Generation Mechanism and Characteristics of Intrinsic Rotation in KSTAR

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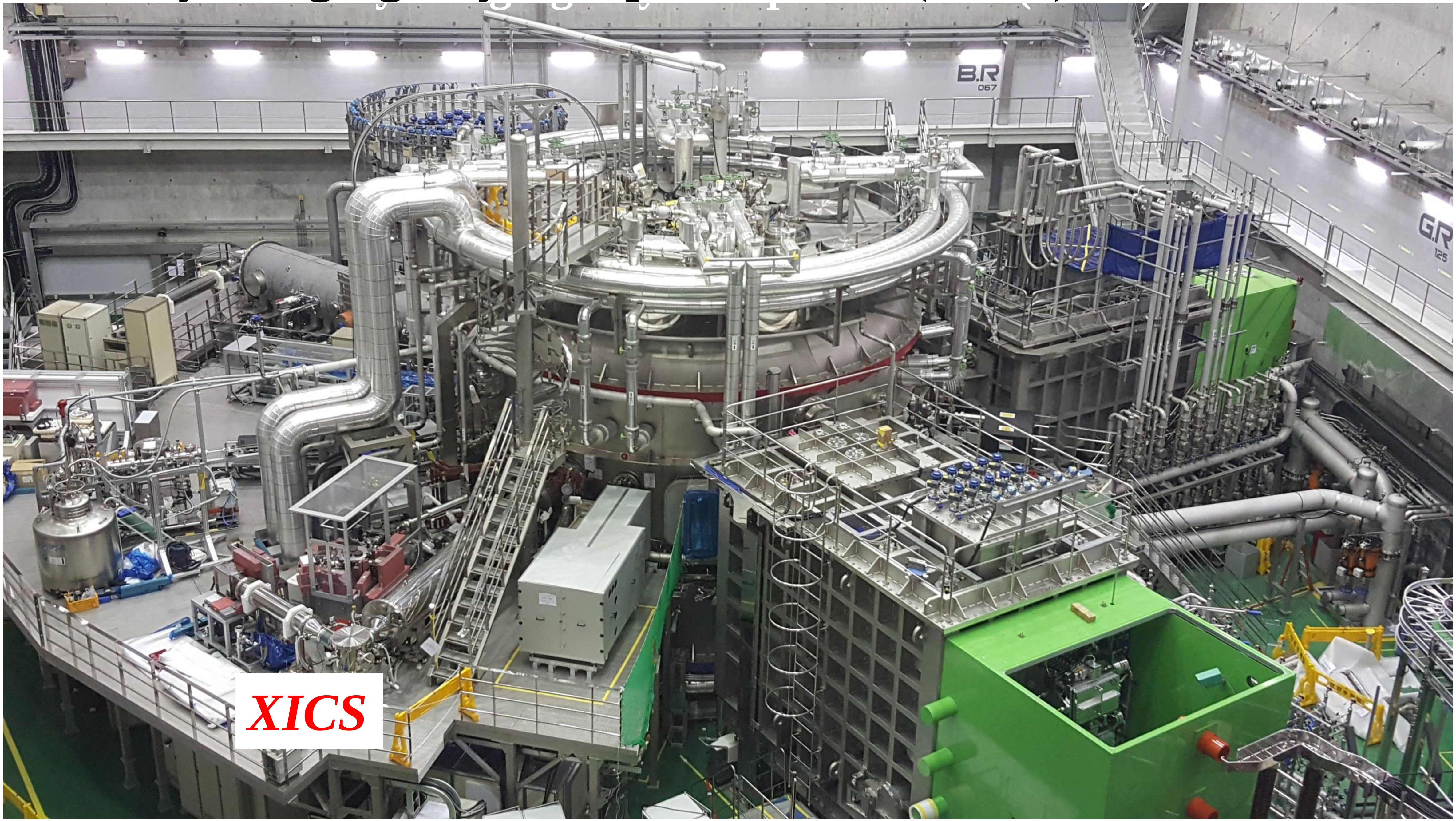
Introduction

- **The intrinsic rotation in tokamak experiments has been importantly recognized since the most effective external torque directed by NBI may not drive enough toroidal rotation for future burning plasmas such as ITER and DEMO**
- **The ohmic rotation without any external momentum sources is one of the earliest examples of intrinsic rotation studies in tokamak devices and typically measured values of the core ohmic rotation are in the range of zero to a few 10 km/s with a co- or counter-current direction depending on the experimental conditions.**
- **The ohmic rotation behaviours have been investigated in KSTAR**
- **The direction and magnitude of the core ohmic rotation strongly depends on the global plasma parameters such as the plasma current and electron density.**
- **The measured ohmic rotation in the plasma current flat-top phase is well scales as T_i/I_p regardless of the rotation direction from KSTAR**
- **Unrevealed origin of the ohmic rotation still needs continuous studies including accurate measurements and various theoretical approaches even in the plasma ramp-up phase**

X-ray Imaging Crystal Spectrometer (XICS) in KSTAR



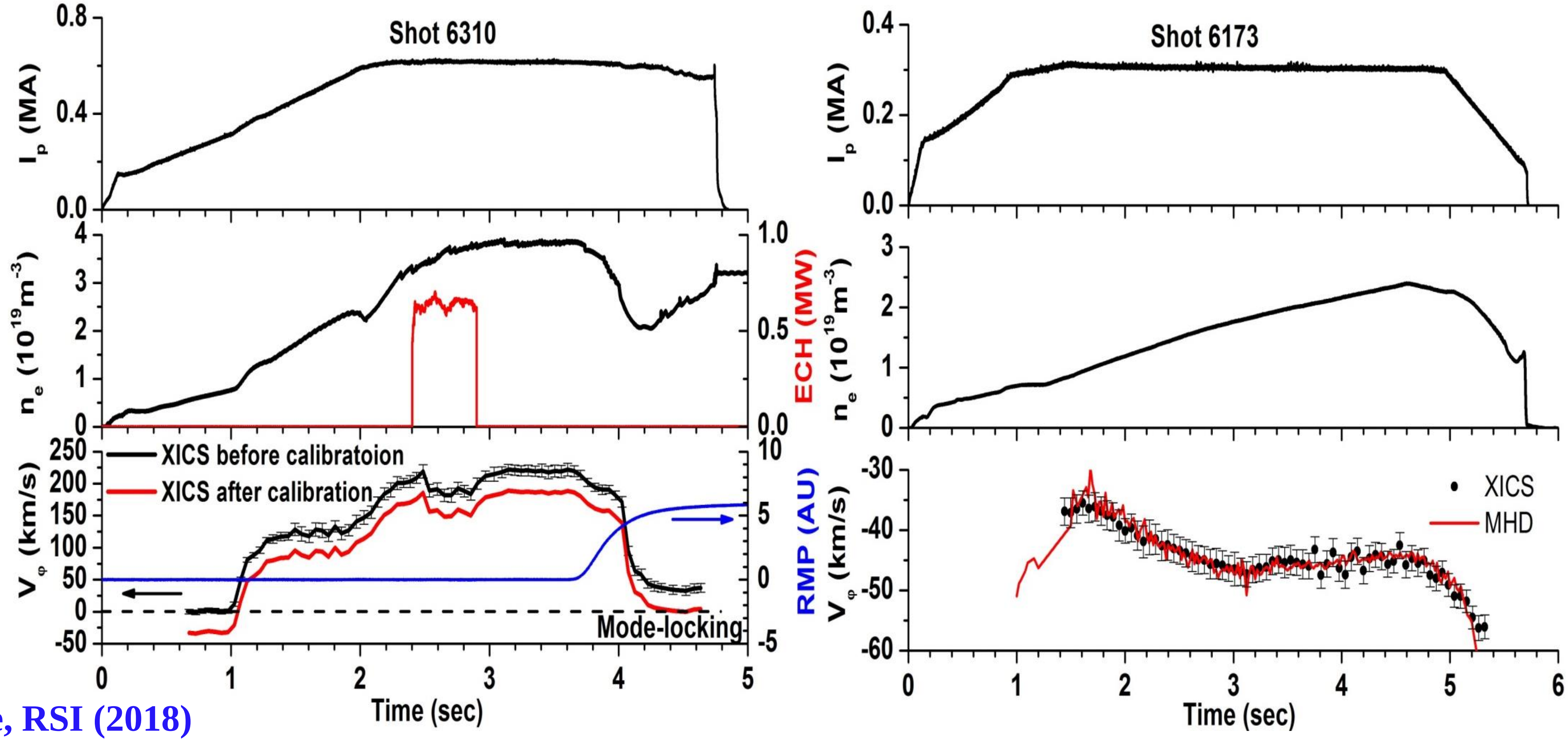
Calibration Methods for XICS

Calibration for XICS has been performed for almost every discharge in KSTAR :

1. Locked-mode : optimum RMP applied in the end of discharge

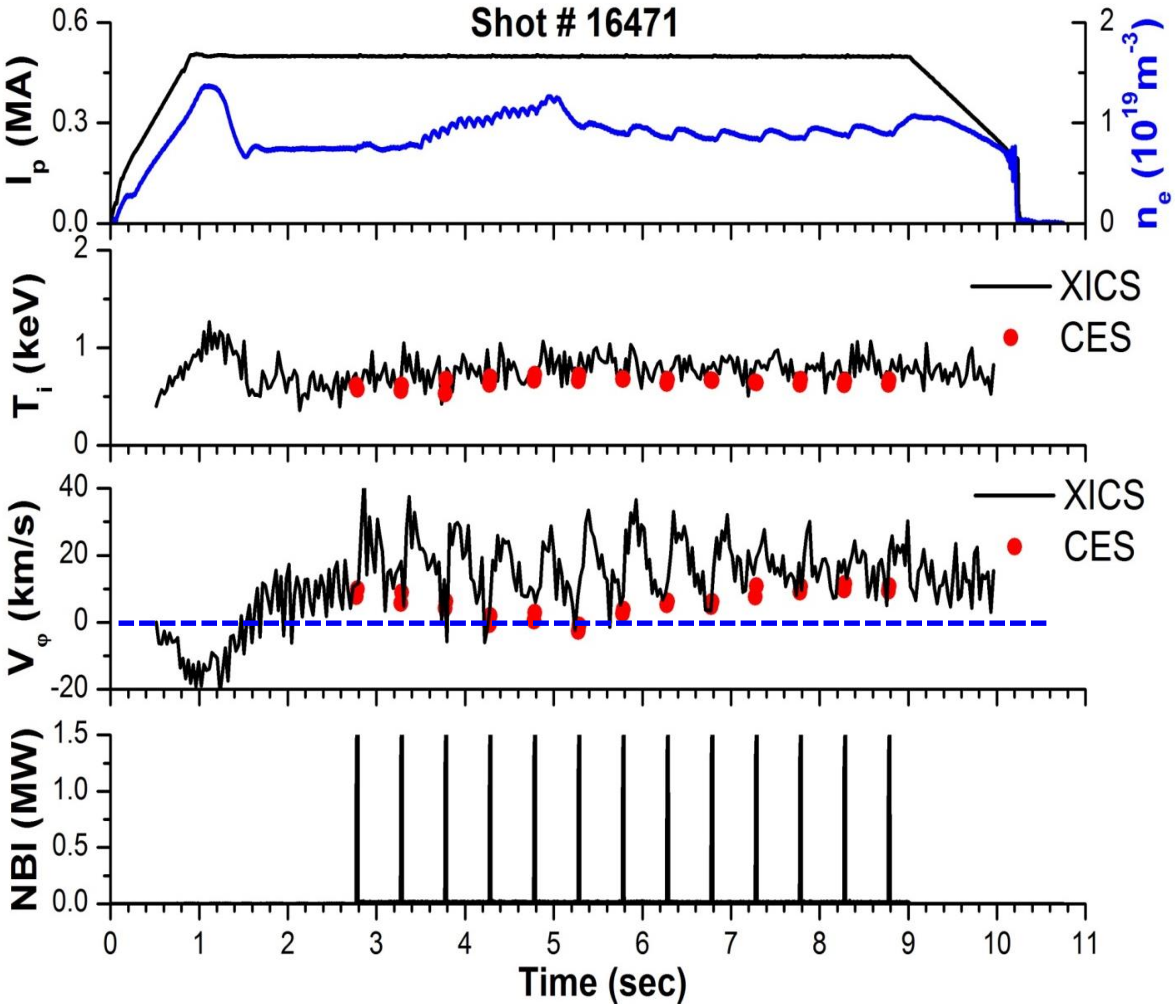
2. MHD frequency : sawtooth pre-cursor (m/n = 1/1)

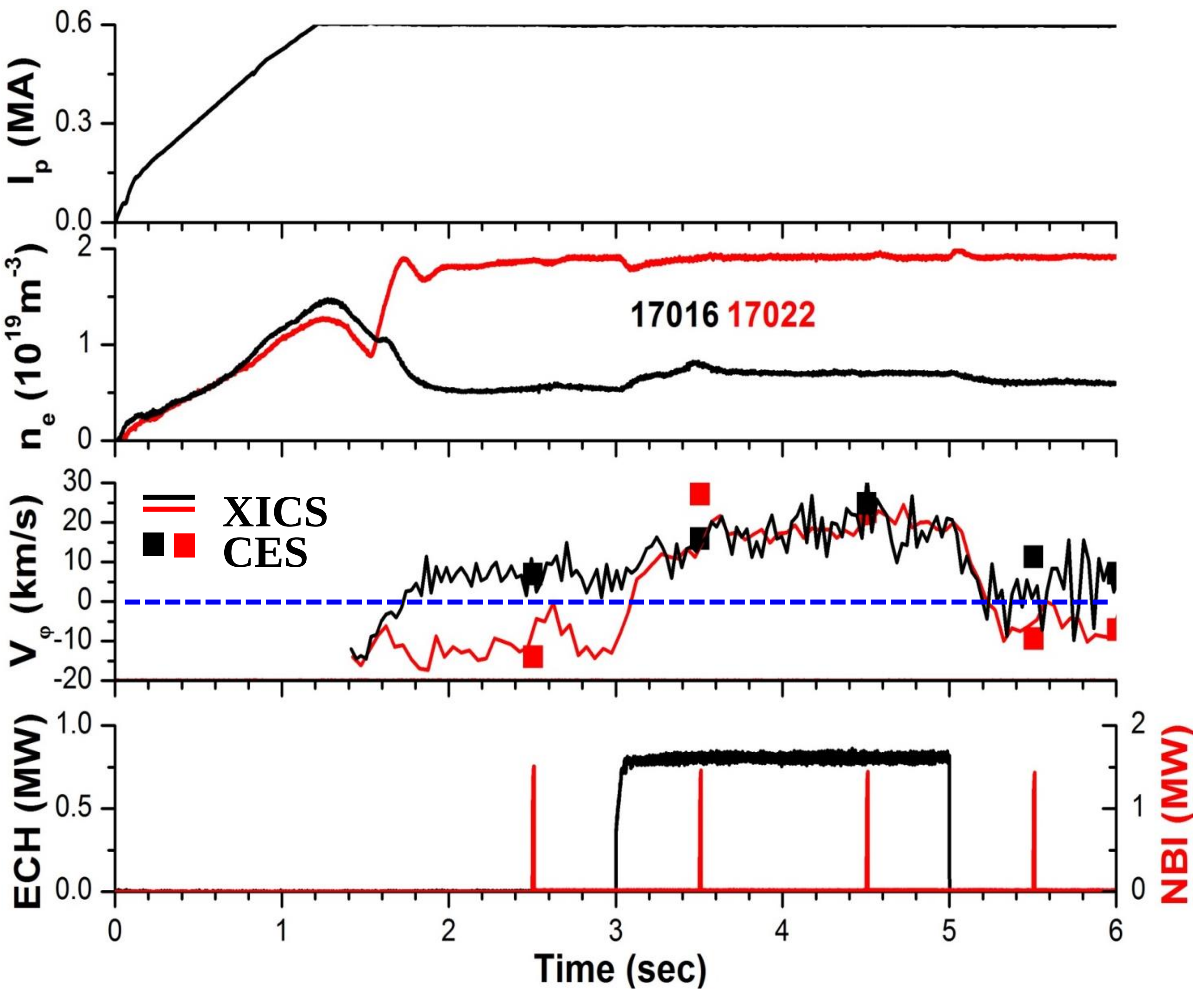
3. CES : cross comparison



S. G. Lee, RSI (2018)

Calibration Method – Cross Comparison/CES

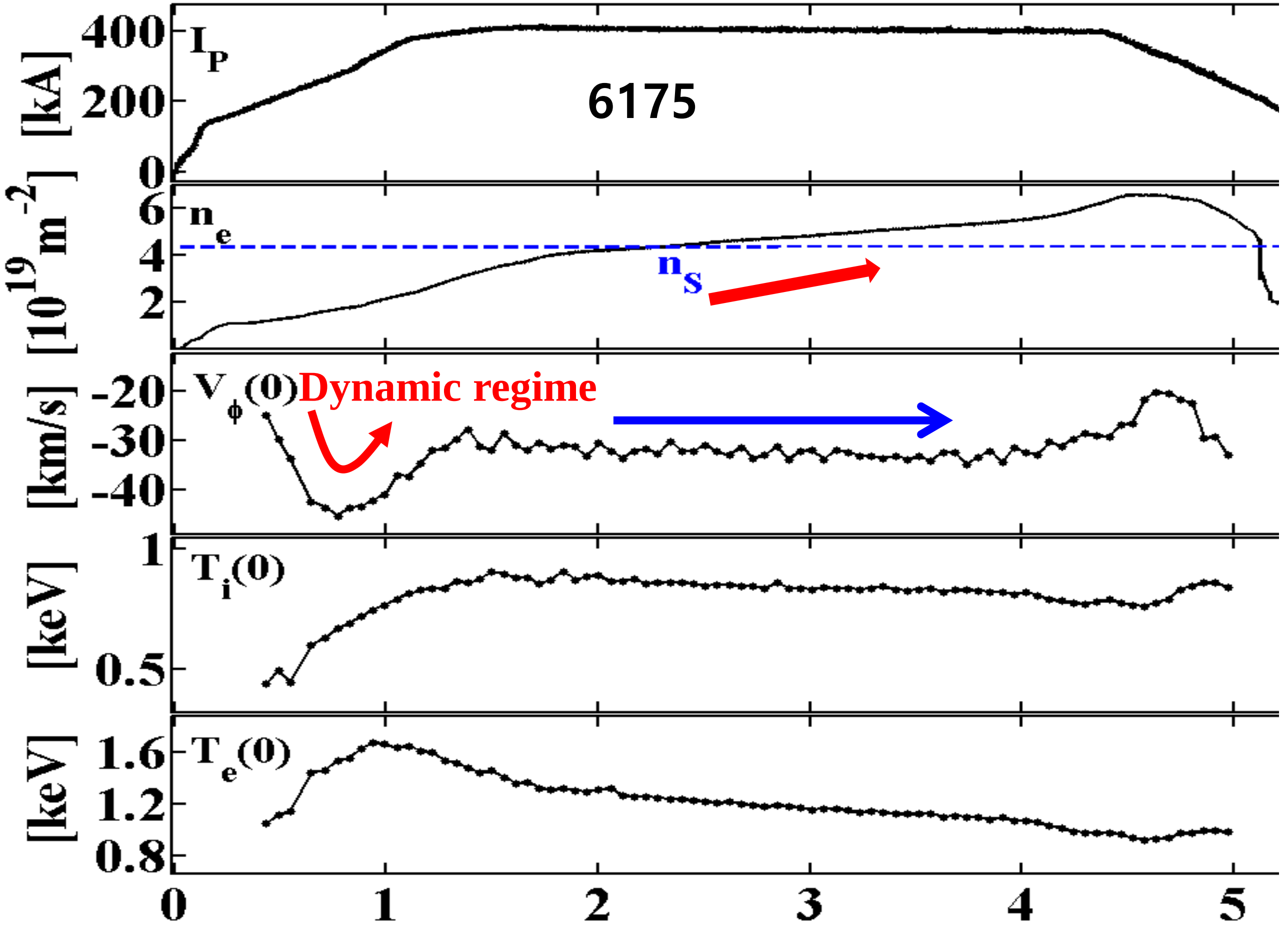


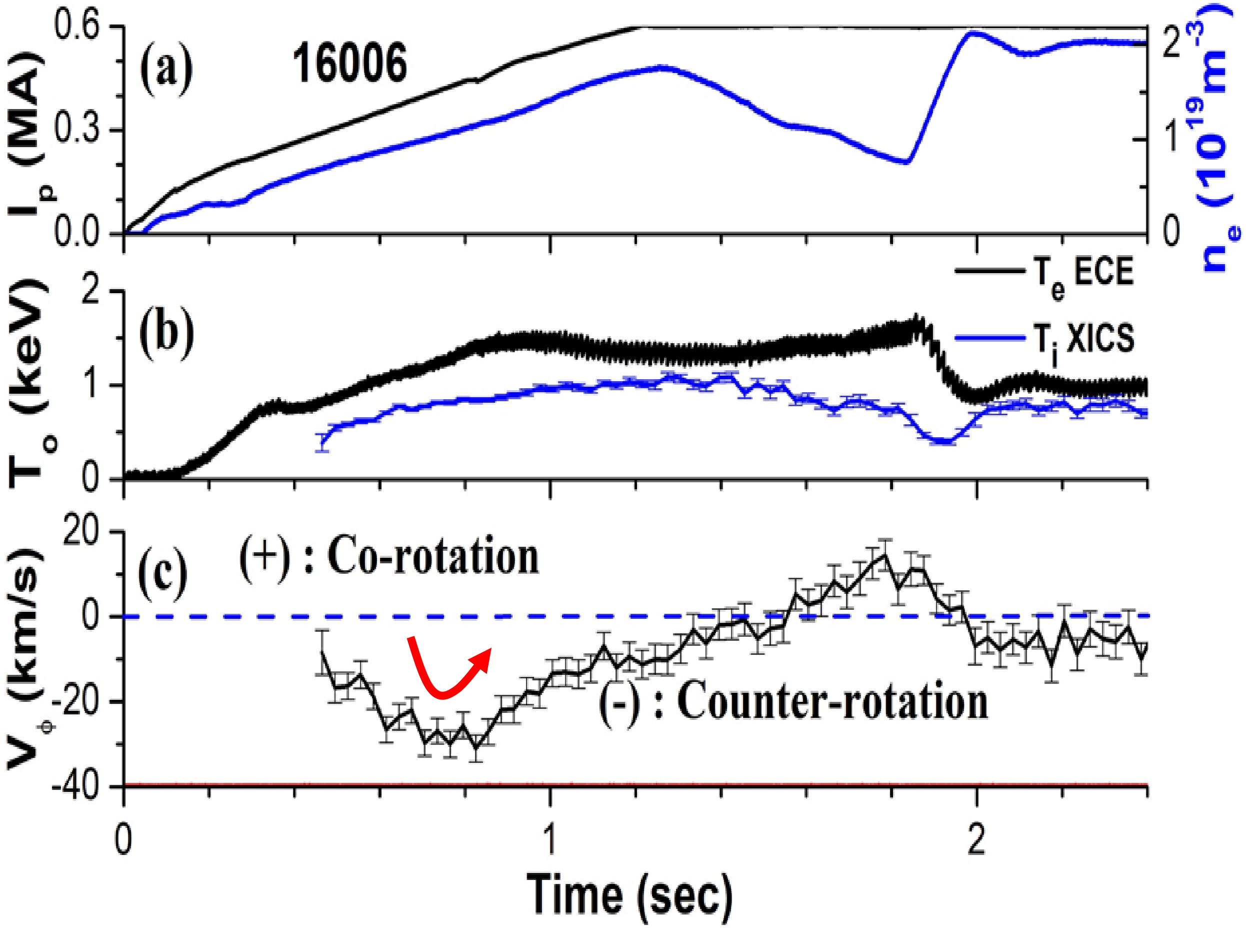


A short beam-blip technology is applied for CES

S. G. Lee, PoP (2018)

Toroidal Rotation Characteristics in Ohmic Plasmas



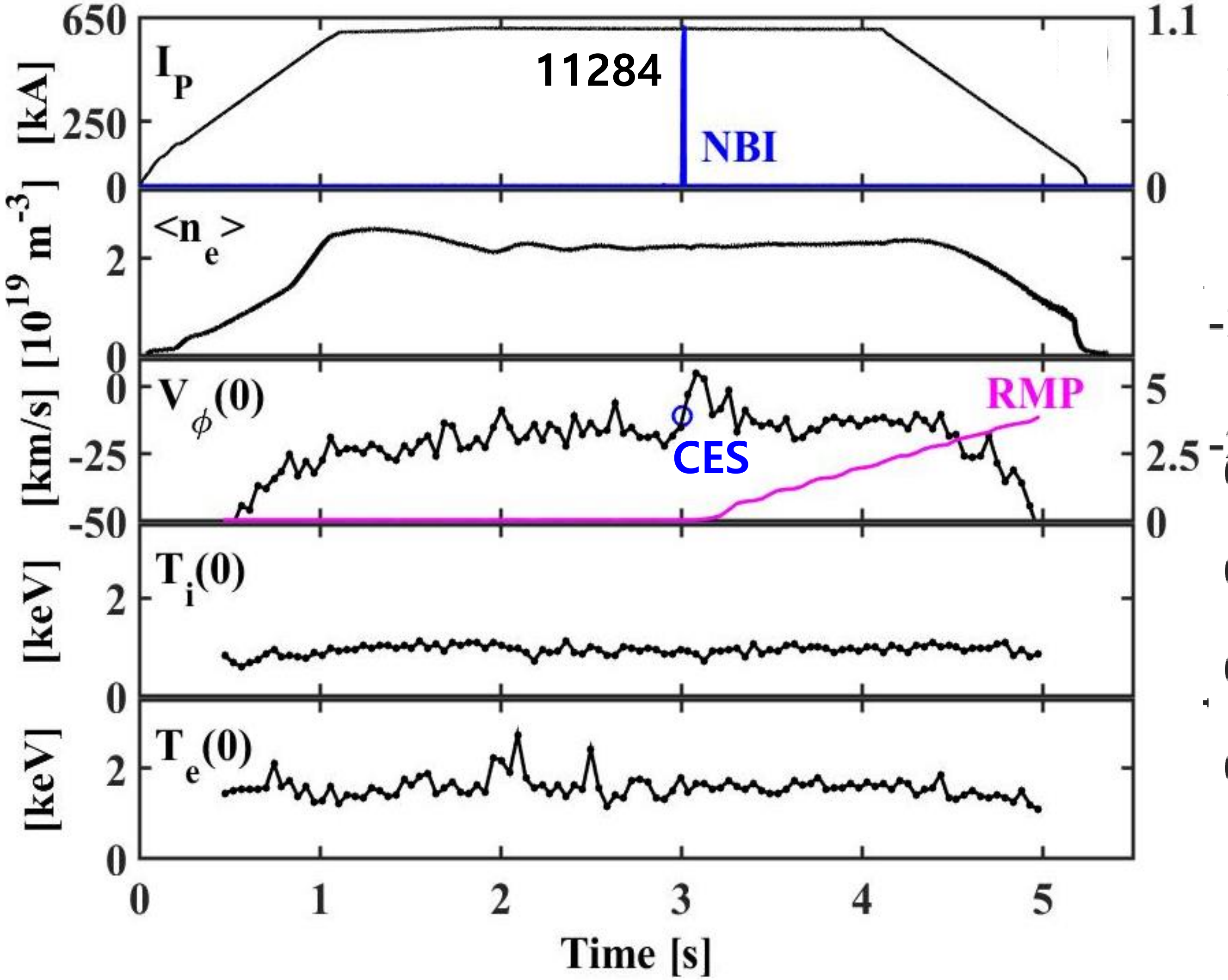


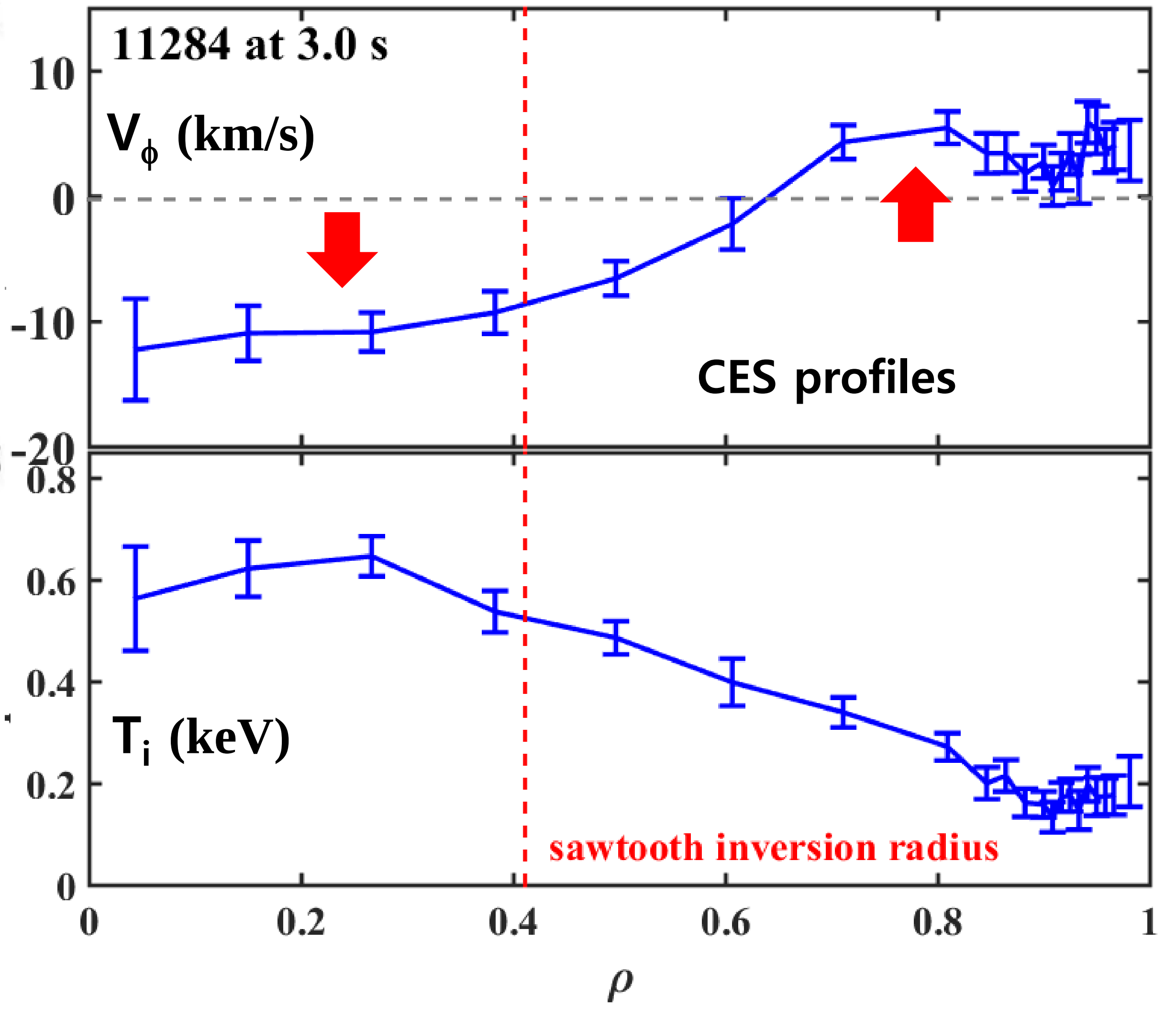
J. W. Yoo, PoP (2017)

n_s : LOC-SOC transition density ($n_s = 0.12\times10^{20} IRA^{0.5}\kappa^{-1}a^{-2.5} \quad m^{-2}$)

- **Toroidal rotation from XICS provides as early as possible even Ip ramp-up phase**
- **Dynamic change of the toroidal rotation during Ip ramp up phase is consistently shown**
- **Rotation reversal phenomena during LOC-SOC transition hardly observed under higher rotation level**

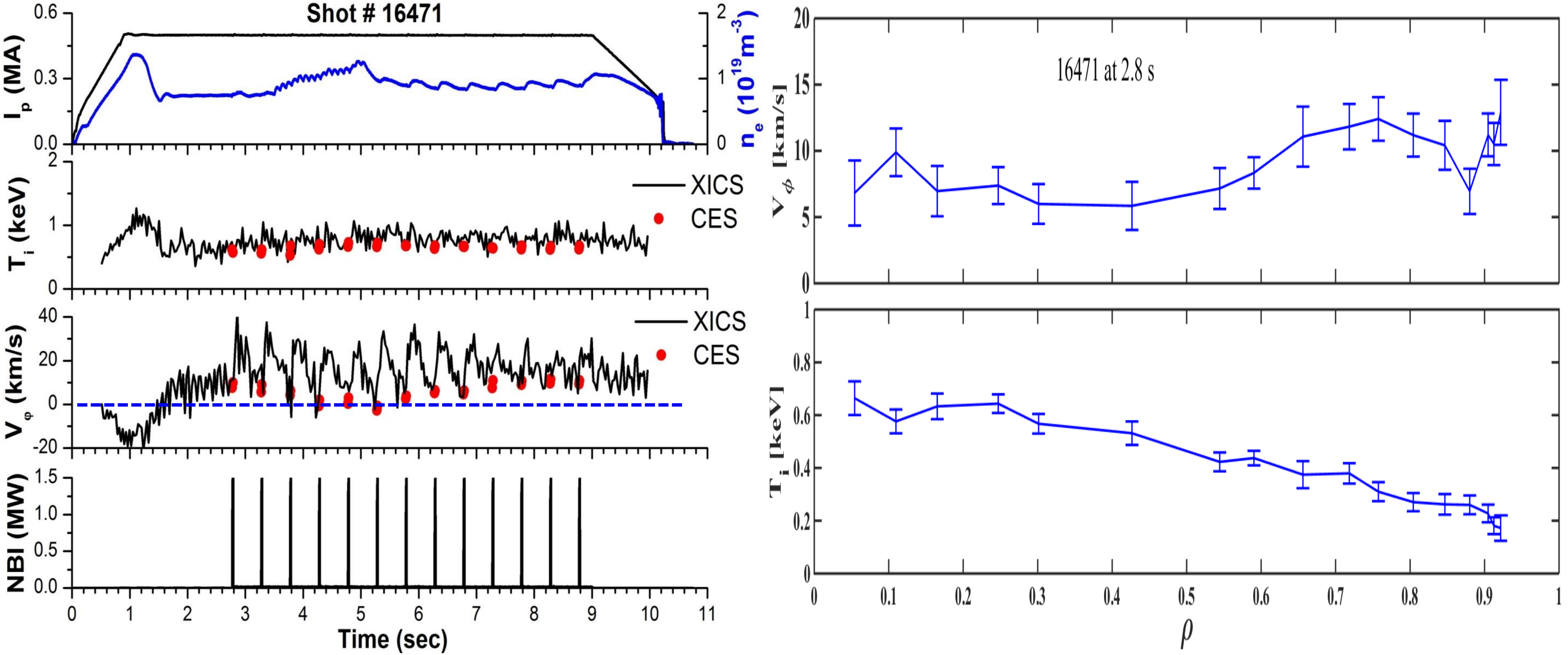
Toroidal Rotation/T_i Profiles for Counter-Rotating Discharge





- The core toroidal rotation decreases radially and changes its direction at about $\rho = 0.6$
- The edge rotation is dominantly in the co-rotation direction
- The intrinsic rotation source in the core and edge regime exists separately

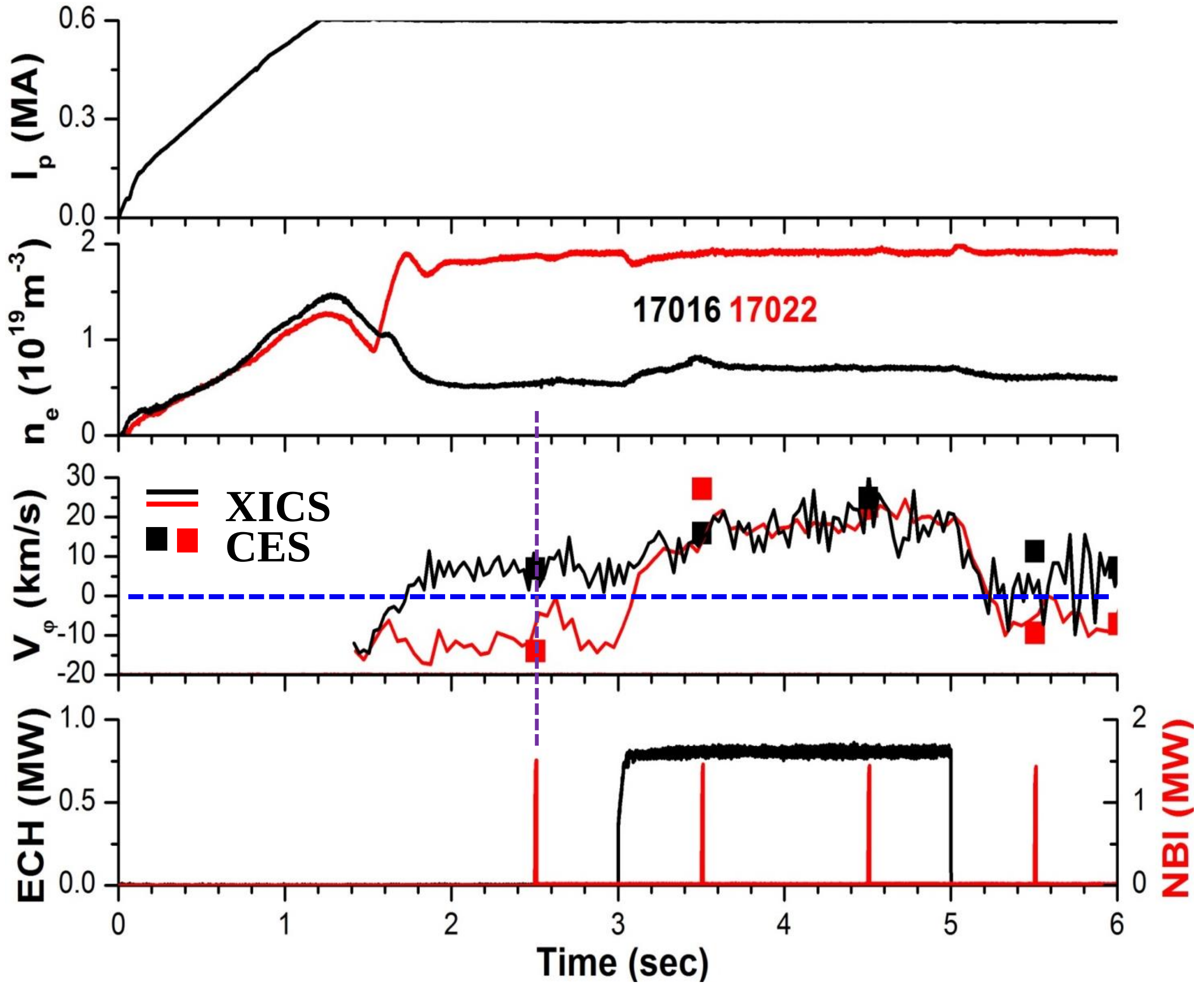
Toroidal Rotation/T_i Profiles for Co-Rotating Discharge



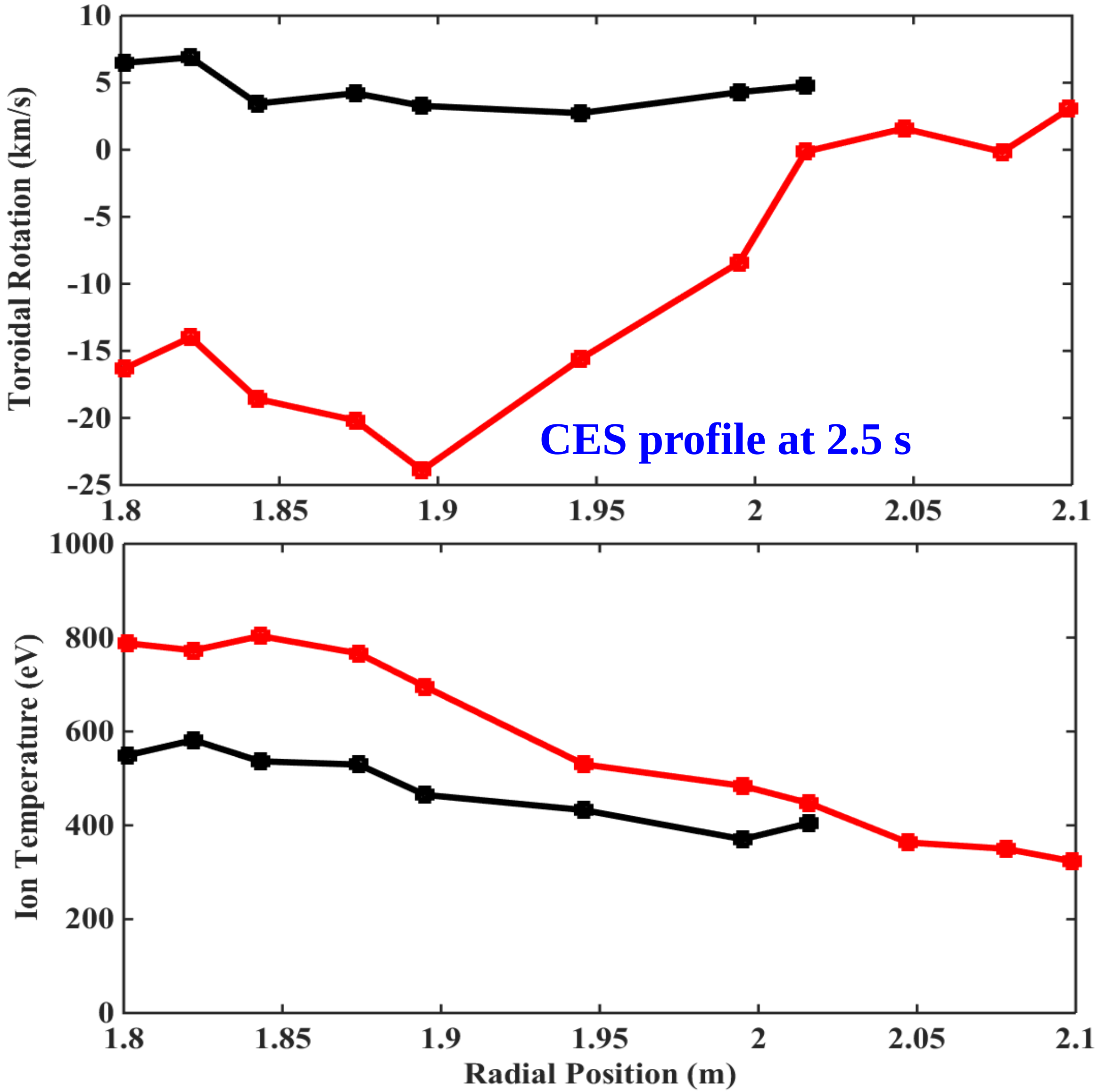
A short beam-blip technology is applied for CES

- Flat toroidal rotation profile without peaking is observed in the core region
- The toroidal rotation increases radially in the edge region

Toroidal Rotation Characteristics in Ohmic Plasmas

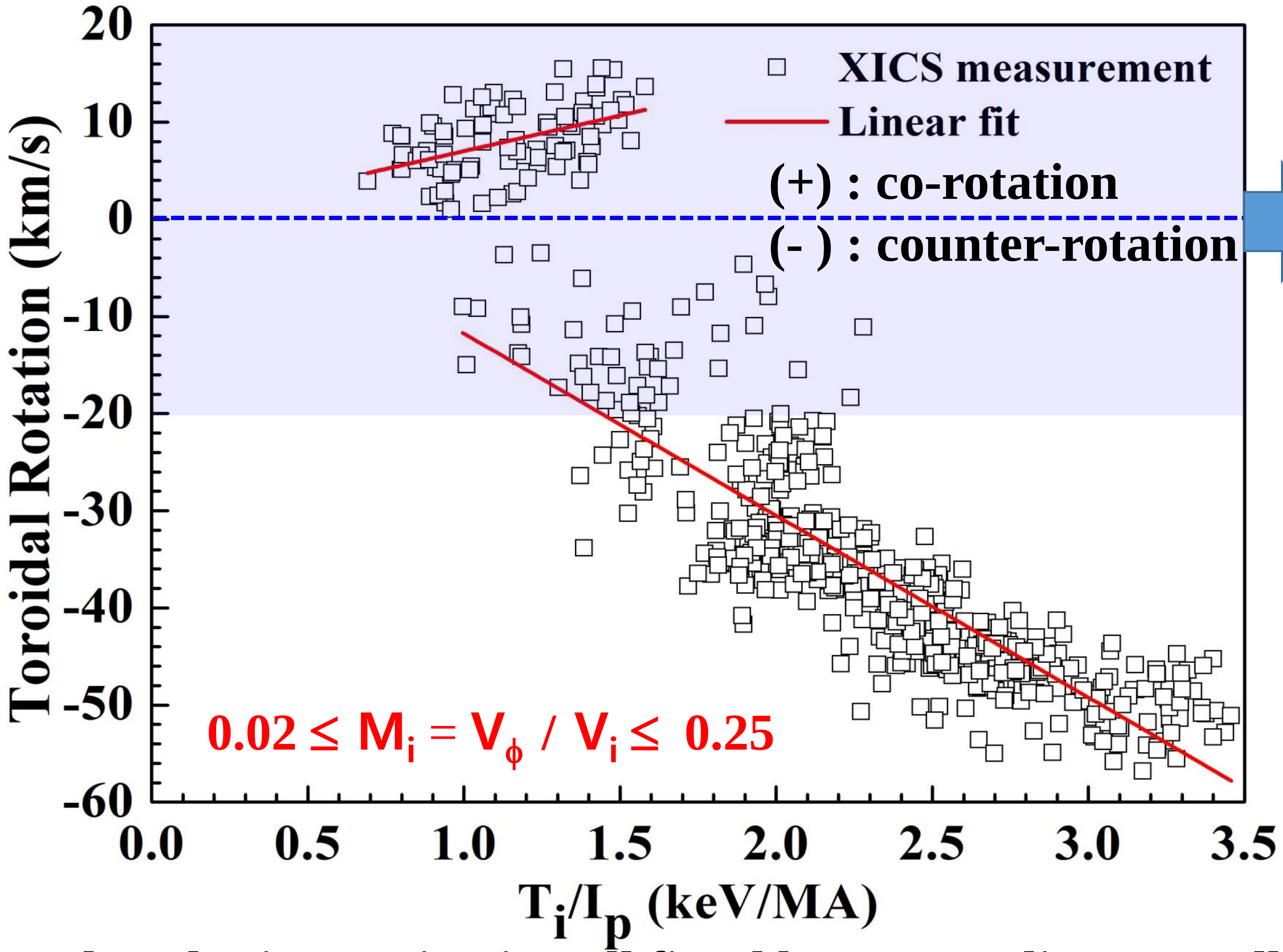


S. G. Lee, PoP (2018, 2020)



- Density is a key parameter to determine the direction of Ohmic rotation under high Ip
- ECH injection at 3.0 s induces a sudden rotation reversal for shot 17022

Core Toroidal Rotation Characteristics in Ohmic Plasmas



(Ip flat-top phase)

Most of rotation-reversal events have been reported :

$\sim -20 \leq V_\phi \leq \sim 20$ km/s

Each data points are collected pure Ohmic discharges during plasma current flat-top phase

J. W. Yoo, PoP (2017)
S. G. Lee, PoP (2018)

- The Ohmic rotation is well fitted by T_i/I_p scaling regardless of the rotation direction
- The maximum ion thermal Mach number (M_i) of the Ohmic rotation reaches up to 0.25

Analysis of Ohmic Rotation from Neutral Particle Contribution

The dynamic behaviours at the early plasma current ramp-up phase in Ohmic L-mode discharges is speculated by momentum transfer from neutral particles

- The Coulomb collisions between ions and electrons are in balance

- However electron-neutral vs. ion neutral momentum exchange is not balanced

Electron-neutral

$$\frac{1}{2}mv_e^2 = \mathrm{eE}\lambda = \frac{eE}{\sigma_{en}n_n}$$

$$\mathrm{m}v_e = -\sqrt{\frac{2eEm}{\sigma_{en}n_n}}. \qquad \nu = \sigma_{en}v_{Te}n_n$$

σ : collision cross section

Main ion-neutral (charge exchange)

$$D^+ \rightarrow D^0 \rightarrow D^0 + D^+$$

impurity ion- neutral reaction result in ionization and not effective as momentum exchange

$$C^{6+} \rightarrow D^0 \rightarrow C^{5+} + D^+$$
$$e \rightarrow C^{5+} \rightarrow C^{6+} + 2e$$

Momentum transfer rate:

$$\dot{P}_e = -2n_e\sqrt{eEkT_e\sigma_{en}n_n}$$

(counter-current direction)

$$\dot{P}_{D+} = 2n_{D+}\sqrt{eEkT_i\sigma_{in}n_n}$$

(co-current direction)

Net plasma-neutral momentum exchange is non-zero unless $n_{D+}/\,n_e\,,\,T_i/T_e\,,\,\sigma_{in}/\sigma_{en}$ are in symmetry

Analysis of Ohmic Rotation from Neutral Particle Contribution

Neutrals return this momentum source to core ions by C.X. without staying in the plasma (edge to core transfer)

$$V_\phi = 2\tau\sqrt{eEn_n}\left(n_{D+}\sqrt{kT_i\sigma_{in}} - n_e\sqrt{kT_e\sigma_{en}}\right)/M_p,$$

(τ is the acceleration time and M_p is the plasma mass)

$\sigma_{en} = 3\times10^{-19}/\sqrt{T_e}$, $\sigma_{in} = 2.7\times10^{-19}\times e^{-T_i/3430}$

Assumptions

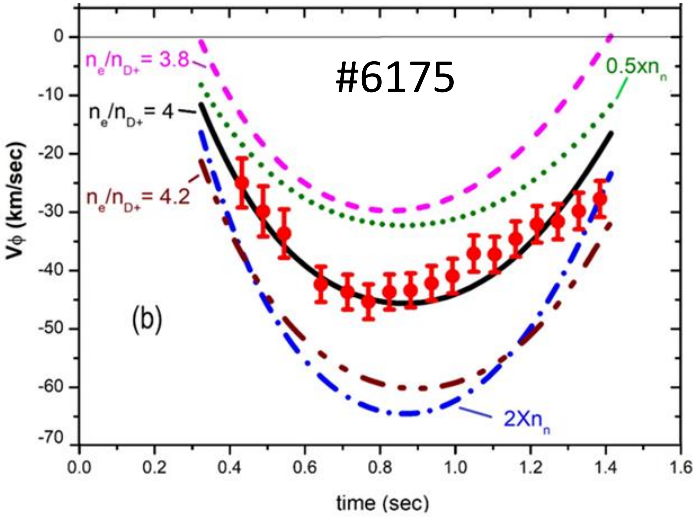
$n_n : 2\sim6\times10^{13}/m^3$

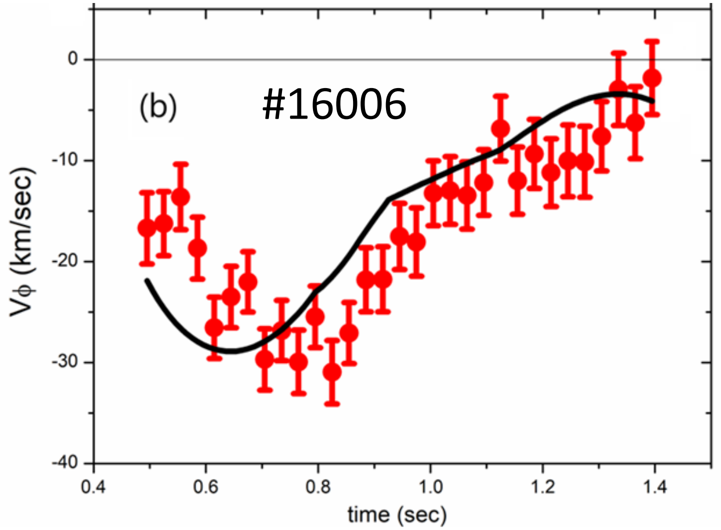
$\frac{n_e}{n_{D+}}$: 3.3~5.8

τ : ~50 msec

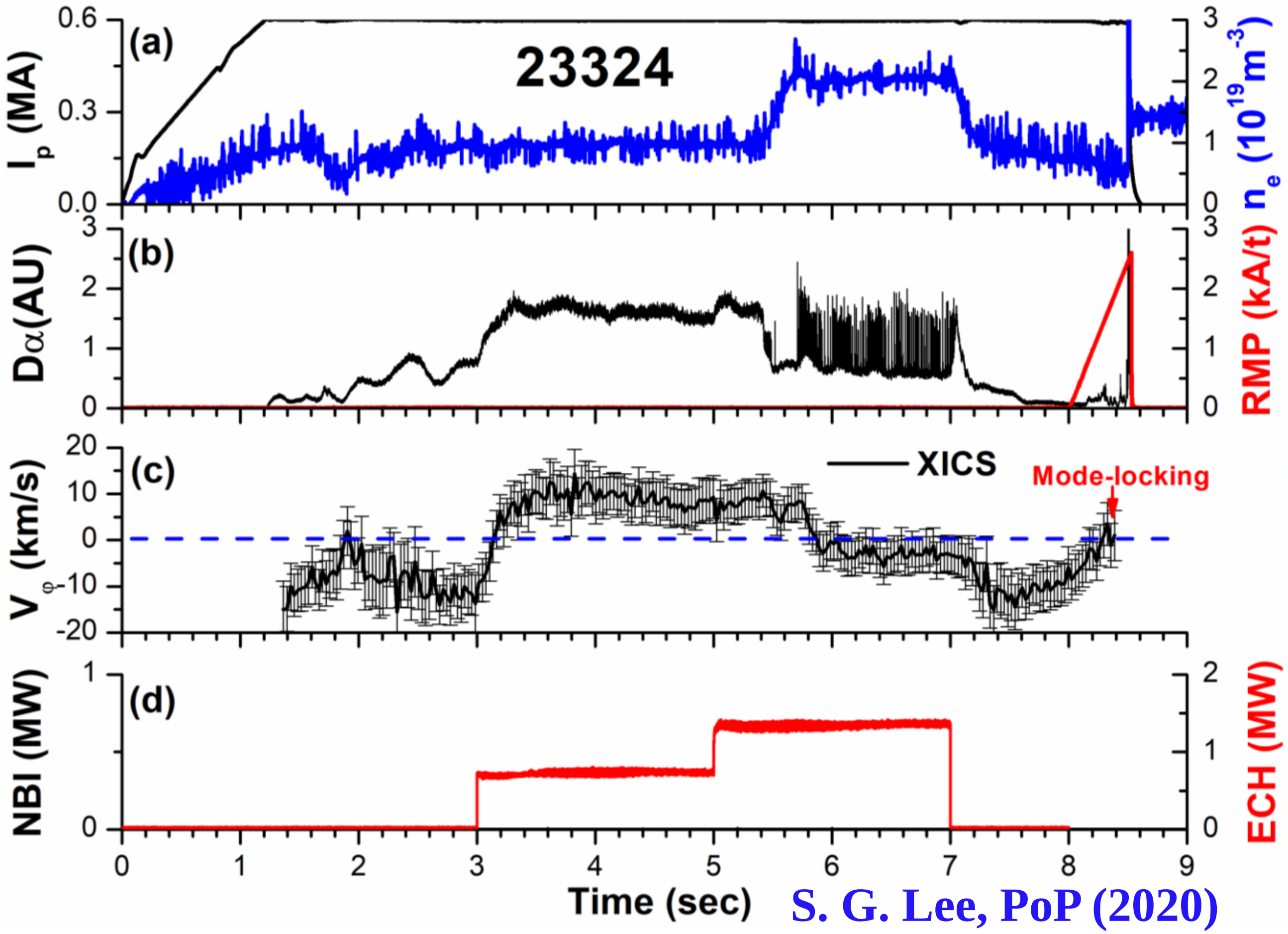
conversion efficiency: proportional to confinement

Calculated V_ϕ is well agreed with measurements

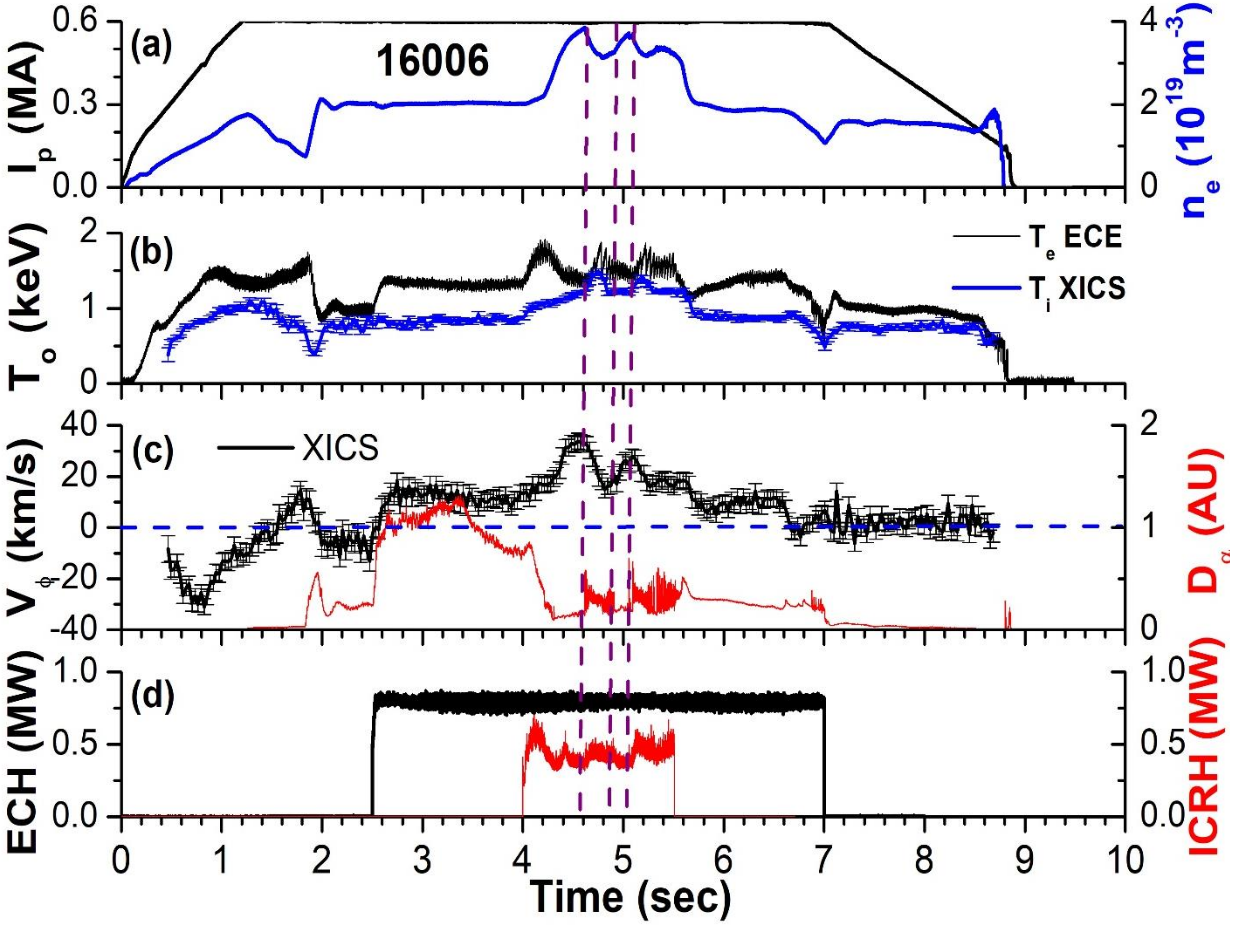




Toroidal Rotation Behaviors from RF Heating



S. G. Lee, PoP (2020)



The distinctive toroidal rotation behavior from the first and second ECH injections is clearly shown from L-mode, during L- to H-mode transition, and H-mode phases.

Vs.

The distinctive toroidal rotation behavior from ECH and ICRH injection is clearly shown from L-mode and H-mode phases.

Summary and Future Work

- **The toroidal rotation characteristics in Ohmic L-mode discharges with a wide range of plasma parameters are investigated to understand the intrinsic rotation behaviours in the KSTAR tokamak.**
- **The counter-current rotation at the early plasma current ramp-up phase in Ohmic L-mode discharges is speculated to be caused by the unbalanced momentum transfer from the electrons to the neutrals that is larger than the momentum transfer from the ions to the neutrals.**
- **The calculated toroidal rotation based on this analysis is sensitive to both the ratio of n_e/n_{D+} and the neutral density.**
- **The calculation of the toroidal rotation evolution based on the momentum transfer activated by neutrals agrees well with the experimental measurements for the early current ramp-up period in the KSTAR tokamak.**
- **The analysis of the toroidal rotation induced by neutral particles including the influence of radial distributions will be helpful for future studies on intrinsic rotation.**