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Enhanced understanding of non-axisymmetric intrinsic and controlled field impacts in tokamaks

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*S.W. Yoon, H. Park****, and the 3D Physics Task Force in KSTAR*

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**PPPL, **ORNL, ***ITER, and ****UNIST*

In acknowledgement of the supports by Ministry of Science, ICT, and Future Planning under KSTAR project

An order of magnitude lower level of intrinsic non-axisymmetry enables us to address 3D field physics and its uncertainties more rigorously

- In a typical tokamak (with intrinsic EF : $\delta B/B_0$ ~ 10^{-4})
  - Resonant Magnetic Perturbation (RMP): $\delta B/B_0$ ~ up to 10^{-3}

    [e.g. 6×10^{-4} for n=4 suppression in ITER design]

  - Requires actively controlled (removed) non-axisymmetry
  - No matter what we do, the presence of "non-axisymmetric fields" cannot be completely eliminated => multiple "uncorrected EFs"

In an extremely low EF tokamak ($\delta B/B_0$ ~ 10^{-5}), the application of δB can be controlled in an unprecedented level of precision!

KSTAR 3D physics research aims to resolve 3D field impacts on stability and transport, along with the state-of-the-art imaging diagnostics

- **Recent KSTAR experiments show that both intrinsic non-axisymmetric error field ($<\delta B_{m/n=2/1}>/B_0 \sim 10^{-5}$) and field ripple ($\delta_{TF}$=0.05%) would be among the lowest in the world**

  - **Stability**
    - ✓ No or little need of separate EFC Y. In *et al*, submitted to NF (2016)
    - ✓ Access to low $q_{95} < 2$ without EFC J. Kim *et al*, FEC (2014)

  - **Transport**
    - ✓ higher plasma rotation ($Mach_D \sim 0.8$) and edge rotation shear (momentum transport barrier) H.H. Lee *et al*, Phys. Plasmas (2016)
    - ✓ Nonlinear interaction of ELM and turbulent eddies in n=1 RMP J. Lee *et al*, PRL (2016)

Exciting 3D Physics experimental themes are being pursued to reach the fusion goals, along with a scientifically enhanced understanding

RMP ELM Physics

- Shape dependence Y.M. Jeon, J. Kim *et al*, FEC (2016)
- Kink-influence J.K. Park, Y. In, J.W. Ahn *et al*
- Urgent ITER request (Divertor heat-flux measurement) A. Loarte, Y. In *et al*
- Mechanism : $\omega_{\perp e} \sim 0$ G.Y. Park, Y. In *et al*

3D Transport

- Lower power threshold for L-H transition (P_{th}) W.H. Ko, Y. In *et al*, FEC (2016)
- Confinement times (vs δB, rotation, rotation shear etc) H.S. Kim *et al*
- Torque dependence (quantification) S.J. Wang *et al*

NTV physics

- Code verification and validation (in quiescent plasmas) J.K. Park, K. Kim *et al*, FEC (2016)
- Clarification of nu vs 1/nu regime with reversed-I_p H.H. Lee, J. Seol *et al*
- NTV Offset (exploration of electron-NTV-dominated regime) S. Sabbagh *et al*

3D Structure

- long-lived mode: S.G. Lee *et al*, PoP (2016), disruption: J. Kim *et al*
- ECEI G.S. Yun *et al*, FEC (2016), MIR W.C. Lee *et al*, FEC (2016)

Quantification of plasma response (incl. EF measurement)

- MHD Spectroscopy: Global MHD (n=1) warning system prep H.S. Han, J.G. Bak *et al*

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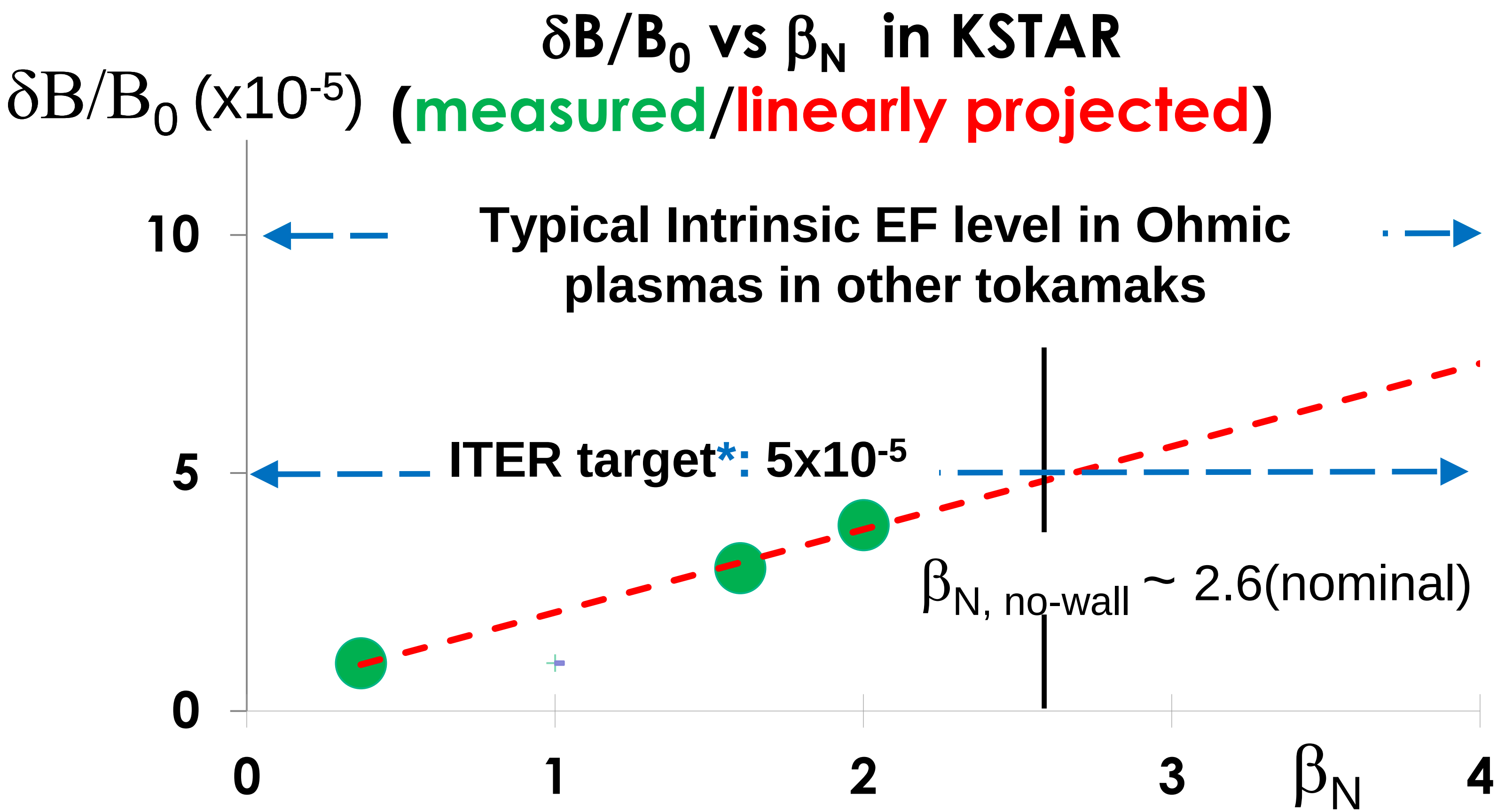
The intrinsic EF in KSTAR is projected to be low enough for us to easily reach the no-wall stability limit without dedicated EF correction



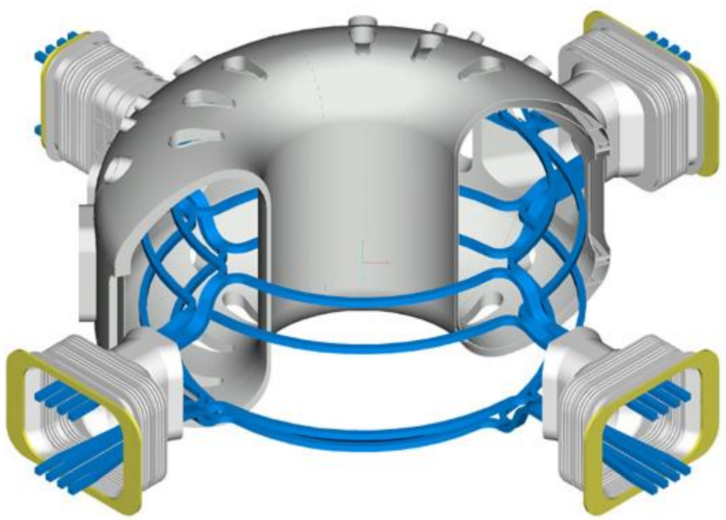
Despite no independent measurement yet, similarly low level of n > 1 harmonics is expected

*T. Hender *et al*, NF (2007)

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

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

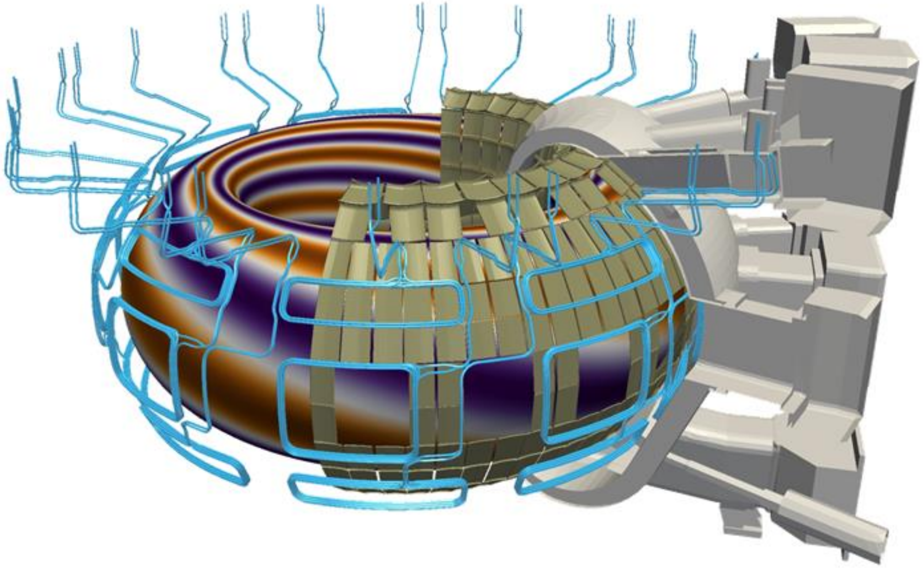
H.K. Kim *et al*, FED (2009)



ITER RMP coils configuration

Up to n=4 with 9 coils in each row

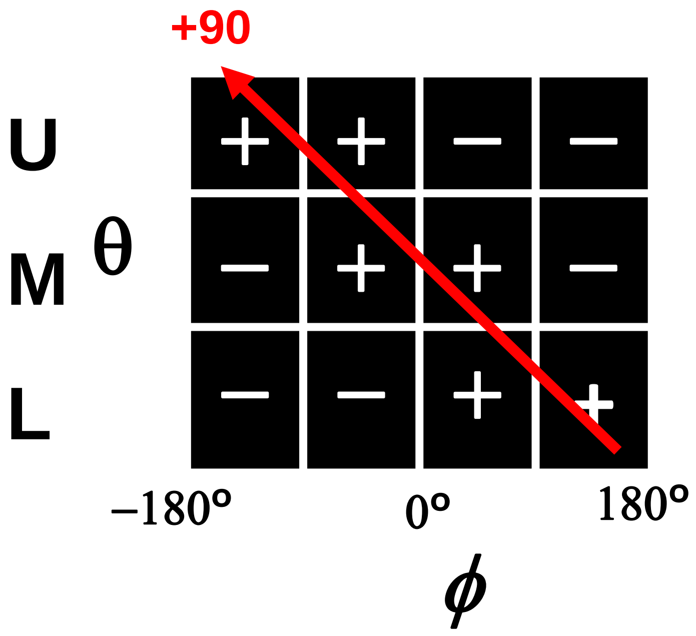
Courtesy of G.T.A. Huijsmans



Uniquely equipped with in-vessel mid-RMP coils

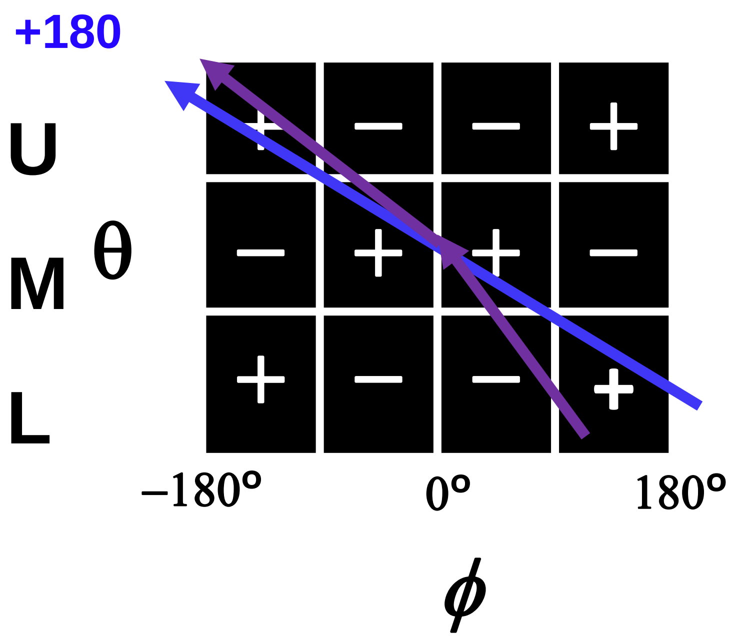
The presence of in-vessel midplane coils enables us to investigate much more sophisticated 3-D configurations

Phasing (= phase difference between rows)
[e.g. $\phi_{UM} = \phi_M - \phi_U = 0^o - (-90^o) = 90^o$]



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

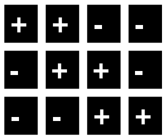
Phasing (= phase difference between rows)
[e.g. $\phi_{UM} = \phi_M - \phi_U = 0^o - (-180^o) = 180^o$]



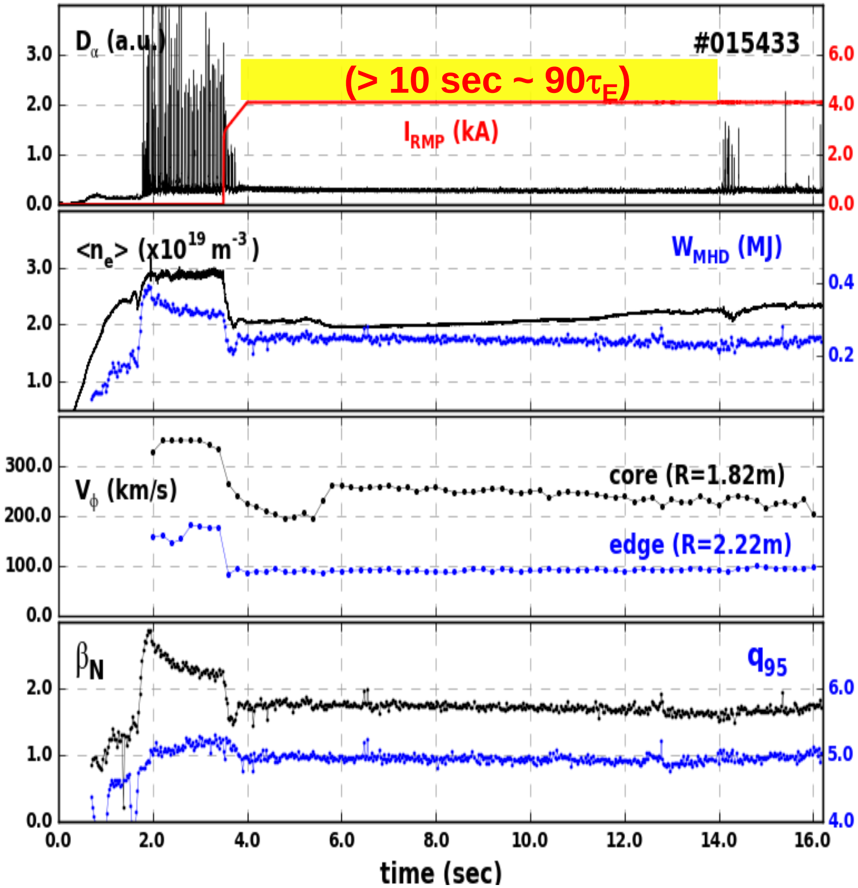
- **Equal phasing ($\phi_{UM} = \phi_{ML}$)**
➔ **IPEC modeling (in this talk)**

- **Non-equal phasing ($\phi_{UM} \neq \phi_{ML}$) 3-D configurations (related to misalignment) that requires the presence of 3rd row**
➔ **ITER task (in this talk)**

Onsets of n=1 RMP-driven ELM-crash suppression, as well as locking threshold, are in excellent agreement with model-based predictions



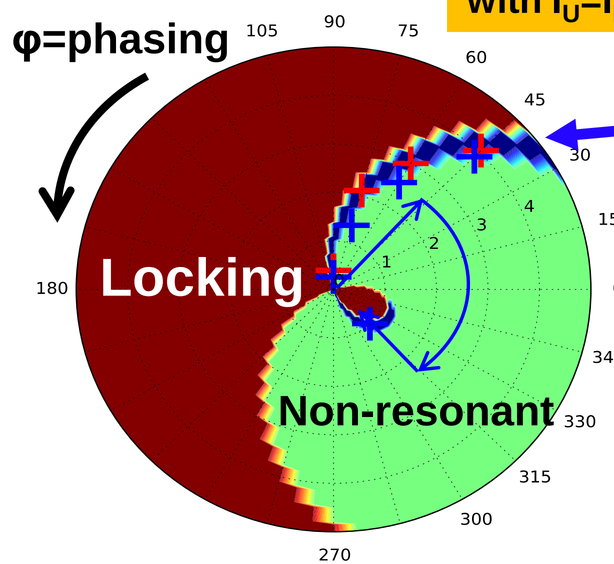
n=1 (+90 phasing)
full RMP at q_{95}~5.0 [~2 kA/turn]



Y.M. Jeon *et al*, FEC (2016)

- Relaxed q_{95} constraint: q_{95} = 5±0.25
- Importance of shape dependence
  - R_x (lower X-pt) = 144±2cm
  - [rather than δ_l =0.74±0.04]
- Prediction of phasing dependence based on ideal plasma response, consistent with expts

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

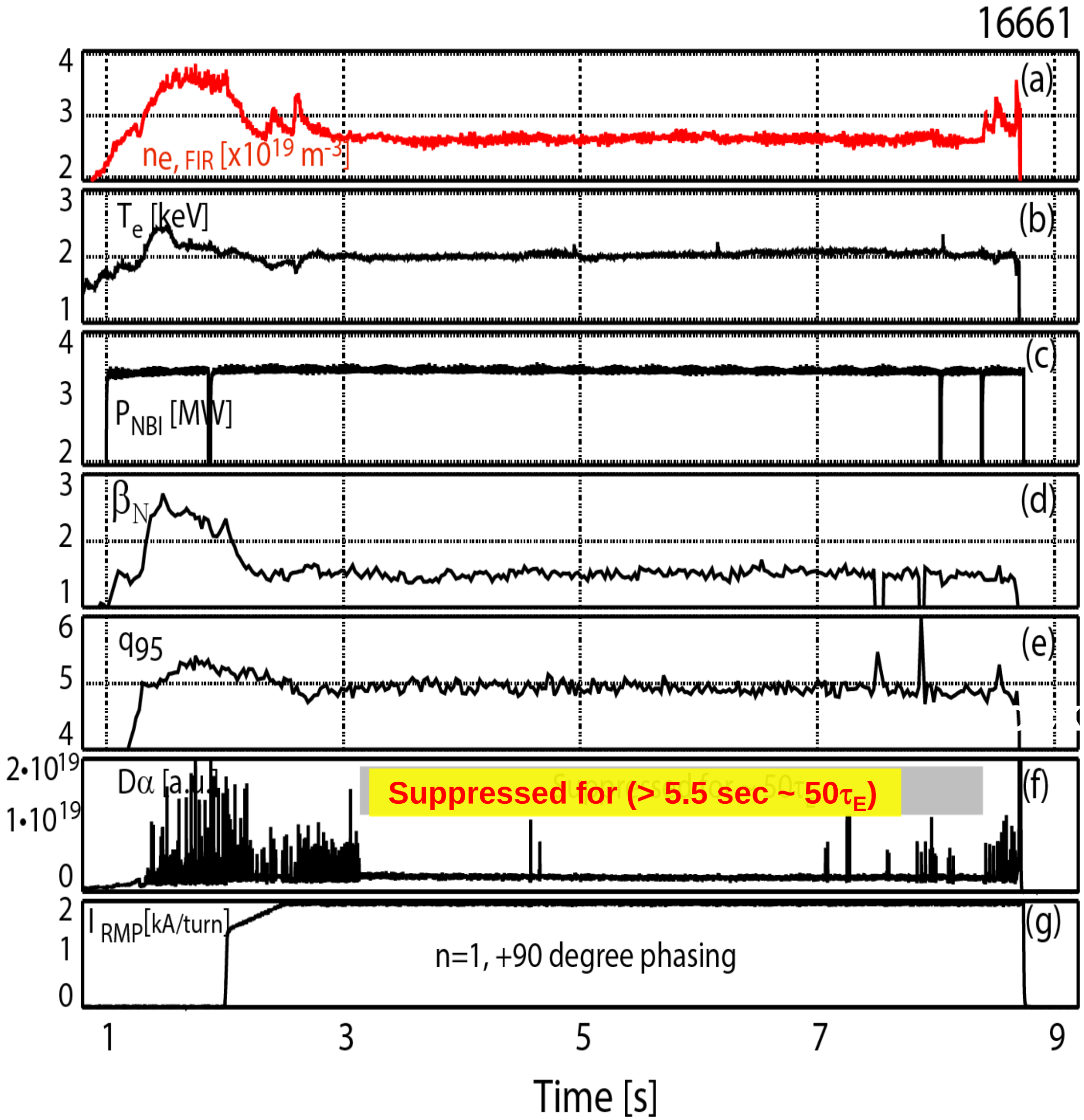


Suppression window

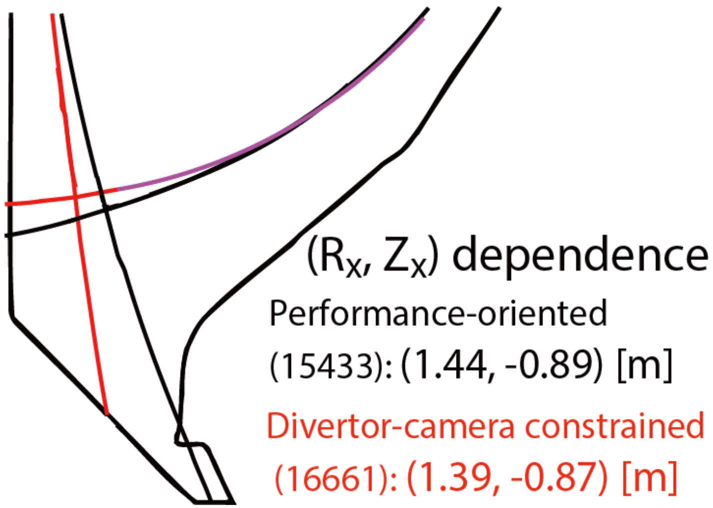
Prediction
vs
Empirical threshold
(Locking "+",
ELM suppression "+")

Minimize EF impacts in core, while maximizing RMP at edge

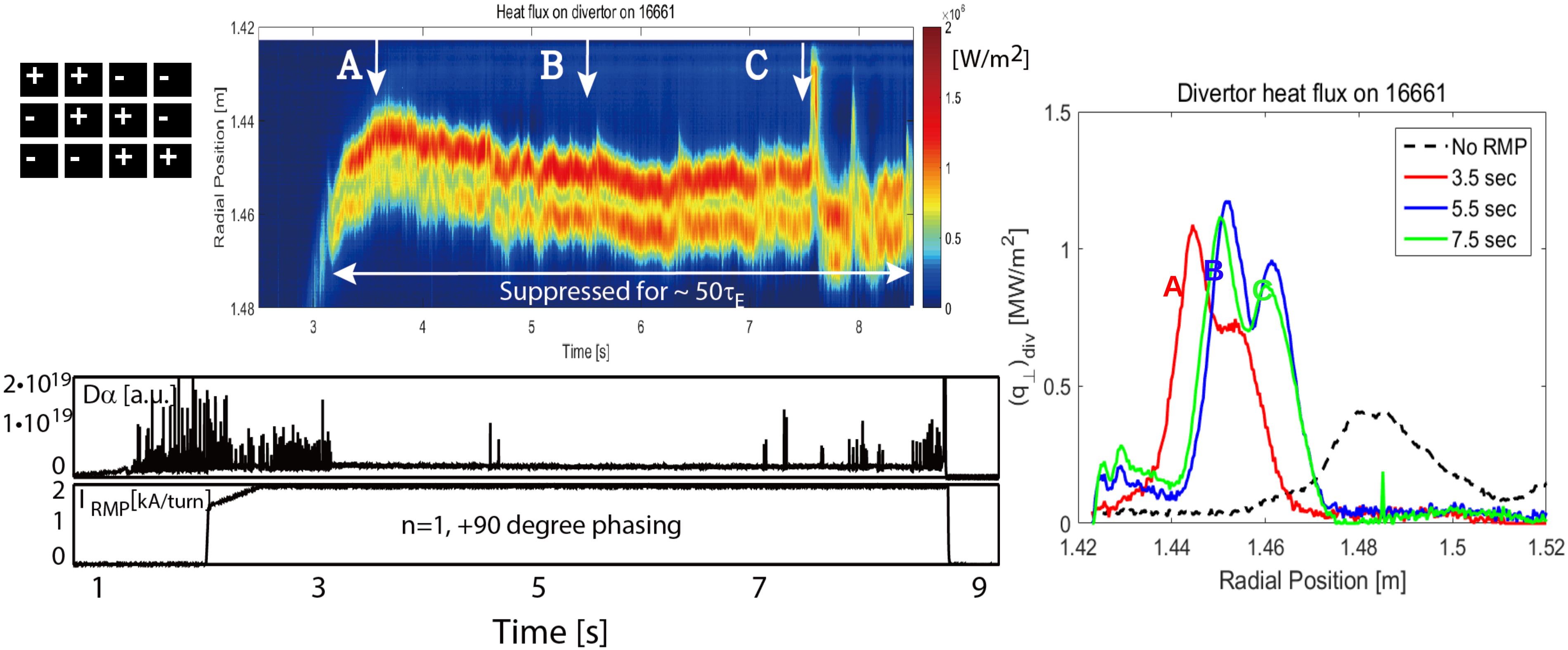
Another optimal window, under X-point constraint, has been found in the vicinity of the performance-oriented configuration



- **Optimal for divertor heat-flux study at the expense of q_{95} = 4.95±0.05 (strict constraint) R_x (lower X-pt) = 139±1cm (equivalent to δ_l~0.85±0.02)**
- **Operationally much more challenging**



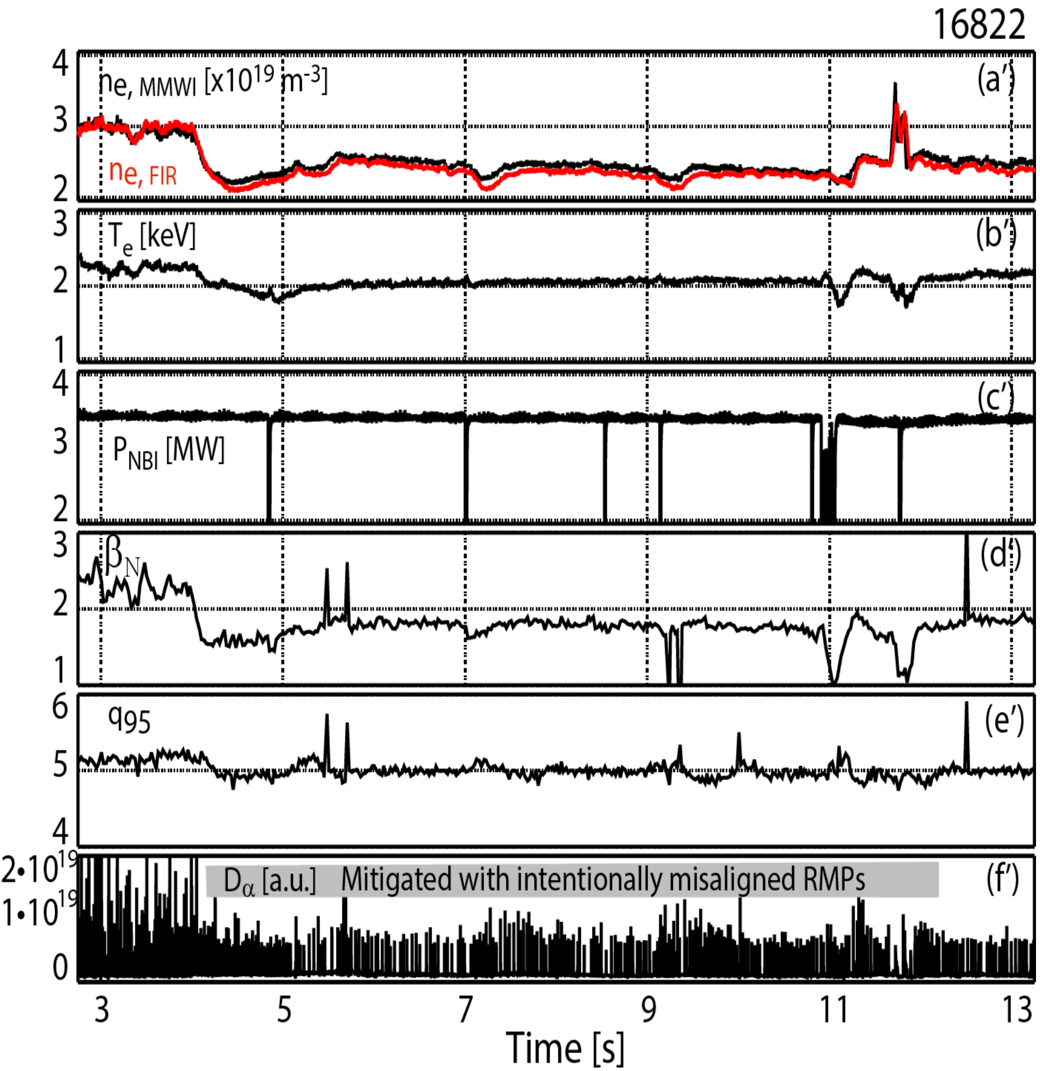
During ELM-crash suppression, both peaks of axisymmetric and non-axisymmetric fields are measured below ~1.2 MW/m^2 at P_{NBI} = 3.4 MW

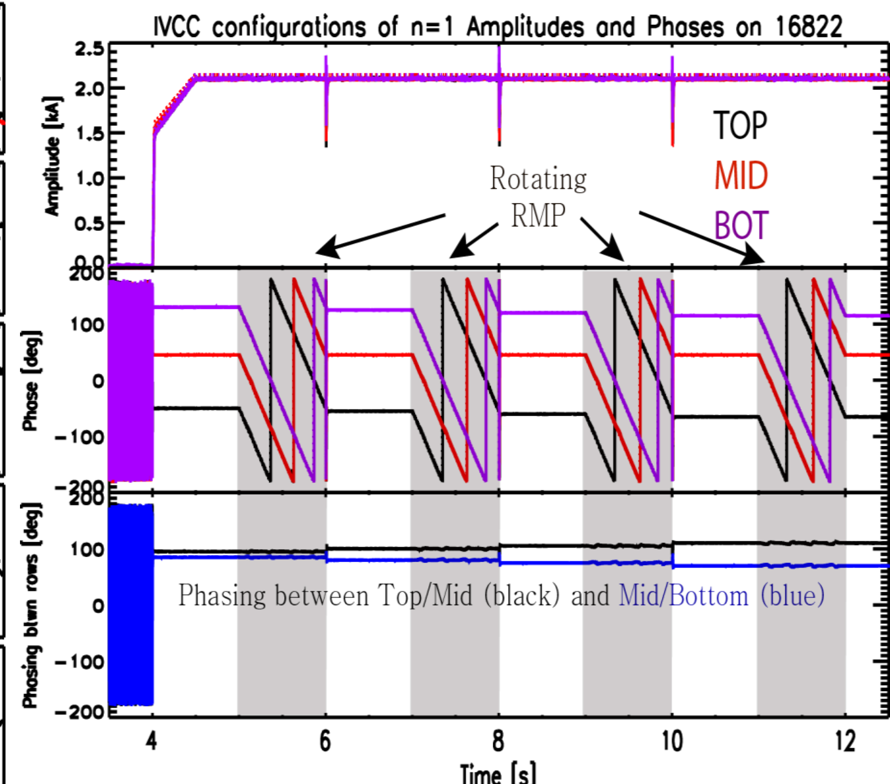


- **Peak of axisymmetric lobe remains higher than that of non-axisymmetric lobe even during ELM-crash suppressed stage**

NOTE: Huge ELM spikes (e.g. up to 50 MW/m^2 measured in fast IR camera) are not out of the camera view for "No RMP case" here H.H. Lee *et al*, FEC (2016)

Intentionally misaligned RMP configurations would spread the divertor heat fluxes in a wider area (in support of ITER)



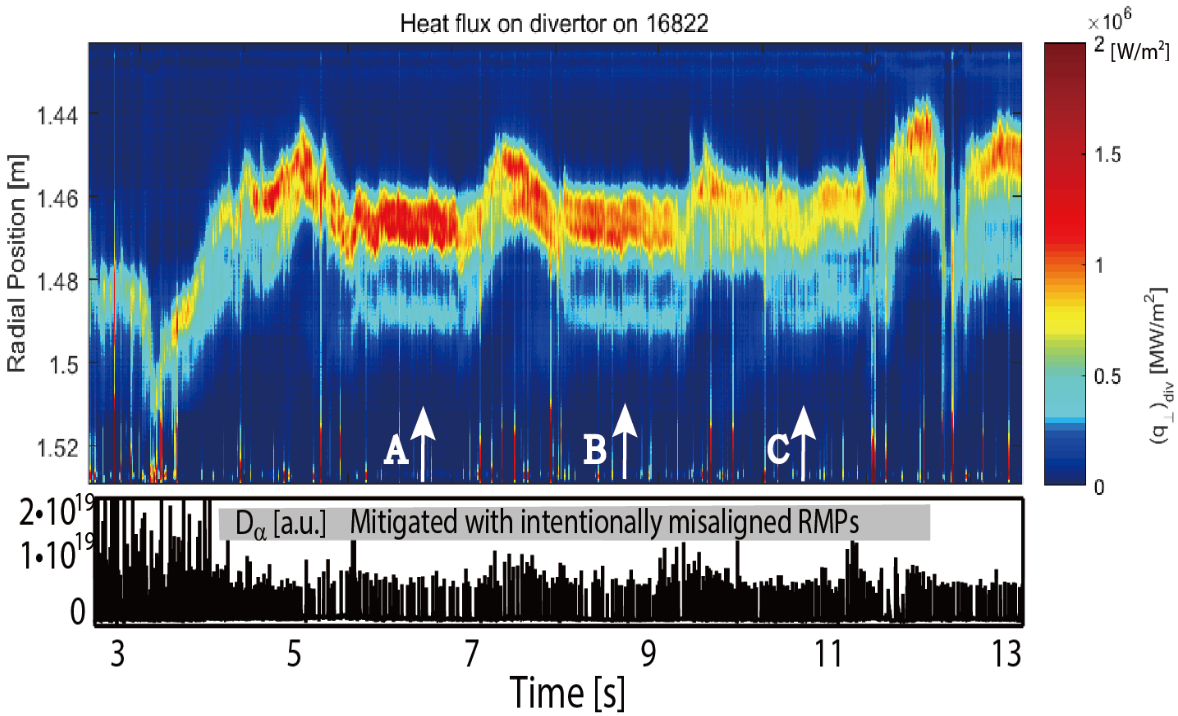


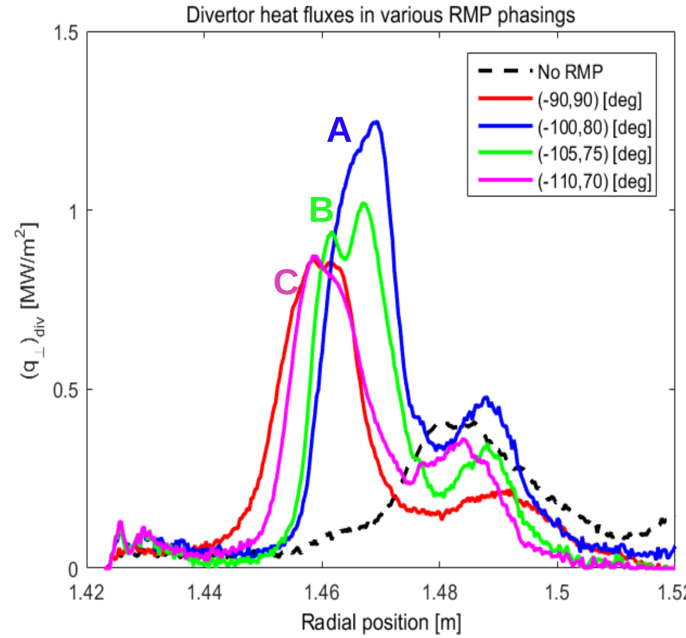
(ϕ_U, ϕ_L)=(-95,85);(-100,80);(-105,75);(-110,70)

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

U	+	+	-	-
M	-	+	+	-
L	-	-	+	+
	–180°		0°	180°

Strongly mitigated ELM-crashes have been measured in misaligned configurations with both static and rotating RMPs



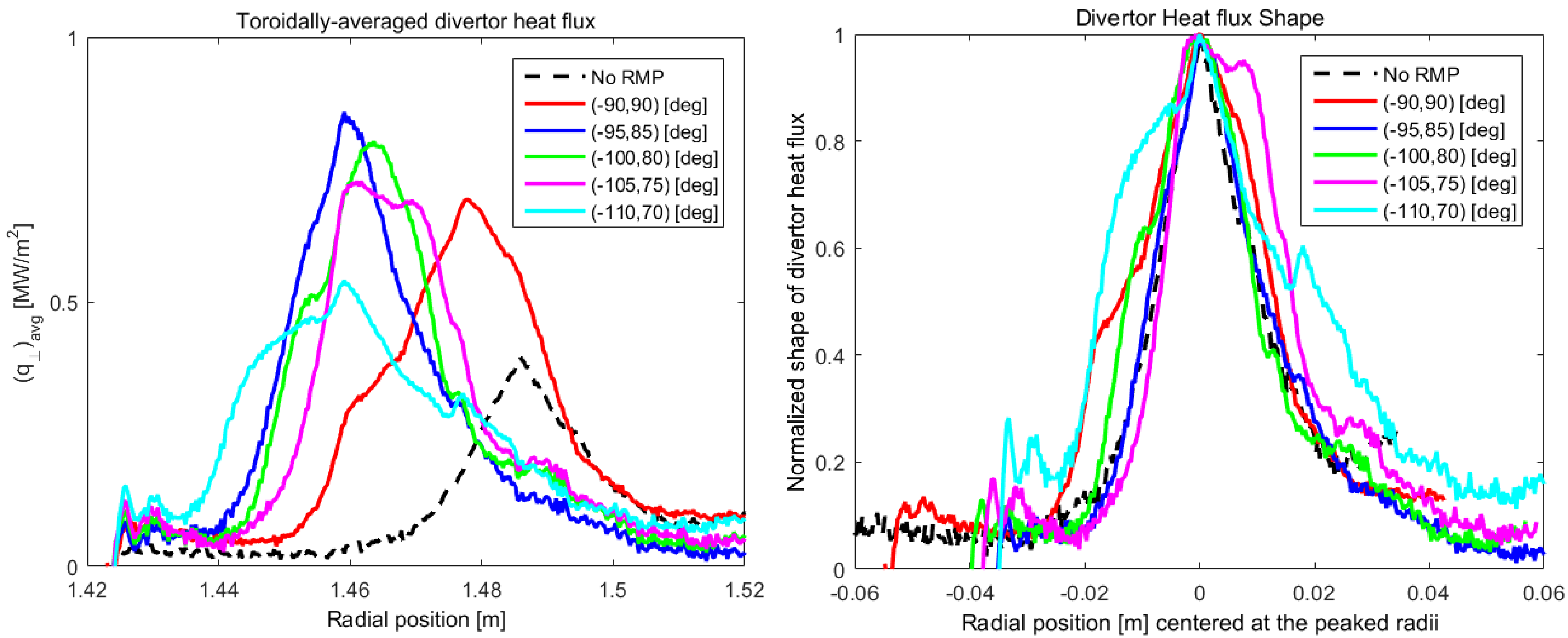


- Despite no suppression of ELMs, the striation patterns of ELM-mitigation appear similar, except the peak of non-axisymmetric lobe

- Among misaligned RMP configurations, dephasing was found to be effective in lowering the peaks, as well as in broadening “wet” areas

J.W. Ahn *et al*, FEC (2016)

Preliminary analysis results suggest that misaligned RMP configurations in ITER could be a way to reduce localized heat flux loading



- **Rotating RMP allows toroidally asymmetric heat flux distribution to be diagnosed, corroborating the analysis results based on static RMPs**

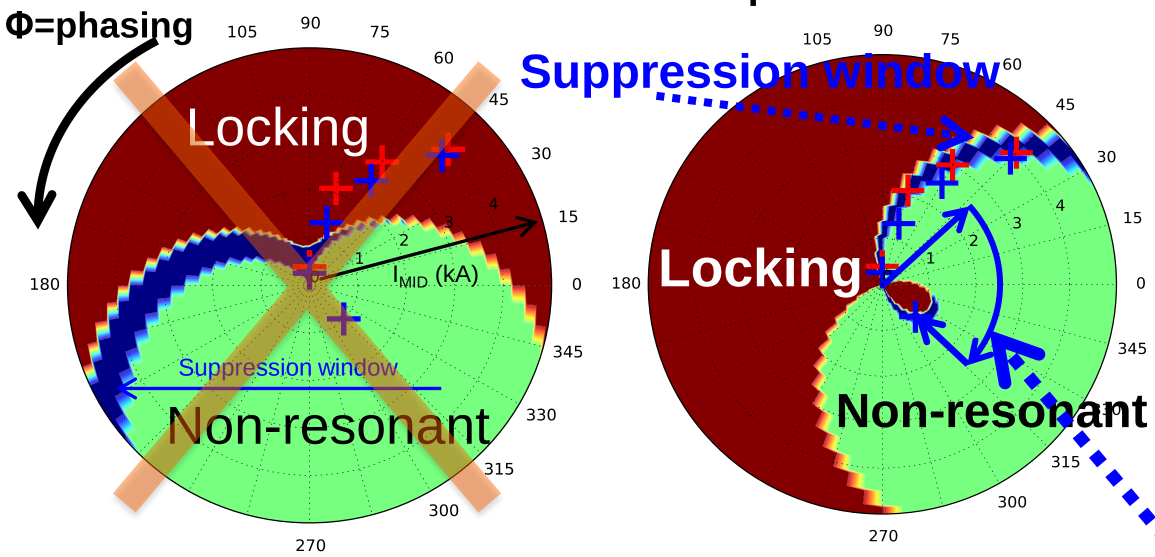
- **Desirable to confirm whether similar trend is observed during ELM-crash-suppression**

IPEC modeling allows us to not only predict an optimal RMP amplitude, but also chart a new route even to an unlikely phasing

- **Overwhelming importance of plasma response calculation over vacuum calculation**

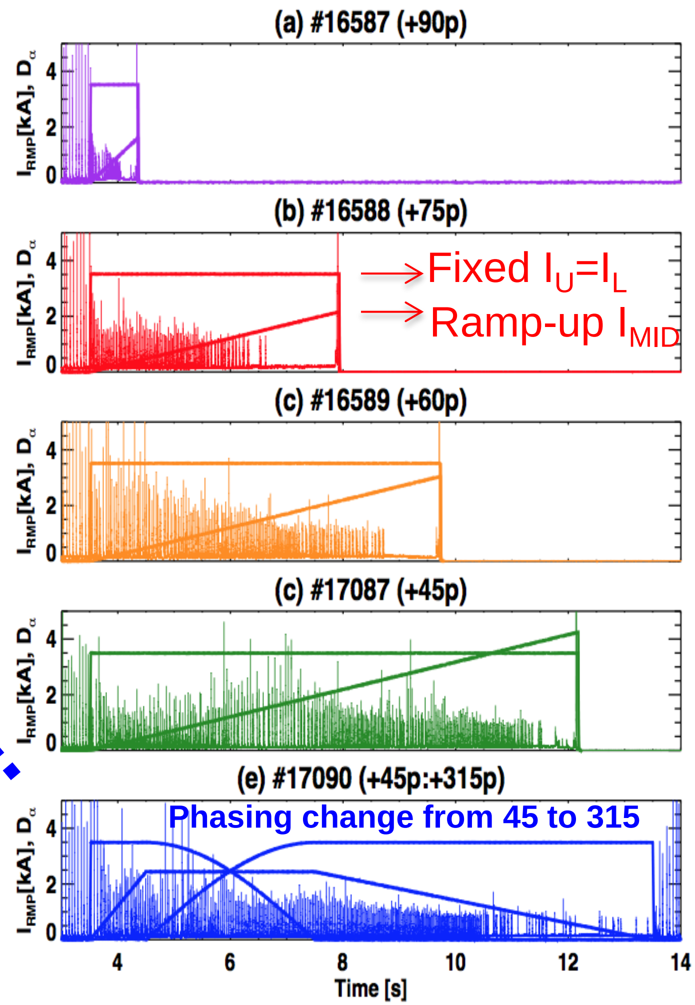
Polar plot of (I_{MID}, ϕ)
with I_U=I_L=5kA and ϕ=$ϕ_{UM}$=$ϕ_{ML}$

Predicted threshold vs. Empirical threshold



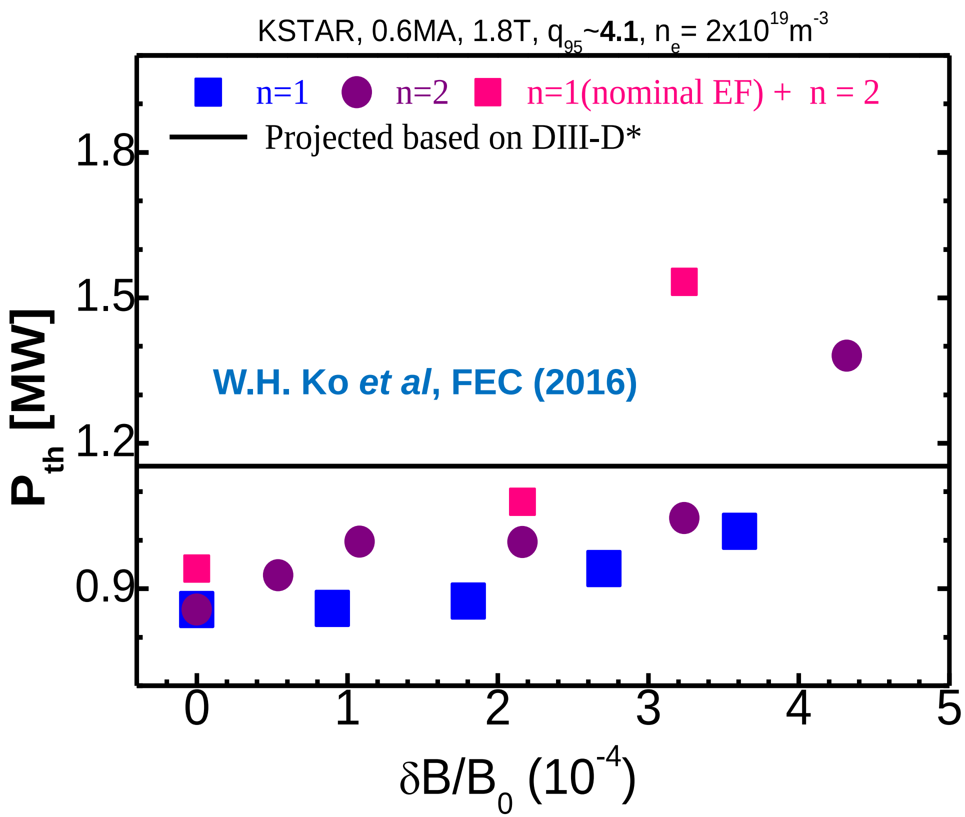
(a) Vacuum superposition (b) With ideal response

(Locking "+", ELM suppression "+")



J.K. Park *et al*, to be published (2016)

The merit of low non-axisymmetry has been quantified in L-H power threshold (P_{th}) dependence on δB



P_{th} dependence on δB does not necessarily appear flat even at low δB

➔ **KSTAR has ~30 % lower P_{th} than projected, based on DIII-D* [Gohil et al, NF (2011)], where P_{th}~1.6MW (w/ "Standard" n=1 EFC)**

Mixed $\delta B/B_0$ scan shows higher P_{th} at high $\delta B/B_0$

$\delta B/B_0^{n=1\,*} + \delta B/B_0^{n=2}$

***nominal intrinsic EF (leftmost pink square), 2.7x10^{-4}**

➔lower P_{th} in KSTAR, attributable to low non-axisymmetry

Accurately controlled non-axisymmetric fields in KSTAR enabled us to extensively address the RMP-driven ELM control physics, and power threshold (P_{th})

- **Robust RMP-driven ELM-crash-suppression sustained for more than 10 sec (~90 τ_E)**
- **Remarkably successful modeling to predict ELM-crash-suppression and locking threshold, in excellent agreement with experiments**
- **Demonstrated divertor heat flux spreading using ITER-like 3-row RMP configurations (confirming the merit of misaligned RMPs)**
- **Quantified the merit of low non-axisymmetry in L-H power threshold (P_{th})**

➔ Aiming to resolve the uncertainties of non-axisymmetric field physics, as well as to establish an optimal 3-D configuration for ITER and future reactors

Strong international collaborations, along with domestic partners in Korea, enabled KSTAR to have made noticeable progress in 3D physics

US:PPPL/ORNL/Columbia U./GA, **Japan**:NIFS, **ITER**, **Korea**:UNIST, POSTECH, KAIST

EX/10-3 **G.S. Yun,** **Edge-Localized Modes on KSTAR: Global Structure and Distinct Evolution Stages Involving Quasi-Steady State and Phase Transitions**

EX/P4-30 **J.-W. Ahn,** *Shielding and Amplification of Nonaxisymmetric Divertor Heat Flux by Plasma Response to Applied 3D Fields in NSTX and KSTAR*

EX/P4-33 **S. A. Sabbagh,** *Isolation of Neoclassical Toroidal Viscosity Profile under Varied Plasma and 3D Field Conditions in Low and Medium Aspect Ratio Tokamaks*

TH/P1-6 **J.-K. Park,** *Self-Consistent Optimization of Neoclassical Toroidal Torque with Anisotropic Perturbed Equilibrium in Tokamaks*

TH/P3-11 **J. Seol,** *Effects of Localized Neoclassical Toroidal Viscosity Effects on the Toroidal Rotation Profile in KSTAR*

EX/P4-4 **W. H. Ko,** *Influences of Nonaxisymmetric Field on H-Mode Power Threshold and Pedestal Rotation in KSTAR*

EX/P4-5 **J. Kim,** *Direct Destabilizations of Macro/Micro Edge Instabilities by Magnetic Perturbations*

EX/P4-6 **M. J. Choi,** *Study of the Locked Mode Disruption with the 3D Imaging Data in KSTAR .*

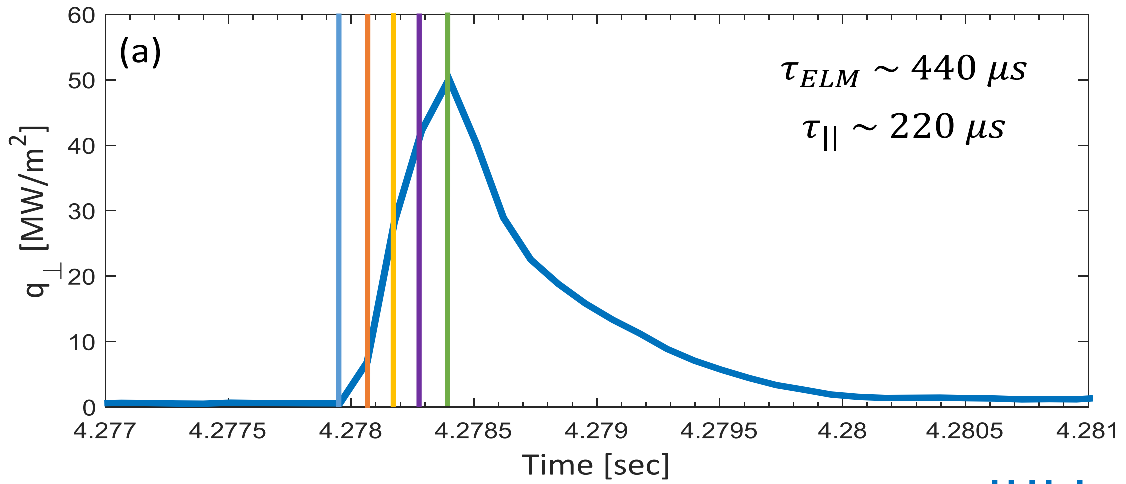
EX/P4-9 **K. Kim,** *Characteristics of Magnetic Braking Depending on 3D Field Configuration in KSTAR*

EX/P4-15 **J. Lee,** *ELM, Edge Turbulence and their Interaction in the ELMcrash Suppression Phase under the n=1 RMP*

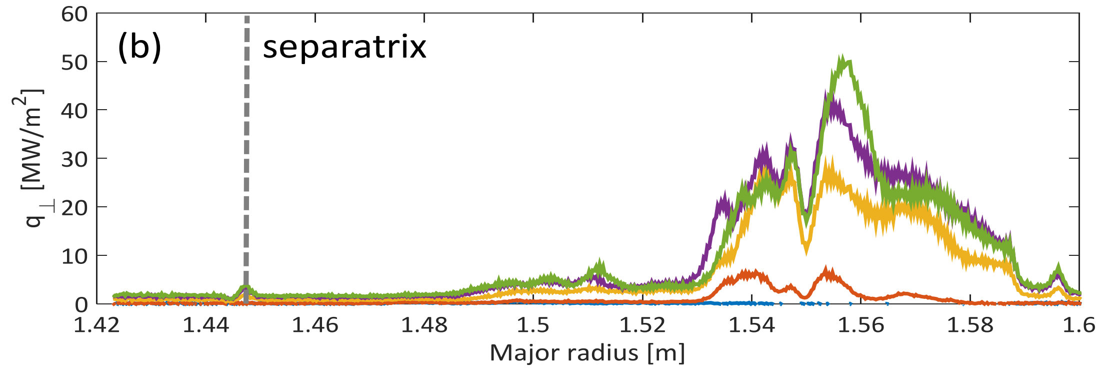
EX/P4-24 **H. Lee,** *H-Mode Divertor Target Heat Load Measurements on KSTAR*

Back-up

Time-resolved ELMy burst has been measured to be peaked up to 50 MW/m² near divertor baffle area

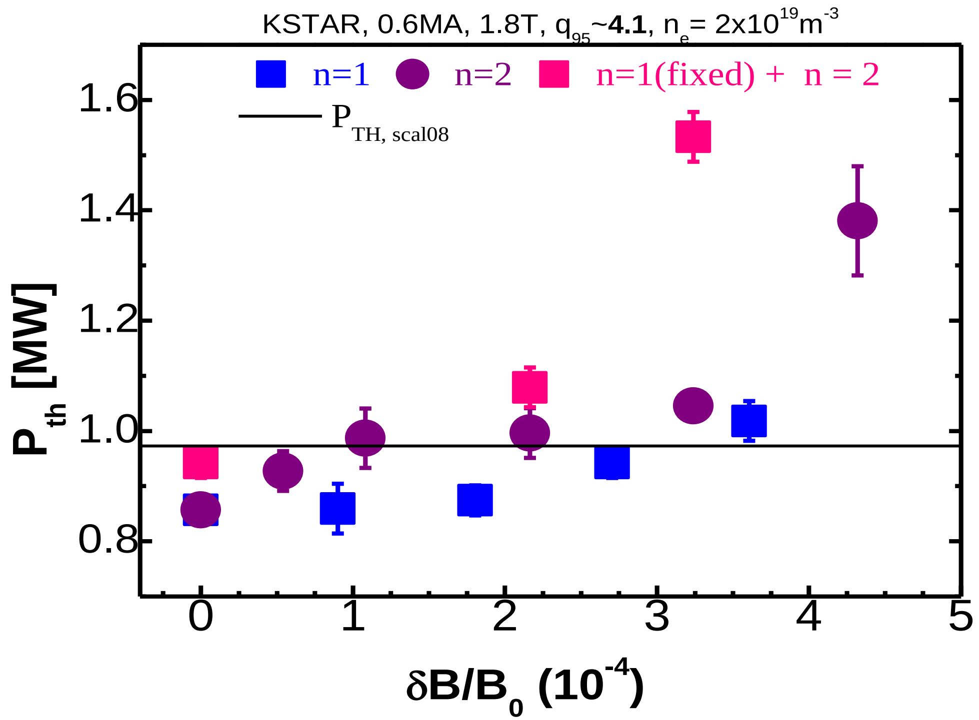


H.H. Lee *et al*, FEC (2016)

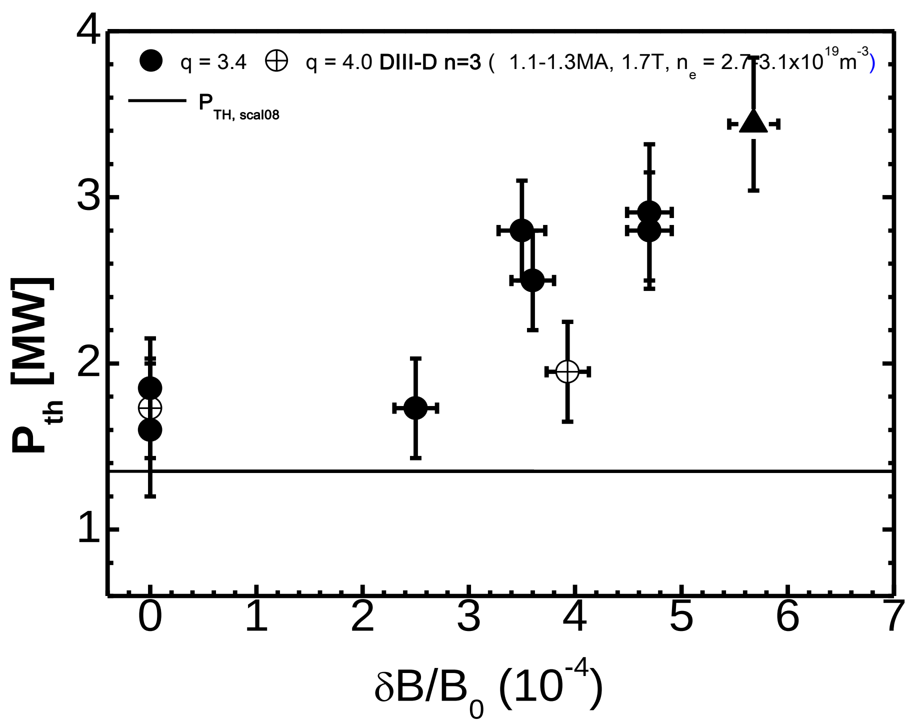


- **The first measurement of the ELM heat load has been measured with fast IR camera acquisition frequency of ~ 9 kHz (integration time: 0.1 ms) on KSTAR**
- **Note that ELM rise time is two times longer than the parallel connection time ($\tau_{||}$)**

In comparison to Martin scaling projections, the power threshold (P_{th}) of KSTAR is ~10% lower, while that of DIII-D is ~ 20 % higher



KSTAR

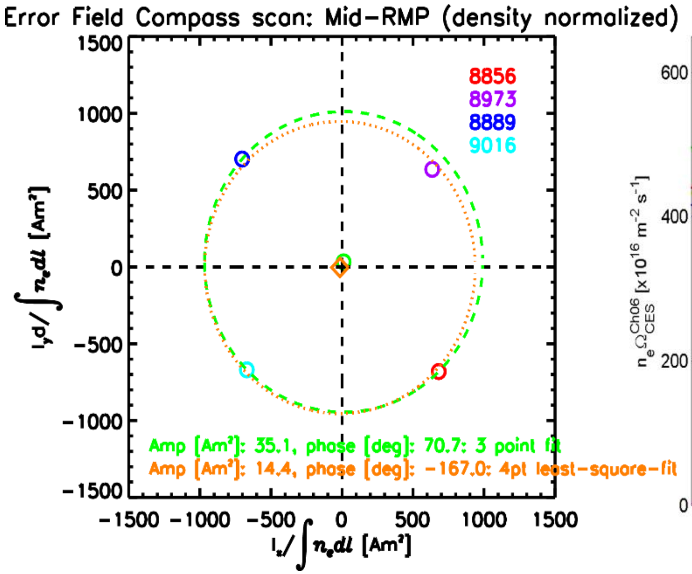


DIII-D

Standard “compass” scan in various plasma conditions using mid-RMP

Low-β

$<\delta B_{m/n=2/1>}/B_0 \sim 10^{-5}$

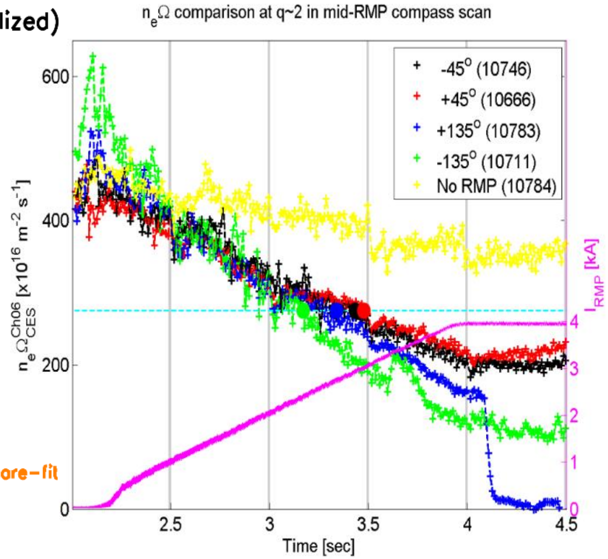


Mode-locking in Ohmic plasmas

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

Intermediate-β

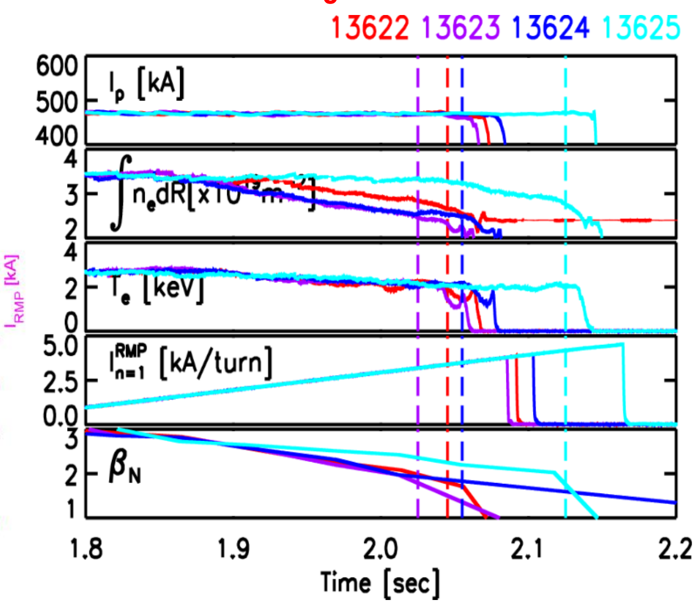
$\delta B/B_0 \sim 3x10^{-5}$



Angular Momentum variations in RMP ELM-suppressible H-mode plasmas

Relatively high-β

$\delta B/B_0 \sim 4x10^{-5}$

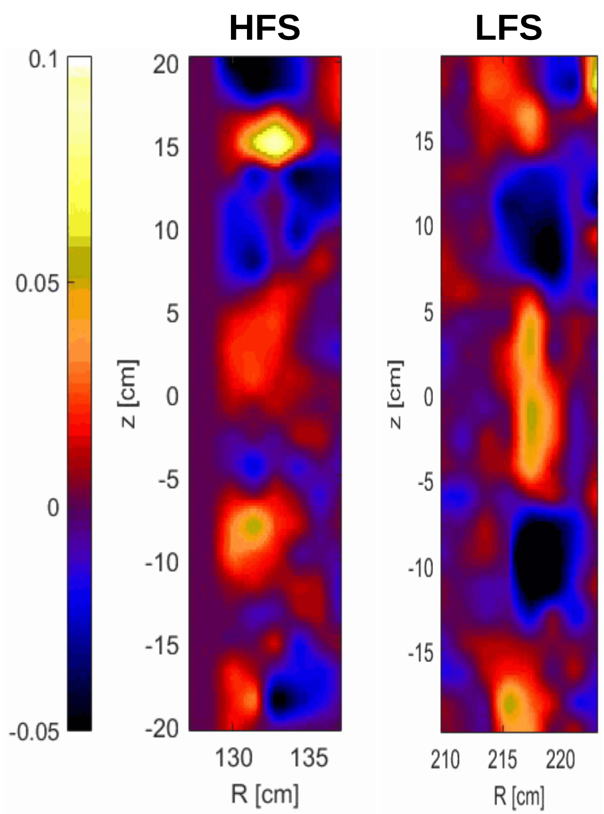


Rotation collapse due to field penet ration

Y. In *et al*, submitted to NF (2016)

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

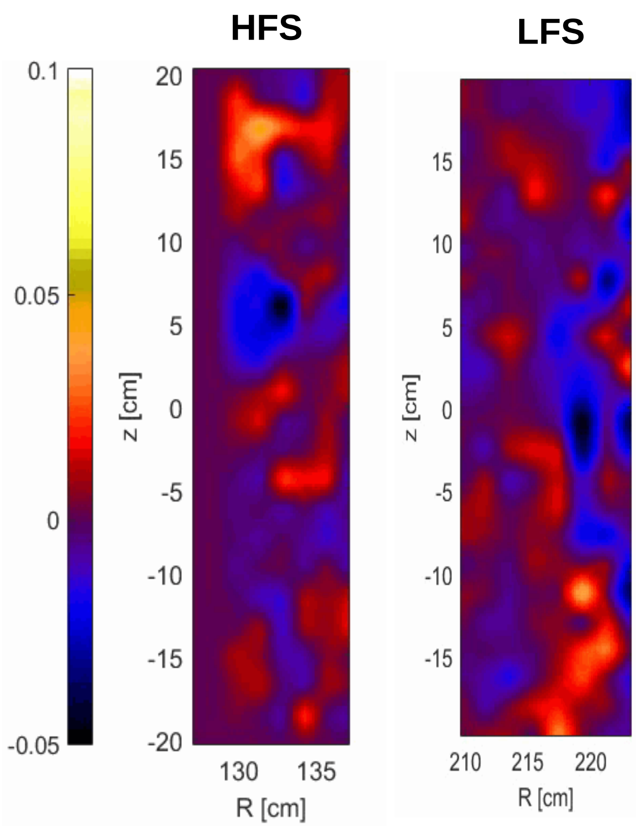
ELM-ing Phase



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-crash-suppression

ELM-crash suppressed Phase



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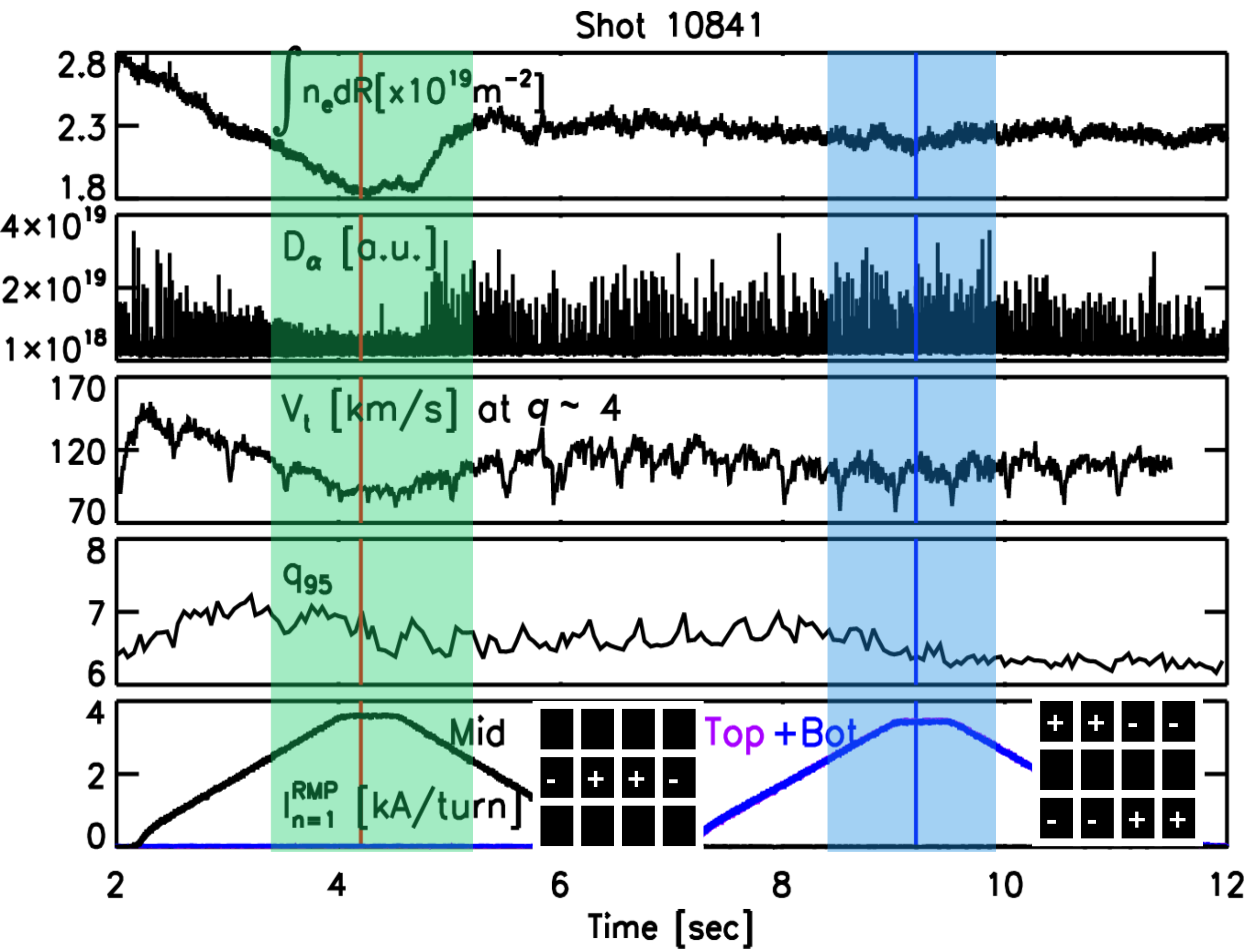
Mid-RMP strongly influences the ELMs, while two off-midplane RMPs appear insignificant on ELMs



n=1 MID only

TOP/BOT: n=1 Odd Parity!

D_α change, accompa nied by density pum pout, and rotation dr ops (like ELM-suppr ession)

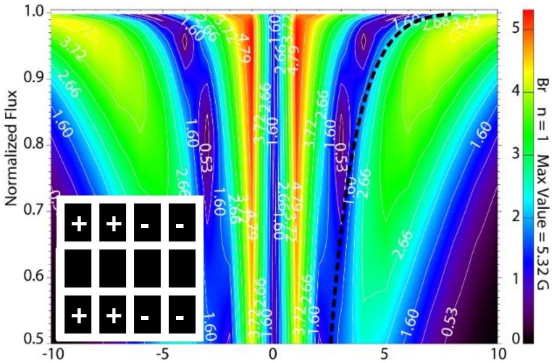
q_{95} ~ 6.5 (not 6); weaker resonant effe ct at n=1 odd parity between TOP/BOT

What makes such va stly contrasting ELM y behaviors?

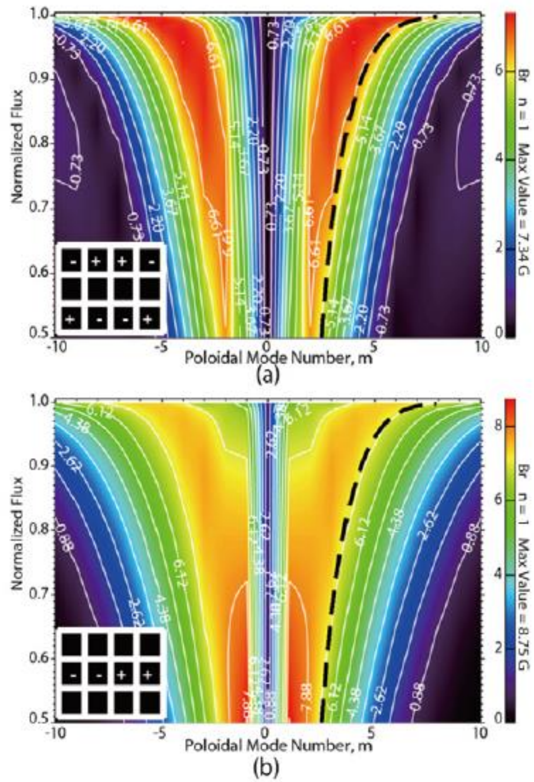
In n=1 off-midplane RMPs, even parity is accompanied by stronger plasma response than odd parity, consistent even with vacuum calculations

TOP/BOT off-plane RMPs

n=1 even parity



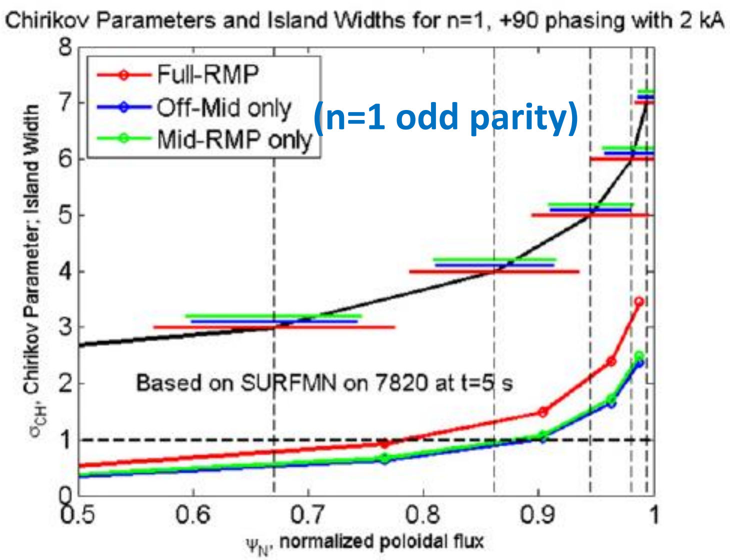
n=1 odd parity



Mid-RMP only

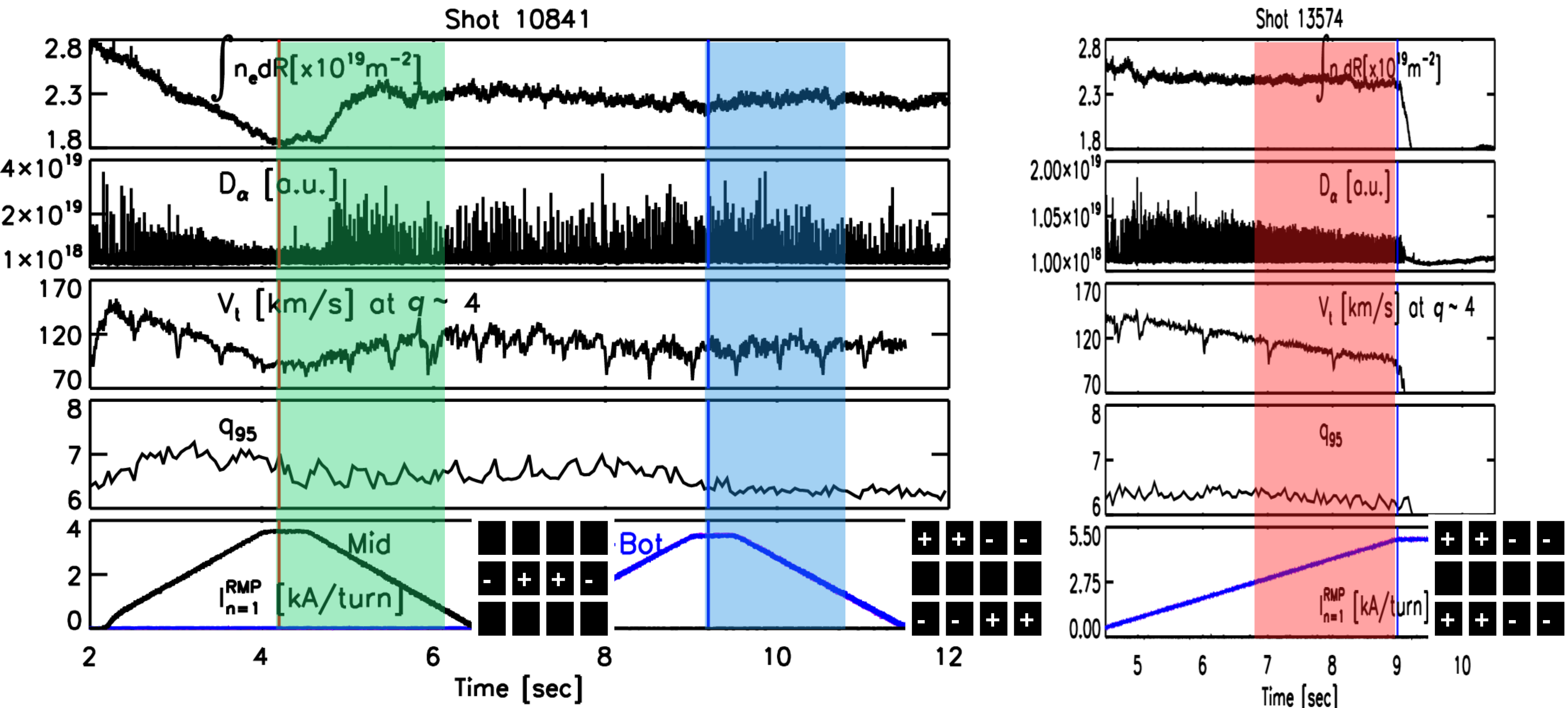
When off-midplane RMPs are configured to n=1 even parity, strongly mitigated D_α has been observed

The effectiveness of 3-D configurations, not just field strengths, needs to be understood possibly in terms of kink-response, and NTV physics



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

Mid-IVCCs is more influential than off-midplane IVCCs, possibly determining the characteristics of the 3-D configurations; *kink vs RMP*

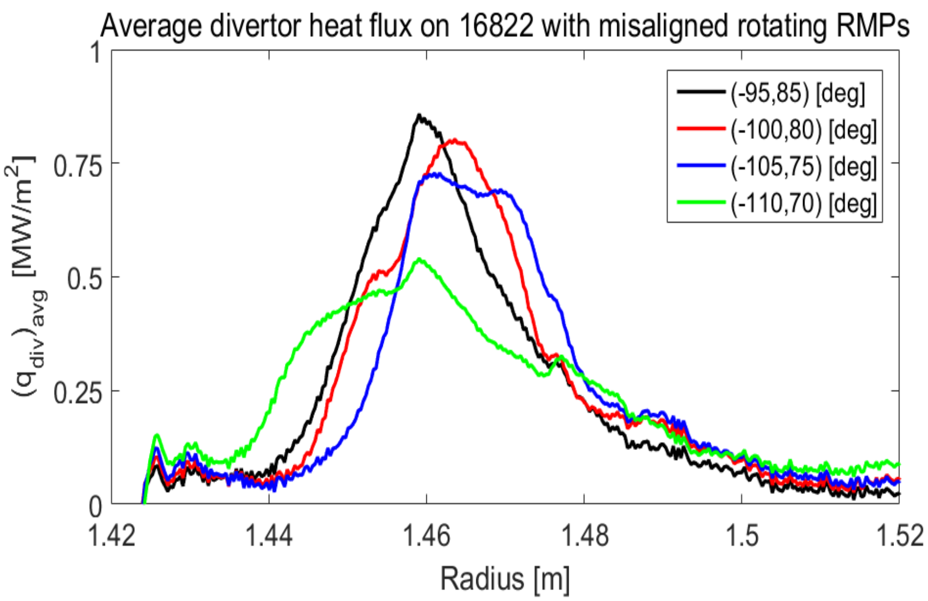


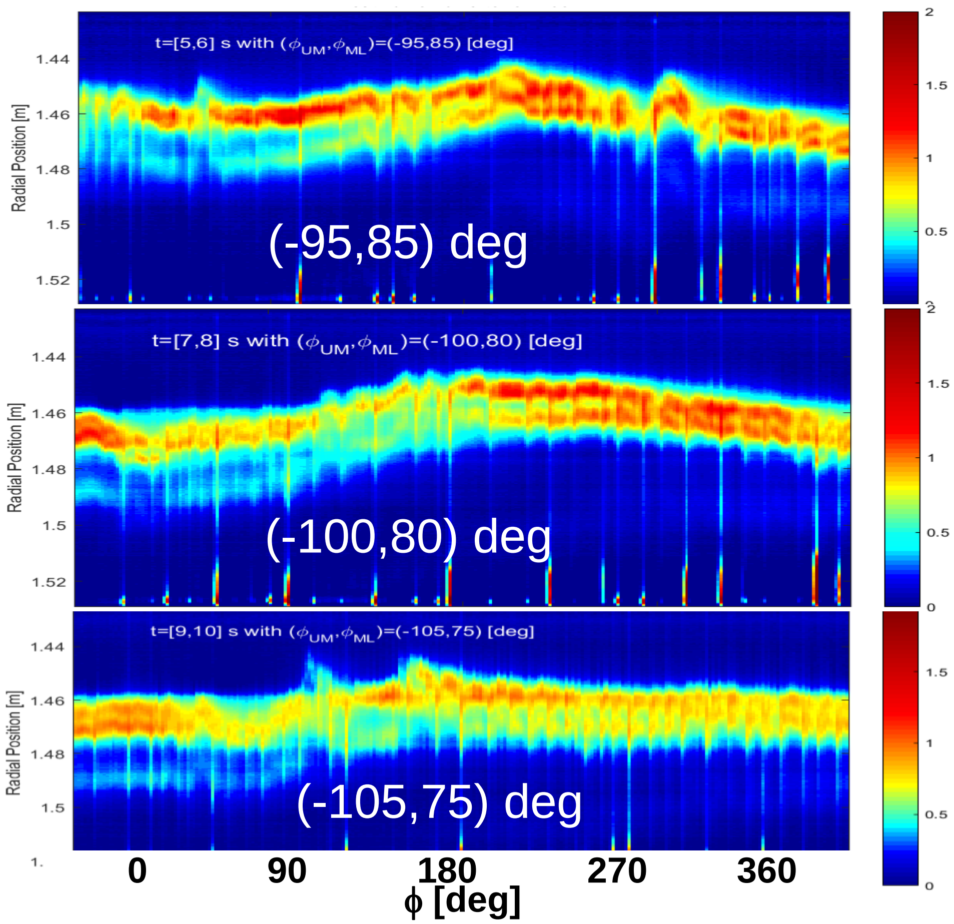
n=1 MID only

TOP/BOT: n=1 Odd Parity!

TOP/BOT: n=1 Even Parity!

Preliminary analysis results suggest that misaligned RMP configurations in ITER could be a way to reduce localized heat flux loading





- **Misaligned RMP redistributes the heat flux in a wider area, while lowering the peak of axisymmetric lobe**