Second Technical Meeting on Long-Pulse Operation of Fusion Devices

IAEA Headquarters, Vienna, Austria, 14th-18th October 2024

Achievement of 102-second High-performance Long-pulse Discharge with Lower W-shaped Tungsten Divertor in KSTAR

Hyun-Seok KIM, Hyunsun HAN, YoungMu JEON, Youngho LEE, and the KSTAR team

*E-mail: hskim0618@kfe.re.kr

Korea Institute of Fusion Energy (KFE), Daejeon, Republic of Korea

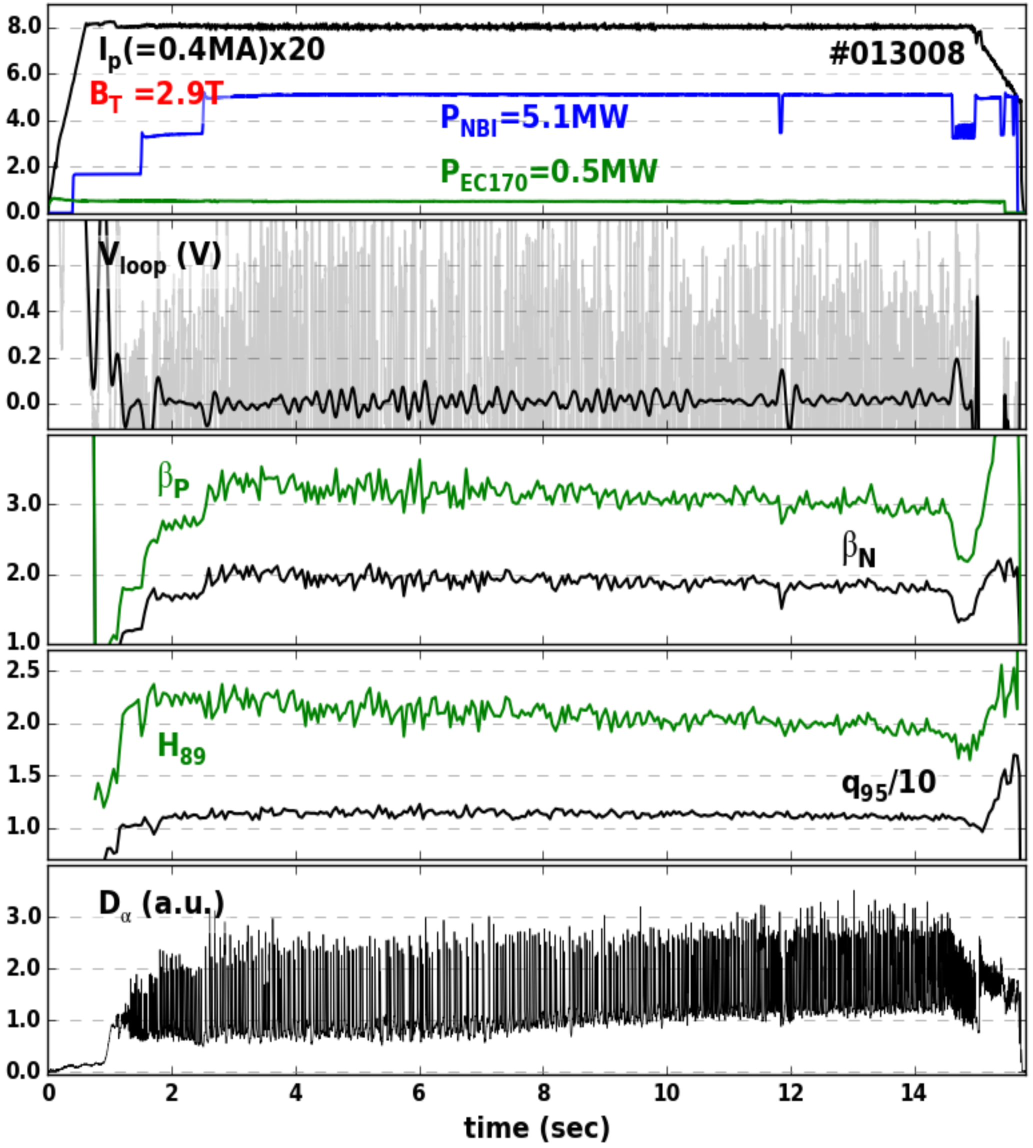
The advancement of long-pulse discharges in KSTAR aims to develop stable and sustainable high-performance scenarios and test the long-pulse operation capabilities of the device, identifying and resolving any issues that may arise during such operations from the points of view of both plasma physics and device engineering.

- The primary H&CD systems employed for long-pulse plasma operation at KSTAR are NBI and ECH. This enables not only the evaluation of the long-pulse capability of the H&CD systems but also the examination of NBI-driven fast ion behavior in a long-pulse discharge.
- In particular, the achievement and continuation of a burning plasma state in ITER heavily relies on effectively preventing the transport of NBI-driven fast ions and fusion-generated α-particles. In this sense, KSTAR can contribute to studying fast ion behavior in conducting long-pulse plasma operations.

- During long-pulse plasma operation, KSTAR has experienced the following issues.

  1. Rapid temperature increase in PFCs due to beam-driven fast ion orbit loss and nonlinear signal drift in magnetic probes.
  2. Insufficient poloidal flux for discharges lasting more than ~10^2 seconds.
  3. Gradual degradation in plasma performance over a long-time scale to ~10^3 τ_E.

KSTAR long-pulse approach began in 2015 with conducting a discharge characterized by high β_P>3.0 and zero V_{loop}.



❖ An example of KSTAR high-β_P discharge (f_{NI}~1.0, f_{BS}~0.5)

- High q_{95} (= 7-11) with high B_T
- Early NB injection at 0.4 s with 170 GHz ECH injection
- Sufficient heating power (=4.0−5.5 MW)

→ Achieved high performance β_P>3.0, but degraded in time

→ Zero loop voltage for ~10 seconds

→ No ITB

→ **Since then, it has not been reproduced due to the changed operating conditions, particularly the absence of 170 GHz ECH.**

KSTAR has faced difficulties in extending pulse length, over ~90 s, in recent years.

2015-2017 Exp. Campaign

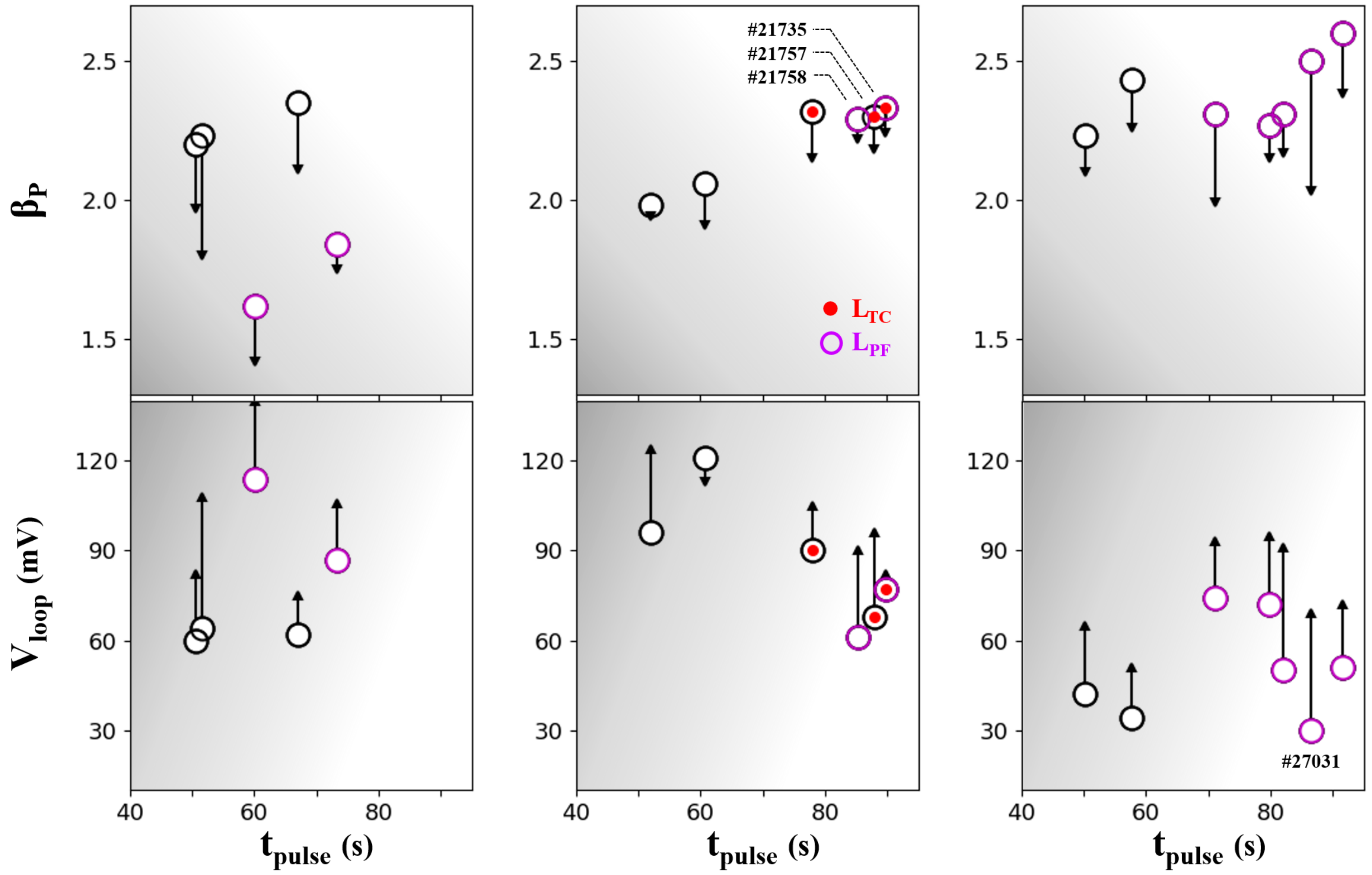
I_P	(kA)	=	400	-	450
B_T	(T)	=	2.5	-	3.0
P_{NBI}	(MW)	=	3.0	-	3.9
P_{ECH}	(MW)	=	0.7	-	0.8

2018 Exp. Campaign

I_P	(kA)	=	400		
B_T	(T)	=	1.8	-	2.4
P_{NBI}	(MW)	=	2.3	-	2.9
P_{ECH}	(MW)	=	0.6	-	0.7

2020-2022 Exp. Campaign

I_P	(kA)	=	400		
B_T	(T)	=	1.8	-	2.5
P_{NBI}	(MW)	=	2.8	-	5.3
P_{ECH}	(MW)	=	1.2	-	1.4



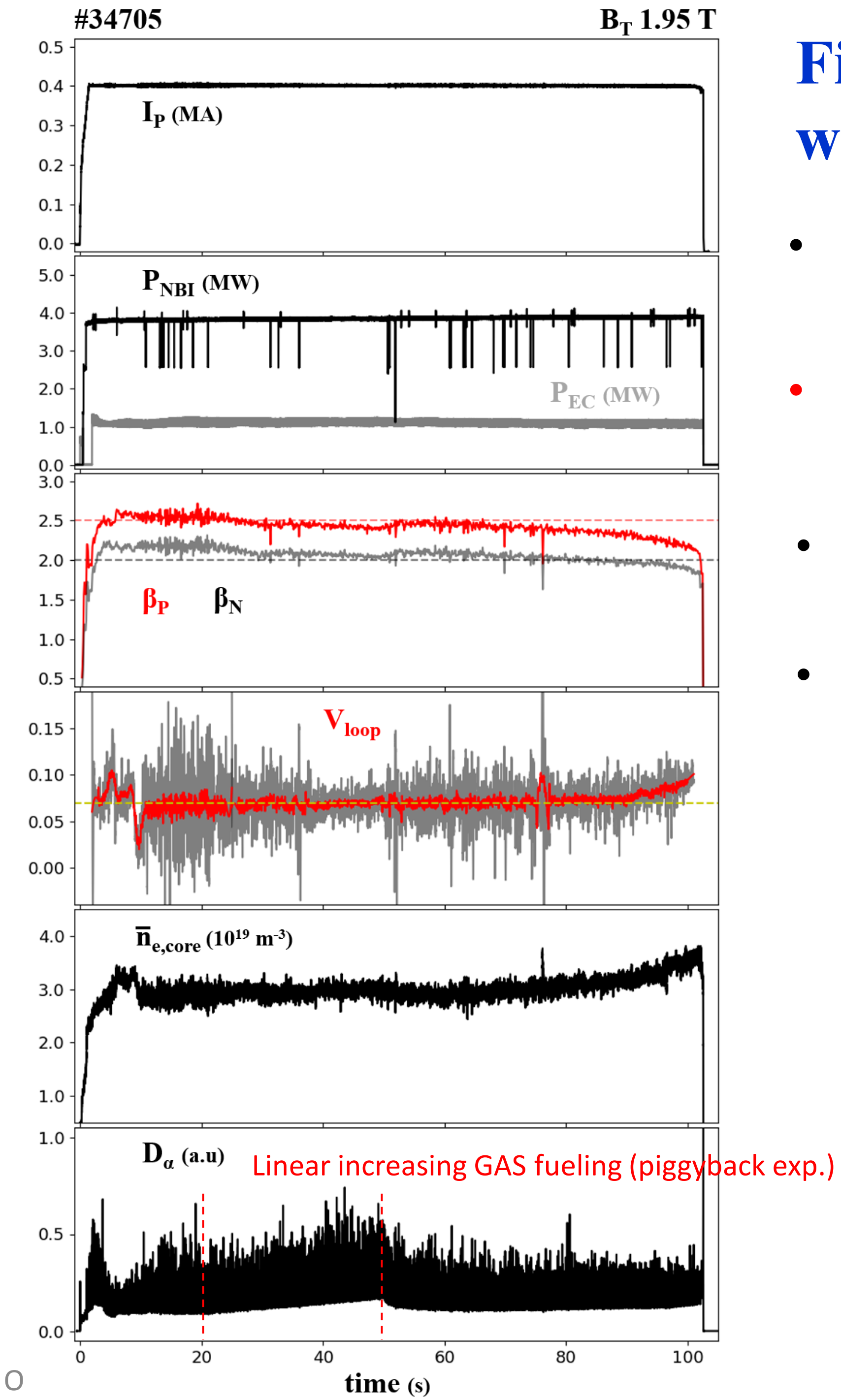
- High β_P scenario adopted for high-performance long-pulse discharge in KSTAR.
  - V_{loop} decreases as β_P increases.
  - TAE should be mitigated/suppressed by precise ECH injection to increase β_P.

- Plasma performance degradation over time makes it difficult to increase the pulse length.
  - Degradation up to ~20%, occurs after ~20 seconds.
  - Degradation is related to TAE activities.
  - Degradation increases V_{loop} and flux consumption, resulted in touching PF coil current limit.

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

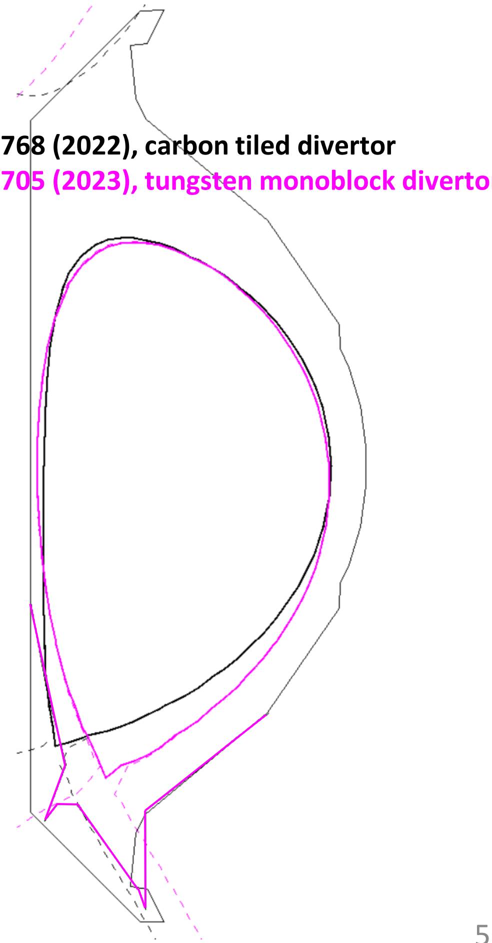
* Hyun-Seok Kim, et. al., Nucl. Fusion 64 (2024) 016033

Finally, 102-second high-performance long-pulse discharge was achieved in 2023 KSTAR experimental campaign.



- V_{loop}~70 mV, β_P~2.5, β_N~2.1, $T_{e,core}$>6.0 keV, $T_{i,core}$~2.5 keV, $\bar{n}_{e,core}$~3.0×10^{19} m^{-3}.
  - Plasma parameters were similar to other long-pulse discharges.
- Performance maintained for ~70 s and its degradation was much minimized.

- Actively cooled W-shaped tungsten divertor was successfully operated.
- Real-time MD linear drift correction algorithm in PCS was successfully worked.



For longer pulse length (>10^2 s) discharge in KSTAR, we have faced to conditions that limit longer pulse operation in KSTAR, "Temperature of PFCs" and "Flux consumption of PF coils" along the existing long pulse discharges

❖ **Plasma Facing Component(PFC) Temperature**

- **Carbon tiled PFCs : 600 °C limit and Tungsten monoblocks of lower divertors : 300 °C limit in thermocouples**
  - **Control and reduction of fast ion loss to PFC → alleviation of Poloidal Limiter temperature (T_{PL})**

    (1) Optimization of plasma shape and operation parameters to reduce fast ion bad orbit loss

    (2) Avoidance of MHDs (Alfven activities, Kink and Tearing modes) to reduce fast ion transport loss
  - **Control and reduction of heat flux to PFC → alleviation of Divertor temperature (T_{CD}, T_{OD}, T_{ID})**

    (1) Control of striking point location to avoid normal impact of heat flux on divertor plate

❖ **Flux consumption**

- **PF Coils : 15 kA/turn limit due to CS preloading and Apparent power limit < 140 MVA**
  - **Development of higher plasma performance, β_p, with controlled MHDs as long as possible**

    (PF coils almost reached their limits at t_{pulse}<~80s)

    (1) Preventing performance degradation in long-time scale

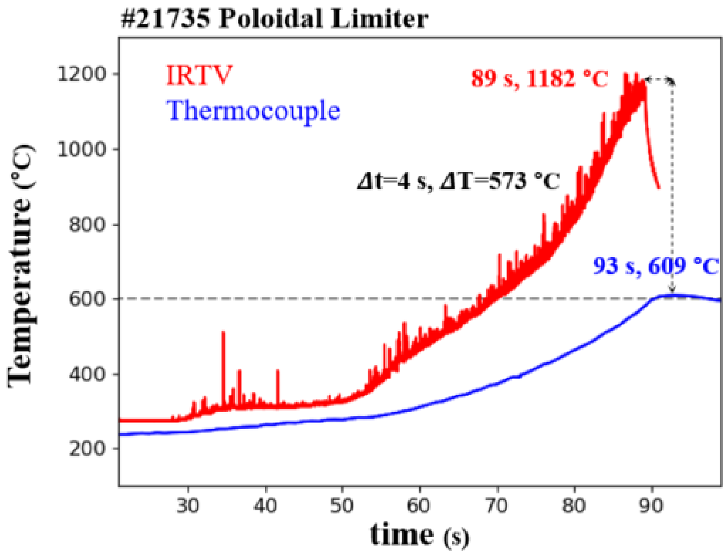
    (2) Reliable real-time EFIT operation by improving drifting signals in magnetics in long-time scale

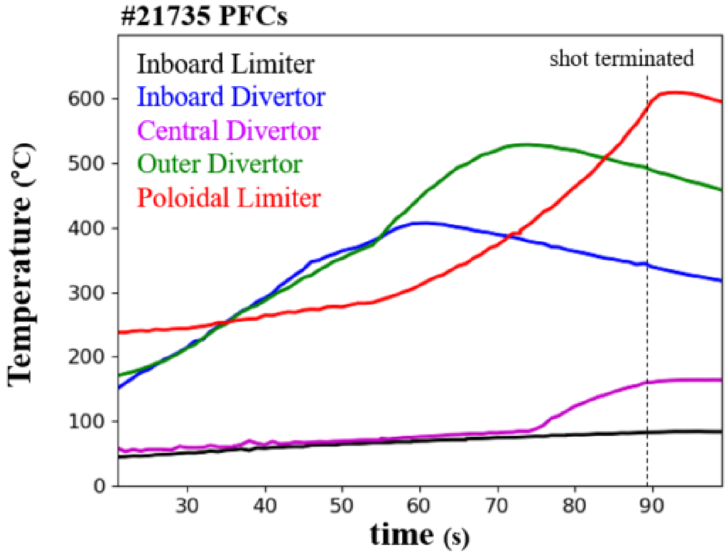
Heat control of PFCs in KSTAR long-pulse discharge

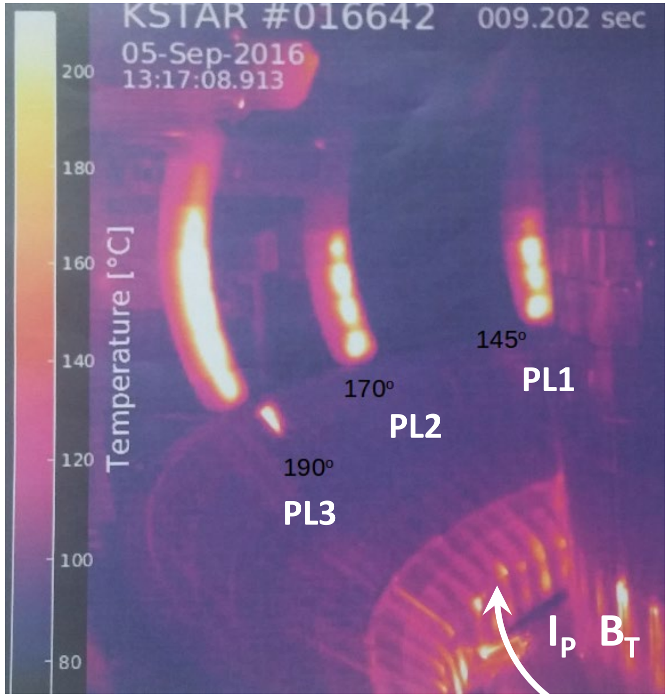
Mitigation of magnetic signal drift in the long-time scale

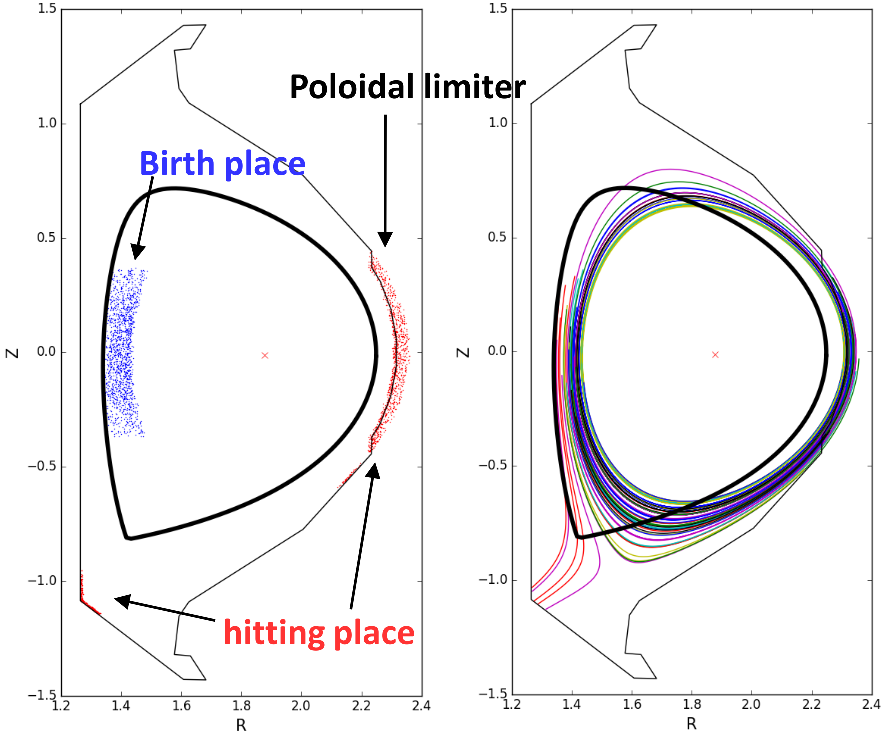
Development of high β_P discharge in KSTAR and identification of performance degradation in long-time scale

Poloidal limiter overheats due to fast ion orbit loss. (1)







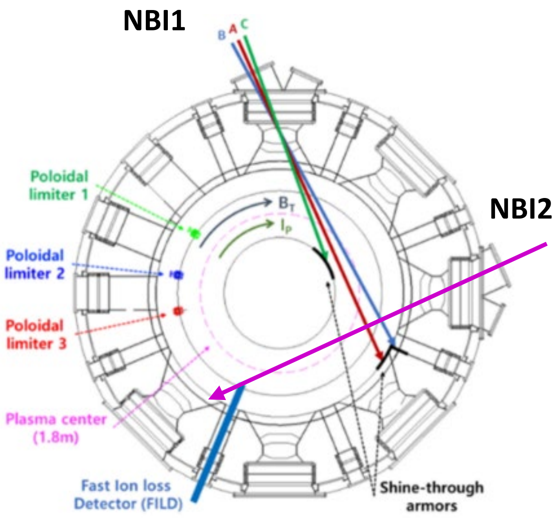


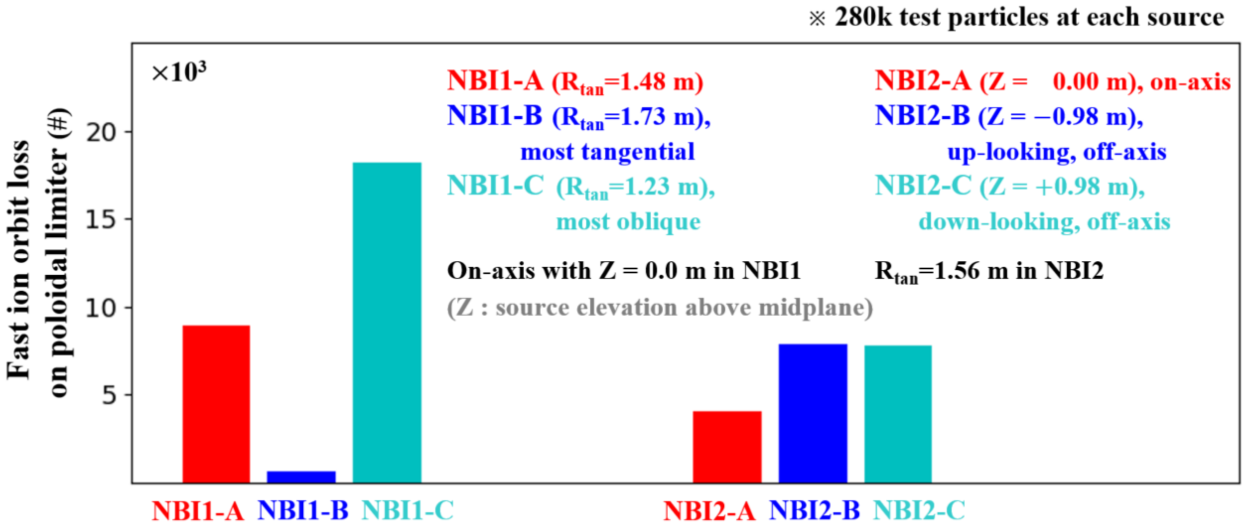
- Low I_P (400kA) long-pulse operation is limited due to **PL overheat** due to fast ion hit on the PL.
- **NuBDeC*** code has been analyzed and produced the consistent result with the experiment.

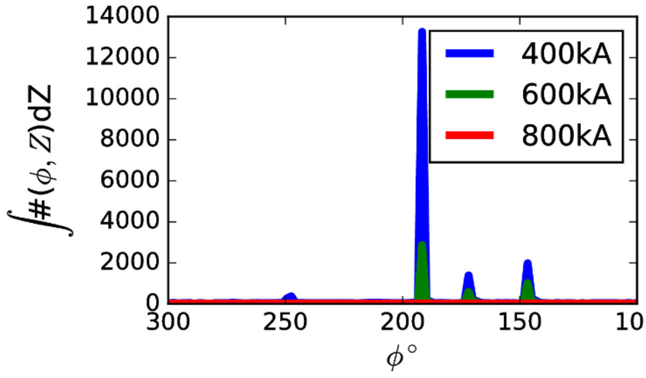
- **Ionized fast ions in the high field side** hit the poloidal limiters and inboard divertor plate.
- If we assumed each beam power is 1MW (total 3MW), maximum loaded power on limiter side is estimated to **~6 MW/m^2**.

*T. Rhee PoP26(2019)112504

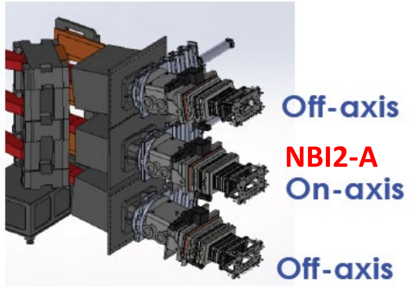
Poloidal limiter overheats due to fast ion orbit loss. (2) NBI source dependency







NuBDec analysis

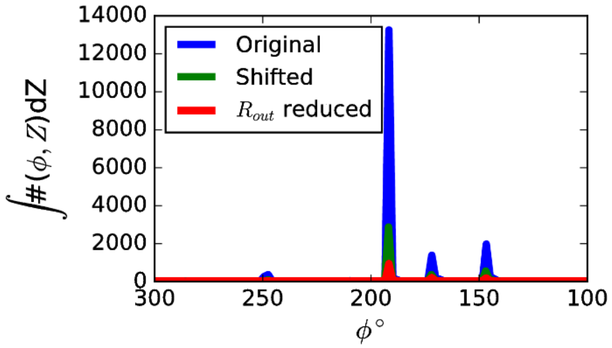


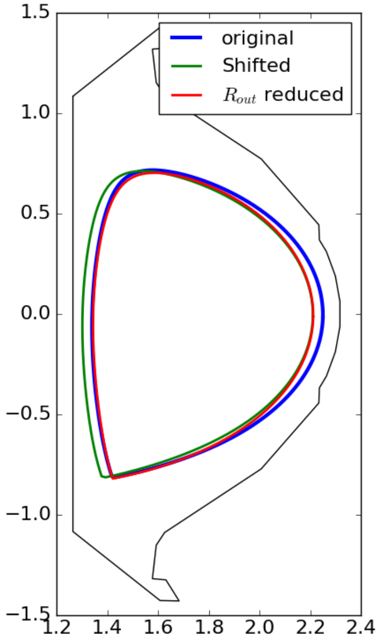
❖ Amount of fast ions lost to Poloidal Limiter varies depending on the beamlines of the NBI sources.

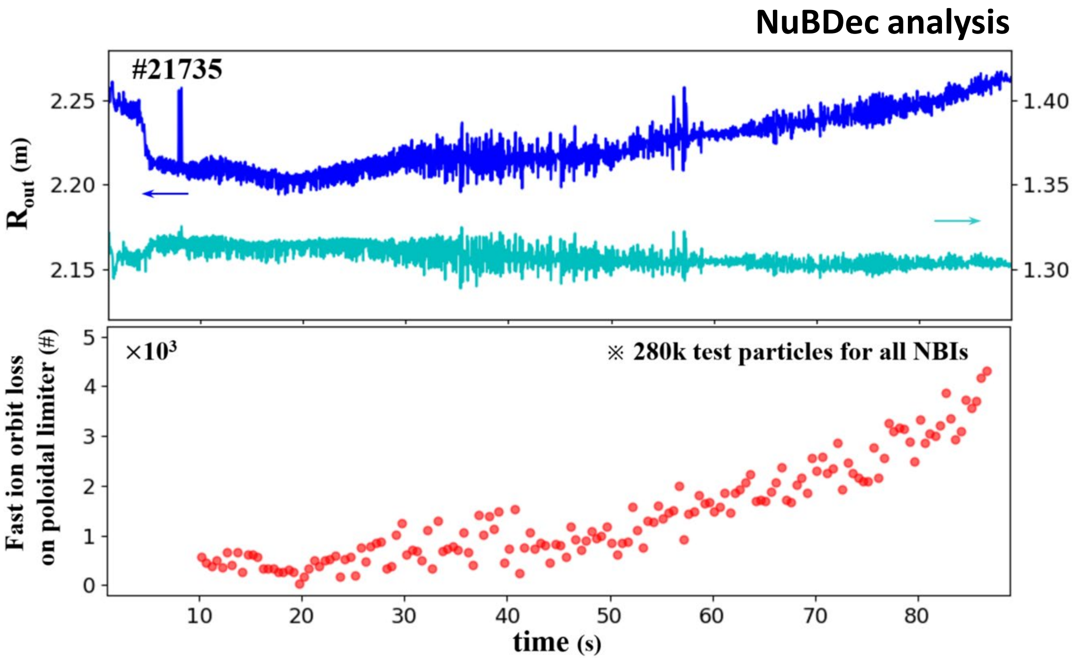
- NBI1-C contributed significantly to the fast ion orbit loss to the poloidal limiter.
  - fast ions ionized in the high-field side drift out and strike the PFCs as they rotate poloidally.
  - tangential radius of NBI1-C is 1.23 m, and its beamline touches the inboard limiter.
  - NBI1-C produces a more significant number of fast ions on the high-field side.
  - NBI1-C is unsuitable for long-pulse experiments where the rapid temperature increase in the poloidal limiter should be avoided.

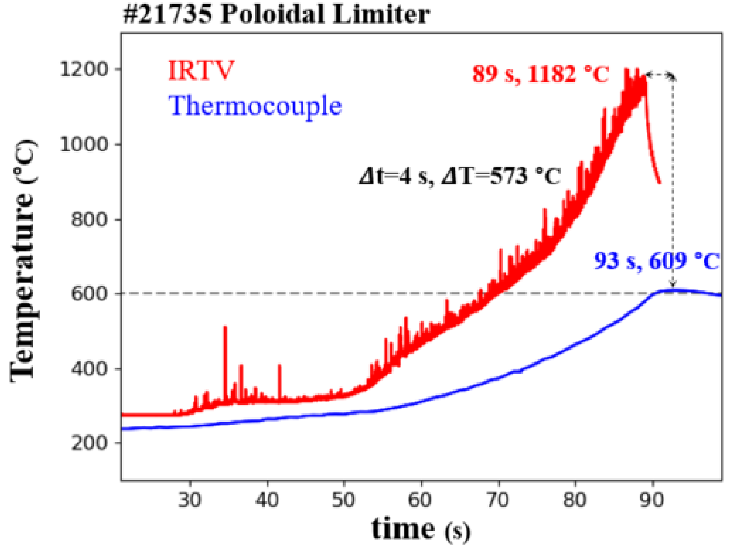
(NBI1-A, NBI1-B, NBI1-C, NBI2-A, NBI2-B, and NBI2-C contributed ~19 %, ~1 %, ~38 %, ~9 %, ~17 %, and ~16 %.)

Poloidal limiter overheats due to fast ion orbit loss. (3) shape dependency





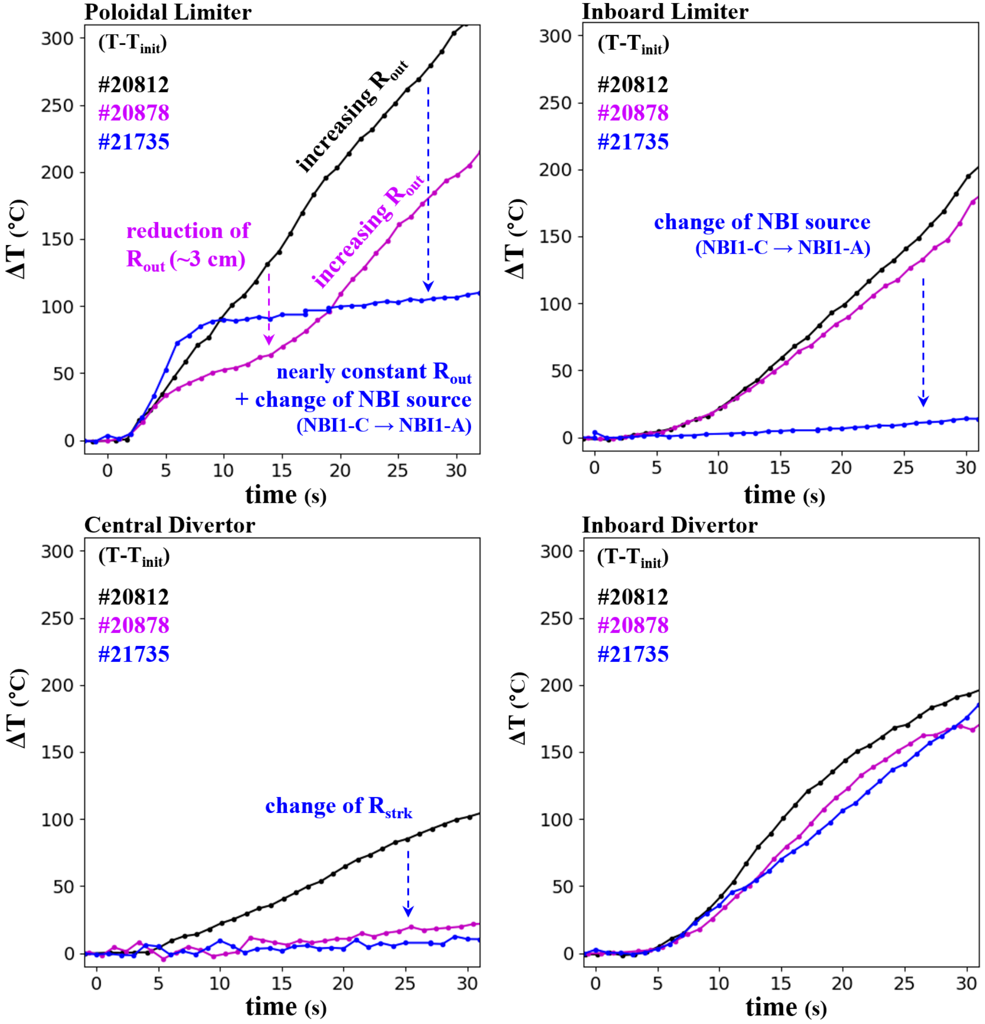


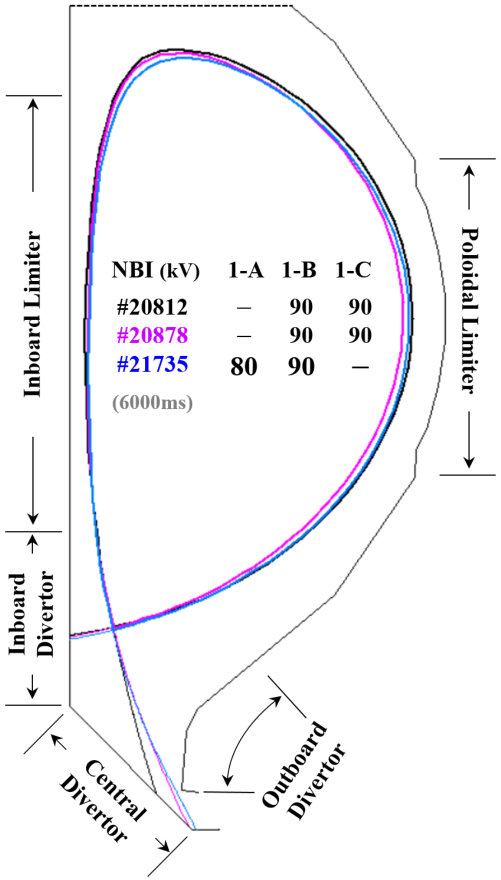


❖ Amount of fast ions lost to the poloidal limiter depends on the plasma shape.

- R_{out} showed an almost linear increase from ~50s, reaching R_{out}=2.27m at 89s.
  (due to significant signal drift in the magnetic probes)
- Increase in R_{out} corresponded to the increase in fast ions lost to the poloidal limiter.
- Poloidal limiter experienced rapid temperature growth after ~50s.

PFCs’ temperatures were able to be controlled with optimizing plasma shape and NBI heating scheme.





NBI (kV)	1-A	1-B	1-C
#20812	–	90	90
#20878	–	90	90
#21735	80	90	–

(6000ms)

❖ To mitigate the temperature increase of the poloidal limiter (T_{PL}),

- appropriate NBI sources are selectively utilized, which is no use of NBI1-C source
- plasma shape is controlled mainly by keeping R_{out}<~2.21m

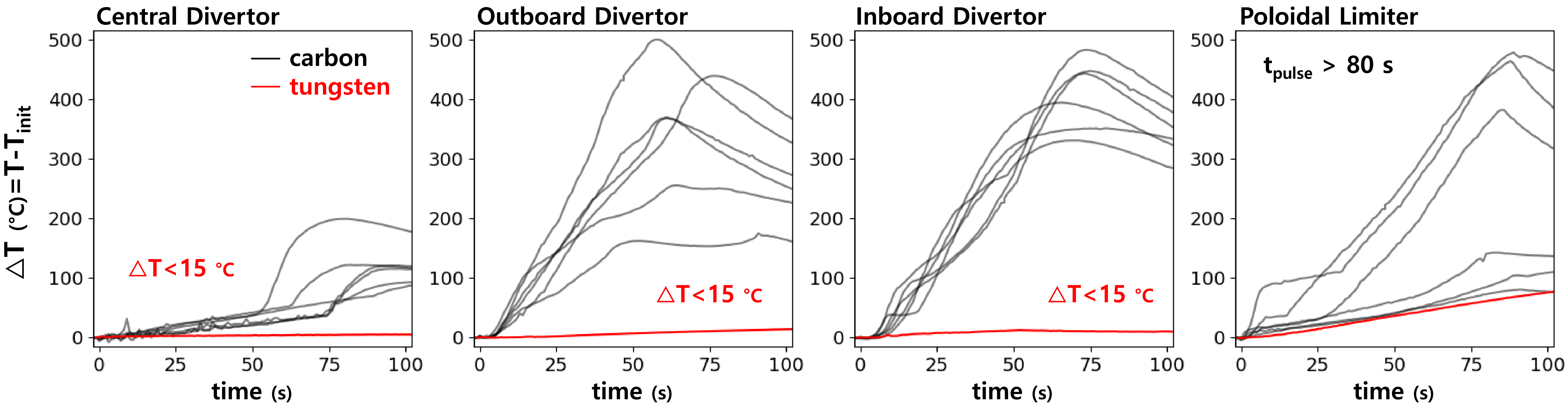
❖ Increasing rate of T_{IL} was reduced when NBI1-C was removed.

- NBI1-C beamline touches the inboard limiter.
- high shine-through power loss with low density plasma, ~2.0x10^{19} m^{-3}.

❖ Increasing rate of T_{CD} was reduced by changing the position of the striking point.

Actively cooled tungsten divertors experienced temperature changes of less than 15 °C in 102-second high-performance long-pulse discharge.

- From a PFC temperature perspective, there are no issues even for operating for 300 seconds with the current injection power.

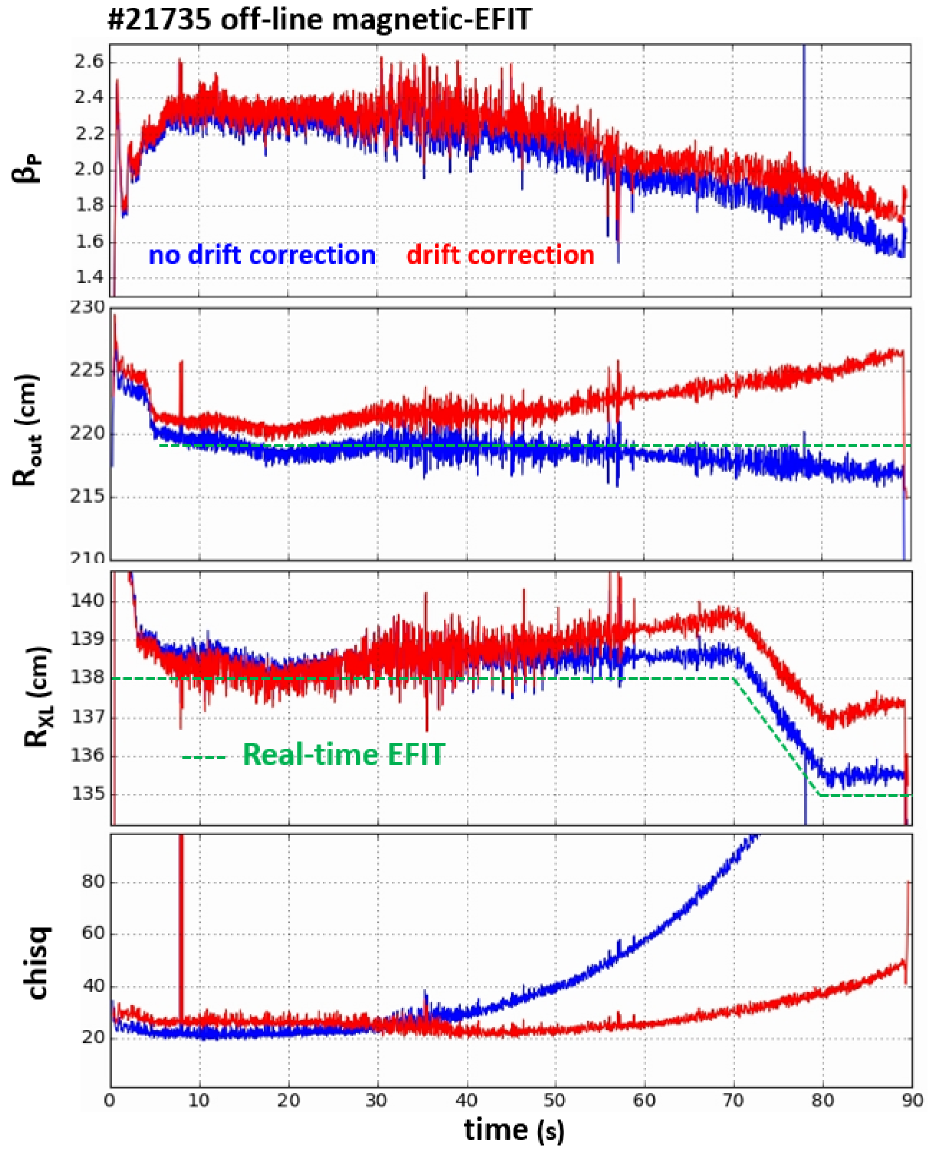


Heat control of PFCs in KSTAR long-pulse discharge

Mitigation of magnetic signal drift in the long-time scale

Development of high β_P discharge in KSTAR and identification of performance degradation in long-time scale

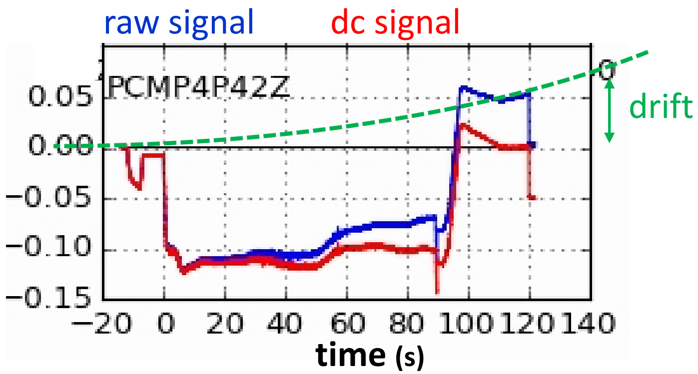
Magnetics were highly suffered from nonlinear drift issue under hot and long-pulse plasma and this impacted on change of unintentional plasma shape.



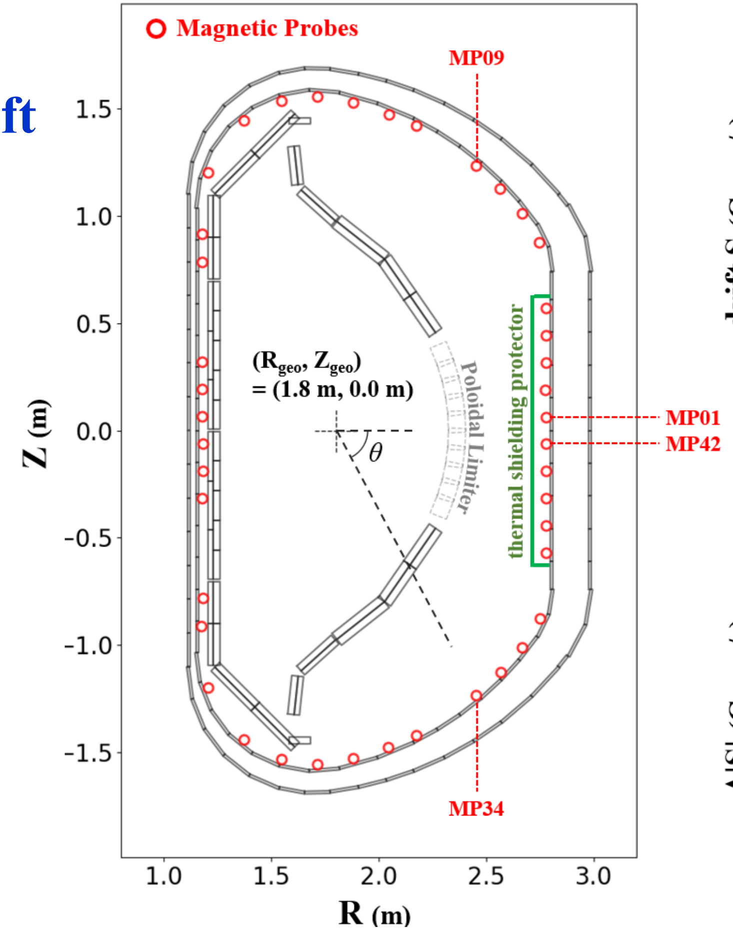
- Shape using drift corrected signals was much different from one using un-corrected signals, but real time EFIT did not know it.
- Especially, R_{out} should be controlled within ~2.21m to prevent from the increase of poloidal limiter temperature.

❖ Following solutions are considered,

  - Installation of thermal shielding block on magnetics
  - Development of real time nonlinear drift correction algorithm

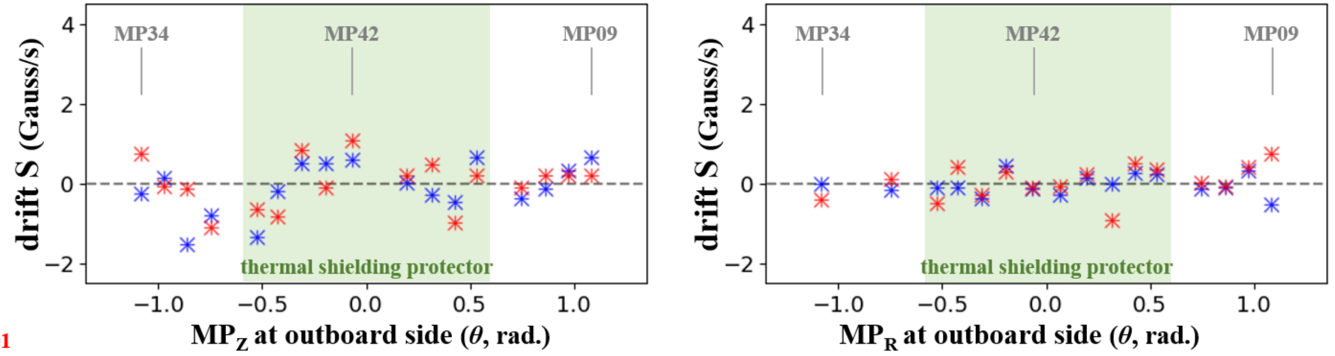


Mitigation of nonlinear signal drift in magnetic probes by installation of thermal shielding protector



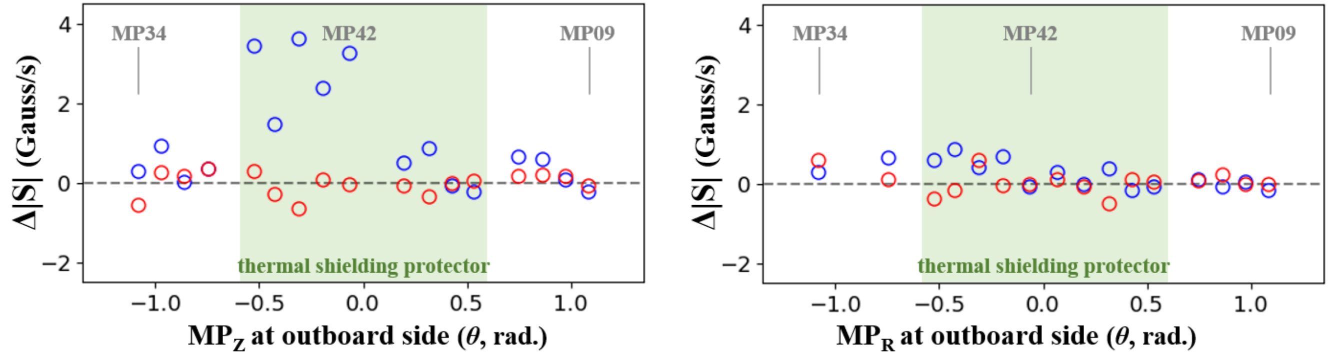
before installation of protector, $S_{\#21756}$ in 2018, normal discharge #21756 t_{pulse}~16 s

after installation of protector, $S_{\#27026}$ in 2020, normal discharge #27026 t_{pulse}~10 s



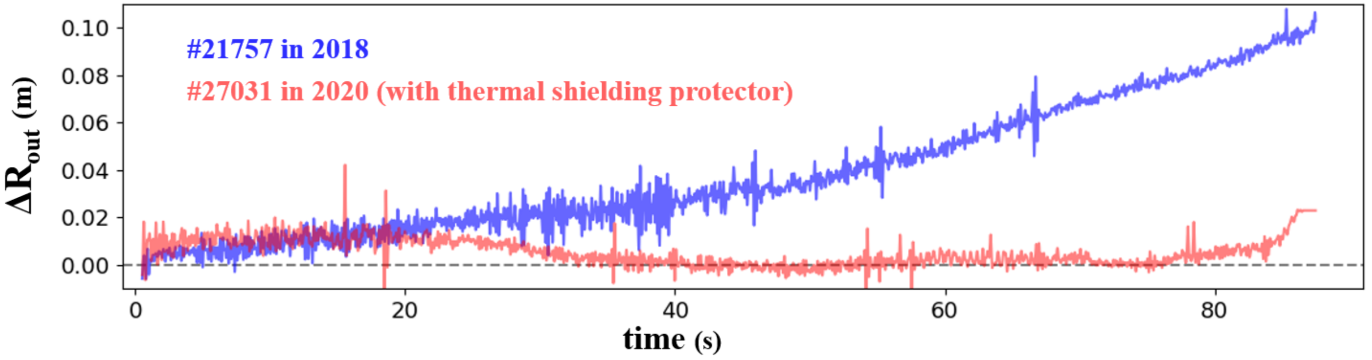
before installation of protector, Δ|S| = $|S_{\#21757}|$ - $|S_{\#21756}|$ in 2018, long-pulse discharge #21757 t_{pulse}~88 s

after installation of protector, Δ|S| = $|S_{\#27031}|$ - $|S_{\#27026}|$ in 2020, long-pulse discharge #27031 t_{pulse}~87 s

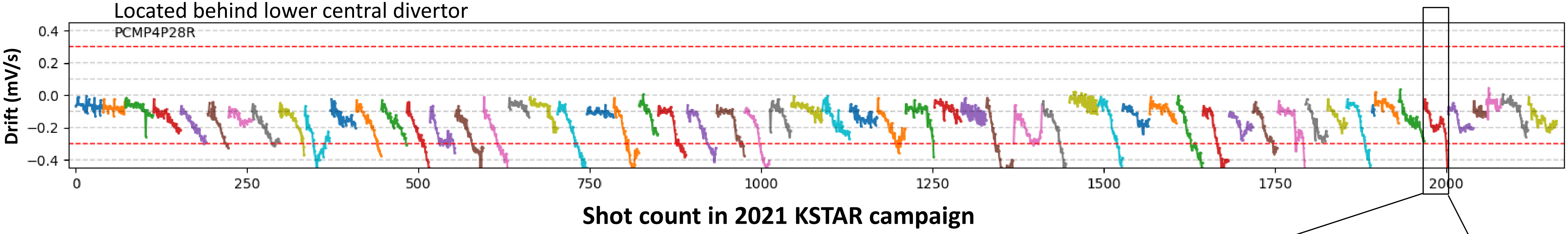


- **MP_Z mainly shows nonlinear signal drift**
  - Coil winding of MP_Z is facing to the plasma
  - Thermal shielding protector effectively blocks plasma heat

Difference of R_{out} between off-line EFITs using un-corrected and corrected drifting signals



We also confirmed that magnetic probes were experiencing accumulated signal drift in a day.



- There are many signals that shows the accumulated signal drift > 0.3mV/s in a day.

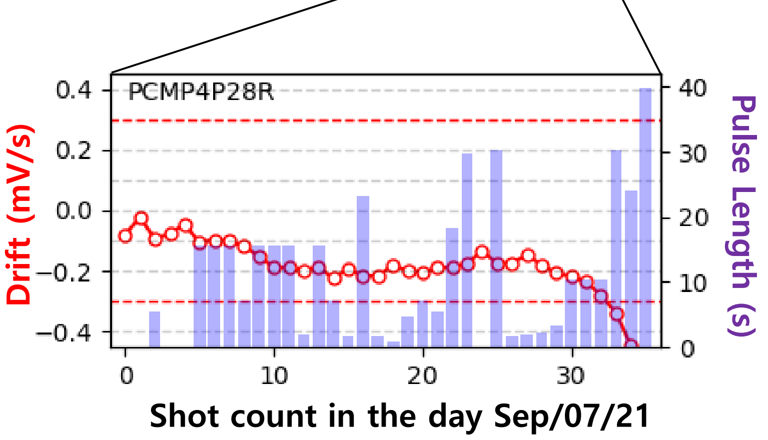
  (Our Drift Criterion <0.3mV/s)

  → The morning and afternoon shots derive different shape results in rtEFIT operation.

  → The next day, the drift level returns to the IDLE state. (Recovered)

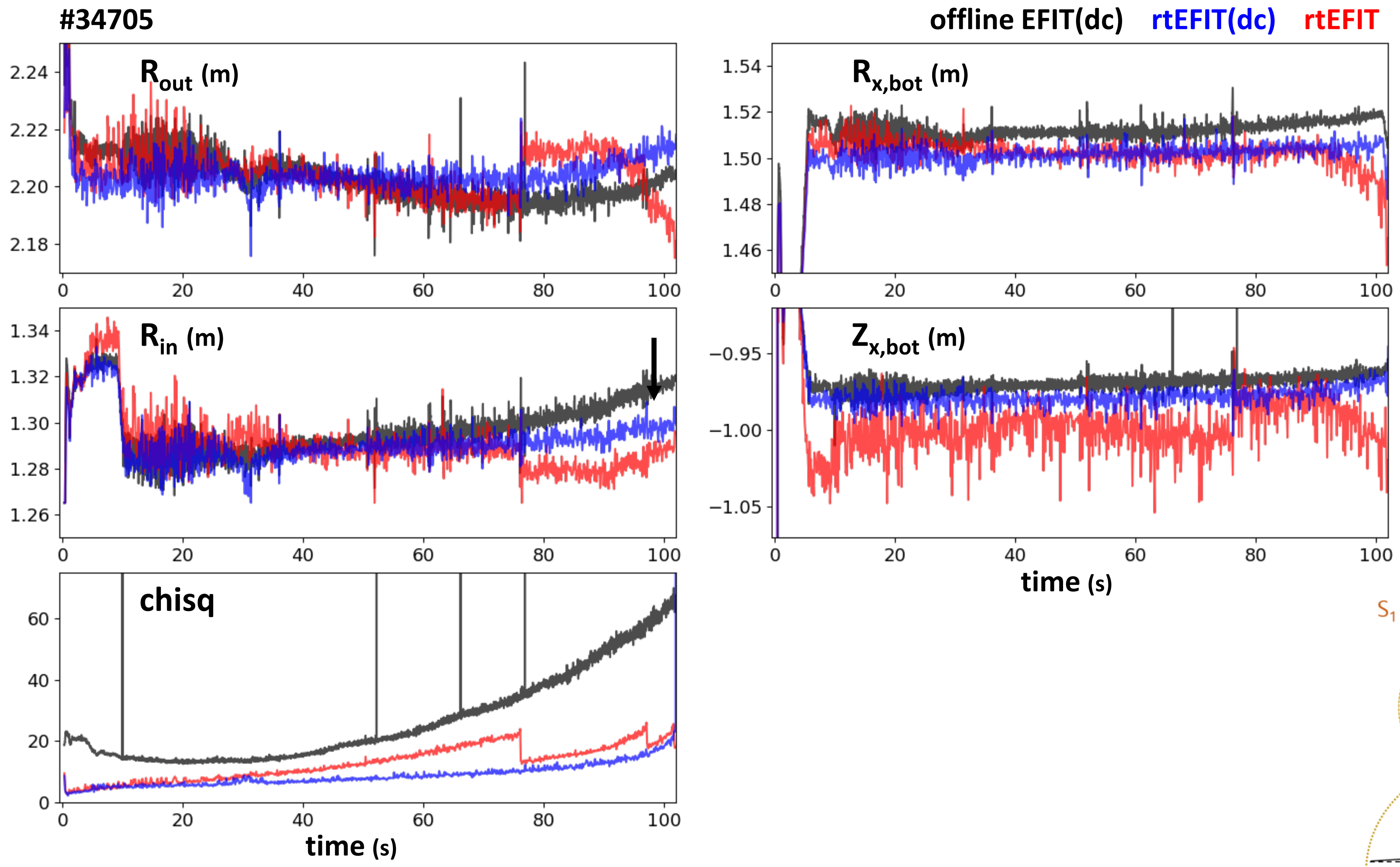
  → 12 min. of shot interval could not fully recover the MPs' drift to its original state.

  → The degree of signal drift appears to be affected by the pulse length of discharge.



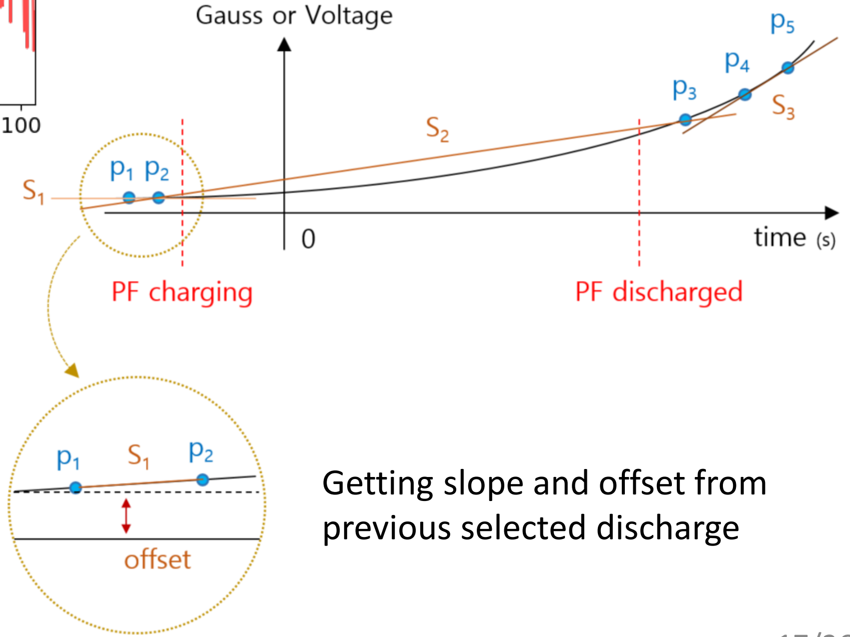
→ We need the method to minimize the drift of magnetic signals in real time.

During 102 seconds, there were changes in the plasma shape of less than 2 cm, and it is perceived that MD drift was significantly reduced by hardware and software improvements.



- Real-time linear MD drift correction algorithm in PCS is well-operated.

(see 'rtEFIT(dc)' signal)



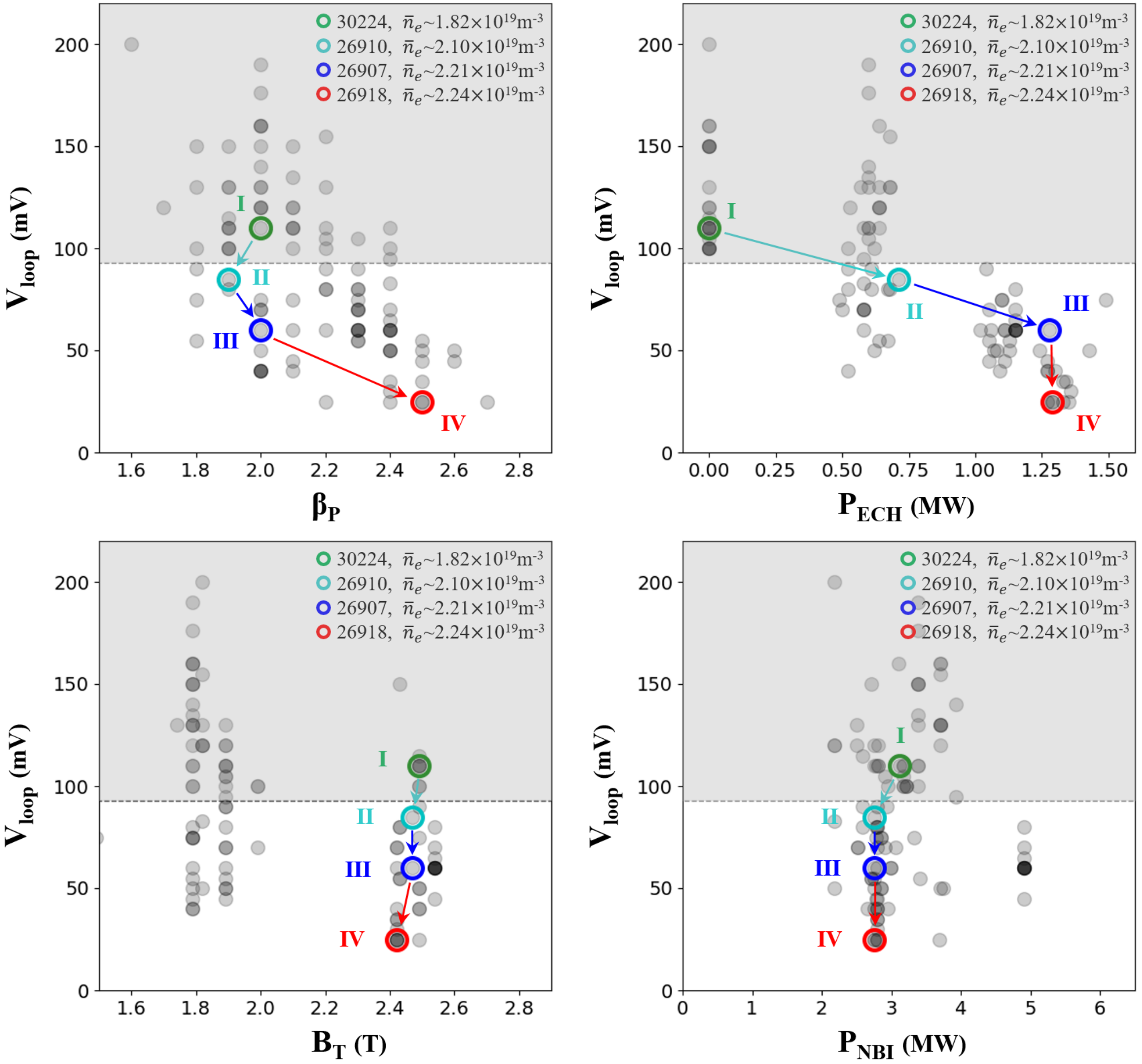
Getting slope and offset from previous selected discharge

Heat control of PFCs in KSTAR long-pulse discharge

Mitigation of magnetic signal drift in the long-time scale

Development of high β_P discharge in KSTAR and identification of performance degradation in long-time scale

We also confirmed that magnetic probes were experiencing accumulated signal drift in a day.



❖ Lower V_{loop} scenario with high β_P

- Flux Consumption
  - $I_{PF} \leq$ 15 kA/turn due to preload uncertainty of CS coils
  - Available flux during discharge ~ 11.9 Wb
  - Available flux during flat-top phase ~ 8.2-9.3 Wb
  - $V_{loop} \leq$ ~82-93 mV for 100s pulse length
  - $V_{loop} \leq$ ~27-31 mV for 300s pulse length

- Generally, in our database,
  - V_{loop} reduces with β increase
  - Weak dependency btw. V_{loop} vs. P_{NBI} and B_T

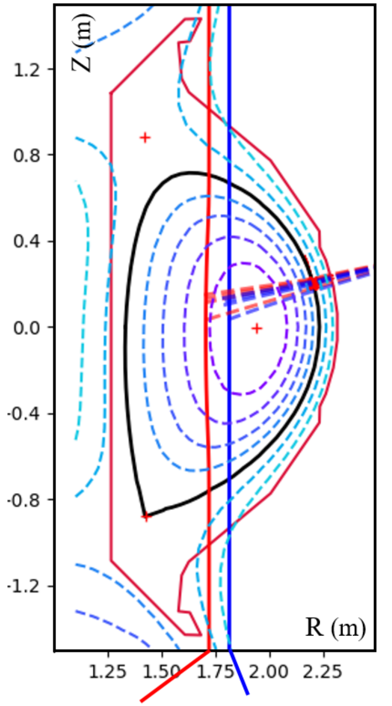
    → Need to seek NBI efficiency ↑

…For robustness of lower V_{loop} scenario,

- Application of ECH helps
  - Increase $I_{NBI} \propto T_{e0}^{0.60} n_{eL}^{-1.04}$ with D_f~0.0 m^2/s
  - Mitigate/suppress TAEs ∝ D_f reduction

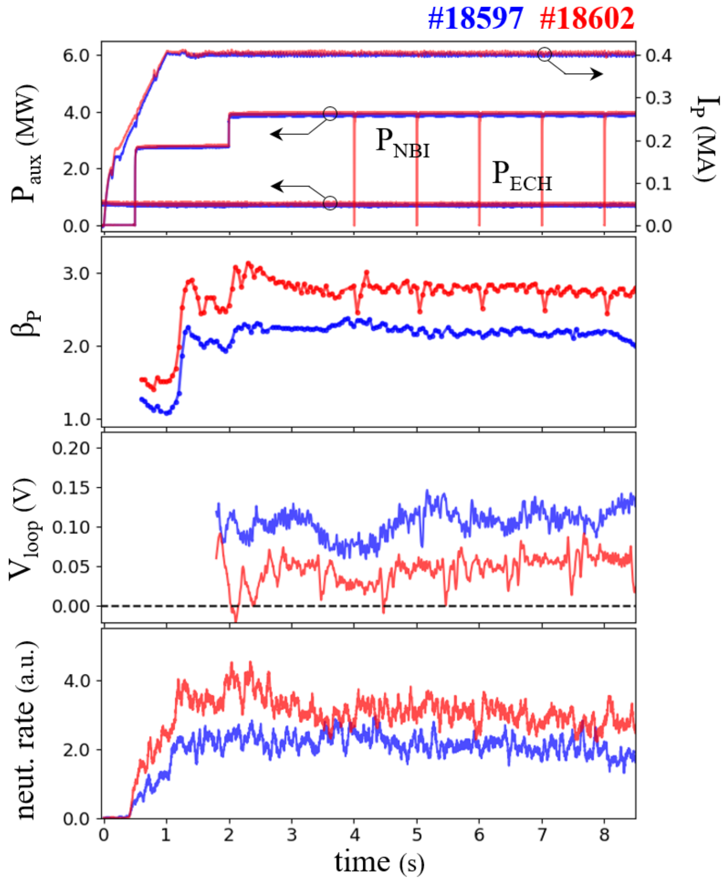
    → KSTAR high β_P operation scenario

To achieve a high β_P state at KSTAR, ECH/ECCD deposition must be accurately controlled to a narrow vicinity near the magnetic axis.

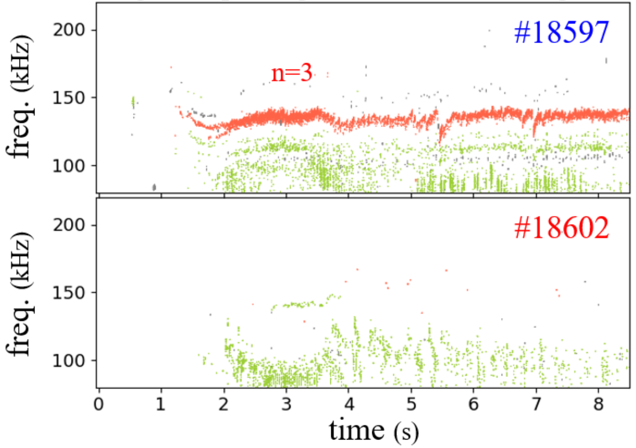


#18602
B_T =1.8 T
R_{res}=1.72 m
(ψ_N~0.2)

#18597
B_T =1.9 T
R_{res}=1.82 m
(ψ_N~0.1)



Magnetic spectrogram of Mirnov coil signal

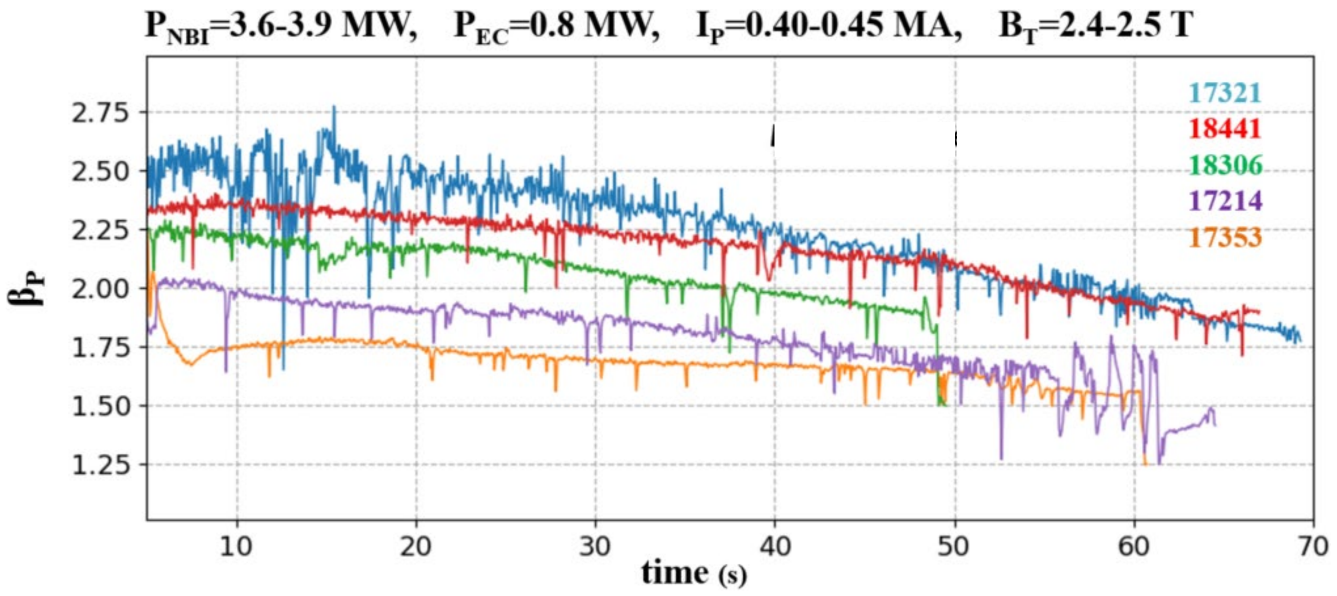


- #18597 typical H-mode, #18602 high β_P mode
- Both discharges shared nearly identical operating conditions, except for B_T.
- In high β_P discharge #18602,
  ~30% improvement in β_P
  ~50% reduction in V_{loop}
  due to the improved fast ion confinement

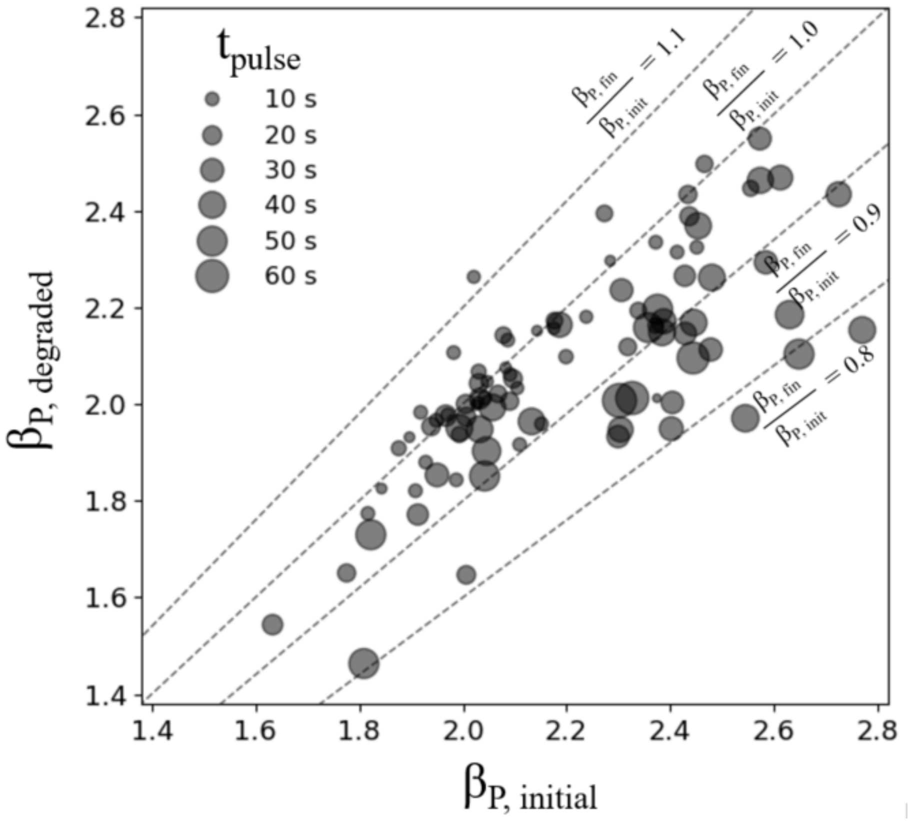
  (see neut. rate and spectrogram)
- The valid deposition of ECH/ECCD was confined to a specific region, denoted as R_{res}~1.72 ± 0.025 m (equivalent to ψ_N~0.2), with B_T=1.8 T.
- No ITB

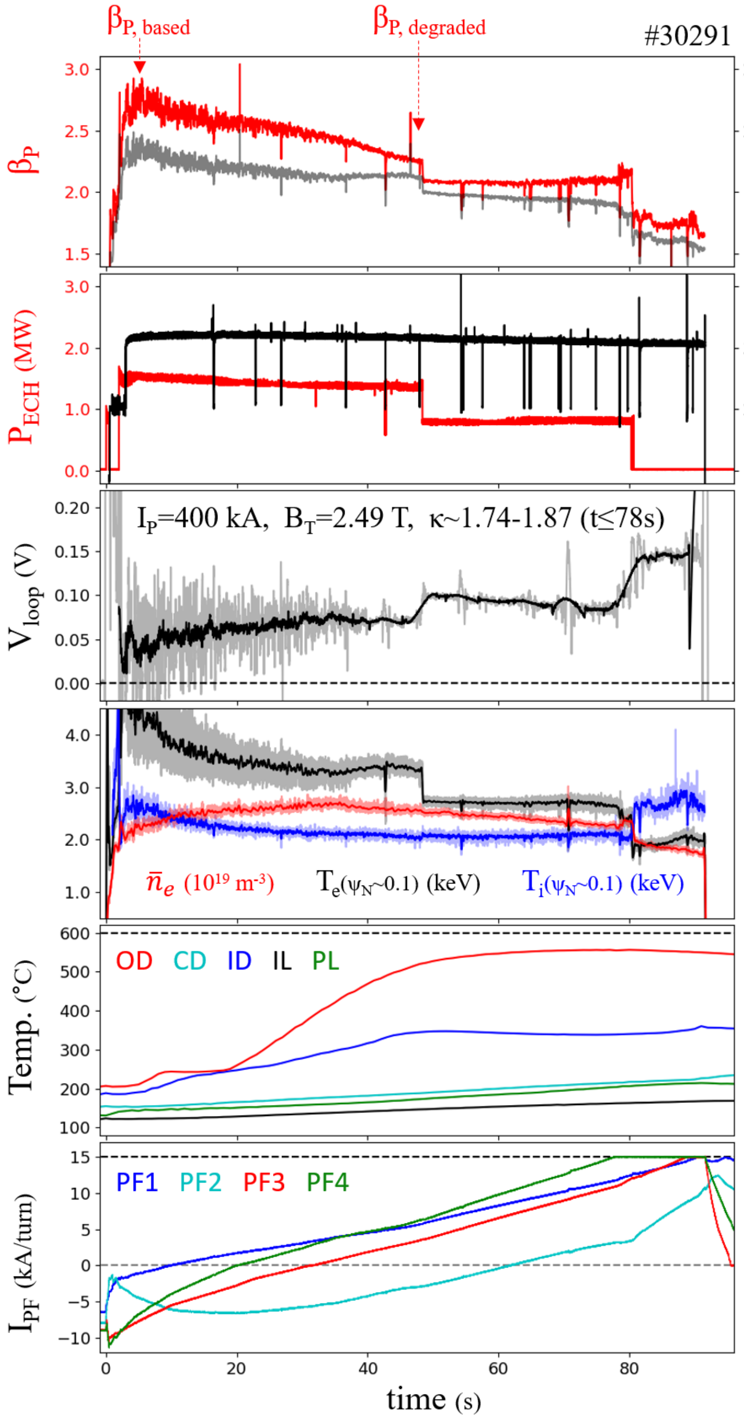
Gradual degradation in plasma performance has been observed over a long-time scale to ~$10^3\ \tau_E$ in the discharges.

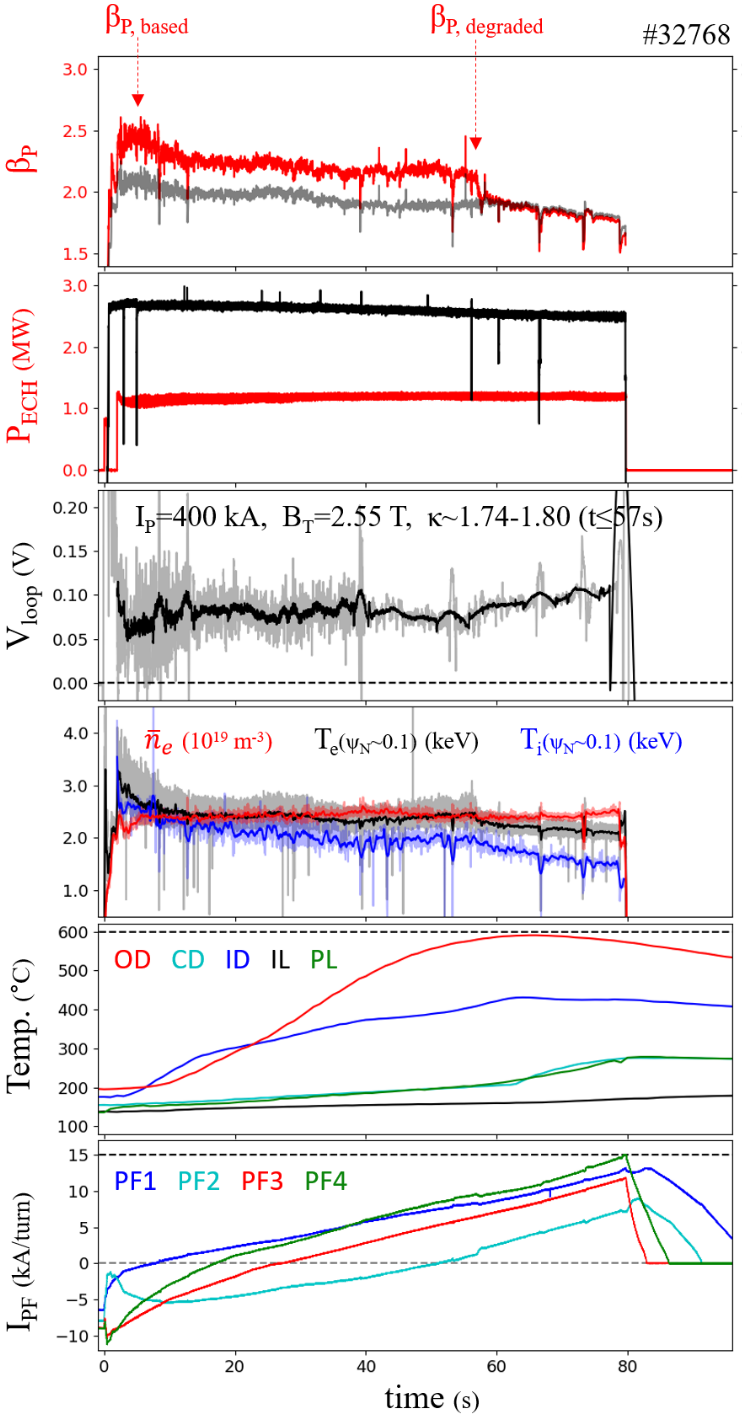
- Generally, in KSTAR,
  the longer the pulse length and the higher the performance, the more severe the degradation of performance.



P_{NBI}=3.6-3.9 MW, P_{EC}=0.8 MW, I_P=0.40-0.45 MA, B_T=2.4-2.5 T







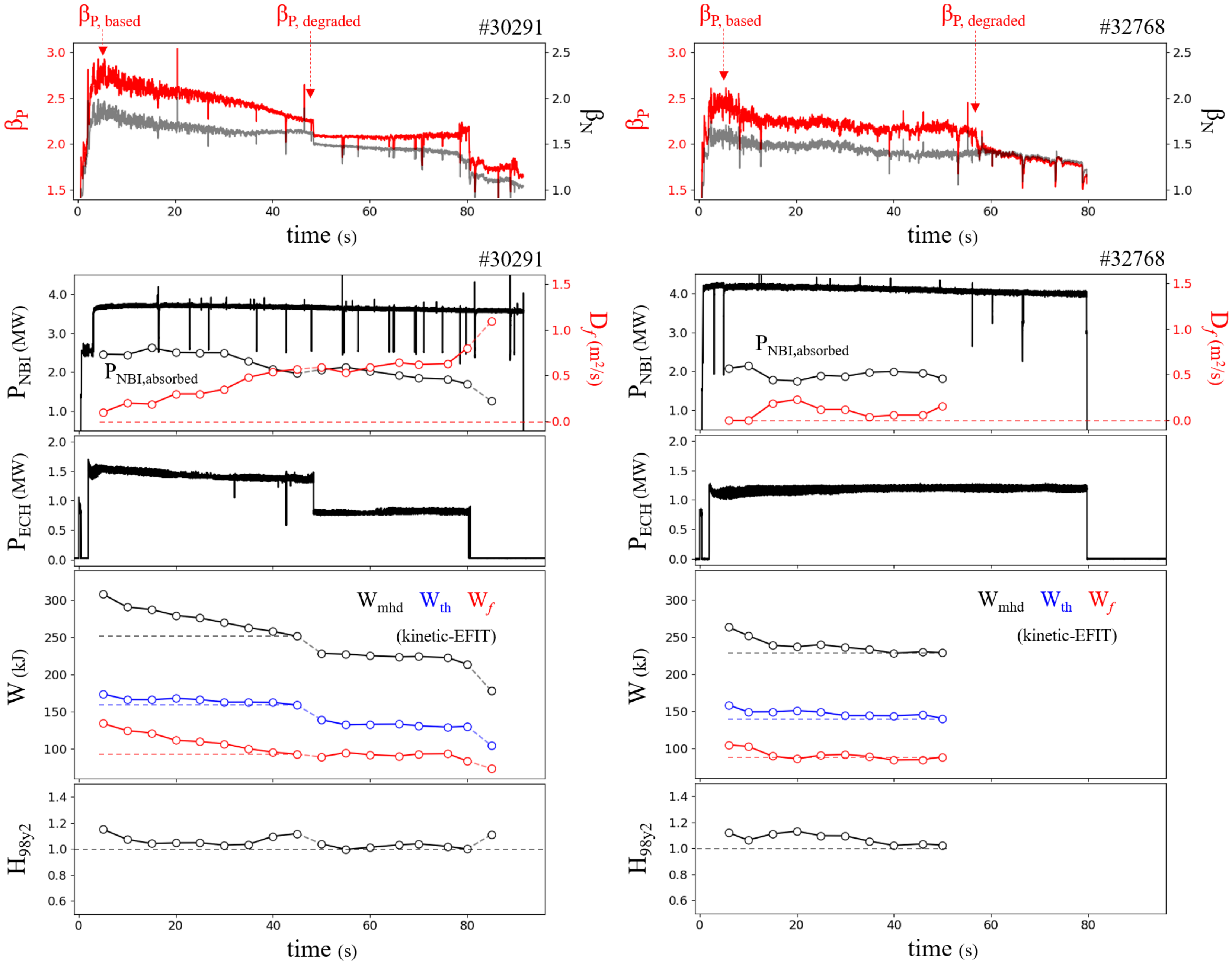
Investigation of performance degradation (1)

❖ **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



Investigation of performance degradation (2)

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

In #30291,

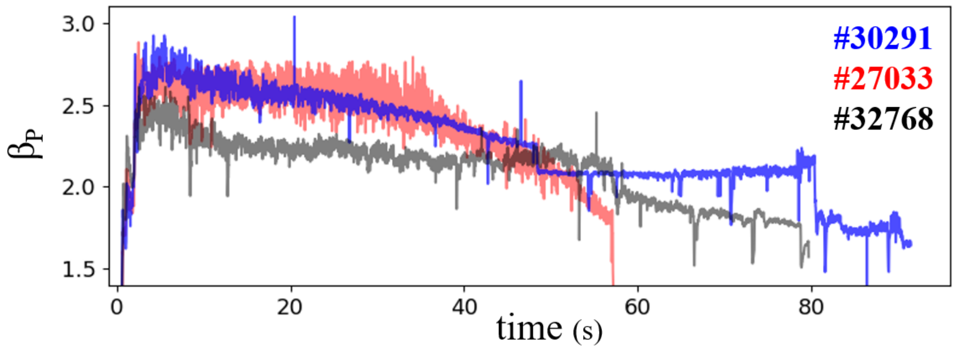
- β_P degradation comes from $\beta_{fast,}$ not β_{th}
- Fast ion transport is increased (see D_f)
- H_{98y2} is almost constant ~1.0-1.1 (typical H-mode confinement)

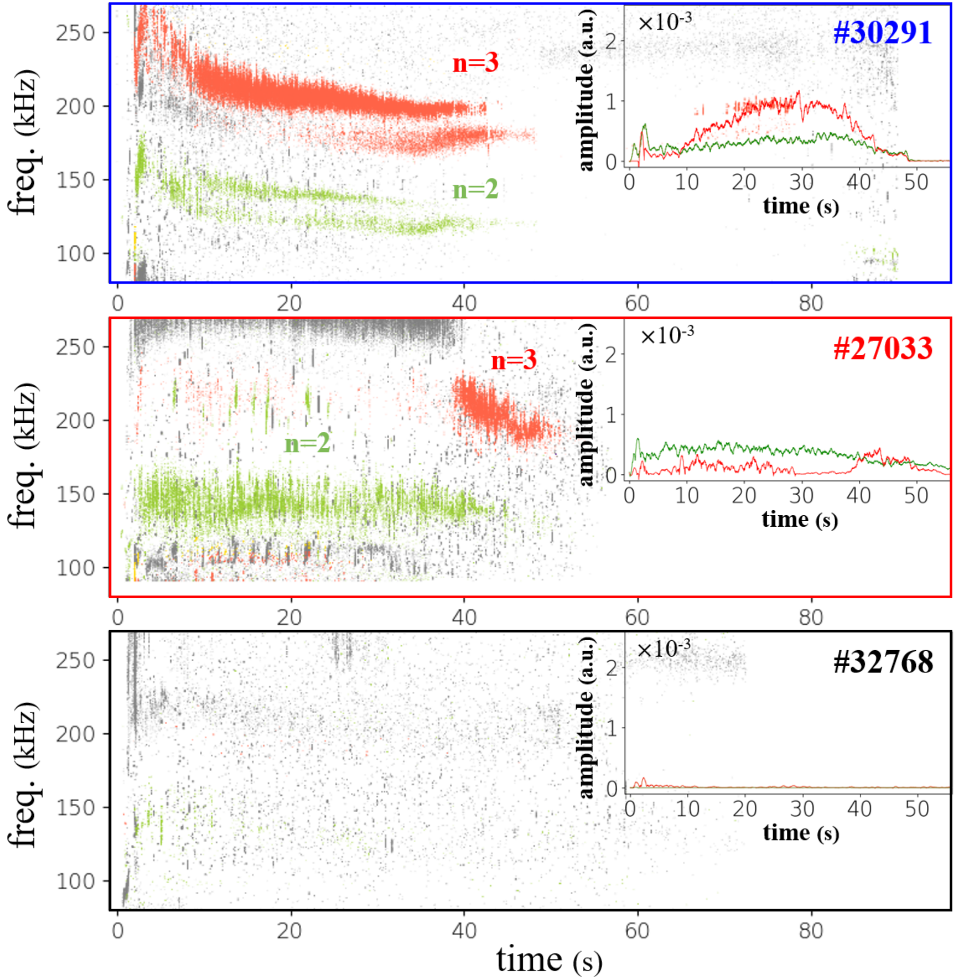
On the other hand, in #32768,

- 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?

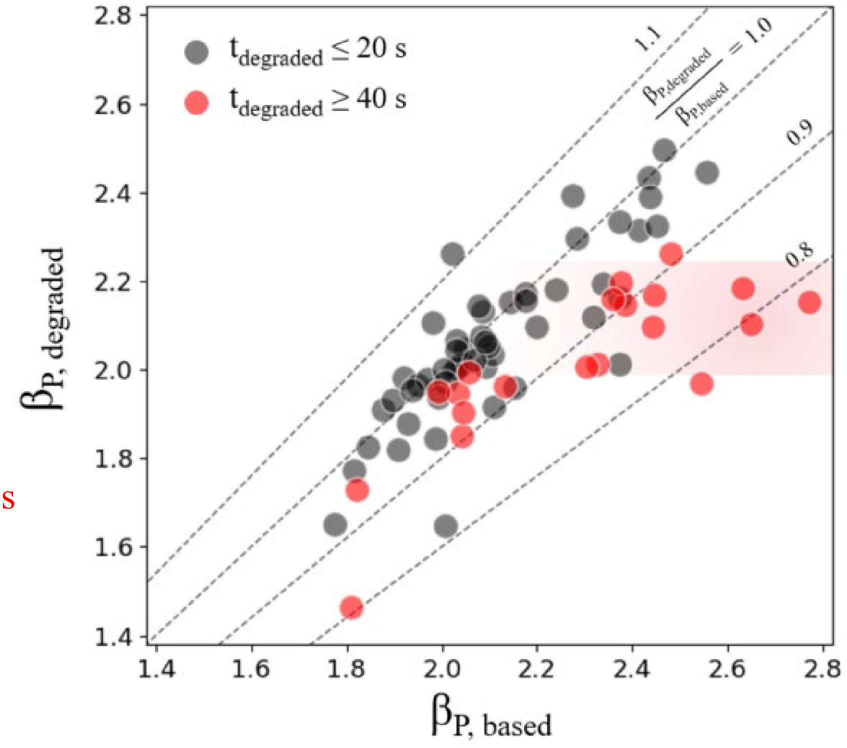
Investigation of performance degradation (3)



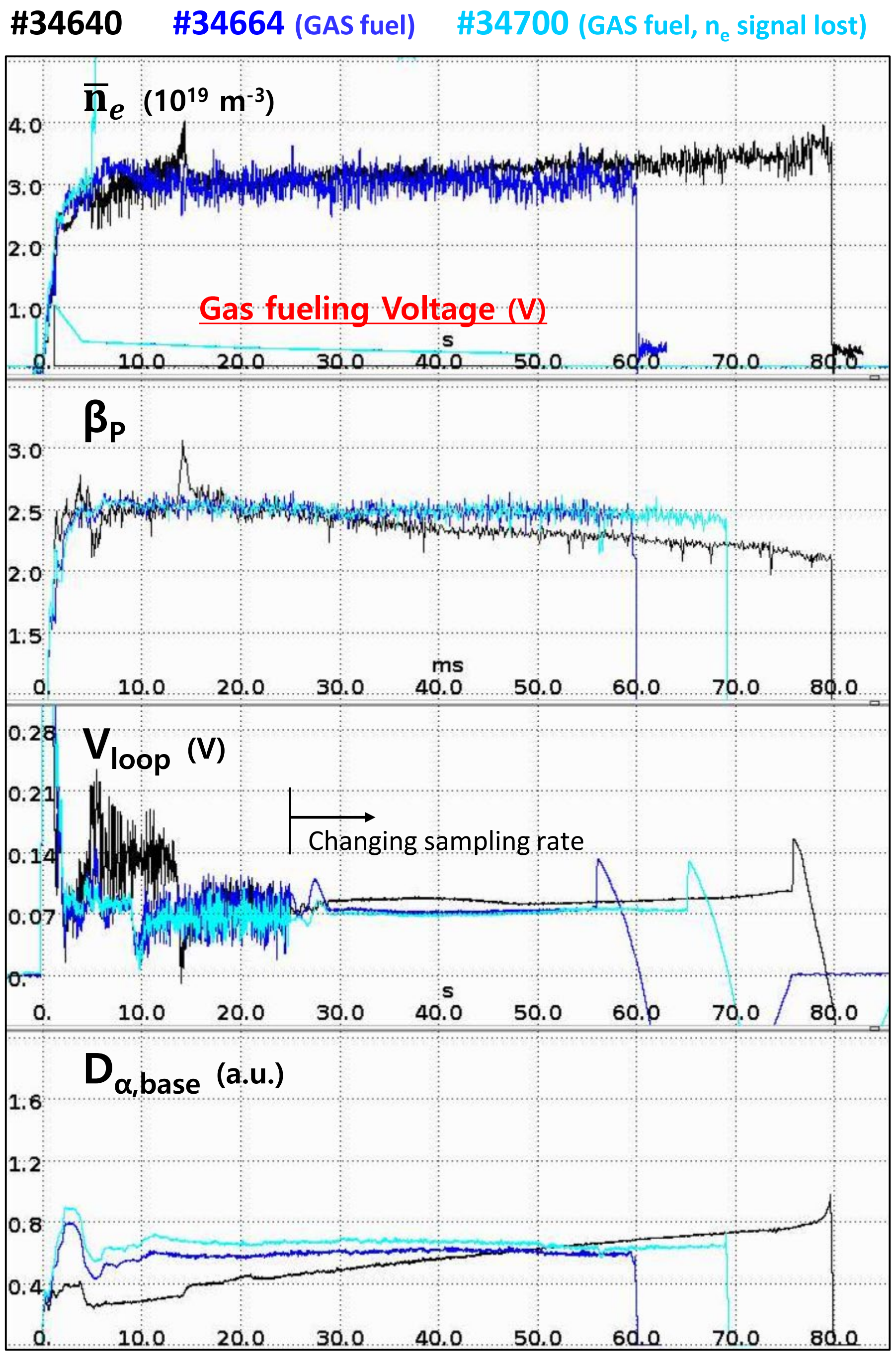

Magnetic spectrogram of Mirnov coil signal and mode amplitudes

- **TAEs impact on β_{fast} degradation → β_P degradation**
  - #30291 has n=2 and n=3 TAEs, degradation, their magnitude is 10^{-1} from conventional cases.
  - #27033 has n=2 TAE, no degradation
  - #32768 has no TAEs, no degradation
  - → It seems that n=3 TAE inhances fast ion transport

- **Process of performance degradation related with TAEs**
  - Our high β_P plasma effectively confines fast ions more
  - Our high high β_P plasma is vulnerable to TAE
  - TAE is activated spontaneously, but weak due to ECH injection
  - Fast ion pressure is reduced until the TAE is self-deactivated
  - Weak and long-lasting TAE induces degradation in long-time scale

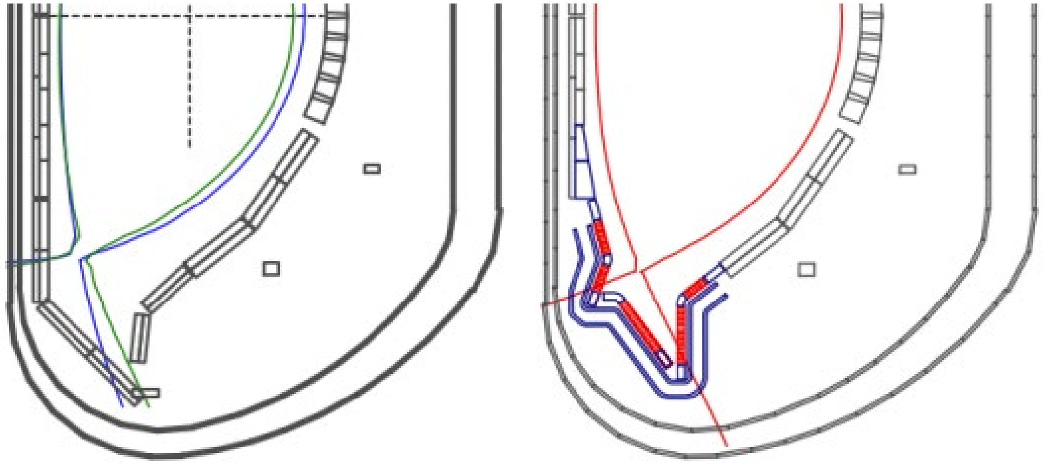


Self-stabilization of TAEs,
in KSTAR high β_P long-pulse discarhges
→ β_P converges to ~2.0-2.2



In 2023, performance degradation is effectively minimized with upgraded W-shaped tungsten divertor configuration.

- Optimized gas fueling scenario in long-time scale effectively mitigates performance degradation, even with high β_P>2.5 state.
- Performance remains relatively constant over ~70 seconds. (highly reproducible)
- It is likely that SOL condition is changed with W-shaped divertor.
  - This was not observed in past divertor configurations and is being examined in the current W-shaped divertor configuration.



Summary and Plan for longer pulse discharge in KSTAR

We are securing further appropriate solutions for the issues of long pulse discharge

- **Heat control on PFC (Solved)**
  - → **Optimizing shape control and heating scheme, and major upgrade of actively cooled W monoblock divertor**
- **Magnetic signal drift in the long-time scale (Solved)**
  - → **Improvement with newly installed thermal shielding block on the magnetic probes and control of PFC temperature**
  - → **Real-time linear drift correction using Software (in PCS) as well as Hardware improvement**
- **Performance degradation in long-time scale (Solved)**
  - → **Identification of Performance degradation – weak and long-lasting TAEs induce fast ion transport**
  - → **Establishment of high β_P long-pulse discharge scenario with constant performance over time, affected by gas fueling scenario under W-shaped divertor**

We are still struggling mainly with flux consumption to meet 300-second discharge.

→ **(plan) Development of reproducible $f_{NI} \geq 1.0$ operation scenario**
→ **(plan) Investigation of how this state keeps for a long time**

Supplements

Magnetics were highly suffered from non-linear drift issue under hot and long pulse plasma and this impacted on change of un-intentional plasma shape.

→ Magnetic signal drift in the region of outboard side are improved.

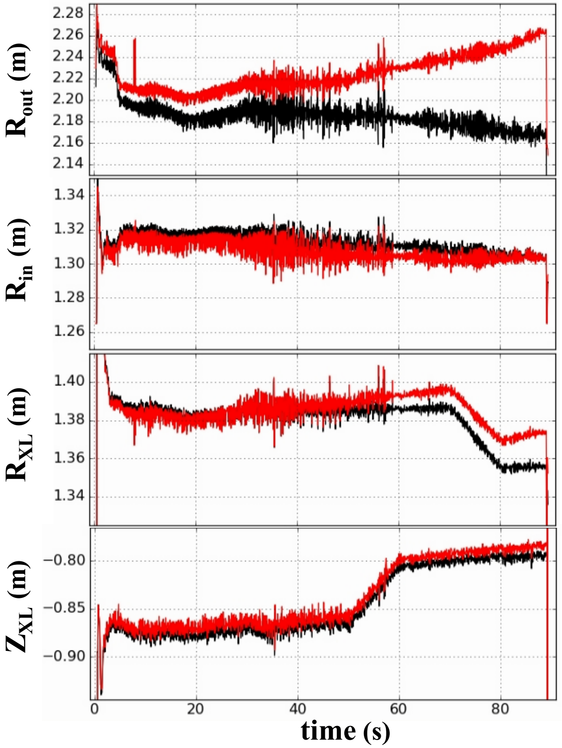
- **Drifting signals are "less" influence on the shape analysis in yr2020.**
  ① Newly installed thermal shielding block on the magnetic probes
  + ICRF limiter ahead the magnetic probes at middle side.
  ② Optimized shape to control the increase of PFC temperature

- **However, control-?**
  real-time EFIT shape is much different from off-line magnetic EFIT shape in long-time scale

- **Δβ(t) ←→ Δshape(t) ?**
  - Performance degradation is occurred even though plasma shape is constant.
  - performance degradation is less related with shape changes.

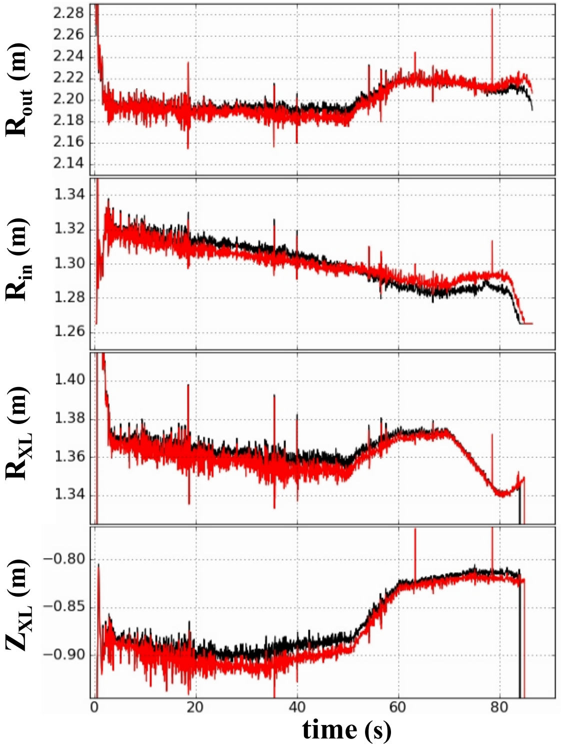
#21735 (yr2018 reference) ↔ **#27031 (yr2020)**

off-line EFIT w/o drift correction
off-line EFIT w drift correction



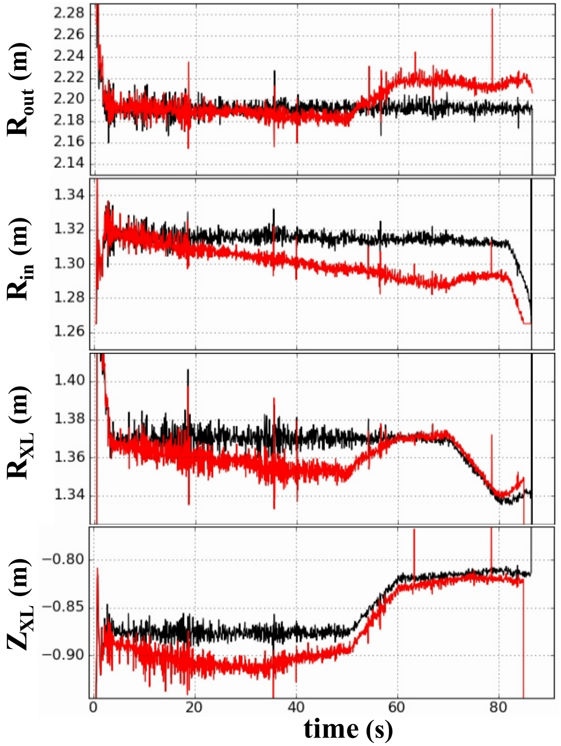
#27031 (yr2020)

off-line EFIT w/o drift correction
off-line EFIT w drift correction



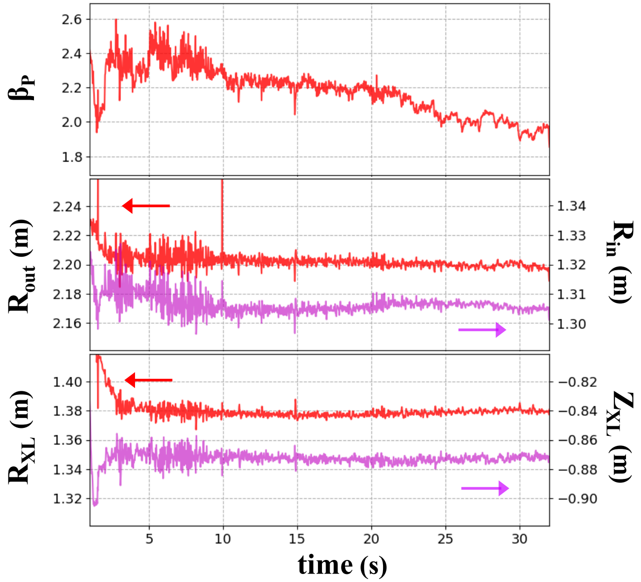
↔ **#27031 (yr2020)**

real-time EFIT
off-line EFIT w drift correction



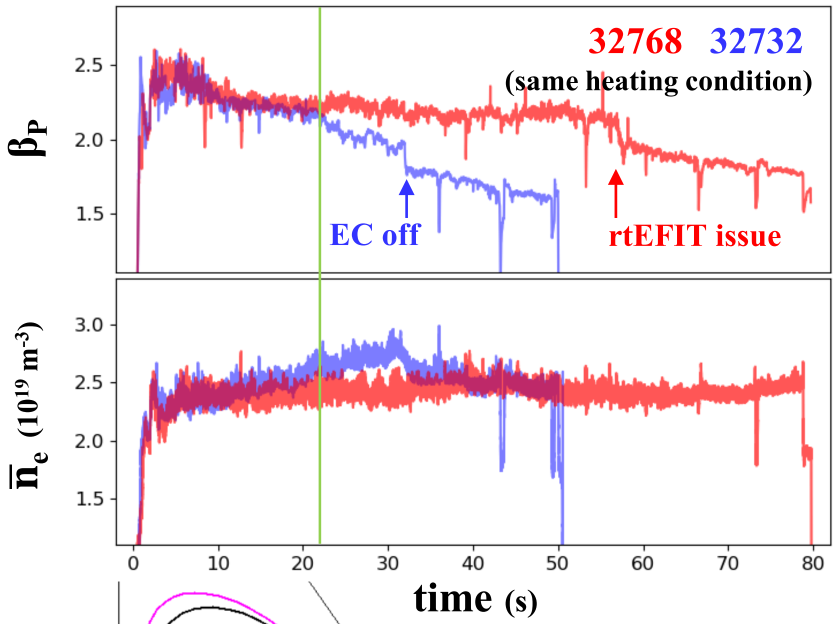
#32732 (yr2022)

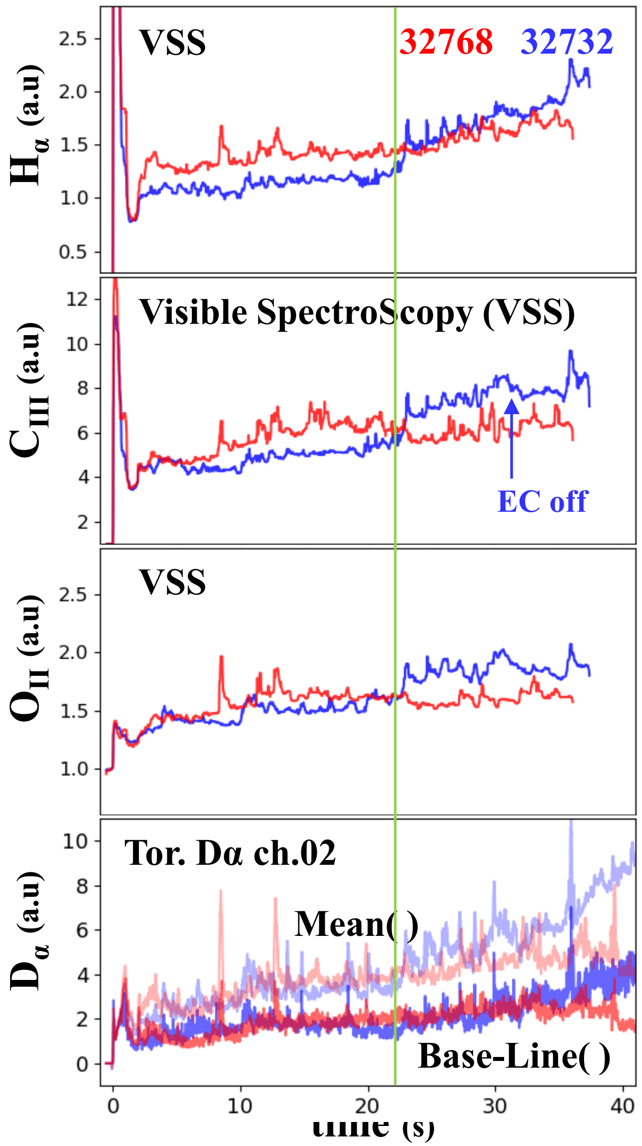
off-line EFIT w drift correction

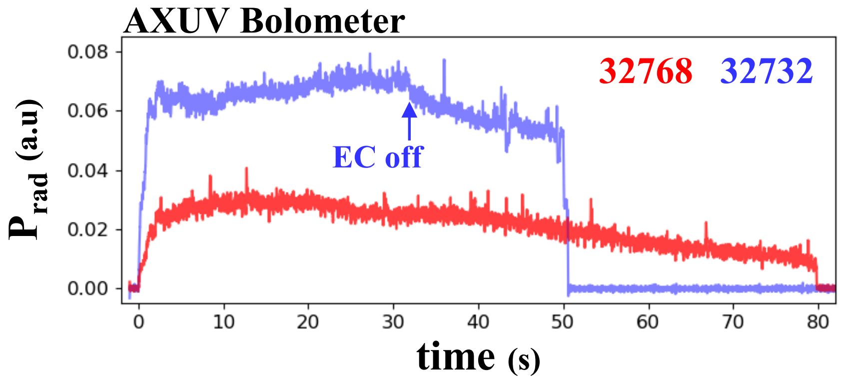


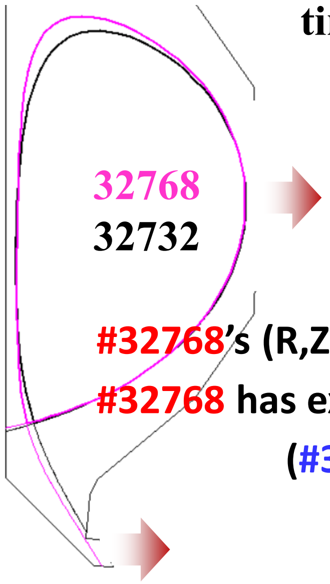
Constant performance in long-time scale was achieved eventually, Performance degradation would be "less" related with impurity contamination in SOL region.

Not all cases, analysis by just these two discharges. This would not be major cause to make performance degradation.









#32768's (R,Z)$_{strk}$ locates on CD.

#32768 has extreme δ_L~0.92.

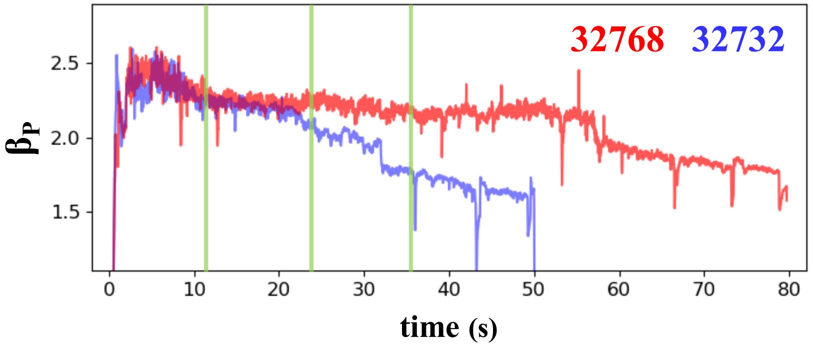
(**#32732**'s δ_L~0.84)

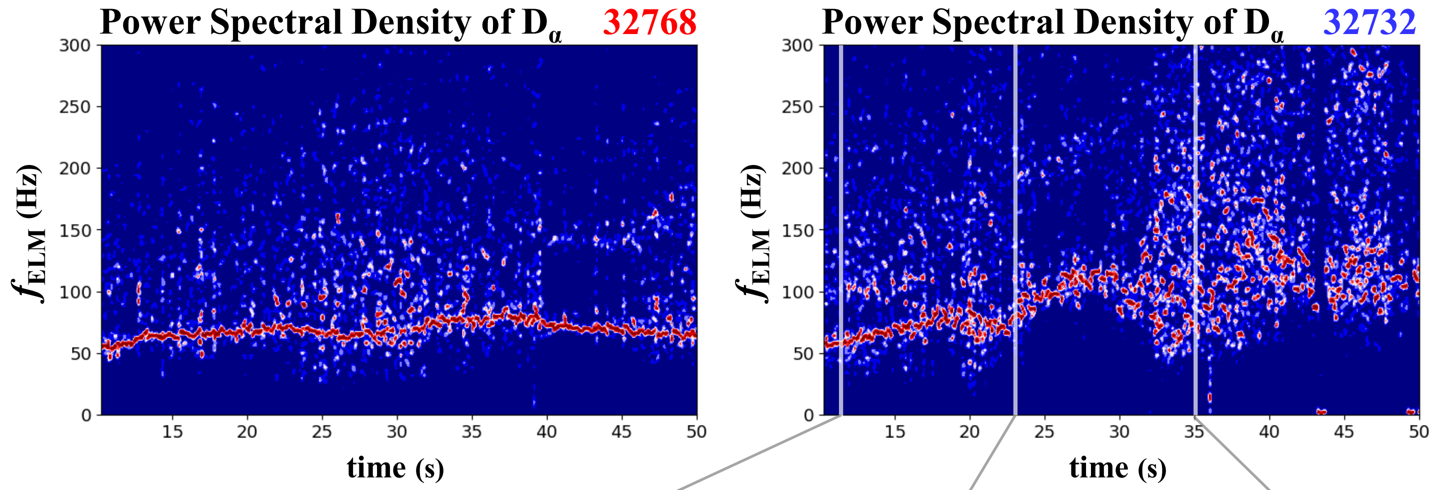
- **VSS (plasma outside) says SOL condition is not major cause to lead performance degradation.**
  - #32768 shows constant performance, even though #32768 VSS is higher than #32732 VSS before t~22 sec.
  - In #32732, VSS increases after t~22 sec, then β_P decreases rapidly.
- **AXUV Bolometer (plasma inside) says P_{rad} is 2 times lower in constant performance discharge.**
  - In #32768, lower P_{rad} is related with higher $P_{absorbed}$.

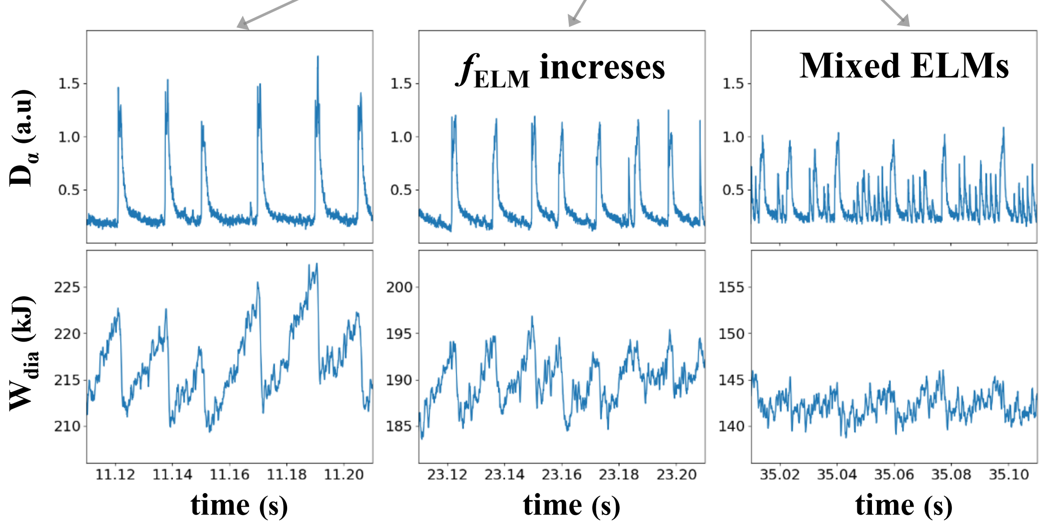
→ Major culprit would be inside the plasma, not outside of the plasma.

Constant performance in long-time scale was achieved eventually, it is confirmed that performance degradation would be "more" related with ELM characteristics.

Not all cases, analysis by just these two discharges. This would be one of causes to make performance degradation.







- **Constant ELM characteristics would lead to minimization of performance degradation in long-time scale.**
  - #32768 constant performance in long-time scale shows constant ELM characteristic with f_{ELM}~50-70 Hz.
  - #32732 performance degradation in long-time scale shows gradually increasing f_{ELM} 50→100 Hz and ΔW~15→10 kJ, and eventually developing mixed ELMs ΔW~5 kJ.

→ This would indicate more plasma energy was released to outside of the plasma in changes of ELM characteristics.

Constant f_{ELM} comes from what? ..Shape? ..Absorbed power? ..Impurities?