Recent Results from The Heliotron J Experiment

Presented by
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Max-Planck-Institut für Plasmaphysik

Outline

1. History of Heliotron Research and Heliotron J
2. Magnetic configuration control
   - Neoclassical transport
   - Anomalous transport
   - Energetic particle confinement
3. Recent experimental results
   - High-density H-mode triggered by high intense gas puffing
   - Isotope effect on edge turbulence
   - Electron ITB
   - Suppression of energetic-particle-driven MHD modes by ECH/ECCD
4. Summary

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Heliotron Fusion Research in Kyoto University

1958 "Cradle" Project Helicon Kyoto Univ.

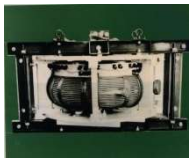
1966 超高温プラズマ研究施設（工学部） PPL, Dep. Eng. Kyoto Univ.

1976 ヘリオトロン 核融合研究センター PPL, Kyoto Univ.

1996 エネルギー理工学研究所 IAE, Kyoto Univ.

エネルギー科学研究科 GSE, Kyoto Univ.

1959

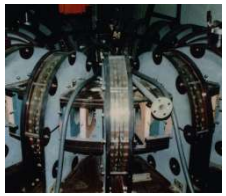


Heliotron A

1960

Heliotron B
R=0.47m
a=0.075m
B=0.6T

1965



Heliotron C

1970

Heliotron D
R=1.085m
a=0.1m
B=0.3T

1975

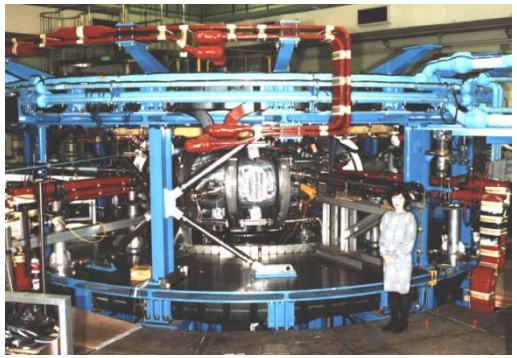
Heliotron DM
R=0.45m
a=0.04m
B=1T

1980

Heliotron E
R=2.2m
a=0.2m
B=2T

Advanced Helical Concept

2000



Heliotron J

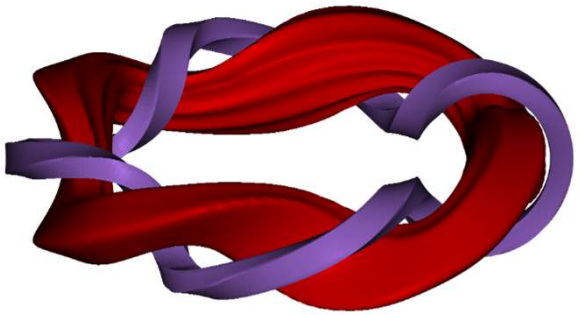
1998
LHD
(NIFS)

Helical-Axis Heliotron Configuration

M. Wakatani, Y. Nakamura et al., Nucl. Fusion 40 (1999) 569

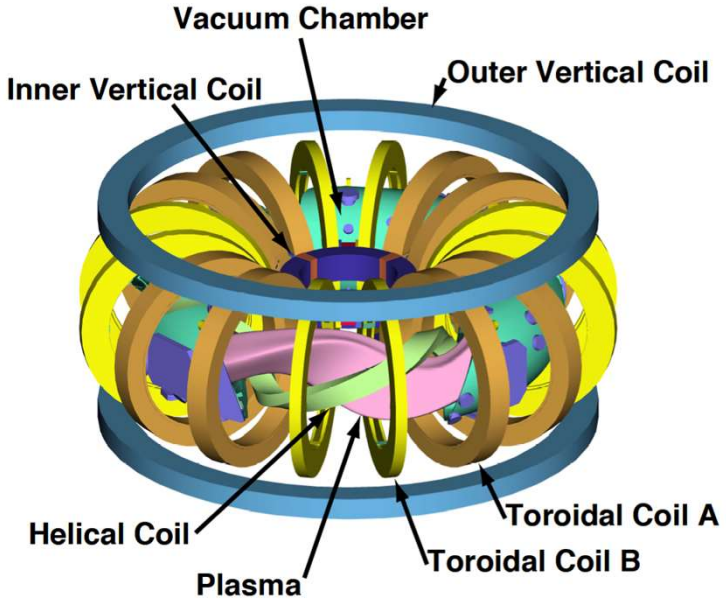
Keywords:

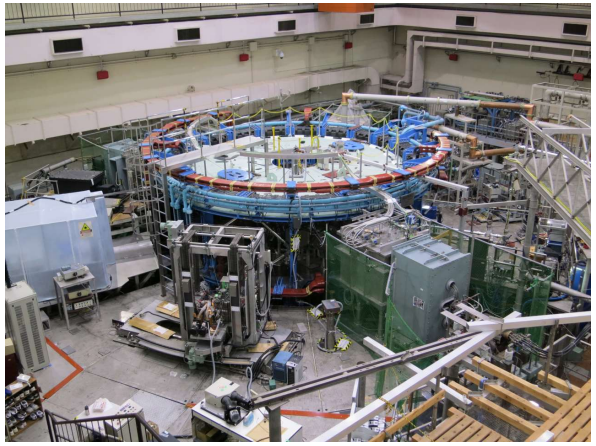
- High-level compatibility between good particle confinement & MHD stability
- Currentless steady state
- Potential for built-in divertor
- Compact & high-β
- Simple helical coil system



1. Omnigeneity for drift optimization and magnetic well for MHD stability are combined with a helical magnetic axis
   - ✓ High-β
   - ✓ Control of neoclassical and turbulent transport
2. Bumpy component as the third knob of configuration control
   - ✓ σ-optimization
   - ✓ Control of BS current
   - ✓ Er effect

Heliotron J Device

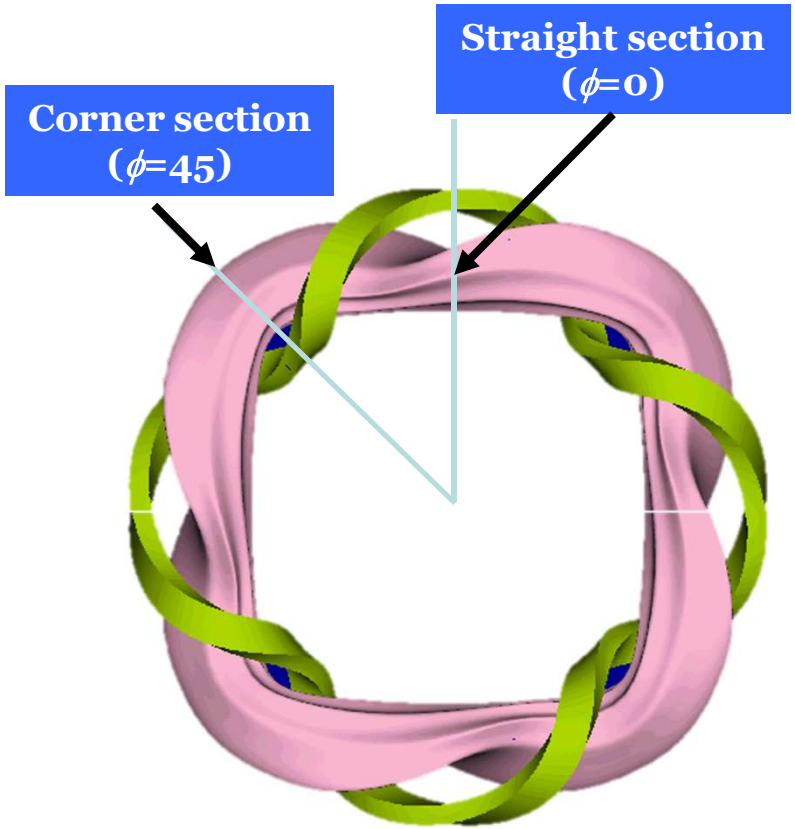


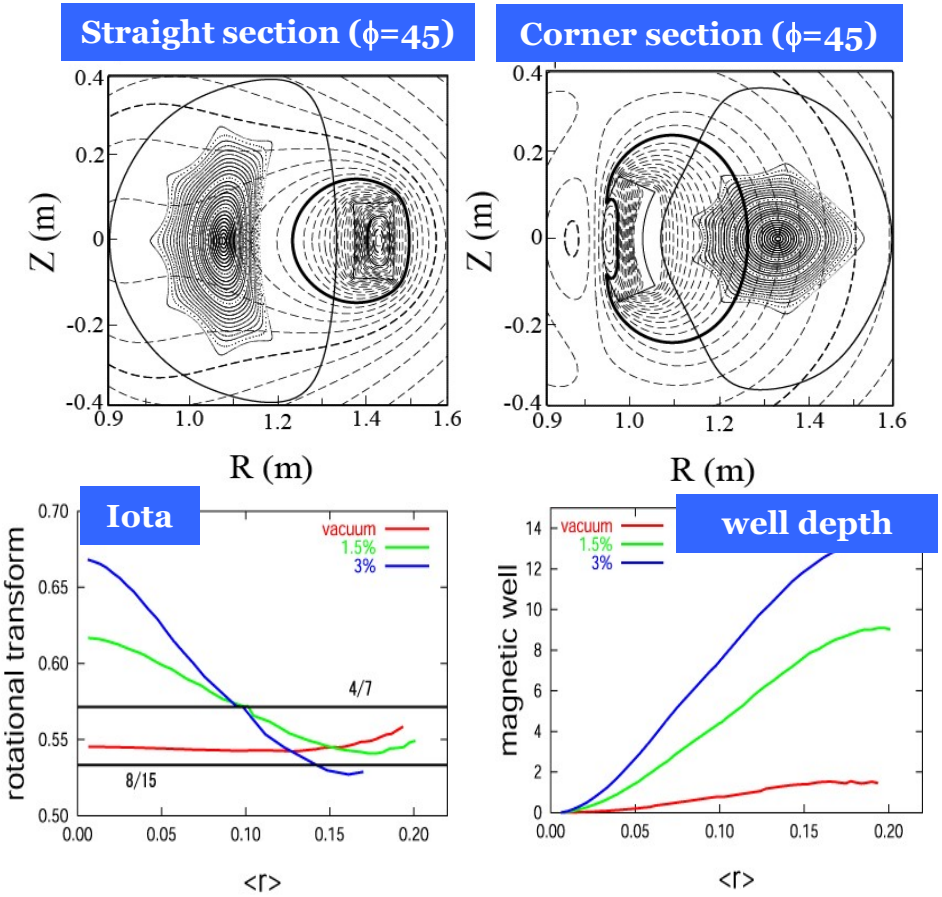


- ✓ Specification
  - Single helical coil (l=1), two kinds of toroidal coil and three pairs of poloidal coil
    ⇨ Flexibility of magnetic configuration
  - R=1.2 m, $\langle a \rangle \leq 0.2$ m
  - $B_t \leq 1.5$ T, $0.4 \leq \iota/2\pi \leq 0.65$
  - $N_f = 4$, helical-axis Heliotron
- ✓ Heating systems
  - ECH: $P < 0.4$ MW, $f = 70$ GHz
  - NBI: $P < 1.6$ MW, $E < 30$ keV (H)
    [co and counter injection]
  - ICRF: $P < 0.8$ MW
- ✓ Achieved plasma parameters
  - $n_e < 1 \times 10^{20}$ m^{-3}
  - $T_e(0) < 3$ keV
  - $T_i < 0.4$keV

Characteristics of Heliotron J Configuration

- ✓ The straight structure is designed where quasi-omgeneity is formed

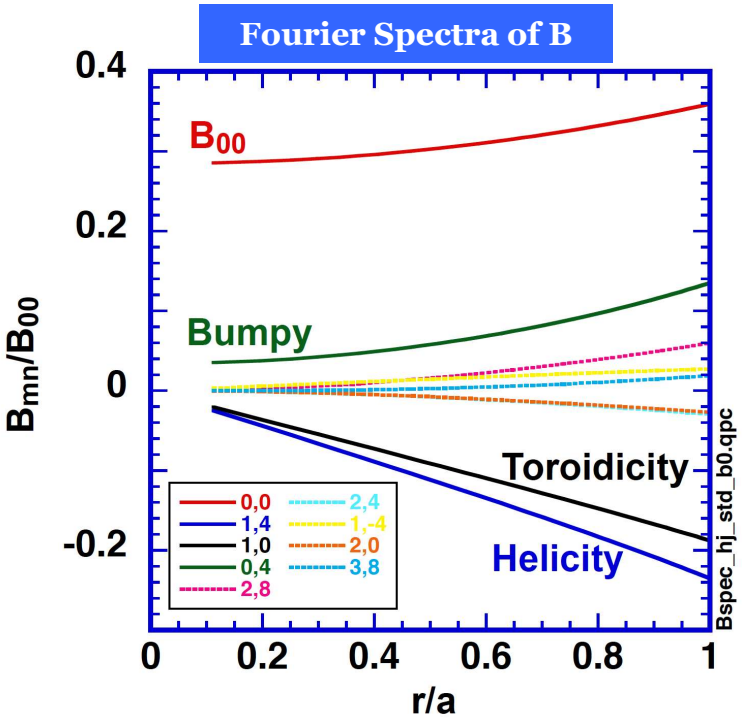




- ✓ The magnetic field strength is flat in the straight section, making the magnetic field gradient gentle.
- ✓ The B contour shape is tokamak-like at corner section

Role of Bumpiness

- Bumpiness provides control of B_{min} contour for deeply trapped particles
- Inward shift of magnetic axis is not necessary for optimization of neoclassical transport



- Field configuration of Heliotron J is mainly composed of toroidicity, helicity and bumpiness
- Helical coil winding law

$$\theta = \pi + \frac{M}{L}\phi - \alpha \sin\left(\frac{M}{L}\phi\right)$$

- The negative α produces magnetic well in the whole plasma region

- Reduction of neoclassical ripple transport
- Control of bootstrap current
- MHD stabilization and good energetic particle confinement

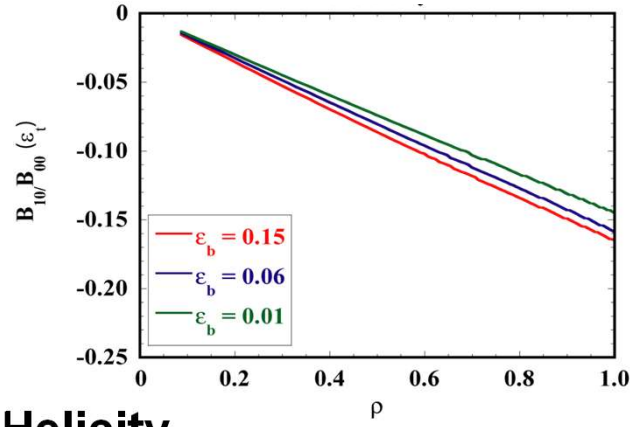
Three Bumpiness Configurations

Bumpiness ($\varepsilon_b = B_{04}/B_{00}$) can be changed with toroidicity and helicity fixed

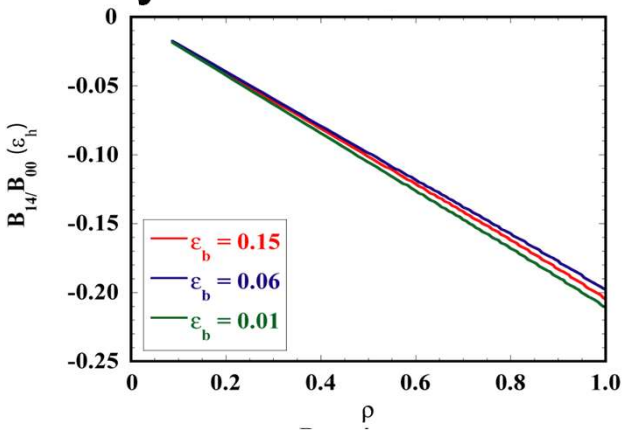
- ε_b = 0.15 (high bumpiness)
- ε_b = 0.06 (medium bumpiness, STD)
- ε_b = 0.01 (low bumpiness)

at ρ~2/3a

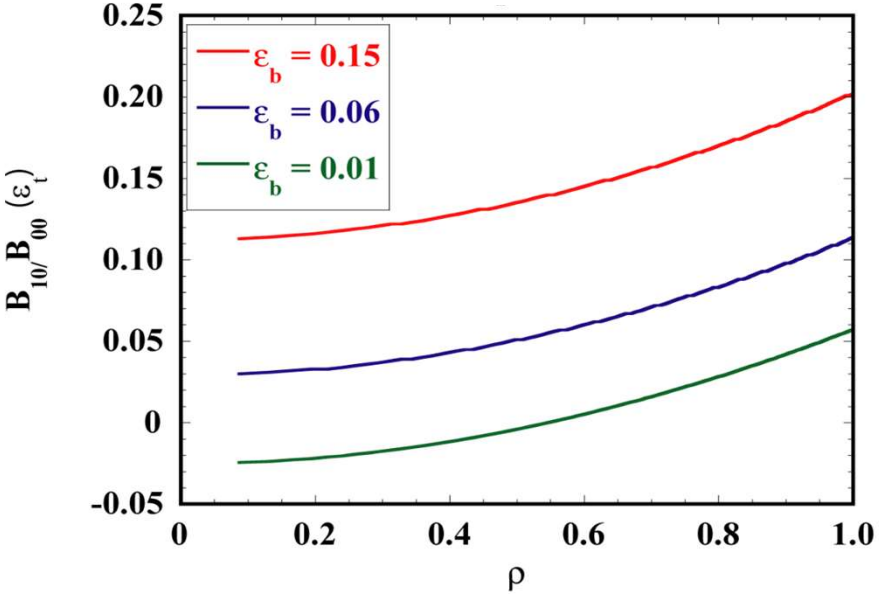
Toroidicity



Helicity



Bumpiness



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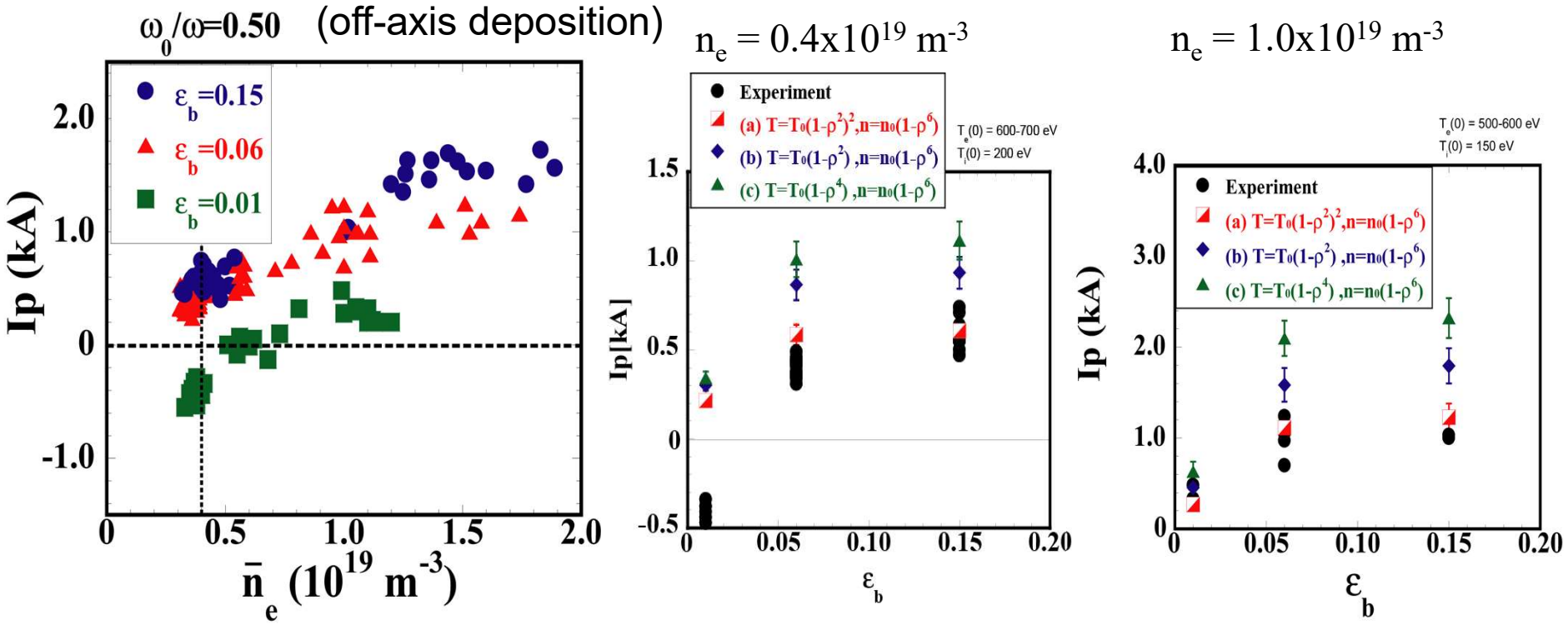
Experimental BS current Agrees with Neoclassical SPBSC Code Results

Experimental bootstrap current agrees with neoclassical prediction within a factor of 2 at $n_e = 0.4\text{-}1.0 \times 10^{19}$ m^{-3}

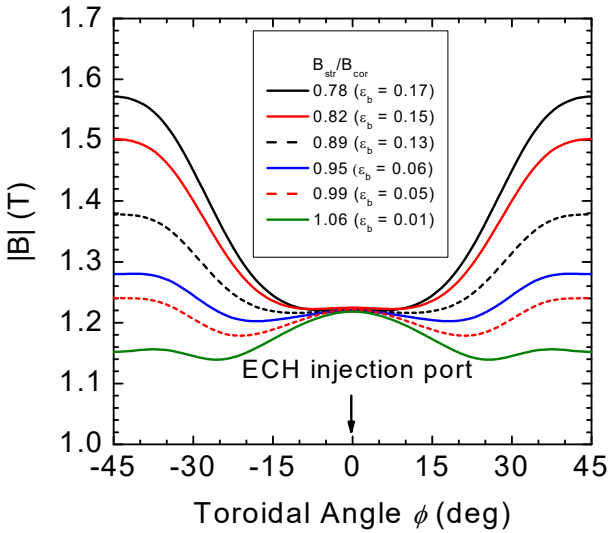


- BS current is dominant at this resonance condition
- Three kind of pressure profiles are assumed

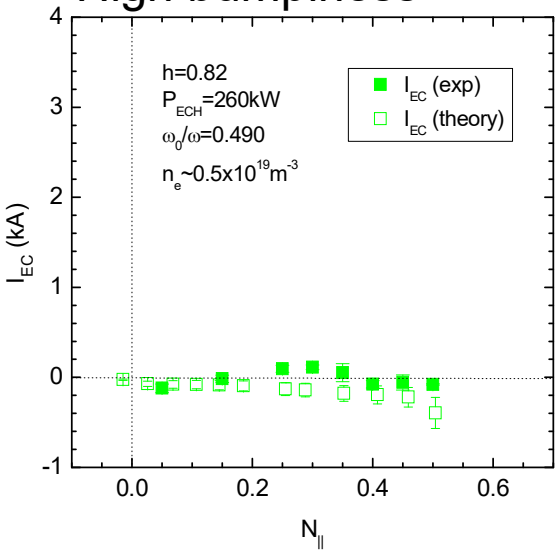
G. Motojima, Fus. Sci. Tech (2007)

Role of Trapped Electrons on ECCD

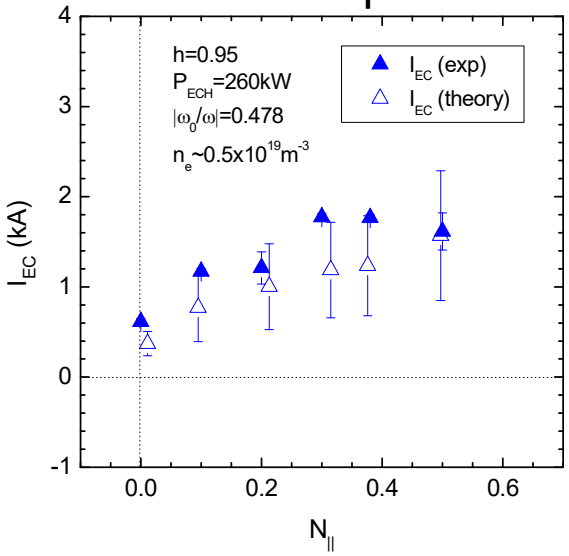
- Experiments on scanning magnetic field configuration in Heliotron J show importance of trapped electrons for ECCD
- The experimental results quantitatively agree with a theoretical calculation using the TRAVIS code which includes parallel momentum conservation



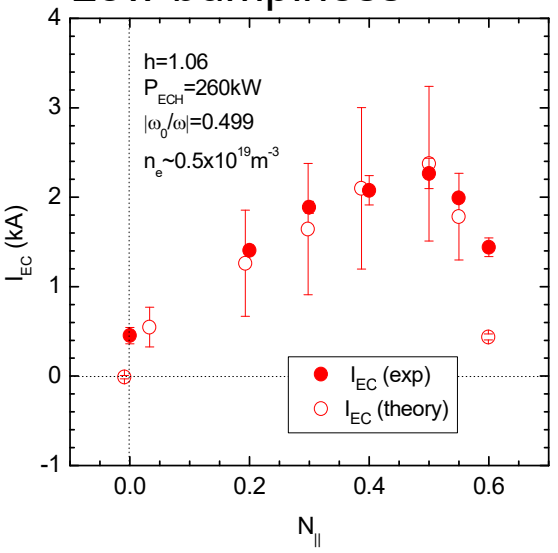
High bumpiness



Medium bumpiness

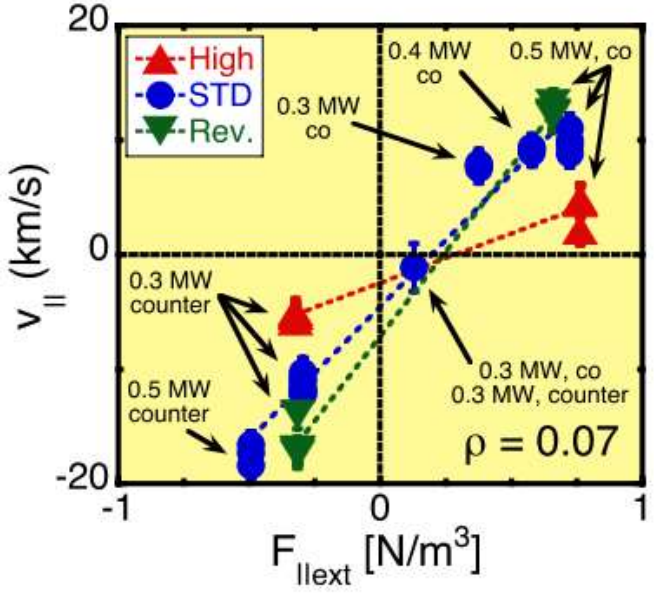


Low bumpiness



K. Nagasaki, Nucl. Fusion (2011)

Effect of Bumpiness on Parallel Plasma Flow



Lee, PPCF (2013)
Nishioka, PoP (2016)

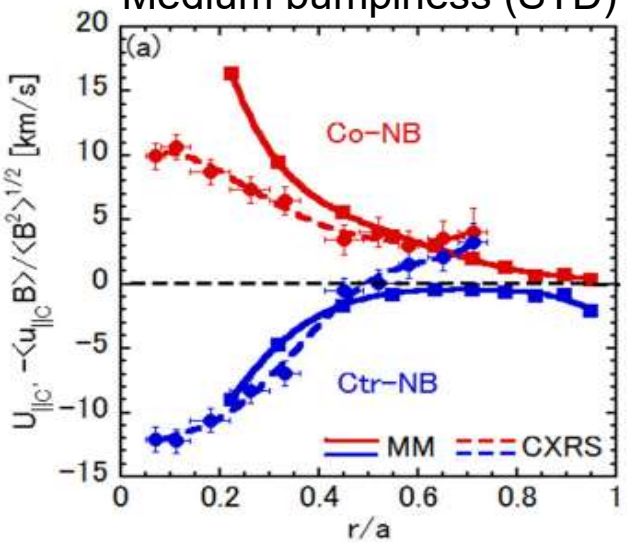
Core $v_{\parallel}$ dependence on

1. **NBI: co – (bal) – ctr**
2. **Ripple strength γ**

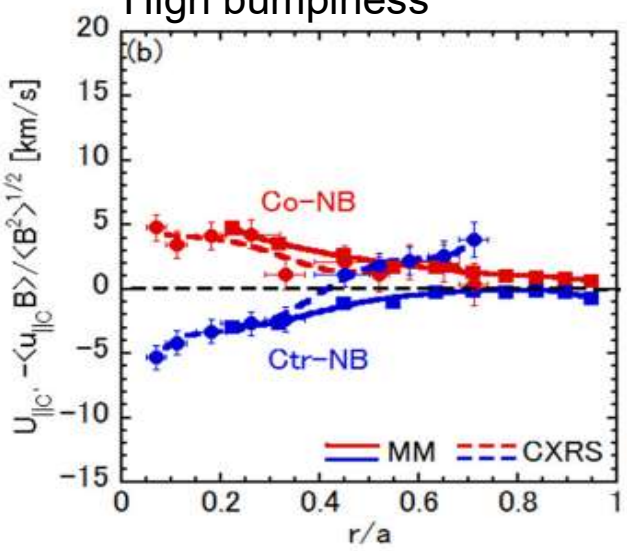
$$\gamma^2 = \left\langle \frac{(fB/fs)^2}{B^2} \right\rangle$$

The measured C^{6+} parallel flow is consistent with the neoclassical prediction with the Sugama-Nishimura method including the edge spontaneous flow

Medium bumpiness (STD)



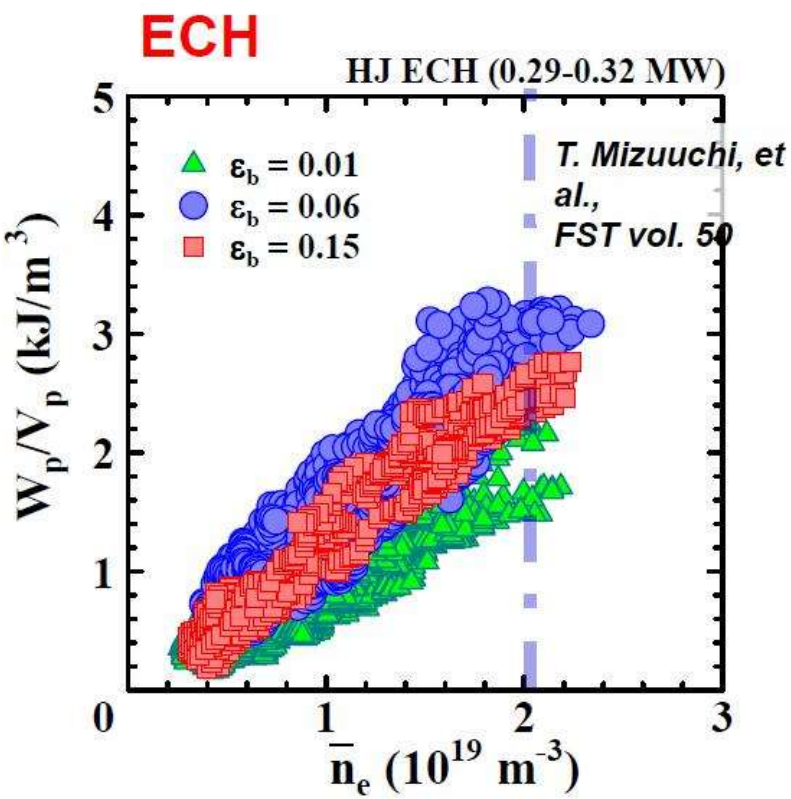
High bumpiness

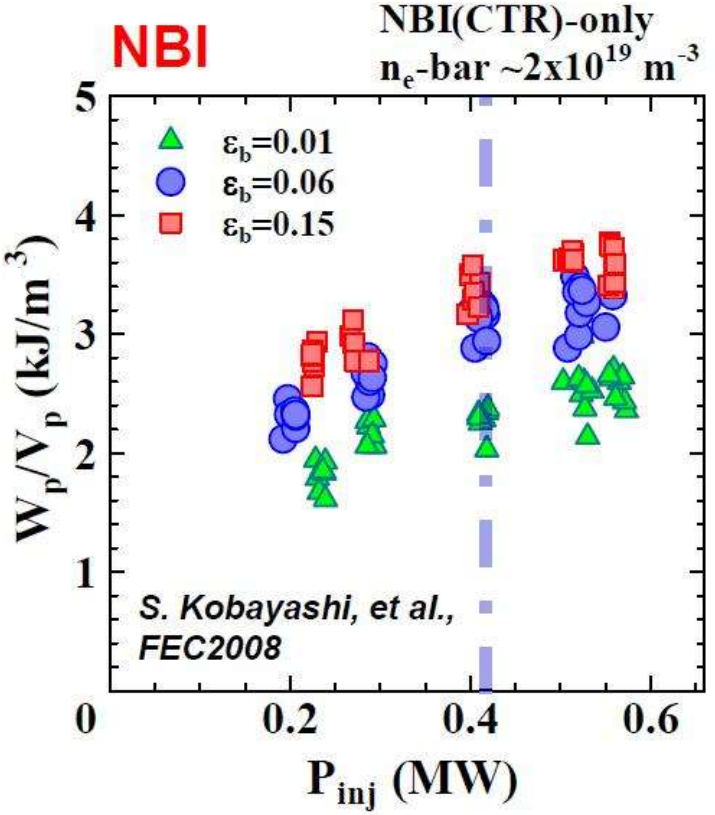


Global Confinement Depends on Bumpiness Component

- Good global energy confinement is obtained at the magnetic configuration with medium bumpiness (ECH) and high bumpiness (NBI)

Power scan experiments





T. Mizuuchi, FST 50 (2006) 352
S. Kobayashi , FEC (2008) EX/P5-13

GKV Code Results Show That Zonal Flow in High Bumpiness Suppresses Turbulence Transport

- GKV code is applied to HJ NBI plasmas.

✓ ITG mode is unstable

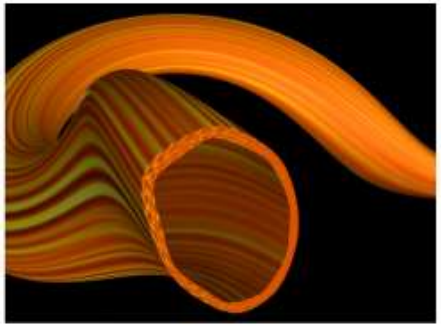
✓ Elongated mode structure in B direction due to weak shear

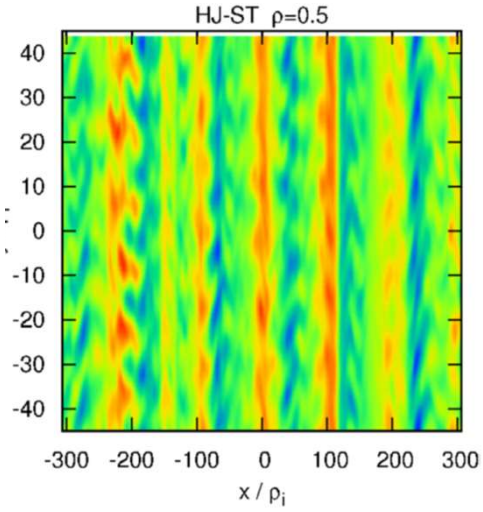
✓ Large amplitude of ZF is expected

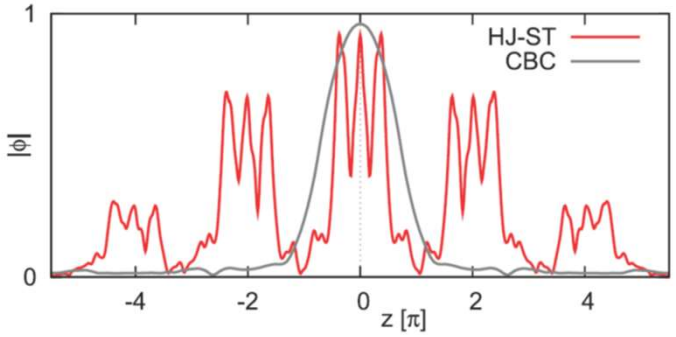
✓ Growth-rate in high ε_b case is smaller than standard one

✓ Nonlinear calculation shows same tendency

- ➢ due to stronger |B| at bad-curvature region
- ➢ Consistent to the experimental result







Electrostatic potential profile of the ITG mode

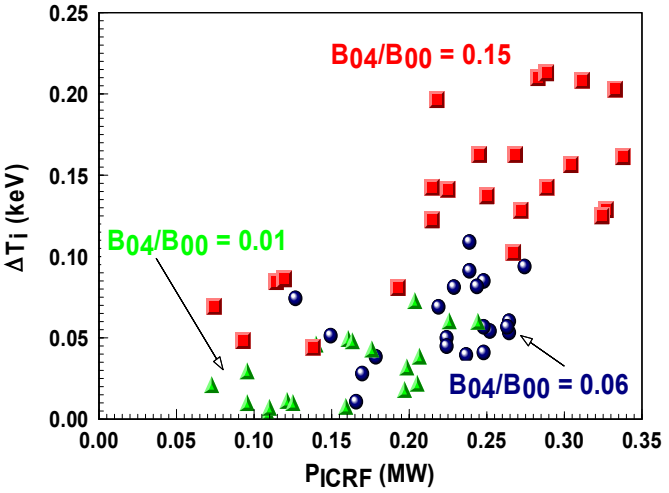
Config	standard	High ε_b
$\gamma(v_{Ti}/R_0)$	0.4	0.26
$\chi_i(v_{Ti}\rho^2_{Ti}/R_0)$	5.9	4.2
$\chi_e(v_{Ti}\rho^2_{Ti}/R_0)$	2.4	1.7

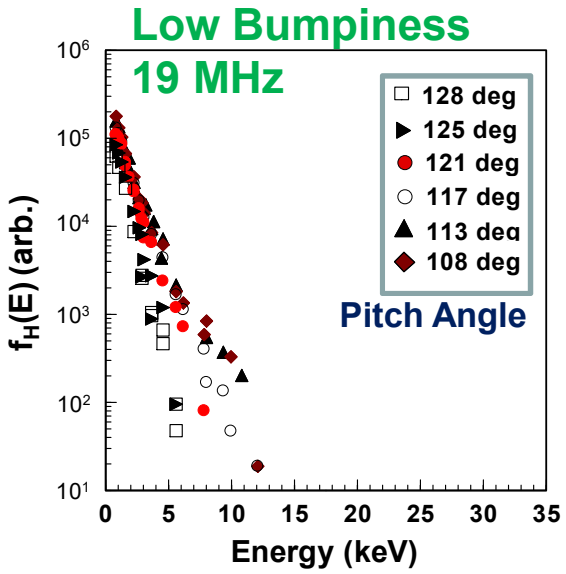
A. Ishizawa *et al* 2017 *Nucl. Fusion* **57** 066010

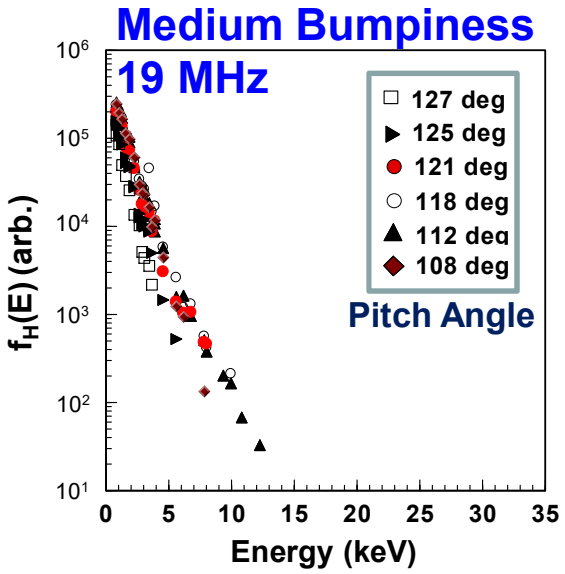
High Bumpiness Is Favorable for Energetic Minority Proton Confinement and Bulk Heating

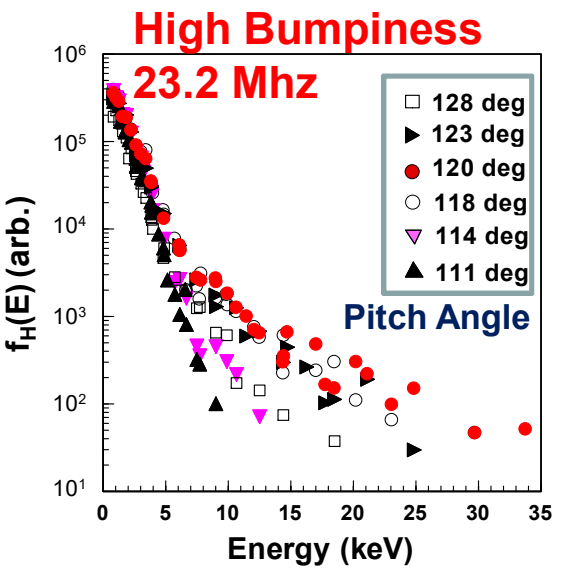
- ICRF pulse of 23.2 MHz or 19 MHz with 250-290kW was injected into an ECH target plasma where $T_i(0)$ = 0.2 keV, $T_e(0)$ = 0.8 keV and n_e = 0.4 x 10^{19} m^{-3}
- High energy ion-flux up to 34 keV is observed at the pitch angle of 120 deg only in the high bumpy case
- The bulk ion heating efficiency in the high bumpiness is highest among three configurations

Bulk Heating vs. Bumpiness









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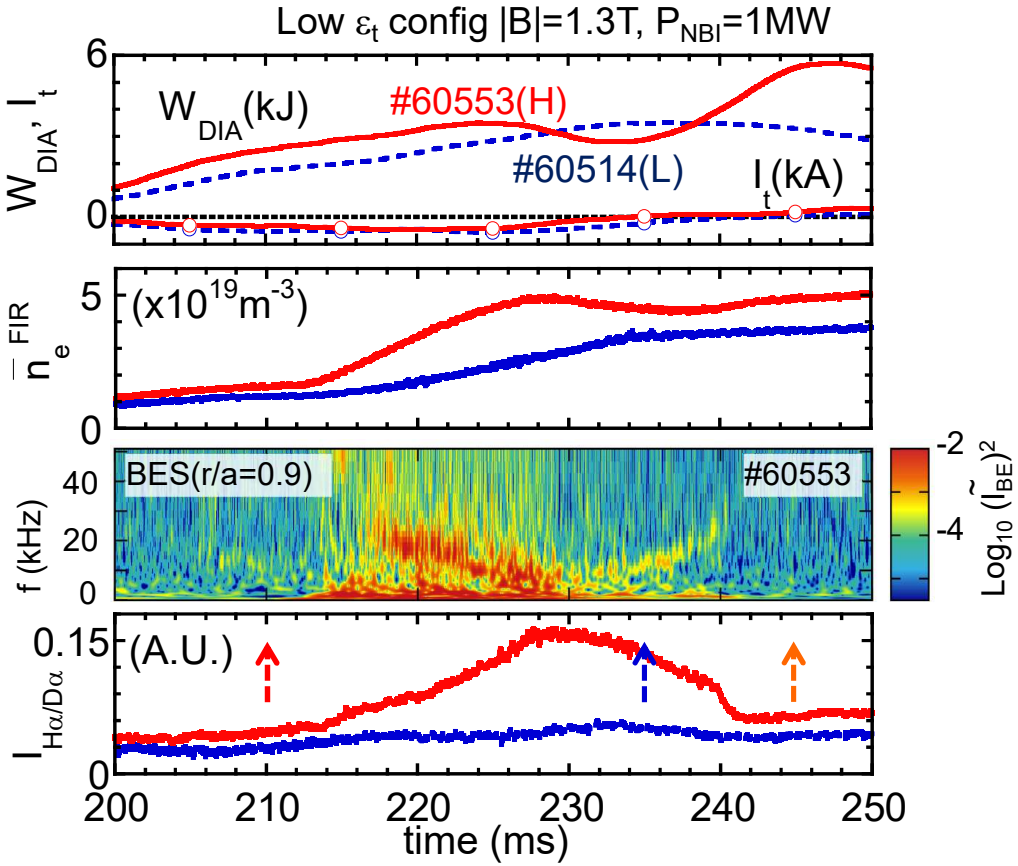
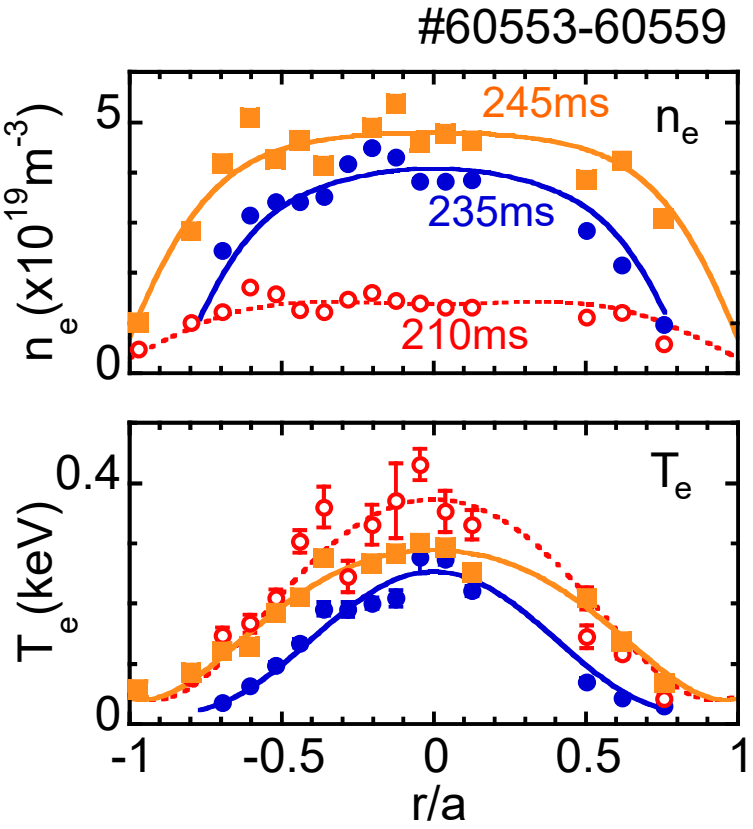
H-Mode Transition Triggered by High-Intensity Gas Puffing in NBI Plasmas



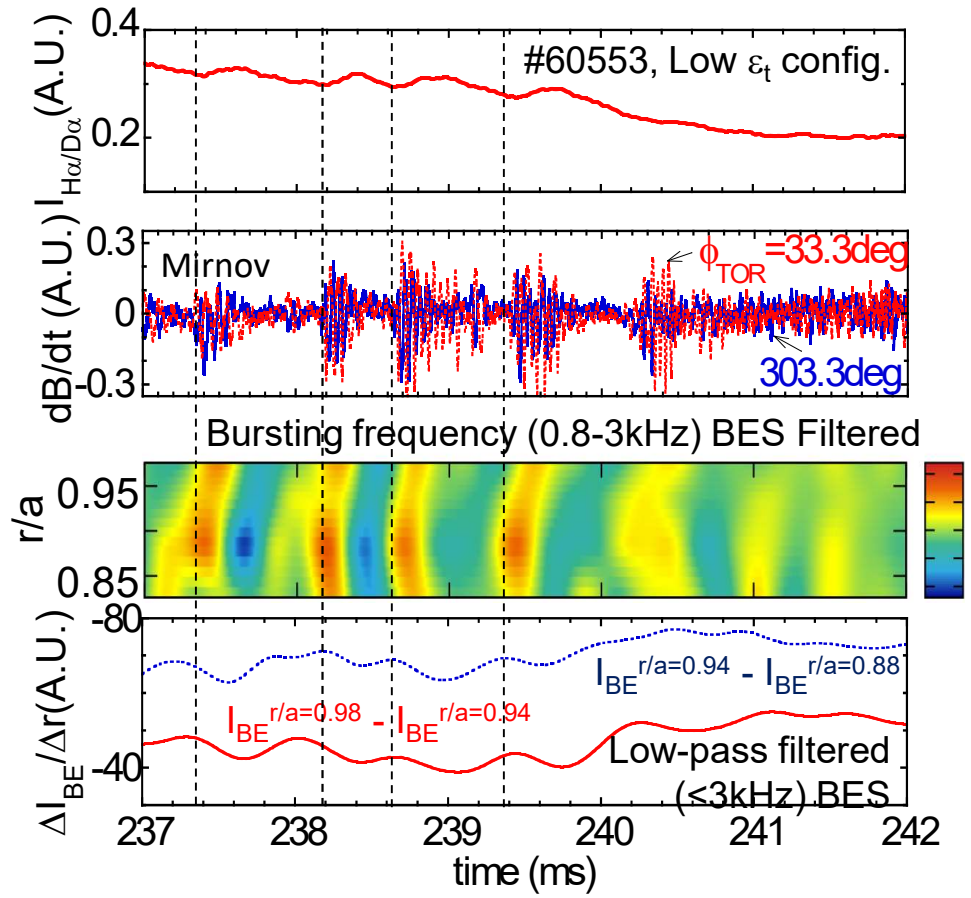


- ✓ A short-pulsed high intensity gas puffing (HIGP) was applied from inboard side.
- ✓ H-mode transition has been observed with formation of steep density gradient at peripheral.
- ✓ Before transition, an n = 2 bursting mode (4-30kHz) and low-f fluctuation (<3kHz), which causes particle exhaust, have been observed.

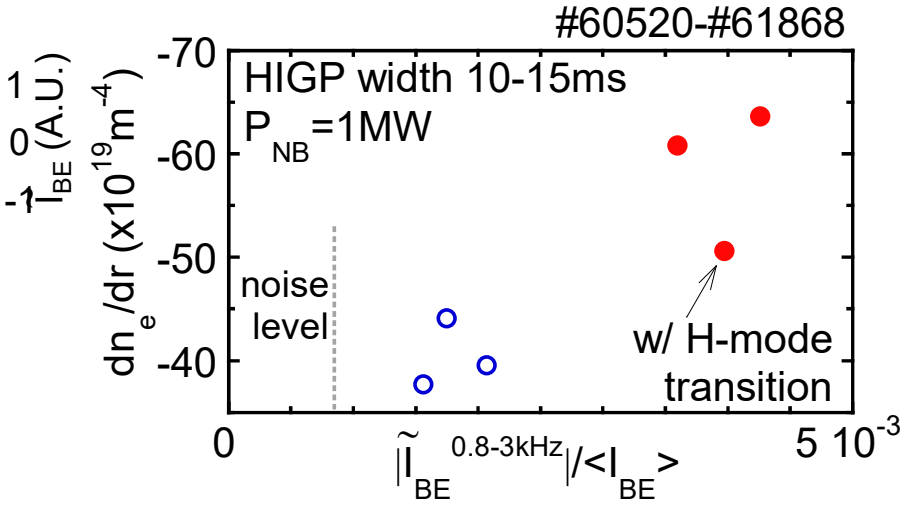
Kobayashi, IAEA FEC 2016

Relation between Bursting Mode and H-mode Transition

- A bursting n=2 mode with f=5-30kHz has been observed in density and magnetic fluctuations before L-H transition



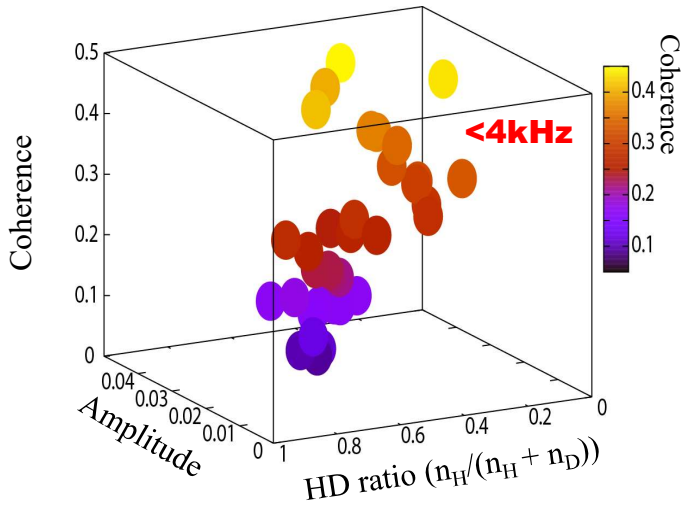
- Reduction in the particle exhaust at transition may trigger formation of the steep density gradient in the peripheral region



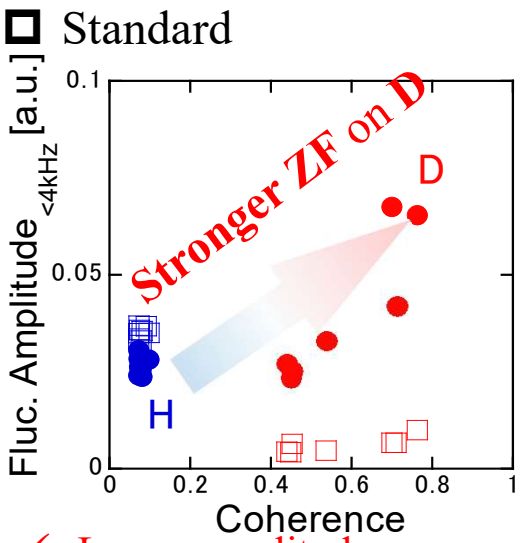
Kobayashi, IAEA FEC 2016

Isotope Effect and Its Configuration Dependence of Zonal Flow

A hypothesis/ ZFs contribute to isotope effect?

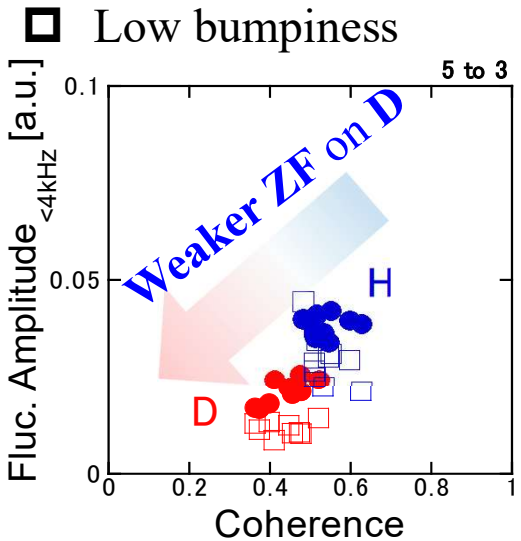


- Isotope effect on long range correlation (ZF) were investigated in Tokamaks (TEXTOR, ISTTOK) and helical devices(TJ-II, Heliotron J).



- ✓ Larger amplitude
- ✓ Stronger correlation

on D plasmas



- ✓ Smaller amplitude
- ✓ Weaker correlation

on D plasmas

- Opposite dependence of isotope effect, **weaker correlation and amplitude of ZF on D plasma**, is observed in low bumpiness configuration.

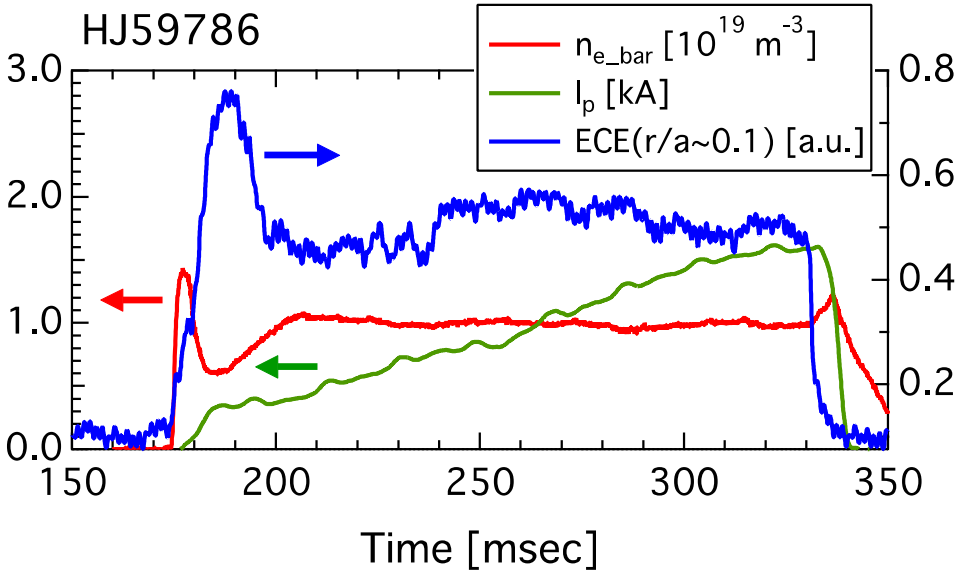
→Configuration optimization might be necessary from the viewpoint of turbulence & isotope effect.

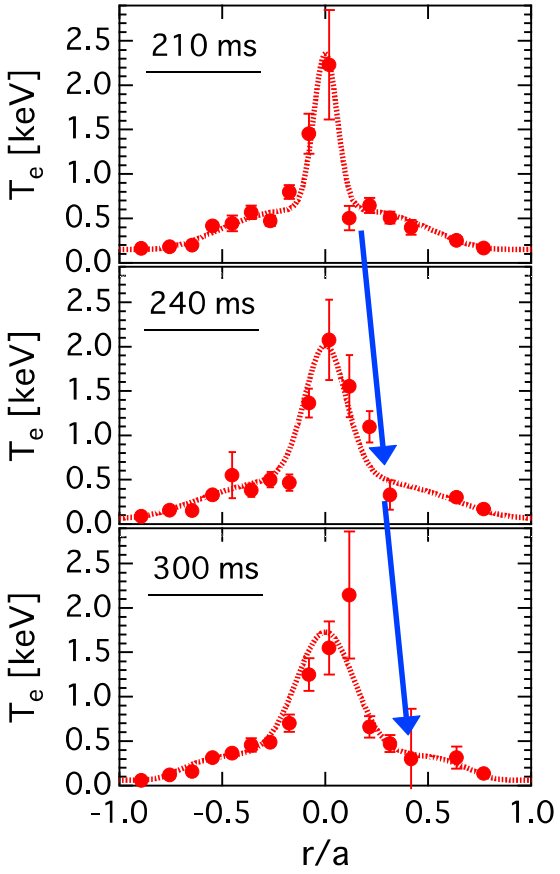
S. Ohshima, ISHW2017, Invited Talk

Expansion of Enhanced Confinement Region in Electron ITB During Plasma Current Ramp-up

ECH Conditions

- Heating position：magnetic axis
- Injection power: 270 kW
- absorption rate(X-mode, single path): ~90%

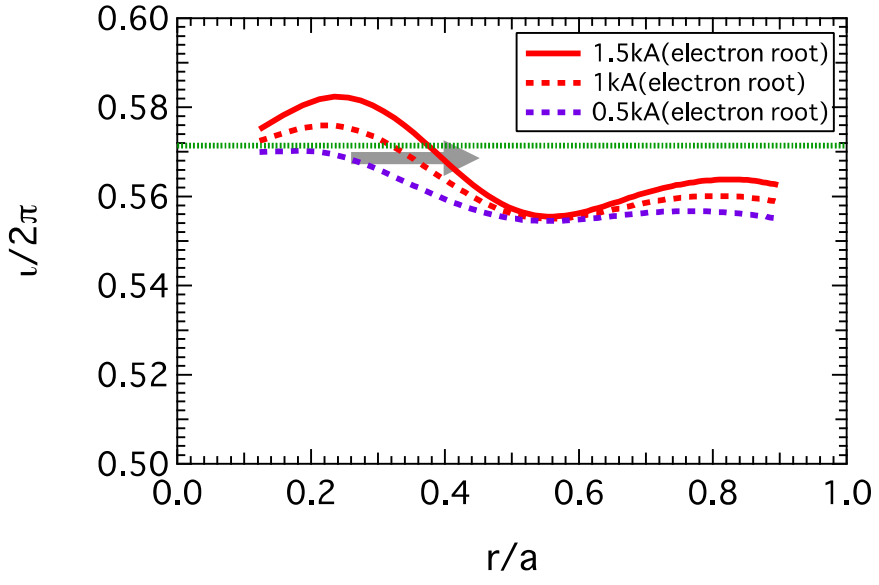




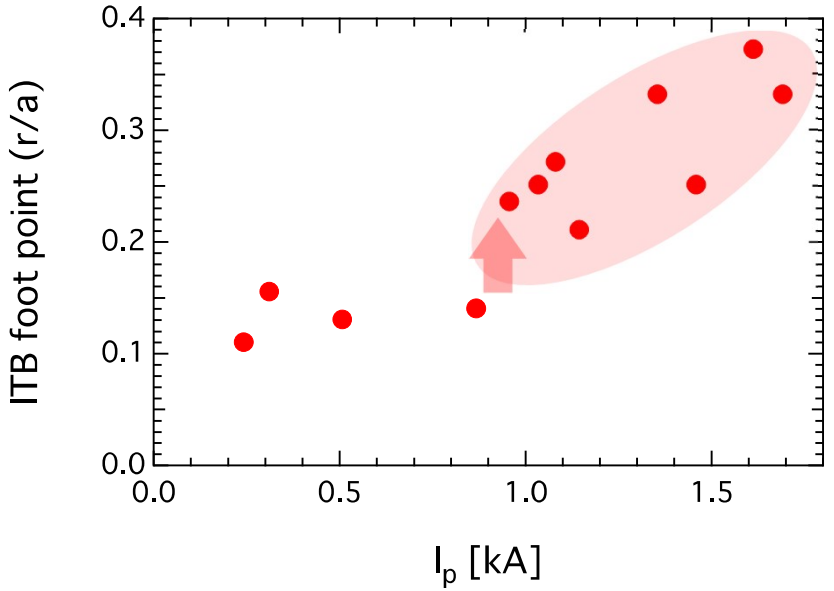
- ✓ The rapid increase of the T_e at r/a~0.1 is observed at the plasma current ~0.6 kA.
- ✓ The eITB foot points moves to the outer region as the current increase.

e-ITB Foot Point Moves As The n/m=4/7 Rational Surface Appears and Shifts Outward

Rotational transform profiles after the formation of n/m=4/7 rational surface



eITB foot point after the formation of n/m=4/7 rational surface

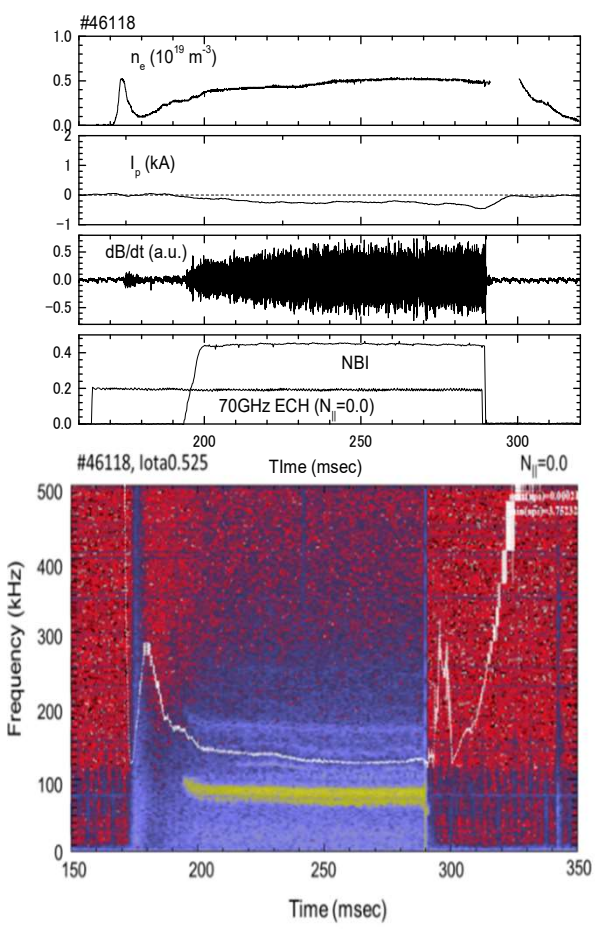


- ✓ When the plasma current exceeds the threshold (Ip ~ 0.9 kA), the ι(r/a)/2π exceeds 4/7 and the rational surface ι/2π= 4/7 appears
- ✓ As the plasma current increases, the ι(r/a)/2π around r/a ~ 0.2 increases, causing the movement of the position of rational surface.

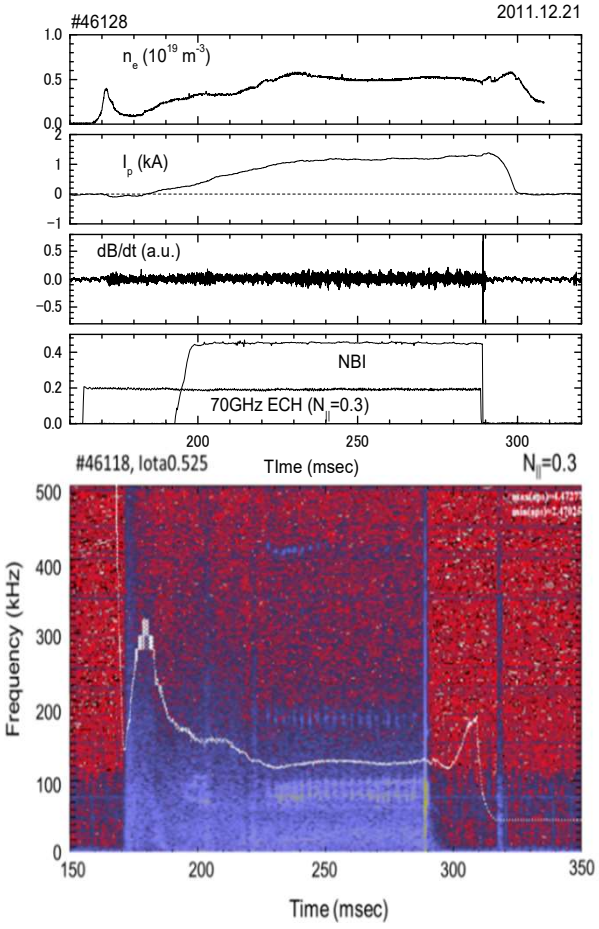
According to the movement of the rational surface, the eITB foot point moves to the outside region.

Both Co and Counter ECCD Stabilize EPM and GAE in Heliotron J

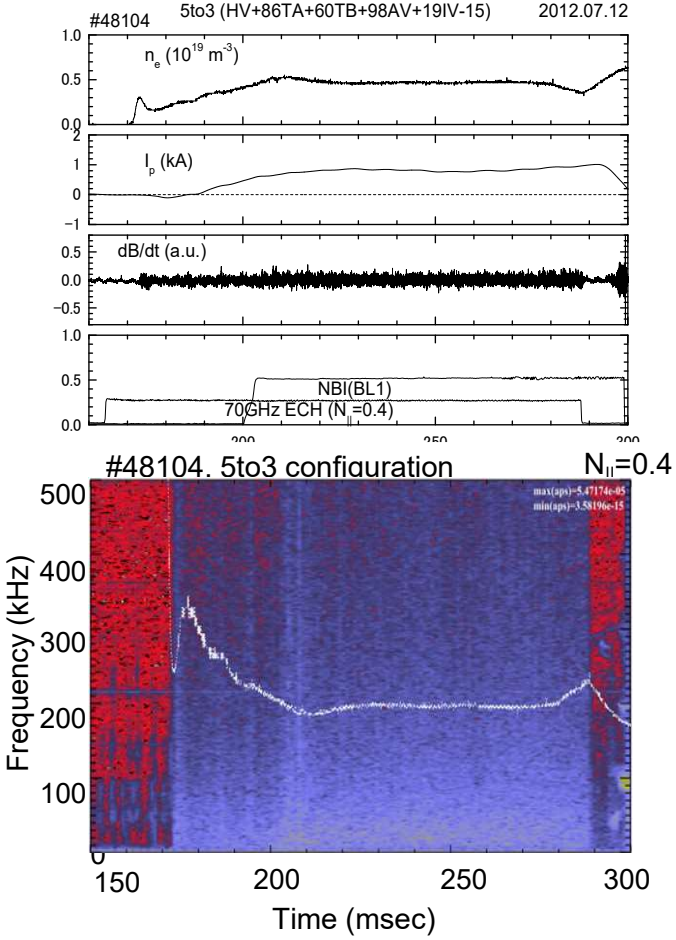
No ECCD ($N_{||}$=0.0)



Ctr-ECCD ($N_{||}$= -0.3)



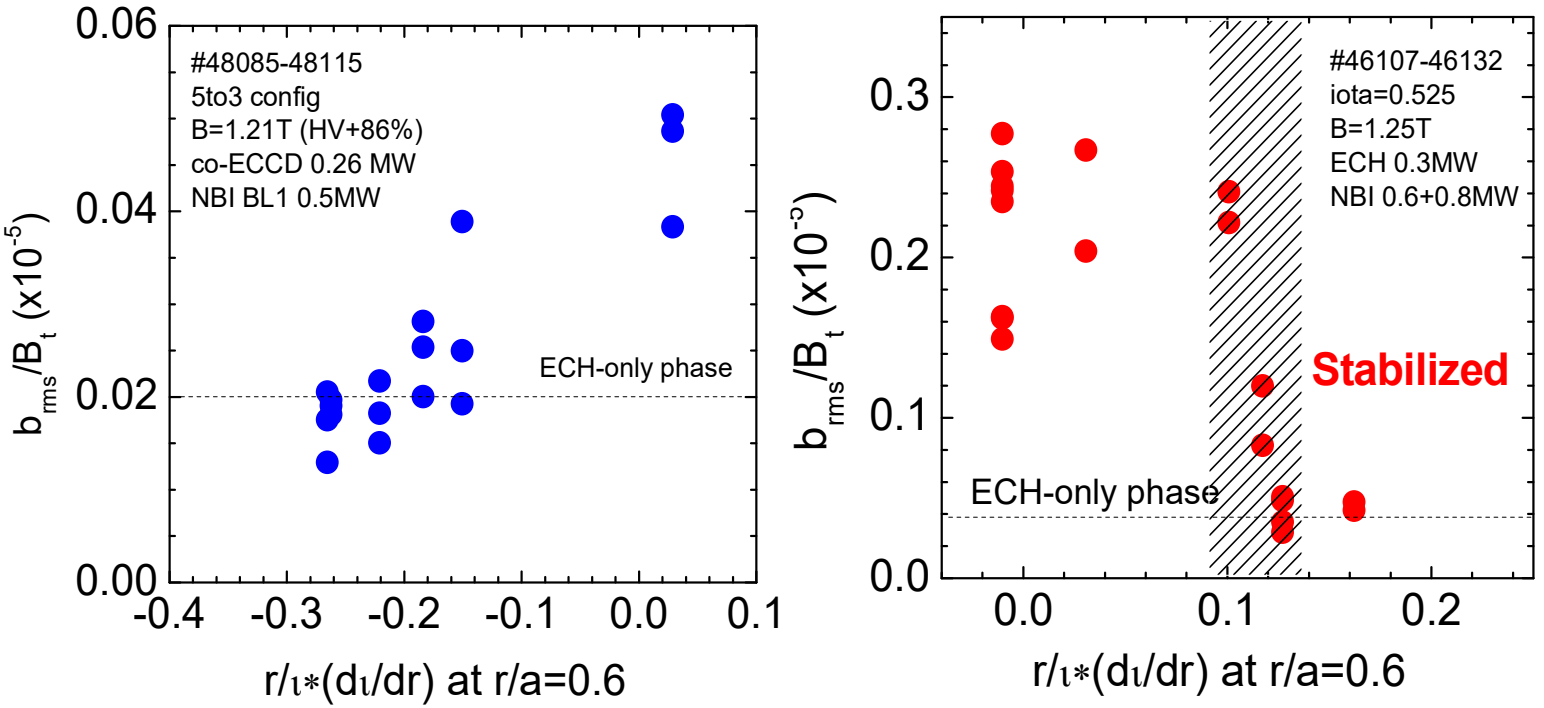
Co-ECCD ($N_{||}$= +0.4)



Nagasaki, Nucl. Fusion (2013)
Yamamoto, Nucl. Fusion (2017)

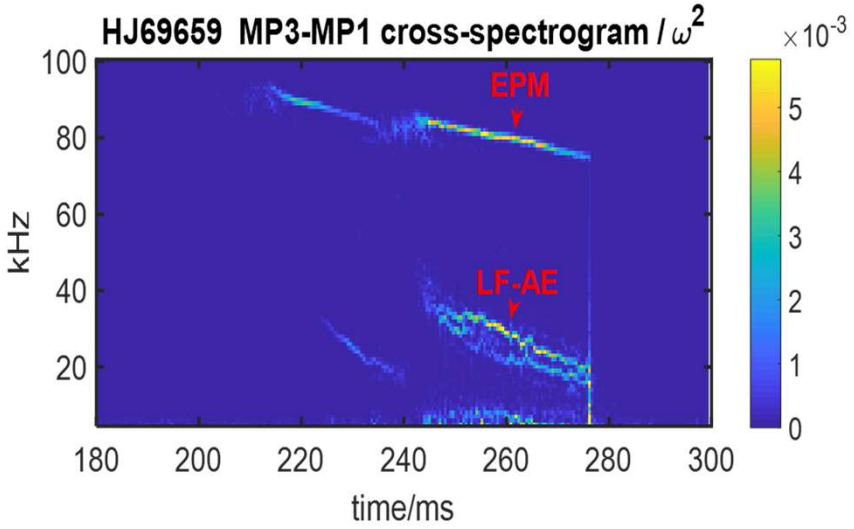
Stabilization Effect Depends on Magnetic Shear Intensity

- EC-driven current enhances magnetic shear (s ~ 0 in vacuum)
- Amplitude of EPMs is obviously suppressed by increasing Ip regardless of its sign

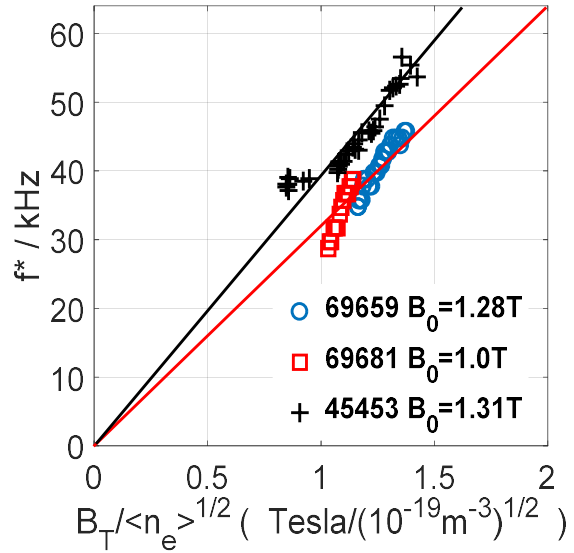


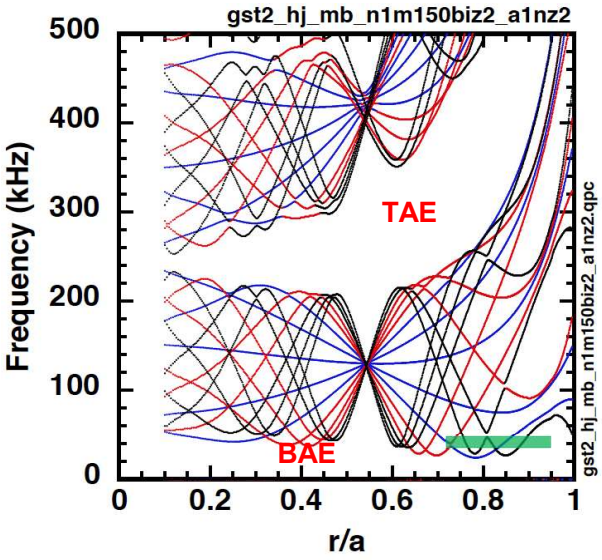
- EPMs suffer from strong continuum damping whose rate is proportional to magnetic shear
- Increase in absolute magnetic shear leads to suppression of EPMs

A Low-Frequency Alfvén Eigenmode (LF-AE) Is Observed in Co-NBI Plasmas

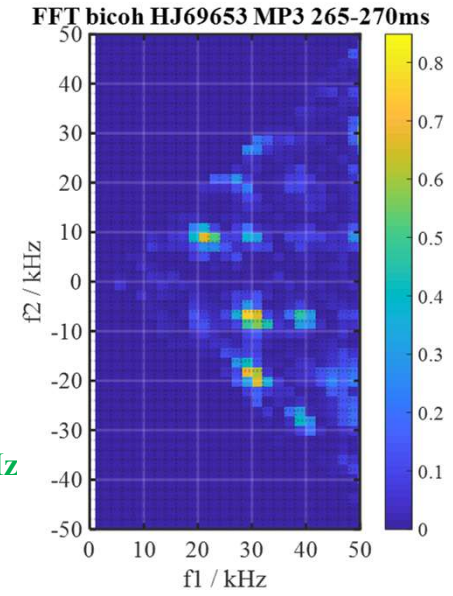


- LF-AE is steadily observed in NBI heated, co-current flowing plasmas in standard configuration.
- Real frequency linearly depends on $B_0/\sqrt{n_e}$.
- Real frequency is near the boundary of BAE gap.
- Nonlinear interaction exists among bands of LF-AE and a very low frequency (<10kHz) m=0,n=0 mode.





DATA
rho≥0.71
f^* = 41 kHz



Near-Future Plans

We will carry out next experimental campaign from July, 2018

- Understanding of MHD and Turbulence
  - Isotope effect (H/D ratio control)
  - Turbulence measurement with fast CXRS, reflectometer, CECE, Langmuir probes, fast digitizer oscilloscope
- Optimization of particle fueling and operation scenario
  - HIGP, SMBI, pellet injection
  - Resonant magnetic perturbation coils
- Control and measurement of plasma profiles and flow
  - Iota (q) control for e-ITB
  - Toroidal and poloidal flow measurement with CXRS
  - Multi-pass Nd:YAG TS system and multi-channel 320GHz FIR system
- Energetic particles and related MHD instabilities
  - Scintillator type lost ion probe, Si FNA, Fast camera
- Impurity transport
  - Laser blow-off method

Summary

- The 3D magnetic configuration scan in Heliotron J has demonstrated
  - The parallel transport such as BS and EC current and toroidal rotation agrees with neoclassical theory
  - The bumpiness affects the global energy confinement and the energetic particles
- Recent experimental results show
  - The high-density H-mode triggered by HIGP is closely related to a bursting mode, forming steep density gradient in the peripheral region
  - Long range correlation is enhanced at D-dominant plasmas
  - Electron ITB formation is linked with a rational surface
  - AEs are effectively stabilized by ECH/ECCD

- We have been carrying out the Heliotron J experiments for 18 years
- We have started discussion about next generation machine