한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

EX-C, ID #3421

Development of High-performance Long-pulse Discharges in KSTAR

[1*]Hyun-Seok Kim, [1]YoungMu Jeon, [1]Hyunsun Han, [1]Kimin Kim, [1]KwangPyo Kim, [1]Heungsu Kim, [1]Tongnyeol Rhee, [1]Juhyung Kim, [1]Junghee Kim, [1]Dongcheol Seo, [1]Eunnam Bang, [1]Hee-Jae Ahn, [1]Hyun-Sik Ahn, [1]Jaesic Hong, [1]Jinhyun Jeong, [1]Jongdae Kong, [1]Jong-Gu Kwak, [1]Jongkook Jin, [1]Jungyo Bak, [1]Kaprai Park, [1]Kyu-Dong Lee, [1]Mi Joung, [1]Sang Woo Kwag, [1]Sang-Hee Hahn, [2]SangKyeun Kim, [1]Si-Woo Yoon, [1]Sonjong Wang, [1]Woong Chae Kim, [1]Young-Ok Kim, and KSTAR Teams

*hskim0618@kfe.re.kr

[1]Korea Institute of Fusion Energy, Daejeon, Republic of Korea

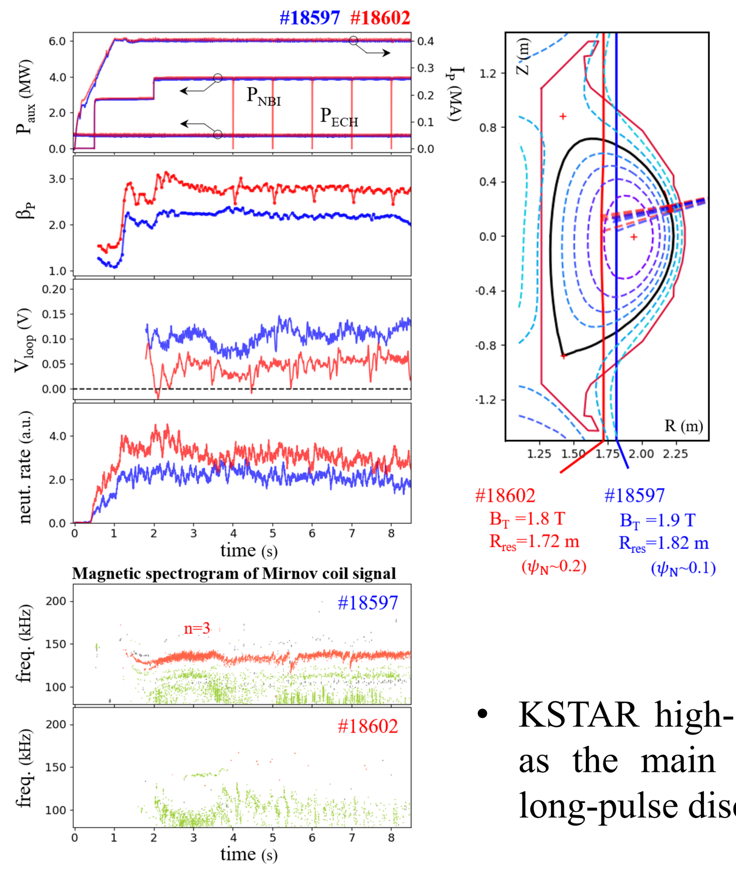
[2]Princeton Plasma Physics Laboratory, Princeton, United States of America

➢ Summary and Plans

Major technical issues limiting high-performance long-pulse operation have been systematically addressed in KSTAR. Heat control on plasma-facing components has been solved by optimizing plasma shape control and upgrading the actively cooled tungsten monoblock divertor. The magnetic signal drift was also resolved through the installation of thermal shielding blocks on magnetics and implementation of a real-time linear drift correction algorithm in the plasma control system. Although performance degradation in the long-time scale remains partially solved—mainly associated with weak, long-lasting TAEs and fast-ion transport—the long-time gas fueling and shape scenario optimization have significantly improved plasma sustainment. Building on these results, a new effort is underway to develop reproducible ITB formation and q-profile control scenarios enabling steady high-β_P operation and long-pulse plasma sustainment.

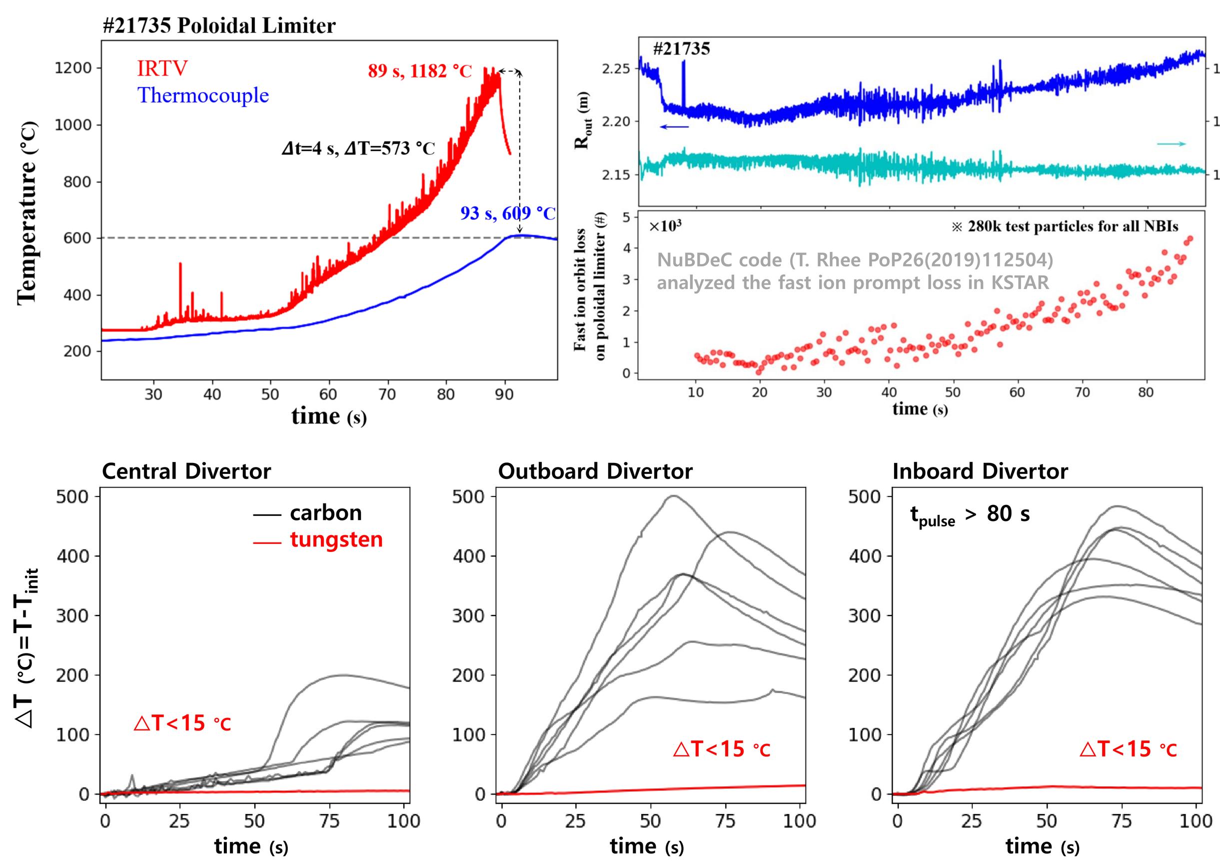
➢ Challenges in achieving high-performance long-pulse discharges — scenario, heat, signal drift

✓ Accurate ECH/CD control for high β_p state



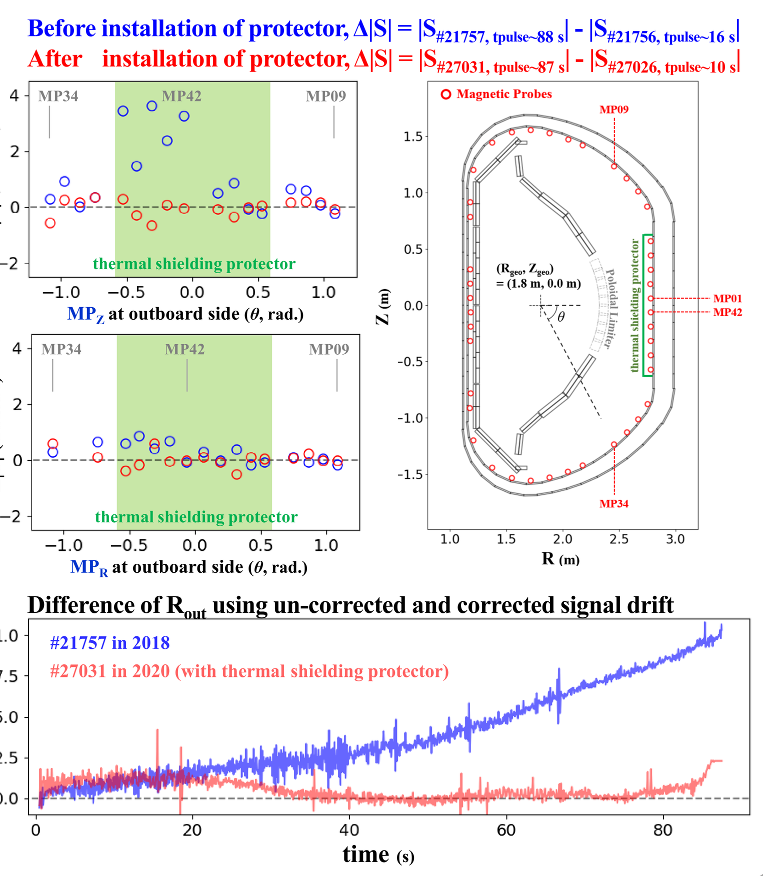
- ECH/ECCD must be deposited to a narrow vicinity near the magnetic axis (ψ_N~0.2).
- Suppressing/mitigating n=3 TAE with ECH/CD injection improves fast ion confinement.
- KSTAR high-β_p discharge adopted as the main scenario of KSTAR long-pulse discharge.

✓ Heat control of PFCs



- Ionized fast ions at HFS strike poloidal limiters & inboard divertor.
- Optimizing shape control
- Actively cooled tungsten monoblock divertor
- MP_Z mainly shows nonlinear signal drift
- Coil winding of MP_Z facing to the plasma.
- **Thermal shielding protector** effectively blocked plasma heat.
- Real-time linear drift correction algorithm in PCS

✓ Mitigation of magnetic signal drift



➢ Challenges in achieving high-performance long-pulse discharges — Progressive performance degradation over a long-time scale

✓ Challenges in extending pulse length beyond ~90 s

2015-2017 Exp. Campaign

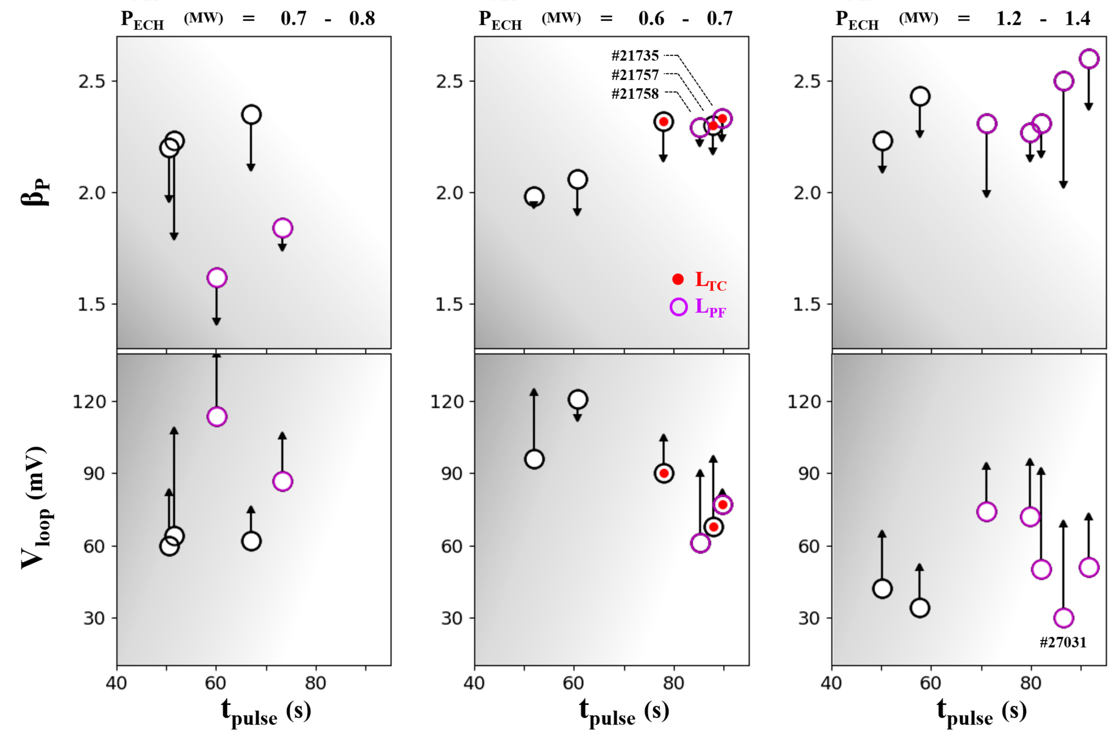
I_P	(kA)	=	400 - 450
B_T	(T)	=	2.5 - 3.0
P_{NBI}	(MW)	=	3.0 - 3.9
P_{ECH}	(MW)	=	0.7 - 0.8

2018 Exp. Campaign

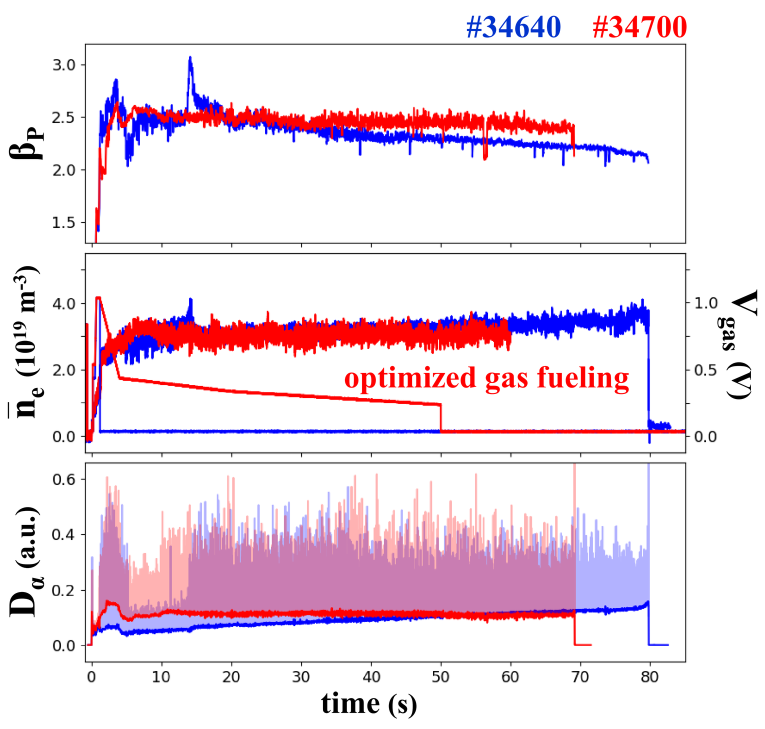
I_P	(kA)	=	400
B_T	(T)	=	1.8 - 2.4
P_{NBI}	(MW)	=	2.3 - 2.9
P_{ECH}	(MW)	=	0.6 - 0.7

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

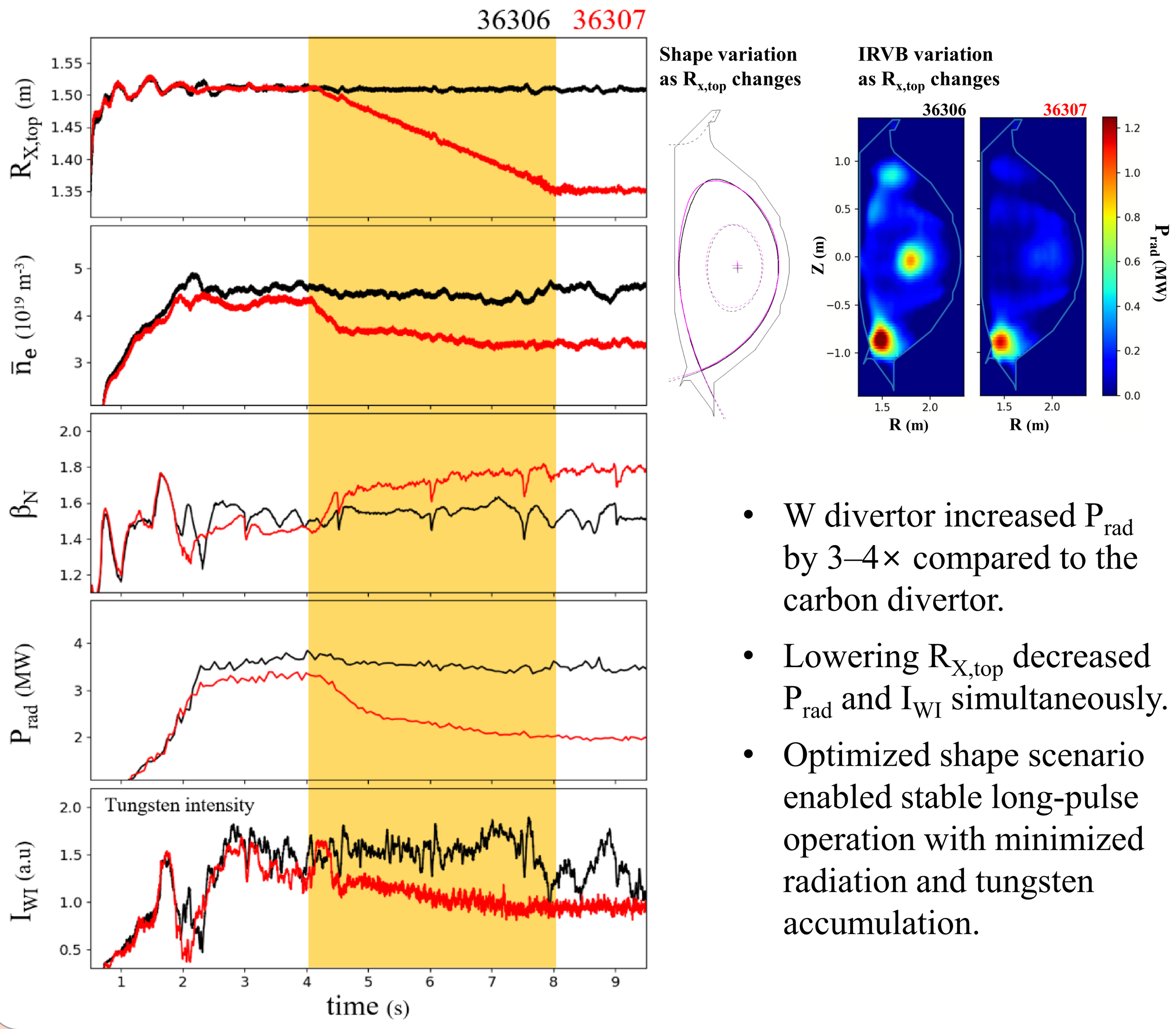


✓ Sustained high-β_P operation achieved through optimized gas fueling scenario



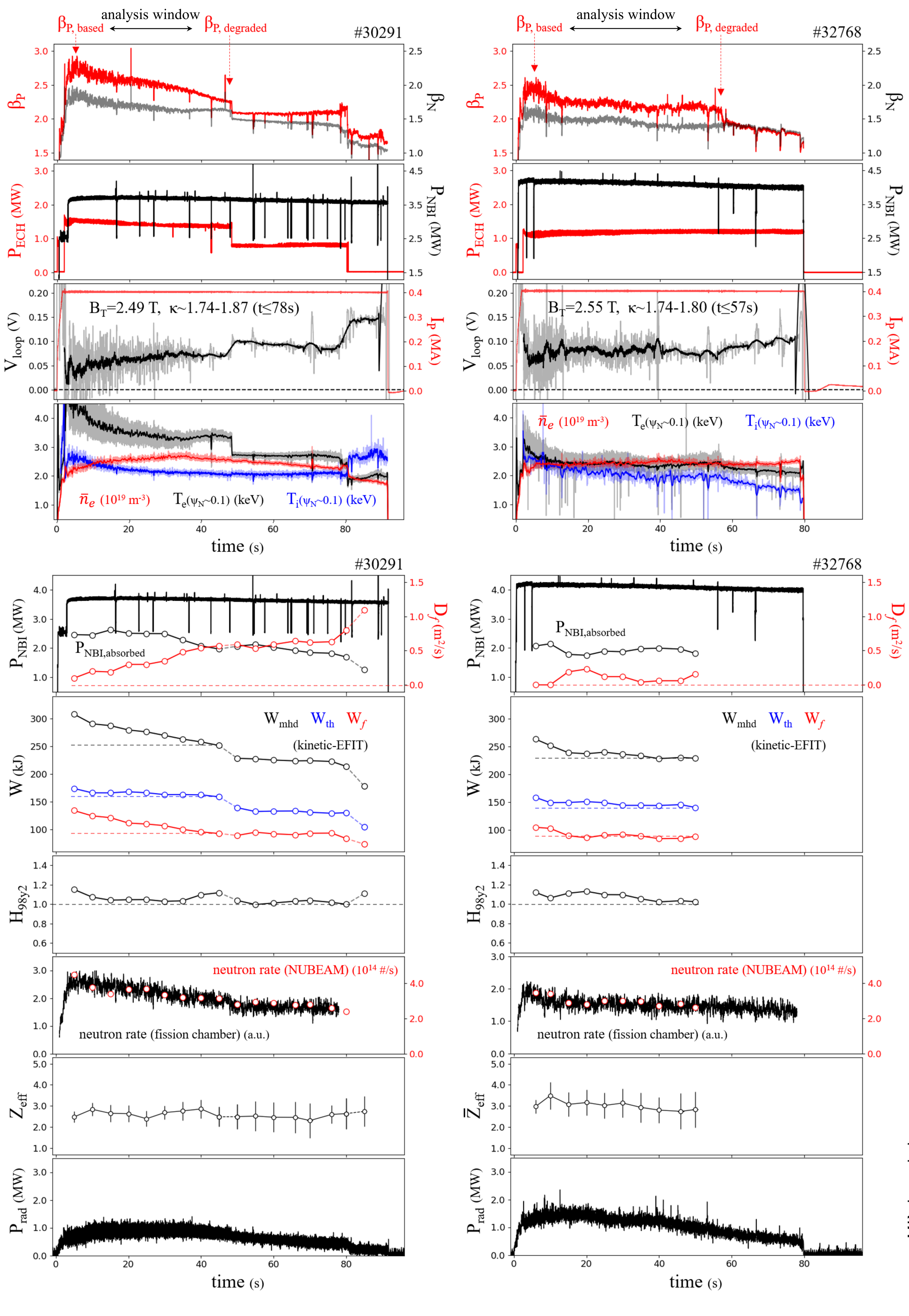
- Optimized long-time gas fueling sustains high β_P (>2.5) plasmas.
- Stable performance maintained for ~70 s. (high reproducibility)

✓ $R_{X,top}$ adjustment effectively reduced tungsten accumulation and Prad



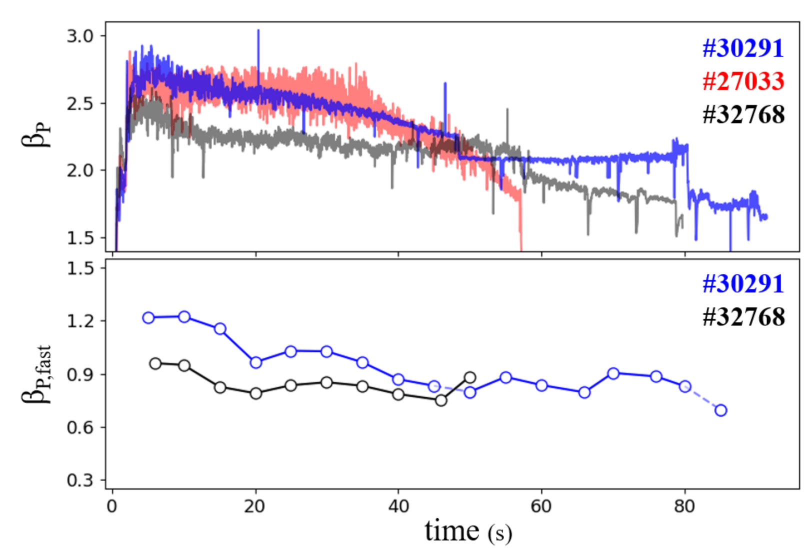
- W divertor increased P_{rad} by 3–4× compared to the carbon divertor.
- Lowering $R_{X,top}$ decreased P_{rad} and I_{WI} simultaneously.
- Optimized shape scenario enabled stable long-pulse operation with minimized radiation and tungsten accumulation.

✓ Representative discharges suffered from performance degradation

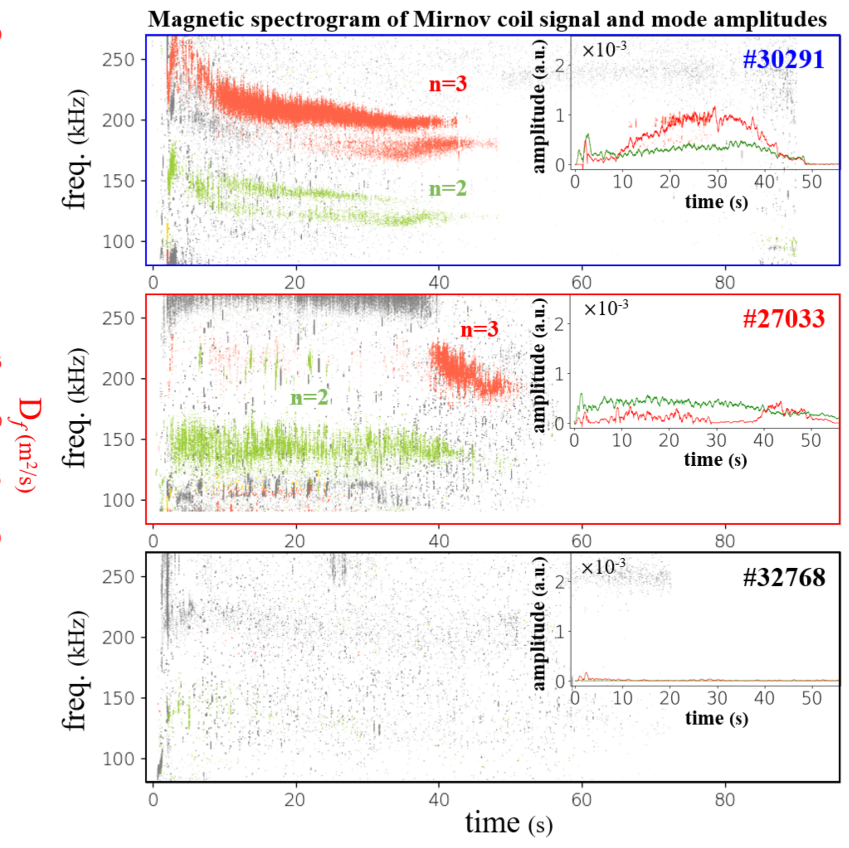


- **β_P degradation in a long-time scale ~8τ_R, ~1067$\tau_{E,th}$**
  - β_P degradation comes from W_{fast}, not W_{th}
  - Fast ion transport is increased (see D_f)
- **Weak & long-lasting TAEs impact on β_{fast} degradation → β_P degradation**
- **Progressive degradation process related to TAEs**
  - 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

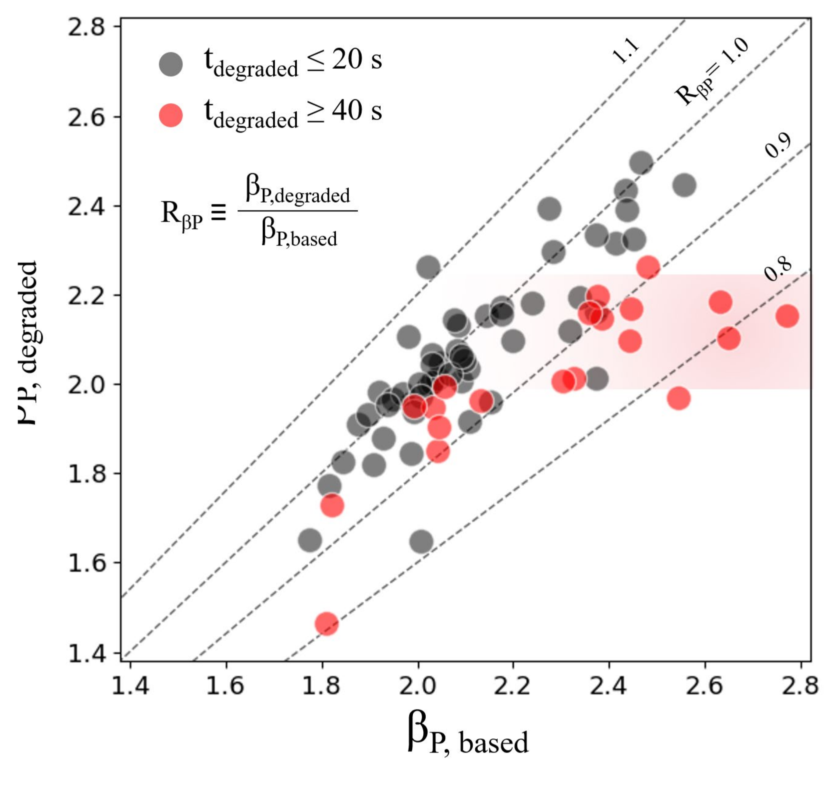
✓ Correlation of TAEs with performance degradation



Magnetic spectrogram of Mirnov coil signal and mode amplitudes



✓ Converging plasma performance as pulse length increased



Acknowledgments
This research was supported by the R&D Program of "High Performance Tokamak Plasma Research Development (EN2501-16)" through the Korea Institute of Fusion Energy (KFE) funded by the Government funds, Republic of Korea.