# Influence of large magnetic islands on flow, turbulence and quasi-coherent modes in tokamak plasmas

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# Outline

## I. Background and motivations

## II. Influence of islands on flow, turbulence and QCMs

-- Influence of rotating islands on flow and turbulence

-- Influence of rotating islands on QCMs

-- Influence of static islands on nonlinear coupling of turbulence

-- Influence of core tearing mode on divertor particle flux

-- Turbulence spreading across the island

## III. Summary and future work

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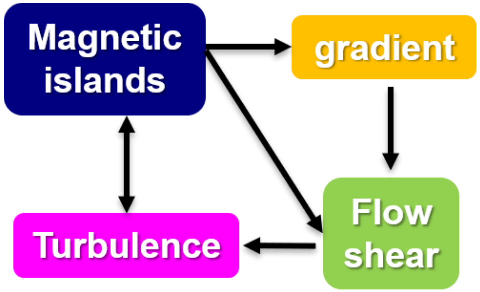
# Background and motivation

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




[*K.J. Zhao NF2016, L. Bardóczi PRL2016&PoP2017, K. Ida PRL2002& PRL2018, M. J. Choi NF2017&Nature Comm.2021, T. Estrada NF2016, Wilson PPCF2009, E. Poli NF2009, D. Zarzoso NF2015, O. Izacard PoP2016, A. B. Navarro2017PPCF, P.J.Sun NF2018*]

■ Experimental results are limited due to diagnostic difficulties, i.e. local measurements of macro-scale TM and micro-turbulence simultaneously.

■ Detailed study on interaction between macro-scale TM and micro-turbulence are essential for further understanding the TM physics and will ultimately lead to a better control of TM (NTM) and optimization of plasma performance in fusion devices. $\frac{dW}{dt} = \frac{\eta}{\mu_0}\left(\Delta' + \frac{D_{NC}W}{W^2 + L_{\chi\perp}^2}\right)$

# Background and motivation

Advanced diagnostics are developed to measure island structure, profiles and fluctuations with high temporal and spatial resolution.

**Diagnostics:**

$T_e$ profile (ECE, 1 cm, 2$\mu$s)

$n_e$ profile (reflectometer and FIR)

$V_\perp$ (DBS, 1cm, 2$\mu$s )

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

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

BES for small k, 0.8-1.2 cm, 0.5 $\mu$s,

interferometer, 3 cm)

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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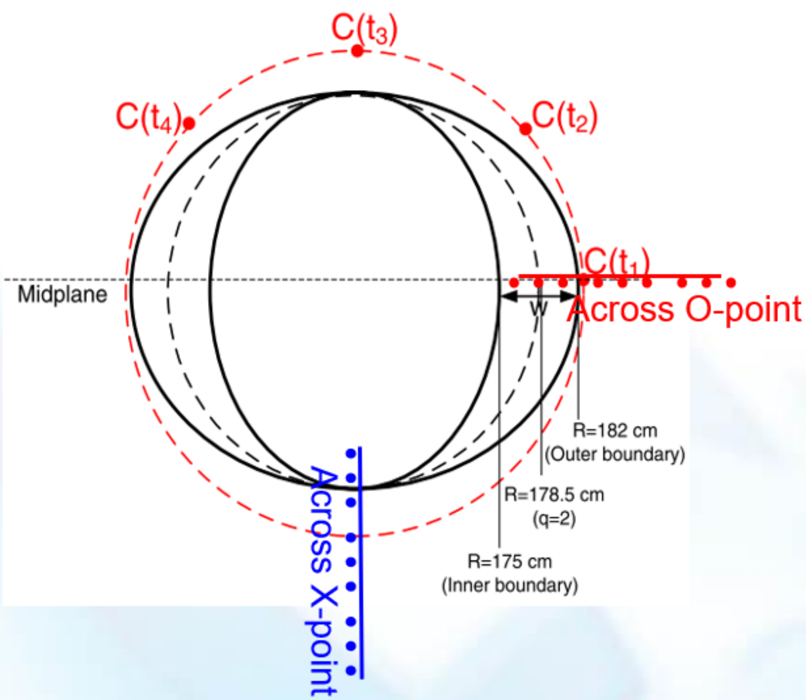
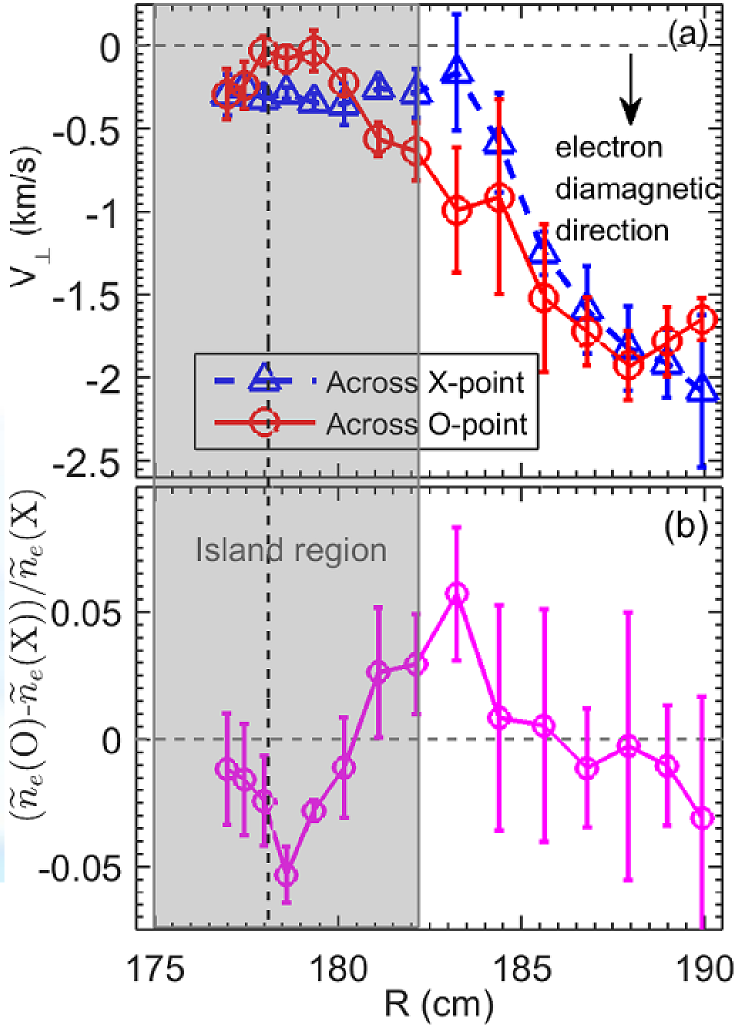
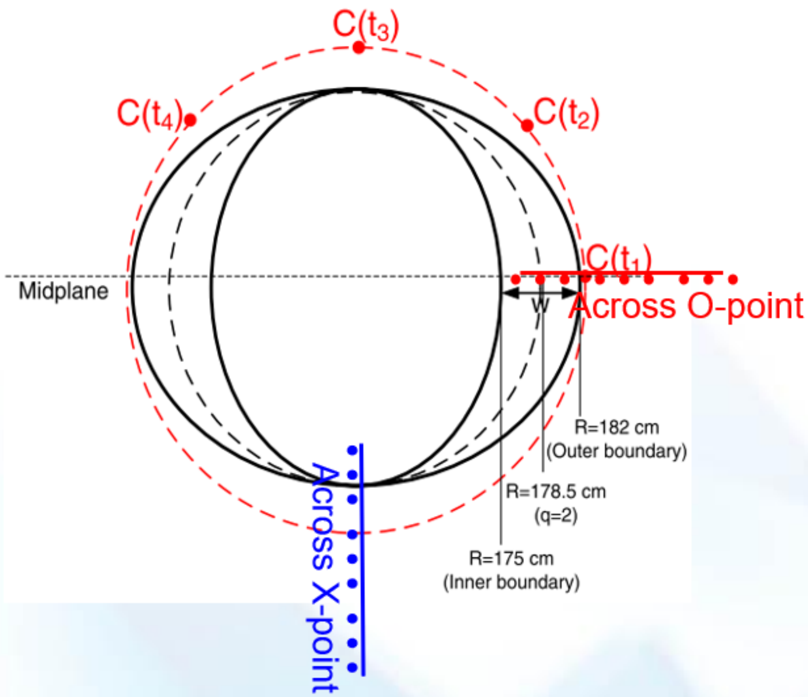
# Impact of 2/1 island on $V_\perp$ and $\tilde{n}_e$

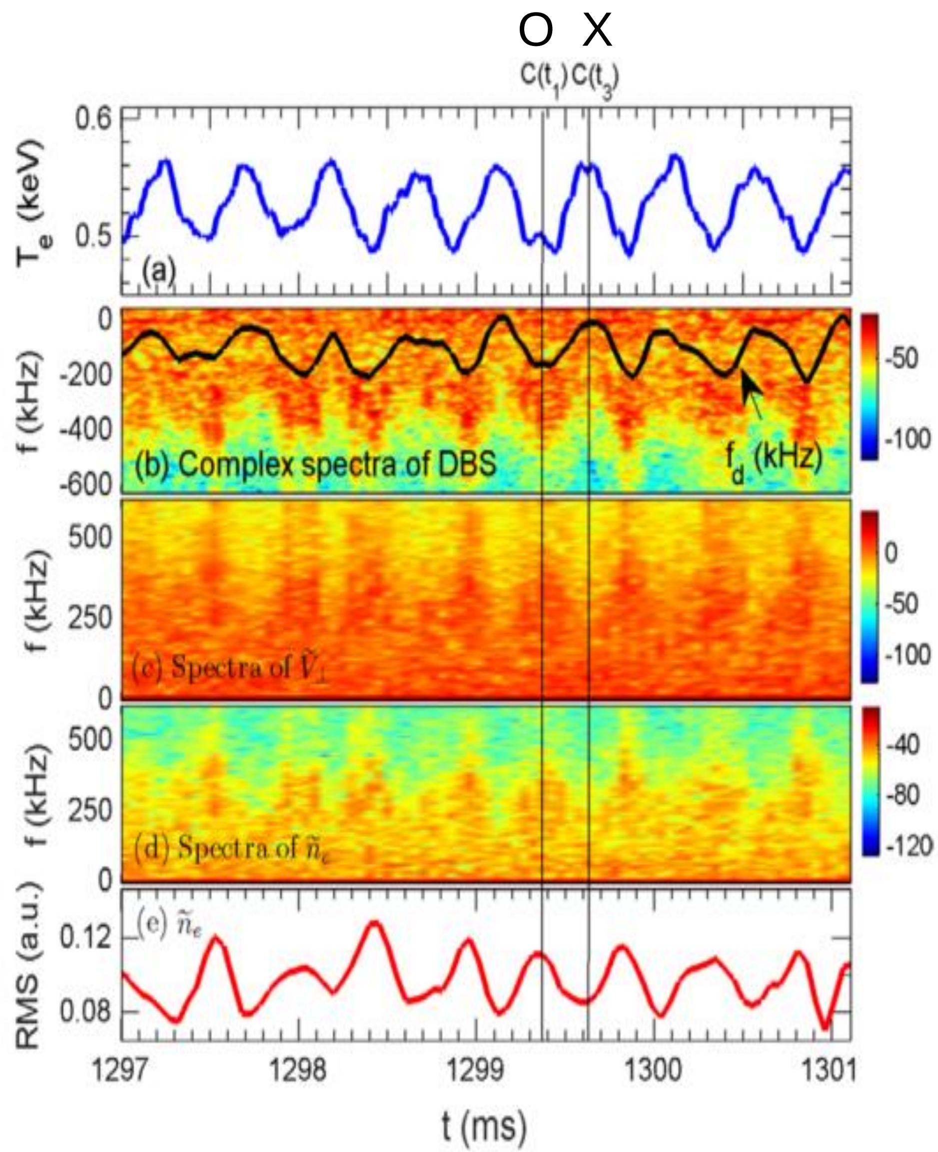



- ✓ Strong flow shear forms at island boundary.
- ✓ $\tilde{n}_e$ was reduced inside island while enhanced at island boundary, consistent with gradient-driven turbulence.

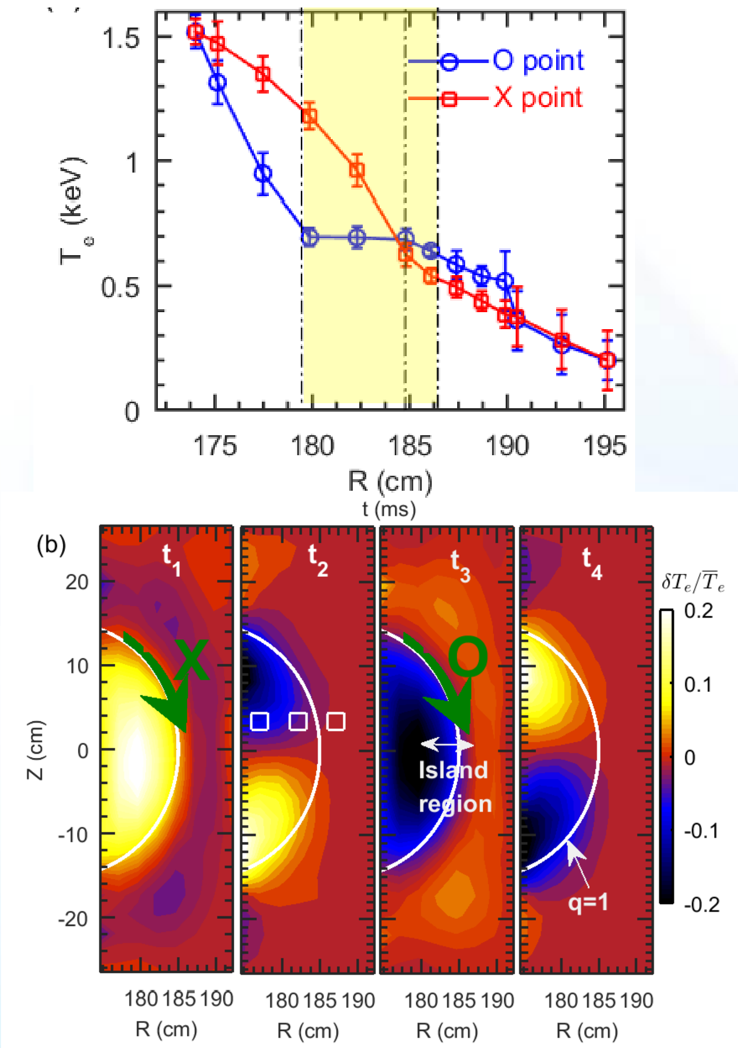
# Impact of 2/1 island on $V_\perp$ and $\tilde{n}_e$

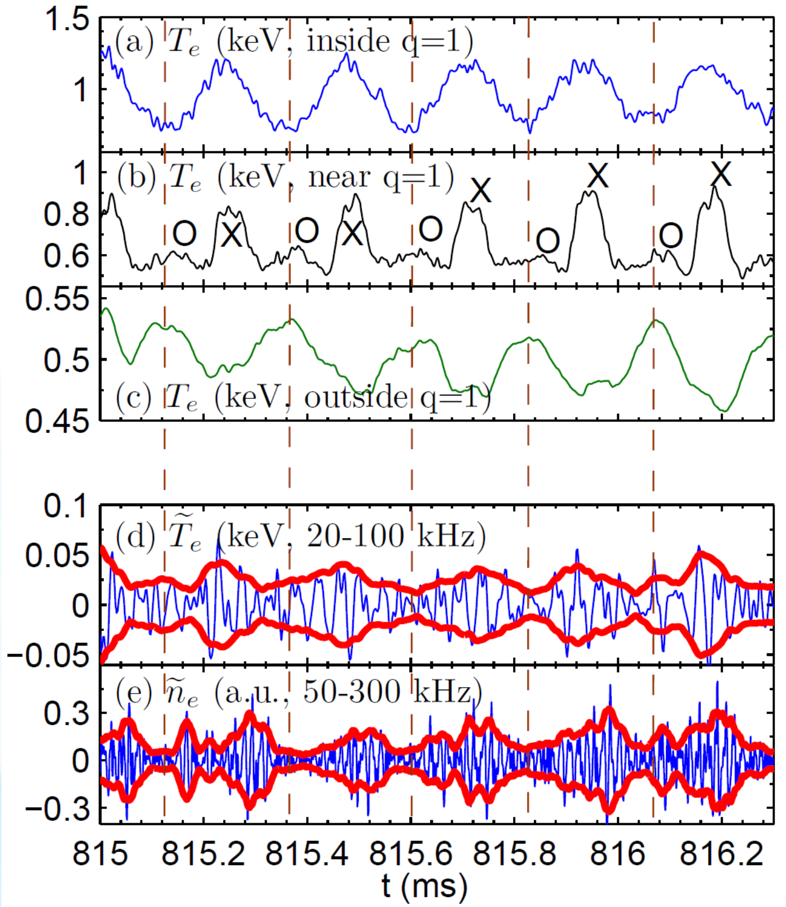



- $V_\perp$, $\tilde{V}_\perp$ and $\tilde{n}_e$ at island boundary are modulated by the rotation of island.
- Maximum (minimum) at O- (X-) point passing-by times.

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

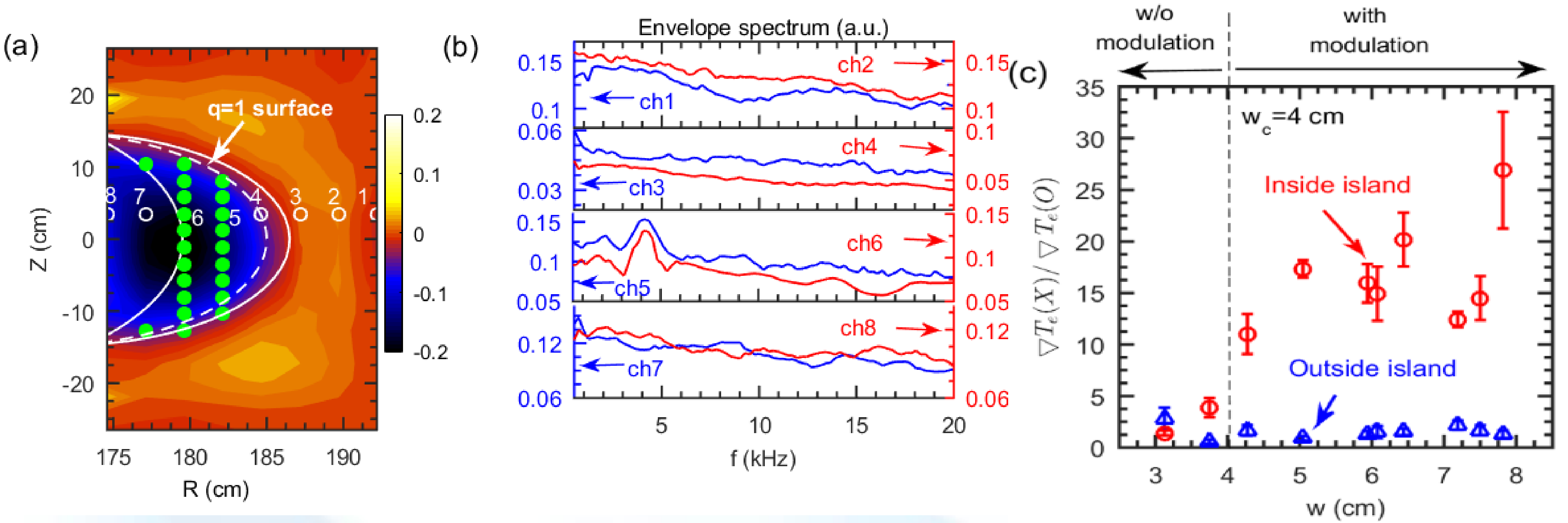



1/1 TM converted from 1/1 ideal kink mode prior to sawtooth crash.

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

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




- The modulation effect on $\widetilde{T}_e$ by the rotating 1/1 mode only appears at the inner area of the island (marked by green solid circles).
- Only when island width exceeds a certain threshold value ($w_c \approx 10\rho_i \approx 4$ cm), and the ratio of $\nabla T_e$ (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).

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

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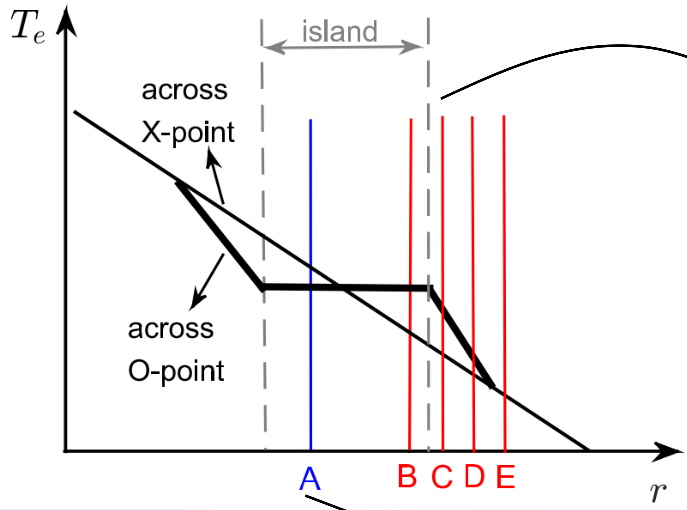
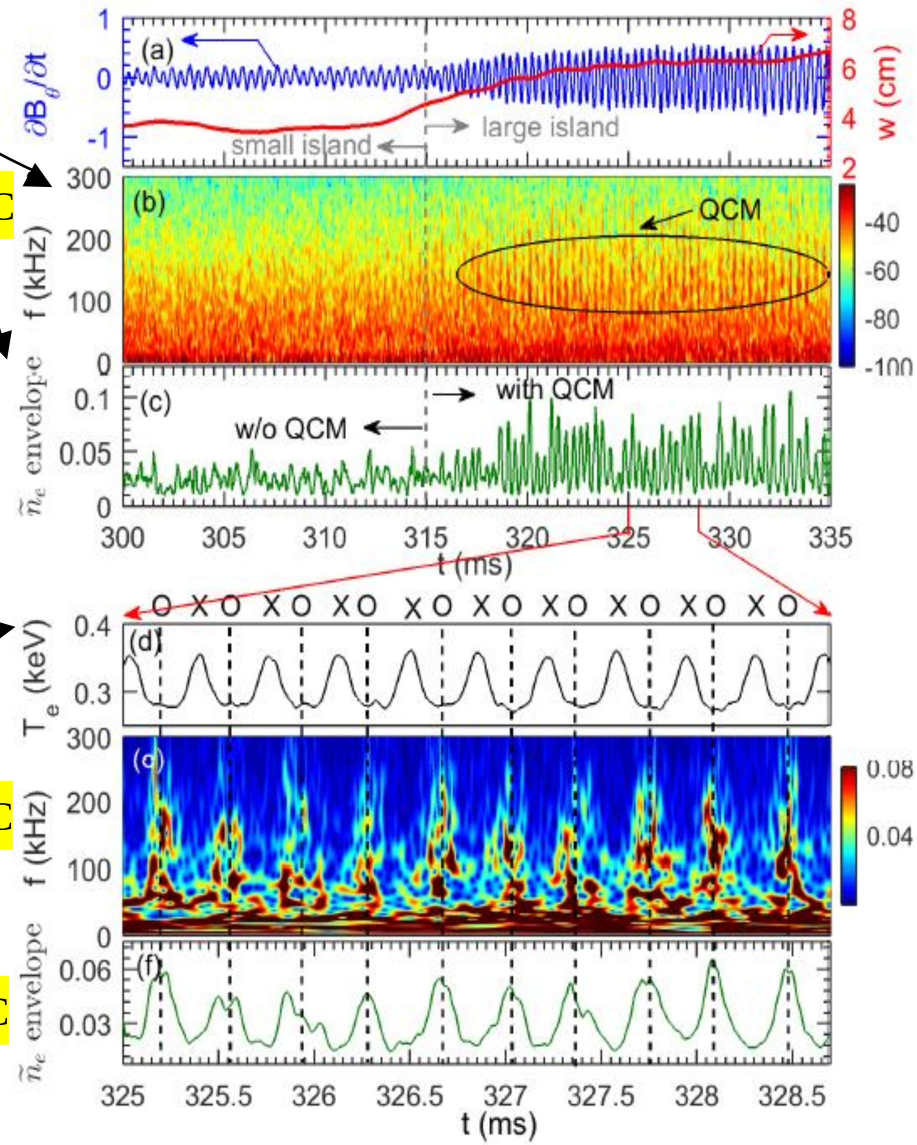
# Modulation of QCM by naturally rotating TM

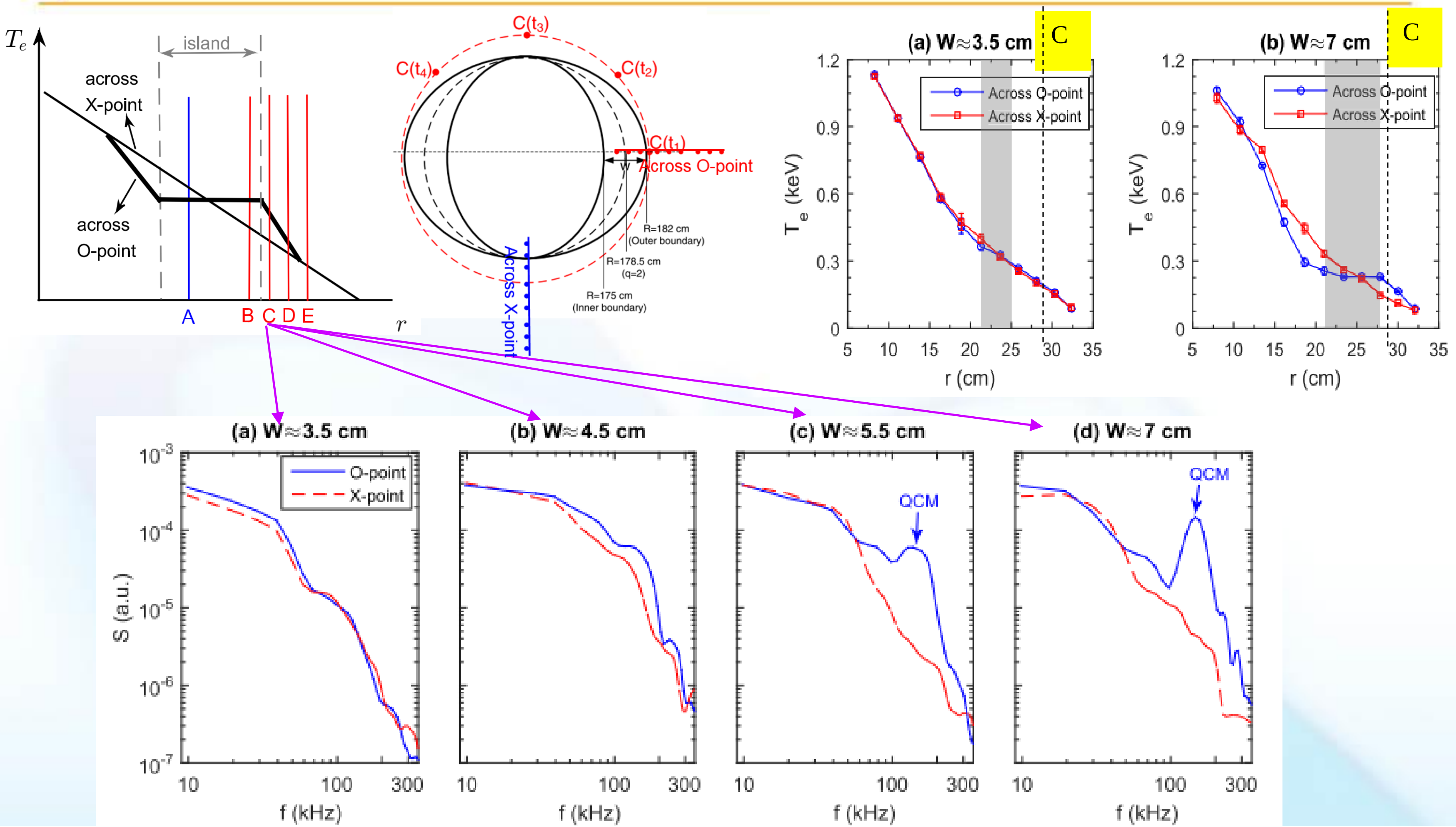



- When $w > 4.5$ cm, QCMs (80-170 kHz) become evident outside the island boundary (location C).
- QCMs are stimulated during the island O-point passing-by times in the large island case.

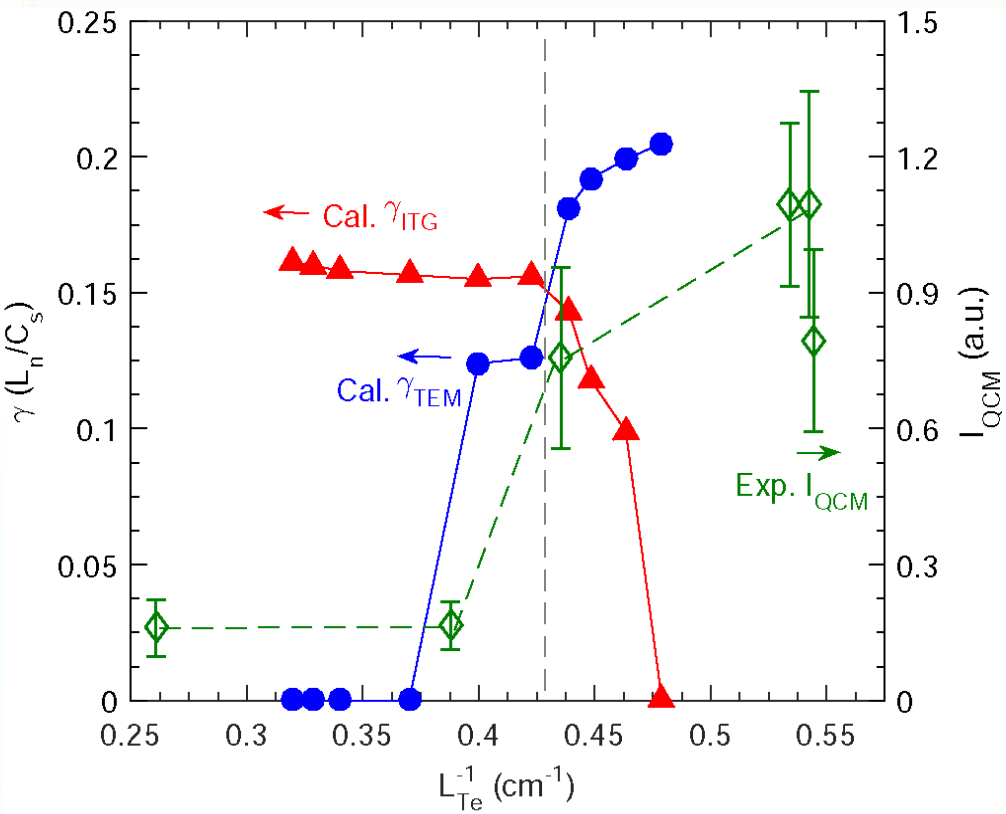
*M. Jiang, NF 60 066006 (2020)*

# QCMs observed at large 2/1 islands




- Both the QCM (100–175 kHz) and broadband turbulence (40–100 kHz and 175–300 kHz) outside the island are significantly enhanced during the O-point phase in comparison with that of the X-point.
- The QCM magnitude increases with the island size.

# Comparison between stability analysis and Exp.




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

- The QCM excitation depends on a critical temperature gradient ($L_{Te}^{-1}$).
- Stability analysis indicates that when $L_{Te}^{-1} > 0.43$ cm$^{-1}$, the TEM overcomes the ITG mode, and 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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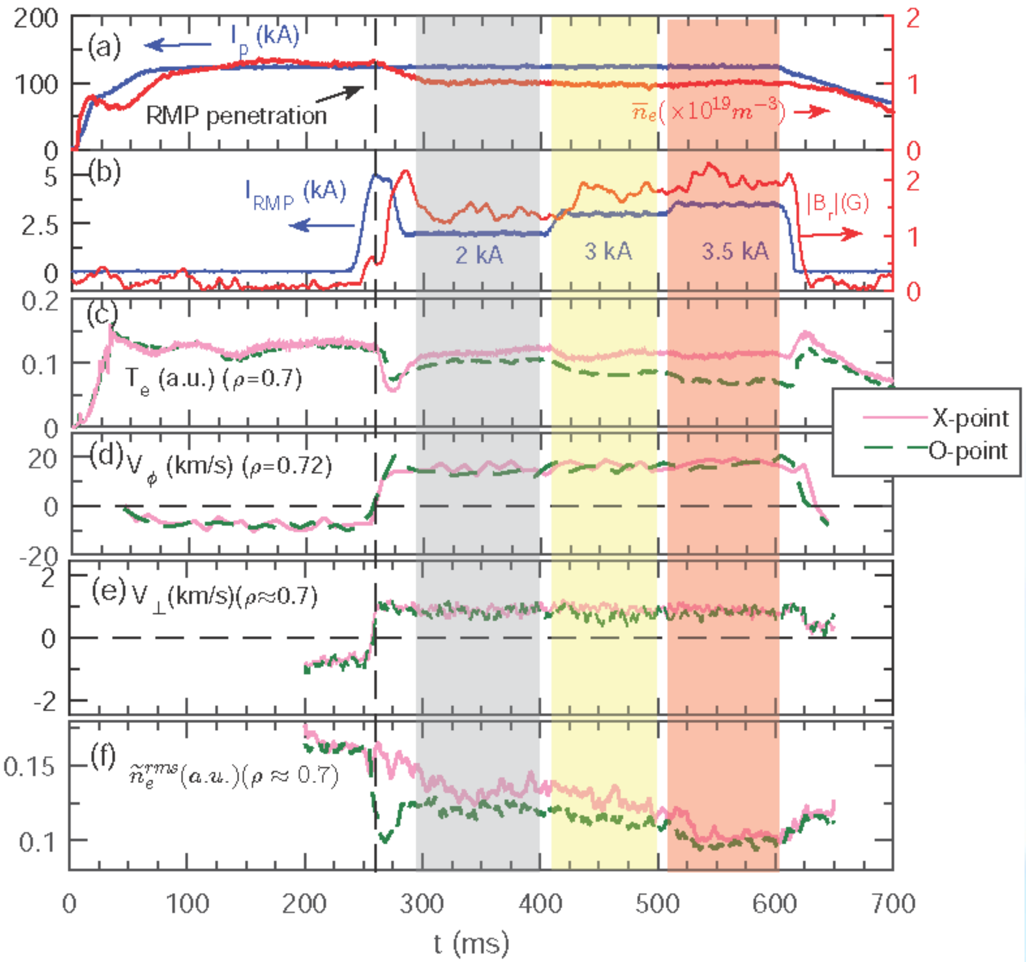
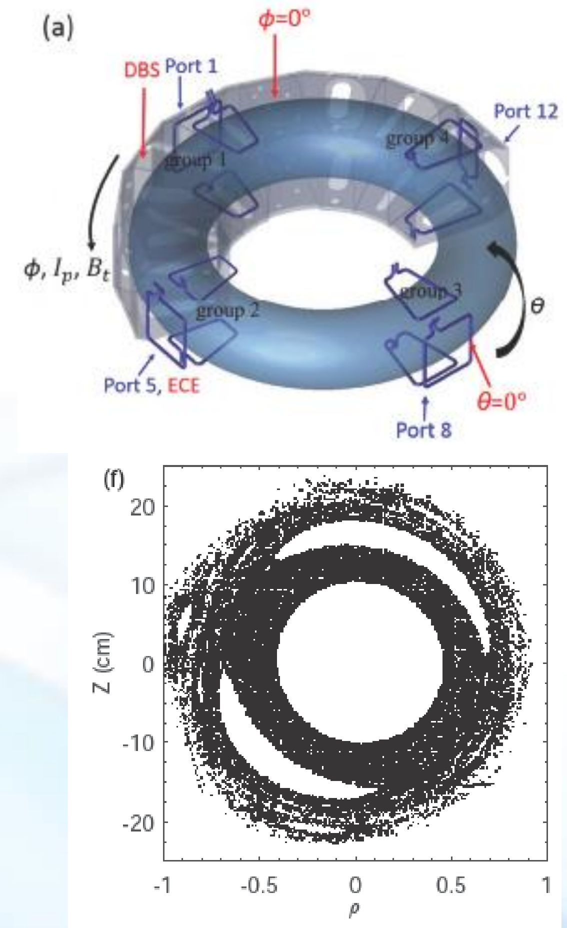
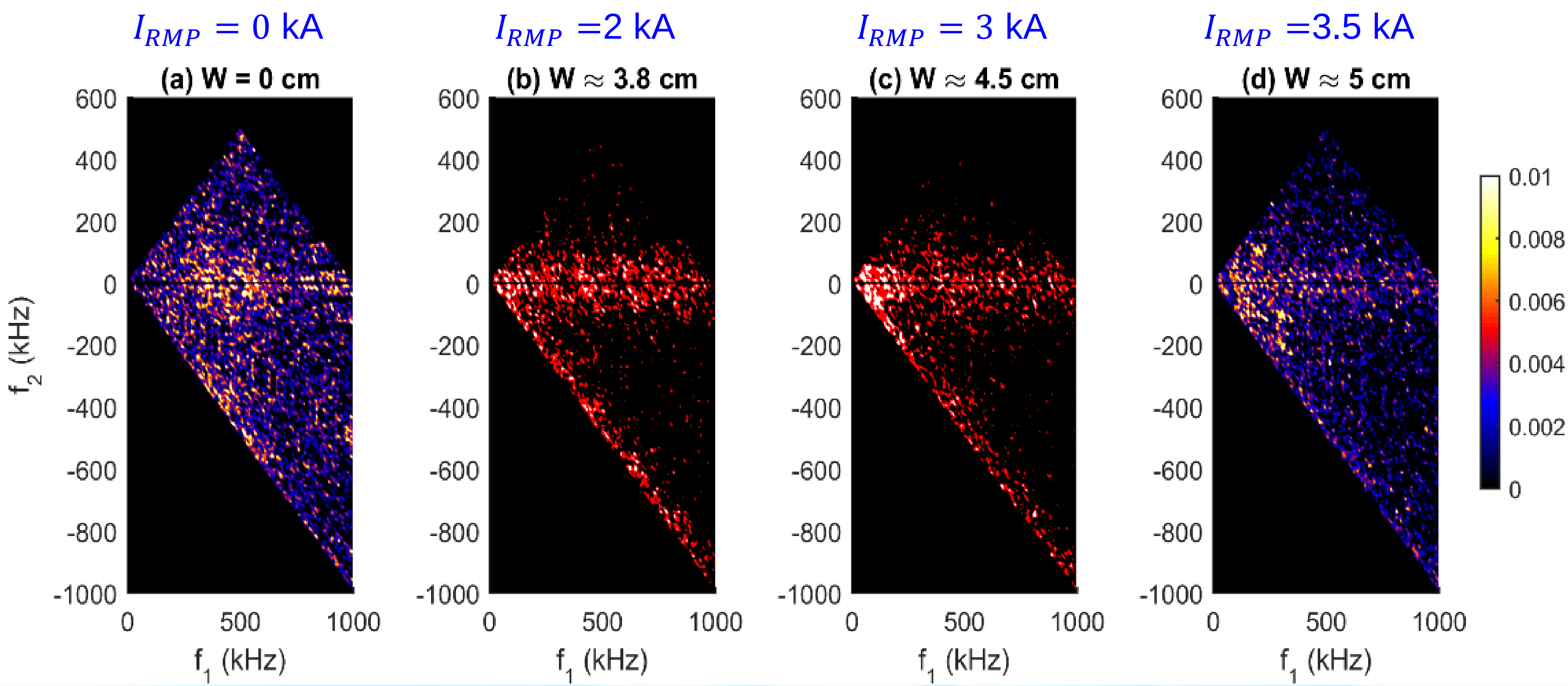
# RMP induced static 2/1 magnetic island




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

# NL coupling of turbulence enhanced by 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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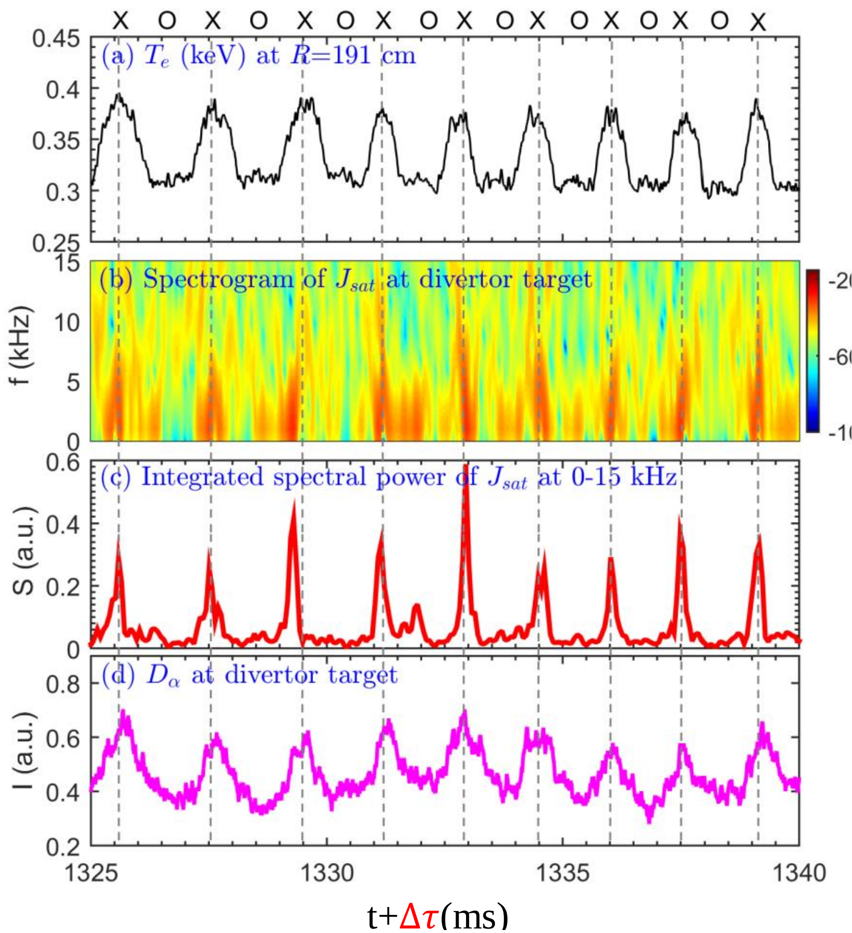
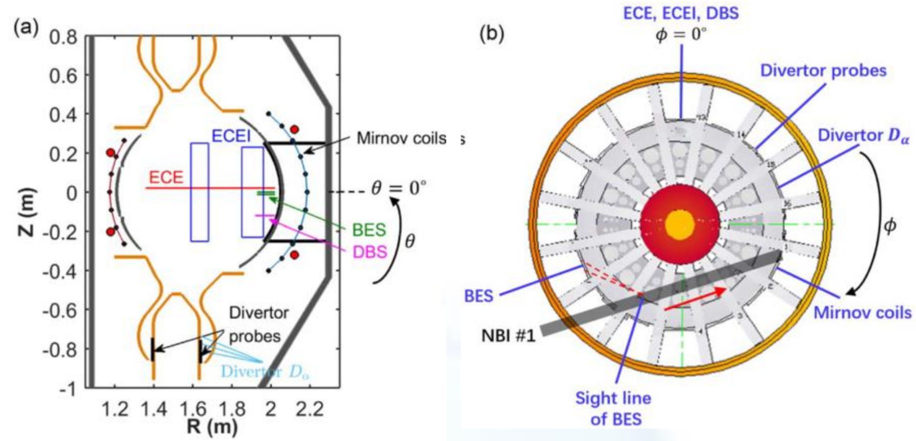
# Impact of core TM on divertor particle flux




$$\Delta\tau = \Delta\xi/(2\pi f_{TM})$$
$$\Delta\xi = m\Delta\theta - n\Delta\phi$$

$\Delta\theta$ and $\Delta\phi$ are the poloidal and toroidal angle difference between divertor probe and ECE

*Jiang, PST 22 080501(2020)*

- TM modulates the particle flux at the strike point, 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 passing by, the particle flux enhances substantially, while for the island O-point passing-by phases, it is quite small.

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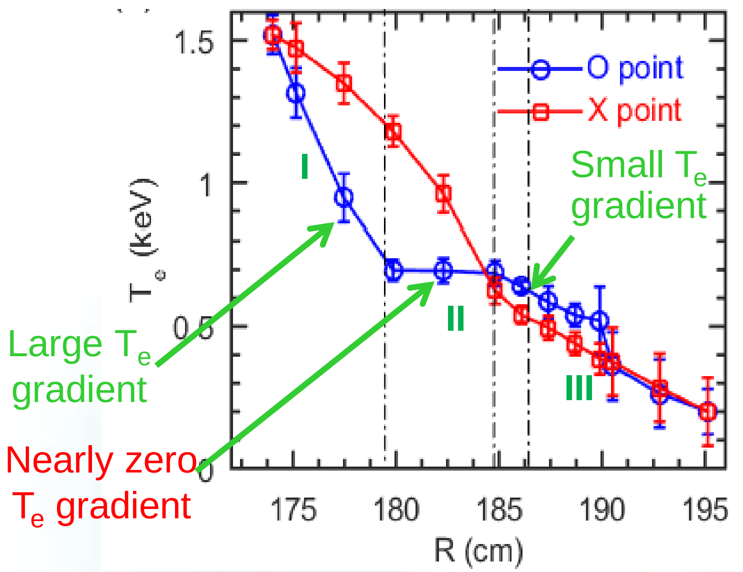
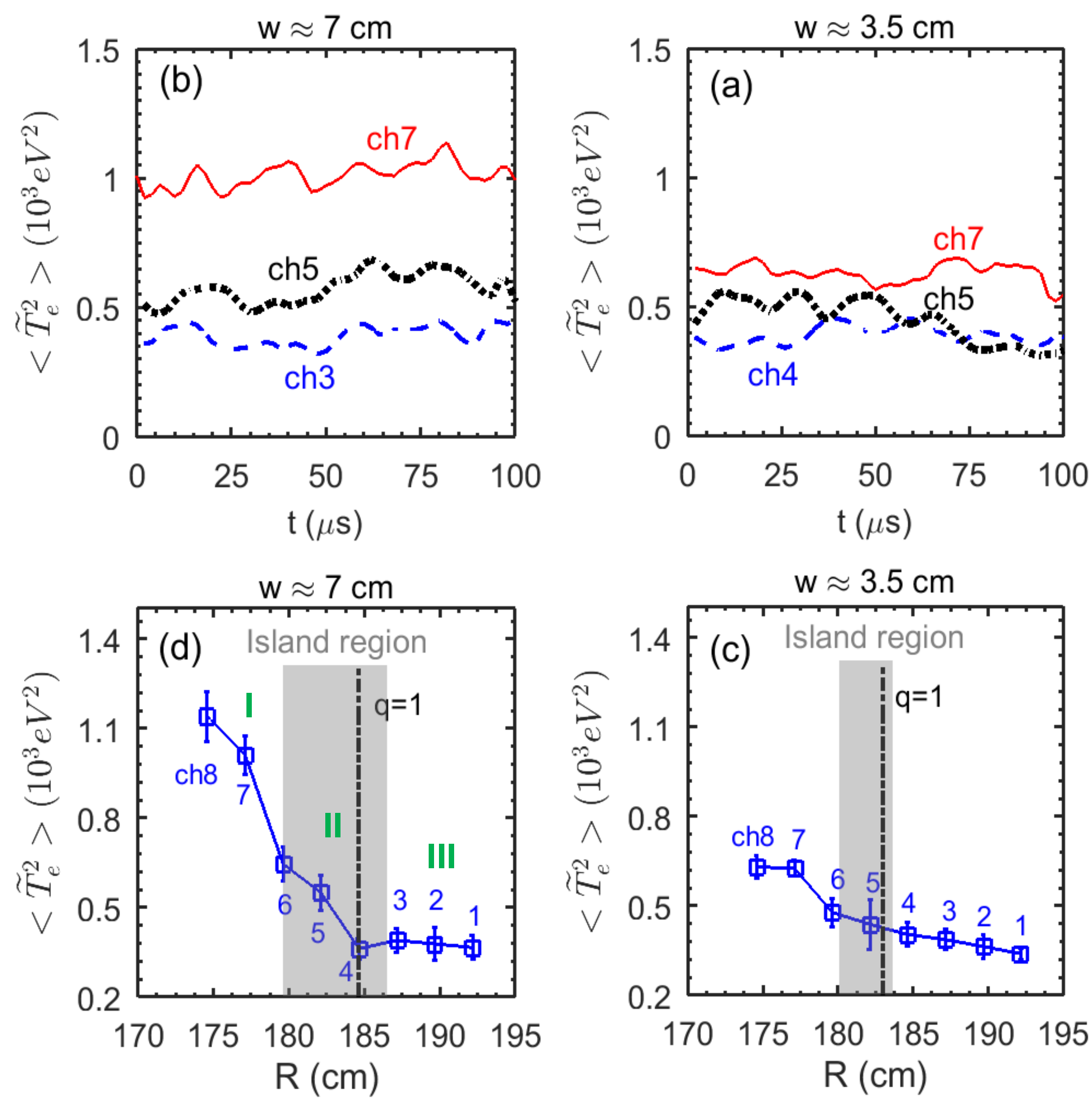
# Turbulence spreading across 1/1 island



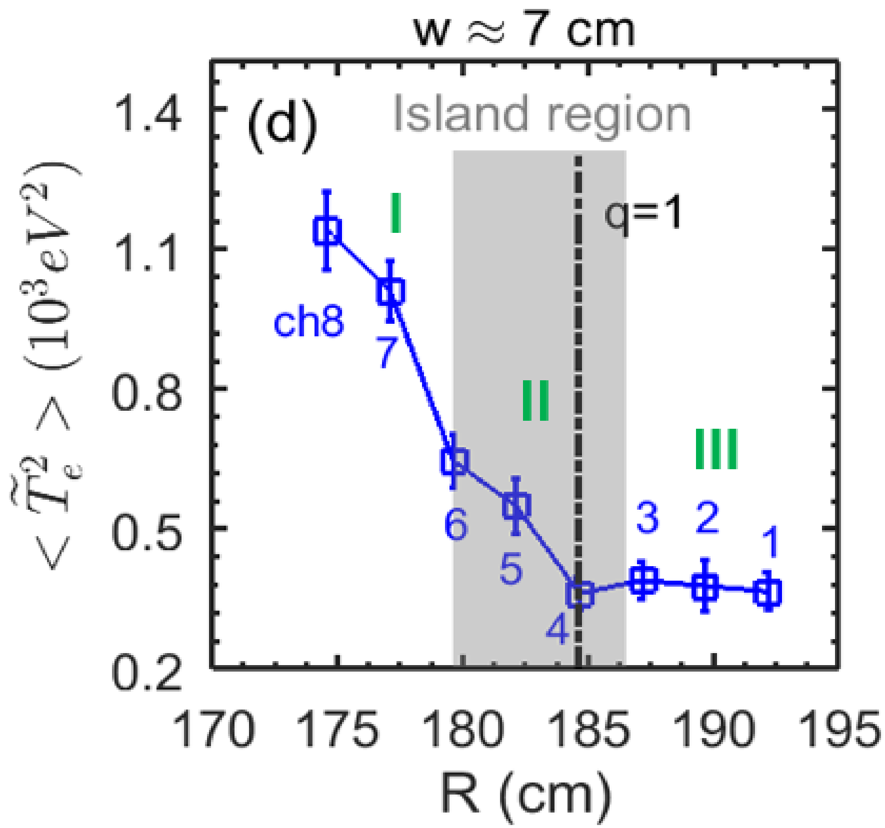




Turbulence spreading across the island occurred only at large island case.

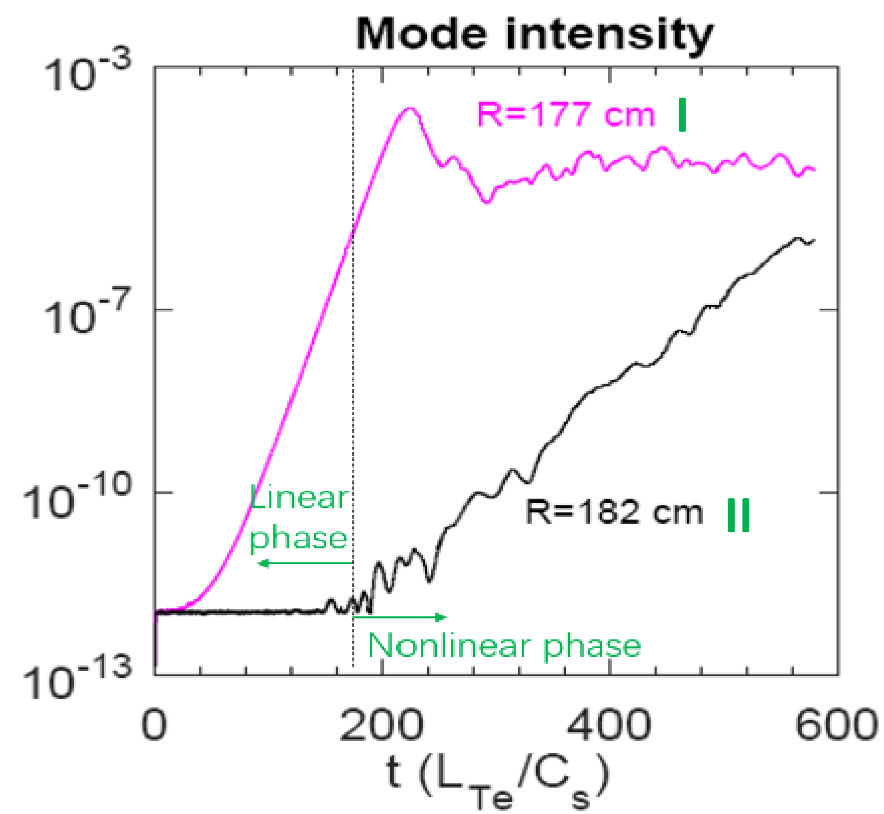
Turbulence spreading effect:
*X. Garbet, NF 34 963 (1994)*
*T. S. Hahm, PPCF 46, A323 (2004)*

# Turbulence spreading across 1/1 island

*Experimental result*



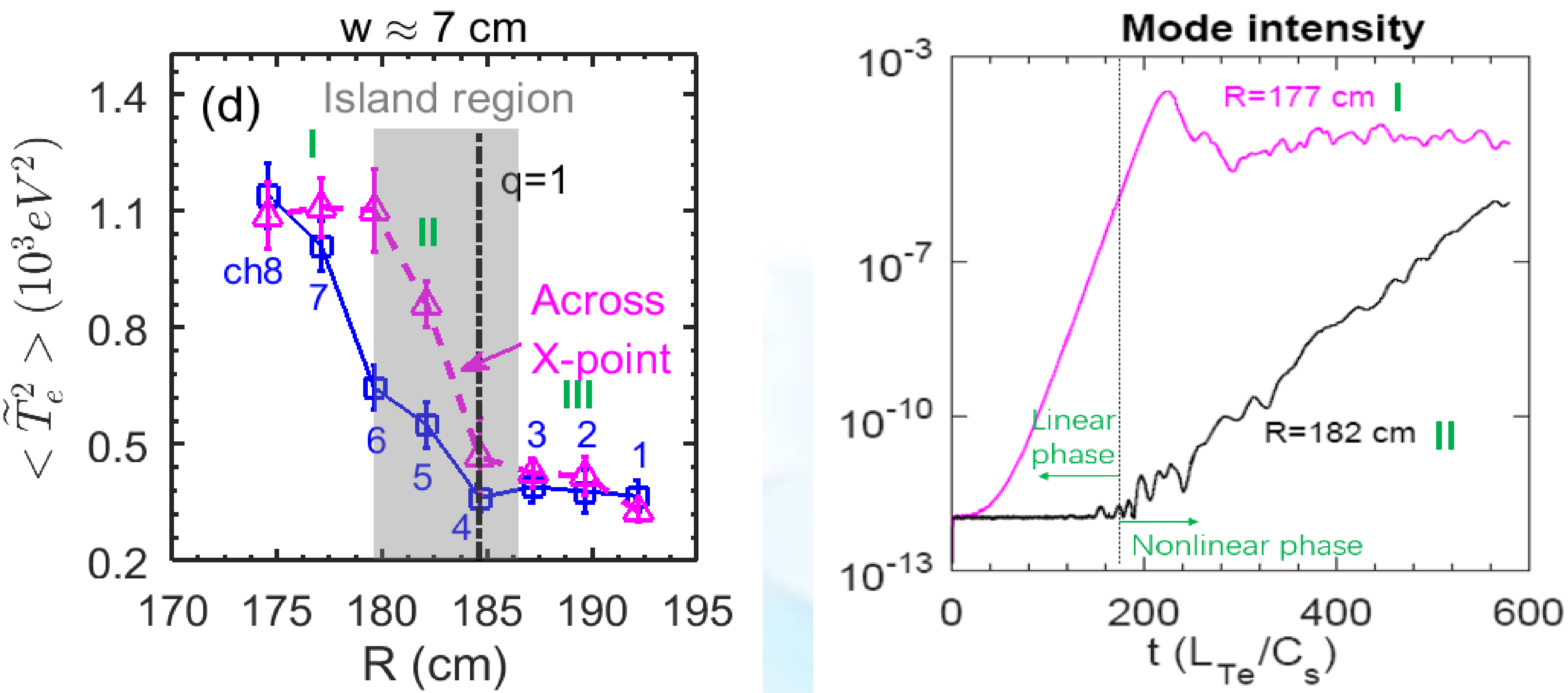

*Gyrokinetic Tokamak Simulation (GTS)*
*Acknowledgement to Prof. W.X. Wang PPL*




- 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 slowly increases and a slight drop is found in region I, consistent with turbulence spreading.

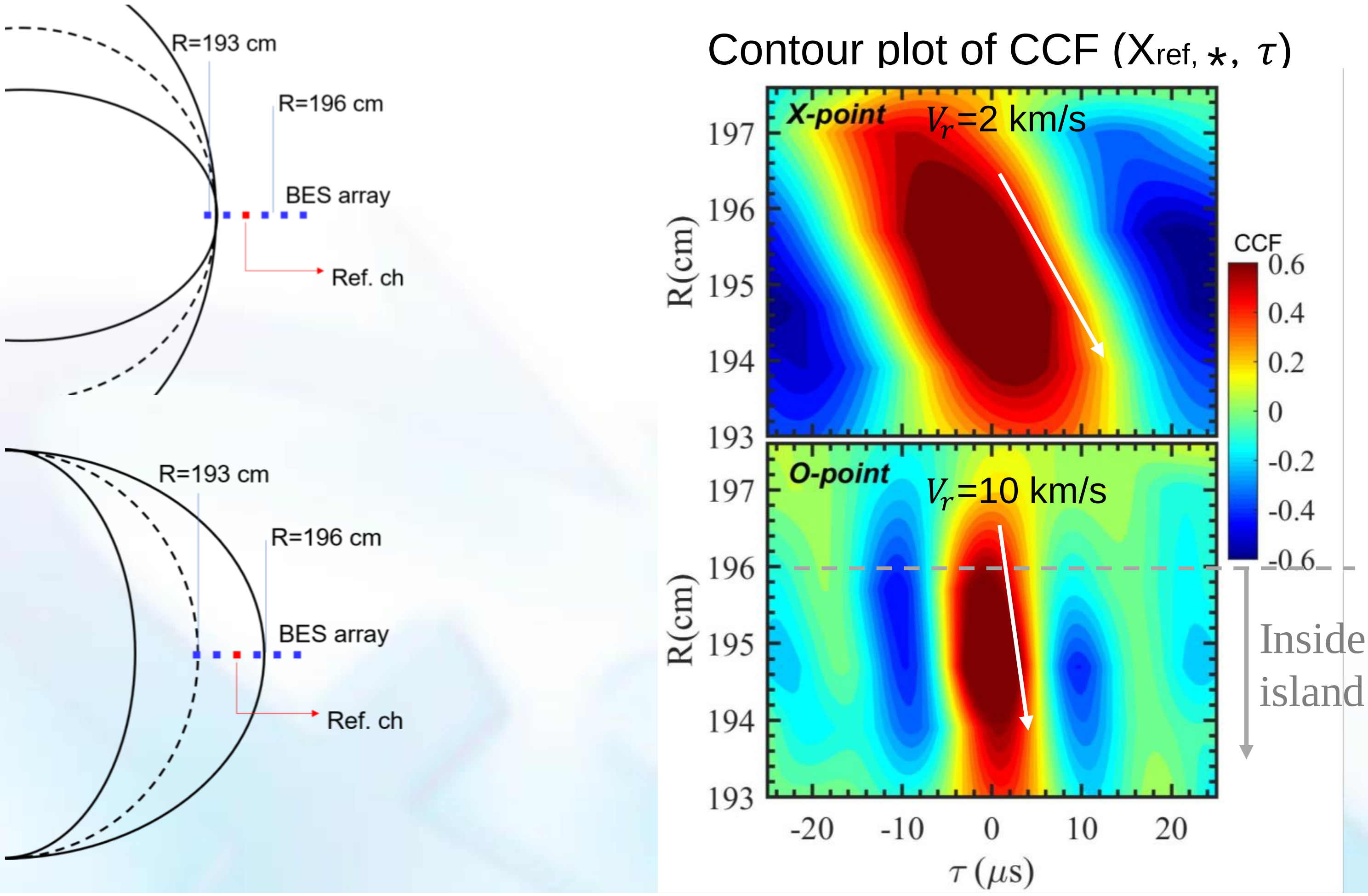
# Turbulence spreading across 1/1 island

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




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

# Turbulence spreading across 2/1 island




- O-point phase, the turbulence propagates radially inwards (10 km/s) from outer region to inside magnetic island, further demonstrating the turbulence spreading.
- Turbulence spreading also observed in DIII-D (Ida PRL2018) and KSTAR (Choi Nat. Commun. 2021)

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## Summary

- ✓ Strong $E \times B$ shear observed at island boundary, and turbulence decreased inside island and elevated at the boundary, consistent with gradient-driven turbulence.
- ✓ Density and temperature fluctuation are modulated by the rotating island, and the modulation effect depends on a critical island width (10~20$\rho_i$), consistent with the Fitzpatrick prediction.
- ✓ The QCMs are excited outside the large island boundary (W>Wc ≈ 4.5 cm) where the $\nabla T_e$ is elevated to exceed a critical value ($L_{Te}^{-1} > 0.42$ cm-1), in agreement with the TEM feature in the simulation.
- ✓ NL coupling of turbulence is enhanced by the RMP-induced static island.
- ✓ The core 2/1 island modulates the divertor particle flux, elevated during X-point passing-by phases.
- ✓ Turbulence spreading takes place across the large island region.

## Future work

Investigate the relationship among the TM, E×B flow (vortex) shear, QCM and AT.

# Thanks for your attention!