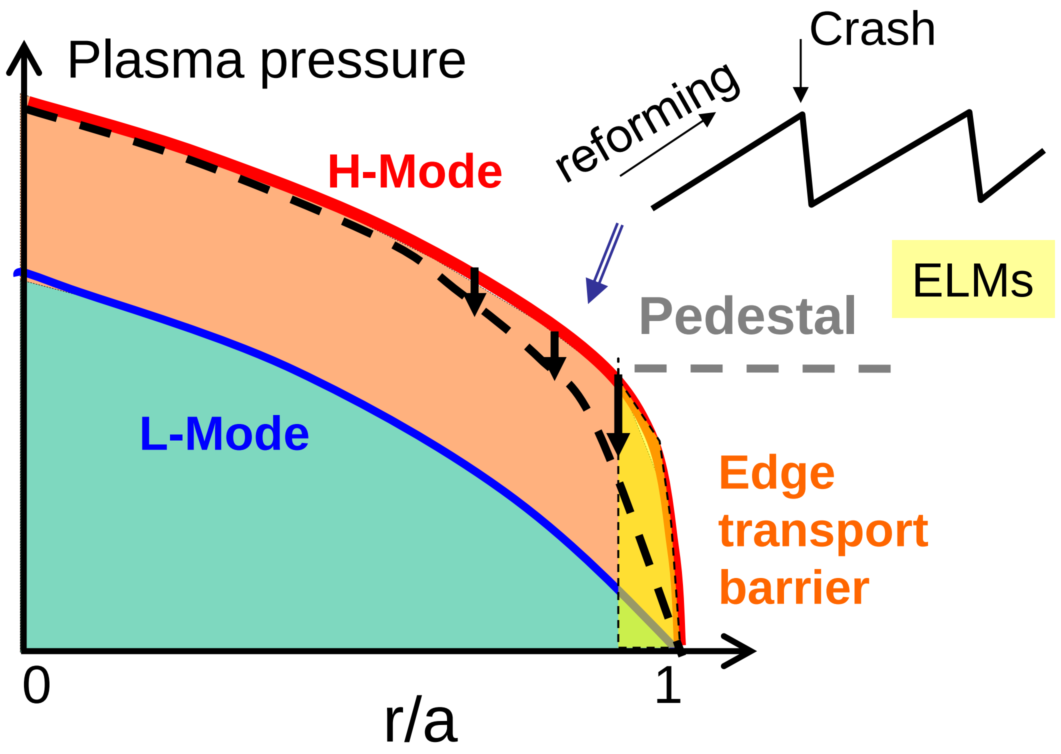
Fusion … **… on Earth**



- A solar flare is a large explosion in the Sun's atmosphere that can release as much as 6 × 10^{25} joules of energy (~ 17% of the total energy output of the Sun each second)
- A ‘natural’ Edge Localized Mode (ELM) size in ITER:

$$\Delta W_{ELM}, \sim 20\ \text{MJ} \rightarrow 10\ \text{MJ/m}^2$$

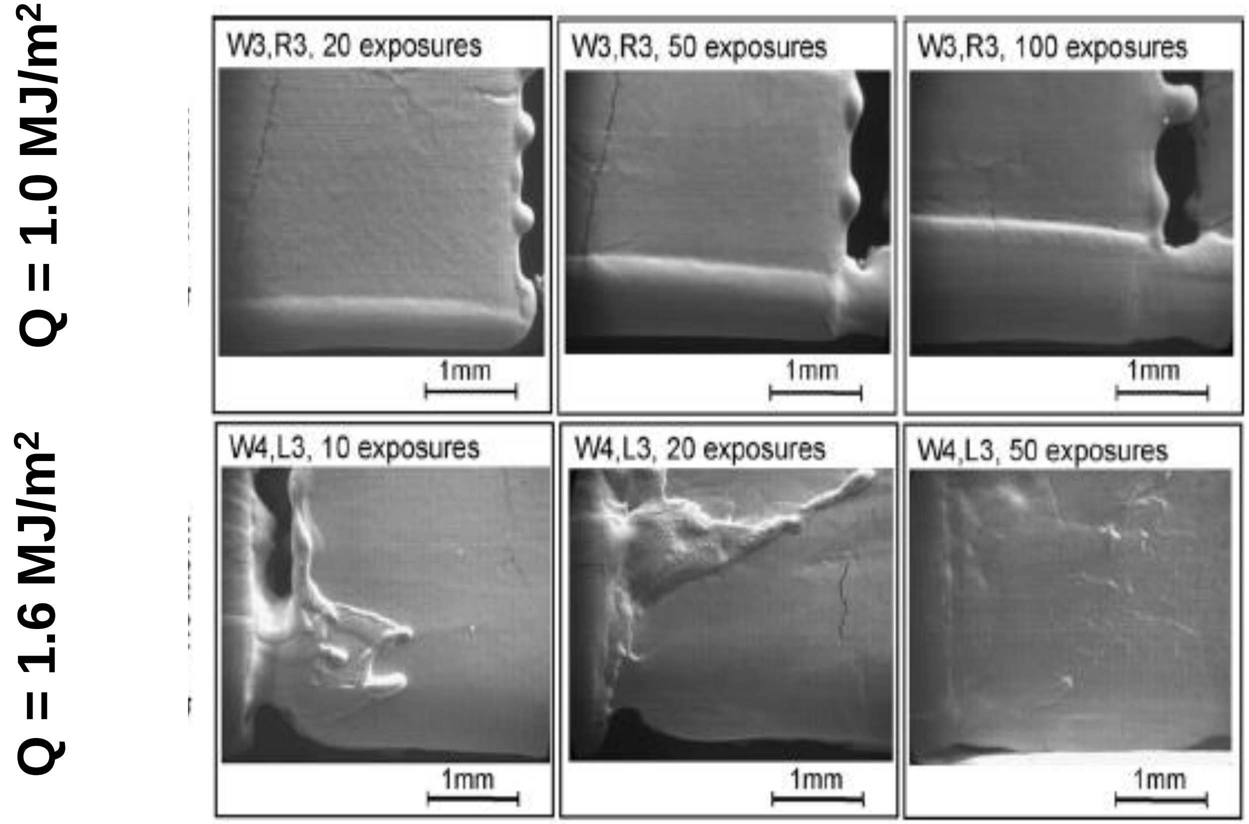
Edge Localized Modes in H-mode plasmas



Large ELM → $\Delta W_p / W_p$ up to 20%

ELM control is important for both tokamak and stellarator H-mode plasmas

ITER need ELM control



Zhitlukhin JNM 2007

- **0.4-1.0 MJ/m^2 (JET<1.0 MJ/m^2) → Edge melting and surface cracking**
- **1.0-1.6 MJ/m^2 → Surface melting, bridge formation and droplet ejection**
- **High frequency ELMs may be required to avoid W accumulation**

ELM trigger: ideal MHD

- It is widely believed that ideal MHD instabilities provide the trigger for the ELM
- Theoretically, the instability properties can be understood from δW for radial displacement, X, at large toroidal mode number, n:

$$\delta W = \pi \int_0^{\psi_a} d\psi \oint d\theta \left\{ \frac{JB^2}{R^2B_p^2} \left| k_\parallel X \right|^2 + \frac{R^2B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} \left(JBk_\parallel X \right) \right|^2 \right.$$

Field-line bending: strongly stabilising unless $k_\parallel$ is small

$$- \frac{2J}{B^2} \frac{dp}{d\psi} \left[\left| X \right|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{i}{2} \frac{f}{JB^2} \frac{\partial B^2}{\partial \theta} \frac{X^*}{n} \frac{\partial X}{\partial \psi} \right]$$

Pressure gradient/curvature drive: destabilising if average curvature is “bad”

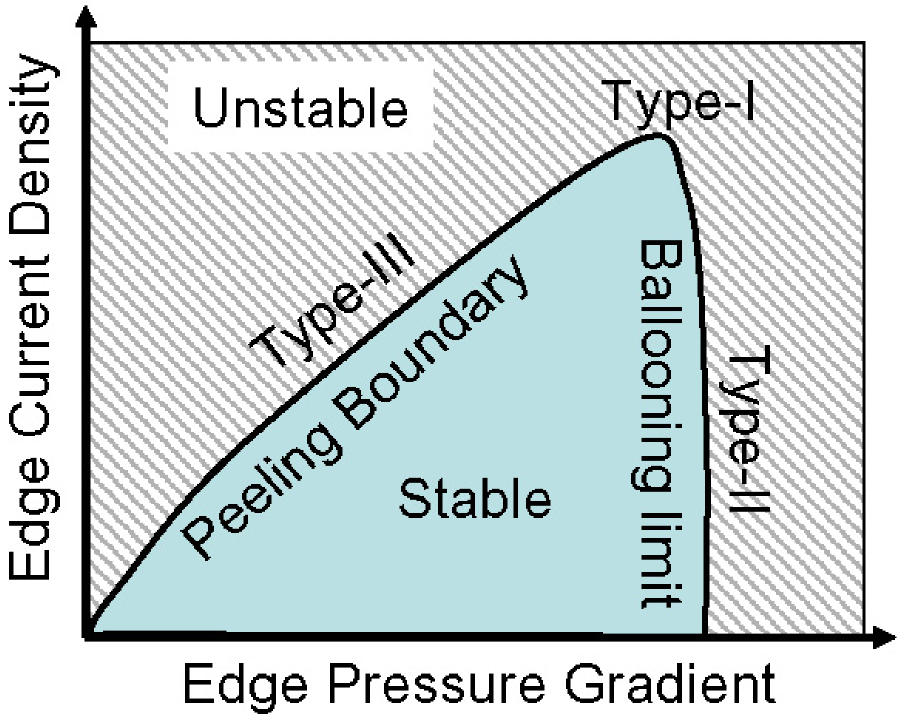
$$- \frac{X^*}{n} JBk_\parallel \left(\frac{\partial \sigma}{\partial \psi} X \right) + \frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} XJBk_\parallel^* X^* \right]$$

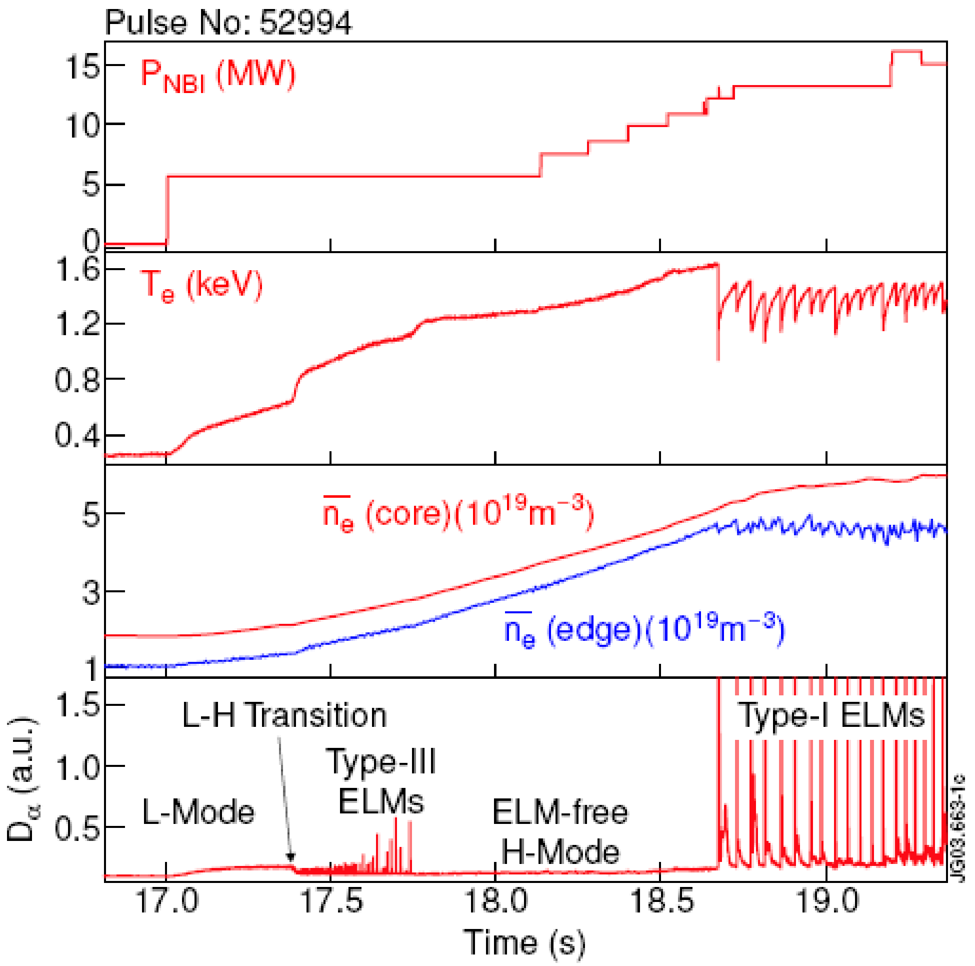
Current density gradient/edge current drives kink/peeling modes

σ=normalised current density

Pedestal Stability Boundaries

Tokamak





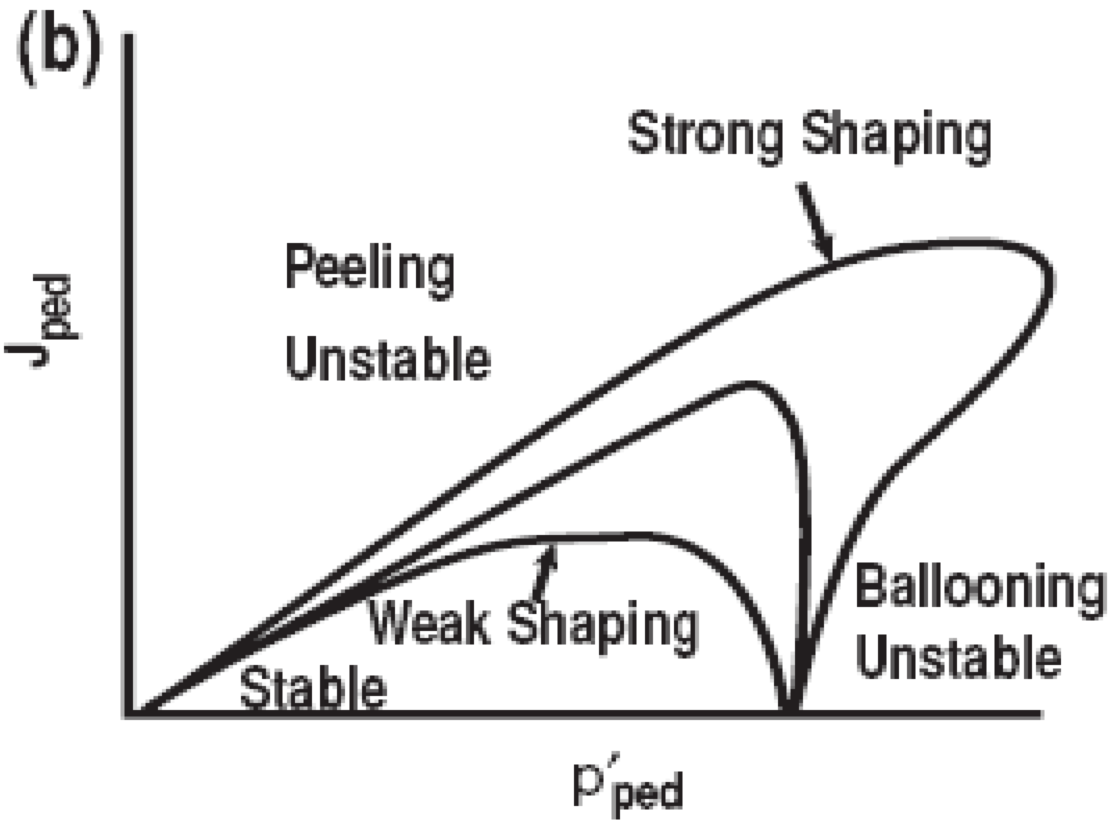
Bhatnagar V P *et al* 1999 *Nucl. Fusion* **39** 353

Stellarator

Edge region in magnetic hill

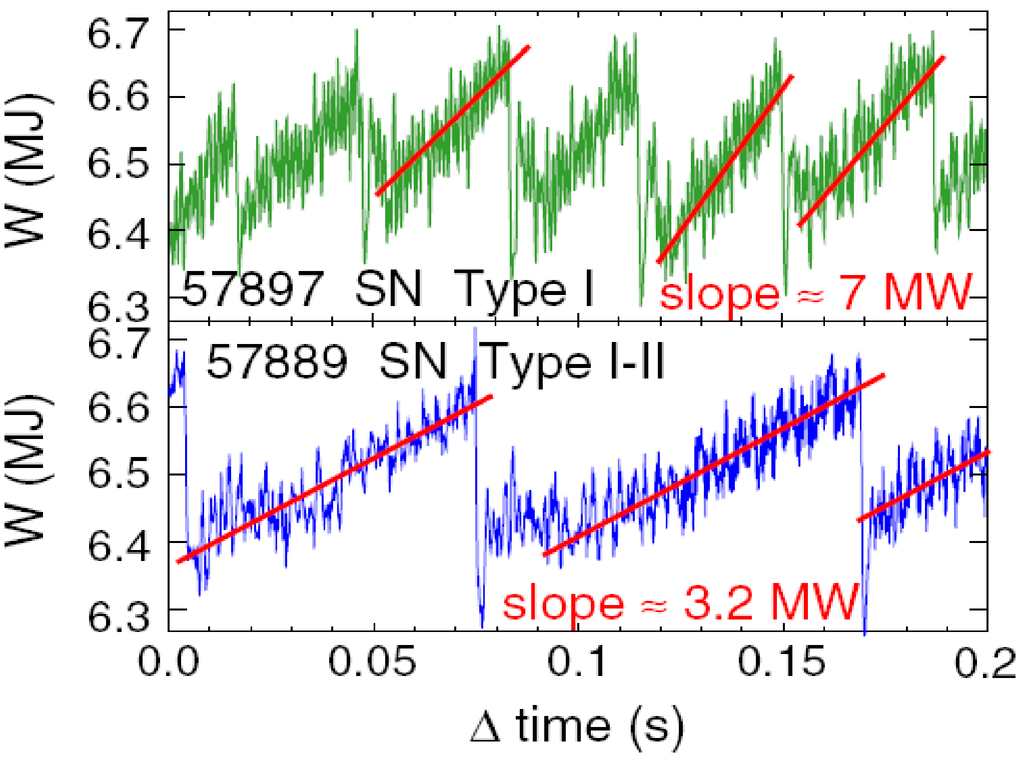
→ Resistive Interchange mode (RIC) are unstable.

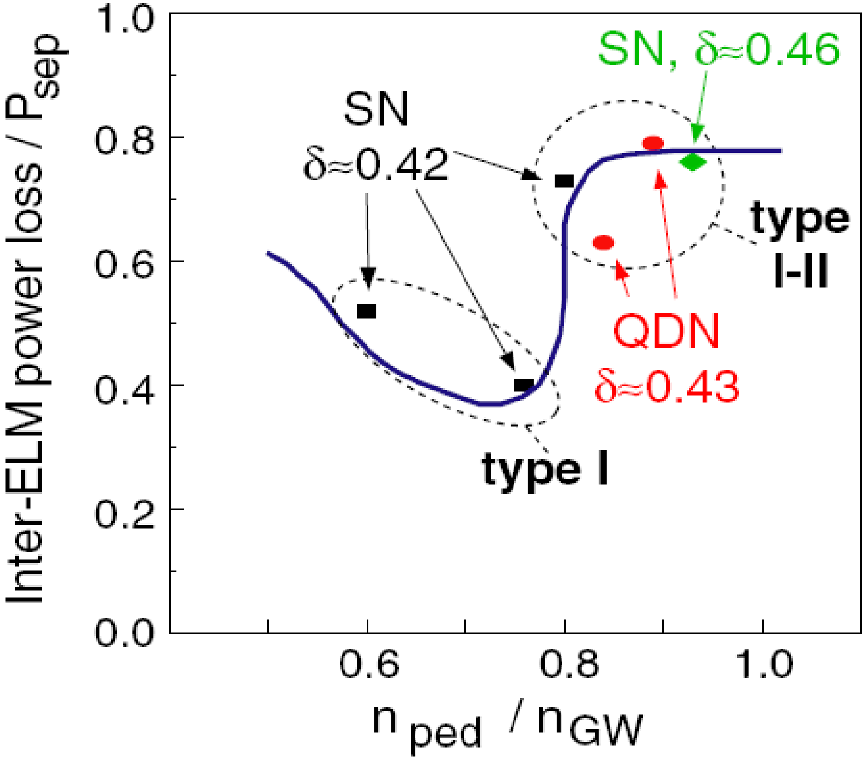
Variation of Pedestal Stability Boundaries with Plasma Shaping



P.B. Snyder *et al,* Nucl.
Fusion **44** (2004) 320

Mixed Type-I and II ELM H-mode Plasmas

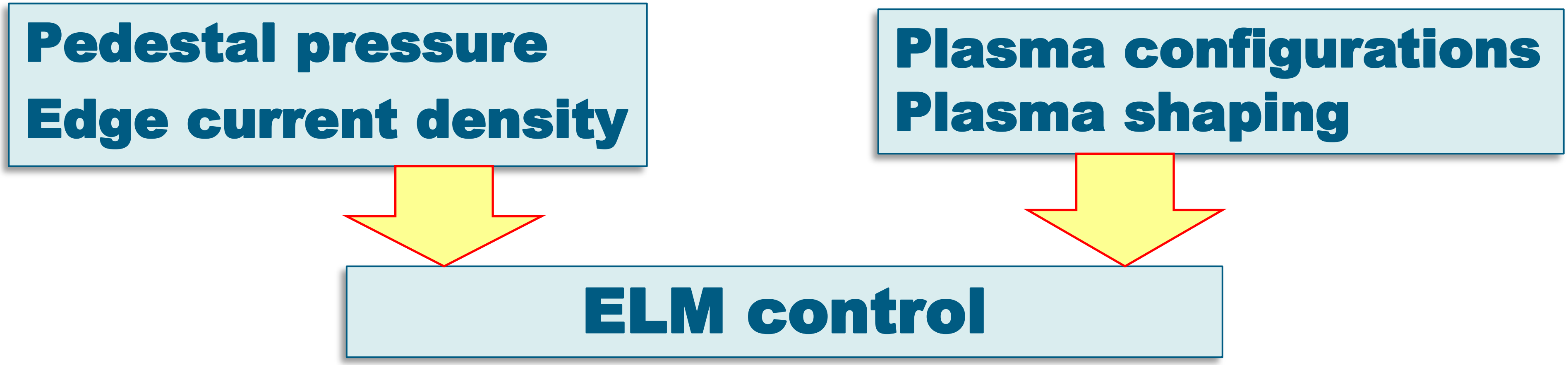




J. Stober, et al., Nuclear Fusion, 45,1213 (2005)

Mixed Type I and II ELM H-mode has been observed in high δ and high density plasmas in JET

Theoretical Prediction



Pedestal pressure
Edge current density

Plasma configurations
Plasma shaping

ELM control

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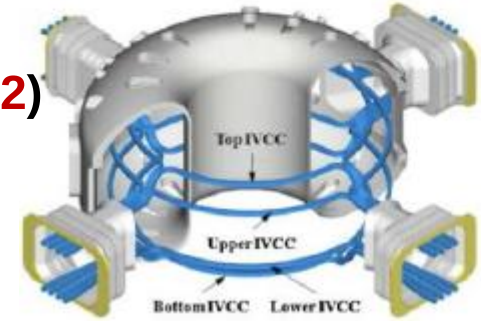
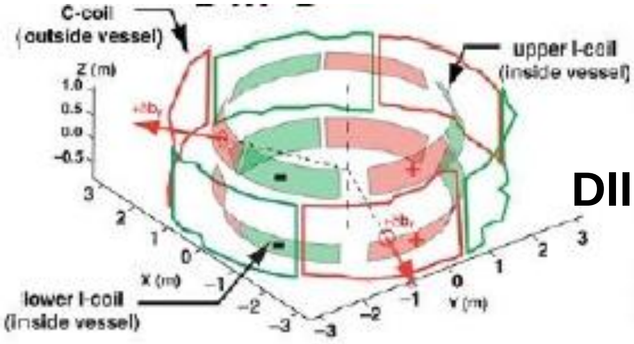
ELM control using RMPs

Toroidal mode number

ELM suppression

KSTAR(2)





DIII-D(3)

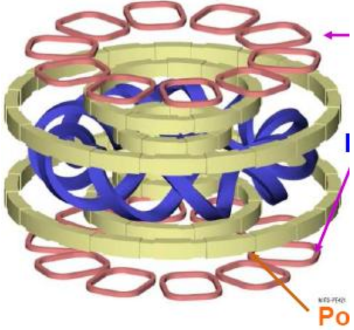
ELM Mitigation

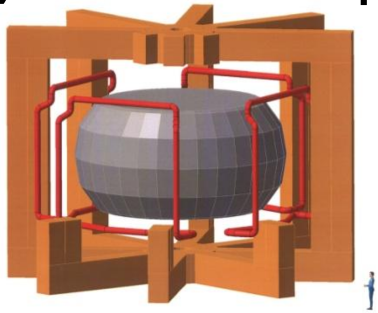
LHD(1)

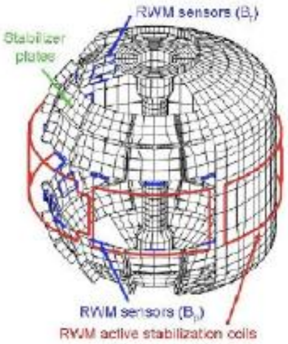
JET(2)

NSTX(3)

External coils







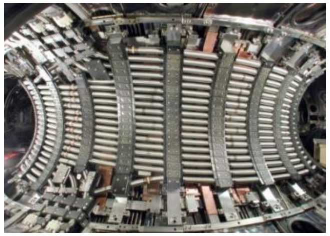
TEXTOR(4)

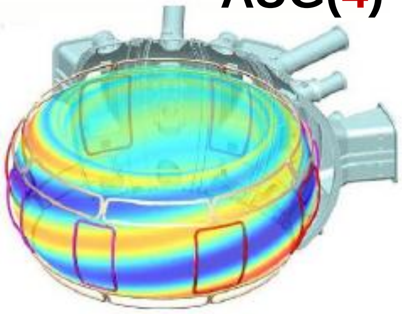
AUG(4)

MAST(6)

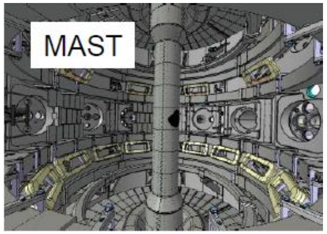
In-vessel coils

COMPASS-D (1)

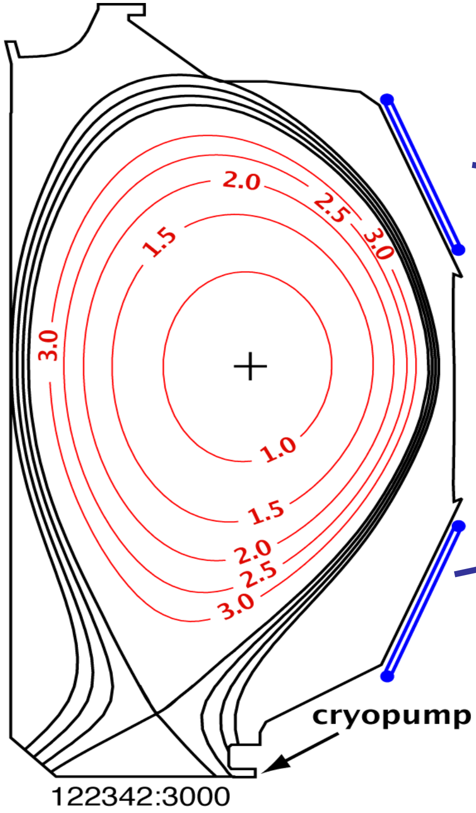




JFT-2M (>4)

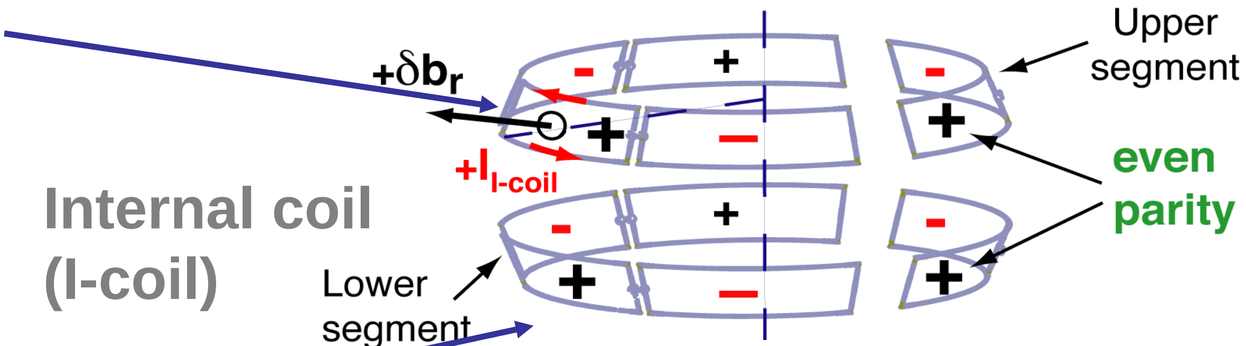


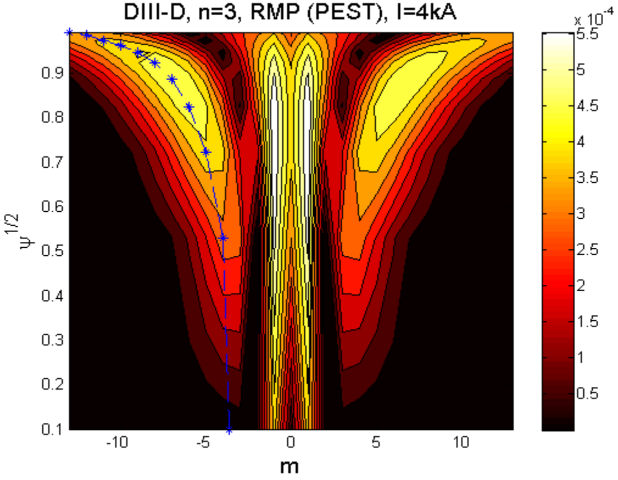
Experiments of Active Control of ELMs with a RMP on DIII-D Tokamak

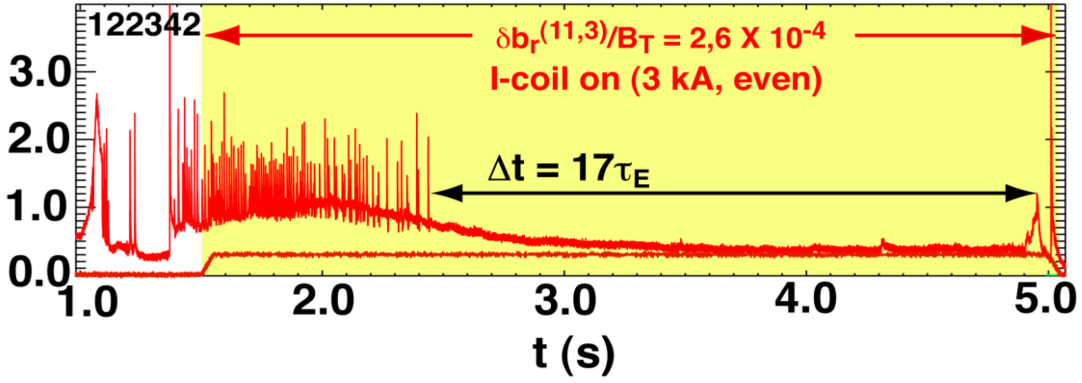


n=3 I-coil configuration

(strong RMP - even parity)





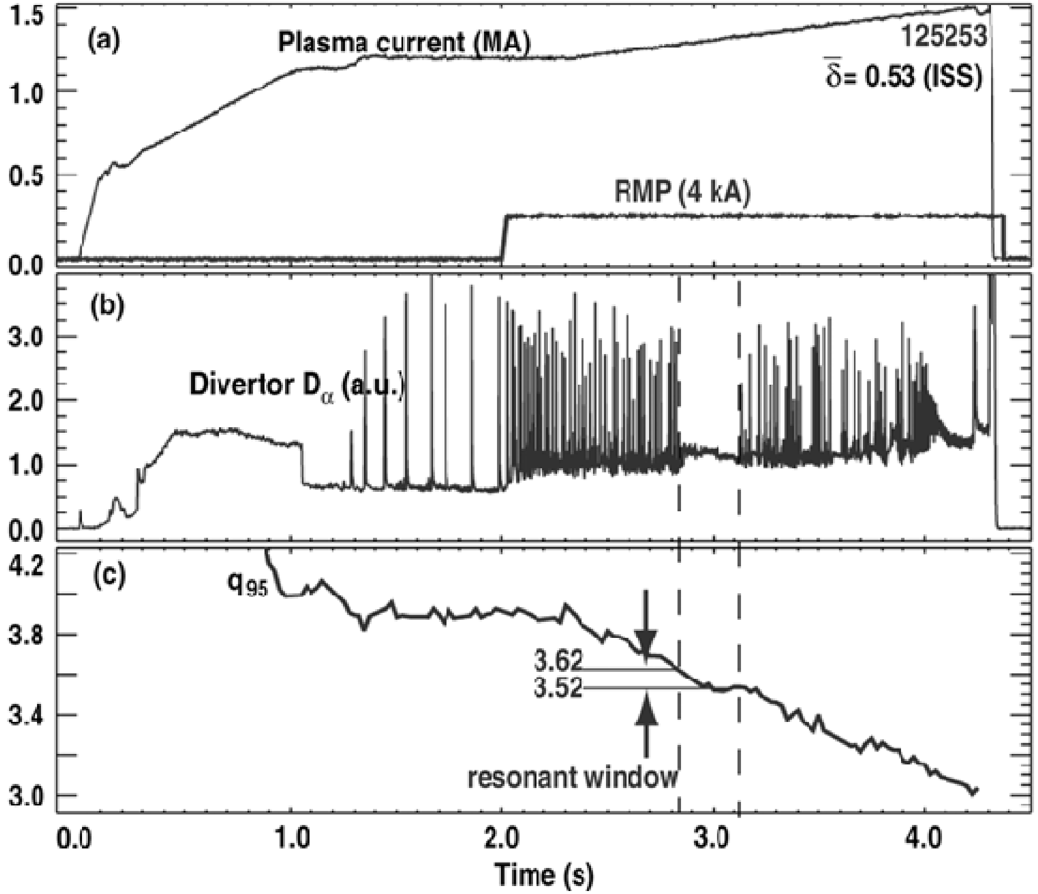


T. E. Evans,et al., PRL, 92, 235003 (2004)

T. E. Evans,et al., Nature physics, Vol. 2, p419, June 2006

T. E. Evans, et al., Phys. Plasmas 13, 056121 (2006).

ELM Suppression Window on DIII-D



T.E. Evans, et al.,
NF **48** (2008) 024002

- ✓ **ELM suppression achieved in a narrow q_{95} window on DIII-D with an *n*=3 field induced by the I-coils.**
- ✓ **q_{95} ELM suppression window can be enlarged slightly with a mixed *n*=1 and *n*=3 fileds.**

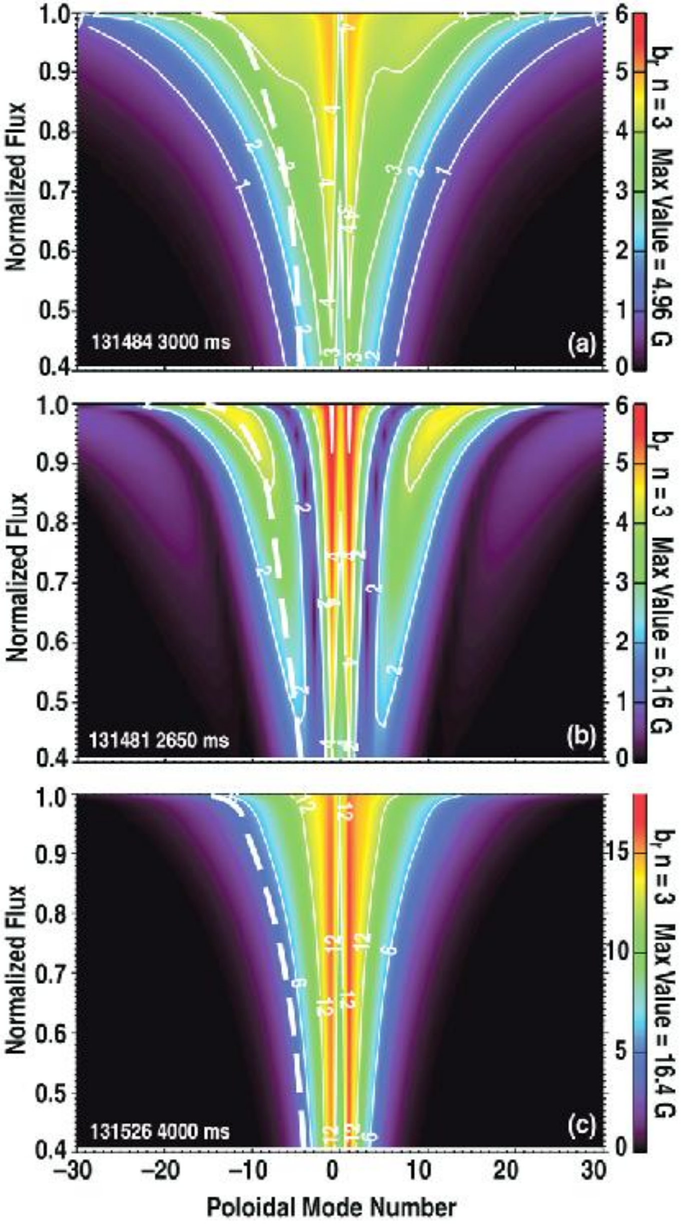
What is the role of the magnetic perturbation spectrum?

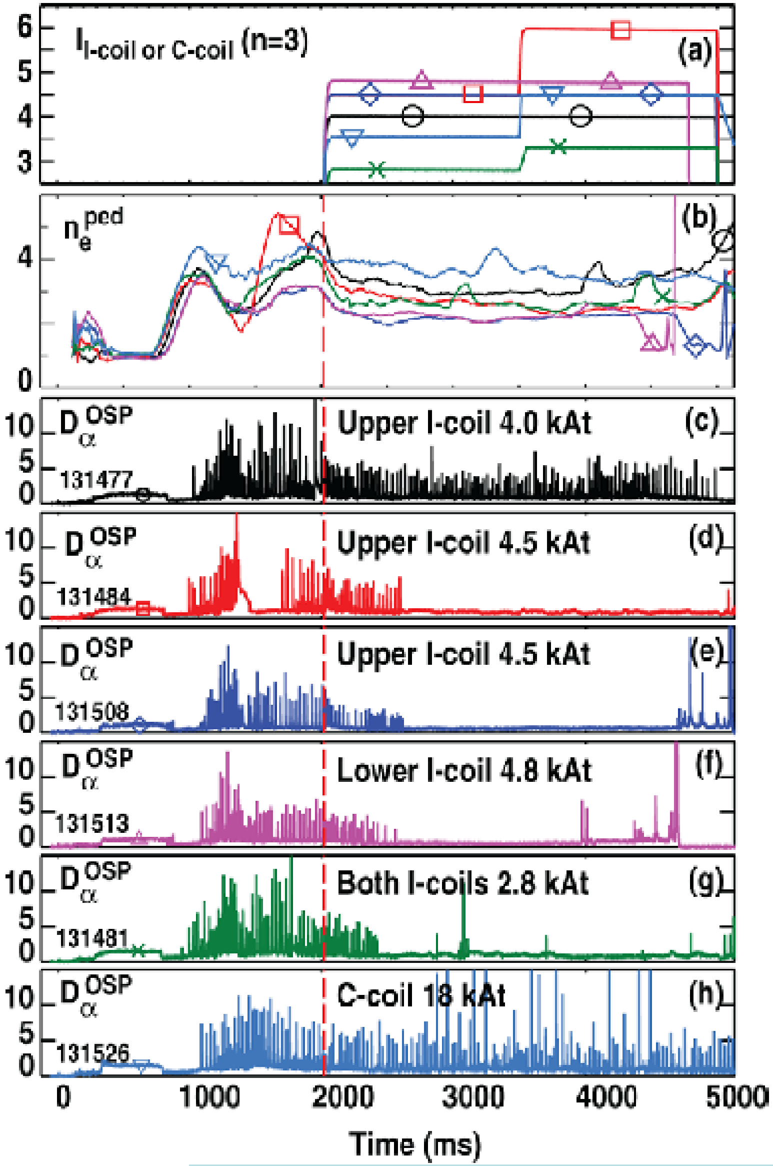
DIII-D

Upper in-vessel coils only

Both Upper and lower In-vessel coils

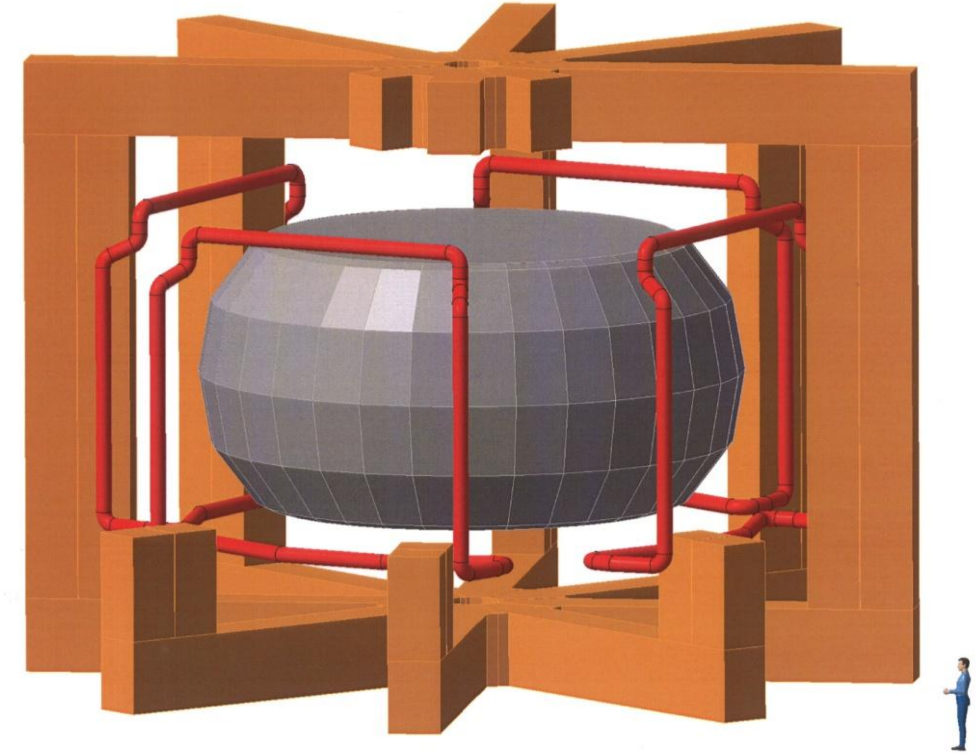
External C coils



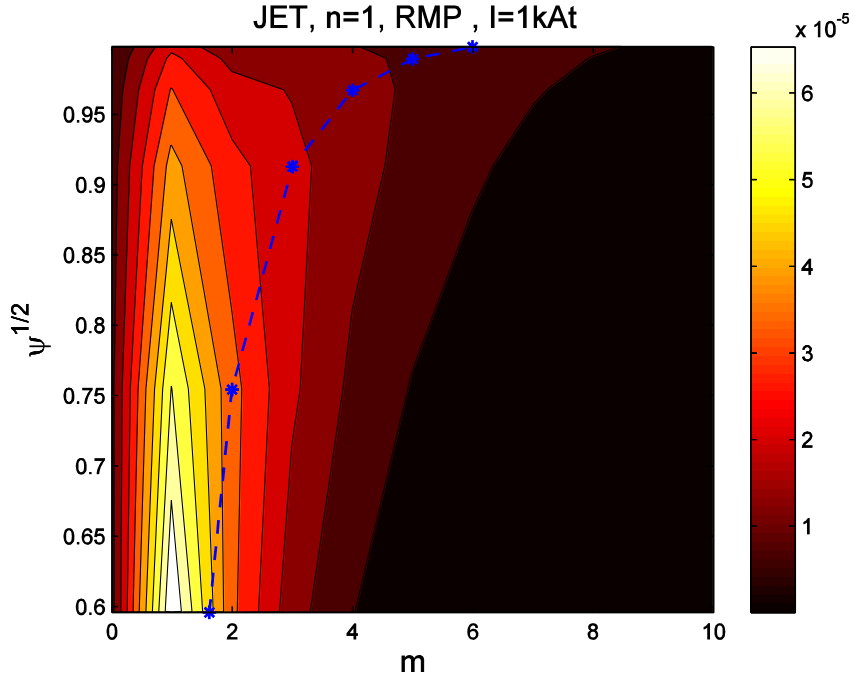


M.E. Fenstermacher, NF (2008)

Error Field Correct Coils (EFCC) on JET



I_{EFCC} = 1 kAt; B_t= 1.84 T



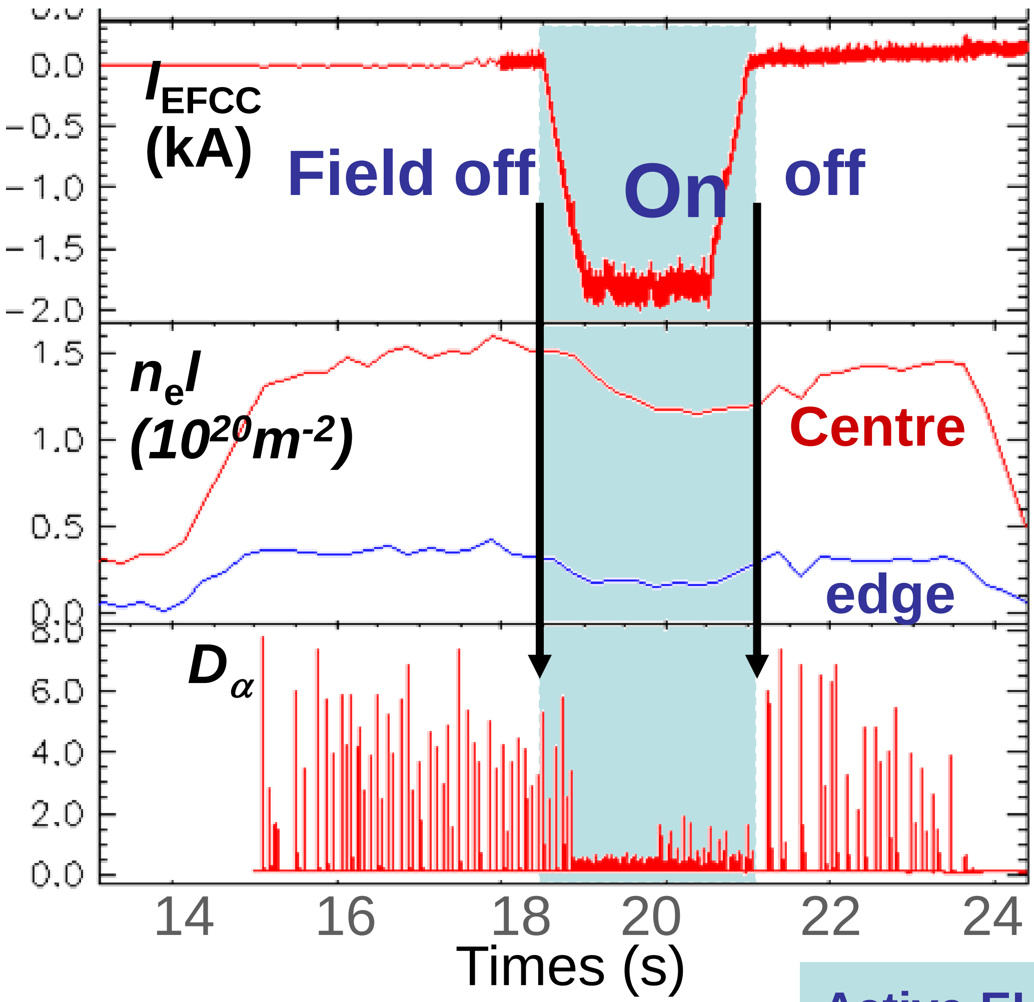
- Depending on the relative phasing of the currents in individual coils, either *n*=1 or *n*=2 fields can be generated
- $I_{Coil} \leq$ 3 (6) kA x 16 turns (*n* = 1 *and* 2)
- *R* ~ 6 m; Size ~ 6 m * 6 m
- B_r at wall ~ 0.25 mT/kAt

Y.Liang et al., PPCF 2007

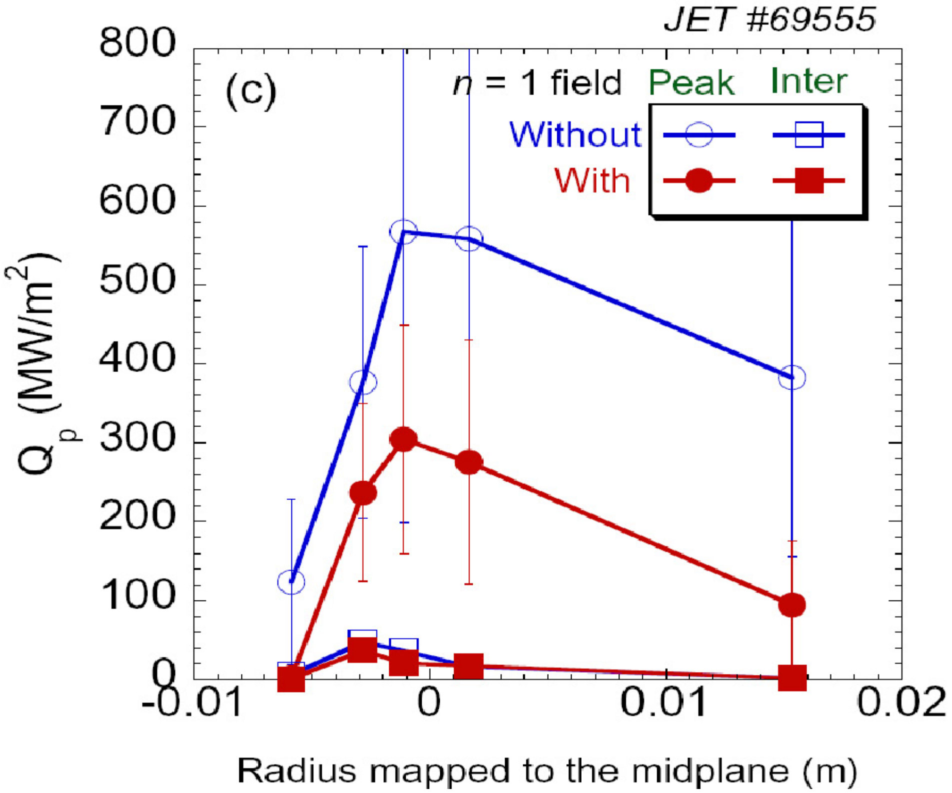
Active ELM Control with Low *n* Magnetic Perturbation fields on JET

I_p = 1.8 MA; B_t = 2.1 T; q_{95} ~ 4.0; δ_U ~ 0.45

JET#69557



Heat flux onto the outer divertor



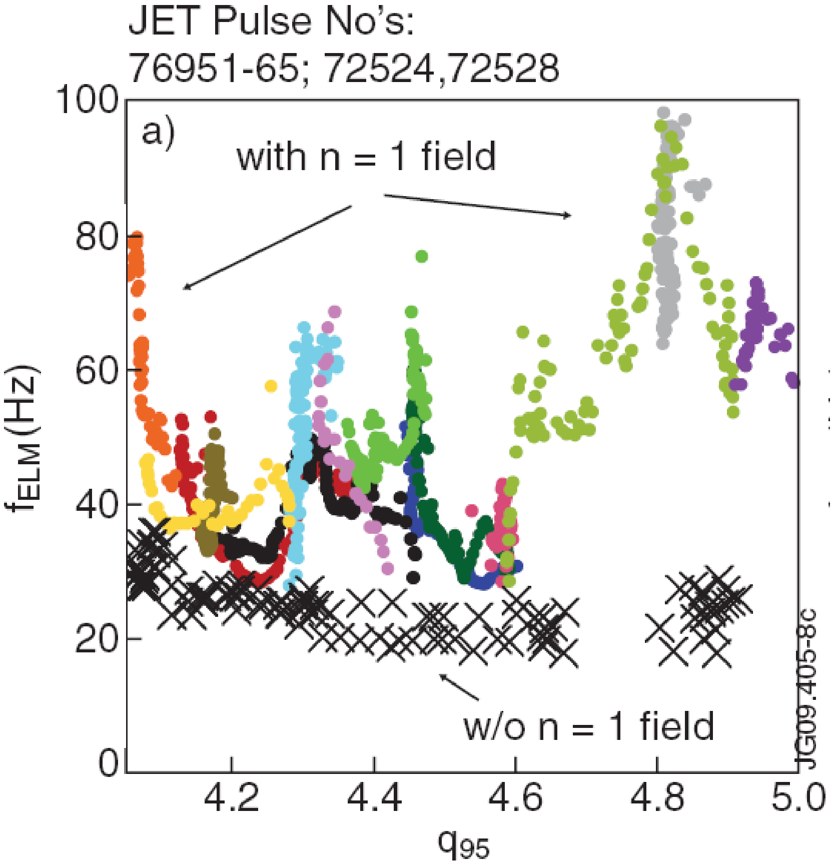
Y Liang, et al, PRL, 98, 265004 (2007)

Y Liang, et al, PPCF , 49, B581 (2007)

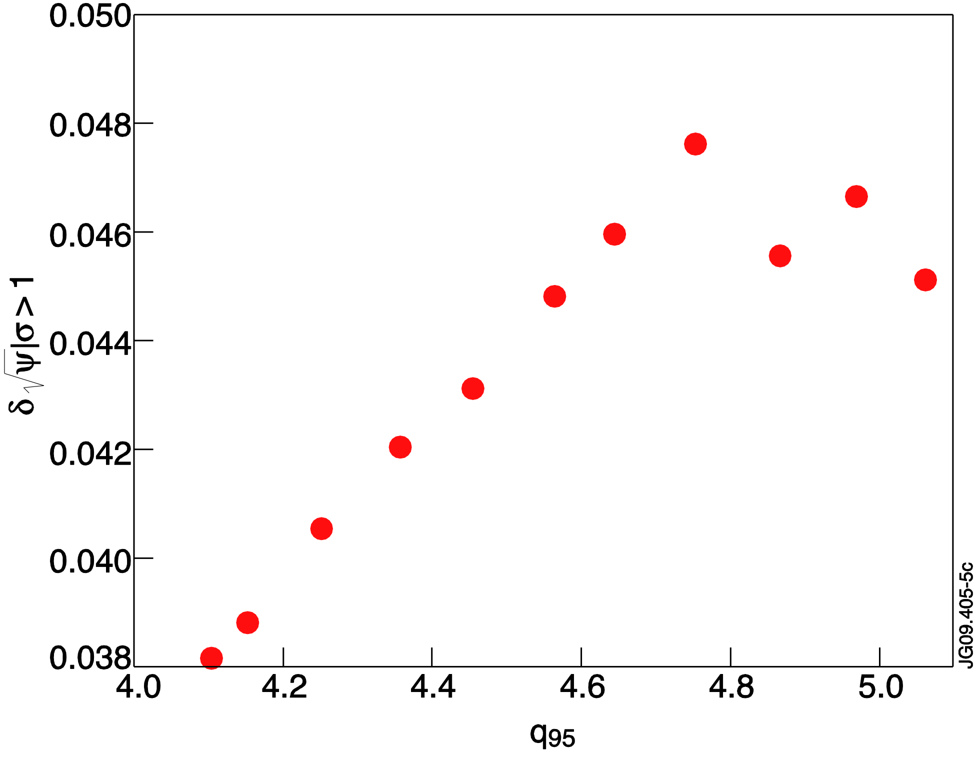
Y Liang et al, JNM, 390–391, 733–739 (2009)

Active ELM control (frequency/size) observed in a wide q_{95} window, but no ELM suppression

Multi-resonance Effect with low *n* Fields on JET


JET Pulse No's:
76951-65; 72524,72528

Y. Liang et al., PRL 105, 065001 (2010)



- Multiple resonances in f_{ELM} vs q_{95} have been observed with n = 1 and 2 fields
- Possible explanation in terms of ideal peeling mode model [*C G Gimblett et al., PRL, **96**, 035006-1-4(2006), J Pearson, Y Liang et al, Nucl. Fusion 52 (2012) 074011*].

ELM control coils on AUG

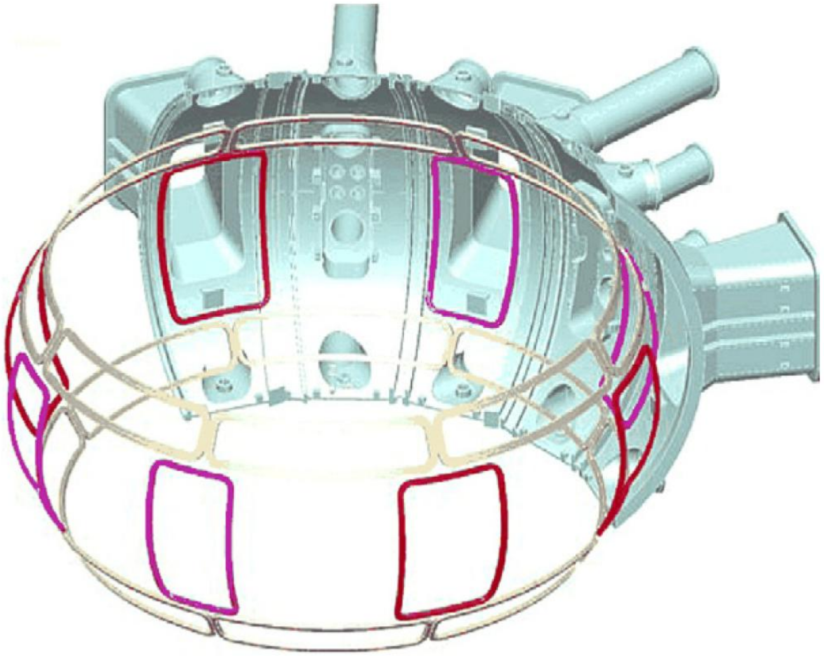
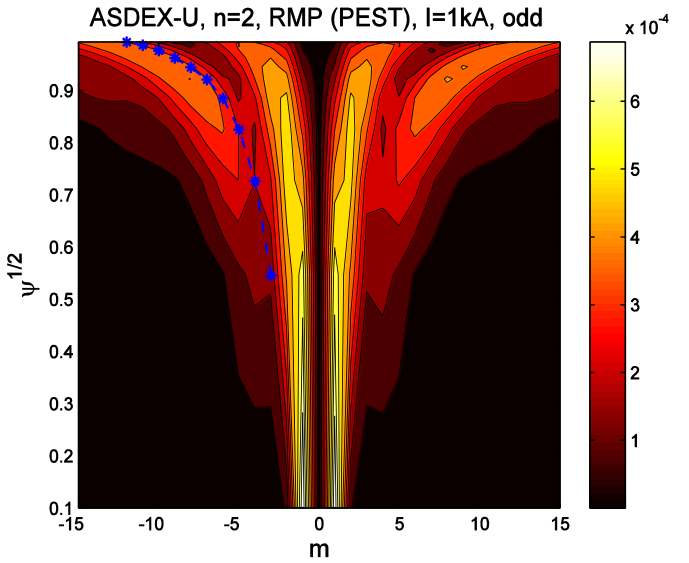
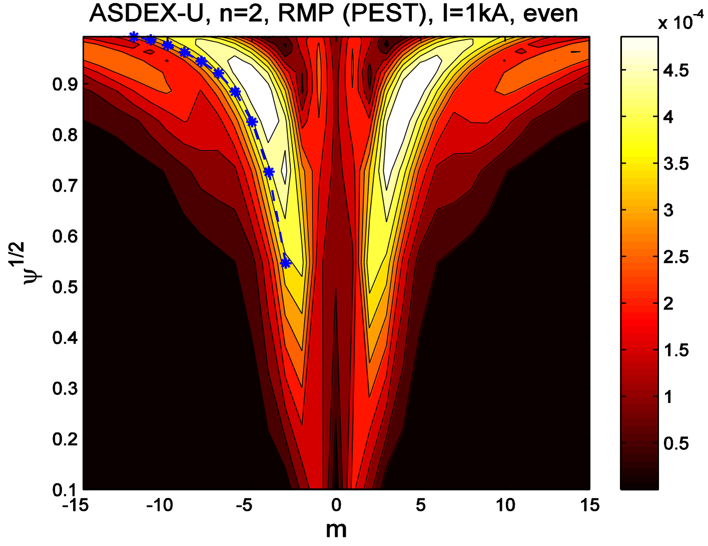


Fig. 1. 3D view of active in-vessel coils.

W Suttrop, Fusion Engineering and Design 84 (2009) 290

In 2011: Two rows ×4 toroidally distributed coils (*n* = 2).
Single DC supply (all coils in series / anti-series).



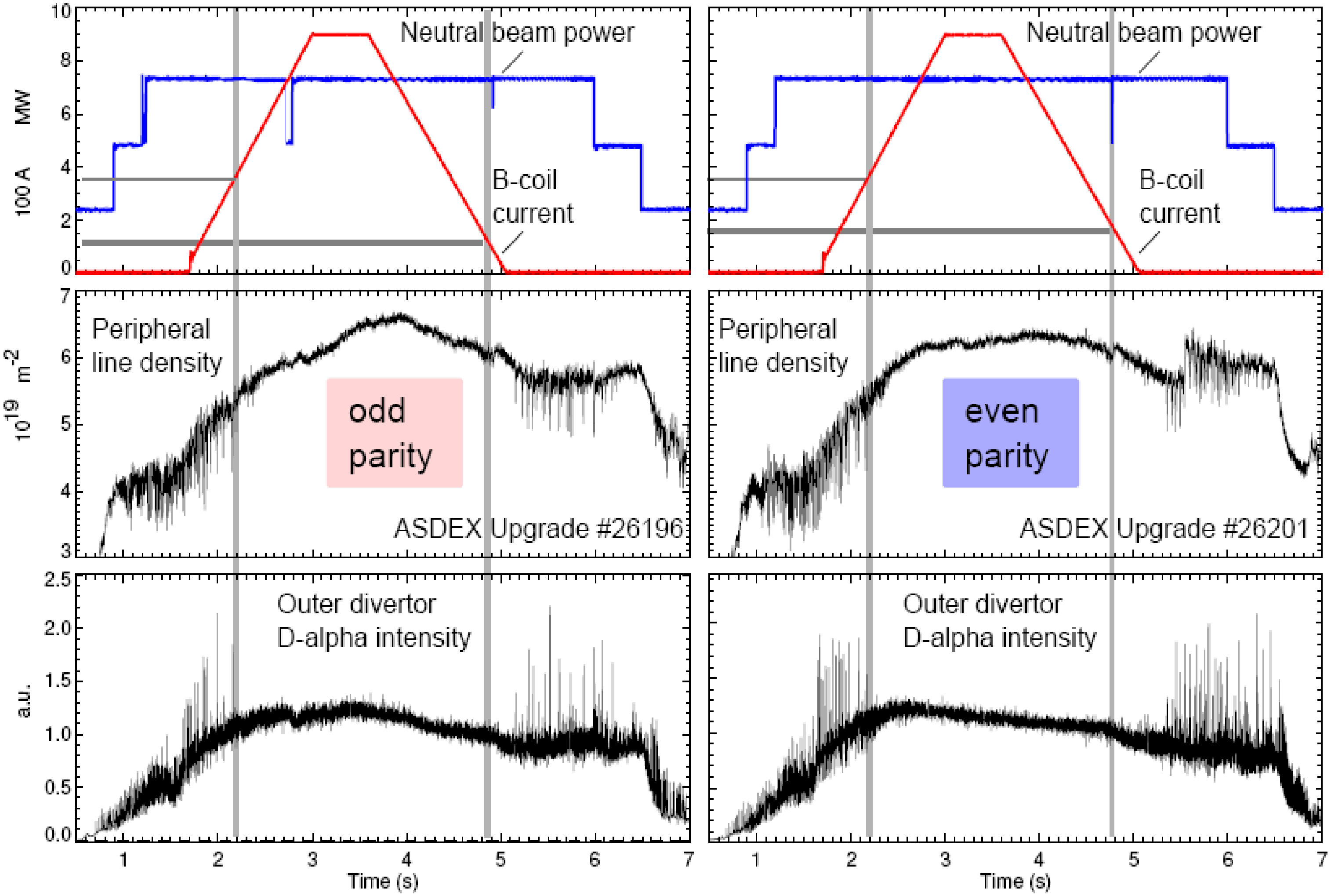


ELM mitigation on AUG

Identical coil current threshold for odd and even parity

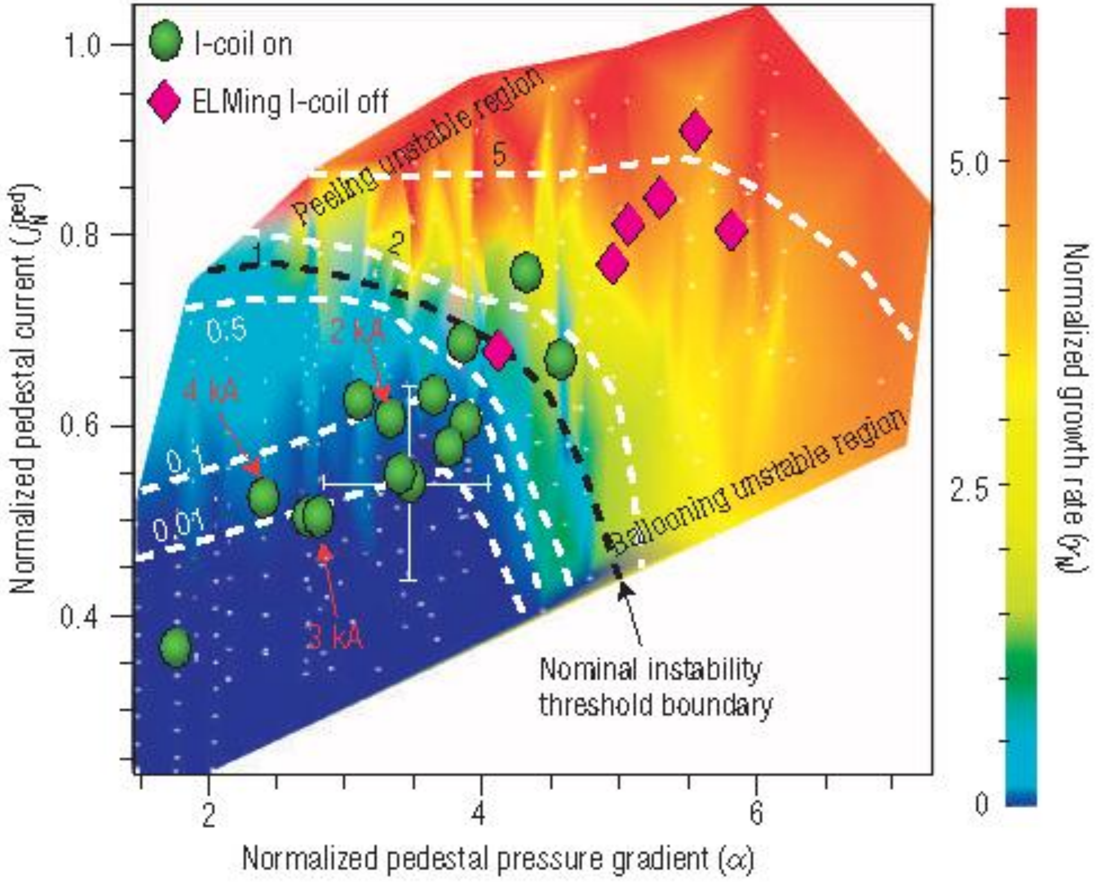
W Suttrop, SFP workshop (2011)

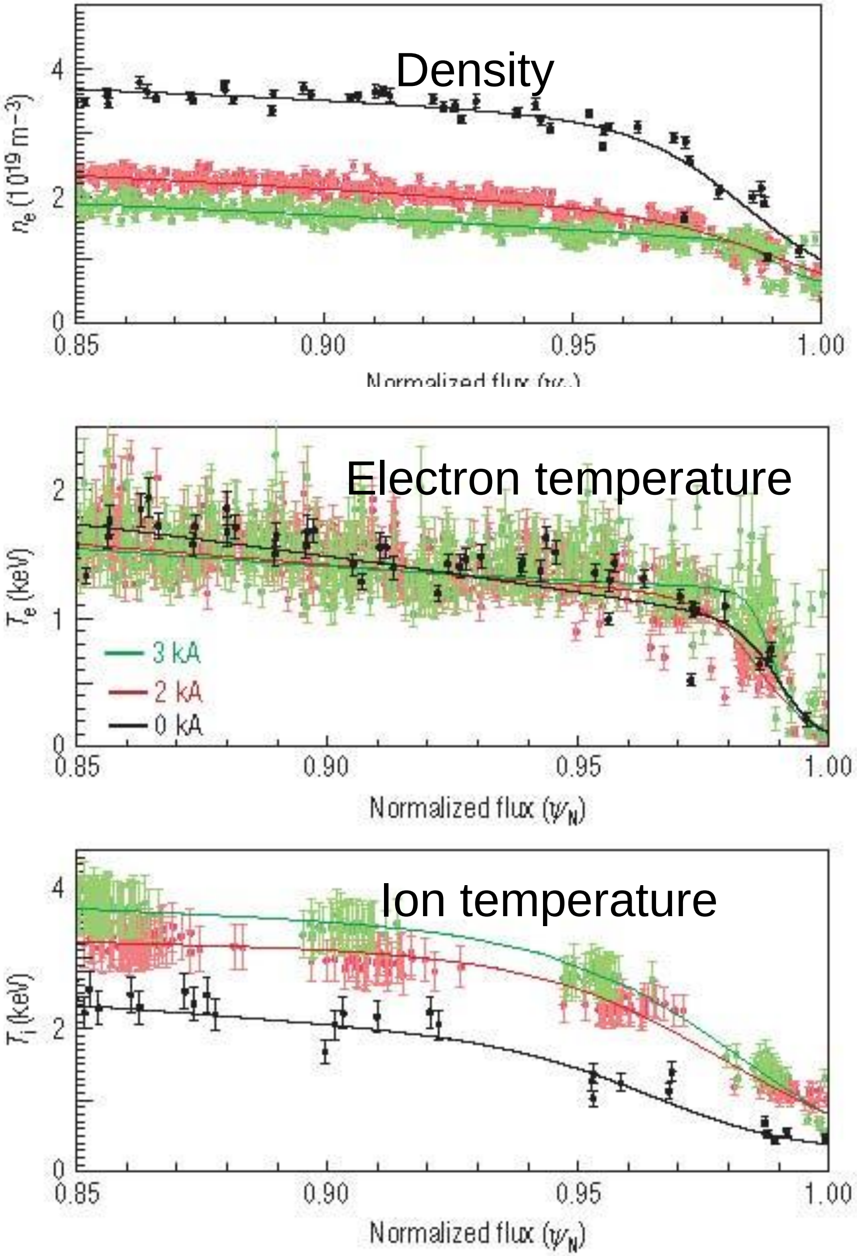
Hysteresis: $I_{\mathrm{coil}} = 350$ A to and ≈ 150 A from ELM-mitigated state



Dominant mechanism of ELM suppression

T. E. Evans,et al., Nature physics, Vol. 2, p419, June 2006

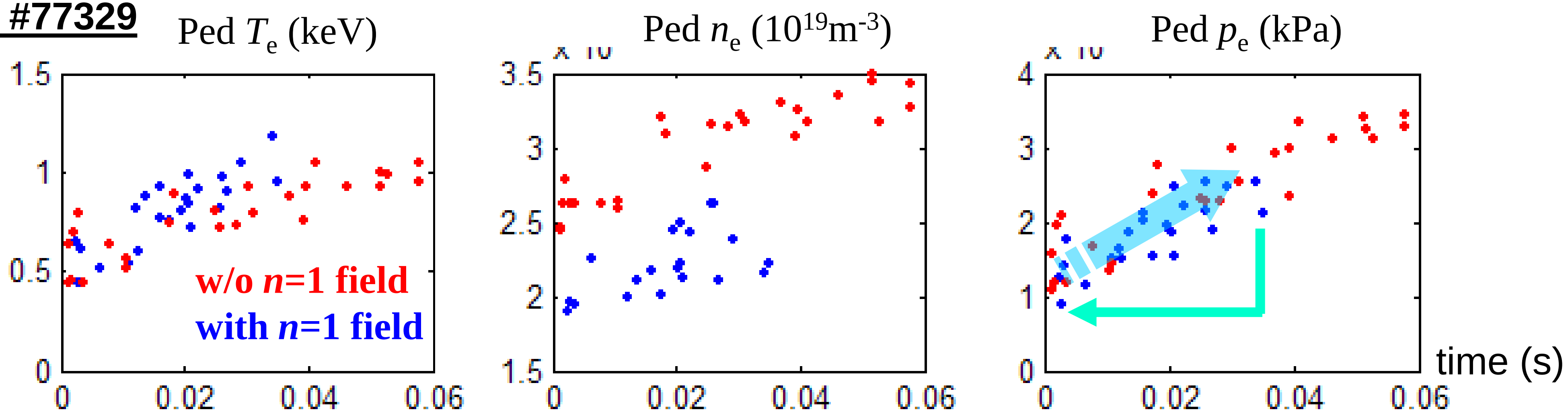


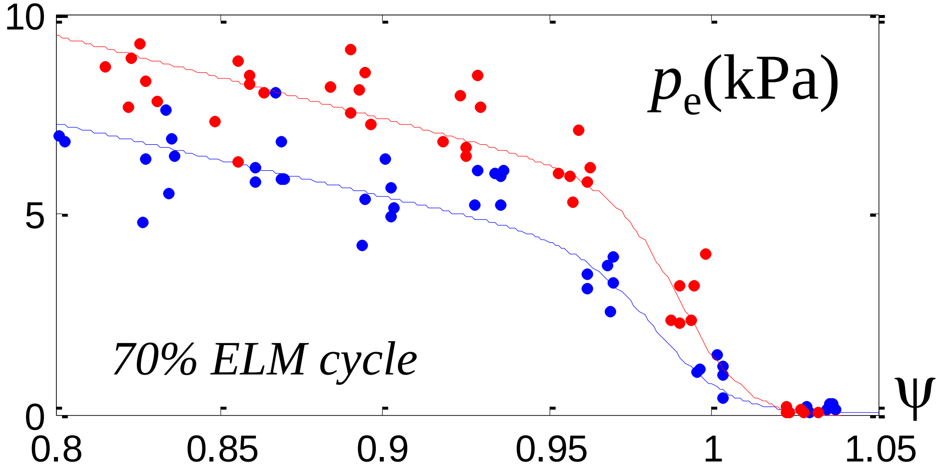


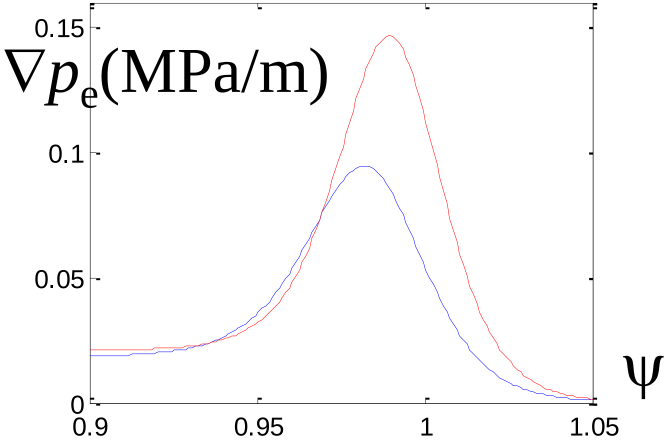
Reduction of edge pressure below instability threshold

Dynamic of Edge Profiles with *n* = 1 Field on JET

JET #77329



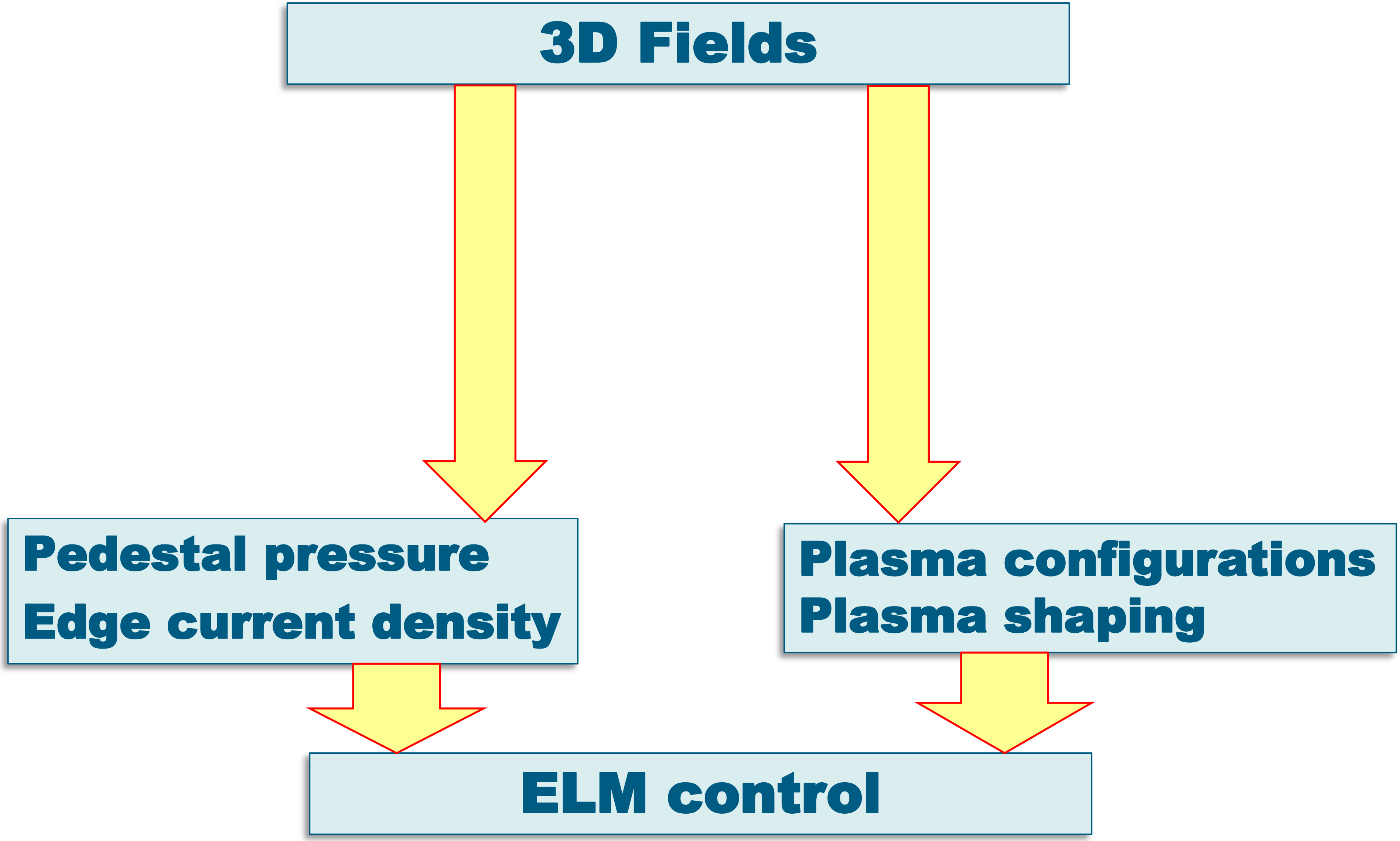




Y. Liang et al., Plasma and Fusion Research: 5, S2018 (2010)

- ➢ Pedestal pressure with *n* = 1 field applied recovers at same rate, but the ELM crash occurs earlier at lower $p_{e,ped}$.
- ➢ Pedestal n_e is reduced by ~20% while the edge T_e is increased. ∇p_e is ~20% smaller.

Experimental Observations

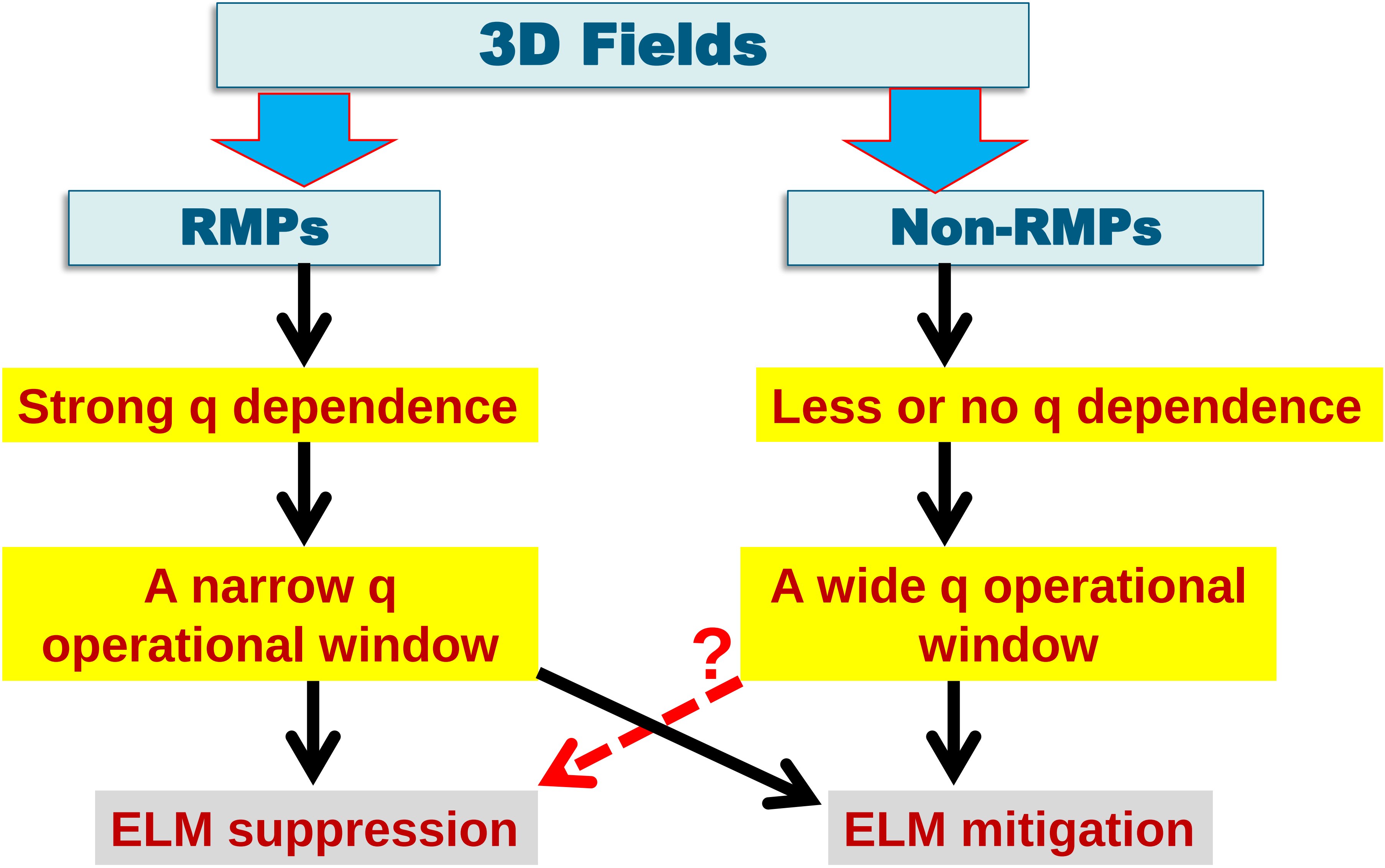


3D Fields

Pedestal pressure
Edge current density

Plasma configurations
Plasma shaping

ELM control



3D Fields

RMPs

Non-RMPs

Strong q dependence

Less or no q dependence

A narrow q operational window

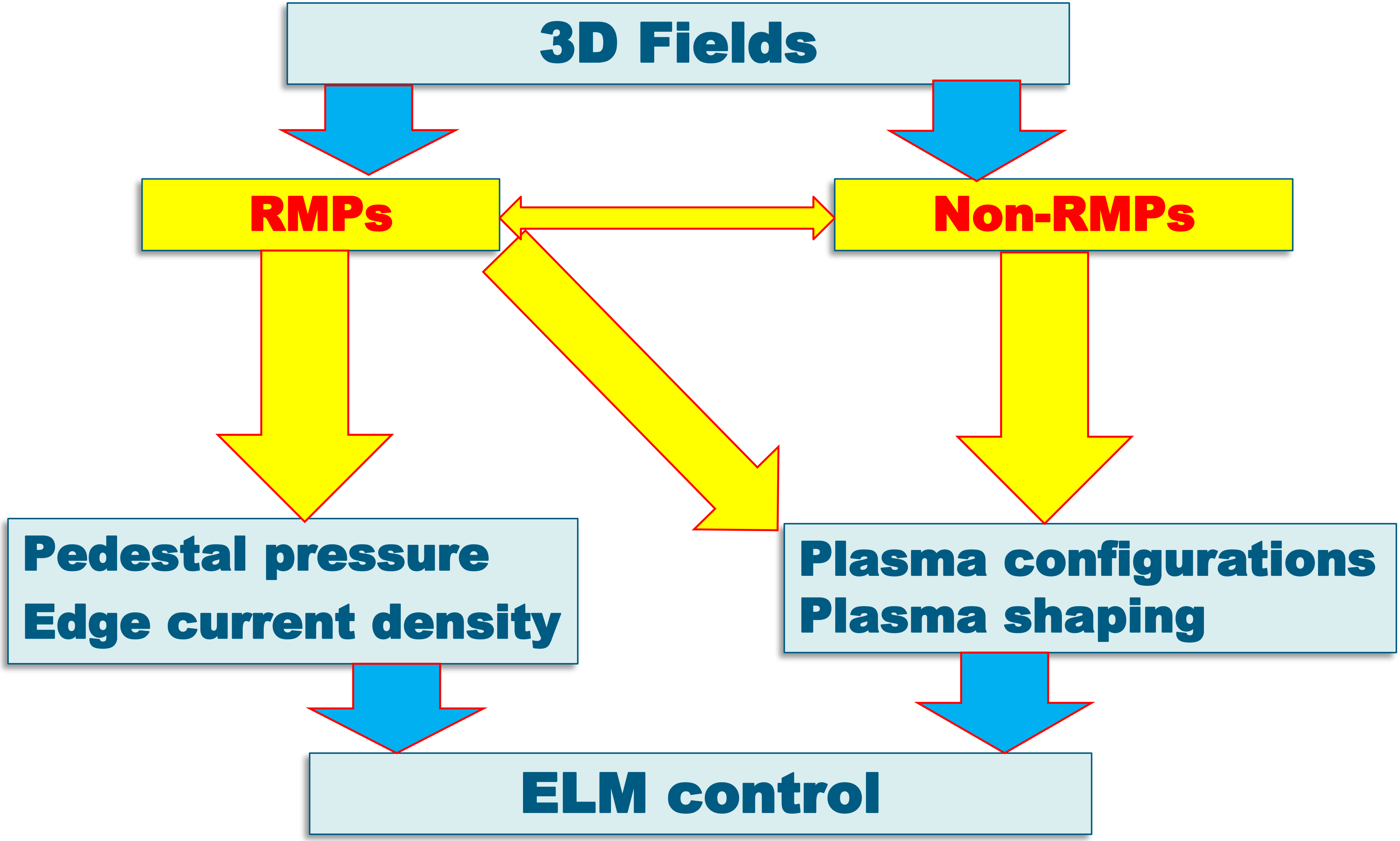
A wide q operational window

?

ELM suppression

ELM mitigation

Experimental Observations



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Magnetic Field 'Frozen in' to the Fluid

In a perfectly conducting fluid

(**Ideal MHD**) $E + v \times B = 0$.

- The magnetic flux through each surface moving with the fluid is constant and consequently that the magnetic flux can be thought of as "**frozen-in**" to the fluid and moving with it.

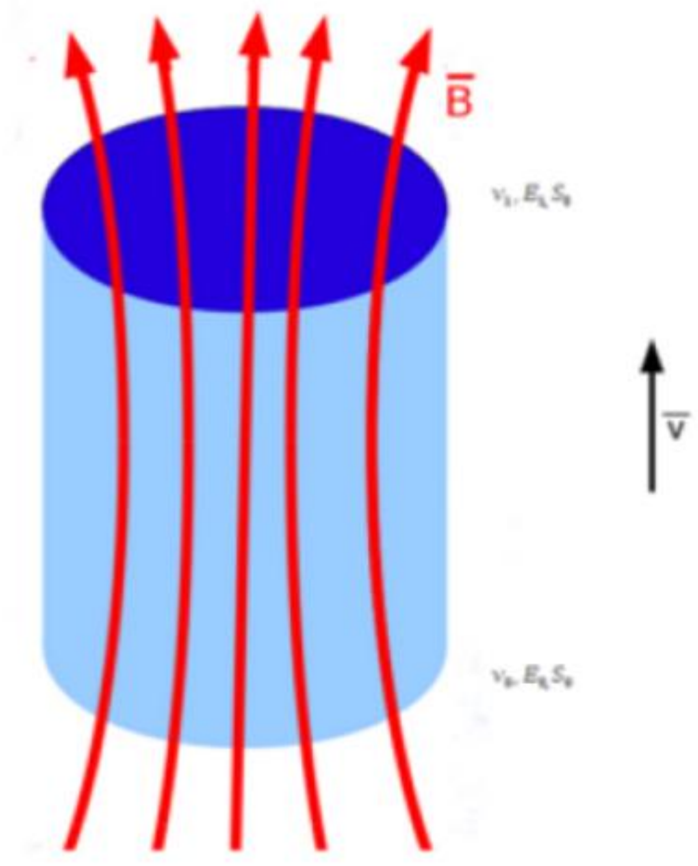
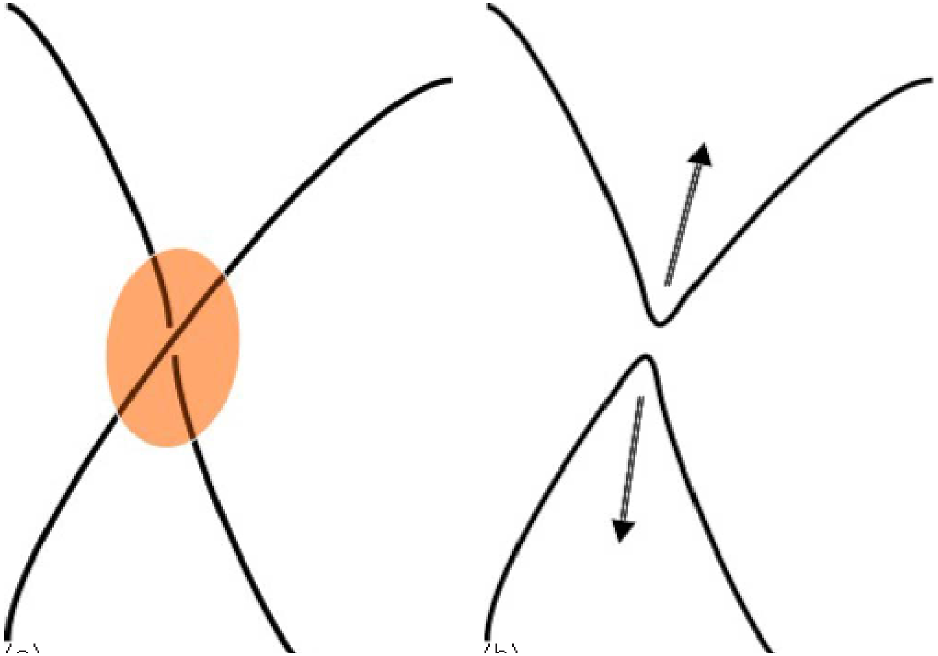


Figure 1.1: sketch to ilustrate a fluxtube

Magnetic Reconnection

Non-ideal (Resistive) modes: $E + v \times B = \eta j$



- When the field lines are reconnected, the topology of magnetic configuration changes and $\boldsymbol{j \times B}$ forces result in the conversion of magnetic energy to kinetic energy.

Resonant Magnetic Perturbation (RMP)

Magnetic field perturbation: $\vec{b} = \nabla\varphi \times \nabla\tilde{\psi}$

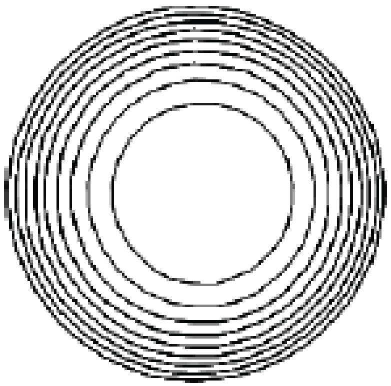
$$\tilde{\psi}(\varphi,\vartheta,r) = \tilde{\psi}_0(r)\cdot e^{\,i(n\varphi - m\vartheta)}$$

$q(r) = \frac{m}{n}$ – inside the plasma

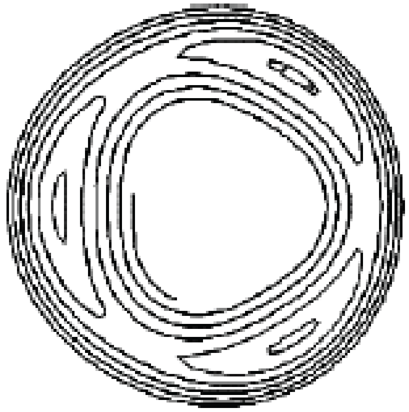
Resistive Responses

$q(r) = \frac{m}{n}$ – outside the plasma

Ideal Responses

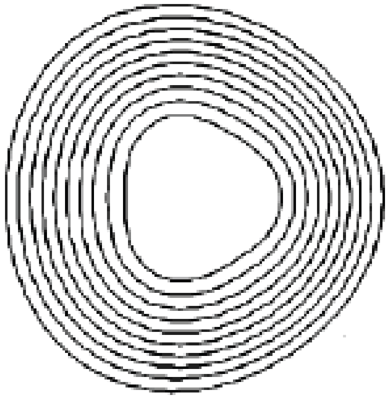


Unperturbed Magnetic Surfaces



Internal (Tearing) Modes

or



External Kink Modes

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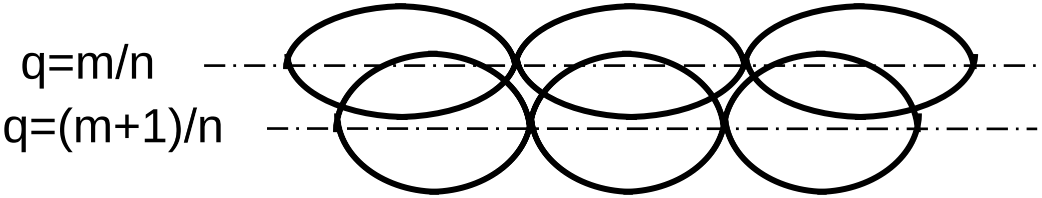
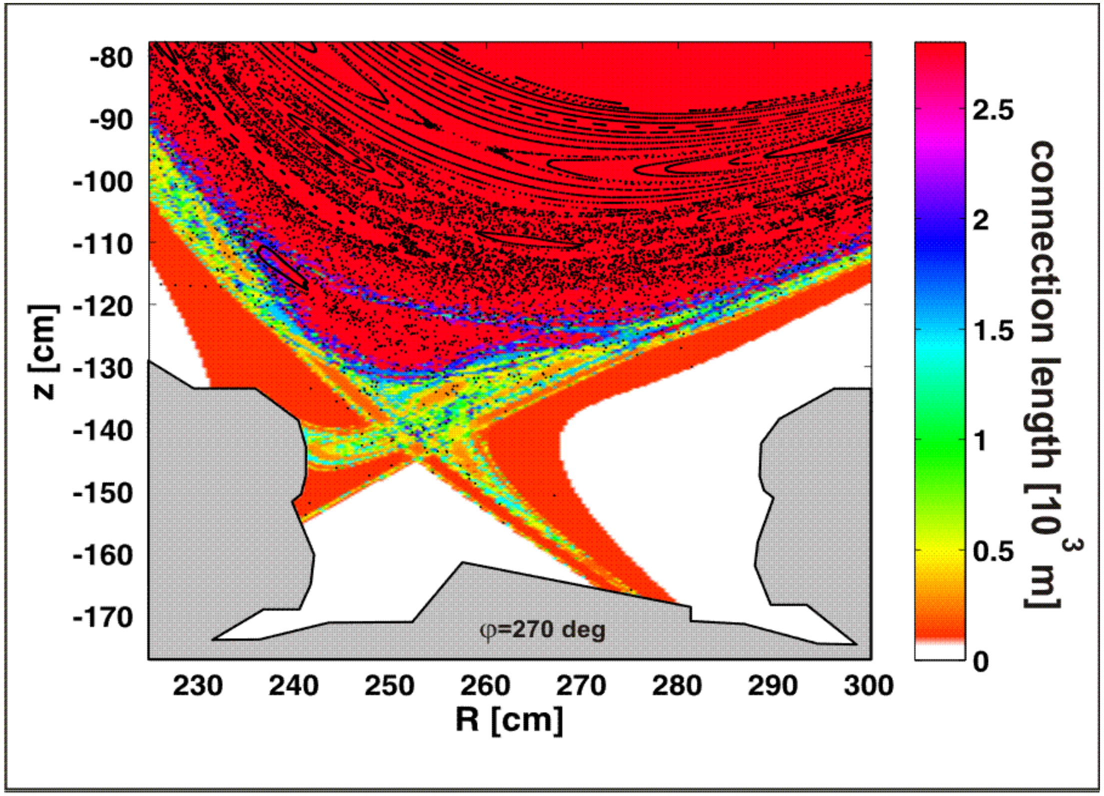
    - Edge Ergodisation
  - Ideal Plasma Responses
    - Rotation Screening Effect
    - Resonant Field Amplification (RFA)
- ELM control through the magnetic topology control by another methods
- Summary

Edge ergodisation

Equilibrium Magnetic Field at Plasma Edge





Chirikov parameter

$$\sigma_{m,m+1} = \frac{w_{n,m} + w_{n,m+1}}{2\delta_{m,m+1}}$$

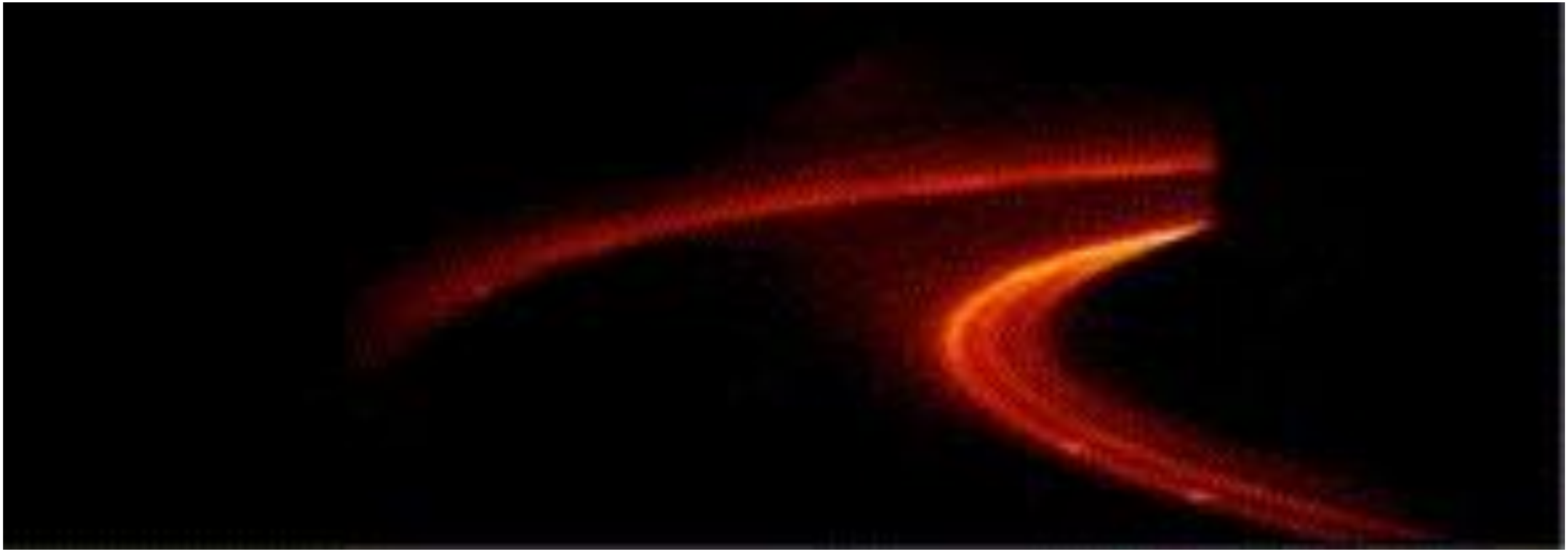
larger than 1

Edge Ergodisation with a magnetic perturbation

- ☐ Splitting of strike point
- ☐ Spin-up plasma rotation

to co-current direction

Strike point splitting on DIII-D

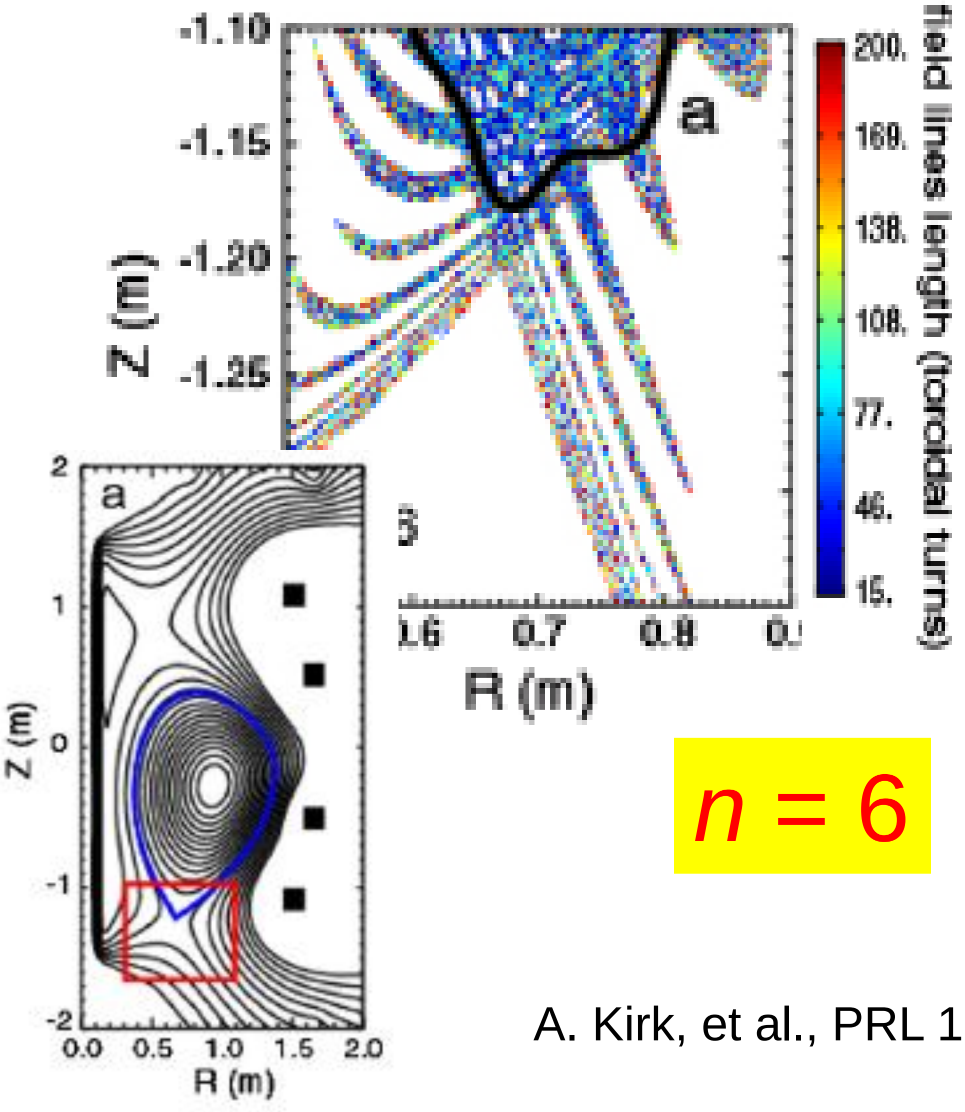


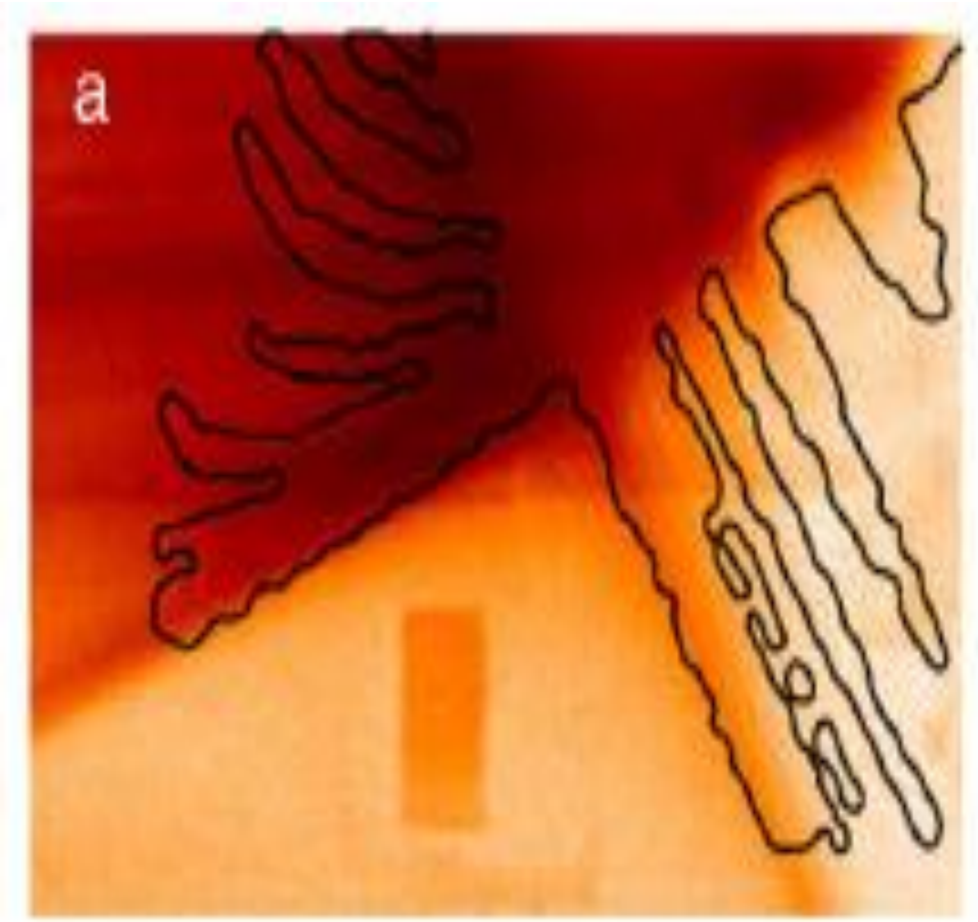
O. Schmitz, PPCF (2008)

I. Joseph JNM, 2007

Splitting of the inner strike-point has been observed during ELM suppression with an *n* = 3 field on DIII-D.

Observation of Lobes near the *X* Point in RMP Experiments on MAST

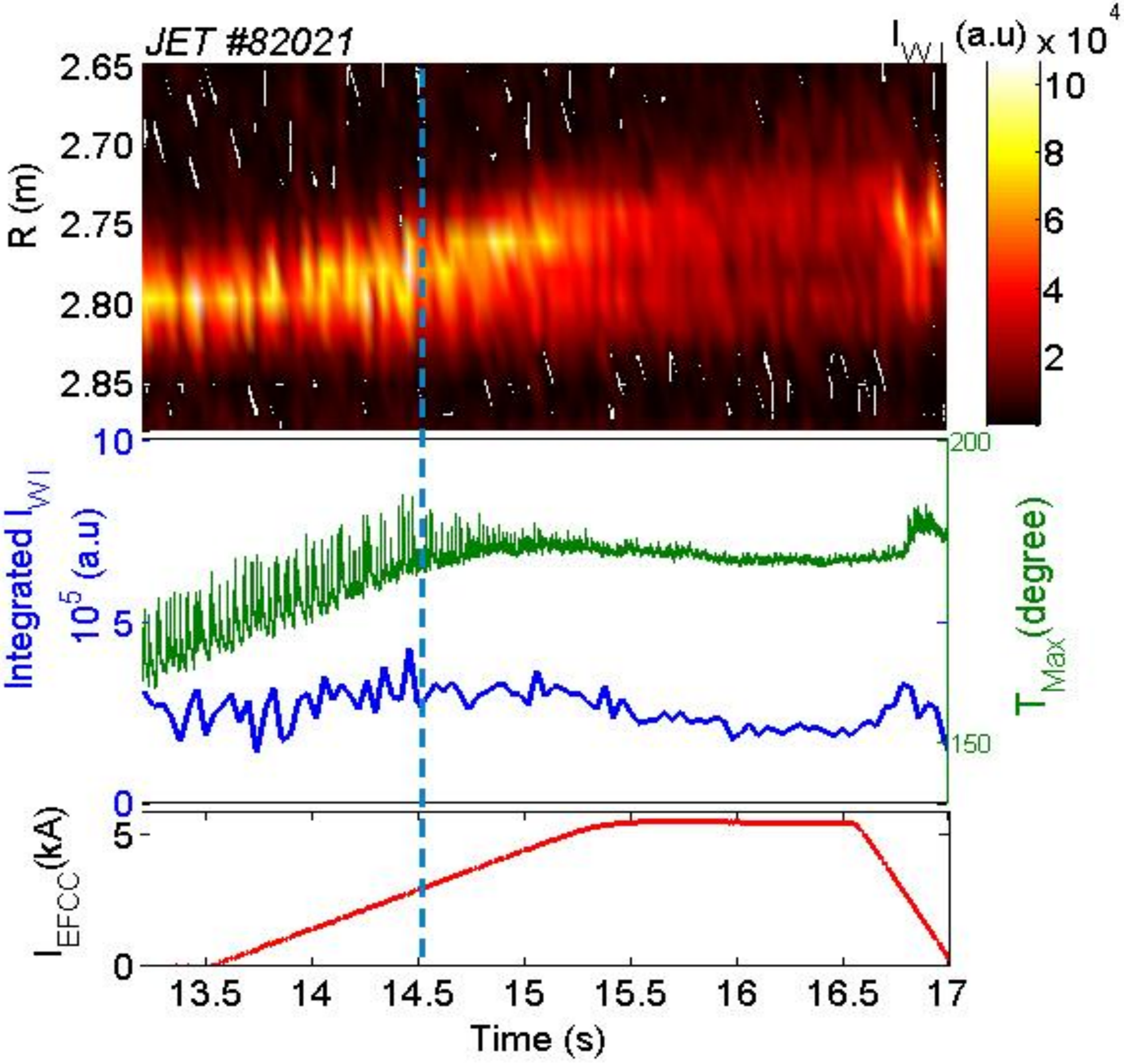




$n = 6$

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

Splitting of Strike Point during Mitigation of Large Type-I ELMs on JET with the ILW



High collisionality

With n = 2 field, splitting of the outer strike point and reduction of the erosion of the outer tungsten divertor have been observed during the mitigation of the large type-I ELMs.

Y. Liang, et al., IAEA, 2012

Influence of Edge Ergodisation on the Plasma Rotation

TEXTOR

Ohmic plasmas

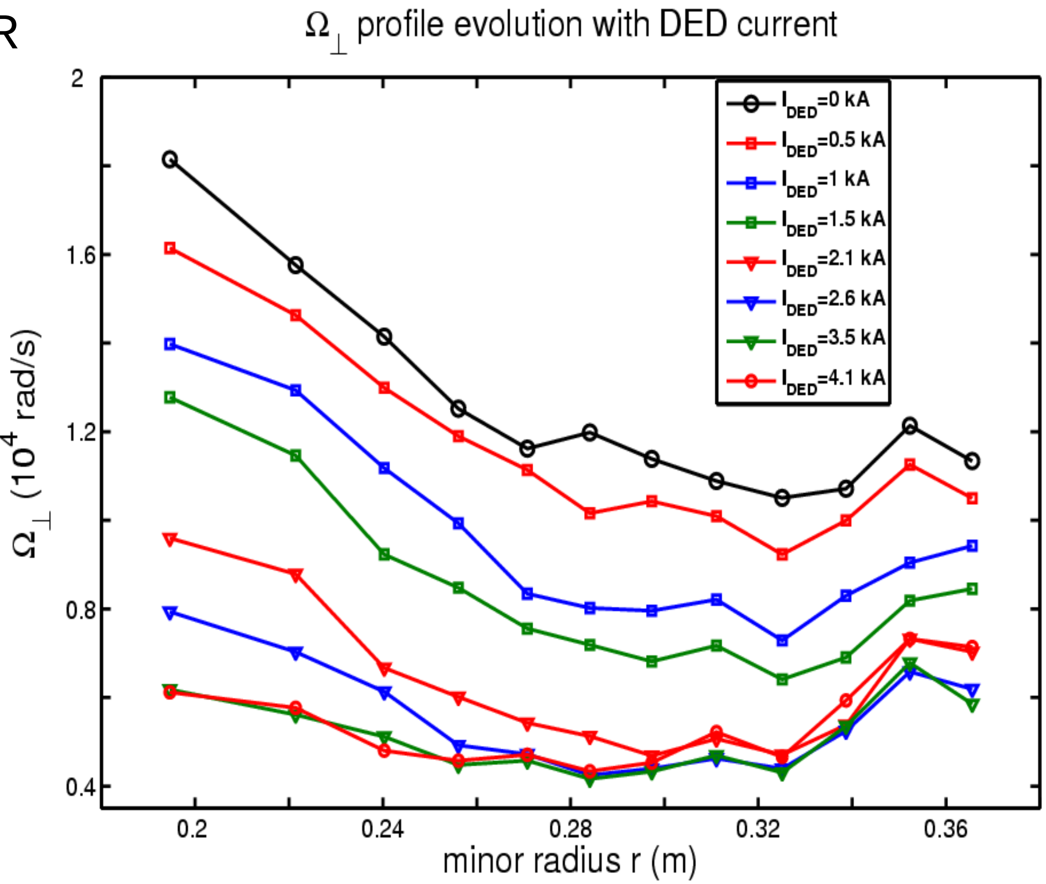
6/2 DED

EDD

Increase I_{DED}

IDD

T Zhang, Y Liang et al., SFP 2011

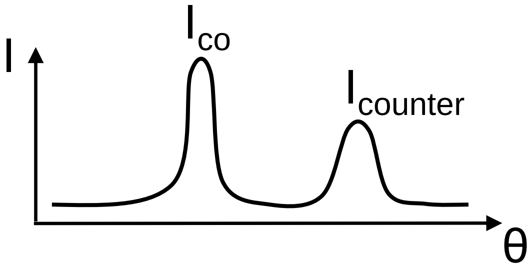

$\Omega_\perp$ profile evolution with DED current

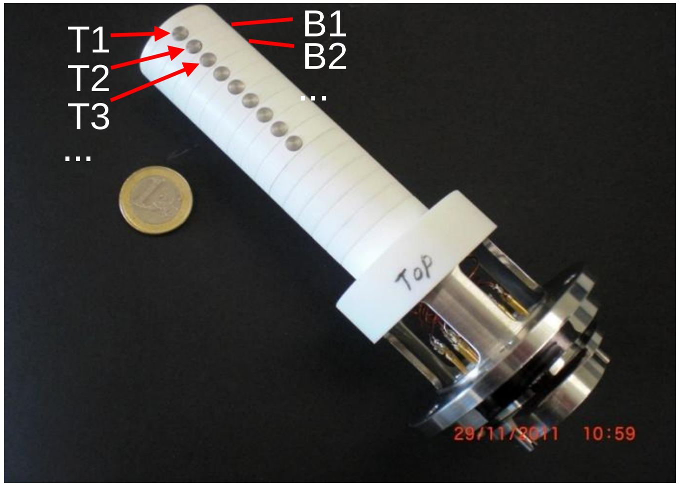
✓ Spin up plasma rotation in IDD direction with m/n=6/2 DED

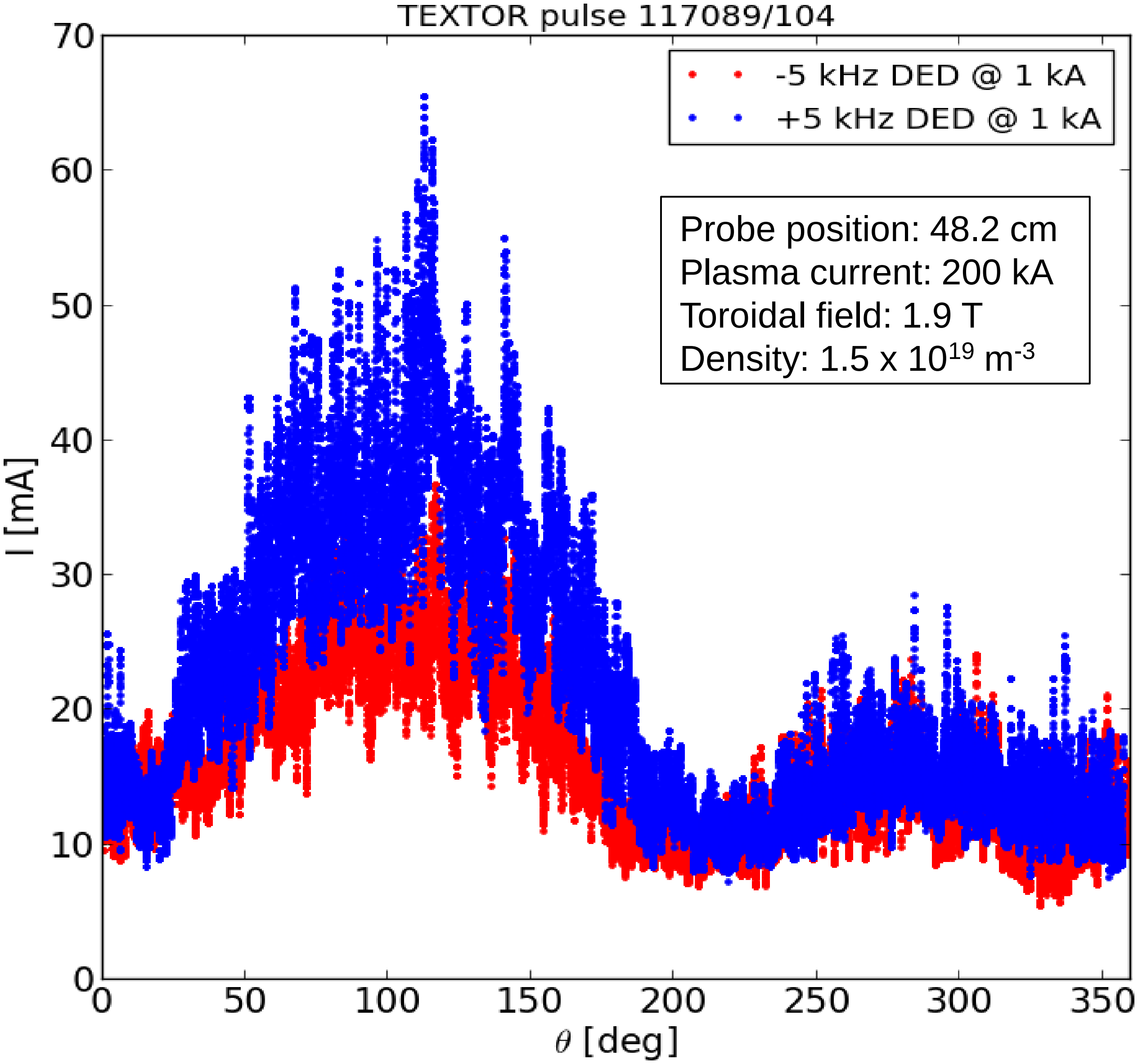
Influence of DED on Fast Ion Losses

Properties of FMDP:

- Negative biasing to measure ion saturation currents
- Measurement of radial profile
- Measure θ dependence of ion saturation currents and fast ion losses by rotating the probe







Probe position: 48.2 cm
Plasma current: 200 kA
Toroidal field: 1.9 T
Density: 1.5 x 10^{19} m^{-3}

Outline

- Introduction to ELMs and 3D fields on tokamak
- Summary of ELM control with 3D fields
  - ELM suppression
  - ELM mitigation
- What are the possible physical mechanisms of ELM control with 3D fields?
  - Resistive Plasma Responses
    - Field Penetration / Mode Excitation
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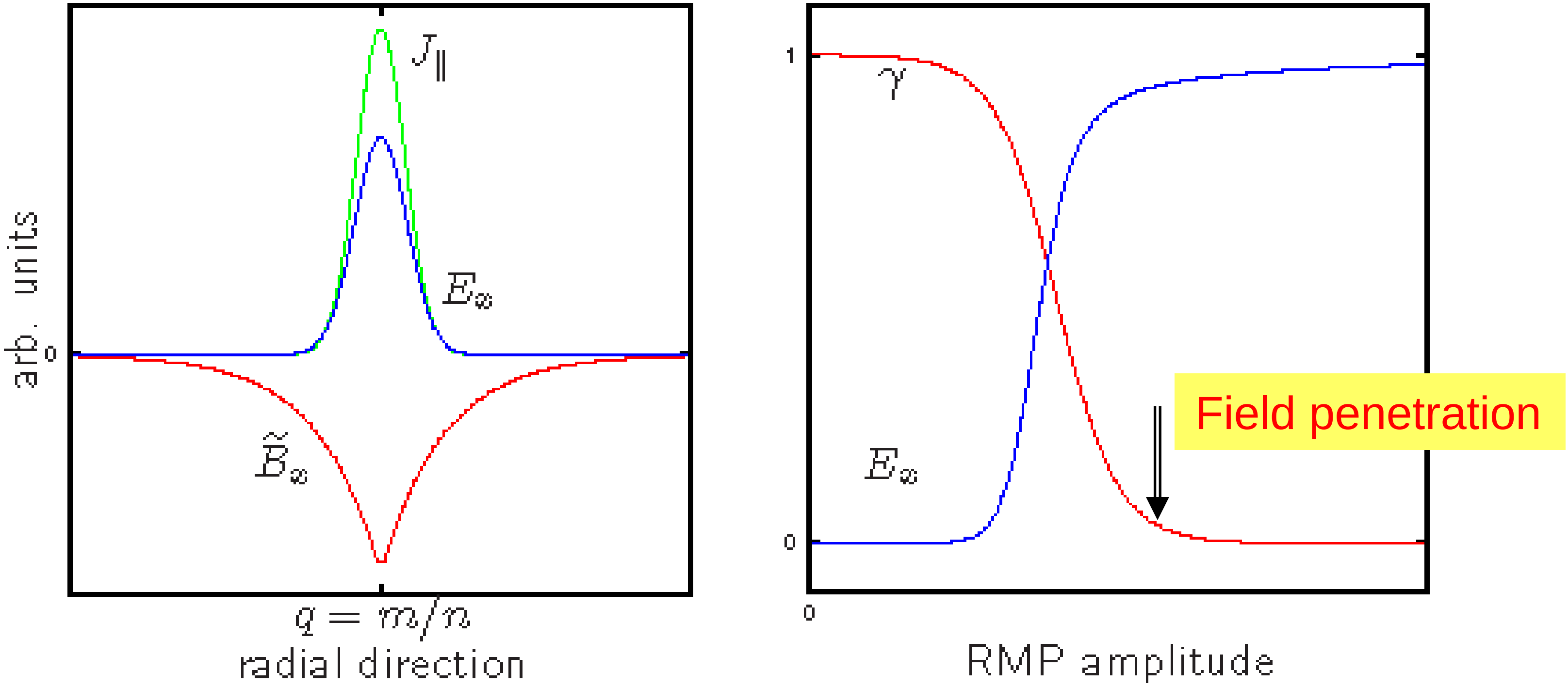
What is the Rotational Screening Effect?

The rotational screening of RMPs results from the motion of the electron fluid across the field lines at the resonant surfaces.

$$V_{\perp,e} = V_{ExB} + V^*_e$$



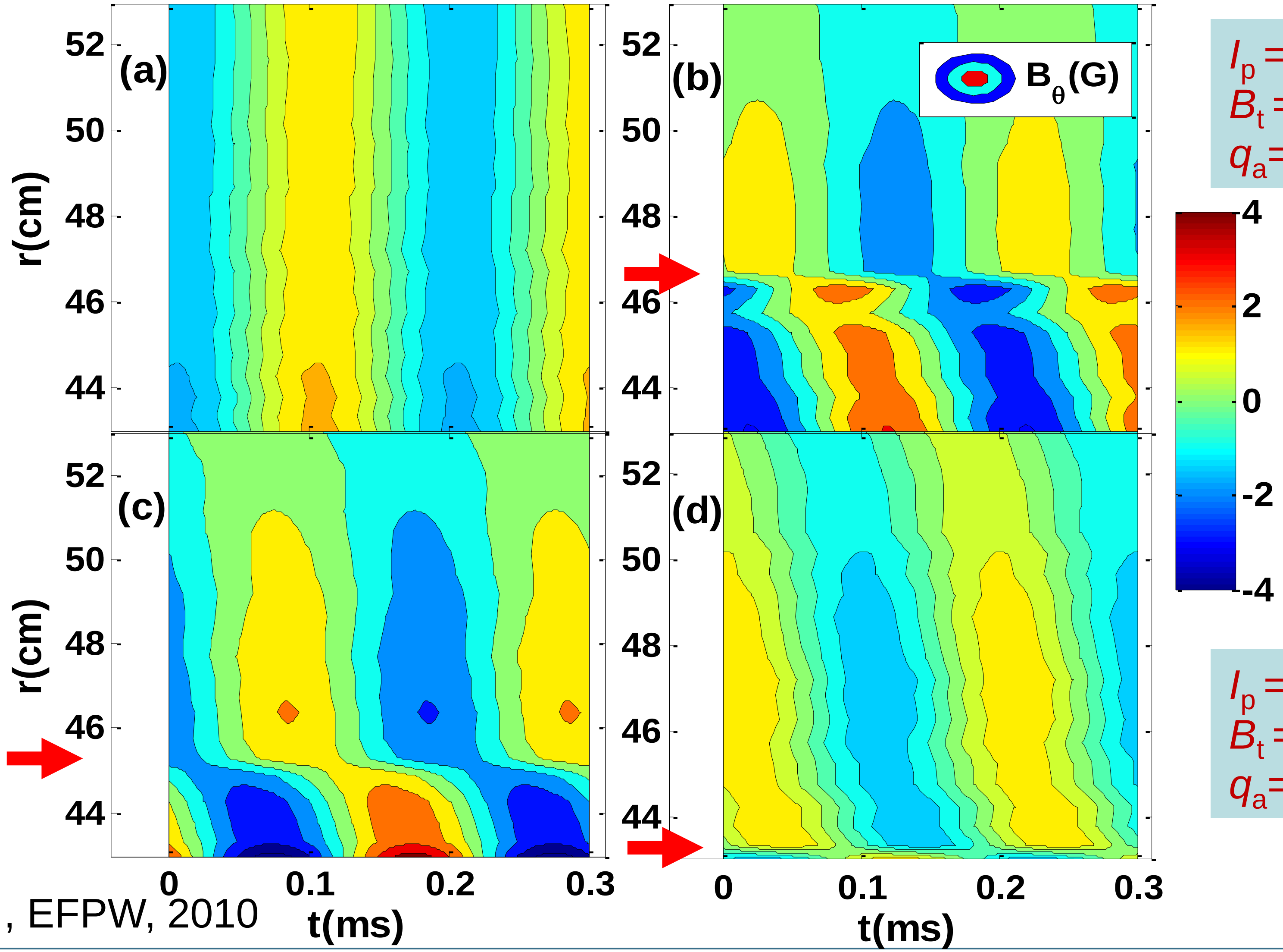
D. Reiser and M. Z. Tokar, Phys. Plasmas ***16****, 122303 2009*

Edge safety factor (q_a) dependence of plasma response to m/n=3/1 DED field

f_{DED}=5kHz   Co-current direction

TEXTOR #113871/86/91

Vacuum



I_p = 300kA;
B_t = 1.6T;
q_a= 3.4

I_p = 290kA;
B_t = 1.6T;
q_a= 3.5

I_p = 250kA;
B_t = 1.6T;
q_a= 3.9

Y. Liang et al., EFPW, 2010

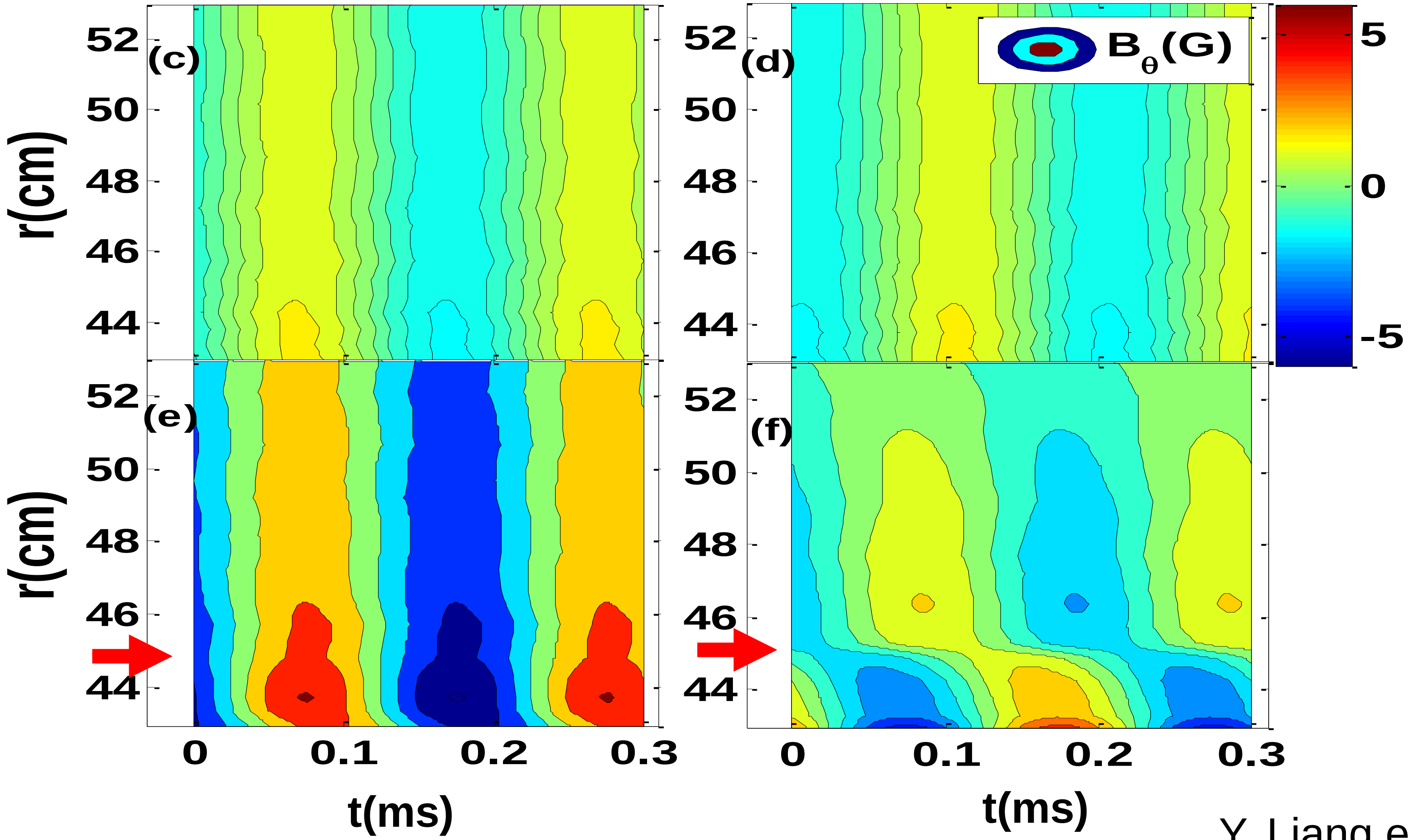
Field rotation direction dependence of plasma response to m/n=3/1 DED field (II)

ctr-current direction

co-current direction

I_p=250kA; B_t=1.6T;
q_a=4.; n_e=1.0x10^{19}m^{-3};

TEXTOR #113869/70/90/91
(c):113869; (d):113870; (e):113890; (f): 113891

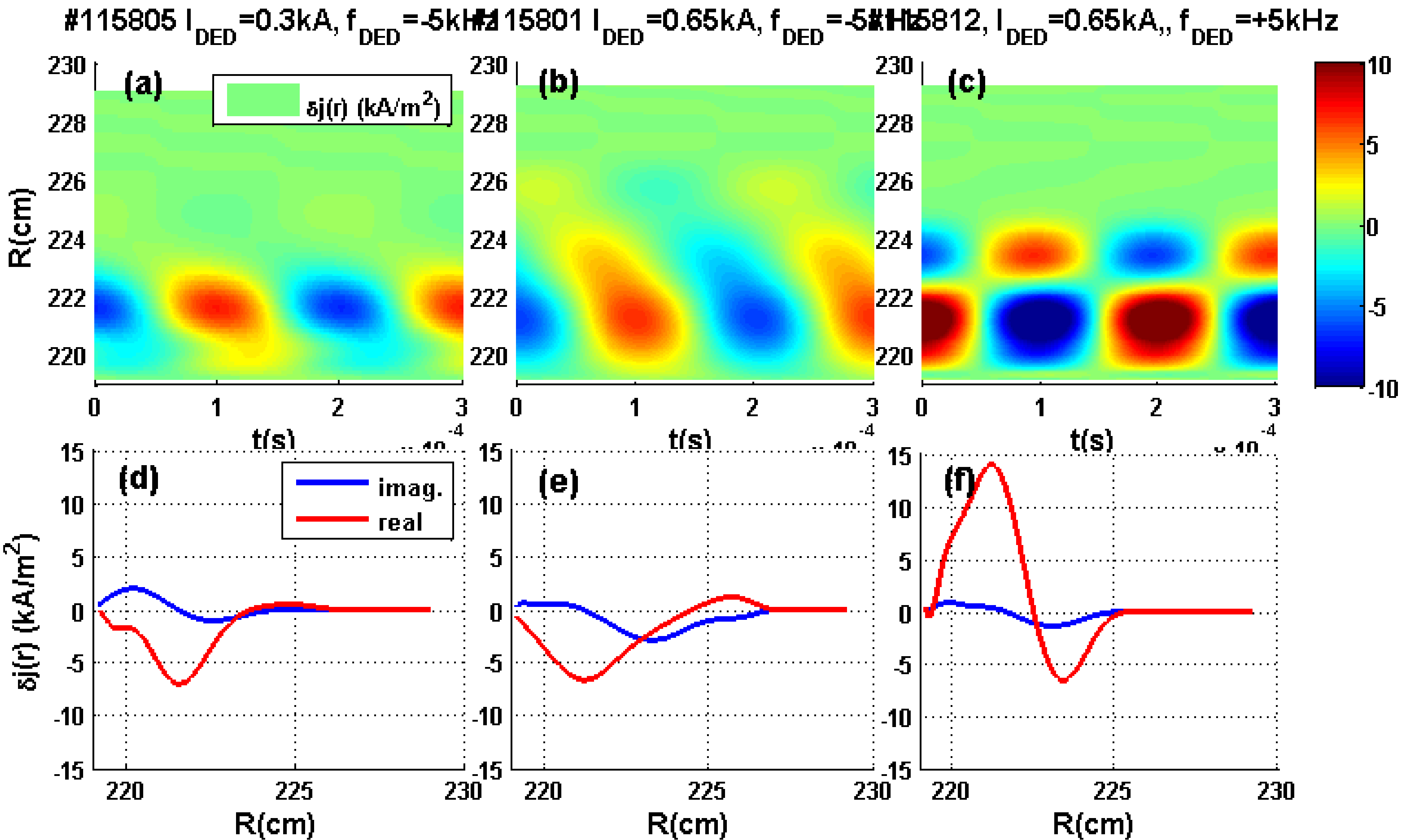


Vacuum

With Plasma

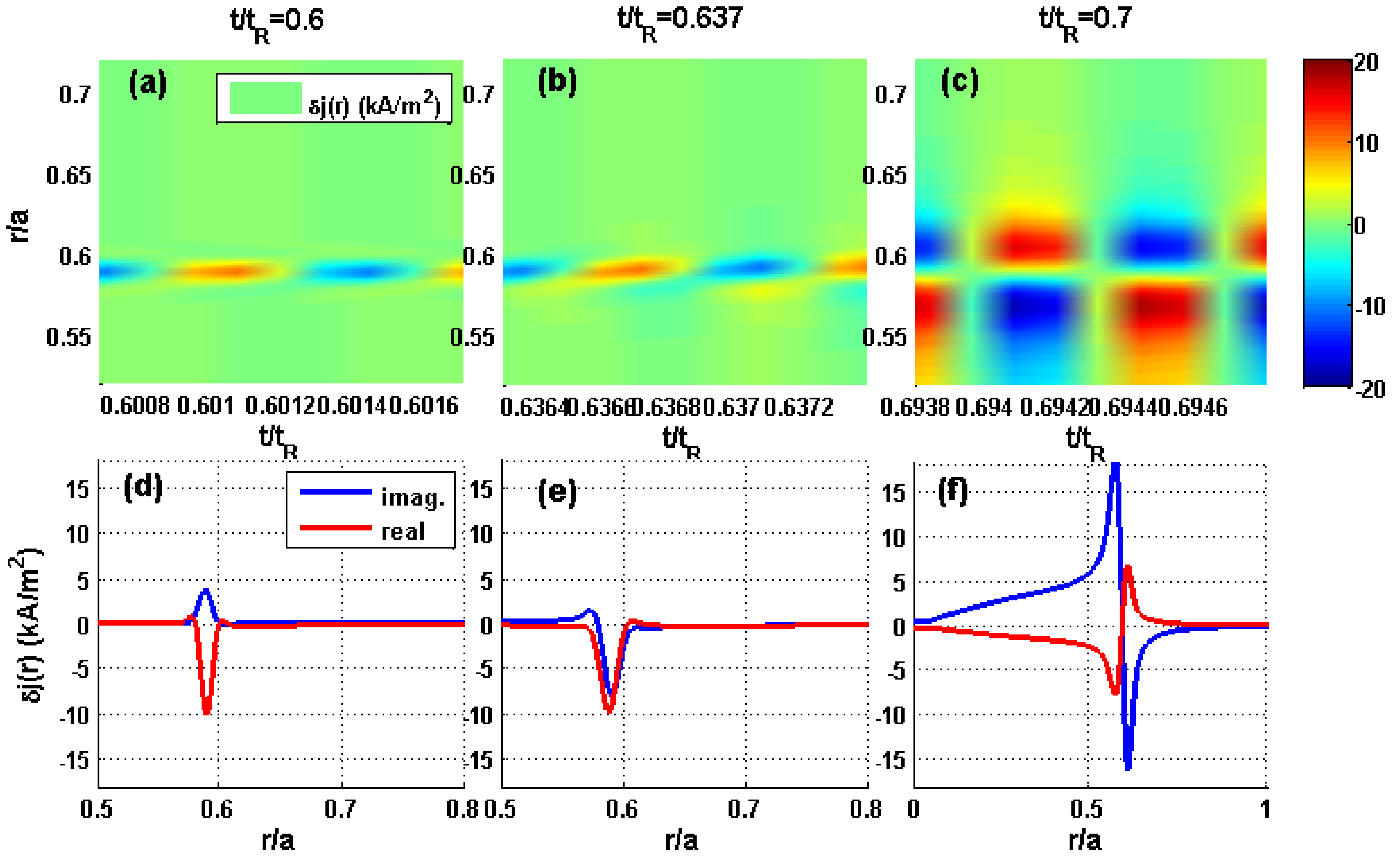
Y. Liang et al., EFPW, 2010

Measurement of surface currents during field penetration process



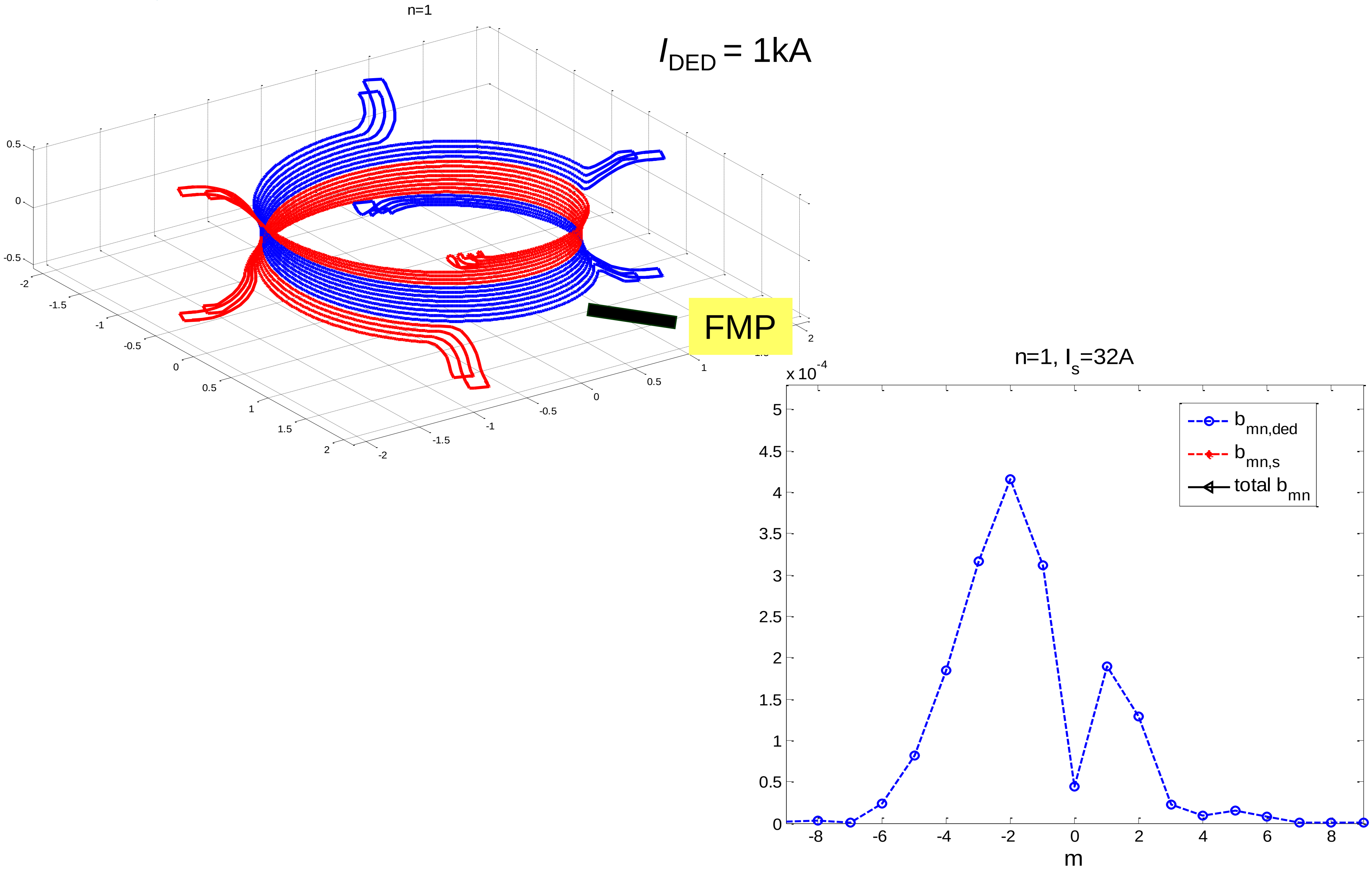
Y. Liang, et al., to be submitted to PRL, 2013

Modelling of Field Penetration Process



Y. Liang, et al., to be submitted to PRL, 2013

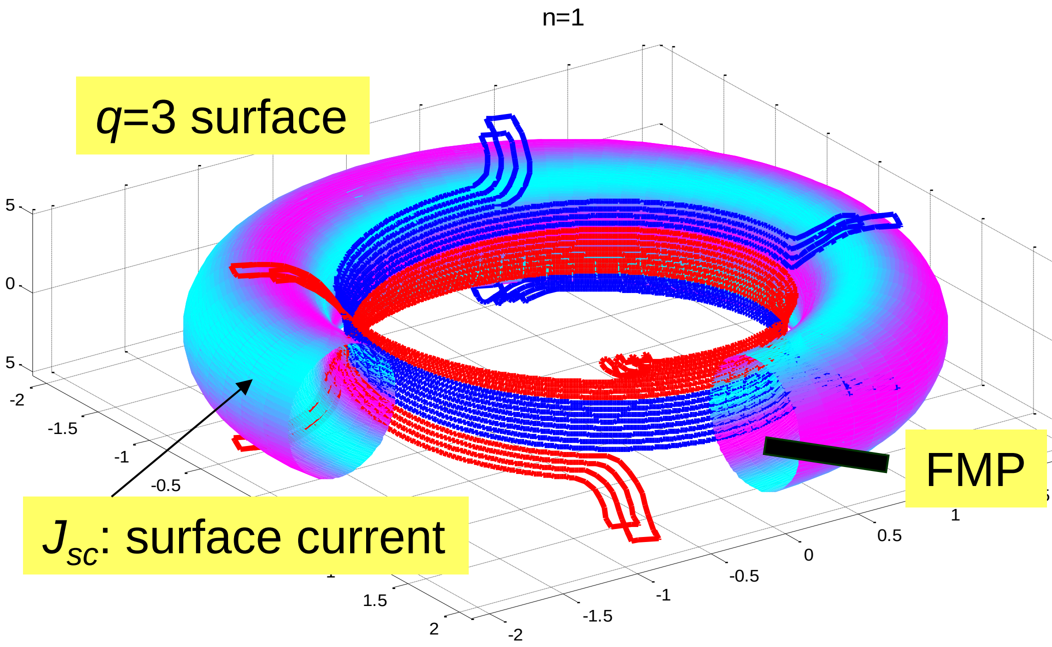
Modelling of pick-up from m/n=3/1 DED field



I_{DED} = 1kA

FMP

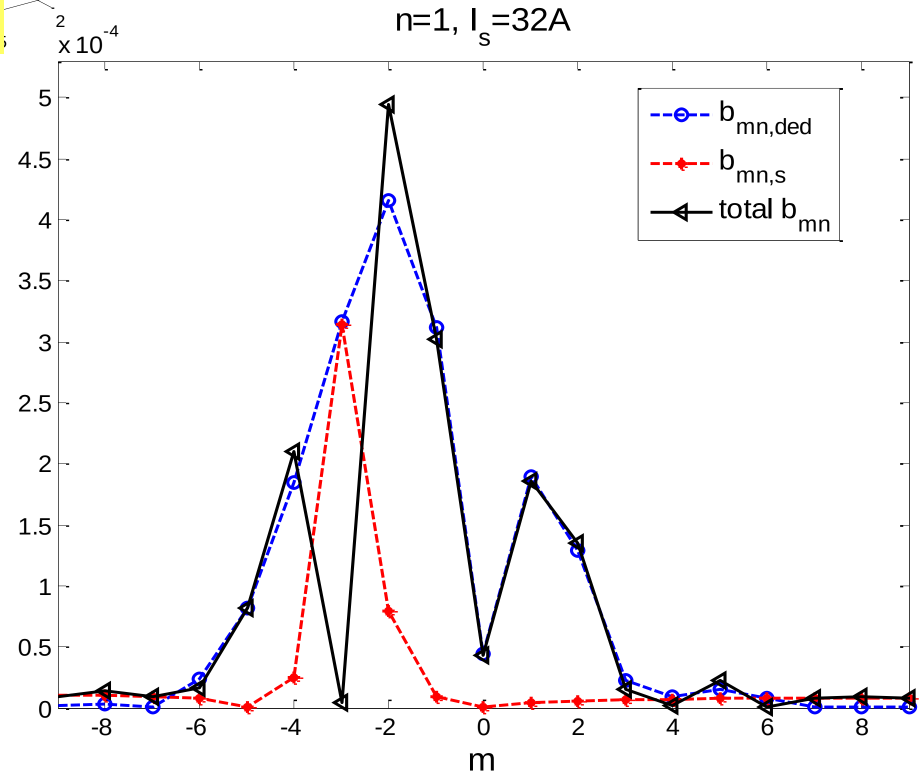
Modelling of the Surface Current



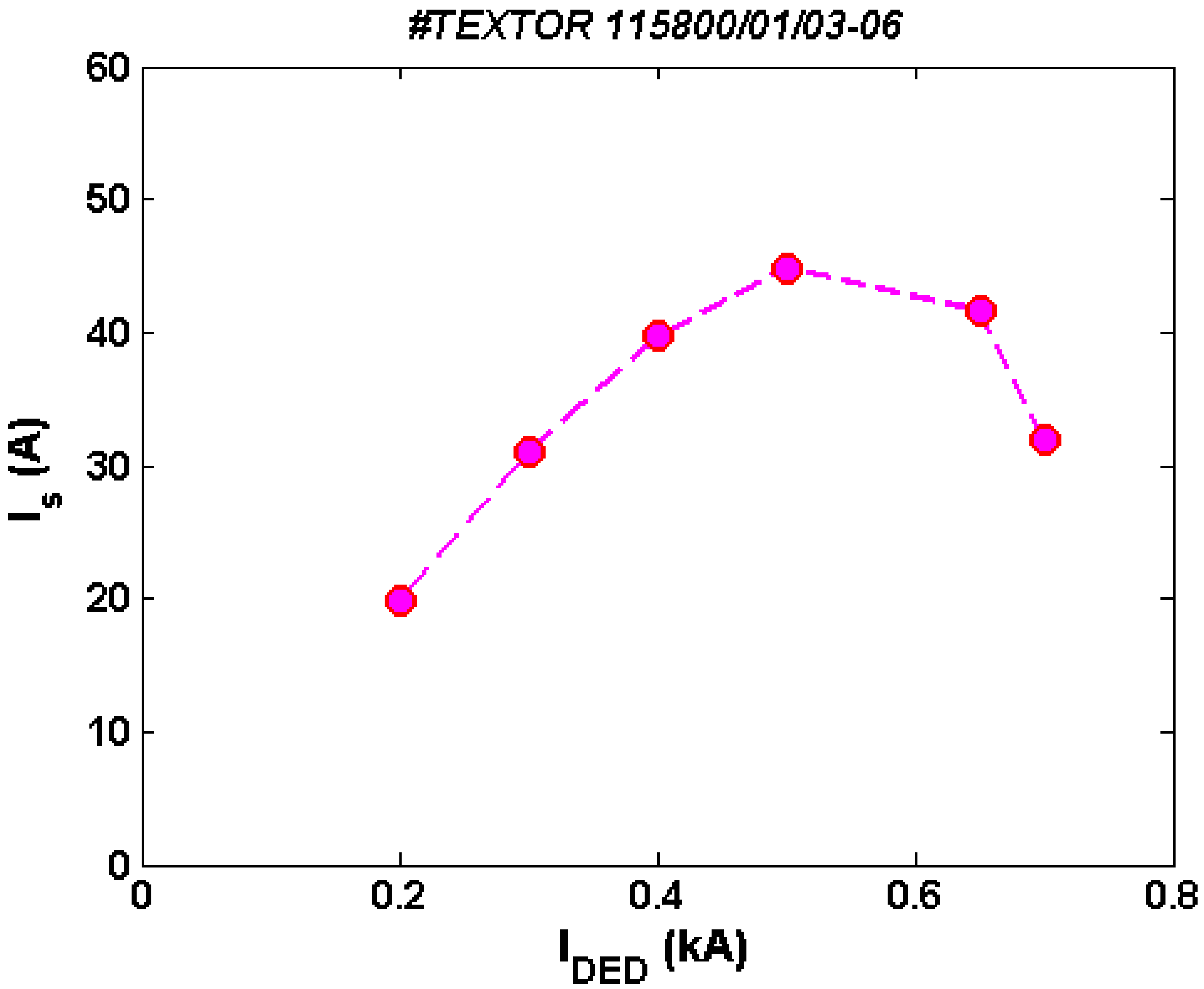
q=3 surface

J_{sc}: surface current

FMP



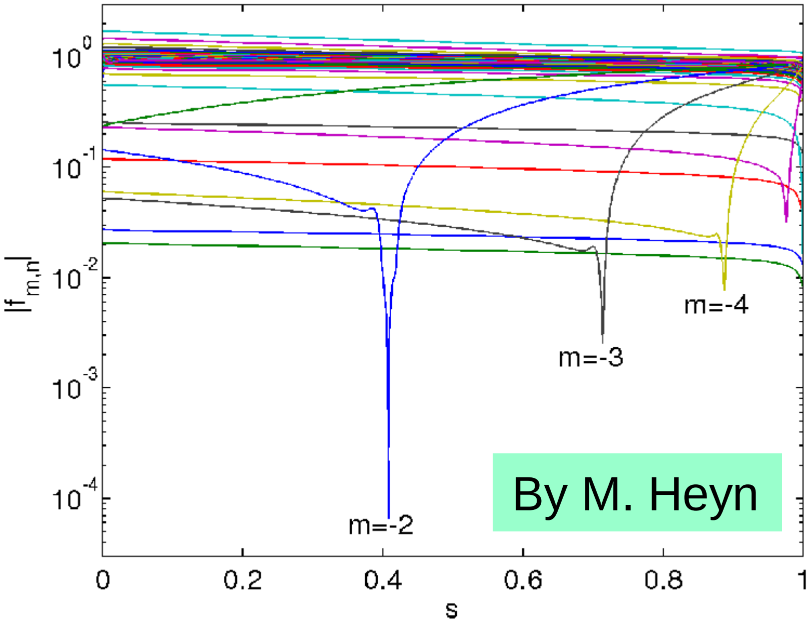
Screening Current vs I_{DED}

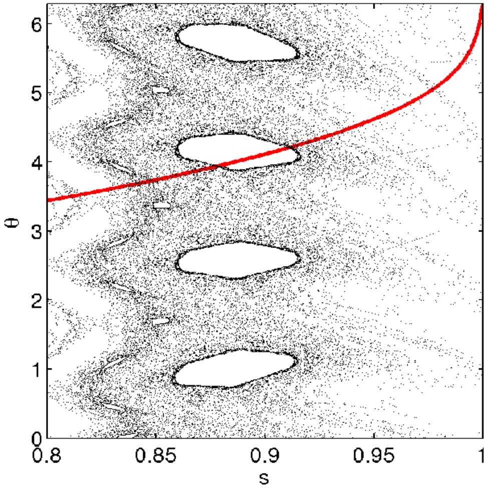


Y. Liang, et al., to be submitted to PRL, 2012

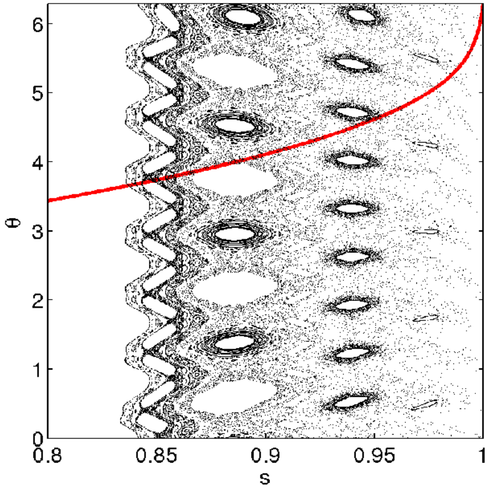
Effect of Plasma Shielding of the RMP

$$f_{mn} = B_{r,mn}^{(\text{plas})} / B_{r,mn}^{(\text{vac})}$$

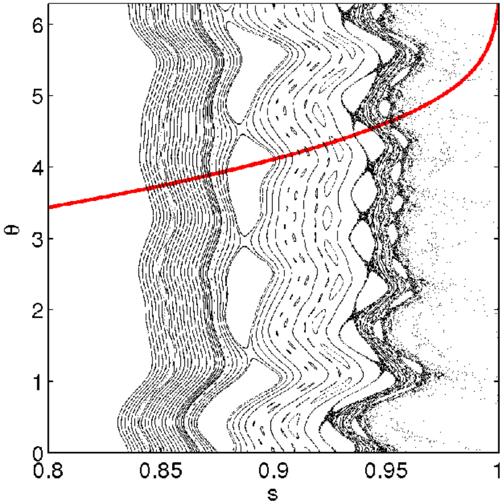




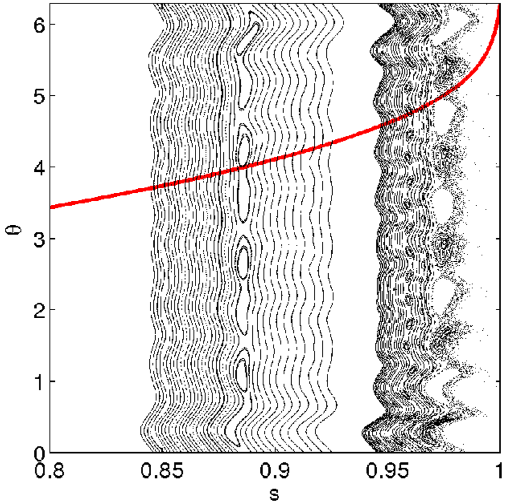
vacuum, $n = 1$



vacuum, $n = 2$



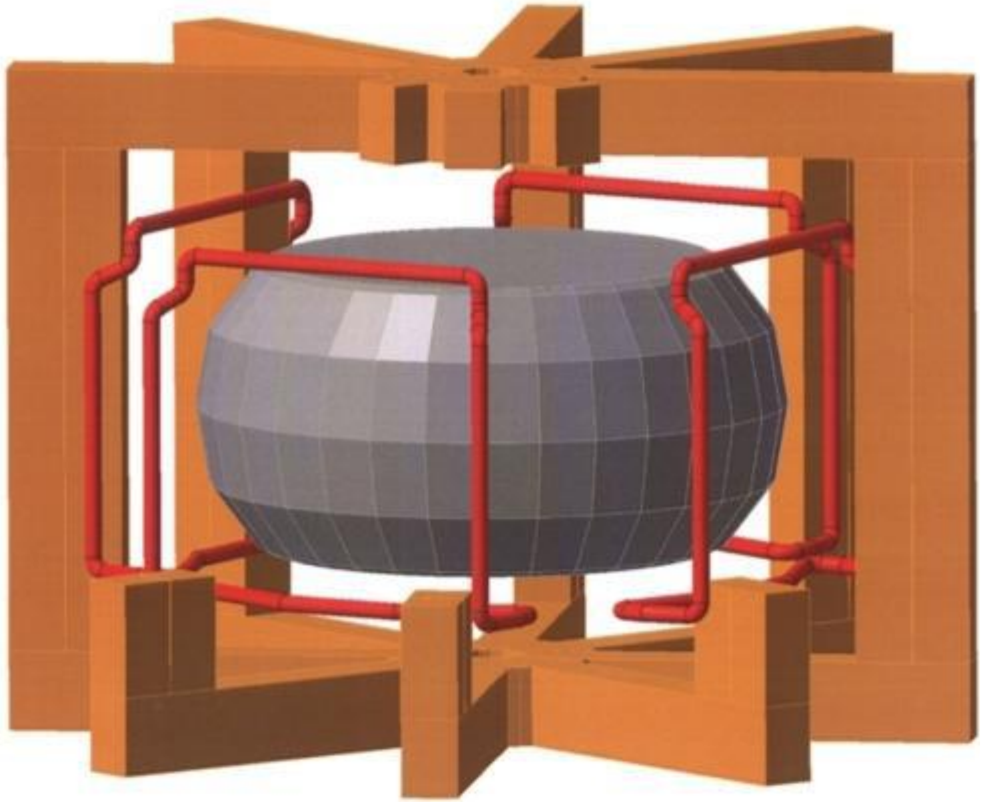
plasma, $n = 1$

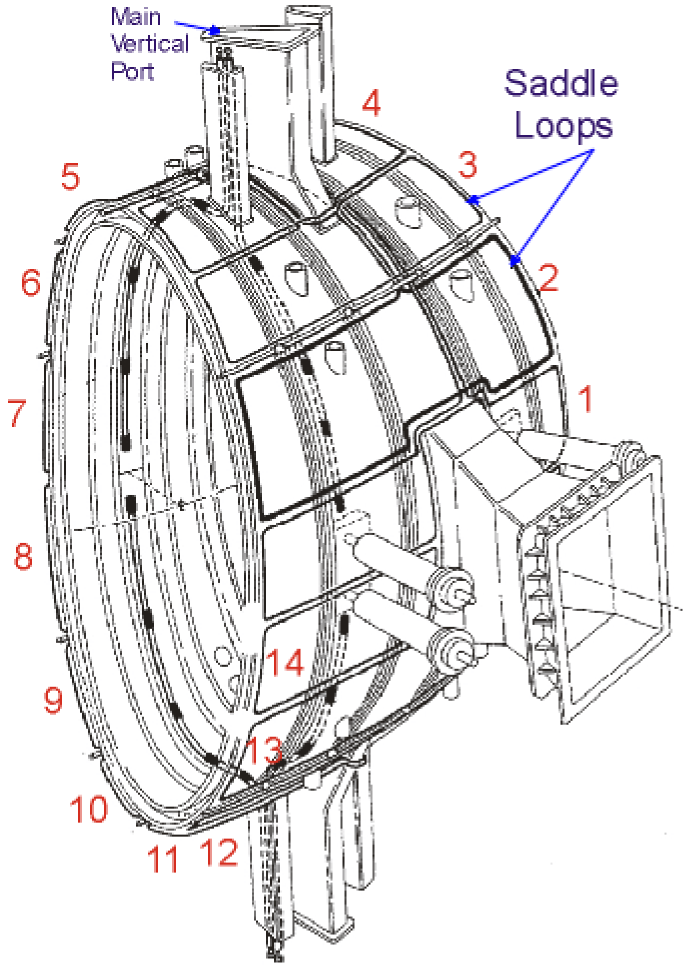


plasma, $n = 2$

The resonant perturbation is shielded due to plasma rotation and the magnetic field topology in the plasma core is not affected by RMP's.

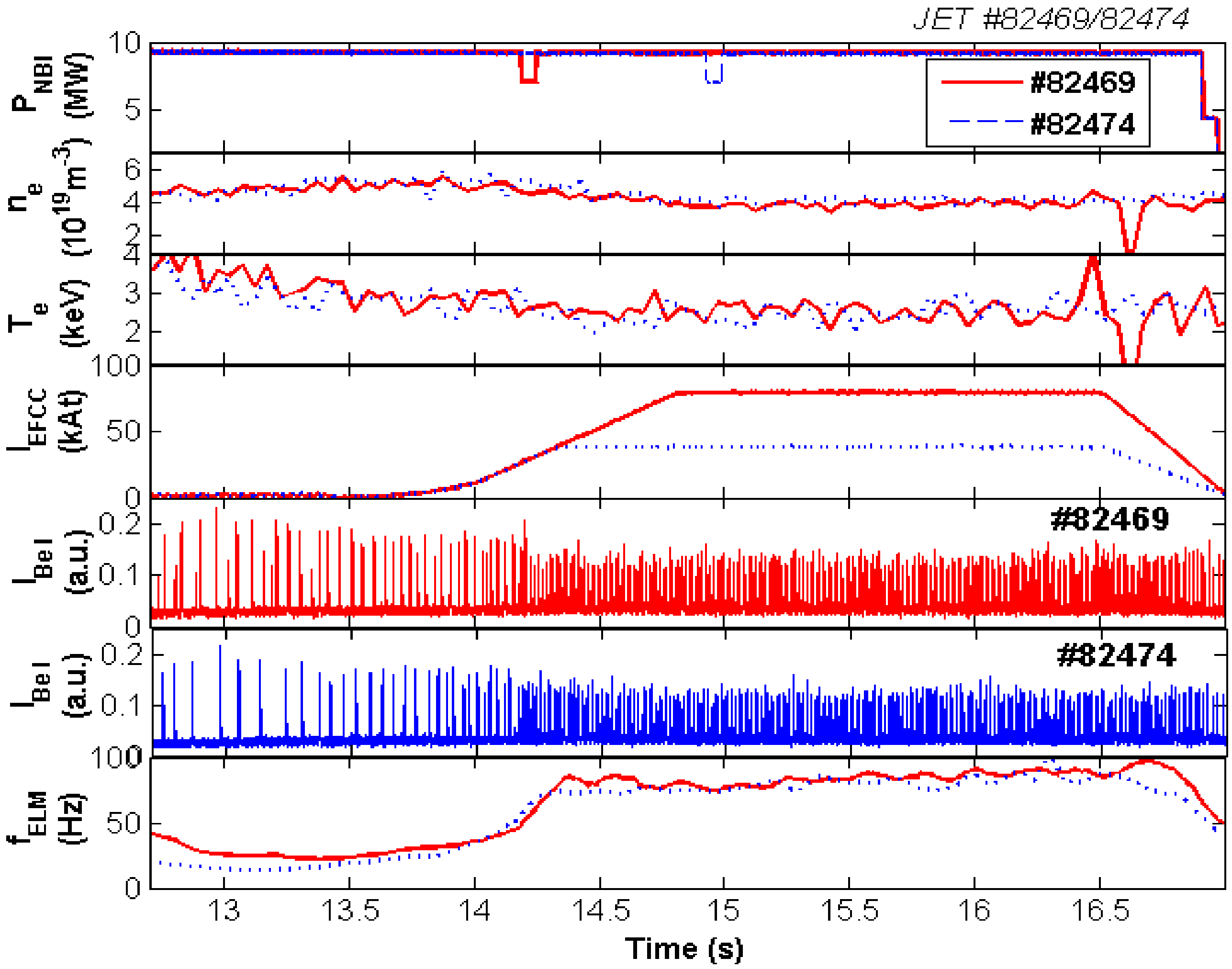
EFCC and Saddle Loops on JET





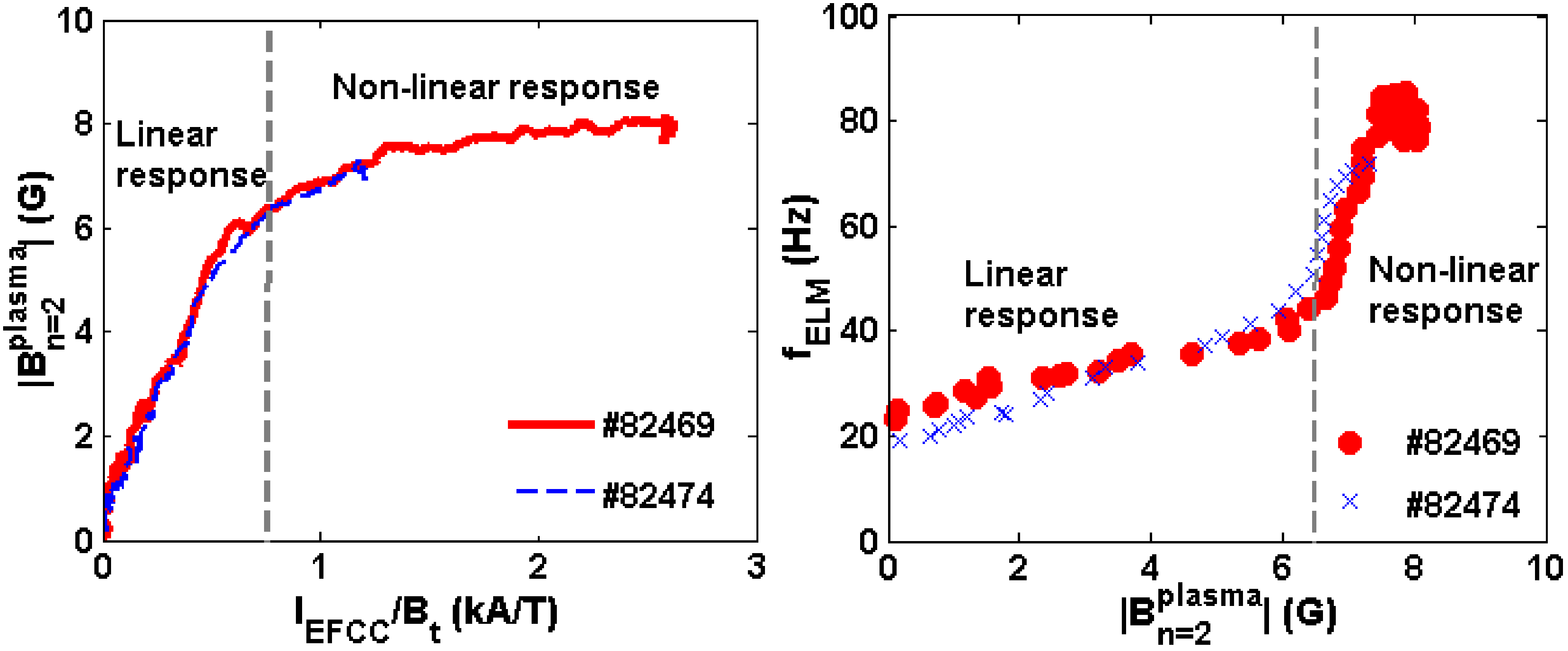
On JET, 14 saddle loops are fitted to the external wall of the each octant of the vacuum vessel and cover basically the whole surface area of the vessel

ELM Mitigation with $n = 2$ Field in Low Collisionality Plasmas on JET with the ILW



- B_t=1.85T; I_p=1.4MA
- There is a threshold of I_{EFCC} for ELM mitigation
- f_{ELM} increases from 20Hz to 80Hz when I_{EFCC}>2.4 kA.
- No further increase f_{ELM} even increasing I_{EFCC} further up to 5.0 kA.

f_{ELM} vs plasma response to n=2 field



f_{ELM} does not change once the plasma response saturated.

Y. Liang, et al., IAEA, 2012

Outline

- Why ELM control is needed?
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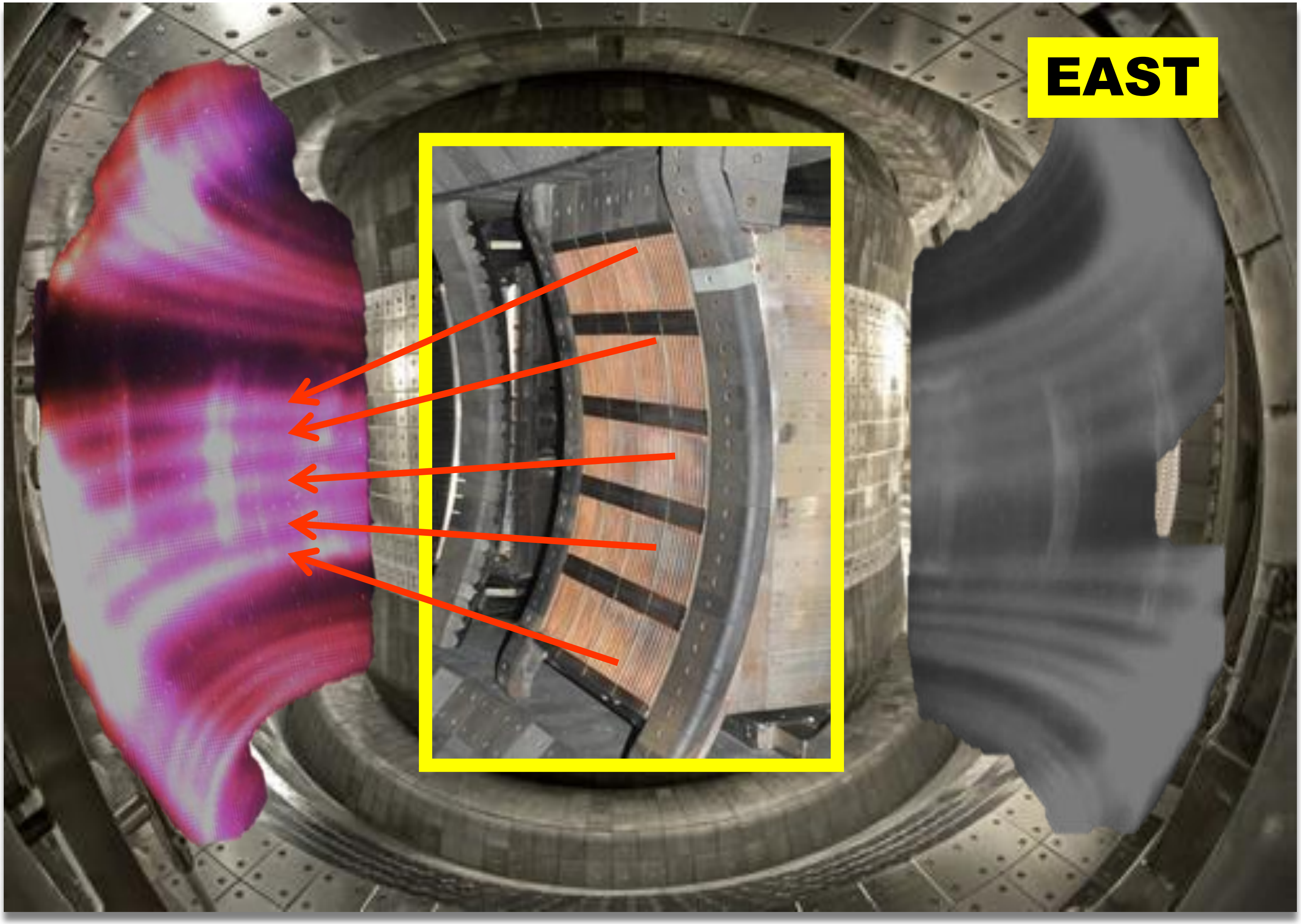
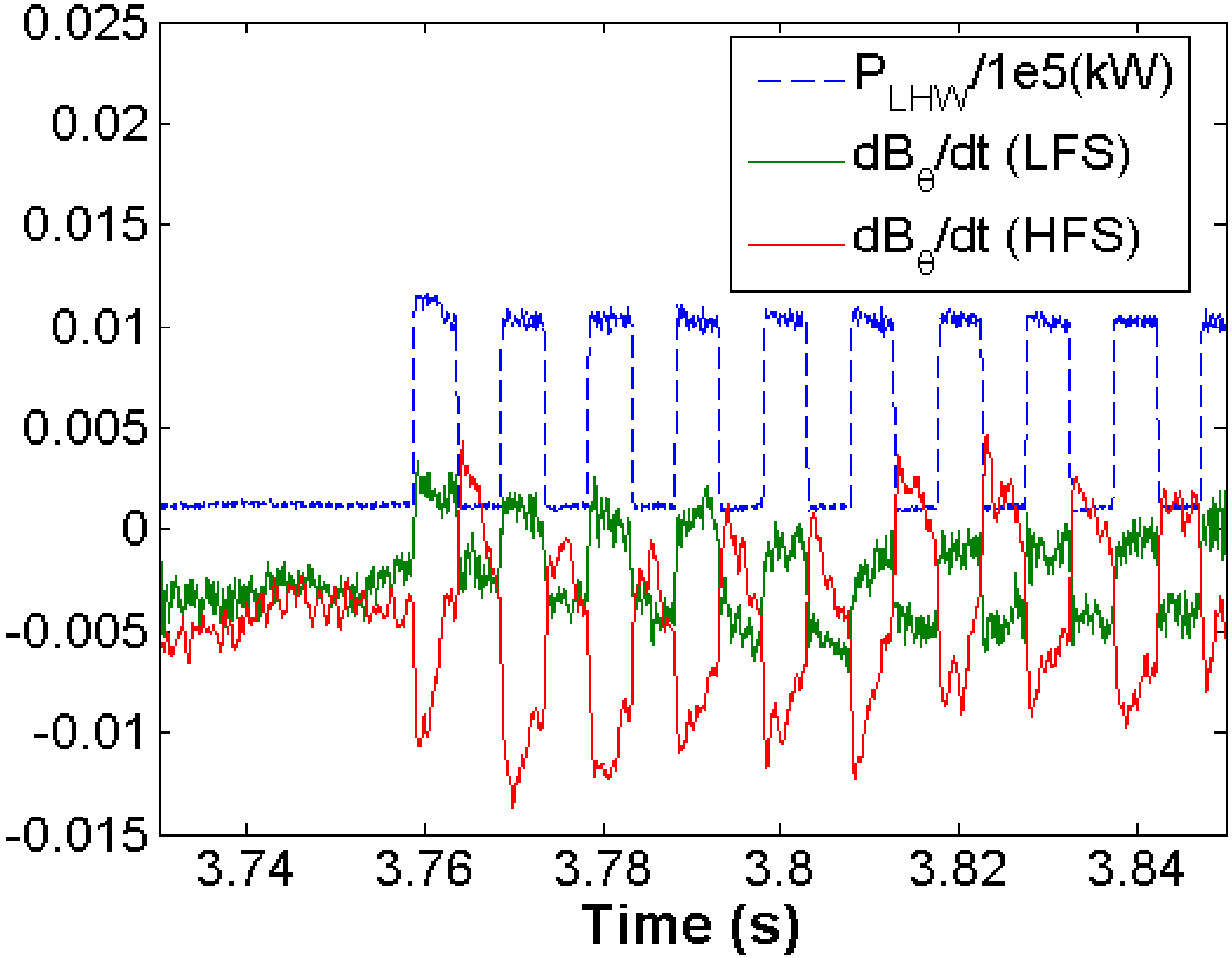
Heat flux and ELM control with LHW



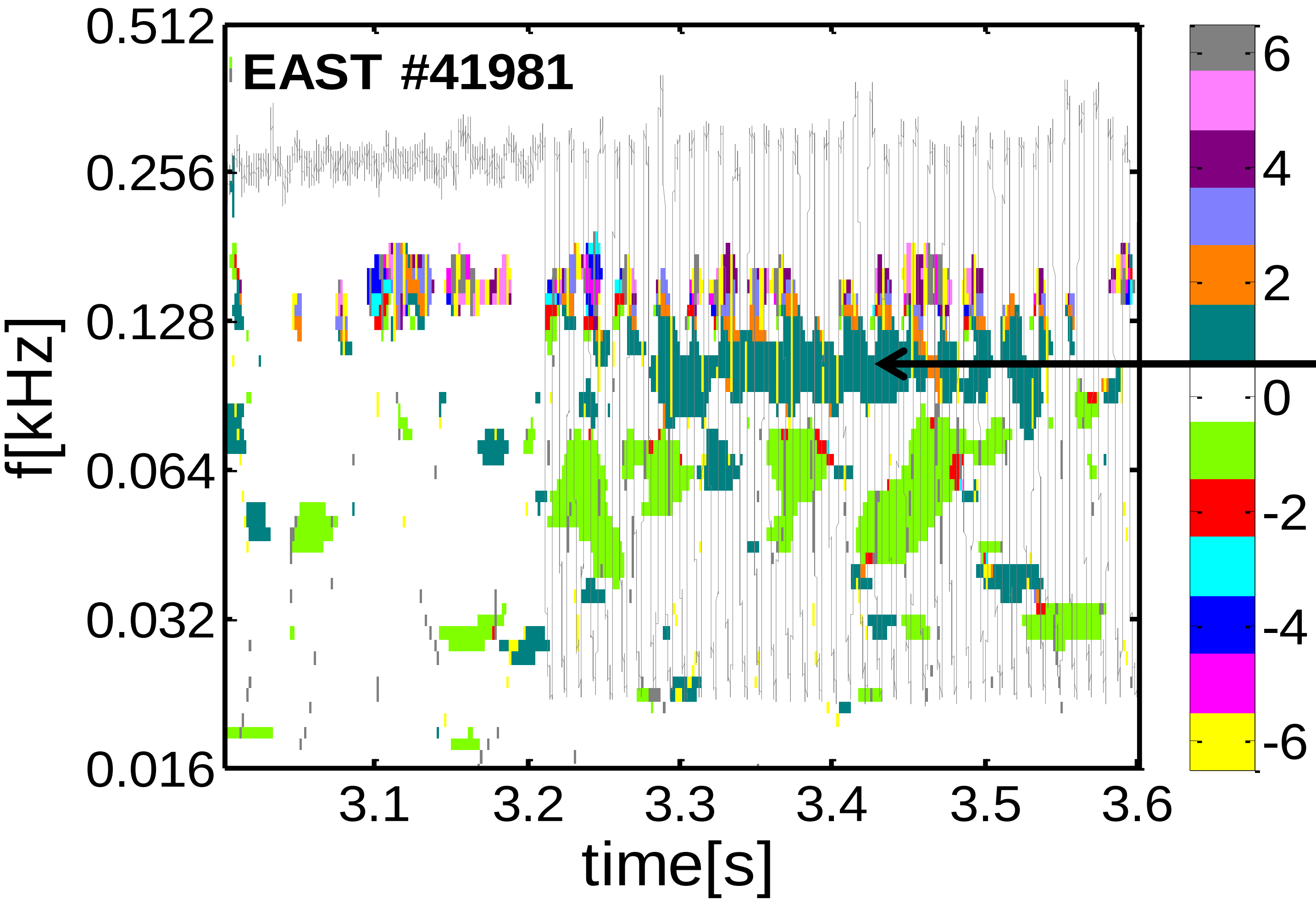
Y. Liang, et al., IAEA, 2012

Helical Current Filaments (HCF_s) Induced by LHCD on EAST



Modulation of P_{LHCD}; f = 100 Hz; P_{LHCD} = 0-1.2 MW

Helical Current Filaments (HCF_s) Induced by LHCD on EAST



***LHW*-induced**

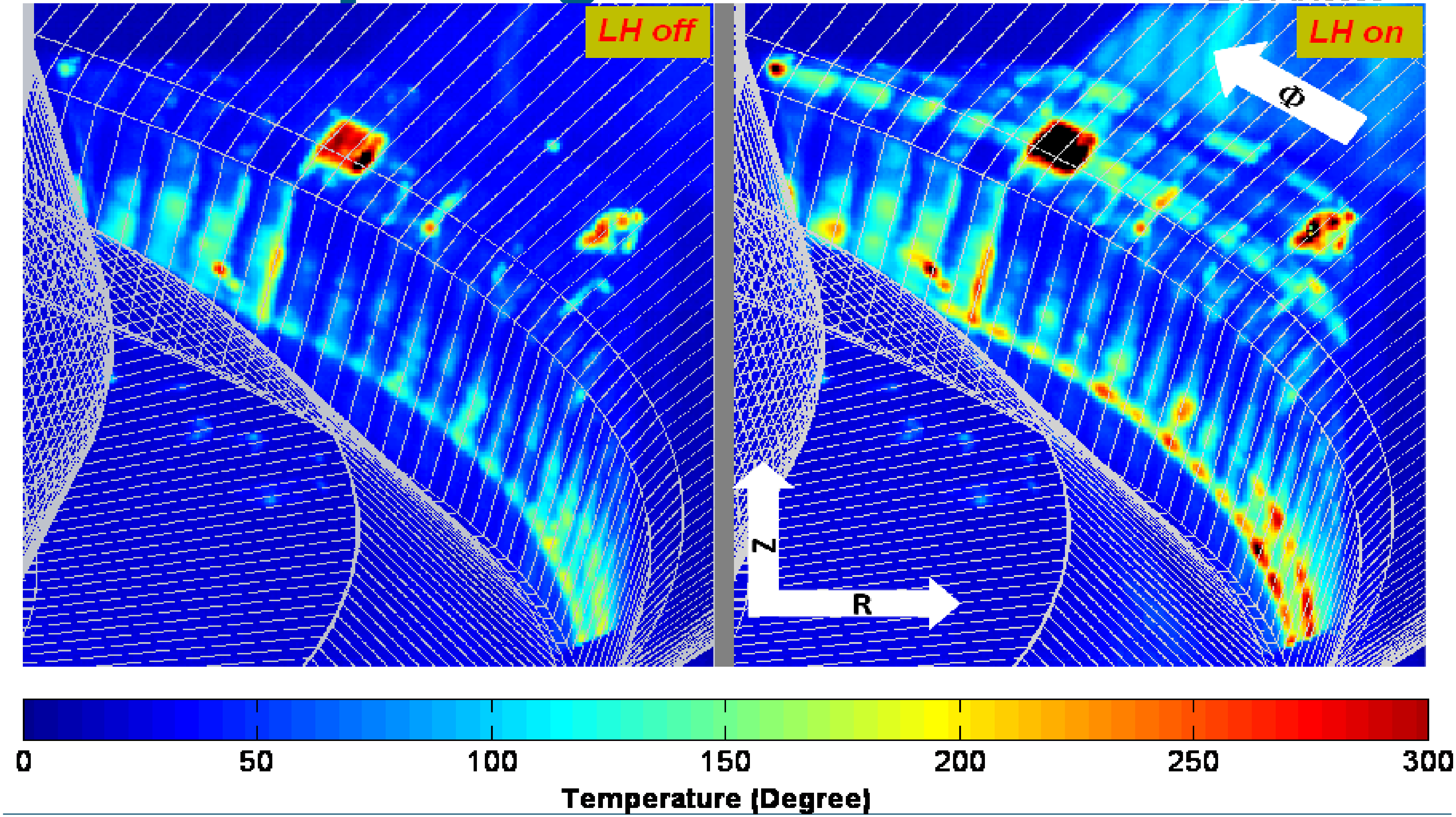
***n* = 1 Magnetic**

perturbation

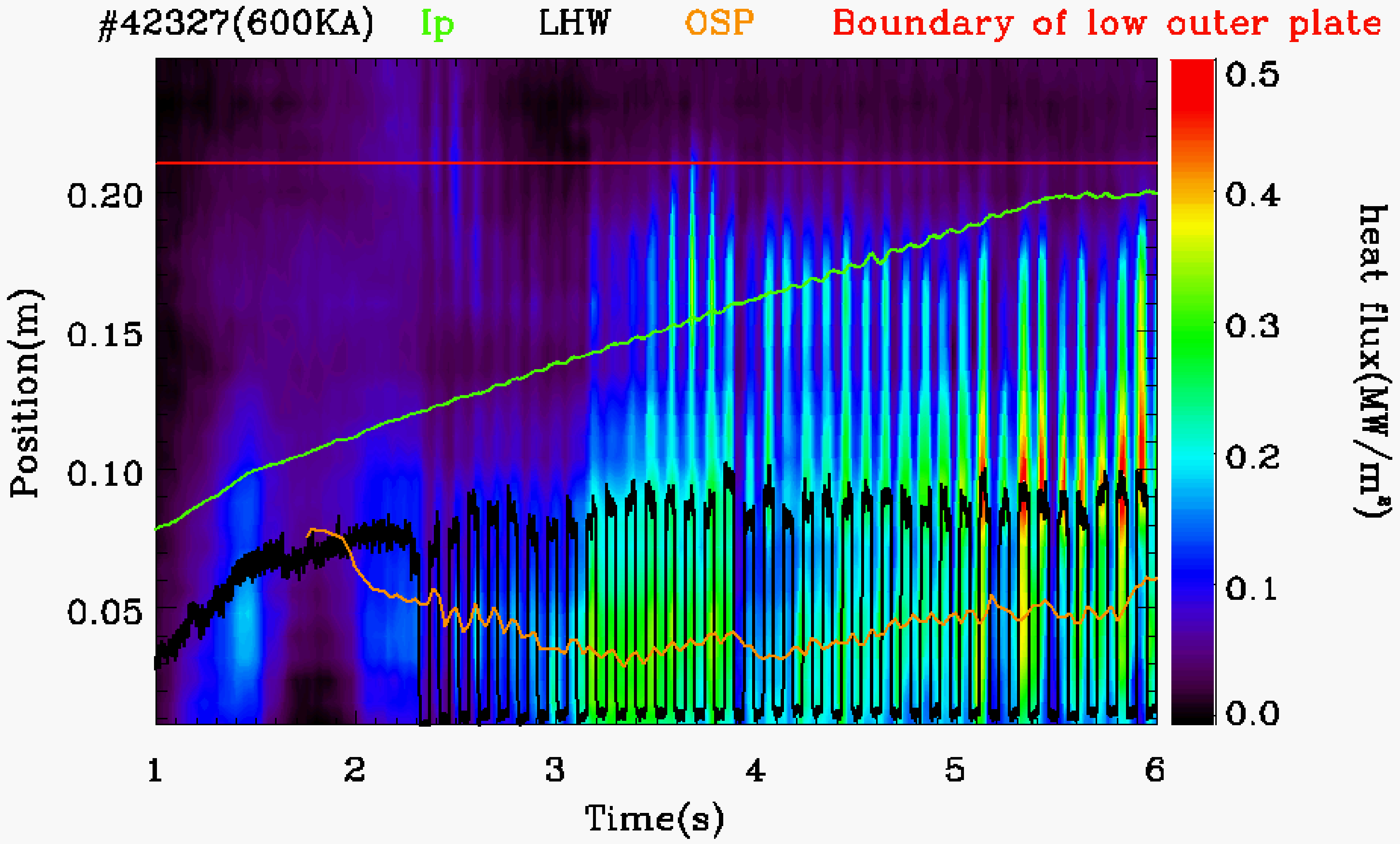
Modulation of P_{LHCD}; f = 100 Hz; P_{LHCD} = 0-1.2 MW

LHW induced Footprint Structures: Splitting of Strike Points

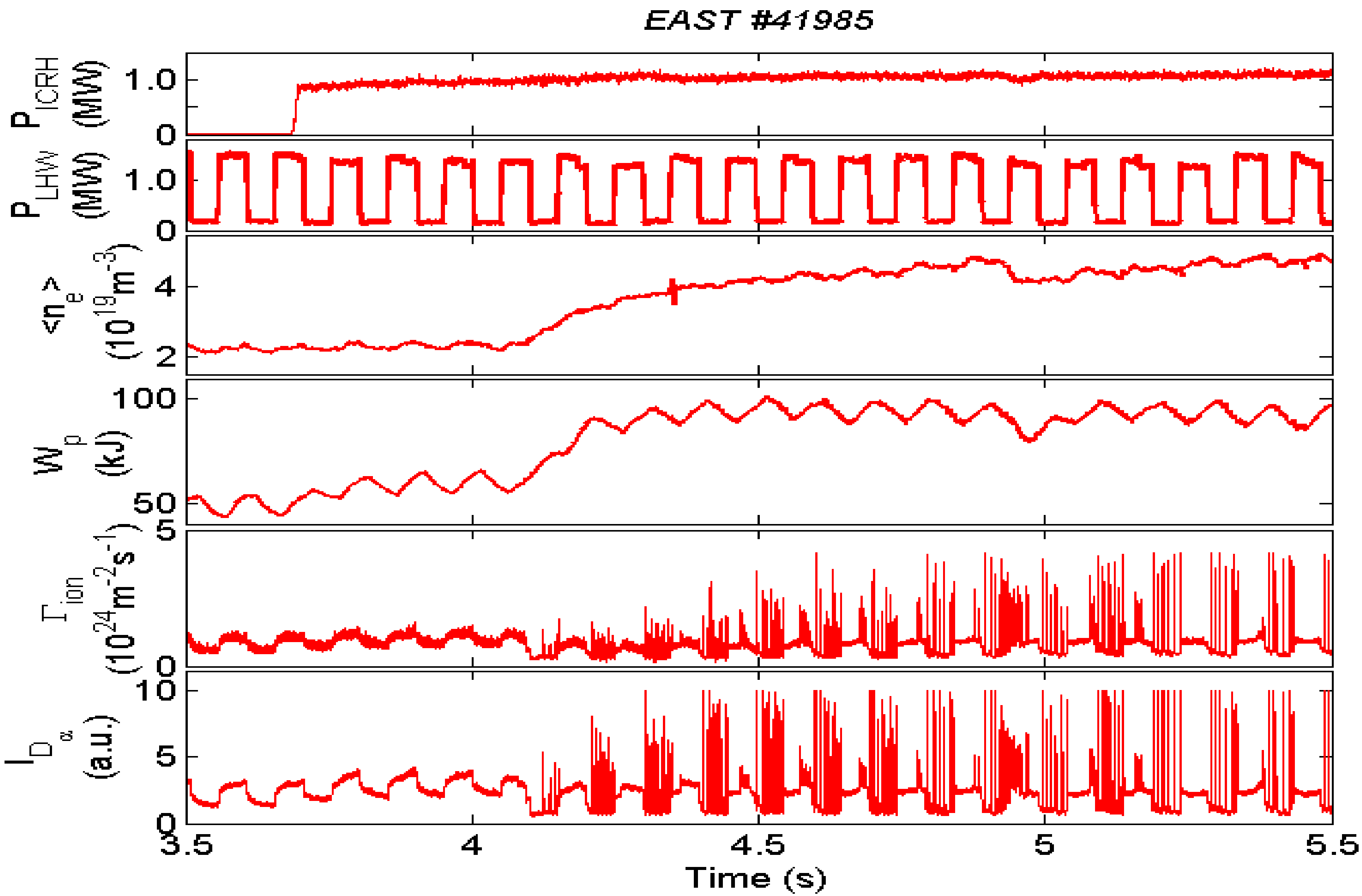
EAST #43380



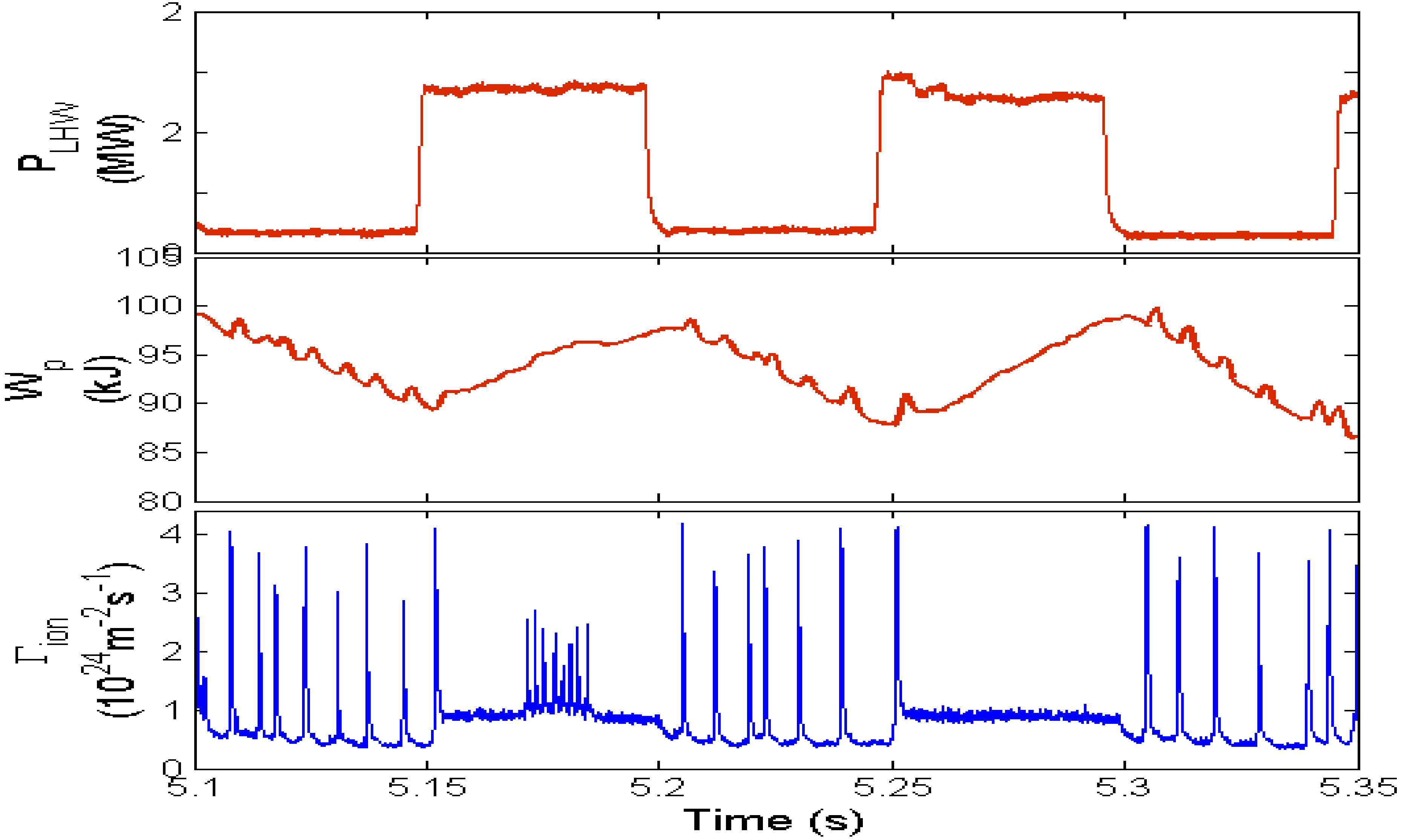
Footprint Structures: Edge Safety Factor Dependence



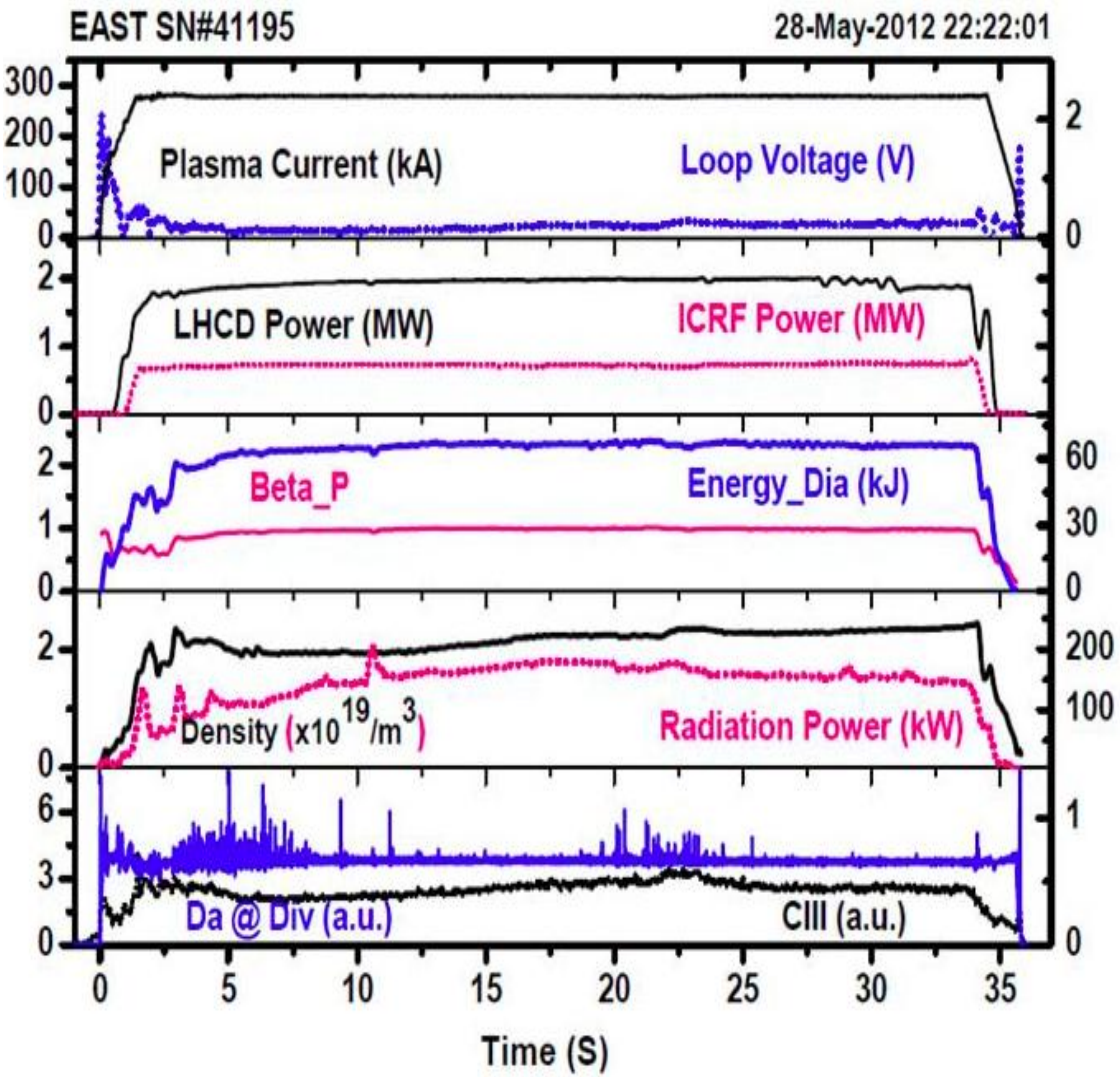
Influence of LHCD on ELMs



Influence of LHCD on ELMs



Over 30s H-mode Operation



- ❑ H-mode duration up to 32s with H98~0.9.
- ❑ Small ELMs with LHCD.
- ❑ Control density at ~2 x $10^{19}/m^3$ for LHCD.

Summary

- 3D magnetic perturbation has been widely applied for active control of edge transport and MHD instabilities.
- The plasma response may modify the applied RMP field substantially, possibly leading to elimination of magnetic islands and the edge stochastic region that the vacuum models predict.
- Further investigation of plasma responses to the RMP is needed for a reliable application of the RMP for plasma transport and stability control on future fusion devices, i.e. ITER.
- On EAST, LHW appears to induce a profound change in the edge magnetic topology and ELMs. It is important information for the on-going discussion of ITER LHW system.

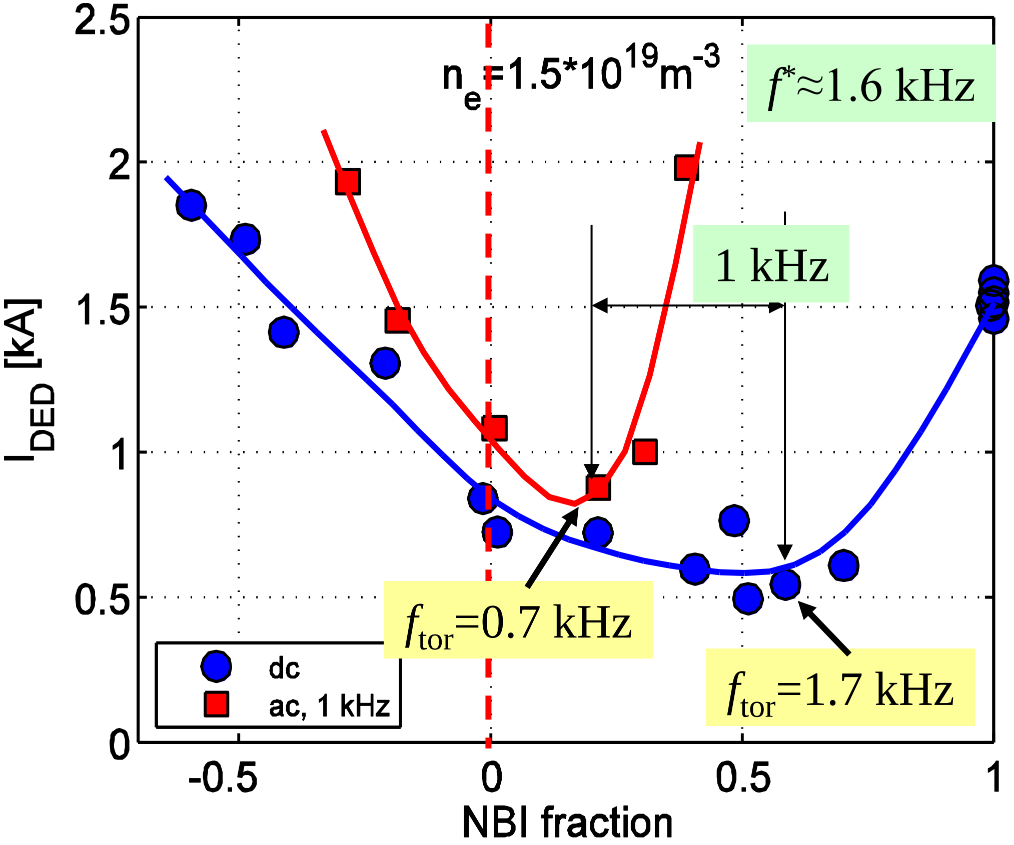
Rotation Dependence of Field Penetration in Core Plasma

Field penetration (formation of islands) in the core plasma is a well studied problem

(Fitzpatrick theory) $V_{\perp,e} = V_{ExB} + V^{*}_{e}$

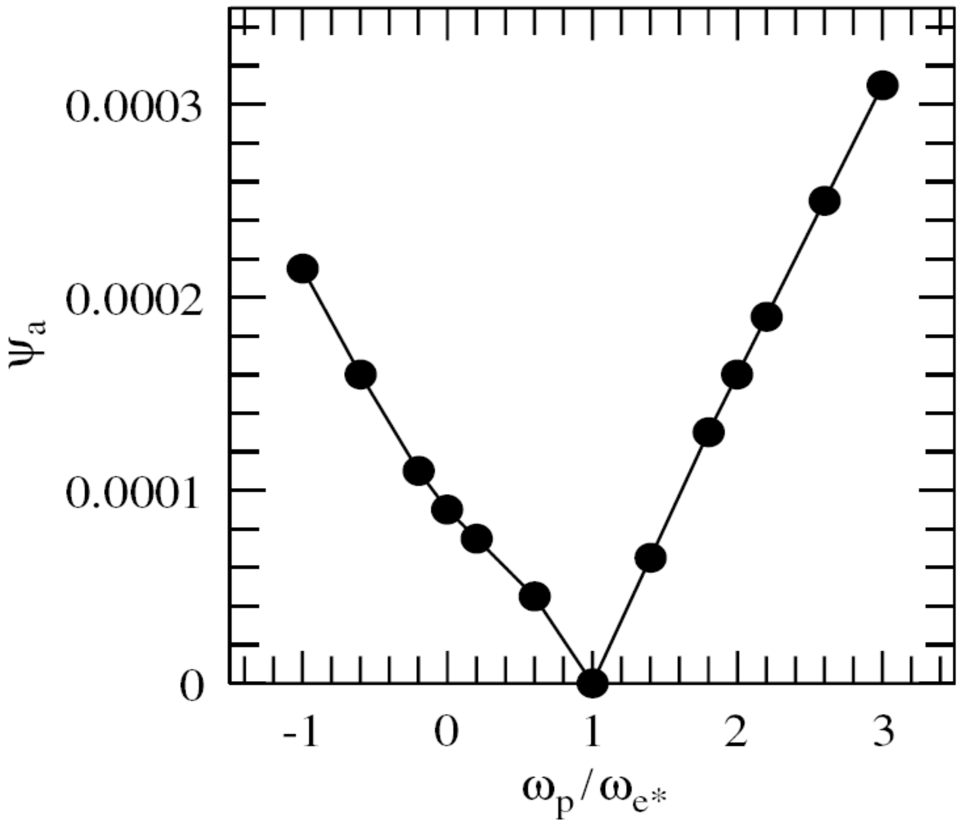
$f_{MHD} = f_{DED}$

TEXTOR Experiment



HR Koslowski, et al., Nucl. Fusion ***46*** *(2006) L1–L5*

Numerical nonlinear two fluids MHD Modeling



Q Yu, et al., Nucl. Fusion ***48*** *(2008) 024007*