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Recent progress in KSTAR long pulse operation

H.-S. Kim, Y.M. Jeon, S.H. Hahn, H.S. Han,
H.S. Kim, K.P. Kim, S.W. Yoon, and the KSTAR team

*Main author's E-mail: hskim0618@kfe.re.kr

Korea Institute of Fusion Energy, Daejeon, Republic of Korea

For longer pulse length (>100 s) discharge in KSTAR,
we need to face to "Temperature of PFCs and IVCC" and "Flux consumption of PF coils"
along the existing long pulse discharges that should be resolved further
and would lead us to the right path and the scenario development.

Temperature (Machine Safety)

- **Plasma Facing Component (PFC) : 600 °C limit**
  - **Control and reduction of fast ion loss to PFC → Poloidal Limiter temperature (T_{PL})**

    (1) Optimization of plasma shape to reduce fast ion prompt 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 → Divertor temperature (T_{CD}, T_{OD}, T_{ID})**

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

- **In-Vessel Control Coil (IRC/IVC) : 70 °C limit**

  (1) Control of Zp with appropriate gains to prevent high freq. and Large amplitude of IVC current

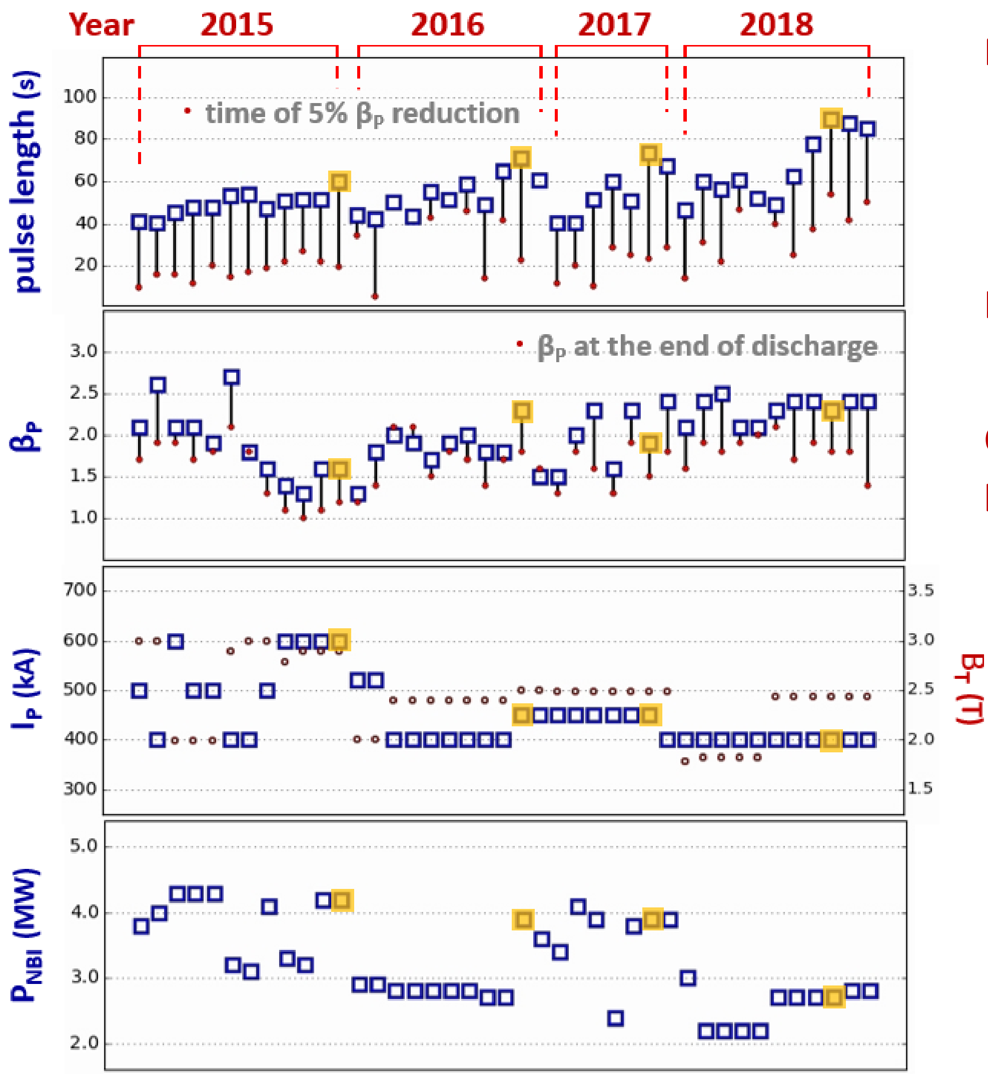
  (2) Installation of heat protection strip on IVCC from high energy particles

Flux consumption

- **PF1-4 Coils : 15 kA/turn limit**

  (1) Application of high β_P operation scenario with β_p>2.5 and controlled MHDs

Since 2015 KSTAR experimental Campaign, long pulse discharges have being explored with development of high β_P scenario and pulse length was closed to 100s by resolving various engineering and plasma issues.



Purpose of development of longer pulse discharge

- Check of KSTAR engineering capabilities
- Development of Sustainable high performance scenario

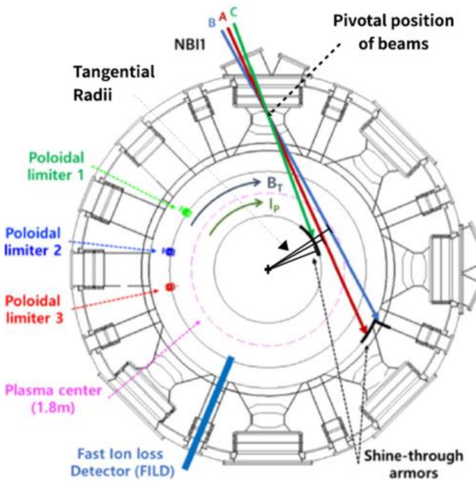
Increase of pulse length of long pulse discharge

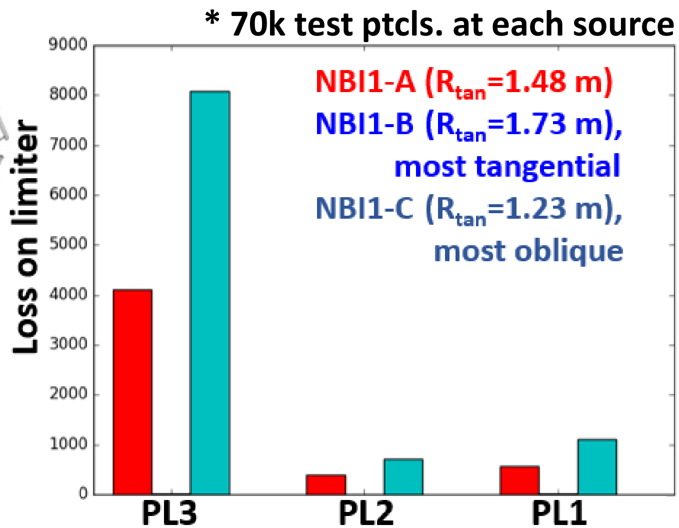
- 60 ('15) → 73 ('16-'17) → 88 sec ('18-'20)

Optimization of operation parameters to conduct longer pulse discharge with higher performance

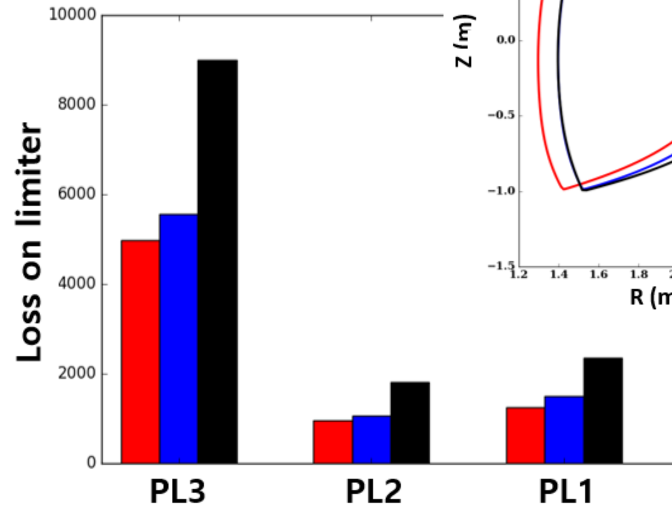
- I_P = 0.6 → 0.4 MA and B_T = 3.0 → 2.4 T
  - High β_P (~2.5) operation condition
- Optimized ECCD against P_{NBI} ~ 4.2 → 2.8 MW
  - Precise injection of ECCD in radial helps discharge longer pulse with lower V_{loop} < 0.1 V
- Optimization of plasma shape
  - Performance has been constant for longer period of time (see time of 5% β_P reduction)
  - Mitigate/relieve heat transfer to PFC

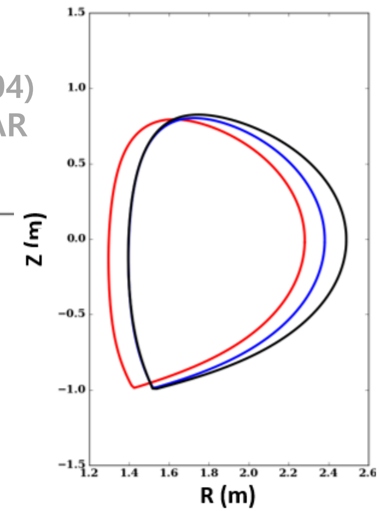
Fast Ion prompt loss was reduced to prevent the increase of Poloidal Limiter temperature by the optimized application of NBI heating source and the optimized plasma shape, especially non-injection of NBI1-C source and reduction of R_{out} respectively.





NuBDeC code (T. Rhee PoP26(2019)112504) analyzed the fast ion prompt loss in KSTAR

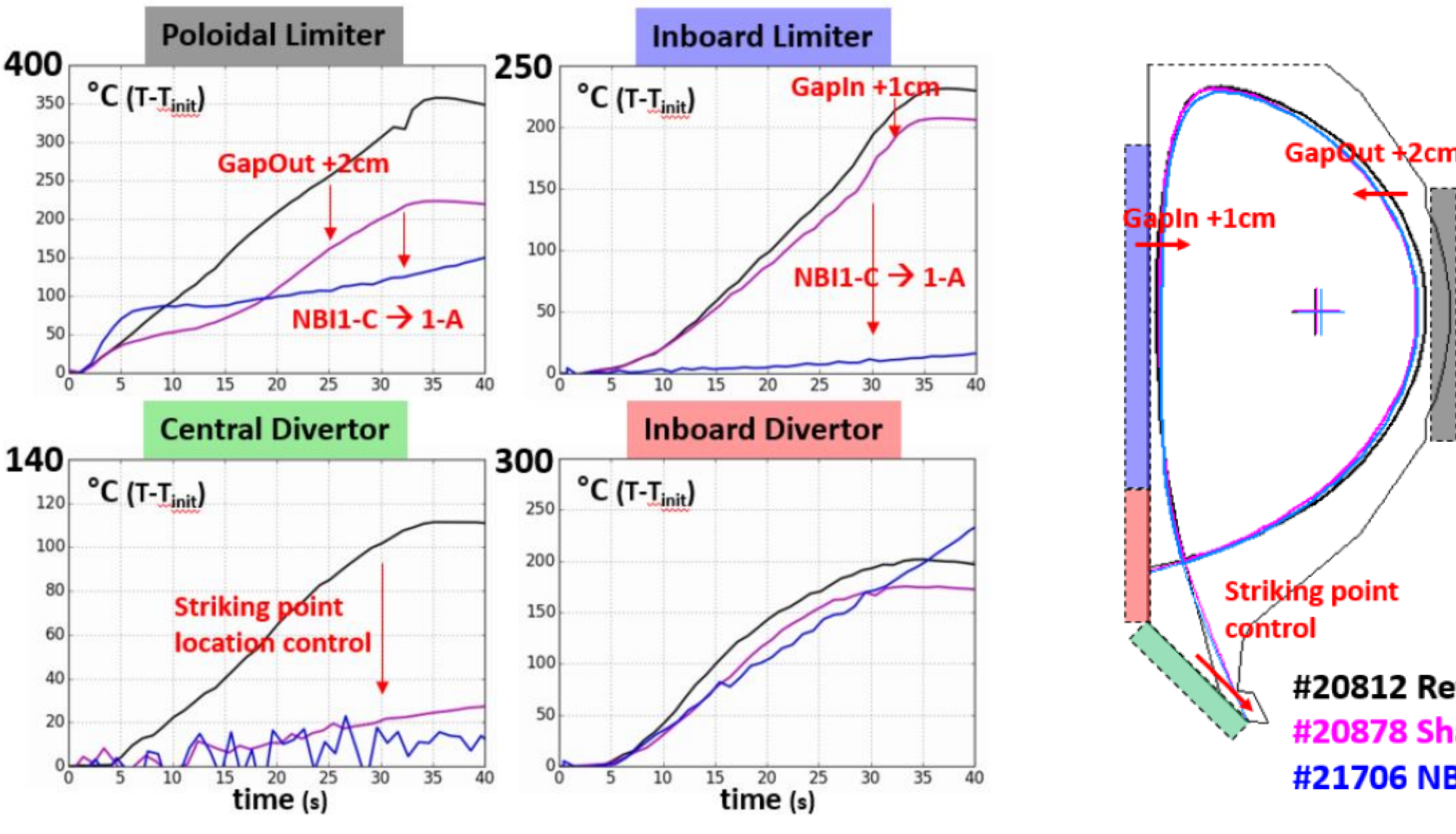




- Fast ion loss particles were mainly concentrated on 3rd Poloidal Limiter due to direction of V_{Φ}.
- NBI1-B contributed little to fast ion hit on the poloidal limiters, but NBI1-C highly contributed.
- Higher R_{out} had 1.5-1.8 times higher fast ion loss and it caused from the increase of shape curvature.

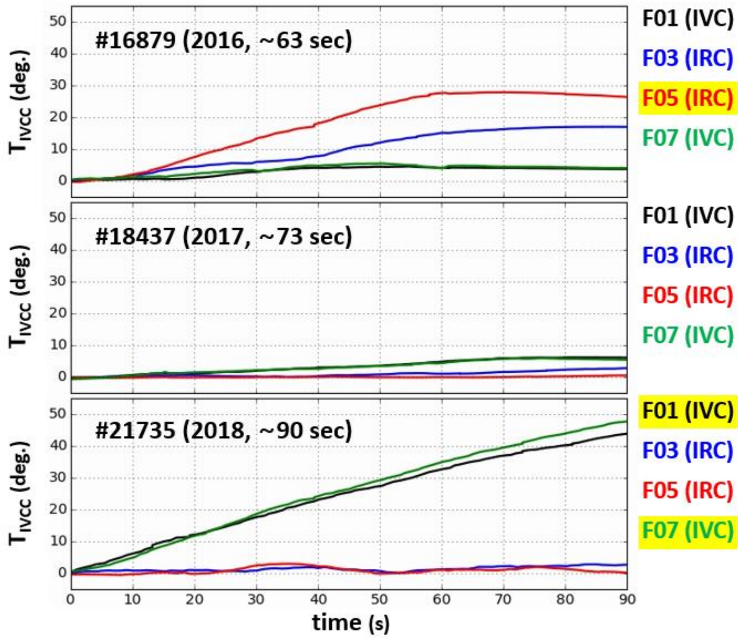
The temperature of PFCs, except Inboard Divertor, was able to be effectively controlled with optimization of plasma shape and NBI heating scheme.

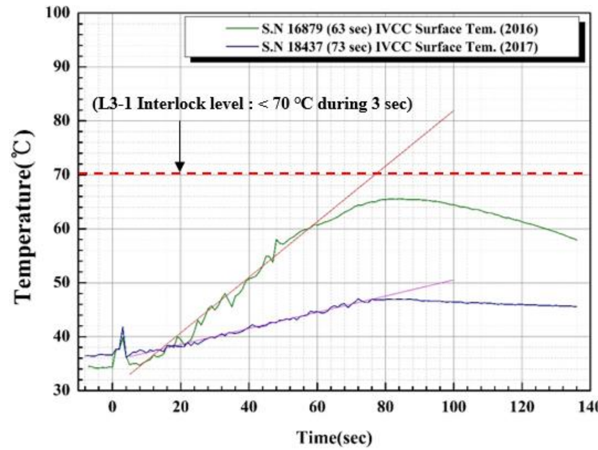
- **Increase of GapOut and GapIn** leads to decrease the temperature of **"Poloidal Limiter"** and Inboard Limiter.
- **Control of striking point location** leads to decrease the temperature of **"Central Divertor"**.
- **Non-injection of NB1-C** leads to decrease the temperature of **"Poloidal Limiter" and "Inboard Limiter"**.

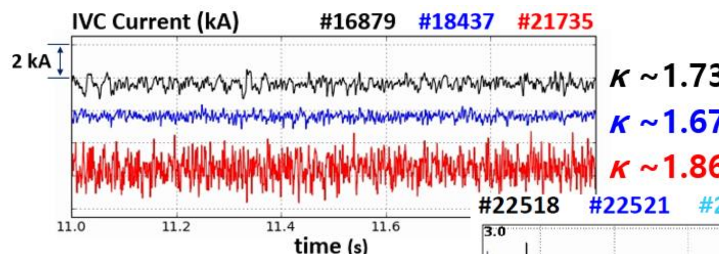


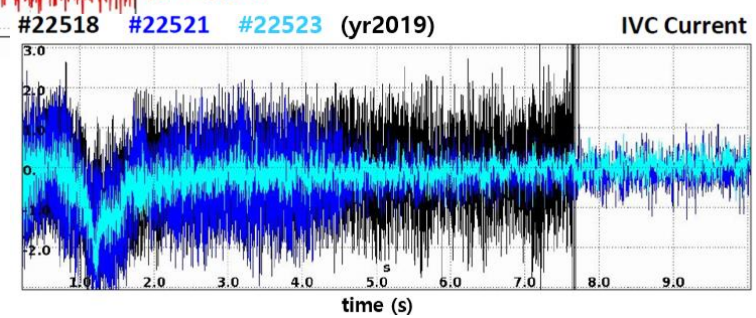
* Result from NuBDeC was tested in KSTAR experiment

IVCC coil temperature was controlled with the installation of heat protection strip on IVCC and the optimization of IVC control gains even with highly elongated plasma with R_{out} reduction.





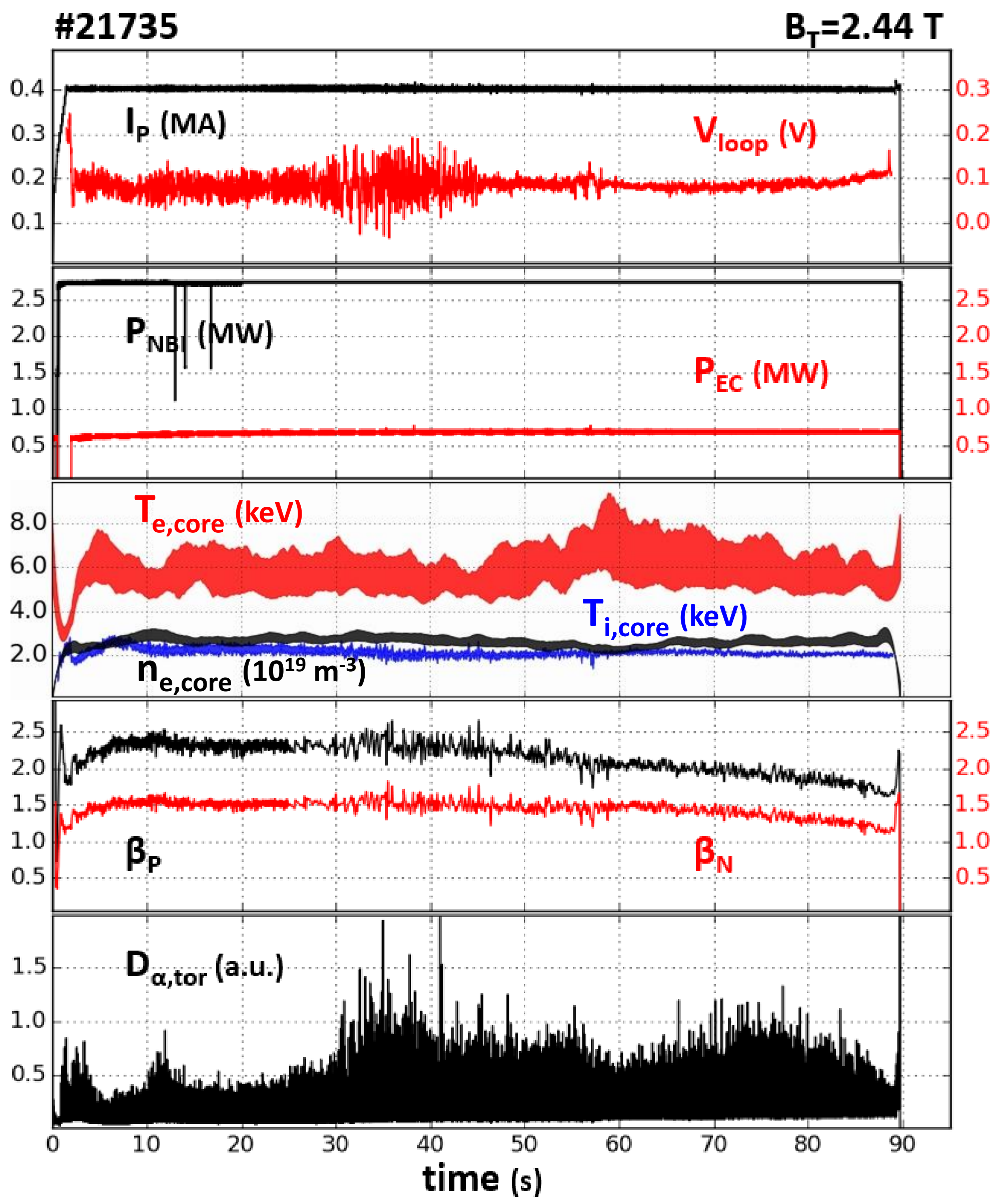




- **STS strip was installed to prevent Upper & Lower IVCC temperature increase from heated particles and power loss.**
- **IVC control gains were tuned to reduce IVC current frequency and its amplitude and it led to stabilize ΔT_{IVCC}~4.0 degree for 20 seconds at #22523.**

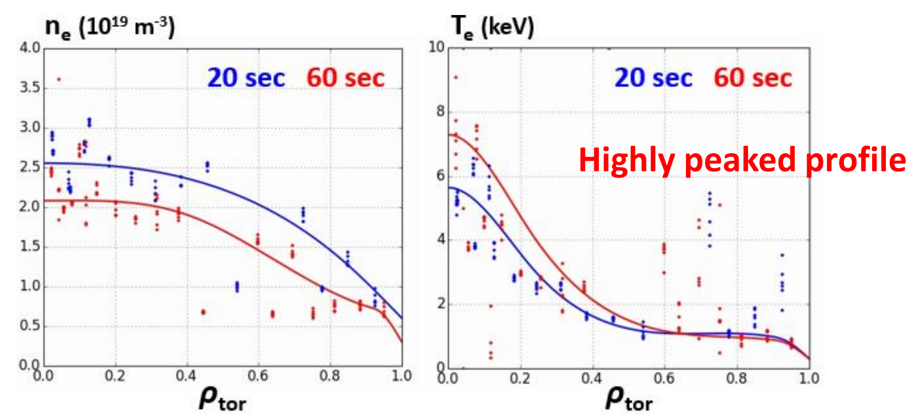
* IVC control gain tuned

KSTAR has achieved new recored of pulse length ~90 seconds with applying former mentioned methods.

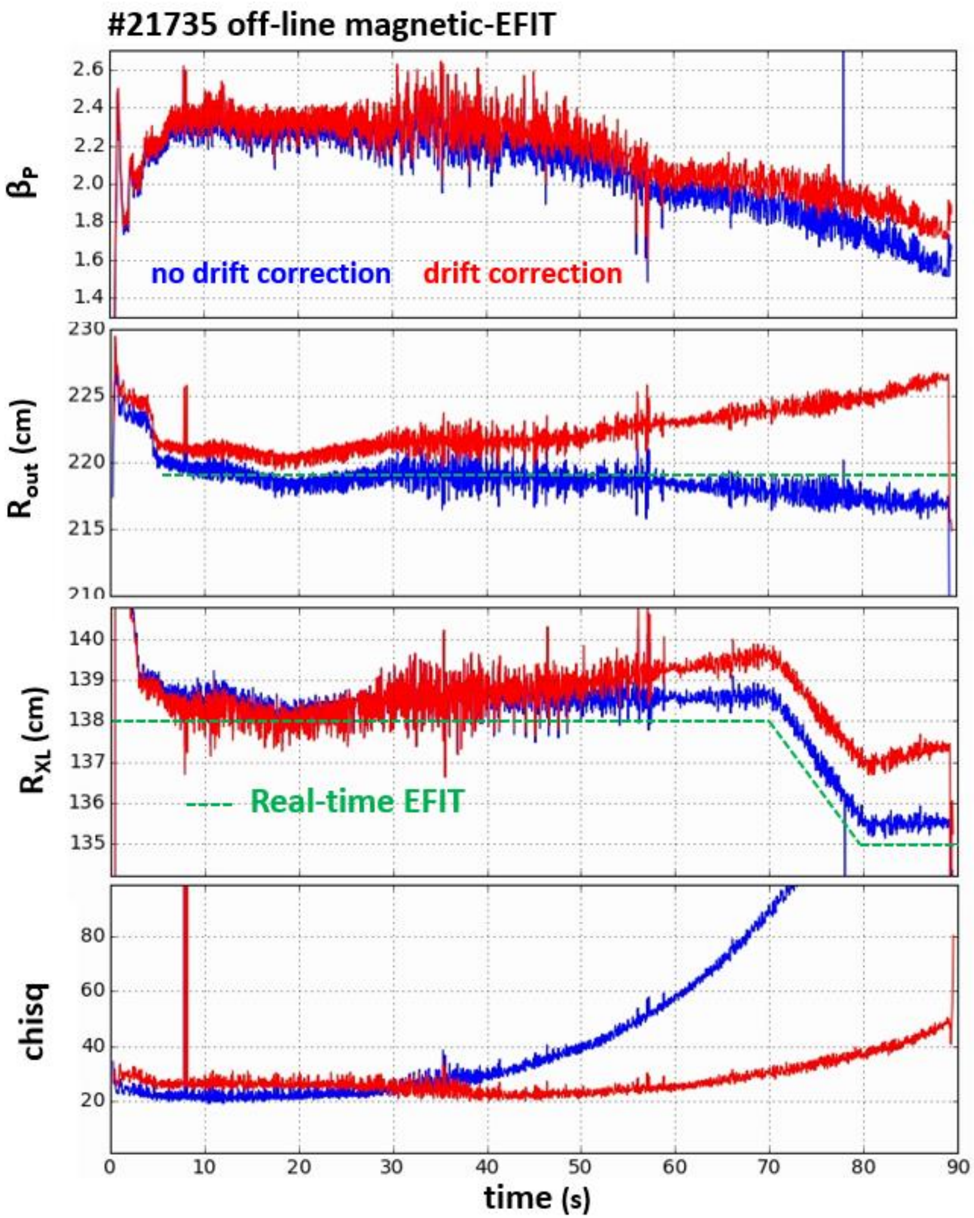


- **Operation Condition :**

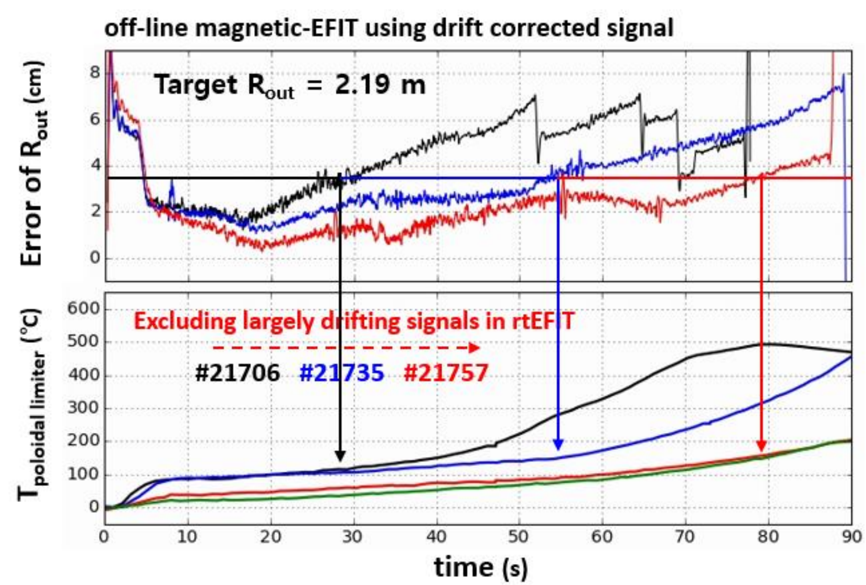
  I_P=400 kA, B_T=2.44 T, P_{NBI}=2.8 MW, P_{EC}=0.7 MW
  - **Optimized application of EC injection is a KEY that discharge was in the High β_P state**
- **V_{loop}~0.1 V was kept constant for whole discharge**
  - **For longer pulse length (>100 s), V_{loop} should be reduced more with additional H/CD and higher performance plasma**
- **$n_{e,core}$ ≤ 2.5 x10^{19} m^{-3}, $T_{e,core}$ ≥ 5.0 keV, $T_{i,core}$~2.0 keV**
- **β_P~2.4 (β_N~1.5) was kept constant for ~45-50 sec**
  - **Gradually decrease of plasmas performance should be resolved**



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



- Shape using drift corrected signals was much different from one using un-corrected signals, but real-time EFIT did not know it. (see R_{out} and R_X)
- Especially, R_{out} should be controlled within ~2.22m to prevent the increase of poloidal limiter temperature.
- Following solutions were considered and are considering,
  - Installation of thermal shielding block on magnetics to protect from the hot environment
  - Development of real-time non-linear drift correction algorithm and implementation it to PCS



Summary

- **KSTAR has achieved new record of pulse length ~90 seconds with high performance plasma of β_p~2.4.**
  - **For the development of longer pulse discharge in KSTAR, the strategy is required to alleviate PFCs and IVCC temperature increase.**
    - **The fast ion prompt loss was well-controlled to prevent the increase of surface temperature of Poloidal Limiter and Inboard Limiter by the optimized application of NBI sources and the optimized plasma shape.**
    - **The heat flux on the Central Divertor plate was effectively controlled by the change of striking point location not to be normal injection.**
    - **The IVCC temperature was also controlled by the installation of heat protection strip and the optimization of IVCC control gains even with high elongated plasma.**
- **KSTAR has been suffered from the non-linear drifting signals in Magnetic Measurements, especially in Magnetic Probes.**
    - **This impacts on accuracy and reliability of real-time EFIT operation and leads to unintentional plasma shape control in real-time.**
    - **The installation of thermal shielding block on Magnetic Measurements could somewhat weaken the non-linear drift signals.**
    - **To improve, the development of real-time non-linear drift correction algorithm is underway.**