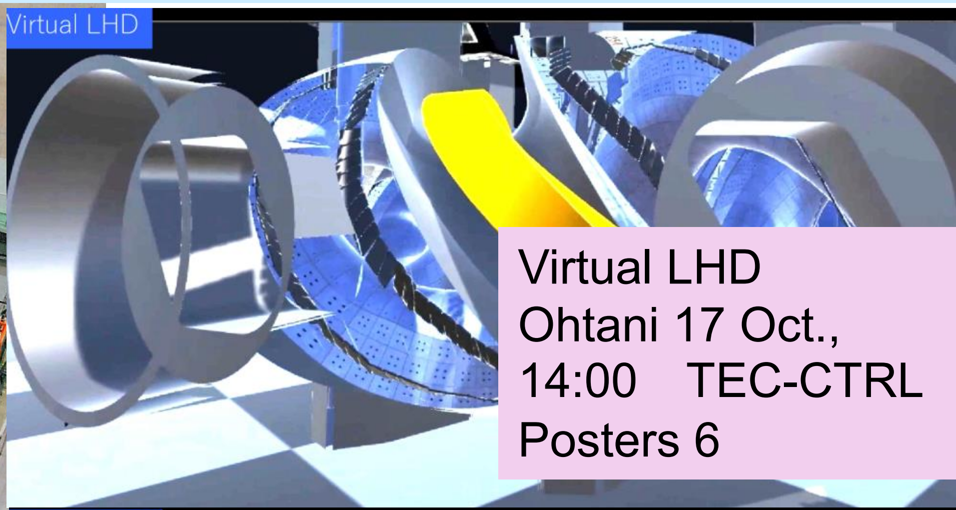
Recent Advances in Plasma Control and Physics Research in the Large Helical Device

Kenji Tanaka and LHD experiment group
National Institute for Fusion Science

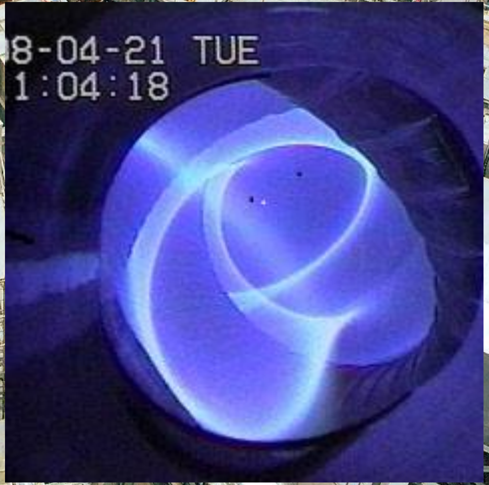
3xNNB (180keV/5MW), 2xPNB(40keV/6MW) total 27MW
ECH 2x77GHz, 2x154GHz ECH(each 1MW) total 4MW
ICRH 38.47MHz 2MW

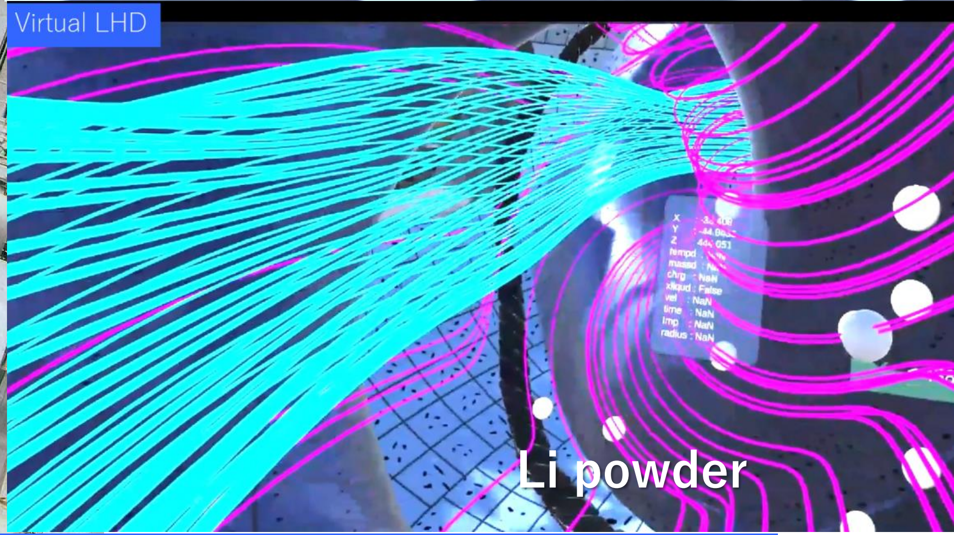
- ✓ 48min. 36GJ input (Muto et al, FST2015)
- ✓ Ti=10keV, Te=6keV at 1x10^{19}m^{-3} (Osakabe et al, NF2022)



Virtual LHD
Ohtani 17 Oct.,
14:00 TEC-CTRL
Posters 6

- ✓ 150chYAG Thomson
- ✓ 50ch CXRS
- ✓ Phase Contrast imaging
- ✓ Doppler reflectometry
- ✓ Millimetre backward scattering
- ✓ HIBP





Physics issues for plasma control

There are interactions and interplay in plasmas, for the reliable control of plasma , it is necessary to understand:

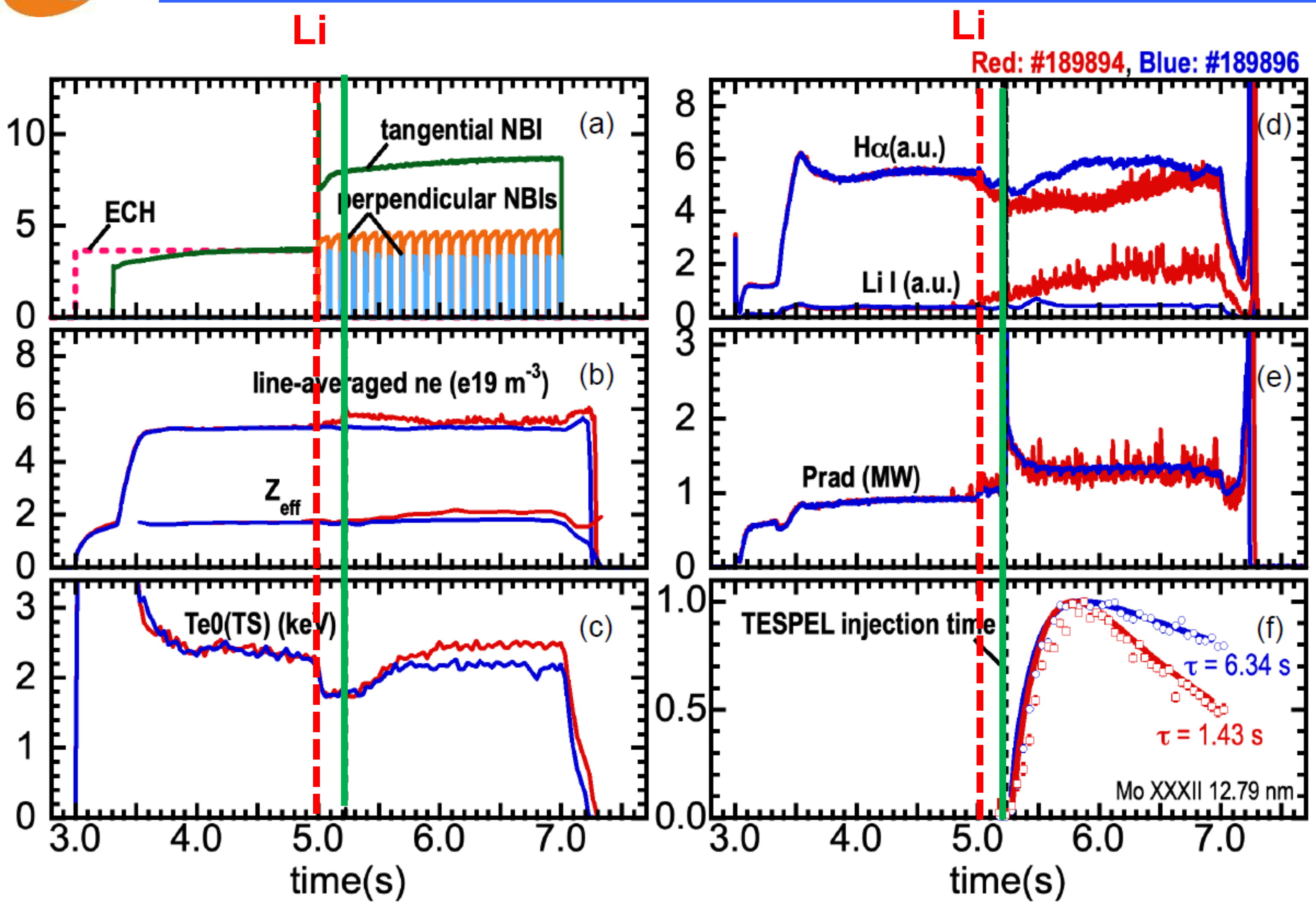
1. Interplay of light and heavy impurity ions to avoid impurity accumulation and to keep good confinement

2. Interactions of turbulence to control transport
i) Interactions of ion and electron scale turbulence
ii) Interplay of local and non-local characteristics
iii) Interactions of different turbulence modes

3. Interactions between EP driven waves and bulk ion
Possibility of the direct ion heating by wave-particle interaction
i) EGAM
ii) MHD burst

Based on physics knowledge, advanced plasma control using data assimilation is presented by Morishita (17 Oct 8:30 TEC-CTRL Oral).

Core heavy impurity transport was enhanced by Li powder



D. Medina-Roque 16th Oct, 8:30
EX-C posters 3

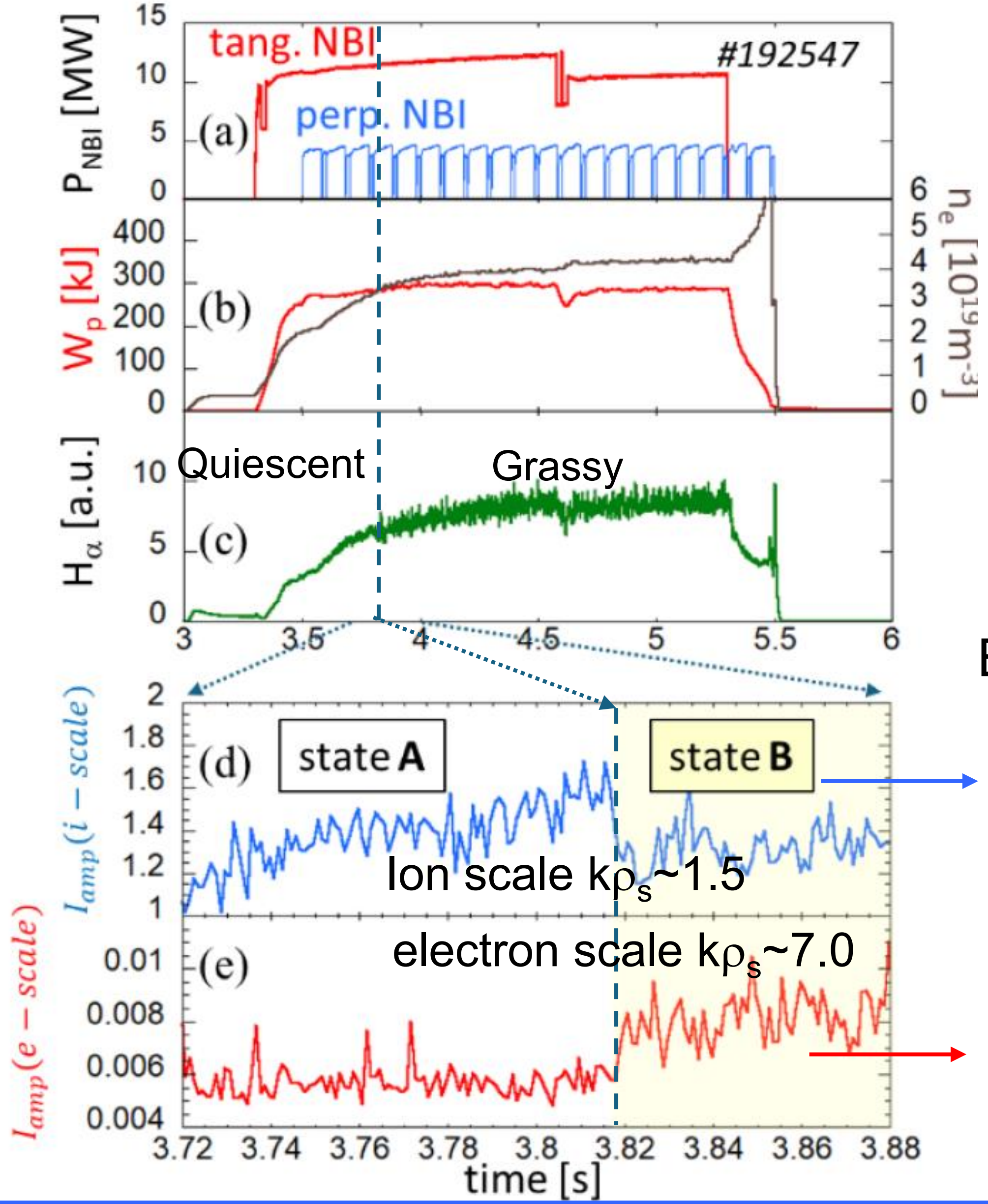
Red; with Li, **Blue without Li**

- ✓ Improvement of energy confinement was found.
- ✓ Decay time of Mo31+ is clearly shorter with Li powder indicating enhancement of heavy impurity transport.
- ✓ **Interplay between low Z and high Z impurity**

Molybdenum TESPEL (Tracer-Encapsulated Solid Pellet) was injected at 5.225s for the investigation of heavy impurity transport.

Simultaneous measurements of ion and electron scale turbulence.

T. Tokuzawa (Comm. Physics 2025)
15 Oct, 10:35 EX-C poster 1



Both at ρ = 0.9

Doppler reflectometry

Millimetre backward scattering

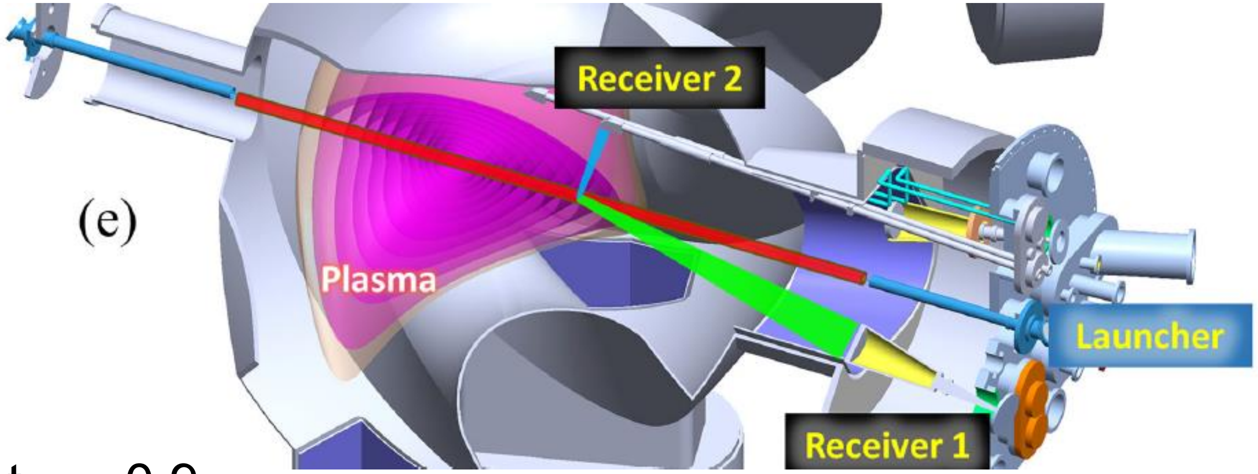
After the bifurcation

Ion-scale turbulence

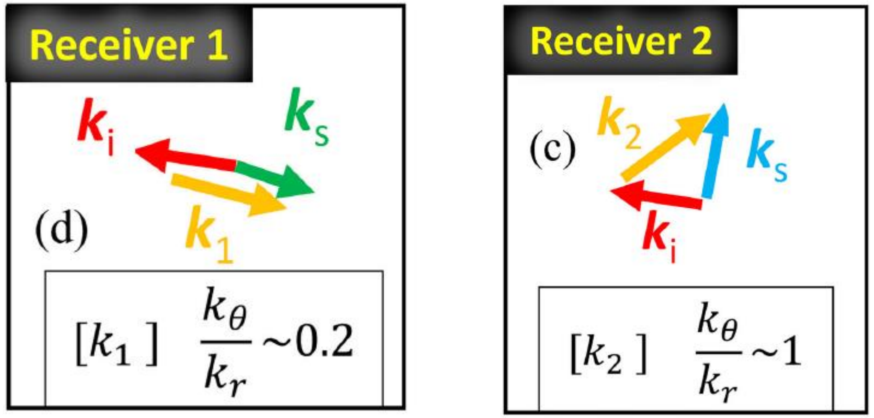
Electron-scale turbulence

Anti-correlation of i-scale and e-scale turbulence was found.

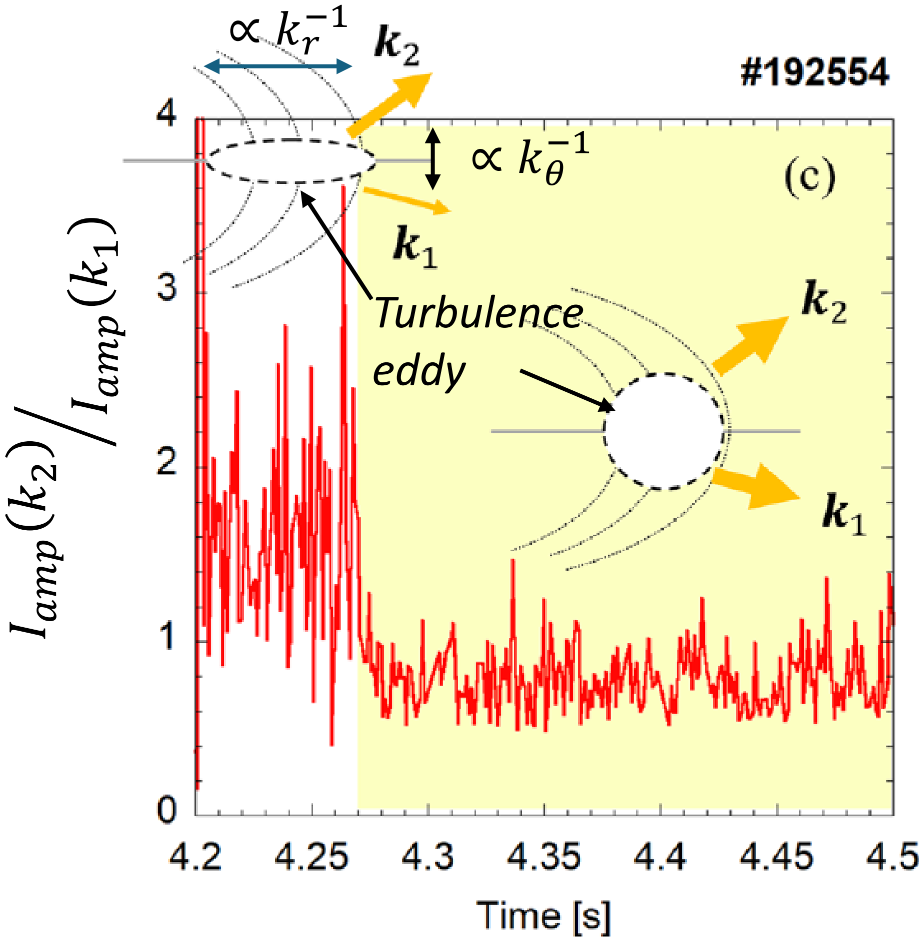
Turbulence anisotropy changes after confinement bifurcation.



at ρ = 0.9



Receiver2/Receiver1 shows turbulence anisotropy

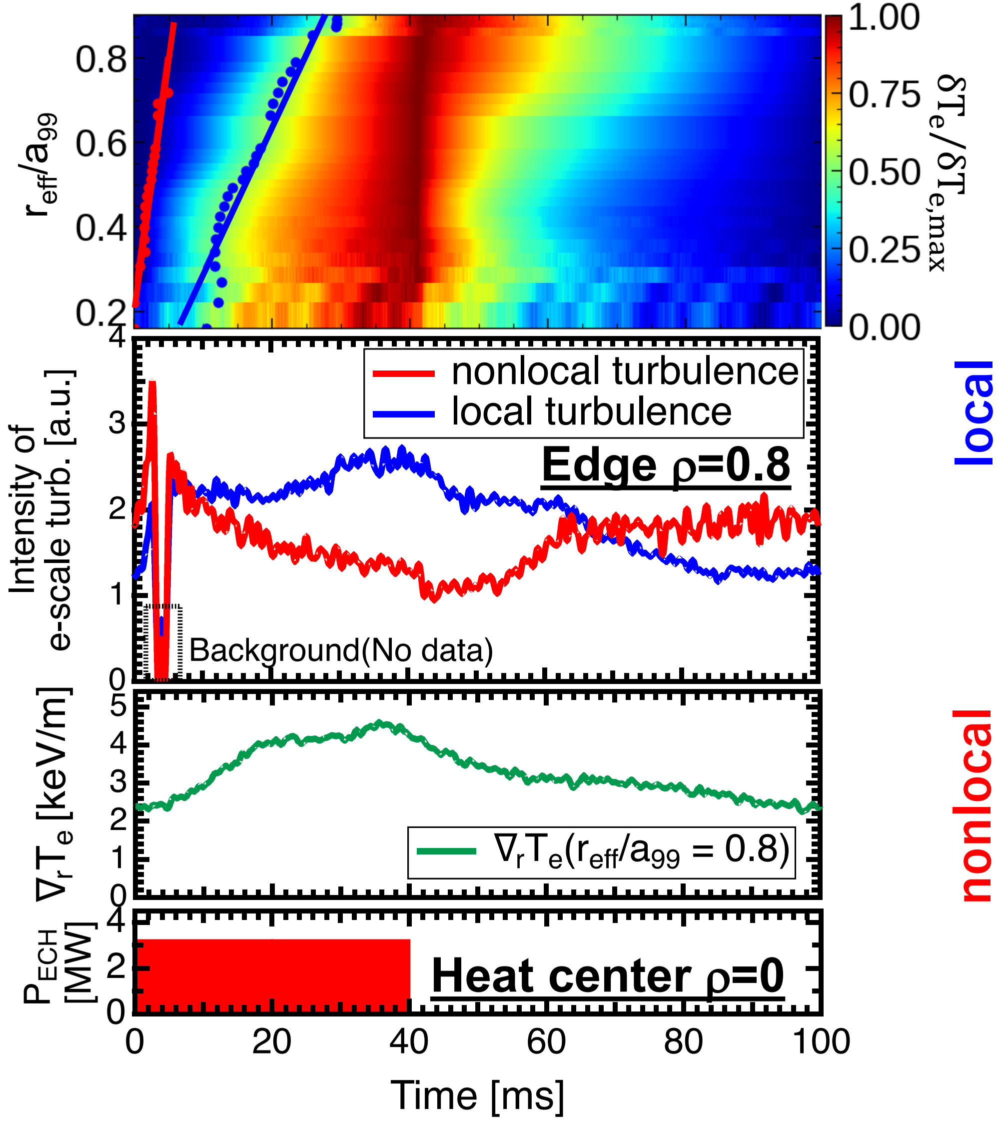


Before bifurcation:
Radially elongated turbulence eddy
After bifurcation:
Isotropic turbulence.

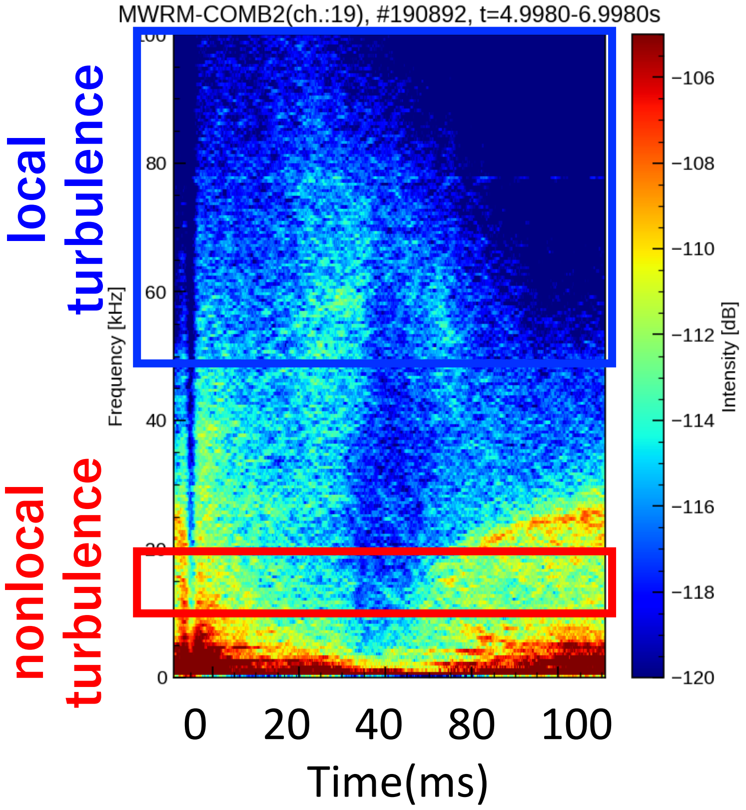
Local and non-local turbulence co-exists in the electron scale turbulence

Kenmochi
15 Oct, 10:35, EX-C Posters 1

Conditional averaged
25Hz ECH modulation



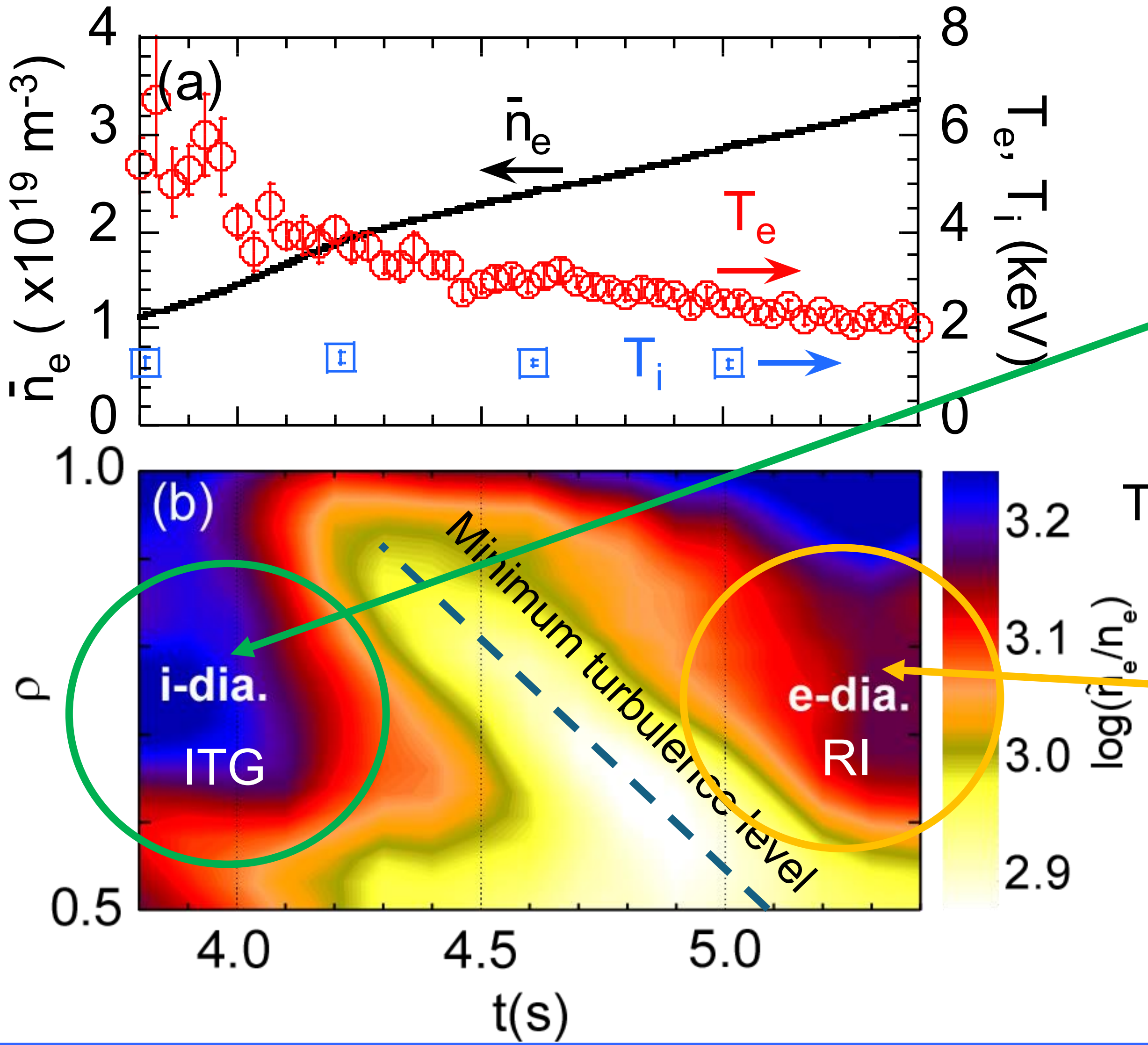
Electron-scale turbulence by backward scatering



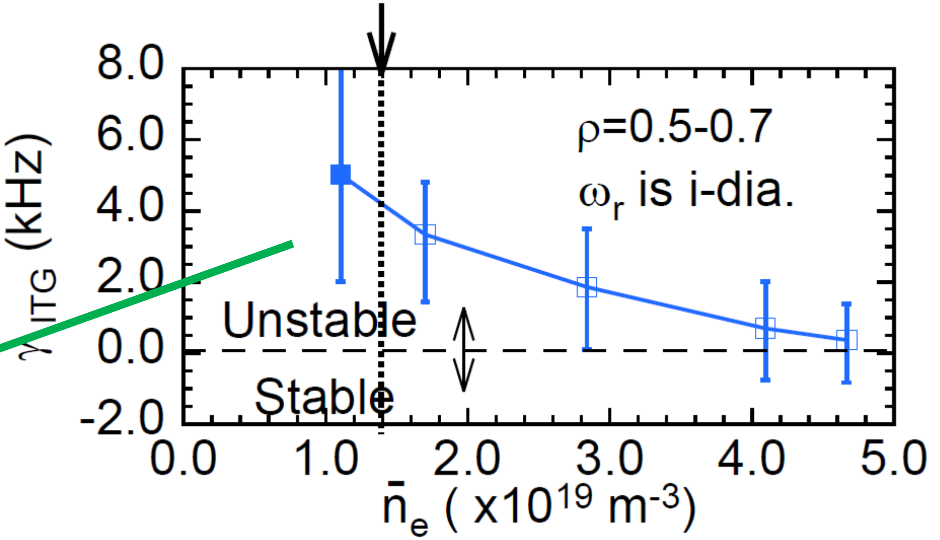
- ✓ Local turbulence (50-100kHz) follows change of Te gradient
- ✓ Non-local turbulence (10-20kHz) is excited almost simultaneously throughout the entire plasma region. → Connection between the edge and core.

Turbulence transitions from ITG to RI

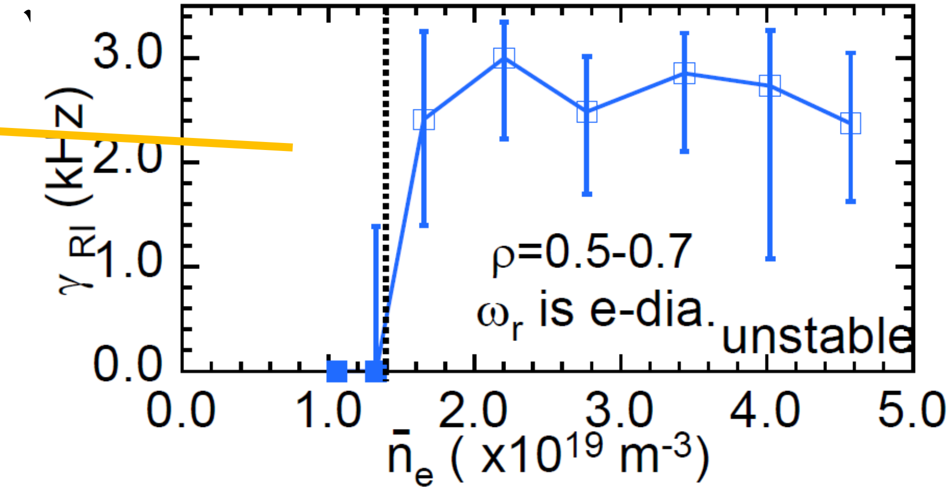
Kinoshita et al. PRL 2024



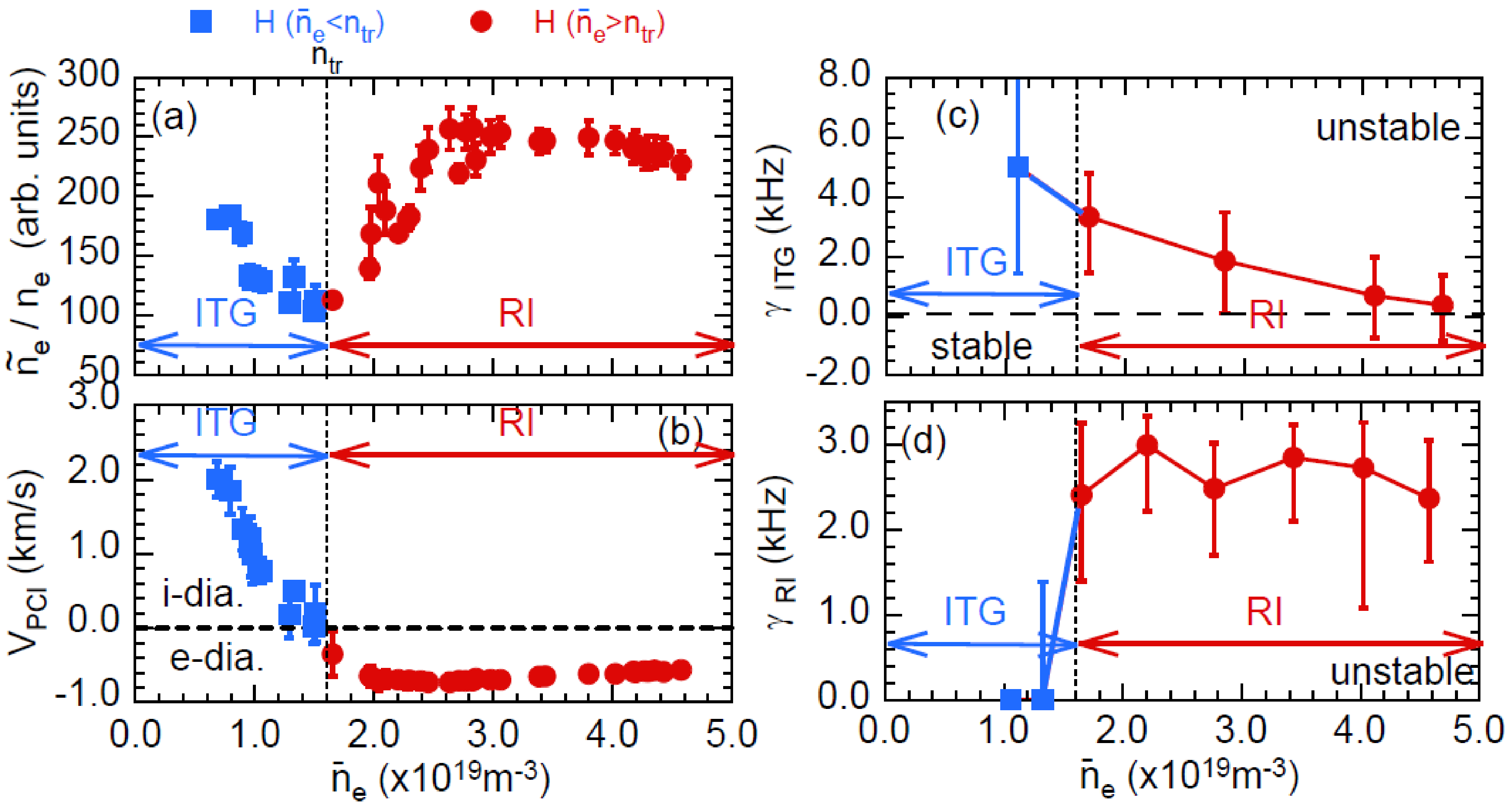
Local flux tube gyrokinetic ITG growth rate



Two fluid MHD Resistive Interchange (RI) growth rate

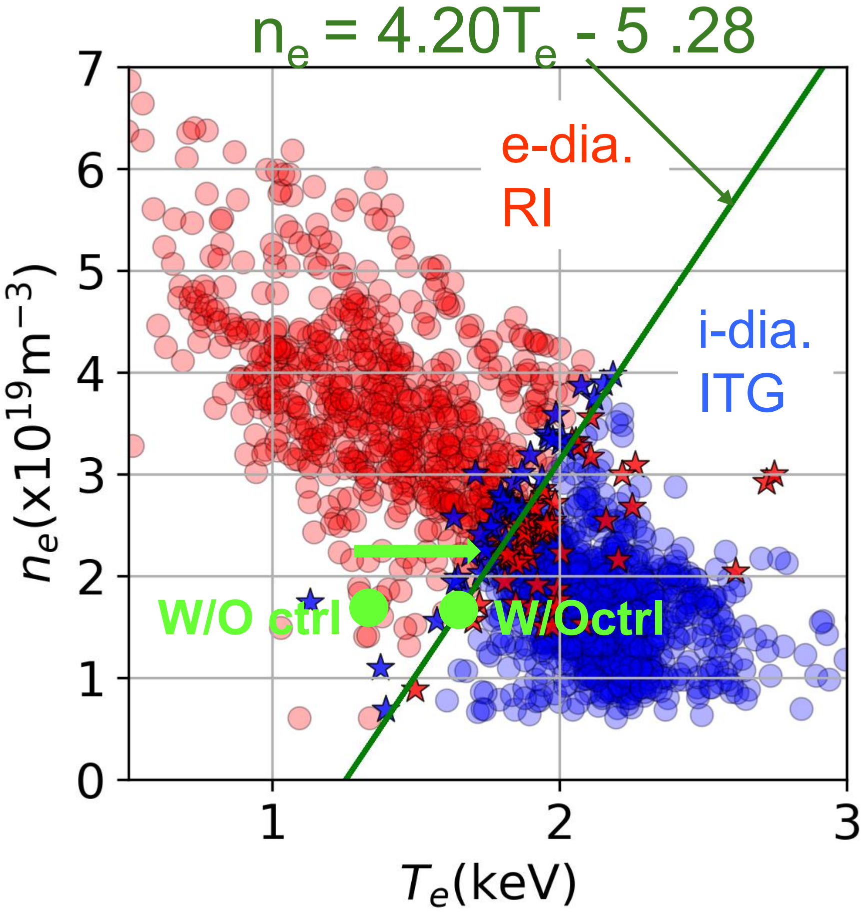


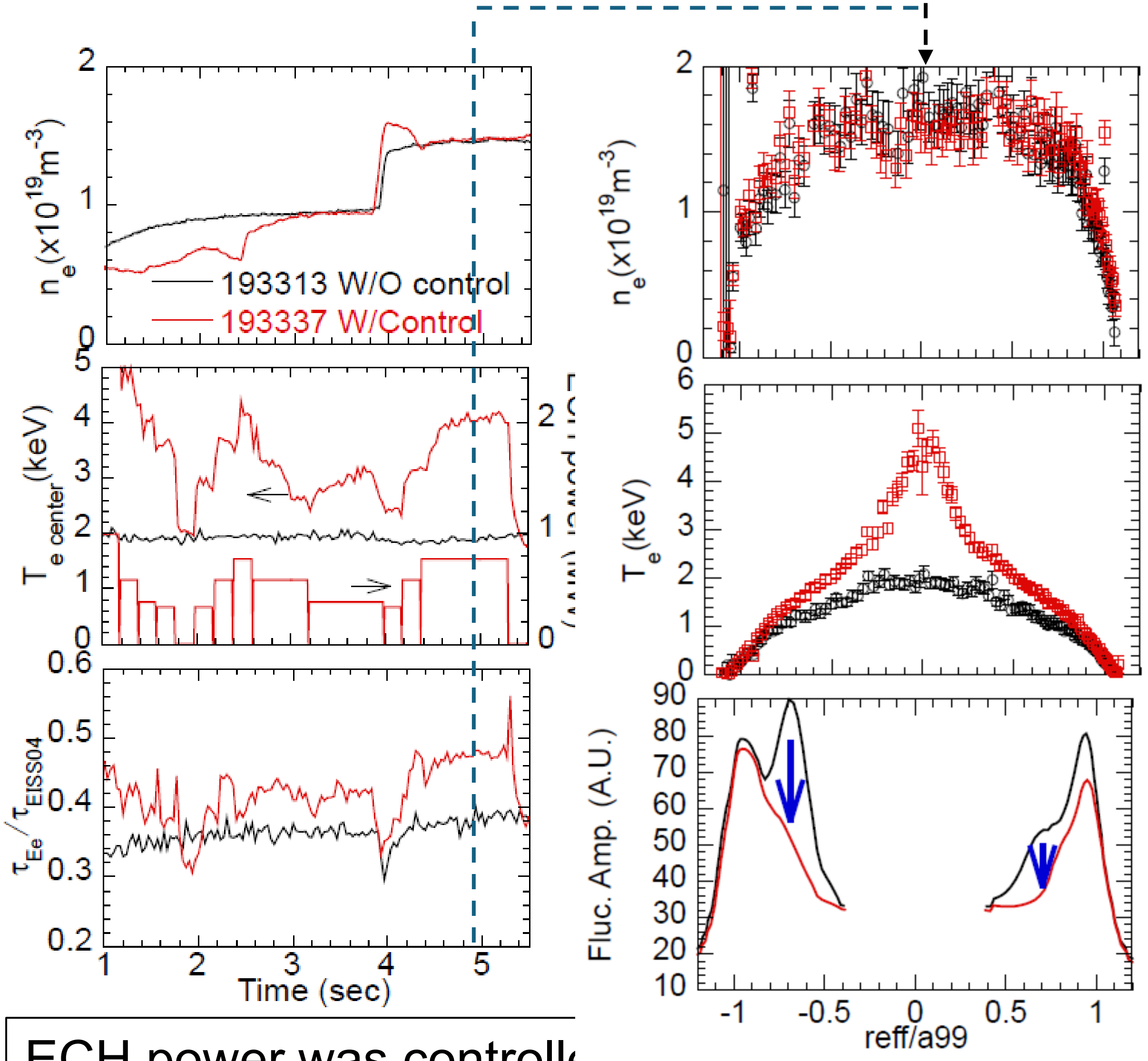
Turbulence phase velocity in the lab frame can be indicator of ITG or RI



- We consider keeping turbulence minimum condition at turbulence transition by feedback control.
- What determines the turbulence transition (n_e, T_e, T_i, T_e/T_i, dn_e/dr, dT_e/dr , dT_i/dr ……)?

Keeping minimum turbulence condition improved confinement.





Kinoshita
17 Oct 11:40 Oral

#193313
W/O control
RI dominant

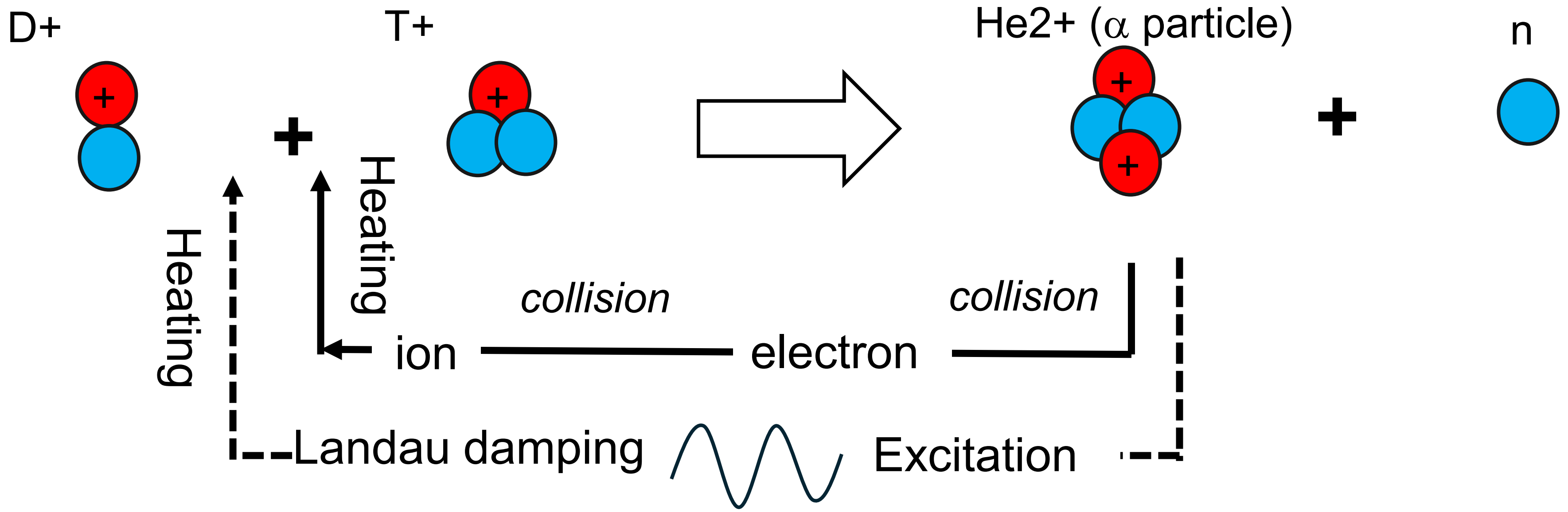
#193337
W/control
RI is supressed
due to the
lowering
resistivity with
ECRH

2000 data machine learning established transition condition.

ECH power was controlled to keep transition

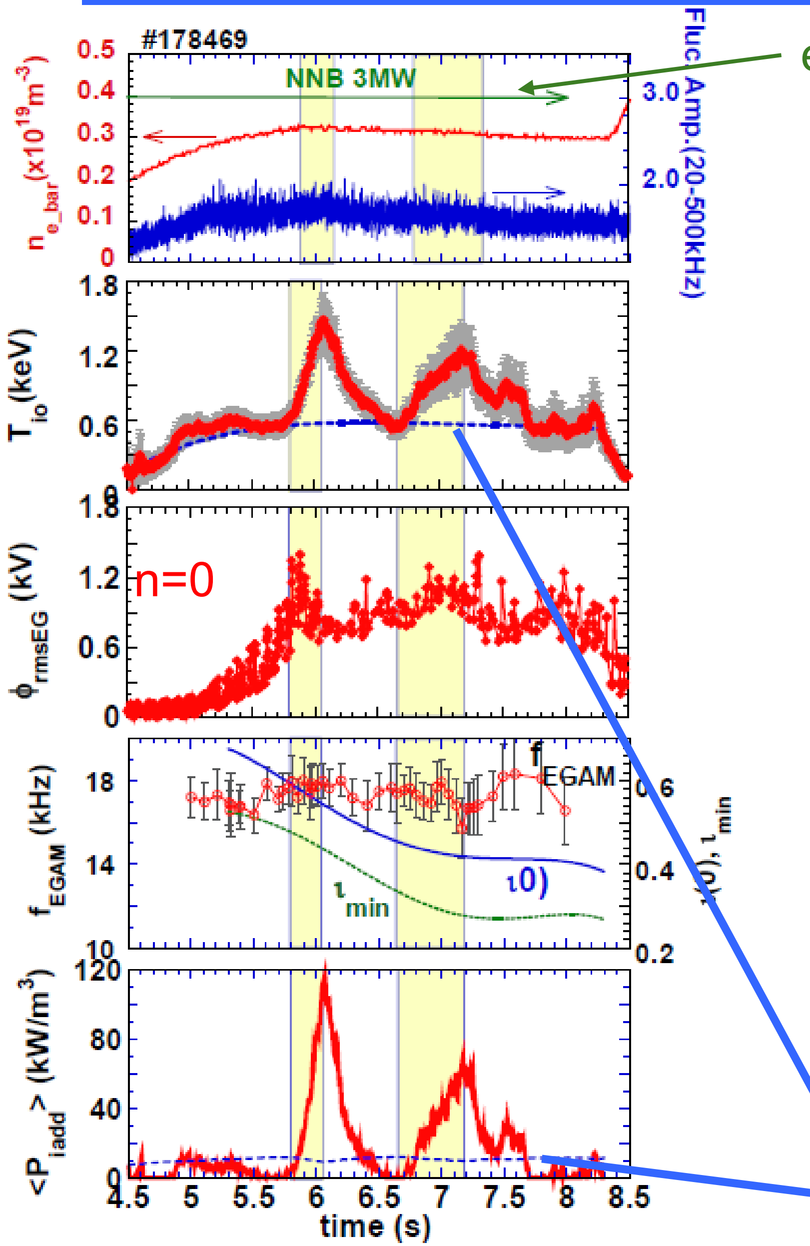
Ion heating by ion Landau damping was found in LHD

In DT-burning plasma under dominant electron heating, hot ion plasma having $T_i \gtrsim T_e$ is required for improved confinement and high fusion performance.
α particles heat electrons predominantly by the collisional slowing down process.
There is a possibility of direct ion heating by the Landau damping of EP driven waves.



1. Landau damping of energetic particle driven Geodesic Acoustic Mode in plasma centre
2. Landau damping of energetic particle driven MHD burst in plasma periphery region

Obvious reduction in EGAM potential fluctuations during T_{io}-increase phase

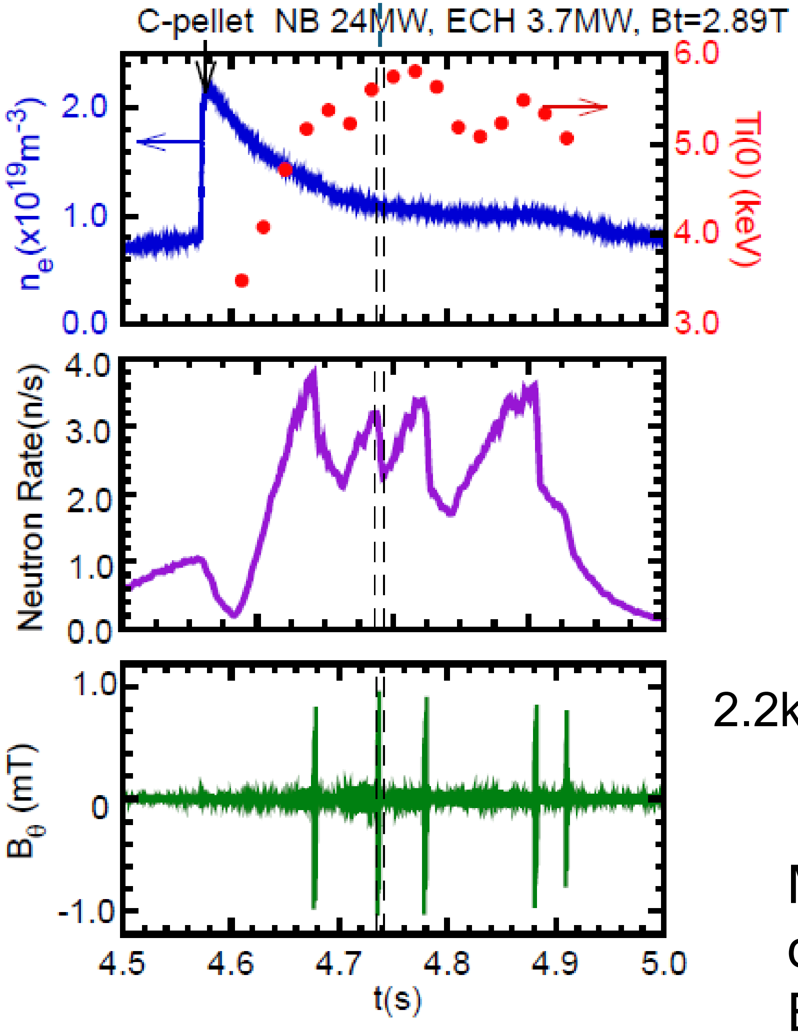


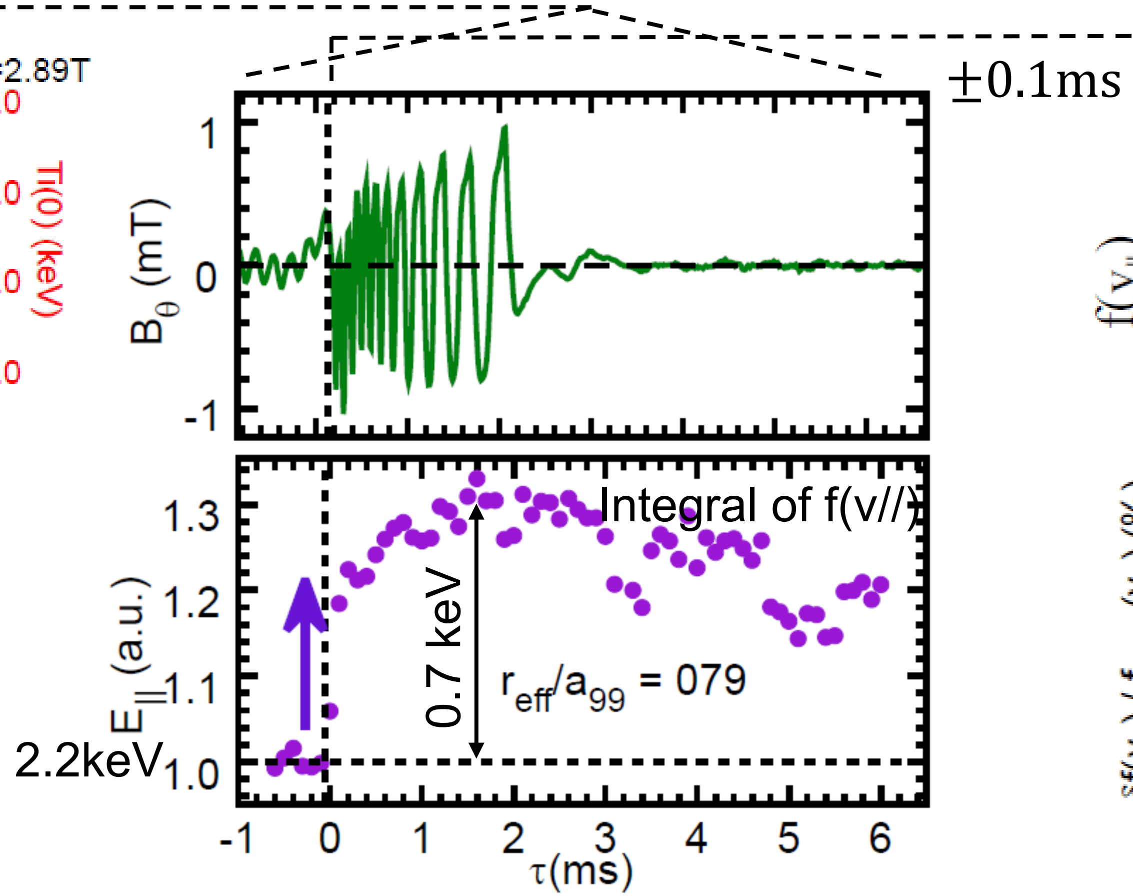
Toi, 16 Oct 14:00 EX- W Posters 4

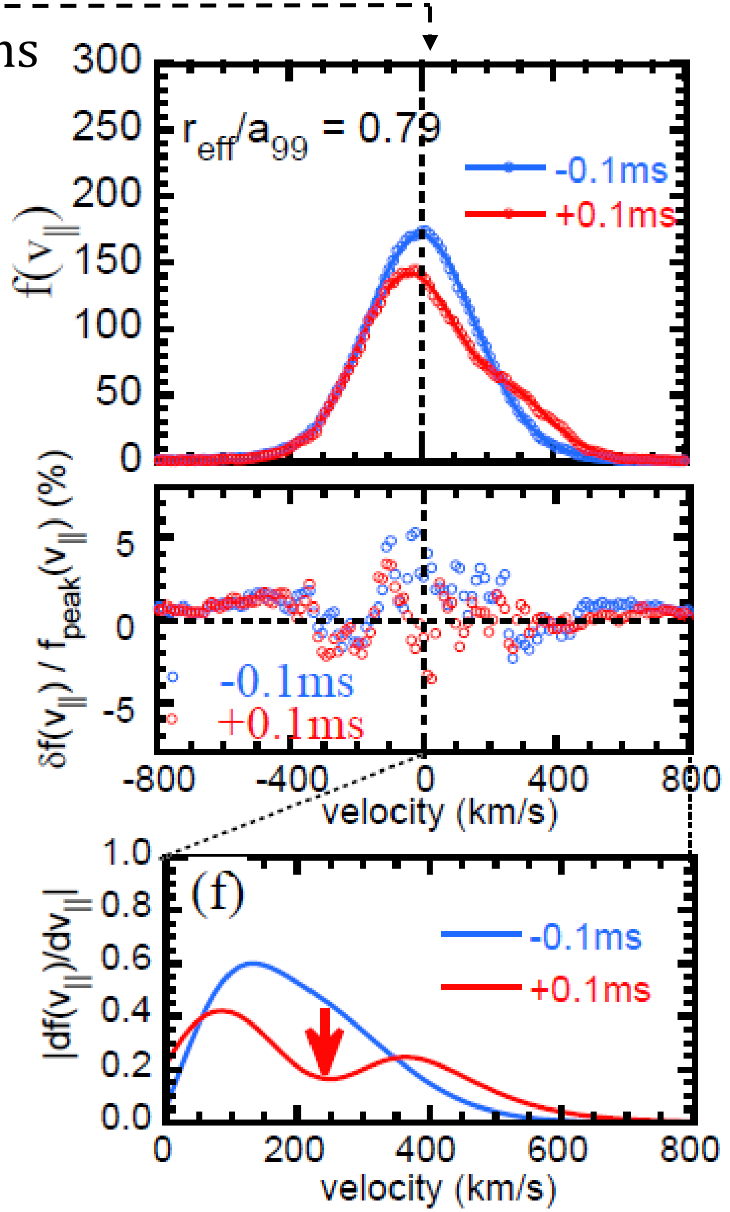
- Turbulence does not change → no improvement in anomalous transport
- Energetic particle driven Geodetic Acoustic Mode (EGAM) is identified by Alfven spectroscopy with magnetic probes, HIBP and AE3D code
- EGAM damping correlates well with T_{io}-increase
- The EGAM frequency does not respond to the T_{io}-increases.→Supporting evidence of EGAM
- Collision process (slowing down of NNB and equipartition heating) does not account for the increase of T_{io} and additional P_i is required

T_{io} and $<P_i>$ with collisional heating process

Ion heating by Landau damping is also found in EP driven MHD burst







MHD burst appears just before decrease of neutron rate → Evidence of EP driven mode

MHD burst deforms ion velocity function and increases ion temperature

Ida, 18 Oct 9:30 PD oral

Summary: We have found the key knowledge to solve issues

1. Interplay of light and heavy impurity ions to avoid impurity accumulation and to keep good confinement → Li powder improves bulk transport and degrades heavy impurity transport.

2. Interaction of turbulence to control transport
   i) Interaction of ion and electron scale turbulence
   → anti-correlation of i-scale and e-scale
   ii) Interplay of local and non-local characteristics → co-existence of both
   iii) Interaction of different turbulence modes → ITG-RI transition is controlled and leads to improved confinement

3. Interactions between EP driven waves and bulk ion
Possibility of the direct ion heating by wave-particle interaction
i) EGAM
ii) MHD burst
→ heating by the ion Landau damping

All presentations from the LHD experiment group

Wed, 15 Oct. 8:55 OV Oral (Tue, 14 Oct 14:00 OV poster)

1. **K. Tanaka+**, "Recent advances in plasma control and physics research in the large helical device"

Wed, 15 Oct. 10:10 EX-C Posters 1

2. **N. Kenmochi+,** "Experimental identification of coexisting local and non-local turbulence"
3. **K. Nagaoka+,** "Configuration dependence of turbulent transport with zonal flow effects"
4. **M. Nishiura+,** "Bifurcated particle transport states driven by regulatory energetic ions in LHD plasmas"
5. **T. Tokuzawa+,** "Discovery of cross-scale nonlinear interaction and bifurcation in multi-scale turbulence in LHD plasma"

Thu, 16 Oct. 8:30 EX-C Posters3

6. **D. Medina-Roque+,** "Impact of Li granule injection in the improvement of bulk energy and particle transport and expulsion of mid/high-Z impurities in the LHD heliotron"

Thu, 16 Oct. 14:00 EX-W Posters 4

7. **H. Igami+,** "Observation of lower hybrid harmonic waves accompanied by sidebands with distinct ion cyclotron frequency intervals excited by nonlinear process at multiple dual resonances in a fusion oriented plasma"
8. **K. Toi+,** "Observation of non-collisional ion heating in helical plasmas under dominant electron heating condition by neutral beam injection on LHD"

Fri, 17 Oct. 11:40 EX-C(Oral) (the same day, 14:00 Posters 6)

9. **T. Kinoshita+, "Direct control of turbulence for improved plasma confinement"**

Fri, 17 Oct. 8:30 TEC-CTL(Oral) (the same day, 14:00 Posters 6)

10. **Y. Morishita+, "Development of data assimilation system ASTI toward digital twin control of fusion plasma"**

Fri, 17 Oct. 8:30 EX-S Posters 5

11. **Y. Takemura+,** "Frequency Hysteresis of MHD Instabilities in Helical and Tokamak Plasmas"

Fri, 17 Oct., 14:00 TEC-CTRL Posters 6

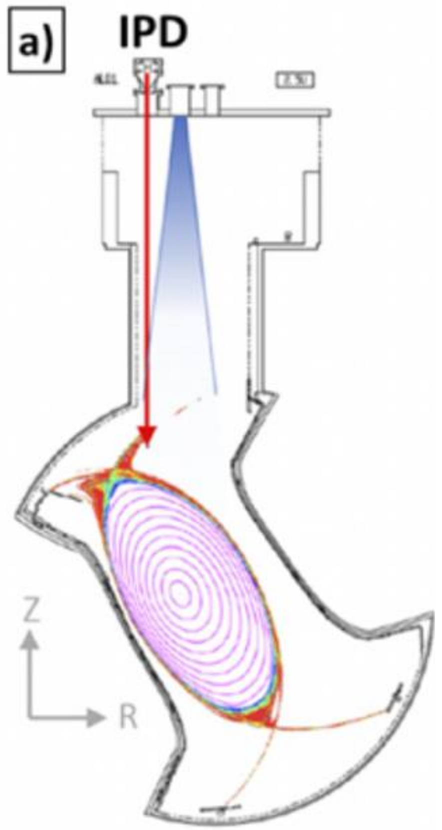
12. **H. Ohtani+(Post Deadline),** "Immersive VR-based visualization and analysis of fusion plasmas using digital-LHD and virtual-LHD"
13. **H. Yamaguchi+,** "An overview of a proposed new experimental stellarator: variable symmetry torus"

Sat, 18 Oct 9:30 Post Deadline Oral (Fri, 17 Oct. 14:00 Poster 6)

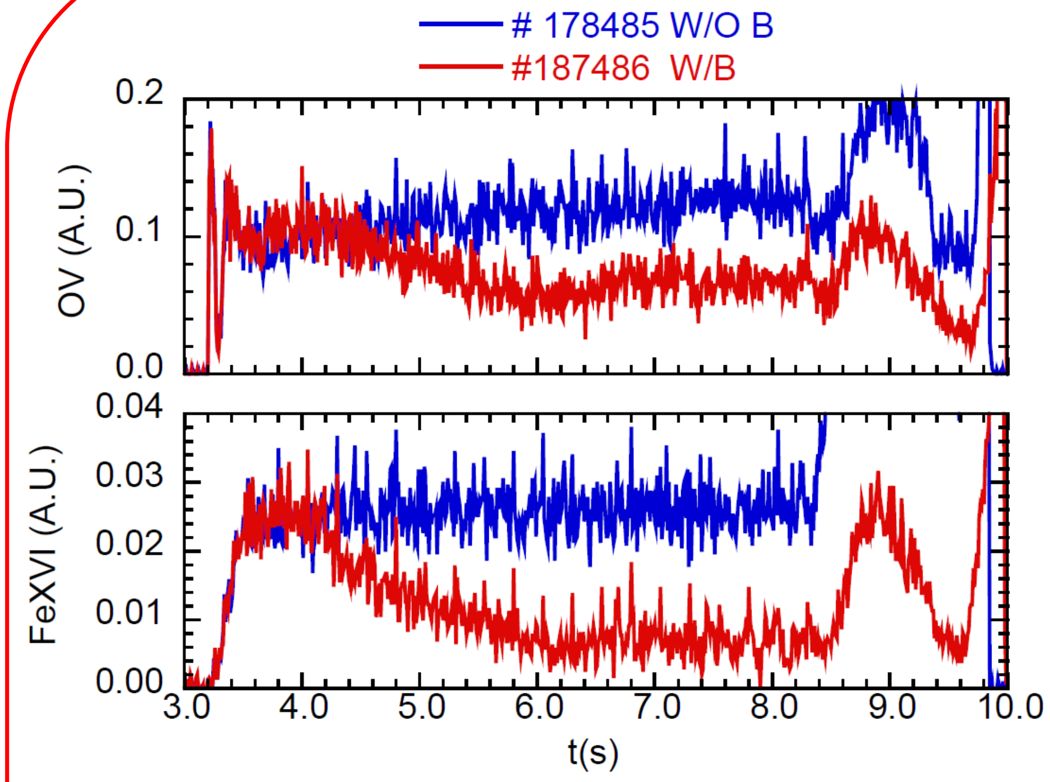
14. **K. Ida+, "Observation of core ion energy increase caused by the Landau damping of MHD wave in the periphery of LHD plasma"**

Backup

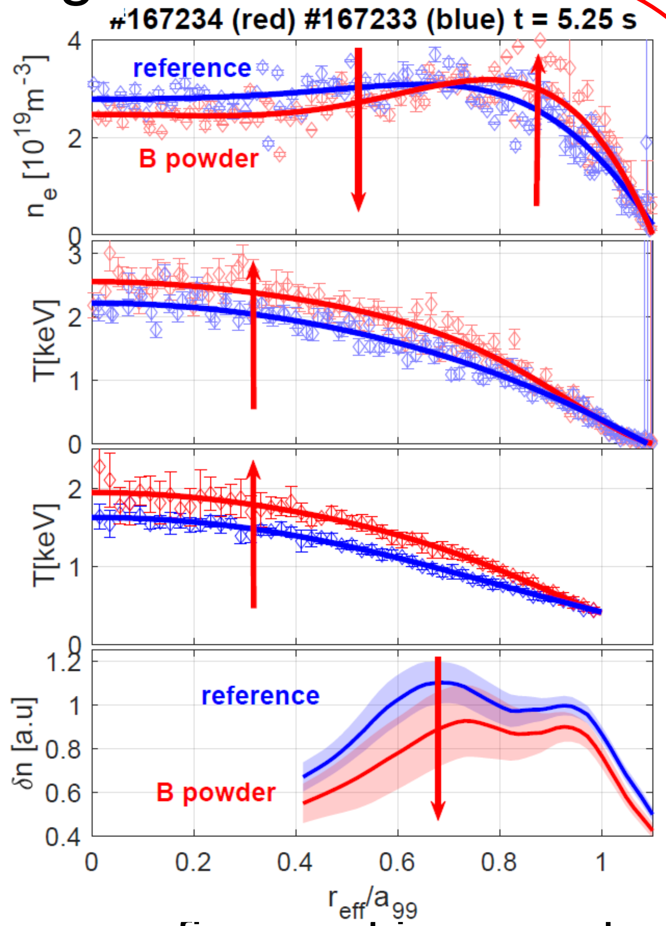
Boron powder dropping



Light Impurity powder (B, BN, C, Li, Si) are dropped. (R. Lunsford et al, NF 2022)

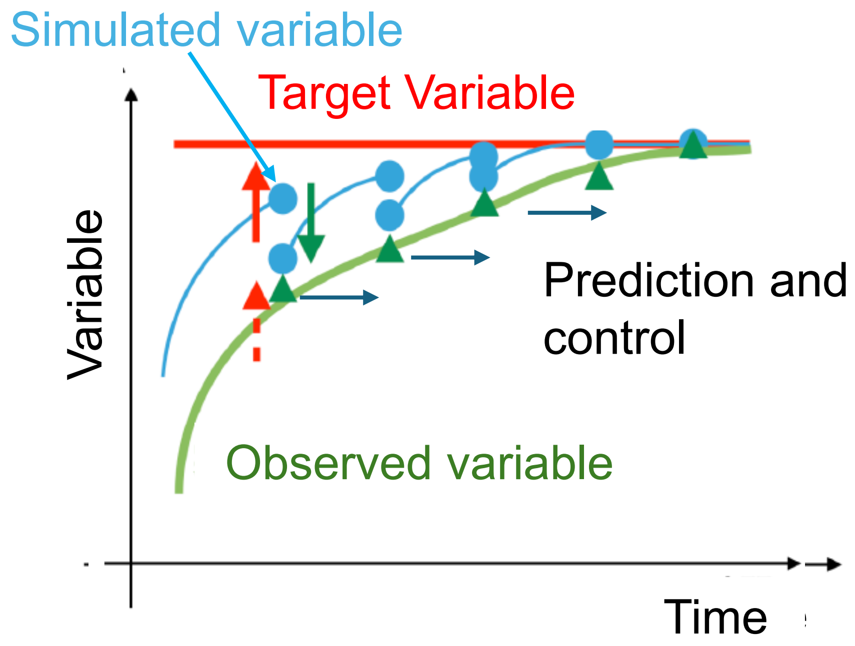


Intrinsic Impurity in-flux reduced with impurity powder (F. Nespoli et al, NF2023)



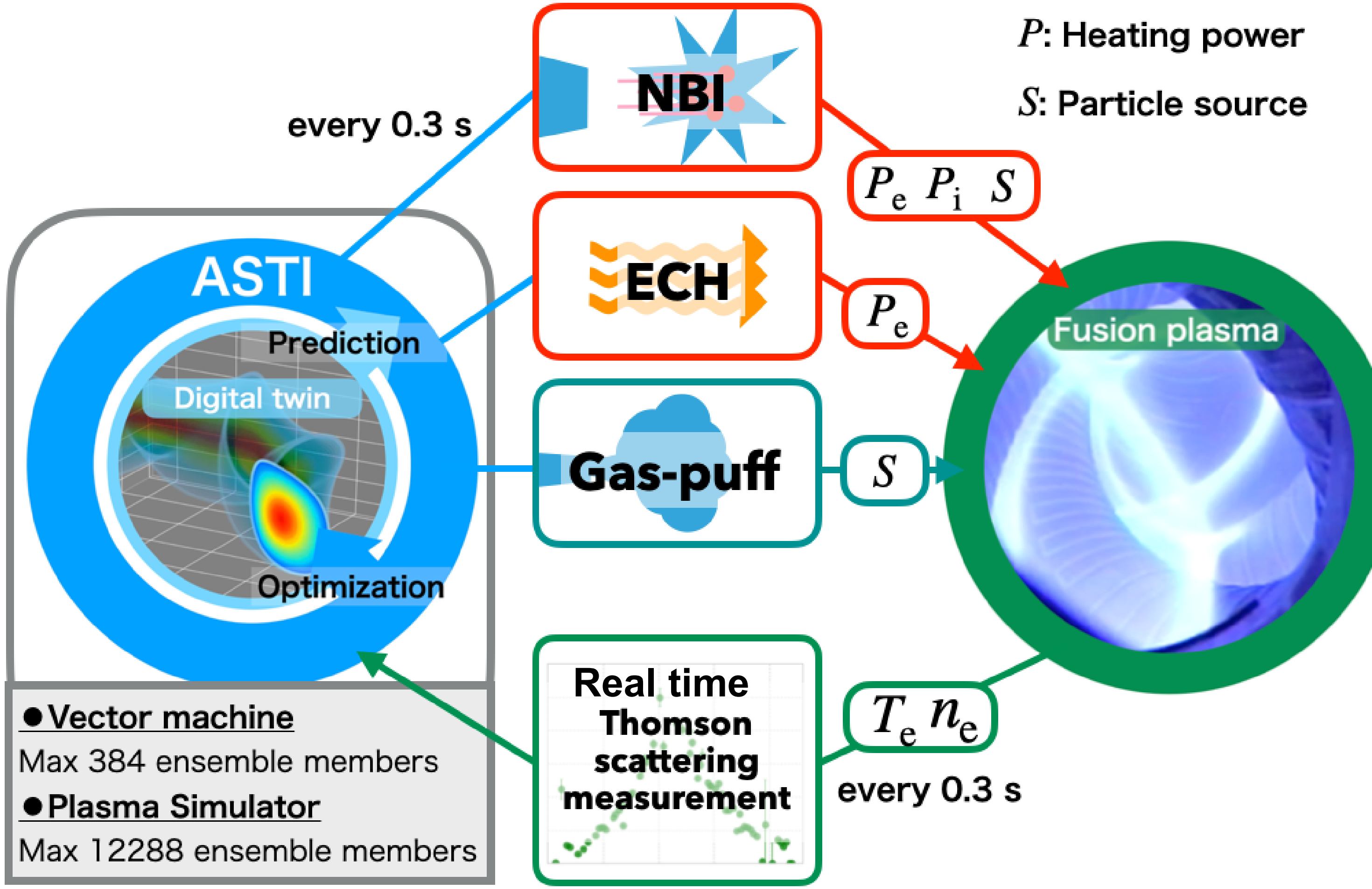
Energy confinement improved with reduction of turbulence (F. Nespoli et al, Nat. Phys. 2022)

DA for control



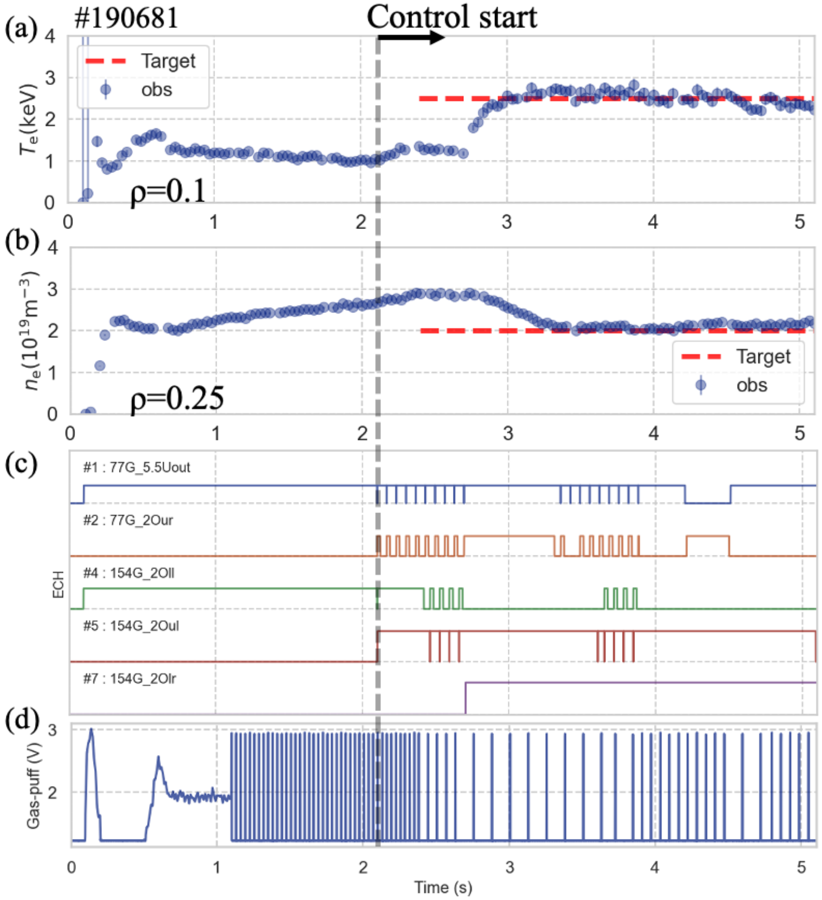
- ✓ Observed variables are assimilated to the target variable
- ✓ Real time simulations with input data from real time signals are carried out and predict the profiles at next timing.
- ✓ The control works to minimize the difference of target and observation/prediction.

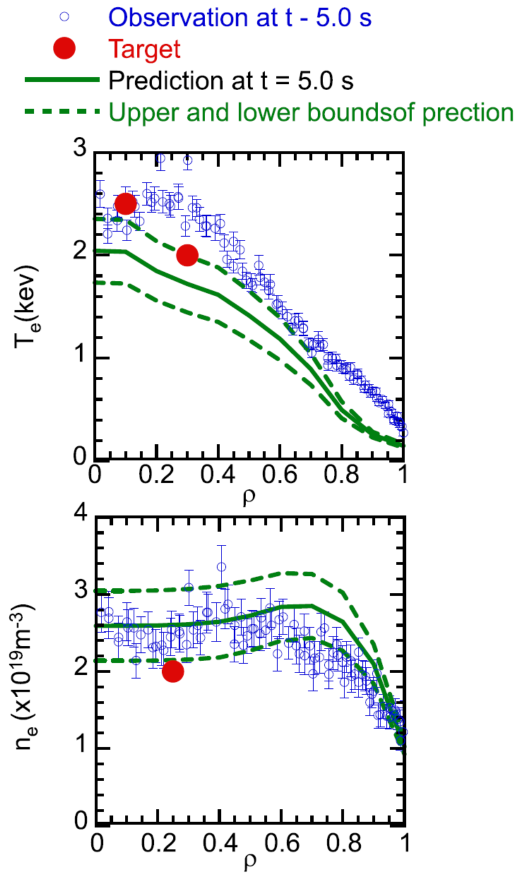
Y. Morishita (Sci. Rep. 2024) 17 Oct 8:30 Oral



Realtime profile control is successfully demonstrated by using ASTI system

State variable		Dim	
T_e	Electron temperature	11	**Obs, Target**
T_i	Ion temperature	11	
n_e	electron density	11	**Obs, Target**
C_e	Factor for thermal diffusivity (electron)	11	
C_i	Factor for thermal diffusivity (ion)	11	
D	Factor for particle diffusivity	11	
V	Particle convection velocity	10	
g	Parameter in gas-puff model	1	
P_{ECH}	ECH power	2	**Actuator**
f_{GP}	Pulsed gas-puff frequency	1	**Actuator**





Heat transport model of electrons and ions is based on Gyro-Bohm model

$$\chi_s = \chi_s^{NC} + \chi_s^{ANO.} \qquad \chi_e^{ANO.} = C_e \frac{T_e}{eB}\frac{\rho_i}{a} \qquad \chi_i^{ANO.} = C_i \frac{T_i}{eB}\frac{\rho_i}{a}\left(\frac{\nabla T_i}{T_i}\right)$$

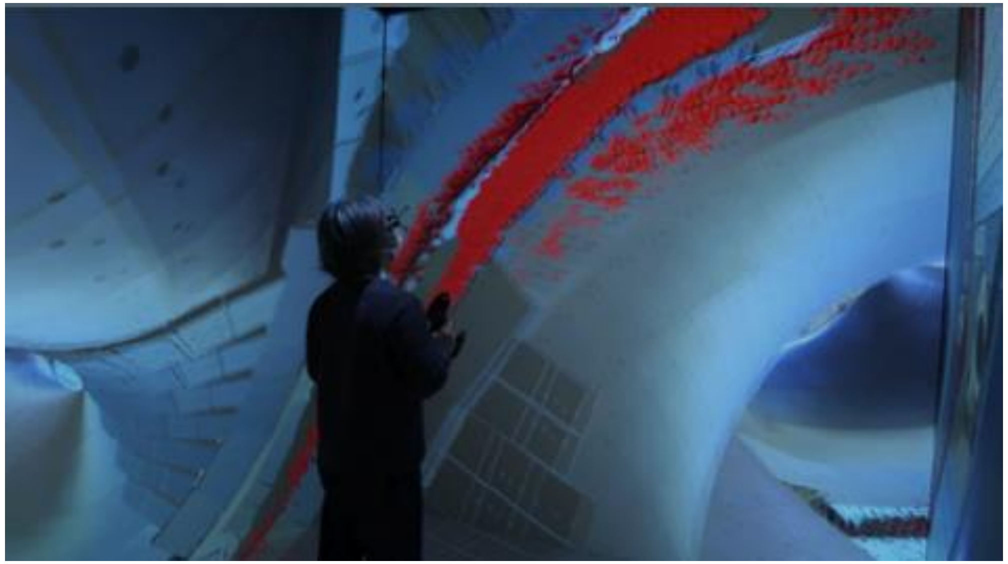
Particle transport uses simple model

$$D = dD^{ANO.} \qquad D^{ANO.}\text{is spatialy constant} \qquad V = V_{neo} + v$$

Coefficients Ce, Ci, d, v are optimized by DA.

Head Mounted Display of Virtual Reality system of LHD was developed

H. Ohtani et al, 17 Oct., 14:00
TEC-CTRL Posters 6 (post deadline)



Visualization of triton impacts
Room size (4x4x4m) VR system
for LHD(CompleXcope)

Kageyama et al,
Proceedings of 16th Int. Conf. on the
Numerical Simulation of Plasmas (1998)

Newly developed HMD VR system
for LHD

Ohtani et al,
J. Visualization. (2022)

Li drop in the Virtual LHD