Center for Fusion Theory

KSTAR

Toroidal Rotation Profile Structure in L- and H-mode KSTAR Plasmas

[a]Y.J. Shi, [a]S.H. Ko, [a]W.H. Ko, [a]J.M. Kwon, [a,b]P.H. Diamond
[c]G.S. Yun, [a]S. Yi, [d]K. Ida, [a]K.D. Lee, [a]J.H. Jeong, [a]S.H. Seo, [a]S.H. Hahn,
[a]S.W. Yoon, [a]Y.S. Bae, [a]L. Terzolo, [e]M. Bitter, [e]K. Hill

[a] National Fusion Research Institute, Daejeon, Korea
[b] CMTFO and CASS, University of California, San Diego, USA
[c] POSTECH, Pohang, Korea
[d] National Institute for Fusion Science, Japan
[e] Princeton Plasma Physics Laboratory, Princeton, USA

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NFRI 국가핵융합연구소 National Fusion Research Institute

Motivation

- Rotation change by ECH well studied before

  on KSTAR, DIII-D, JT-60U,LHD, AUG, ...
- Counter torque due to ECH effects → Rotation change
- Our working hypothesis → counter torque by change in turbulence

Highlight of this talk- new findings from 2013 KSTAR campaign

– Focus/Results: Macro-Micro connection

Macro
- Experimental observations:

  ECH resonance layer scan, modulation experiments
- 1D transport analysis: χ_i , χ_ϕ and $\Pi_{non-diff}$

Micro
- ECEI fluctuation data analysis
- Gyro-Kinetic stability study

Outline

I. **ECH Experiments : resonance layer scan, modulation experiments**

II. 1D transport analyses of modulation experiments
→ heat (χ_i) and momentum(χ_ϕ) and non-diffusive momentum flux($\Pi_{non-diff}$)
→ strong correlation between Π_{non} with ∇T_e

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Comparisons of Vϕ changes by on/off ECH for H- & L-mode

Main parameters:

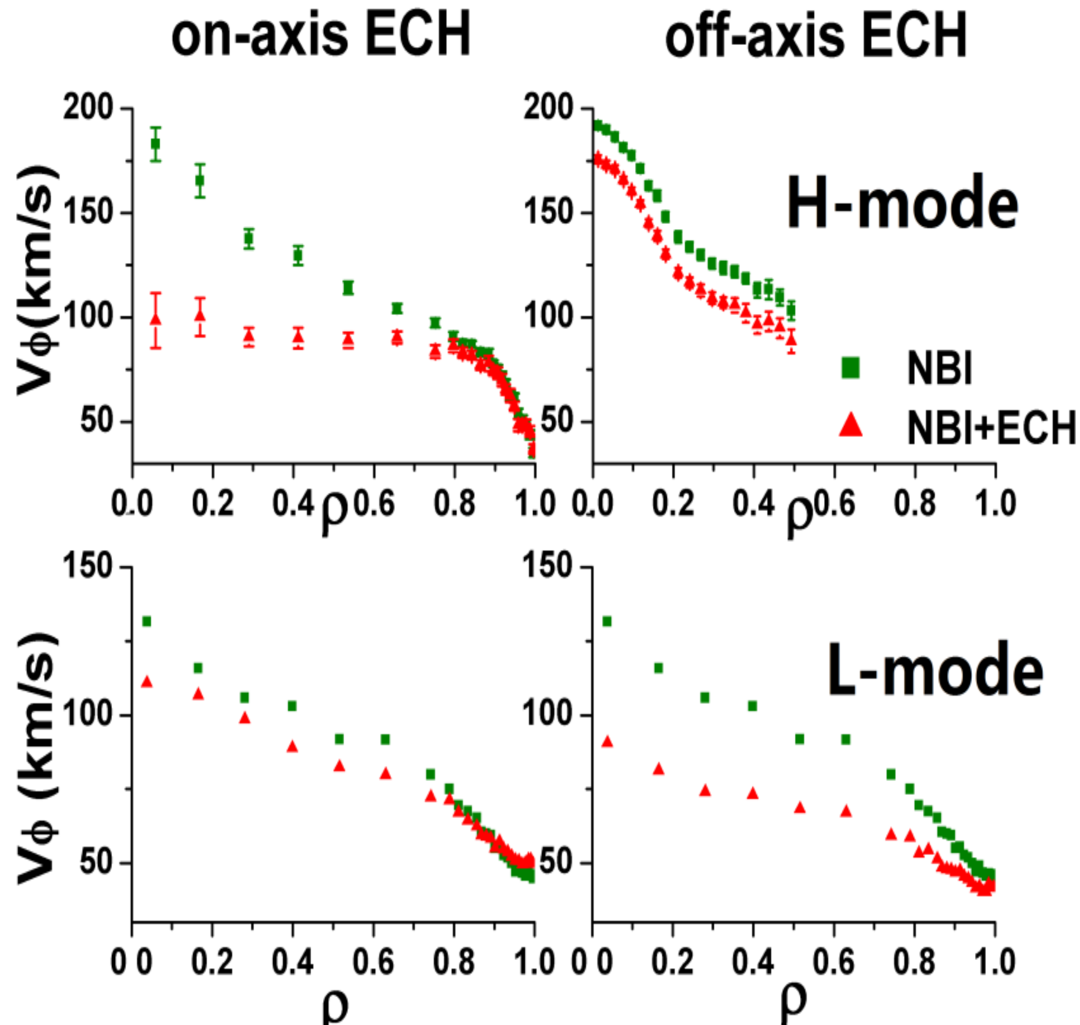
B_T=2 T(H-mode) 3T(L-mode)
I_p~0.6 MA, n_e:2~4e19 m^{-3}
co-P_{NBI}~1.3 MW
P_{ECH}~0.35 MW@110GHz,
0.7 MW@170GHz

H-mode

- On-axis ECH make larger $\Delta V\phi$
- Clear pivot point inside pedestal

L-mode

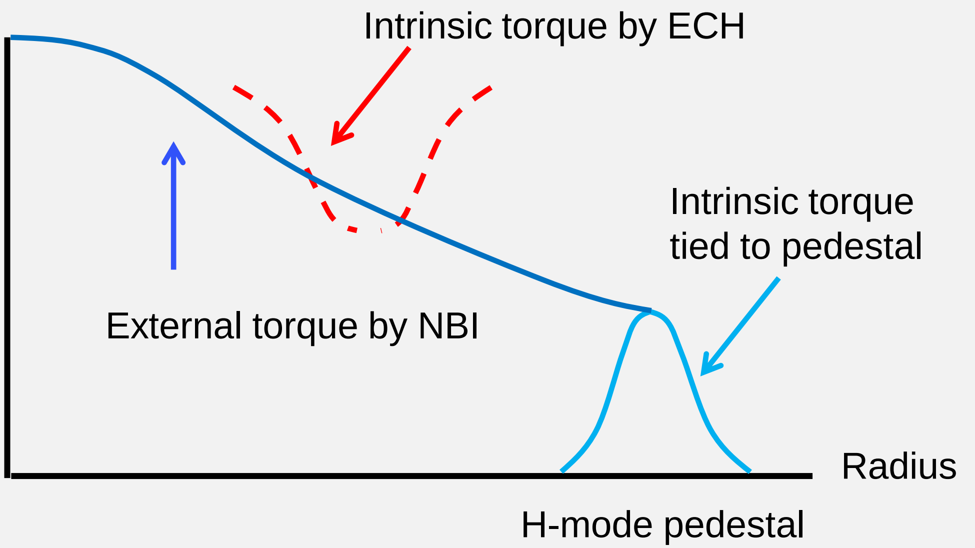
- Off-axis ECH make larger $\Delta V\phi$
- No pivot point in rotation profile



Rotation scenario for ECH+NBI plasmas on KSTAR: Interplay of different torques

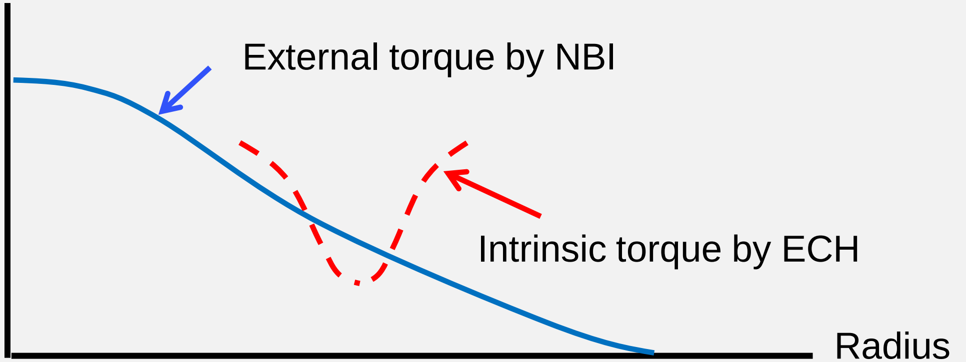
H-mode

- External torque by NBI
  - → co-current direction
- Pedestal intrinsic torque
  - → co-current direction
- Core intrinsic torque (due to ECH)
  - → counter-current direction

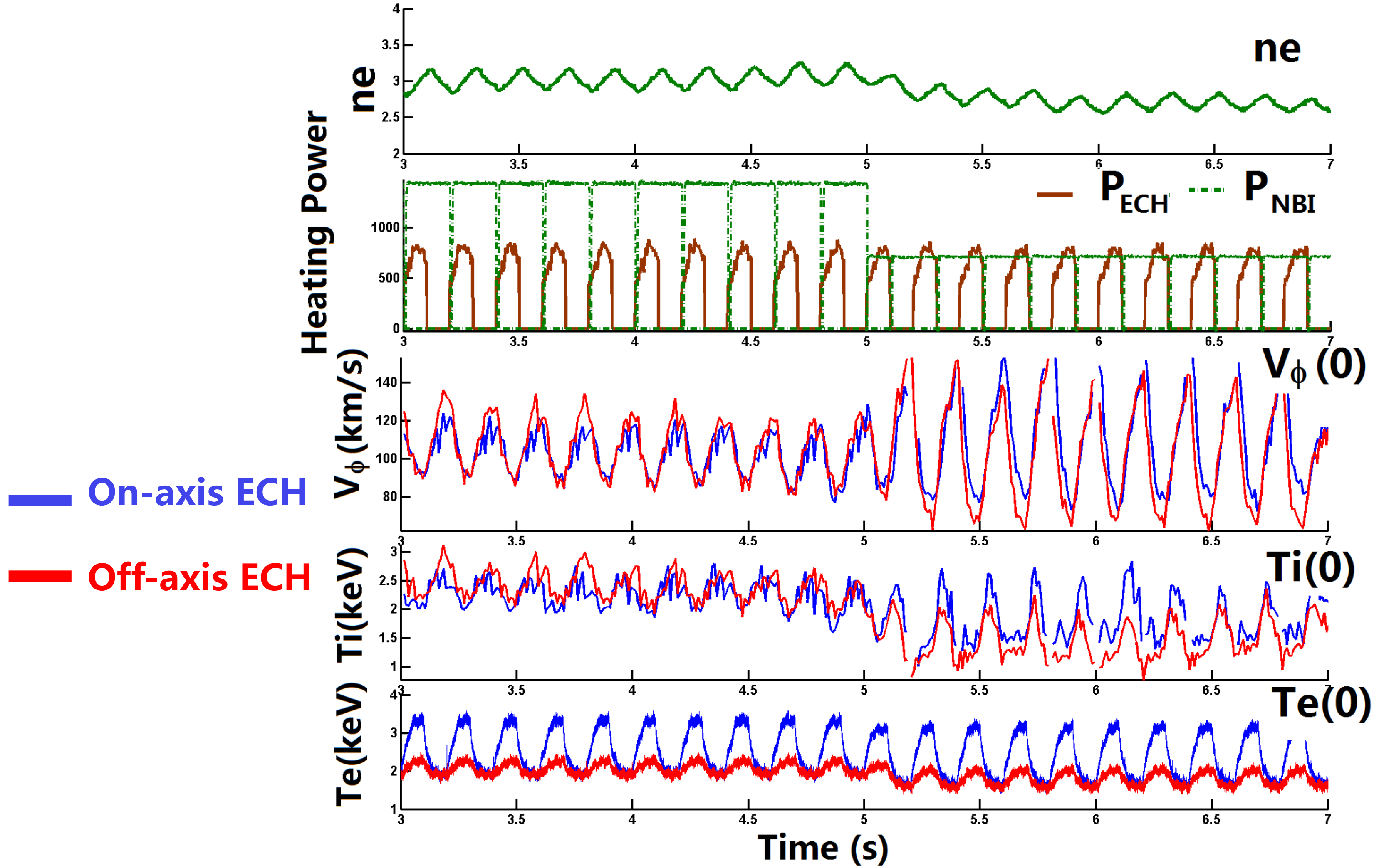


L-mode

- External torque by NBI
  - → co-current direction
- Core intrinsic torque (due to ECH)
  - → counter-current direction



Modulation Experiments with both on/off ECH in L-mode

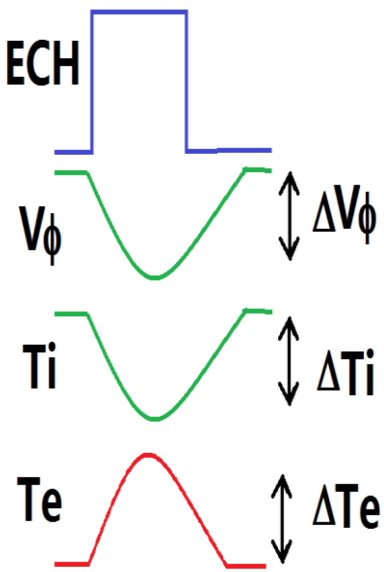


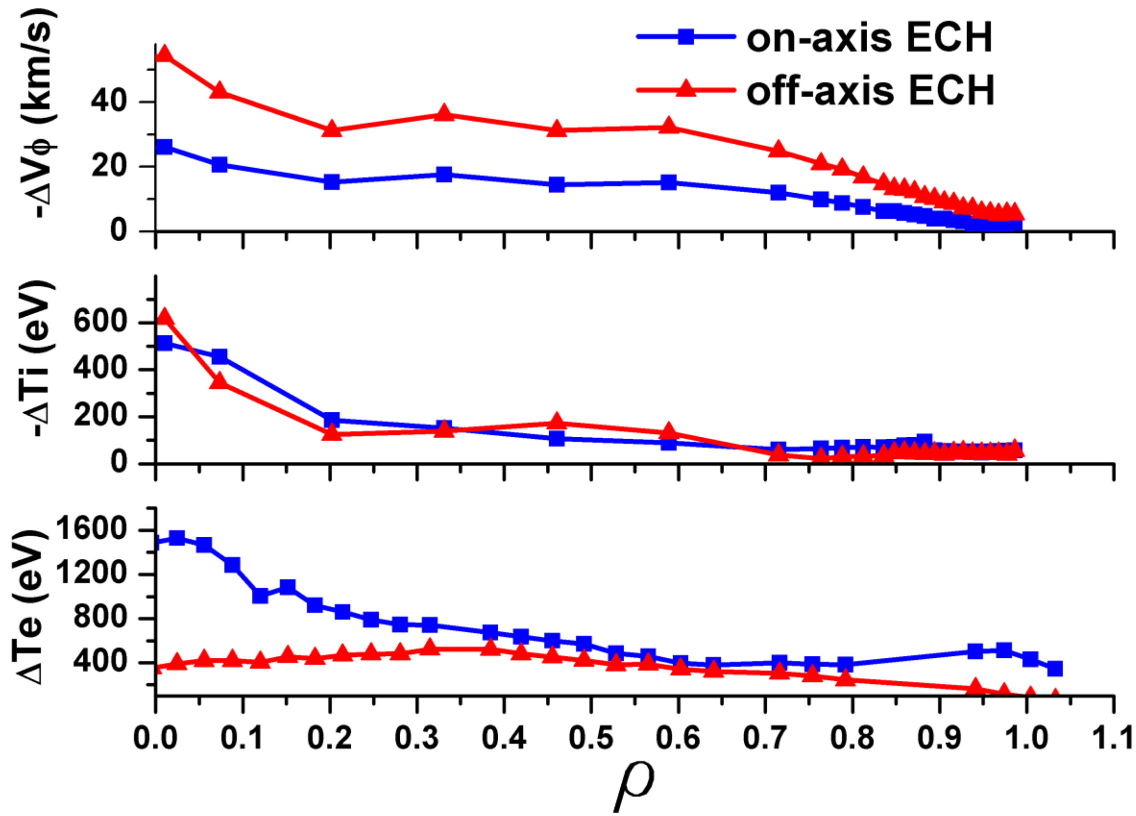
- Pnbi=1.3MW (1-5s) and 0.7MW (5-8s)

Correlation btw ECH & V_ϕ

- ΔVtor increase with Pech/Pnbi
- Line-integrated density (nel) increase during ECH (both on-axis and off-axis)

V_ϕ, Ti and Te profiles changes by on/off ECH





- Larger ΔT_e for on-axis ECH
- Location of maximum ΔT_e → ECH resonance layer
- Similar ΔT_i for both on- and off-axis ECH → degradation of confinement
- Larger ΔV_ϕ for off-axis ECH → intrinsic torque change

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1-D transport analysis

➔ **Goal: Calculation of non-diffusive momentum flux $\Pi_{non-diff}$**

$$n_i \frac{\partial T_i}{\partial t} = -\nabla \cdot \vec{q} + Q$$

Heat balance equation

$$m_i \frac{\partial n_i V_\phi}{\partial t} = -\nabla \cdot \Pi + F$$

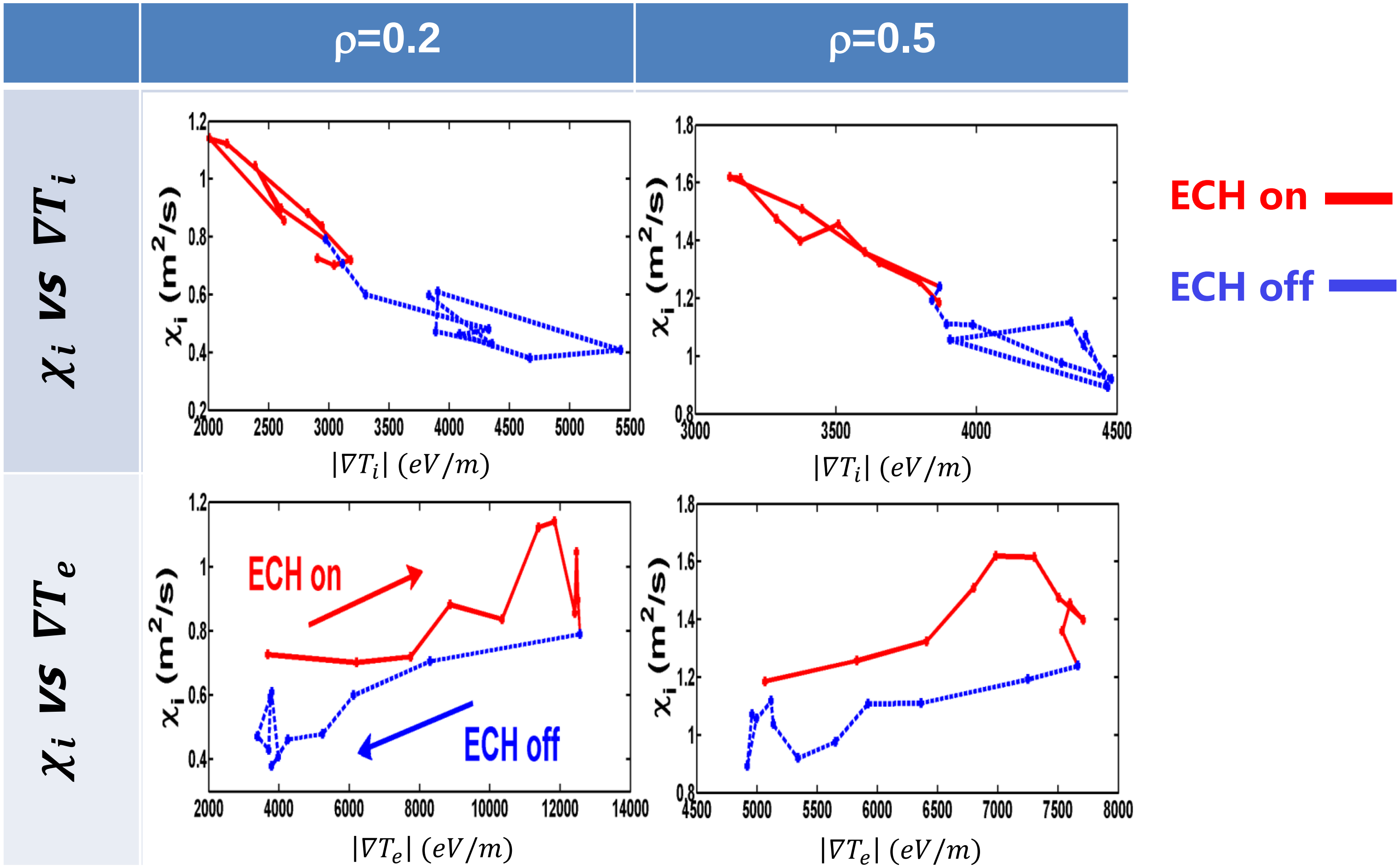
Momentum balance equation

$$\vec{q} = -n_i \chi_i \frac{\partial T_i}{\partial r}, \quad \Pi = -m_i \chi_\phi \frac{\partial n_i V_\phi}{\partial r} + \Pi_{non-diff}$$

- n_i , T_i , V_ϕ are measured.
- NBI heat source Q, and NBI torque F are calculated by NUBEAM
- χ_i is evaluated from heat balance equation
- χ_ϕ is given under the assumption that $\chi_i = \chi_\phi$ **i.e.** $Pr = \chi_\phi / \chi_i = 1$ (P. Diamond et al, NF2012)

→ $\Pi_{non-diff}$ **can be calculated**

χ_i shows different responses to $\nabla \mathrm{T_i}$ and $\nabla \mathrm{T}_e$ changes

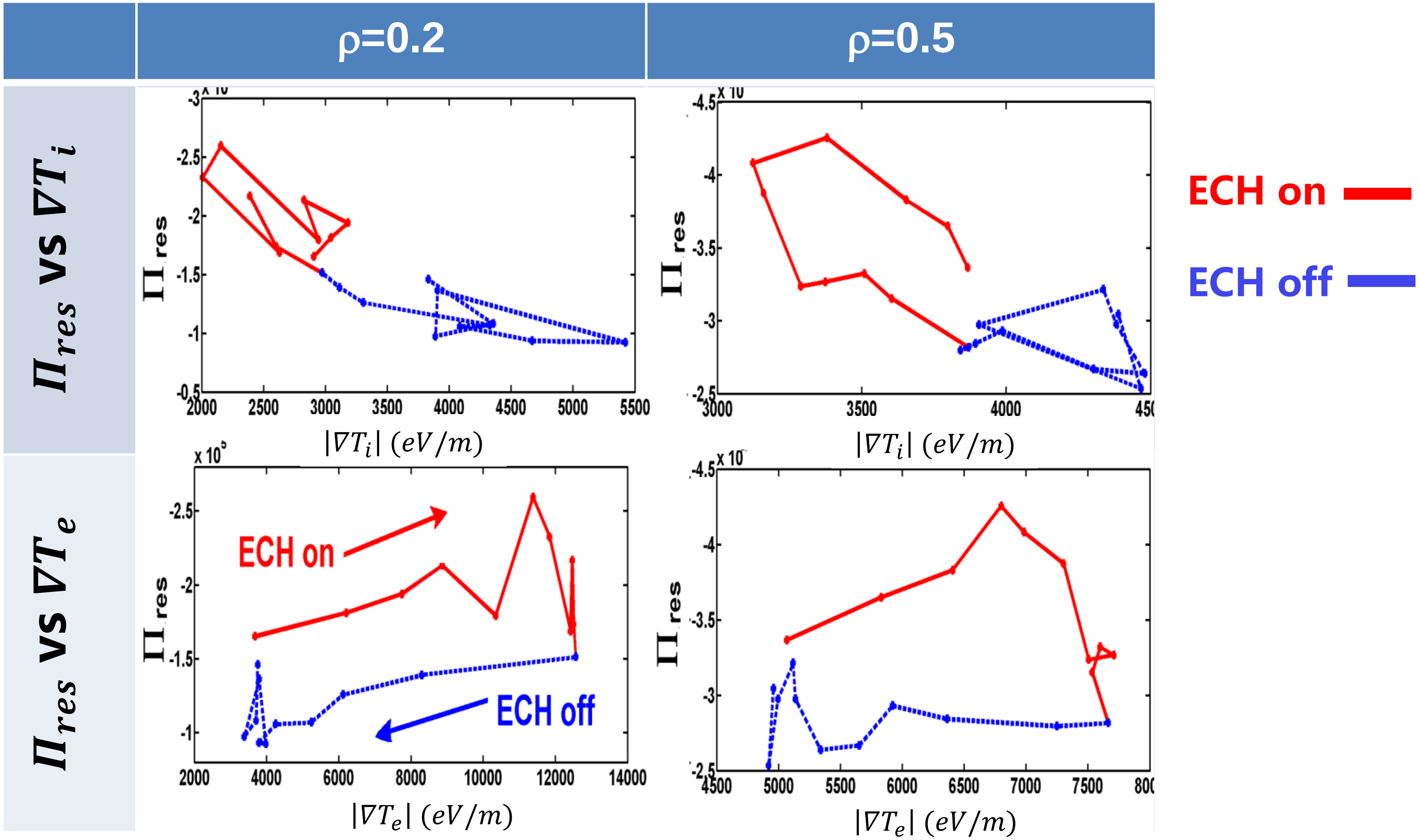


- ➢ ECH on → χ_i increases as $|\nabla T_e|$ increases, while $|\nabla T_i|$ decreases
- ➢ ECH off → χ_i decreases as $|\nabla T_e|$ decreases, while $|\nabla T_i|$ increases

→ ∇T_e is the main driving force of transport → TEM excitation

→ Clear hysteresis loop for χ_i vs ∇T_e (time lag between two quantities)

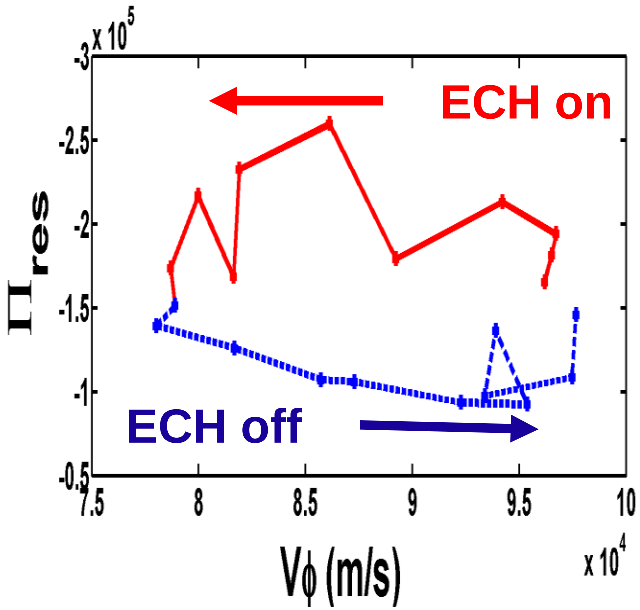
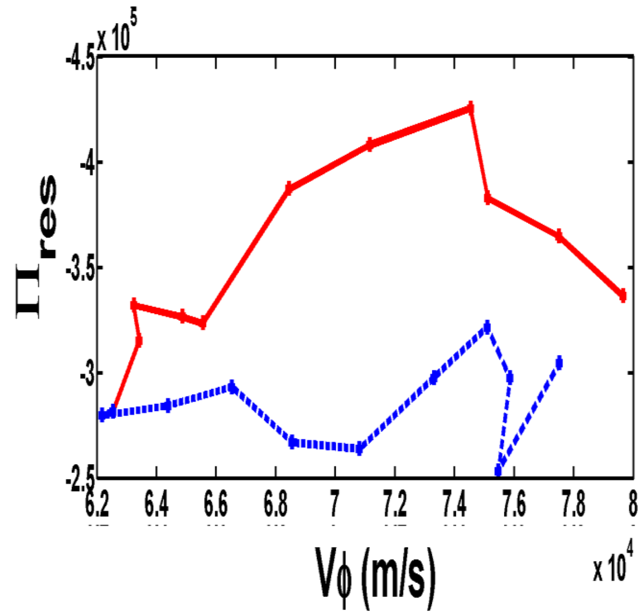
$\Pi_{non-diff}$ proportional to changes of ∇T_e during ECH modulation



- ➢ **ECH on → $|\Pi_{\text{non-diff}}|$ increases as $|\nabla T_e|$ increases, while $|\nabla T_i|$ decreases**
- ➢ **ECH off → $|\Pi_{\text{non-diff}}|$ decreases as $|\nabla T_e|$ decreases, while $|\nabla T_i|$ increases**

→ ∇T_e is the main driver of non-diffusive $\Pi_{non-diff}$ ***(K. Ida NF2010, J. Rice PRL2011)***

Study for the correlation between $\Pi_{non-diff}$ and V_ϕ

<table>
<tr><th></th><th>ρ=0.2</th><th>ρ=0.5</th></tr>
<tr><td>$\Pi_{non-diff}$ vs V_ϕ</td><td>
</td><td>
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- No clear proportionality between $\Pi_{\mathrm{non-diff}}$ and V_ϕ

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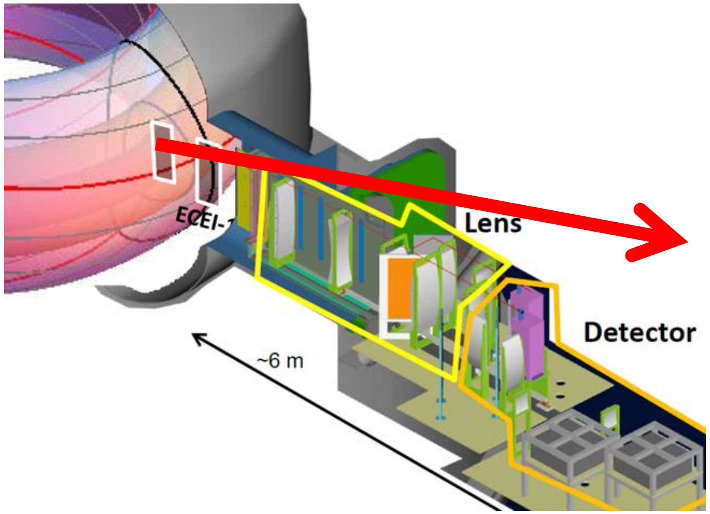
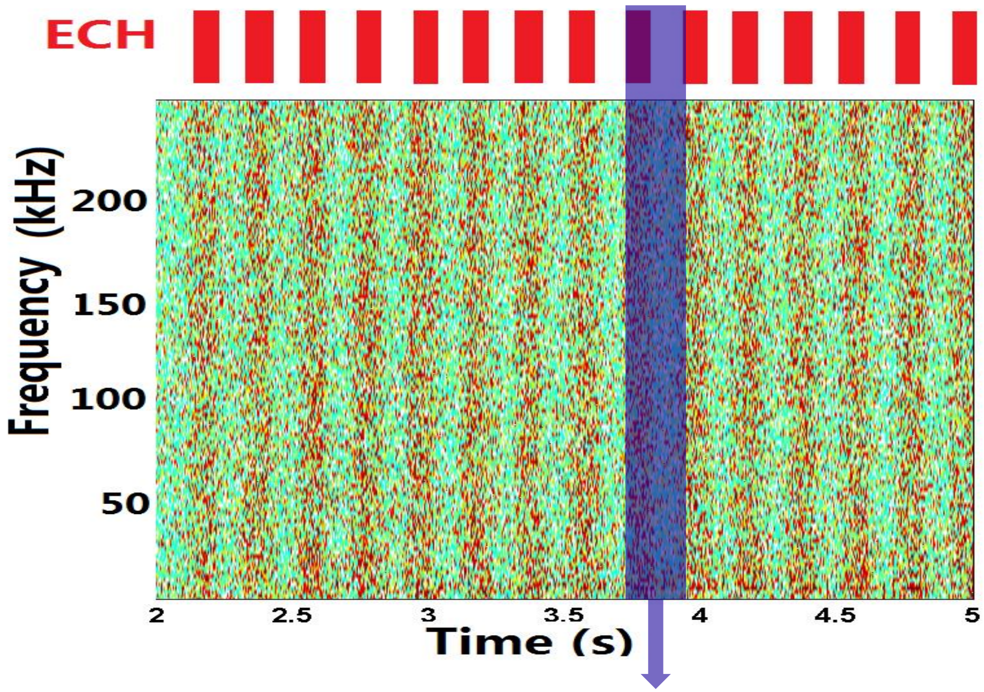
T_e Fluctuations from ECEI



ECEI on KSTAR (H. Park, EX/8-1)
Spatial resolution : 1cm(Z), 2~3cm(R)
Time resolution: 2μs

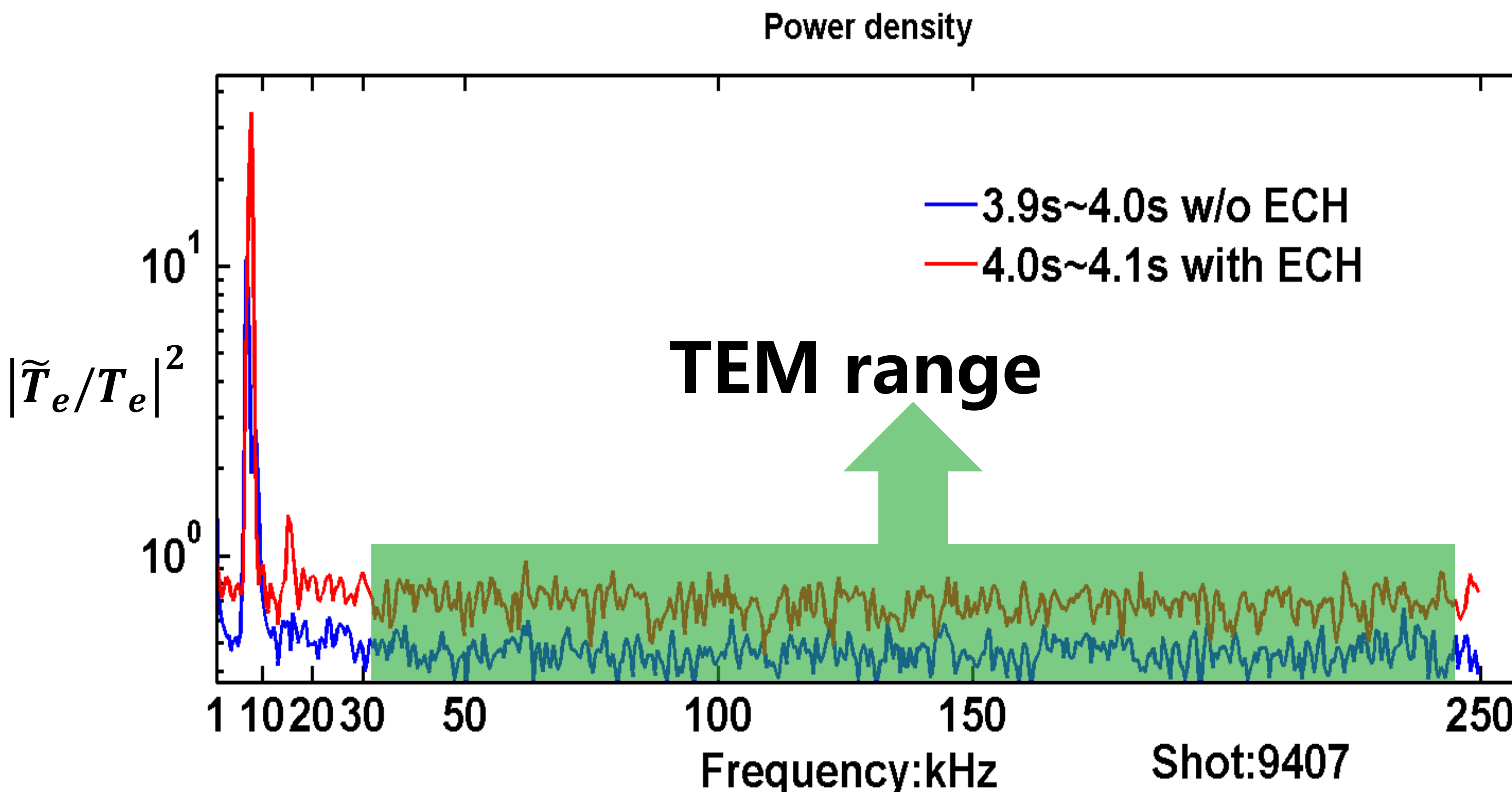
Time-Frequency spectra of T_e at core for on-axis ECH in L-mode



Detailed Power spectra in next page

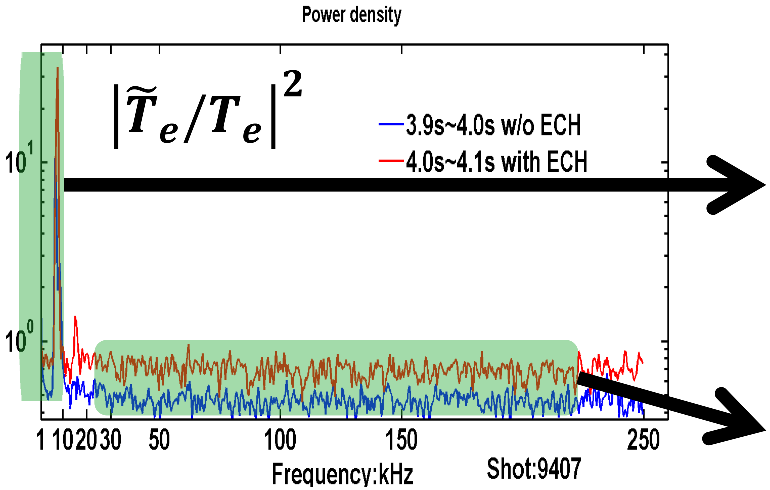
$\left|\tilde{T}_e/T_e\right|^2$ bursts over wide frequency range in every ECH modulation cycle

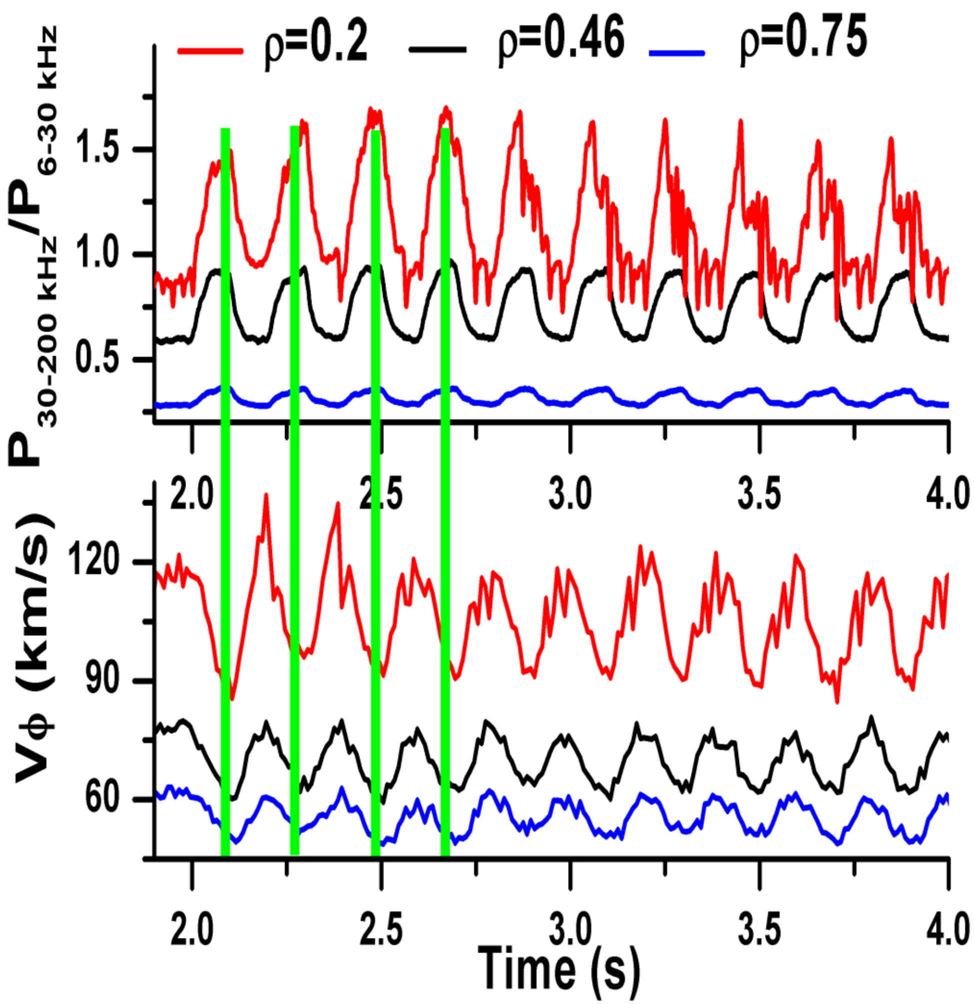
High frequency fluctuations of T_e increase with ECH



Power spectra of T_e at core region

- Intensity of high frequency range (TEM frequency range) increases with ECH
  $\rightarrow$ evidence of TEM excitation
- There is no peak in higher frequency due to limited ECEI spatial resolution.
- The peak at 8 kHz (coherent mode, MHD?) becomes narrower (intensity decrease) with ECH.





- **Peaks of $P_{30\text{-}200kHz}/P_{6\text{-}30kHz}$ closely correspond to the peaks in counter-current rotation for every ECH cycle**

- **$\Delta(P_{30\text{-}200kHz}/P_{6\text{-}30kHz}) \propto |\nabla V_\phi|$**

→ Explicitly shows the connection of micro $|\tilde{T}_e/T_e|$ to macro rotation ΔVϕ

Waveforms of power ratio between high frequency $\tilde{T}_e$ and low frequency $\tilde{T}_e$, and V_ϕ at three positions in modulated ECH plasma

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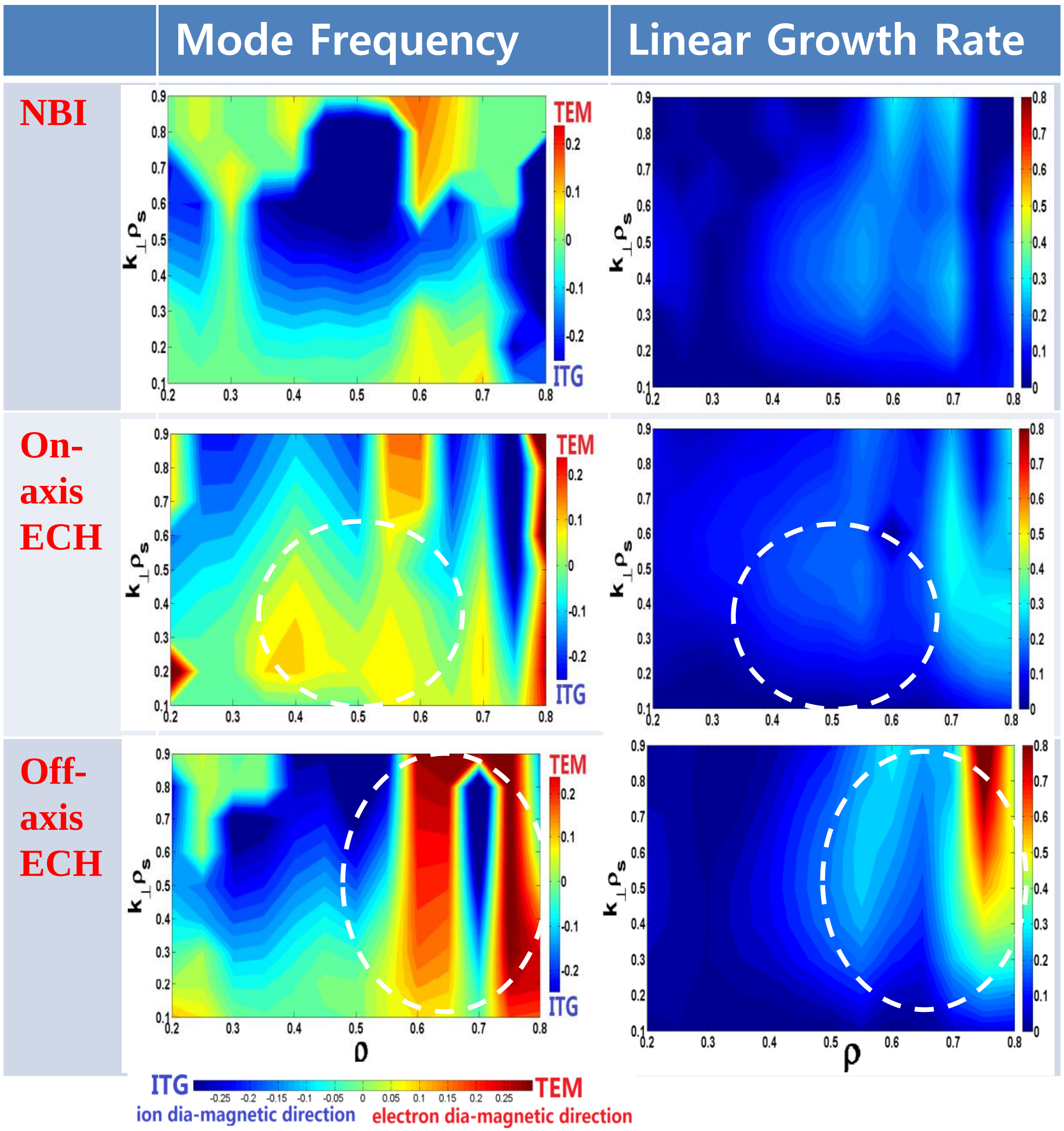
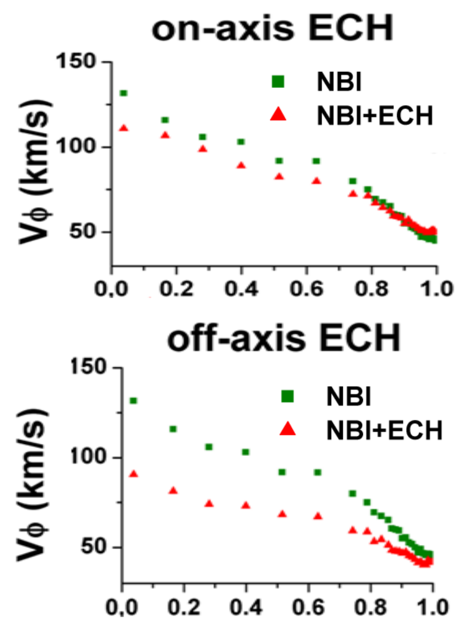
Gyrokinetic Linear Stability Study

➔ ITG ↔ TEM matches macro-trend of V_ϕ



- ITG→TEM transition occurs at
  ρ=0.4~0.6 for on –axis ECH
  ρ=0.6 ~0.8 for off –axis ECH
- Off-axis ECH excites stronger TEM at outer region even though ΔT_e is smaller due to increased trapped particle population
- Matches with macro-trend of ΔV_ϕ



Conclusion

- In L-mode, off-axis ECH induces stronger counter-current torque than on-axis ECH
- 1D transport analysis shows
  - Clear correlation between χ_i and ∇T_e → TEM driven transport
  - Strong correlation between $\Pi_{non-diff}$ and ∇T_e → ∇T_e drives $\Pi_{non-diff}$
  - No clear correlation between $\Pi_{non-diff}$ and V_ϕ
- Power spectrum of T_e fluctuation indicates the excitation of TEM and ΔV_ϕ closely follows the changes of high frequency T_e fluctuations.
- Linear gyrokinetic analysis indicates that ITG→TEM occurs and stronger TEM excitation for off-axis ECH due to increased trapped particle population → match of micro-instability and macro-V_ϕ trend

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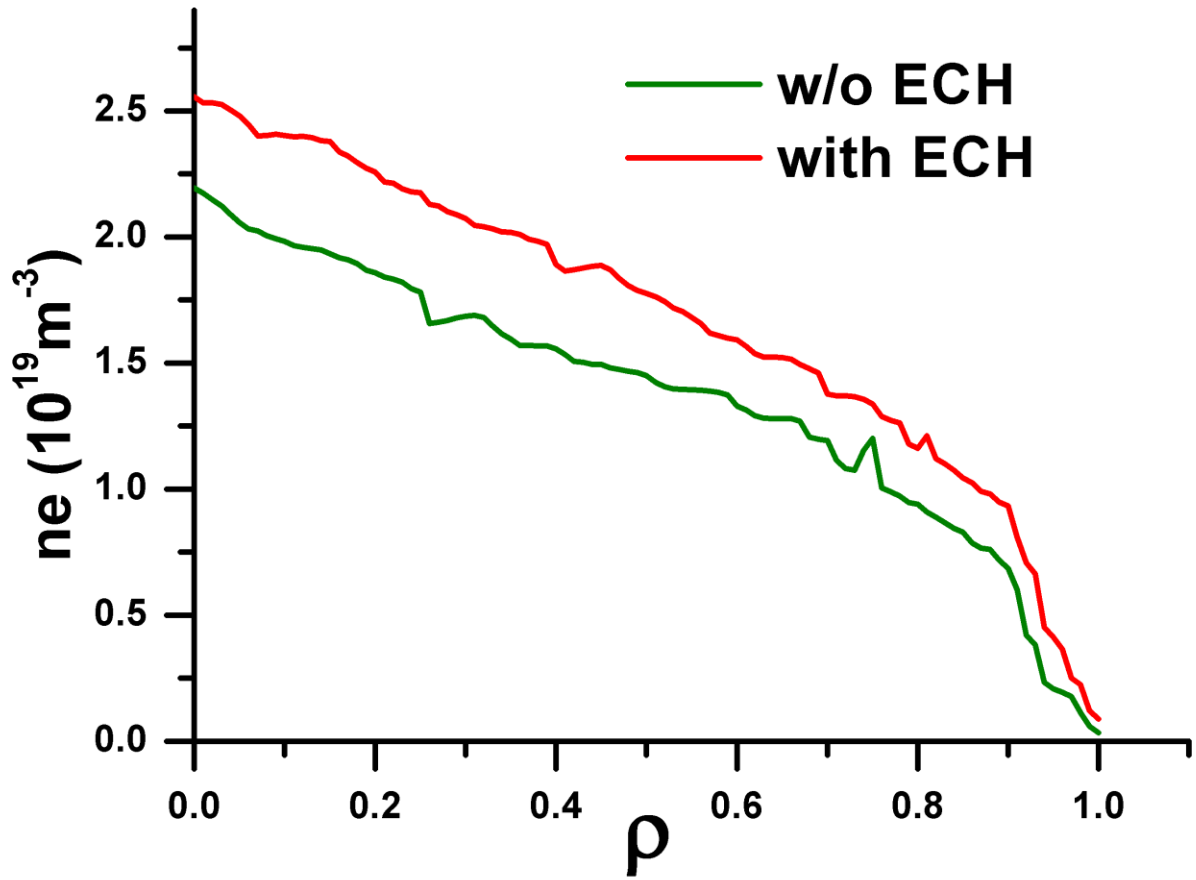
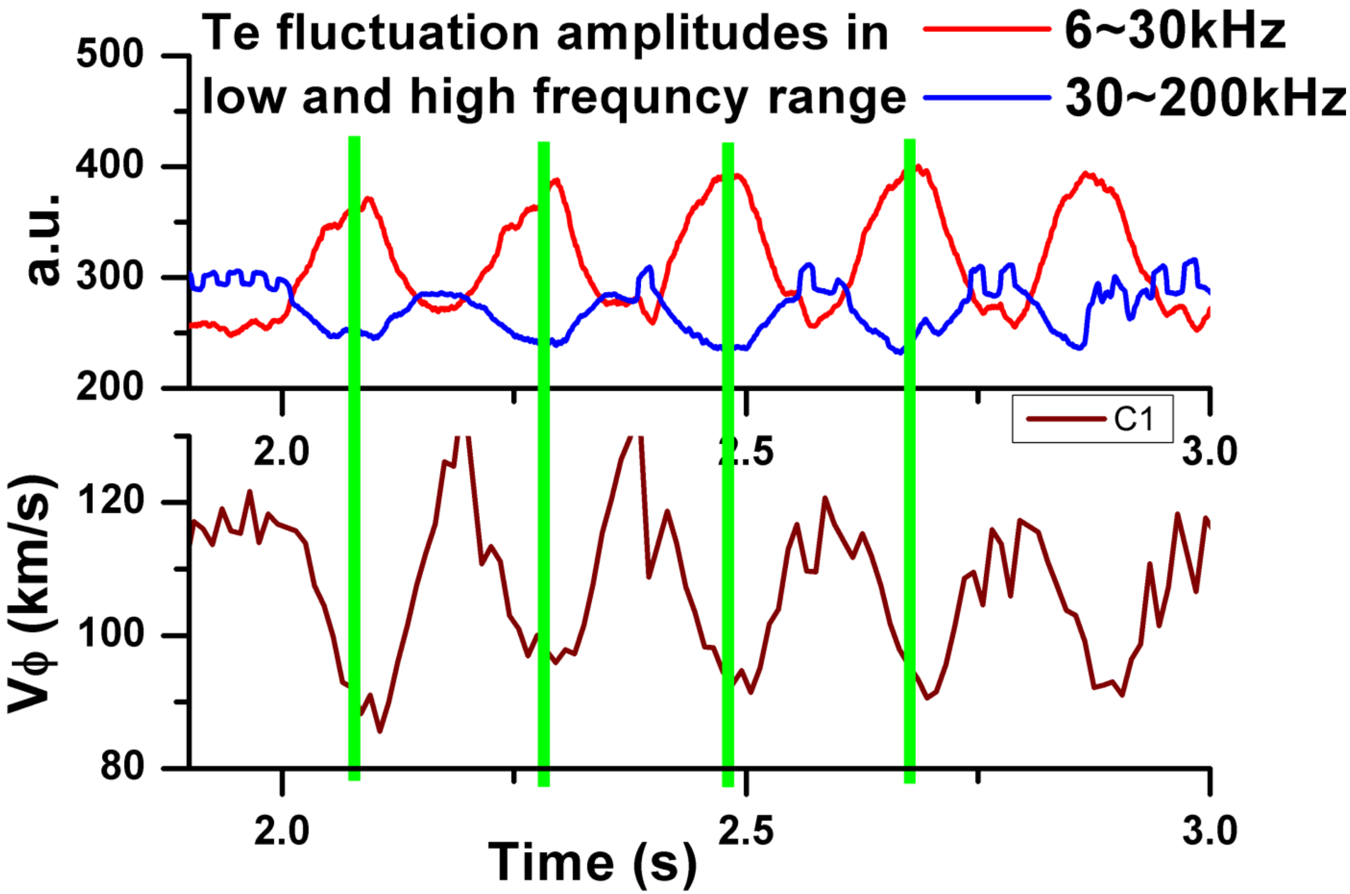
Future plan

- Coordinated experimental studies of coupling momentum and particle transport
- Combined ECEI and BES fluctuation studies, coordinated with macro-scopics
  - Fluctuation intensity profile?
  - Fluctuation propagation direction in plasma frame? Flip of propagation direction?
- Nonlinear gyro-fluid simulations of dynamically competing domains with ITG and TEM turbulence populations

Thank you
for your attention!

Density profiles with and without ECH (off-axis ECH in L-mode)





Waveforms of Te fluctuation amplitudes in low and high frequency ranges