Influence of large magnetic islands on turbulence and quasi-coherent modes (QCMs) in tokamak plasmas

M. Jiang[1], Y. Xu[2], W. L. Zhong[1], Z. B. Shi[1], W. Chen[1], Y. H. Ding[3], W. X. Wang[4], Z. Y. Chen[3], Z. P. Chen[3], Z. J. Yang[3], N. C. Wang[3], D. Li[3], Q. M. Hu[3], J. Q. Li[1], X. T. Ding[1], X. Q. Ji[1], Z. C. Yang[1], J. Wen[1], A. S. Liang[1], K. R. Fang[1], Y. Liu[1], Q. W. Yang[1], M. Xu[1] HL-2A team[1] and J-TEXT team[3]

[1]Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China
[2]Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, 610031, China
[3]International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, Huazhong University of Science and Technology, Wuhan 430074, China
[4]Princeton University, Plasma Physics Laboratory, Theory Division MS 27, Princeton, NJ 08543, USA
Email: jiangm@swip.ac.cn

Outline

I. Background and motivations

II. Influence of islands on turbulence and QCMs

-- Influence of rotating islands on turbulence and QCMs

-- Influence of static islands on nonlinear coupling of turbulence

-- Turbulence spreading across the island

-- Influence of core tearing mode on divertor particle flux

III. Summary and future work

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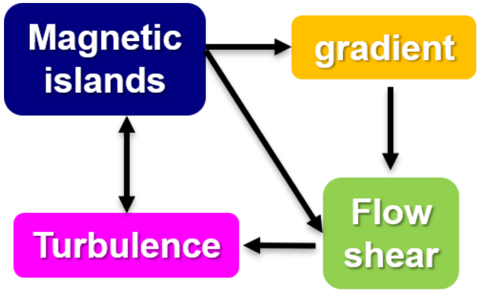
Background and motivation



- Multi-scale interaction between large-scale tearing modes (TM) and micro-scale turbulence has been found to play an important role in regulating turbulent transport and evolution of TM/NTM.

Bardóczi PRL2016&PoP2017&2019
Ida PRL2002& PRL2018
Choi NF2017&Nat. Commun.2021
Zhao NF2015&2017
Estrada NF2016
et al.

Wilson PPCF2009
Poli NF2009,
Zarzoso NF2015,
Muraglia PRL2011
Hornsby PoP2010
et al.

Izacard PoP2016,
Navarro PPCF2017
Hu NF2020
Agullo PoP2014
ishizawa PoP2010

- However, experimental results are limited due to diagnostic difficulties, i.e. local measurements of rotating TMs and turbulence simultaneously.

- Detailed study on interaction between TM and turbulence is essential for further understanding the TM physics, and eventually leads to a better control of TM/NTM and optimization of plasma performance in fusion devices.

Background and motivation

In this work, advanced diagnostics have been developed to measure island structures, profiles and fluctuations with high temporal and spatial resolutions.

Diagnostics:

T_e profile (ECE, 1 cm, 2μs)

n_e profile (reflectometer and FIR)

$\tilde{T}_e$ (ECEI, CECE for small k, 1-2 cm, 2μs)

$\tilde{n}_e$(DBS for intermediate k, 1cm, 2μs

BES for small k, 0.8-1.2 cm, 0.5 μs,

interferometer, 3 cm)

Main features:

-- Naturally rotating island to investigate O and X-point independently (HL- 2A)

-- static island to ensure enough ensemble average for bicoherence (J-TEXT).

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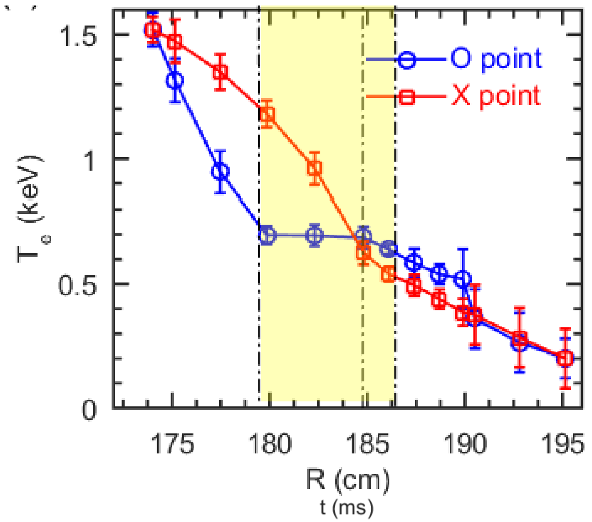
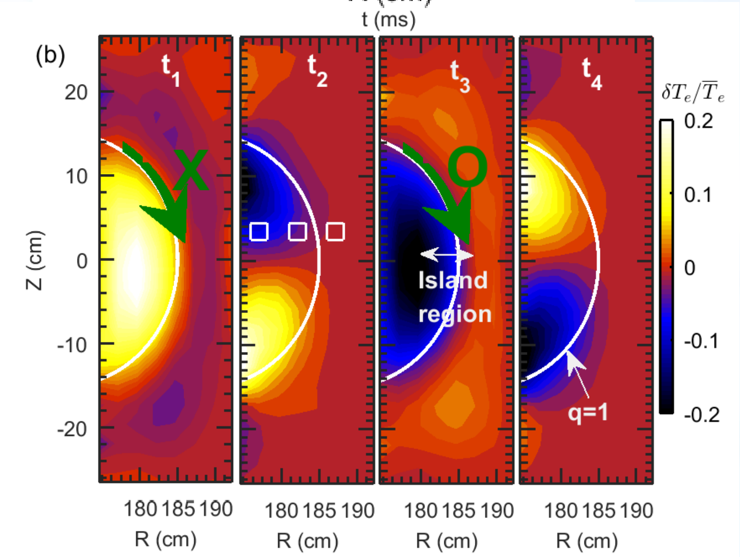
Impact of 1/1 island on $\tilde{T}_e$ and $\tilde{n}_e$





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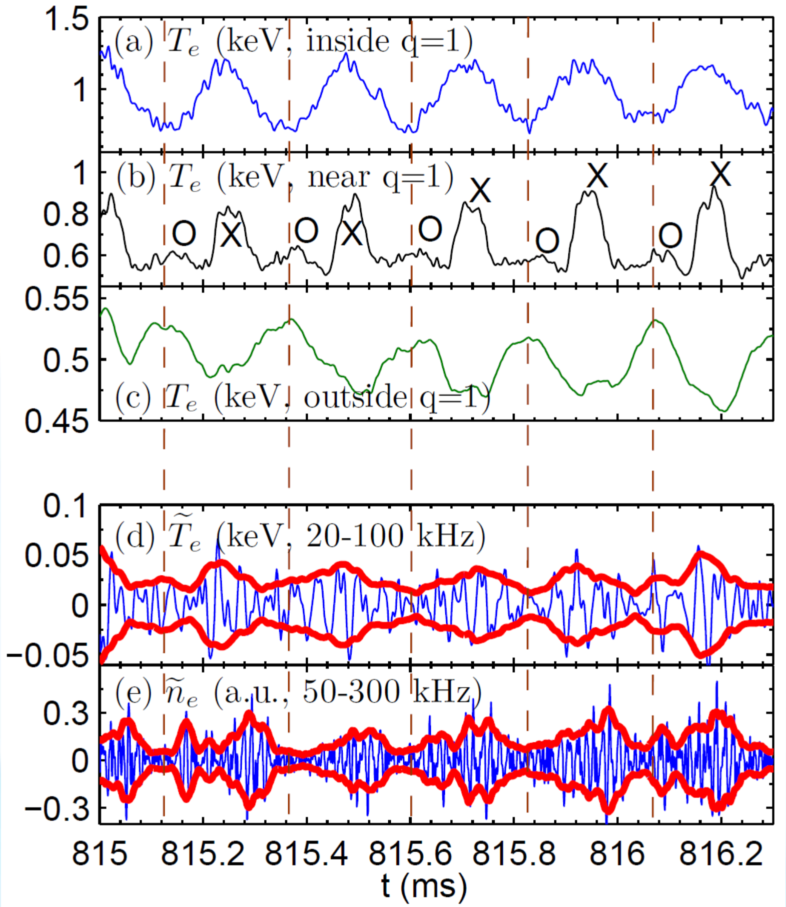
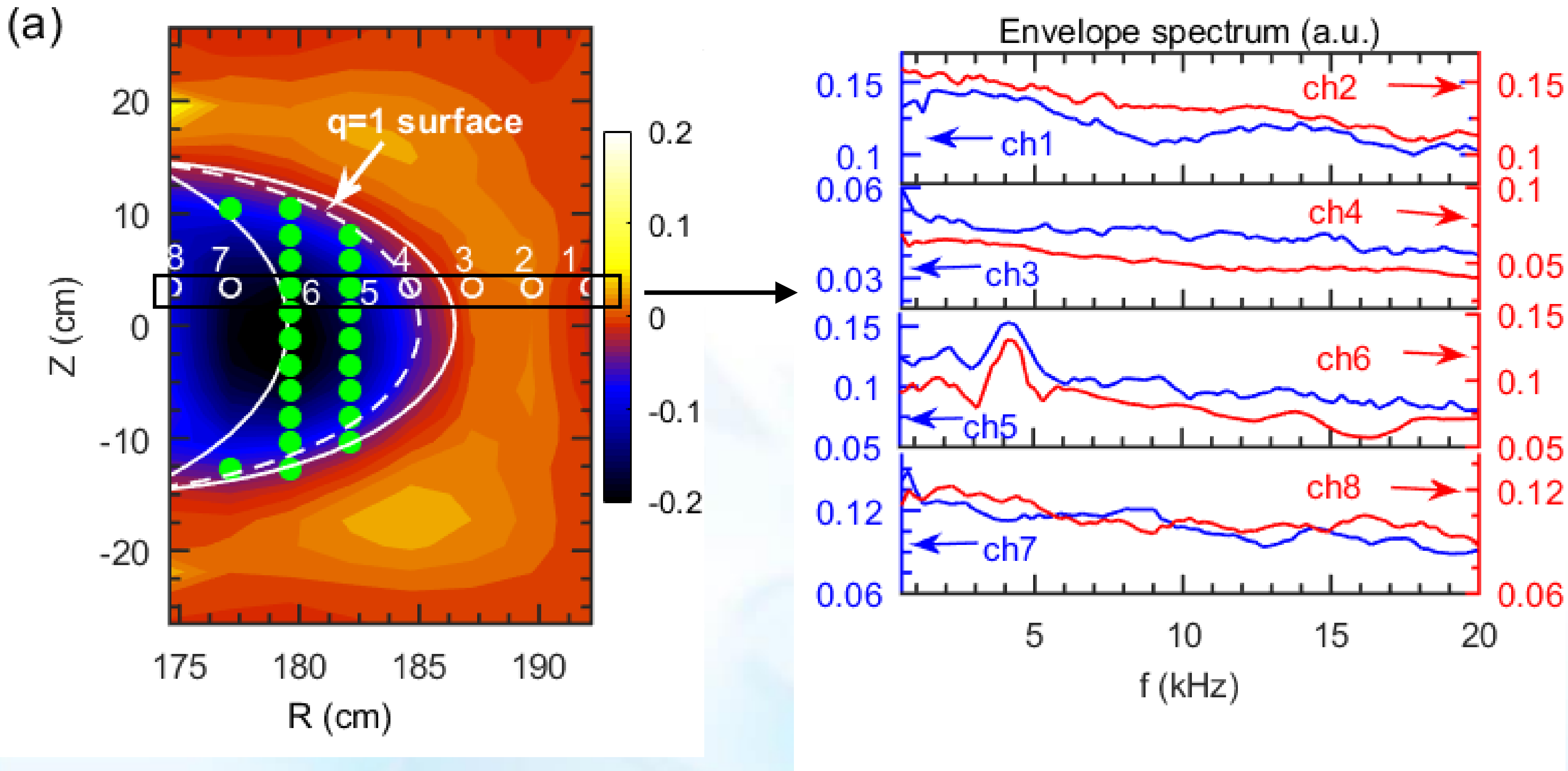


1/1 TM converted from 1/1 ideal kink mode prior to sawtooth crash.

Both $\tilde{T}_e$ and $\tilde{n}_e$ are minimum (maximum) at O(X)-point. ⇒ envelope modulation

Localized modulation of $\tilde{T}_e$ by 1/1 island



The modulation effect on $\tilde{T}_e$ by the rotating 1/1 mode only appears at the inner area of the island (marked by green solid circles).

Localized modulation of $\tilde{T}_e$ by 1/1 island

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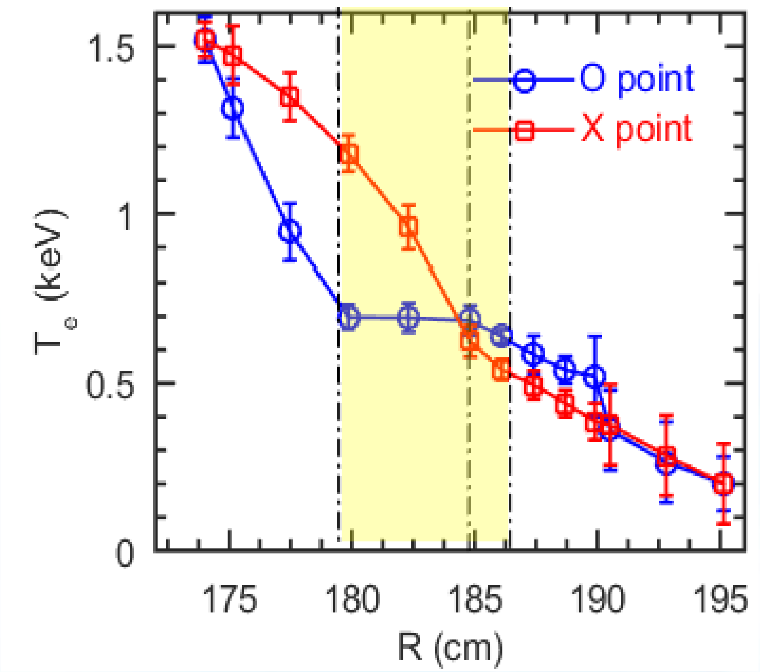
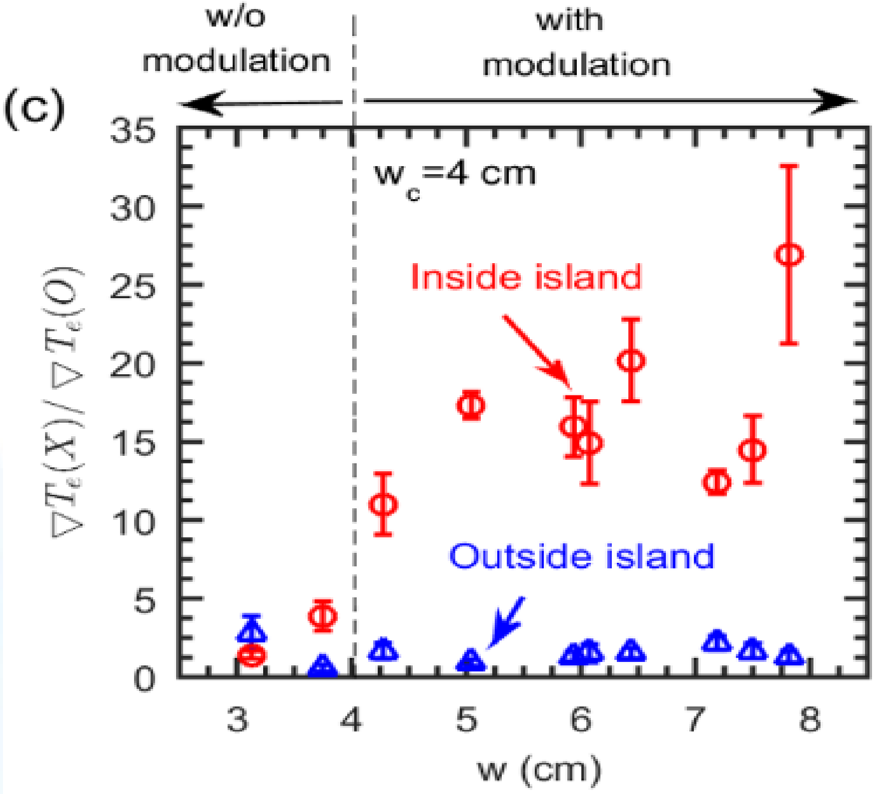


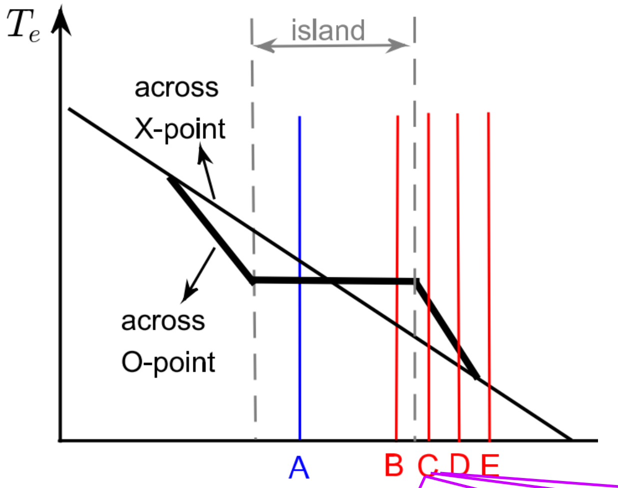


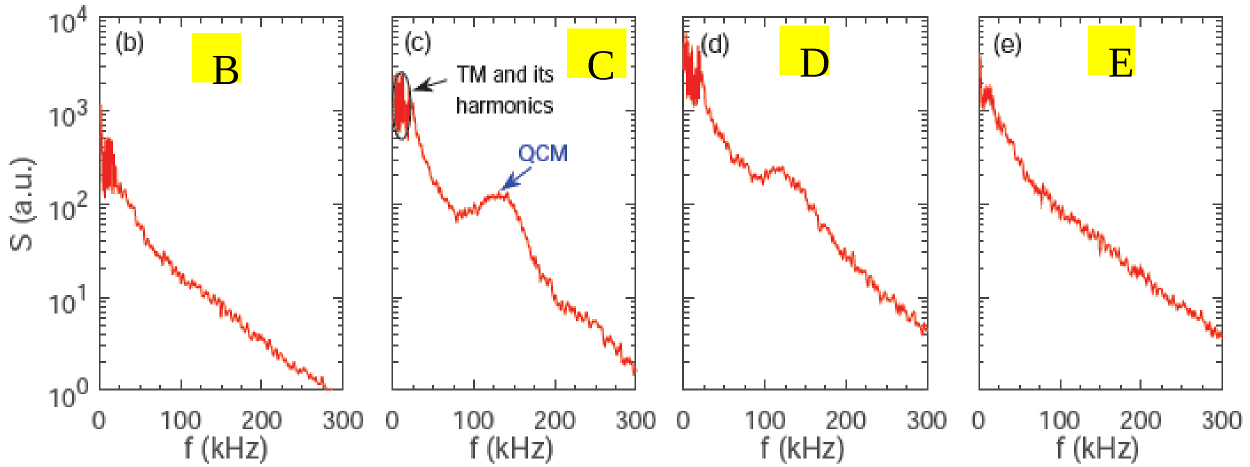
- Only when island width exceeds a certain threshold value ($w_c \approx 10\rho_i \approx 4$ cm), and the ratio of ∇T_e (X-point over O-point) is larger than 10, the modulation can be observed.

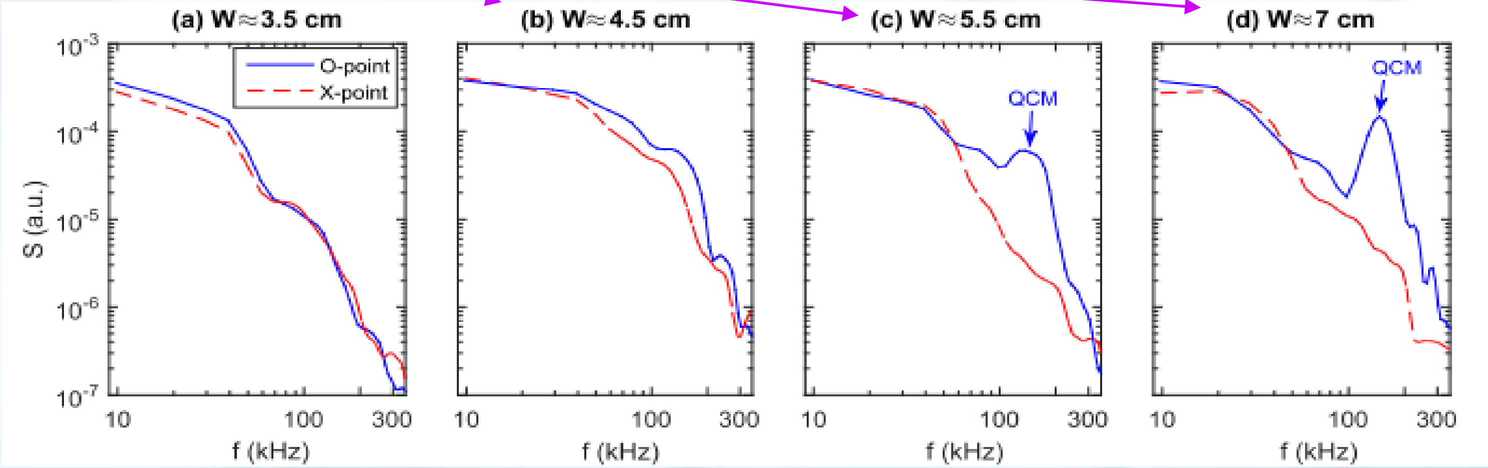
- The observed w_c is consistent with the Fitzpatrick prediction (2016PoP).

$$W_c = 4\triangle_c \approx 4\left(\frac{\chi_\perp}{\chi_\parallel}\right)^{1/4}\left(\frac{L_s}{k_\theta}\right)^{1/2} \approx 4\left(\frac{\rho_s^2 C_s}{a k_\parallel' V_{\text{the}}}\right)^{1/3} \approx 5.1\,\text{cm}$$

QCMs observed outside island region







- ☐ QCMs are excited during O-point passing-by times in outer island region.
- ☐ The QCM magnitude is enhanced with increasing island size.

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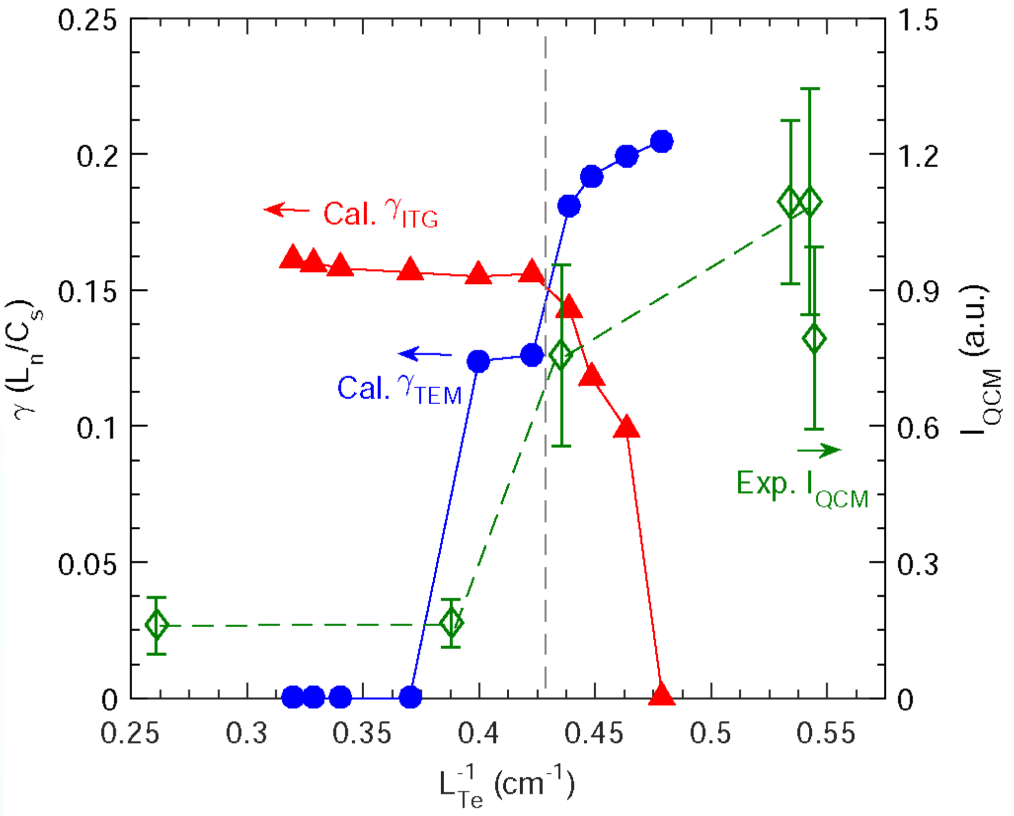
Comparison between stability analysis and Exp.



Extended Fluid Code (ExFC)
Acknowledgement to Prof. J.Q Li and Dr. H. Li (SWIP)

- The change tendency of QCM magnitude with L_{Te}^{-1} follows up that of TEM turbulence.
- The observed critical L_{Te}^{-1} for QCM excitation is consistent with that of TEM in simulation.

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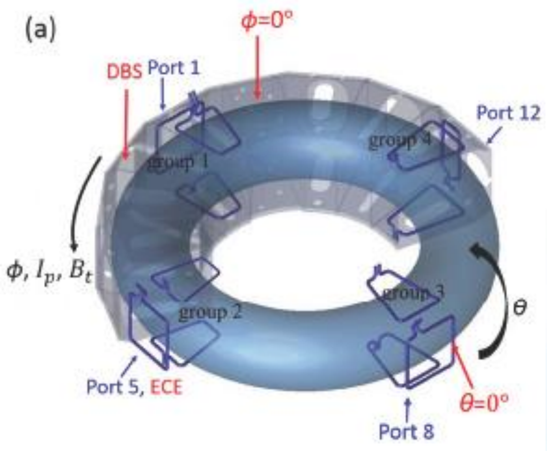
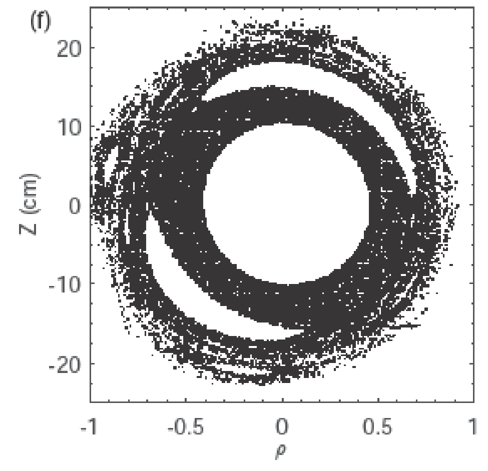
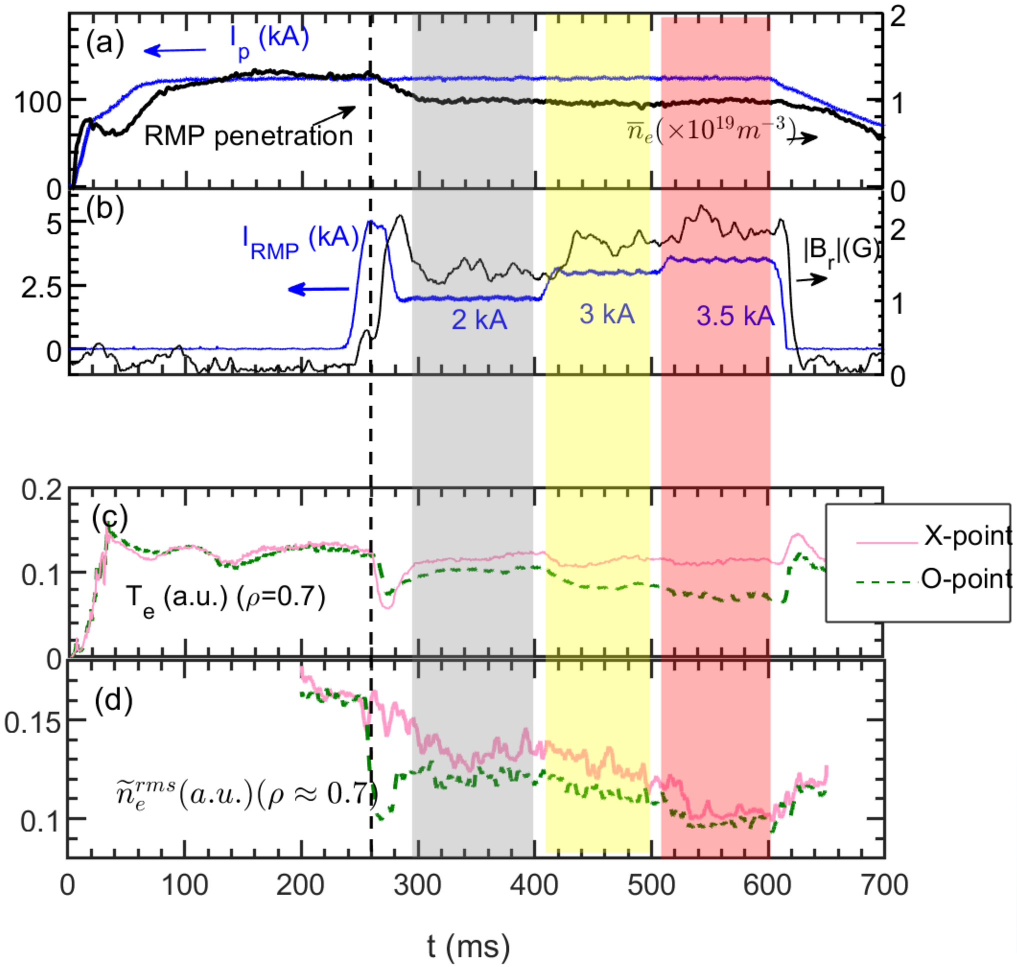
RMP-induced static 2/1 magnetic island (J-TEXT)







- RMP is applied to excite static island at the q=2 surface.
- The island size can be varied by changing the RMP current.
- $\tilde{n}_e$ is much lower at O-point than at X-mode, consistent with rotating island cases.

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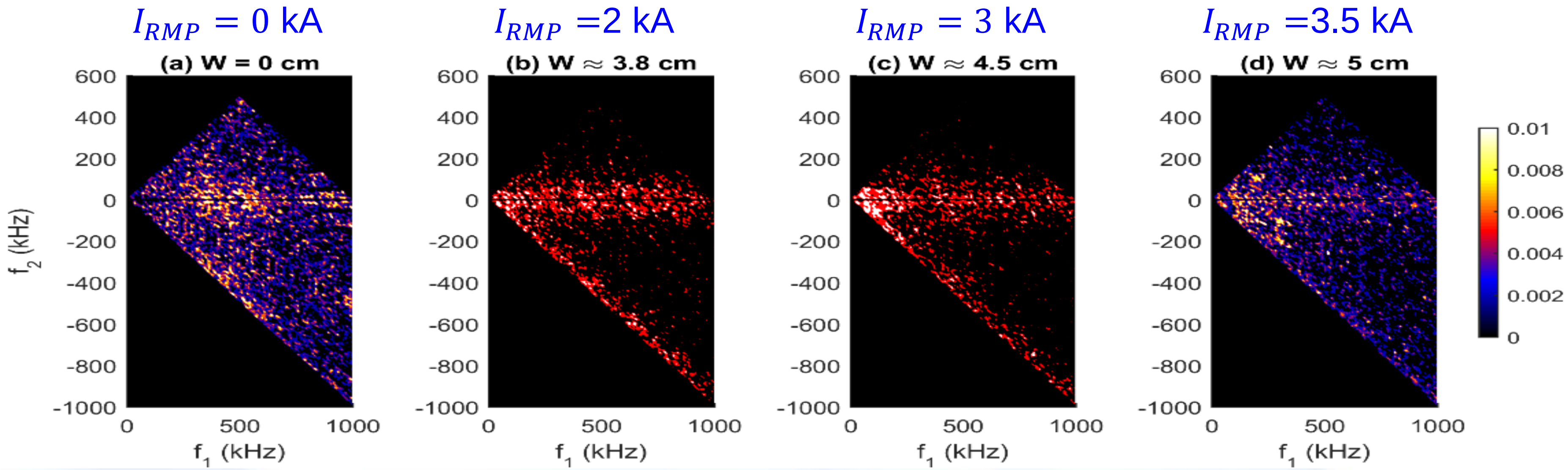
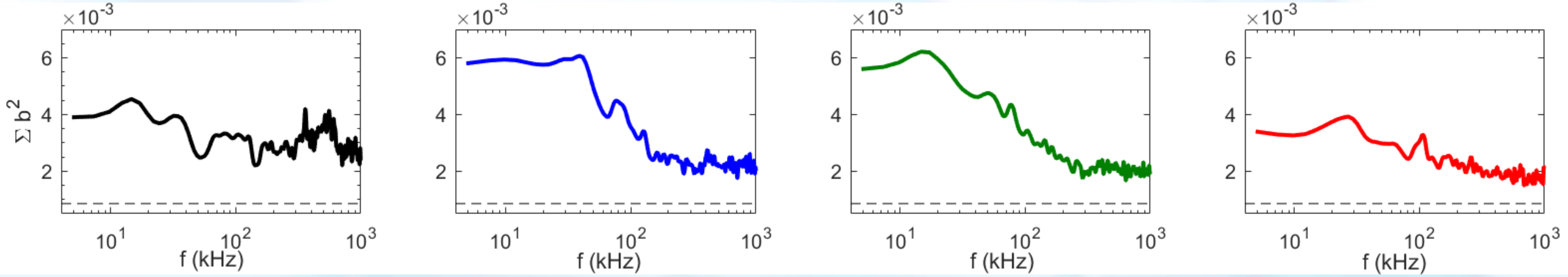
Nonlinear coupling of turbulence is enhanced by the static island





At certain island size (e.g., W ≈3.8 and 4.5 cm) the nonlinear coupling among ambient turbulence near the island region is considerably enhanced through the inverse energy cascading from high frequency to low frequency.

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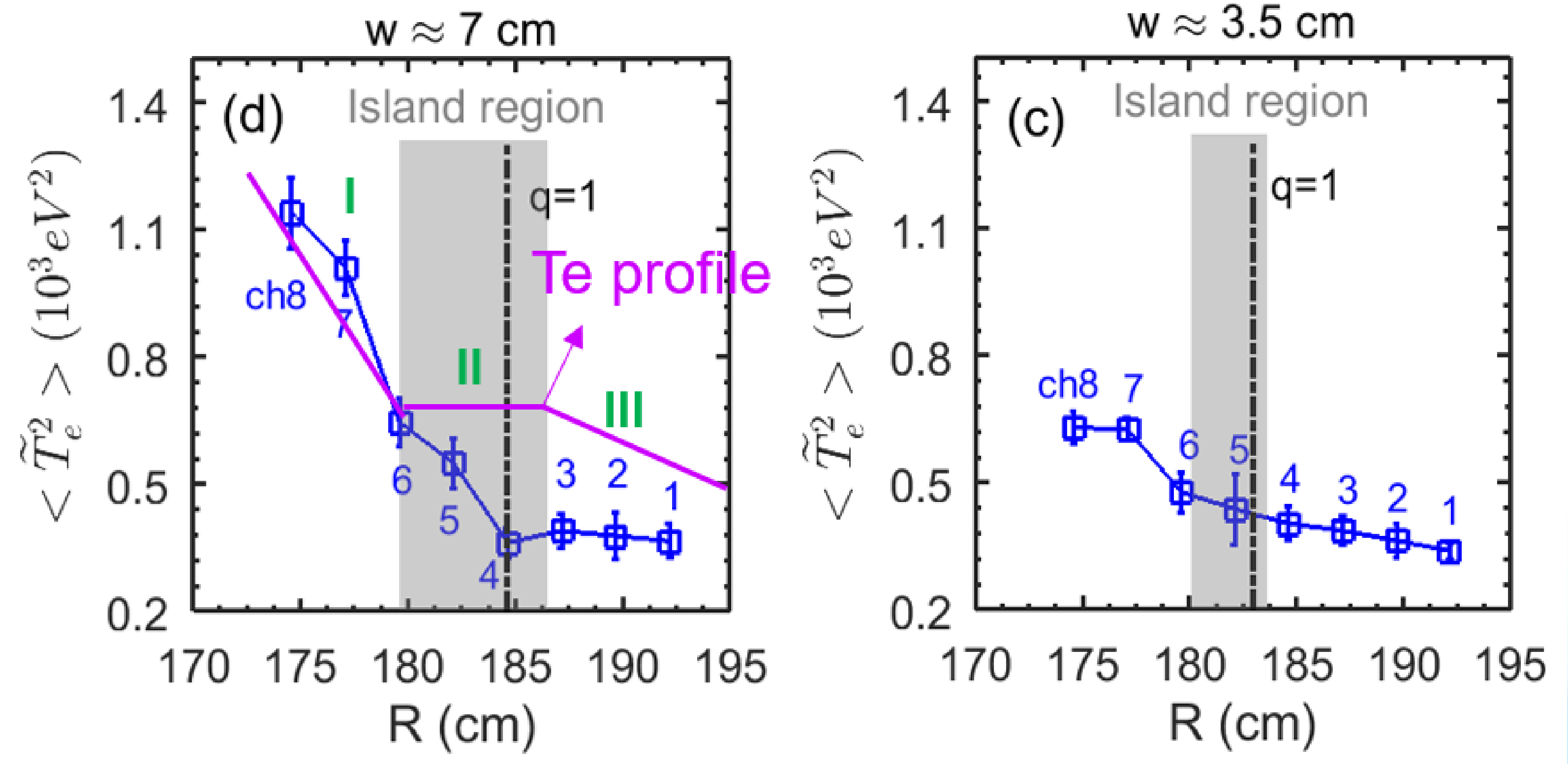
Turbulence spreading across 1/1 island

[P. Manz, PoP] $$\frac{1}{2}\frac{\partial\langle\tilde{n}^2\rangle}{\partial t} = -\langle\frac{\partial n}{\partial r}\rangle\langle\tilde{V}_r\tilde{n}\rangle - \boxed{\frac{1}{2}\frac{\partial}{\partial r}\langle\tilde{V}_r\tilde{n}^2\rangle}$$ NL coupling term



Turbulence spreading across the island occurred only at large island case.

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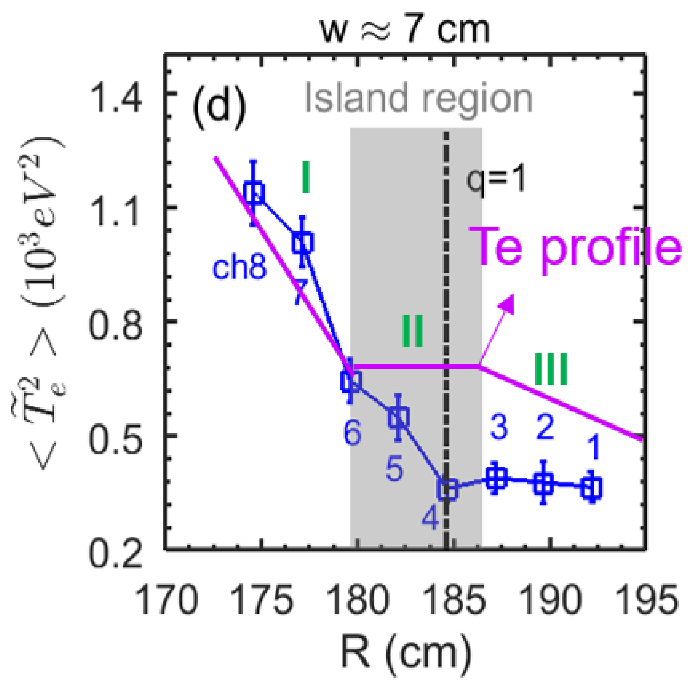
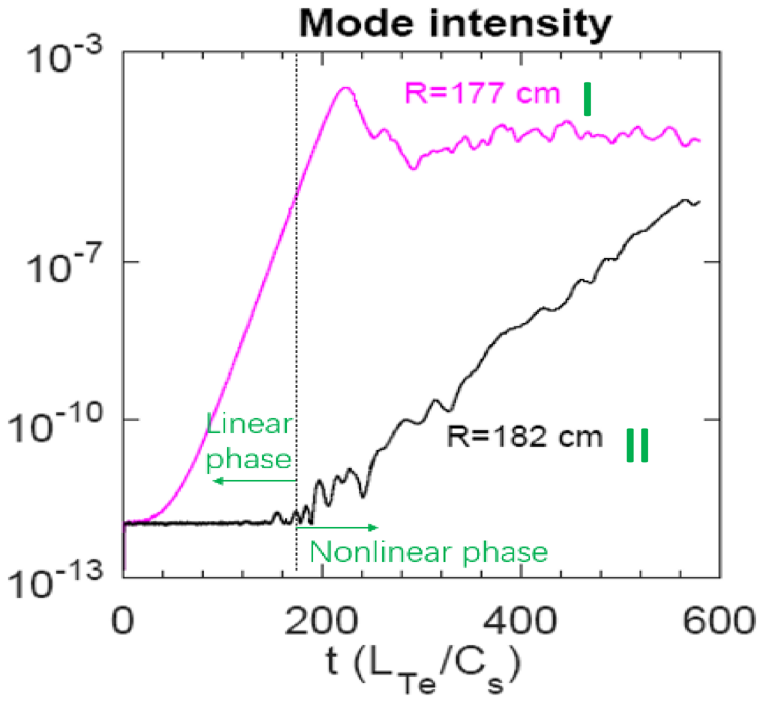
Turbulence spreading across 1/1 island

Experimental result



Gyrokinetic Tokamak Simulation (GTS)
Acknowledgement to Prof. W.X. Wang PPL



- In linear phase, the turbulence level in region I grows fast, and it is very low in region II.
- In the nonlinear phase, turbulence level in region II slowly increases and a slight drop is found in region I, consistent with turbulence spreading.

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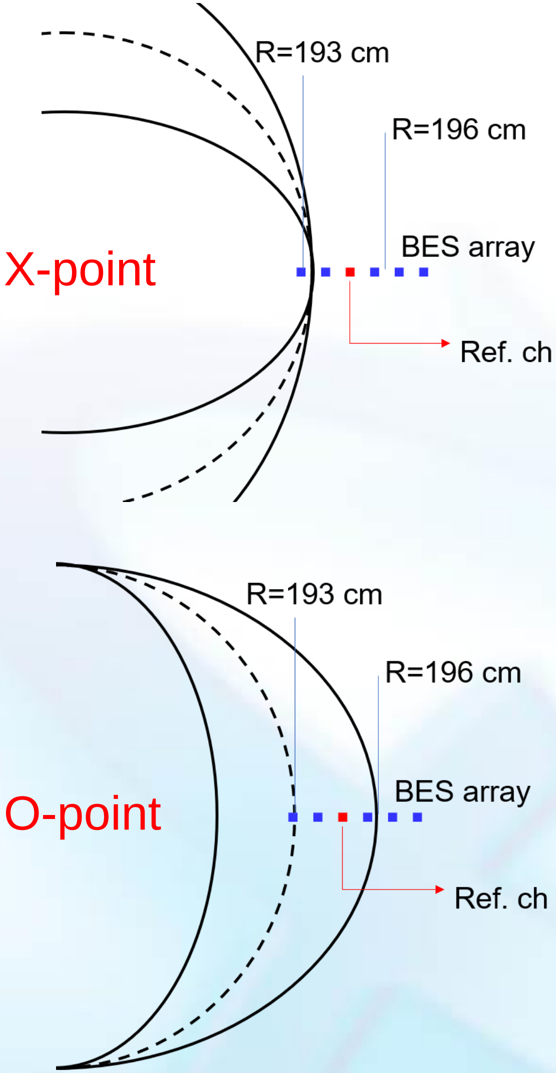
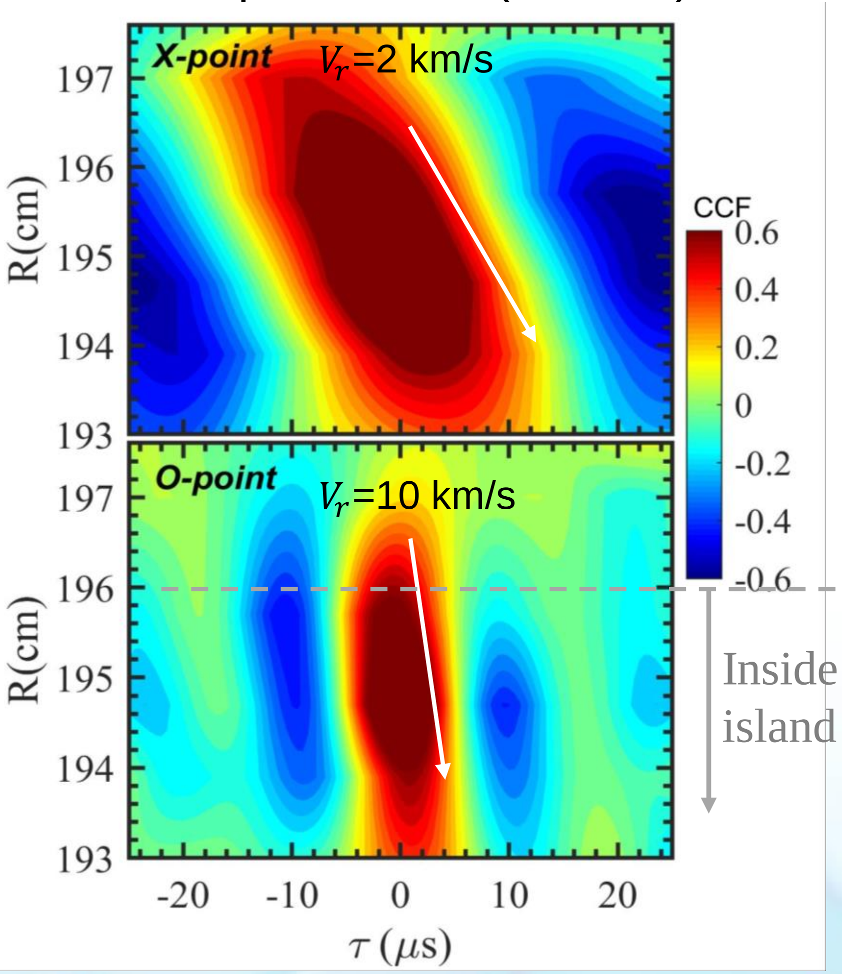
Turbulence spreading across 2/1 island



Contour plot of CCF (Xref, *, τ)



- ☐ O-point phase, the turbulence propagates radially inwards (10 km/s) from outer region to inside magnetic island, further demonstrating the turbulence spreading.

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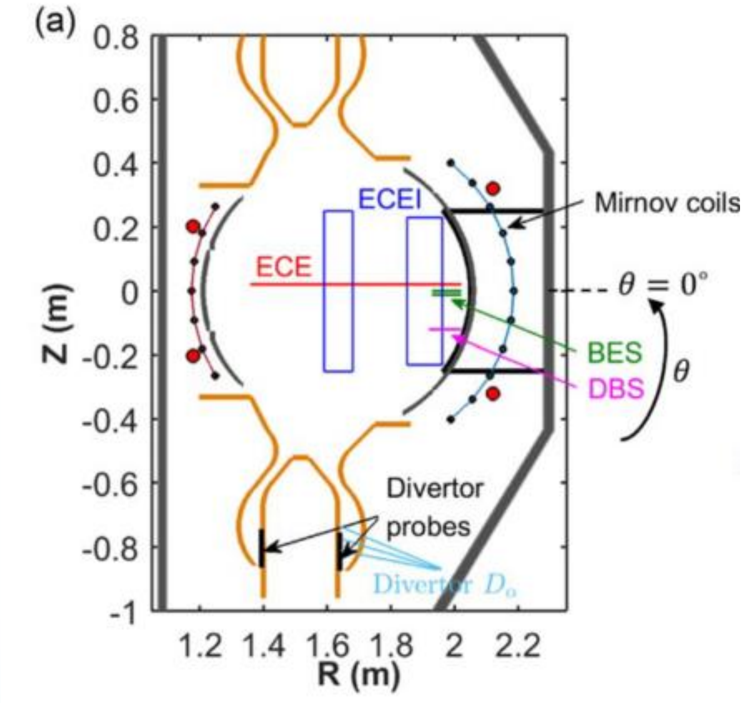
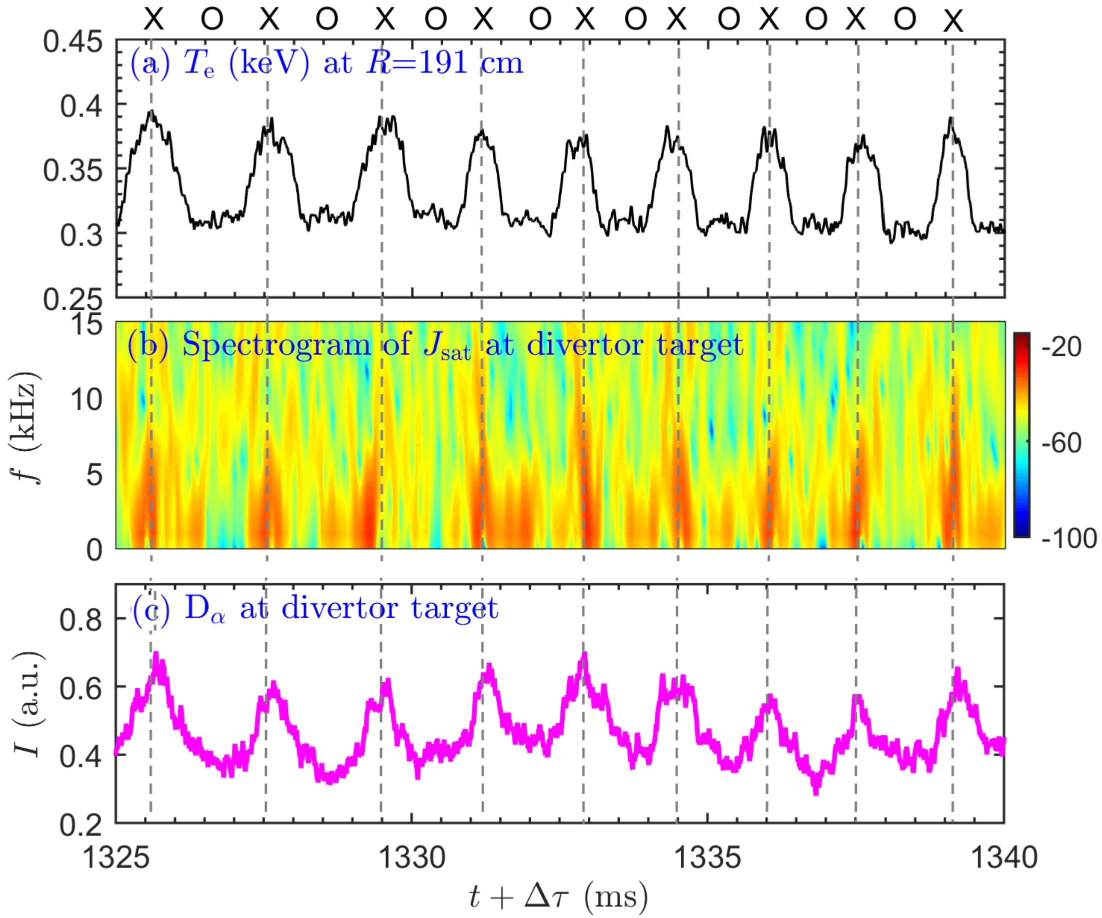
Impact of core TM on divertor particle flux





- ☐ TM modulates the divertor particle flux, and can influence the particle transport nonlocally, further verified by the evolutions of the Dα intensity signal.
- ☐ At the instantaneous of the island X-point times, the particle flux enhances substantially.

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Summary

- We have experimentally investigated the impact of rotating/static islands on turbulence levels, QCMs, nonlinear coupling of turbulence and turbulence spreading in HL-2A and J-TEXT tokamaks.

- The main results indicate:

1. The rotating island (X-/O-point) can modulate density and temperature fluctuations and QCMs due to changes of gradient-driven dynamics;

2. The nonlinear coupling of turbulence can be enhanced by magnetic island at certain values of the island width (induced by RMP);

3. Turbulence spreading has been clearly observed across the magnetic islands.

4. The divertor particle flux can be significantly affected by the core TMs;

5. The influence of the island on turbulence properties strongly depends on island width, consistent with related theoretical predictions.

Future work

- Investigate the impact of turbulence on the evolution of TM/NTM instabilities.

Thanks for your attention!

Turbulence spreading across 1/1 island

Gyrokinetic Tokamak Simulation (GTS)
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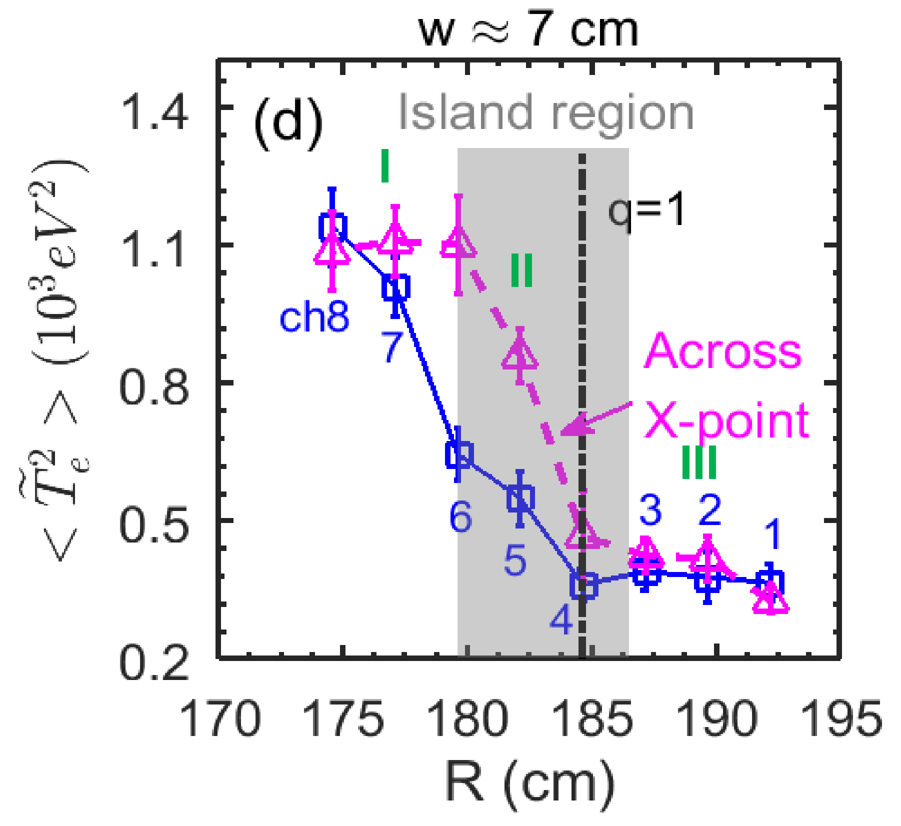

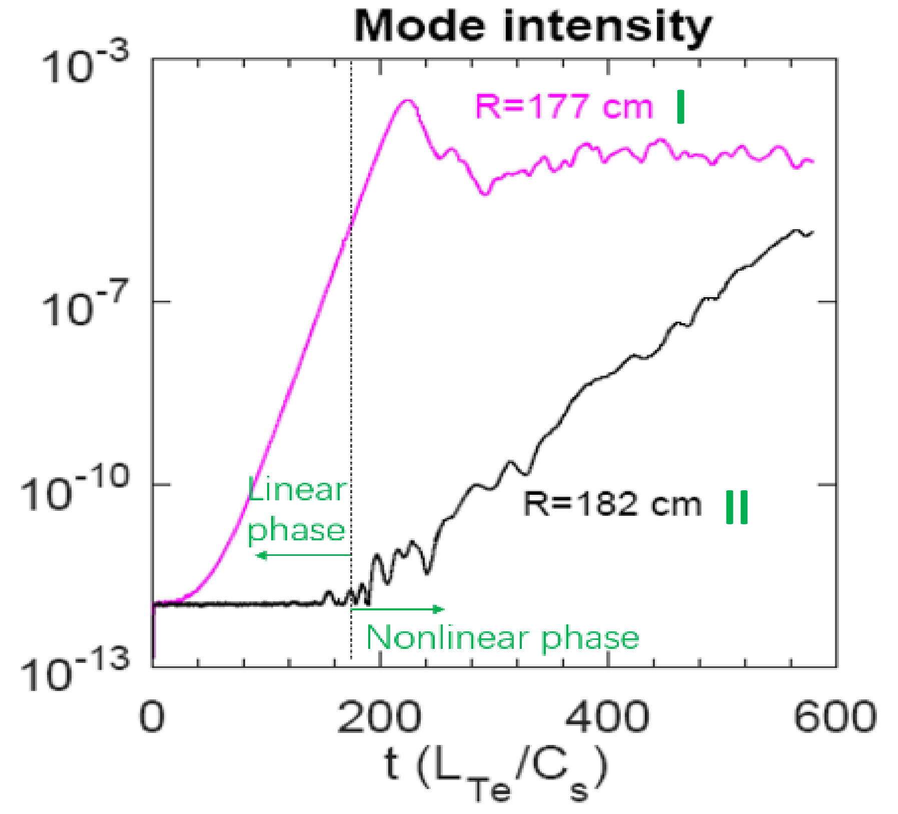

Turbulence spread into island O-point is much weaker than that driven at X-point, so that modulation of $\widetilde{T}_e$ inside island was observed.