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Development of High-performance Long-pulse Discharge in KSTAR

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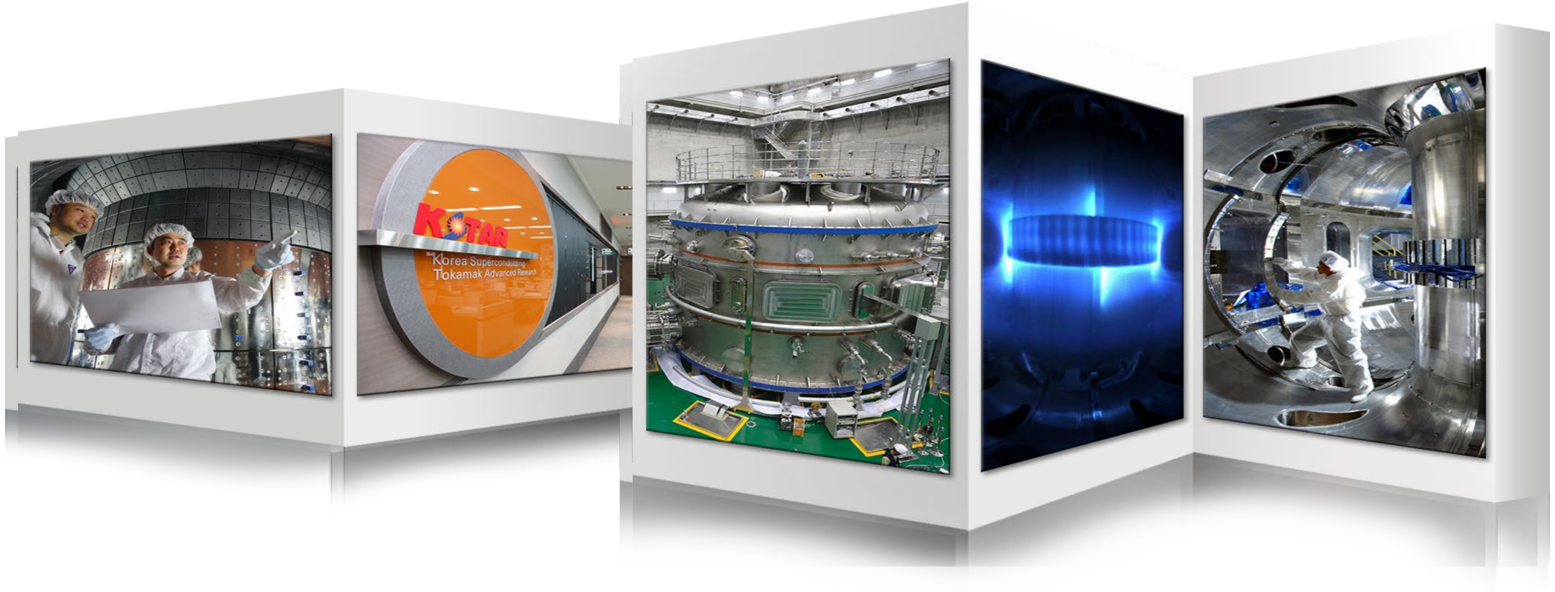
Physics Basis and Objectives of Long-pulse operation in KSTAR

- **Goal** — To establish ***stable and sustainable high-performance plasma operation scenarios*** that can support long-pulse tokamak experiments and future steady-state fusion reactors
- **Objective** — To demonstrate and evaluate the ***long-pulse operation capability of the KSTAR device*** through integrated plasma control and system performance tests
- **Focus** — To identify and address ***physics and engineering challenges*** encountered during long-pulse operation
- **Methodology** — Employing ***NBI and ECH as the primary H&CD systems and KSTAR high β_P scenario*** for sustaining high-performance long-pulse plasma, enabling investigation of NBI-driven fast ion transport
- **Significance** — Utilizing KSTAR long-pulse operation as ***a unique experimental platform*** to investigate ***NBI-driven fast ion transport and its impact on plasma sustainment***, providing ITER-relevant physics insight into steady-state operation

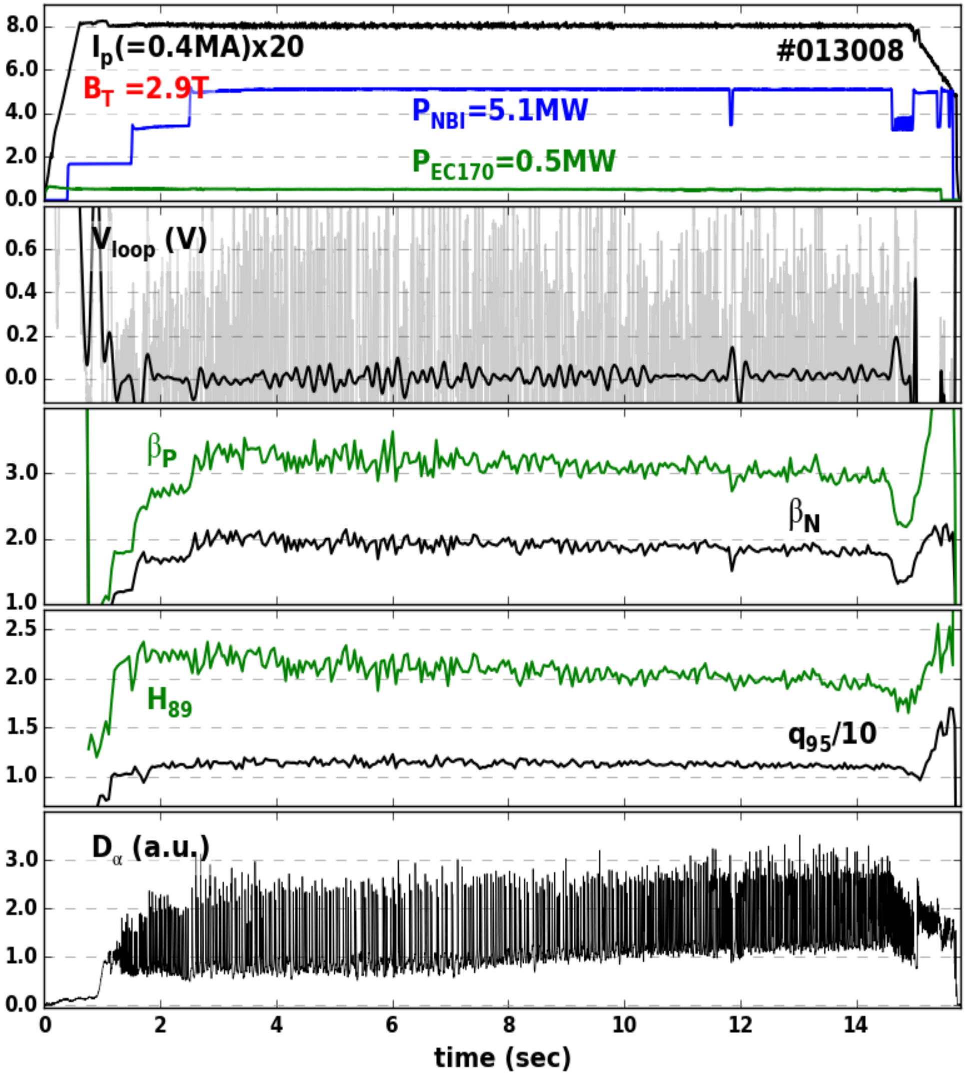
Outline

1. KSTAR High β_P Discharge
2. Heat Control of PFCs
3. Mitigation of Magnetic Signal Drift
4. Progressive Performance Degradation

KSTAR High β_P Discharge



KSTAR Long-pulse Approach Began in 2015

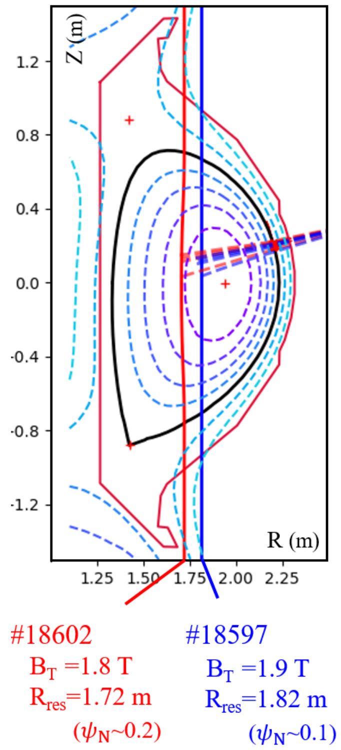


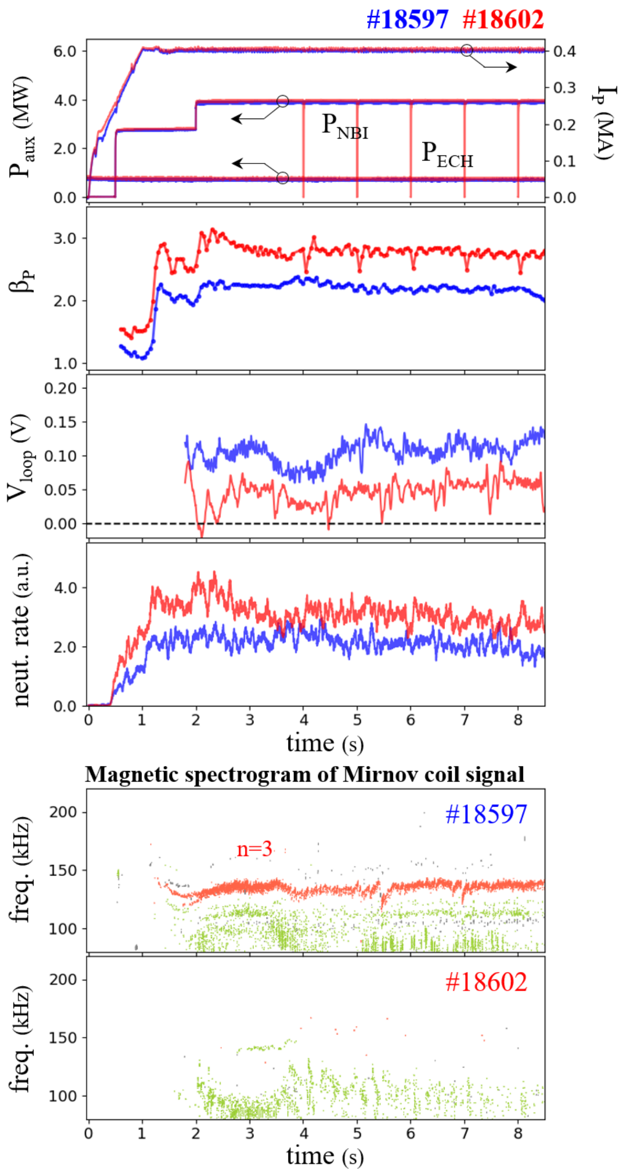
❖ KSTAR high-β_P discharge is adopted as the main scenario of KSTAR long-pulse discharge.

- achieved high performance $\beta_P \geq 3.0$ with high q_{95}=7-11.
- f_{NI}~1.0 for ~10 s, f_{BS}~0.5.
- *but its β_P degraded in long-time scale.*
- without ITB.

- Since then, *full reproduction has been limited* by the change in conditions, mainly due to the reduced availability of 170 GHz ECH.

Accurate ECH/CD Control for High β_P State



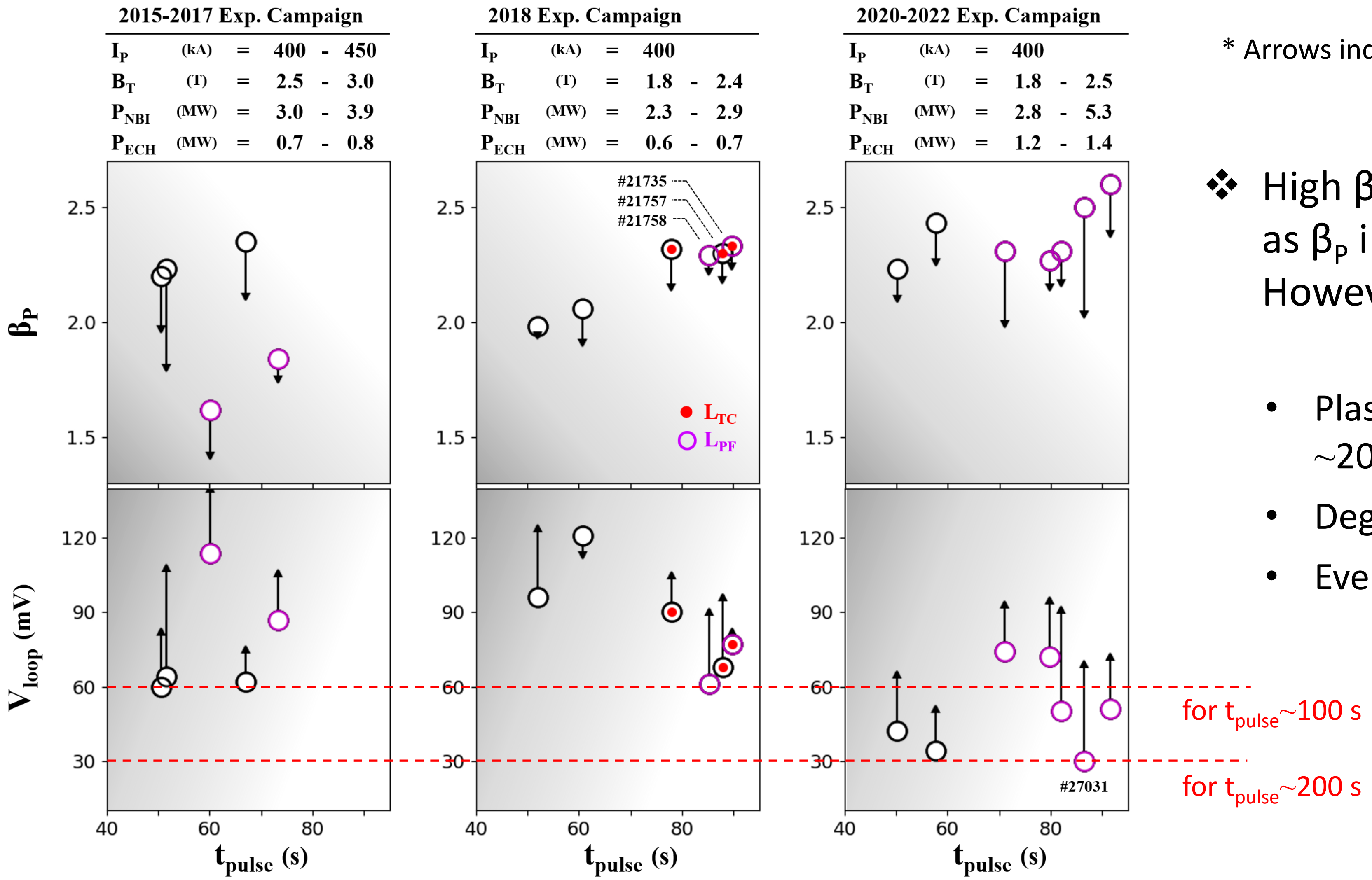


❖ ECH/ECCD must be deposited to a narrow vicinity near the magnetic axis (ψ_N~0.2).

- #18597 typical H-mode, #18602 high β_P mode
- Both discharges share nearly identical operating conditions, except for B_T.
- In high β_P discharge #18602,
  - ~30% improvement in β_P
  - ~50% reduction in V_L
- *Suppressing/mitigating n=3 TAE with ECH/CD injection improves fast ion confinement.*

✓ *For more detailed results on the KSTAR high-β_p discharge, please refer to Y. Jeon's talk on Saturday morning session.*

Challenges in Extending Pulse Length Beyond ~90 s

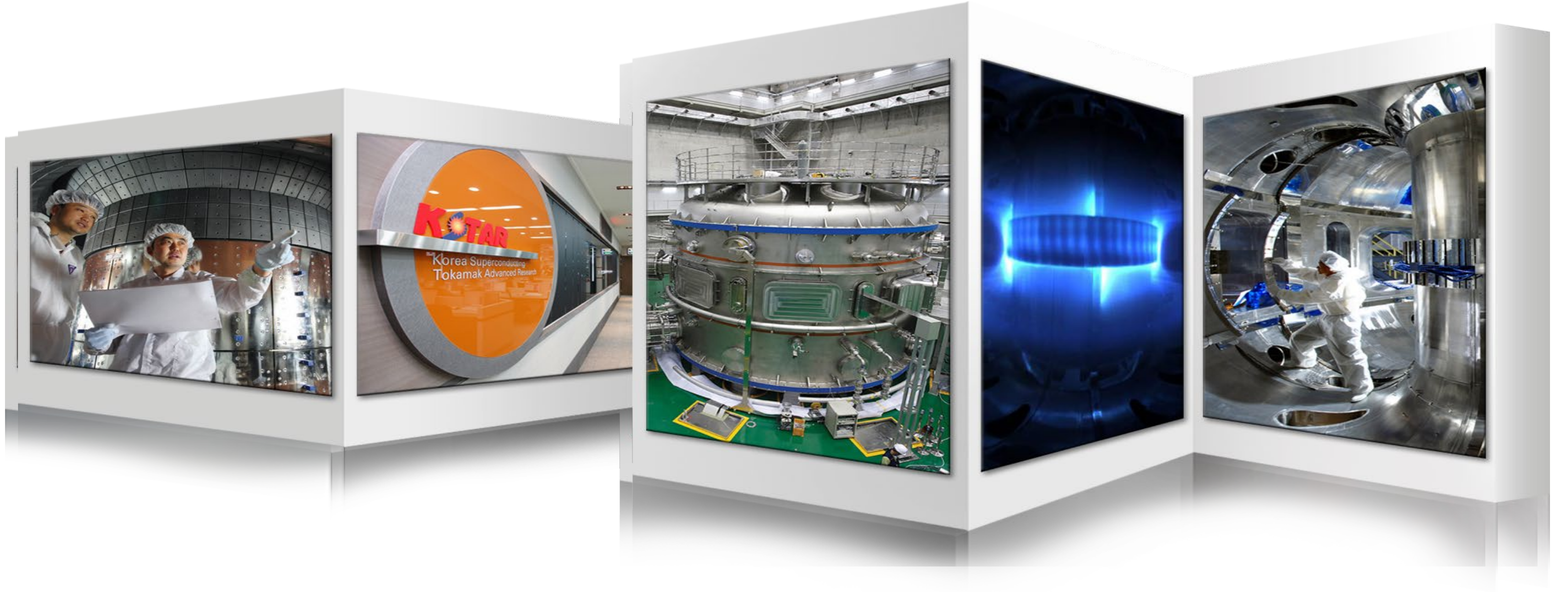


* Arrows indicate ***"degradation in time"*** occurred up to ~40 s.

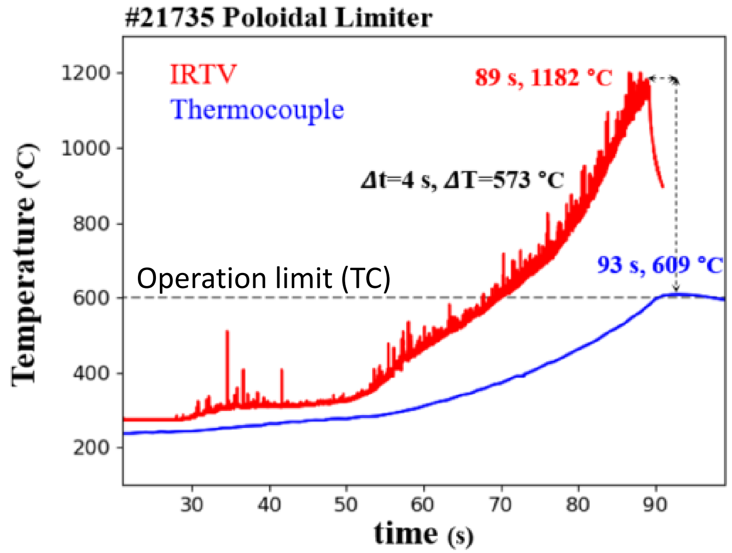
❖ High β_P scenario optimized over years, as β_P increased and V_L decreased. However,

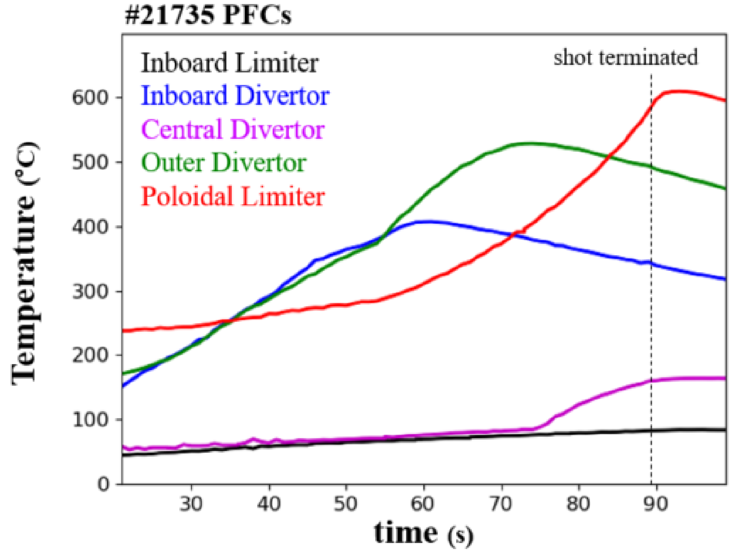
- Plasma performance degrades over time, ~20% after 20 s.
- Degradation increases V_L & flux consumption.
- Eventually reaches PF coil current limit.

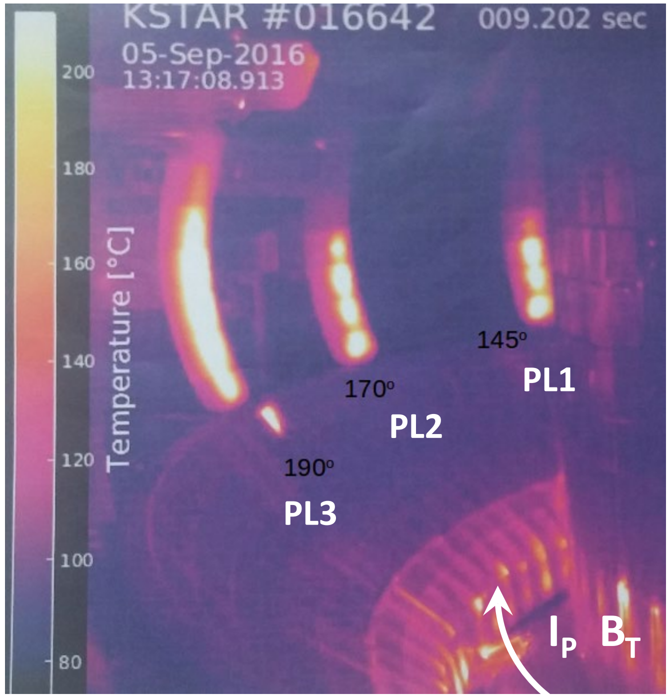
Heat Control of PFCs



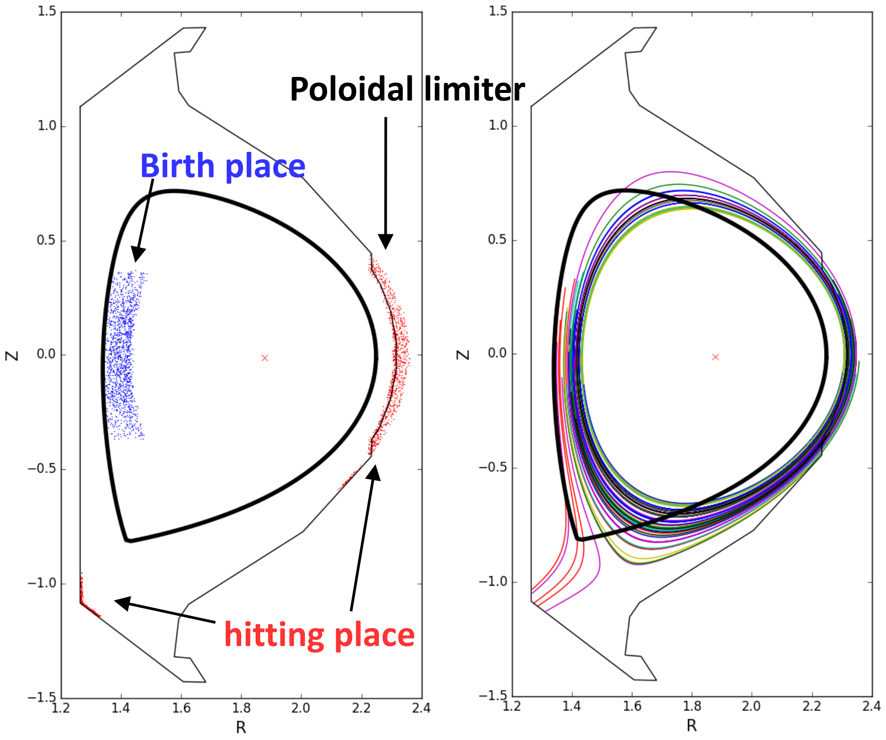
Poloidal Limiter Overheats due to Fast Ion Orbit Loss





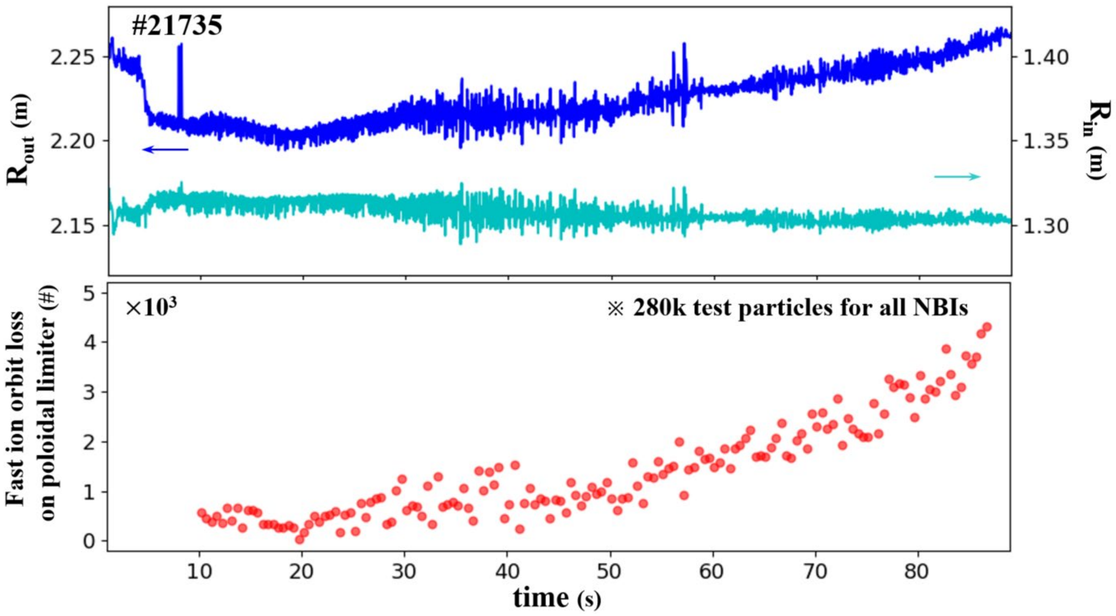


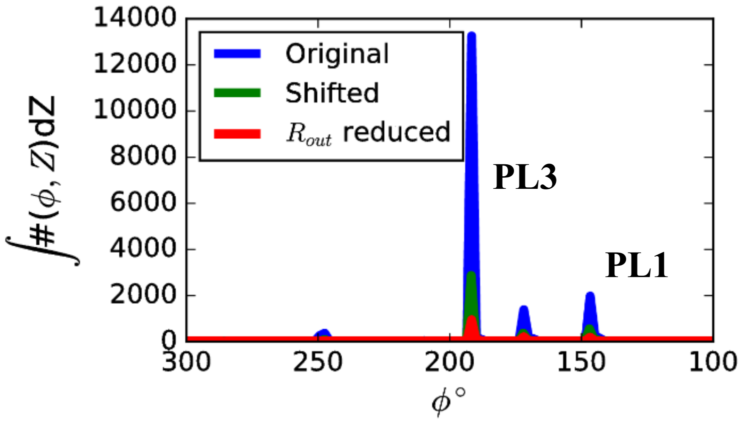
*NuBDeC code, T. Rhee PoP26(2019)112504

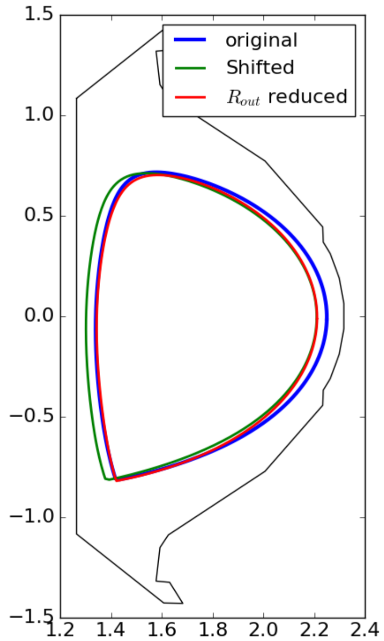


- Low I_P (400 kA) long-pulse limited by PL overheating from fast ion impact.
- Ionized fast ions at HFS strike poloidal limiters & inboard divertor.
- With 3 MW P_{NB}, max limiter load ≈ 6 MW/m².

Plasma Shape Dependence of Fast Ion Loss to Poloidal Limiter





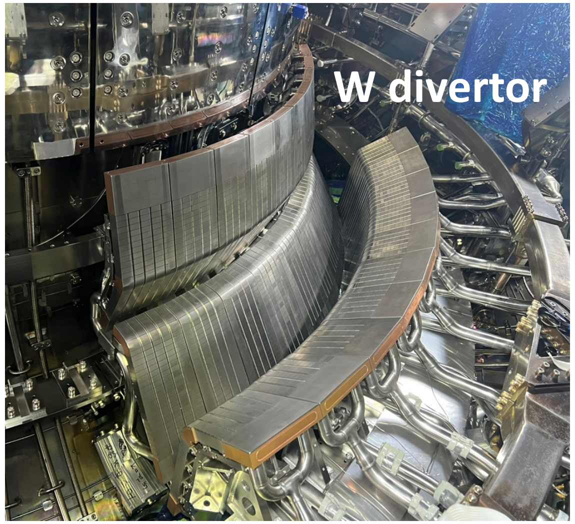


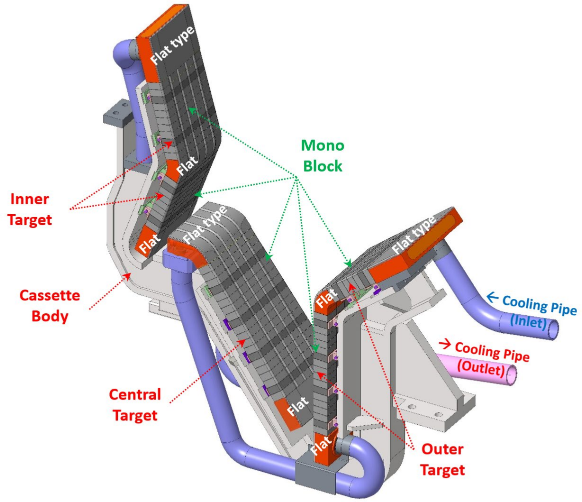
- R_{out} increased almost linearly from ~50 s, reaching 2.27 m at 89 s, affected by magnetic probe signal drift.
- Increase in R_{out} → more fast ions lost to poloidal limiter.

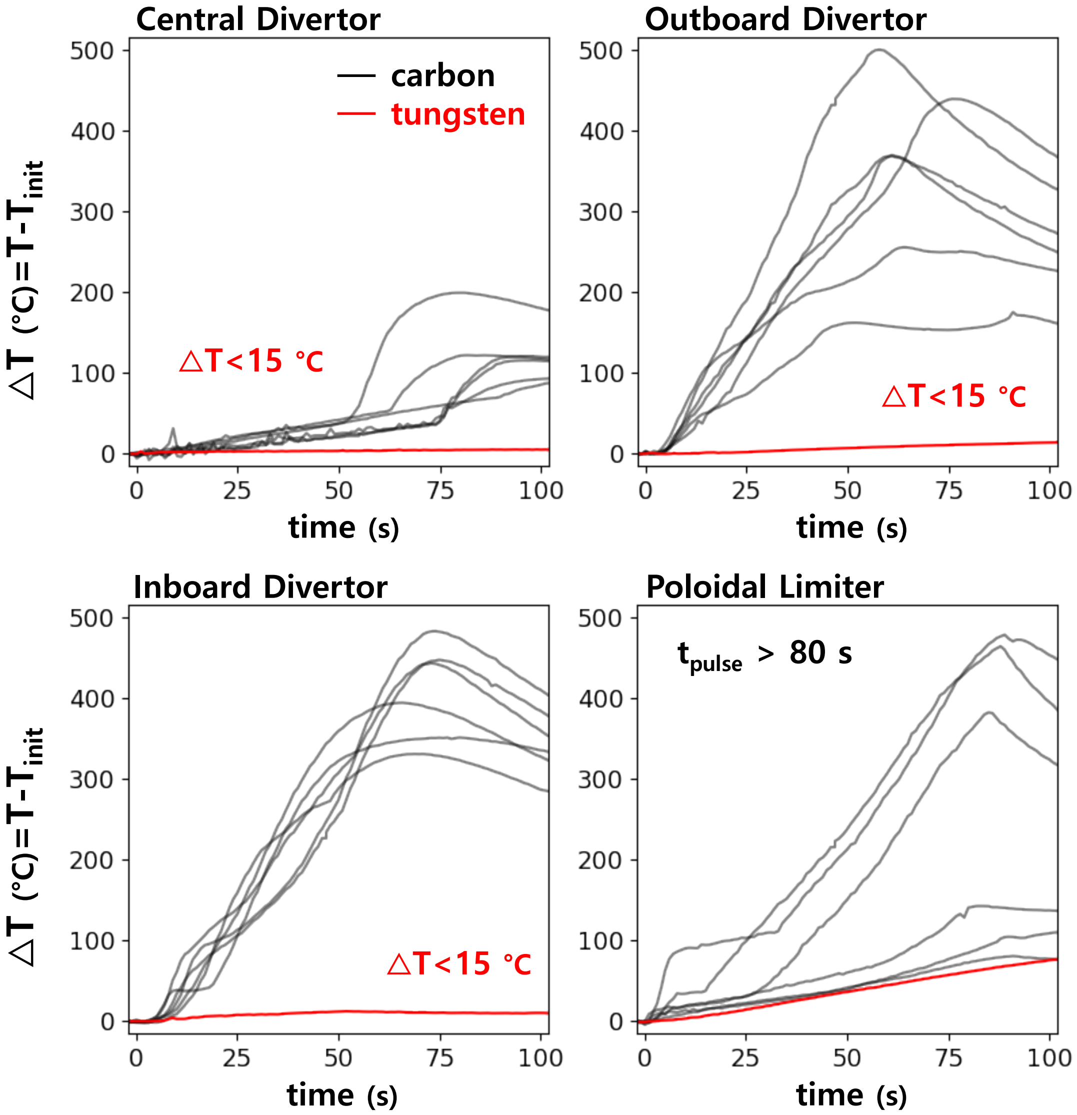
❖ For long-pulse discharge, plasma shape optimized by maintaining R_{out} < ~2.21 m.

Actively Cooled W-shaped Tungsten Divertor

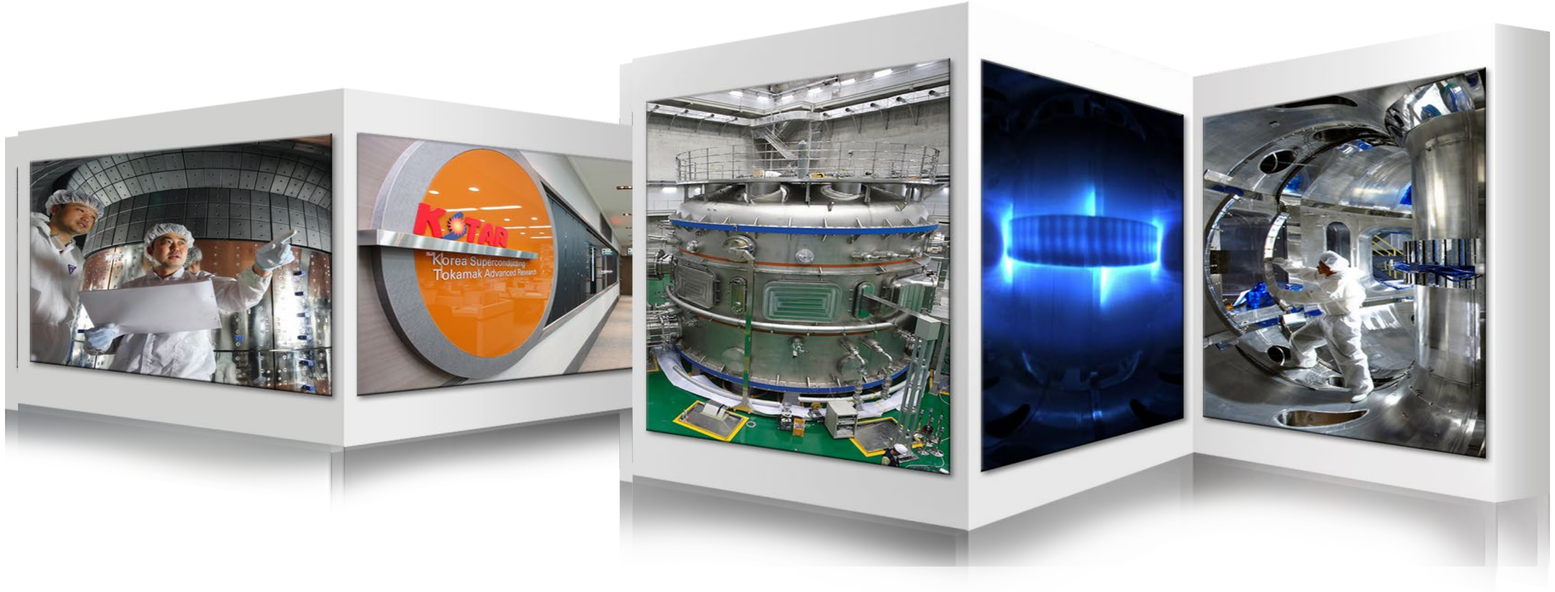
- Capable of handling ***~10 MW/m² steady-state heat flux***, demonstrating ITER-relevant thermal performance.
- Actively cooled divertors: ***ΔT < 15 ℃*** in 102-s high-performance discharge.
- No PFC temperature issues expected up to 300 s (KSTAR goal) with present injection power ~12 MW.







Mitigation of Magnetic Signal Drift



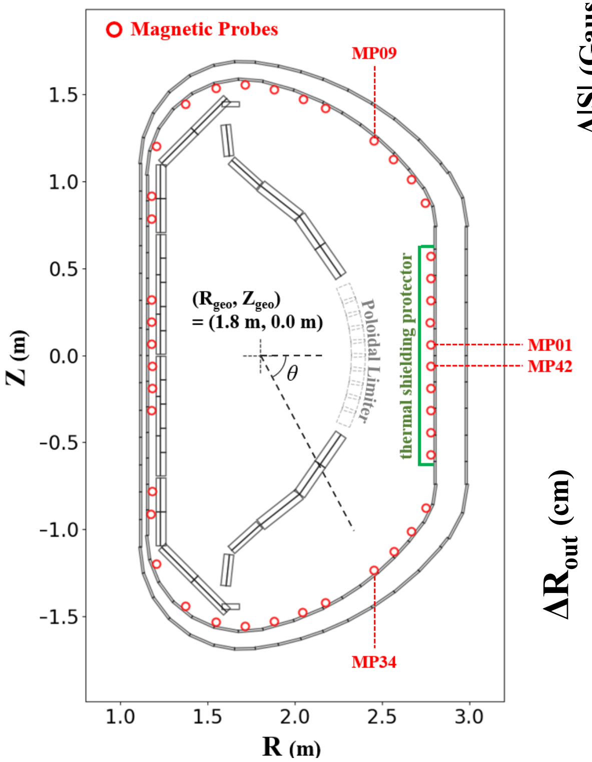
Mitigation of Nonlinear Signal Drift in Magnetics

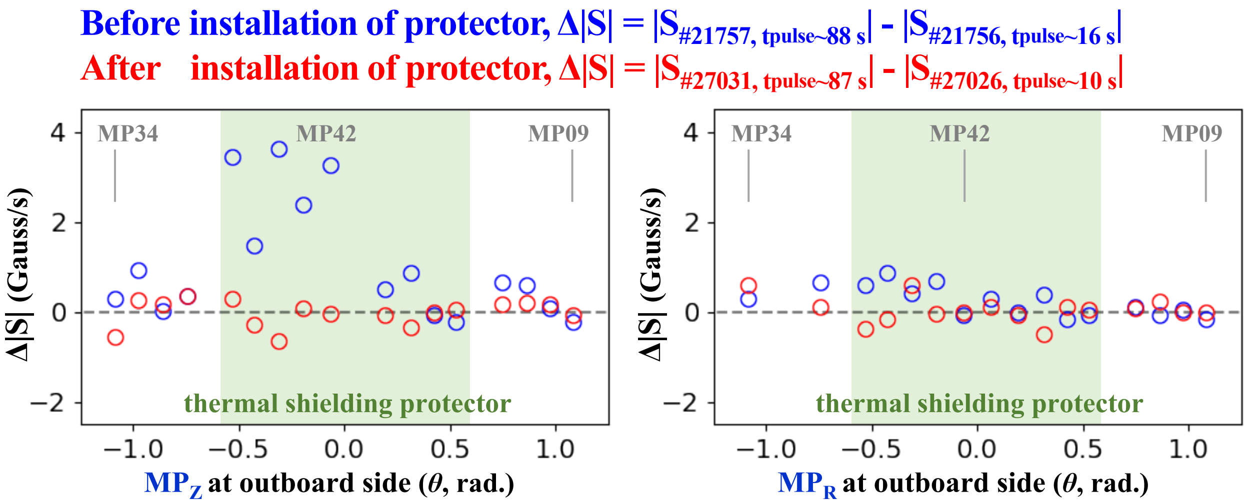
❖ Nonlinear magnetic drift impact on plasma shape

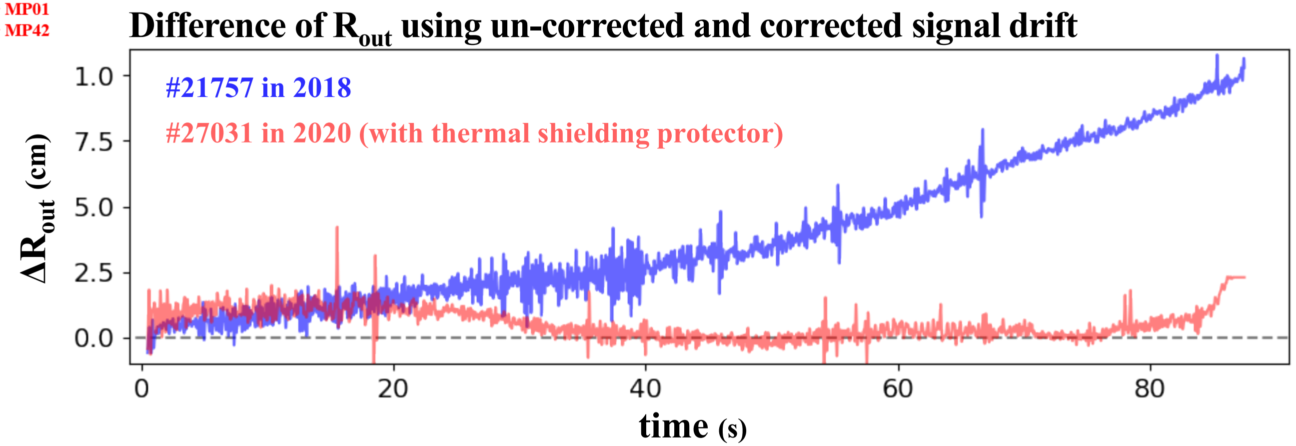
- Magnetics strongly affected by nonlinear drift in hot, long-pulse plasma.
- Drift led to unintended plasma shape change.

❖ MP_Z mainly shows nonlinear signal drift

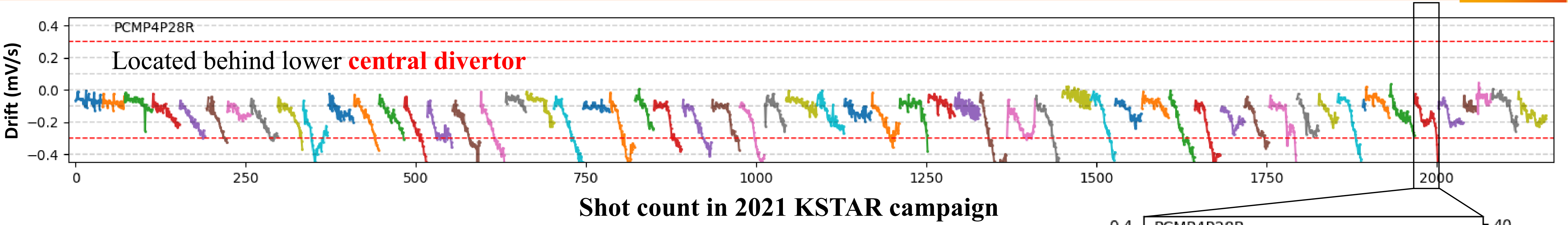
- *Coil winding of MP_Z facing to the plasma.*
- ***Thermal shielding protector*** effectively blocked plasma heat.

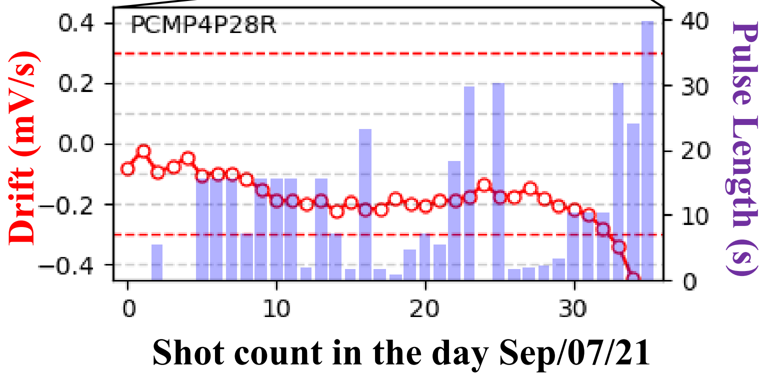






Successful Operation of Real-time Linear Drift Correction



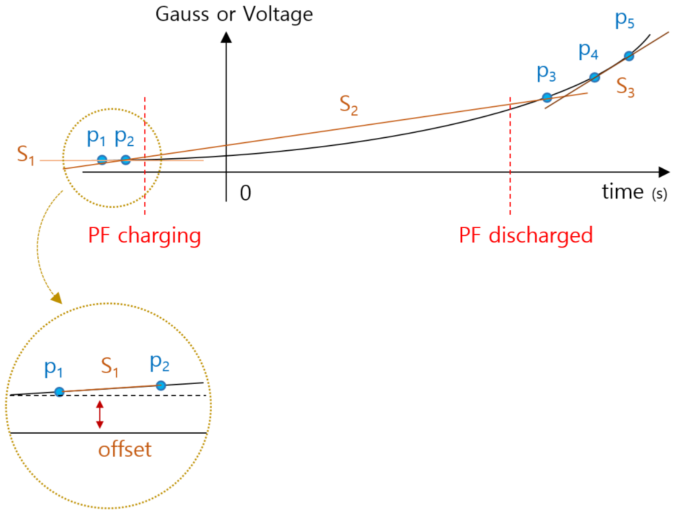


❖ *Accumulated Signal Drift of Magnetic Probes in a day*

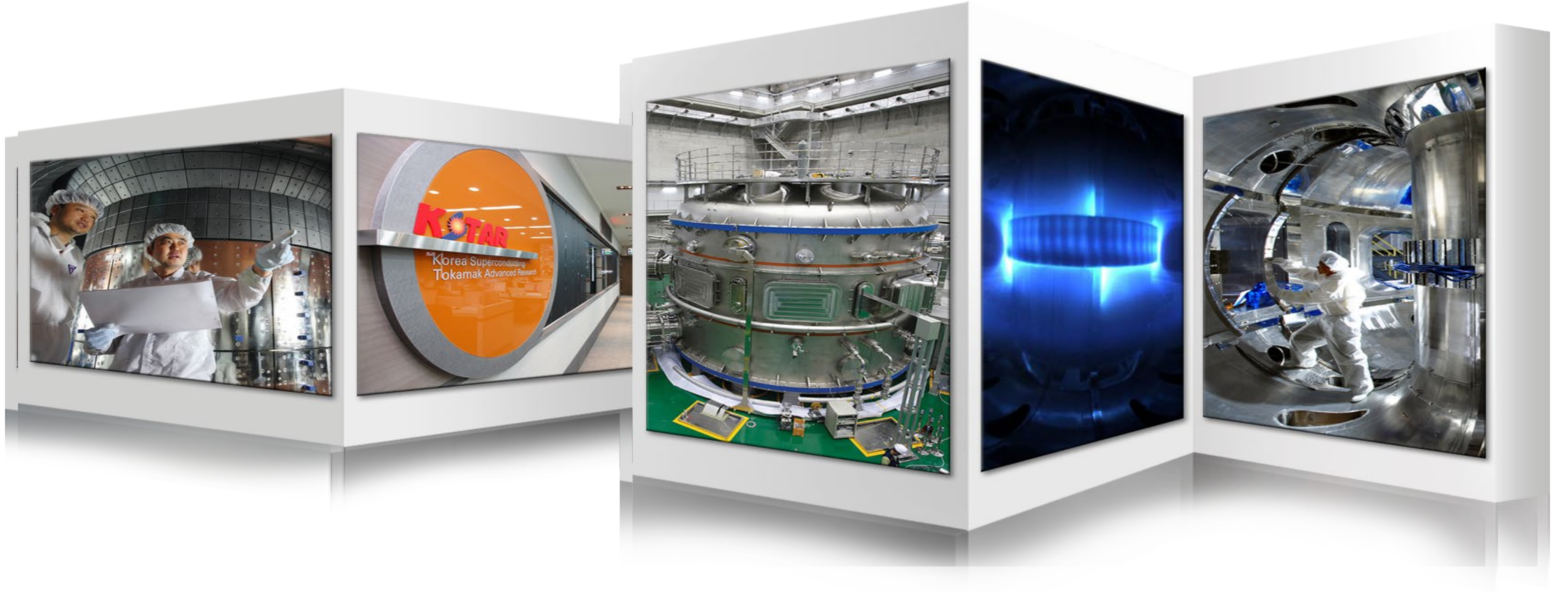
- Many signals show drift > 0.3 mV/s per day. (criterion < 0.3 mV/s)
- Morning vs. afternoon shots → different shapes in rtEFIT.
- Drift returns to IDLE next day. (recovered)
- Drift level influenced by discharge pulse length.

❖ *Implementation of real-time linear signal drift correction algorithm in PCS*

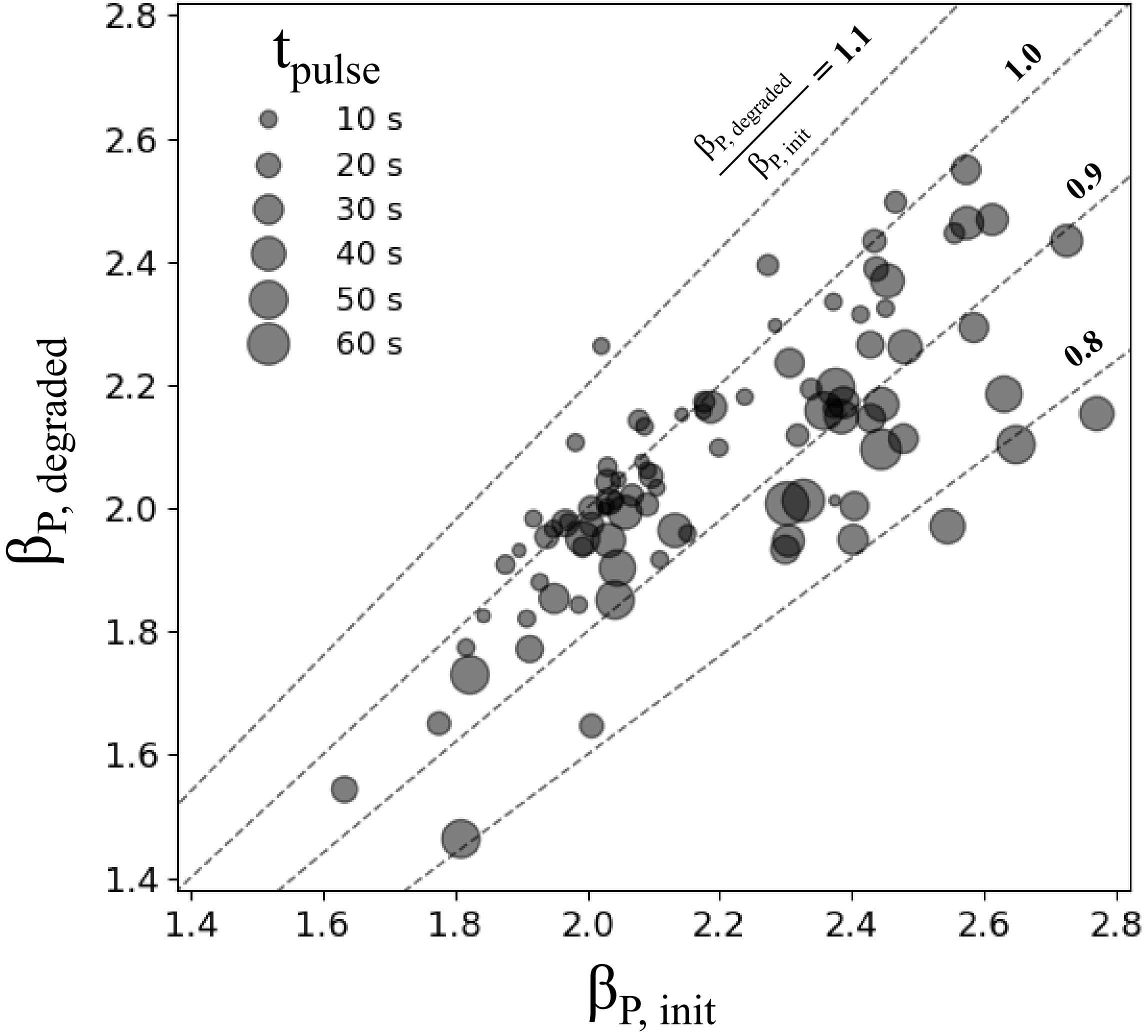
- Getting linear slope and offset of drift from previous selected discharge.
- < 2 cm plasma shape change during 102 s.

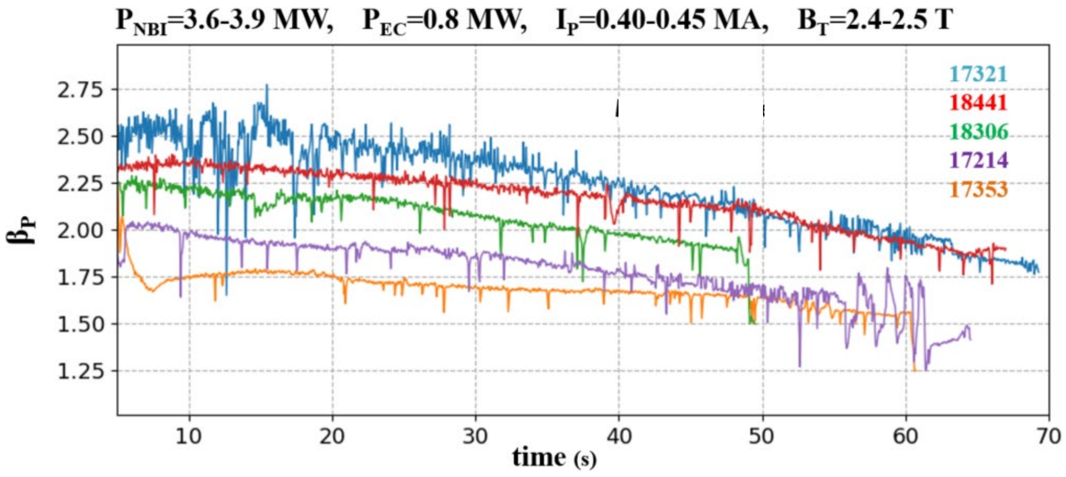


Plasma Performance Degradation



Progressive Degradation of Plasma Performance over Time



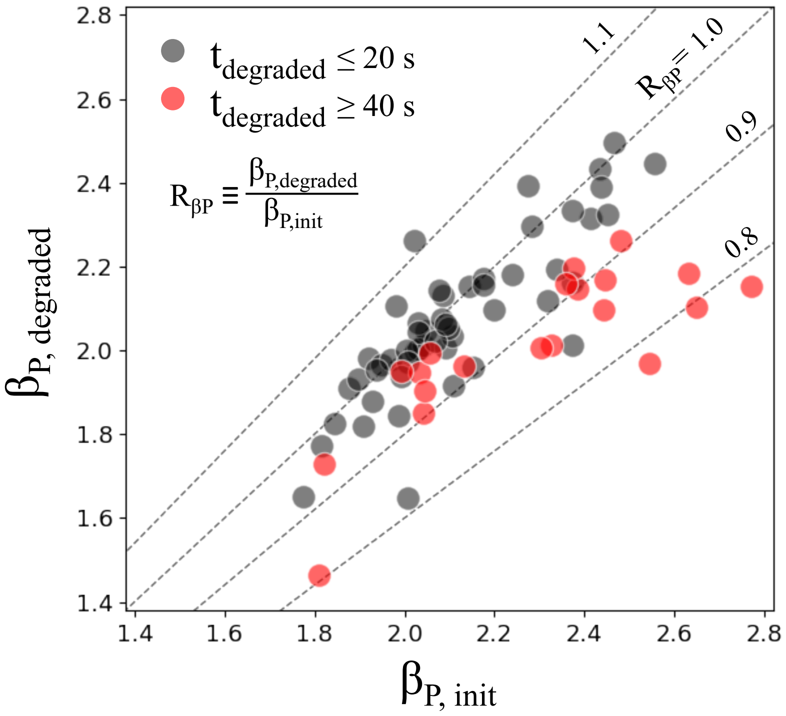


- Degradation observed over long-time scale (~10^3 τ_E)
- Degradation more severe with longer pulse length
- Degradation more severe with higher performance

Impact of TAEs on Progressive β_{fast} Degradation

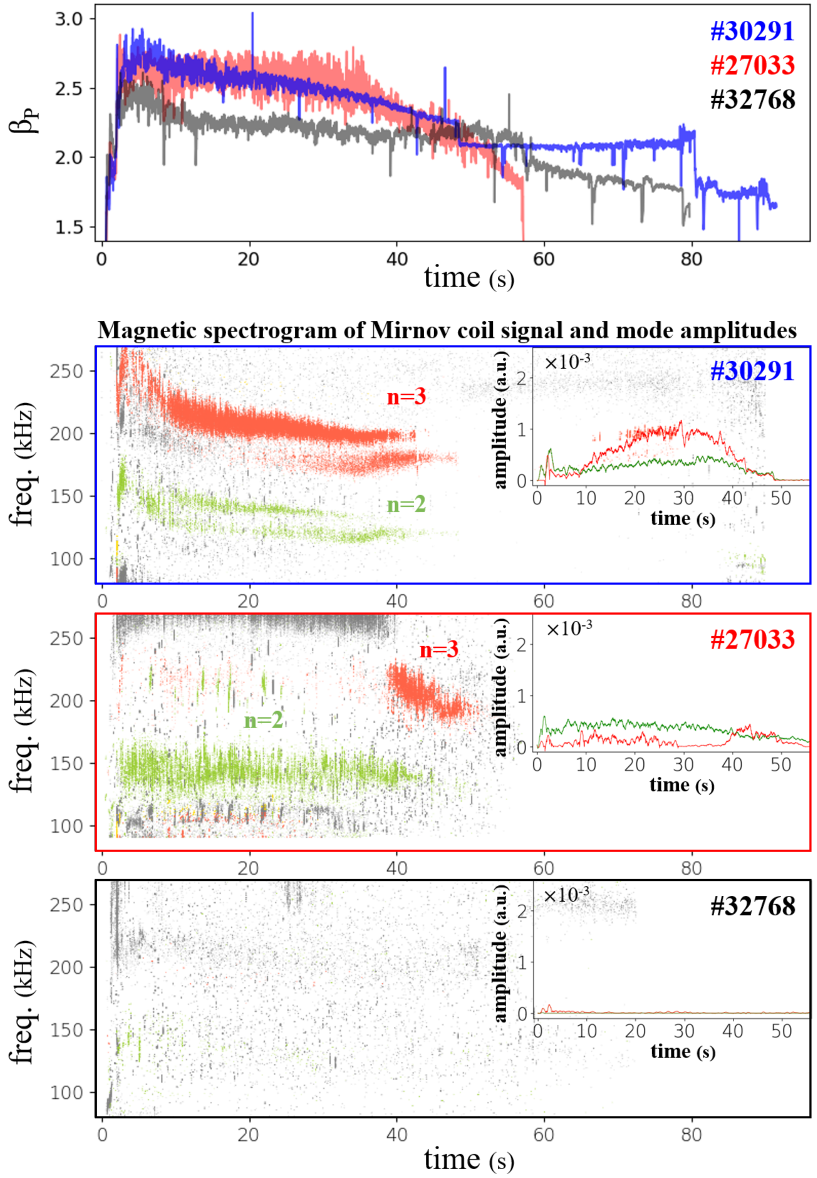
❖ **degradation process related to TAEs**

- High β_P plasma → better fast-ion confinement, vulnerable to TAE
- TAE activated spontaneously, but weakened by ECH injection
- *Weak, long-lasting TAE → progressive degradation on long-time scale*
- Fast-ion pressure reduced until TAE self-disappeared

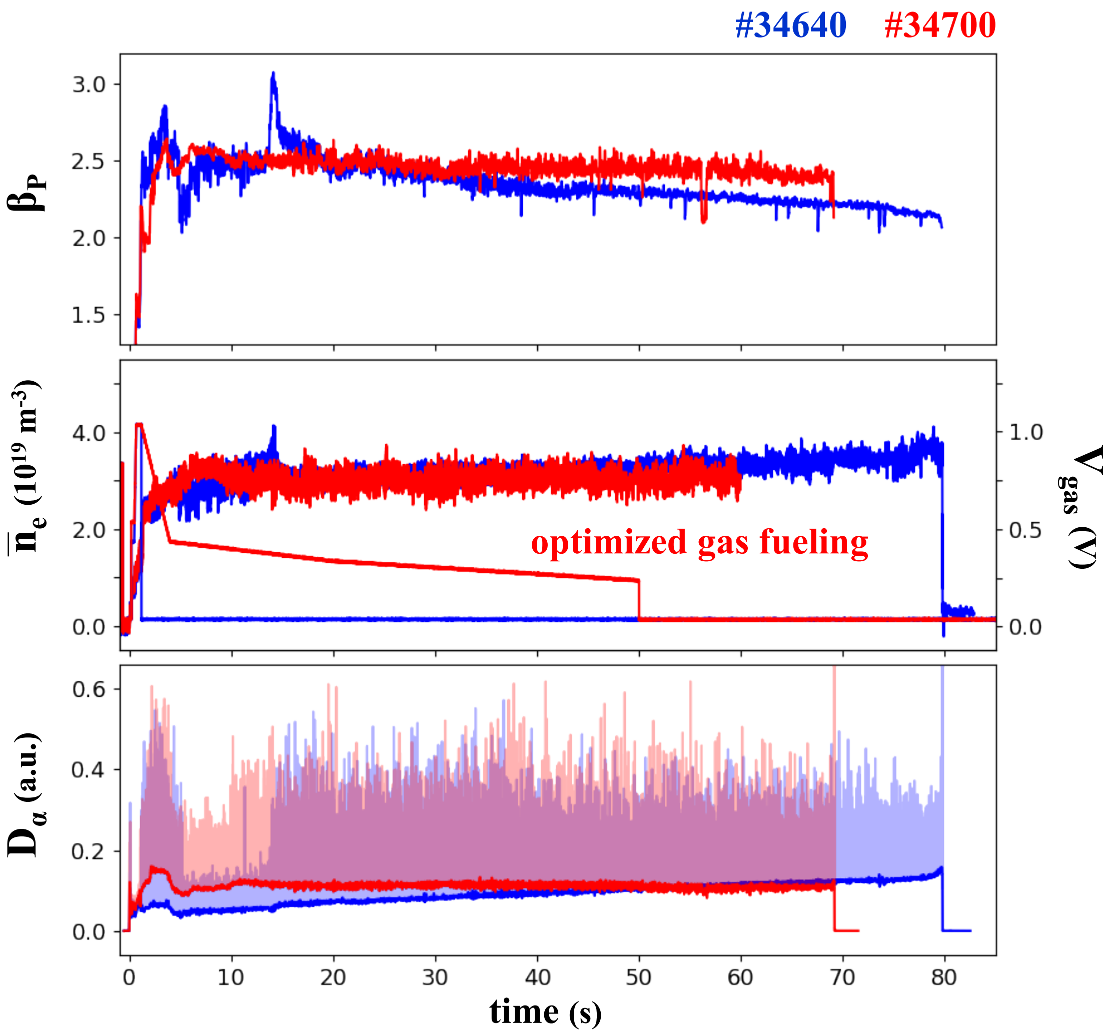


- TAEs self-disappeared
  → β_P converges
  to ~2.0–2.2

✓ H.-S. Kim and Y. Jeon et al., Nucl. Fusion 64 016033 (2025)



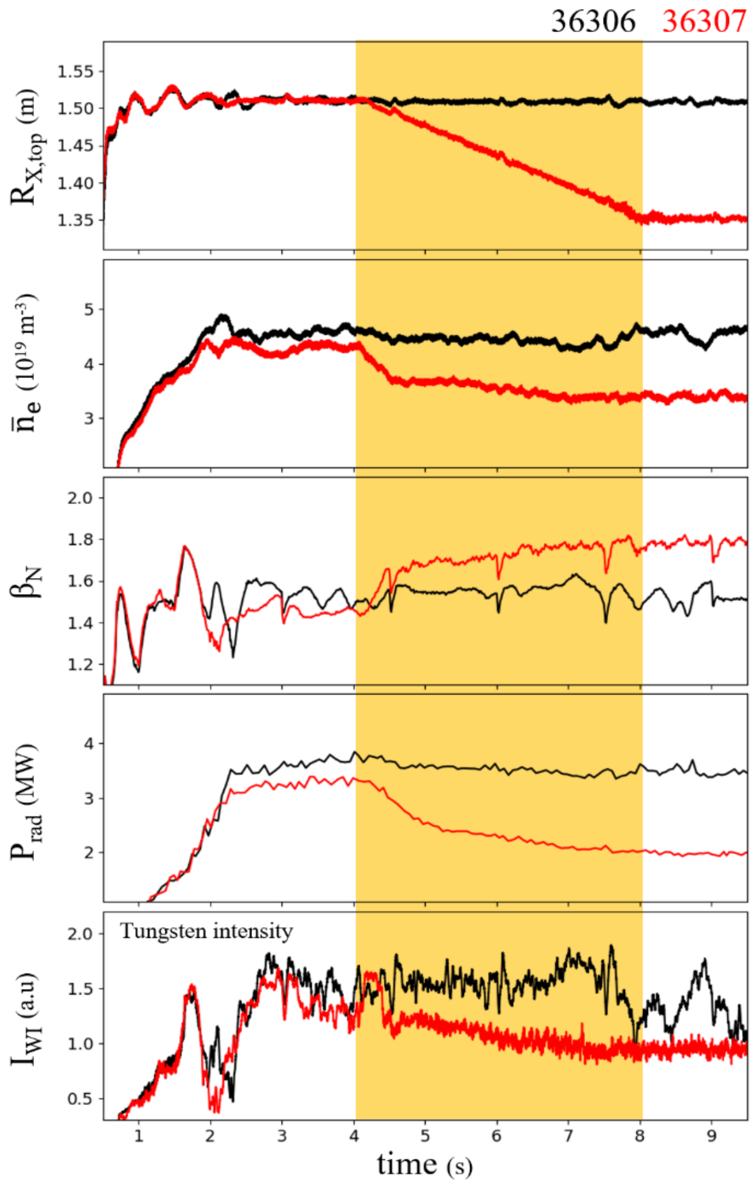
Minimized Performance Degradation with W Divertor



❖ Sustained high-β_p operation achieved through optimized gas fueling scenario

- Performance degradation effectively minimized in 2023.
- *Optimized long-time gas fueling sustains high β_P (>2.5) plasmas.*
- Stable performance maintained for ~70 s. (high reproducibility)
- Effect not observed in past carbon divertor configurations.
- With W-shaped divertor, SOL conditions appear modified.

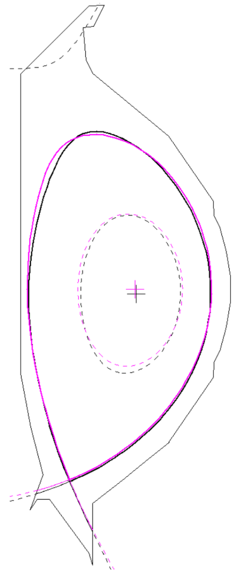
Control of Radiative Power in W Divertor Plasmas



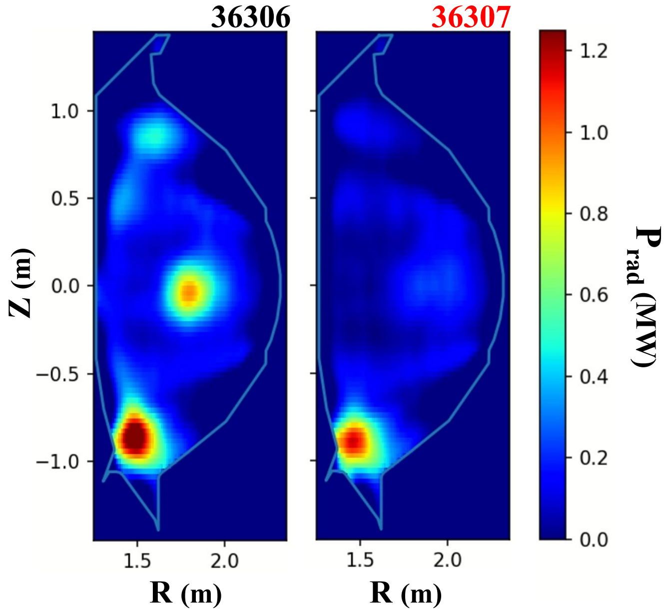
❖ $R_{X,top}$ adjustment effectively reduced tungsten accumulation and P_{rad}

- W divertor increased P_{rad} by ***3–4×*** compared to the carbon divertor.
- ***Lowering $R_{X,top}$*** decreased P_{rad} and I_{WI} simultaneously.
- ***Optimized shape scenario*** enabled stable long-pulse operation with minimized radiation and tungsten accumulation.

Shape variation as $R_{x,top}$ changes



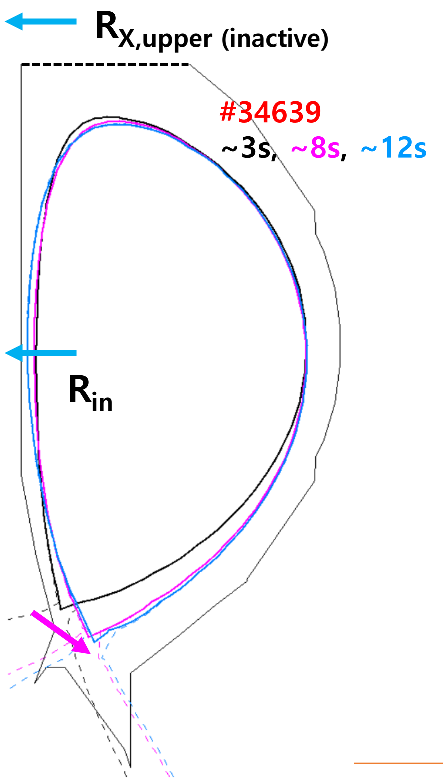
IRVB variation as $R_{x,top}$ changes

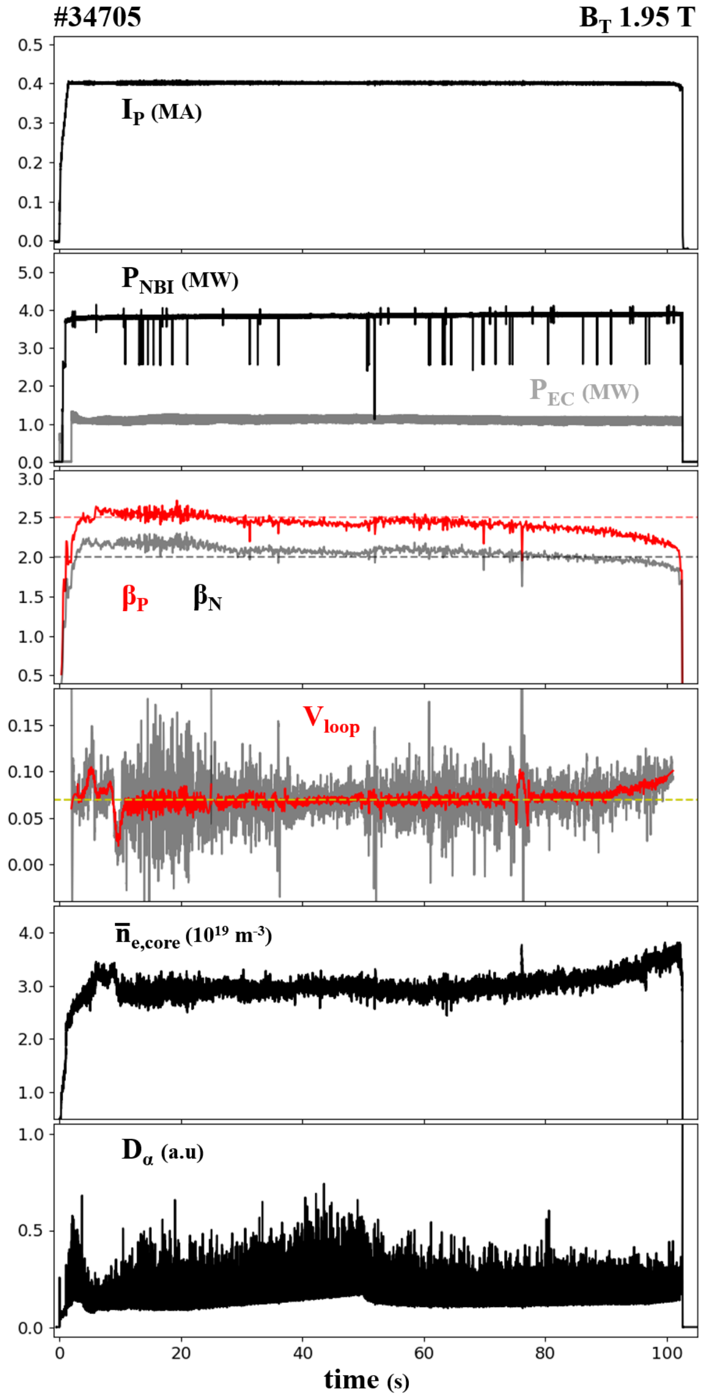


102-s Sustained High-performance Plasma

❖ Performance maintained for ~70 s with greatly minimized degradation.

- V_{loop}~70 mV, β_P~2.5, β_N~2.1, $T_{e,core}$>6.0 keV, $T_{i,core}$~2.5 keV, $\bar{n}_{e,core}$~3.0x10^{19} m^{-3}.
  - Plasma parameters comparable to other long-pulse discharges.
- Actively cooled W-shaped tungsten divertor successfully operated.
- Real-time linear drift correction algorithm of magnetics successfully implemented in PCS.
- Re-optimized shape scenario for W divertor applied.
- Optimized long-time gas fueling scenario applied.





Summary and Plans for Longer Pulse Discharge

❖ Securing solutions for high-performance long-pulse discharge issues

- Heat control on PFC (solved)
  → Optimizing shape control and major upgrade of actively cooled W monoblock divertor
- Magnetic signal drift in the long-time scale (solved)
  → Thermal shielding block on the magnetic probes
  → Real-time linear drift correction algorithm in PCS
- Performance degradation in long-time scale (partially solved)
  → Identified cause: weak, long-lasting TAEs → fast ion transport → $\beta_{P,fast}$ degraded
  → Long-time gas fueling & shape scenario optimization under W-shaped divertor

❖ Plans for longer high-performance discharges

- Achieve 300-s high-performance operation by realizing a nearly full non-inductive plasma state ($f_{NI} \geq 0.95$).
- *Develop reproducible ITB formation and q-profile control scenarios enabling steady high-β_p sustainment.*

(in collaboration with DIII-D)

FUSION: Fundamental, Unlimited, Sustainable, Innovative, Overturning, No Radioactive Waste

"KFE's Vision:

Creating a New Sun

to Illuminate the Next Generation"

"Thank you for your attention!"

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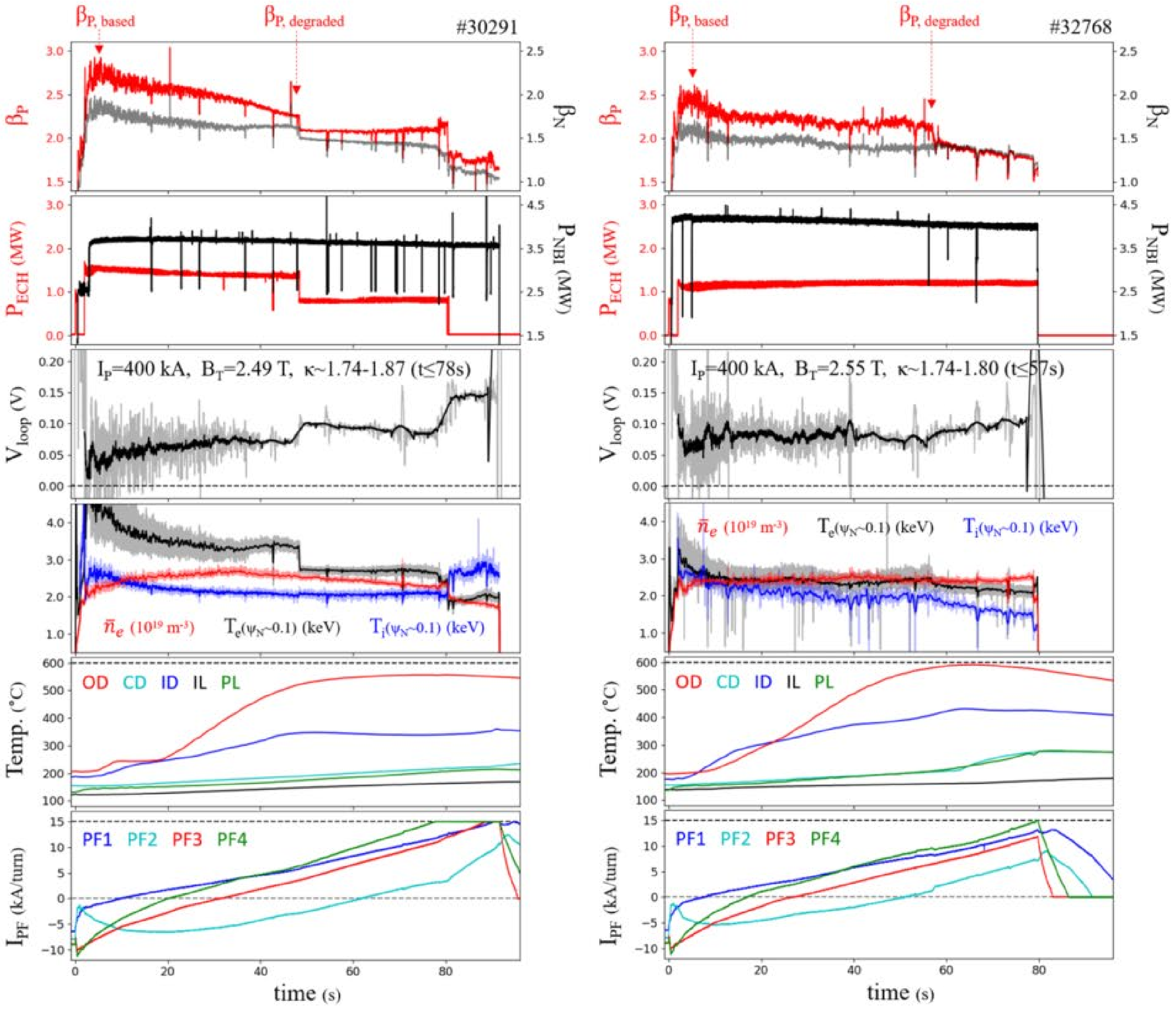
Supplements



Investigation of performance degradation (1)

❖ **Representative two discharges,**

#30291, linearly degrading performance
#32768, almost constant performance

- Similar operating conditions
- P_{NBI} : #30291 < #32768, ~0.5 MW
- P_{ECH} : #30291 > #32768, ~0.5 MW
- β_P : #30291 > #32768
- V_{loop} : #30291 < #32768

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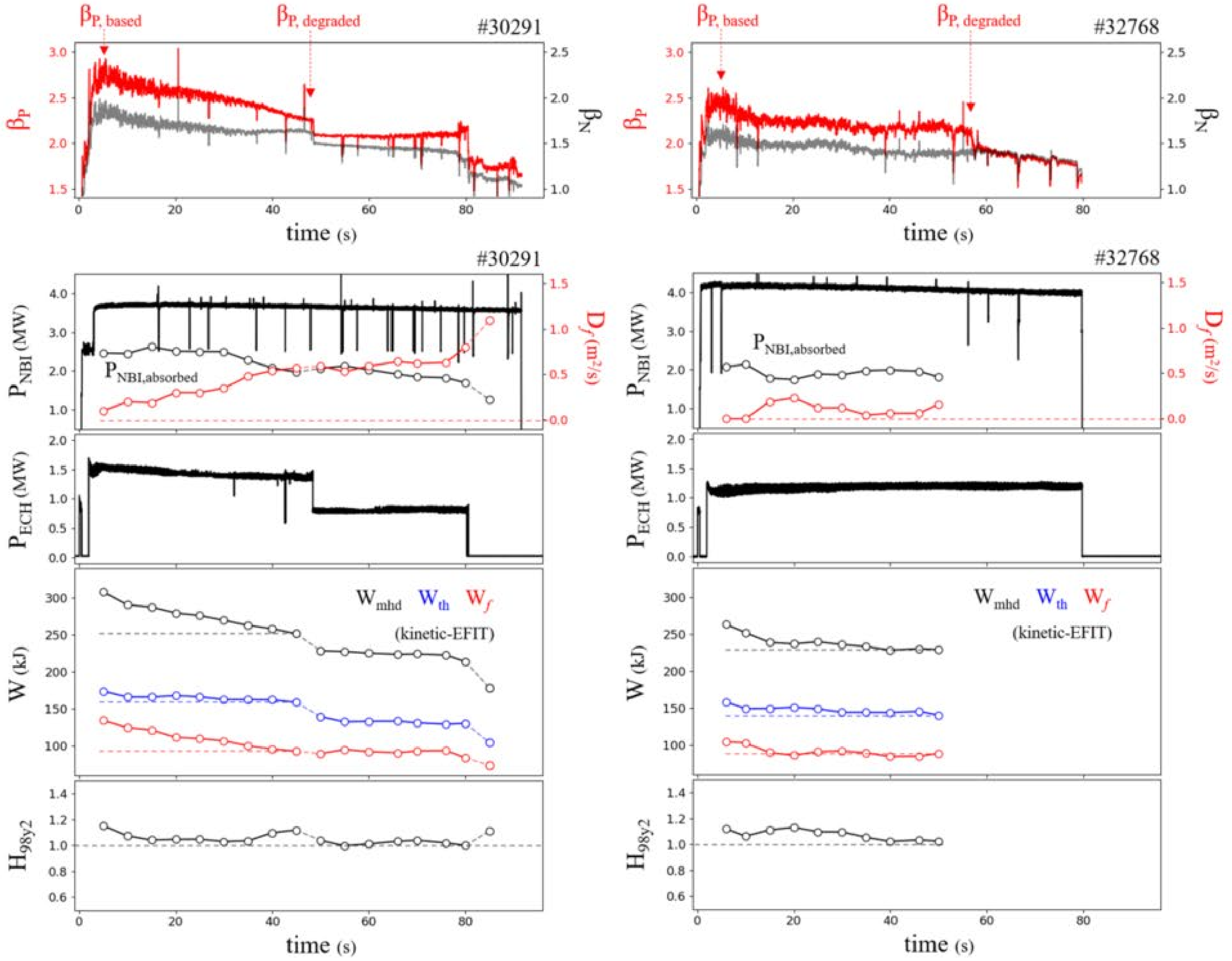
Supplements



Investigation of performance degradation (2)

❖ **0-D plasma characteristics analyzed using KSTAR kinetic-EFIT packages**

In #30291,

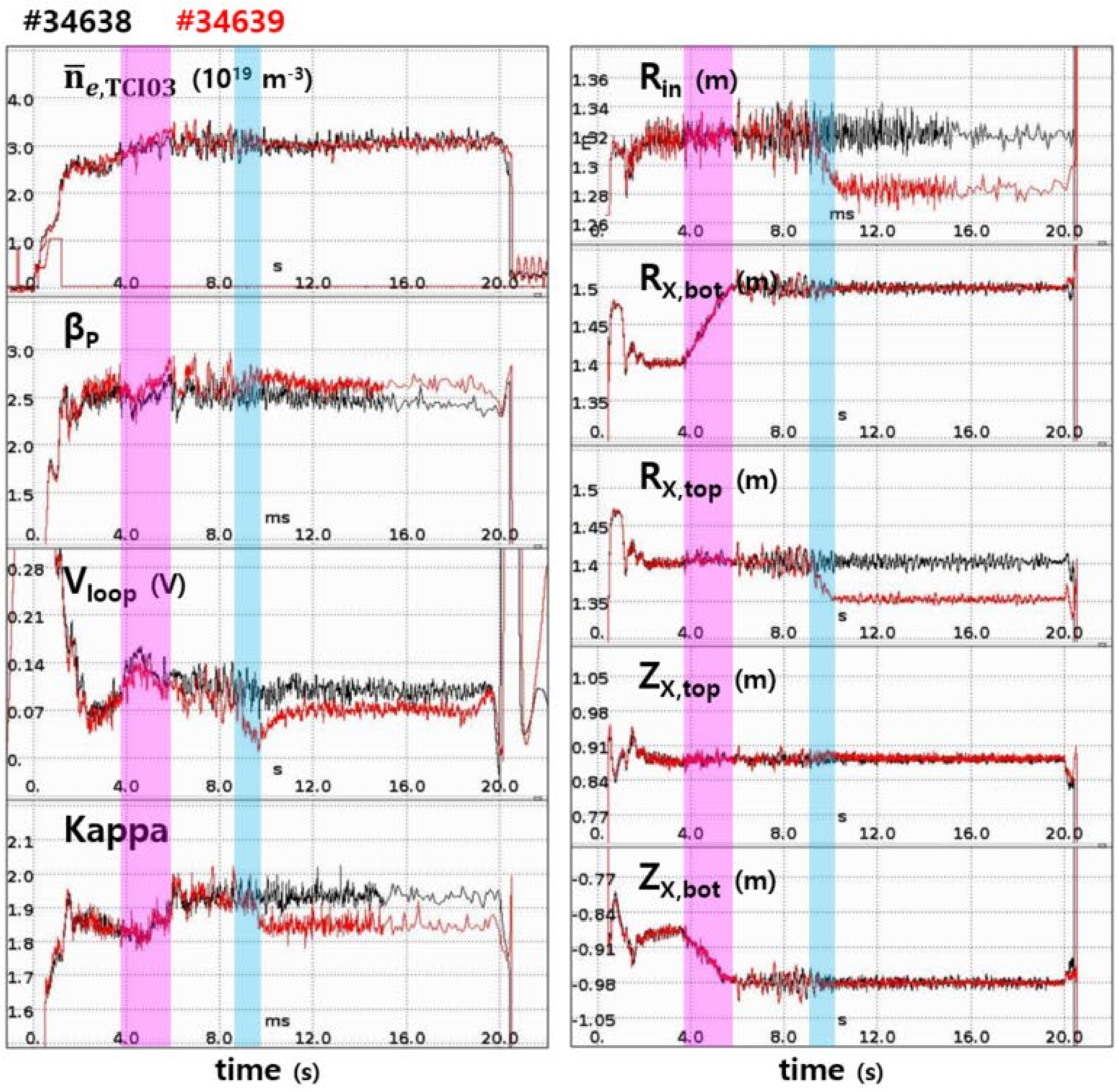
- <u>β_P degradation comes from β_{fast}, not β_{th}</u>
- Fast ion transport is increased (see D_f)
- H_{98y2} is almost constant ~1.0-1.1 (typical H-mode confinement)

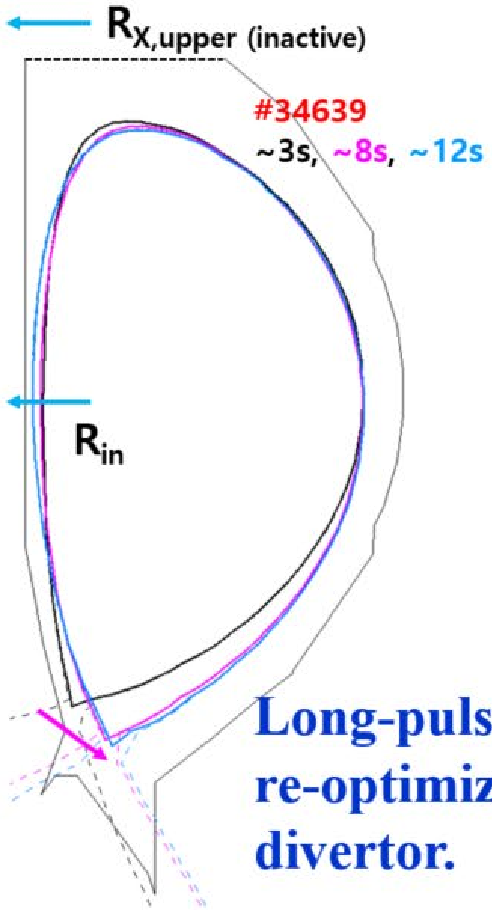
On the other hand, in #32768,

- β_{fast} and β_{th} are almost constant
- β_P is almost constant over time
- H_{98y2} is almost constant ~1.0-1.1
- Mainly NBI2 sources are applied
  - Even with higher $P_{NBI,injected}$, $P_{NBI,absorbed}$ is lower compared with #30291 → relatively lower β_P

Why is fast ion transport increased in #30291?

Supplements





Long-pulse shape scenario is re-optimized for W-shaped divertor.

- Keeping former plasma shape to get high β_P (t<3.5s)
- Moving lower X-point to suit W-shape divertor (t<9.0s)
- Reducinge $R_{x,top}$ and R_{in} to get lower V_{loop}