Overview of the KSTAR Experiments and Future Plan

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Outline

Overview

Suppression of Tungsten Impurities

impact of W divertor, W mitigation, ITER-relavant W study, ...

Advanced Scenario Development

advanced scenarios (high-li, high-Ti, hybrid, high-βp, ...) on W environments

Implemetation of Control Schemes

control adopting innovative (physics-based, AI, ML, surrogate model, ...) schemes

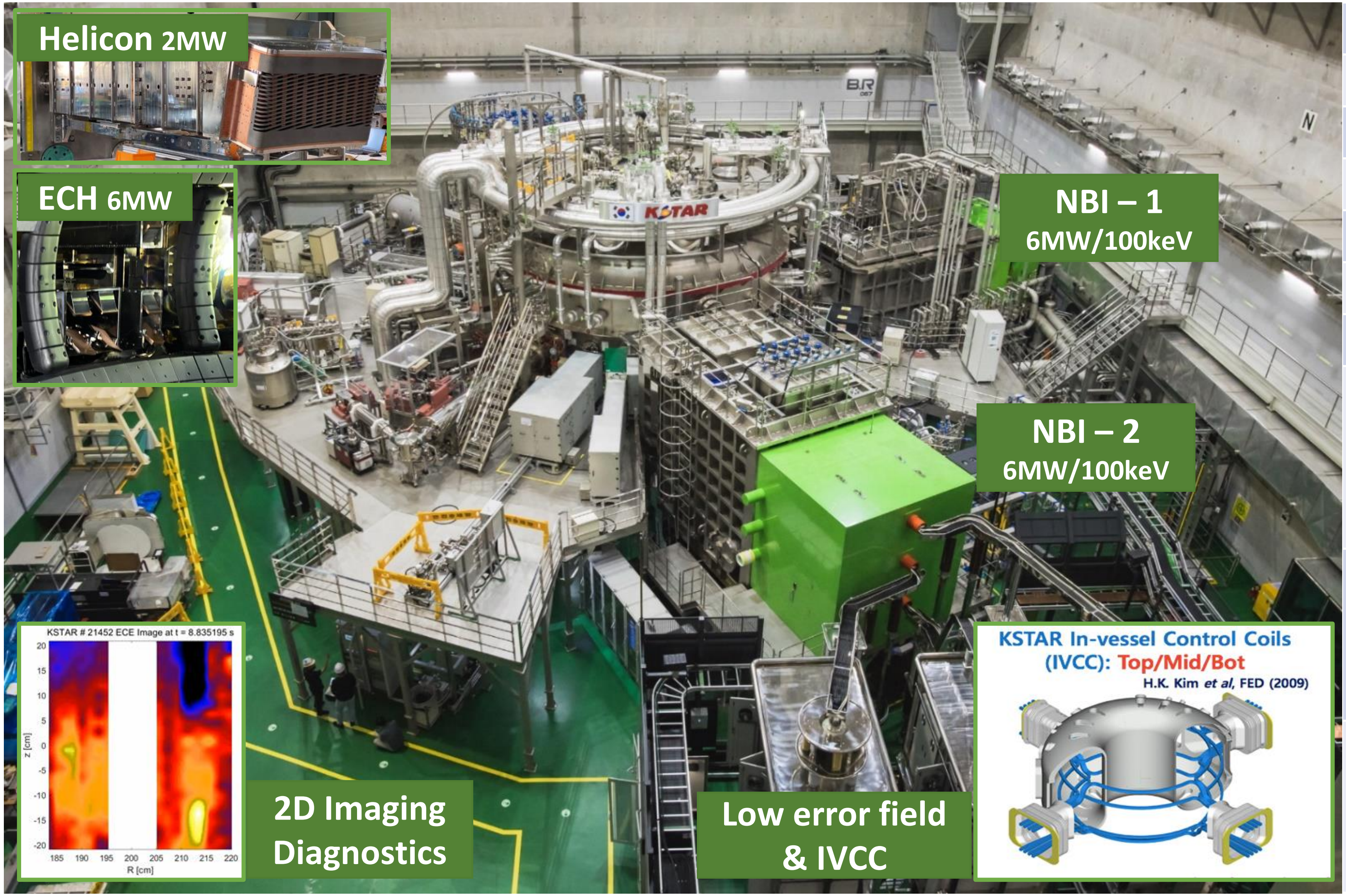
Investigatsion on Physical Mechanism

focusing on reactor & burning plasma physics

Future Plan

align with Korea fusion development program

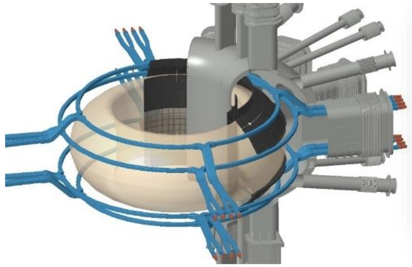
KSTAR is a mid-size superconducting tokamak for high performance & steady-state operation

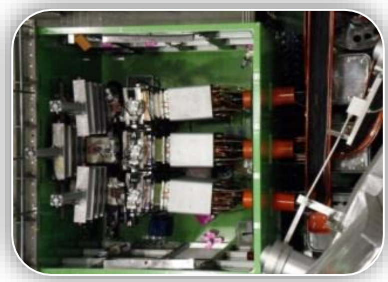


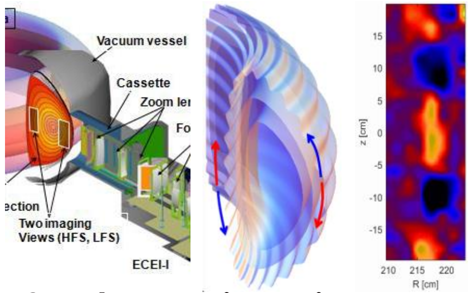
SC	NB_3Sn, NBTi
R0	1.8 m
a	0.5 m
κ	2.0
δ	0.8
Ip	2.0 MA
B0	3.5 T
<u>Pulse Length</u> designed achieved	 300 s 102 s (β_N > 2) 48 s (high Ti)
<u>H & CD</u> NBI ECH Helicon	 12 MW 6 MW 2 MW
<u>PFC</u> Wall Divetor	 C tile W monoblock

KSTAR is tackling key issues for burning plasma operation with newly installed W divertor

~ 2022 Campaign	2023 – 2024 Campaign
Advanced Research with Superconducting Tokamak	**Transition to Burning plasma Research on Tungsten Environment**
Extention of the operation boundary - High beta Steady-state	Reproducing & developing adv. scenarios - Assessing solutions for W impurity impact
Resolving ITER-relavant control issues - ELM, Disruption, Detachment, ...	Adopting cutting-edge tech. for control - AI, ML, Surrogate model, ...
Understanding on the fundamental physics - Turbulence & Transports (2D, 3D), ...	Physics for reactor & buring plasma - Fast ion, 3D simulation, ...

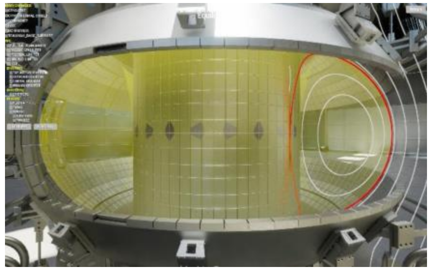

Unique In-vessel coils


Long-pulse H/CD



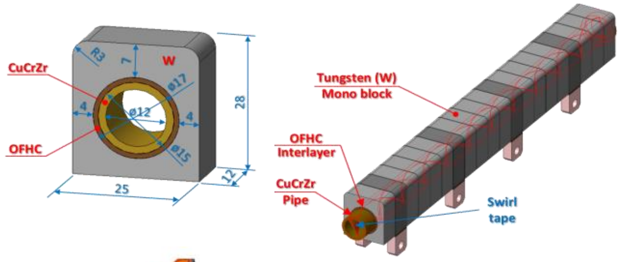
2D Fluctuation Diag.

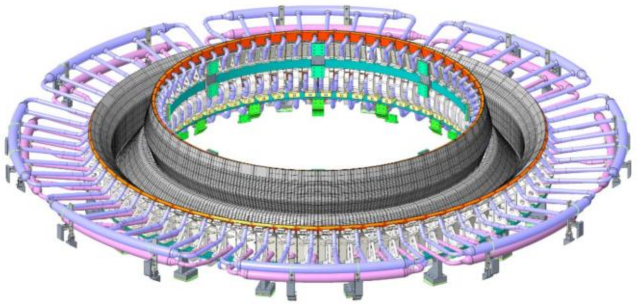
W monoblock Divertor

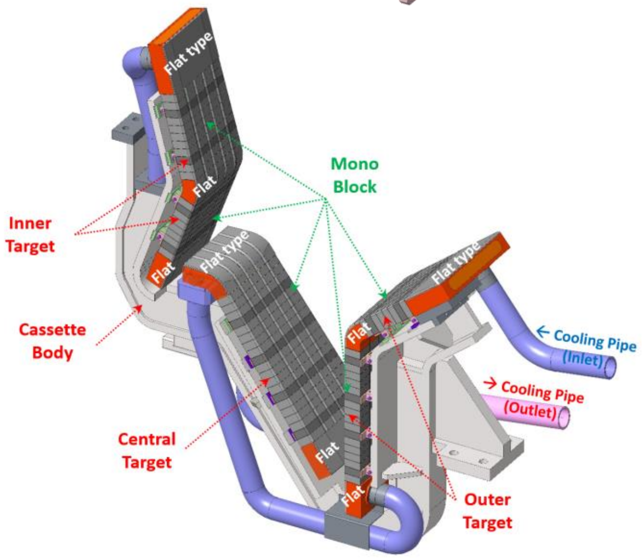

Virtual KSTAR

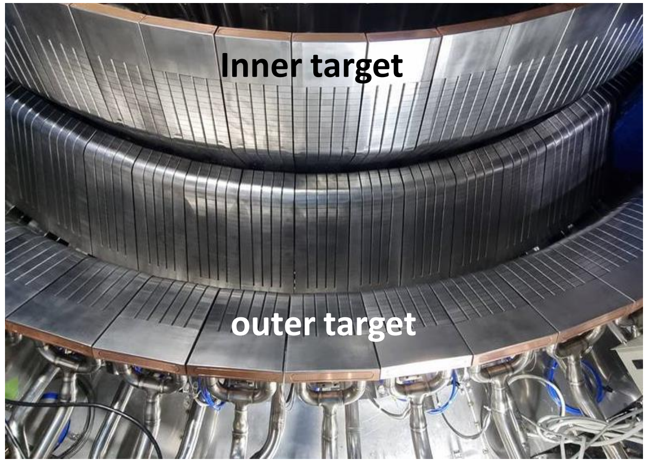
Tungsten (W) mono-block divertor, providing opportunities to study tungsten transport and control

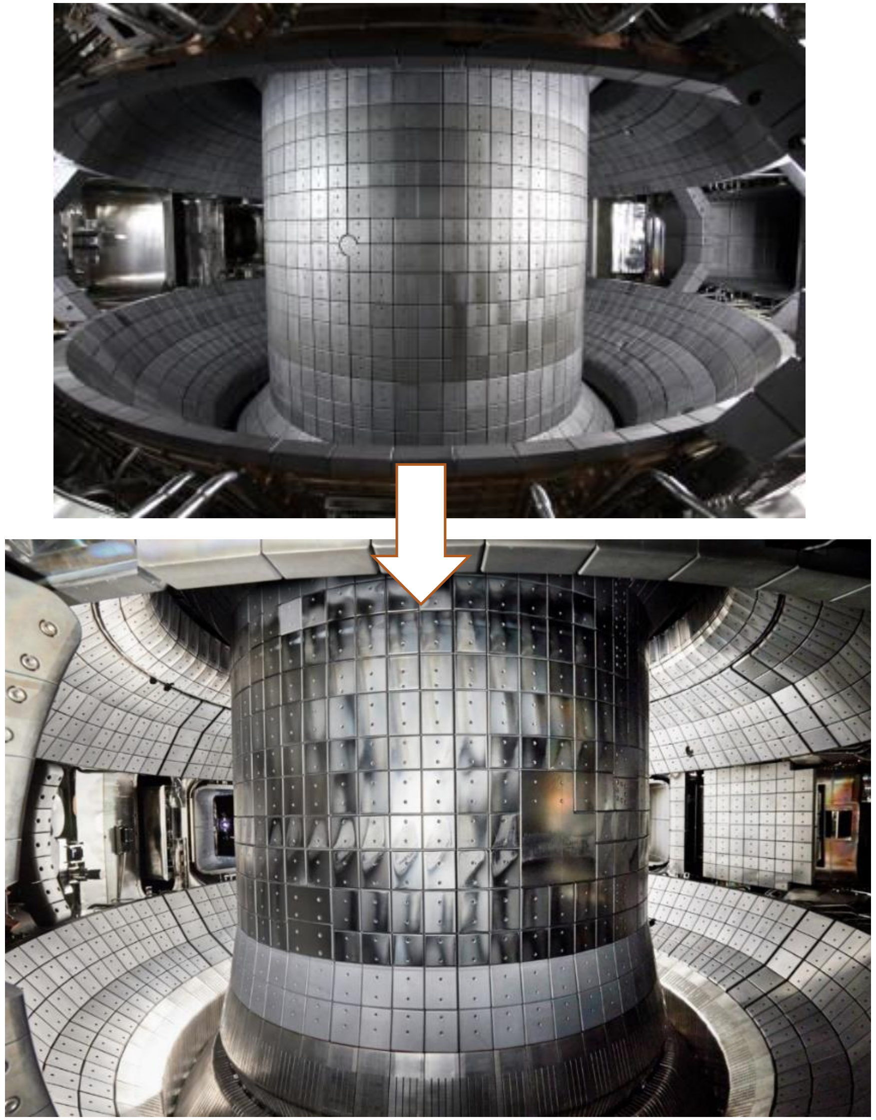
- Preparing high-power (max 24MW) long-pulse operation
- Peak heat flux: 4.3 MW/m^2 (C) ⇒ 10 MW/m^2 (W)
- Successfully installed & commissioned
- **W transport & control** experiments enabled



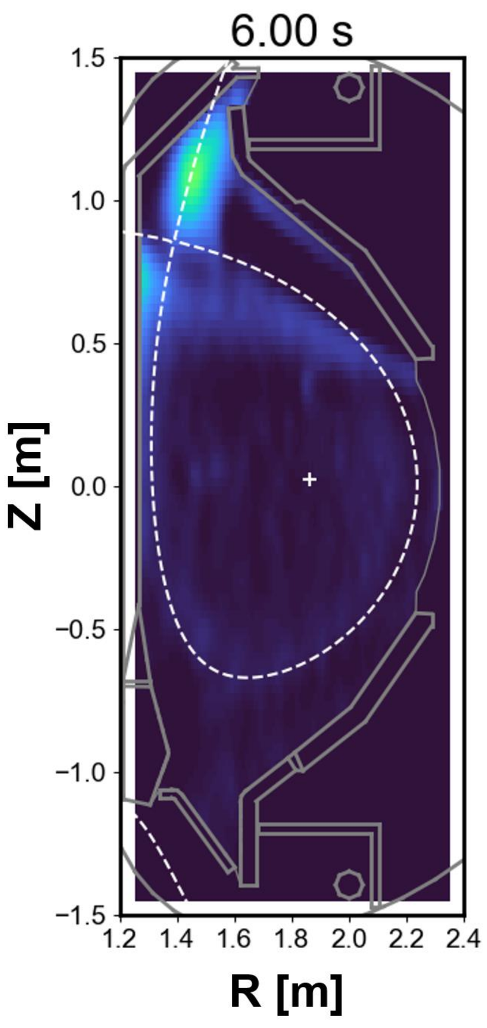




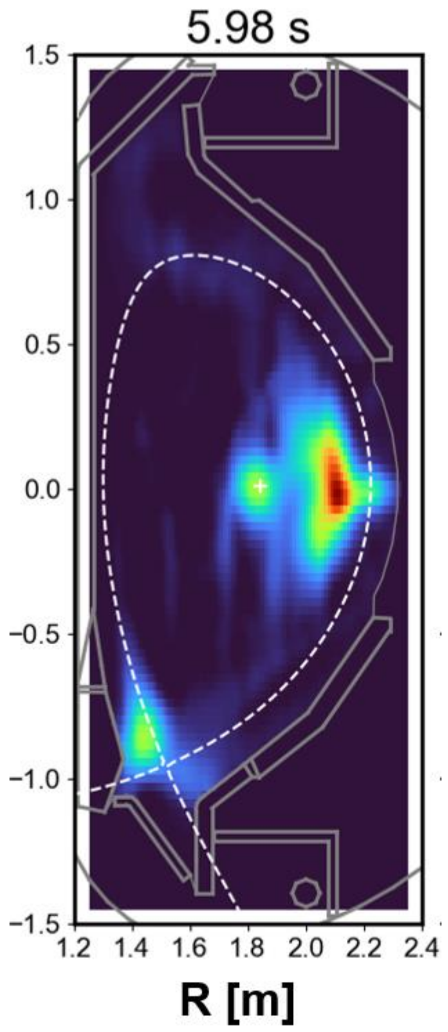




Effect of W divertor was identified from LSN/USN comparison



34036 (USN)



34049 (LSN)

- USN (C div.) – radiation near the divertor
- LSN (W div.) – **core radiation with pattern of W rad.**
- Reconstruction of tungsten cooling rate was compared with IRVB measurement (**n_W/n_i ~ 2×10^{-3}**)

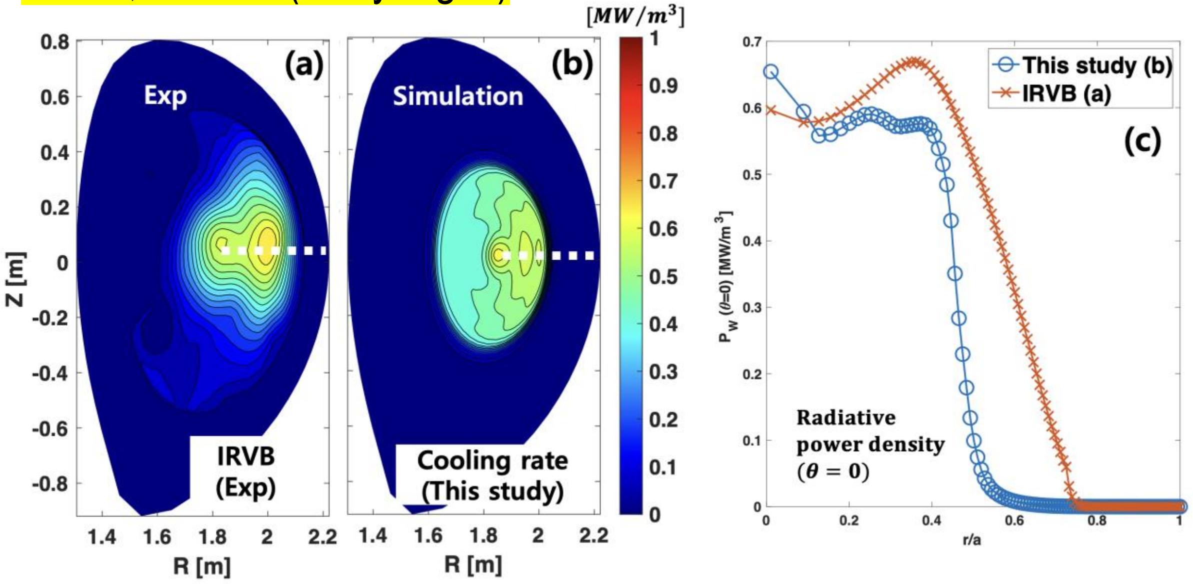
Realistic tokamak geometry & 2-D impurity distribution

Neoclassical transport from FACIT + Turbulent transport from TGLF + High plasma rotation

(a) IRVB image

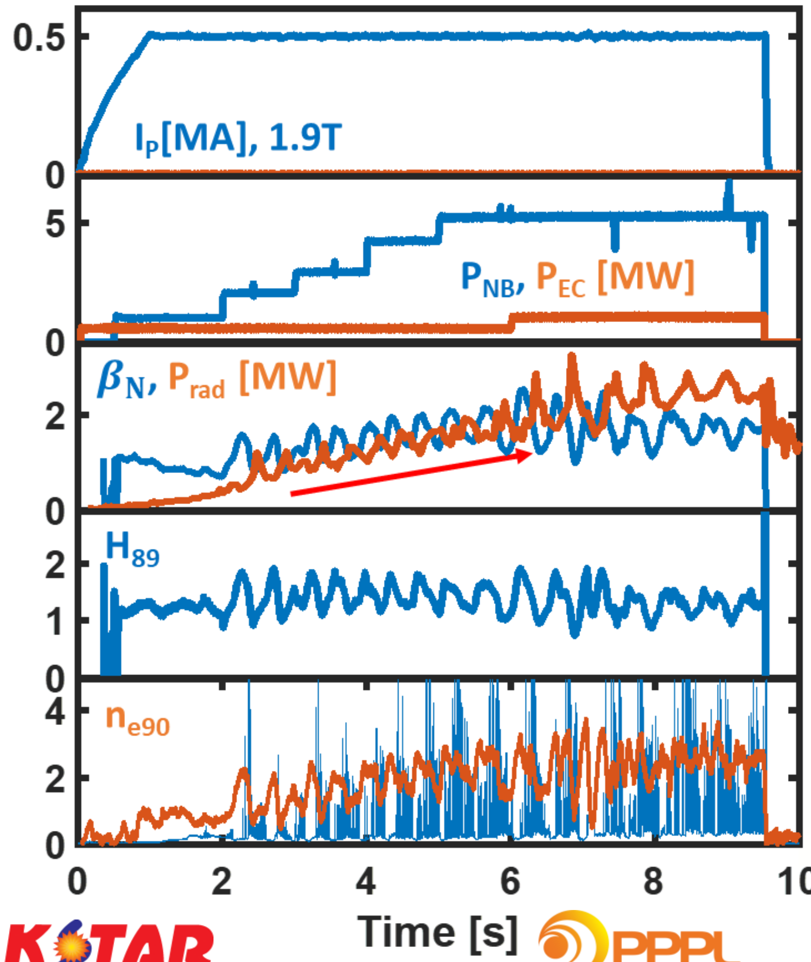
(b) Reconstruction of W cooling rate

J Lee, HJ Lee (Hanyang U)

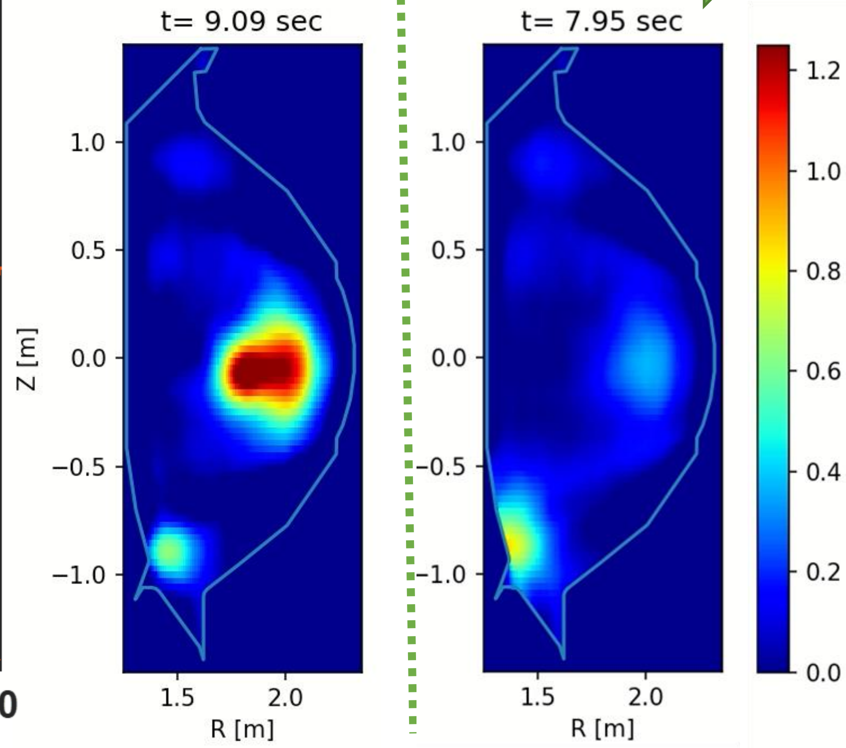


Strong W-mitigation was achieved in H-mode by beta-kicking heating

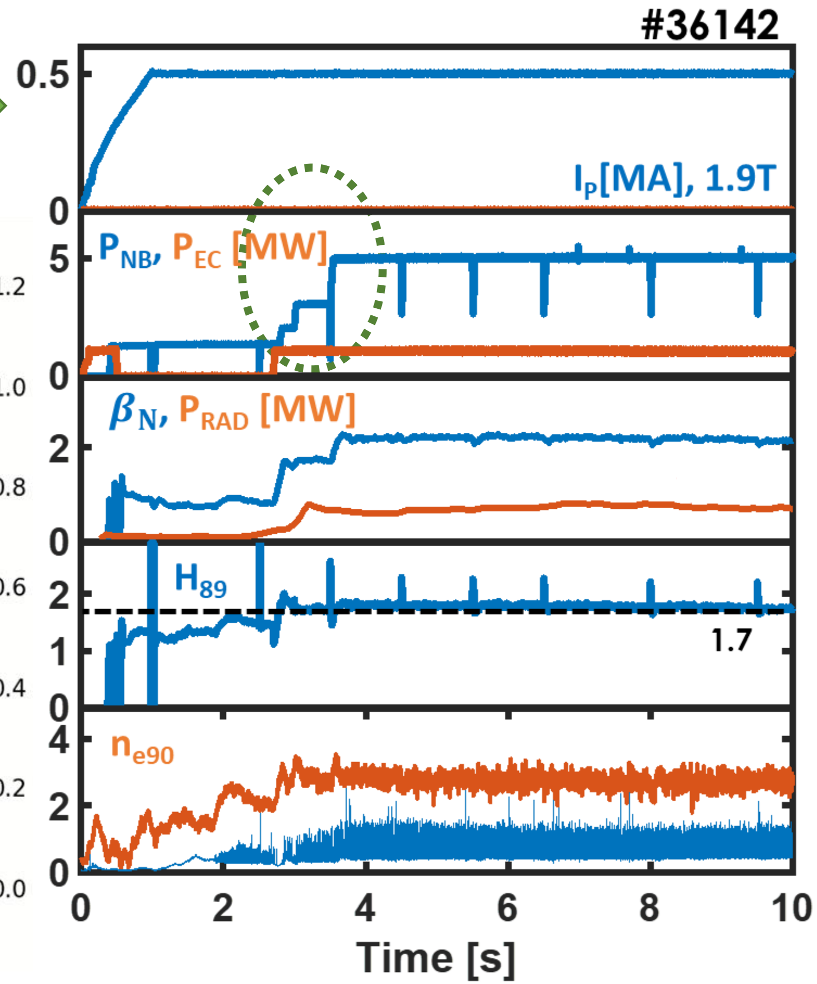
- 5.2MW + 1.1MW of NB and EC
- β_N=1.65, H_{89}=1.23 with P_{rad}~2.8MW (f_{rad}~45%)
- **Large oscillation in pedestal**



delaying strong aux. heating imposing D gas puff



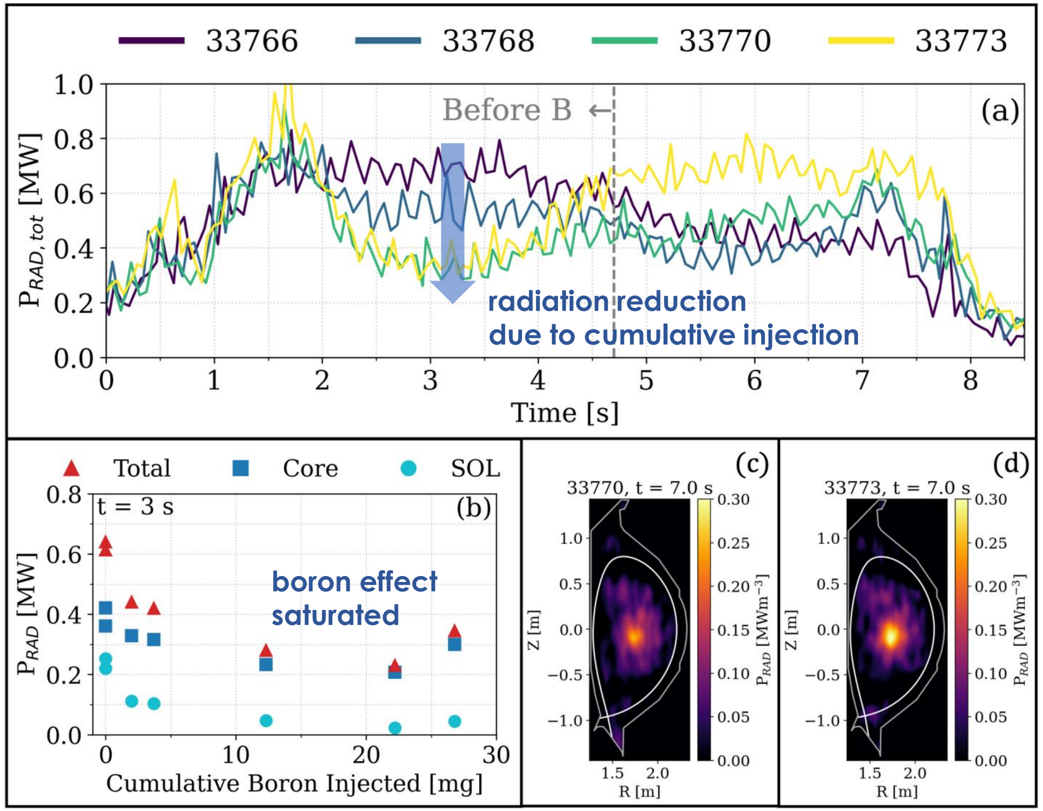
- 5.0MW + 1.0MW of NB and EC
- **β_N=2.2**, H_{89}=1.69 (**H_{98}~0.97**) with P_{rad} ~ 0.7 MW (f_{rad}~12%)



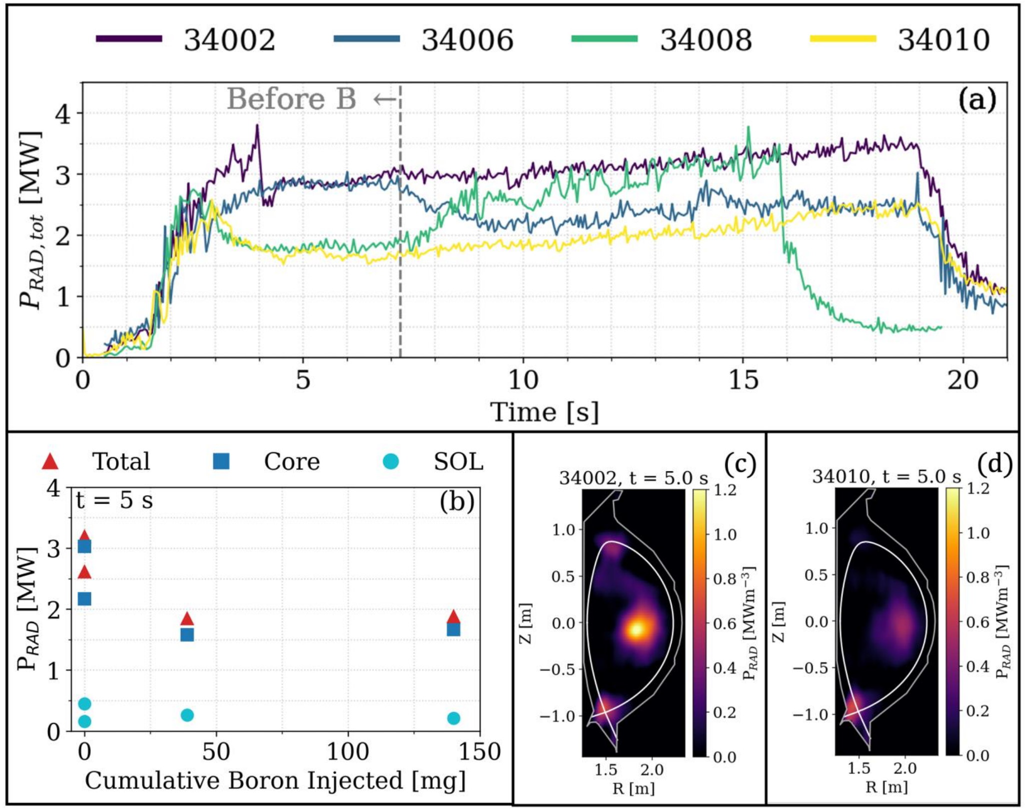
Boron Injection quantity was assessed to determine the optimal cumulative effect of the boron powder dropper

- Effect of boron powder injection was assessed in L-mode and H-mode plasmas
- **Lower plasma density** and **reduced radiation loss** were achieved
- **Fine control of the injection** amount remains necessary

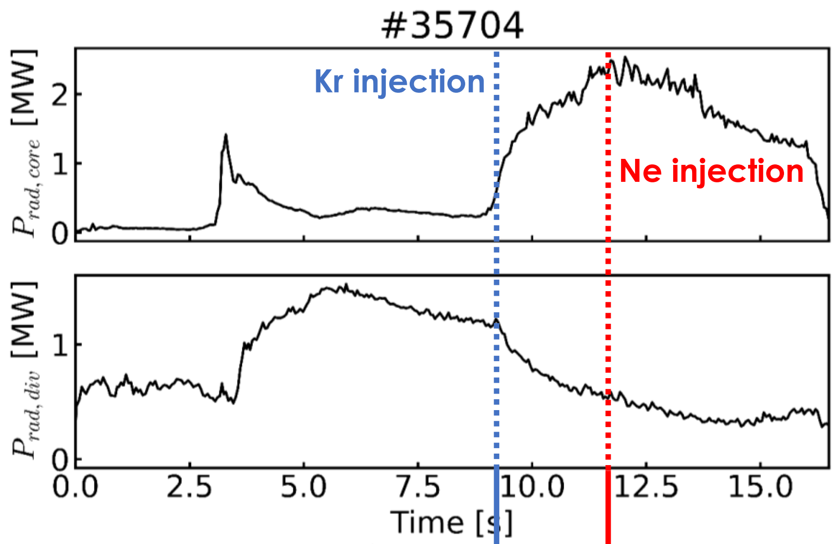
L-mode plasmas



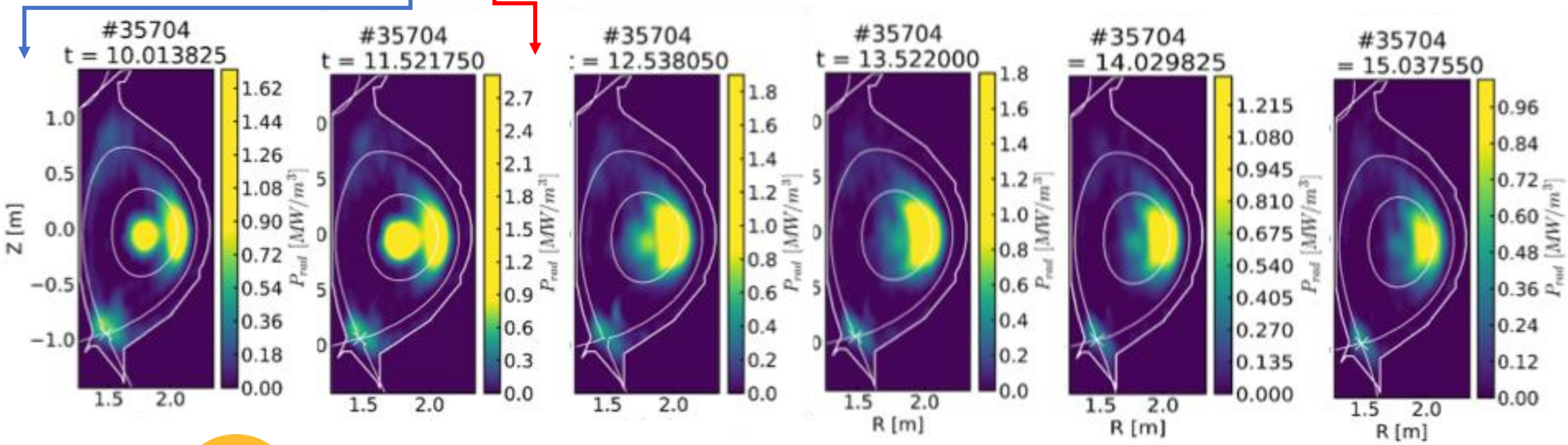
H-mode plasmas



High-Z impurity transport and accumulation with ITER-relavant condition were demonstrated on KSTAR

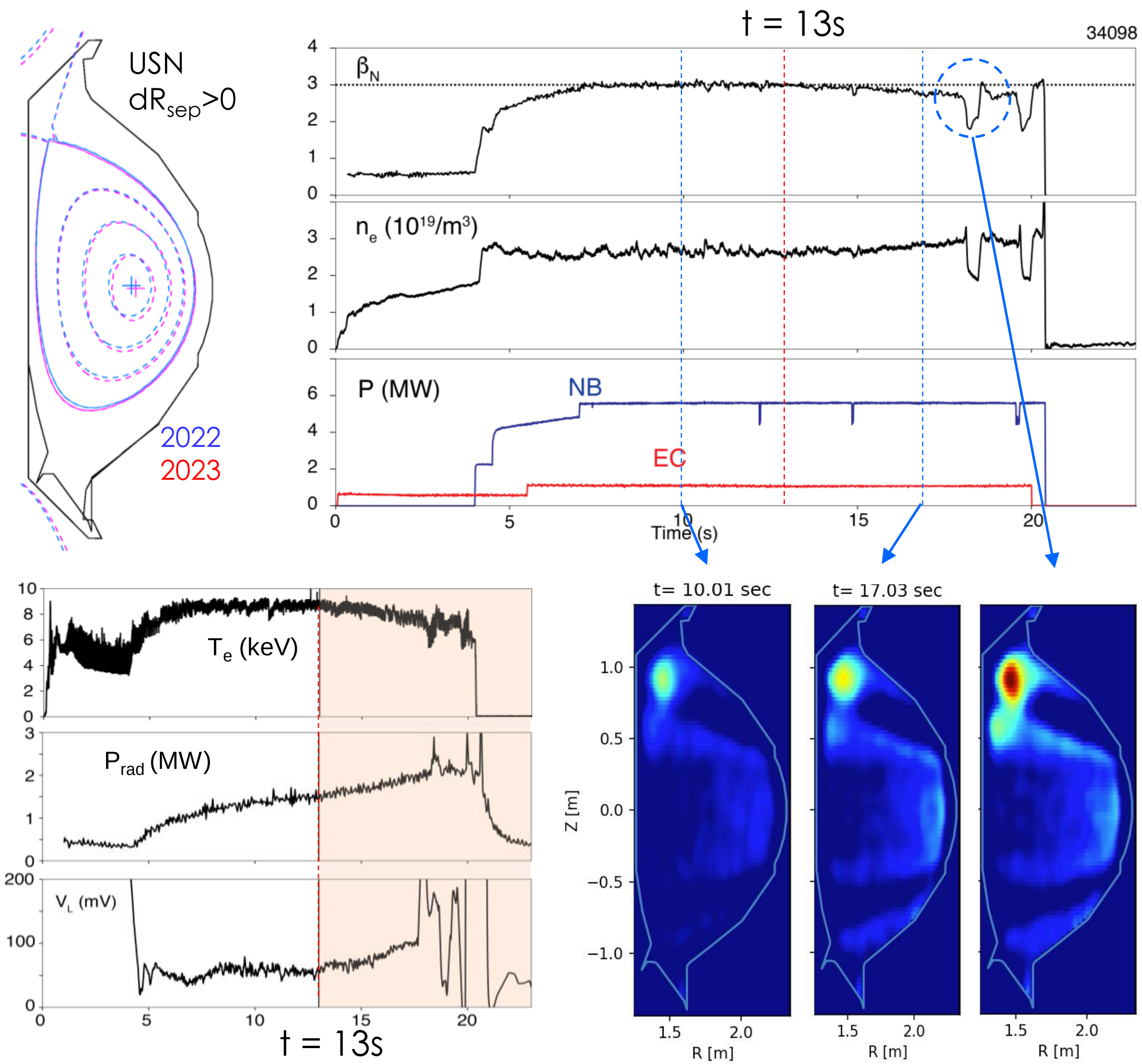


- A high-priority ITER R&D for ITER wall material change **(Be → W)**
- **Kr** injected (8-9s) as a W-equiv. **high-Z radiator** at KSTAR **(2-3keV)**
  Ne injected as a **low-Z impurity** of ITER
- Kr injection produced **highly radiative plasma with small ELMs (~300Hz)**
- Ne injection decreased **total radiative power loss slowly** and the **centrally peaked radiation moved off-axis**

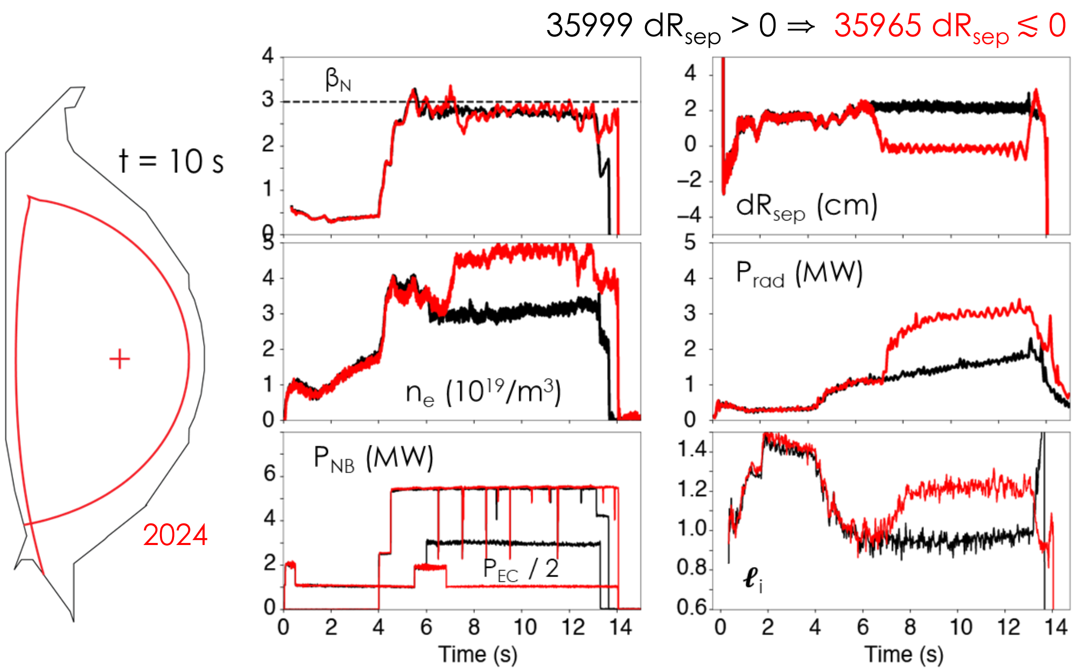


SH Kim (IO)

High ℓ_i scenario successfully reproduced β_N ~ 3 on USN and DN shows a promising path to W-compatible high β_N operation

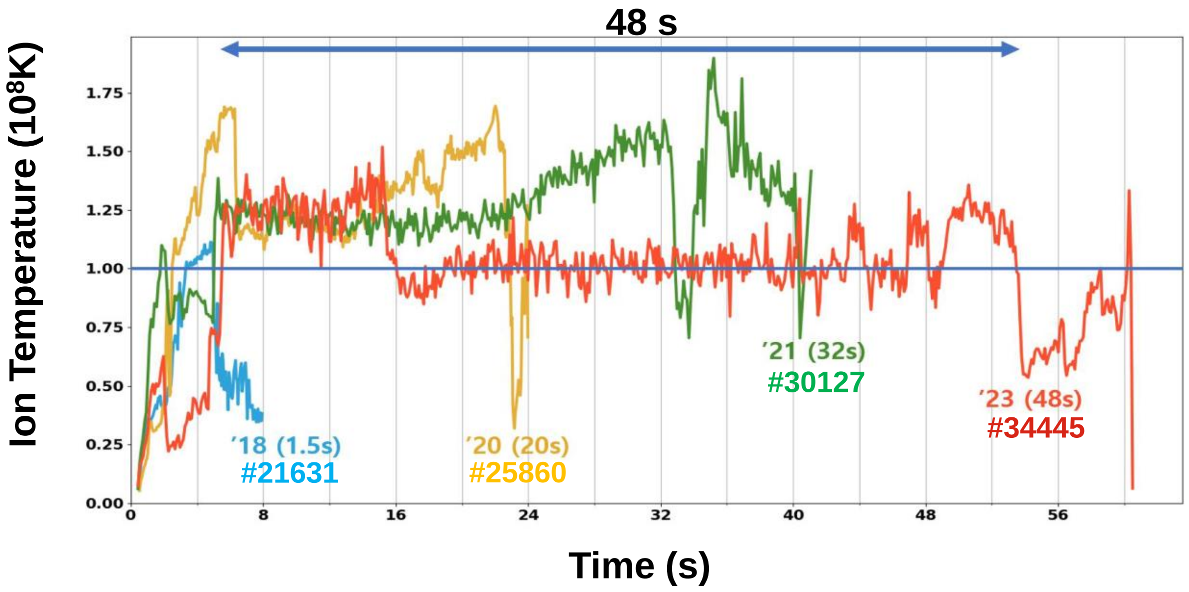


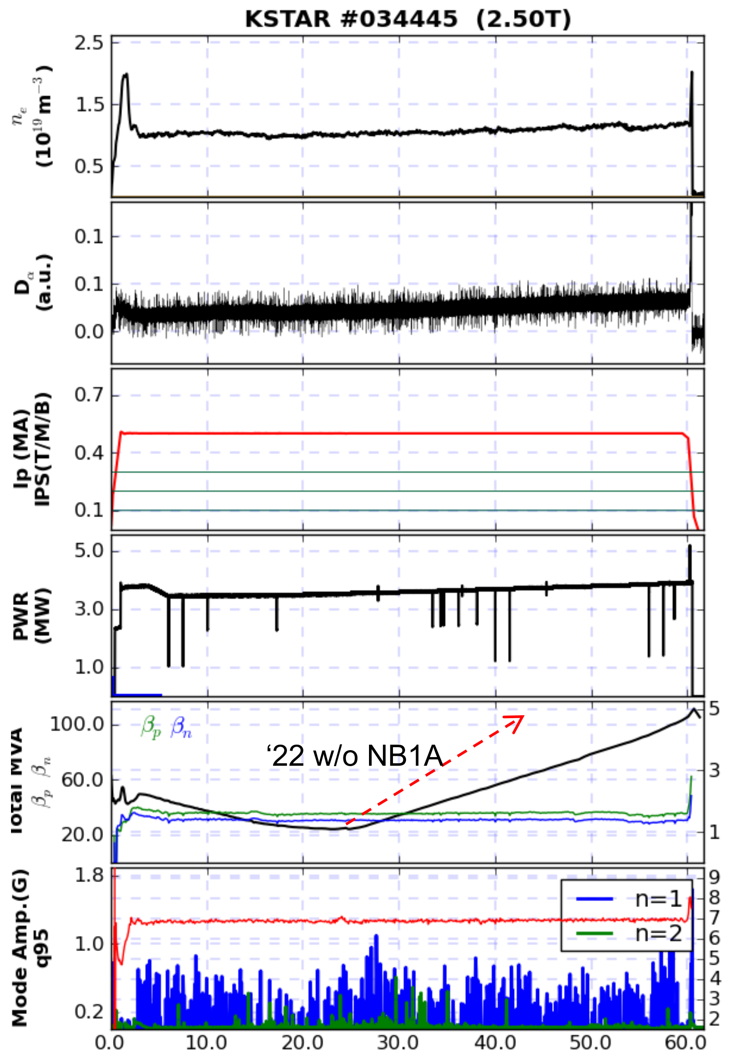
- Performance degradation from **13 s** **(USN)**
- **No significant changes in MHD**, associate with increase of radiation/impurity
- Decrease of T_e, Increase of V_{loop} and n_e consistent with **increase of radiation**
- High **β_N ~ 2.8** was achieved in a **biased DN** configuration with $dR_{sep} \lesssim 0$



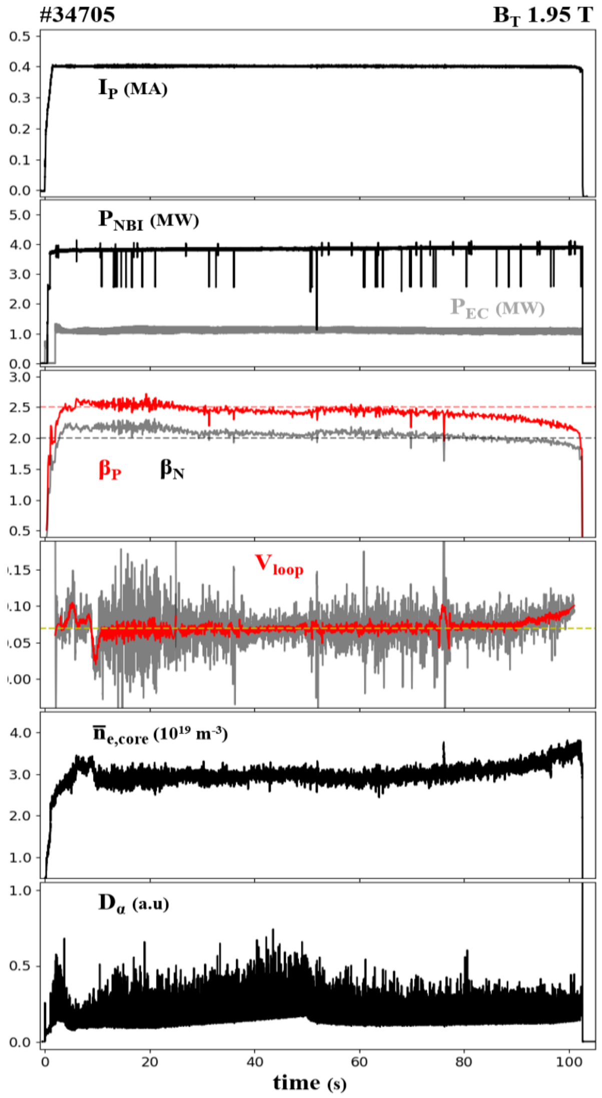
Stationary high-T_i ($\geq 10^8$ K) operation maintained for ~ 48 s with optimized conditions

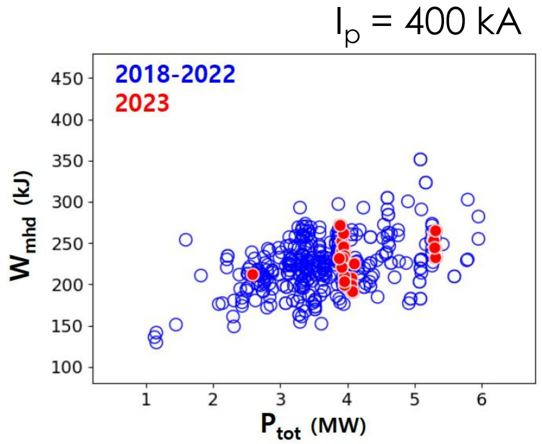
- **USN is unfavorable to the H-mode** transition, so the injected beam power devotes to the **ITB formation**
- Need to find optimum **NB combinations**
- Need to ensure good **wall conditions** to avoid severe MHDs
- **Higher B_T** ⇢ higher beam power (CD) ⇢ lower V_{loop}/flux consumption
- **Beam shine-through** is a significant problem during longer pulse discharge

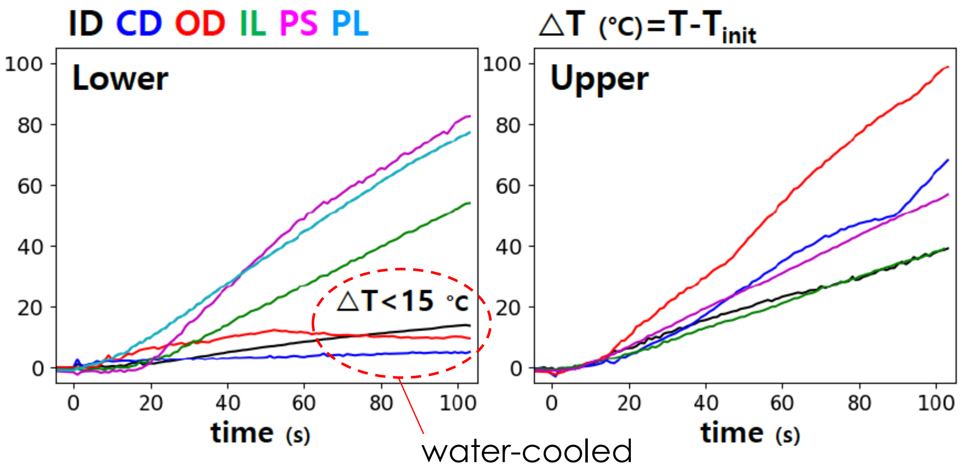


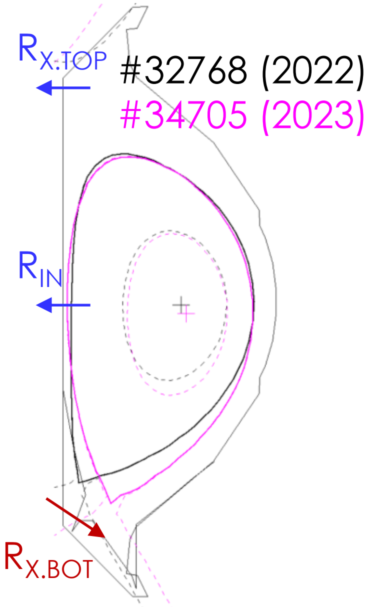


A 102 s high-performance long-pulse achieved with W divertor



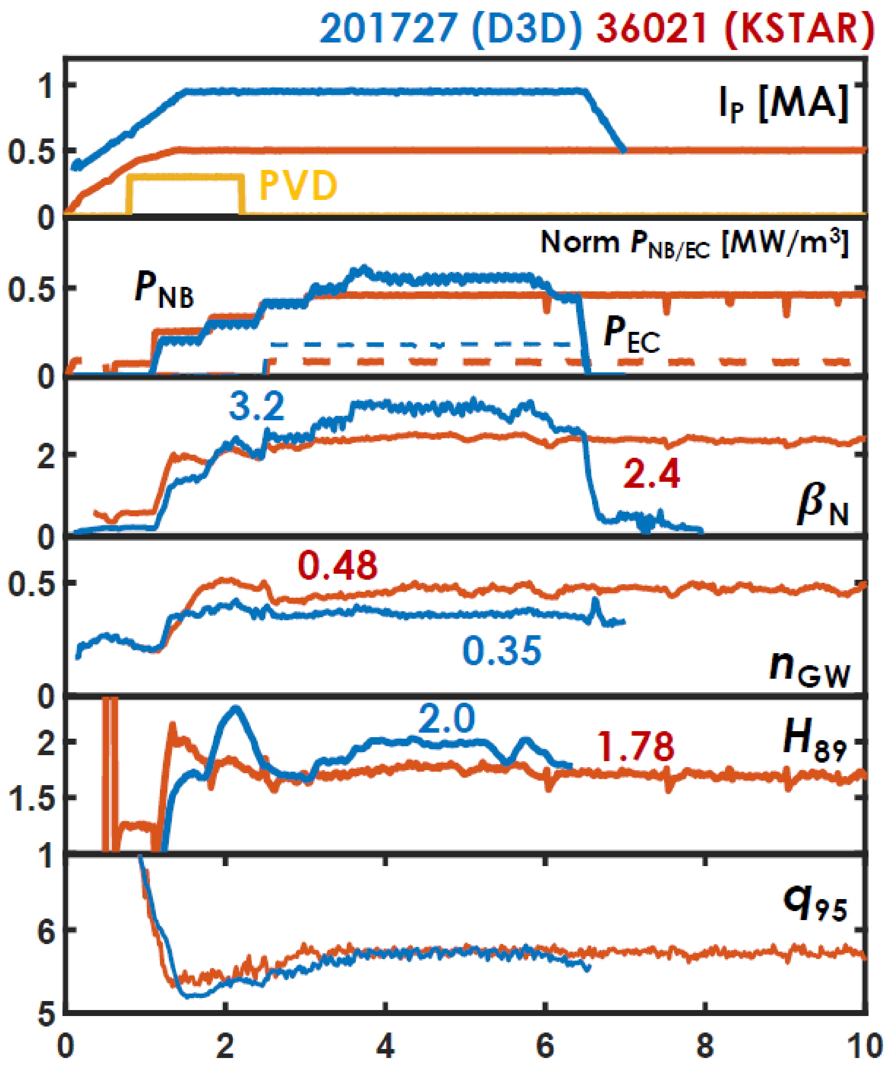




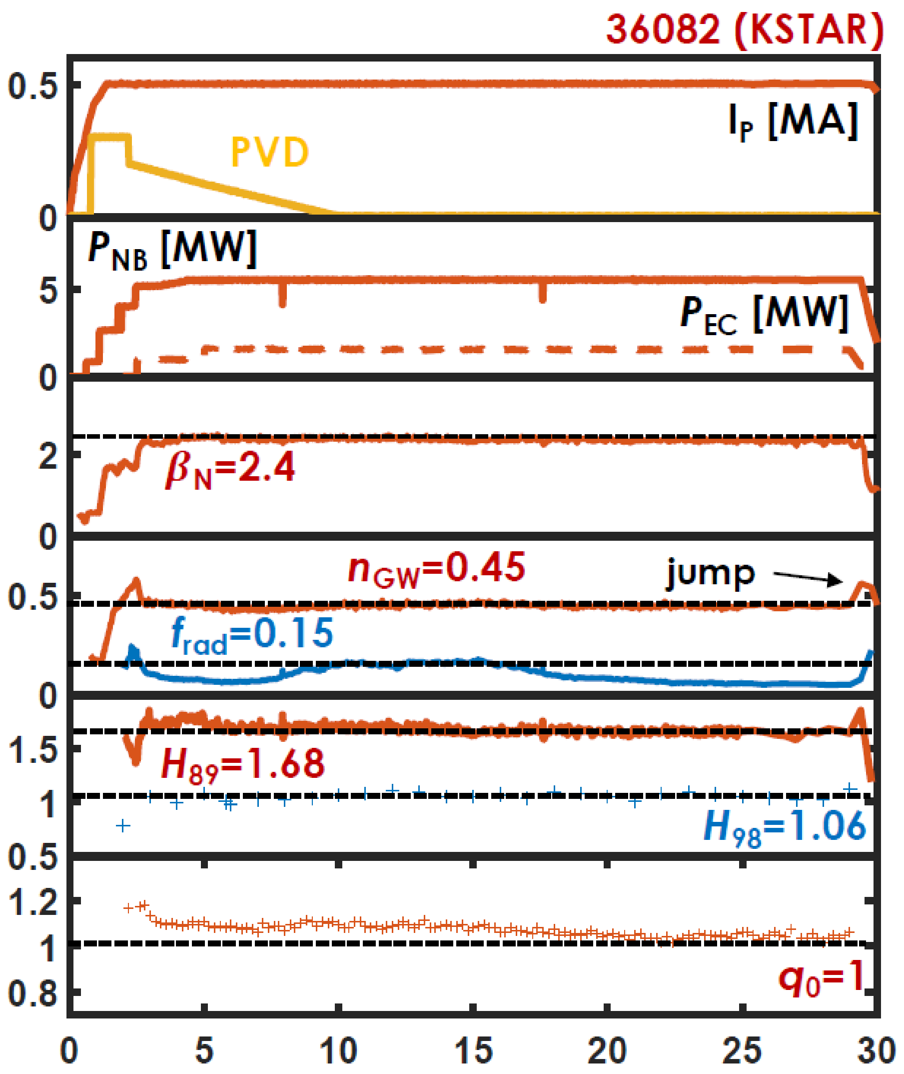


- The P_{thr} and the plasma performance in partially tungsten-covered PFC are **nearly similar**
- V_{loop} ~ 70 mV, β_P ~ 2.5, β_N ~ 2.1, T_e > 6.0 keV, T_i~ 2.5 keV
- Performance is maintained for **~70 s** and its degradation is minimized
- **MD drift** has been significantly **improved**
- Water-cooled PFCs experienced temperature changes of less than 15 °C
- For a 300 s pulse length, a "fully non-inductive"-like (V_{loop}< 30 mV) is necessary

DIII-D hybrid scenario demonstrated in a W environment under KSTAR constraints, confirming long-pulse applicability



DIII-D hybrid scenario optimized for KSTAR was **successfully demonstrated on KSTAR in W-environment**, showing similar characteristics

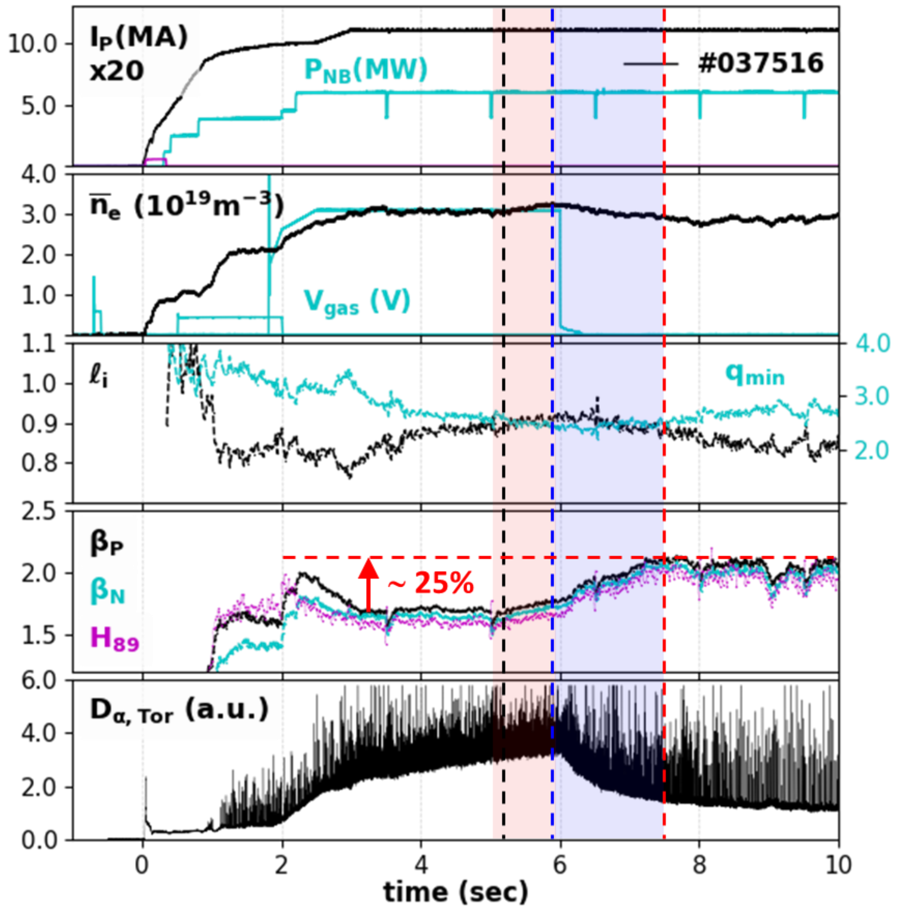


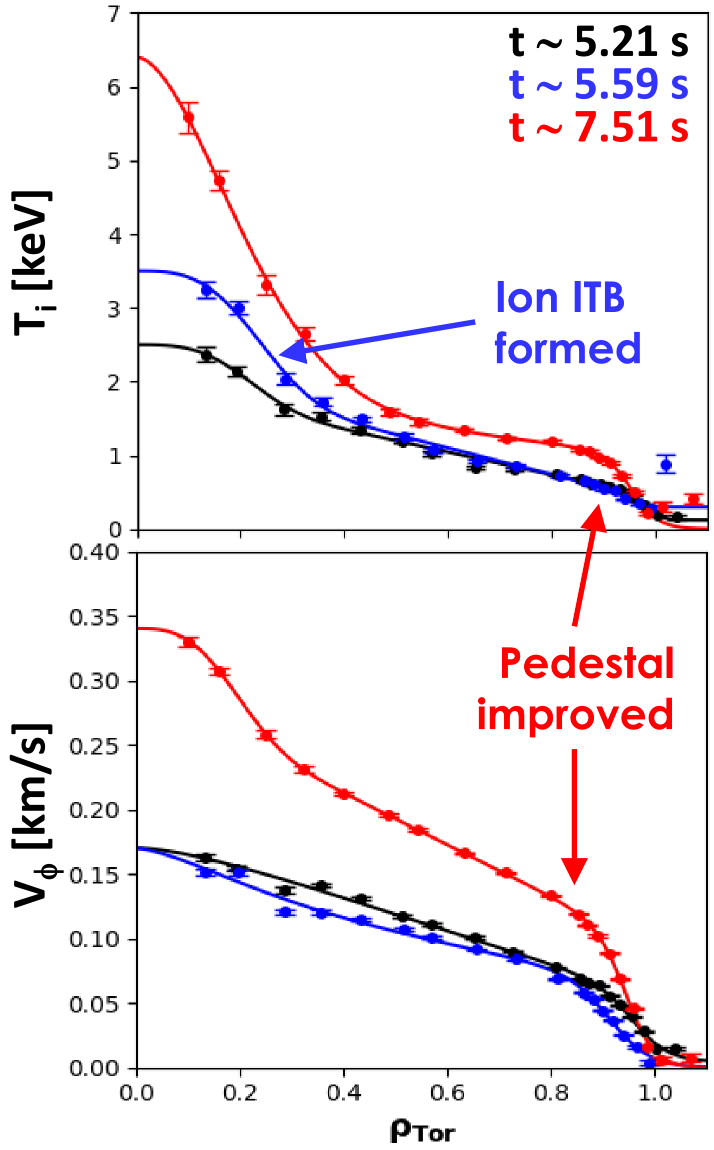
Long-pulse extension is promising, but several issues emerged

- Insufficient current drive for SS-operation (V_{loop} ~ 80 mV)
- Long-term evolution of density
- Temporal evolution of P_{rad} with V_{rot} pedestal

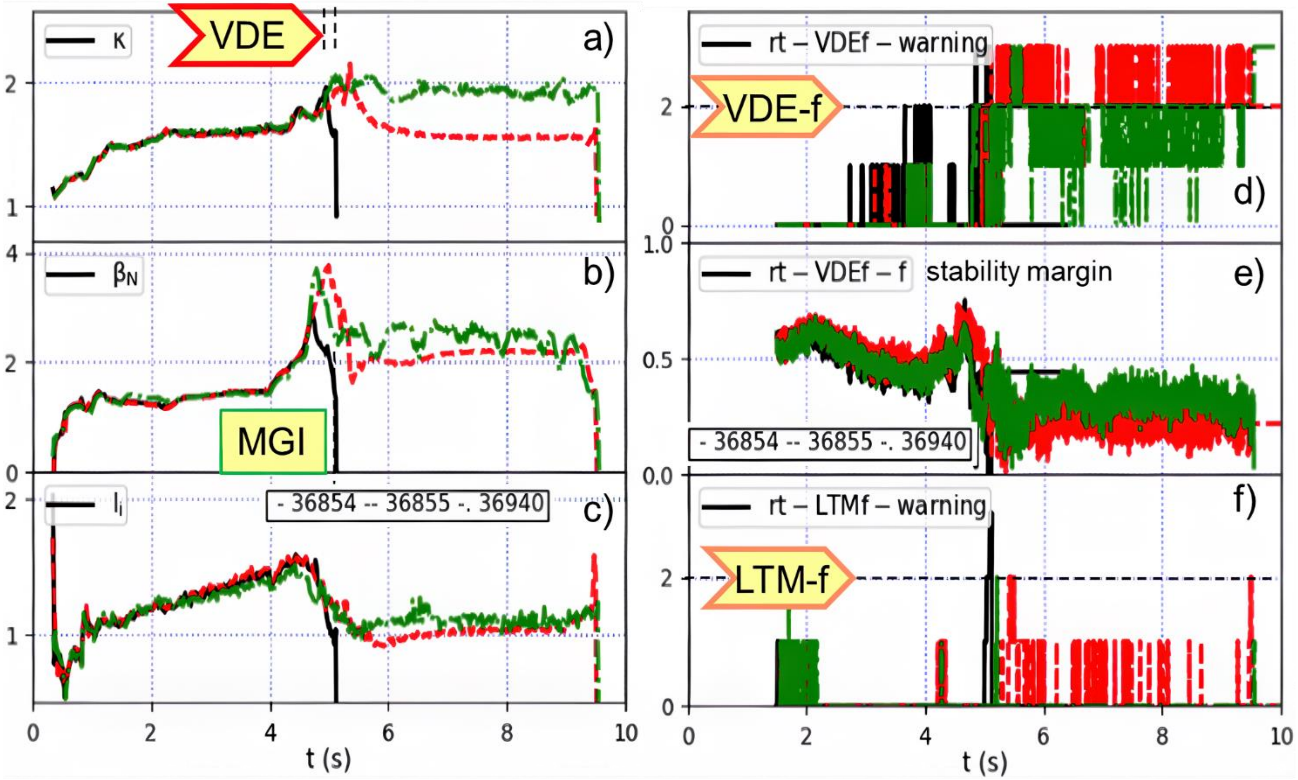
DIII-D high β_p discharge was implemented in KSTAR for long pulse application, showing promising initial results

- A **high-β_P scenario** combined with **large-radius ITB** was successfully established in DIII-D with KSTAR-like constraints
- The scenario was implemented in KSTAR, showing promising initial results such as **weak ion ITB**



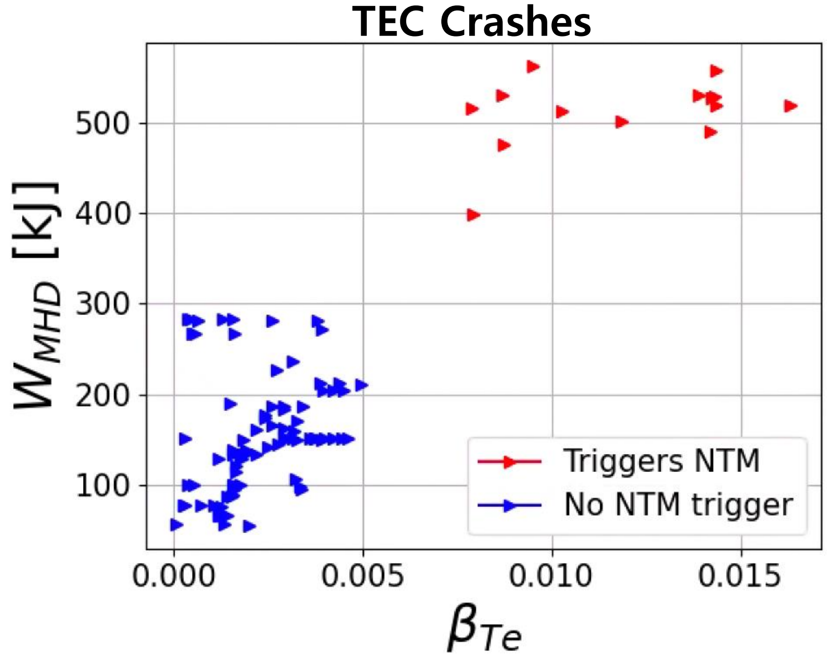


RT DECAF disruption avoidance was demonstrated with simultaneously acting physics based multi-event modules



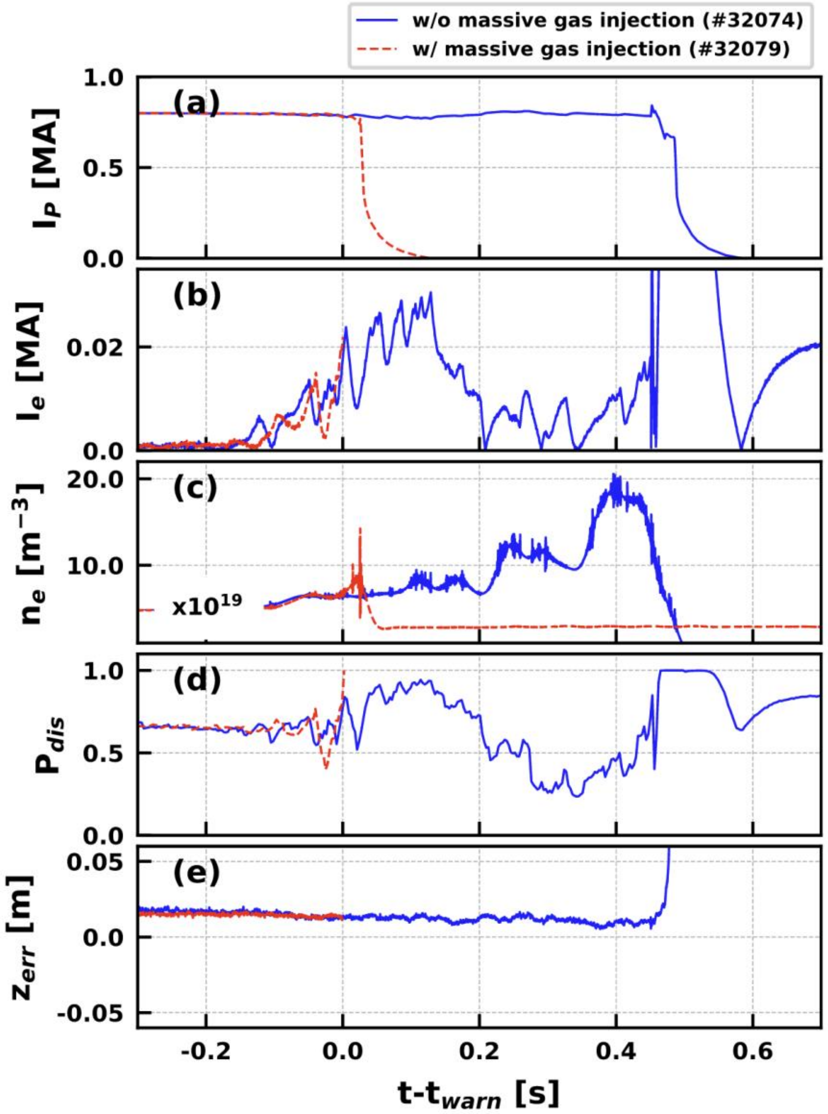
Disruption avoidance and optimization with DECAF
Disruption mitigation triggers by VDE Event when feedback is disabled

- The **multi-Event feedback** now cues KSTAR actuators to produce **disruption avoidance**
- The KSTAR 2024 run campaign included the **first demonstration** of real-time DECAF disruption avoidance

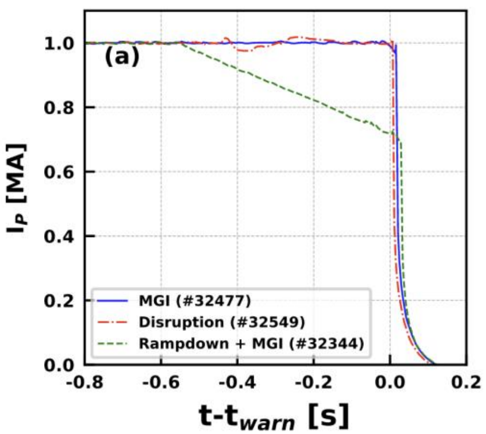


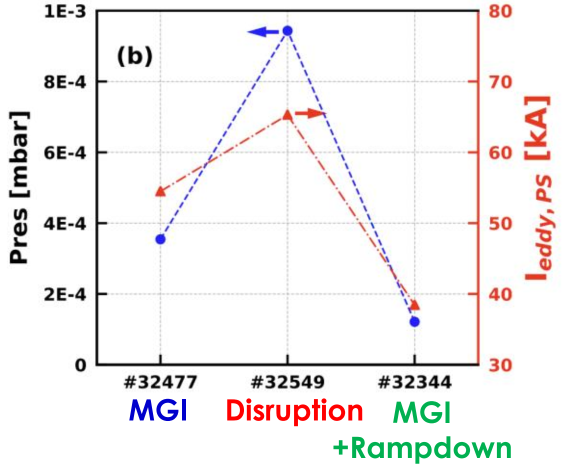
Clear separation in parameter space between electron temperature crashes triggering (or not) NTMs in KSTAR

Disruption mitigation by MGI & Ip soft-rampdown with ML demonstrated for 1 MA discharge



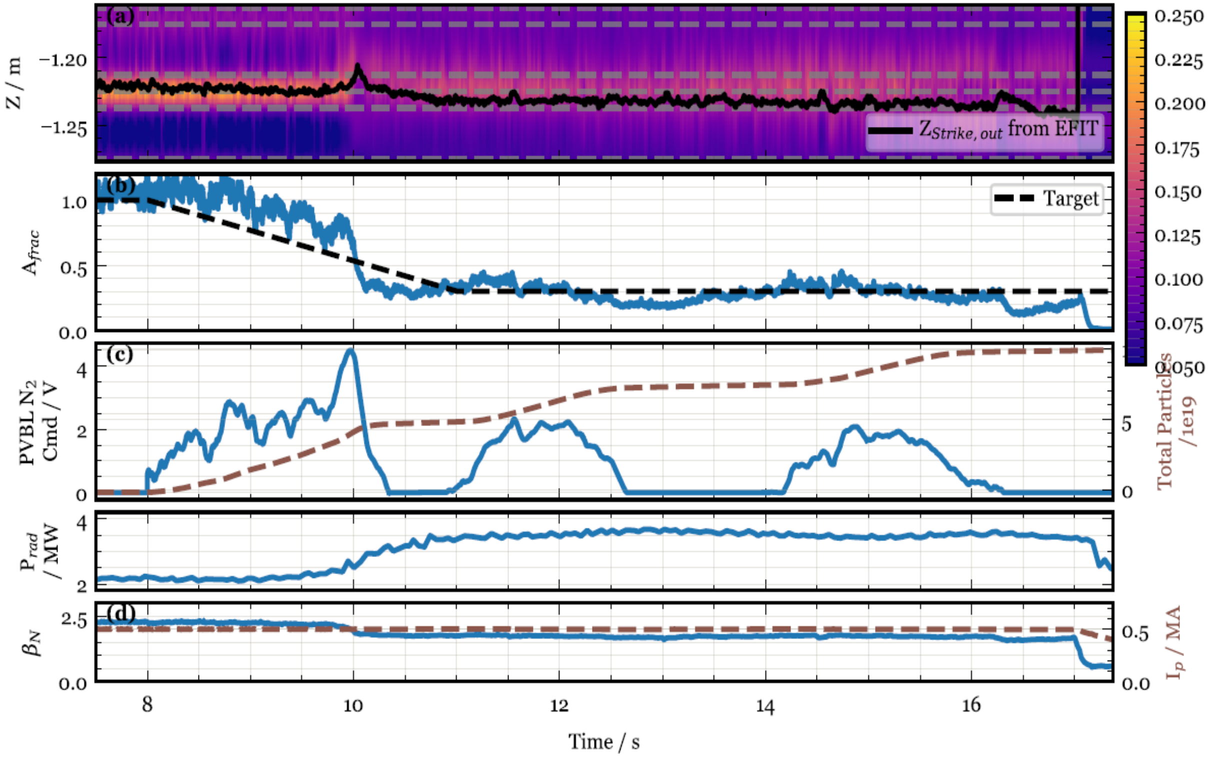
- **Real-time neural network–based predictor** for early warning combined with **empirical model** to improve reliability
- Disruption mitigation by **massive gas injection & Ip soft-rampdown**
- High accuracy in early disruption prediction
- **Ne-D_2 mixed gas injection** successfully reduced thermal and current quench loads
- Provides a pathway toward disruption control in ITER and future devices
- Marks substantial progress in **AI-driven plasma control** research

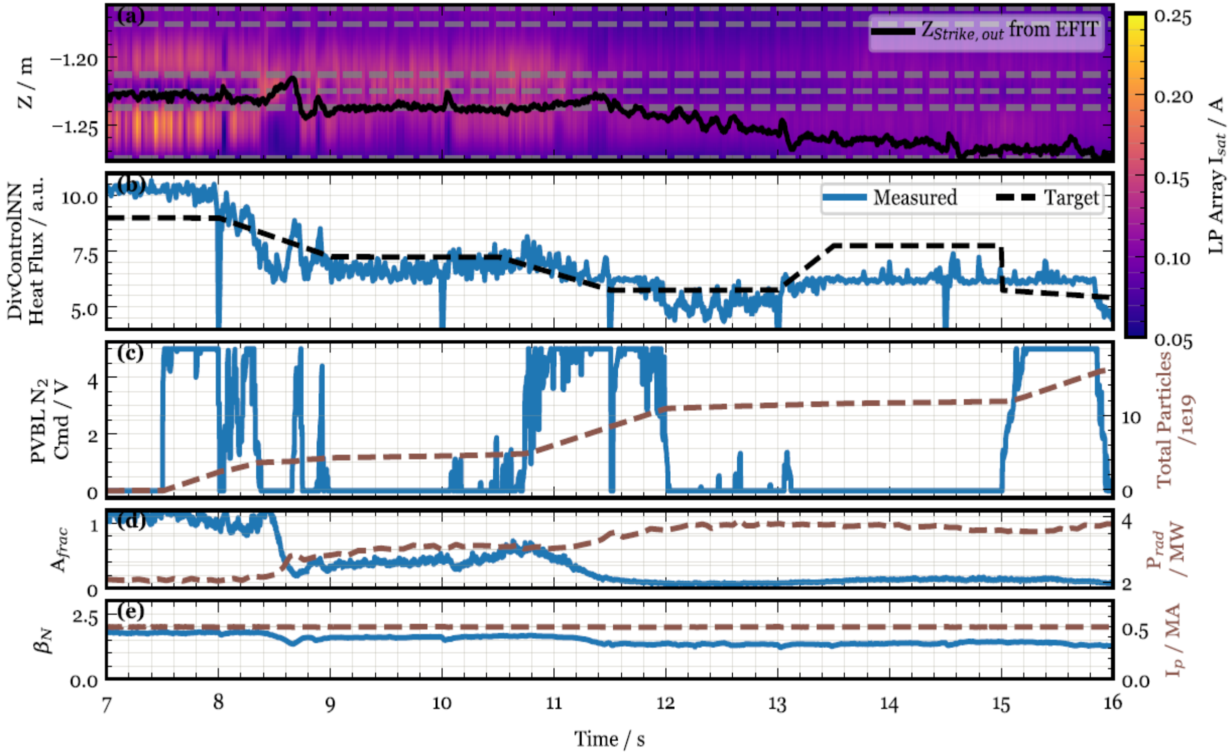




Real-time detachment controls were demonstrated via A_{frac} control PCS algorithm & heat flux control by surrogate model

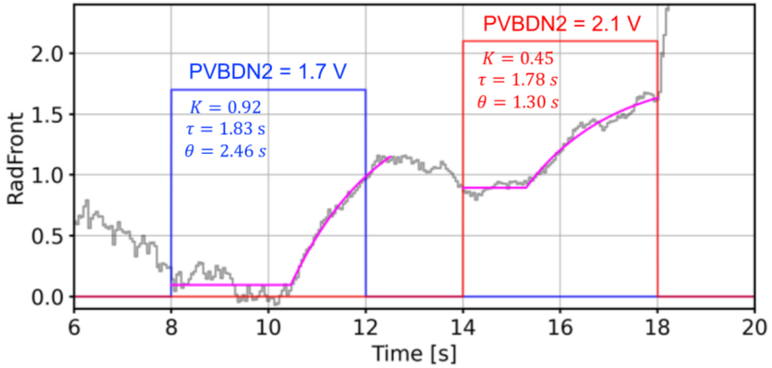
- **A_{frac} algorithm** – estimates detachment ratio using global plasma parameters & I_{sat} on div. probes
- **Heat flux surrogate model** – calculates div. heat flux using global plasma parameters & gas puffing
- Both approaches demonstrated successful **divertor detachment** by dynamically adjusting **N seeding**

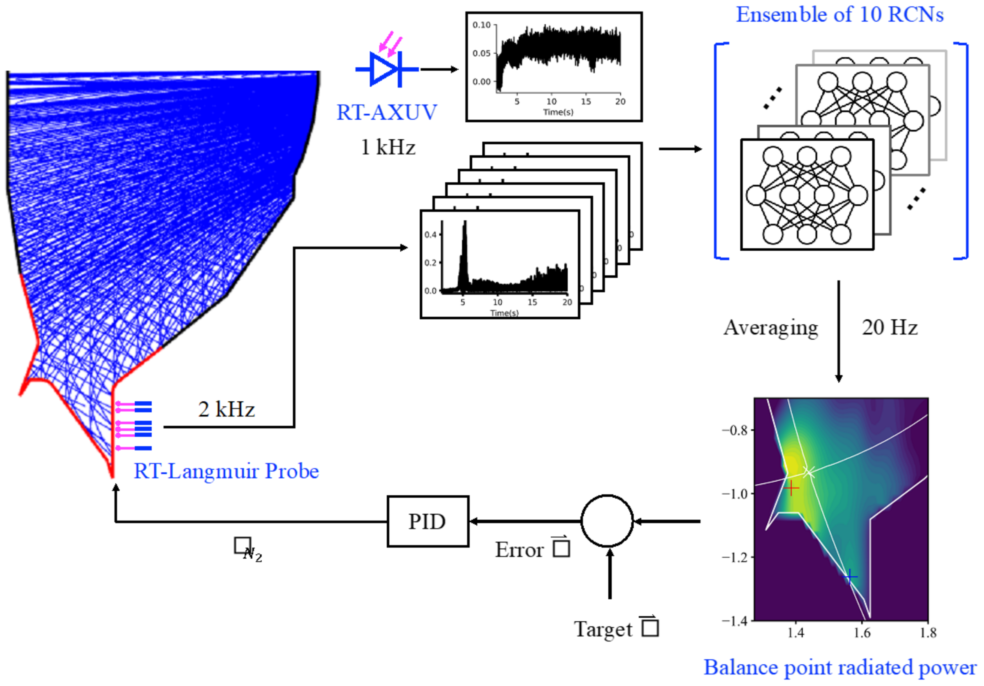




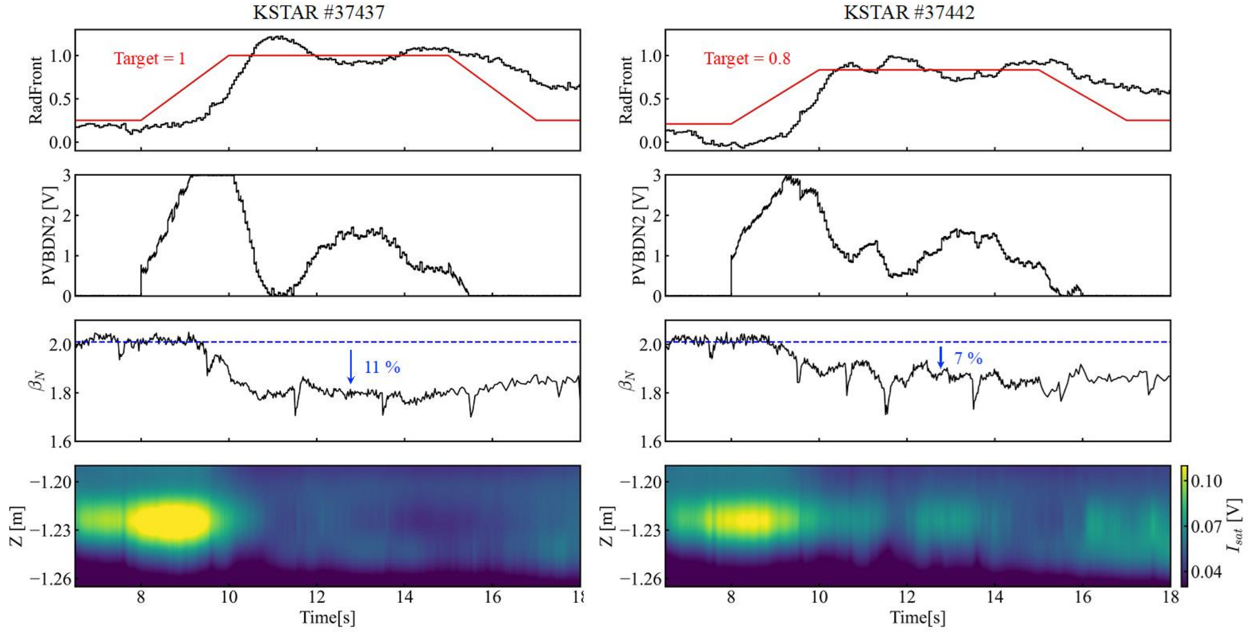
RT radiation front position control demonstrated via ML based construction of IRVB images

- **IRVB images were constructed** from RT-LP, RT-AXUV signals using **ML based algorithm**
- **Radiation front position** was successfully controlled
- can be applied to reactor environment with limited diagnostics



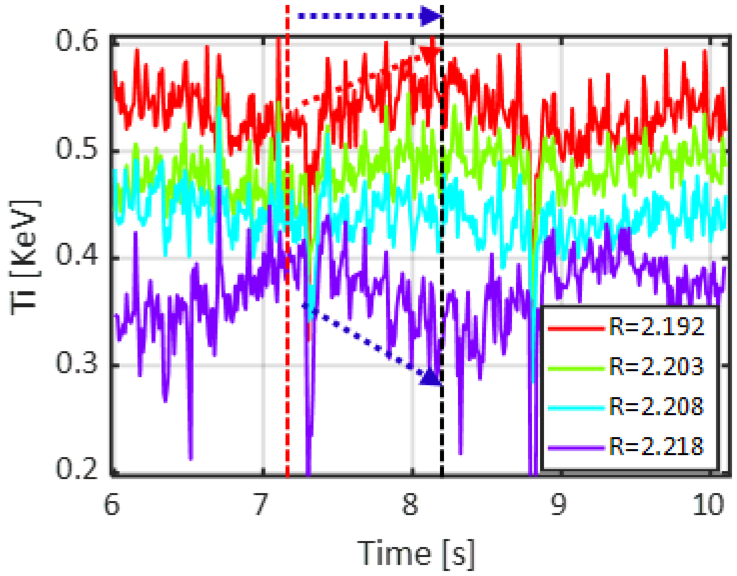


ML using RT-LP, RT-AXUV based algorithm

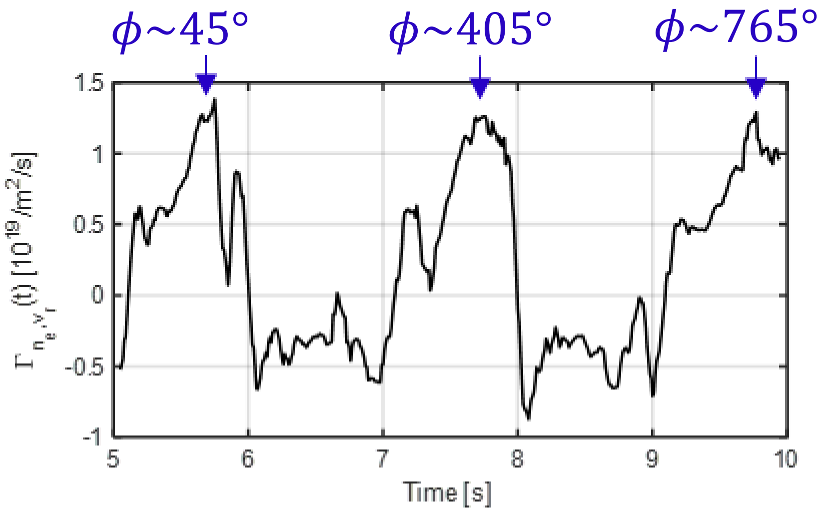


Magnetic island during ELM suppression was directly measured via phase flip

- **Direct evidence of island, phase flip, is observed** for the first time with ELM suppression
  - **Phase flip (π difference)**, indicator of magnetic island, is clear only for ELM suppressed phase
  - The estimated island center is located around the **pedestal top region** at $\psi_N \sim 0.9$
- Edge magnetic Island leads to **3D localized filament-like structure** and particle flux
  - **Filament-like structure** is localized at the specific toroidal angle
  - **Maximum particle flux** measured at this angle, implying its role in optimizing ELM suppression state

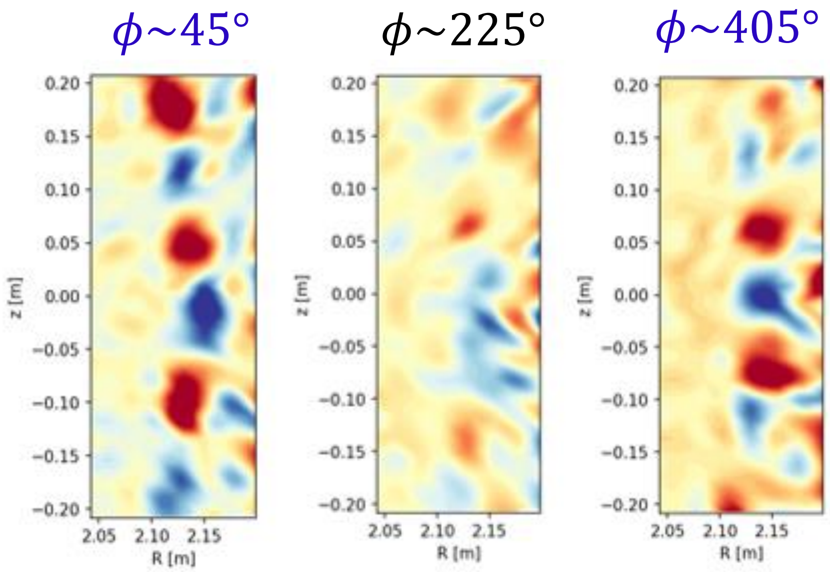


Measured particle flux



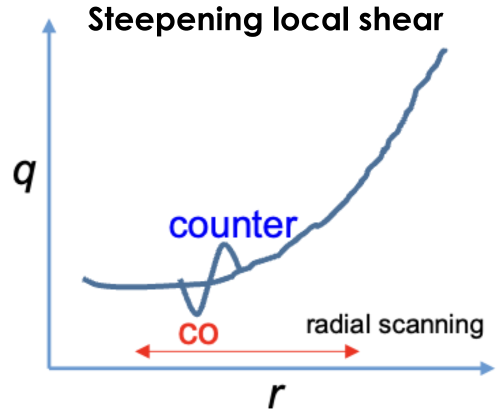
[Courtesy of Dr. Jaehyun Lee]

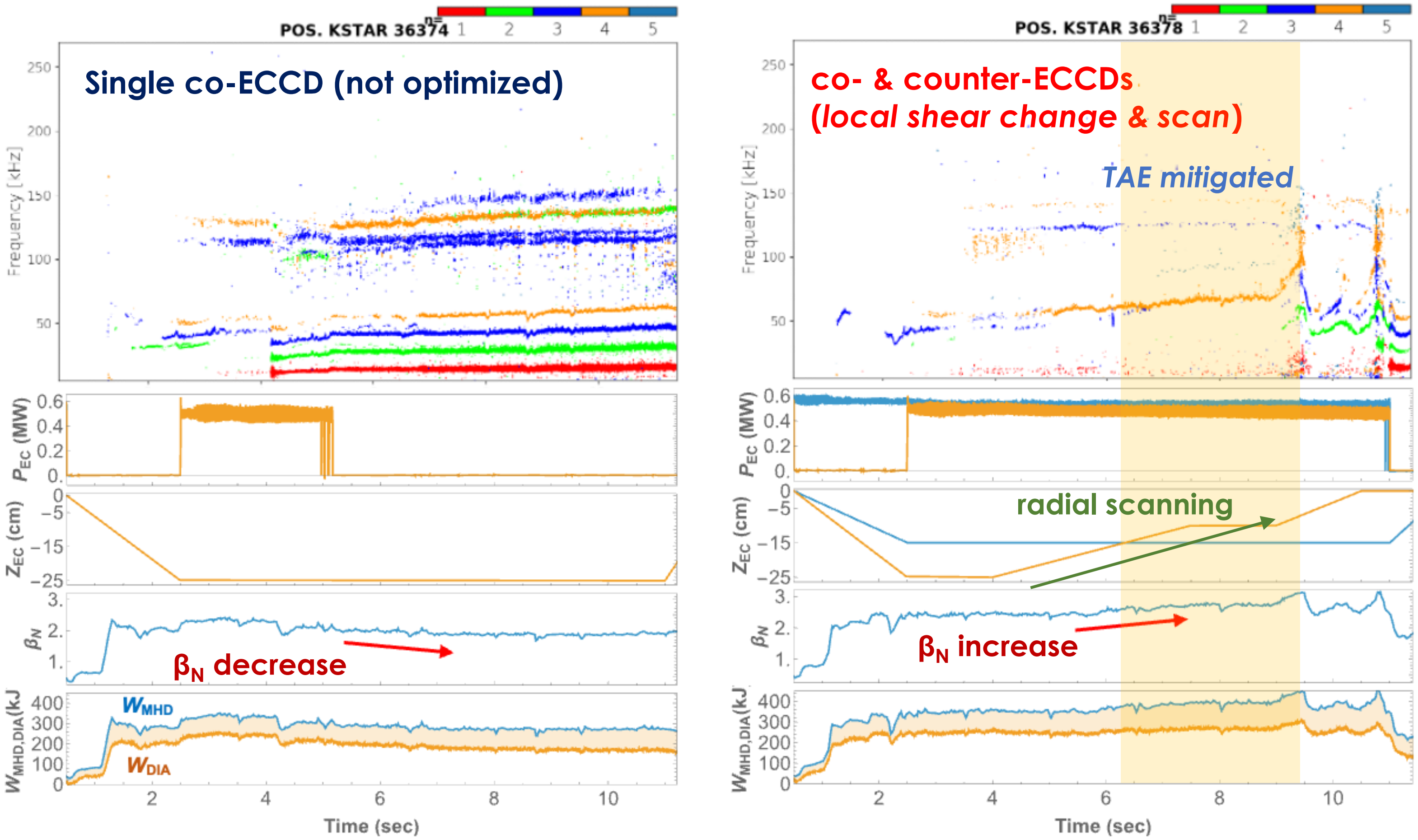
3D-localized filament-like structure



Condition for TAE control using ECCD was identified via local magnetic shear change & beam-ion profile modification

- Primary mechanism to mitigate TAEs ➔ **Continuum damping**
- **Local magnetic shear change** by two ECCDs (**radial inward scan**)
  ➔ Enhances the coupling to the Alfvén continuum
  ➔ TAE control, β_N enhancement
- **Beam-drive reduction** by changing NBI combination
  ➔ damping overcome drive
  ➔ ECCD-assisted TAE control





Transport in the ITG-near-marginal regime was investigated through cross-machine analysis

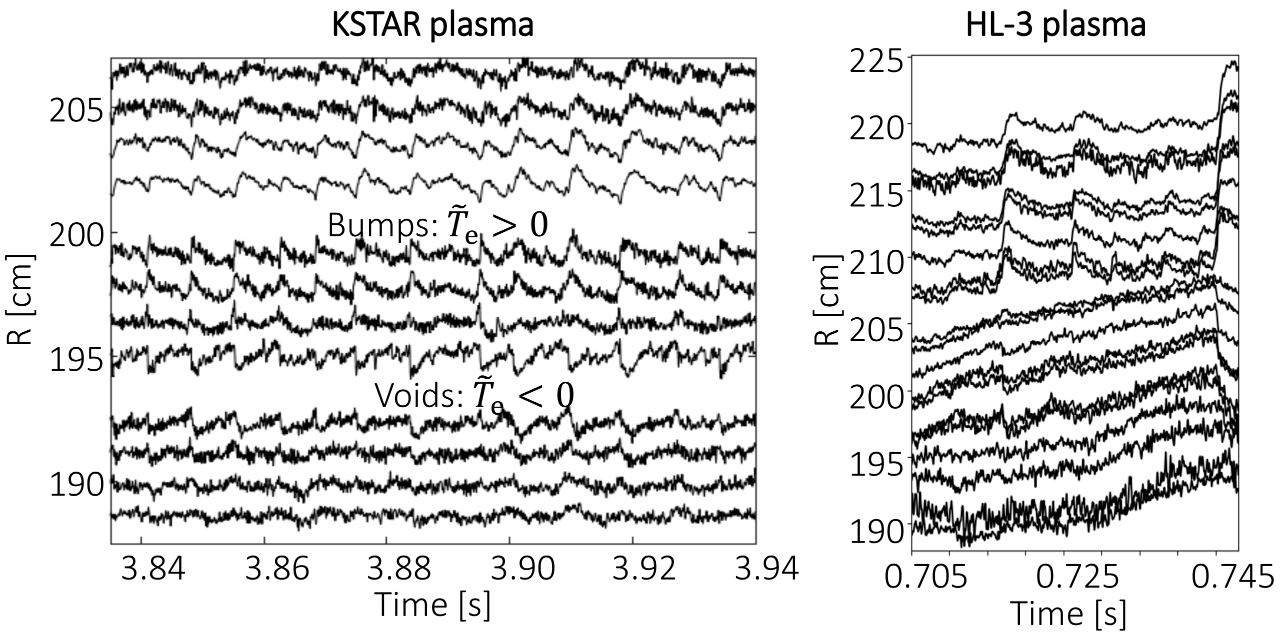
- The **near-marginal** is the most challening reigme to develop/validate a transport model
- **Transport characteristics** in the ITG-near-marginal regime has been investigated in KSTAR
  - **Avalanche-like transport** events and **mesoscopic transport barriers** are analyzed

M.J. Choi+, Plasma Phys. Control. Fusion 66 (2024) 065013

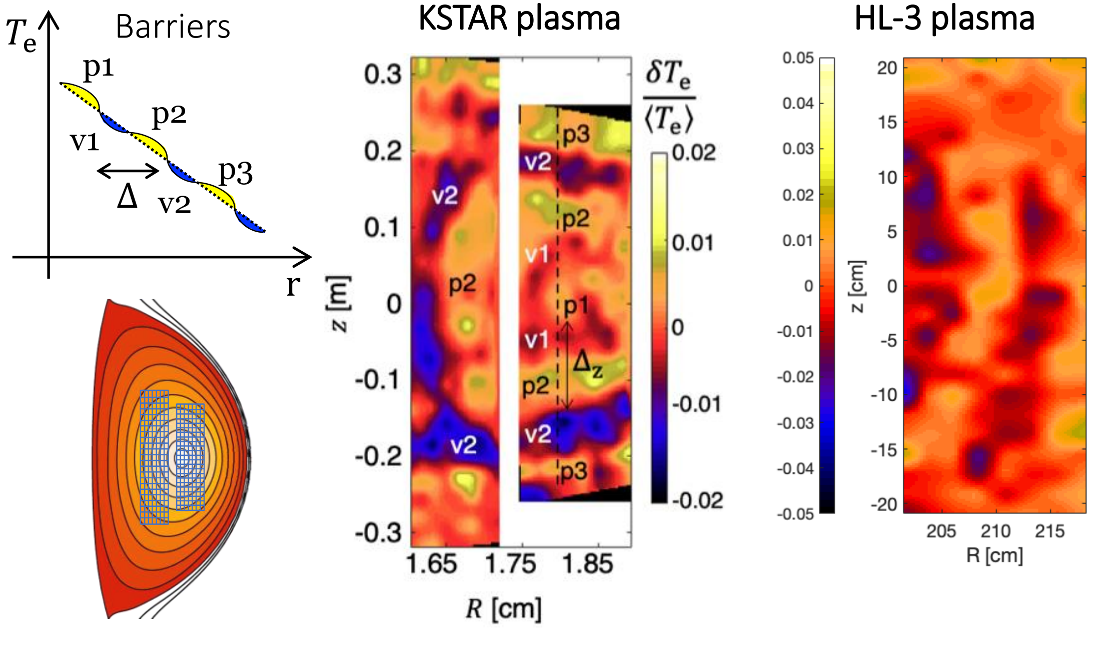
- Similar plasmas have been recently reproduced in **HL-3** and **DIII-D** experiments and **cross-machine analysis** is on-going

In collaborations with M. Jiang and Y. Zhang (SWIP) and P.H. Diamond (UCSD), G. McKee, and F. Khabanov (UW-Madison)

Transport events in various sizes in KSTAR and HL-3 plasmas



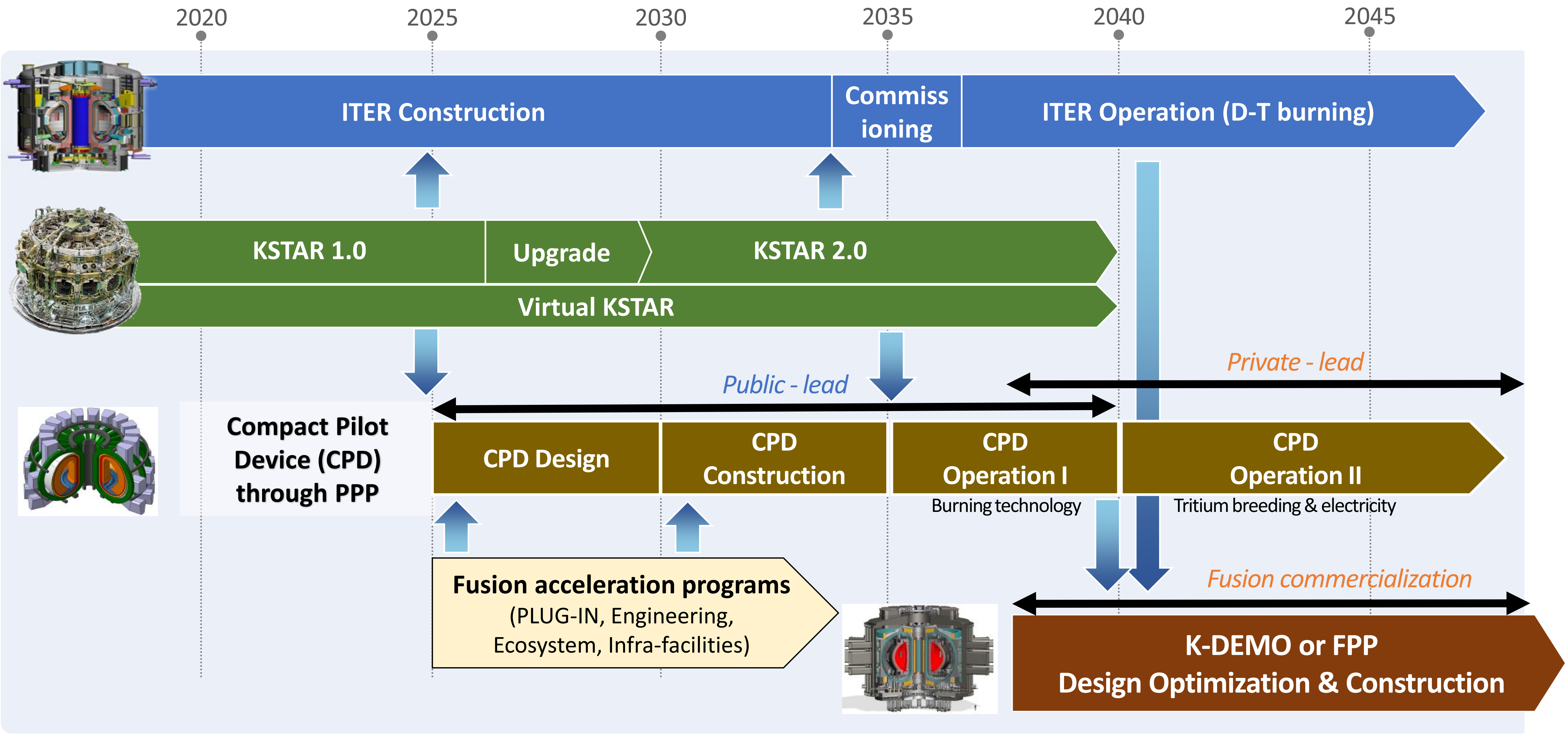
Mesoscopic transport barriers in KSTAR and HL-3 plasmas



Korea will accelerate FPP development with CPD program (tentative)

PLANS

PWF-3360 J.M. Kwon



PPP : Public-Private Partnership, CPD : Compact Pilot Device, K-DEMO : Korean Demonstration Fusion Reactor, FPP (Fusion Power Plant)

KSTAR will support CPD development and will explore advanced physics for future reactors

2023 – 2024 Campaign

Transition to BP plasma Research on W Environment

~ 2022 Campaign

Advanced Research with SC Tokamak

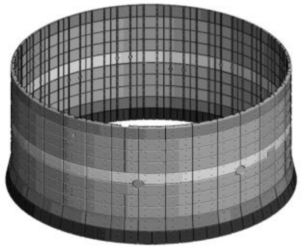
2025 Campaign ~

Assessment of CPD scenarios & RT control schemes

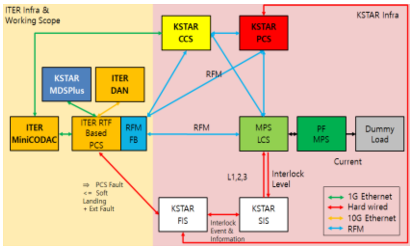
Assessment of CPD scenario candidates
- Higher confinement & bootstrap current

Control for next-gen. devices (CPD, ITER, ...)
- Adaptive control for performance & stability

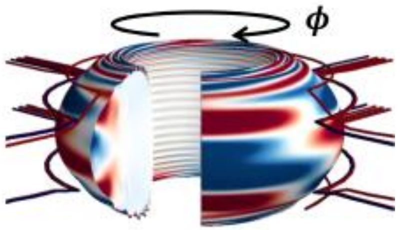
Physics for reactor & buring plasma
+ search for alternative physics for break-through



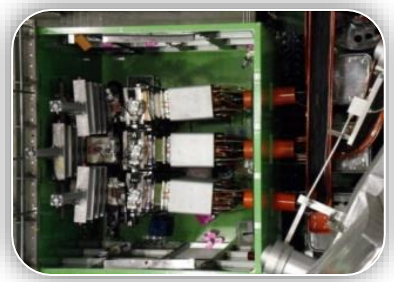
Full W wall



New KSTAR PCS

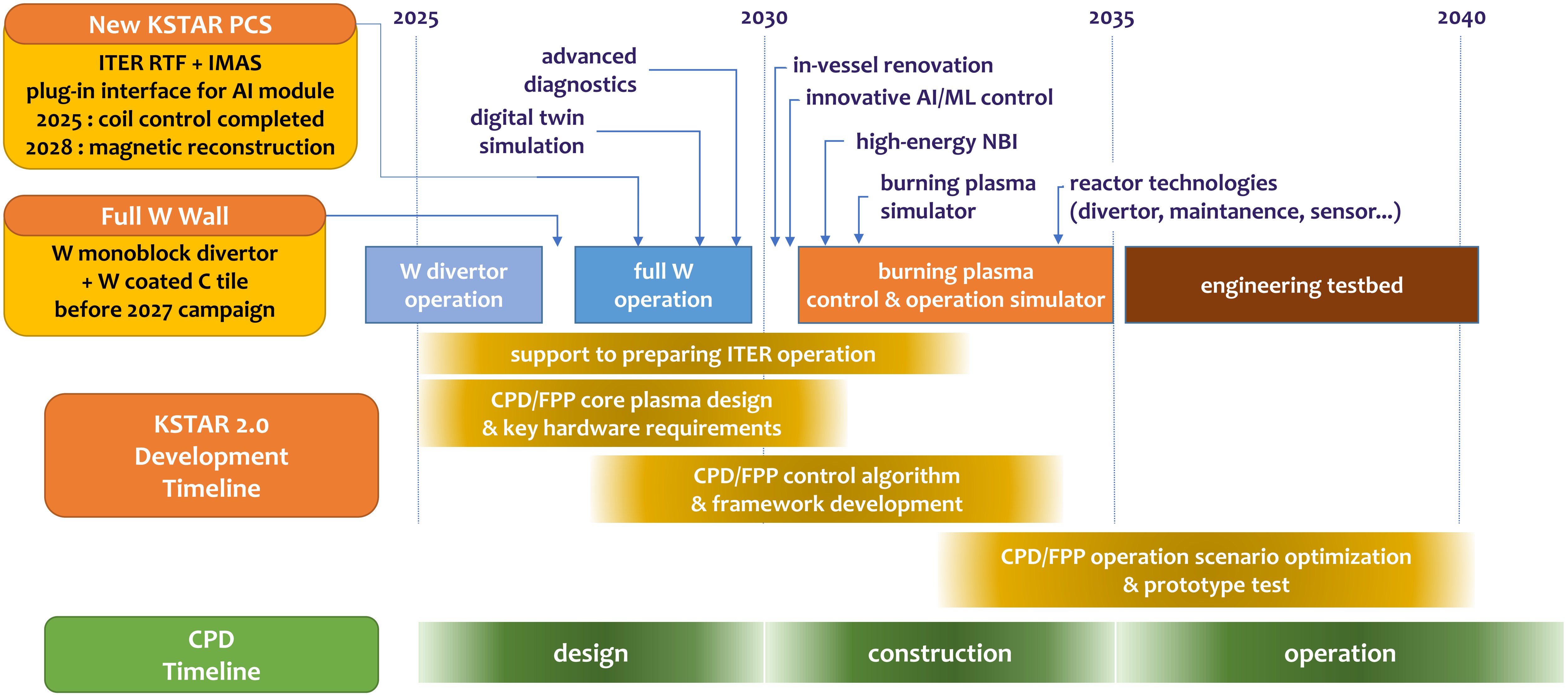


Innovative diagnostics & actuators



additional H/CD

KSTAR will support CPD with staged approaches for design, construction and operation



Collaboration is essential to achieve nuclear fusion sooner rather than later

Domestic Collaborators

KAERI, KIST, UST, KENTECH, Hanyang U, Daegu U, SNU, KAIST, UNIST, POSTECH, CAU, Ajou U, Yonsei U, Dankook U, Jeju NU, Chongbuk NU, Kyungpook NU, Chungnam NU, Jeonbuk NU

EU UK Russia

UKAEA, CCFE, EFDA-JET, York U, Coventry U

NRC-KI, JINR, TRINITY, Gycom, PELIN

ITER, EUROfusion, F4E, IPP, CEA-IRFM, ENEA, Politecnico di Torino, Wigner RCP, TU/e, CRPP-EPFL, IPP-CR, KIT, VTT

US

DOE, GA, PPPL, ORNL, LBNL, SLAC, FNAL, Caltech, Columbia U, Princeton U, MIT, UCSD, UC Davis, Wisconsin U, Lehigh U, NC State U

Asia Austrailia

ASIPP, SWIP, HUST

QST, NIFS, Kyoto U, Tokyo U, Nagoya U, Kyushu U

NCKU

IPR

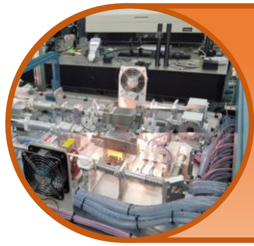
TINT

ANU

KSTAR

Experiments
Joint experiments for tokamak & other fusion devices

GA PPPL NIFS ASIPP
CEA-IRFM IPP …



Diagnostics
Diagnostics developments & data analysis
(TS, ECE, CES, MSE, BES, XICS, Spectroscopy, …)

NIFS QST Nagoya-U Kyushu-U GA ORNL MIT JINR
ASIPP HUST ANU Wigner RCP ENEA TU/e …

Heating & CD
NBI / RF Devices & Technologies

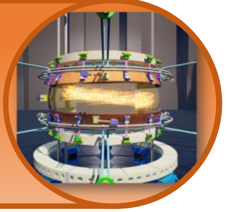
QST NIFS PPPL GA SLAC
CEA-IRFM Tokyo-U Gycom …

Operation & Control
Advanced scenarios & event controls

ITER GA PPPL ORNL Columbia-U FNAL
Princeton-U Lehigh-U …

Theory & Simulation
MHD, Turbulence & Transp., PWI, …

ENEA UKAEA York-U Coventry-U VTT
Caltech NC State-U SWIP NCKU …



Summary

- The newly installed W monoblock divertor was used to **analyze the impact of W impurities** on plasma performance.
- Established **advanced scenarios** and **control techniques** were applied in W environment.
- Various **impurity mitigation methods** were tested to minimize W effects.
- Research will continue under **full W wall** condition to provide **reactor-relevant environments**.
- **Operational boundaries** of diverse advanced scenarios will be explored W environment.
- Candidate **scenarios suitable for the CPD** will be identified and further developed.
- Advanced **control methods incorporating AI** and cutting-edge technologies will be pursued.
- Key physical processes required for **burning plasma** will be investigated.
- **Innovative concepts** for enhancing reactor-relevant performance will be explored.

KSTAR Presentation

EX-C-2961 H.S. Kim	Development of high-performance long-pulse discharge in KSTAR
EX-C-2965 Y.M. Jeon	Development of high poloidal beta scenario for long-pulse operation in collaboration between DIII-D and KSTAR
TH-S-2988 Y.S. Lee	Modelling of mildly relativistic RE –development of reduced-kinetic model and validation in KSTAR ohmic startup
PWF-3506 J.M. Kwon	Establishment and Progress of Korean Fusion Reactor Design Activities: A Coordinated National Approach
EX-C-2741 S. Hong	Applications of in-shot continuous nbi control system to fire mode in KSTAR
EX-C-2892 B. Kim	Exploitation of stable high-Ip regime under new tungsten divertor environment in KSTAR
EX-C-2962 H. Jhang	Electron cyclotron heated low to high mode transition in KSTAR
EX-C-2993 J. Jang	Characteristics of tungsten impurity sources and transport in KSTAR
EX-D-2948 A. Gupta	Detachment control in W divertor KSTAR with real-time 2D boundary surrogate model
EX-D-3014 J.H Hwang	Experimental investigation of deuterium and nitrogen-seeded H-mode plasmas in KSTAR with new W divertor
EX-S-2975 J.K. Lee	ELM suppression by eccd-controlled benign mhd modes in the KSTAR tokamak
EX-S-2829 J. Kim	Multi-scale interation near locked magnetic islands and resulting disruption delay in KSTAR
EX-P-2849 J.W. Kim	Bayesian data fusion for enhanced edge plasma density profile estimation in KSTAR
EX-P-2986 C. Heo	Growing nonlinearity in KSTAR FIRE mode pedestal provides clue to undesirable H-mode transition in I-mode plasmas
TH-C-2974 D. Kim	Gyrokinetic analysis for electron-scale turbulence in KSTAR FIRE mode discharge
TH-H-2916 T. Moon	Predictive study of non-axisymmetric neutral beam ion loss on the upgraded KSTAR plasma-facing components
TEC-CTL-3209 J.W. Juhn	Progress on real-time density control capability of the KSTAR tokamak