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Effect of multiscale interaction between the m/n=2/1 mode and micro-instabilities on transport in KSTAR plasmas

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SEOUL NATIONAL UNIVERSITY

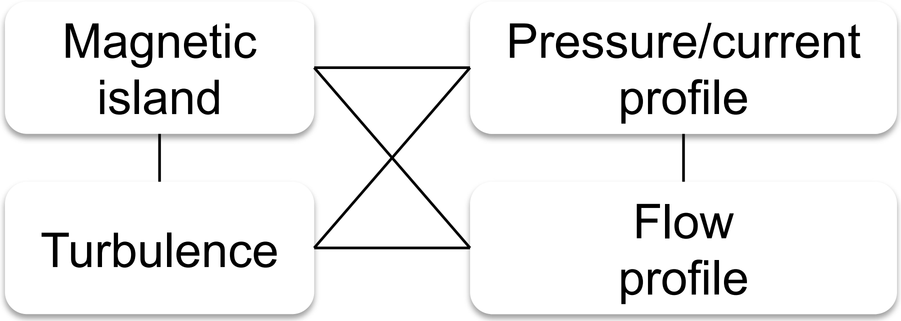
NFRI 국가핵융합연구소 National Fusion Research Institute

UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2009

POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Motivation of research

- Magnetic islands are frequently observed in tokamak plasmas
  - MHD instabilities such as neoclassical tearing mode (NTM)
  - The external magnetic perturbation field
- Effect of islands on transport is not trivial
  - Properly controlled islands are shown to be beneficial, but explosive growth of islands leads to disruptions
- This complicated behavior is thought to result from various interactions between



- Experimental validation/demonstration is more than necessary

Outline

- Part 1: Turbulence intensity is redistributed by the magnetic island

- Part 2: Role of the strong turbulence intensity

Outline

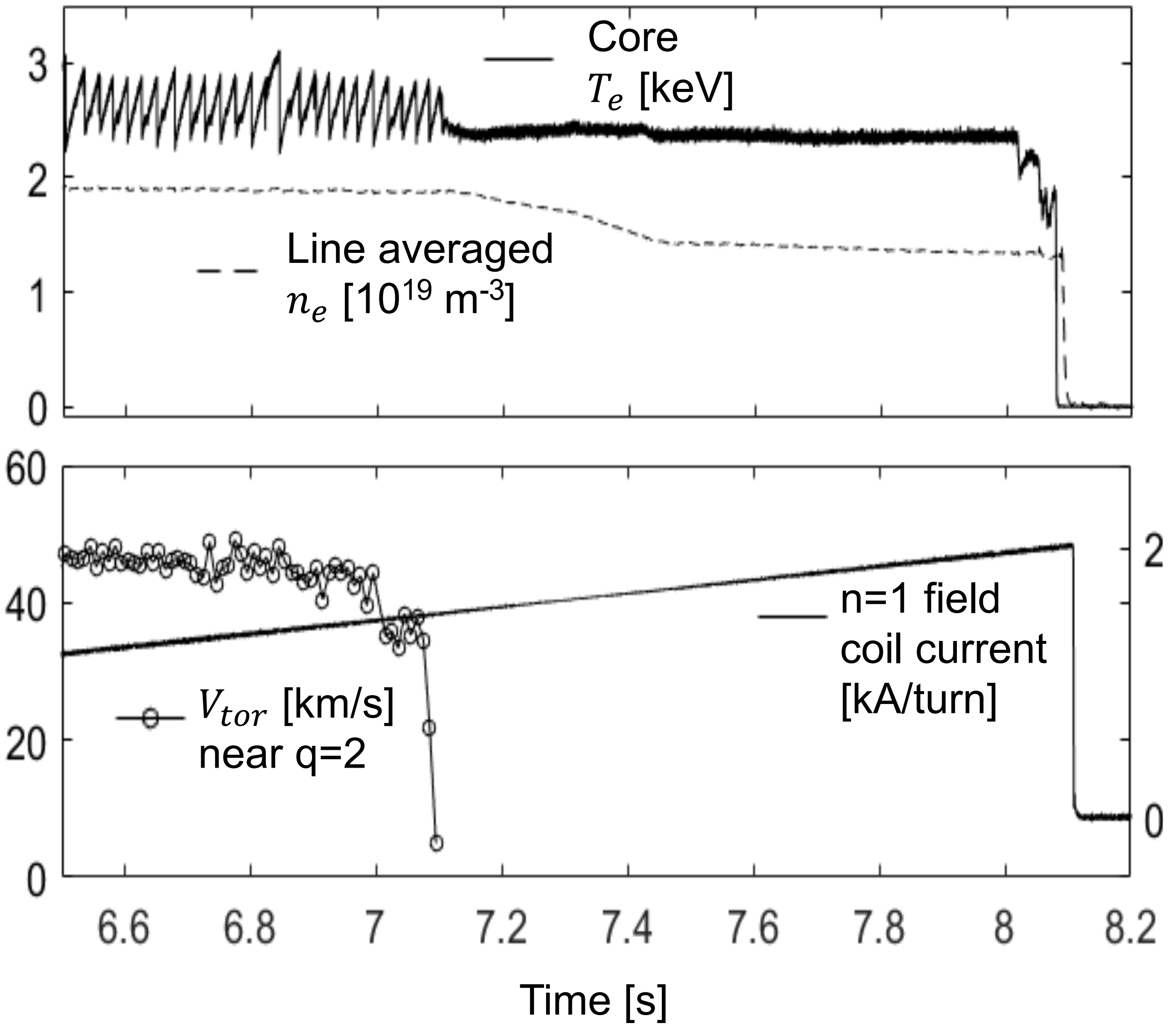
- Part 1: Turbulence intensity is redistributed by the magnetic island
  - Full 2-D picture of turbulence intensity
    - More than ”weak around the O-point and strong near the X-point”
  - Flow shear generated by the island or turbulence can be responsible for this turbulence intensity redistribution

- Part 2: Role of the strong turbulence intensity

Experimental set-up for the controlled island experiment

- Discharge conditions
  - 1 MW neutral beam injection (NBI) L-mode diverted plasma
  - Plasma current = 700 kA and q_{95} = 4.6
  - Average density = 1.3—1.6 x 10^{19} m^{-3}
  - The n=1 (middle) magnetic perturbation field is applied to induce a locked magnetic island

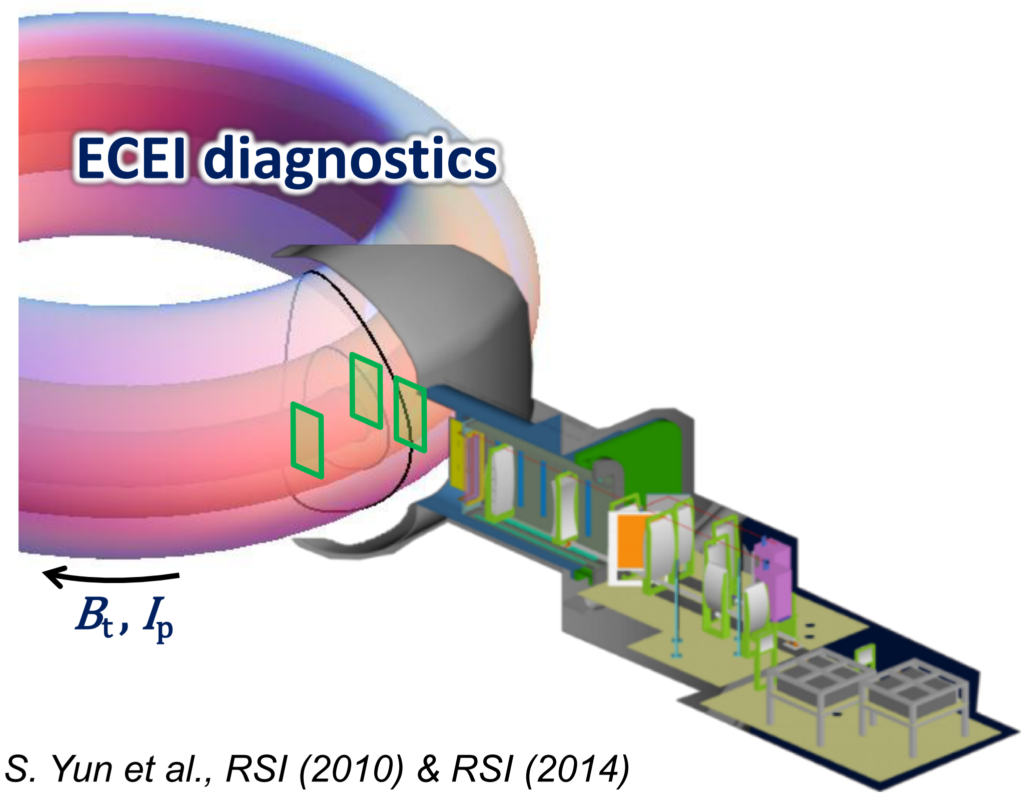
KSTAR #13371



M.J. Choi et al., NF (2017)

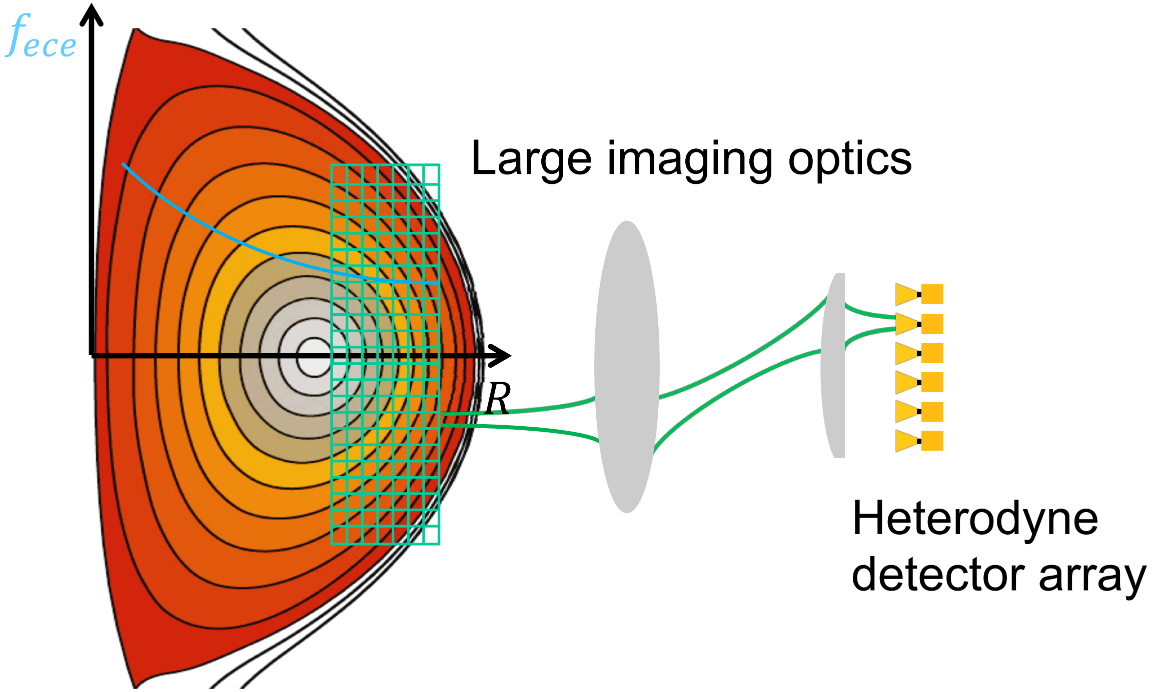
Diagnostics: electron cyclotron emission imaging (ECEI) diagnostics

- Multi-dimensional diagnostics are essential to understand the complicated dynamics correclty



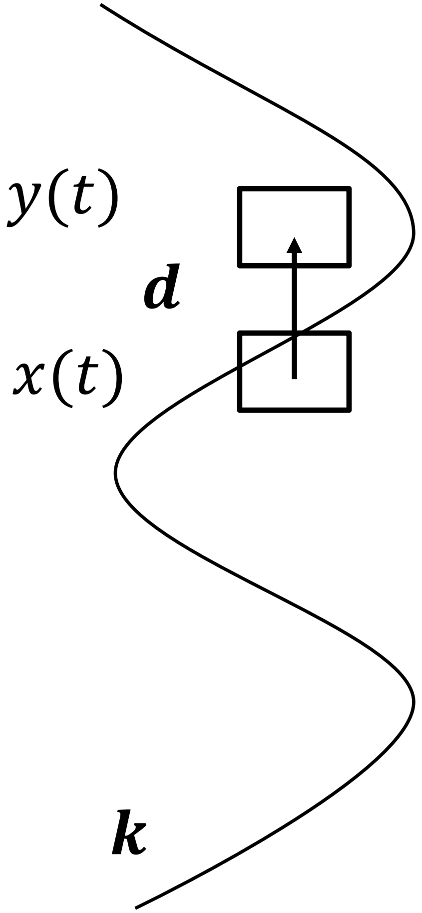
G.S. Yun et al., RSI (2010) & RSI (2014)

Each ECEI system is composed of 24x8 channels
Each channel measures local (~2x2 cm^2) intensity of ECE which is proportional to local electron temperature



T_e profile, turbulence, and flow measurements using the ECEI diagnostics

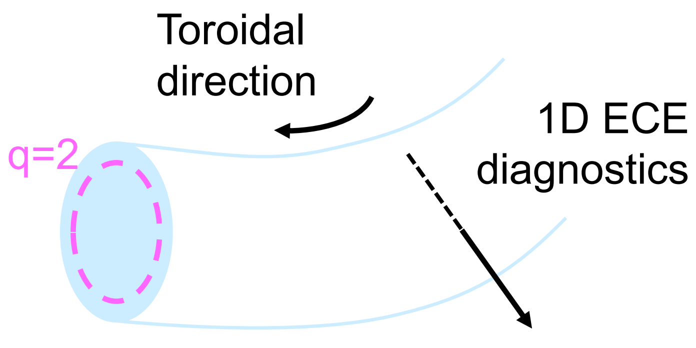
- T_e profile from cross calibration
- T_e turbulence intensity from cross coherence between ECEI channels
  - Cross coherence $\gamma_{xy}(f) = \frac{\text{A coherent fluctuation power}}{\text{total power (including all noise)}}$
- Flow from local dispersion relation measurement using ECEI channels
  - Cross phase $\theta_{xy}(f) = K(f) \cdot d$

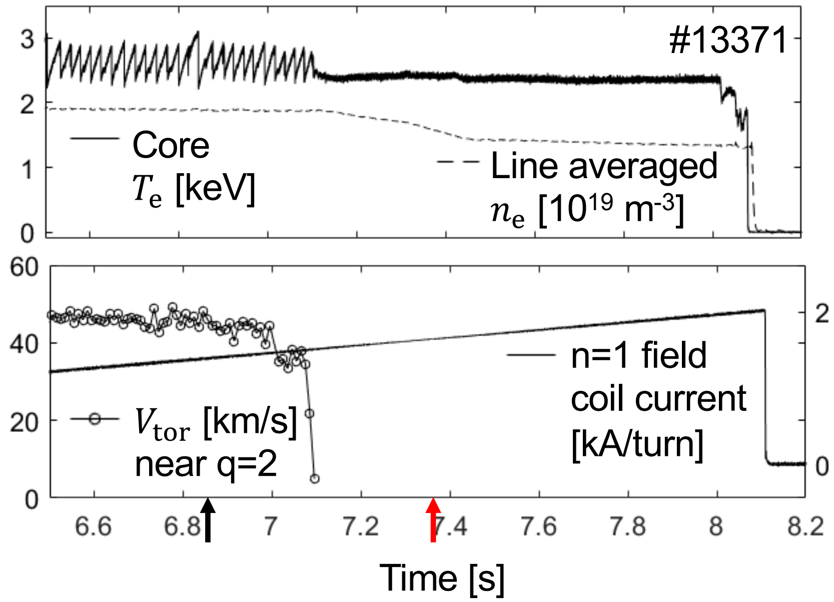


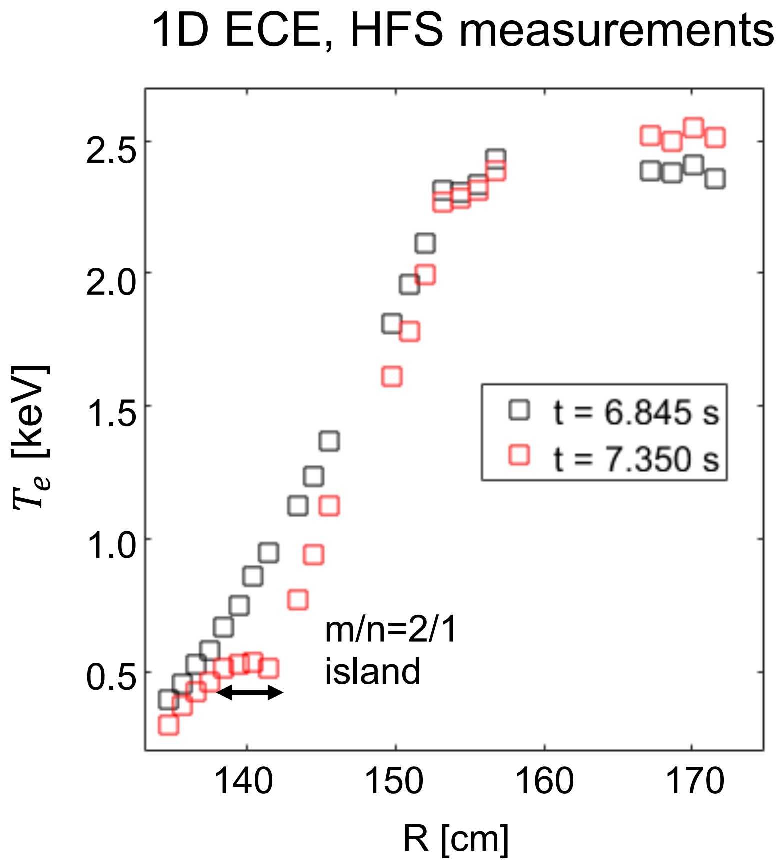
J.M. Beall et al., JAP (1982)
M.J. Choi et al., APS (2011) & RSI (2016)

T_e profile modification due to the m/n=2/1 island

- The flat (steep) T_e profile inside (outside) the magnetic island







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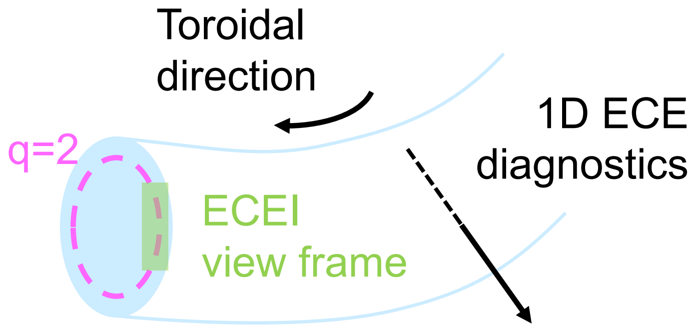
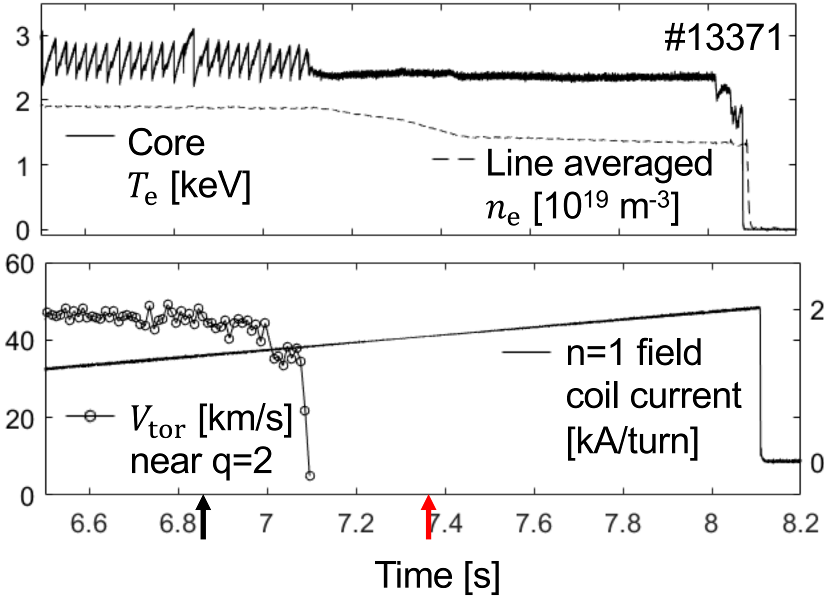
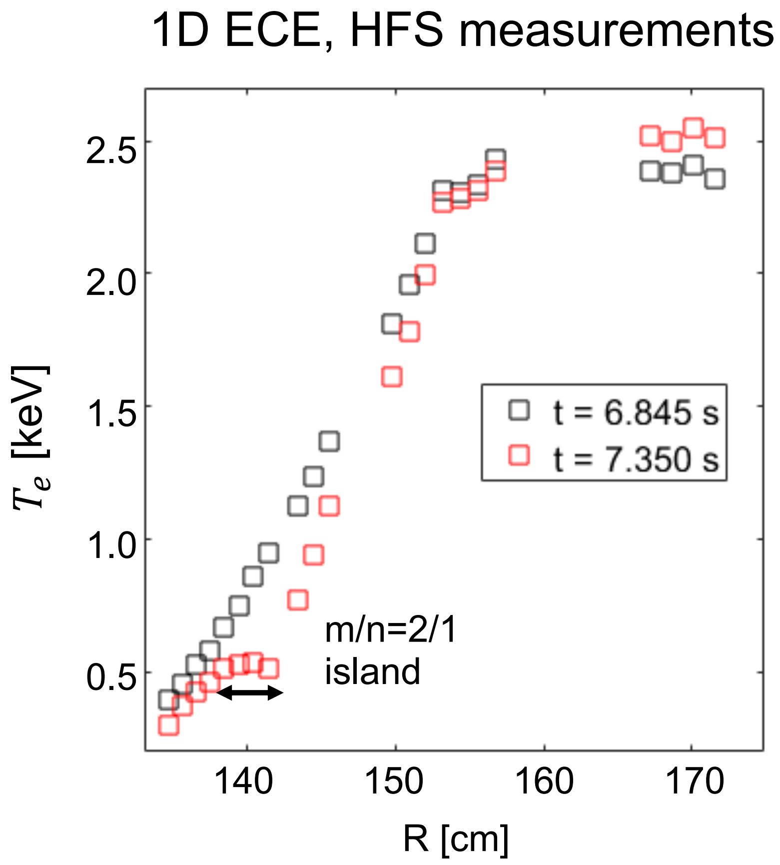
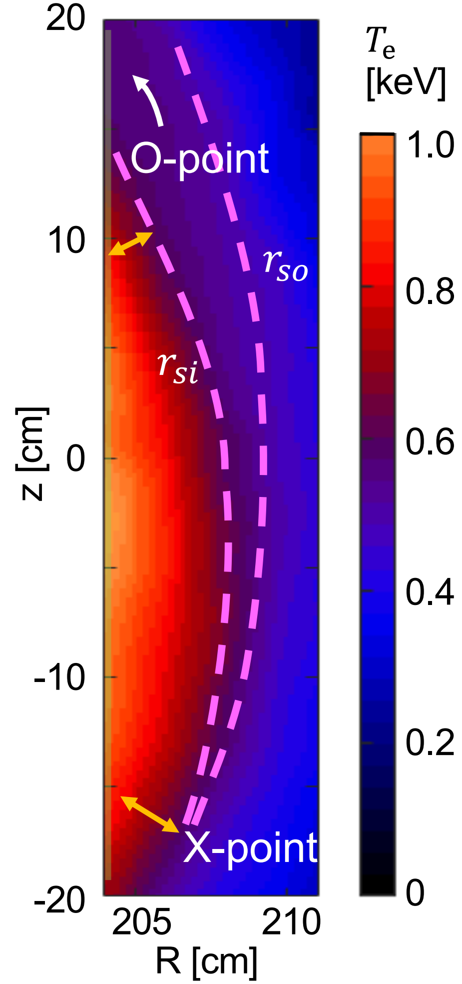


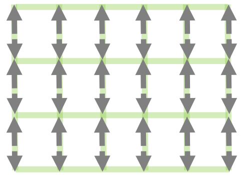




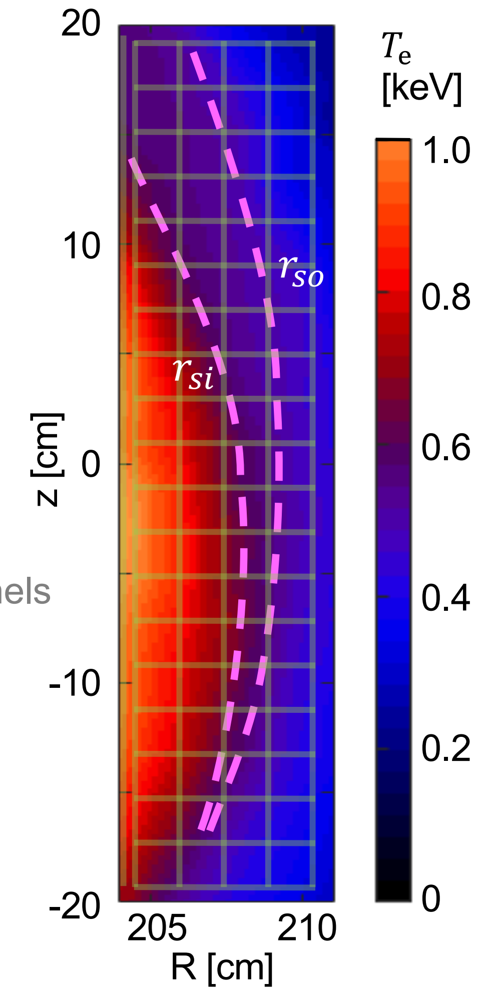


2D inhomogeneous T_e turbulence intensity near the island

ECEI
channel grid



cross coherence btw
vertically adjacent channels



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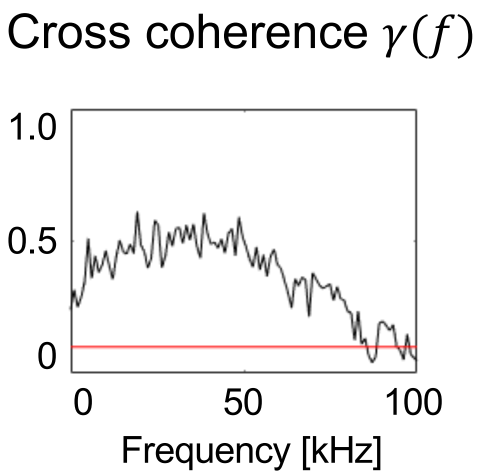
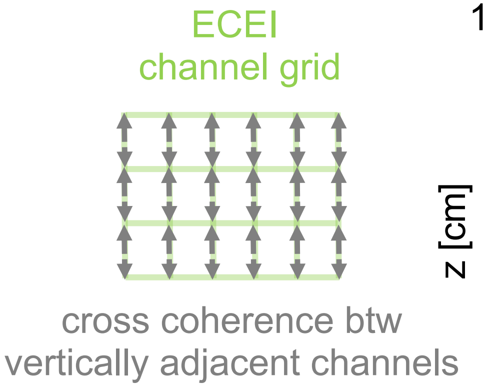
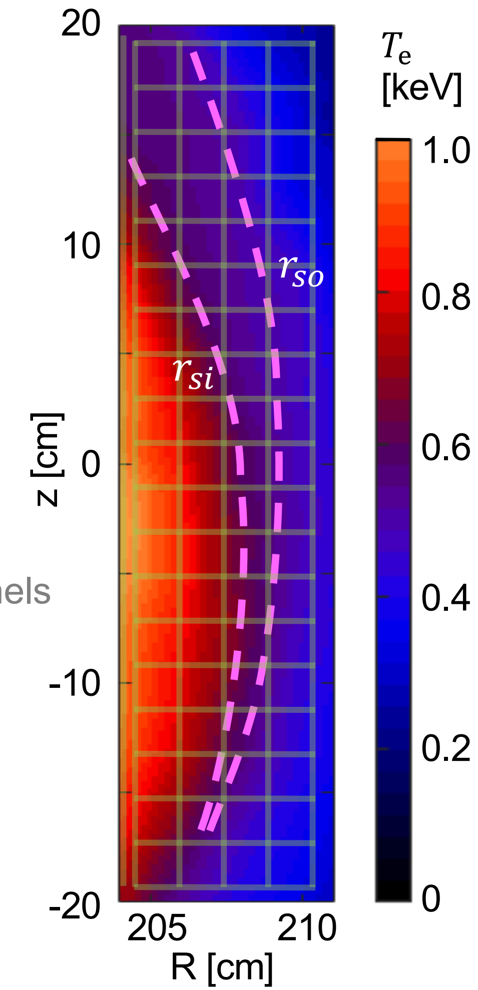


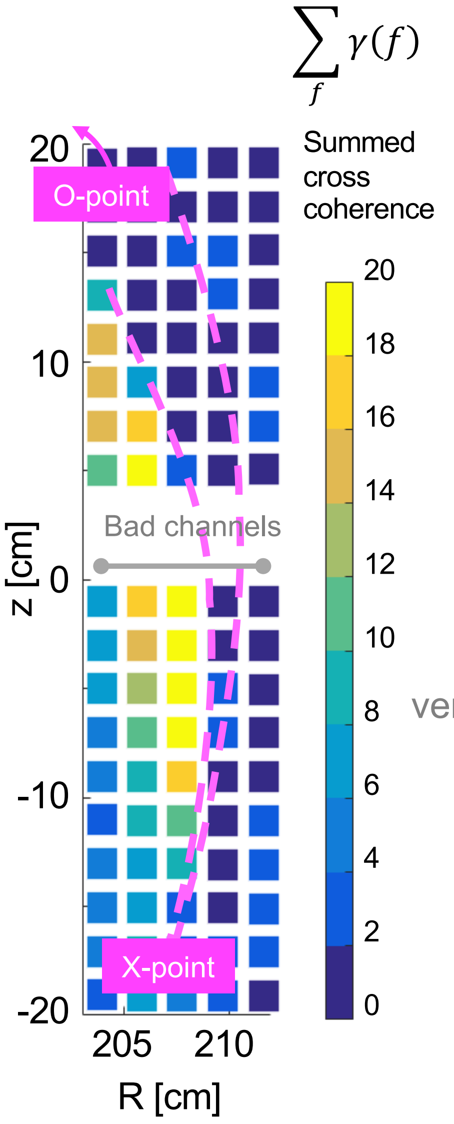


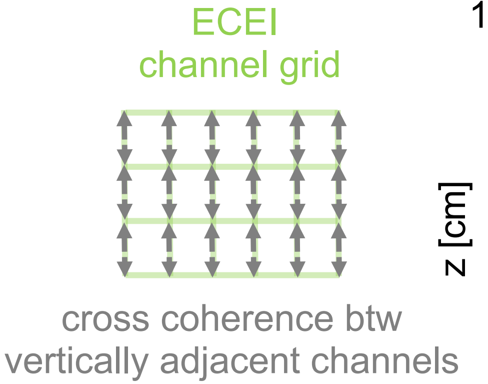


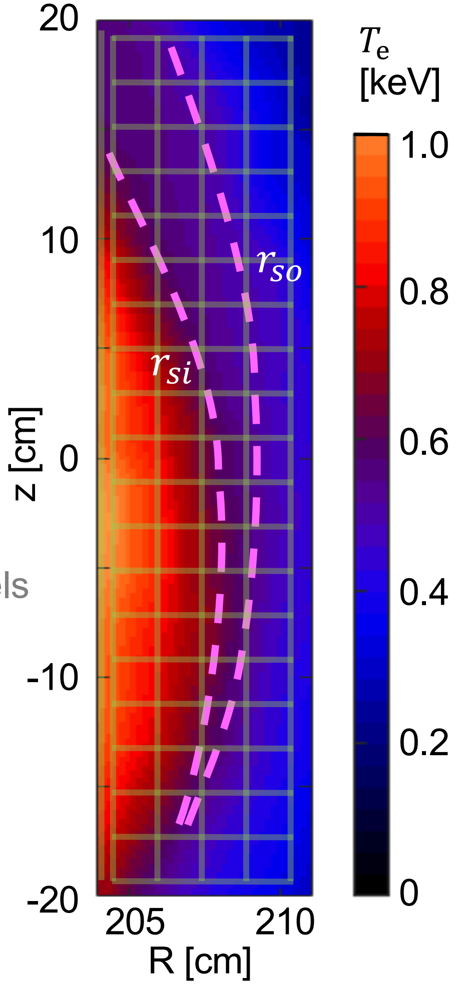
2D inhomogeneous T_e turbulence intensity near the island

- Inside the island, no significant turbulence intensity
- Outside the island, significant turbulence intensity in both inner ($r < r_{si}$) and outer ($r > r_{so}$) regions

J.-M. Kwon et al., PoP (2018) & TH/8-1 found TEM ($r < r_{si}$) and ITG ($r > r_{so}$) unstable







For similar experimental observations
K. Zhao et al., NF (2015)
L. Bardóczi et al., PRL (2016)

2D inhomogeneous T_e turbulence intensity near the island

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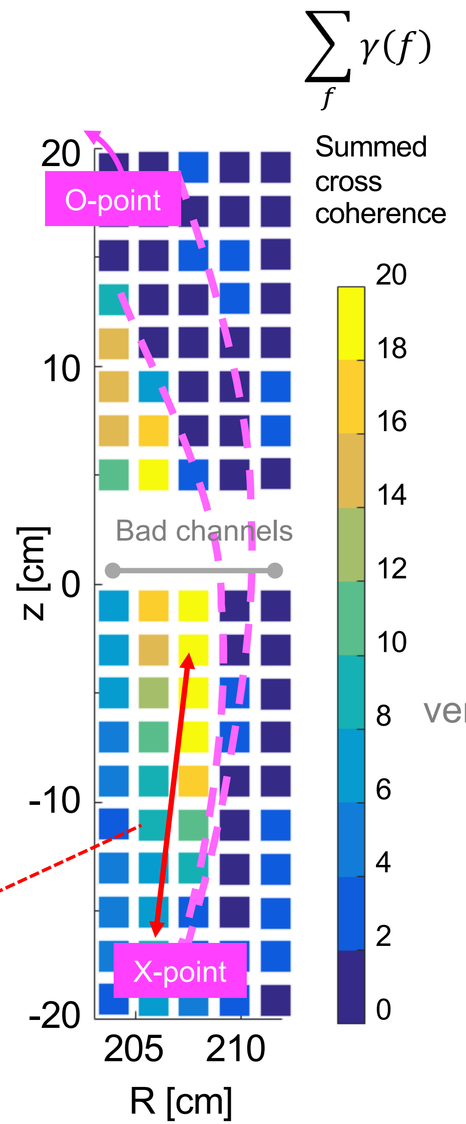
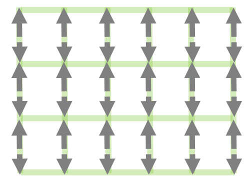
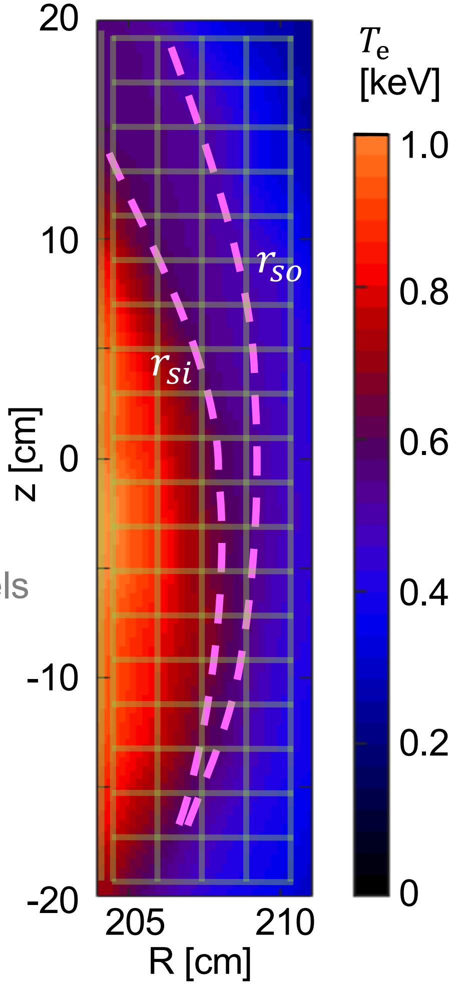
Localized close to the X-point with a distance







J.-M. Kwon et al., PoP (2018) & TH/8-1

M.J. Choi et al., NF (2017)

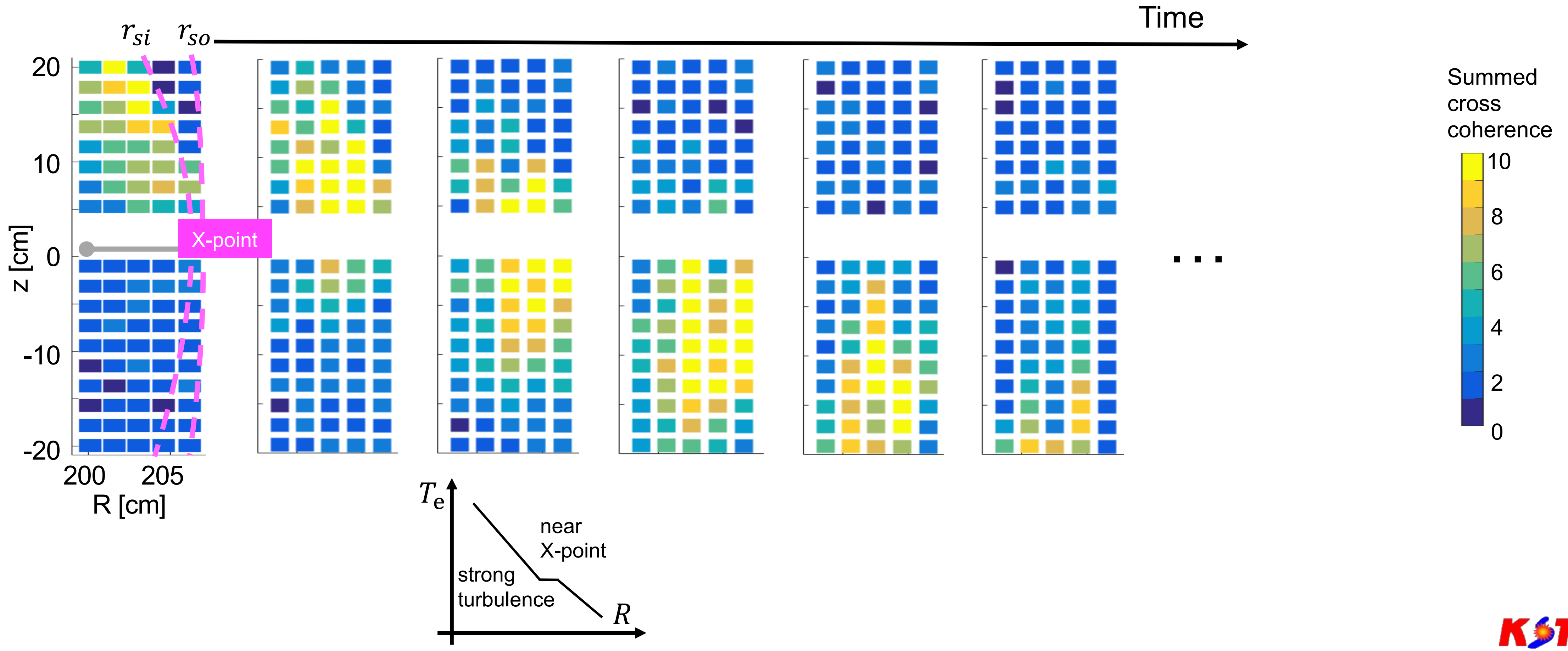
NFRI

KSTAR

Absence of T_e turbulence in the O-point regions

- Slowly rotating RMP experiment demonstrates full picture of the T_e turbulence around the island

KSTAR #15638; rotating n=1 field



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- Slowly rotating RMP experiment demonstrates full picture of the T_e turbulence around the island

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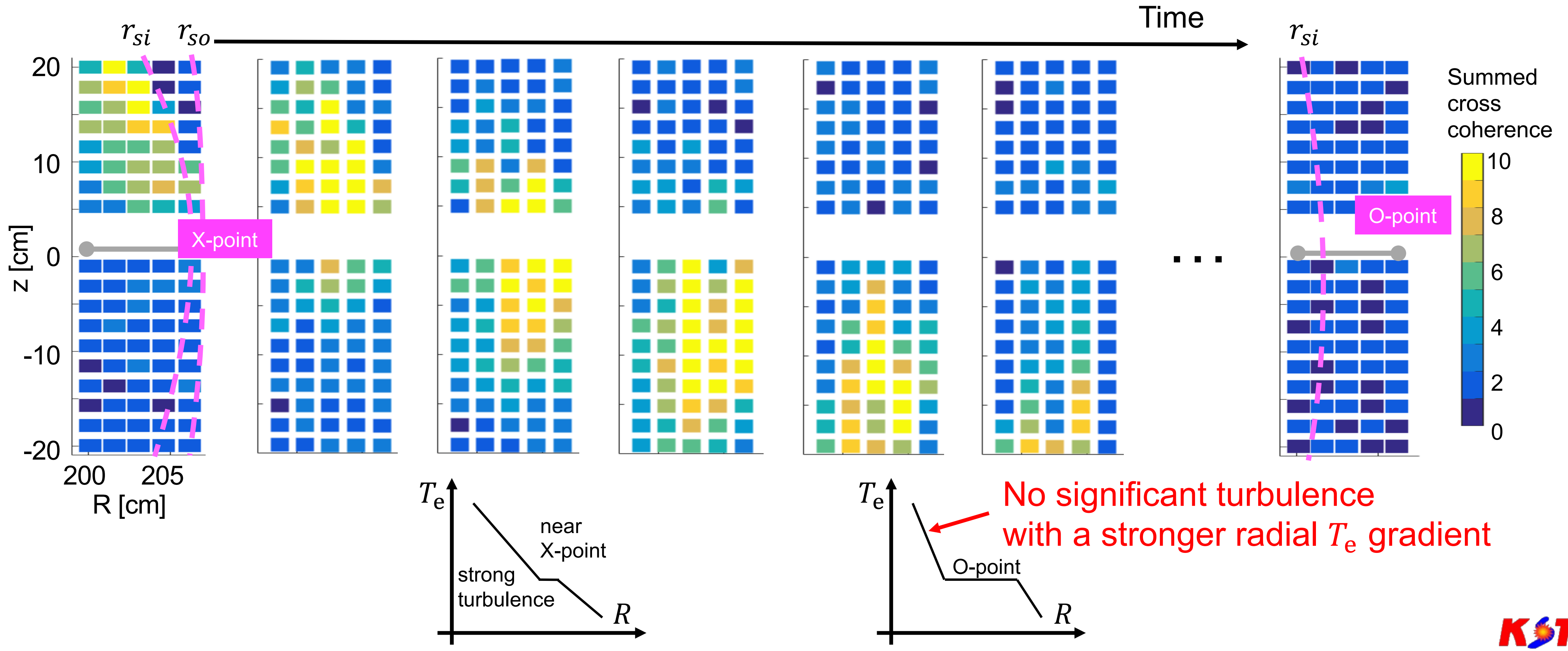
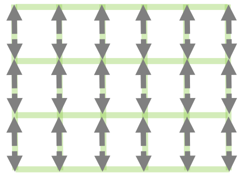
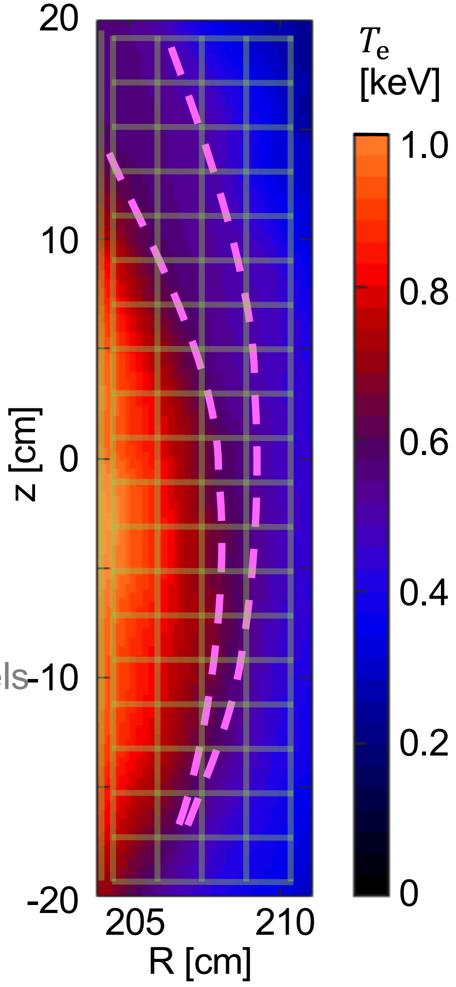


2D flow measurements near the island

ECEI
channel grid

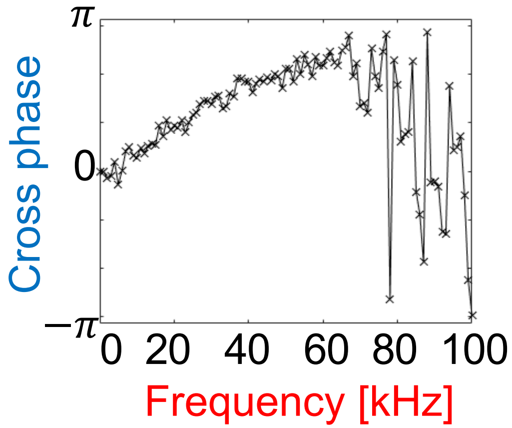


local dispersion relation
$\omega(K)$ is found
from cross phase btw
vertically adjacent channels



2D flow measurements near the island

$$\theta_{xy} = K \cdot d$$



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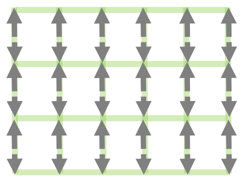

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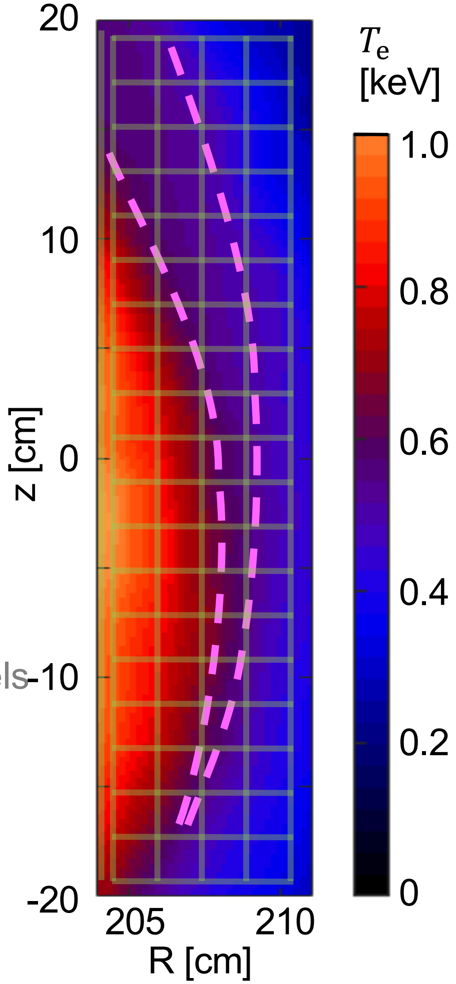
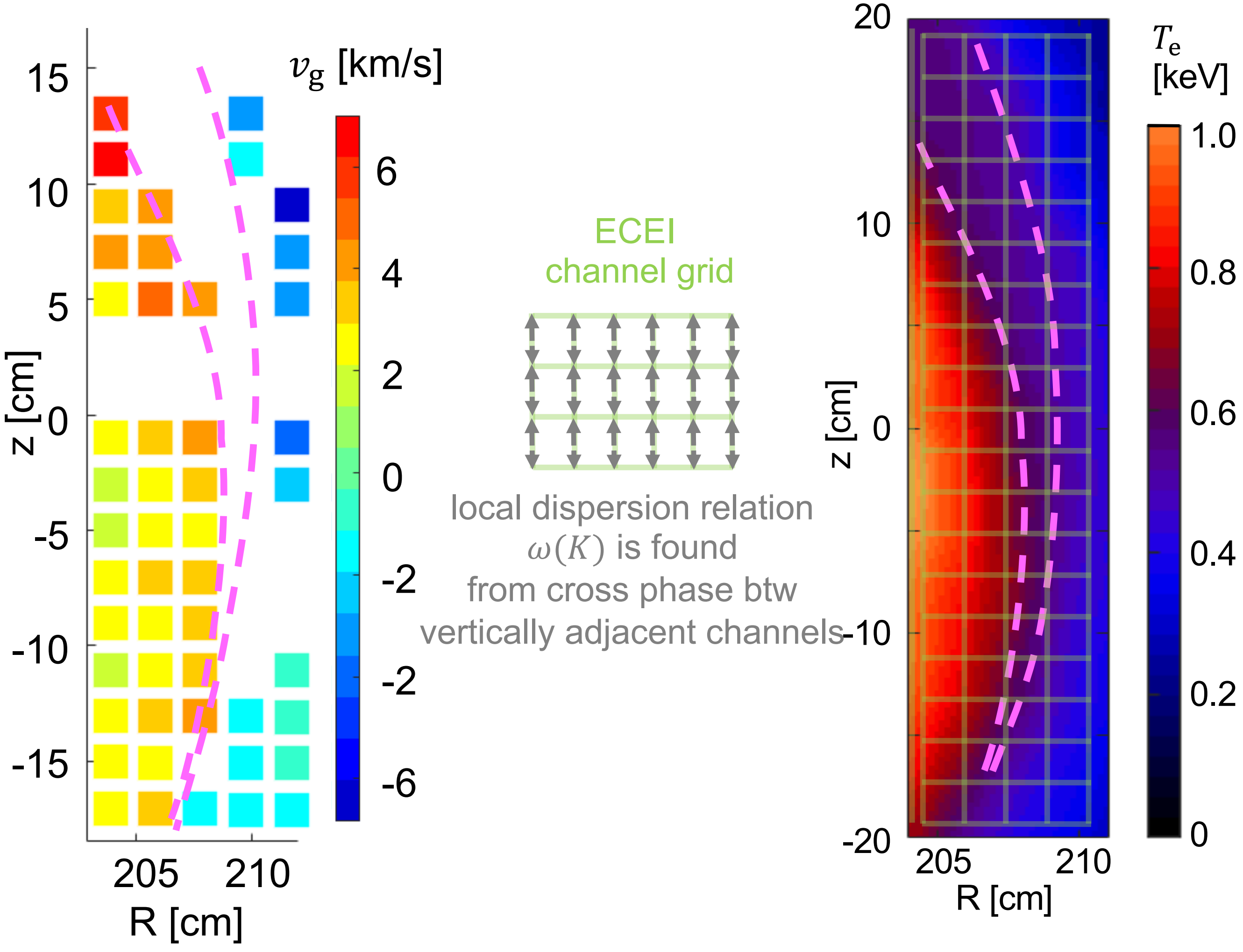


2D flow measurements near the island

- The 2-D vertical group velocity measurements found
  - v_g is stronger near the separatrix
  - The radial shear of v_g increases towards the O-point direction
  - Reversal across the island



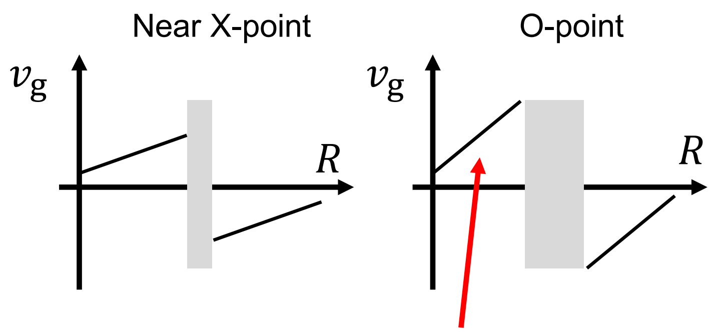
M.J. Choi et al., NF (2017)

For other experimental measurements
K. Ida et al., PRL (2001)
T. Estrada et al., NF (2016)
K. Zhao et al., NF (2017)

The strong $E\times B$ shear ($\geq 10^5$ s^{-1}) can suppress turbulence in the O-point regions

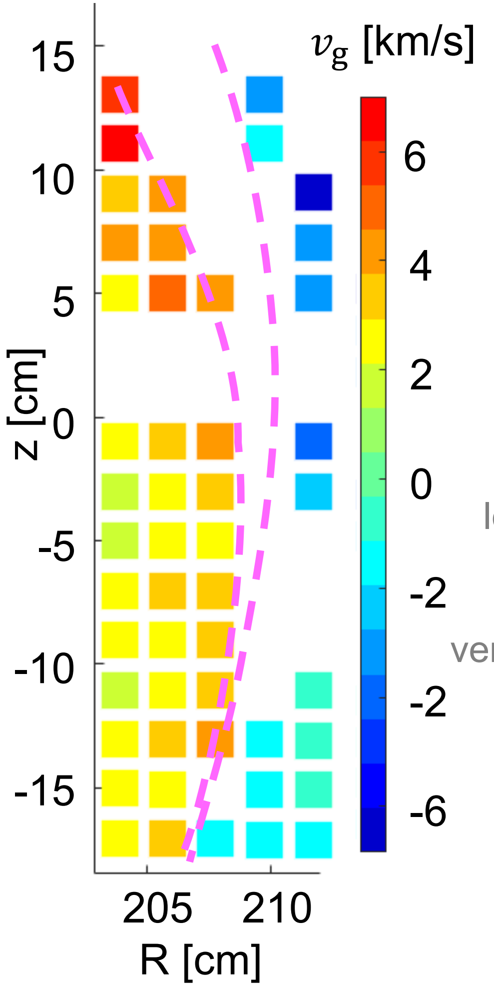
$$\frac{\partial v_g}{\partial r} = \frac{\partial}{\partial r}\left(v_{E\times B} + v_{ph} + \cdots\right)$$

Strong shear can be explained by the shear of $v_{E\times B}$ (or v_{zonal}?)

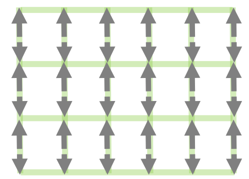


No significant turbulence

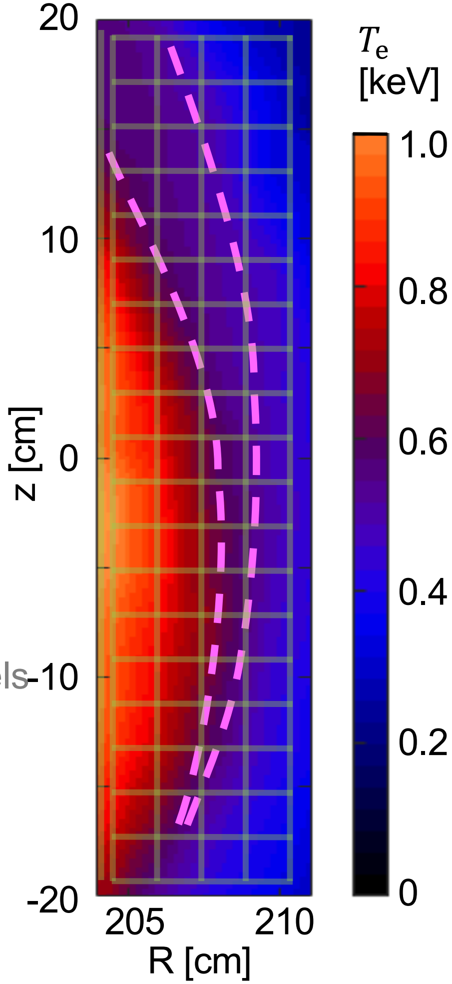
J.-M. Kwon et al., PoP (2018) & TH/8-1



ECEI channel grid



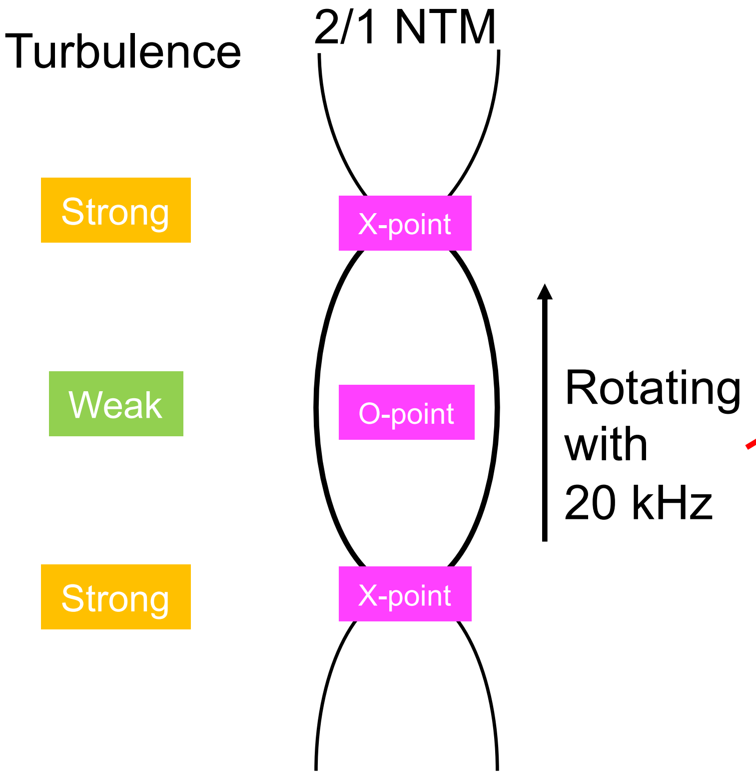
local dispersion relation $\omega(K)$ is found from cross phase btw vertically adjacent channels

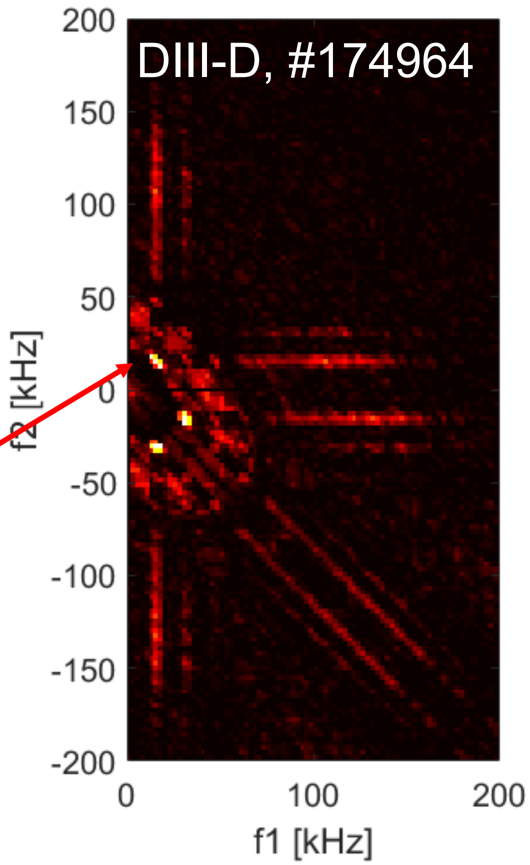


For other simulation researches
E. Poli et al., PPCF (2010) + more

Turbulence intensity modulation by the NTM

- Significant bicoherence between the NTM rotating frequency (20 kHz) and the broad turbulence (50—150 kHz)





Cross (squared) bicoherence between BES measurements (local density fluctuations) around the NTM

in collaboration with
Dr. L. Bardóczi and Dr. G. McKee

For other experimental observations
L. Bardóczi et al., PoP (2017)
M. Jiang et al., NF (2018)
P.J. Sun et al., PPCF (2018)

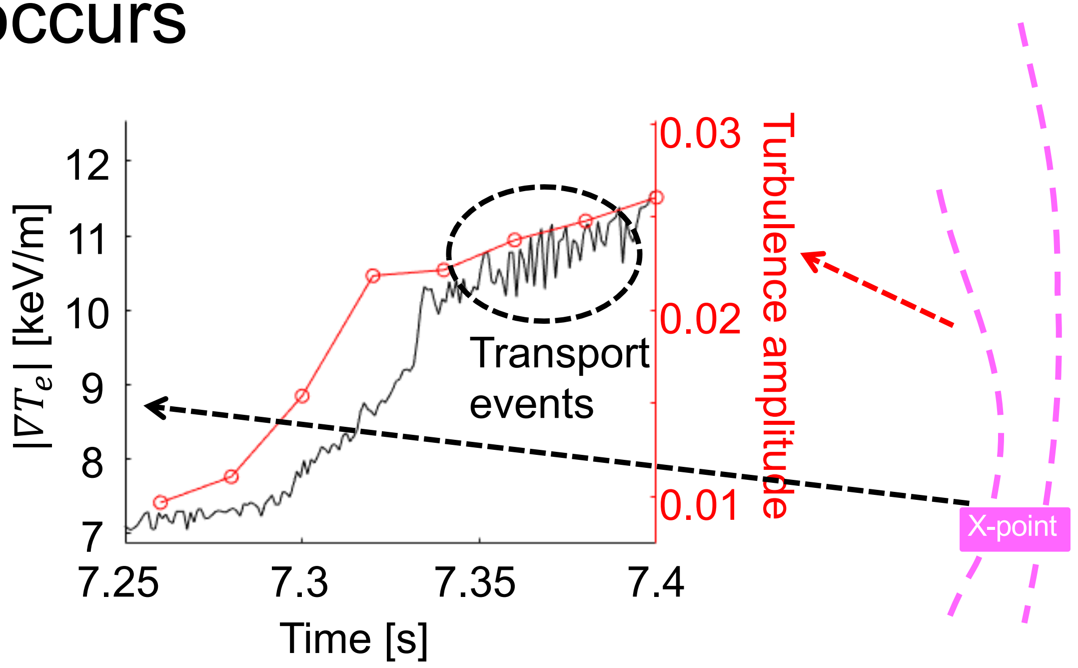
Outline

- Part 1: Turbulence intensity is redistributed by the magnetic island
  - Full 2-D picture of turbulence intensity
    - More than ”weak around the O-point and strong near the X-point”
  - Flow shear generated by the island or turbulence can be responsible for this turbulence intensity redistribution

- Part 2: Role of the strong turbulence intensity
  - Heat flow into the magnetic island; potentially beneficial
  - Minor disruption

Heat flow into the magnetic island with turbulence increase

- When the turbulence intensity is strong enough, T_e transport events occurs



KSTAR #13371

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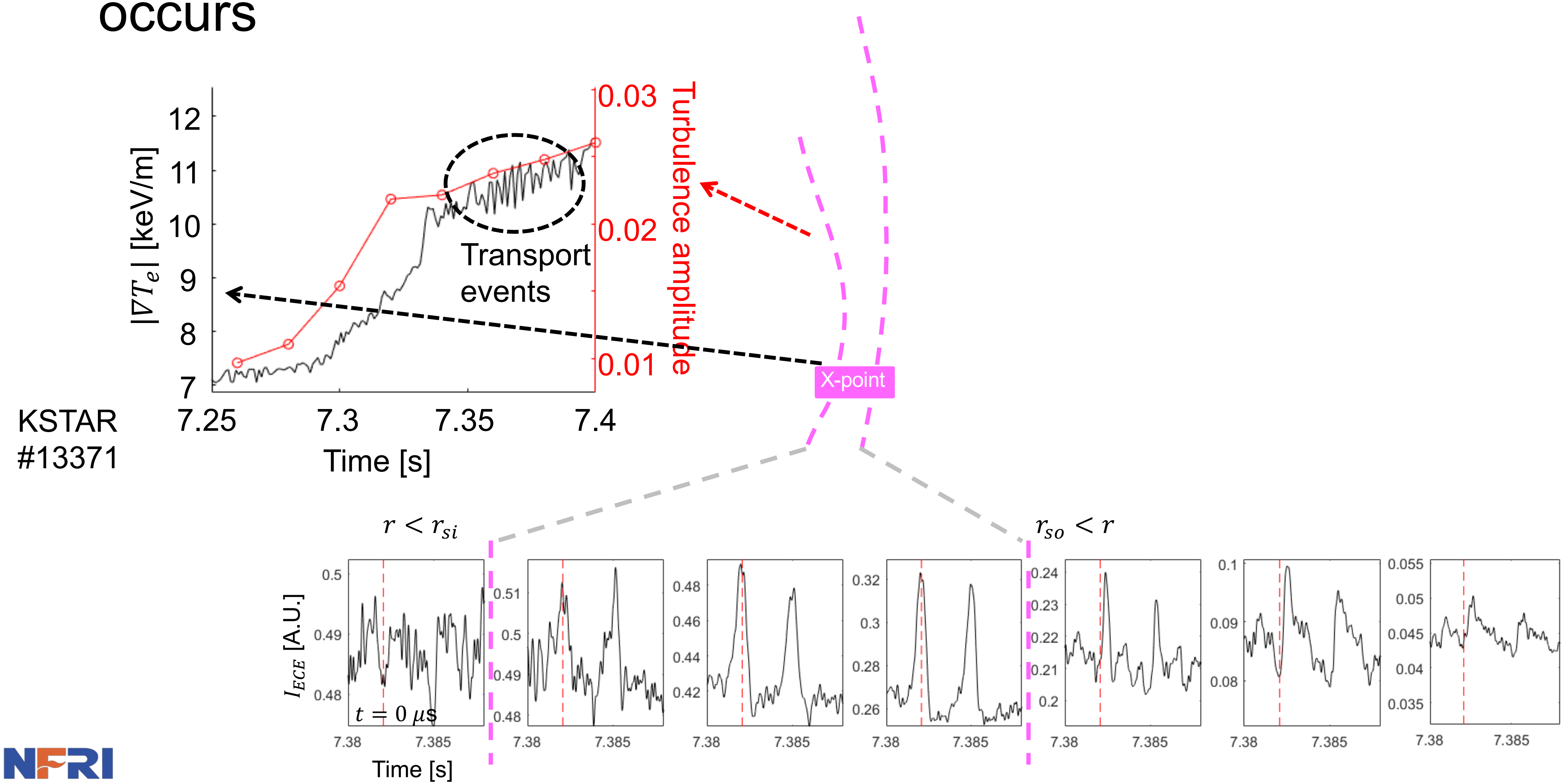
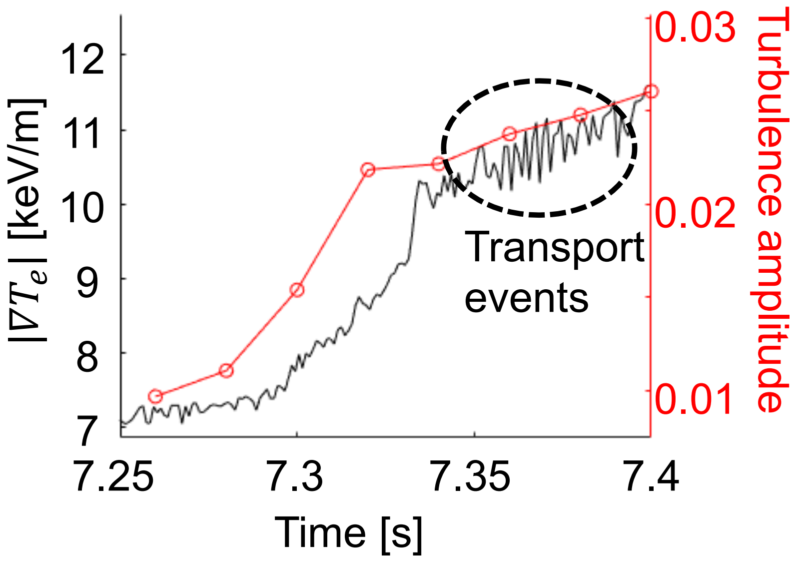
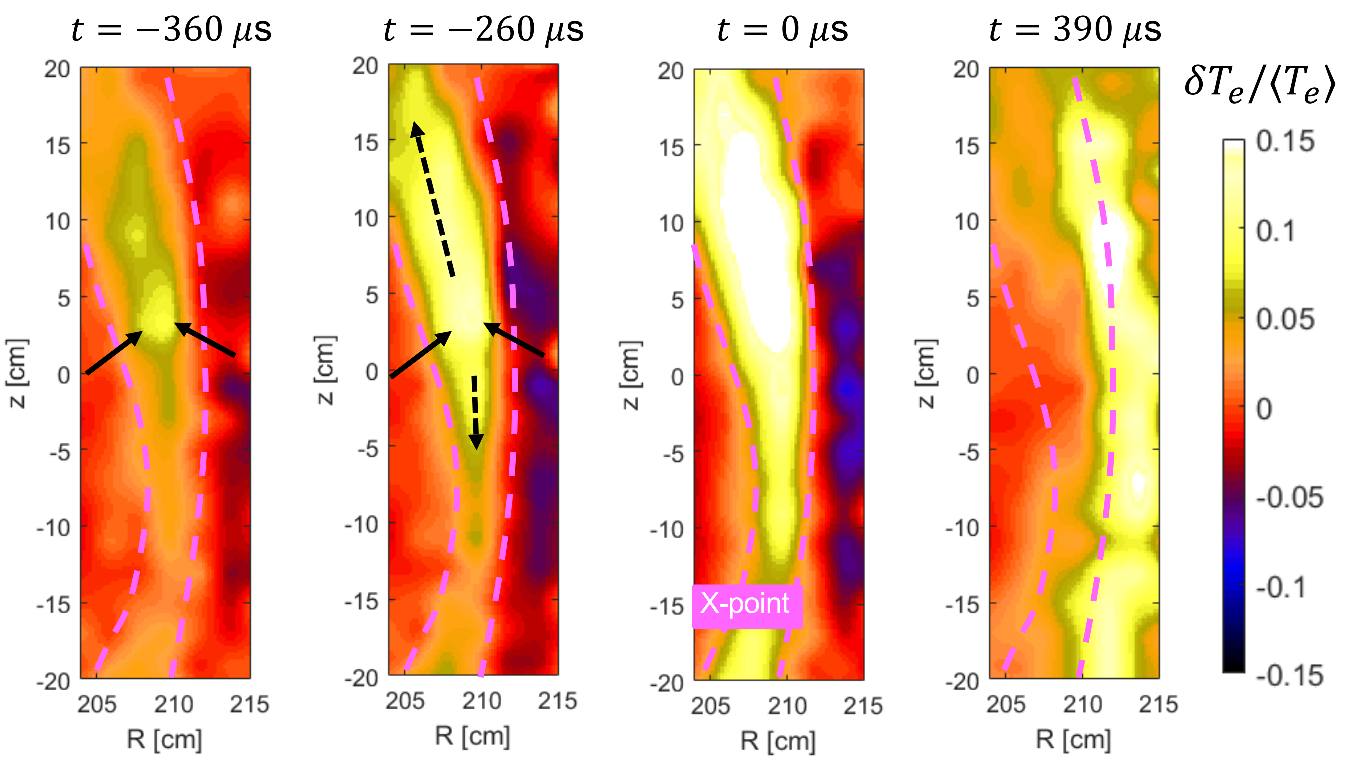


Heat flow into the magnetic island with turbulence increase

- 2D $\delta T_e/\langle T_e \rangle$ images found the fast heat flow from outside to inside of the island: this may indicate turbulence spreading



KSTAR #13371

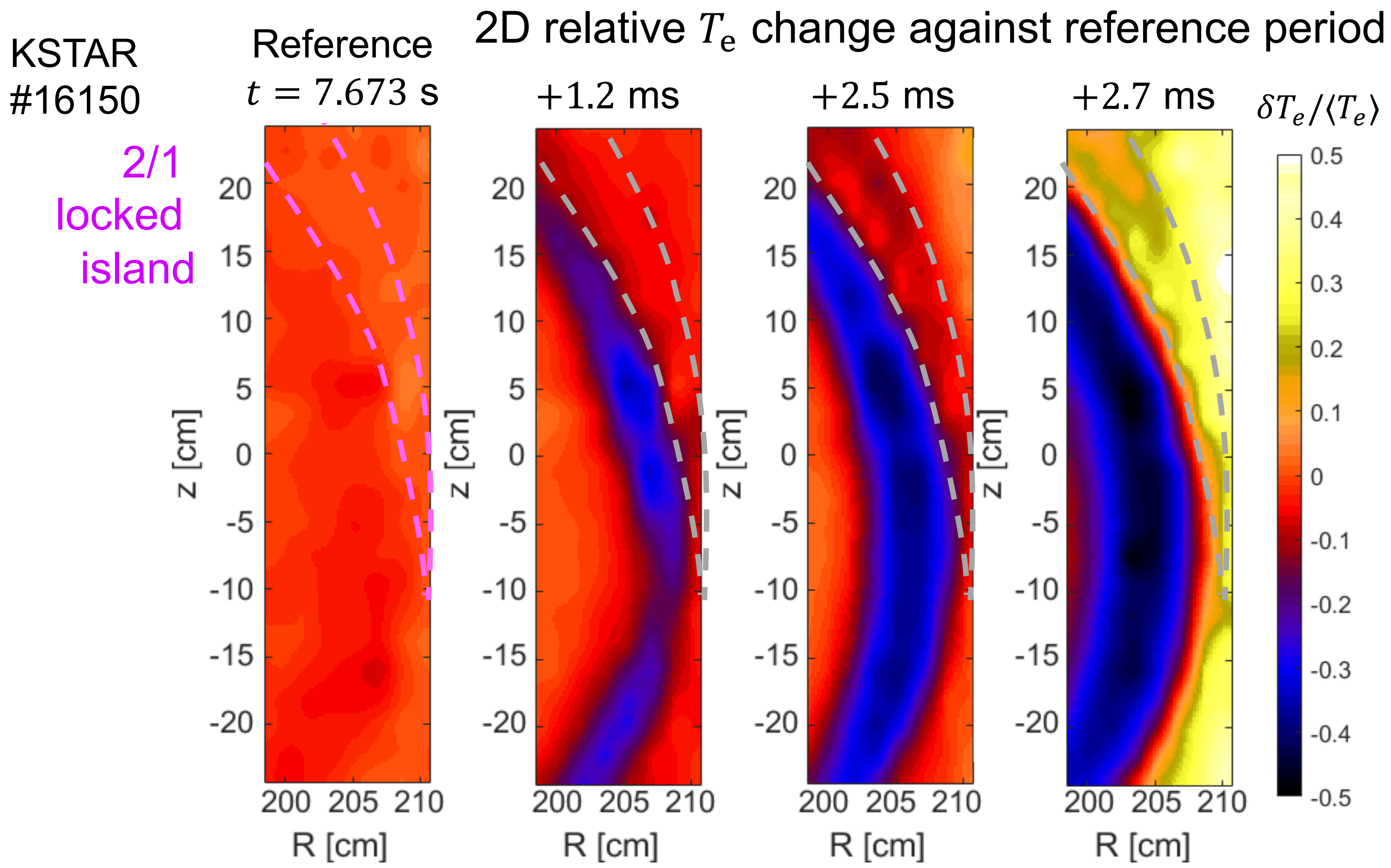


Profile peaking can be beneficial for NTM suppression

For more understanding of turbulence spreading
T.S. Hahm et al., PPCF (2004)
K. Ida et al., PRL (2018)

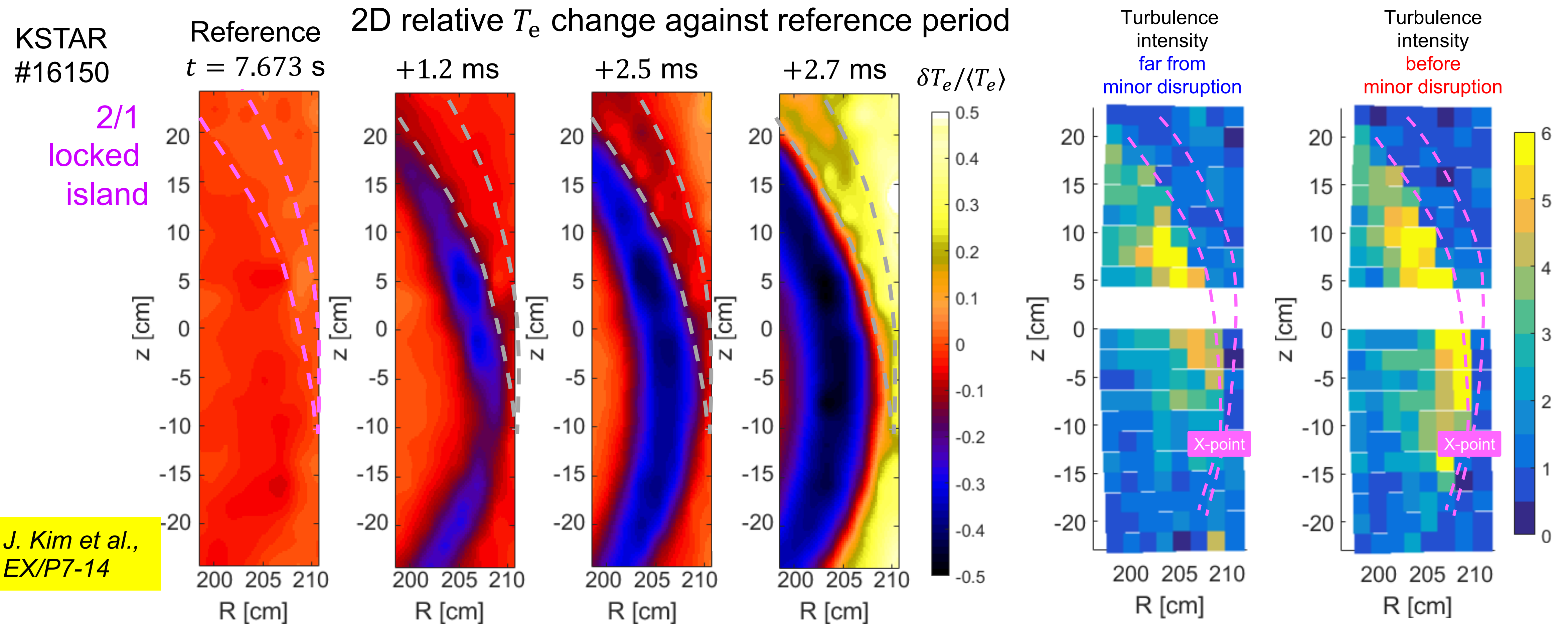
Minor disruption with stronger turbulence intensity

- Turbulence near the proximity of the X-point can be vulnerable to minor disruption (explosive growth of TM or stochastization)



Minor disruption with stronger turbulence intensity

- Turbulence intensity further increases and spreads to the X-point before minor disruption occurs

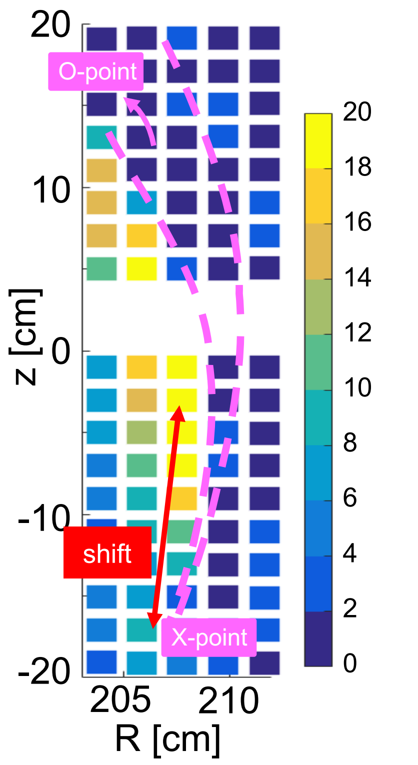


J. Kim et al., EX/P7-14

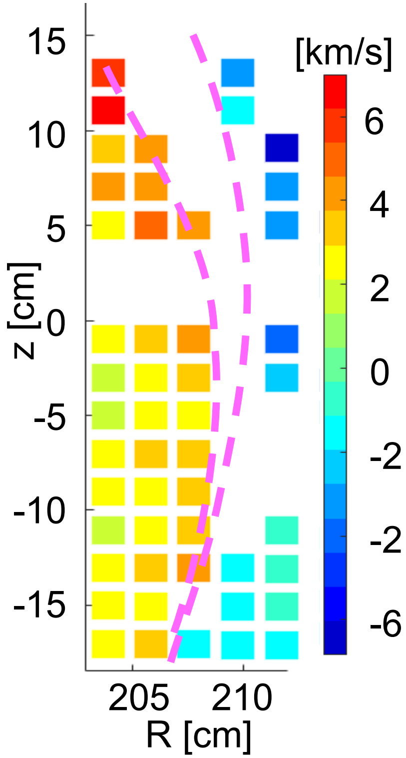
Summary

- Spatial distribution of the turbulence is determined by the combined effect of the temperature gradient and the flow shear around the island

Turbulence intensity



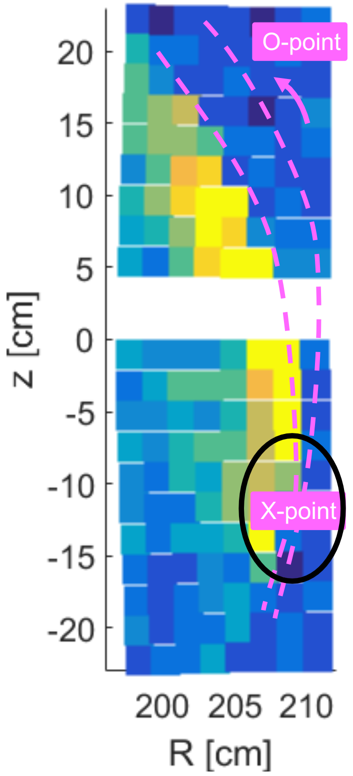
Flow



M.J. Choi et al., NF (2017) *J.-M. Kwon et al., PoP (2018)*

- Minor disruption or profile peaking can occur due to the strong turbulence intensity outside the magnetic island

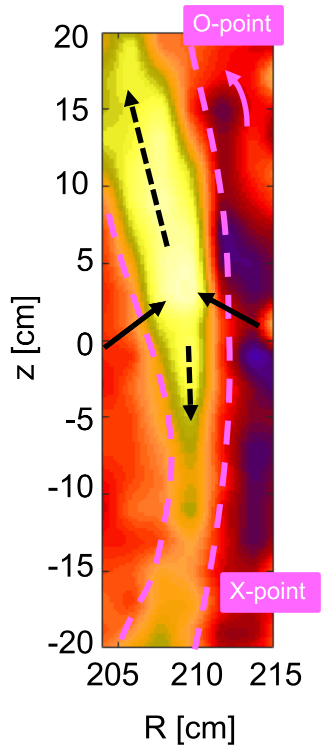
Summed cross coherence image



Turbulence increases at the X-point
→ minor disruption

Turbulence spreads into the island
→ profile peaking

$\delta T_e / \langle T_e \rangle$ image



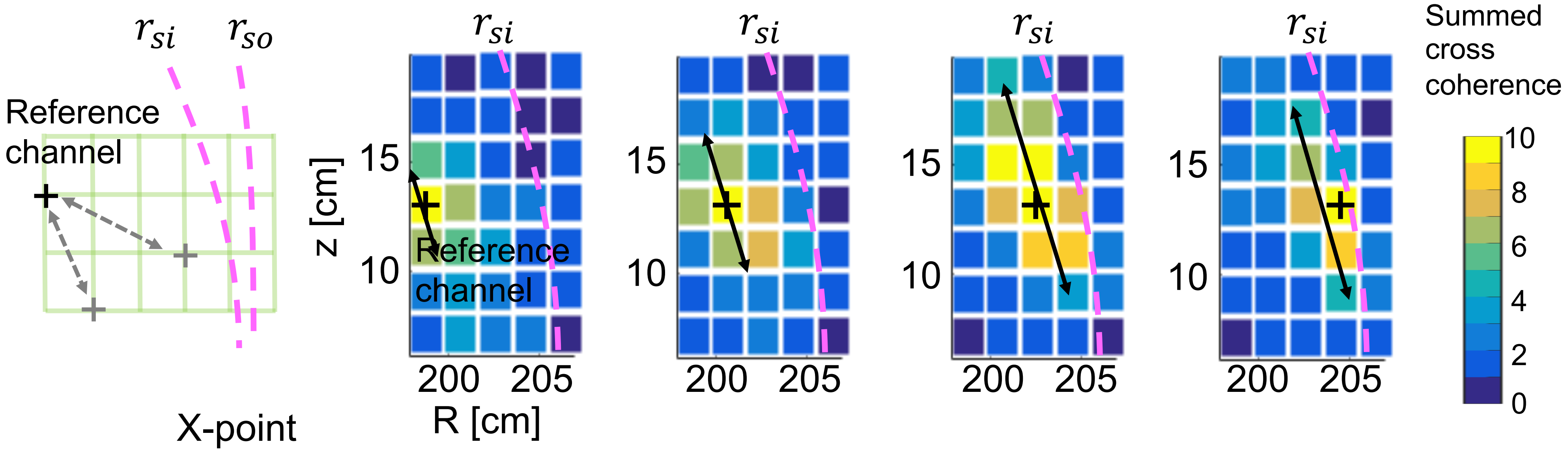
Acknowledgements

- I acknowledge helpful discussions with Dr. S. Zoletnik, Dr. J. Seol, Dr. J.-H. Kim, Dr. M. Leconte, and Dr. L. Bardóczi, Dr. H. Jhang and references
  - Ida PRL 2001 & PRL 2018, Rea NF 2015, Zhao NF 2015 & NF 2017, Bardoczi PRL 2016 & PoP 2017, Estrada NF 2016, Morton APS 2016, Jiang NF 2018, Sun PPCF 2018
  - Ishizawa NF 2009, Poli NF 2009 & PPCF 2010, Hornsby PoP 2010, Hu NF 2016, Izacard PoP 2016, Navarro PPCF 2017, Kwon PoP 2018, Hahm PPCF 2004 & JKPS 2018

- Supports: Korea Ministry of Science, ICT and Future Planning under Contract No. OR1509 and NRF Korea under Grant No. NRF-2014M1A7A1A03029865 and NRF-2014M1A7A1A03029881

Another evidence for the increasing flow towards the separatrix

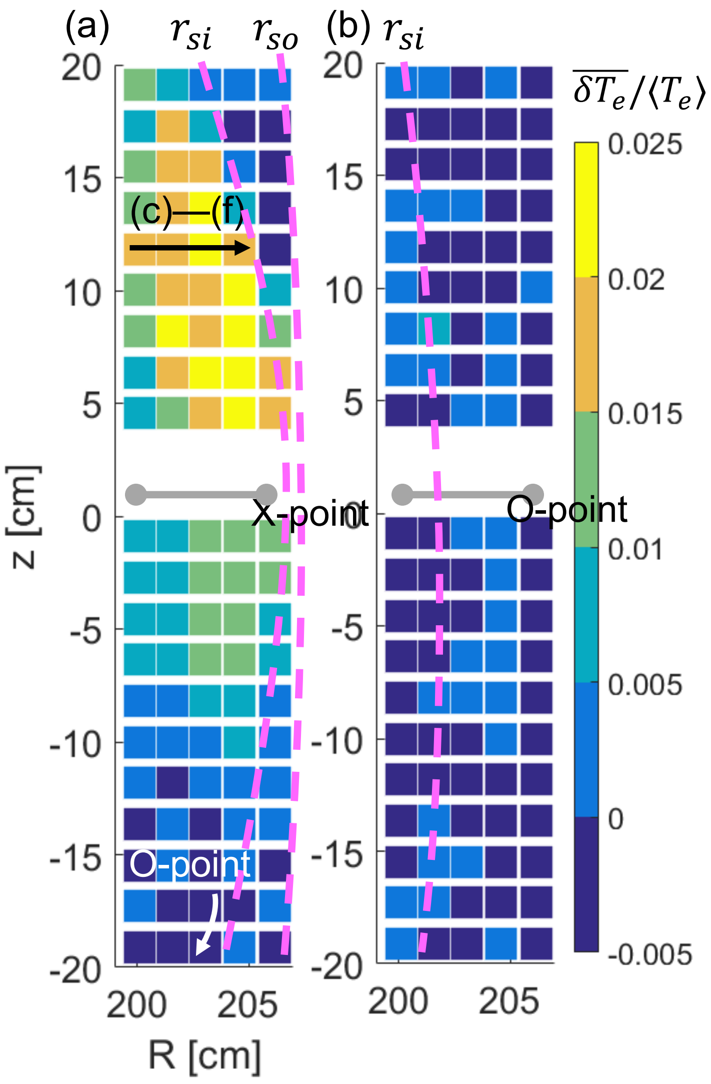
- 2D measurement of the turbulence correlation length found that the poloidal correlation length increases toward the separatrix
  - It can result from stronger poloidal flow toward the separatrix



M.J. Choi et al., NF (2017)

Back-up: change of fluctuation power

Fluctuation power before island
- fluctuation power after island



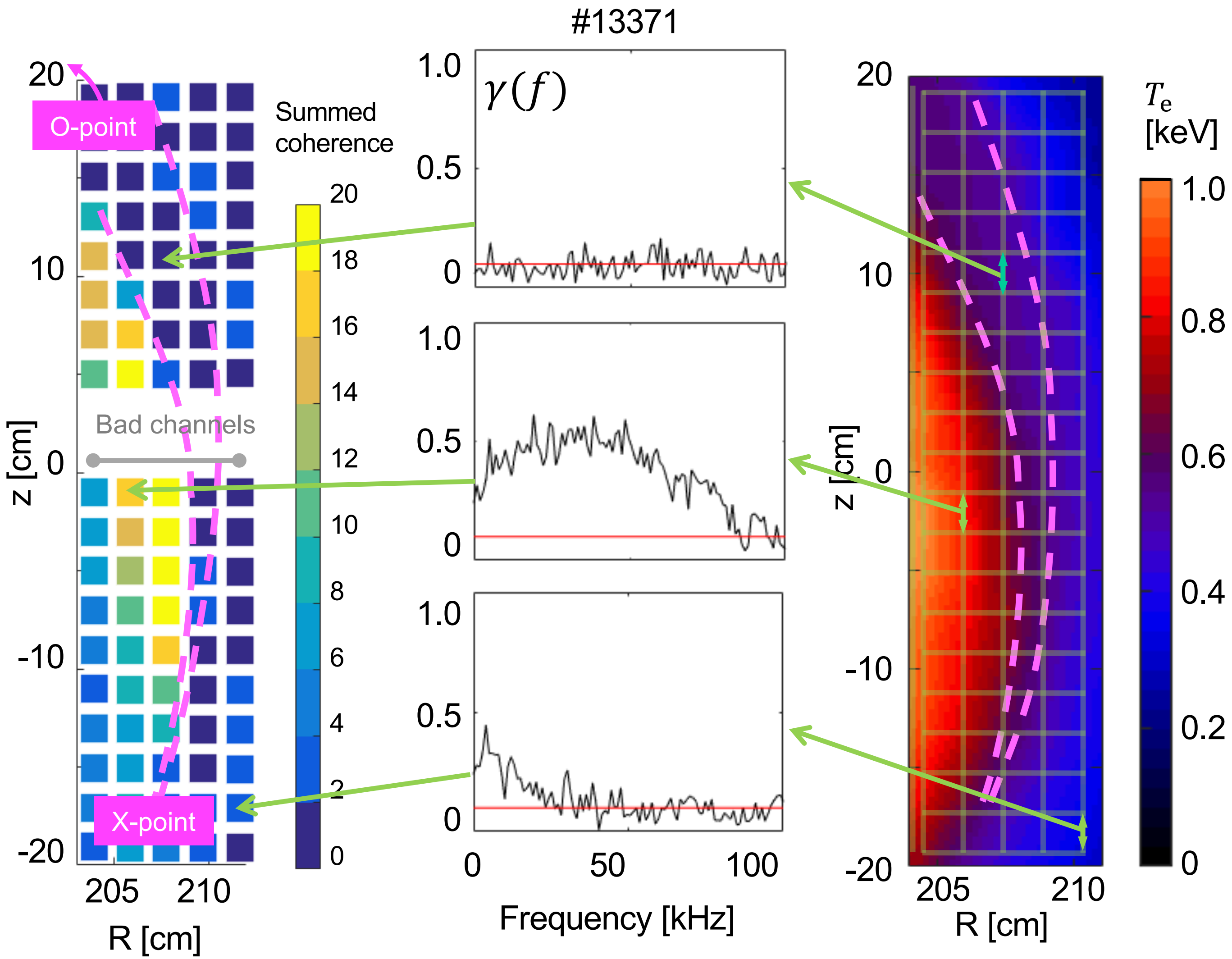
Back-up: cross coherence

Summed cross coherence image

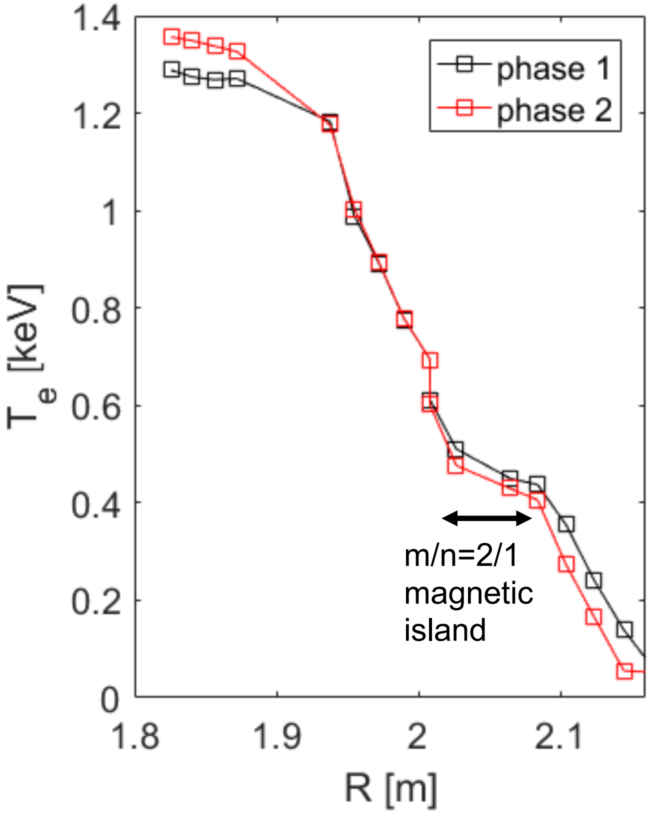
$$\sum_{f=f_1}^{f_2} \gamma(f)$$

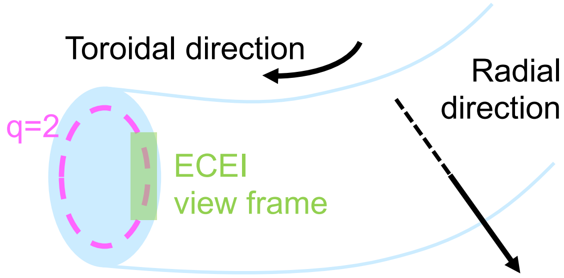
$$\gamma(f) = \frac{|\langle XY^* \rangle|}{\sqrt{\langle XX^* \rangle \langle YY^* \rangle}}$$

$X(f)$: FFT of an ECEI signal $x(t)$
$Y(f)$: FFT of an ECEI signal $y(t)$

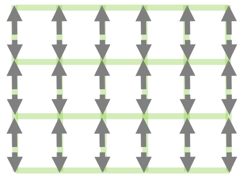


Back-up: different turbulence distributions

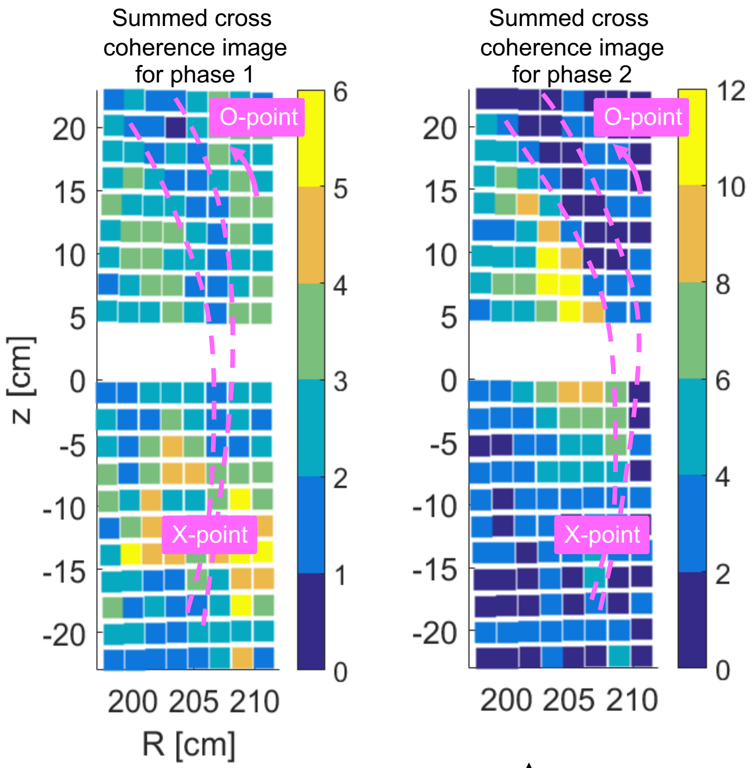




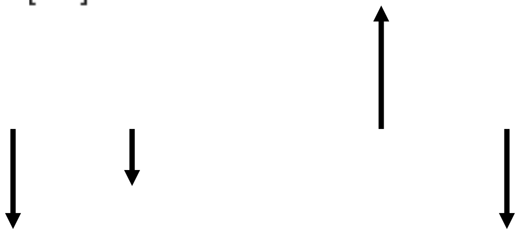
ECEI
channel grid



cross coherence btw
vertically adjacent channels

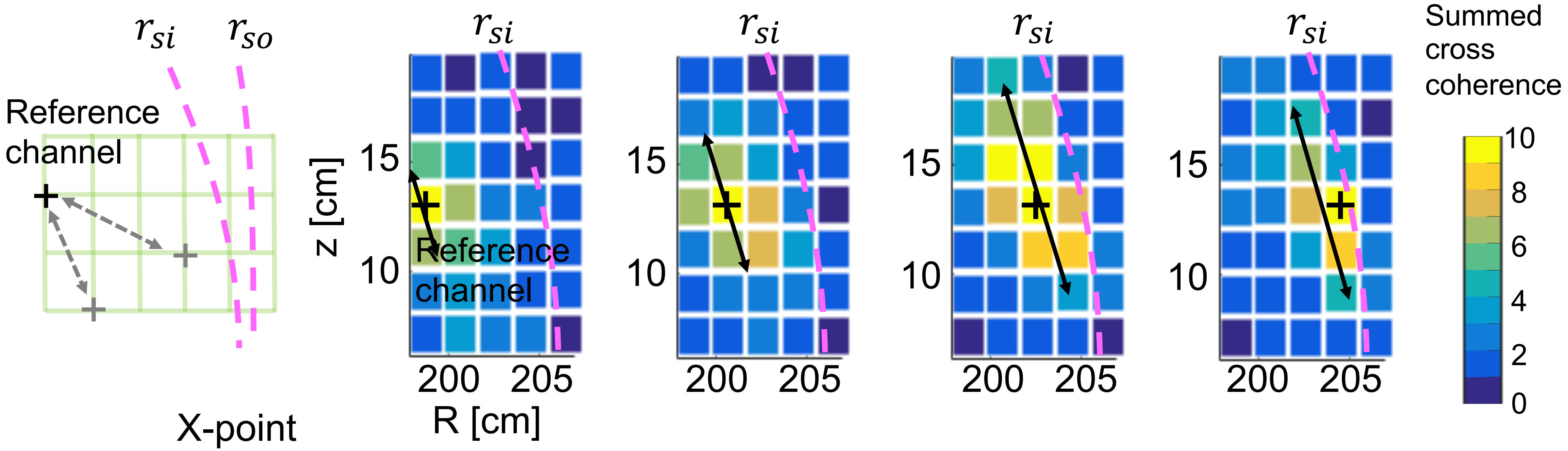


Flow pattern



Another evidence for the increasing flow towards the separatrix

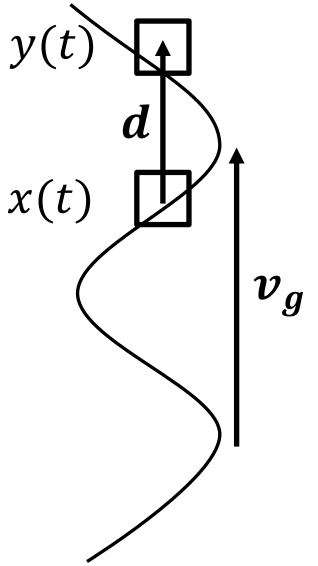
- 2D measurement of the turbulence correlation length found that the poloidal correlation length increases toward the separatrix
  - It can result from stronger poloidal flow toward the separatrix

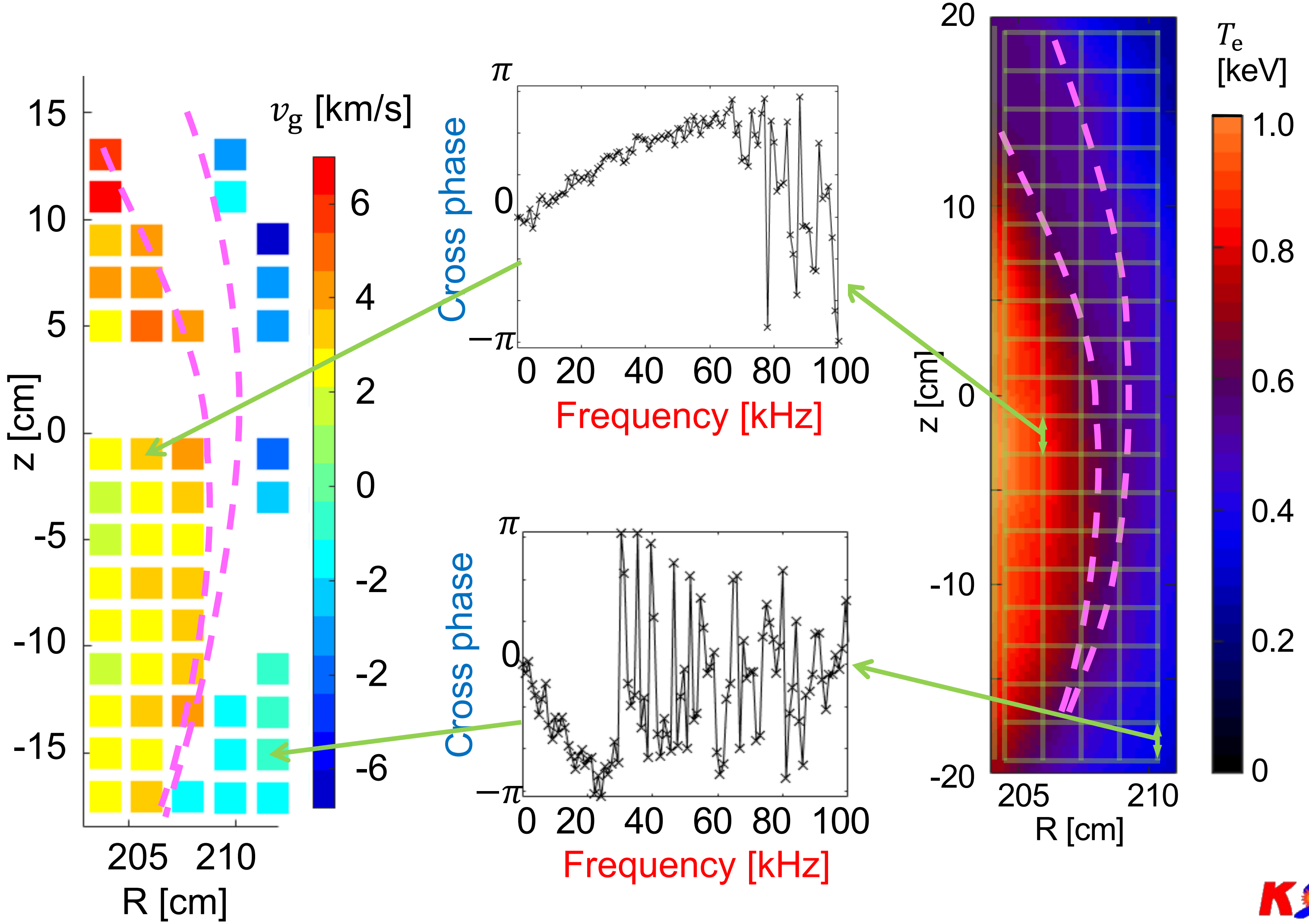


M.J. Choi et al., NF (2017)

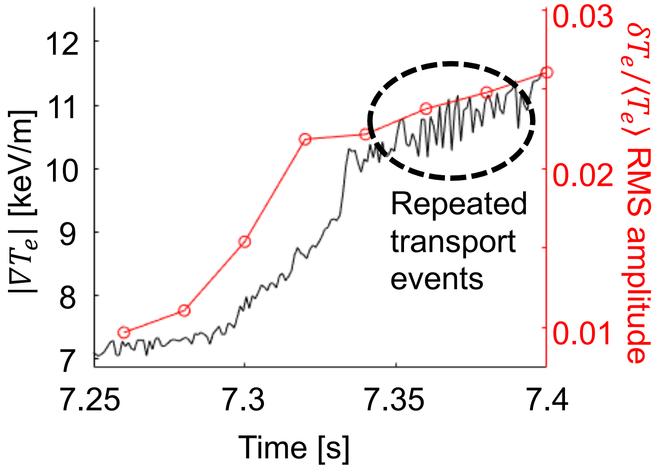
Back-up: cross phase

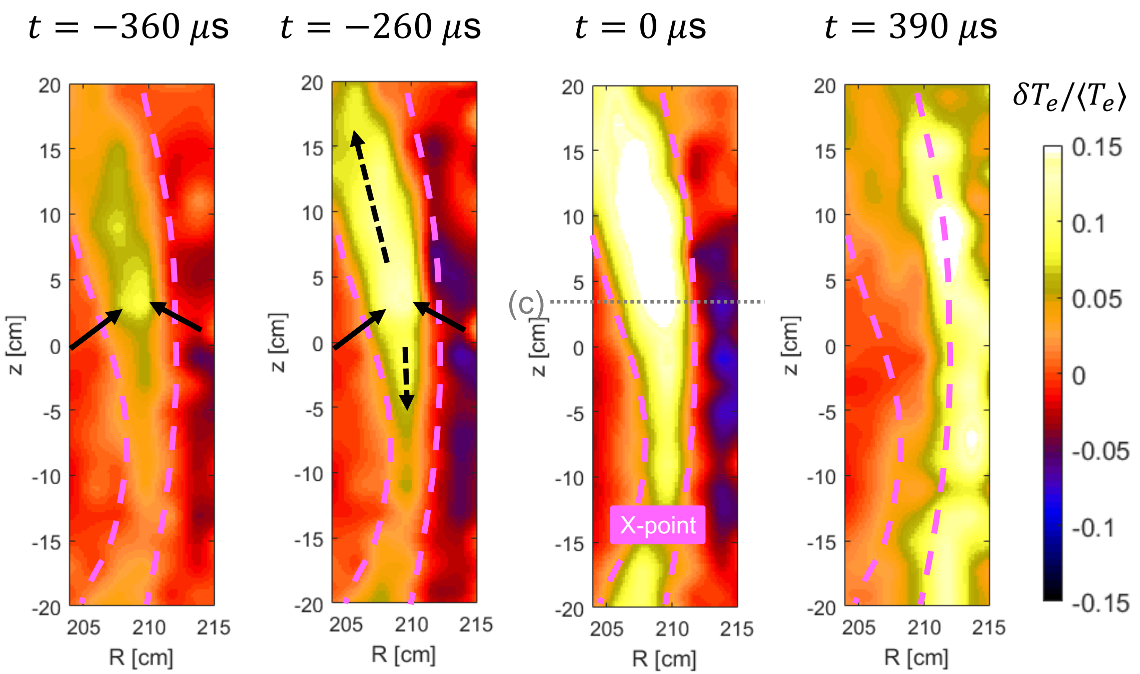
Cross phase between two channels, i.e. $\theta_{xy}(f) = k(f) \cdot d$ provides local dispersion relation

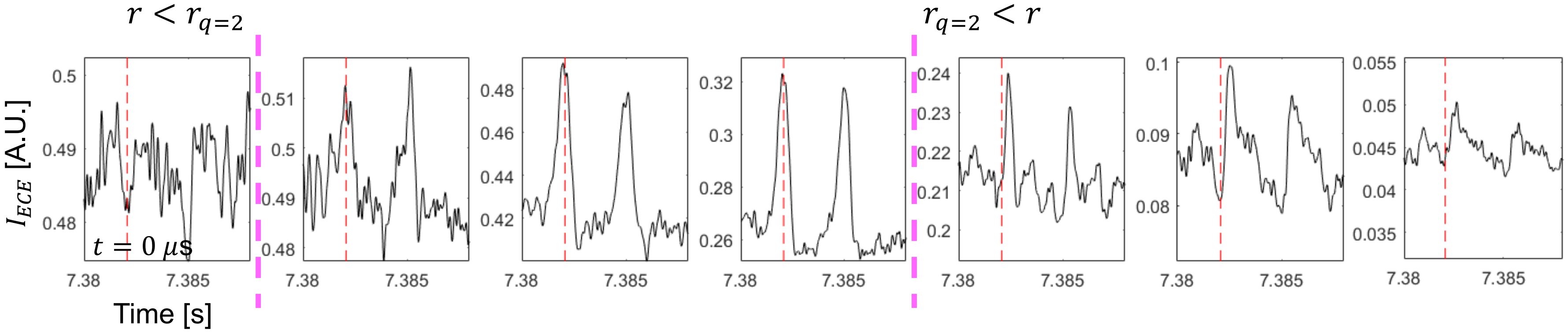




Back-up: time trace







Back-up: another cross phase

#15638
X : 8.729—8.749, 50 bins,
Towards O : 8.709—8.729, 50 bins,
More O : 8.689—8.709, 50 bins