Direct Control of Turbulence for Improved Plasma Confinement

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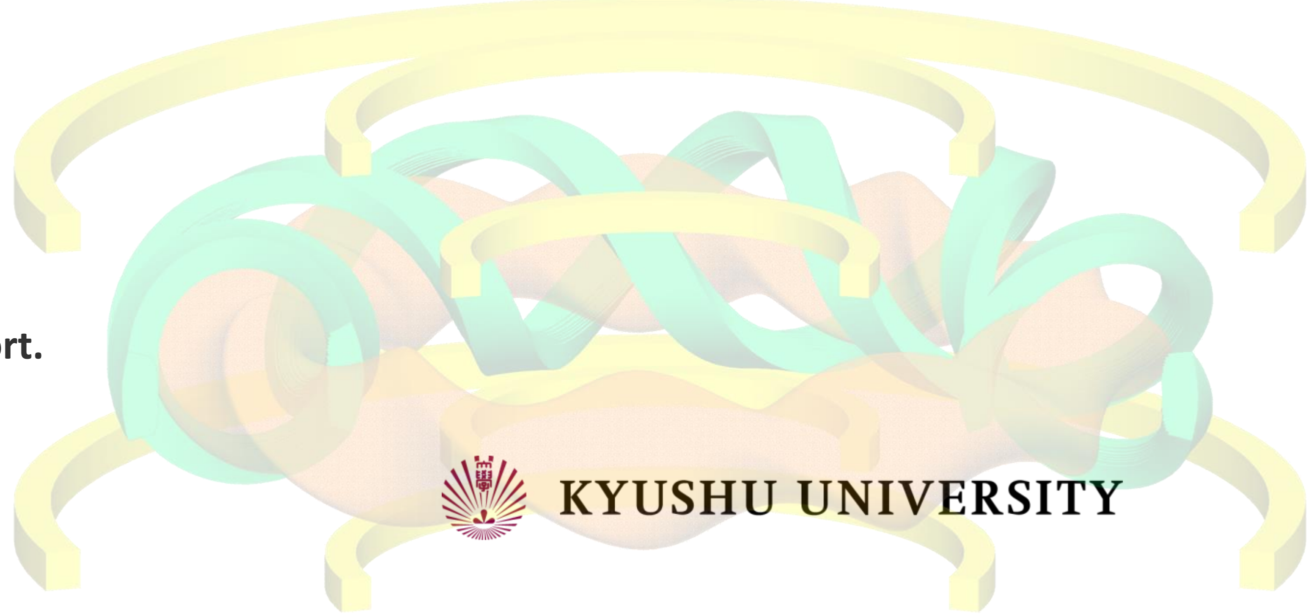

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- Efficient attainment of a high triple product requires **suppression of turbulence-driven (anomalous) transport**.

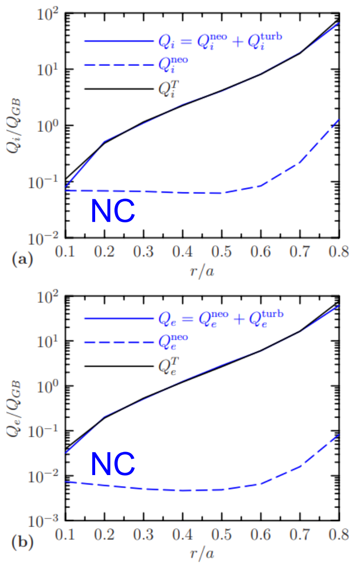
- Transport Characteristics
  - Tokamaks
    - Transport is dominated by turbulence
      → Relatively well understood
  - Stellarators / Heliotrons
    - Neoclassical (NC) transport is inherently larger
      → Can be mitigated through optimization
    - Anomalous transport still plays an important role
      → **Turbulent transition has recently been discovered in LHD**

T. Kinoshita+ PRL2024

- Real-time control
  - Extensively implemented for:
    - Plasma equilibrium control
    - ELM suppression
    - etc.
  - For turbulence suppression:
    - IPD reduces core turbulence
    - **Active feedback control to optimize for anomalous transport not yet demonstrated**

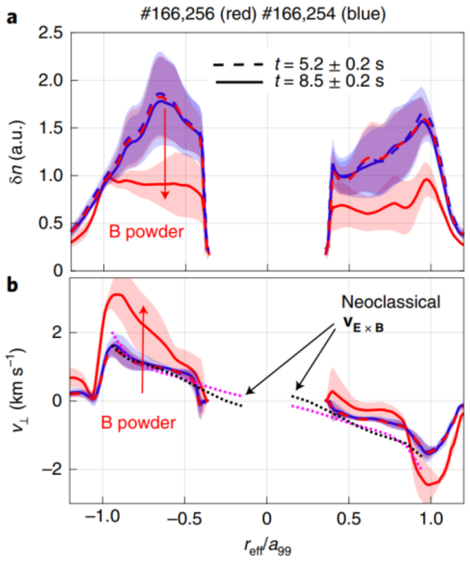
neoclassical vs turbulence in tokamak

J. Candy+ PoP2009

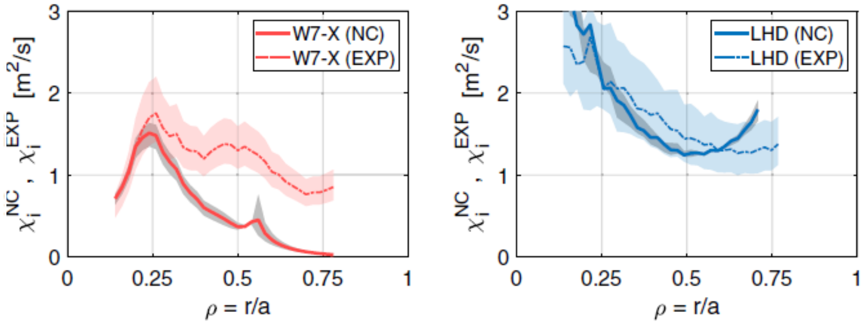


turbulence suppression by Boron power injection

F. Nespoli+ Nat. Phys.2022

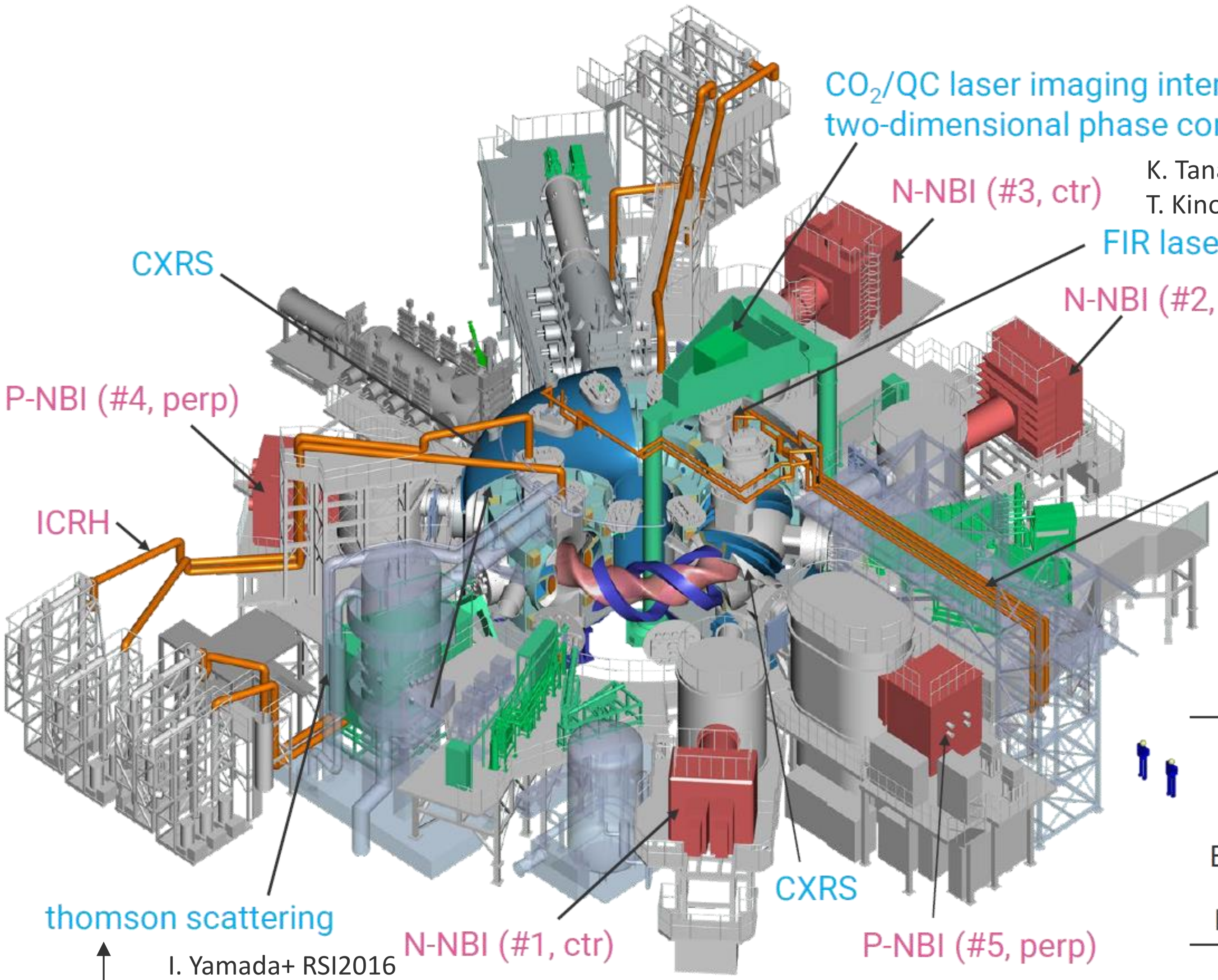


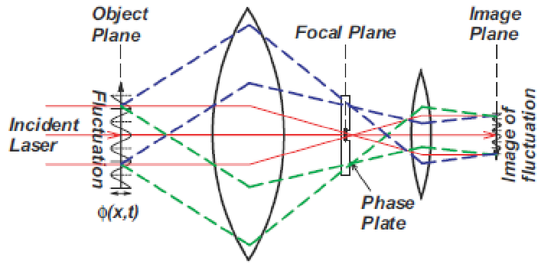
transport in stellarators/heliotrons W7-X vs LHD



F. Warmer+ PRL2021

Large Helical Device (LHD)





K. Tanaka+ RSI2008

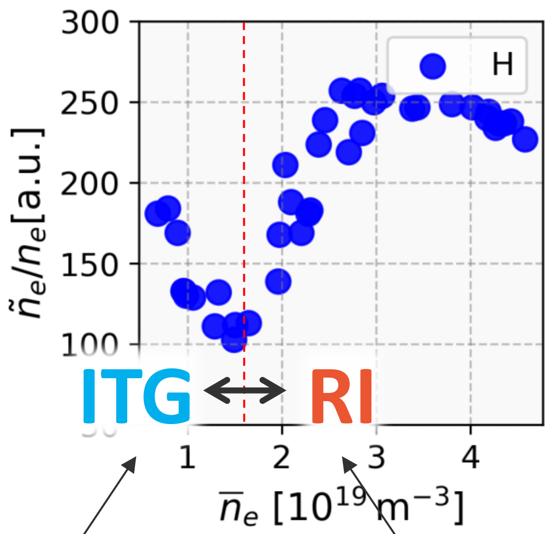
NBI	34MW (N-NBI#1#2#3:16MW in total) (P-NBI#4#5:18MW in total)
ECRH	5.5MW (77GHzx2, 154GHzx3)
ICRH	3MW

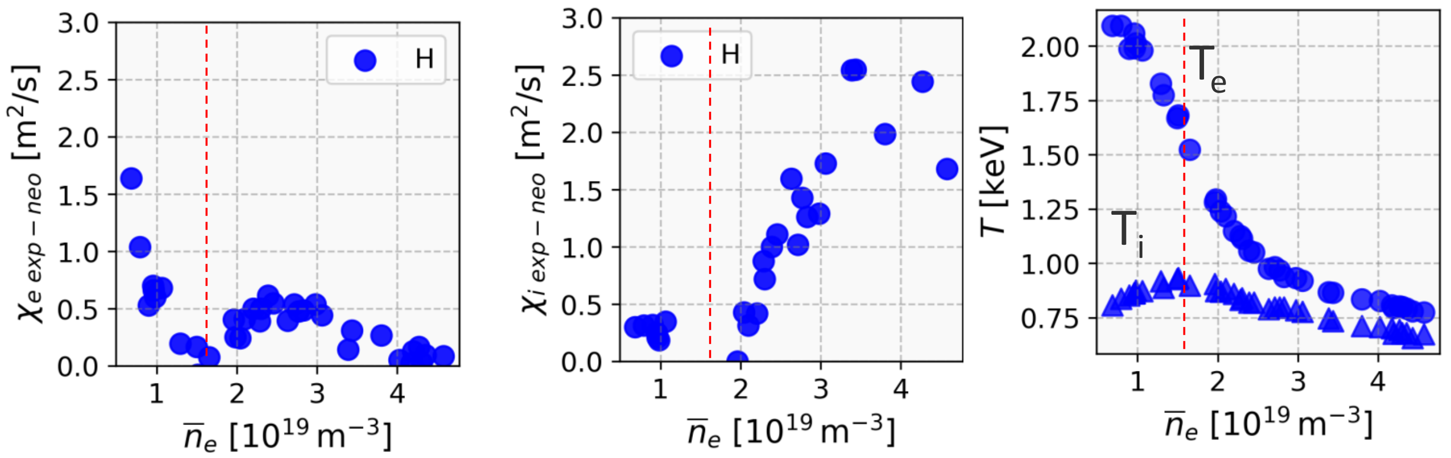
Device diameter	13.5m
Device height	9.1m
Major radius	3.6~3.9m
Minor radius	0.6~0.65m
Plasma volume	20~30m^3
Coil minor radius	0.975m
Magnetic field	3[4]T
Magnetic energy	0.9[1.6]GJ

Turbulence transition between ITG and RI

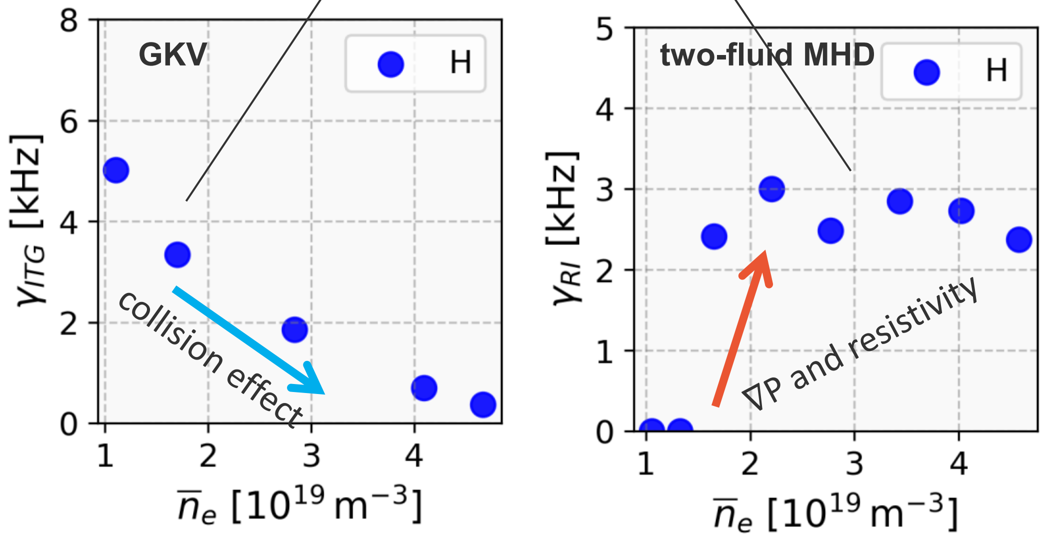
T. Kinoshita+ PRL2024

Experiment





Simulations



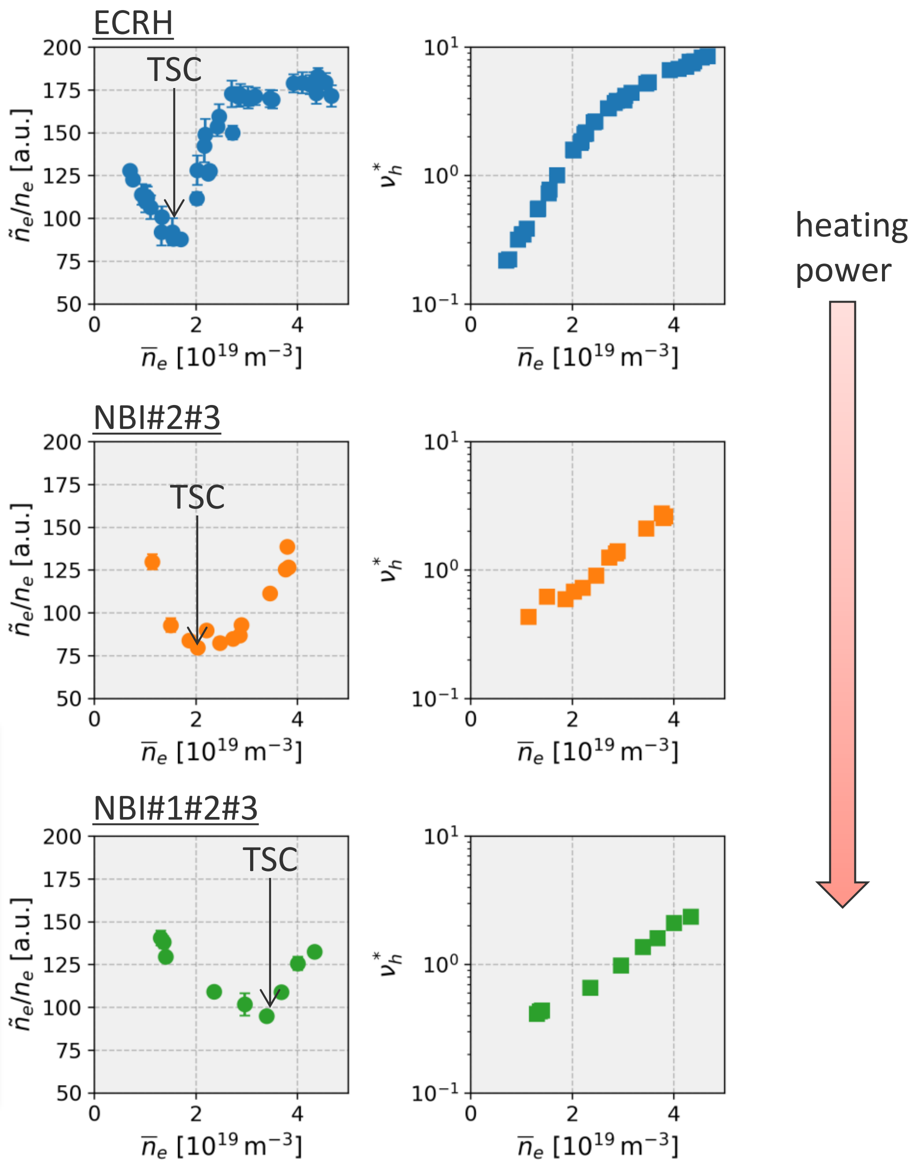
- ❑ **Turbulence transitions between ITG and resistive interchange (RI) modes**
- ❑ When turbulence transitions:
  - Turbulence and anomalous transport are minimized
  - Ion temperature reaches a maximum

  → Efficient confinement is achieved
- ❑ This study focuses on turbulence transitions and attempts operations that minimize turbulence.

Turbulence suppression is not determined by density alone

- ❑ Turbulence transition condition
  = Turbulence Suppression Condition (TSC)
- ❑ Operating around TSC → optimized anomalous transport
- ❑ TSC varies with heating (even for the same magnetic configuration)

Higher heating power
↓
Temperature ↑ ↗ Collisionality ↓ → ITG ↑ weak stabilization effect
↘ Resistivity ↓ → RI ↓ weak driving force
↓
ITG ⇄ RI transition density shifts higher



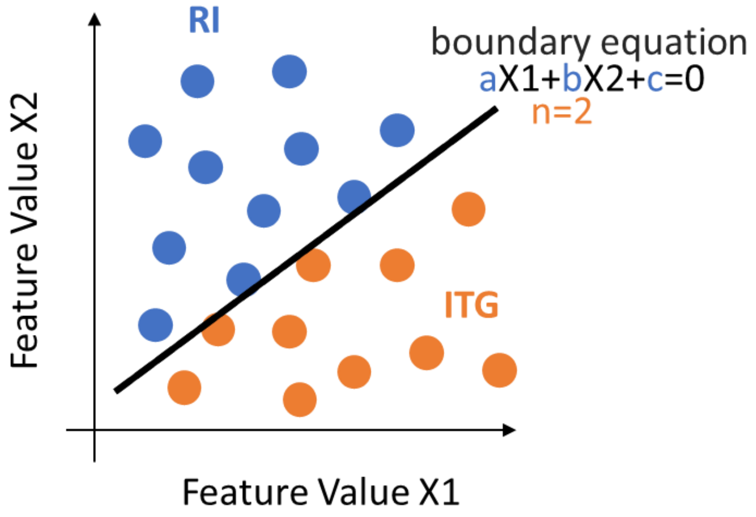
Determination of TSC using SVM

- TSC is not uniquely determined by the magnetic configuration
- **Exhaustive-search SVM (ES-SVM) used to determine TSC**

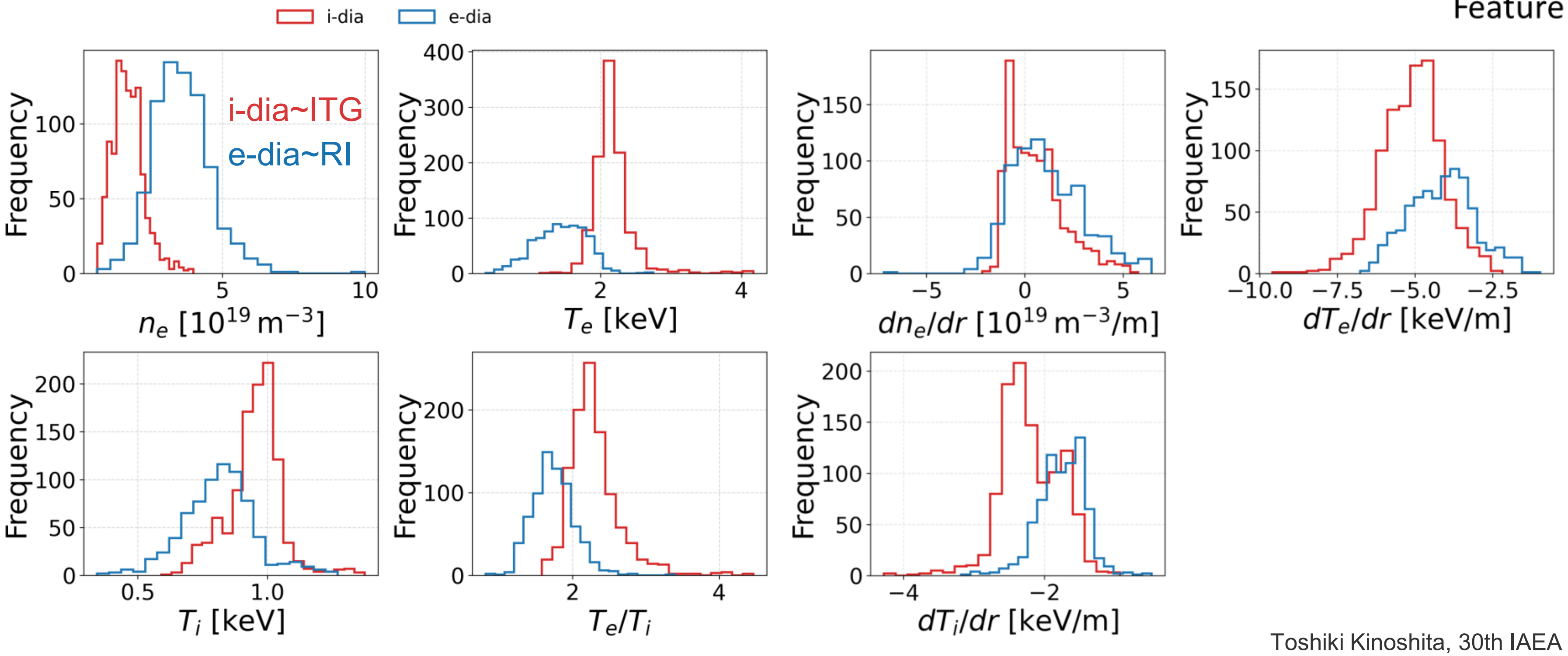
Y. Igarashi+ JPSJ2018, T. Yokoyama+ JFE2020

ES: a method that investigates all parameter combinations.

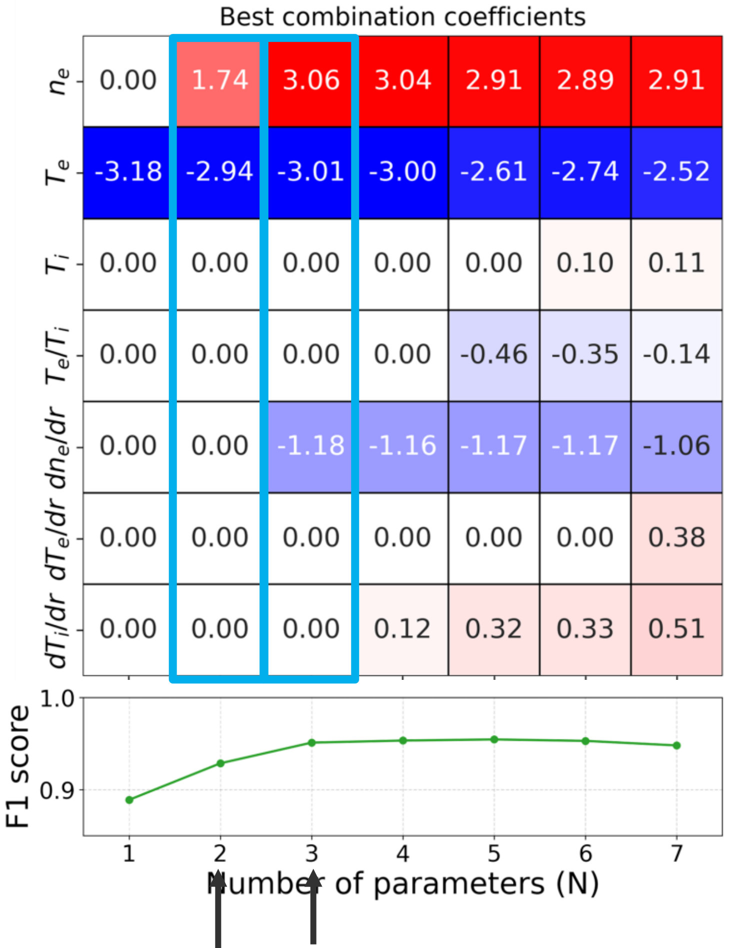
SVM: a way to find a **boundary that separates classes**

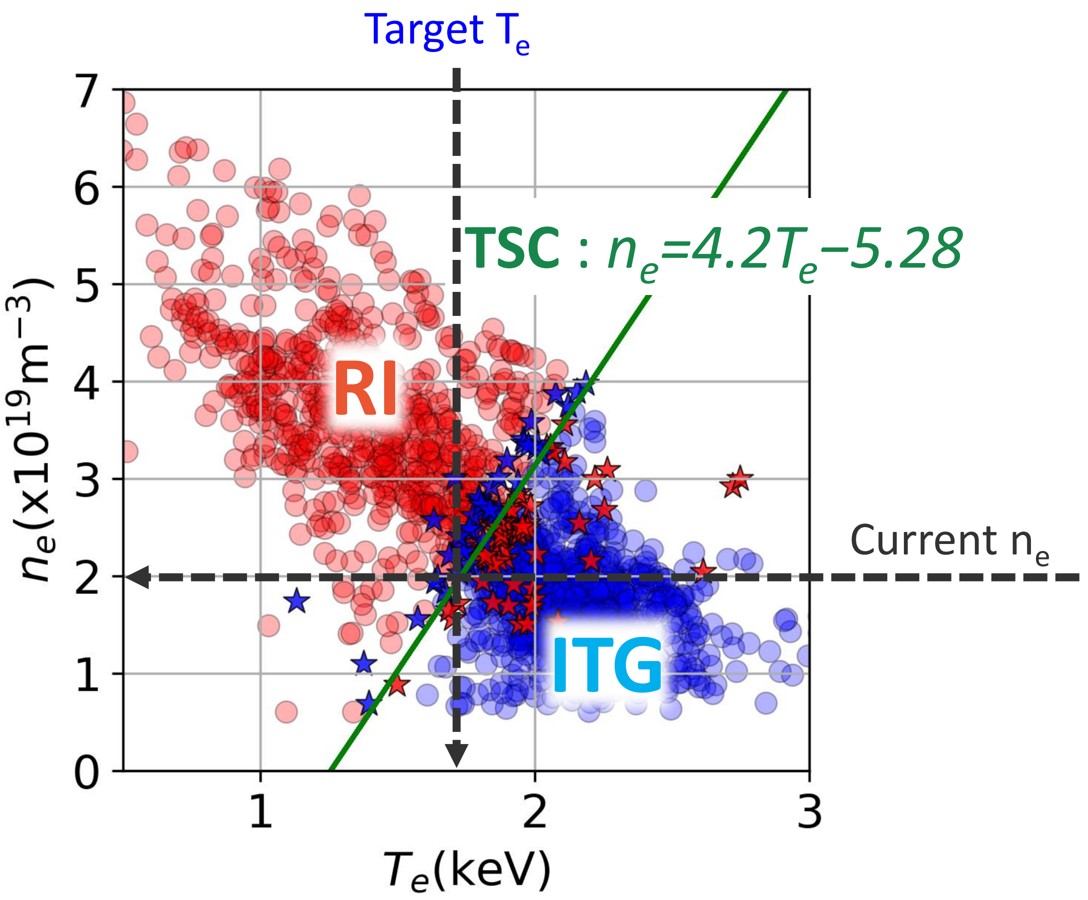


Dataset for Machine Learning



Exploring turbulence suppression conditions via ES-SVM





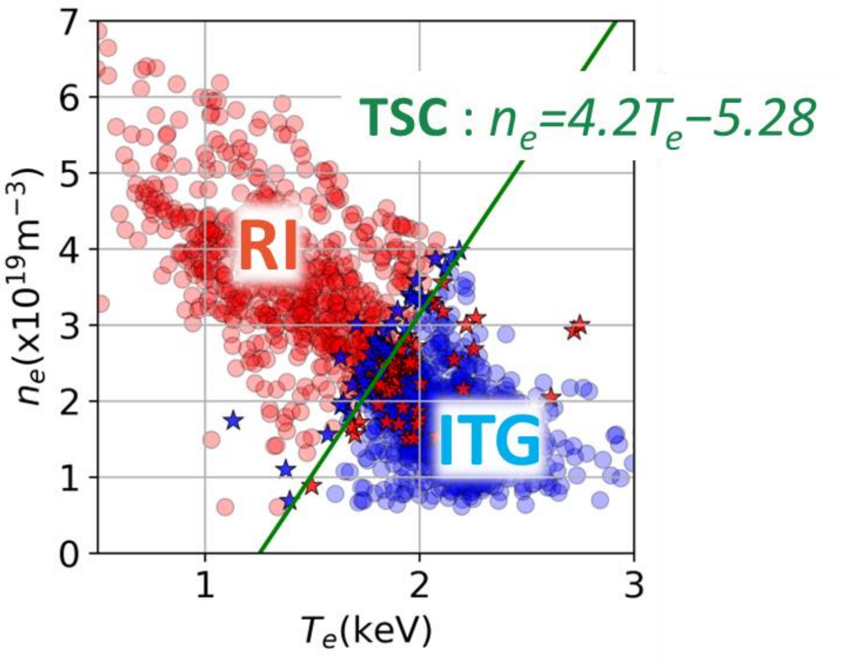
Best score obtained; controlling dn_e/dr is challenging

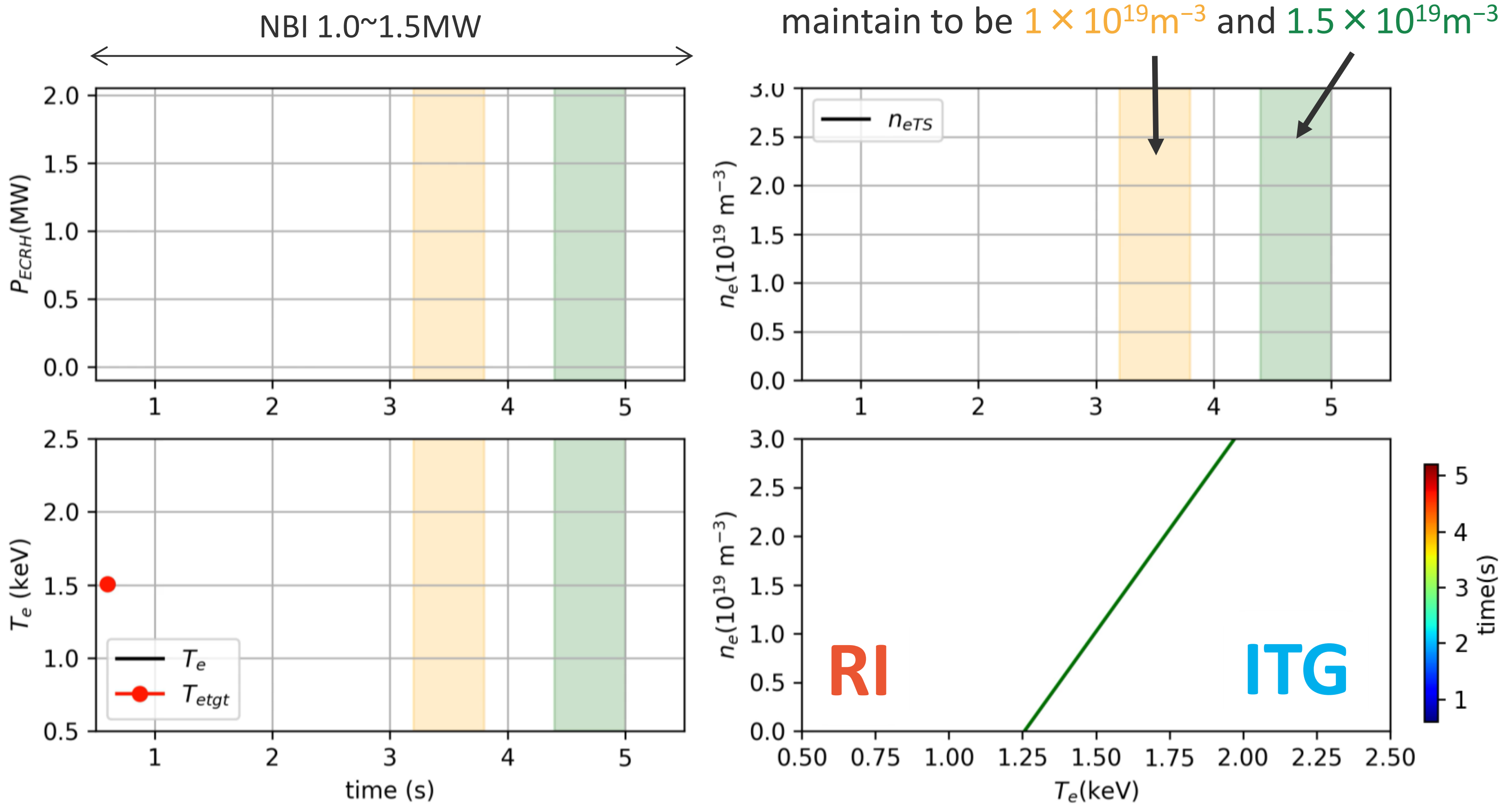
Good classification score; n_e and T_e can be easily controlled

approach 1: Adjust heating

approach 2: Adjust gas-puff

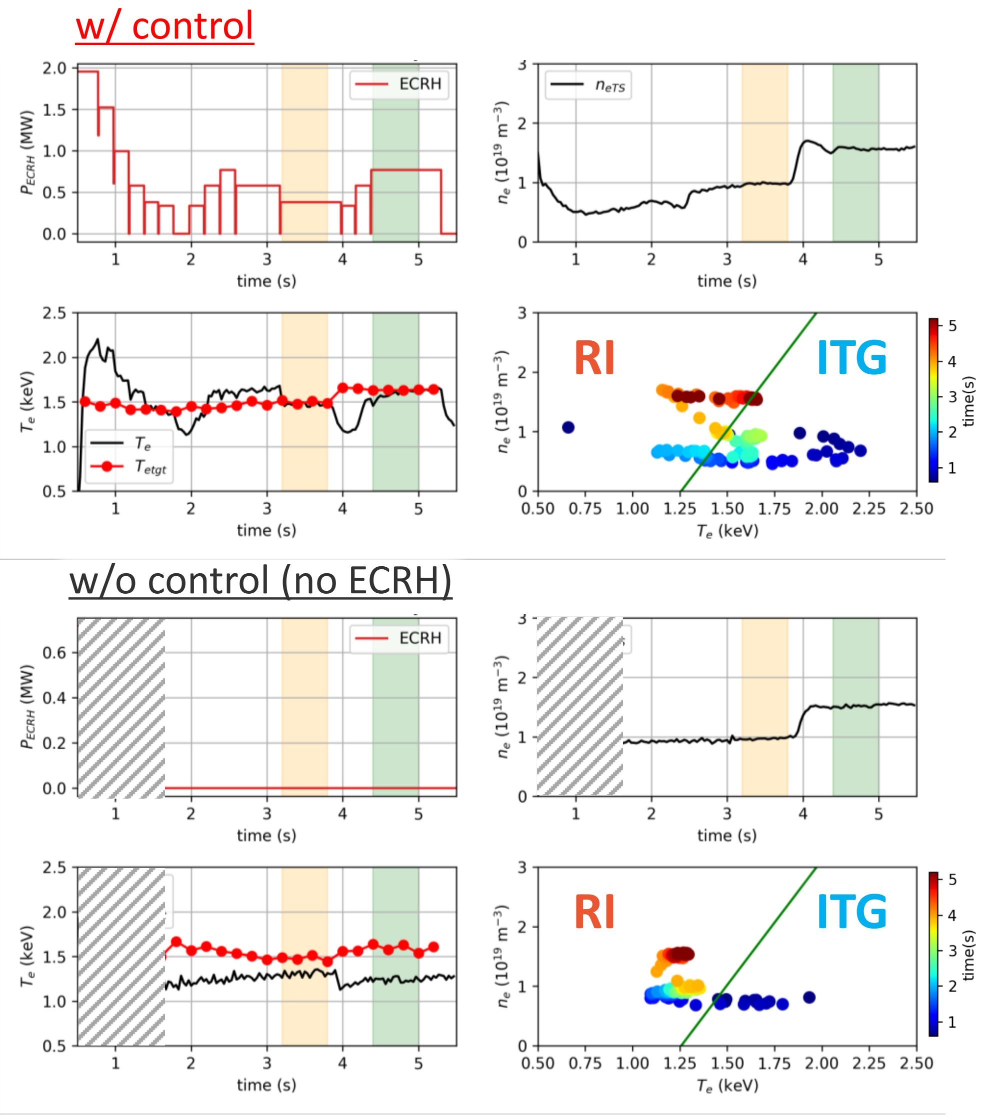
Controlling plasma heating to achieve the TSC

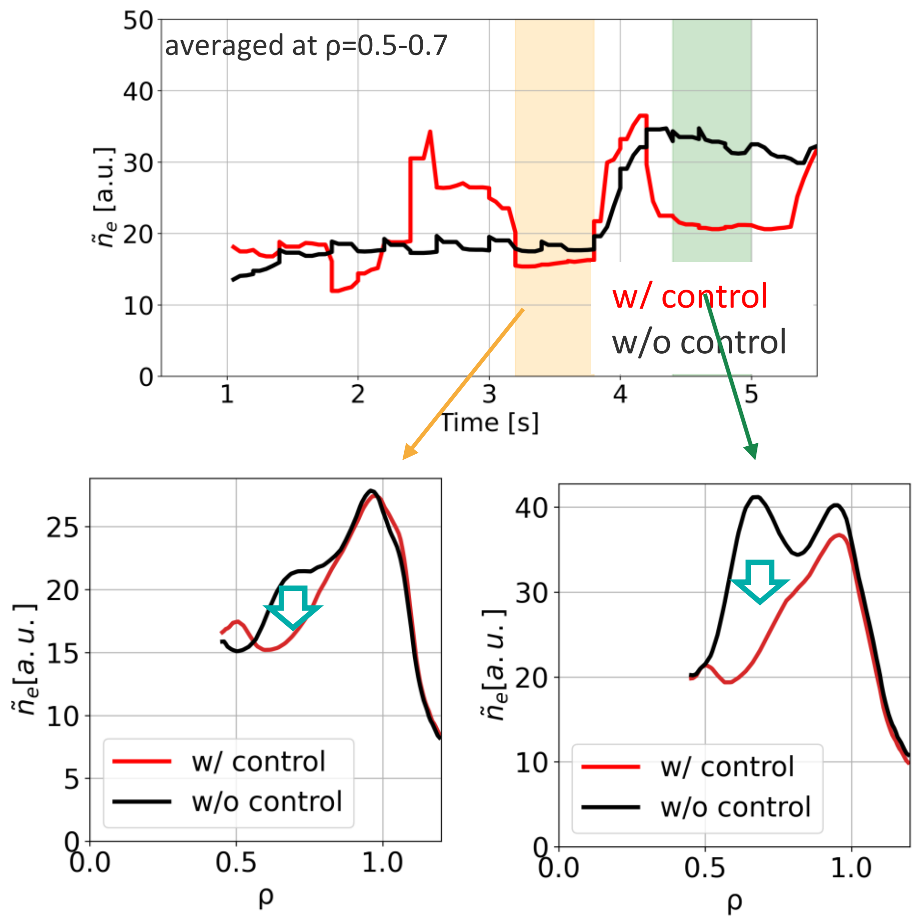




- ❑ Electron temperature successfully controlled to meet TSC at density feedback timing
- ❑ Plasma evolves along n_e=4.20T_e−5.28

Turbulence suppression by heating control





- ❑ w/o ECRH → RI observed in the core region
- ❑ **Turbulence successfully suppressed**

Effect of turbulence suppression control

- **Total transport slightly higher**

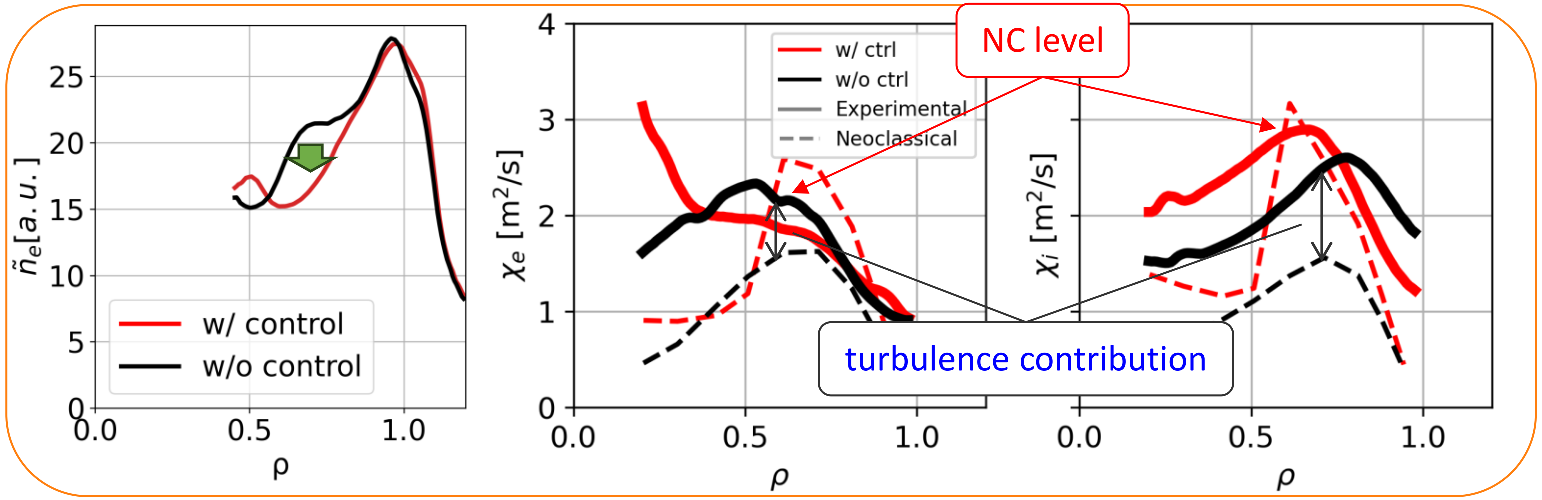
→ mainly due to increased NC from additional ECRH

- **Anomalous transport strongly reduced**
  - at ρ = 0.5–0.7, transport is close to the neoclassical level
  - consistent with turbulence suppression

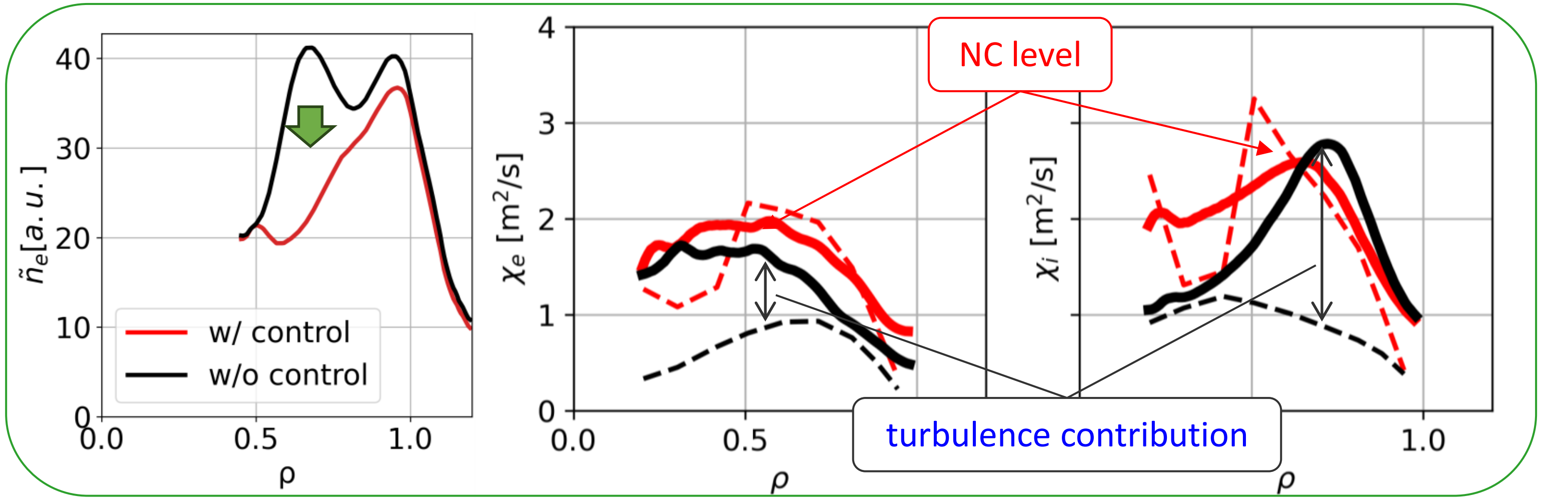
Next step

Simultaneous reduction of both neoclassical and anomalous transport

n_e=1.0x10^{19}m^{-3}



n_e=1.5x10^{19}m^{-3}



Impact on confinement

❑ Total confinement slightly deteriorated
→ Increase in neoclassical transport due to additional heating

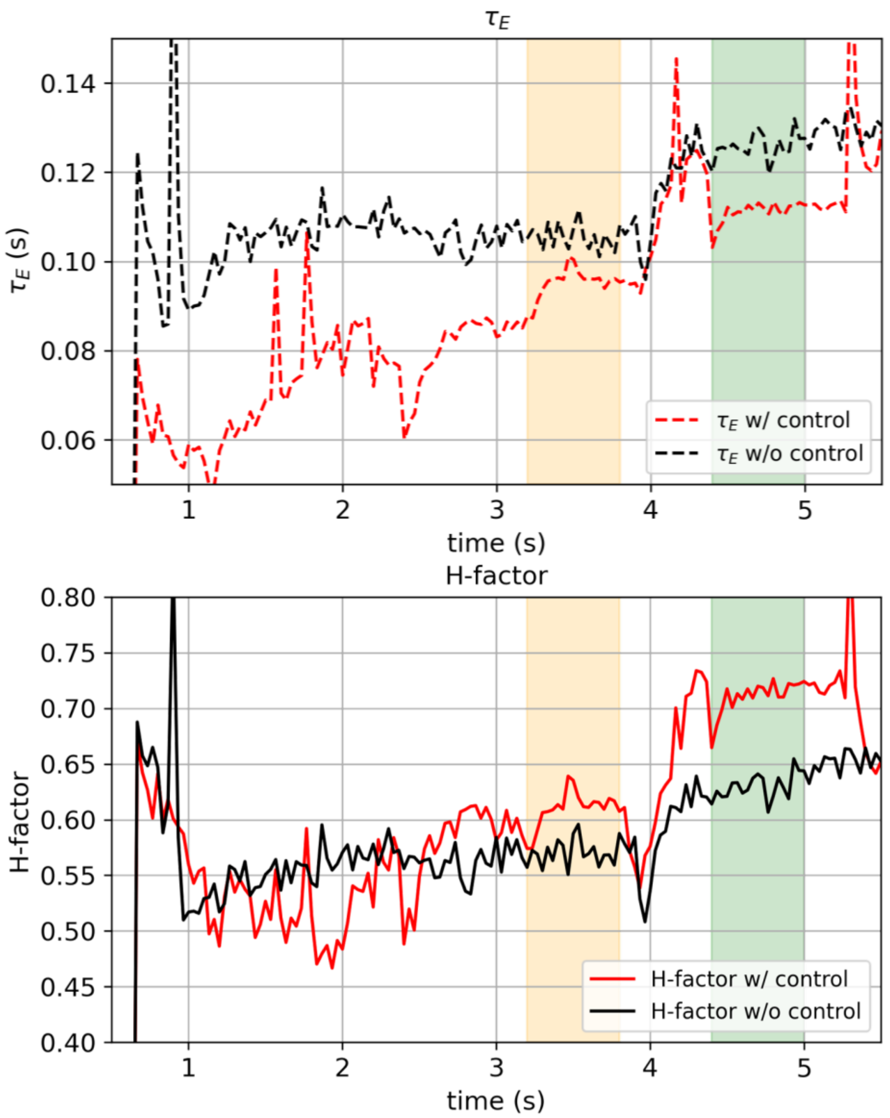
❑ **H-factor (ISS04 normalized) improved**
→ Demonstration of improved confinement through turbulence suppression

⇩

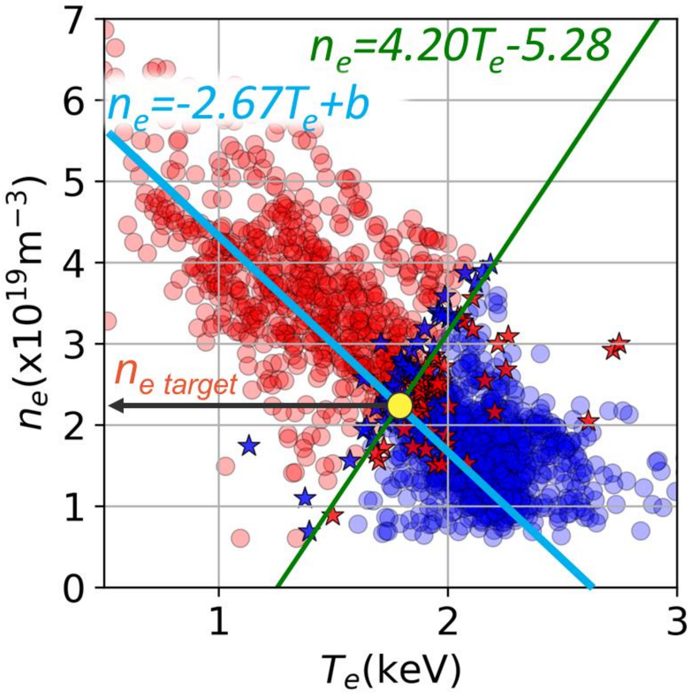
This clearly demonstrates the effectiveness of improving confinement through turbulence suppression.

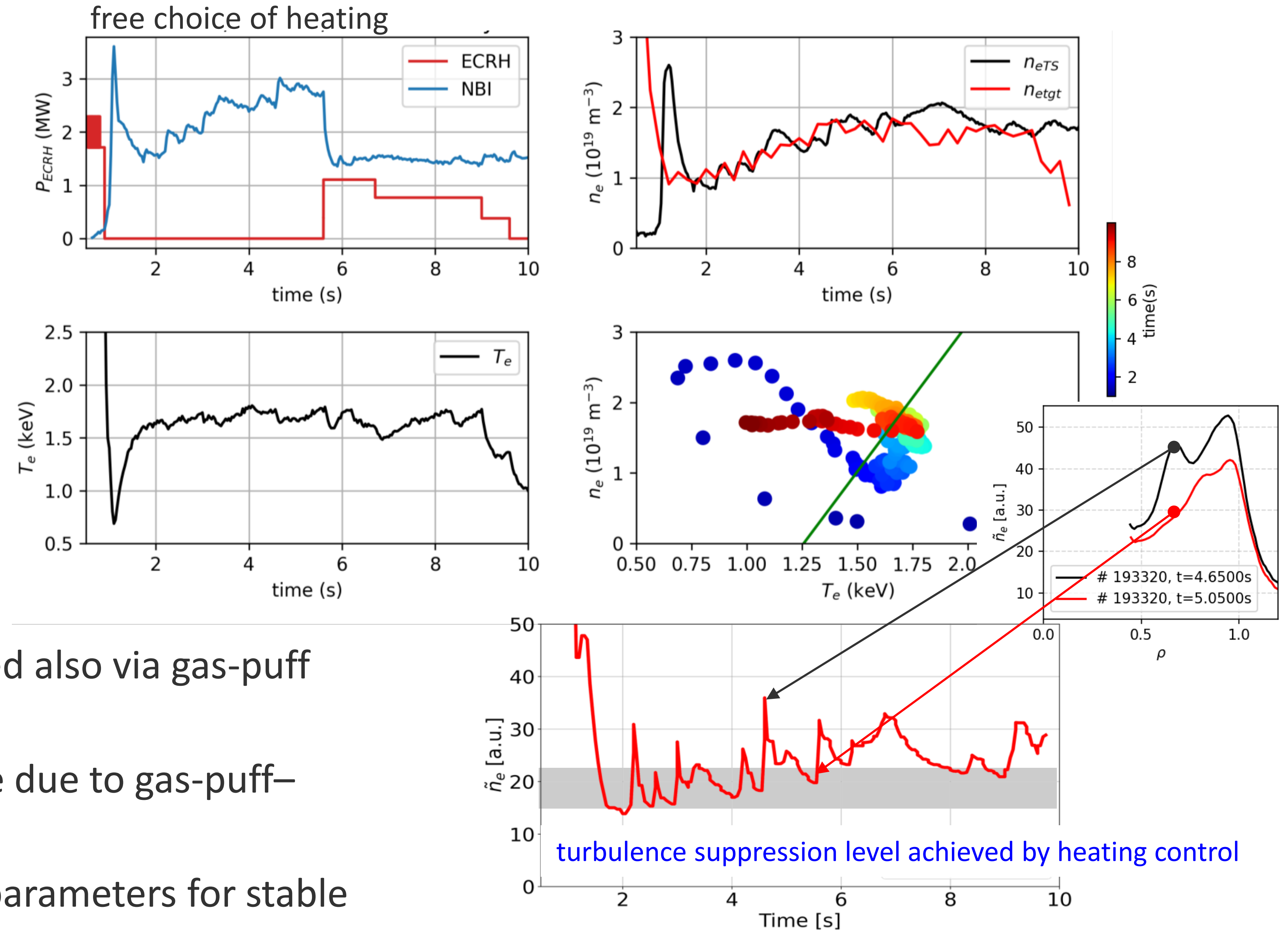
approach 1: Adjust heating

approach 2: Adjust gas-puff



Turbulence suppression also achieved through density control





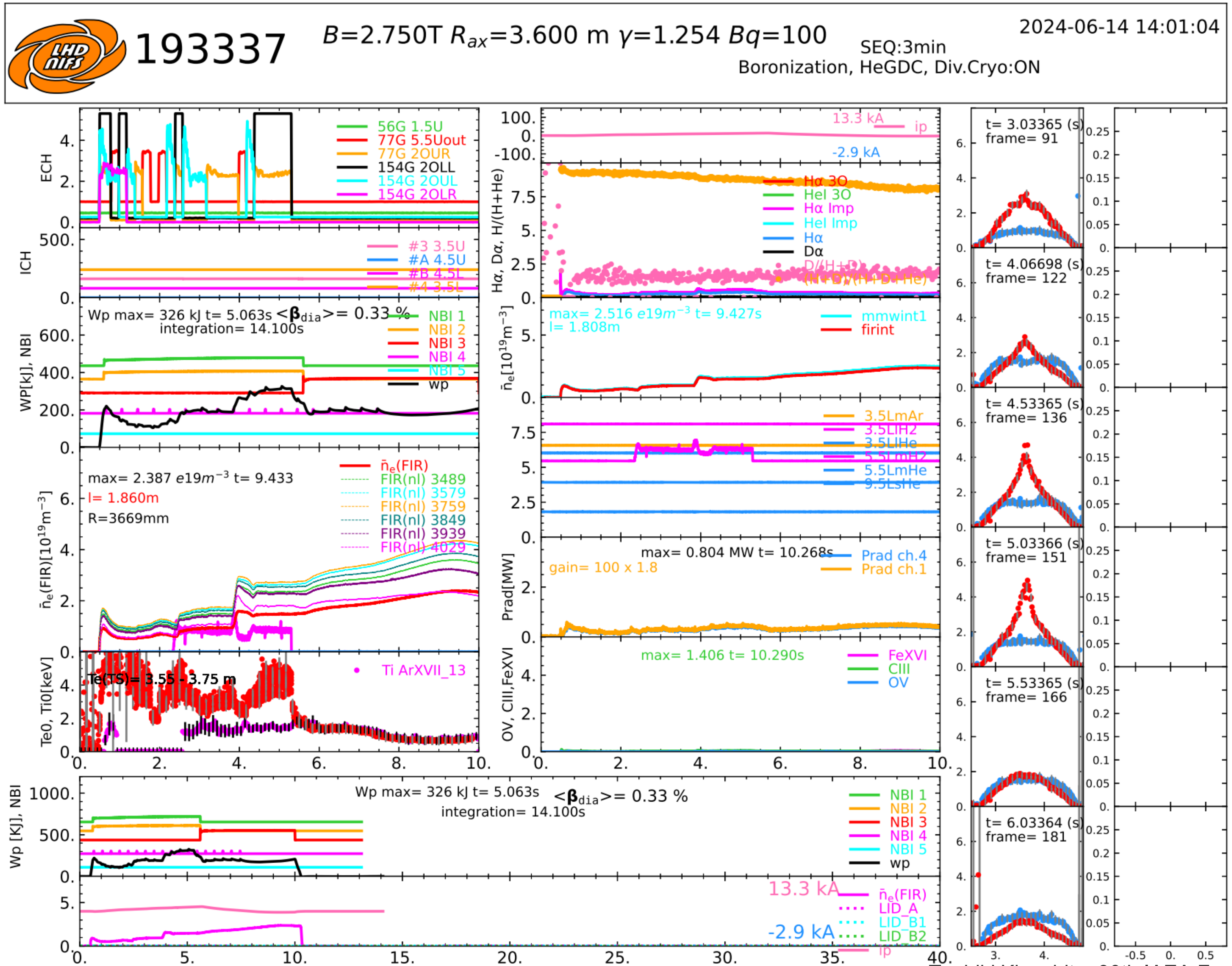
- ❑ Turbulence suppression achieved also via gas-puff control
- ❑ Transient increase in turbulence due to gas-puff–induced density redistribution
- ❑ Future work: Optimize control parameters for stable suppression

Summary / Key Takeaways

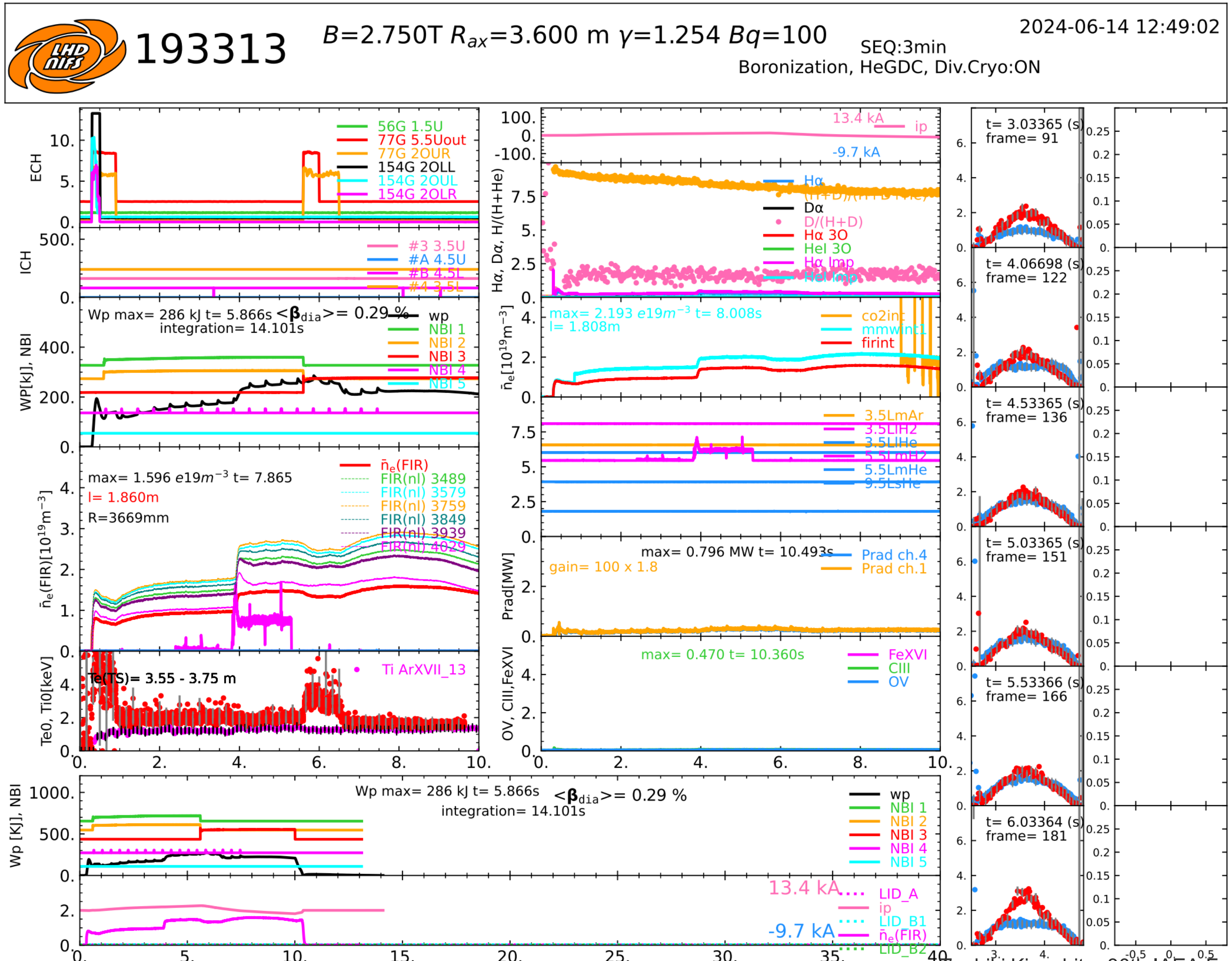
- **Turbulence suppression achieved via real-time plasma control**
  - Temperature control adjusts ECRH to follow the Turbulence Suppression Condition (TSC)
  - Density control uses gas puffing to maintain target density along TSC
- Turbulence suppression reduces anomalous transport
  - Transport in ρ = 0.5–0.7 approaches neoclassical level
- Suppression of anomalous transport improves the confinement
  - Total confinement slightly reduced due to increased neoclassical transport
  - H-factor improved, demonstrating the effectiveness of turbulence suppression

- Future Work
  - Density control: Optimize parameters for more stable turbulence suppression
  - Another approach: Explore operation without prior machine learning
  - Extension to other devices: Investigating the applicability in tokamaks and optimized stellarators

Summary) w/ heating control experiment



Summary) w/o heating control experiment



Summary) Density control experiment