KSTAR TRANSPORT & TURBULENCE RESEARCHES

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On behalf of
Transport and Turbulence Working Group
KSTAR center

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KSTAR

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(year 2011-2013)

1. Kinetic pedestal profile evolution during L-H transition
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3. **V_Φ** damping by on-axis ECH in ohmic/NBI-heated plasmas
4. Core rotation reversal in ohmic plasmas

III. **Future Collaboration Opportunities**

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I. Overview of KSTAR T&T Experiments

- **KSTAR T&T WG mainly addresses the issues identified by ITPA Transport and Confinement Topical Group**
  - Current researches mainly focused on momentum transport
  - Thermal and particle transport researches limited

- **4 chosen and interesting topics…**

1. **Kinetic pedestal profile evolution during L-H transition**
2. **On-axis ECH effects on Ar impurity transport**
3. **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasmas**
4. **Core rotation reversal in ohmic plasmas**

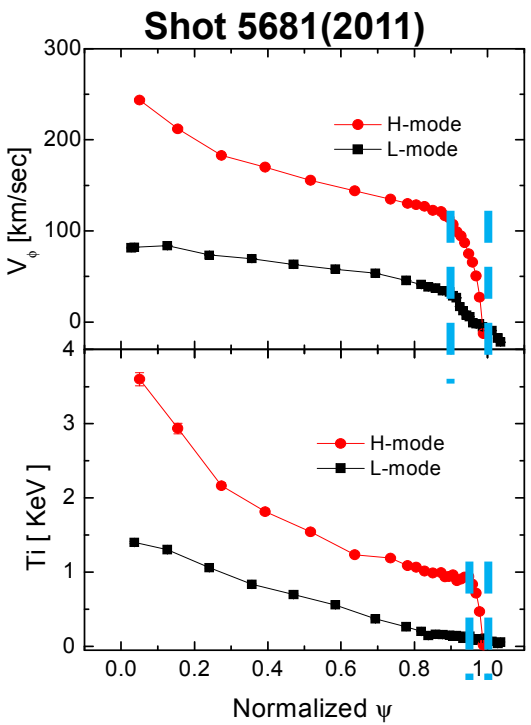
II. Recent KSTAR T&T Experiments/Analyses

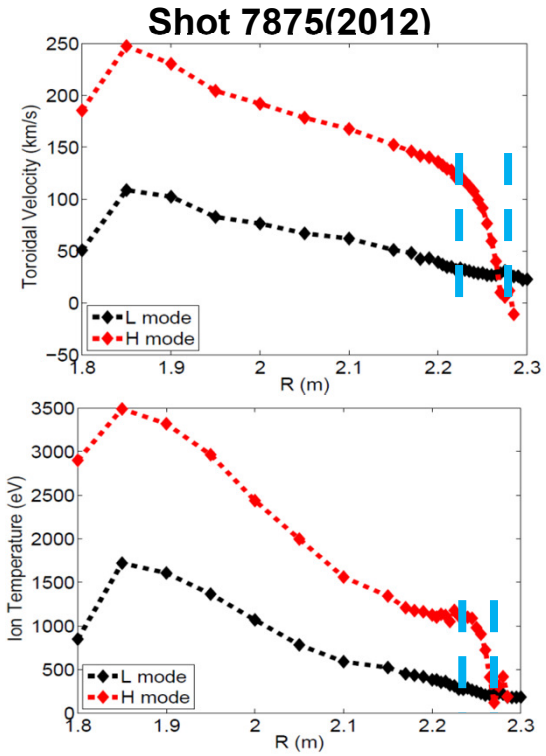
- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

◆ **V_ϕ pedestal broader than T_i pedestal ($\Delta_\phi^{ped} > \Delta_i^{ped}$) in KSTAR**

- Contrary to usual profiles ($\Delta_i^{ped} > \Delta_\phi^{ped}$) observed in other tokamaks
- Same results for two consecutive years(2011-2012)
- Edge profile highly reliable due to small plasma radius(thus no fitting)
- Banana orbit width calculation shows no effect(small enough banana width)

◆ **Why $\Delta_\phi^{ped} > \Delta_i^{ped}$ ($\chi_\varphi > \chi_i$)?**





II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

◆ **Simple 1-D analysis for H-mode pedestal**

➔ $\chi_i^{calculated} \sim \chi_{i,neo}$ **and** $\chi_{\varphi,calculated} \gg \chi_{\varphi,neo}$

- **Large χ_φ in H-mode pedestal not be explained neoclassically ➔ turbulence theory!**

◆ **Assuming electrostatic, two modes are candidates**

- **Ion temperature gradient (ITG) mode?**
  - It is reported that $\chi_{i,\text{measured}} >> \chi_i^{neo}$ when ITG mode exists in H-mode(Nucl. Fusion. 27, 129) ➔ negligible ITG mode
- **Parallel shear flow (PSF) mode?**
  - When $V_{||}$ has a gradient, PSF instability(PSFI) can be excited ➔ could be the dominant channel to transfer toroidal angular momentum (P.J. Catto et.al PoF 73)

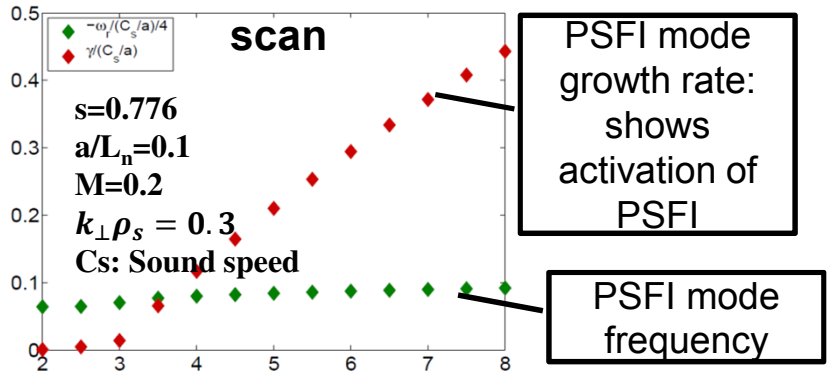
II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

◆ **From the scanning study of basic PSFI properties(GYRO simulation)**
- **Flow shear ↑ ➔ PSFI excited**

➢ **PSFI transfers toroidal angular momentum ➔** $\Delta_{\phi}^{ped} > \Delta_{i}^{ped}$

Parallel shear flow scan

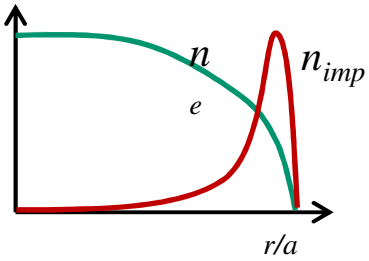


$$PSFI: \gamma = -R_0 \frac{\partial}{\partial r}\left(\frac{U_\parallel}{R_0}\right)$$

◆ **Collaboration opportunities**
- **Experiments**
  - Experiments to confirm the measurements
- **Analysis**
  - More detailed/advanced GYRO simulation
  - Less approximation/electromagnetic environment
  - Investigate other theoretical explanation
    - Both neoclassical and turbulence

II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)



◆ **Understanding impurity transport issue important for ITER operations**

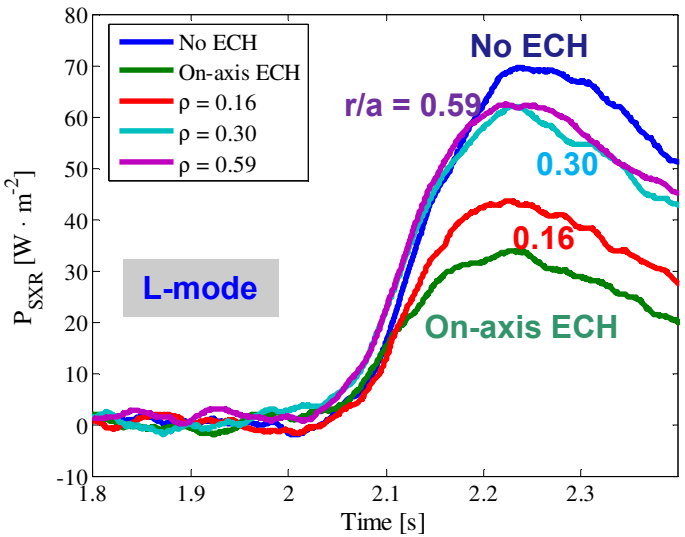
- Accumulation in the core ➔ radial transport to the edge

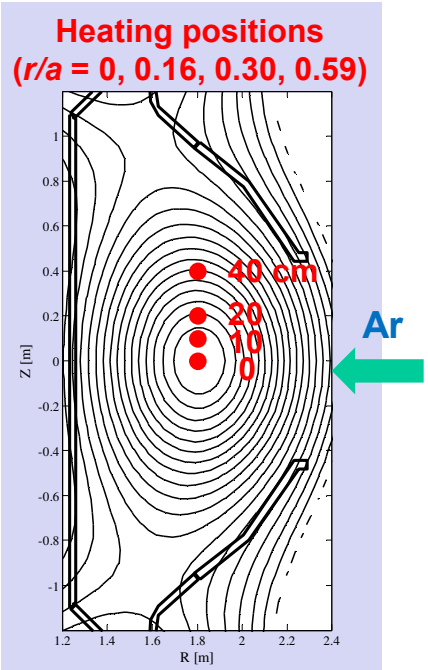
◆ **Ar impurity injection study in KSTAR**

- Use Ross filters in SXR to measure Ar^{16+}, Ar^{17+}
- Use VUV spectroscopy to measure Ar^{15+} and verify Ar^{16+}, Ar^{17+} measurements

◆ **2012 campaign**

- Vertical scanning at four locations
- Both SXR and VUV showed a **decrease** in emission intensities of Ar^{15+} - Ar^{17+} due to ECH
  - Most effective with on-axis ECH
  - **Less core accumulation** of Ar



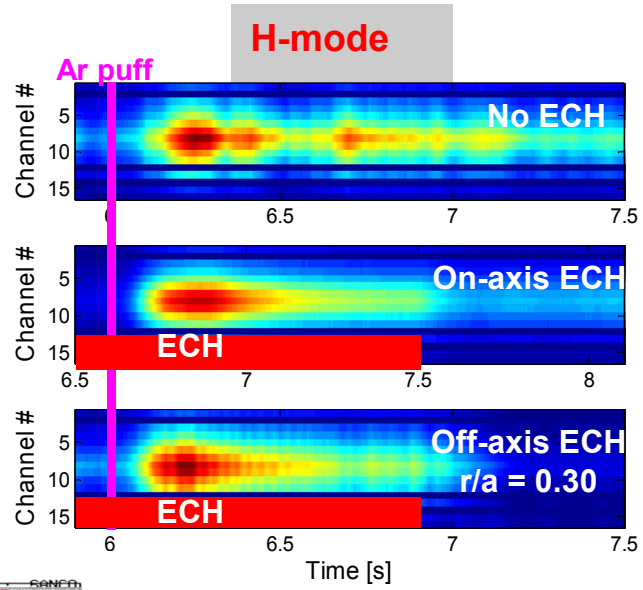


II. Recent KSTAR T&T Experiments/Analyses

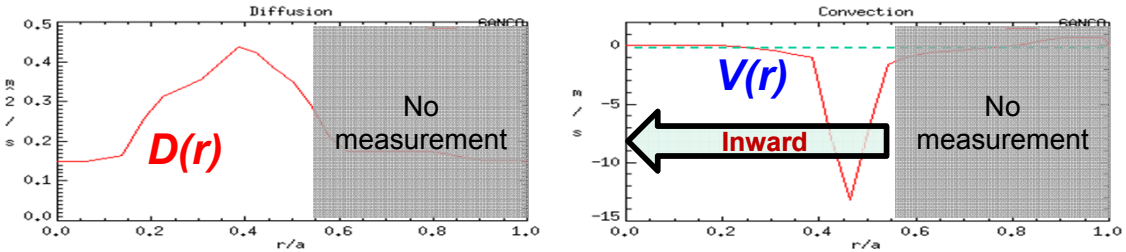
- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ 2012 campaign

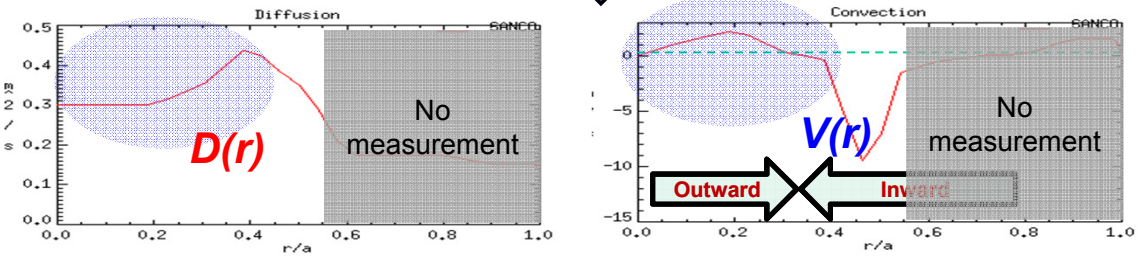
- Both L- and H-mode showed a reduction of Ar emissivity due to ECH
- SANCO-ADAS analysis
  - With ECH, central diffusion(D) and convection(V) are increased
    - ➔ Suggests that **local electron heating can be an effective measure of Ar transport control**



No ECH (#7566)



On-axis ECH (#7574)



II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ **2013 campaign results**

- Tried to reproduce the 2012 L-mode result
- But both SXR and VUV show an **increase** in emission intensities of Ar^{15+} - Ar^{17+} with ECH
  - **Opposite to the 2012 cases**

◆ **Why different results?**

- **Transition probability(ϵ_Z)** of $Ar^{15+} \rightarrow Ar^{16+}$ and $Ar^{18+} \rightarrow Ar^{17+}$

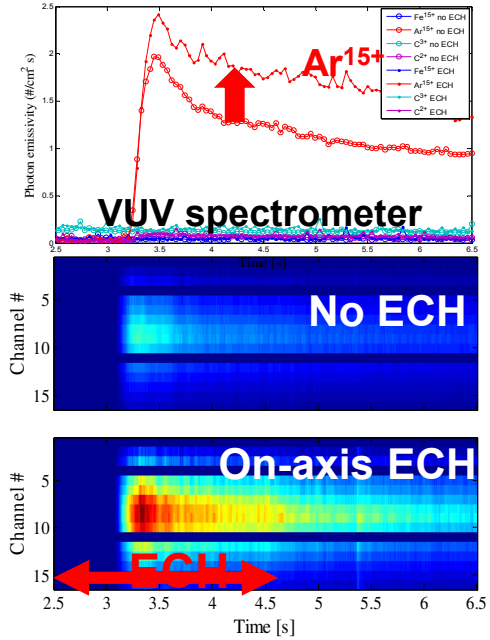
$$\epsilon_Z(n_e, T_e) = n_e \boldsymbol{n_Z} A(n_e, T_e)$$

  - a function of T_e and n_e (M. Valisa *et al* 2011 *Nucl. Fusion* 51 033002)
  - ϵ_Z is converted to P_{SXR} (not to n_Z)

    → **Core ϵ_Z decreased in 2012**

    → **Core ϵ_Z increased in 2013**

- **SANCO-ADAS to calculate n_Z in progress**



Ar Transport from Ross Filters (2013)

◆ **Collaboration opportunities**

- ECH/sawtooth/RMP versus Ar transport experiments in the future
- Most tokamaks seem to use similar analysis method
- Validation of theories to understand the mechanism: turbulent? neoclassical?

II. Recent KSTAR T&T Experiments/Analyses

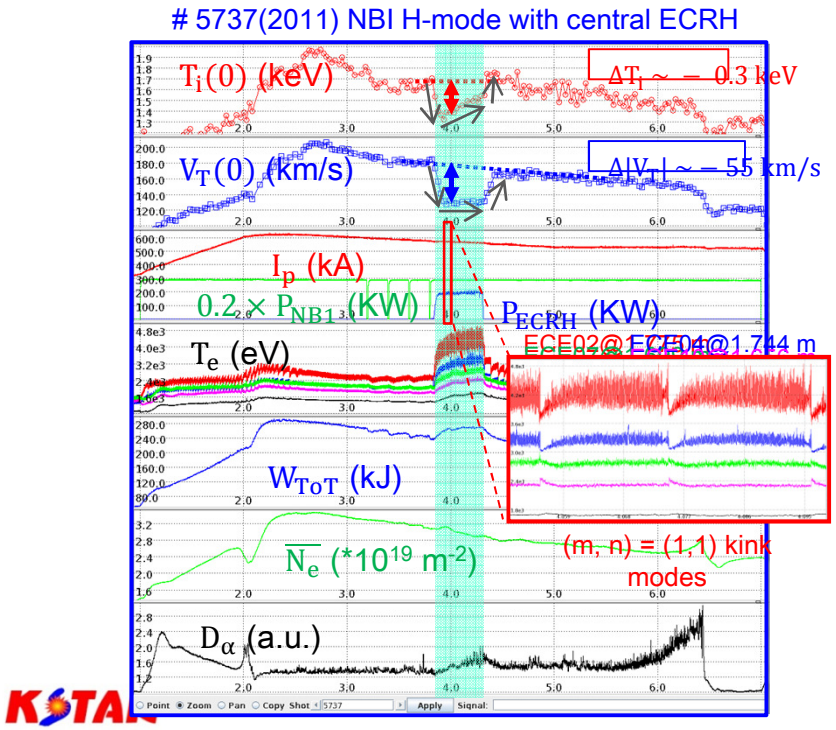
• V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma(H.H. Lee/J.C. Seol-NFRI)

◆ **Rotation damping due to on-axis ECH observed in many tokamaks**

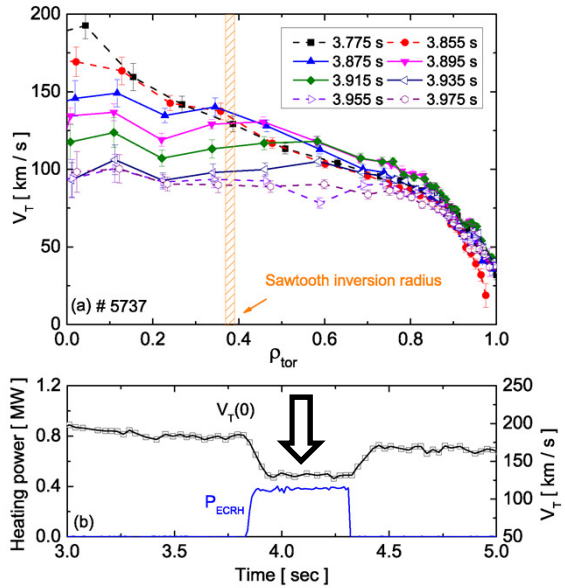
- Consistently observed in KSTAR(2011-2013)
- Important to understand the damping mechanism for ITER operation

◆ **Two track analyses on the possible causes**

1. NTV torque caused by internal kink modes (J. Seol-NFRI)
   - Rotation damping always accompanies **internal kink modes**
     - identified by radial displacement picked up by ECE (Visual verification with ECEI)
2. Turbulence-driven residual stress due to the transition ITG ➔ TEM (Angioni)



NTV



H-mode plasma

II. Recent KSTAR T&T Experiments/Analyses

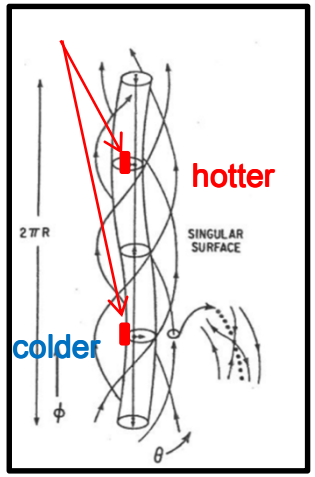
• V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma (H.H. Lee/J.C. Seol-NFRI)

◆ V_Φ damping analysis with NTV theory (J. Seol *et al.* PRL (2012))

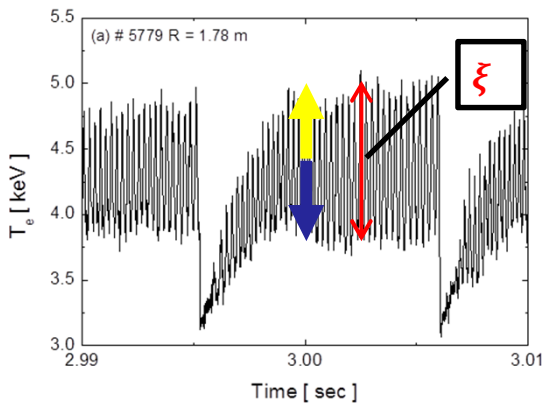
- Central ECH -> internal kink modes inside the q=1 surface
- drives magnetic field perturbation inside q=1 surface(sawtooth inversion radius)

$$\frac{\delta B}{B} = \frac{\left(A_1^2+B_1^2\right)^{1/2}}{B_0} \sim \left(\frac{\xi}{2}\right)\left(\frac{1}{B_0}\frac{\partial B}{\partial r}\right) \sim O(10^{-3})$$

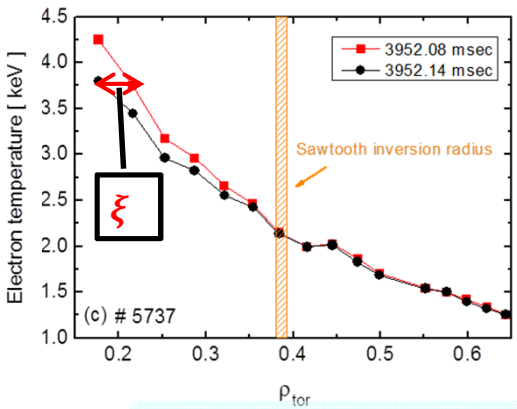
ECE measurement volume

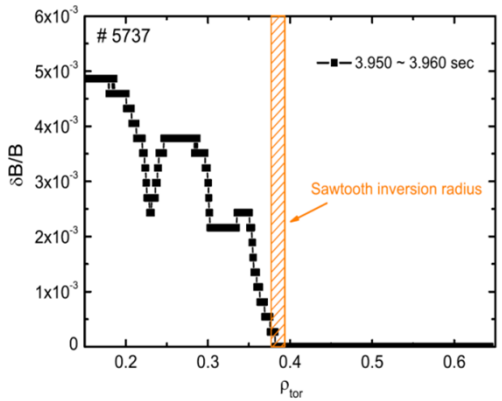


Time trace of T_e measured by ECE



Radial profile of T_e measured by ECE





$$T_{1/\nu} \sim -6.1 N_i M_i v_{ti}^2 \frac{\epsilon^{3/2}}{\nu_i} n^2 \left(\frac{A_n^2+B_n^2}{B_0^2}\right) \times \left\{V^\zeta - q\left(V^\theta + 2.367\frac{1}{erB_0}\frac{\partial T_i}{\partial r}\right)\right\}$$

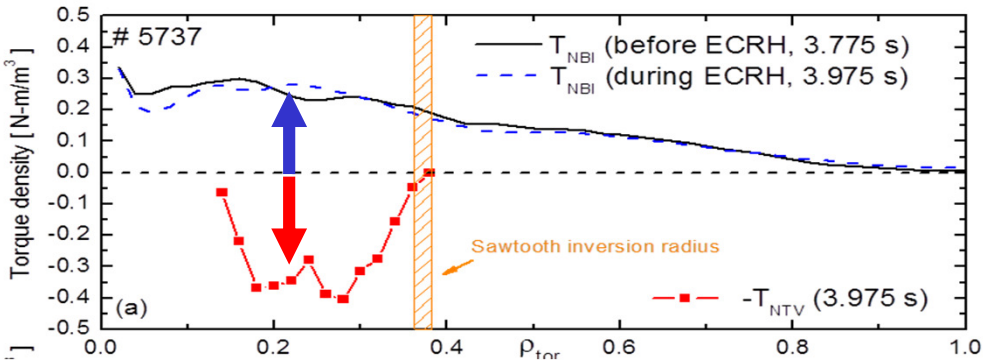
$$T_{\sqrt{\nu}} \sim -0.09 N_i M_i v_{ti}^2 \sqrt{\epsilon}\sqrt{\nu_E}\{\ln(8/\sqrt{\nu_{Ei}})\} n^2 \left(\frac{A_n^2+B_n^2}{B_0^2}\right) \times \left\{V^\zeta - q\left(V^\theta + 0.356\frac{1}{erB_0}\frac{\partial T_i}{\partial r}\right)\right\} / q\omega_{Ei}$$

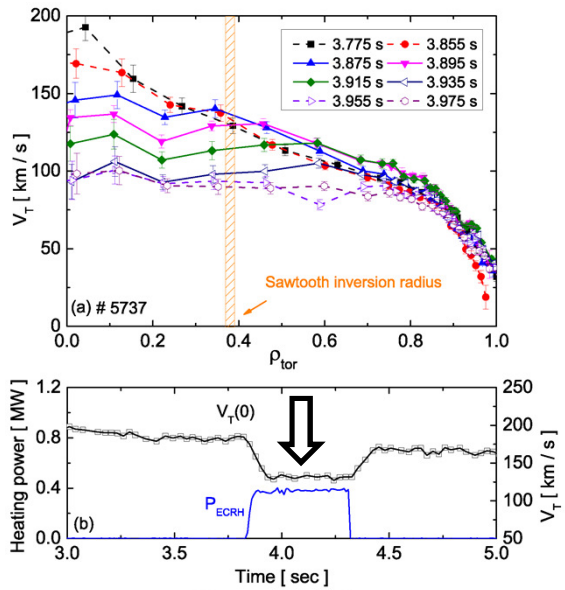
II. Recent KSTAR T&T Experiments/Analyses

- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(Y.J. Shi-WCI)

1. V_Φ damping analysis with NTV theory (J. Seol *et al.* PRL (2012))

- causes toroidal axisymmetry breaking
- enhances **NTV torque**
- damps V_Φ (counter to V_Φ)
  - NTV torque density calculated to be comparable to NBI torque density
  - NTV torque always damps the rotation (regardless of I_p direction)





H-mode plasma

◆ Collaboration opportunities

- **Experiments**
  - Overall, well established experimental data
- **Analysis**
  - Any other theories to explain?
  - Apply NTV theory explanation to your experiments?

II. Recent KSTAR T&T Experiments/Analyses

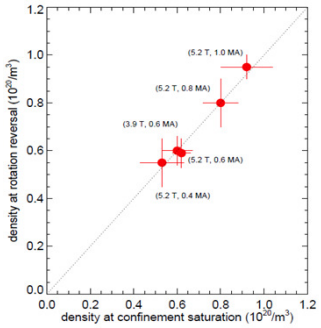
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ **Intrinsic rotation is an ITER-relevant issue**
- NBI alone not enough in ITER
- Need strong intrinsic rotation in ITER

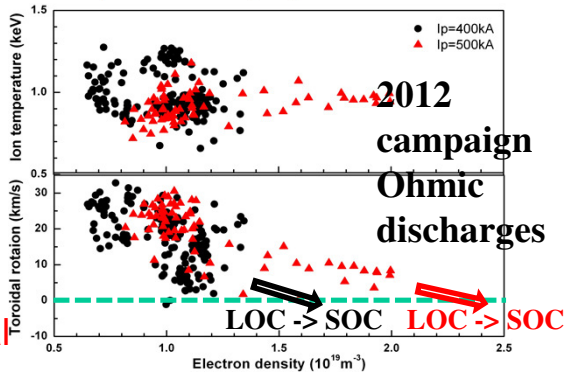
◆ **Intrinsic rotation experiments in:**
- **Core rotation reversal**
  - LOC-SOC transition with density dependency
    - **TCV / C-Mode / AUG**
- **Edge intrinsic rotation**

◆ **Experiments based on I_p and n_e scanning**
- ➢ **2011-2012**
  - Tried to verify n_e dependency
  - LOC → SOC transition occurred(300-500kA) but no reversal
- ➢ **2013**
  - Failed to reach higher densities
  - Stayed in LOC region(500 kA) but some reversal-like behaviors observed at ne~1.5 [10^{19} #/m^3]
  - Recent investigation suggests no n_e dependency

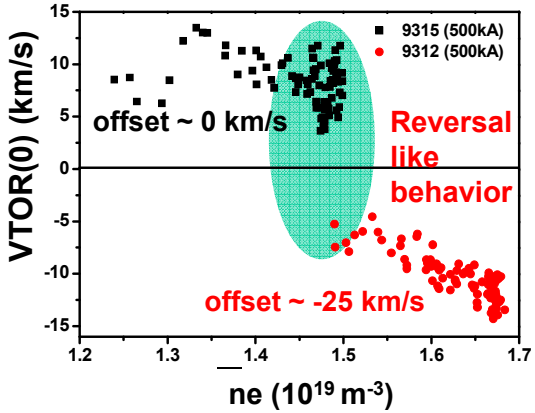
❖ **Not corresponding with Rice 2011**
❖ **Rice 2012 suggests collisionality dependency!**



J. E. Rice *et al*, Nucl. Fusion **51**(2011)



S.G. Lee(2012 experiments)

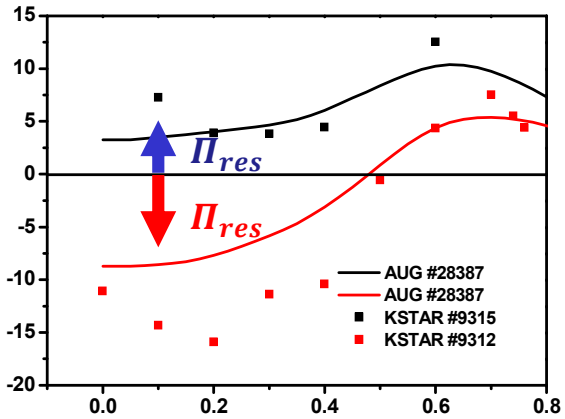


II. Recent KSTAR T&T Experiments/Analyses

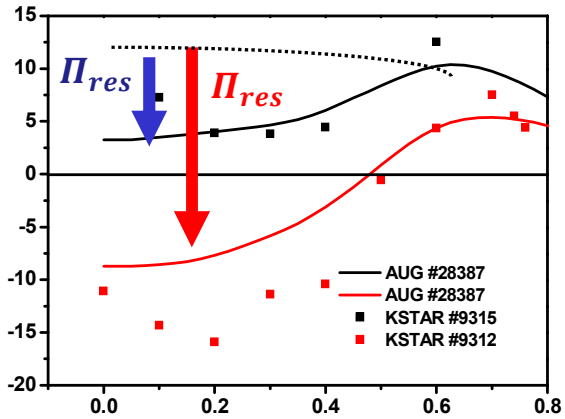
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ **Analyses by SNU**

- **Check collisiionality dependency**(2013)
  - Studies verifies better correlation
- Π_{res} **due to TEM(LOC) → ITG(SOC) used widely**
  1. Continue to investigate with this view to explain rotation reversals
  2. A paradigm shift in the application of the Π_{res} model
     - Π_{res} lowers the rotation profiles with different magnitudes along the profile



VS.



◆ **Collaboration opportunities**

- **Experiments**
  - Need for better density control for more data collection
- **Analysis**
  - Investigate collisionallity dependency with more KSTAR/AUG data
  - Investigate the paradigm shift of residual stress or another novel approach

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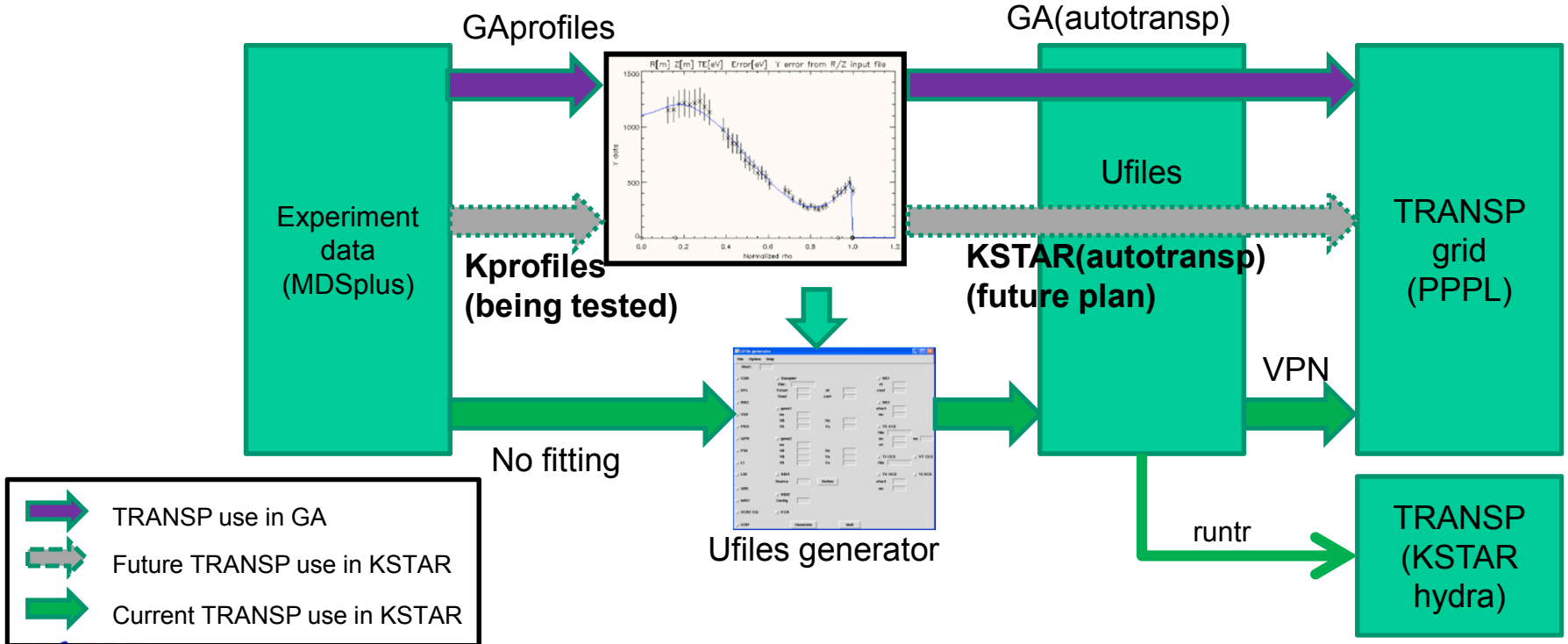
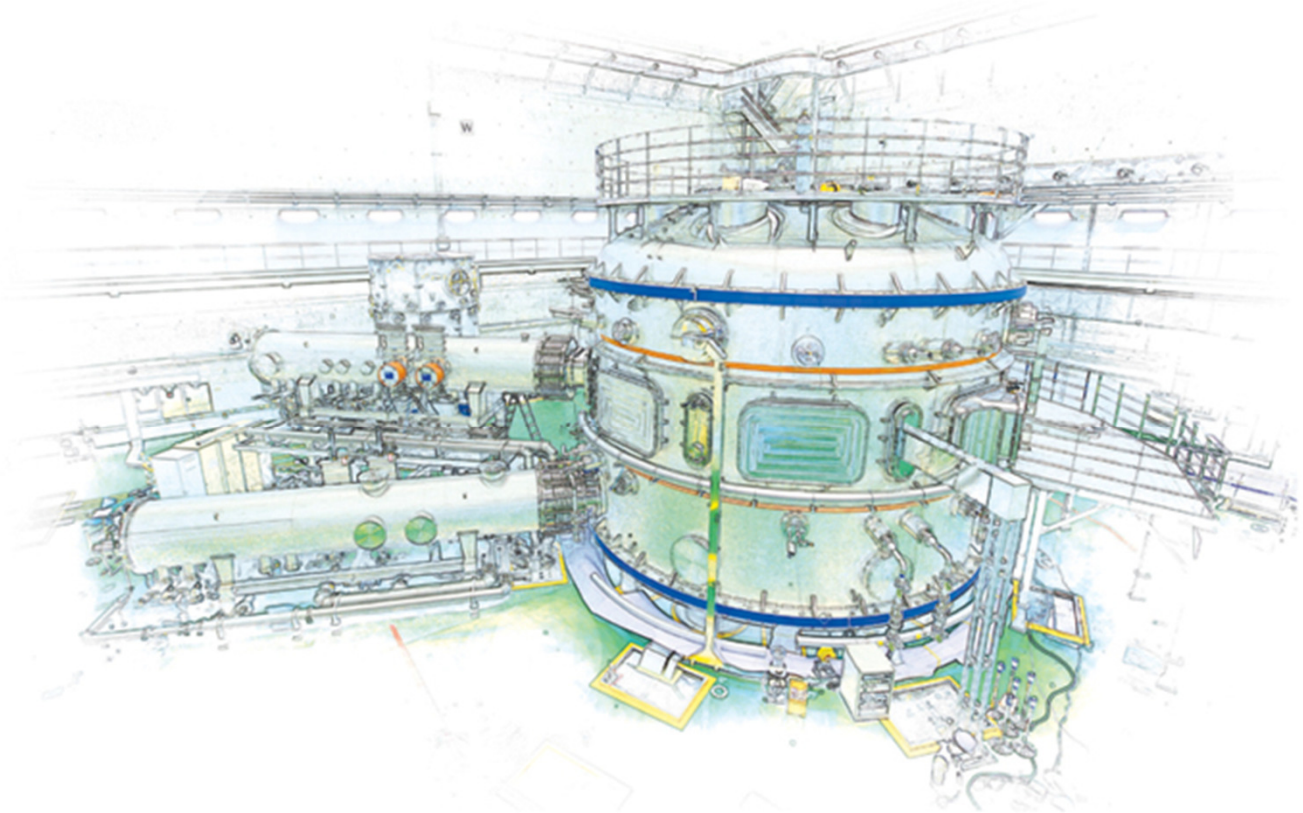
III. Future Collaboration Opportunities

- **Diagnostic improvements**
  - More channels to Thomson system / Poloidal CES(2015) / MIR/BES
- **Areas not currently covered in KSTAR**
  - Your opportunities to pioneer these researches with KSTAR
- **Current status of TRANSP access**
  - Ongoing effort for automatic TRANSP run access for KSTAR community
  - Access to PTRANSP will greatly benefit KSTAR experiment design/analysis



IV. Questions/Comments



Backup slides

II. Recent KSTAR T&T Experiments/Analyses

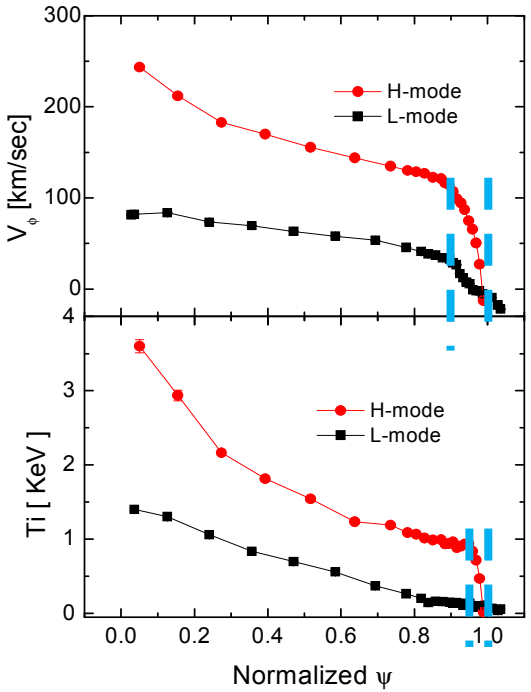
- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

◆ **In KSTAR, V_ϕ pedestal broader than T_i pedestal ($\Delta_\phi^{ped} > \Delta_i^{ped}$)**

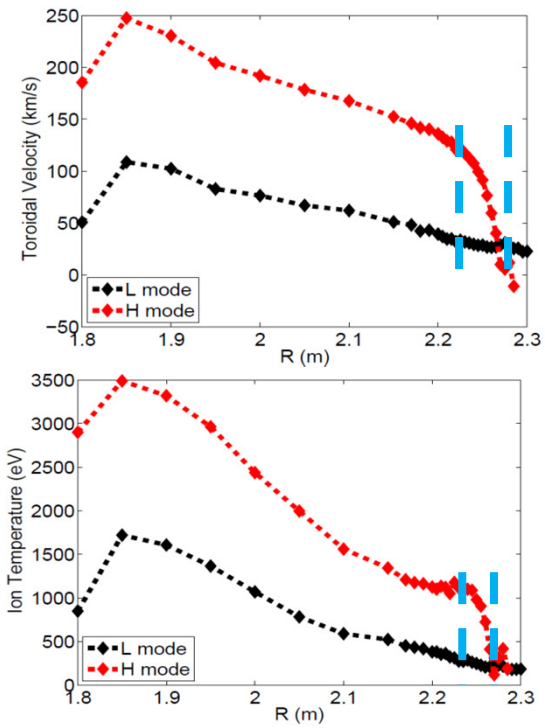
- Contrary to usual profiles ($\Delta_i^{ped} > \Delta_\phi^{ped}$) observed in other tokamaks
- Same results for two consecutive years(2011-2012)
- Edge profile data highly reliable due to small plasma radius(thus no fitting)
- Banana orbit width calculation shows no effect(small enough banana width)

◆ **Why $\Delta_\phi^{ped} > \Delta_i^{ped}$ ($\chi_\varphi > \chi_i$)?**

Shot 5681(2011)



Shot 7875(2012)



II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

◆ **Early analysis based on turbulence theory(S.H. Ko-WCI)**

- **Steady state momentum equation:** $-\chi_\varphi \frac{dV_\varphi}{dr} + V_{pinch}V_\varphi + \Pi_{res} = S_{tor}$
  - Residual stress assumed as $\Pi_{res} = -C\,\chi_{i,eff}\frac{dV_{E\times B}}{dr}$ (N. Fedorczak et.al. Nucl. Fusion 52, 103013)
  - pinch term ($V_{pinch}V_\varphi$) neglected for simplicity
- **Steady state heat equation:** $-\chi_{i,eff}\frac{dT_i}{dr} = S_Q$

➢ In L-mode, $Pr = \chi_\varphi/\chi_{i,eff} \sim 1$ (i.e. $\chi_\varphi \sim \chi_{i,eff}$) ➔ C can be evaluated from plasma and torque density profiles in L-mode

➢ For H-mode

  ➢ using C from L-mode, $-\chi_\varphi \frac{dV_\varphi}{dr}$ and Π_{res} can be calculated

    - Neglecting Π_{res}, use $-\chi_{\varphi,eff}\frac{dV_\varphi}{dr} = S_{tor}$ to get $\chi_{\varphi,eff}$
    - Use $-\chi_{i,eff}\frac{dT_i}{dr} = S_Q$ to get $\chi_{i,eff}$

  ➢ In H-mode pedestal(turbulence suppressed), neoclassical physics is dominant so heat diffusivity, measured in experiment, is similar order to neoclassical heat diffusivity (reported in Nucl. Fusion. 27, 129) ➔ $\chi_{i,eff} \sim \chi_{i,neo}$

  ➢ Neoclassical momentum diffusivity is negligible(reported fact) ➔ $\chi_{\varphi,eff} \gg \chi_{\varphi,neo}$

◆ **Simple 1-D analysis for H-mode pedestal**

➔ $\chi_i^{eff} \sim \chi_{i,neo}$ **and** $\chi_{\varphi,eff} \gg \chi_{\varphi,neo}$

II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

L-mode

$$-\chi_\varphi \frac{dV_\varphi}{dr} + \cancel{V_{pinch} V_\varphi} + C\,\chi_{i,eff} \frac{dV_{E\times B}}{dr} = S_{tor}$$

$$-\chi_{i,eff} \frac{dT_i}{dr} = S_Q$$

$$\chi_{i,eff} = -S_Q / \left(\frac{dT_i}{dr}\right)$$

$$\chi_\varphi \sim \chi_{i,eff}$$

$$C(L-mode) = \left(-S_{tor} + \chi_\varphi \frac{dV_\varphi}{dr}\right) / \left(\chi_\varphi \frac{dV_{E\times B}}{dr}\right)$$

$$C(L-mode)$$

?

H-mode

$$-\chi_\varphi \frac{dV_\varphi}{dr} + \cancel{V_{pinch} V_\varphi} + \cancel{\Pi_{res}} = S_{tor}$$

$$\chi_{\varphi,eff} = -S_{tor} / \left(\frac{dV_\varphi}{dr}\right)$$

Known fact: $\chi_{\varphi,neo}$ very small

$$\chi_{\varphi,eff} \gg \chi_{\varphi,neo}$$

Known fact:

$\chi_{i,eff} \sim \chi_{i,neo}$

$$\chi_{i,eff} \sim \chi_{i,neo}$$

II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

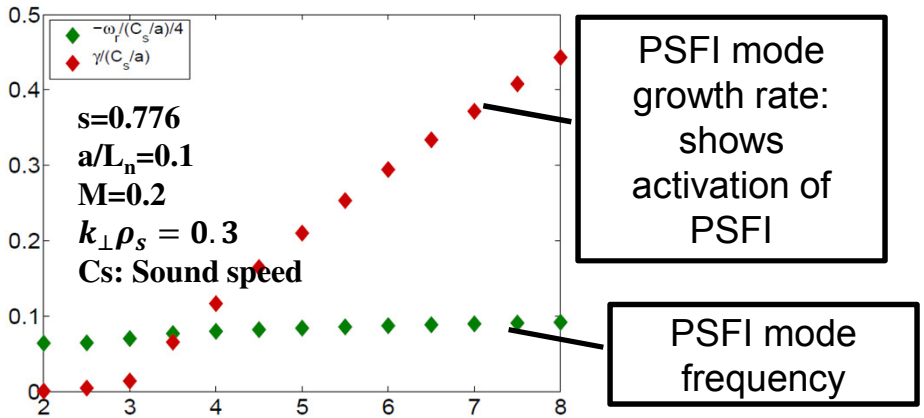
Large χ_φ in H-mode pedestal not be explained neoclassically ➔ turbulence theory!

◆ Assuming electrostatic, two modes are candidates

- **Ion temperature gradient (ITG) mode?**
  - It is know that $\chi_{i,\text{measured}} >> \chi_i^{neo}$ when ITG mode exists in H-mode(Nucl. Fusion. 27, 129)
  - But we have $\chi_{i,\text{calculated}} \sim \chi_i^{neo}$ ➔ no or negligible ITG mode
- **Parallel shear flow (PSF) mode?**
  - When parallel velocity has gradient, PSF instability(PSFI) can be excited ➔ could be another channel to transfer toroidal angular momentum (P.J. Catto et.al PoF 73)

**** In electromagnetic environment, other candidates(?) exist but not considered at this point***

Parallel shear flow scan



$$PSFI:\ \gamma = -R_0 \frac{\partial}{\partial r}\left(\frac{U_\parallel}{R_0}\right)$$

◆ **From the scanning study of basic PSFI properties**

- Density gradient ↑ ➔ PSFI stable
- Magnetic shear ↑ ➔ PSFI stable
- Mach number ↑ ➔ no effect
- **Flow shear ↑ ➔ PSFI excited**

➢ **PSFI transfers toroidal angular momentum ➔** $\Delta_\phi^{ped} > \Delta_i^{ped}$

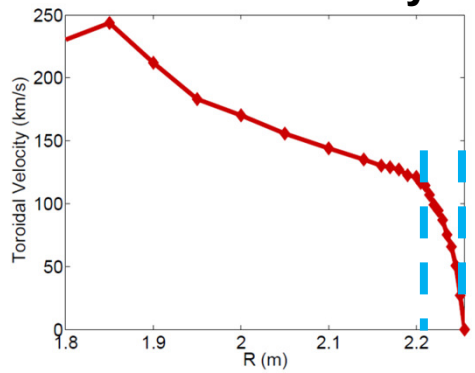
KSTAR

• Kinetic pedestal profile evolution during L-H transition (W.H. Ko / S.H. Ko-NFRI)

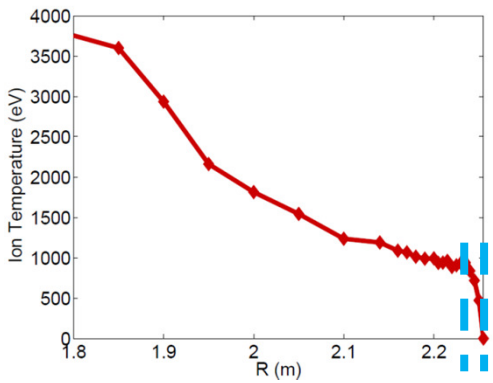
◆ Simulation of PSFI mode effect with GYRO code

- No reliable n_e profile in 2011 ➔ assume two other profiles
- Assume $n_e \sim n_e$
- Calculated PSFI mode frequency and growth rate at three radial locations (rho=0.95,0.97, and 0.98)

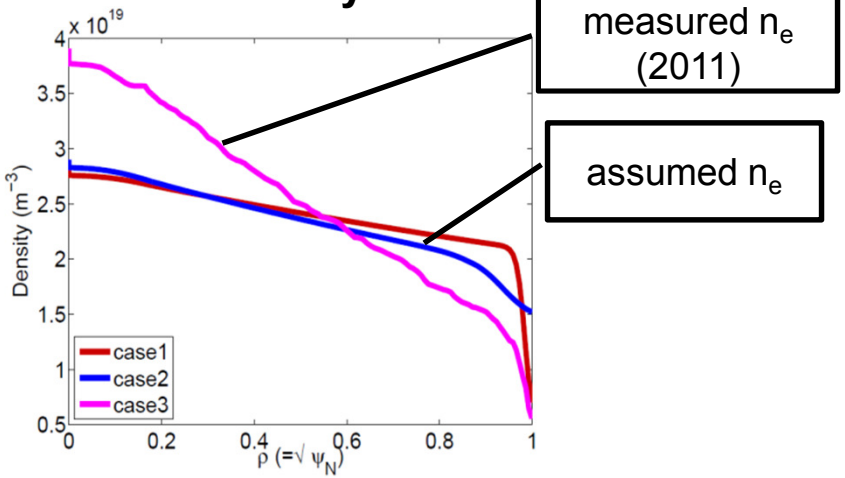
Toroidal Velocity



Ion Temperature



Density



II. Recent KSTAR T&T Experiments/Analyses

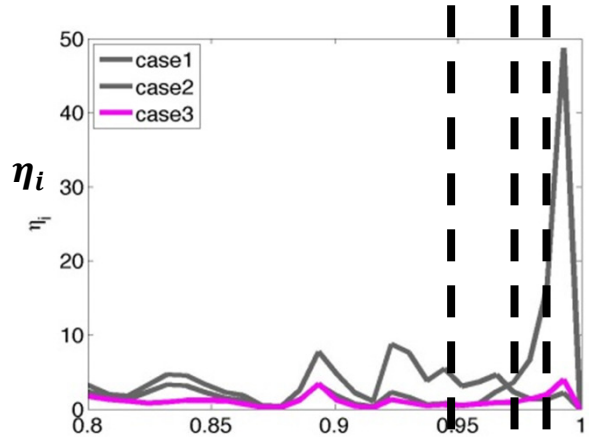
- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

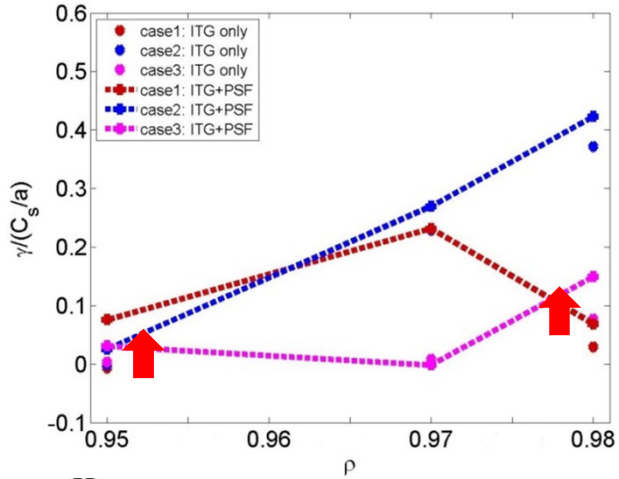
◆ **Compare PSFI growth rates with and without PSFI**

- **With PSFI, increase of growth rates for all densities**
  - ➔ PSFI transfers toroidal angular momentum
  - ➔ $\Delta_{\phi}^{ped} > \Delta_{i}^{ped}$

◆ **Case 2 shows large peak in $\eta_i = \frac{L_n}{L_T}$**

- η_i is related to ITG mode (high η_i means larger ITG)
- So the growth rate of case 2 starts at higher value
- But the increase of the growth rate due to PSFI is also observed





: without PSFI (ITG mode ONLY)
: with PSFI (ITG mode + PSF mode)

◆ **Collaboration opportunities**

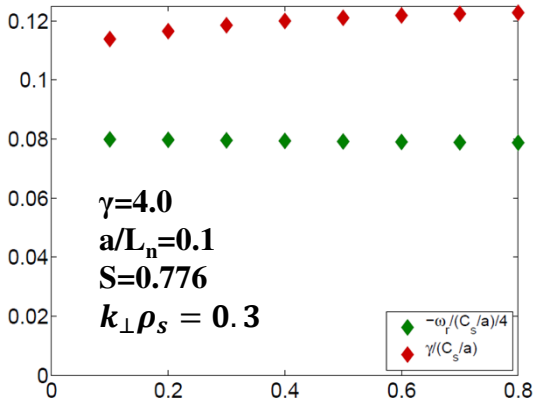
- **Experiments**
  - Experiments to confirm the measurements
- **Analysis**
  - More detailed/advanced GYRO simulation
  - Less approximation/electromagnetic environment
  - Investigate other theoretical explanation
    - Both neoclassical and turbulence

II. Recent KSTAR T&T Experiments/Analyses

- **Kinetic pedestal profile evolution during L-H transition** (W.H. Ko / S.H. Ko-NFRI)

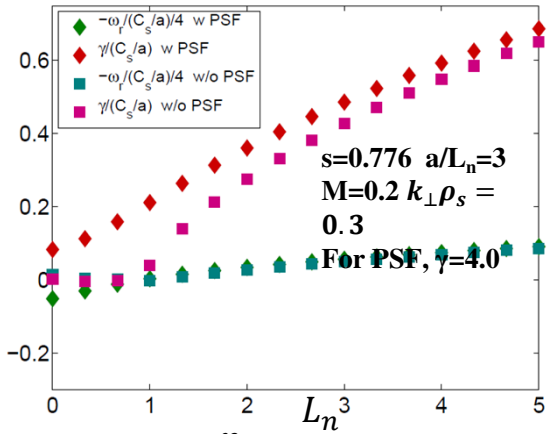
◆ Turbulence theory

Mach number scan



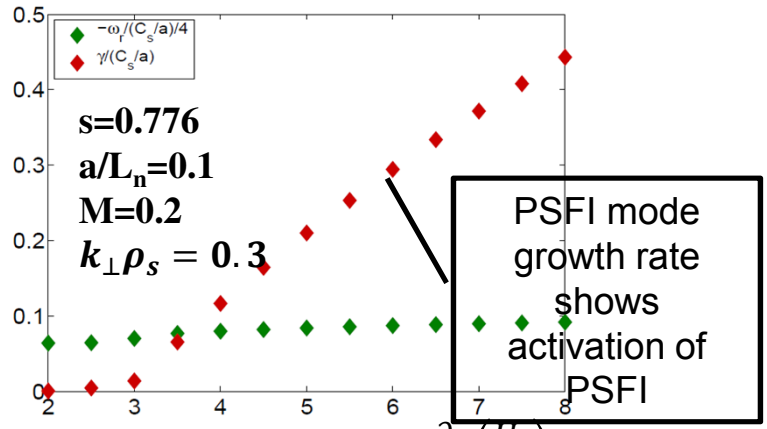
$$M = \frac{V_\parallel}{C_s}$$

η_i scan



$$\eta_i = \frac{L_n}{L_T}$$

Parallel shear flow scan



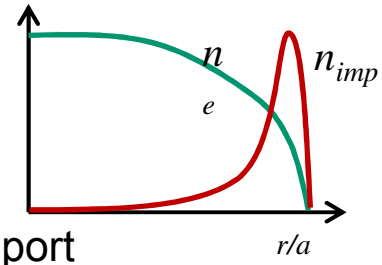
$$PSFI:\ \gamma = -R_0 \frac{\partial}{\partial r}\left(\frac{U_\parallel}{R_0}\right)$$

◆ From the scanning study of basic PSFI properties
- Density gradient ↑ ➔ PSFI stable
- Magnetic shear ↑ ➔ PSFI stable
- Mach number and η_i ➔ no effect
- Flow shear ↑ ➔ PSFI excited

➢ **PSF makes mode unstable even when ITG mode is stable**

II. Recent KSTAR T&T Experiments/Analyses

• On-axis ECH effects on Ar impurity transport (S.H. Lee-KAIST)



◆ **Understanding impurity transport issue important for ITER operations**

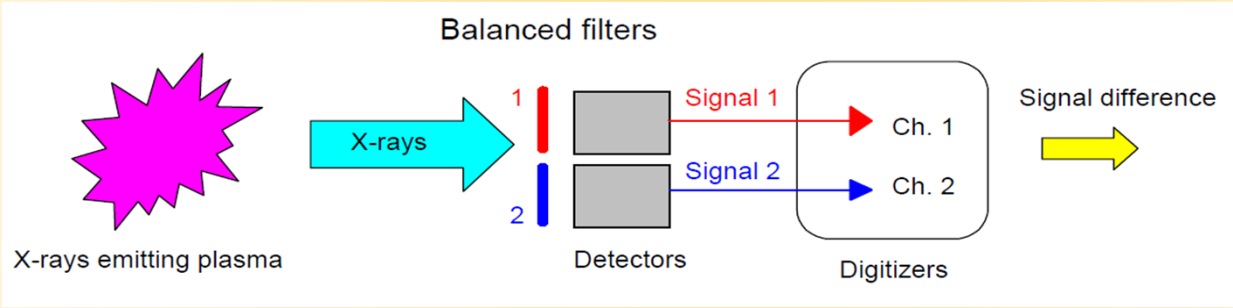
- Accumulation in the core ➔ radial transport to the edge
- DIIID uses Ar / NSTX uses Ar & Mo / JET uses Ar to study impurity transport

◆ **Argone impurity injection study in KSTAR**

- Inject Ar (n_{Ar} < 0.1% n_e)
- Use Ross filters in SXR to measure Ar^{16+}, Ar^{17+} (Ross filter used in DIIID before-2002 report)
- Use VUV spectroscopy to measure Ar^{15+} and verify Ar^{16+}, Ar^{17+} measurements
- SANCO-ADAS analysis to determine diffusion(pinch) velocity(V) by matching the measure emmissivity with

$$\Gamma = -D\nabla n + nV$$

Ar Ross filters(collaboration with I. N. Bogatu(FAR-TECH))



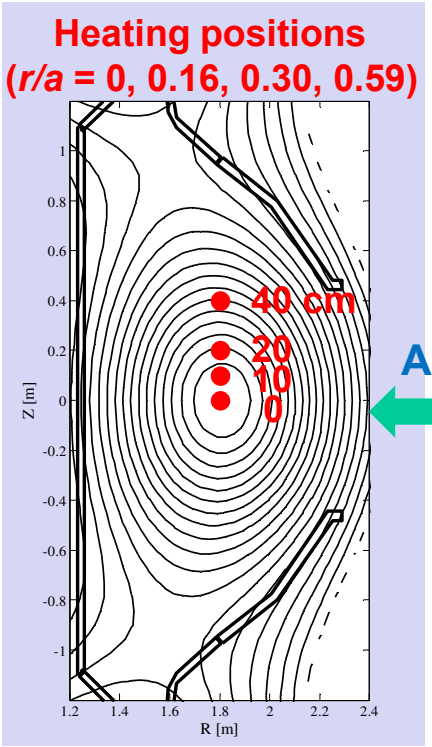
Ar^{16+}, Ar^{17+}

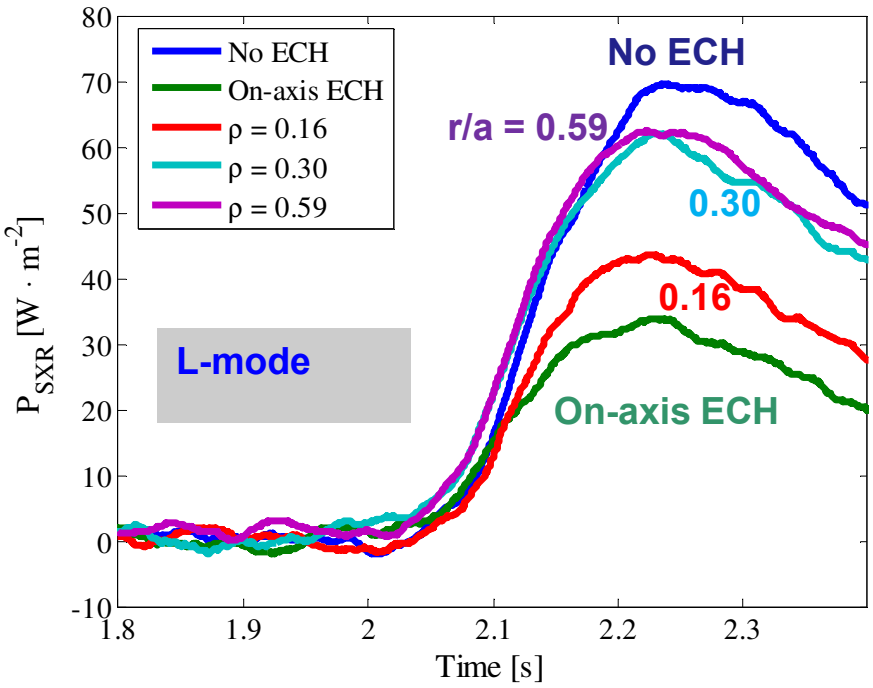
II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ 2012 campaign results

- Both SXR and VUV show a **decrease** in emission intensities of Ar^{15+} - Ar^{17+} due to ECH
  - **Less core accumulation** of Ar
- Vertical scanning at four locations
  - Most effective with on-axis ECH



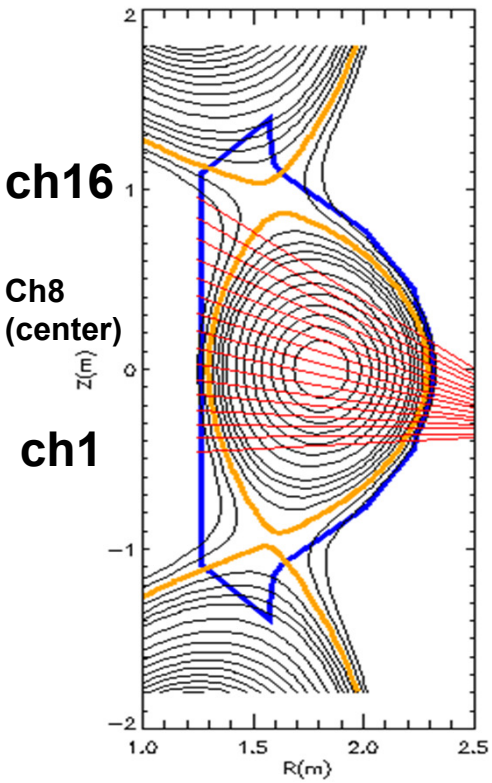


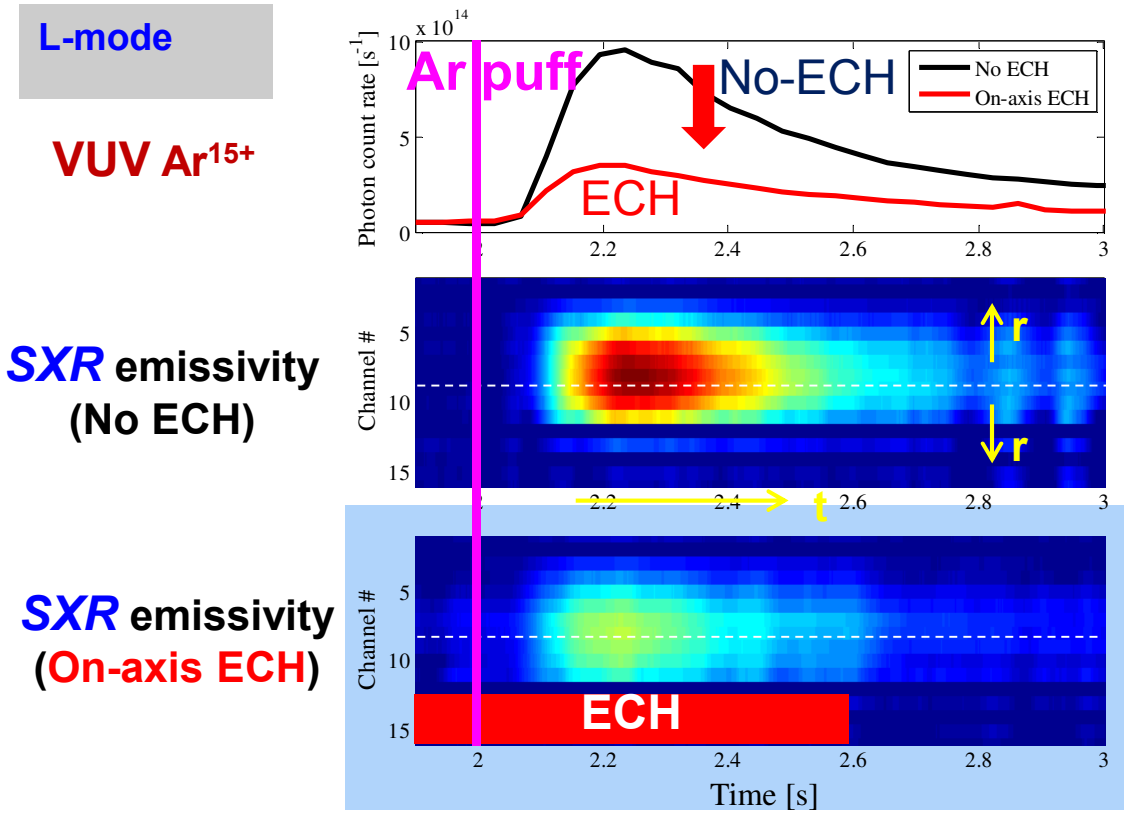
II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ 2012 campaign results

- Visualized SXR emissivity for all 16 channels
  - Most effective with on-axis ECH





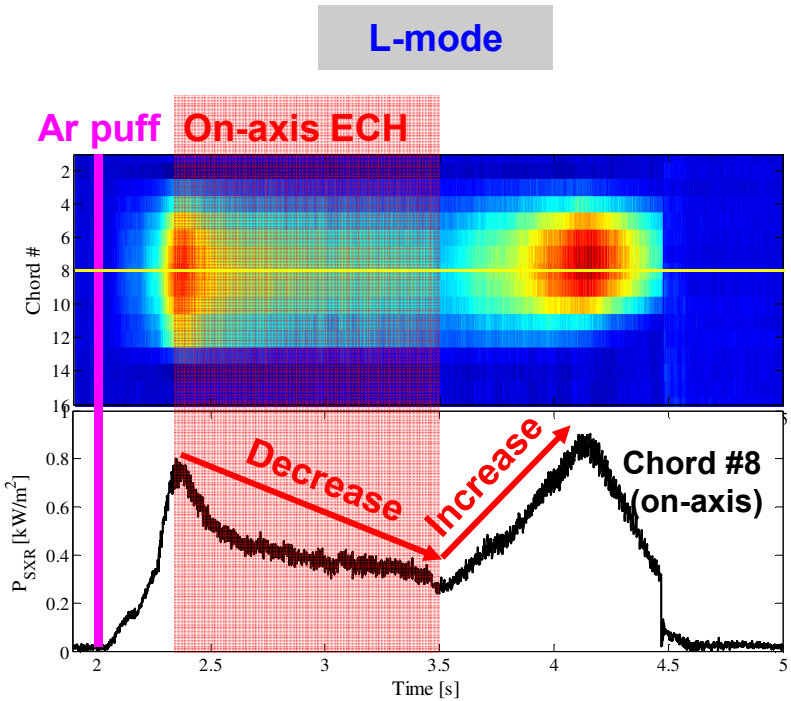
II. Recent KSTAR T&T Experiments/Analyses

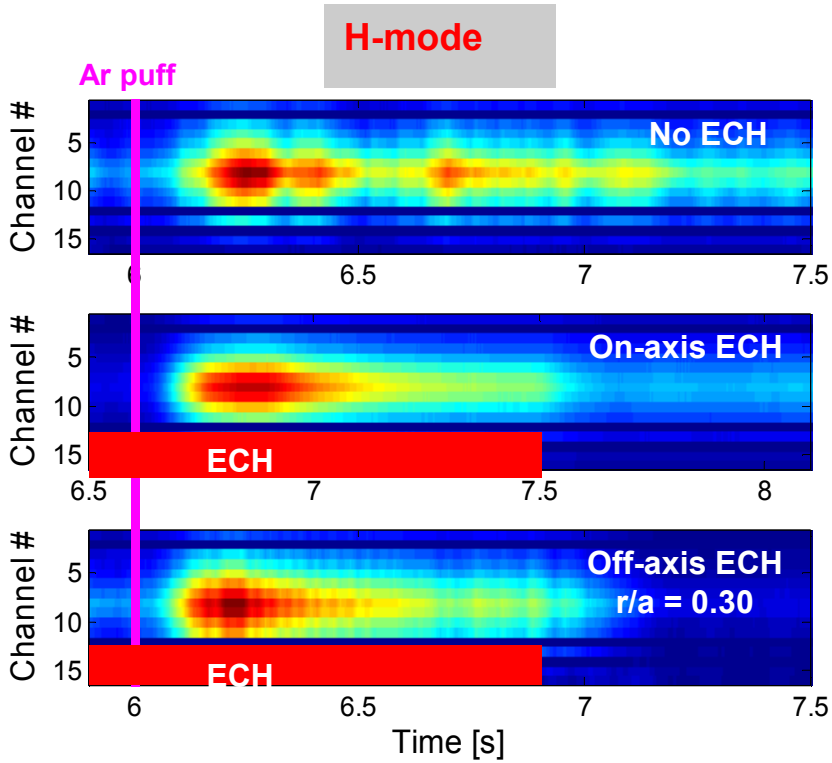
- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ 2012 campaign results

- Time evolution of emissivity
  - Both L-mode and H-mode shows reduction of Ar emissivity due to ECH

  ➔ Suggests that **local electron heating can be an effective measure of Ar transport control**





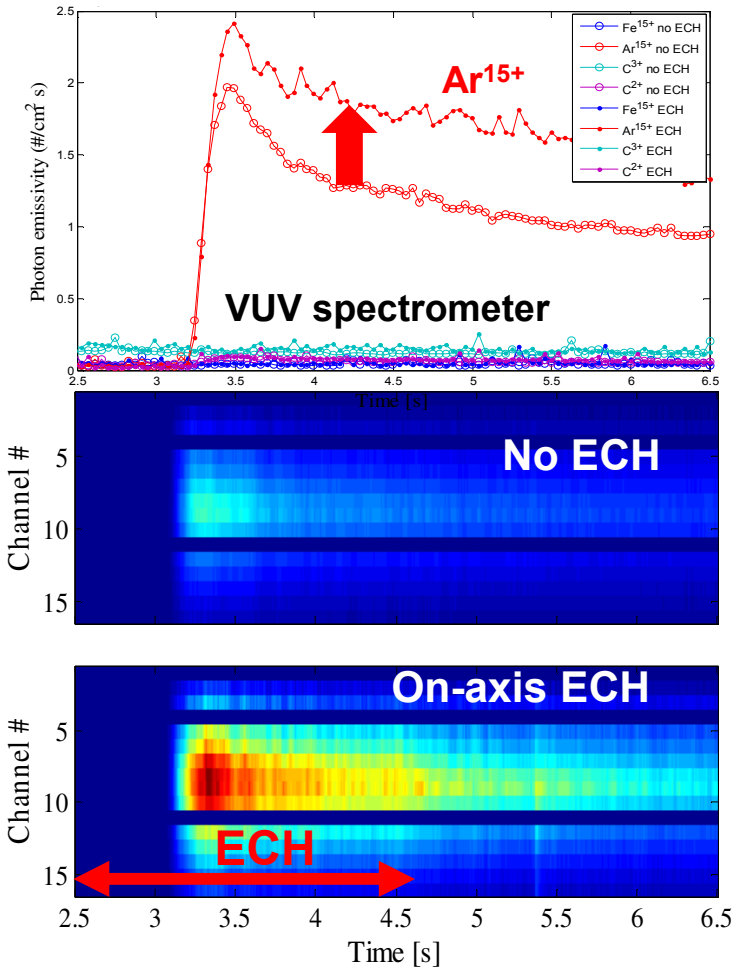
II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ **2013 campaign results**

- Using the same method, tried to reproduce the 2012 L-mode result
- But both SXR and VUV show an **increase** in emission intensities of Ar^{15+} - Ar^{17+} with ECH
  - **Opposite behavior compared to the 2012 cases**

- **How can we explain it?**



Ar Transport from Ross Filters (2013)

II. Recent KSTAR T&T Experiments/Analyses

- **On-axis ECH effects on Ar impurity transport** (S.H. Lee-KAIST)

◆ **Why different results?**

- **Transition probability(ϵ_Z)** of $Ar^{15+} \rightarrow Ar^{16+}$ and $Ar^{18+} \rightarrow Ar^{17+}$
  - a function of T_e and n_e (M. Valisa *et al* 2011 *Nucl. Fusion* 51 033002)

$$\epsilon_Z(n_e, T_e) = n_e n_Z A(n_e, T_e)$$

  - ϵ_Z is converted to P_{SXR} (not to n_Z)

    → **Core ϵ_Z decreased in 2012**

    → **Core ϵ_Z increased in 2013**

◆ **Need n_Z to explain the difference**

- n_e from Thomson(used XGC in 2012 due to lack of TS data)
- Atomic coefficient $A(n_e, T_e)$ from ADAS
  - A function of n_e and T_e
- We can actually calculate n_Z

- Accurate n_e and T_e profiles important

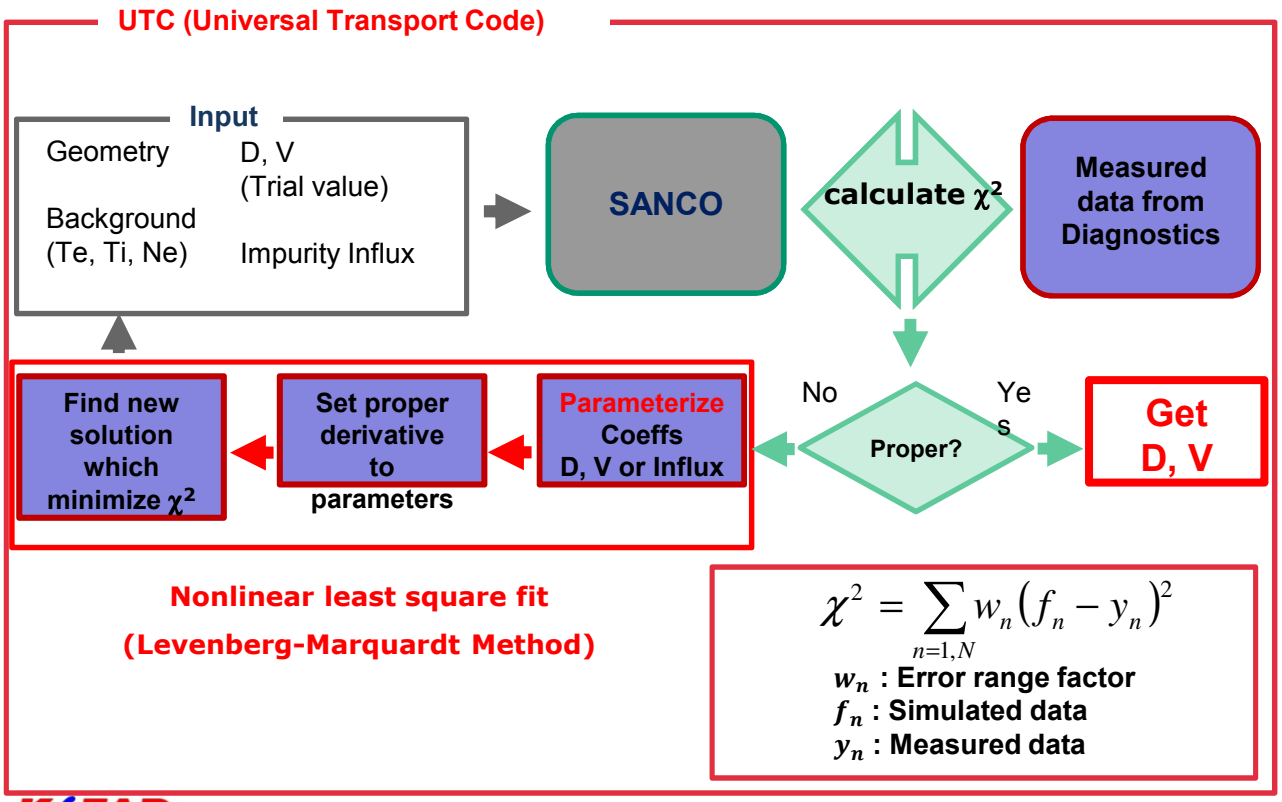
II. Recent KSTAR T&T Experiments/Analyses

• On-axis ECH effects on Ar impurity transport (S.H. Lee-KAIST)

◆ SANCO-ADAS analysis *(In collaboration with JET & U. Strathclyde)*

- With initial guesses of D, V → calculate the standard deviation $\chi^2 = \sum_{n=1}^{N} \omega_n \left(\epsilon_{Z,SANCO} - \epsilon_{Z,exp}\right)^2$ where ω_n is the error range factor
- Iterate until χ^2 is small enough

❖ ***SANCO uses EFIT equilibrium geometry while MIST assumes circular geometry***



Inputs:

(1) Radial profiles
- T_e: ECE (and XICS) (no TS data in 2012)
- n_e: XGC with interferometer(no TS data in 2012)

(2) Geometry
- EFIT magnetic equilibrium (from S. Sabbagh)

(3) Argon impurity influx($S_z(r,t)$)
- Piezo-valve flow meter signal

Fitting:

(1) Soft X-ray arrays with Ross filters
- Filters 2.8-4 keV (mainly Ar lines)
- Reconstructed radial emission profile

(2) VUV spectrometer
- Argon lines between 5-60 nm

(3) X-ray imaging crystal spectrometer
- Ar16+ w & z lines
- On-going (for tangential view)

II. Recent KSTAR T&T Experiments/Analyses

• On-axis ECH effects on Ar impurity transport (S.H. Lee-KAIST)

- Guess D and V to get $\Gamma_z(\mathrm{r},\mathrm{t})$ ➔ $$\Gamma_z(\mathrm{r},\mathrm{t}) = -D(r)\frac{\partial(n_z(r,t))}{\partial r} + V(r)n_z(r,t)$$
- Use $\Gamma_z(\mathrm{r},\mathrm{t})$ to get $n_z(r,t)$ ➔ $$\frac{\partial n_z(r,t)}{\partial t} = -\nabla\cdot\Gamma_z(r,t) + S_z(r,t)$$

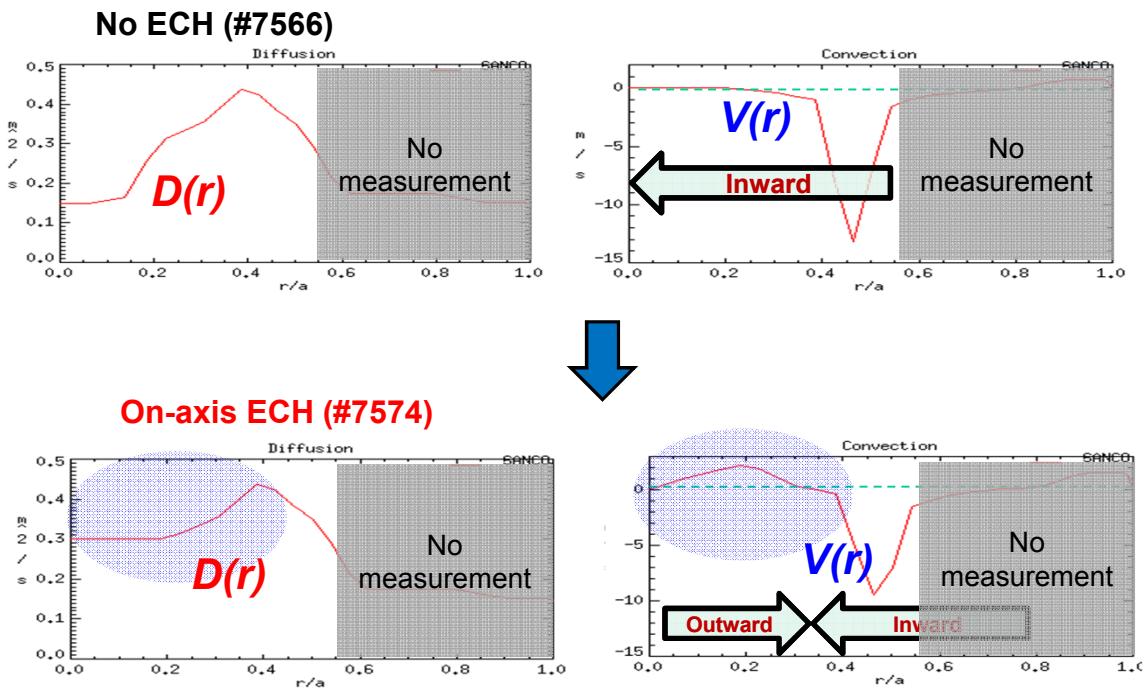
n_z: impurity ion density
Γ_z: particle flux
S_z: source and sink (ioniz & recomb)

◆ Findings

- With ECH, central diffusion and convection are increased
  - This explains 2012 results
- 2013 analysis ongoing

◆ Collaboration opportunities

- **Experiments**
  - Better/different shot design?
  - ECH/sawtooth/RMP versus Ar transport experiments in the future
- **Analysis**
  - Most tokamaks seem to use similar analysis method
  - Validation of theories to understand the mechanism: turbulent? neoclassical?



KSTAR

II. Recent KSTAR T&T Experiments/Analyses

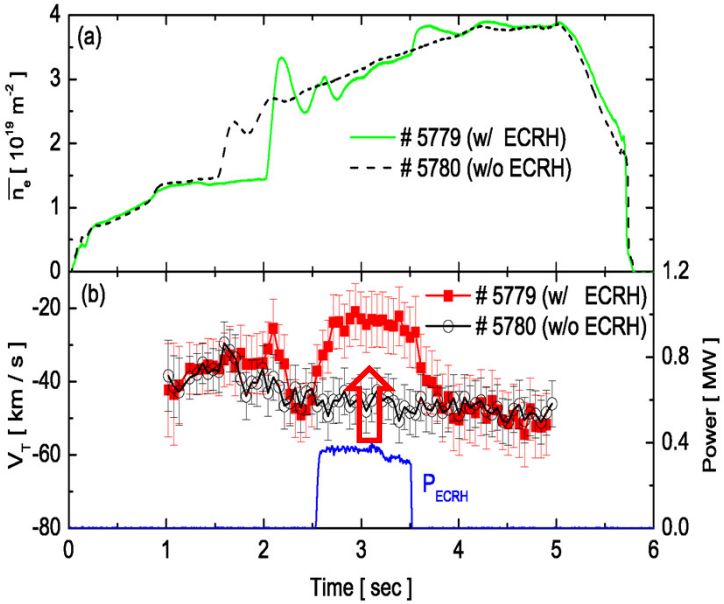
• V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma(H.H. Lee/J.C. Seol-NFRI)

◆ **Rotation damping due to on-axis ECH observed in many tokamaks**

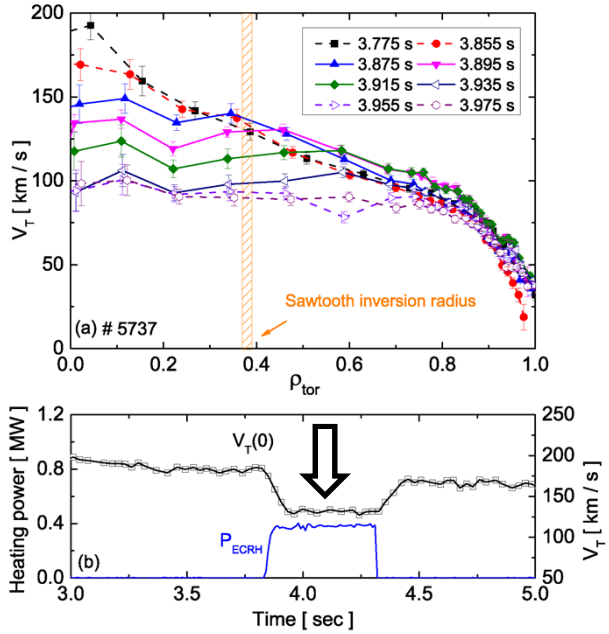
- Consistently observed in KSTAR(2011-2013)
- Important to understand the damping mechanism for ITER operation

◆ **Two track analyses on the possible cause**

1. NTV torque caused by the internal kink mode introduces rotation damping(J. Seol et al. PRL(2012)-NFRI)
2. A reversal of the turbulence-driven residual stress due to the transition between ITG and TEM(Angioni)



Ohmic plasma



H-mode plasma

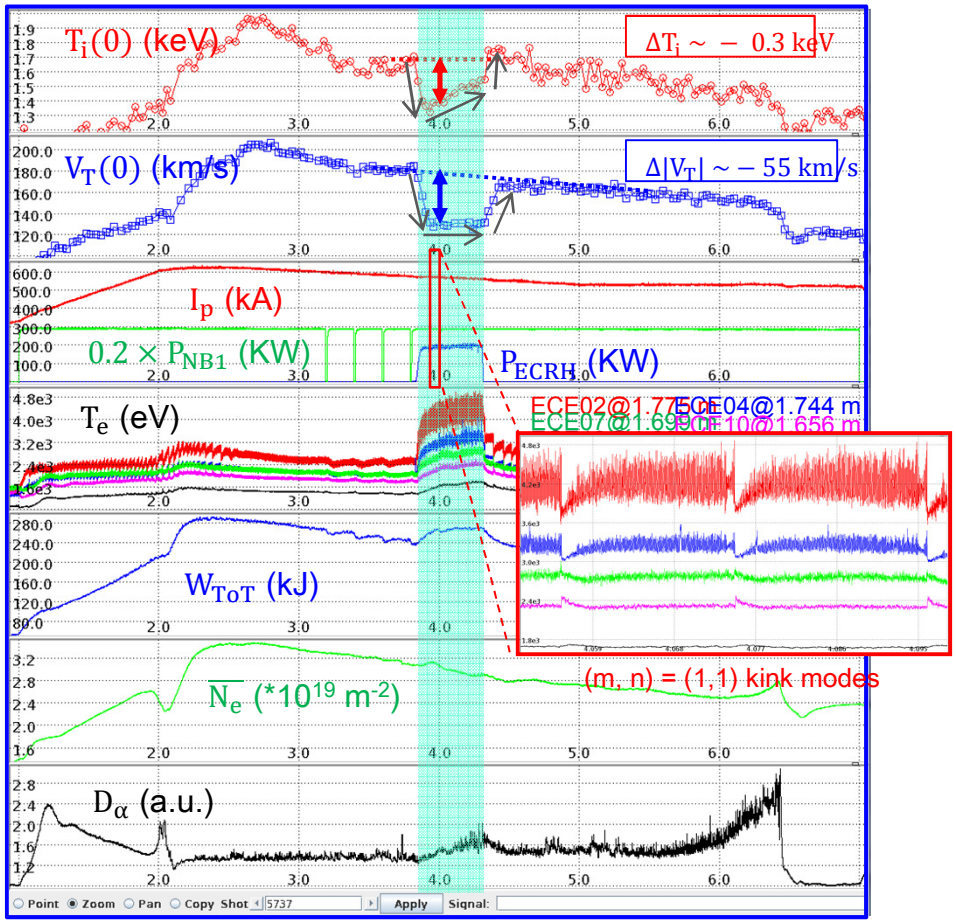
KSTAR

II. Recent KSTAR T&T Experiments/Analyses

- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(H.H. Lee/J.C. Seol-NFRI)

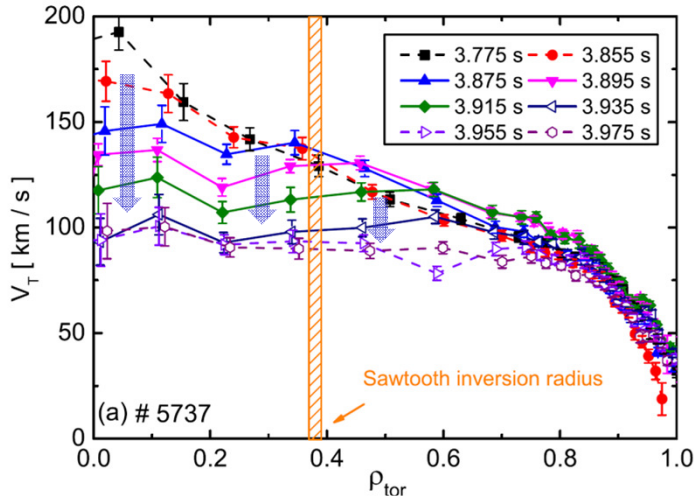
◆ ECH-induced Rotation damping in KSTAR

5737(2011) NBI H-mode with central ECRH ($R_{res} = 1.8$ m, $\phi = 10°$, $z = 0$ m)



Observations

- ✓ Both ion temperature and toroidal rotation decreases with ECH injection
- ✓ Although the ion temperature is restored, the toroidal rotation still stays reduced during ECRH is injected
- ✓ Toroidal rotation profile becomes flattened or hollowed during ECH injection
- ✓ Sawtooth inversion indicates existence of q=1 surface
- ✓ For range q<1, ECH induces (m, n)=(1, 1) kink modes(high frequency fluctuations between the sawtooth
- ✓ Momentum diffusion seem to propagate its effect into q>1 region



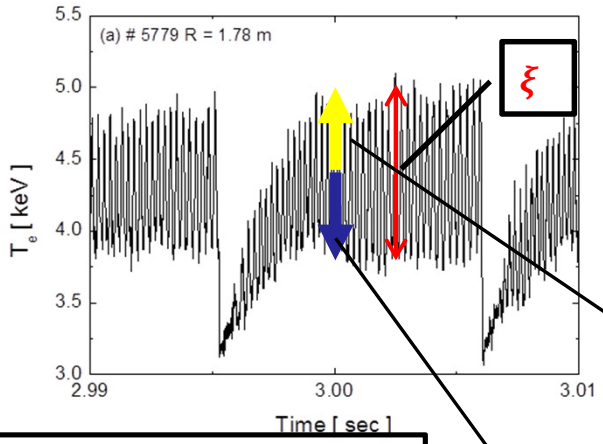
II. Recent KSTAR T&T Experiments/Analyses

- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(H.H. Lee/J.C. Seol-NFRI)

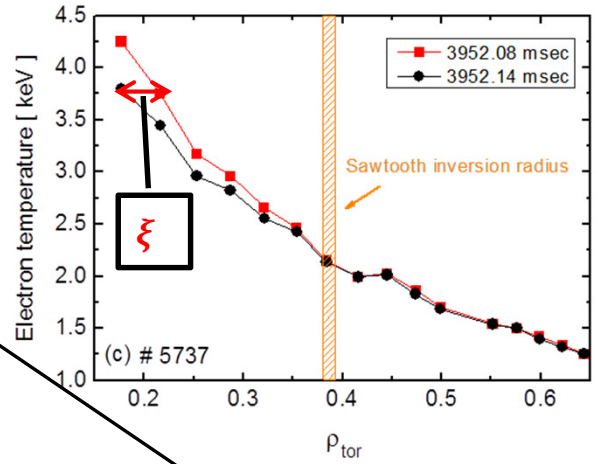
◆ Identification of the internal kink modes during on-axis ECRH injection

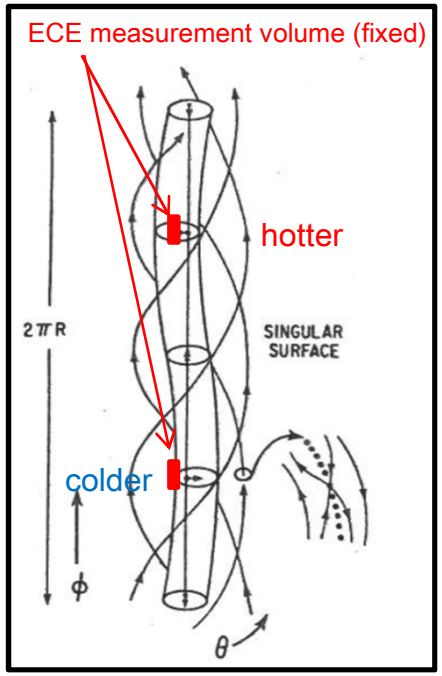
- Identified by radial displacement picked up by ECE
- Visual verification with ECEI

Time trace of T_e measured by ECE



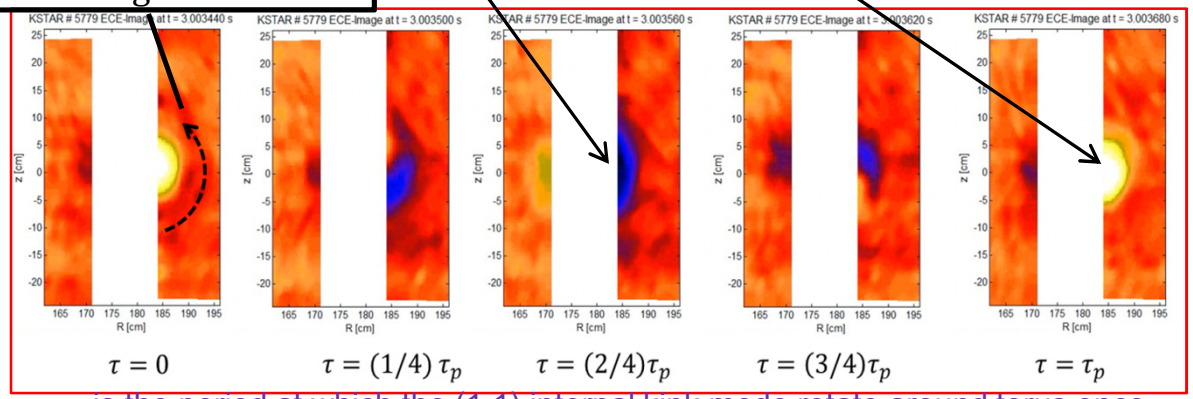
Radial profile of T_e measured by ECE





Helical motion picked up as rotating structure

2D image by ECEI



τ_p is the period at which the (1,1) internal kink mode rotate around torus once

II. Recent KSTAR T&T Experiments/Analyses

- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(H.H. Lee/J.C. Seol-NFRI)

1. V_Φ damping analysis with NTV theory (J. Seol, S. G. Lee *et al.* PRL (2012))

- Central(on-axis) ECH -> internal kink modes inside the q=1 surface
  - generally accompanies sawtooth oscillation since q decreases below 1 in the core region with the appearance of m=1, n=1 mode ➔ indicates existence of q=1 surface
- drives magnetic field perturbation inside q=1 surface(sawtooth inversion radius) $\frac{\delta B}{B} \sim O(1e-3)$
- causes toroidal axisymmetry breaking
- enhances **NTV torque**
  - Calculated to be comparable to NBI torque
- damps V_Φ (counter to V_Φ)

❖ **This analysis published in PRL(2012) / a talk presented at ITPA conference 2013**

◆ **NTV torque density in $1/\nu$ and ν regimes can be evaluated by**

$$T_{1/\nu} \sim -6.1 N_i M_i v_{ti}^2 \frac{\epsilon^{3/2}}{\nu_i} n^2 \left(\frac{A_n^2 + B_n^2}{B_0^2}\right) \times \left\{V^\zeta - q(V^\theta + 2.367 \frac{1}{erB_0}\frac{\partial T_i}{\partial r}\right\}$$

$$T_{\sqrt{\nu}} \sim -0.09 N_i M_i v_{ti}^2 \sqrt{\epsilon}\sqrt{\nu_E}\{\ln(8/\sqrt{\nu_{Ei}})\} n^2 \left(\frac{A_n^2 + B_n^2}{B_0^2}\right) \times \left\{V^\zeta - q(V^\theta + 0.356 \frac{1}{erB_0}\frac{\partial T_i}{\partial r}\right\} / q\omega_{Ei}$$

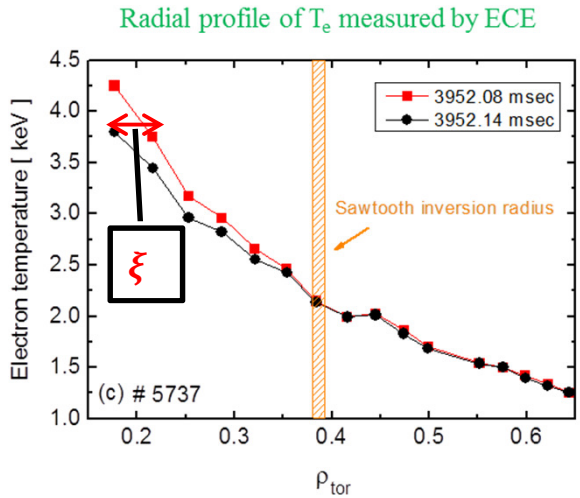
II. Recent KSTAR T&T Experiments/Analyses

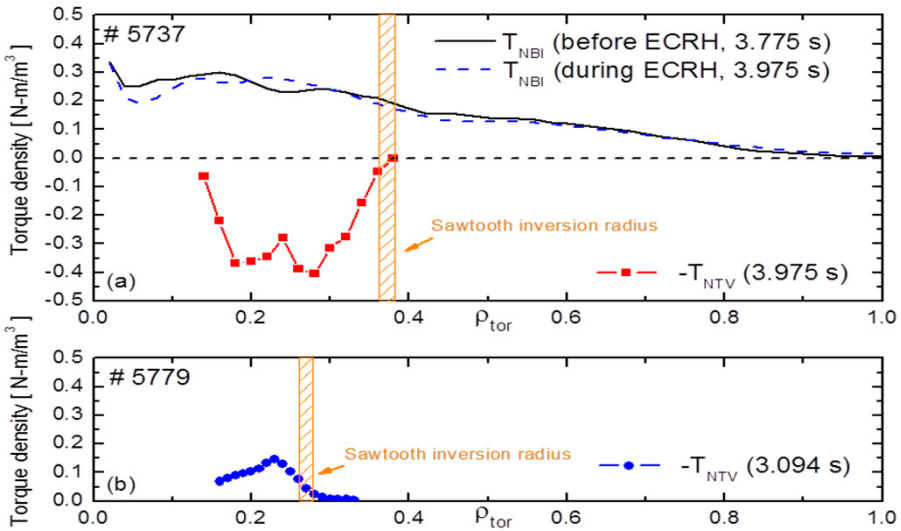
• V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma(H.H. Lee/J.C. Seol-NFRI)

◆ Calculation of magnetic perturbation

$$\frac{\delta B}{B} = \frac{(A_1^2 + B_1^2)^{1/2}}{B_0} \sim \left(\frac{\xi}{2}\right)\left(\frac{1}{B_0}\frac{\partial B}{\partial r}\right)$$

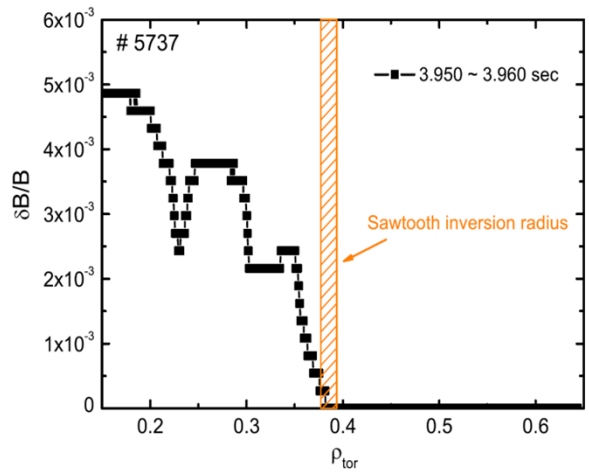
- **Displacement (ξ)** can be found from T_e profiles
- NTV torque density calculated to be comparable to NBI torque
- NTV torque always damps the rotation(regardless of I_p direction)





H-mode

Ohmic



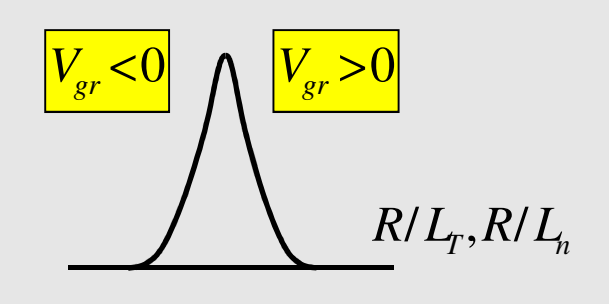
II. Recent KSTAR T&T Experiments/Analyses

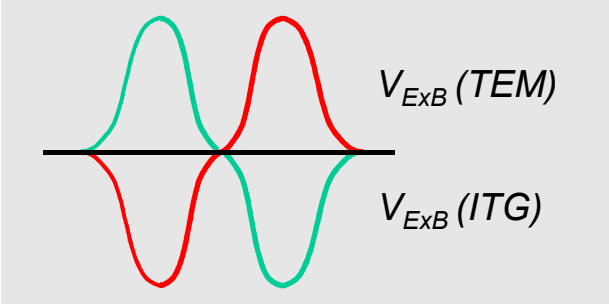
- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(Y.J. Shi-WCI)

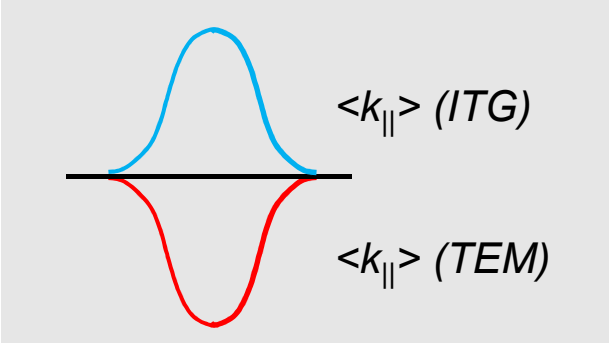
2. V_Φ damping analysis with ITG ➔ TEM transition

- Radially inward/outward propagation of fluctuation energy
- opposite Reynolds stress
- opposite Zonal flow profile
- opposite $k_{||}$ - symmetry breaking
- opposite residual stress

$$\Pi_{r\|}^{W} = \sum_k \left[-\tau_{c,k} k_{\|} V_{gr}^2 \frac{\partial}{\partial r}\langle N_k \rangle + \tau_{c,k} V_{gr} k_\theta k_{\|} \langle V_E \rangle' \frac{\partial}{\partial k_r}\langle N_k \rangle \right]$$







◆ **Analysis** (YJ Shi-WCI)

- Not match with experiment very well
- Further investigation in the future with fluctuation diagnostics such as BES are essential to assess this mechanism(Li_BES installed in 2013)

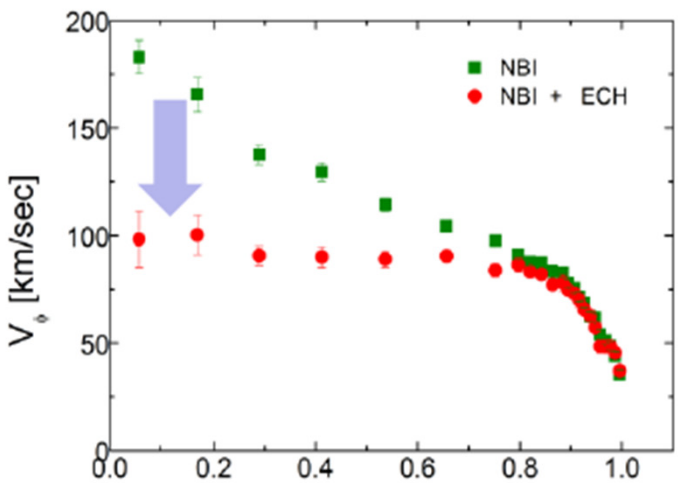
◆ **Collaboration opportunities**

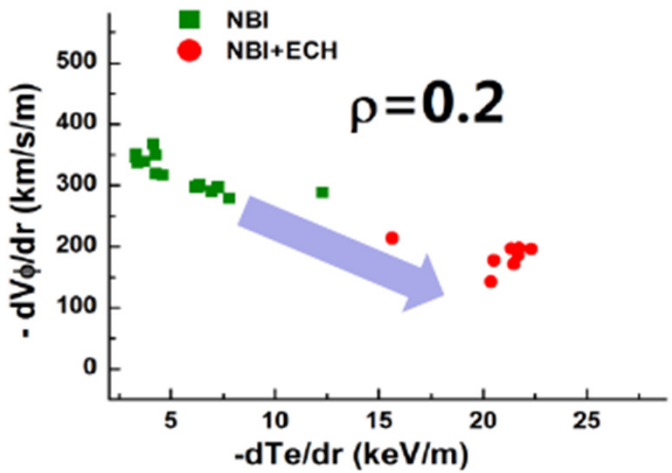
- **Experiments**
  - Overall, well established experimental data
- **Analysis**
  - Any other theories to explain?
  - Apply NTV theory explanation to your experiments?

KSTAR

II. Recent KSTAR T&T Experiments/Analyses

- **V_Φ damping by on-axis ECH in ohmic/NBI-heated plasma**(Y.J. Shi-WCI)





On-axis ECH (400kW) to co-NBI plasmas

- Counter-current torque in core: $-\Delta V_\phi/V_\phi \sim 30\%$
- Strong correlation: $-\Delta(\nabla V_\phi) \sim +\Delta(\nabla T_e)$

Core intrinsic torque reversal upon ITG→TEM by T_e steepening

- Linear gyrokinetic analysis: ITG→TEM occurs for ρ=0.2 ~0.5 depending on density profile ➔ density profile is important!
- Momentum and particle transport are strongly coupled
- More data analysis (density and fluctuation) ongoing

- Toroidal rotation profile is flattened by (core decrease, edge not change) by ECH with pivot point $\rho \sim 0.7$
- Macro-scaling: linear relation $-\Delta V_\phi \sim \Delta T_e$ akin Rice scaling
- Local-scaling : $-\Delta(\nabla V_\phi) \sim \Delta(\nabla T_e)$ → ∇V_ϕ flattening tracks ∇T_e steepening

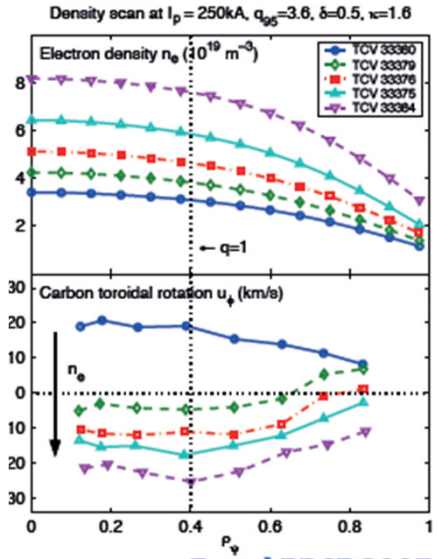
KSTAR

II. Recent KSTAR T&T Experiments/Analyses

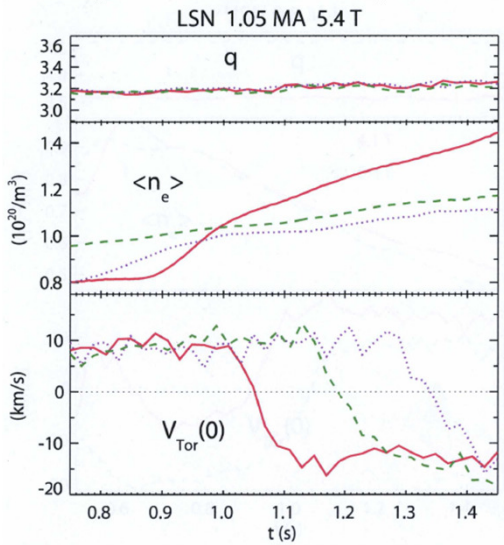
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ **Intrinsic rotation is an ITER-relevant issue**
- NBI alone not enough in ITER
- Need strong intrinsic rotation in ITER

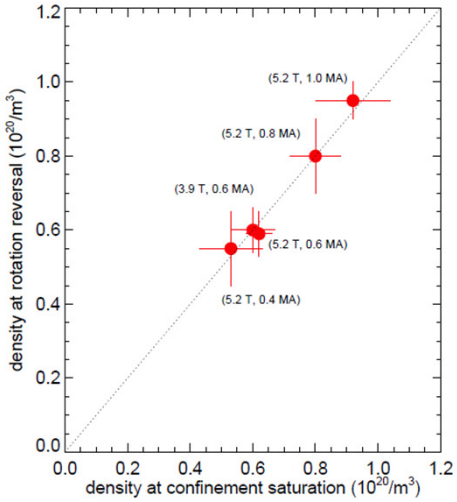
◆ **Intrinsic rotation experiments in:**
- **Core rotation reversal**
  - Density dependency: **TCV** [Duval PPCF 2007]
  - LOC-SOC transition with density dependency
    - **C-Mode** [Rice PoP 2011]/**AUG** [Angioni PRL 2011]
  - Different analyses ongoing
    - Collisionality[Rice PoP 2012]?
    - Residual stress widely used for analysis
- **Edge intrinsic rotation**



Duval PPCF 2007



Rotation reversal at <n_e>~1.1 in Alcator C-Mod



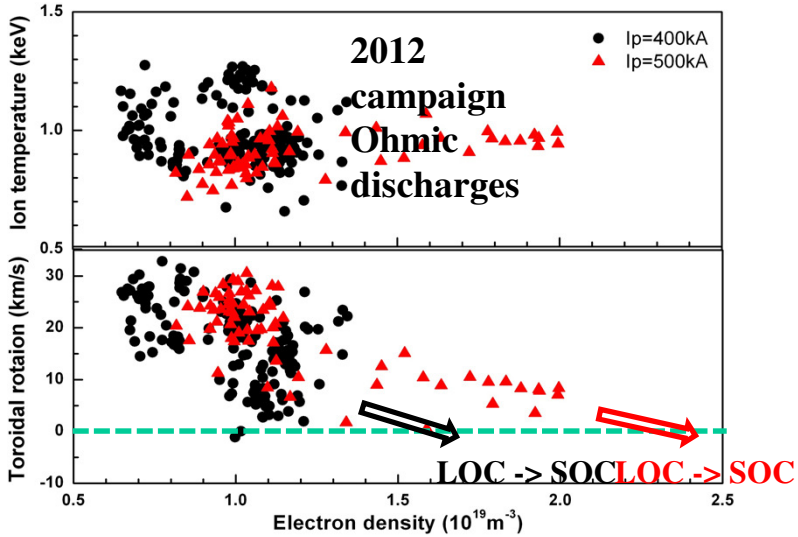
J. E. Rice *et al*, Nucl. Fusion **51** (2011)

II. Recent KSTAR T&T Experiments/Analyses

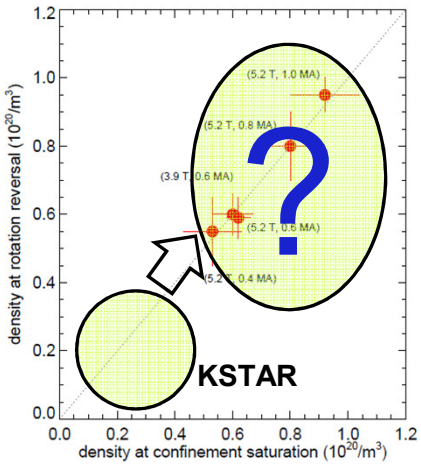
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

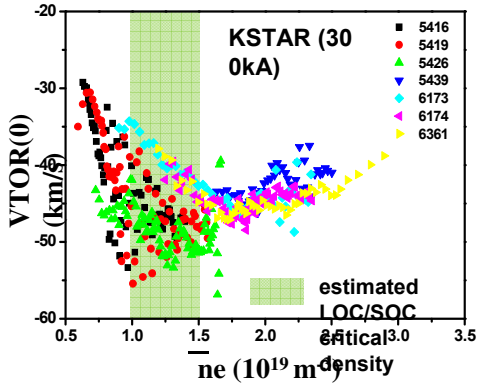
◆ **Core rotation reversal experiments in KSTAR**

- **Experiments**
  - based on both Ip and n_e scanning
  - ➢ **2011-2012 campaigns**
    - Tried to verify n_e dependency
    - LOC → SOC transition occurred(300-500kA) but no reversal observed
      - Doesn't match with Rice 2011
  - ➢ **2013 campaign**
    - Tried at higher density but failed to reach higher densities
    - Stayed in LOC region(500 kA) but some reversal-like behaviors observed
  - Not corresponding with Rice 2011
- **Analysis**
  - Use KSTAR/AUG data to analyze rotation reversal
  - Mostly analyzed by residual stress (TEM → ITG transition model) (since Rice 2011)



S.G. Lee(2012 experiments)





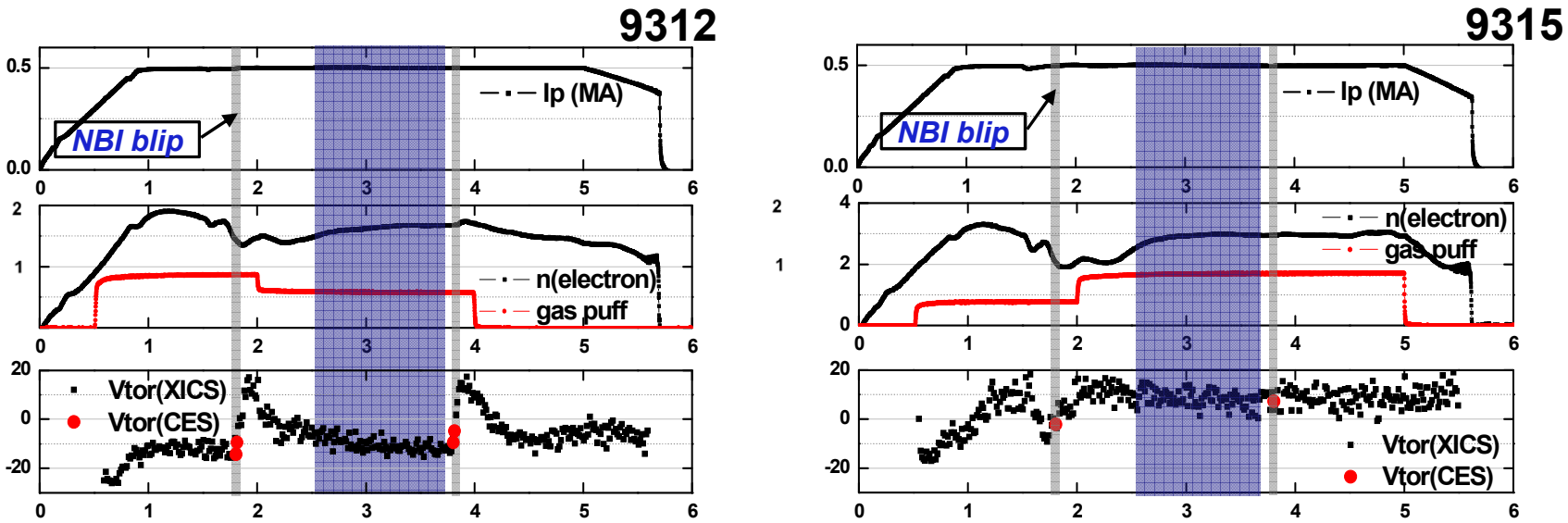
KSTAR analysis show no reversal at LOC → SOC

II. Recent KSTAR T&T Experiments/Analyses

- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ 2013 experiments

- NBI blips used for the calibration of XICS using CES measurements
  - NBI blip times - 20ms for #9312/10ms for #9315 (CES resolution 10ms)
- Reversal-like behaviors in three shots
  - Comparison of two shots seems to suggest the rotation reversal at ne~1.5 [10^{19} #/m^3]
  - ❖ **No MHD except sawtooth (other MHD free)** → no influence of NBI blip(used short blip time)
  - ❖ **Relatively steady condition & similar condition in the analysis region(purple area)**

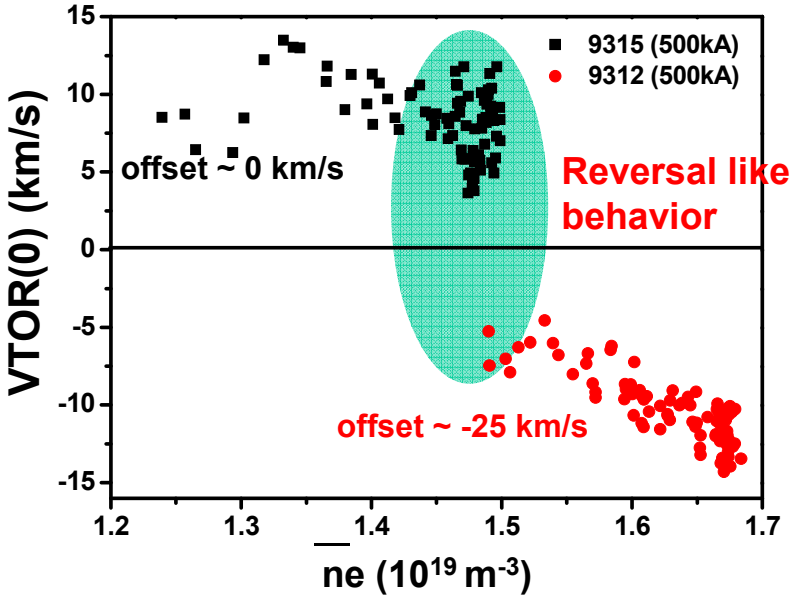


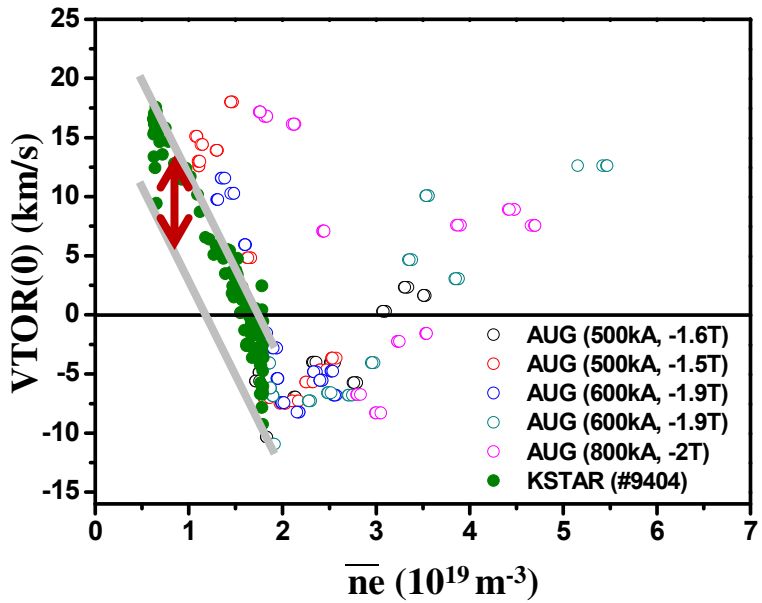
II. Recent KSTAR T&T Experiments/Analyses

- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ **2013 experiment analysis**

- Rotation reversal-like behavior at ne~1.5 [10^{19} #/m^3]
- #9404 did not have NBI blips for $\mathbf{V_\Phi}$ measurement
  - But similar to #9312 and #9315
  - Thus, trust region of $\mathbf{V_\Phi}$ suggests another reversal-like behavior at similar density



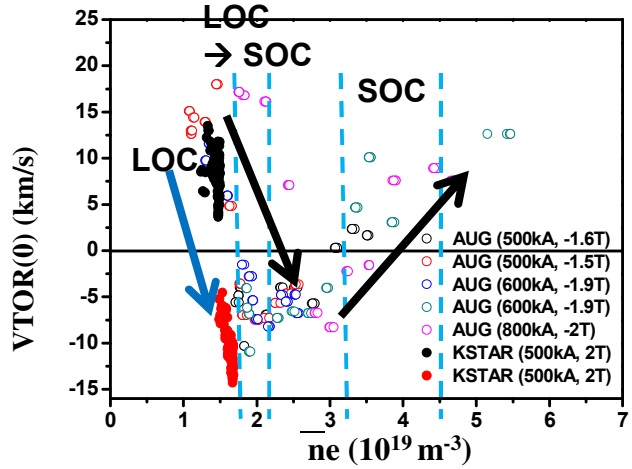


II. Recent KSTAR T&T Experiments/Analyses

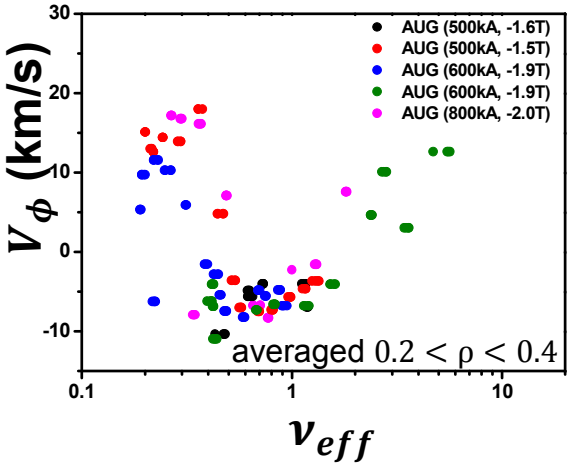
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

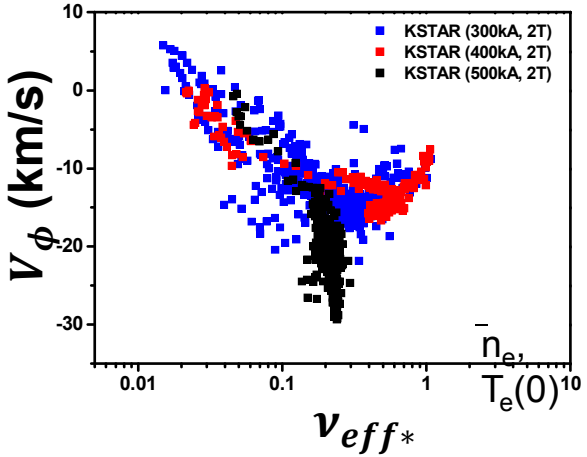
◆ **Analyses by SNU**

- **Recheck density dependency**(2011-2013)
  - **Density dependency → Collisionality**
    - reversal-like behaviors in LOC region(2013)
    - 2013 studies from KSTAR/AUG data show another reversal in SOC regions
    - Also mentioned earlier by TCV team
    - Rice 2011 suggests collisionality dependency
- **Check collisiionality dependency**(2013)
  - Studies verifies better correlation
  - Will continue investigating it with more data



Investigation of rotation reversal vs. density in LOC/SOC regions (2013 data)



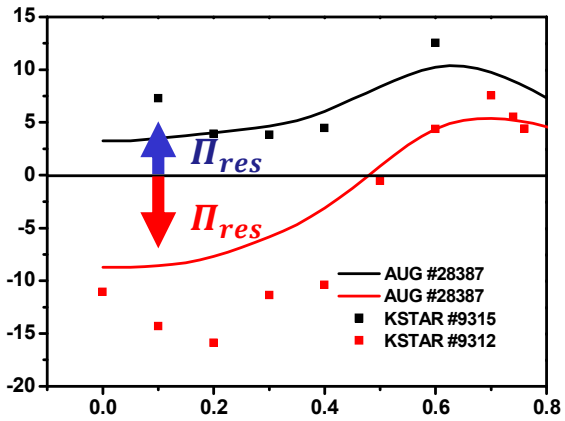


II. Recent KSTAR T&T Experiments/Analyses

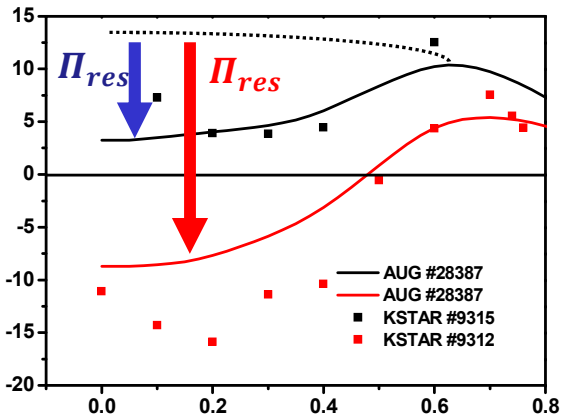
- **Rotation reversal in ohmic plasmas** (D.H. Na-SNU/S.G. Lee-NFRI)

◆ Analyses by SNU

- **Π_{res} due to TEM(LOC) → ITG(SOC) used widely**
  1. Continue to investigate with this view to explain rotation reversals
     - Π_{res} rotates the plasma in certain directions
  2. A paradigm shift in the application of the Π_{res} model
     - Π_{res} lowers the rotation profiles with different magnitudes along the profile
     - Under certain conditions (i.e., LOC and SOC)



VS.



◆ Collaboration opportunities

- **Experiments**
  - Need for better density control for more data collection
- **Analysis**
  - Investigate collisionallity dependency with more KSTAR/AUG data
  - Investigate the paradigm shift of residual stress or another novel approach

II. Recent KSTAR T&T Experiments/Analyses

• Core intrinsic rotation study in KSTAR (SG Lee-NFRI)

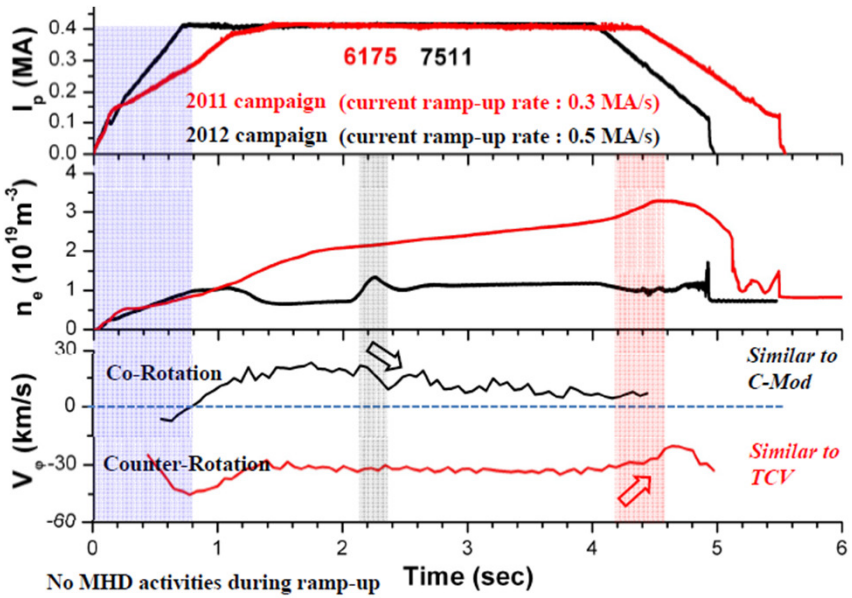
- **Core intrinsic rotation study in ohmic plasmas**
  - **Motivation**
    - Core rotation direction may be determined based on certain parameters/conditions
      - Diverse core rotation directions reported during ohmic discharges
    - Understanding on the dominant factor to determine the initial rotation directions
  - **Investigation on rotation direction vs. current ramp-up rate in KSTAR**
    - Two campaigns show two different directions from 2011 and 2012
    - Current ramp-up rate believed to the only noticeable difference
      - No MHD activities during ramp-up
    - Is the ramp-up rate a factor to determine the initial rotation direction?
      - More experiments to verify

Table I. Central Toroidal Rotation during Ohmic Discharges

Device	V_{Tor} (cm/s)	Ref.
LT-3	$+5 \times 10^5$	[1]
PLT	-1.5×10^6	[2]
JFT-2	-1.3×10^6	[3]
Torus II	$+1.6 \times 10^6$	[5]
PDX	$\leq 3 \times 10^5$	[6]
TM-4	-7×10^5	[7]
ISX	~ 0	[10]
DIII-D	-2.5×10^6	[14]
TCA	$\pm 4 \times 10^6$	[18]

(+) : co-rotation
(-) : counter-rotation

J. Rice *et al.*



II. Recent KSTAR T&T Experiments/Analyses

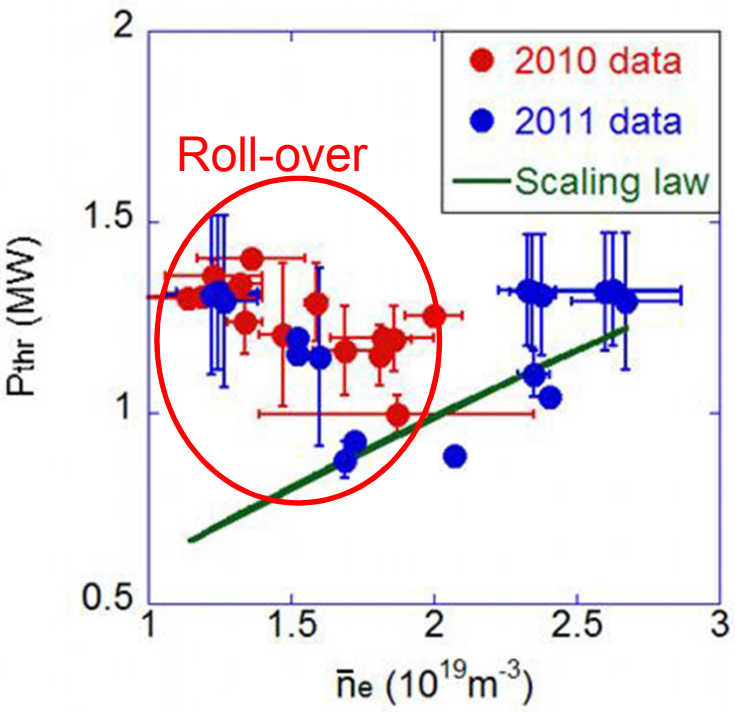
- **Core intrinsic rotation study in KSTAR** (SG Lee-NFRI)

- **2013 campaign**
  - Tried to change the ramp-up rate with other parameters fixed
    - All dedicated shots failed
    - Difficult with density control may remain
  - Searching for other successful shots ongoing

- **Collaboration opportunities**
  - **Experiments**
    - Key is to control ramp-up rate only with no change to other parameters
  - **Analyses**
    - Simulation of core rotation direction vs. ramp-up rates may help understand the physics in advance

II. Recent KSTAR T&T Experiments/Analyses

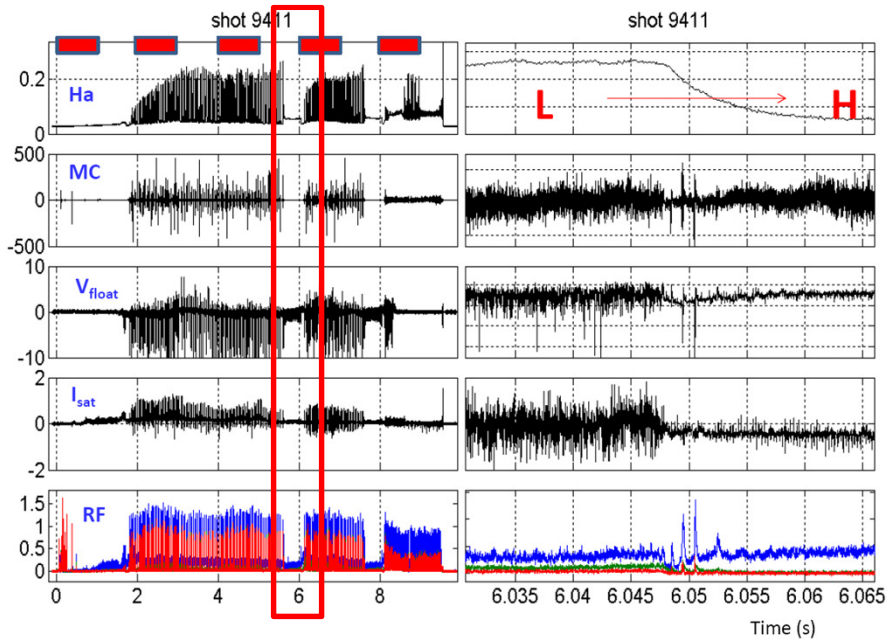
- **L-H transition characteristics in KSTAR** (H.S Kim-SNU)



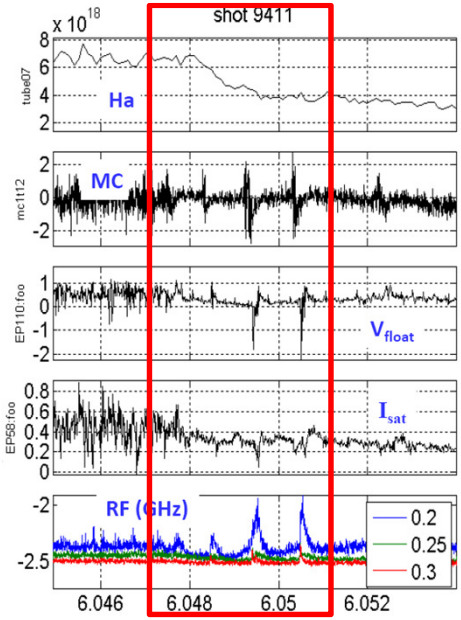
- L-H transition obtained with 0.8-3.0 MW NBI power in both single- and double-null configuration
- P_{thr} defined as "minimum loss power during L-H transition
- Evaluated P_{thr} agrees with the multi-machine scaling laws above ~$2x10^{19}m^{-3}$
- Roll-over of minimum P_{thres} at n_e ~$2x10^{19}m^{-3}$
- Similar as other tokamaks
- Transition occurred after diverting(???)
- In 2012 campaign, due to excessive H content, P_{thr} increased significantly
  - **H/D ratio(2011) : ~20 %**
  - **H/D ratio(2012) : ~40 % (less than 10% variation in H_{89-p})**

Quasi-periodic transport studies during L-H transition(GS Yun-Postech)

- The basic idea is to trigger L-H transition using ECH at the marginal constant NBI power
- Quasi-periodic transport behavior in Mirnov Coil(MC) signal, immediately followed by the same behavior in RF signal



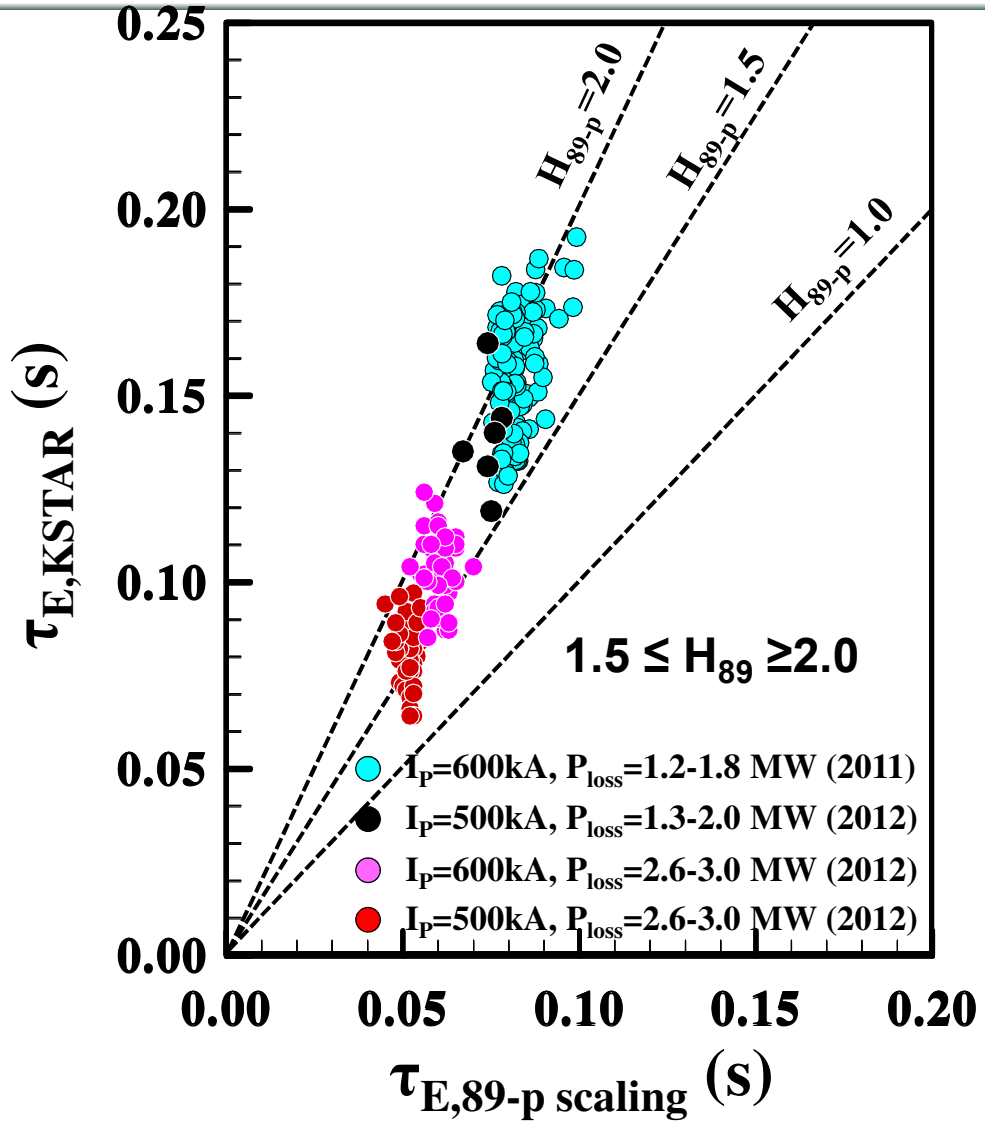
Second transition at t=6.048 s

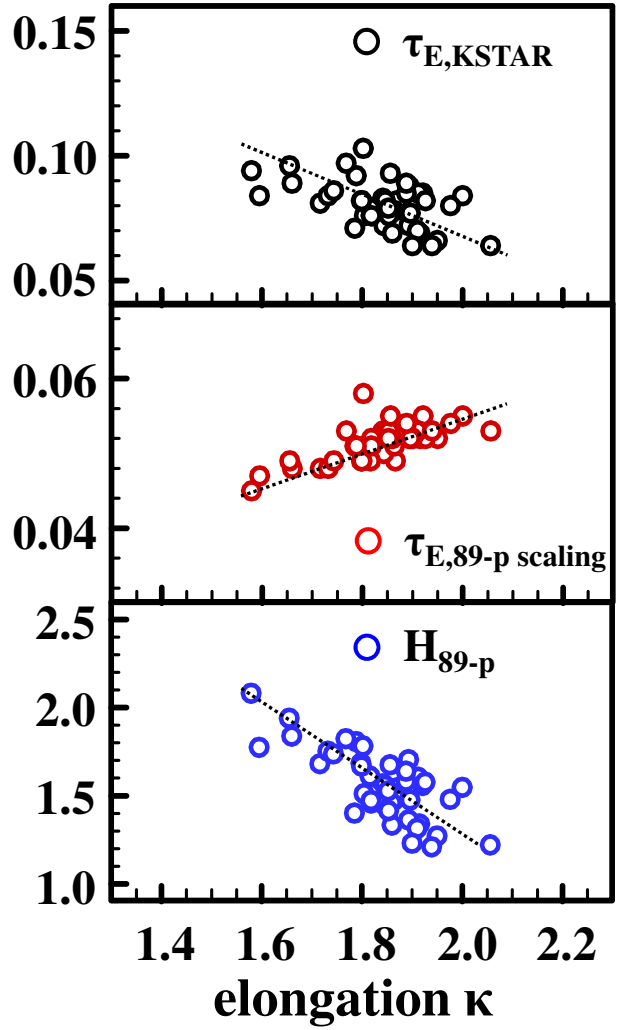


- Burst in RF and MC → a fast electromagnetic event
- Very little change in H_alpha → negligible ion transport?
- Large V_{float} spike → transport dominated by fast electrons?

These may indicate a missing piece in the PPM:
Turbulence → Flow shear and ∇p → **MHD instabilities (ballooning) and crash (prompt loss of fast electrons and current)** → Replenishment of particles from inside → Repeat

H-mode Confinement is in accordance with ITER89 scaling (except for negative trend with elongation)



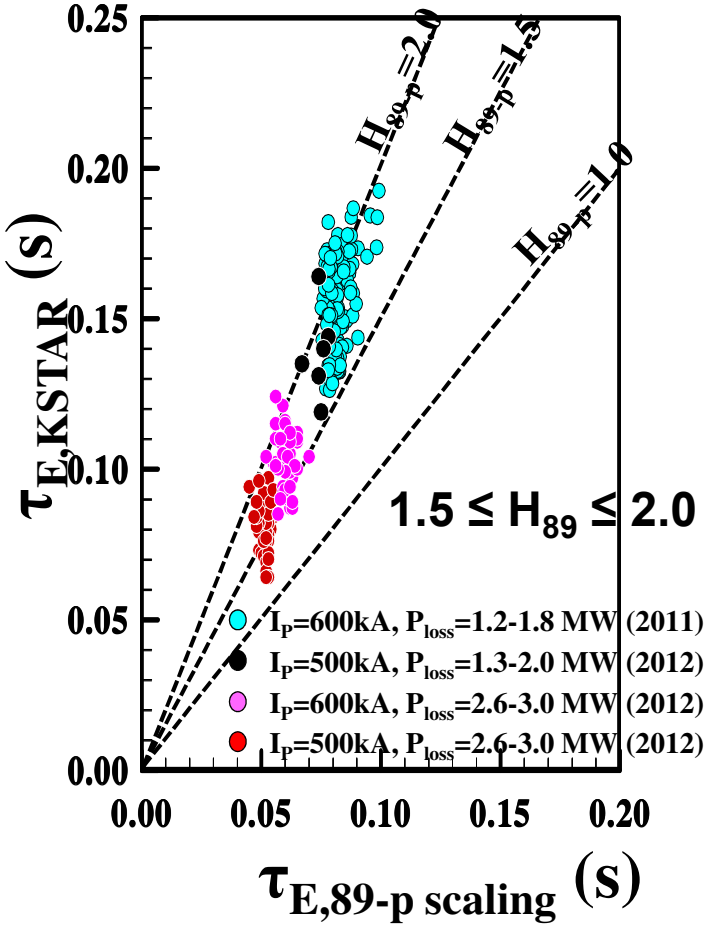


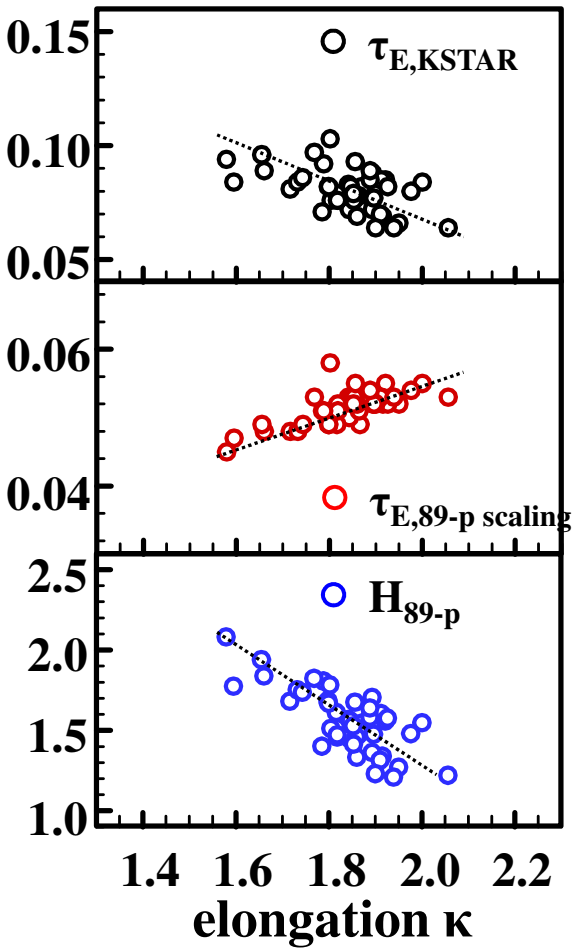
Larger impurity build-up at high κ

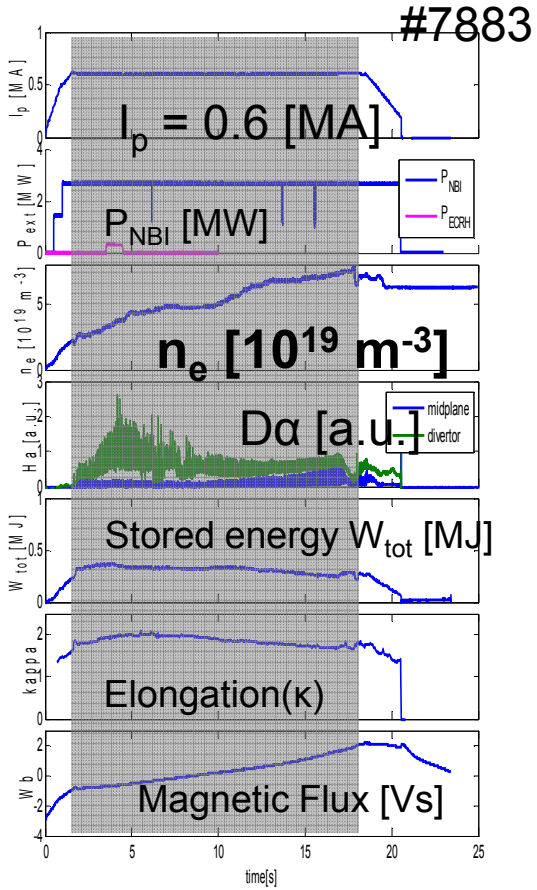
H/D ratio 2011 : ~20 % vs 2012 : ~40 % (less than 10% variation in $H_{89\text{-}p}$)

KSTAR

-mode confinement is in accordance with ITER89 scaling except for negative trend with elongation)







Larger impurity build-up at high κ in 2012

H/D ratio at 2011 : ~20 % vs ~40 % at 2012 (less than 10% variation in H_{89-p})

KSTAR

I. KSTAR T&T WG

Where we belong?

KSTAR T&T WG mainly addresses issues related to Transport and Confinement

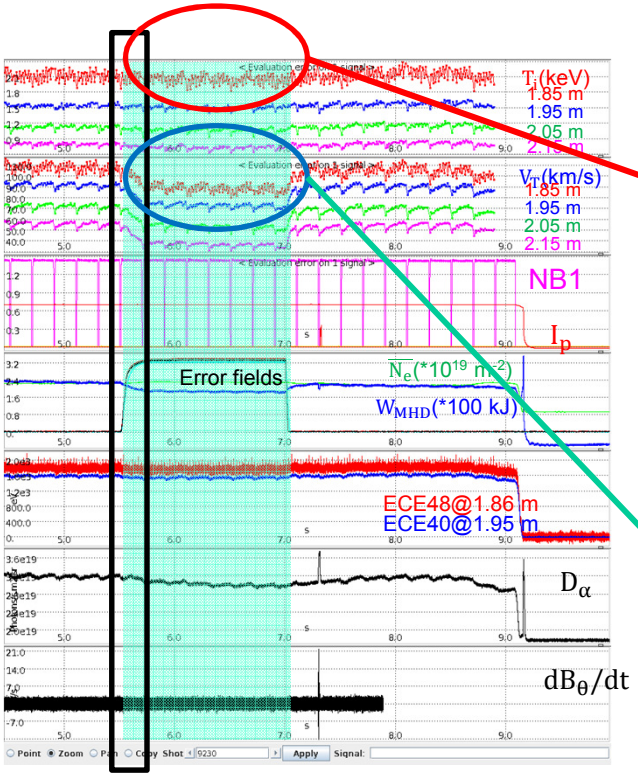
- Diagnostics
- Pedestal & Edge Physics
- Energetic Particle Physics
- MHD, Disruptions & Control
- Integrated Operation Senarios
- Scrape-Off-Layer & Divertor
- **Transport & Confinement**

Who are participating?

- **Mainly from NFRI(Plasma Transport Division)**
  - Approx. 20?? Researchers
- **World Class Institute** (lead by Prof. Diamond)
  - Approx. 20?? Researchers
  - Mostly theoretical and simulation studies
    - assist theoretical analyses of experiments
- **Domestic participants**
  - KAIST/SNU/Postech/UST/
- **International Participants**
  - PPPL/GA/FAR-TECH/NIFS/Univ. of Strathclyde, Glasgow/ENEA/Columbia Univ./ANU/

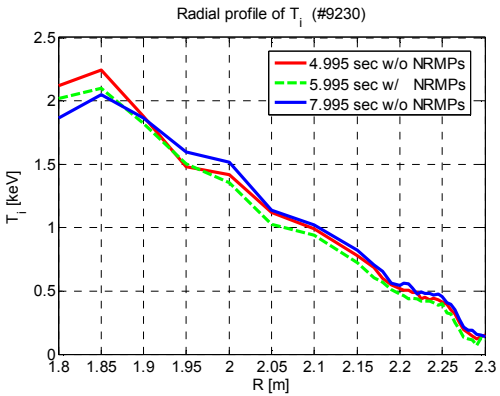
• Non-axisymmetric RMP(n=2) effect on rotation (HH Lee)

- KSTAR capable of applying NRMP at $\delta B/B \sim 10^{-4}$
  - Intrinsic $\delta B/B$ in KSTAR $\sim 10^{-5}$
  - Gives KSTAR unique opportunity to study NRMP effect
- Results(2013)
  - Vt damping in the entire profile while Ti shows practically no change
  - May mean "a significant increase in momentum" but "not much heat transport"(??)
  - X_i may differ from X_Φ (???)
- 원래 Vt drop이 많은 상태에서 Ti drop을 관찰하여 shear에 의한 효과를 볼려고 한것인데(???) 계획대로 실험결과가 안 나와서 발표하기 추천 안함(이형호 박사님)

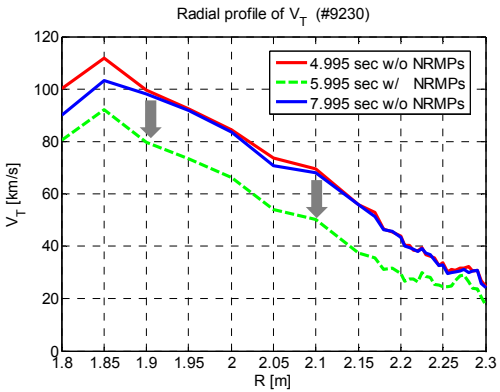


NRMP applied at 5.5s

No clear change in T_i during NRMPs



V_t decreases during NRMPs



Steven Sabbagh 연구내용