ELM-crash-suppression using 3-D magnetic fields

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in appreciation of the contributions from
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and the 3D Physics experts in KSTAR
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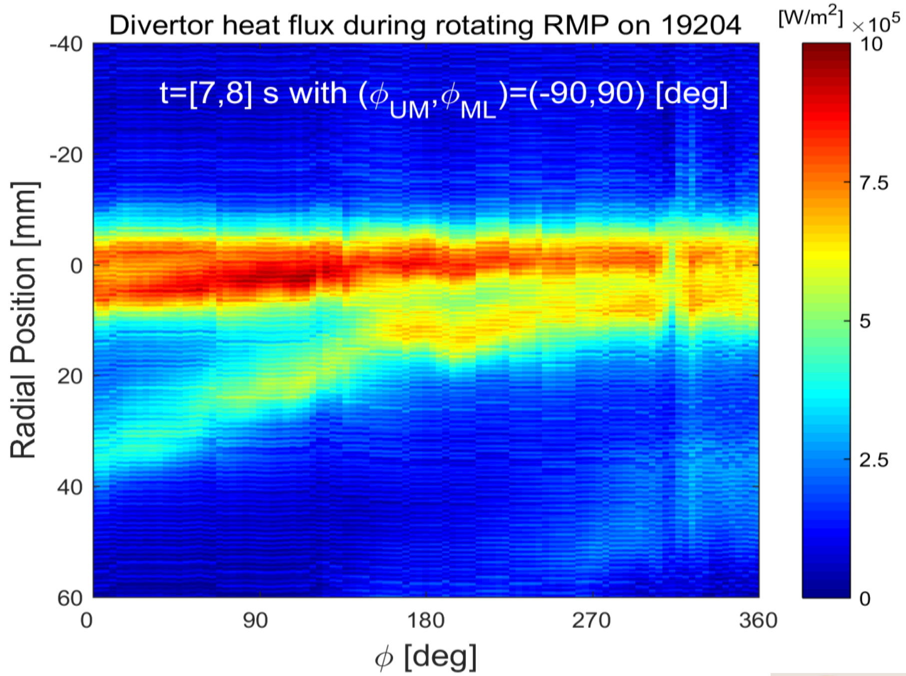
[3] Princeton Plasma Physics Laboratory, U.S.A.
[4] ITER Organization
[5] Oak Ridge National Laboratory, U.S.A.



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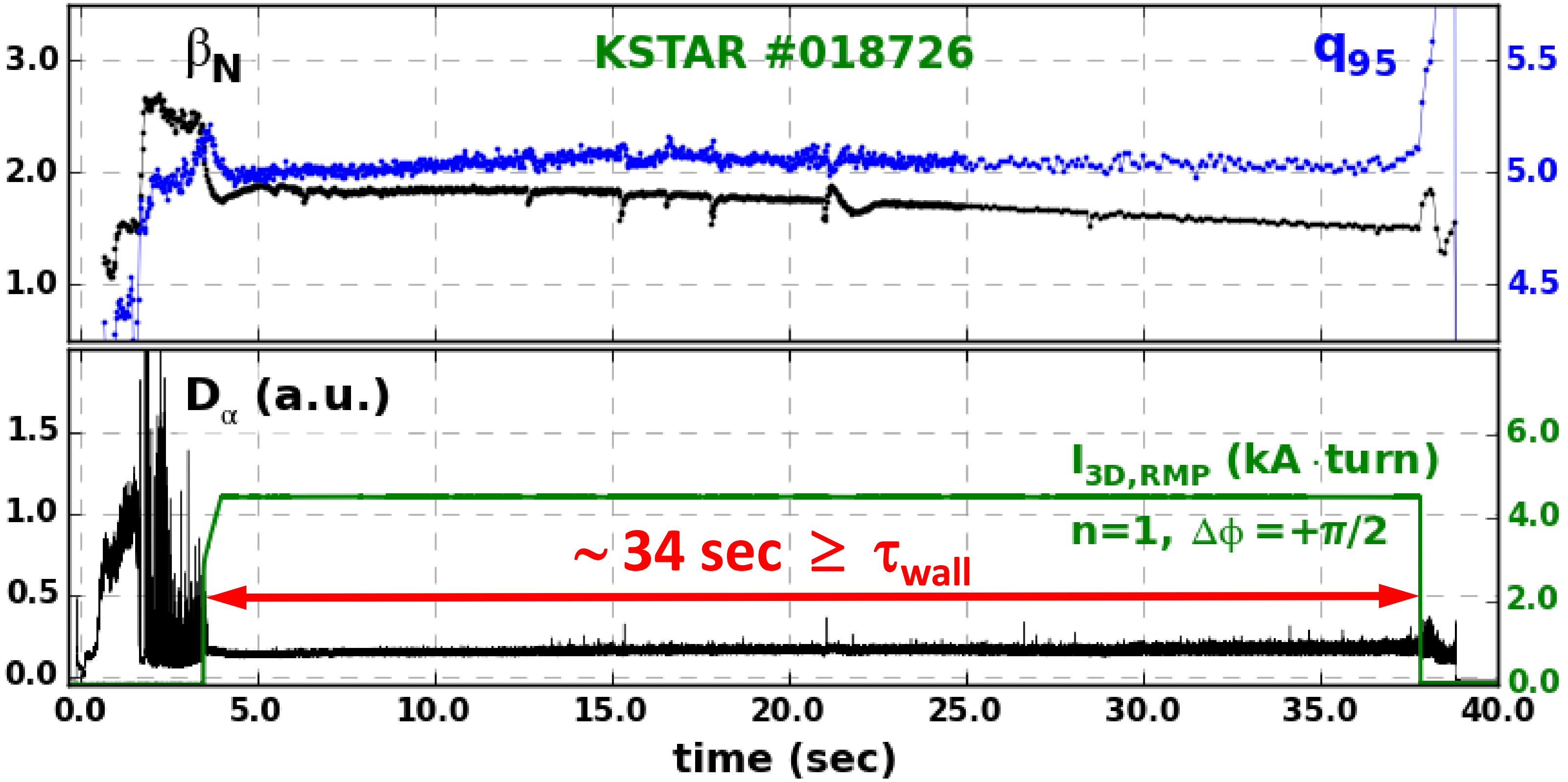
ITER Fusion School, January 21 - 25, 2019, Daejeon, Korea

Nearly stationary "H-mode with full ELM-crash-suppression" has been accomplished using RMP in KSTAR

As of 2017, the longest sustainment of RMP-driven ELM-crash-suppression !



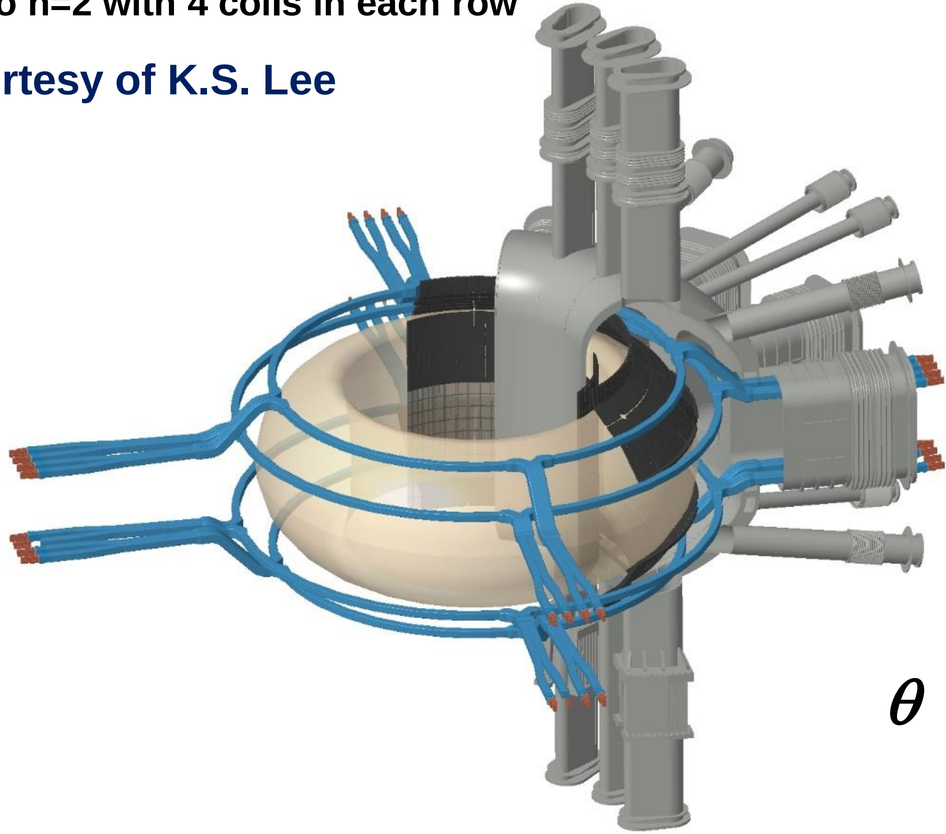
Elevating the confidence about the effectiveness of ITER RMP to be similarly configured to that of KSTAR

The 3-row in-vessel coils in KSTAR can be tailored to address ITER 3-D physics issues, including the assessment of mid-RMP coils

KSTAR In-vessel Control Coils (IVCC): Top/Mid/Bot

Up to n=2 with 4 coils in each row

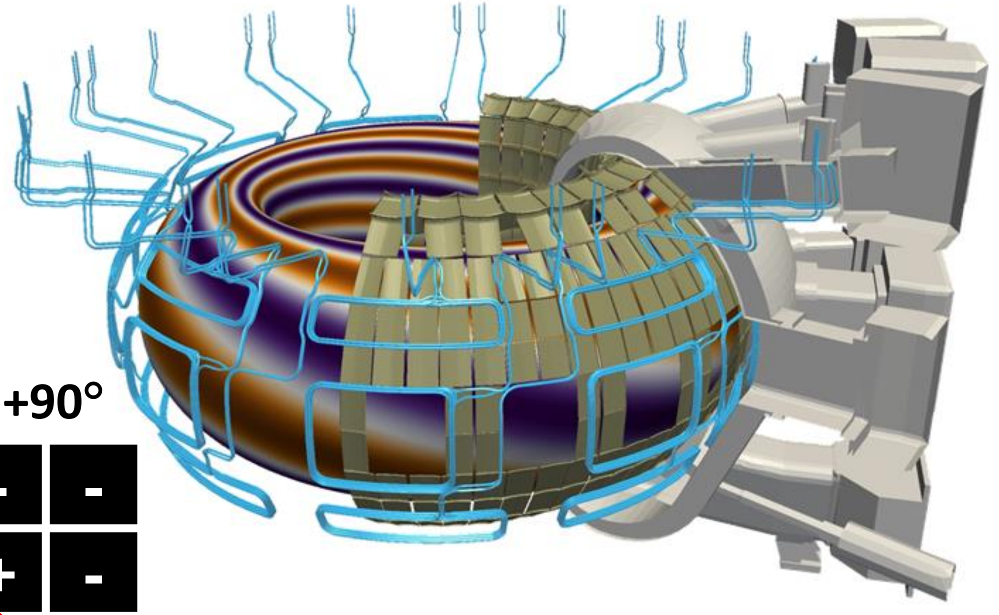
Courtesy of K.S. Lee



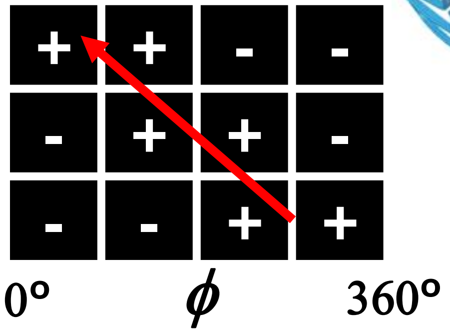
ITER RMP coils

Up to n=4 with 9 coils in each row

Courtesy of G.T.A. Huijsmans



n=1, $\Delta\phi = +90°$



+	+	-	-
-	+	+	-
-	-	+	+

Uniquely equipped with in-vessel mid-RMP coils

Contents

Introduction

Physics behind various ELM control methods

- **RMP**, **pellet pacing**

RMP-driven, ELM control

- What is RMP? Stochasticity; vacuum and plasma response;
- Decoupling core mode-locking and edge RMP
- Prevailing understanding of physics mechanism

(Parameters: q_{95}, ν^*, δB-spectra, shape-dependence)

Divertor heat flux during ELM-controlled periods

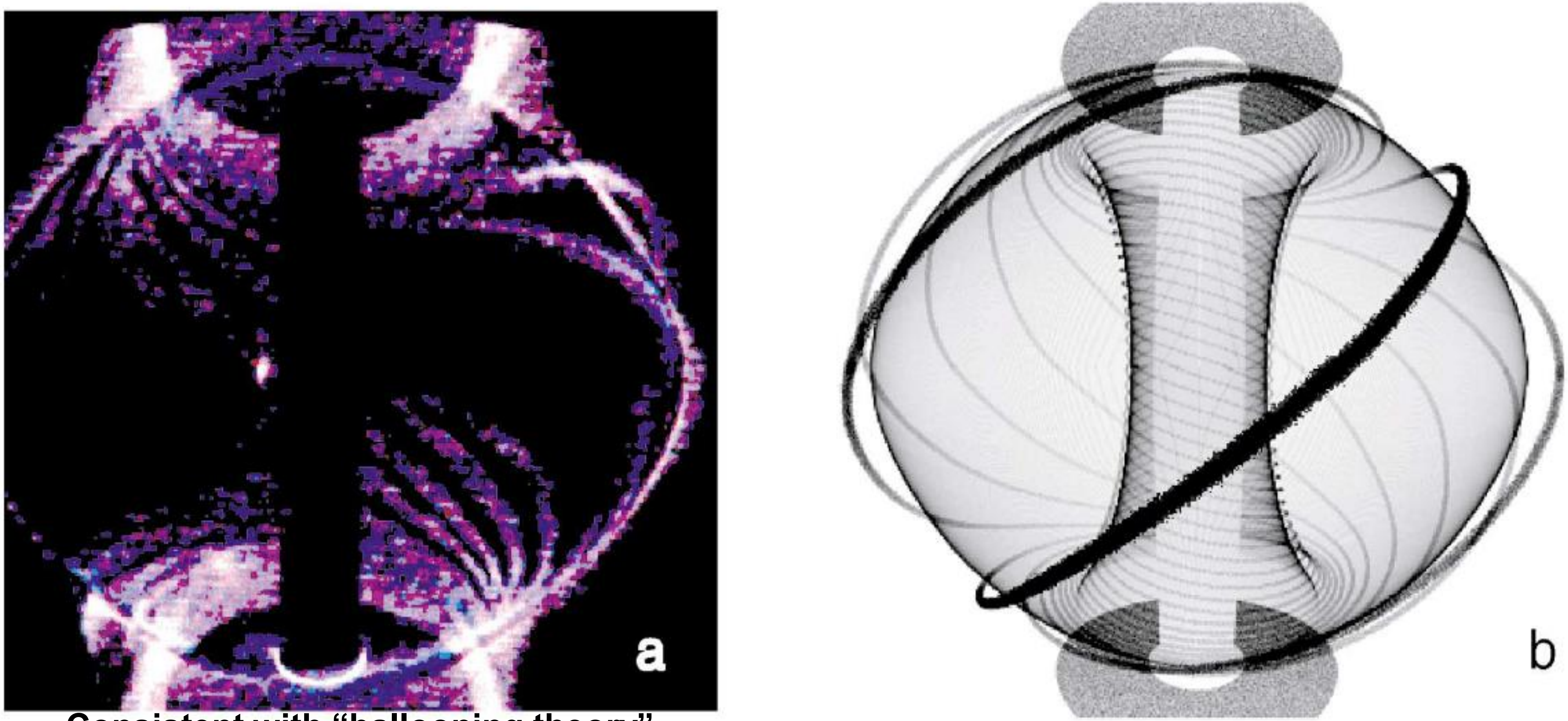
- 3-D field influenced heat flux broadening during ELM-crash-suppression

Discussion

- “ELM-less” vs ELM-controlled plasmas

Concluding Remarks

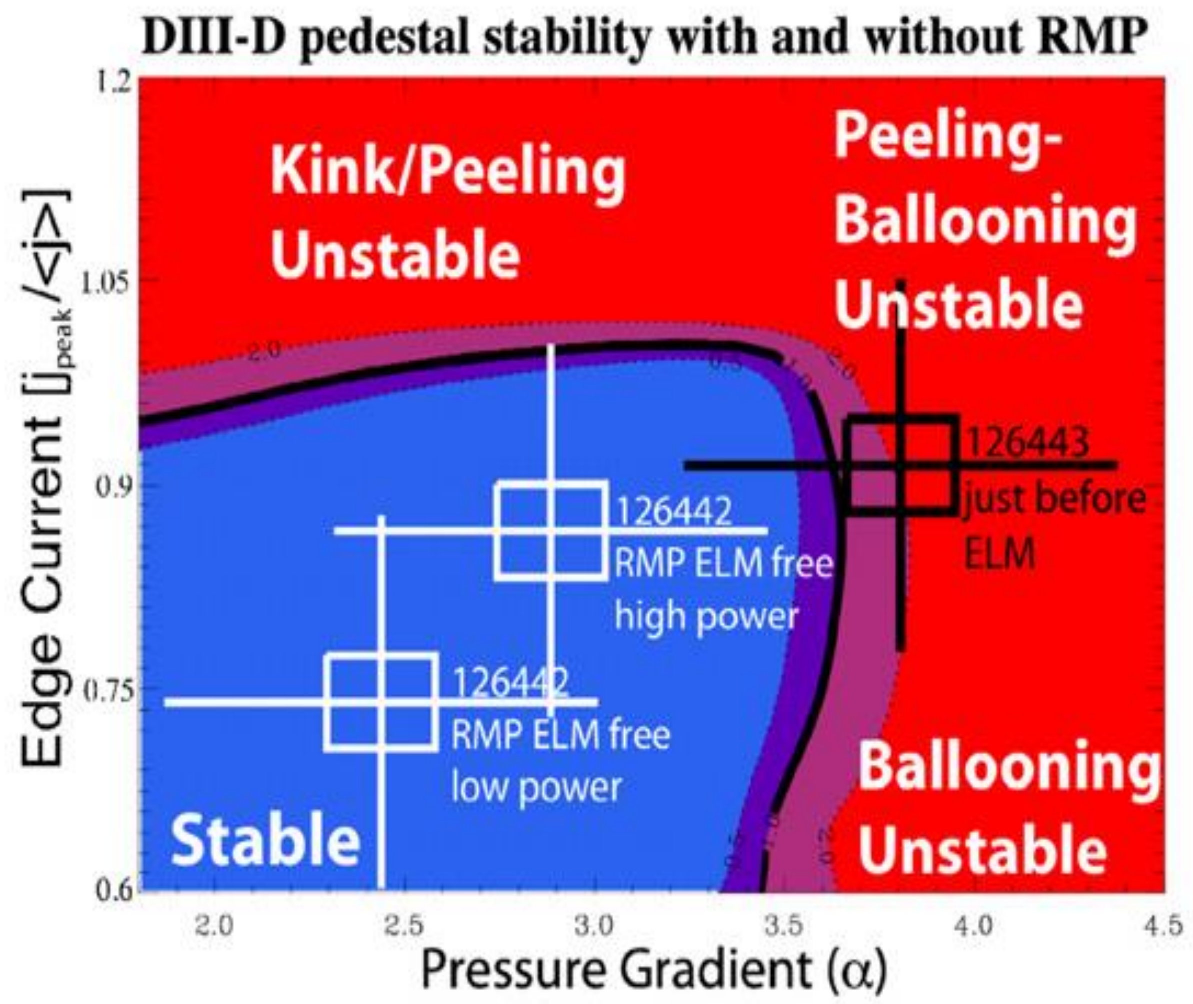
Both simulation and experiments of edge-localized-modes (ELMs) are in a remarkable agreement with each other



Consistent with "ballooning theory"

A. Kirk *et al*, PRL (2004)

Peeling-ballooning theory may explain a majority of ELM avoidance/mitigation techniques, despite a few unresolved issues



P. Snyder *et al*, NF (2009)

- Natural Type-I ELM outburst both heat and particle fluxes beyond the acceptable level of machine safety and material lifetime

e.g. ITER : 0.5MJm^{-2} per ELM

Enhancement factor of ~ 30 x natural frequency of ELM is needed

- RMP, Pellet Pacing, Vertical jog, ECCD, SMBI, Impurity injection etc

Arguably, the best example of current-driven 'peeling mode' on the plasma surface has been numerically suggested from ASDEX

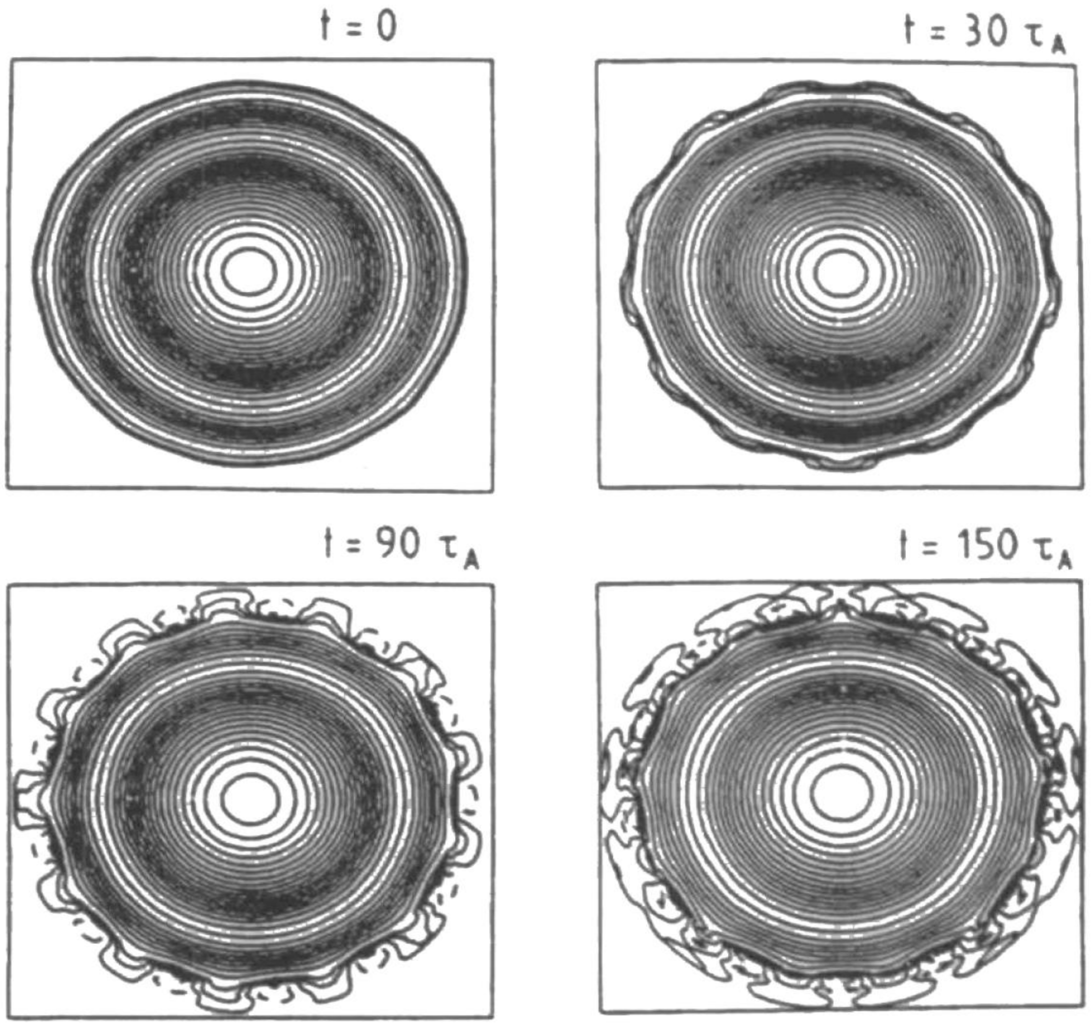


FIG. 92. Contour plots of the pressure for the non-linear evolution of free-surface modes.

Model for Type III ELM

Refer to PPCF review paper by Zohm (1996), as well

ASDEX team, NF (1989)

Pellet pacing, rather than pellet fueling, is deemed as one of the main ELM mitigation techniques adopted in ITER

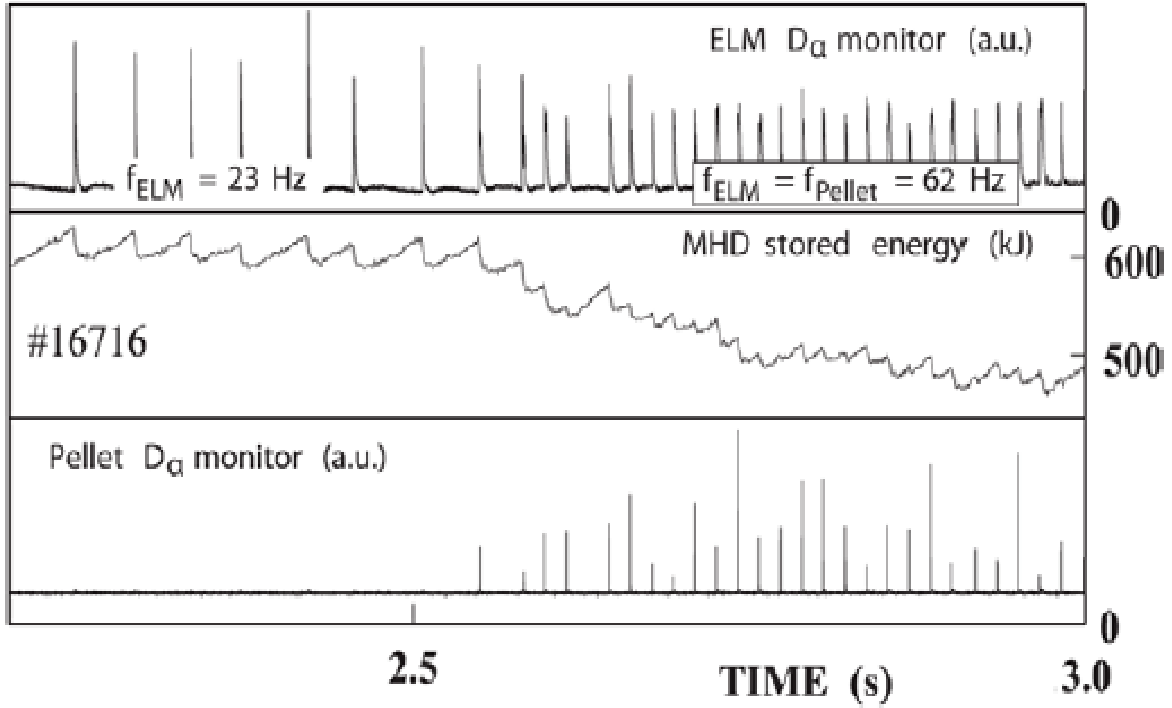


Figure 10. Onset of pellet pacing sequence in ASDEX-Upgrade: the ELM frequency follows immediately the pellet rate resulting in a ∼ threefold increase of the frequency and a corresponding ELM energy loss reduction. Additional convective losses associated with the expulsion of pellet injected particles (fuelling size pellets are used in this experiment) cause a mild confinement loss [94].

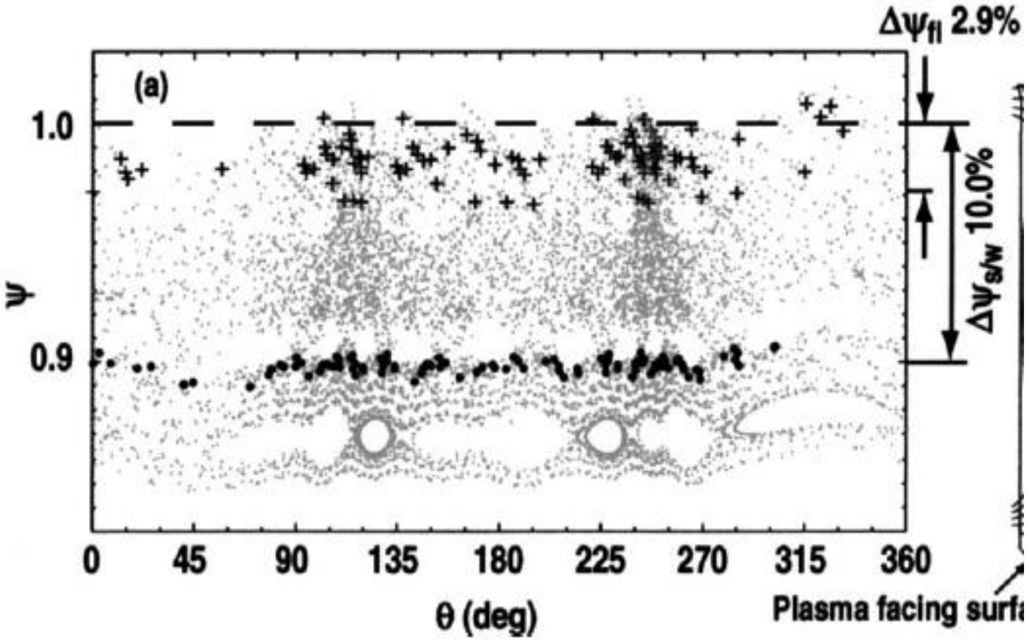
- **Originated from ineffective pellet fueling: ASDEX-Upgrade [P.T. Lang *et al*, NF (2004)]**
- **A few fraction of ablated pellet was sufficient to drive controlled ELM, which is almost the same as natural ELMs, except for a reduced ΔW_{ELM} and less reduction of τ_E**

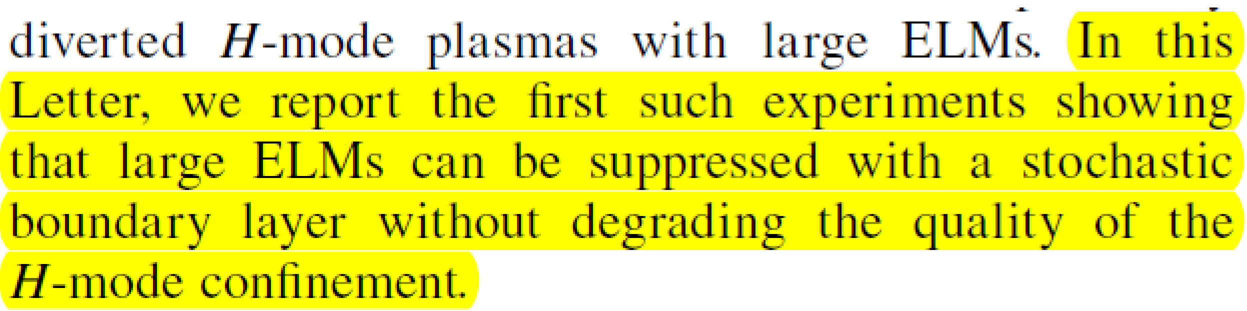
$$\frac{\Delta W_{\mathrm{ELM}} \times f_{\mathrm{ELM}}}{W} \times \tau_E = \frac{\Delta W_{\mathrm{ELM}} \times f_{\mathrm{ELM}}}{P} = 0.2\text{–}0.4$$

- **Tasks remain to clarify the impact on τ_E, smallest optimal size, and its concentrated heat load on divertor**

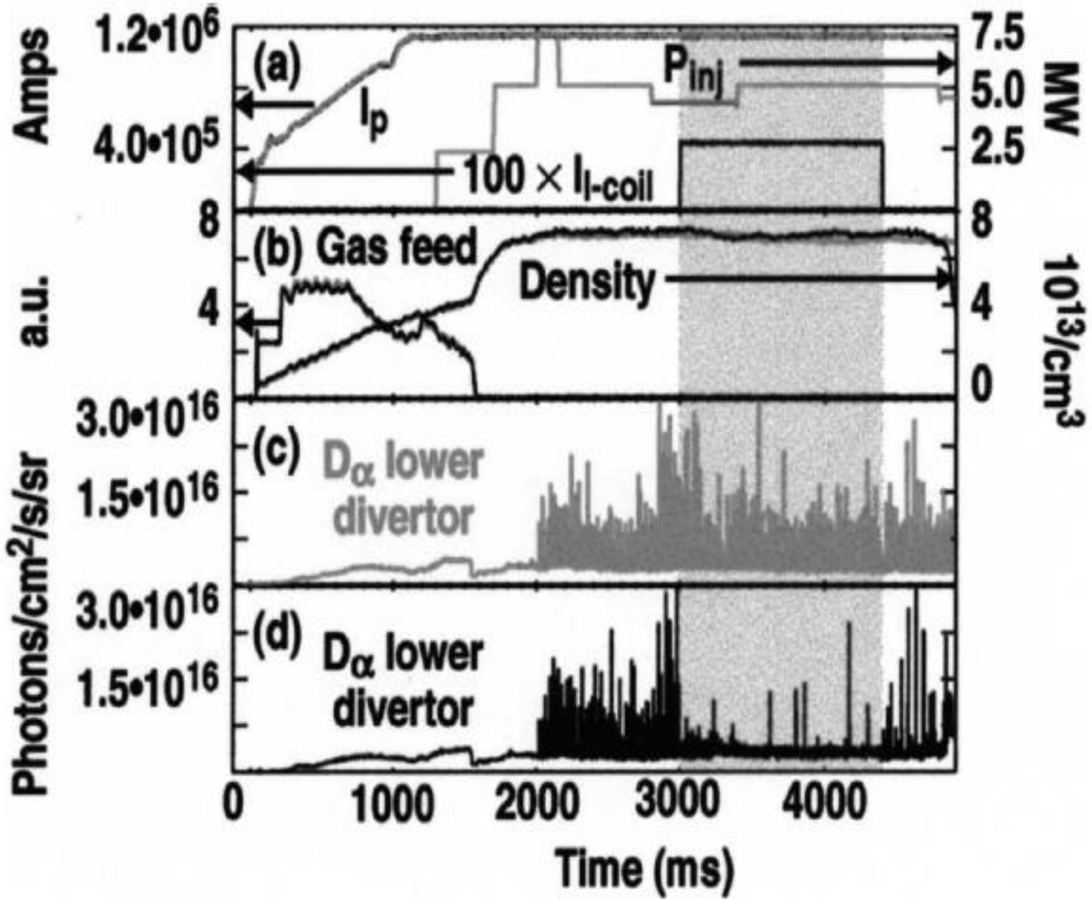
P.T. Lang *et al*, NF (2013)

First RMP-driven, ELM suppression is conceived based on the “stochastic magnetic boundary” that enhances edge transport



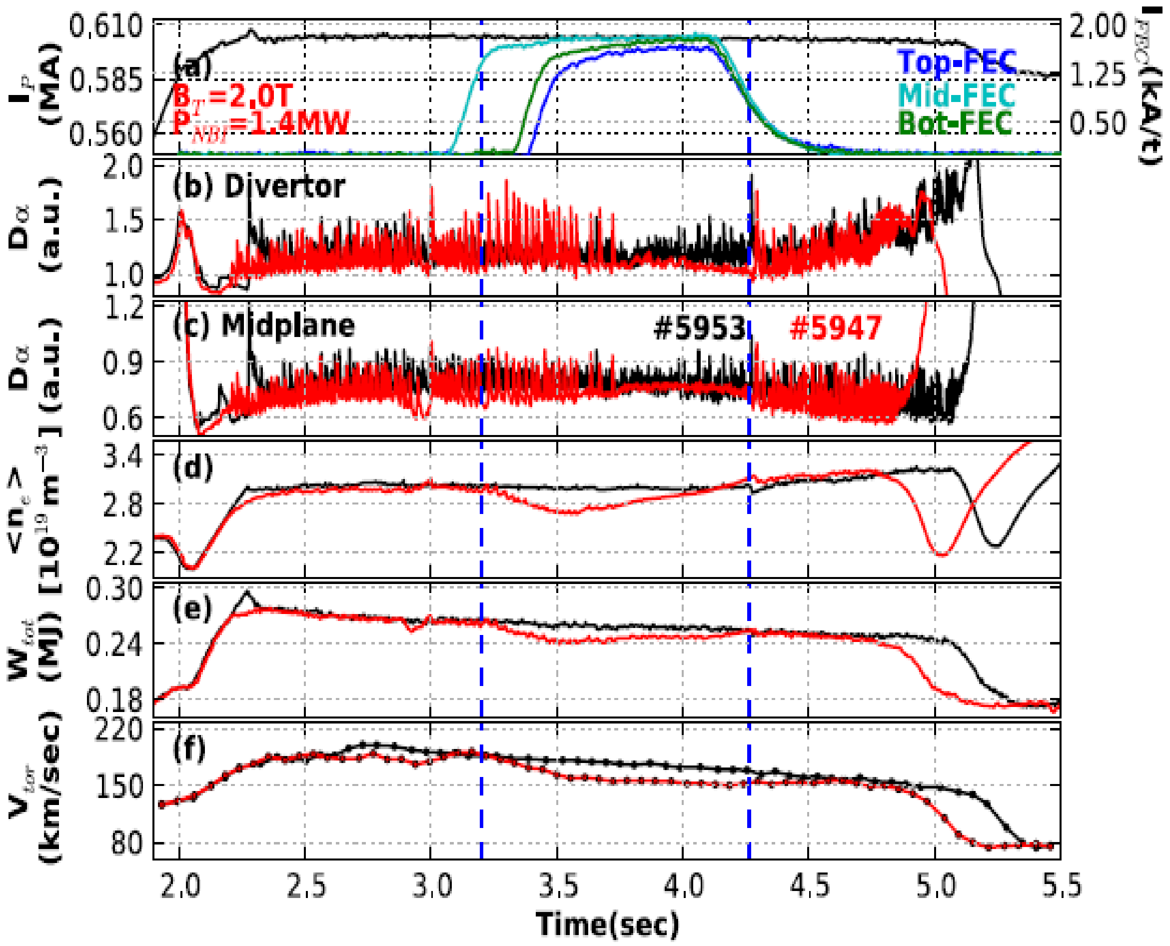


diverted *H*-mode plasmas with large ELMs. In this Letter, we report the first such experiments showing that large ELMs can be suppressed with a stochastic boundary layer without degrading the quality of the *H*-mode confinement.



T.E. Evans *et al*, PRL (2004)

KSTAR accomplished full suppression of ELMs using n=1 RMP for the first time, challenging conventional wisdoms!



Y.M. Jeon *et al*, PRL (2012)

- Ever since DIII-D (2004) reported the success of n=3 RMP-driven, ELM-suppression, many devices attempted but produced mostly mitigations

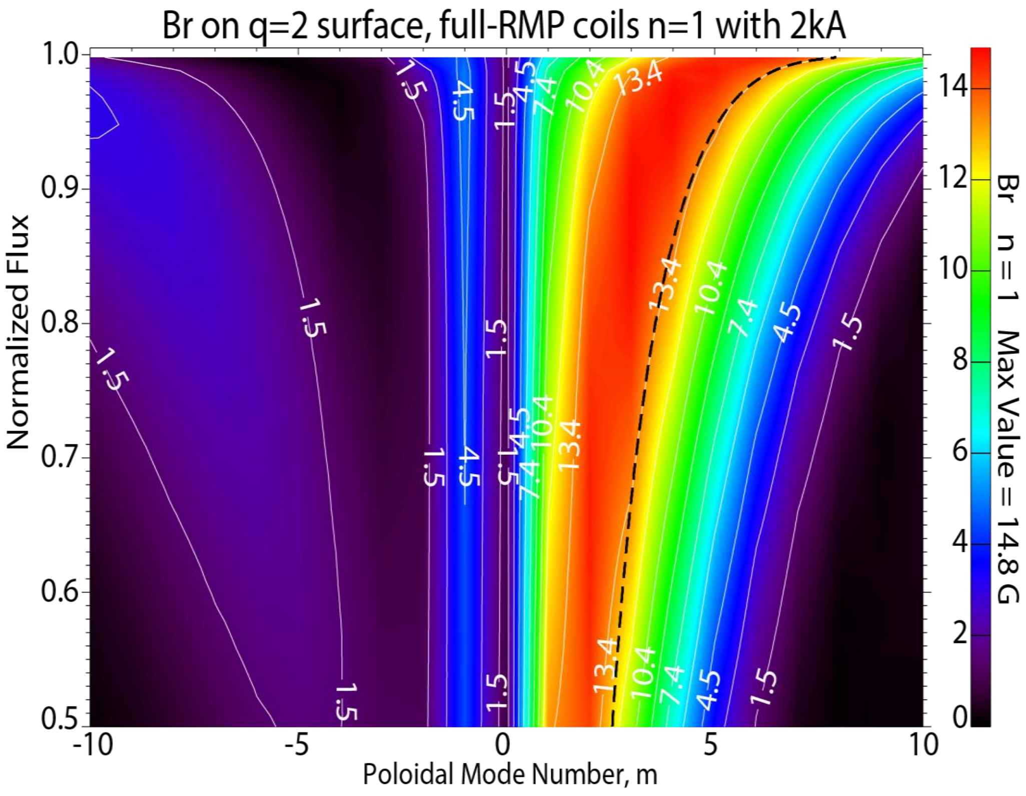
JET (2007): n=1 mitigation
MAST(2011): n=3 mitigation
AUG (2011): n=2 mitigation

until KSTAR (2012) accomplished the full n=1 suppression

- Recently, EAST(2016) succeeded in n=1 suppression and then AUG reported the suppression with DIII-D-like shape (2018)

RMP is expected to drive magnetic island at each surface of *m-nq=0* , whose overlap between adjacent surfaces leads to stochasticity

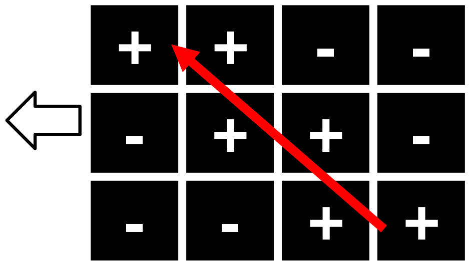
n=1 dominantly resonant configuration

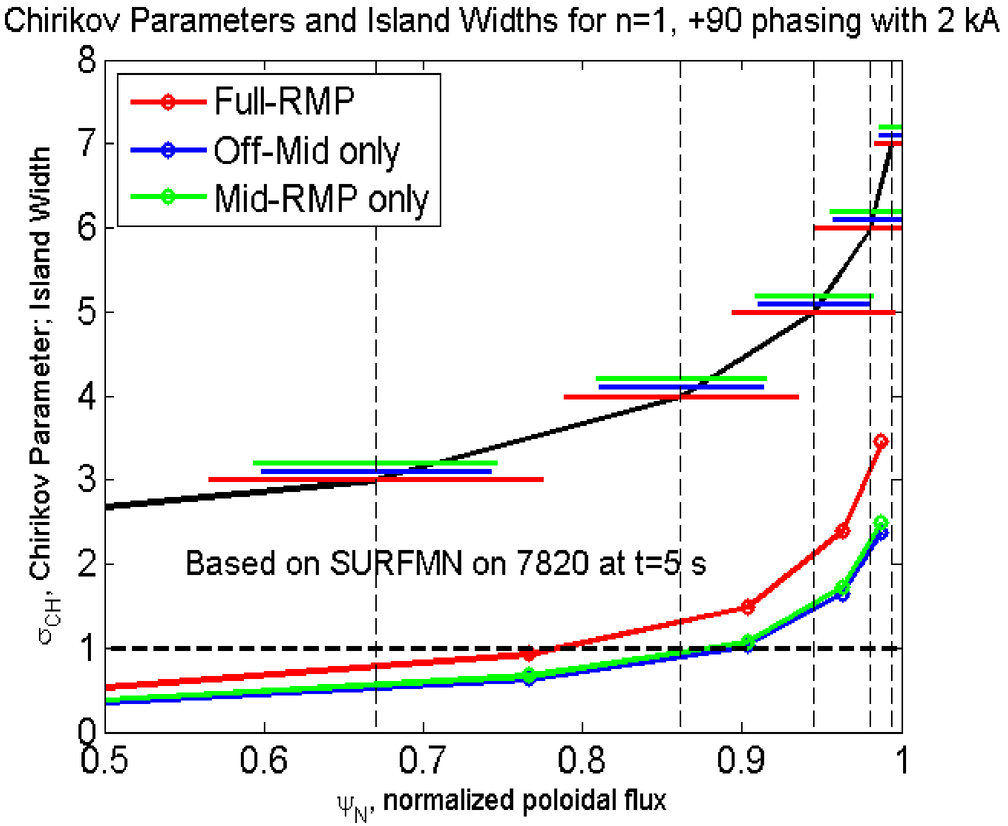


Y. In *et al*, NF (2015)

n=1 resonant,

Δϕ = +90°





$$\sigma_{CH} \equiv \left(w\left(\psi_{m+1}\right)+w\left(\psi_m\right)\right)/\left(2\left(\psi_{m+1}-\psi_m\right)\right)$$

Chirikov, Phys. Rep (1979)

Slowly decaying nature of n=1 field could be potentially a merit, rather than an obstacle in RMP ELM control in future reactors

So far, ITER RMP control has discarded the option of n=1 RMP due to

1) wide spacing between adjacent islands

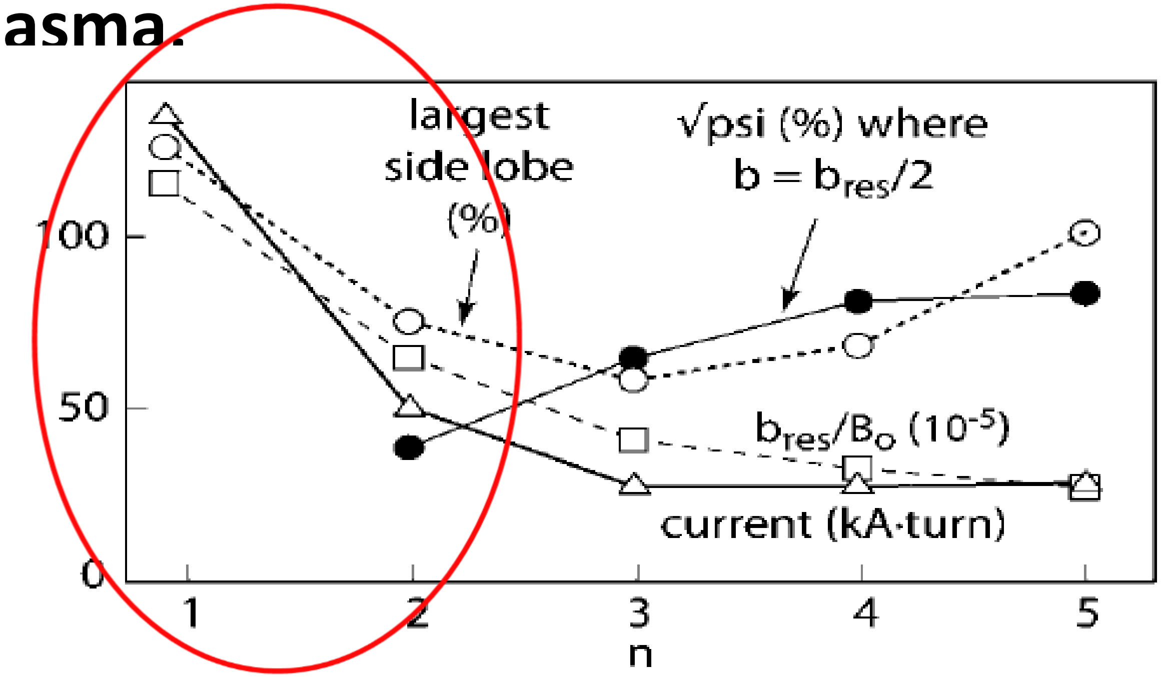
➔ high field strength required to meet $\sigma_{Chirikov} > 1$

2) hardly decaying into the core plasma.

susceptible to mode-locking

Discussed by Y. In *et al*, KSTAR-Conference (2015)

Likely, KSTAR would be the most suitable device to address the validity of n=1 RMP ELM-control



[Schaffer *et al*, NF (2008)]

KSTAR specializes in low-n RMP ELM control challenges !!!

Several key criteria for ELM suppression can be listed up, but they may not be complete yet

- **δB perspective**
  - **Maximal edge resonance/Minimal core resonance:**

(associated with q_{95}, phasing, poloidal spectra, plasma response, and mode-locking (kink-influence))

  - **Sufficient stochasticity (above threshold)**

- **Plasma perspective**
  - **Inside separatrix**

(edge collisionality, bootstrap current, pressure gradient, pedestal location,

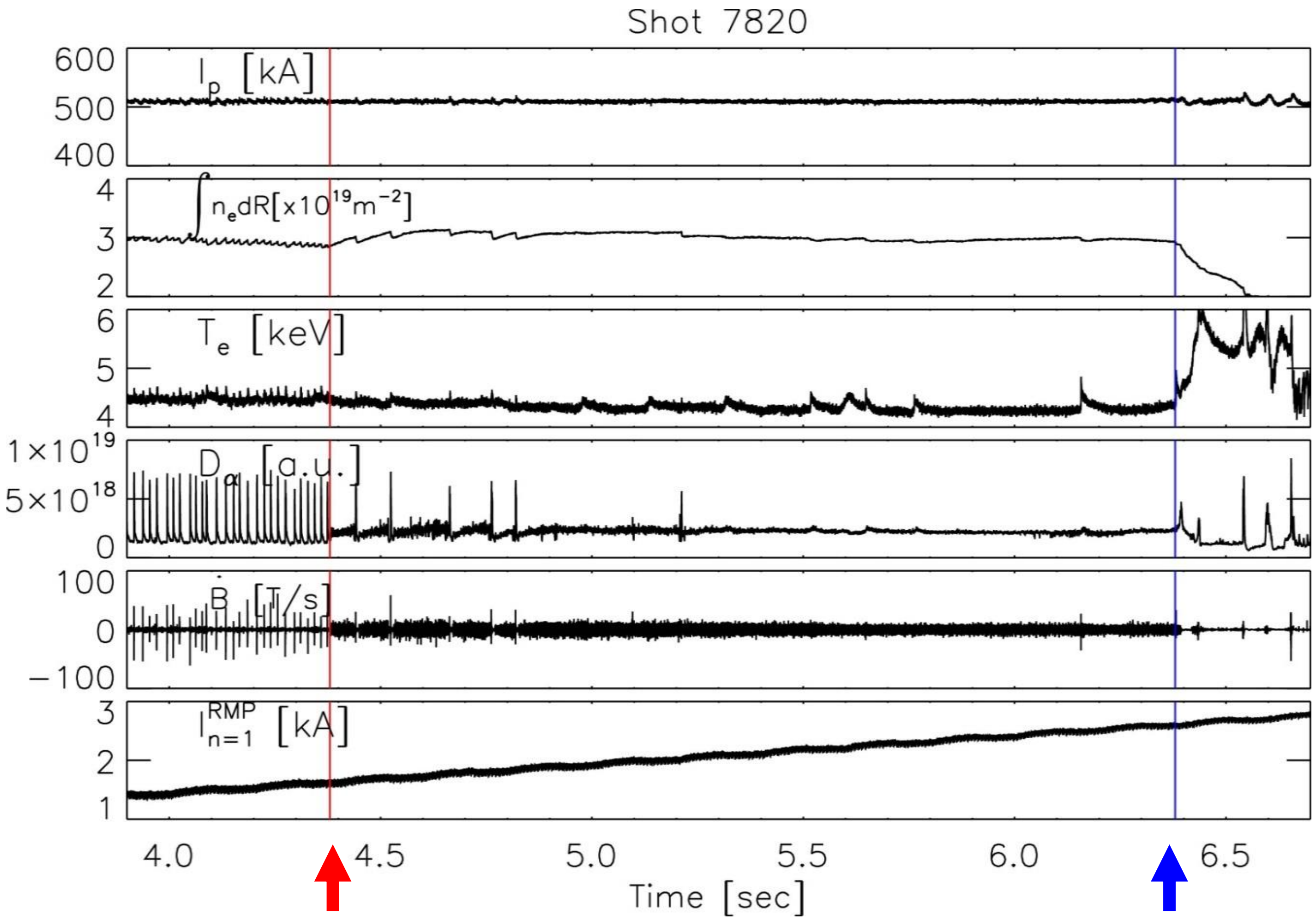
ExB profile, turbulence) **+ plasma shape**

  - **In open-field area**

Interaction with divertor and PFC (recycling, impurity); influence of neutral particles

➔ **Whatever can avoid/suppress/mitigate ELMs in a manageable level would prevail in ITER and beyond, let alone the scientific merits**

An excessive RMP current even with an optimized phasing in KSTAR leads to a mode locking



Onset of ELM suppression

Mode-locking

Y. In *et al*, NF (2015)

A portion of the RMP currents might have contributed to kink-associated mode-locking

Consistent with the frequent mode-locking behaviors during n=1 RMP attempts in other devices (e.g. DIII-D)

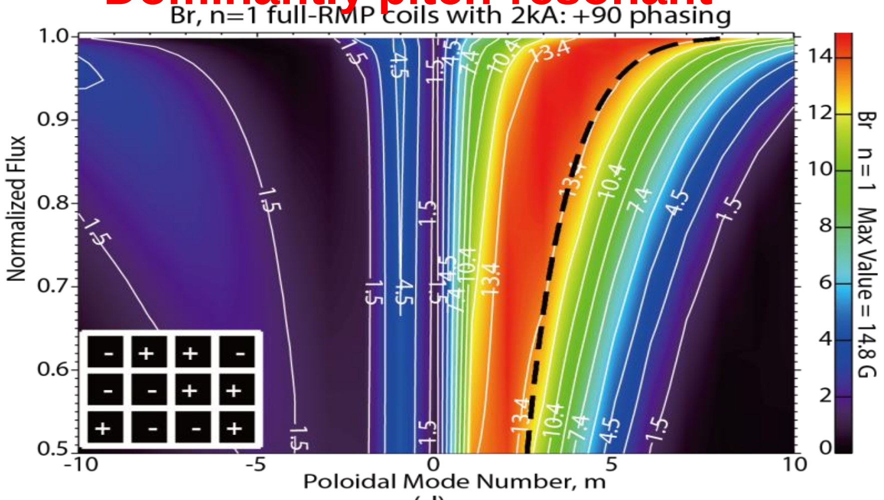
Distinction from kink- vs pitch-resonant components may explain the rare observations of n=1 ELM-suppressions in KSTAR and EAST

- **ELM-suppression: pitch-resonant (90º phasing)**
  Mode-locking: kink-resonant (180º phasing)

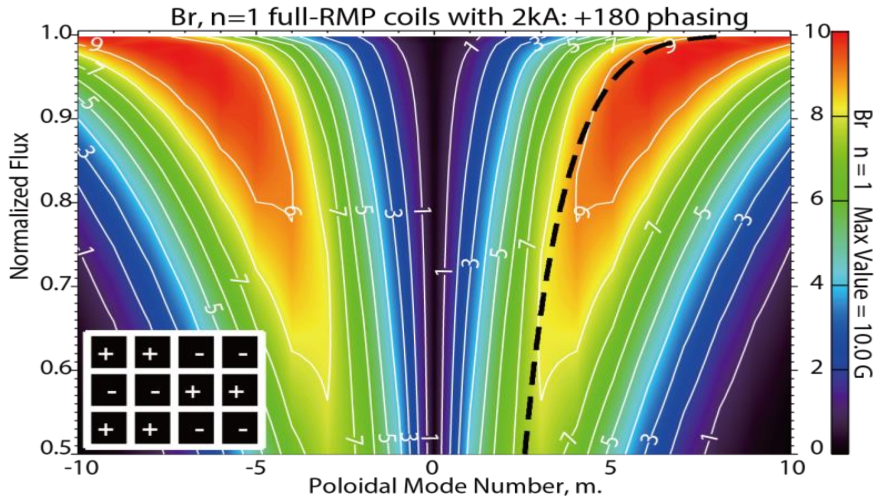
- Low level EF, less susceptible to kink-resonant mode-locking

- The EFC minimizes the unwanted kink-resonant non-axisymmetric field, while the RMP application maximizes the benefits of intentionally applied pitch-resonant non-axisymmetric field

Dominantly pitch-resonant



(d)



(e)

Here, negative m are left-handed, while positive m are right-handed.

Dominantly kink-resonant

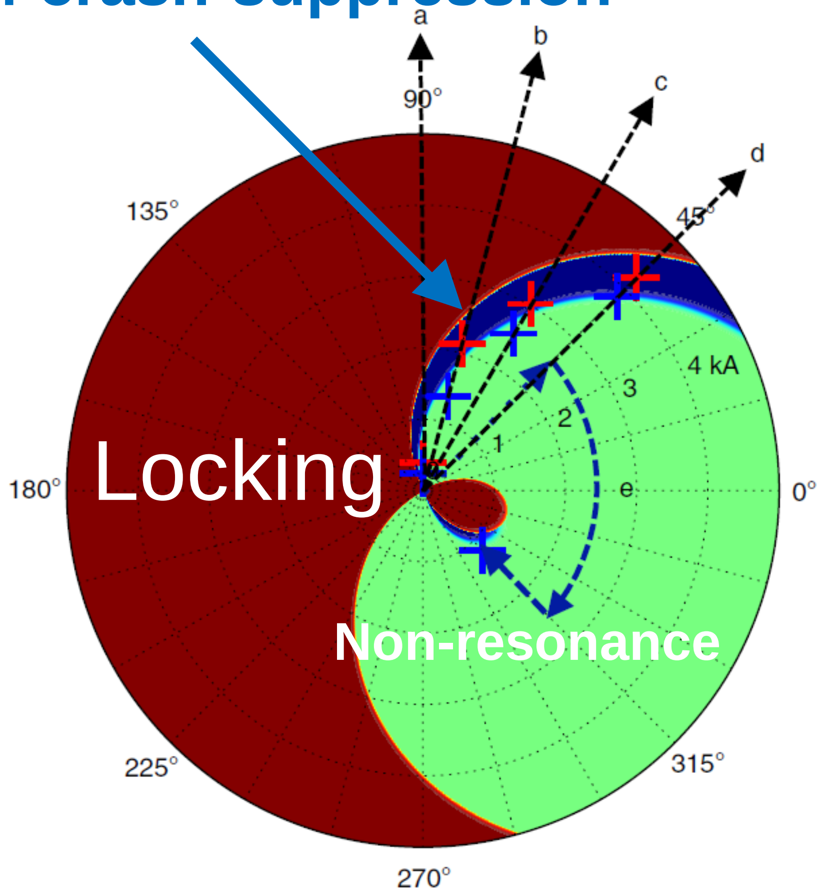
Y. In *et al*, NF (2015)

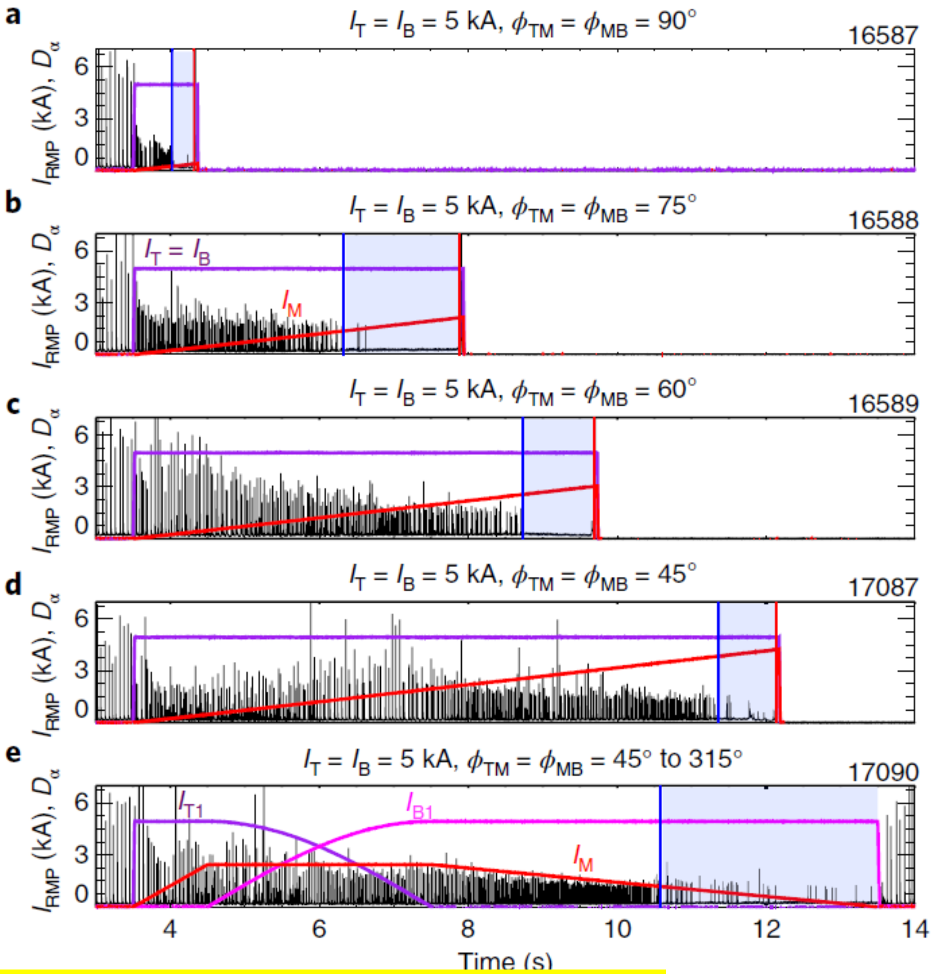
To suppress ELM-crashes using n=1 RMP, edge resonant components are required to be effectively decoupled from core resonant components

Polar plot of (I_{MID}, ϕ)
with I_U=I_L=5kA and ϕ=ϕ_{UM}=ϕ_{ML}

- **Minimize core resonant components**
  → Avoid mode-locking
- **Maximize edge resonant components**
  → ELM-control

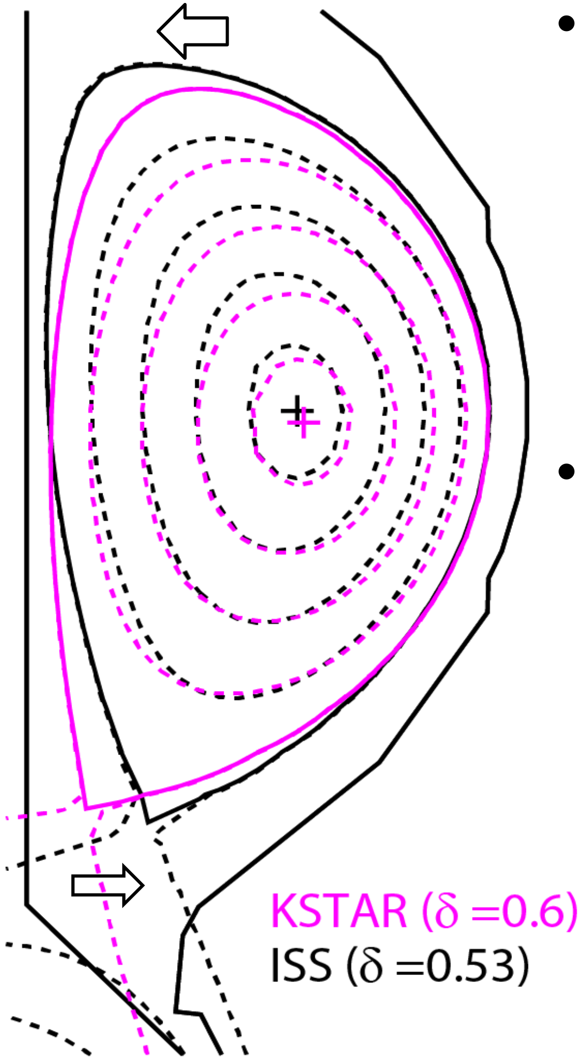
ELM-crash-suppression





J.K. Park *et al*, Nature physics (2018); Y. In *et al*, NF (2017)

Highly shaped plasmas (δ~0.6) would be much more desirable for both low-n RMP-driven, ELM-crash- suppressions



- **Depending on triangularity, the plasma response greatly changes**
  [**outward shift** – prone to mode-locking
  (consistent with IPEC prediction)
  inward shift – changes of ELM characteristics]

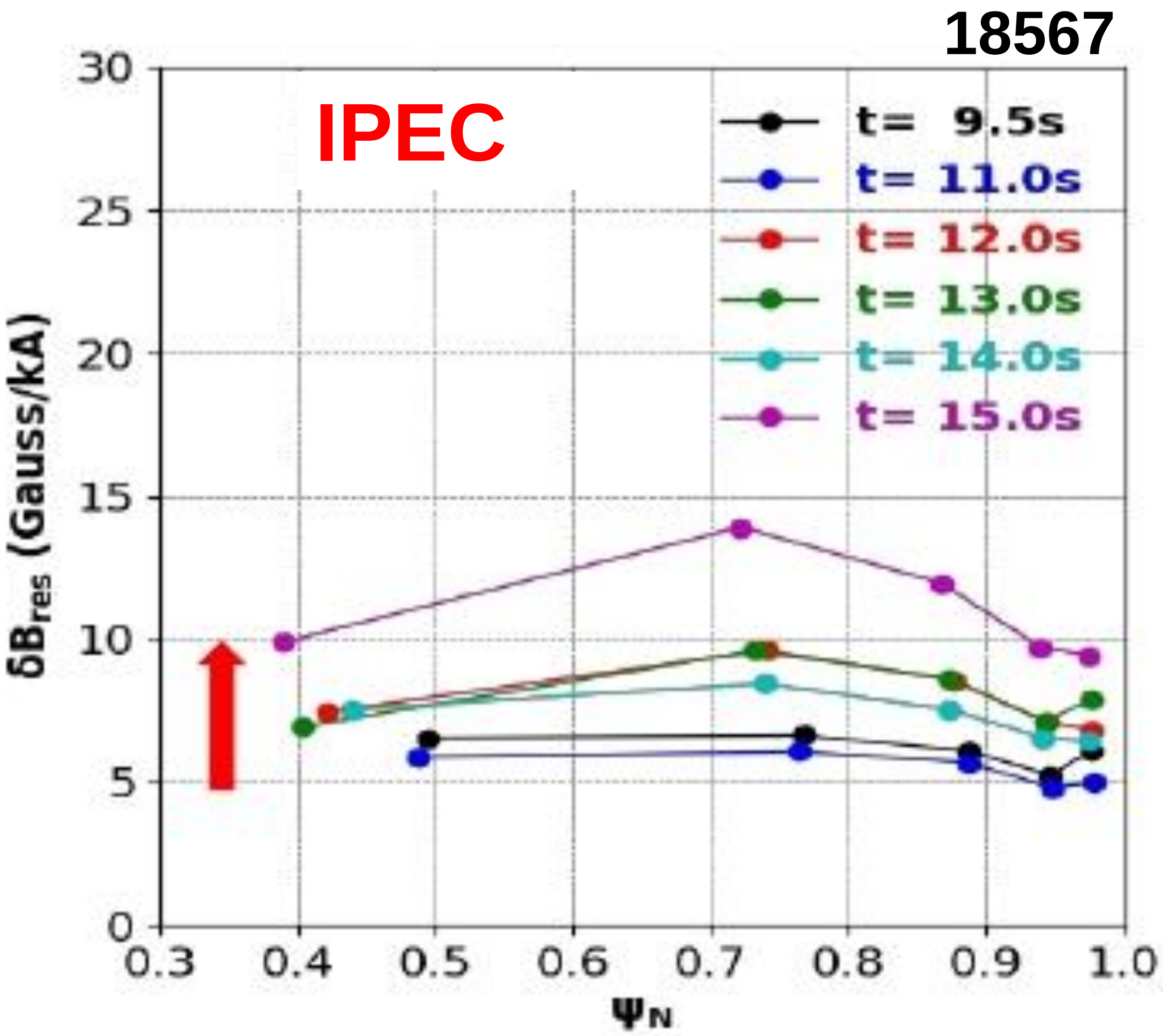
- **Expected to be feasible even with ITER-similar shape (ISS) plasmas** [collaboration experiment between DIII-D and KSTAR]

KSTAR [$\delta = 0.6$]
0.5 < ISS (δ~0.53) < 0.6

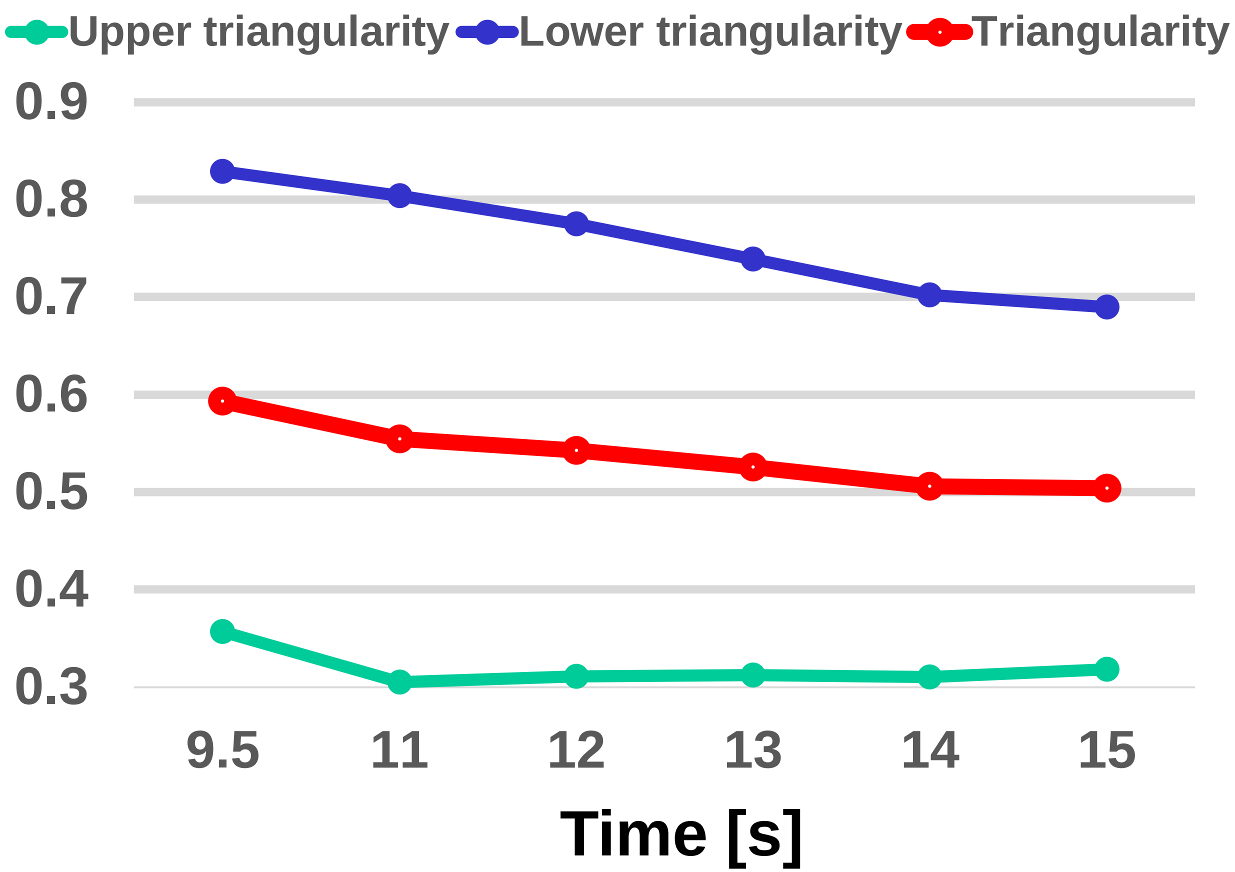
	upper X-pt, δ_u	lower X-pt, δ_l ($R_{x,l}$)	$\delta \equiv (\delta_u + \delta_l)/2$
Innermost	**0.36**	**0.83 (1.39 [m])**	**0.60**
Outermost	**0.32**	**0.69 (1.46 [m])**	**0.50**

Y. In *et al*, APS-DPP (2017)

Depending on the triangularity (i.e. shape change), the resonant components in theoretical calculations support the experimental observations



Y.M Jeon *et al*, APS-DPP (2017)

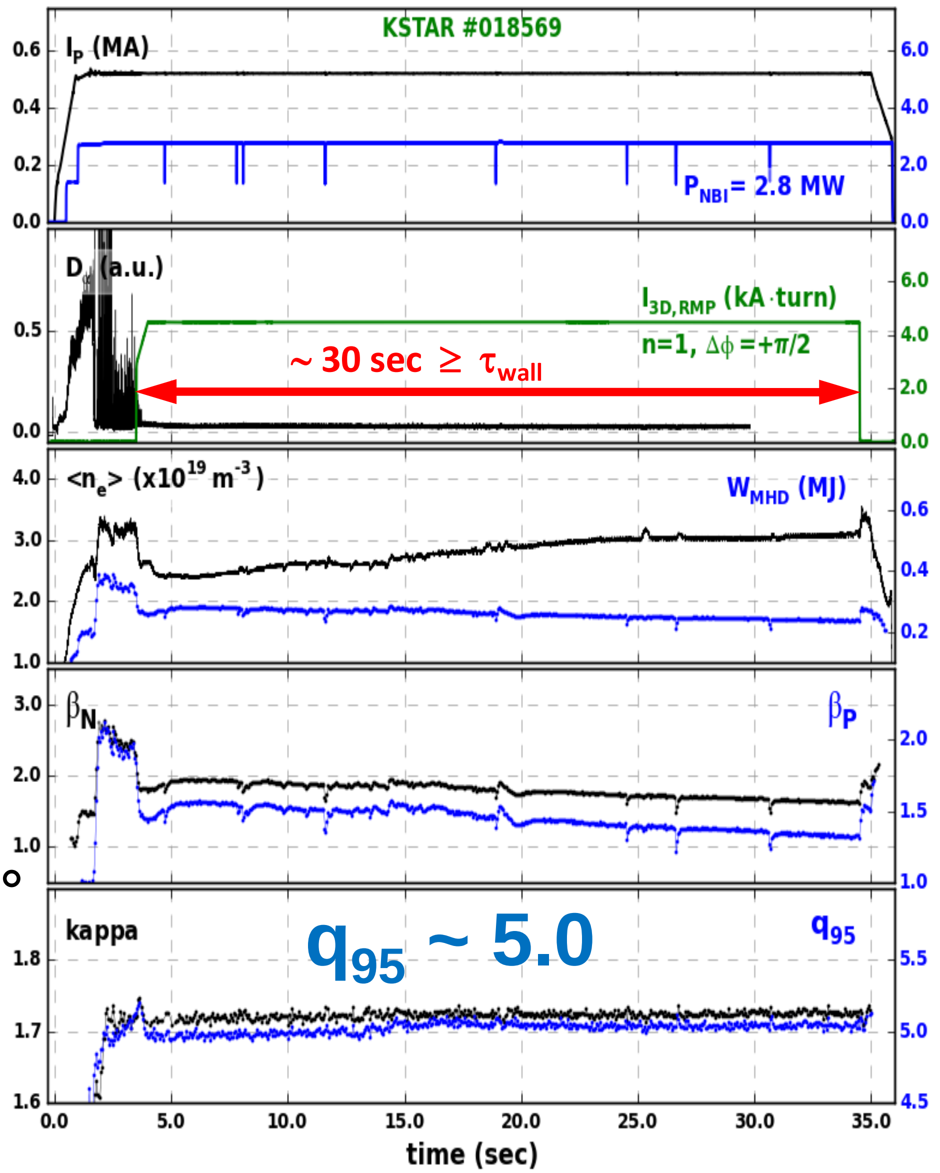


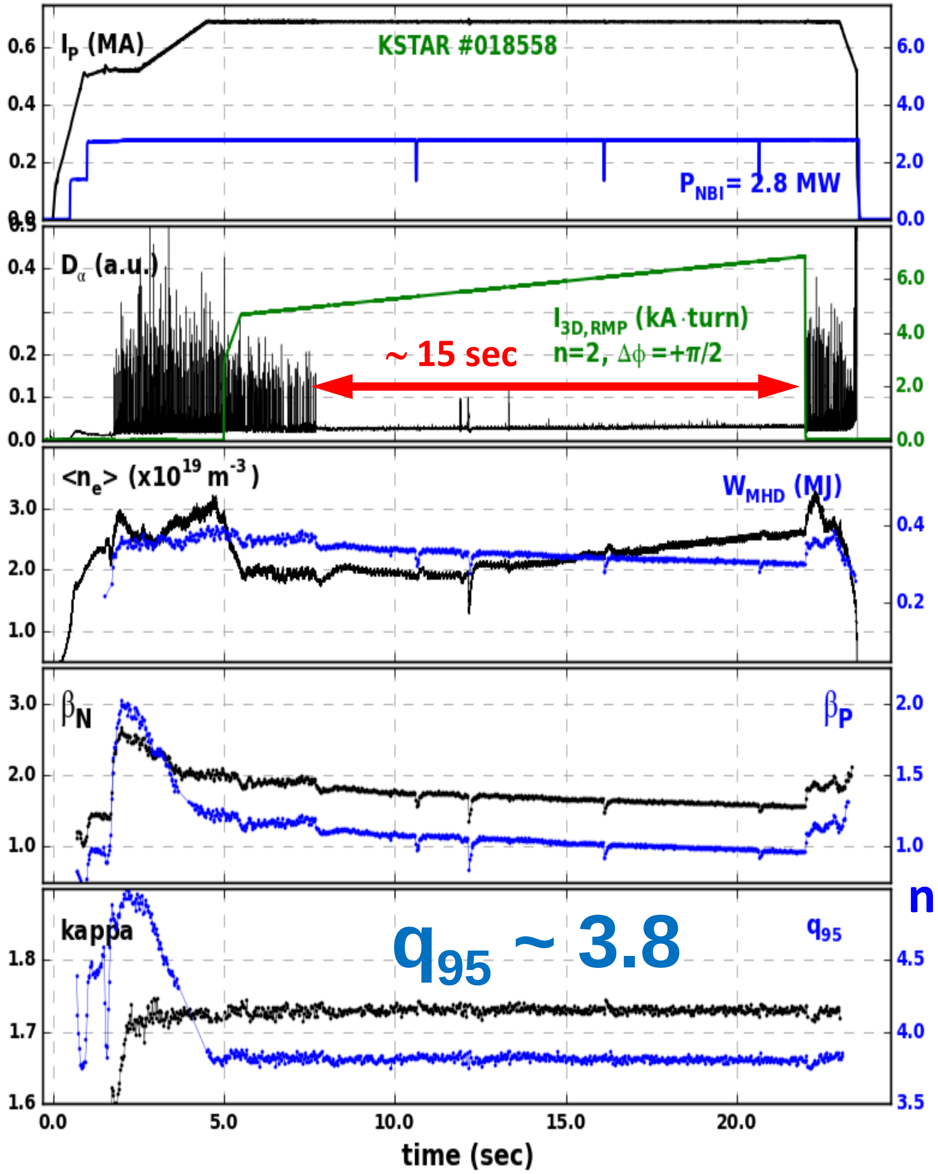
- **As δ decreases ($R_{X,low}$ increases), the resonant δB strengthens**

The access to RMP-driven, ELM-crash-suppression in KSTAR has been robustly established, along with the enhanced scientific understanding of the critical conditions for ELM suppression

- **Expanded operation boundary and capability of RMP-driven, ELM-crash-suppression**
  - q_{95} = 3.4 – 6.4 (not just a single value), $\nu^* \sim 0.2$ (close to ITER-target value)
  - Compatible with n=1 and n=2 RMPs
- **Confirmed excellent predictability of ideal response modeling for ELM-crash-suppression**
  - Newly accomplished the n=1 off-midplane RMPs
- **Enhanced the understanding on the critical onset conditions of ELM-crash-suppression**
  - Torque-controlled access to ELM-crash-suppression under fixed RMP
  - First direct (ECEI) measurement of $\omega_{\perp e}$ (or ω_{ExB}) ~ 0 bifurcation dynamics at the onset

Robust ELM-crash-suppression has been successfully developed using either n=1 or n=2 RMPs





n=1, Δϕ = +90°

+	+	-	-
-	+	+	-
-	-	+	+

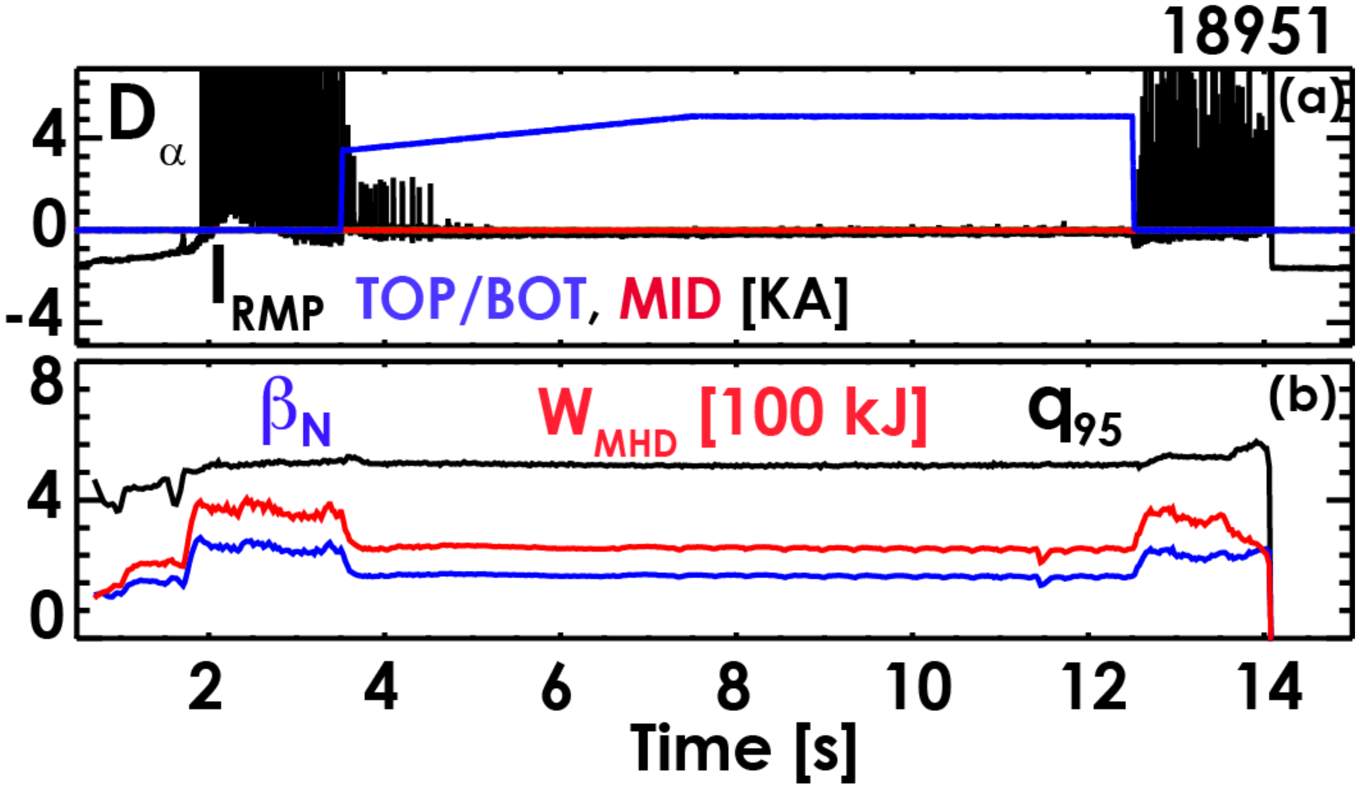
n=2, Δϕ = +90°

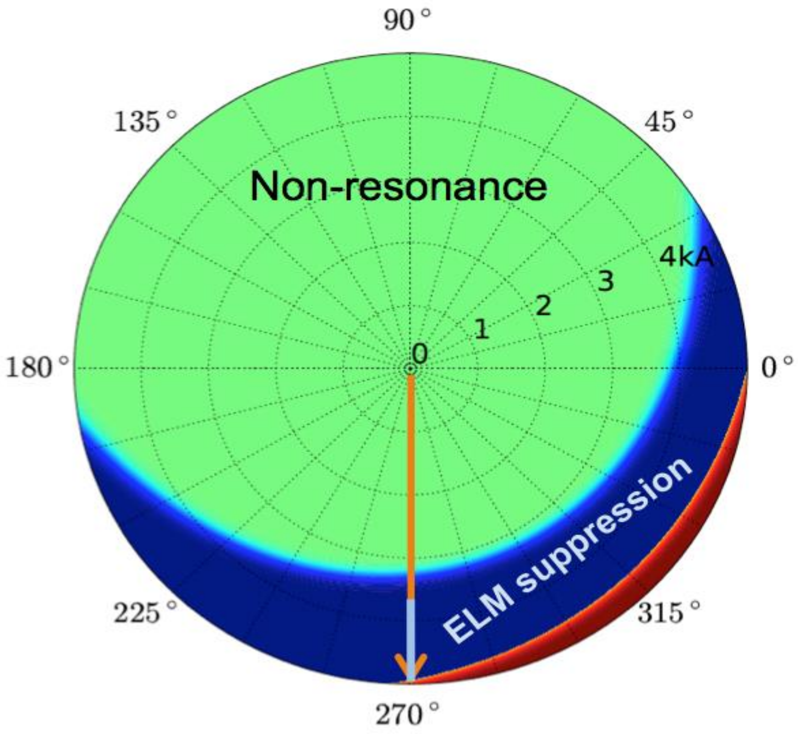
+	-	+	-
-	+	-	+
+	-	+	-

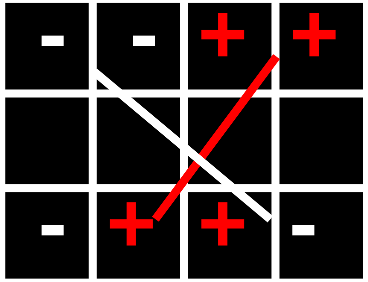
Newly achieved RMP ELM-crash-suppression using n=1 off-midplane coils has been configured to be operationally perpendicular to conventional RMP configuration

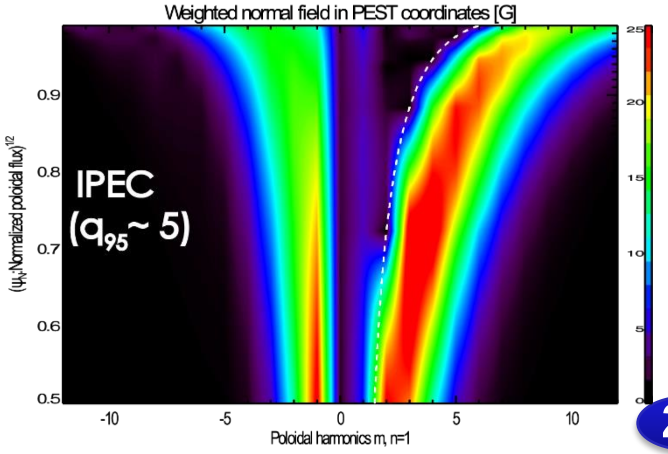
First “off-midplane” only ELM suppression using n=1 RMP in KSTAR

($\Delta\phi_{TB}$ = -90° phasing)



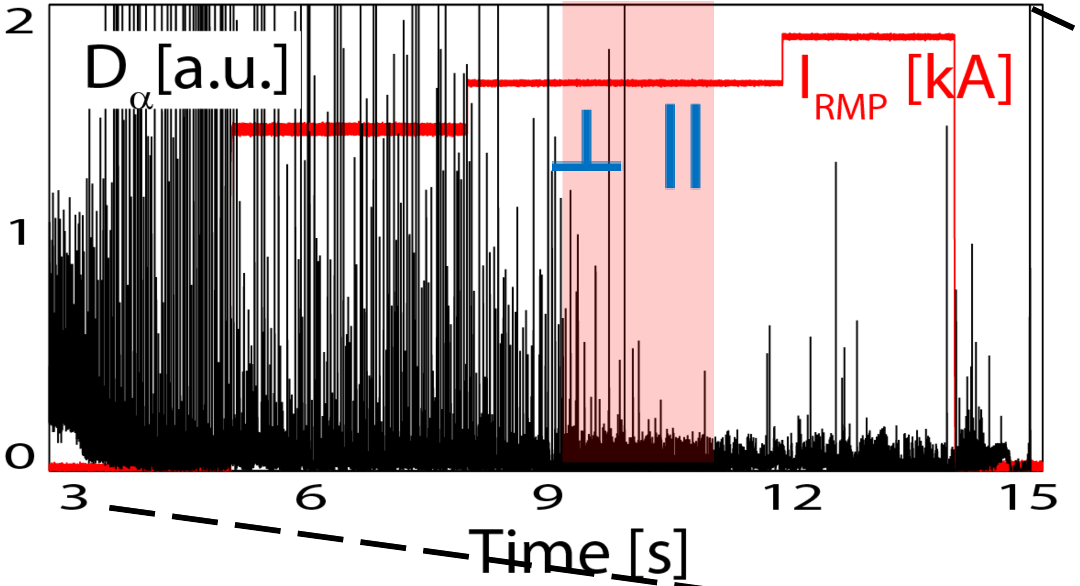




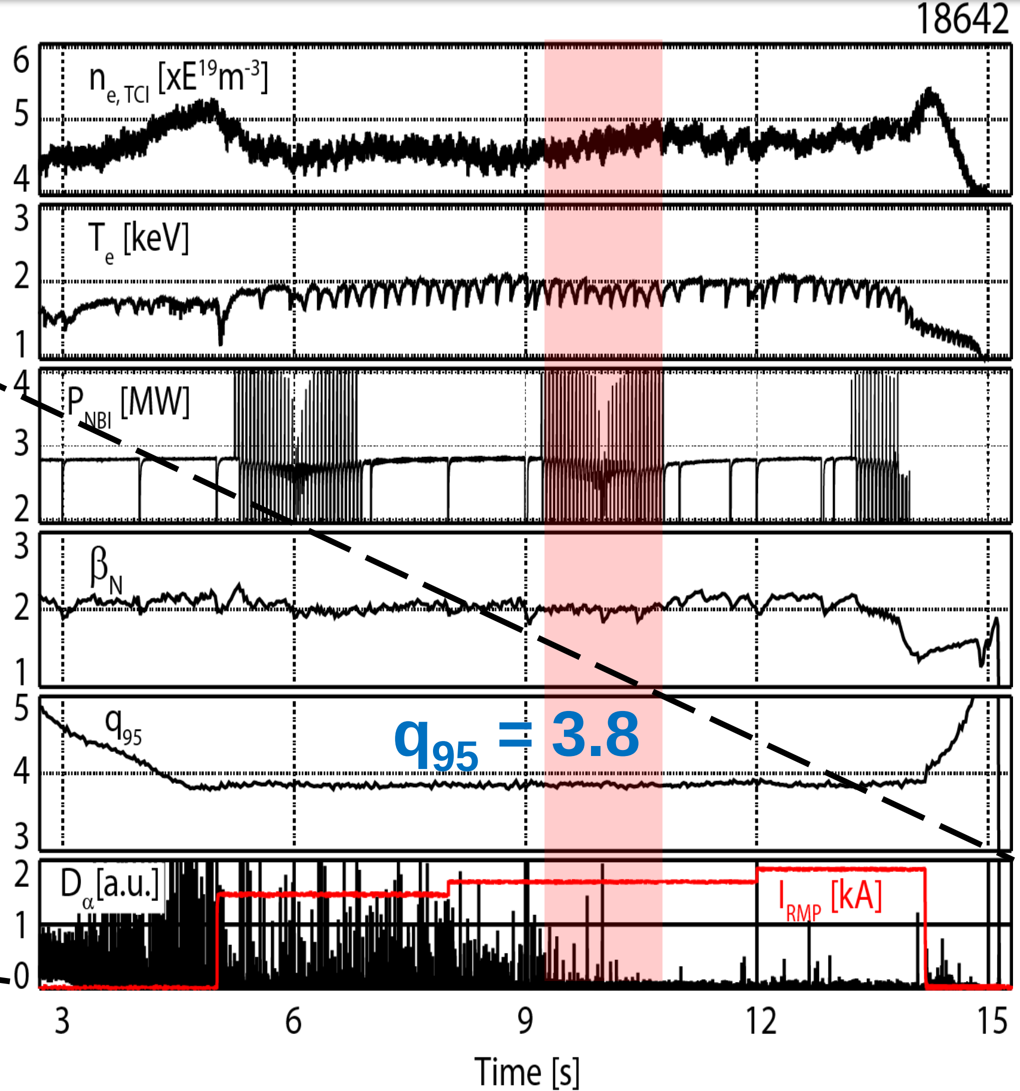


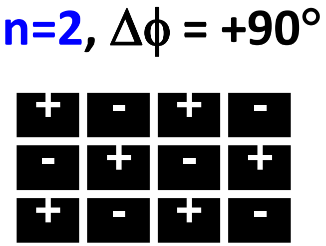
Torque-controlled transition to ELM suppression has been confirmed without changing RMP, strongly endorsing the existence of $\omega_{\perp,e} \sim 0$

With cryopump on, a much lower value (~30 %) of n=2 RMP led to ELM-crash suppression, possibly attributable to a lower edge collisionality, ν^*



Refining the transition time appears quite robust (from dominantly perpendicular to parallel components at fixed power)



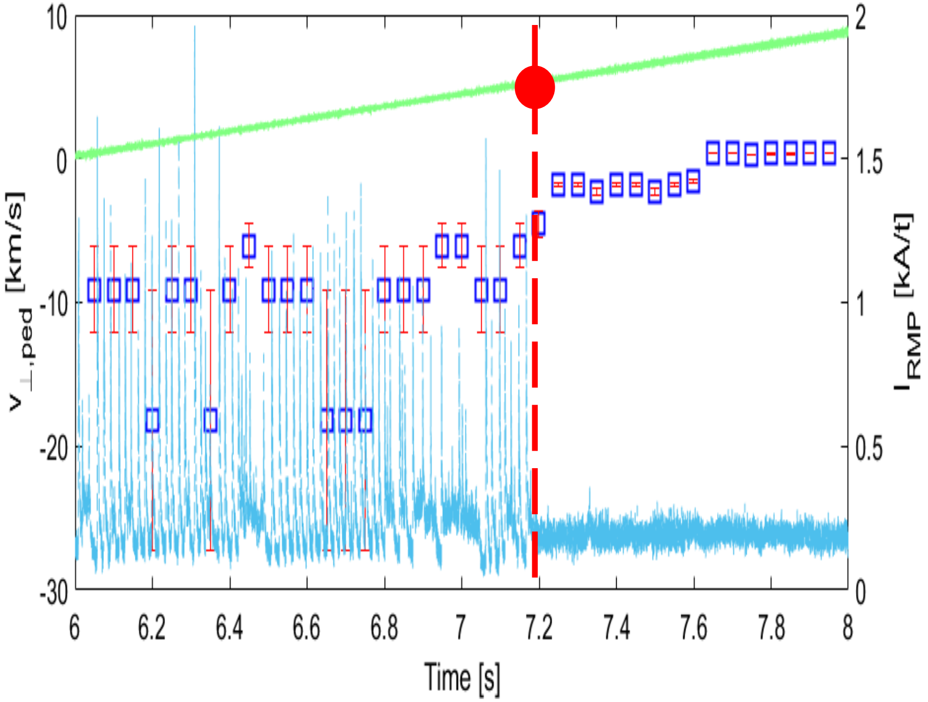


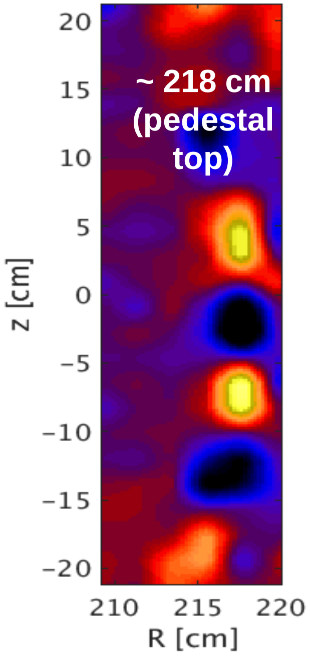
Transition occurs at a fixed I_{RMP} = 1.8 kA, when torque variations take place at fixed P_{NBI} =2.8 MW

Y. In *et al*, APS-DPP (2017)

Bifurcation of $\omega_{\perp e}$ (or ω_{ExB}) ~ 0 dynamics at the onset of ELM suppression has been directly measured on ECEI for the first time

Mitigation to Suppression (19347), n=1





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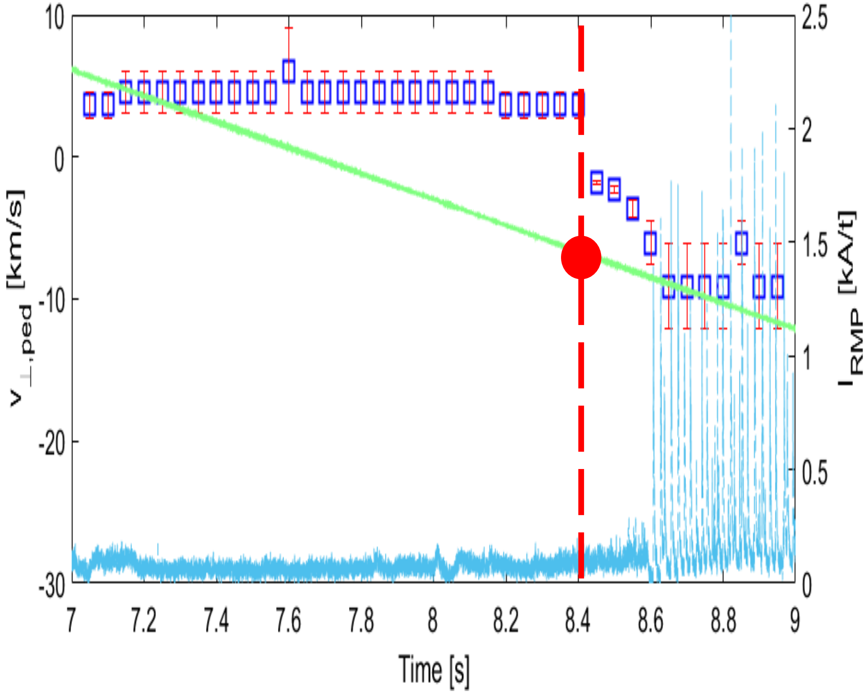
Suppression to mitigation (19348), n=1



- **Consistent with the resonant field penetration triggering the onset of ELM suppression**
- **NOTE the bifurcation point of $v_{\perp,ped}$ slightly precedes or nearly synchronizes the onset of ELM suppression, which could be possibly used for a good precursor for RMP ELM suppression (indicative of RMP strength hysteresis for ELM-suppression)**

J.H. Lee *et al*, APS-DPP (2017)

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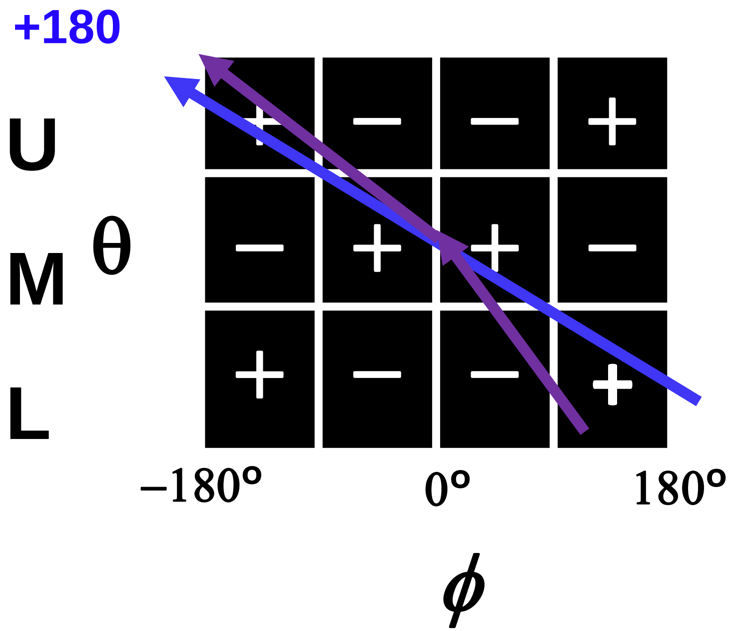
The presence of in-vessel midplane coils enables us to investigate much more sophisticated 3-D configurations

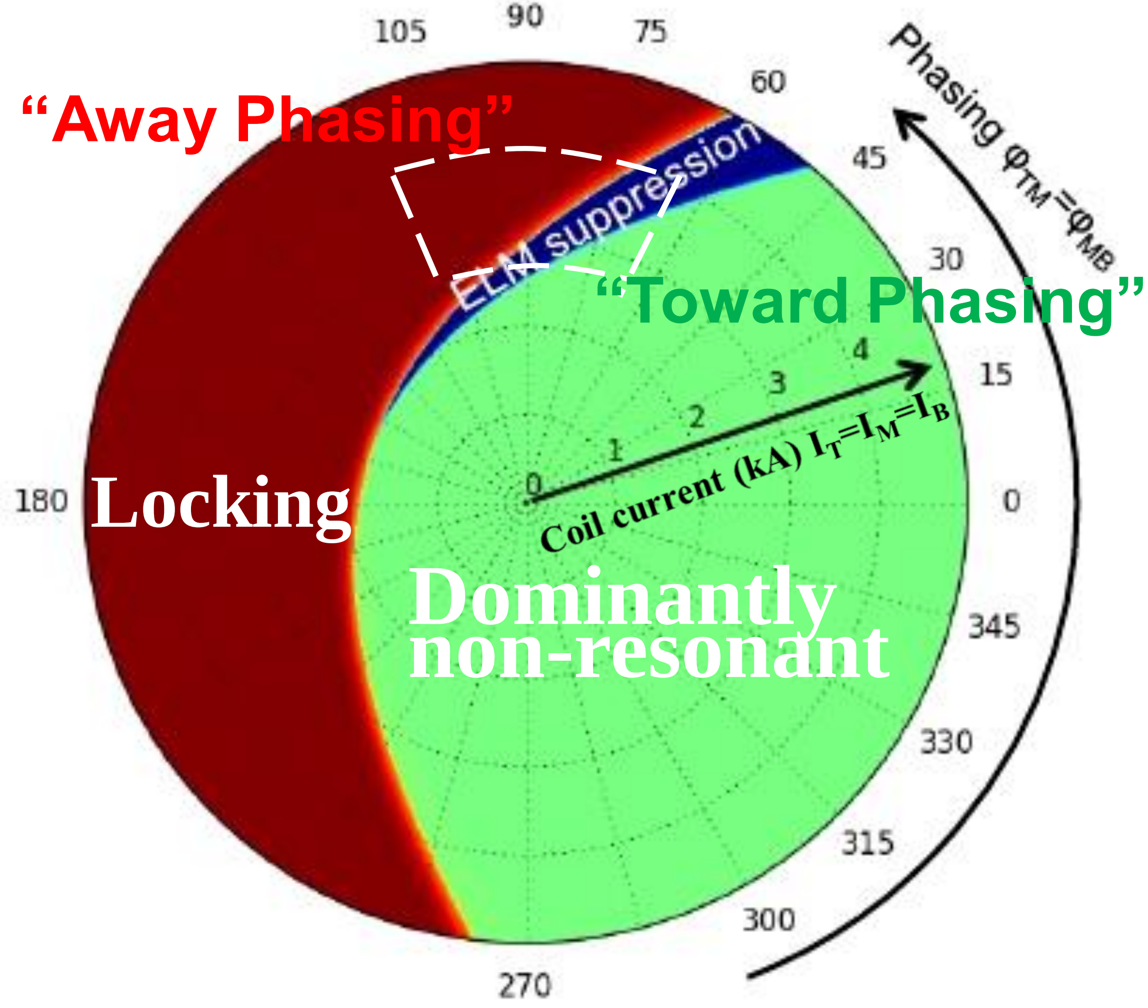
Phasing (= phase difference between rows)

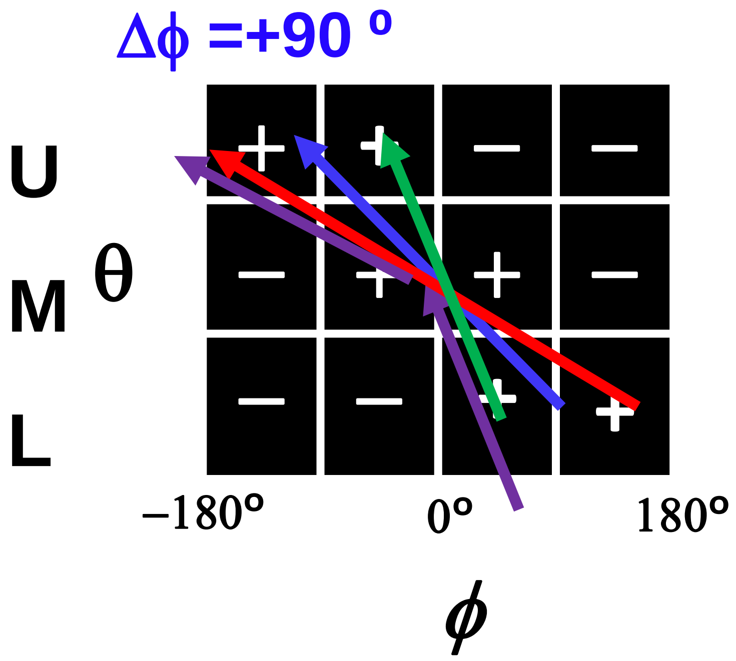


- Equal phasing ($\phi_{UM} = \phi_{ML}$): common
- Non-equal phasing ($\phi_{UM} \neq \phi_{ML}$): unique 3-D configurations (related to misalignment) that requires the presence of 3rd row

Without adding time-varying RMPs, spatially-modified configurations could relieve the material fatigues, possibly leading to a longer lifetime of materials in ITER

Intentionally misaligned configurations are not only compatible with ELM-crash-suppression, but also effective in dispersing the divertor heat flux, while minimizing EM loads on RMP coils



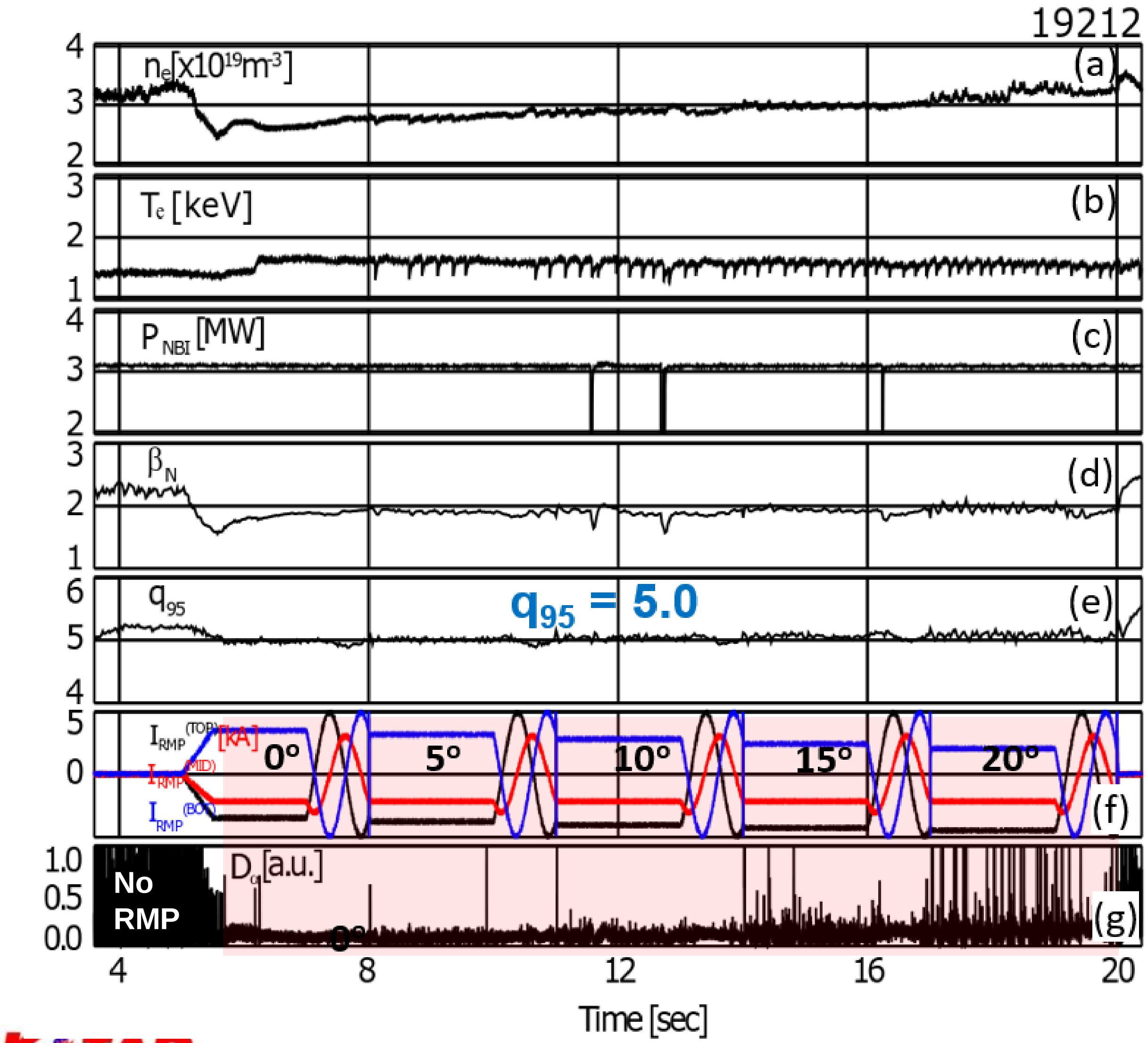


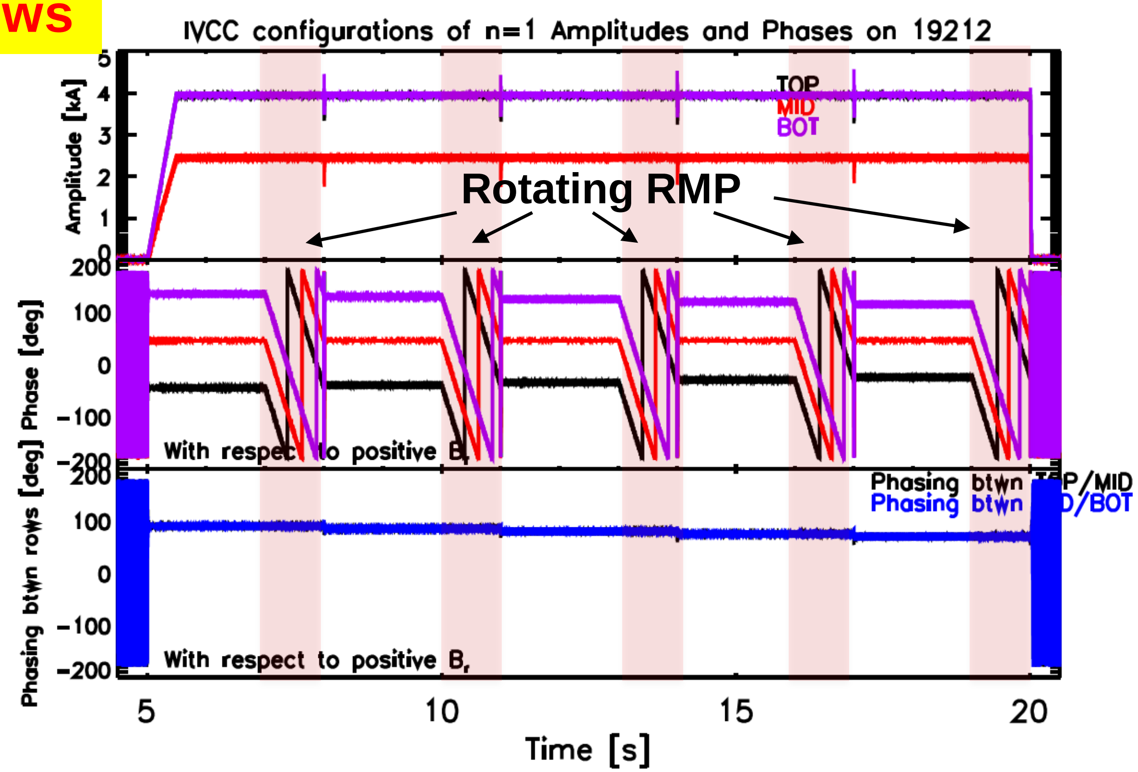
Y. In *et al*, IAEA-FEC (2018)

"Toward" Phasing in n=1 RMP appears as equally effective as "Away" phasing in terms of ELM-crash-suppression, suggesting a broad optimal phasing

"Toward" each other at Upper/Lower rows

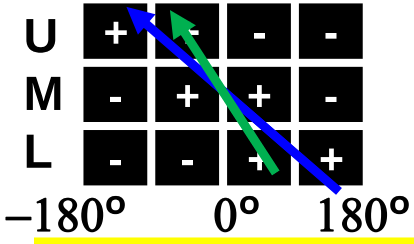
3-rows





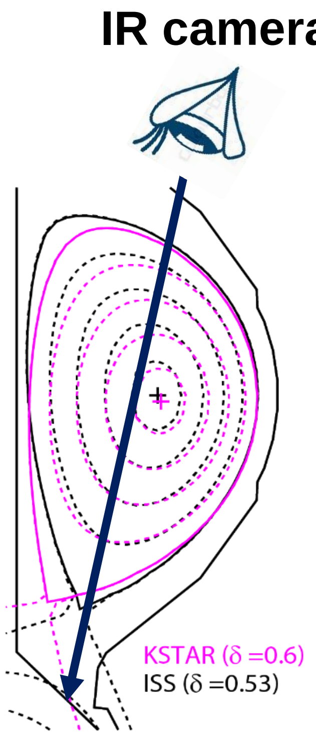
(ϕ_{UM}, ϕ_{ML})= (-90,90); (-85,85);(-80,80);(-75,75);(-70,70)

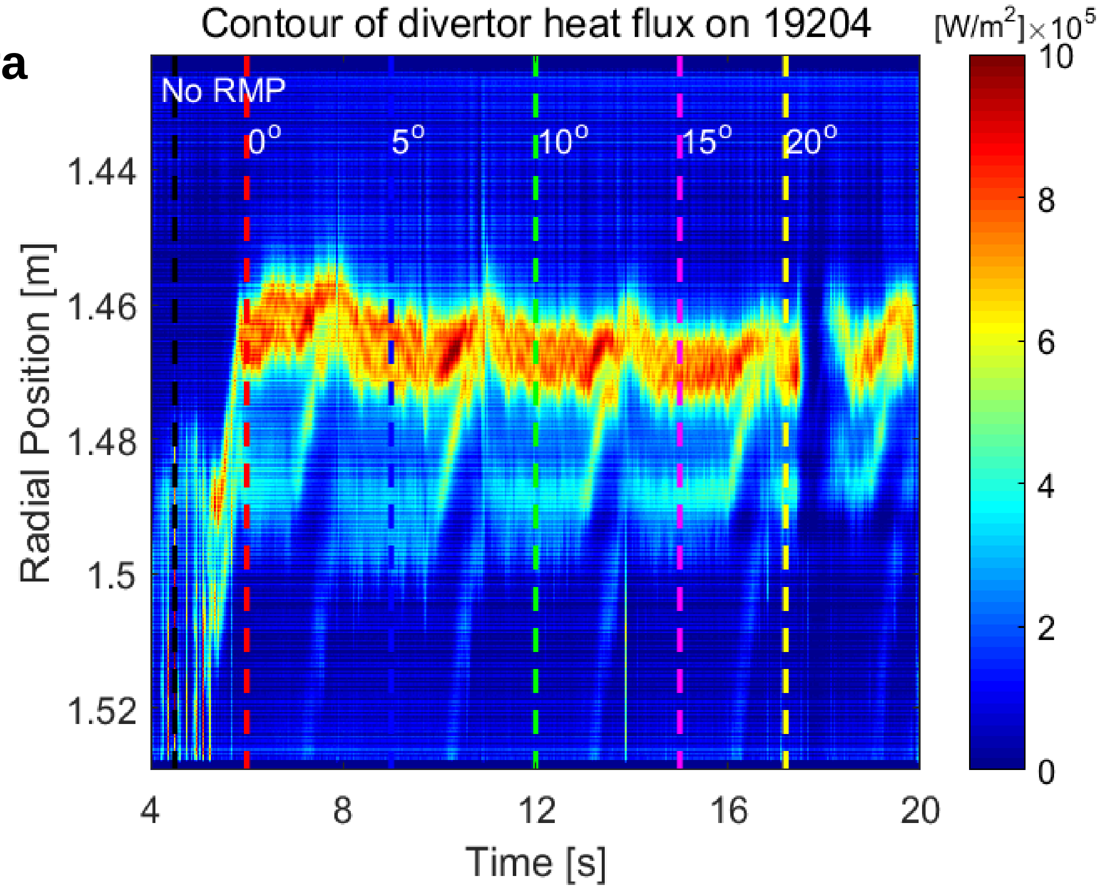
w.r.t. ϕ_M =0 deg [e.g. +90deg phasing (-90,90)]

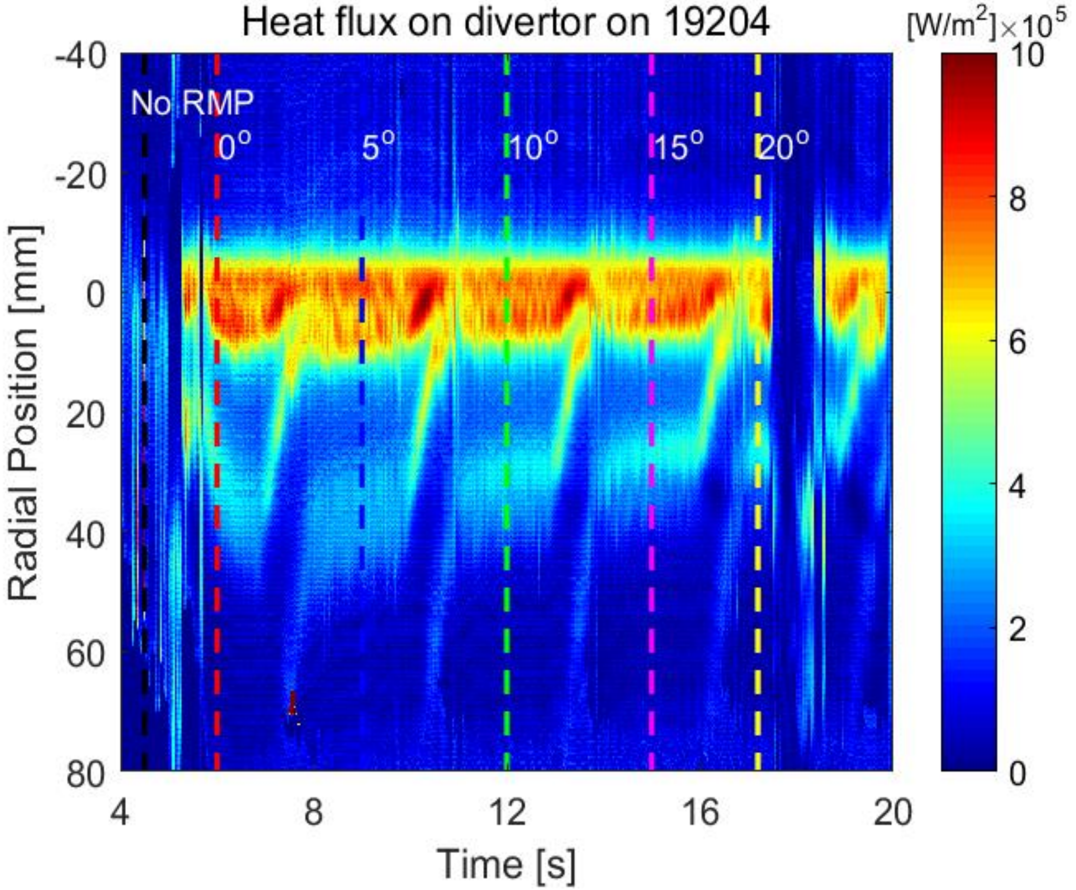


Y. In *et al*, IAEA-FEC (2018)

Given various uncertainties in fixing the outer strike point, the realigned heat flux patterns would help us assess the most stringent conditions on divertor

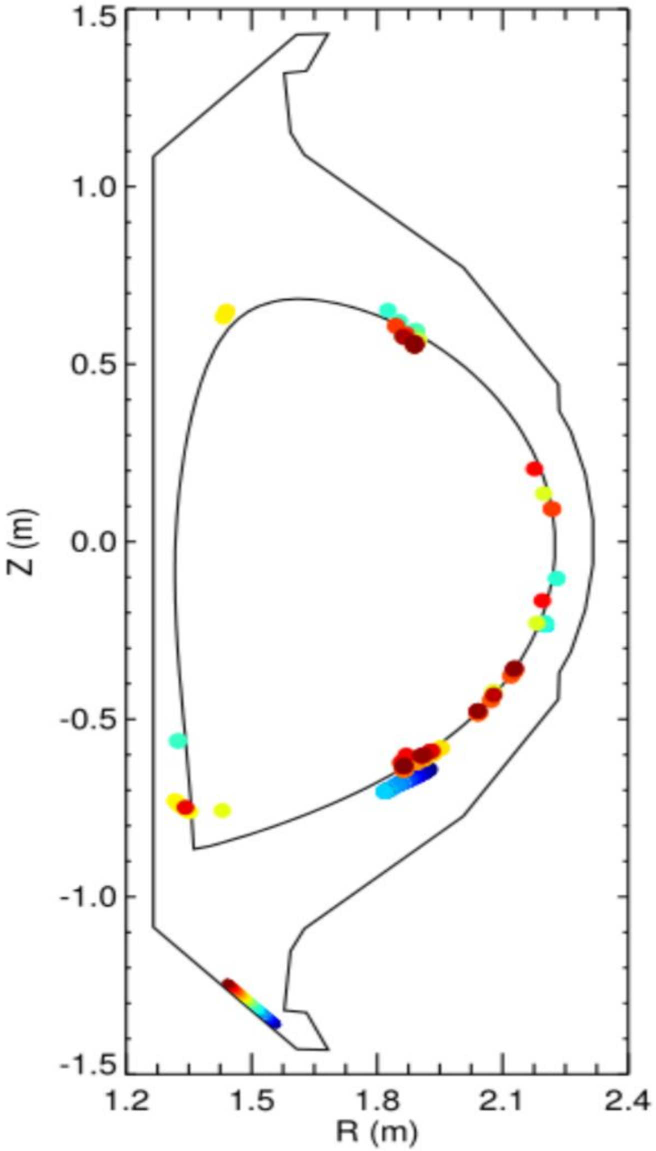


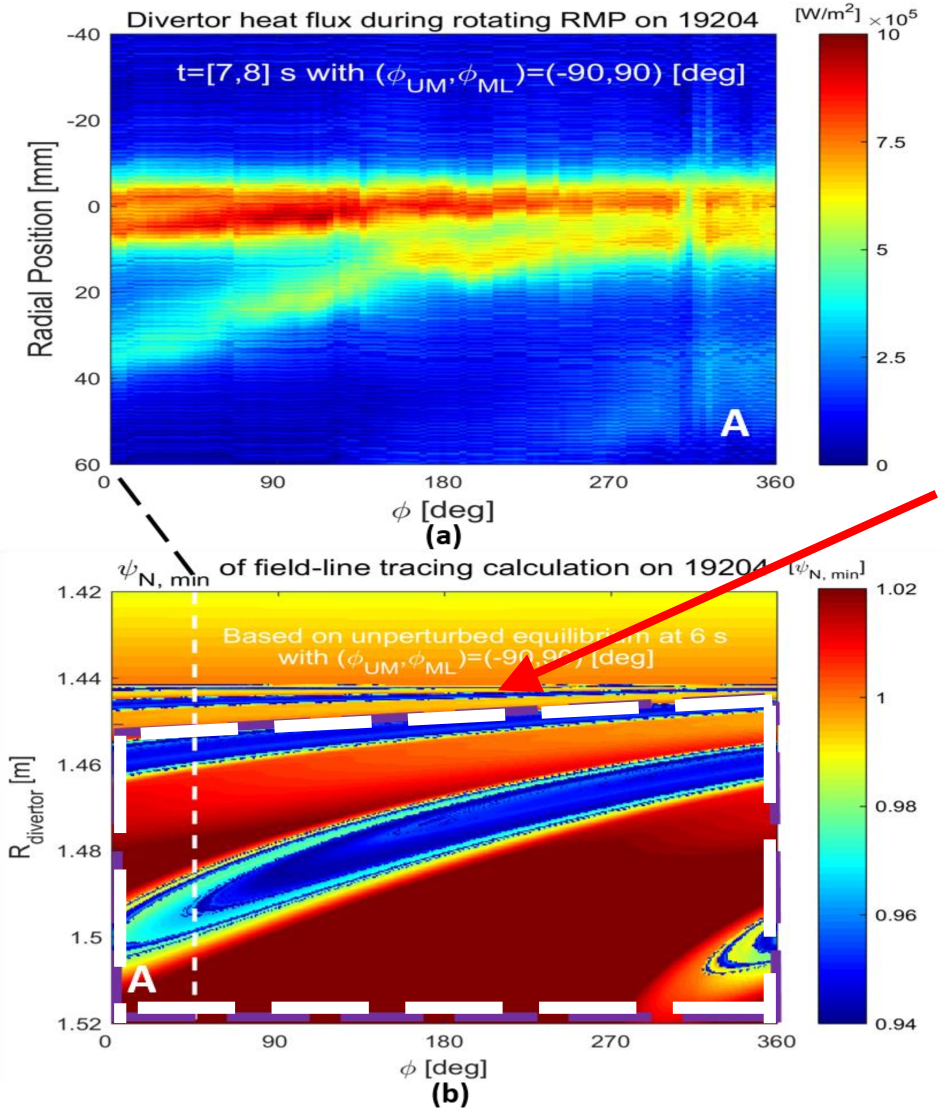




Hitting the same spot with the peaked heat flux throughout the discharge would be the most severe conditions, which could be regarded as the maximal heat flux on divertor

Field-line-tracing suggests minimum ψ_n surface, possibly corresponding to the vicinity of the outer striking point





No effect on power loads in narrow regions of long connection lengths, attributable to a ‘smearing’ effect due to perpendicular transport effects

[Kobayashi *et al*, NF (2007); Stangeby & Mitteau, JNM (2009)]

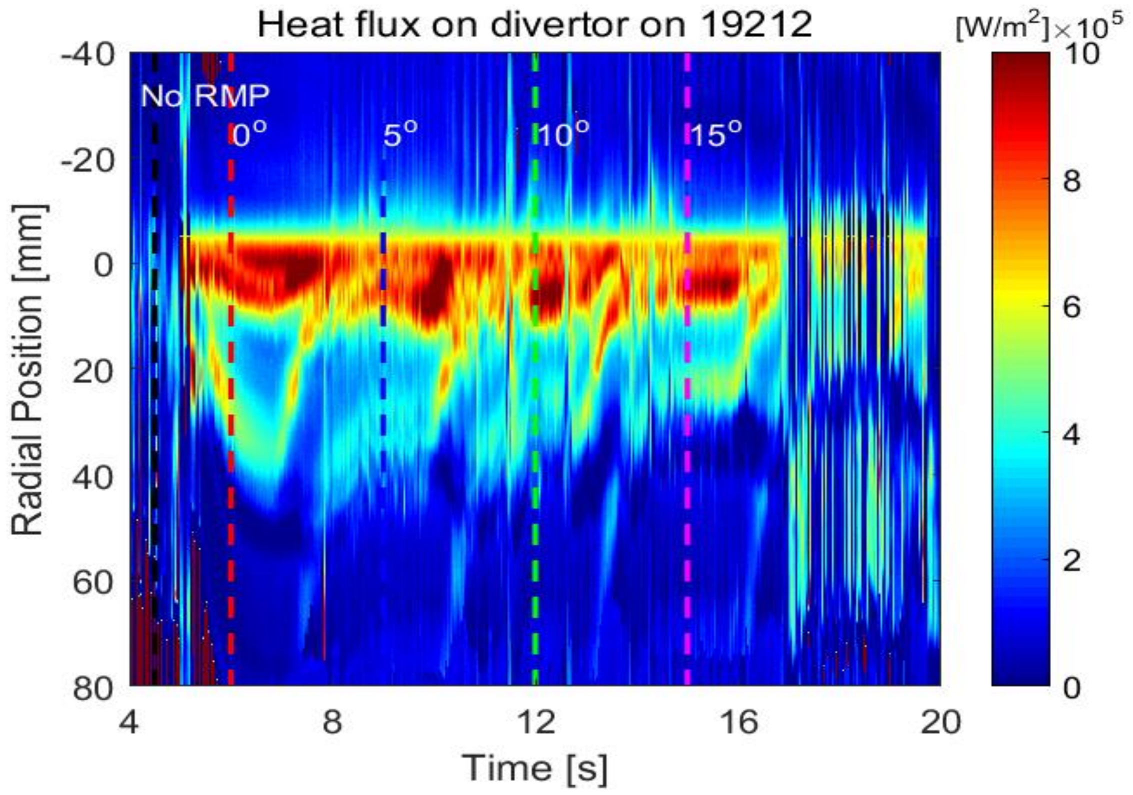
Refer to K. Kim *et al*, PoP (2017)

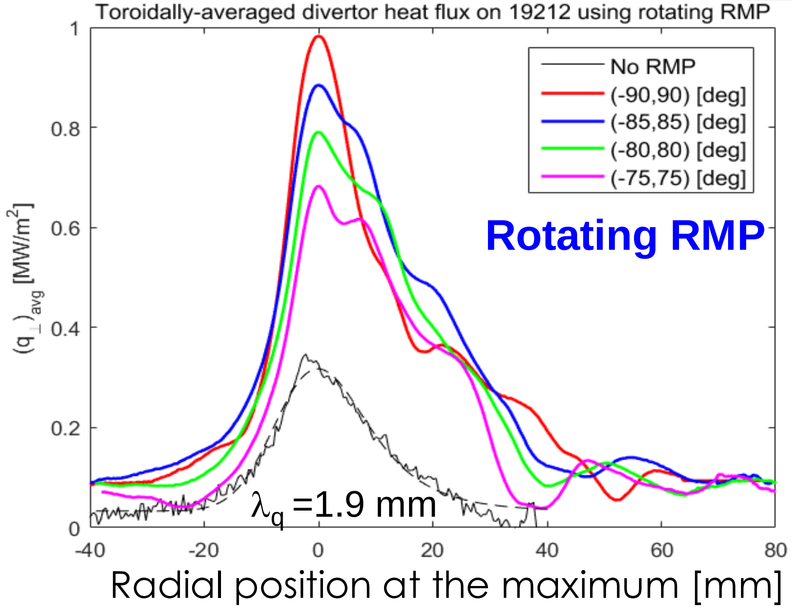
Y. In *et al*, IAEA-FEC (2018)

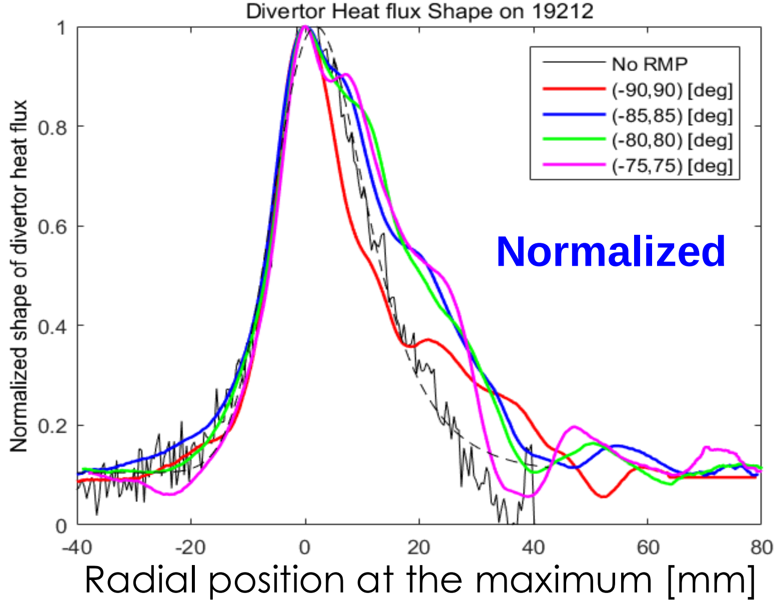
“Toward” phasing in n=1 RMP appears as equally effective in dispersing divertor heat flux as found in “Away” phasing (kink-aligned)

3-rows

Realigned divertor heat flux (19212)



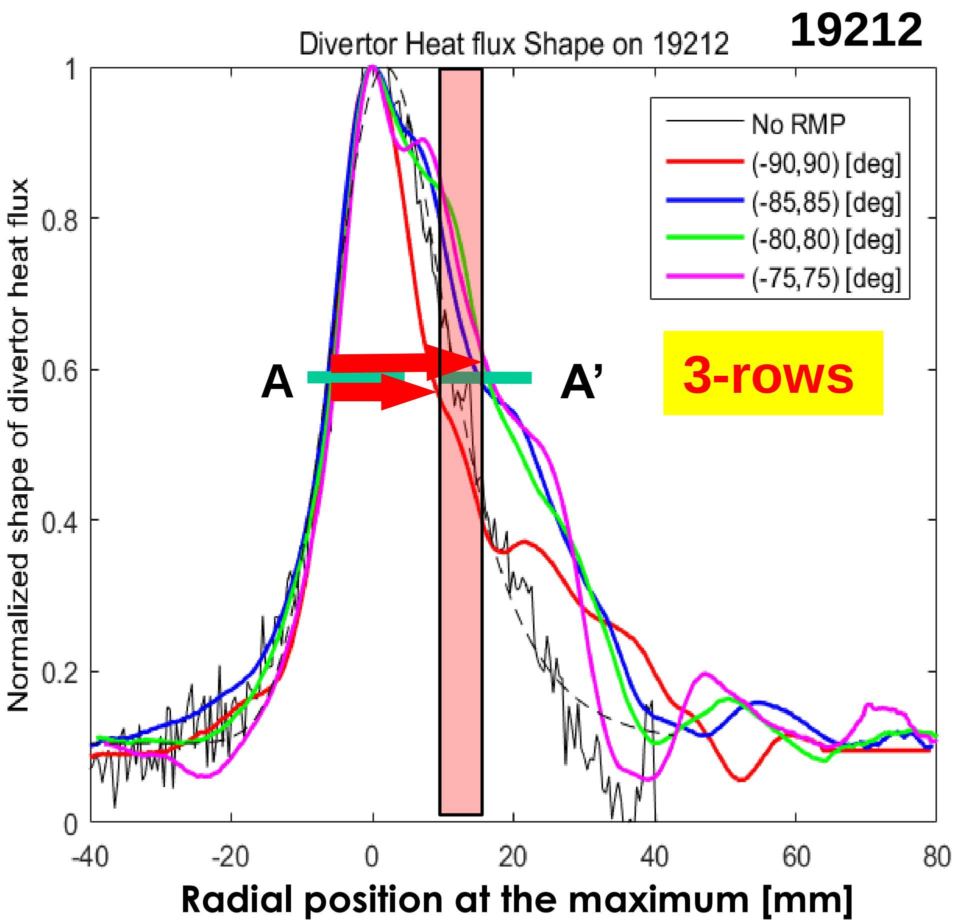


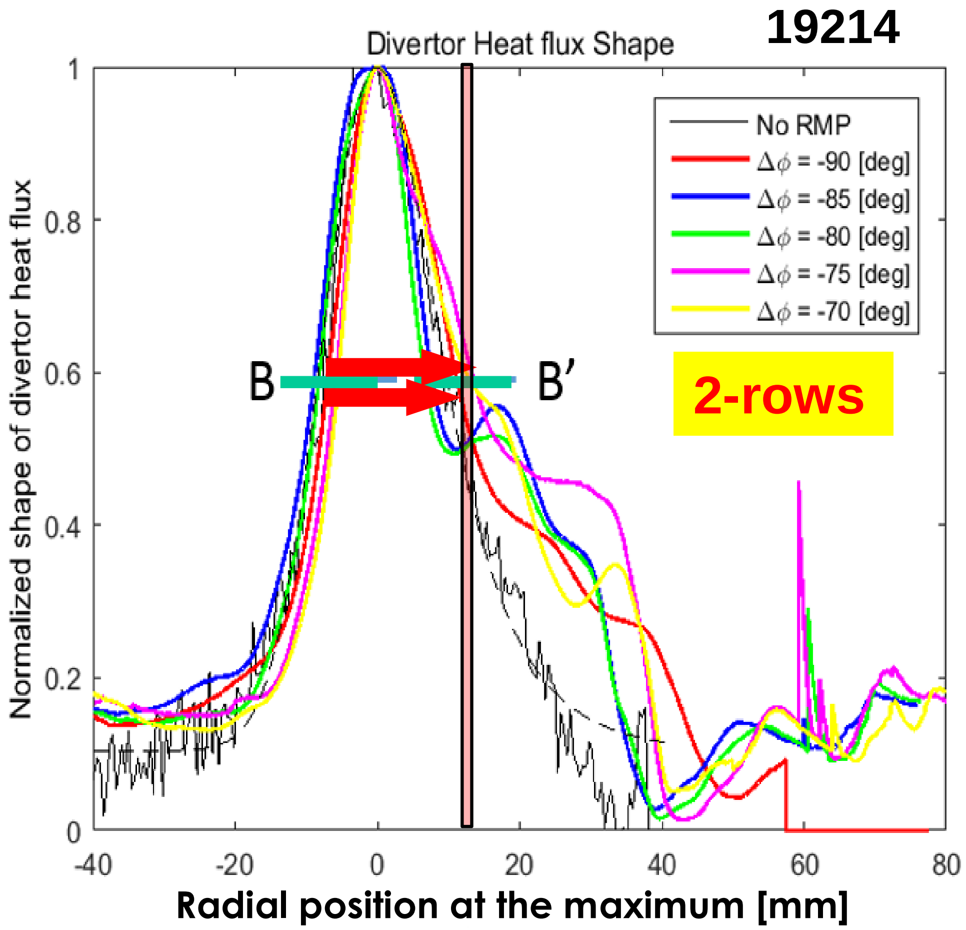


“Toward” dephasing benefits are clearly observed in terms of divertor heat flux dispersal, prior to the loss of ELM-crash-suppression, avoiding mode-locking!

Y. In *et al*, IAEA-FEC (2018)

ITER-like 3-row RMPs have broadened the divertor heat flux during ELM-crash-suppression at the near SOL, which cannot be seen with 2-rows

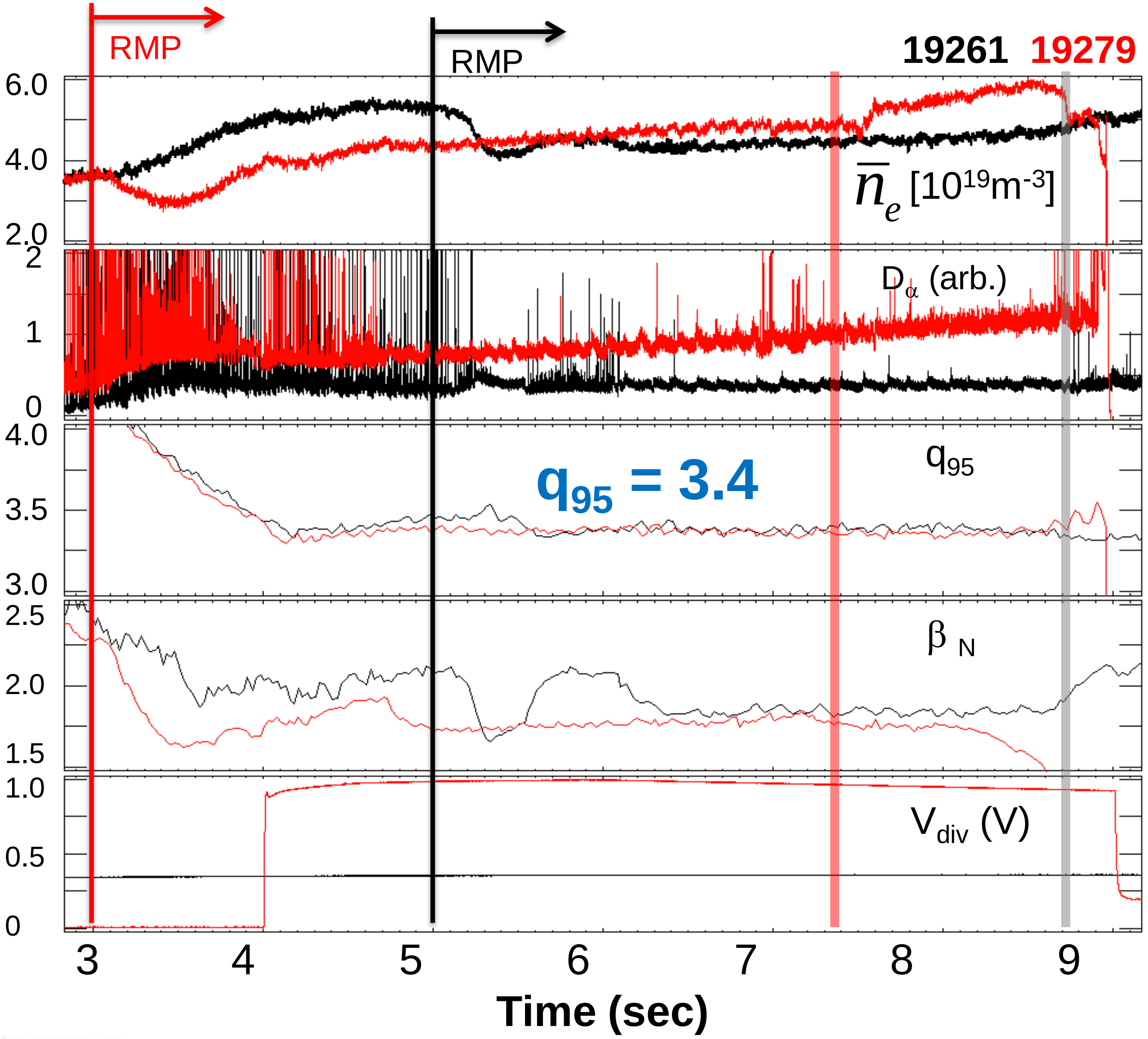




Additional degree of freedom in 3-rows in RMPs, beyond usual 2-rows, appears responsible for the broadening of the heat flux near SOL, favorable to the ITER system

Y. In *et al*, IAEA-FEC (2018)

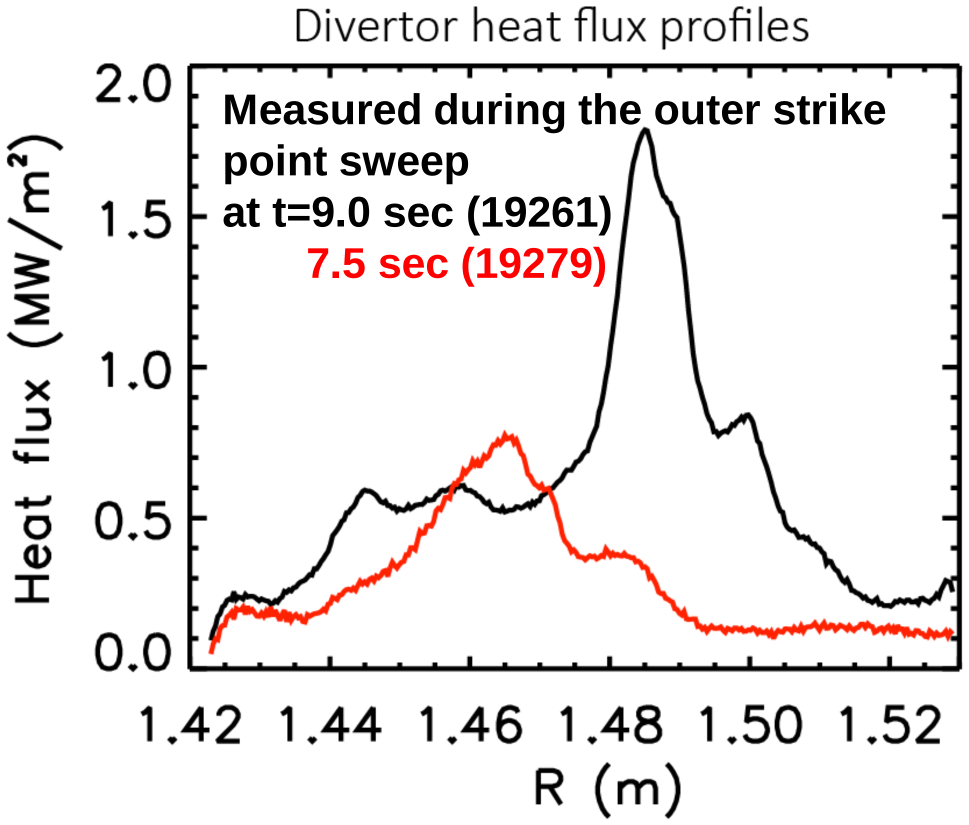
High density ELM-crash-suppression has been achieved for n=2 RMP with substantial reduction of divertor heat flux, despite no detachment yet



q_{peak} = 1.8 MW/m^2 (19261): typical density

vs

0.8 MW/m^2 (19279): high density



J.W. Ahn *et al*, APS-DPP (2017)

Contents

Introduction

Physics behind various ELM control methods

- **RMP**, **pellet pacing**, vertical jog, (ECCD, SMBI, Impurity injection; NOT Covered here)

RMP-driven, ELM control

- What is RMP? Stochasticity; vacuum and plasma response;
- Decoupling core mode-locking and edge RMP
- Prevailing understanding of physics mechanism

(Parameters: q_{95}, ν^*, δB-spectra, shape-dependence)

Divertor heat flux during ELM-controlled periods

- 3-D field influenced heat flux broadening during ELM-crash-suppression

Discussion

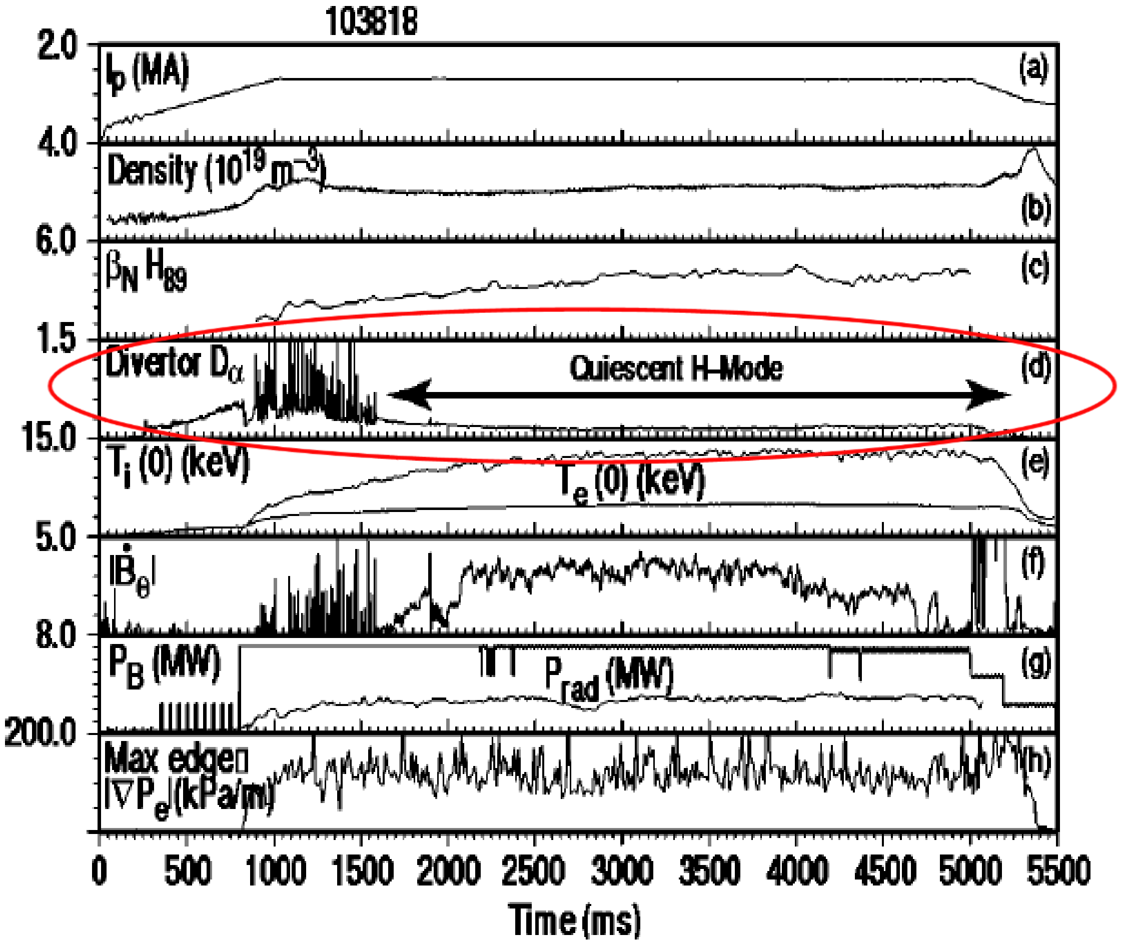
- "ELM-less" vs ELM-controlled plasmas

Concluding Remarks

Inherently ELM-less plasmas would be ideal, while requiring further explorations beyond a few devices

QH-mode (w/ edge harmonic oscillators (EHO))

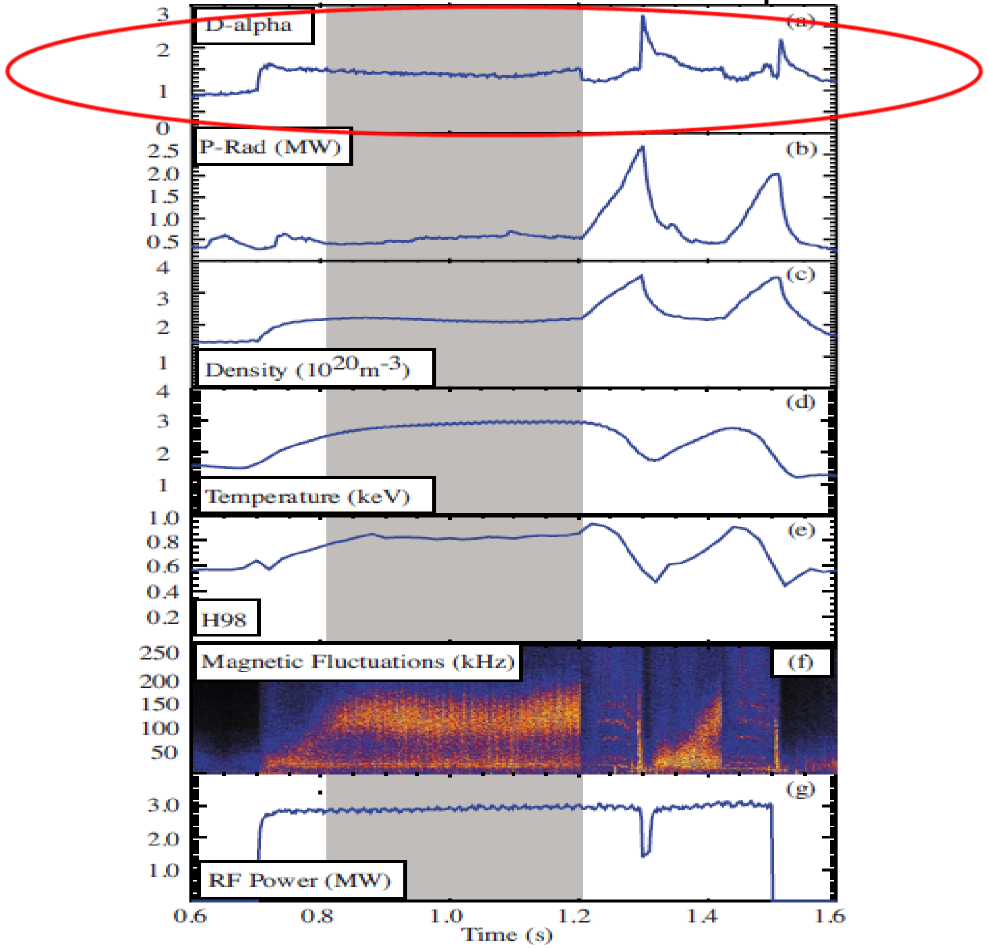
“Saturated kink-peeling associated with high δ”



K.H. Burrell *et al*, PoP (2001)

I-mode (w/ weakly coherent modes)

“compatible with ITER-relevant $\nu_{ped}* \sim 0.1$”

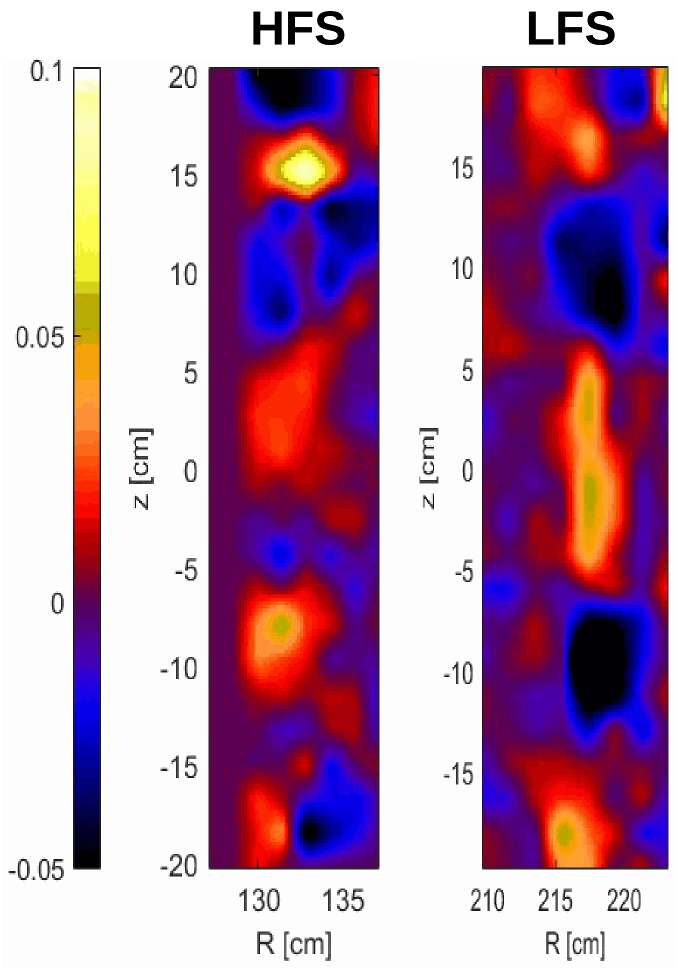


R.M. McDermott *et al*, PoP (2009)

See M. Fenstermacher’s talk

Even during n=1 RMP ELM-crash suppression, lively edge activities are undoubtedly present in both HFS and LFS

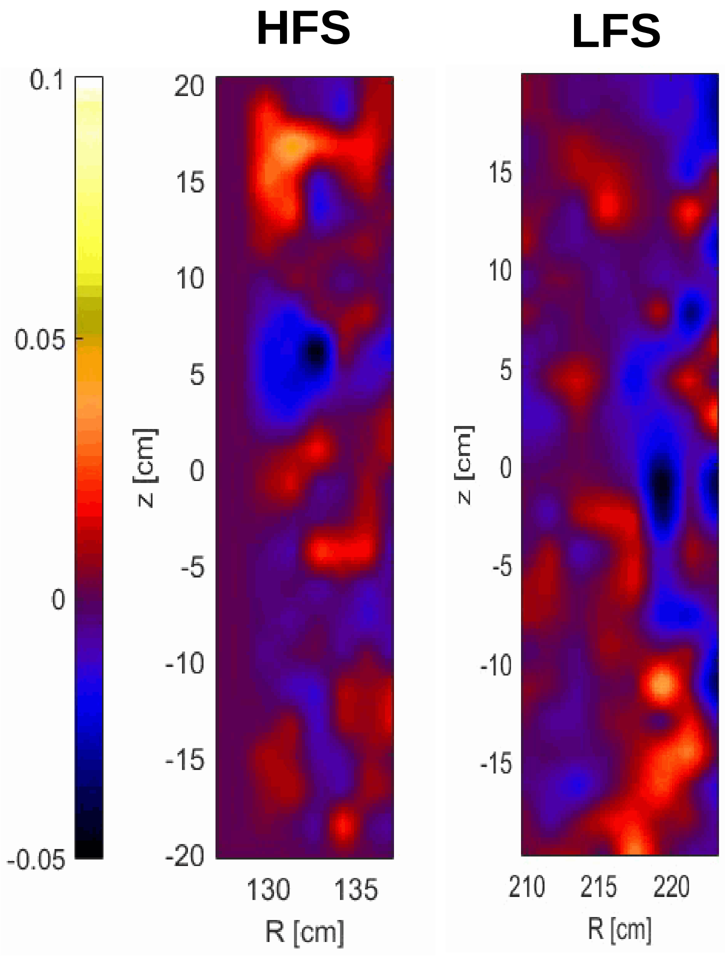
ELM-ing Phase



Peeling-ballooning transition from unstable to stable boundary in theory may need to be revisited to understand lively edge activities, as observed on ECEI during RMP ELM-crash suppression

Similar/Dissimilar to what DIII-D magnetics showed with n=2 RMP ELM suppression

ELM-crash suppressed Phase (14058)



Y. In *et al*, APS-DPP (2015)

The physics mechanism of RMP-driven, ELM-crash-suppression has not been fully resolved in both theory and experiments yet

Theoretical perspective

- Stochastic layer

(“…eventually abandoned” due to

‘no temperature gradient change’

==> response current (shielding) even on a single-rational flux surface near the pedestal top

➔ two-fluid nonlinear model

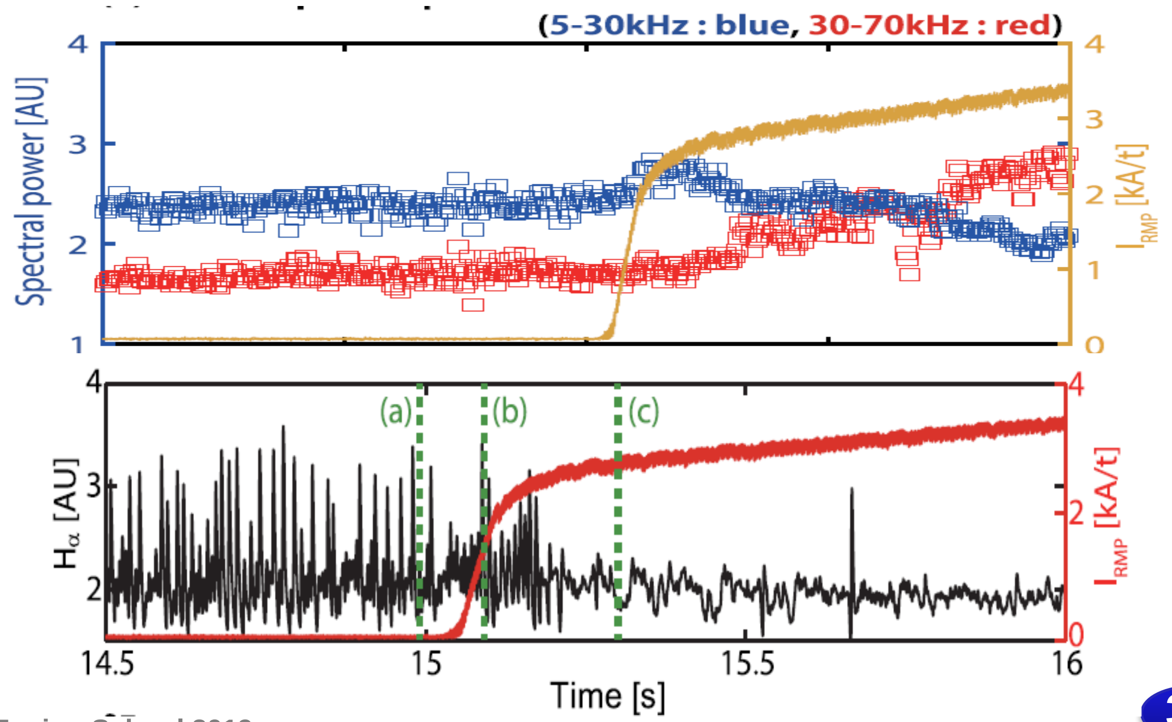
[e.g. Fitzpatrick’s PoP (2018)]

- Presence of filamentary structure even after the ELM-crash-suppression

Experimental perspective

- Puzzling: island formation prior to stochastic transport
- Nonlinear interaction of RMP with turbulent eddies

J.H. Lee *et al*, PRL (2016)



Universality of critical 3D Physics issues needs to be pursued, while further contributing to the physics understanding on urgent ITER needs

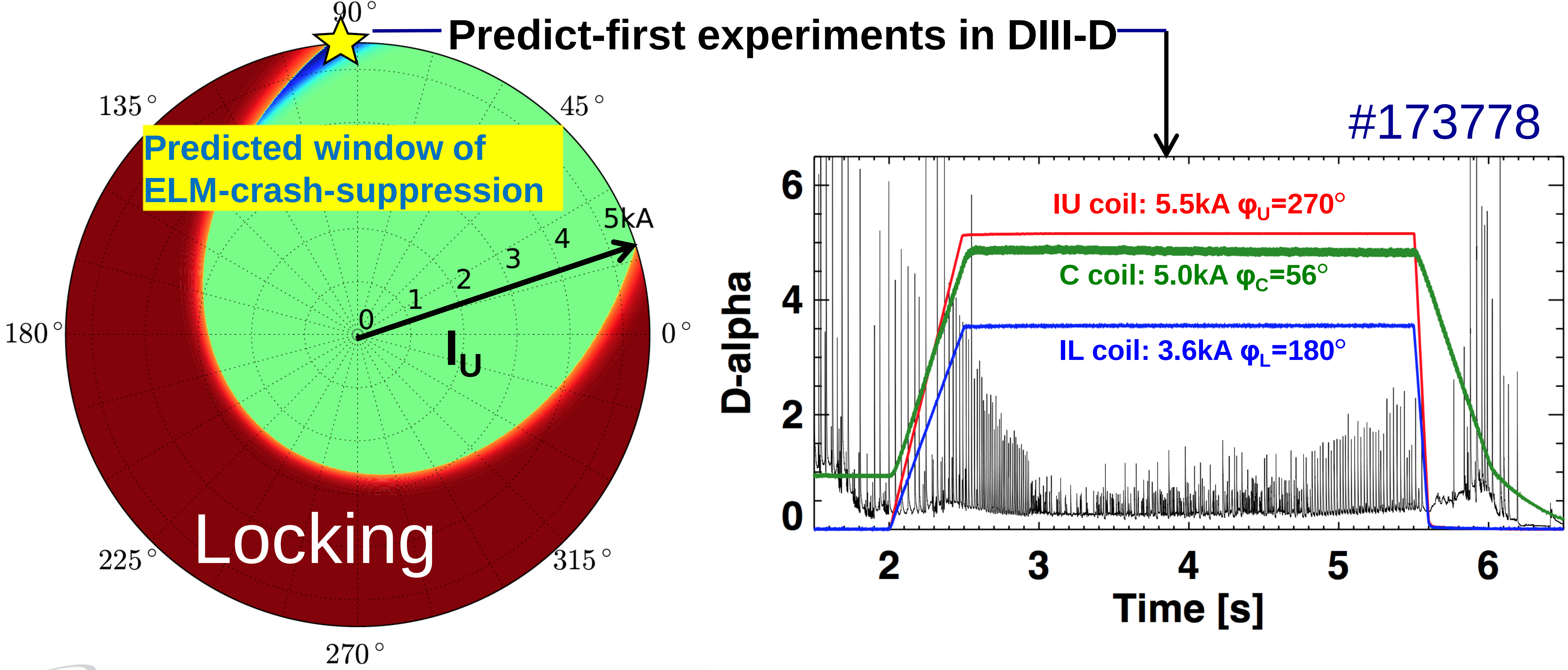
- **Universality of RMP ELM suppression physics**

  [**shape dependence (R_x, δ_{lower}, δ_{upper}),** q_{95}, ν^*, δB-spectra/strength]
  - Low q_{95} RMP ELM suppression with ITER-similar shape (ISS)
  - Compatibility of RMP with detached plasmas
  - Inter-machine comparison
- **RMP ELM suppression model prediction and validation with and without accurate edge modeling**

  - IPEC : global plasma response; no rotation or "kinetic" effects
- **Any benefits of mixed RMPs vs single-n RMP?**
- **Merits of 3-rows over 2 rows (in ITER-like RMP configuration)**
- **Turbulence impact on critical transitions, including L to H and the onset of ELM-crash-suppression**

Including all the affordable I-coil and C-coil currents in DIII-D, the predictive 3-D optimization has been tested, casting hope and homework

3-D optimization using I and C-coils shifts the optimal phasing window



NOTE no mode-locking, despite the huge n=1 currents in both C- and I-coils

Y. In, J.K. Park *et al*, APS-DPP (2018)

Demonstration of ELM-suppression using 3-D fields in multiple devices elevated the confidence about ITER RMP, despite a few on-going physics questions

- RMP-driven, ELM control is expected to be effective to suppress/mitigate ELMs in ITER, along with pellet-pacing technique
- A ‘big-picture’ of ELM control is quite consistent with a leading theory, while several critical points still need to be resolved (e.g. onset of suppression)
- Recent outstanding progress in KSTAR assures the merits of RMP-driven ELM control in ITER
  - Demonstrated broadened divertor heat flux during RMP ELM-crash-suppression using intentionally misaligned 3-D configurations (URGENT ITER needs)
- ELM control, as well as ELM-less operations, is expected to help us accomplish fusion reactors more reliably and safely beyond scientific merits

Back-up

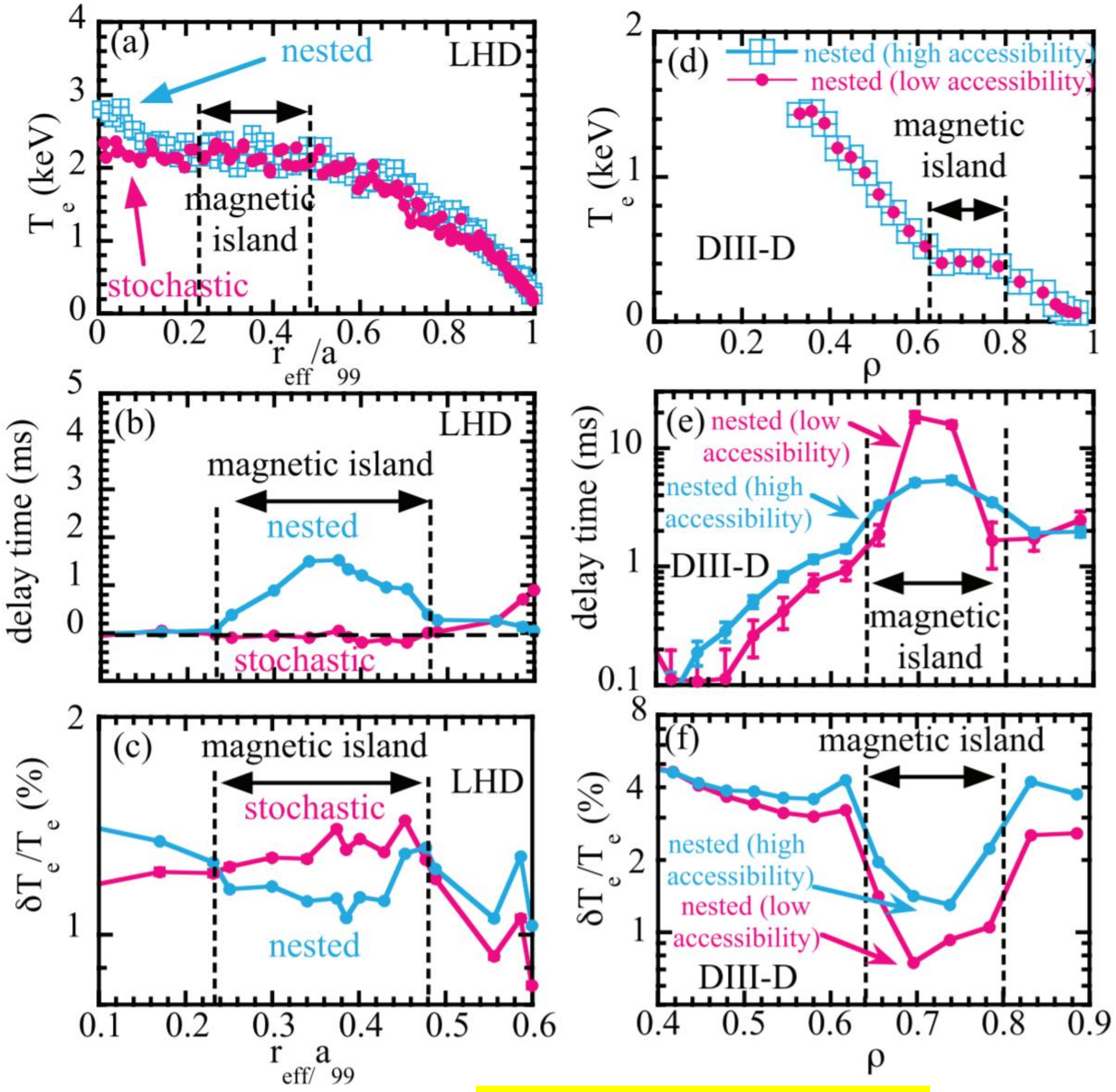
Stochasticity can be greatly contrasted with magnetic islands in terms of transport time scales

Magnetic islands (in nested flux surfaces)

- Heat pulse propagates inward and outward

Stochasticity

- Heat pulse propagates instantaneously



K. Ida et al, NF (2016)