Acceleration of ion rotation during the internal reconnection event in Versatile Experiment Spherical Torus

ID: EX/P7-7

Seongcheol Kim[1], J. Y. Jang[1], Y. S. Kim[1], and Y. S. Hwang[1]*
[1]Department of Energy System Engineering, Seoul National University
*yhwang@snu.ac.kr

0. ABSTRACT

Acceleration of impurity ion rotation is observed during the internal reconnection event (IRE) in Versatile Experiment Spherical Torus. By utilizing Ion Doppler Spectroscopy (IDS) with high temporal resolution ~0.2 ms acceleration of impurity ion toroidal rotation in the opposite direction of the plasma current as well as ion heating are observed during the IREs. We also find that increase time of the two phenomena are a litter different. The results suggest that different mechanism act on the ion during the IRE. It is though that ions are accelerated due to a neoclassical viscous torque based on several reasons rather than other mechanisms such as reconnection out flow and toroidal electric field. We compare the experimental results to 0D simple torque balance model with NTV torque and the model results are well agreement with the experimental results.

1. INTRODUCTION

Internal Reconnection Event

- A relaxation phenomena which occurs frequently in spherical torus
- Mechanism research [1-3], Change of various plasma parameters [1-8]
- **Lack of studies about relationship between the plasma rotation and IRE**

Interaction between MHD instabilities and plasma rotation

- Enhancement of MHD stability with plasma rotation and its shear [9-13]
- MHD instabilities effect on plasma rotation [14-16]

Research objectives

- **First observation of ion acceleration phenomena using ion Doppler spectroscopy during the IRE in spherical torus**

→ Investigation of detail spatio-temporal behavior of ion properties during the IRE

→ Discussion of the physical mechanism to account for the experimental observations

2. EXPERIMENTAL SET UP

Ion Doppler Spectroscopy

Parameters	Values
Wavelength coverage (nm)	460-474 (Fixed)
Linear dispersion (nm/pixel)	0.014
f-number	f/2.8
Spatial coverage (m)	~ 0.39-0.71
Spatial resolution (mm)	~ 20
Temporal resolution (ms)	1 (for 10ch) 0.2 (for 1ch)

Specification of IDS system in VEST

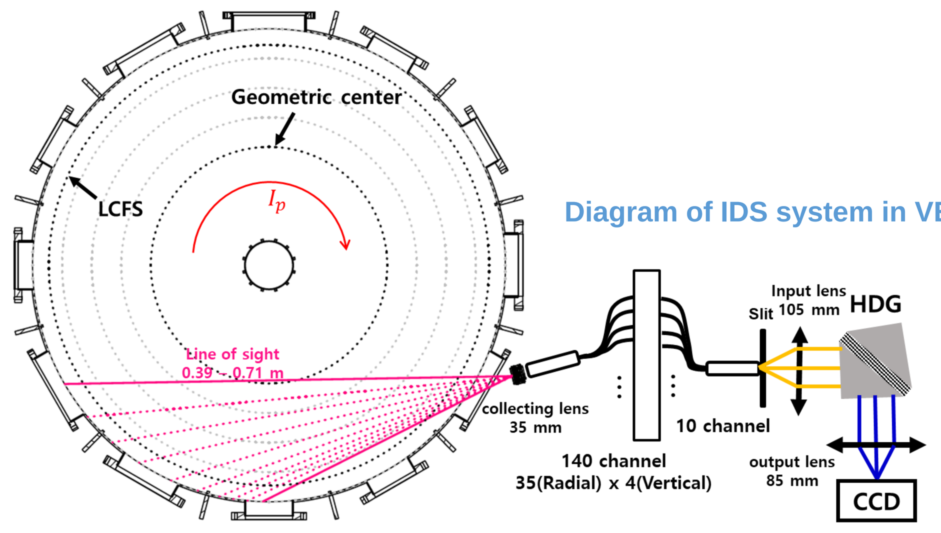
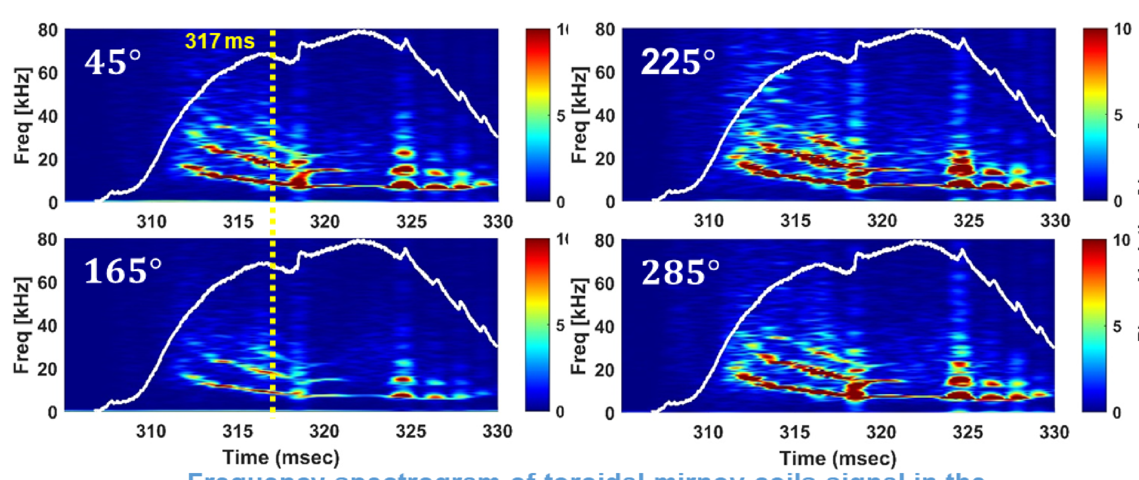


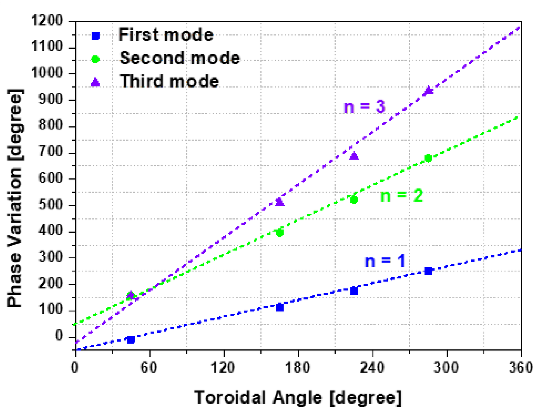
Diagram of IDS system in VEST

Mode analysis

- Identification of (*m*,*n*) by relative phase information in mirnov coils
- Toroidal mode number, n~ 1-3 / Poloidal mode number, m~3-6 in this shot

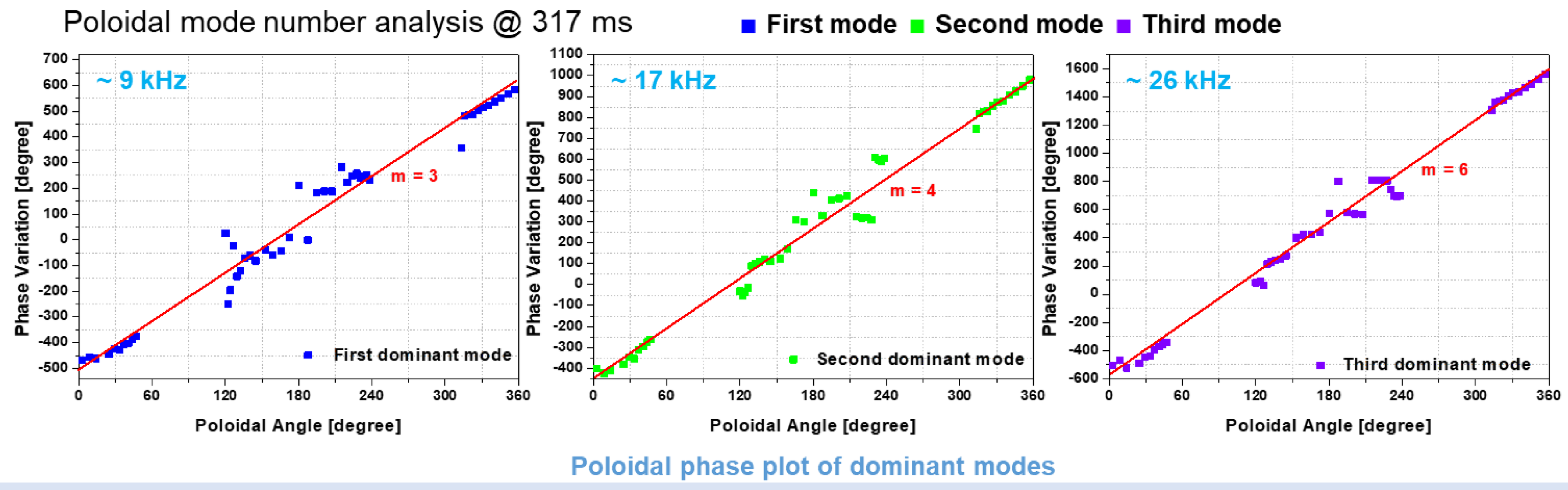


Frequency spectrogram of toroidal mirnov coils signal in the Shot#31355



Toroidal phase plot of dominant modes

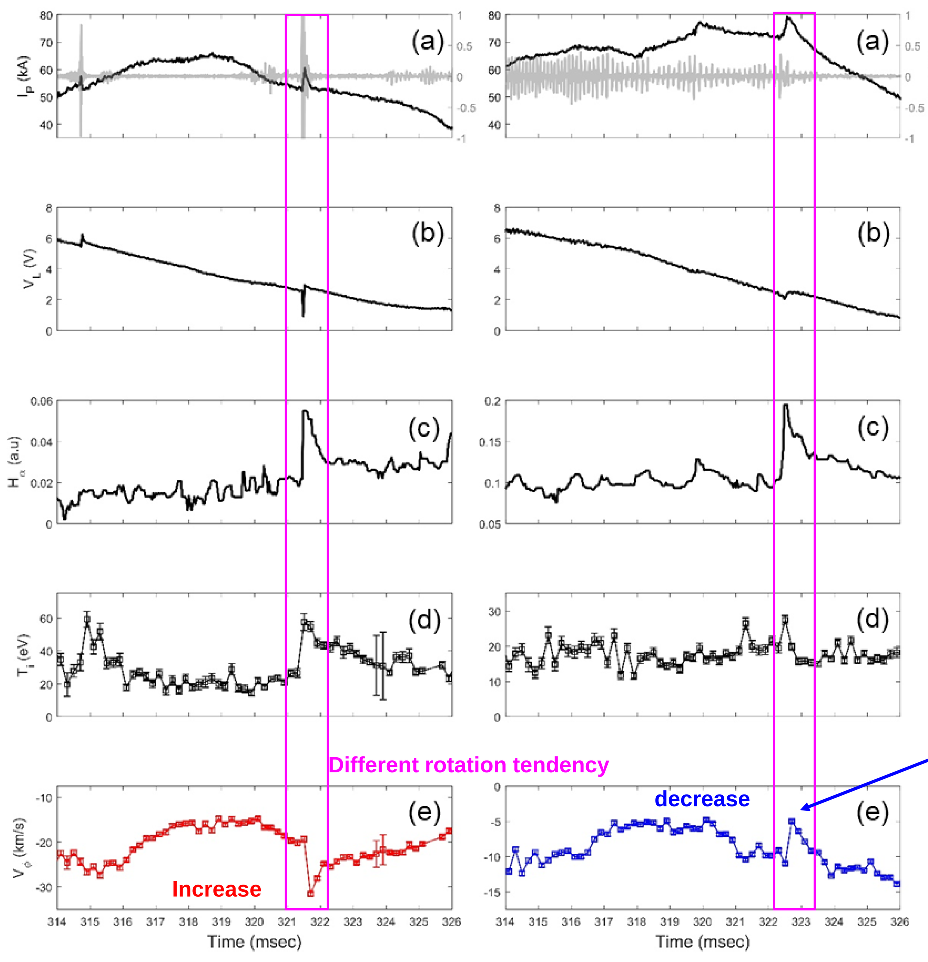
Poloidal mode number analysis @ 317 ms ■ First mode ■ Second mode ■ Third mode



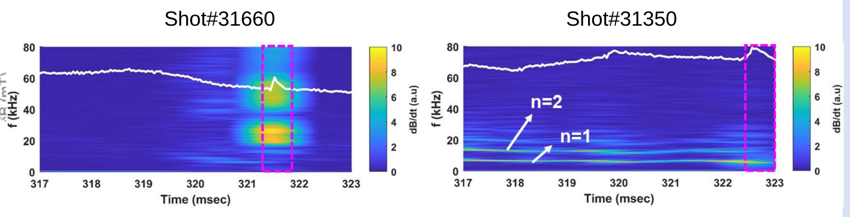
Poloidal phase plot of dominant modes

3. EXPERIMENTAL RESULTS AND DISCUSSION

Comparison of two IRE discharges with different rotation tendency



IRE discharges with two different rotation tendency: (Left) Shot#31660, (Right): Shot#31350 [a-e]



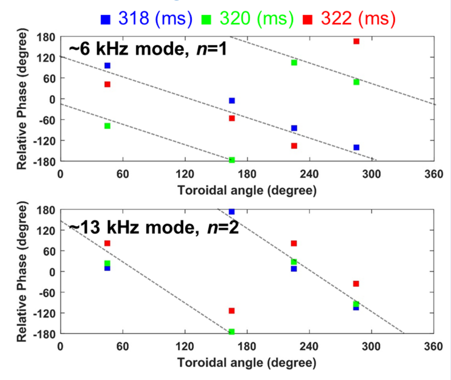
Frequency spectrogram of mirnov coils signal in the Shot#31660

Frequency spectrogram of mirnov coils signal in the Shot#31350

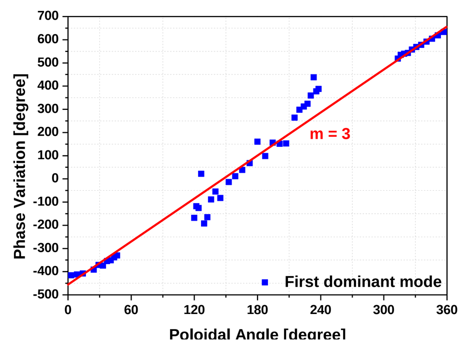
No indication of MHD modes before the IRE

Low-n Multiple tearing instabilities (m~3-4)

Lockig features?



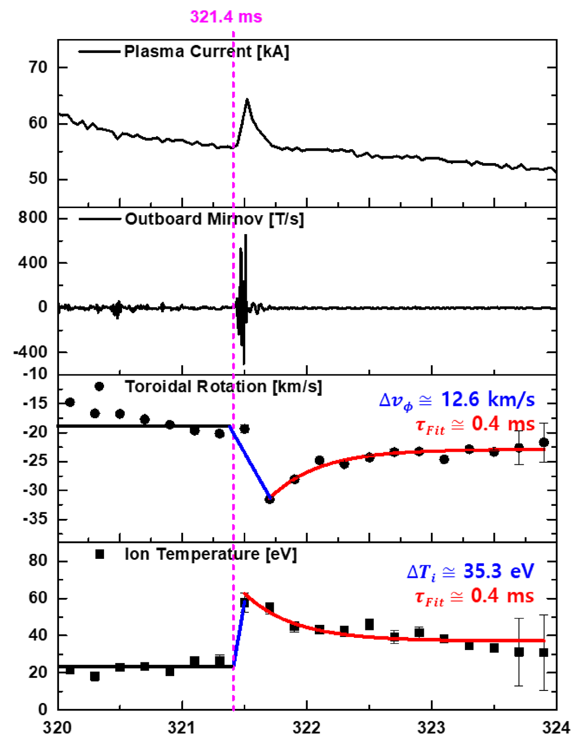
Phase plot for toroidal mode number



Phase plot for poloidal mode number

Possible candidate mechanisms for rotation acceleration

- Reconnection outflows



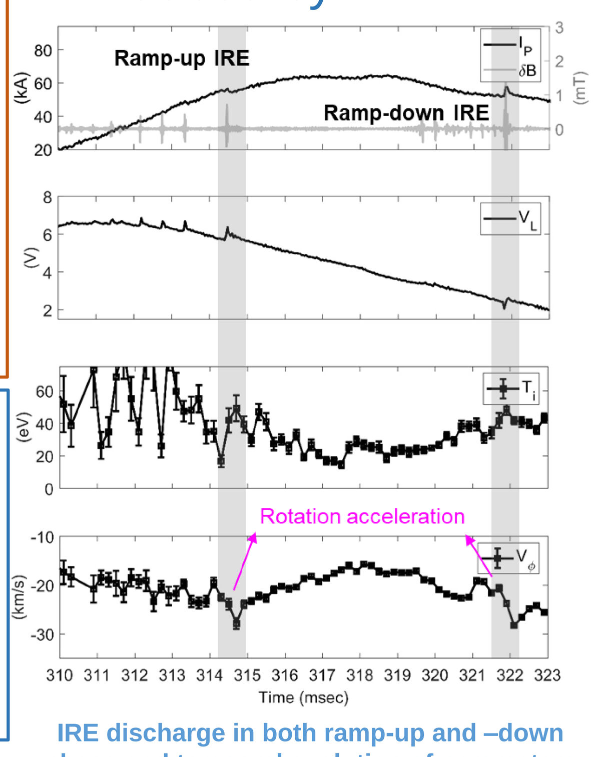
Temporal behavior of T_i and v_ϕ in the Shot#31660

✓ Ion acceleration come before the ion heating
✓ Bidirectional flow → Total momentum~0

❖ Observation in VEST
- **Fast temporal measurements show that ion heating precede rotation acceleration**
- Sequence discrepancy
  → Inconsistent with reconnection outflow mechanism

→ **Different drive mechanism?**

- Toroidal electric field induced by IRE



IRE discharge in both ramp-up and –down phase and temporal evolution of parameters

✓ Significant toroidal E-field due to the current profile redistribution during IRE
✓ Generation of energetic particles

❖ Observation in VEST
- **Current redistribution occurs in the different way at ramp-up & down phase but same rotation accelerations**

→ **Different drive mechanism?**

- Neoclassical toroidal viscosity (NTV) torque from the fluctuating magnetic field
  - In presence of **non-axisymmetric magnetic perturbations**, neoclassical transport theory predict the NTV torque [10]
  - This NTV torque damps toroidal rotation throughout **the plasma towards an 'offset' toroidal plasma rotation velocity, which is in the counter-I_p direction**
  - Collisionality regime in VEST: $\omega_{ti}\sqrt{\varepsilon}=\frac{v_{ti}}{qR}\sqrt{\varepsilon}\sim 6.4\times10^4\ s^{-1}$, $\frac{\nu_i}{\varepsilon}\sim1.3\times10^4\ s^{-1}$, $\omega_E\sim7\times10^3\ s^{-1}$

→ NTV torque in 1/ν regime , $S_{NTV}\approx -n_i m_i \mu_\parallel \left(\frac{\delta B}{B}\right)^2 (v_\phi - v_{\phi,NTV})$ $\quad \omega_E < \frac{\nu_i}{\varepsilon} < \omega_{ti}\sqrt{\varepsilon}$ [1/ν regime]

→ NTV offset velocity, $v_{\phi,NTV}\approx \frac{k_c}{Z_i e B_\theta}\frac{dT_i}{dr} < 0$, $k_c\sim3.5$ in 1/ν regime

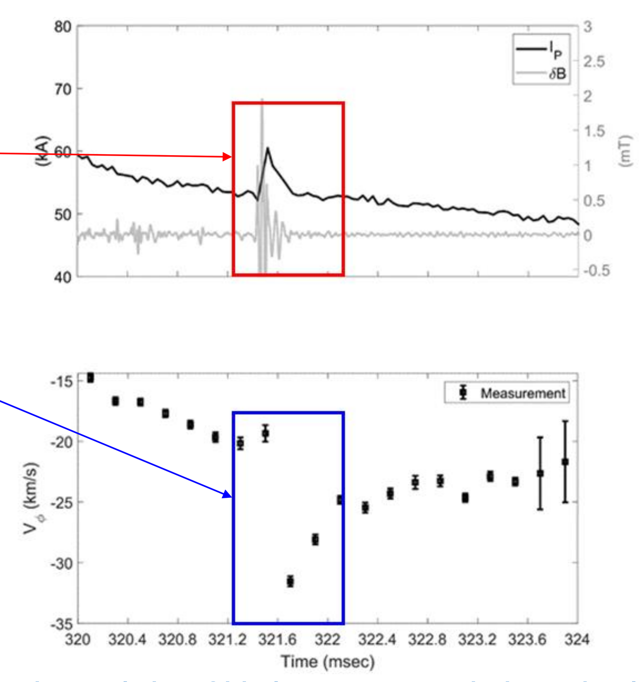
❖ Observation in VEST
- **Accompanied by magnetic fluctuations**
- **Rotation in counter-I_p direction**

❖ Simplified 0-D momentum balance eq. with NTV torque
- $m_i n_i R\frac{d\Delta v_\phi}{dt} = S_{NTV} - \frac{m_i n_i R \Delta v_\phi}{\tau_M}$ → Transport effect from confinement time

Where S_{NTV} [14] $\approx 6.1 n_i m_i v_{ti}^2 \frac{\epsilon^{3/2}}{\nu_i}(\delta B/B)^2(v_\phi - v_{\phi,NTV})$

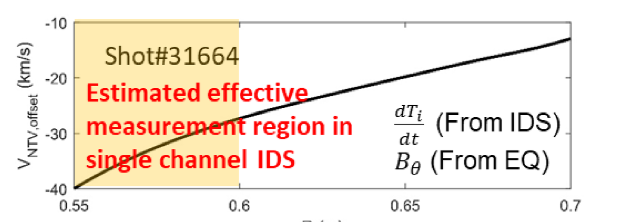
$n_i\sim10^{17}-10^{19}(m^{-3})$ (Assumption)
v_{ti} (From the IDS measurement)
$\epsilon^{3/2}$ (From the equilibrium reconstruction)
$\delta B/B$ (From the mirnov signal and equilibrium reconstruction)
τ_M (proper assumption with measurement)

Assumption: Carbon2+ rotation ~ Hydrogen rotation

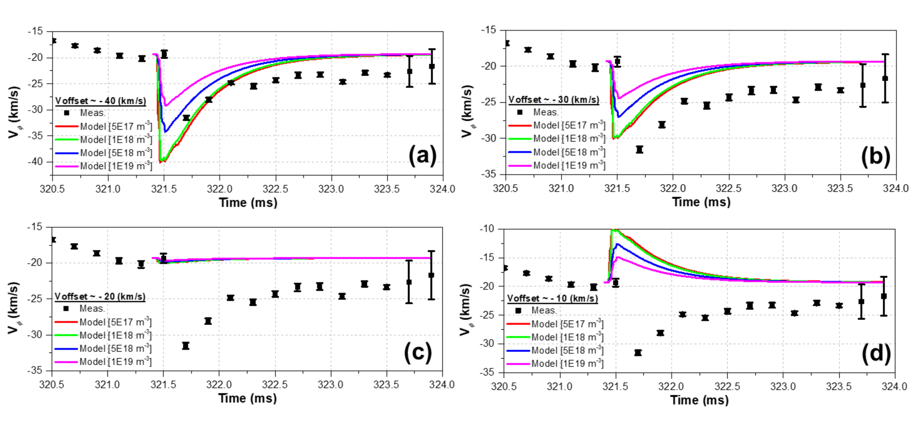


Time evolution of (a) Plasma current and mirnov signal (b) plasma rotation during the IRE in the Shot#31660

- From the profile measurement in the shot#31664, we estimate the NTV offset velocity: $-40\sim-10\ (km/s)$
- It is difficult to estimate the effective radial position at fast measurement mode [~ 0.2 (ms)] of IDS, we vary the offset velocity value in the 0-D model: $[-40,-30,-20,-10\ (km/s)]$



Estimated NTV offset velocity in the Shot#31664



Parametric scan for 0-D momentum balance model with NTV torque and comparison of model results and measurements in rotation evolution during IRE (Shot#31660)

- With the offset velocity, it can be calculated in which the plasma rotation reduces [Figure(d)]
- In the case of $v_{\phi,NTV}\sim-40\ (km/s)$ and $N_i\sim10^{17}-10^{18}\ (m^{-3})$, the model results are good agreement with the measurement

4. CONCLUSION AND FUTURE WORKS

❖ **Conclusion**
- Significant toroidal rotation change as well as ion heating are observed when IRE occurs
- Magnetic reconnection during the IRE contribute to the ion heating
- Two IRE discharges with different toroidal rotation tendency
  - Instant locking feature in the presence of multiple tearing instabilities
  - Rotation acceleration in the counter-I_p direction in discharge with quiet MHD mode
- Several candidate mechanisms for rotation acceleration are discussed
  - Reconnection outflow, toroidal electric field by reconnection, NTV torque
  - NTV torque with offset velocity in counter-I_p direction is a strong candidate mechanism

❖ **Future works**
- Investigation of MHD instabilities responsible for NTV torque with internal fluctuation measurements such as soft x-ray or internal magnetic probes
- Analysis of the discharge with rotation decrease: Other mechanisms such as electron stochastic parallel transport or electron NTV torque
- Improvement of momentum balance model with NTV
  - Reliable model input parameters from measurements (n_i-TS, δB-IMPA or SXR…)
  - 1-D momentum balance model with profile information

5. ACKNOWLEDGEMENTS / REFERENCES

This research was supported by the National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2019M1A7A1A03089797).

[1] Nucl. Fusion **40**, 721 (2000)
[2] Phys. Plasmas **7**, 940 (2000)
[3] Phys. Plasmas **24**, 032503 (2017)
[4] Phys. Rev. Lett **89**, 235002 (2002)
[5] Nucl. Fusion **43**, 547-552 (2003)
[6] Phys. Rev. Lett **98**, 075001 (2007)
[7] Phys. Plasmas **10**, 3 (2003)
[8] Phys. Plasmas **24**, 062504 (2017)
[9] Nucl. Fusion **49**, 032003 (2009)
[10] Phys. Plasmas **15**, 056115 (2008)
[11] Plasma Phys. Control Fusion **44**, B339-355 (2002)
[12] Nucl. Fusion **46**, 635-644 (2006)
[13] Nucl. Fusion **50**, 025020 (2010)
[14] Phys. Rev. Lett **109**, 195003 (2012)
[15] Phys. Plasmas **16** ,055903 (2009)
[16] Phys. Plasmas **23**, 056107 (2016)
[17] Phys. Rev. Lett. **76**, 3328 (1996)
[18] Phys. Plasmas **17**, 102106 (2010)
[19] Phys. Rev. Lett. **110**, 215007 (2013)
[20] Phys. Rev. Lett. **121**, 025002 (2018)
[21] Plasma Phys. Control Fusion **44**, B247 (2002)