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KSTAR's Role and Plans for Applying AI in Fusion Research

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Korea Institute of Fusion Energy

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KSTAR : what KSTAR is doing, and why

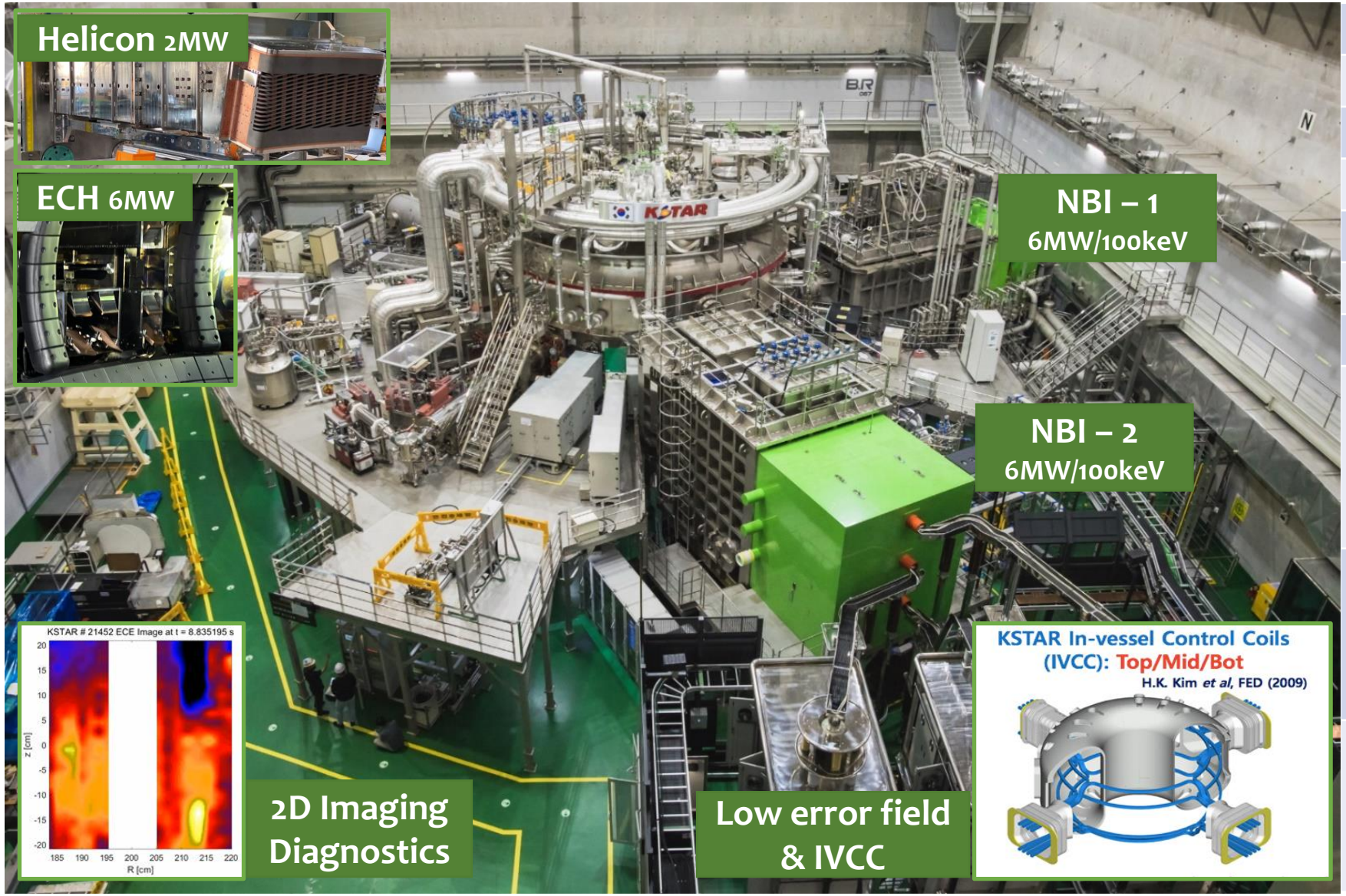
AI : why fusion needs AI, and where to use it

Pathway : what KSTAR is preparing

KSTAR

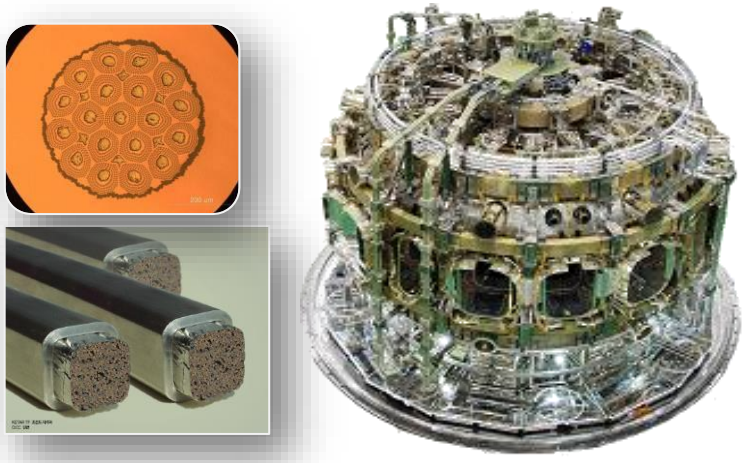
what KSTAR is doing, and why

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



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

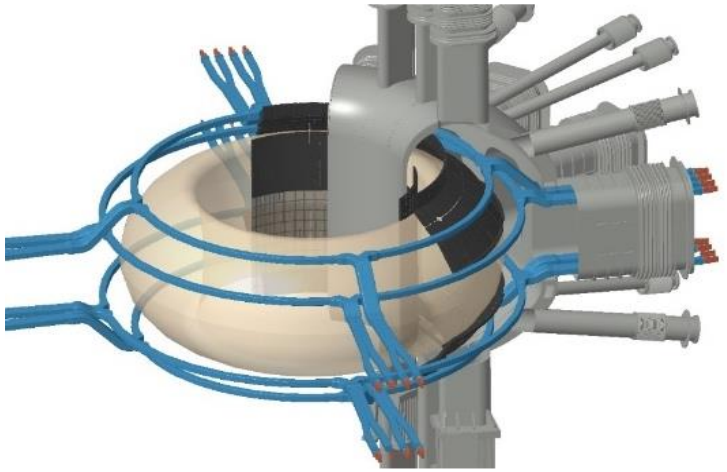
What makes KSTAR unique in the fusion research landscape



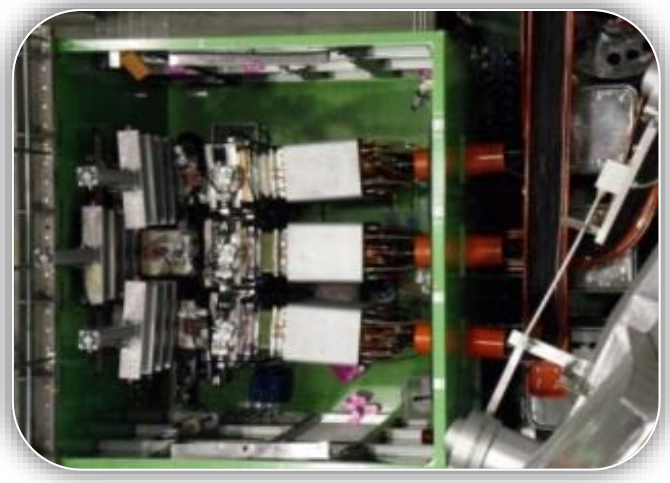
Highly engineered SC magnets with ideal symmetry & extremely low error field

Exceptional toroidal symmetry:
extremely low error fields ($\delta B/B_0 \sim 1\times10^{-5}$) and minimal ripple, supporting stable high-performance plasma scenarios

Versatile in-vessel control coils:
enable effective ELM suppression and divertor heat load management.



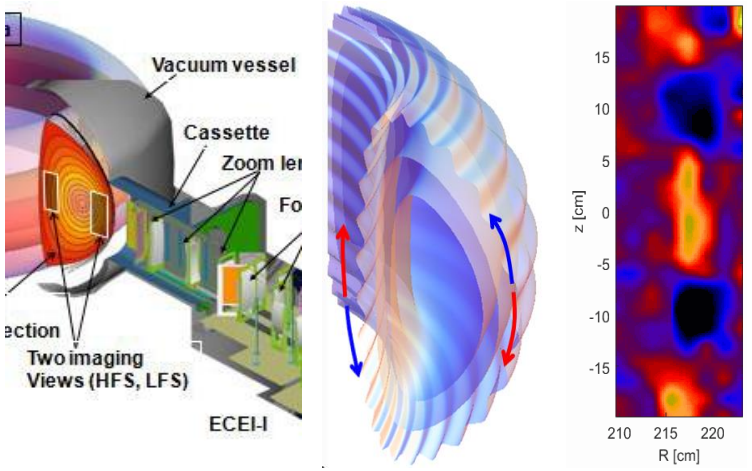
In-vessel coils with flexible 3D mode control (n=1, 2) up to 10 kHz



Long-pulse capable p-NBI systems with various injection angles (3 beams * 2 sets)

Long-pulse heating systems:
support long-duration operation in high-performance regimes

Advanced imaging diagnostics:
provide spatially resolved, 2D/3D validation of core plasma physics.



Advanced 2D/3D imaging diagnostics to validate fundamental plasma physics

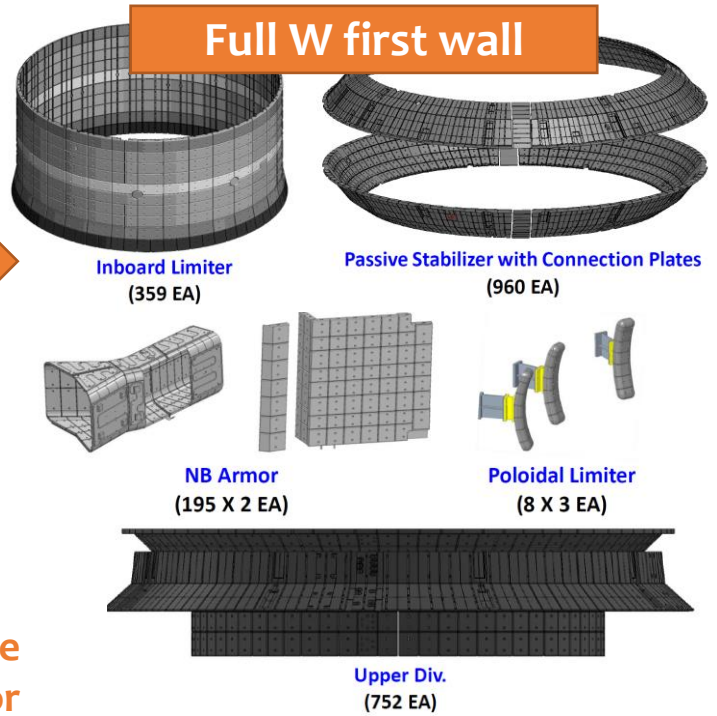
KSTAR moves to a full-tungsten first wall for reactor-relevant validation



’23. 10.



’27. 2.

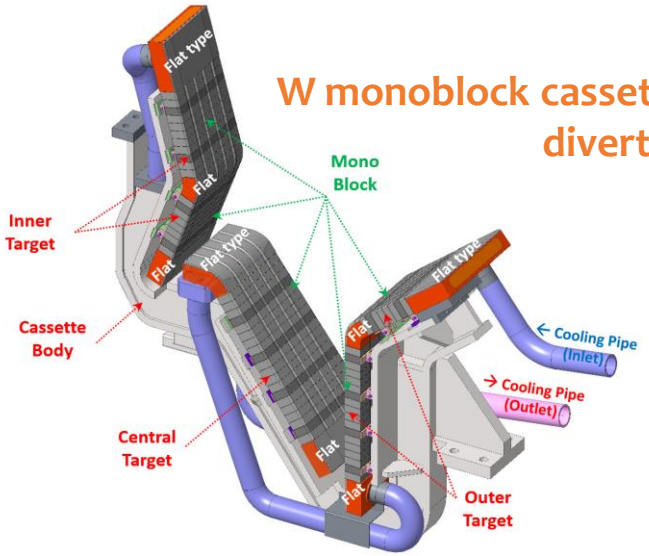


W monoblock divertor :

- Raises peak heat flux handling capacity (4.3 → 10 MW/m²)
- Characterizes W impurity effects on performance and develops reference scenarios for high-performance
- Engineering validation of the monoblock divertor design & operation

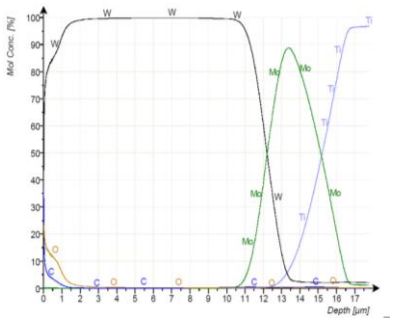
Full tungsten first wall :

- Characterizes W impurity effects during plasma start-up and develops mitigation scenarios
- Assesses performance sensitivity to the W/C impurity ratio
- Checks the lifetime of W coated tiles

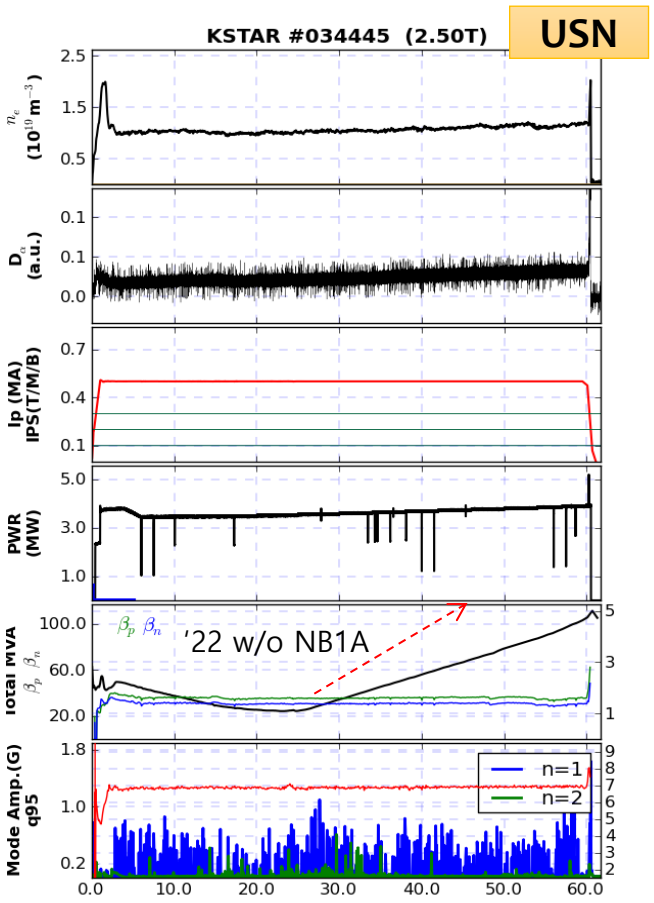


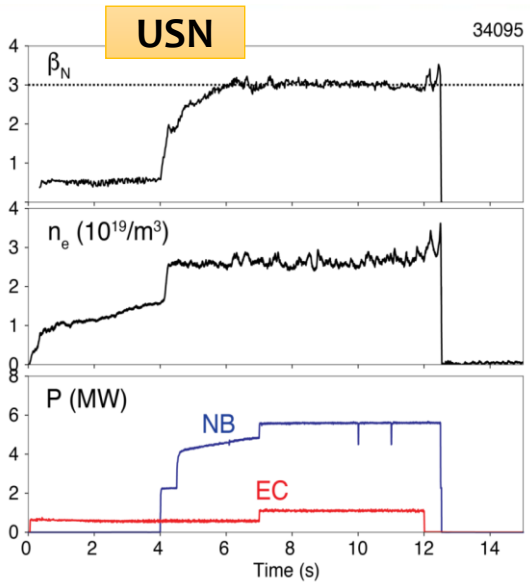
W coated (~15μm) C tile

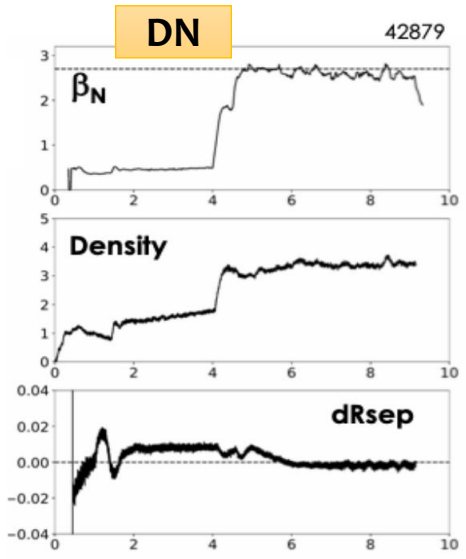


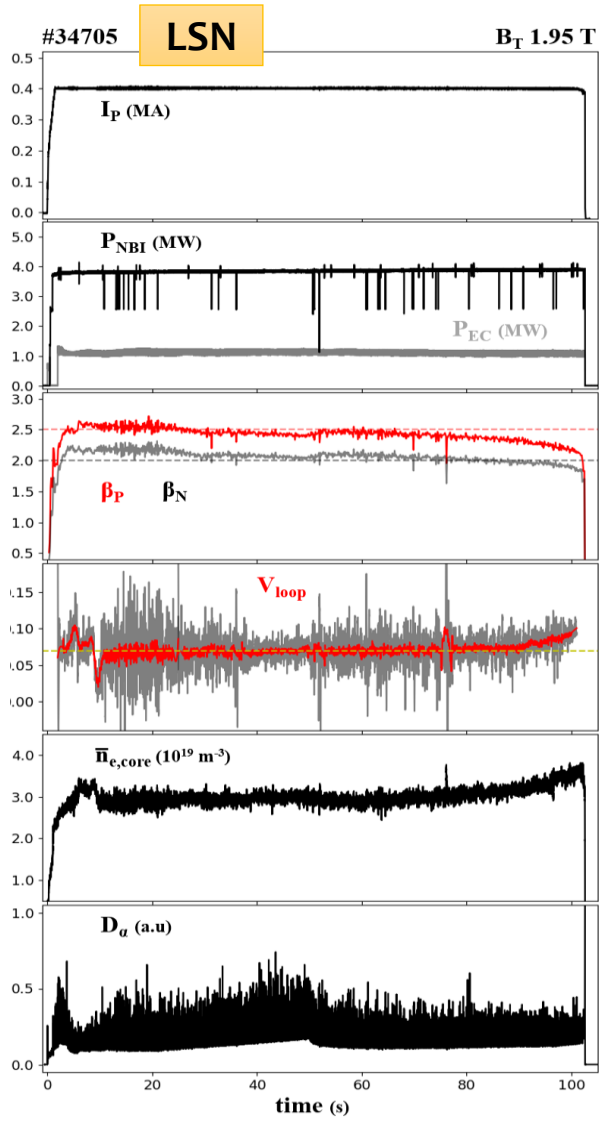


Advanced scenarios were reproduced on the W divertor environments









High ℓ_i :

- The high ℓ_i scenario at stationary $\beta_N = 2.8$ achieved an excellent confinement ($H_{98} > 1.4$ and $H_{89} > 2.7$)
- A new DN high ℓ_i approach shows a promising path to W-Compatible high β_N operation
- Tradeoff between High ℓ_i and Hybrid in low q_{min} regimes

High T_i (FIRE) :

- High T_i (> 10^8 K) operation lasted for 48s on USN.
- Reproducing FIRE mode with LSN are ongoing

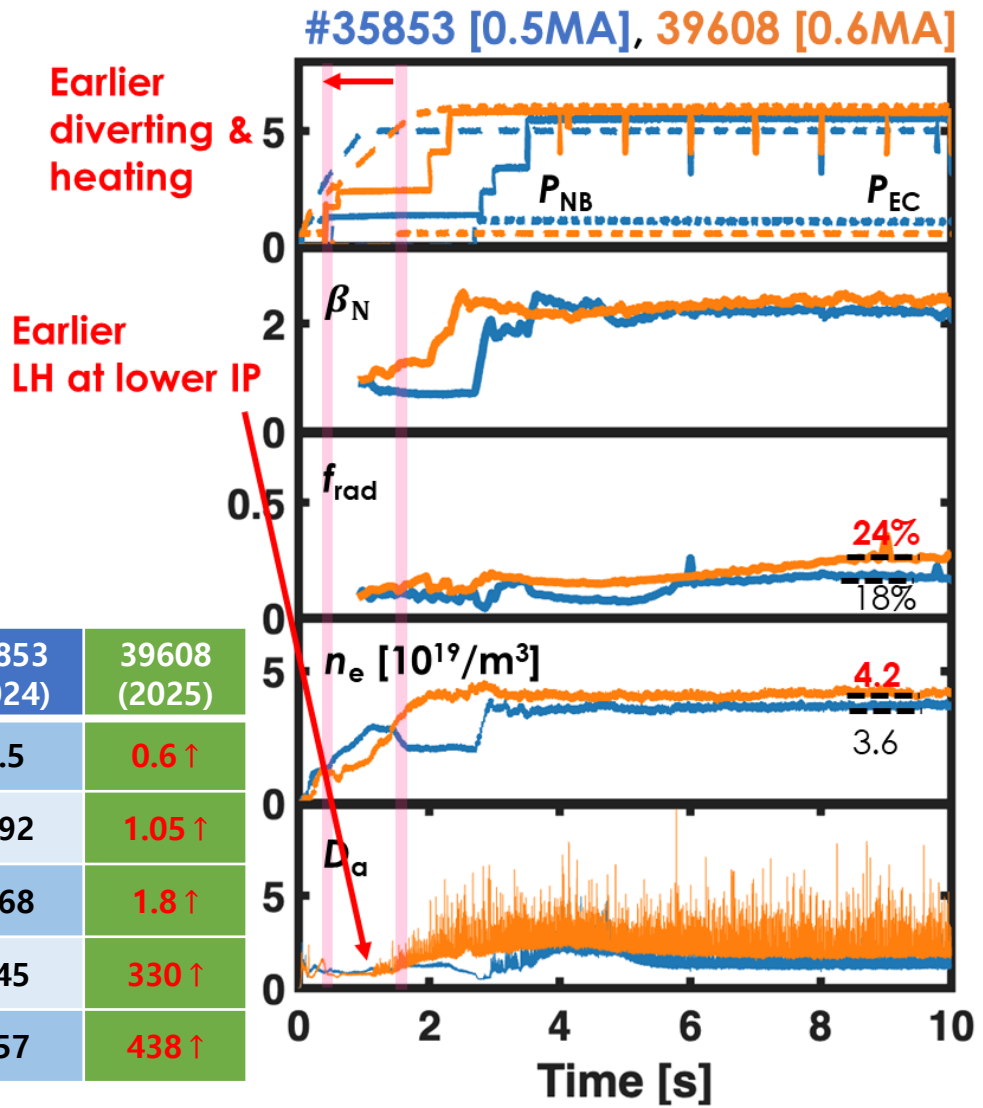
High β_P :

- Performance is maintained for ~70 s and its degradation is minimized
- Water-cooled PFCs experienced temperature changes of less than 15 °C

W-accumulation mitigation methods were explored and reference H-mode scenario was developed

Leveraging W mitigation methods

core ECH-injection - Increasing radially outward transport	Alone is insufficient
W-flush out by ELMs - Increasing ELM frequency	Fast β ramp
plasma shaping - Narrower inner gap and higher triangularity	Gas puffing at divertor for favorable ELMs
early diverting - Mitigate early ELMs with LH transition at lower IP	Early LH transition with low IP and gas bleeding
RMP - Minimize early ELMs to avoid W-influx after LH transition	Finely tuned RMP is effective but less robust

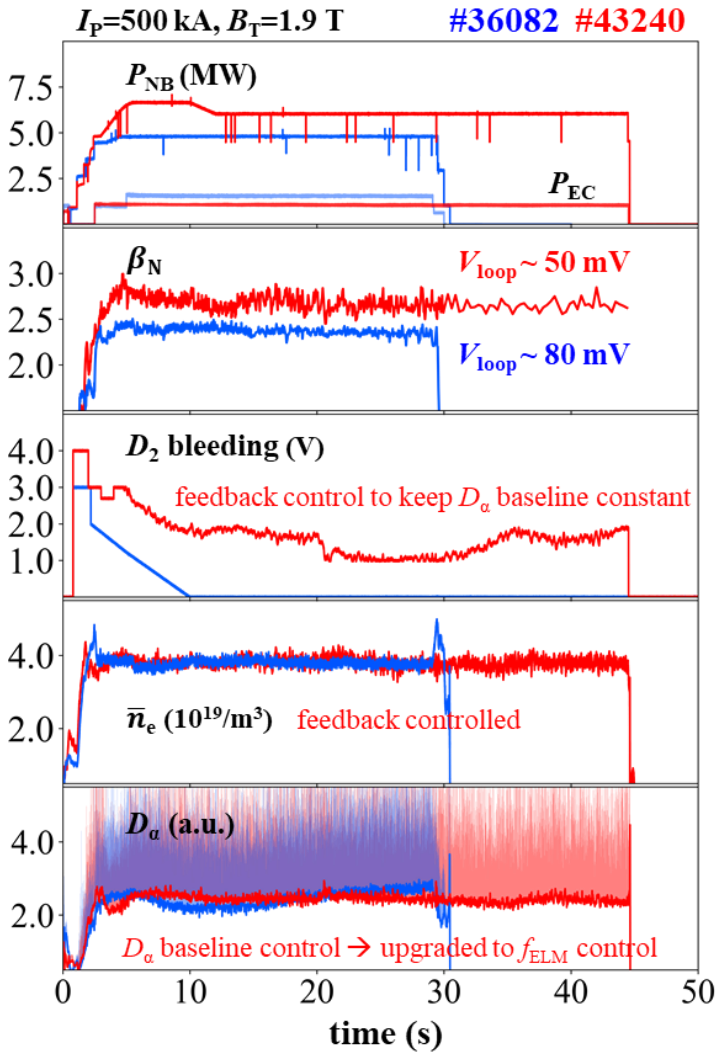


- H-mode scenario compatible with the W-divertor is developed
  - W-mitigation at the core (Cw~2.e-4, frad<15%)
- Integrated recipe leveraging reports from previous metal-wall devices
  - ECH + Fast heating ramp + Divertor gas puff+ shaping + Early diverting
- Further scenario improvement is needed for wall upgrade
  - Improving scenario flexibility and higher confinement
  - Leveraging B/Li-IPD for optimized wall condition and ELM characteristics

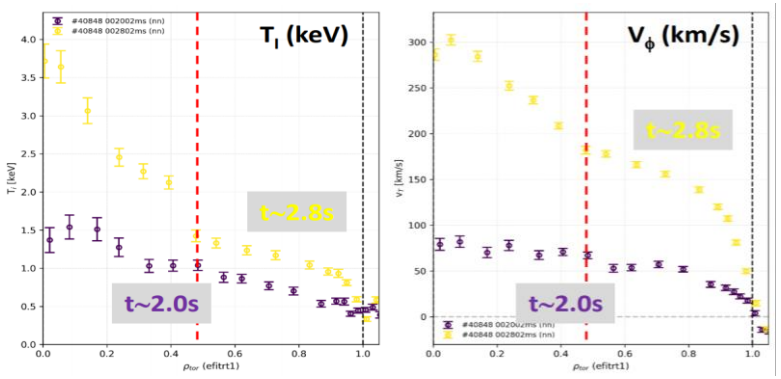
	35853 (2024)	39608 (2025)
I_p [MA]	0.5	0.6 ↑
H_{98}	0.92	1.05 ↑
H_{89}	1.68	1.8 ↑
W_{therm} [kJ]	245	330 ↑
W_{total} [kJ]	357	438 ↑

DIII-D high-performance scenarios were reproduced on KSTAR to validate long-pulse capability in W environment

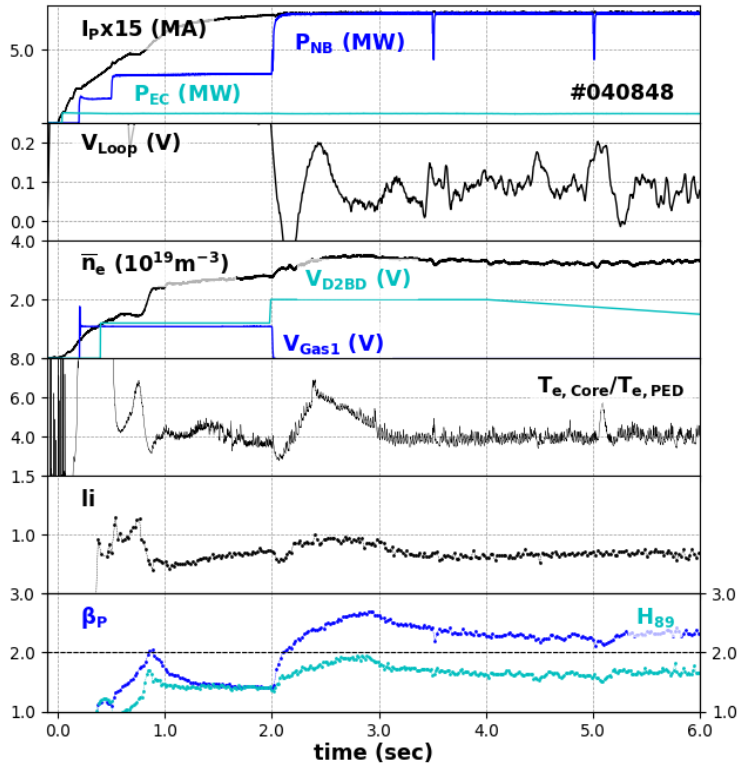
Long-pulse extention of hybrid scenario



- Long-pulse operation (β_N ~ 2.7 / 53 sec) was achieved with W-accumulation mitigation
  - Early diverted shaping
  - Fast heating-power ramp
  - ELM-frequency control
  - Localized divertor D_2 bleeding
  - Real-time D_α-baseline feedback

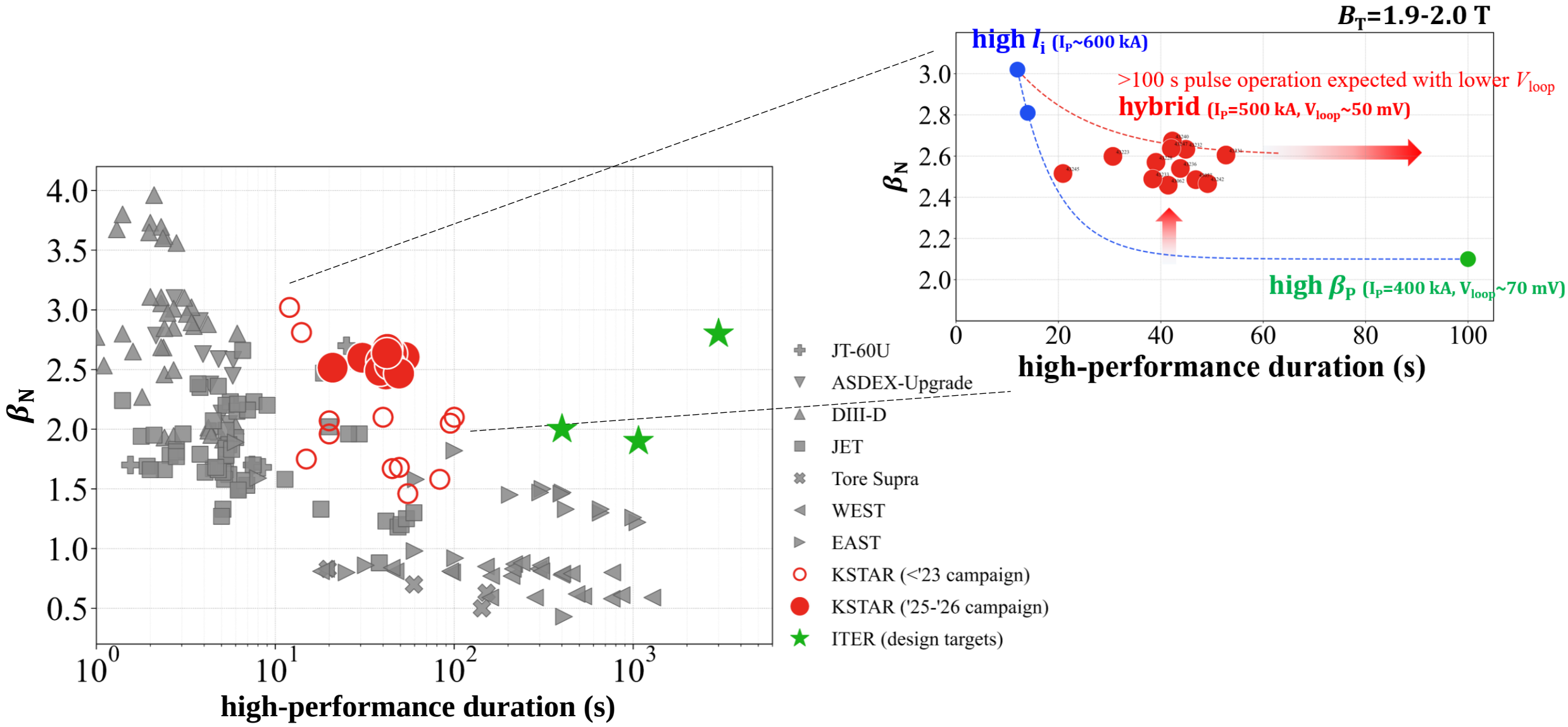


High β_P scenario with large-radius ITB



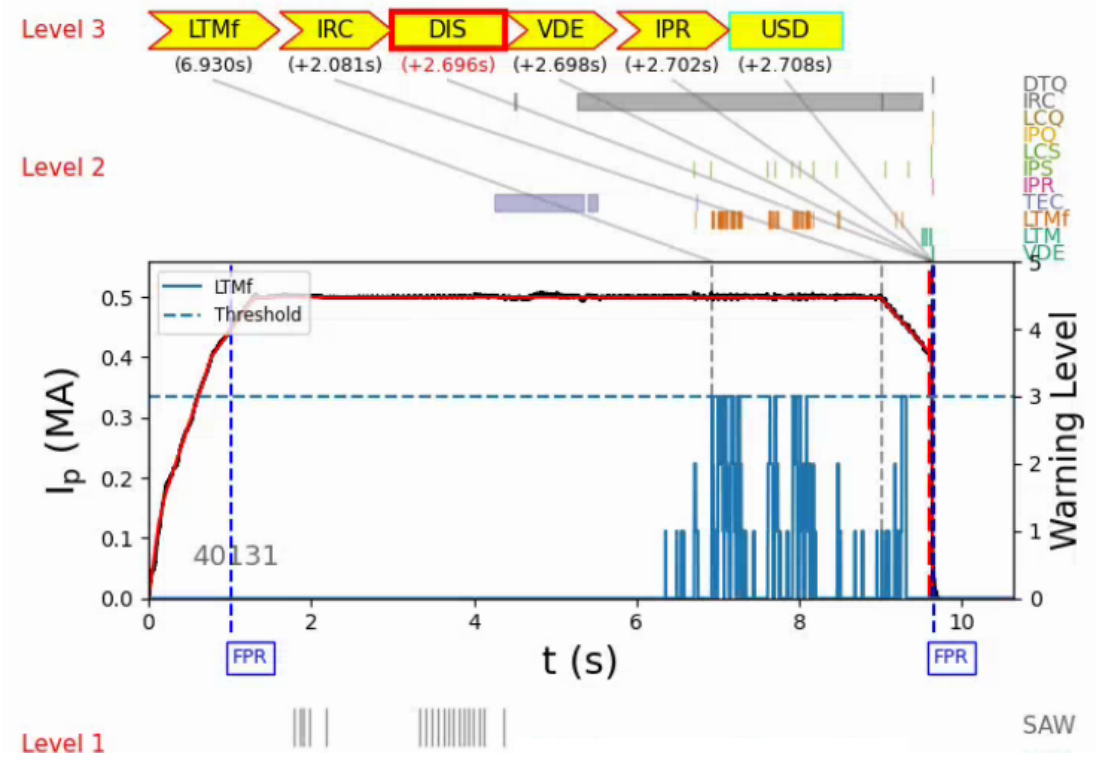
- Improved high β_P discharge achieved on KSTAR with a moderate ITB and gradually improving confinement
  - more peaked current profile, lower density and q_{95} with less NBI powers
- W accumulation becomes an issue when ITBs forms

KSTAR is extending the high-β_N regime toward long-pulse operation based on the W-mitigation reference scenario



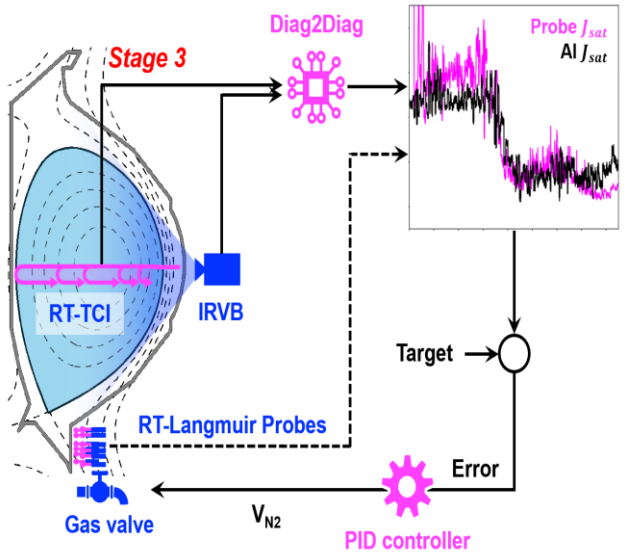
RT diagnostics & advanced control schemes enable the disruption avoidance and detachment control needed for a demonstration reactor

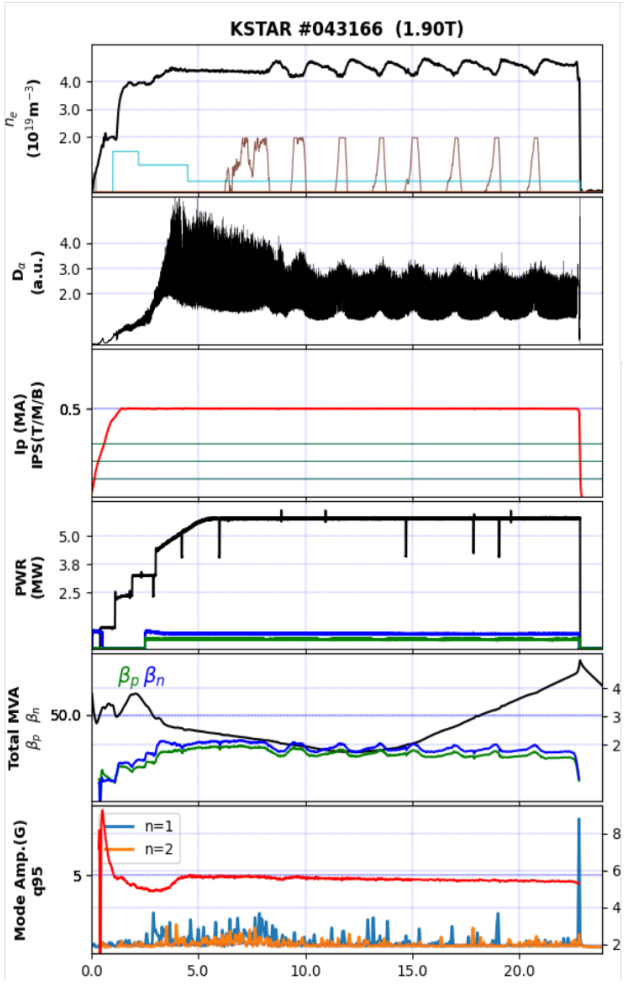
DECAF (Disruption Event Characterization and Forecasting)



- DECAF system produced the first demonstration of real-time disruption avoidance with multi-event feedback
- Locked tearing mode and VDE forecasters, T_e collapse, and Impurity radiative collapse Event feedback actuated

W divertor detachment control with RT diagnostics





- Radiation-front feedback control was demonstrated using GPU-based RT IRVB tomography
- Stable divertor detachment was maintained upto 20 sec by ML surrogate model (virtual IRVB or LP)

Long pulse detachment control (~20 sec)

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK · GENERAL ATOMICS · PPPL · KAIST

KSTAR aims to develop high-performance plasma scenarios for a demonstration reactor

KSTAR

Mid-size SC tokamak
D-D operation
High performance &
Long-pulse scenario

supports baseline-scenario demonstration and validation

- PCS base on ITER RTF
- Disruption mitigation (dual SPI)
- IVCC-based ELM suppression

- Full W environments

- DEMO-relevant robust PCS including diagnostics / actuators
- Extension of experimental results

develops reactor-relevant scenarios with robust control scheme

ITER

D-T burning-plasma operation
SRO plasma scenario
Q = 10 baseline scenario

DEMO

Electricity generation
Robust steady-state scenario
Limited diagnostics / actuators for RT control

A compact demonstration reactor - smaller than ITER is being pursued to accelerate fusion commercialization

Parameter	ITER	CPD*	Ratio	Notes
GEOMETRY		* CPD (compact pilot device, tentative)		
Major/Minor Radius R_0/a [m]	6.2/2.0	**4.0/1.14**	**0.65×/0.57x**	*A=3.1(ITER), 3.5(CPD)*
Plasma Volume V [m^3]	840	**182**	**0.22×**	*Compact but compensated by high density and temperature*
EQUILIBRIUM				
Toroidal Magnetic Field B_0 [T]	5.3	**8.2**	**1.55×**	*HTS(REBCO) vs Nb_3Sn - key enabler*
Plasma Current Ip [MA]	15	**9.15**	**0.61x**	*q95~3(ITER), 4.66(CPD)*
THERMAL				
Central Electron Density ne0 [10^{20} m^{-3}]	~1.0	**3.65**	**3.65×**	*$P_{fus} \propto n^2$ → quadratic density contribution*
Greenwald Fraction fGW	~0.85	**1.21**	**1.42×**	*CPD operates above the Greenwald limit*
Core Temperature Te0/Ti0 [keV]	~25/25	**~27/27**	**~1.1x**	
POWER				
Alpha Power P_alpha [MW]	100	**120**	**1.2×**	*P_fus/5 - burning plasma self-heating*
Fusion Power P_fus [MW]	500	**600**	**1.2×**	
Energy Gain Factor Q	10	**10**	**1.0×**	*Same Q, higher absolute power*

much higher core pressure than ITER : requires ultra-high performance (+ robust) scenarios !!

Requires scenarios that go well beyond what is achievable today : AI might offers a route to the breakthrough to close the performance gap

SCENARIO REQUIREMENTS

Reaching high plasma pressure

- Wide-radius ITB
- Double transport barriers
- Super H-mode ...

control is a trade-off between performance vs. stability : we want holding both at once

Under strict control constraints

- Steady-state operation with no room for a single failure
- Limited diagnostics and actuators

THE CONTROL GOAL

Passive control will not be enough

Adaptive control tracks the performance-stability boundary in real time, using every available sensor and actuator together

WHY AI

*Not because AI is a **MAGIC** fix for problems beyond us*

1. Fusion reactors we are designing will operate a decade or more from now
2. Over that same decade, AI capability will advance beyond what we can imagine today
3. Designing the device to make full use of that technology may be the surest route to a breakthrough

AI

why fusion needs AI, and where to use it

AI can be widely applied in fusion research

Device Design Optimization

AI aids in optimizing reactor components and overall system configuration.
Accelerates design cycles and evaluates numerous design scenarios efficiently.

Data-Driven Modeling and Knowledge Extraction

AI provides surrogate models for complex simulations and processes massive experimental datasets.
Detects patterns, predicts outcomes, identifies anomalies, and uncovers new physical insights.

Predictive Maintenance, Safety, and Experimental Guidance

AI predicts equipment failures, monitors system health, and enhances operational safety.
Suggests optimal experimental parameters and supports rapid, efficient research cycles.

Autonomous Operation

AI enables automated and adaptive operation of tokamak systems.
Reduces human intervention while maintaining safety and performance targets.

Plasma Control and Optimization

AI models high-dimensional, nonlinear plasma dynamics to optimize control parameters in real time.
Maintains plasma stability, improves confinement, and enables predictive adjustments.

Why is AI well-suited for fusion plasma control

High-dimensional, nonlinear dynamics

Plasma is a chaotic system with many coupled variables (temperature, density, currents, magnetic fields, turbulence).
Traditional controllers use simplified models and cannot capture the full physics.
AI can learn effective strategies directly from experimental data and adapt to complex behavior.

Multi-objective optimization

Plasma control must balance competing goals: stability, confinement, long-pulse sustainment, and machine protection.
Achieving this requires synthesizing diverse sensor inputs and control actuators.
AI handles high-dimensional inputs and enables real-time trade-offs between objectives.

Global optimization capability

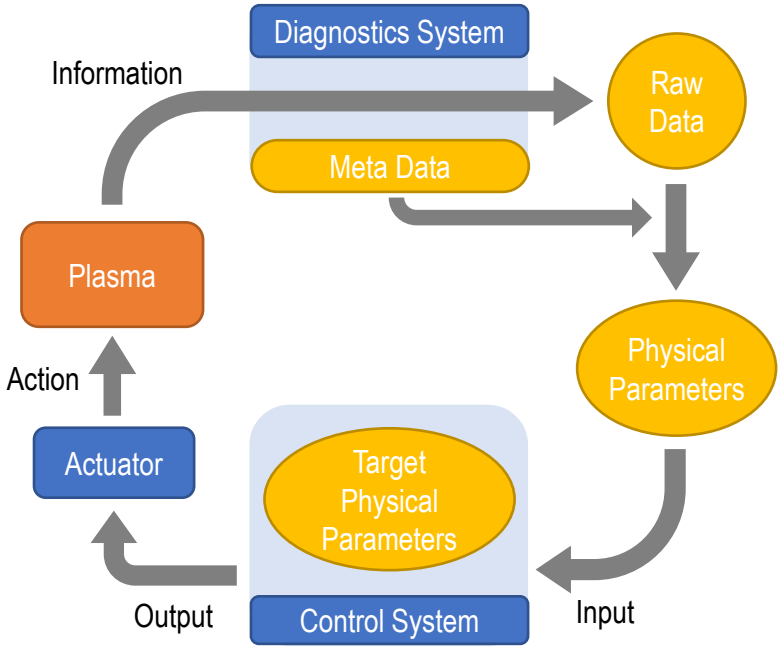
Classical controllers often converge to local optima, limiting performance.
AI can explore nonlinear solution spaces, find better global strategies, and improve overall operation robustness.

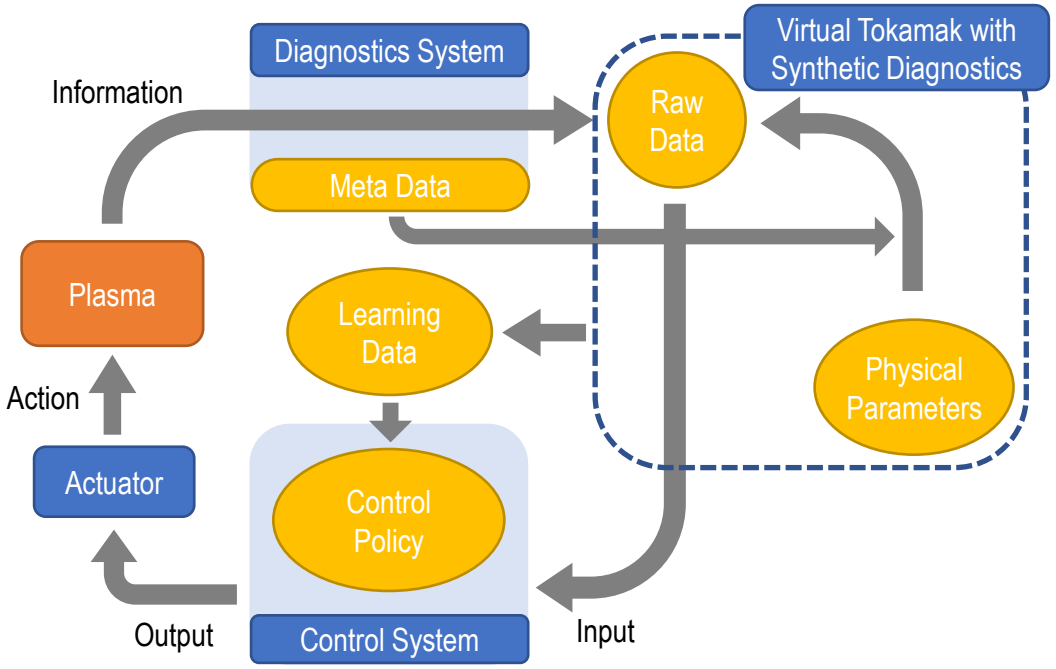
Real-time response and adaptability

Plasma instabilities evolve on millisecond timescales and require fast corrective action.
Once trained, AI models run inference extremely quickly, suitable for feedback control.AI can also adapt online, improving resilience to unforeseen plasma conditions.

Why is AI especially well-suited for plasma control on fusion reactor

Commercial fusion reactor should be operated with minimum/optimum sensor & actuator set





lack of sensors & actuators

	conventional control scheme		control scheme based on AI
Information Loss	Converts raw data into physics parameters, losing part of the information in the process	*"AI does not need physics parameters to understand plasma state"*	Uses raw data directly to determine control policy and actuator actions
Coupling	Treats diagnostics, variables, and actuators one-to-one, even when several diagnostics feed the same variable or changing one variable requires several actuators to act together	*"AI does not need variables and actuators to be defined one-to-one"*	Takes multiple raw channels in and decides on multiple actuators at once, capturing their coupling directly

Why is AI not suited for fusion plasma control

Lack of physics understanding

Most AI models, especially deep learning systems, act as “black boxes.”
AI lacks a deep understanding, hard to develop, validate, or improve models based on physical insight.
In safety-critical plasma control, AI decisions can be unreliable.

Data limitations

Training AI requires large, diverse, high-quality datasets.
Plasma experiments are costly and limited in number, and conditions vary across devices.
Simulations help but are not perfect representations of real plasma behavior.

Extensive trial-and-error required

Many AI approaches rely on iterative trial-and-error to learn effective control policies.
In real plasma experiments, each trial is expensive, time-consuming, and potentially risky.
Unlike simulations or controlled lab experiments, repeated errors in a fusion reactor could damage equipment or compromise safety, limiting the practical applicability of AI.

Risk of catastrophic errors

Plasma disruptions can damage reactors within milliseconds.
Wrong AI actions could lead to irreversible damage before humans can intervene.
Traditional controllers provide safer, well-tested responses.

The same reasoning already plays out in robotics

Applies the same way

High-dimensional, nonlinear dynamics

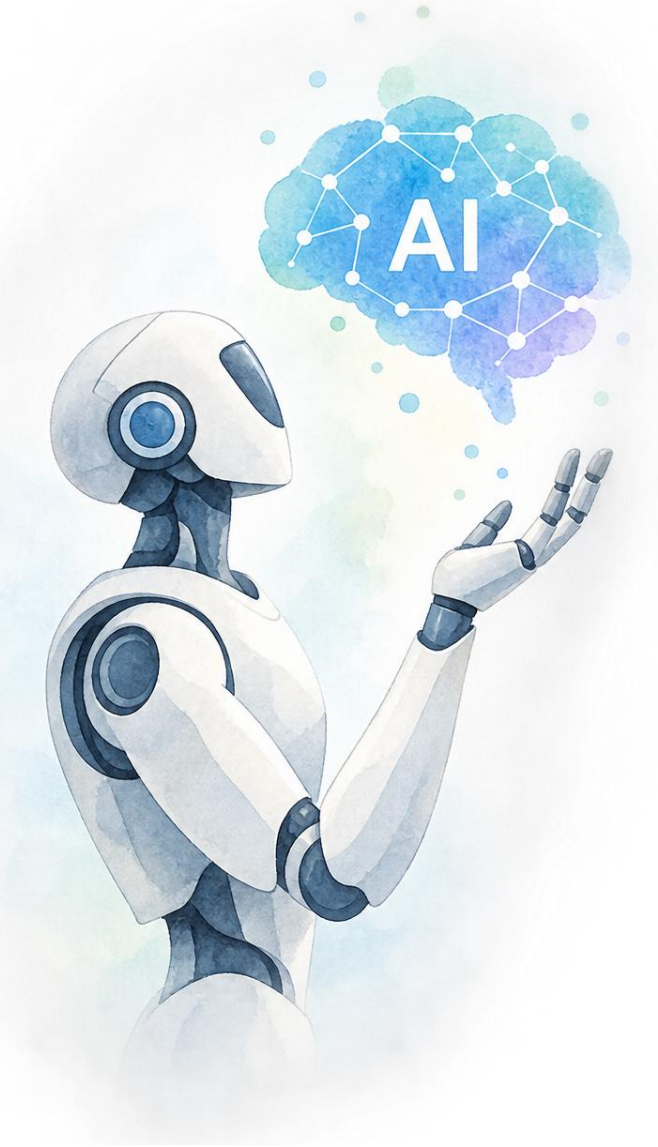
Many physically coupled joints and contact dynamics that simplified models cannot fully capture

Multi-objective, real-time control

Balancing stability, precision, speed, and safety at once, within tight timescales

Global optimization

Learned policies reach strategies hand-tuned controllers miss



Already resolved in robotics

Data limitation

Internet-scale vision-language pretraining transfers into robot action, alongside abundant teleoperation and simulation data

Trial-and-error experiments

Extensive sim-to-real training moves most iteration into simulation, off physical hardware

Risk of error

Lower stakes per failure allow far more aggressive real-world learning than a reactor would permit

Closing that gap for fusion requires a device fit for that purpose



Should be resolved in fusion research

Data limitation

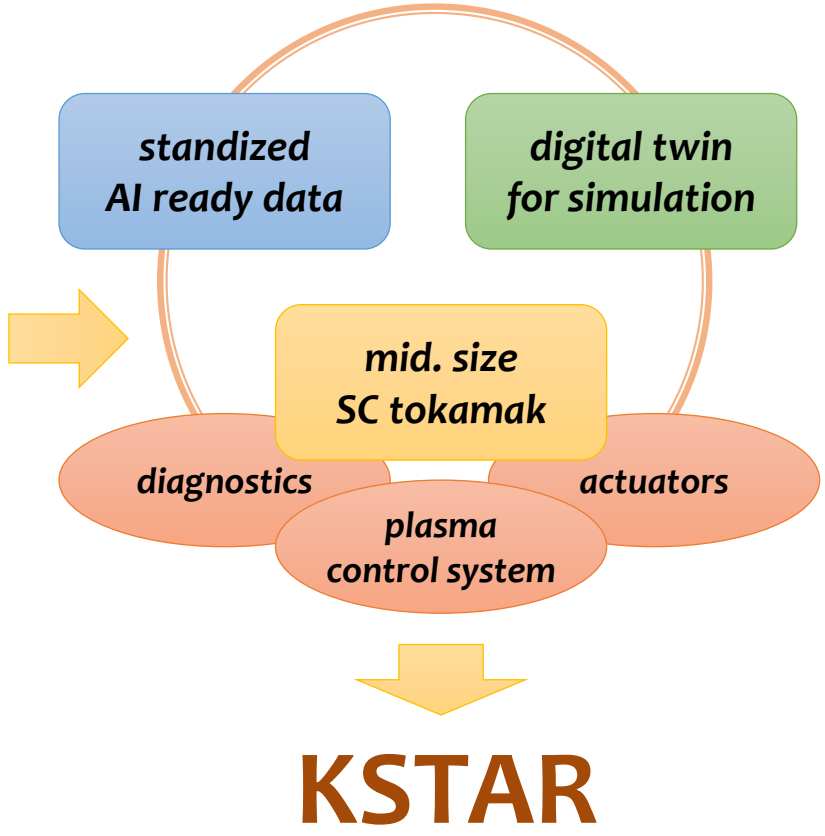
Data standardization and cross-device comparison are needed to mine more information from available data

Trial-and-error experiments

A high-performance, long-pulse device is needed to check real experiments against simulation

Risk of error

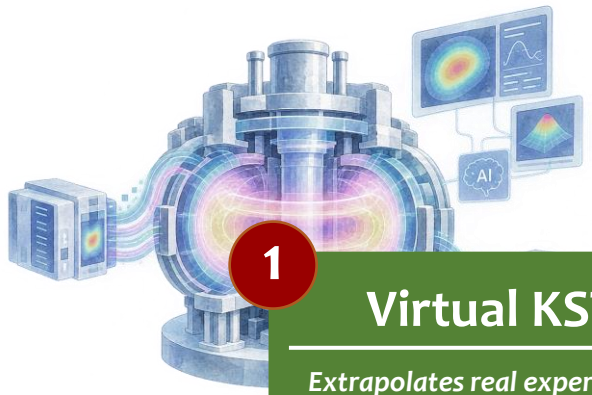
A mid-size device is optimum, one that can withstand disruptions without catastrophic damage



Pathway

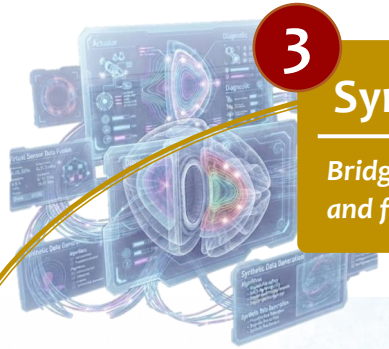
what we are preparing

KSTAR will be an innovative testbed to apply AI on fusion research and to develop operation scenarios for next-gen reactors



1 Virtual KSTAR

Extrapolates real experiments into full-scale, burning-plasma scenarios

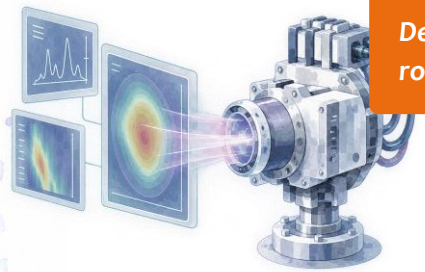


3 Synthetic Diagnostics

Bridges simulation, data interpretation, and future diagnostic design

4 Reactor -relevant Diagnostics

Develops radiation-proof, compact, and robust sensors for reactor condition



KSTAR



2 AI-ready Data

Standardizes a large body of research data into an AI-ready pipeline



5 Reactor -relevant Actuators

Tests a wide range of actuator options to find the optimal set for reactor

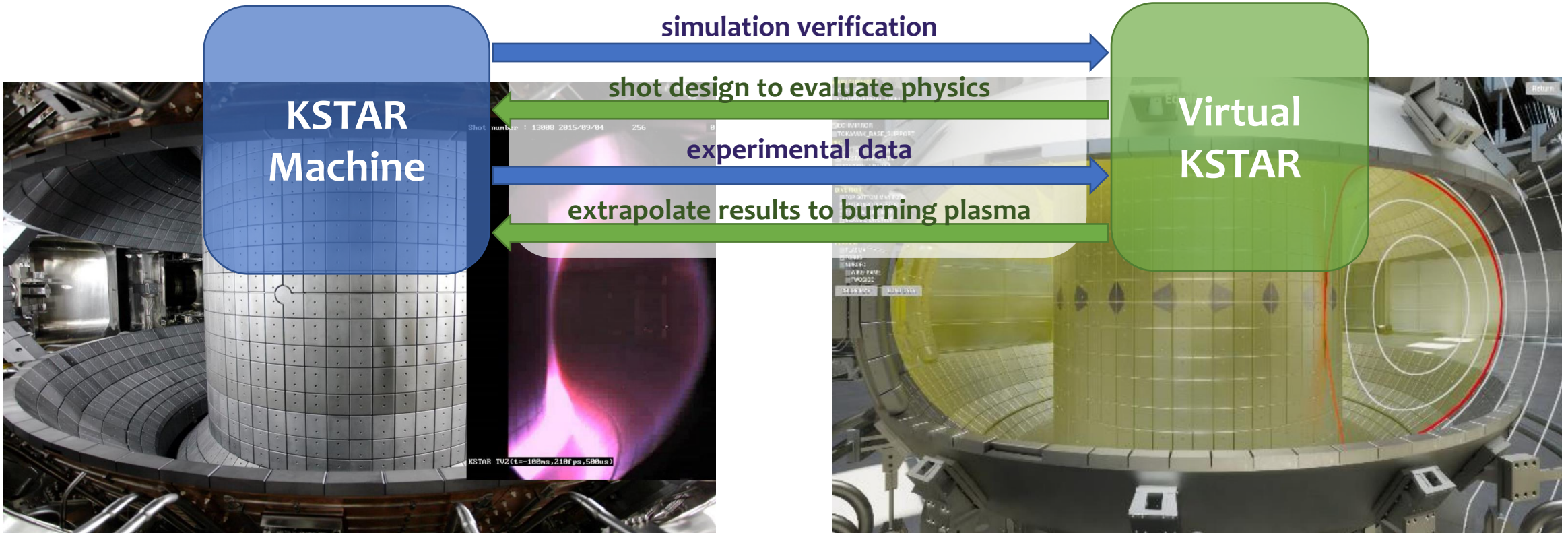


6 Adaptive PCS

ITER-relevant & AI-friendly control framework merging sensors / actuators

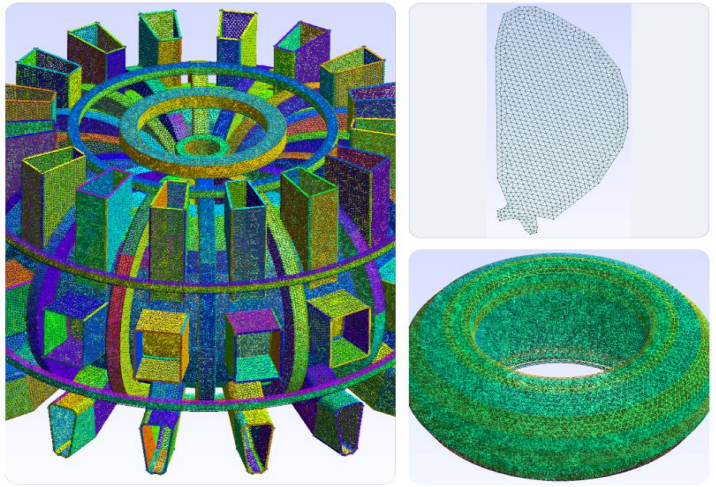
KSTAR will extrapolate experimental results using digital twin technology

- Virtual tokamak platform is being developed for real time visualization & system engineering design
- Virtual KSTAR will expand its capabilities to advanced simulation & AI control

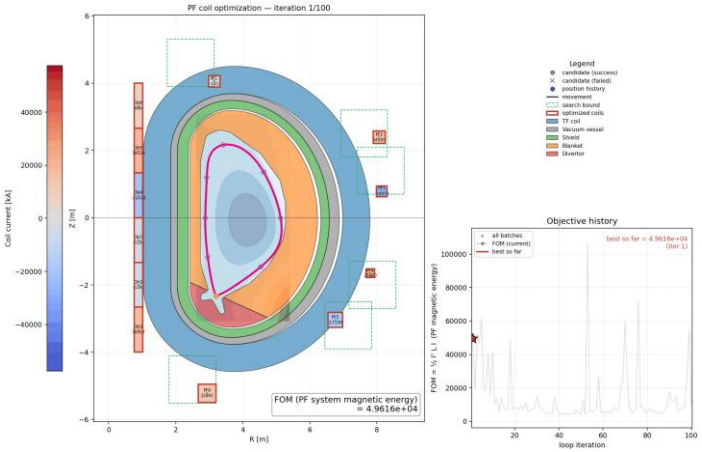


Virtual KSTAR development is already producing concrete tools

Machine Design

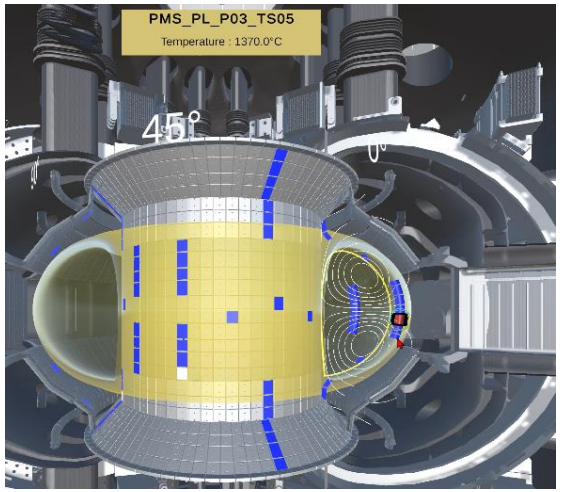


Auto mesh generation for machine & plasma

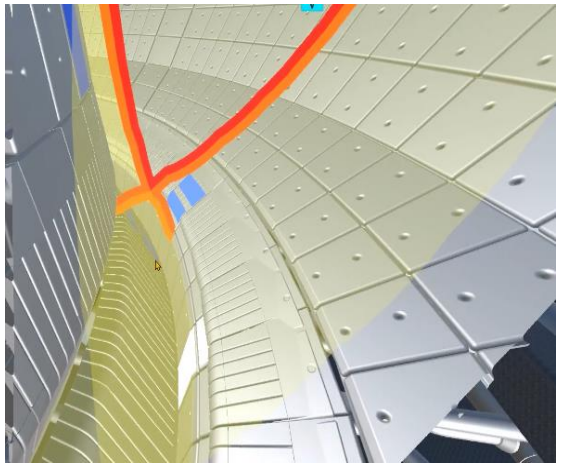


Auto mesh + Free-boundary equil. + NBI sim.

3D Visualization

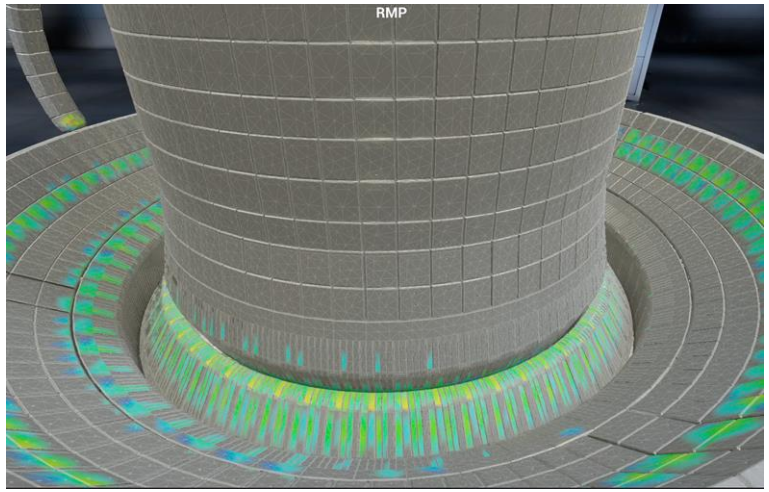


PFC temperature distribution

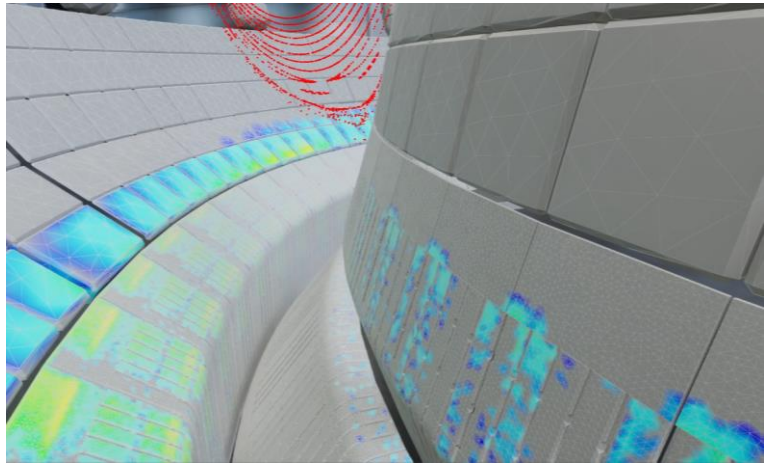


RT equilibrium with X point

3D Simulation



NBI fast ion loss (Monte-Carlo)



RMP induced heat flux pattern

more Full 3D simulation

Synthetic diagnostics

PCS simulator

Virtual experiments

TriTech Virtual.Art.Clean

UNIST KAIST

KSTAR already holds a large and valuable body of research data

What KSTAR already has

340 TB
MDS+ experimental raw data

~70 TB/year
Recent annual raw data growth

14 TB
EPICS operational time-series data

Multi-modal assets
logbook, documents, images, videos, CAD

Data have been accumulated across experiments, documents, and design assets.

What limits data reuse today

Data silos
MDS+, EPICS, logbook, documents, images, and CAD are stored in separate forms.

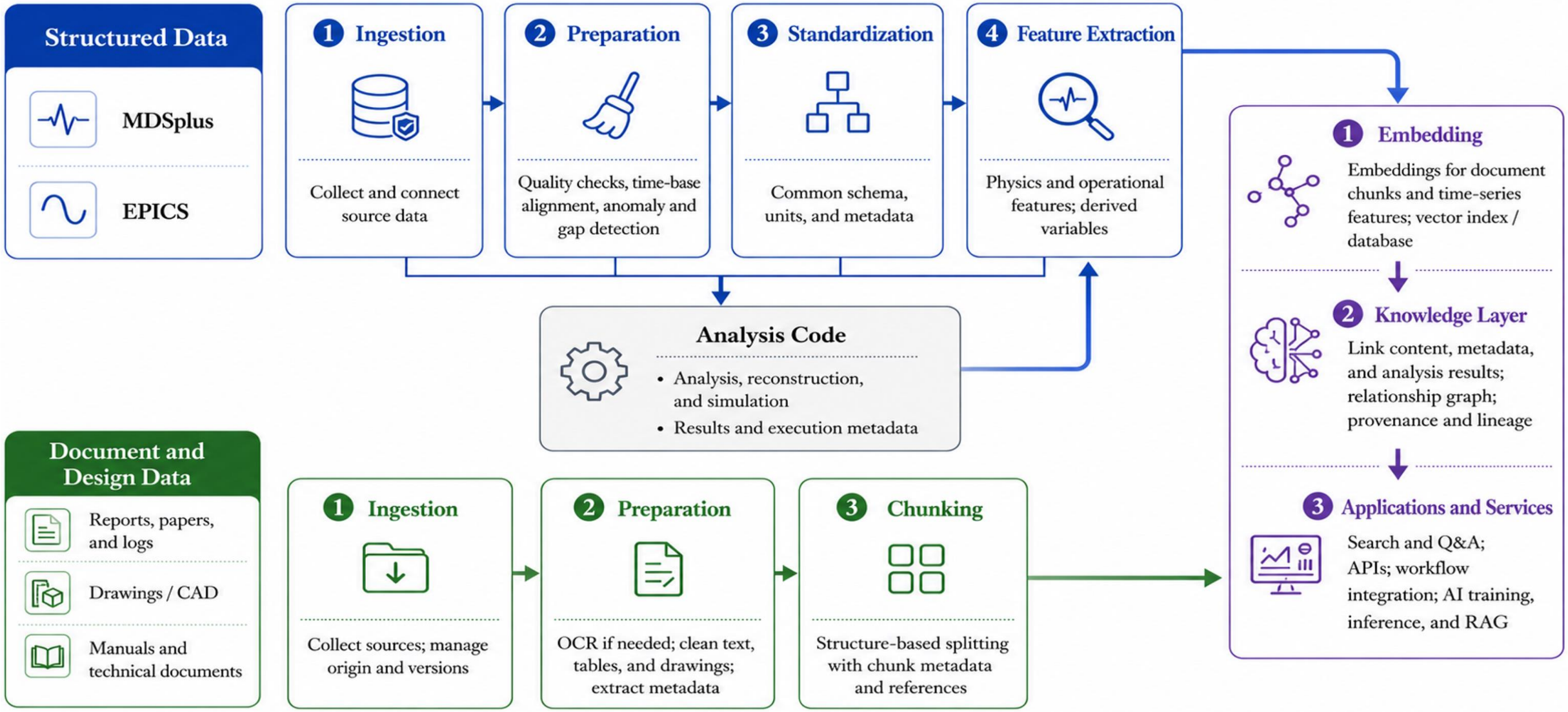
Legacy limitations
Large-scale processing, metadata use, and modern analysis workflows are difficult with legacy formats alone.

Manual analysis burden
Researchers spend substantial time preparing inputs, running codes, and organizing outputs.

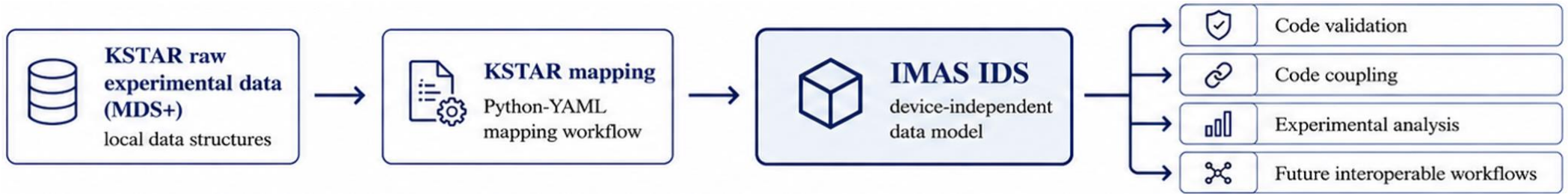
Weak AI readiness
Raw time-series data are not immediately suitable for scalable AI/ML workflows.

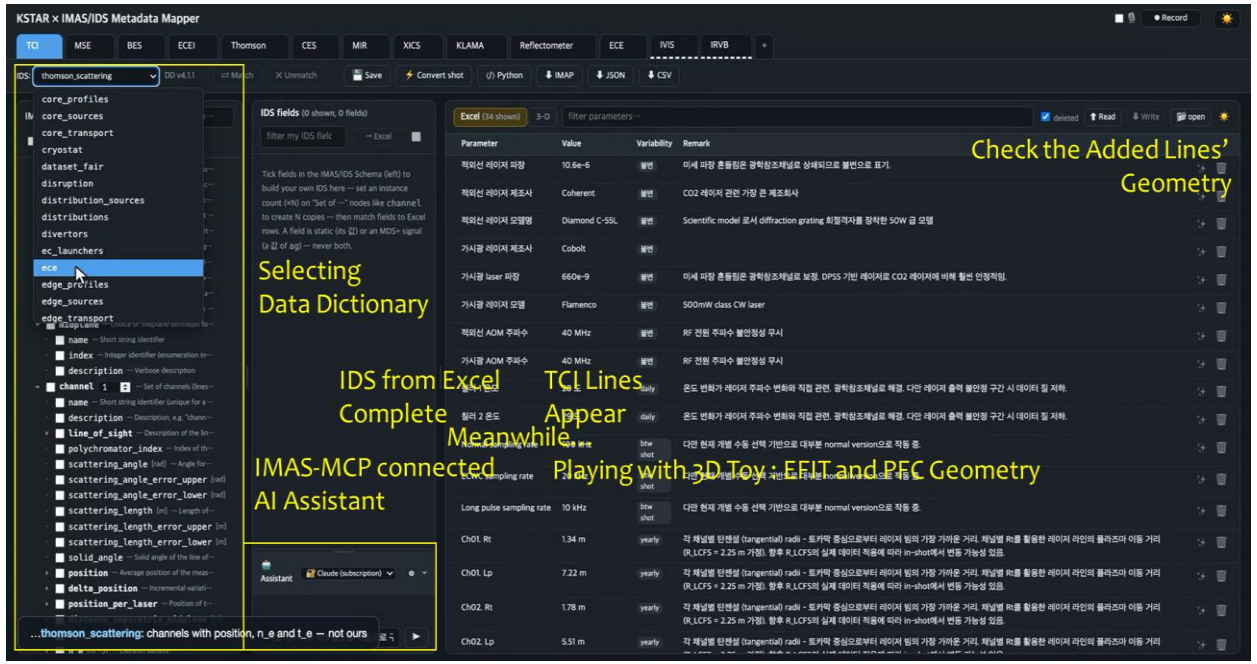
We need a reproducible data framework that connects experimental data, standardization, analysis workflows, and future AI-assisted research.

Development of the pipeline into AI-ready knowledge is already underway



IMAS/IDS is a key standardization layer in the framework





Why IMAS/IDS matters

- **reduces interface fragmentation**
  Minimizes bespoke interfaces between codes and experiments.
- **supports interoperability across tools**
  Enables consistent data exchange across diverse applications.
- **aligns experimental data with integrated modelling**
  Provides the right inputs in the right form for modelling workflows.
- **provides a structured basis for broader community reuse**
  Facilitates sharing, benchmarking, and long-term sustainability.

An AI-assisted IMAS/IDS mapper (K-MAS) was developed to accelerate AI-ready data conversion

Synthetic diagnostics bridges interpretation, simulation, and device design

IMAS/IDS Framework

Virtual KSTAR
Simulation Comparison

Converts simulated plasma state into diagnostic signal space enables direct comparison with real measurements and testing of scenarios never actually measured

KSTAR
Data Interpretation

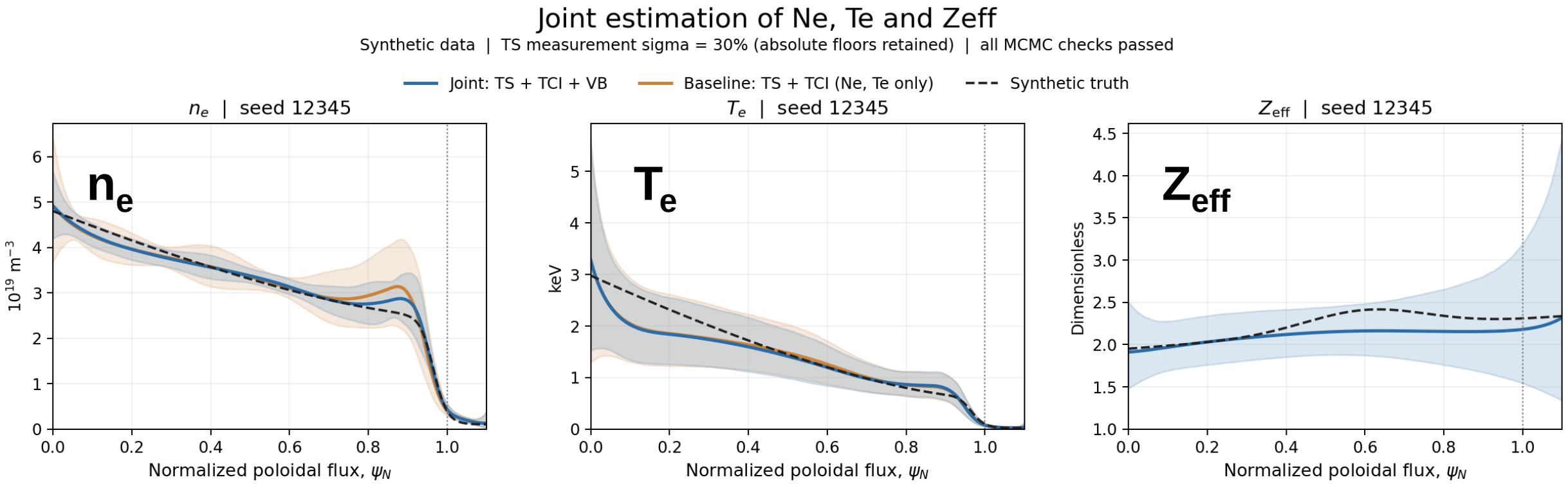
Combined with Bayesian analysis joint interpretation of multiple raw channels into consistent physical variables, not one-diagnostic-to-one-variable



DEMO Reactor
Diagnostics Design

Tests candidate diagnostic sets in digital twin & control simulator before hardware exists identifies data effectiveness and optimized configuration meeting control needs

Combined analysis using bayesian inference provides multiple parameter profiles estimation : TS + TCI + VB

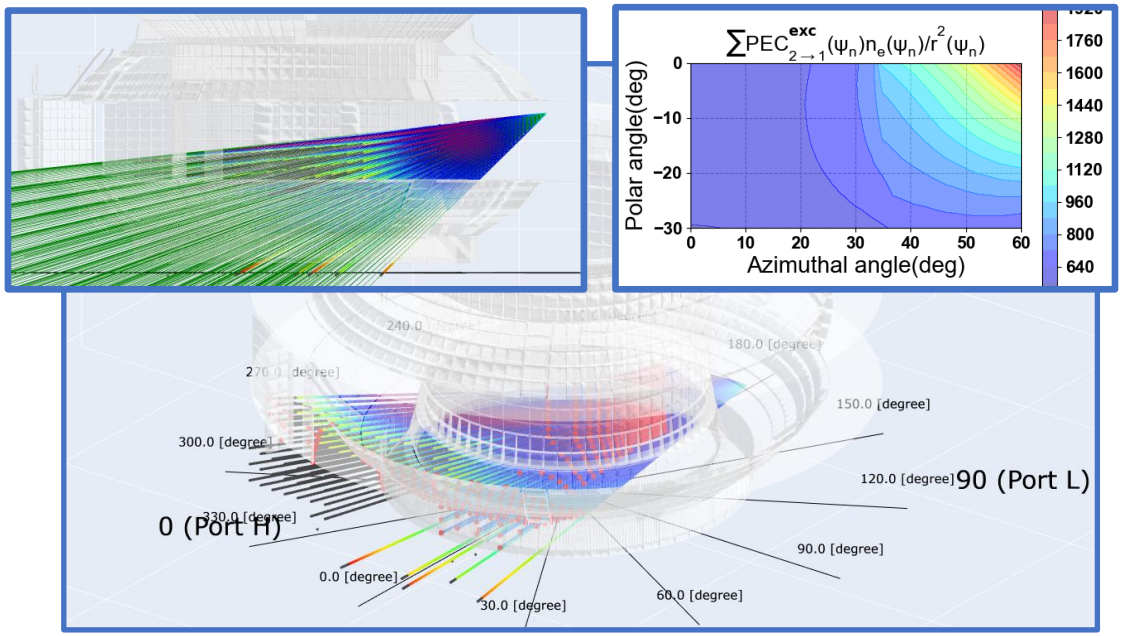


TS : Thomson Scattering
TCI : Two-color Interferometer
VB : Visible Bremstrahlung

Other Diagnostics Will be Joining Soon

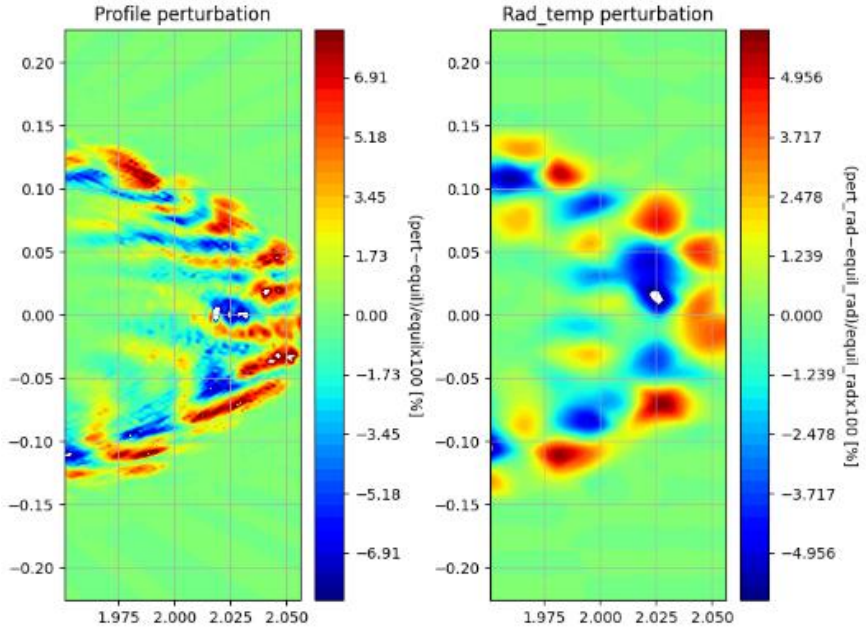
Integration of synthetic diagnostics in virtual KSTAR is on-going

- Employing unstructured mesh and 3D data analysis algorithms, full 3D interactions of particles and beams can be calculated and recorded very efficiently
- A new full 3D code was developed to design the new Ly-α diagnostics for neutral particles on KSTAR
- Other synthetic diagnostic codes are also being developed (e.g. ECEI)



Beam tracing for line-of-sight modeling and calculation of expected Ly-α signal

Jaesuk Lee, Taeuk Moon, K.-C. Lee, Y.-c. Ghim, KAIST, KFE, iFPC2025



Synthetic ECEI diagnostics on GK turbulence simulation data

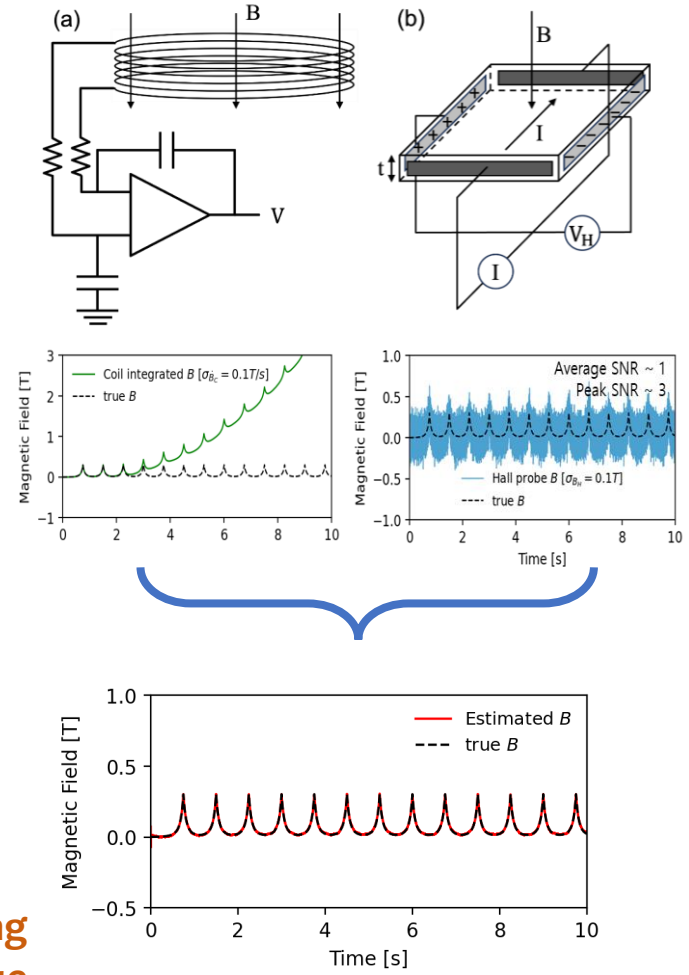
Taeyoung Ahn, Sumin Yi, Gunsu Yun, 2024, POSTECH, KFE

Reactor-relevant diagnostics will be desiged and installed on KSTAR environment for hardware testing & control evaluation

Diagnostics	State Estimation	Plasma Control	Actuators*
Magnetics	Real-time equilibrium (EFIT)	Ip (≤ ± 0.5 MA)	PF coils
Real-time equilibrium (EFIT)	MSE-class AI inference	Shape (boundary, X-point)	Gas puff
MSE-class AI inference	Kinetic EFIT	q95 (≤ ± 0.1)	SMBI
Kinetic EFIT		β_N	ECH
Interferometer, > 100 kHz		Electron density (~ 1%)	RMP
Reflectometer, > 100 kHz		Temperature (5 ~ 10%)	NBI
Thomson-class AI inference			*Prediction horizons vary (5 ~ 100 ms)
Multi-layer neutron detectors		Fusion power (5 ~ 10%)	
Bolometer, IR, AI inference		Divertor condition (detachment)	
ECE/CES-class AI inference		MHD, ELM (Type I: 30 ~ 50 ms)	
mm-wave (ECEI etc), 50 ~ 100 kHz			

Control concept and control requirements for pilot devices

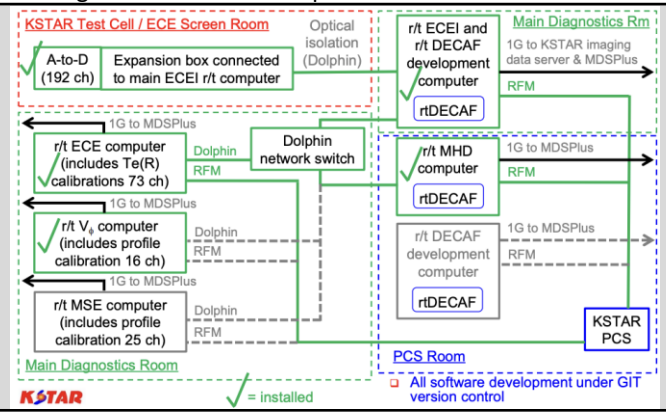
Synthetic magnetic sensor (coil + Hall sensor)



Design of reactor-relevant magnetic diagnostics using synthetic diagnostics technique

Jaewook Kim et al., Nucl. Fusion 65, 046008 (2025)

Most KSTAR diagnostics are already equipped with RT capabilities

Short -	Full- name	Main Roles in RT	Progress/Current Status	Future Plans/Remarks
TCI	Two-Color Interferometer	RT Line- and Profile n_e Control	✓ Full 5-chord RT measurement is routinely available ✓ Density profile control was demonstrated by a collaboration with Princeton University	• Extends total chord number up to 10 (8 by FY 2026) for more accurate ne profile reconstruction • Automation and feedback alignment for robustness
TS	Thomson Scattering	RT T_e profile - measurement	✓ Neural-network (NN)-based RT calculation was demonstrated successfully by facilitating GPU & 5 GSPS digitizer	• Ready for RT Te control in the PCS
MSE	Motional Stark Effect	Current density j_p and q profile to PCS	✓ RT current density profile j_p to KSTAR PCS via rt FFT modules from analog polarization signal. Local test is complete and delivered on site.	• Integrated and tested in FY2025-2026 • Will be online in FY2027
		rtMSE system to DECAF for pitch angle and deltaB		• In DECAF system, led by Columbia Univ. USA, (Disruption Event Characterization & Forecasting) • most rt systems are installed and integrated. • Test and integrated operation of each part is ongoing
ECE(I)	Electron-Cyclotron-Emission (Imaging) Radiometer	rt Te and δTe data streaming to DECAF		
MD	Magnetic Diagnostics	rt-MHD spectrogram by rt FFT streaming to DECAF		
CES	Charge Exchange Spectra	rt-V_ϕ (toroidal rotation velocity) and Ti (ion Temperature) to DECAF		
		RT V_ϕ and Ti To the KSTAR PCS	✓ NN-based RT calculation without heating neutral beam modulation ✓ that extends RT capability significantly	• To be applied for RT beta control & locked mode detection
VSS	Visible Spectroscopy	Machine-learning based L-H transition detection including ELMy H-mode identification.	✓ One D-alpha channel has been used in PCS w/ RT measurement since 2020. The algorithm is based on artificial neural-network.	• More advanced L-H transition related physics study and control
		RT control of impurity sources	✓ One impurity filter channel and one visible bremsstrahlung (VB) are being ready for PCS connection.	• W avoidance scenario will be developed based on RT impurity signal
LP	Langmuir Probes	RT I_{sat} (saturated current) measurement	✓ Up to 6 RT channels are installed and demonstrated under RT feedback control of divertor detachment	• Extends application for specific experiments. • Increase the number of RT channels if necessary
IRVB	Infra-Red Video Bolometer	RT Radiation power distribution in 2D image	✓ RT feedback loop of radiation front control by N_2 seeding has been established and demonstrated its working	• Many potential subjects of RT control applications • w/ system optimization and improvements

⇒ **Contribution to ITPEA Diagnostics RTSWG :** *Develop diagnostic RT measurement processing algorithms following the IO guideline and consistent with ITER SRO diagnostics.*

We need more actuators:
DEMO may need fewer - finding the optimal set requires many now

- Actuators in DEMO are more limited, (magnet, fuel/seeding, H&CD)
  not bidirectional, (increasing density/power)
  and coupled (control of single parameter is not intuitive)
- More actuators with difference types in different position

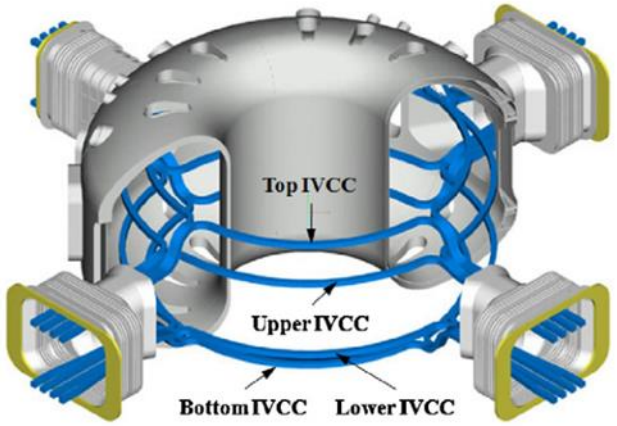
Actuator Candidates for KSTAR Upgrade

- alternative IVCC (or relevant control experiment with current IVCC)
- controllable on/off-axis H & CD (NBI, ECH, in-vessel LHCD, top ECCD, ...)
- varius type of fueling/seeding/pellet injectors
- more innovate actuators and passive controller (RE mitigation coil, passive stabilizer)

⇒ KSTAR as the best machine to develop & verify AI/ML control algorithm for burning plasma high-performance operation

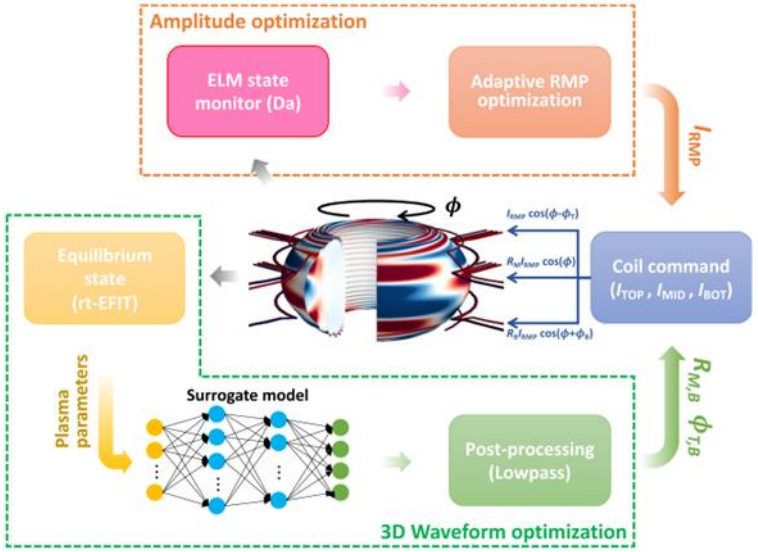
KSTAR has powerful IVCC capable of various physics studies and control experiments

- ITER-like in-vessel three-row coils
- 2 turns x 3 rows x 4 window-pane-like coils
- Flexibility in spectrum through independent amplitude and phasing control

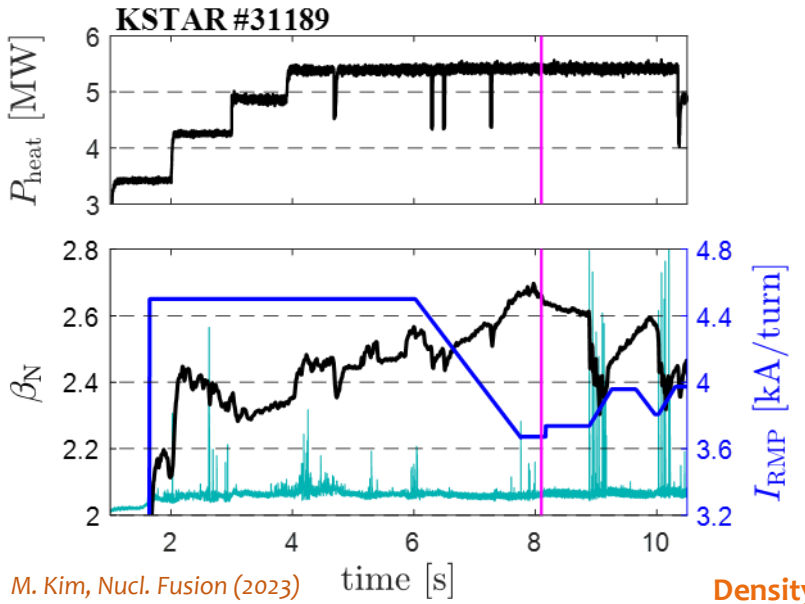


TOP1	TOP2	TOP3	TOP4	$I_{TOP}\cos(\phi - \phi_T)$
MID1	MID2	MID3	MID4	$I_{MID}\cos\phi$
BOT1	BOT2	BOT3	BOT4	$I_{BOT}\cos(\phi + \phi_B)$

H. K. Kim, Fus. Eng. Des. (2009)
H Han, Fus. Eng. Des. (2016)

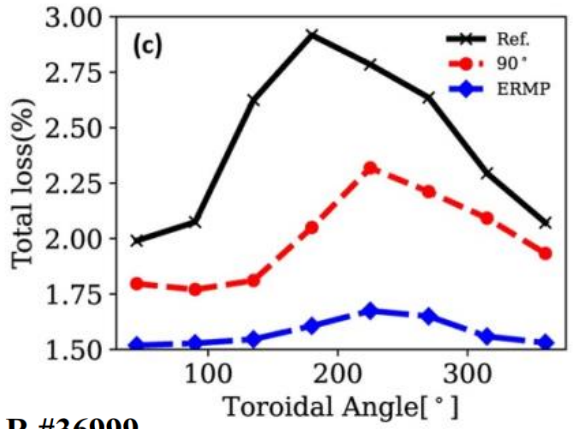


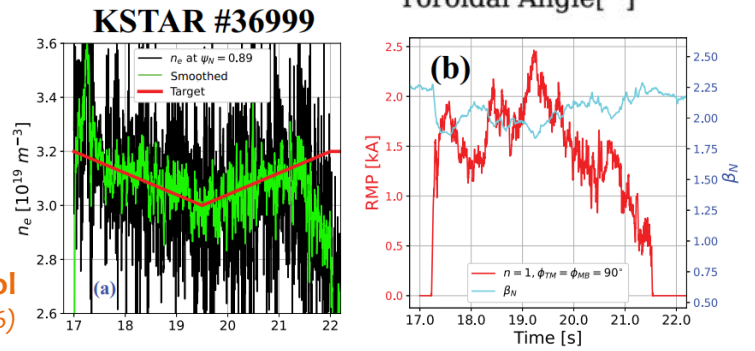
ELM crash control using IVCC
S. K. Kim, Nature Comm. (2024) / R. Shousha, Nucl. Fusion (2024)



M. Kim, Nucl. Fusion (2023)

Fast ion confinement enhancement
S.M. Yang, Nucl. Fusion (2023)



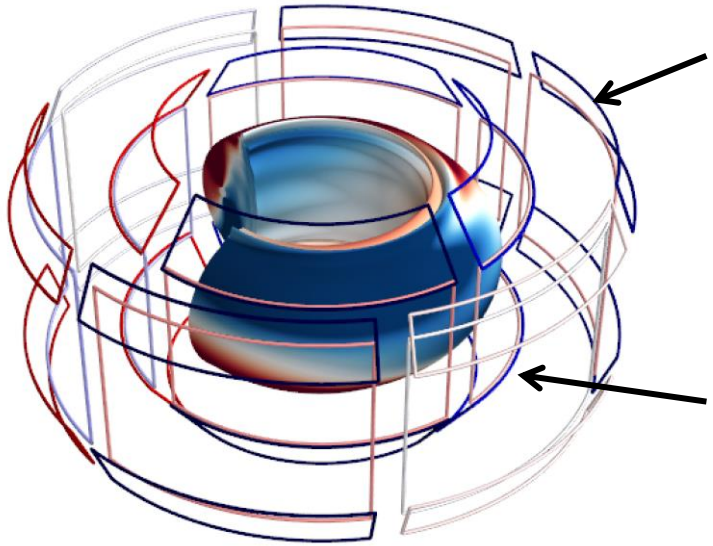


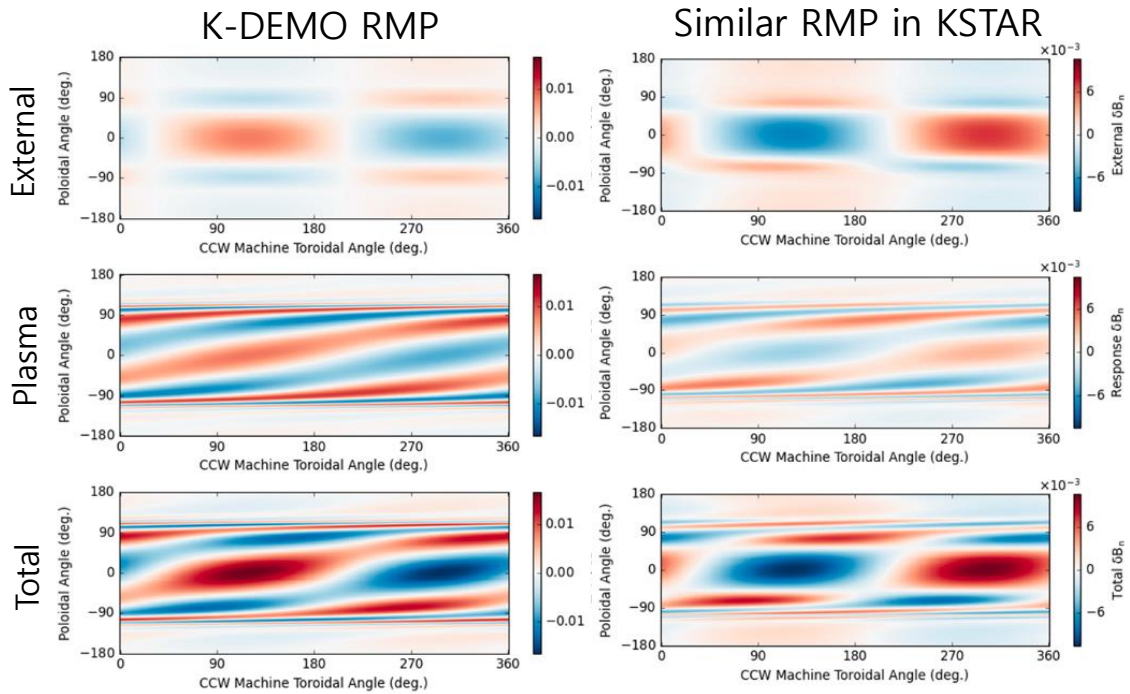
Density control
M. Kim, Plamsa Phys. Control. Fusion (2026)

IVCC will be significantly beneficial for burning plasma but difficult to implement

- IVCC is a powerful tool for stabilizing vertical instability, and controlling ELMs and RWMs.
- However, challenges at the reactor stage: massive radiation and heat threatening its availability, and difficult maintenance as an in-vessel component
- It is necessary to develop durable materials for IVCC and make its design maintenance-friendly.
- As an alternative, ex-vessel control coils can be considered, but their coupling is weaker.

- Flexibility in KSTAR IVCC system can allow to simulate the RMP effect in future machine.



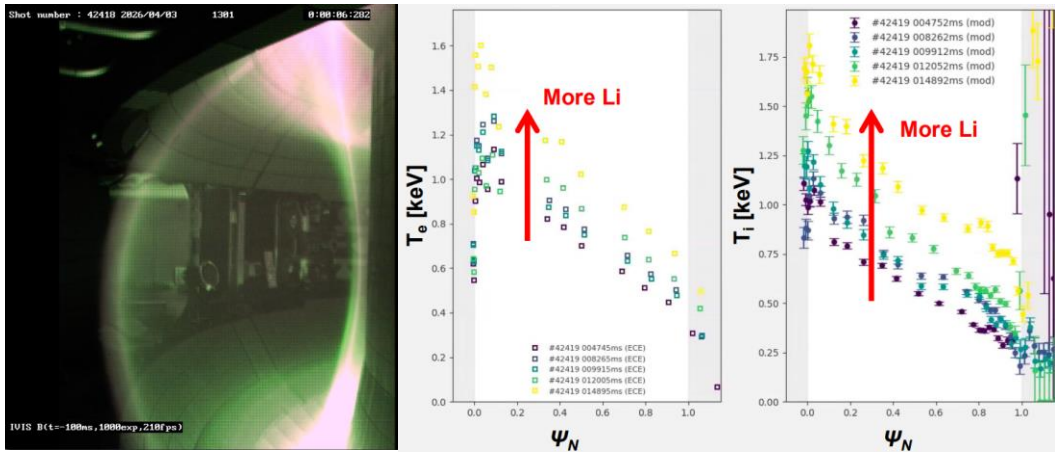


Courtesy of Prof. J.-K. Park (SNU)

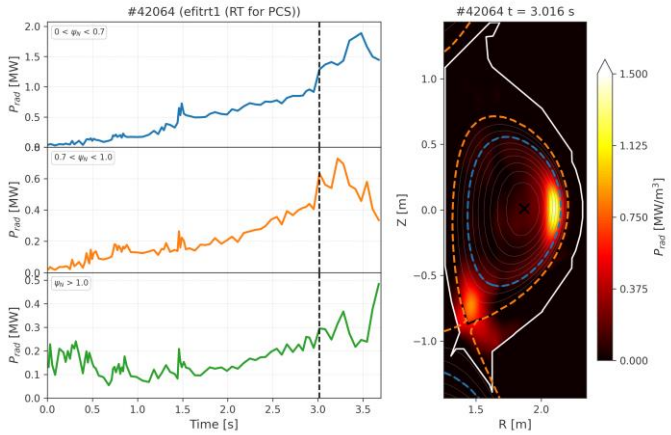
Burning plasma control is strengthened by diverse fueling and seeding strategies

- **Fueling**
  - Sustains D–T density for self-sufficient burn while staying below disruption limits (e.g., Greenwald).
  - Shapes core and pedestal-top density, supporting helium ash transport and fusion power regulation.

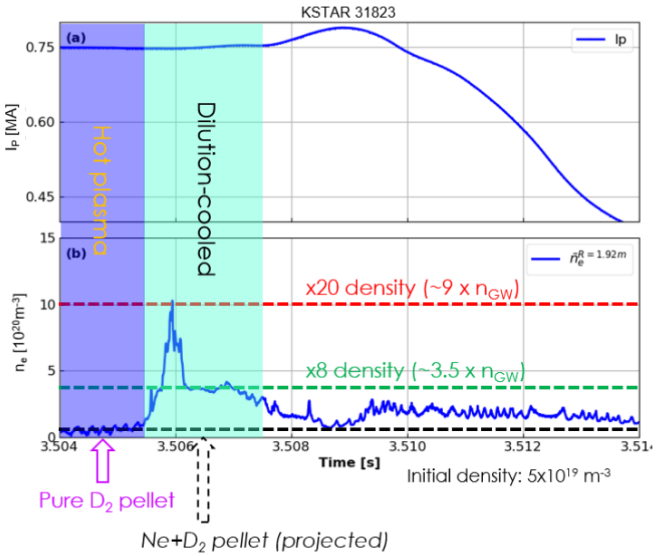
- **Impurity Seeding**
  - Enables radiative exhaust and divertor detachment, protecting plasma-facing components.
  - Tunes edge radiation and pedestal dynamics to preserve confinement with minimal fuel dilution.



Li injection experiments using impurity power dropper

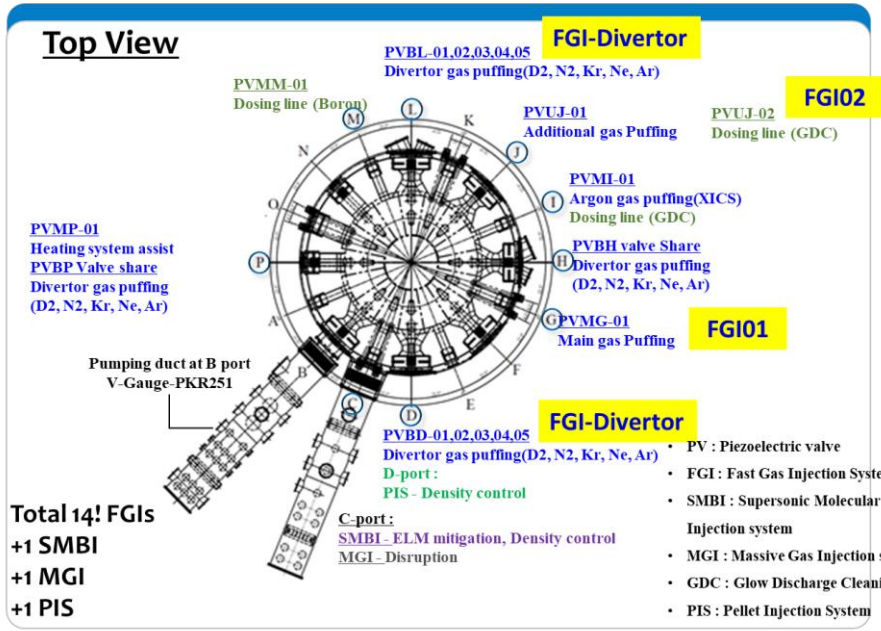


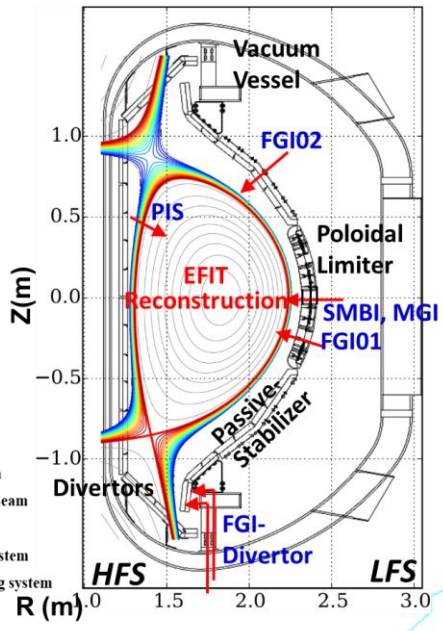
N seeding experiments for W screening



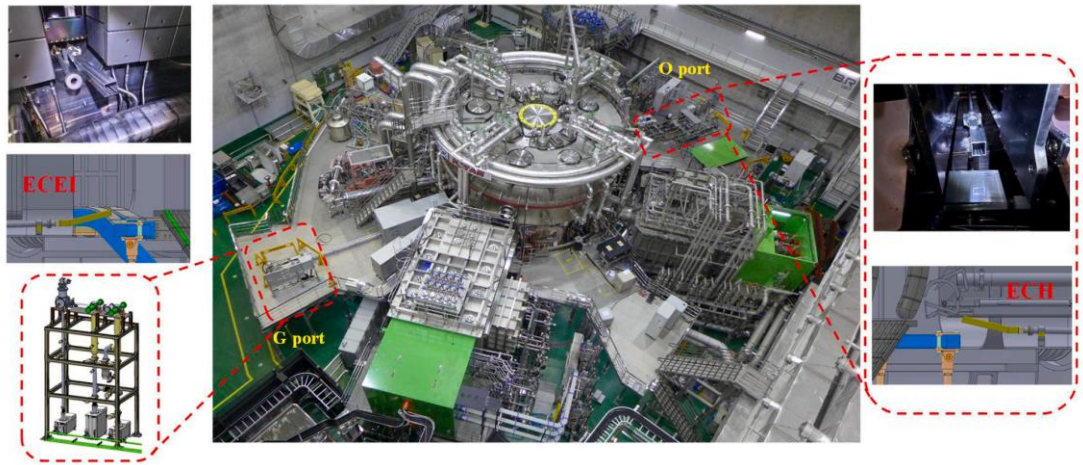
Disruption mitigation using shatterd pellet injectors

KSTAR is equipped with diverse fueling and seeding actuators



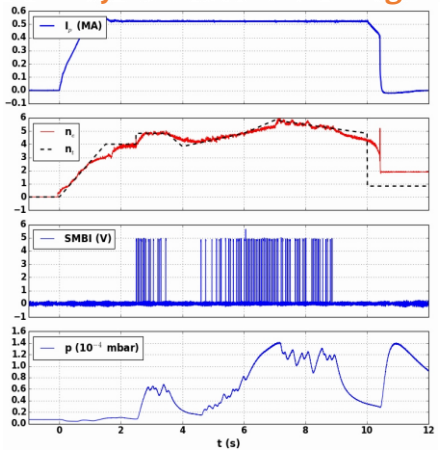


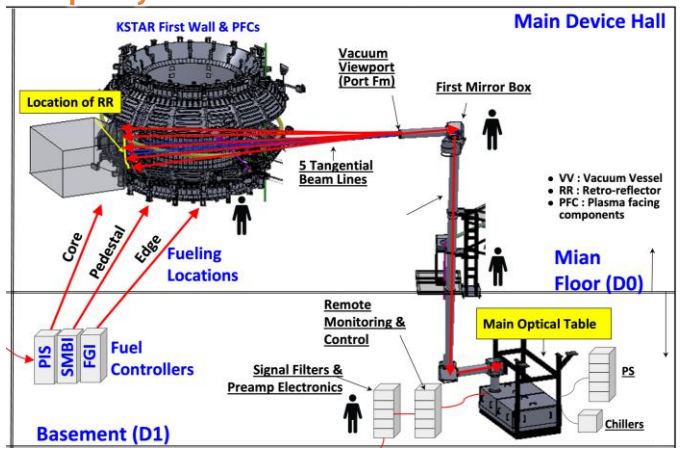
Locations of the Fueling Systems on KSTAR

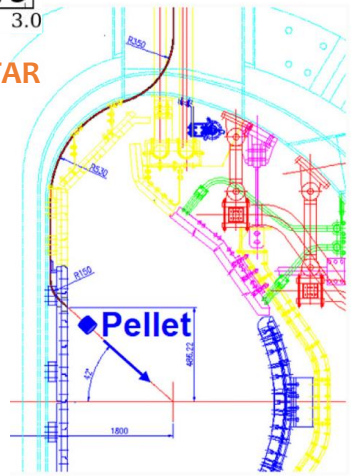


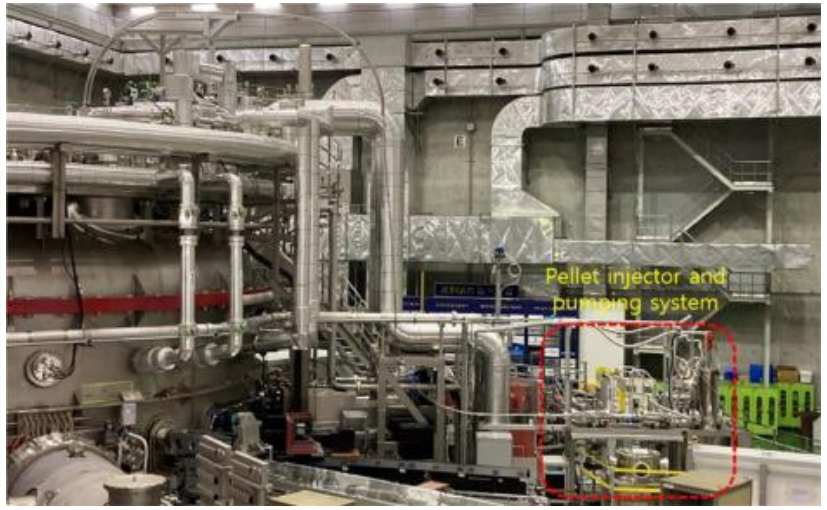
Duel Shattered Pellet Injector with relevant diagnostics

Density control results using multi-input system







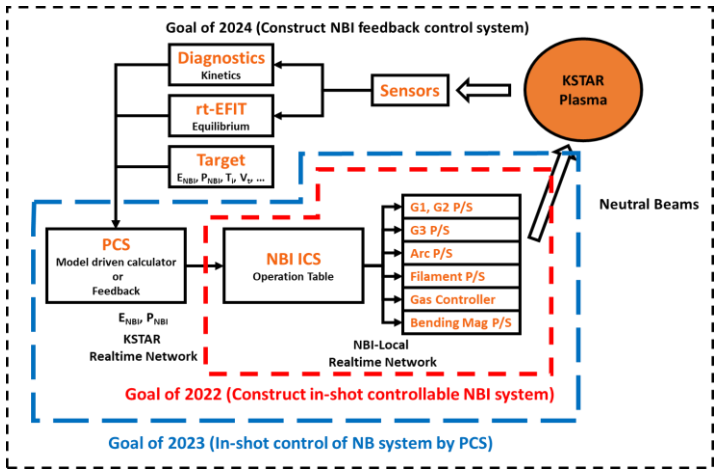


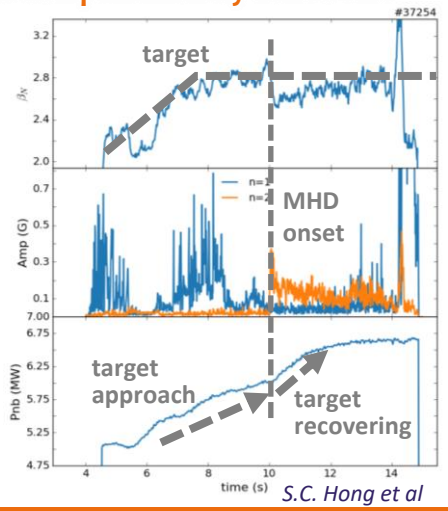
Pellet Injector system with guiding tube

Heating and Current Drive systems play a key role in controlling plasma stability and shaping profiles

- **MHD Mode Stabilization**
  - Suppresses tearing modes and neoclassical tearing modes (NTMs).
  - Localized current drive techniques (e.g., ECCD, LHCD) are used for precise current profile shaping.
- **Pressure and Shape Control**
  - RF heating (ECH, ICRH) can modify local pressure profiles.
  - Balances pressure and current distributions to optimize plasma shaping and extend beta limits.
- **Support for Long-Pulse Steady-State Operation**
  - Compensates for current and profile evolution during extended operation.
  - Enables sustained steady-state burning plasma conditions.

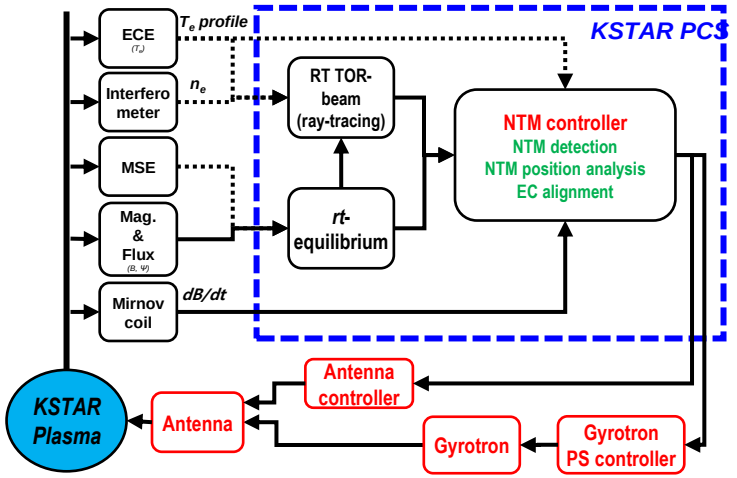
Plasma pressure degradation by MHD onset was compensated by active NBI

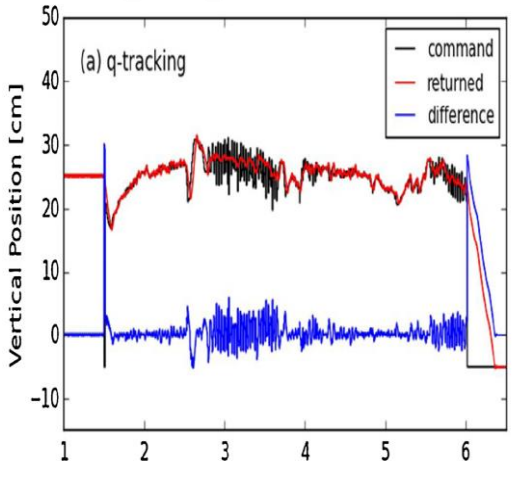




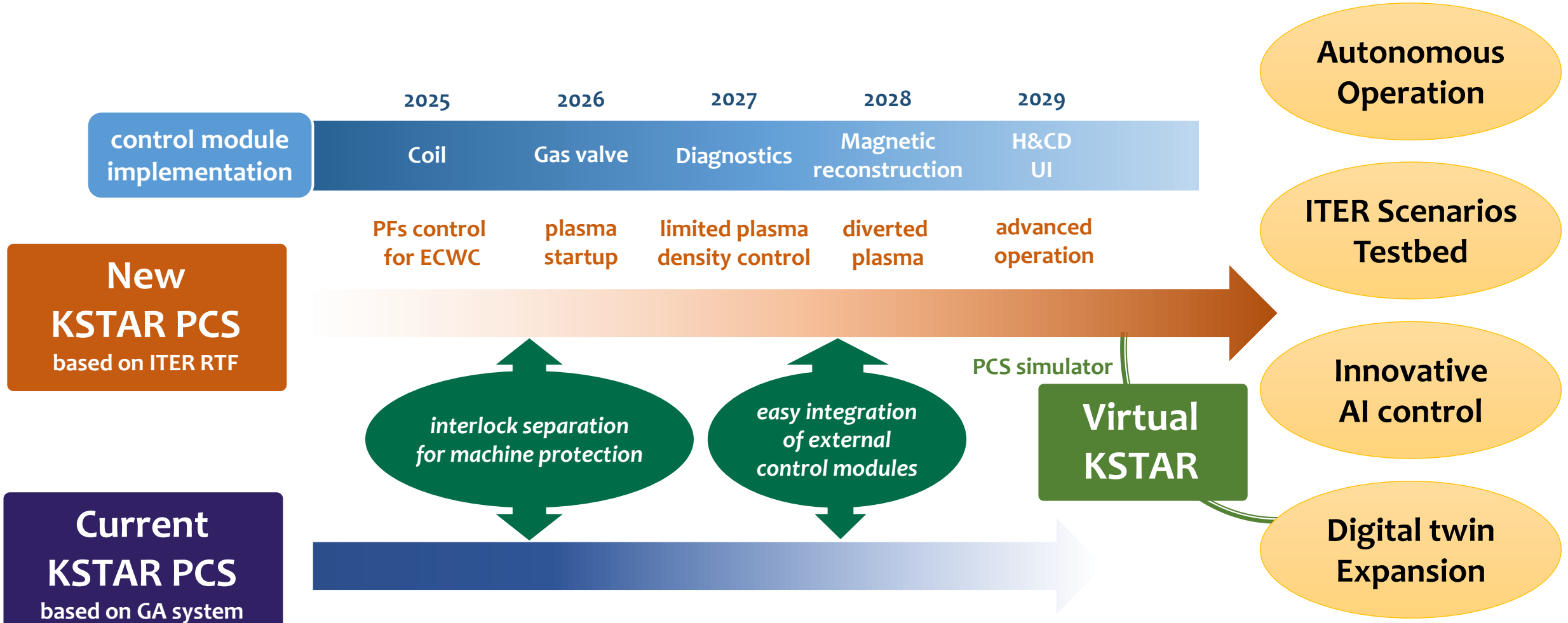
S.C. Hong et al

q=2 surface tracking by vertical target positioning using EC control



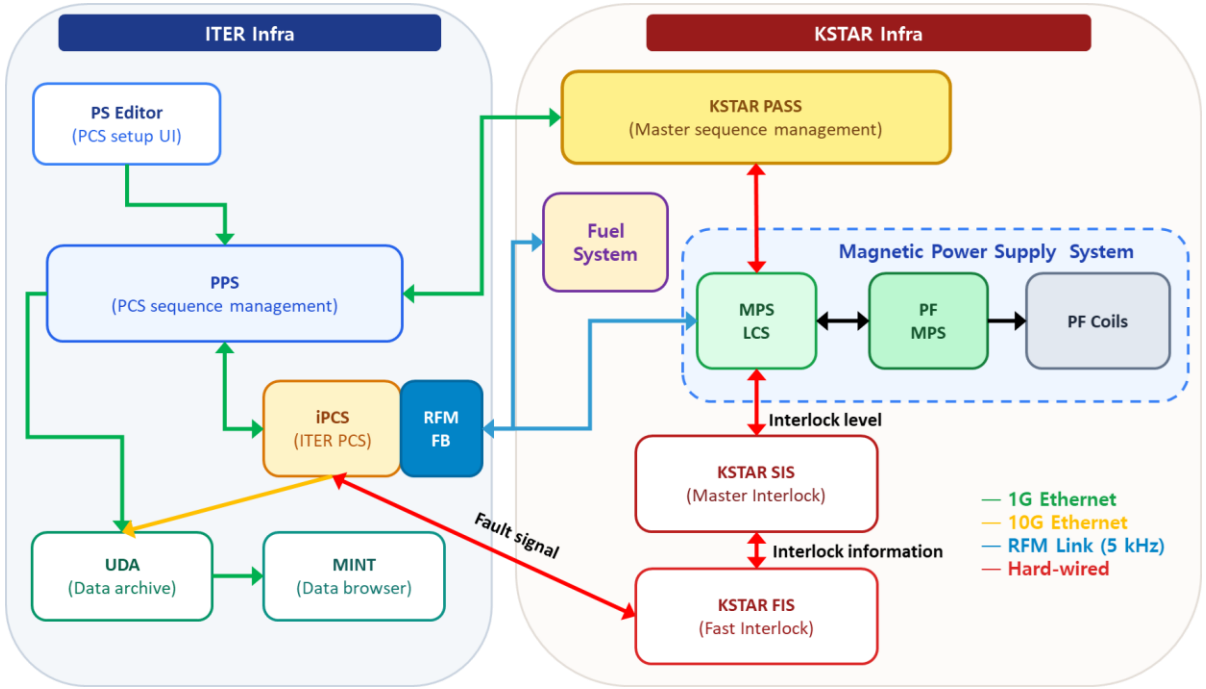


A new PCS is being developed for ITER compatibility, innovative control logic integration, and built-in machine protection



Plasma startup experiment was successfully executed on the new PCS

1 ITER PCS – KSTAR integration

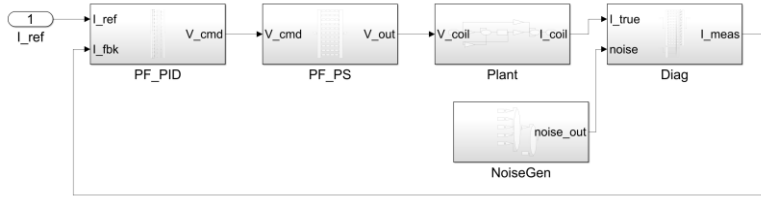


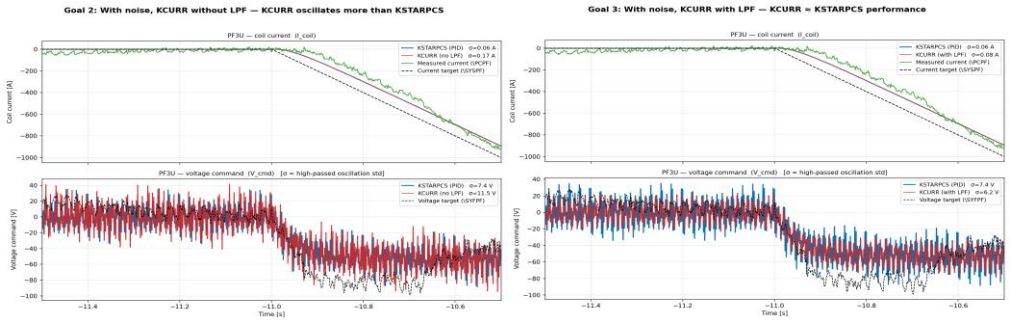
Key results

- iPCS and its supporting infrastructure successfully ported to the KSTAR environment — PPS and KSTAR PASS sequence interoperation verified
- KCURR, the iPCS PF coil controller, reproduces the behavior of the KSTAR PCS PF controller in simulation
- Plasma startup experiment successfully executed — prefill fueling, breakdown and Ip ramp-up all operated as intended

2 SIMULINK validation of KCURR

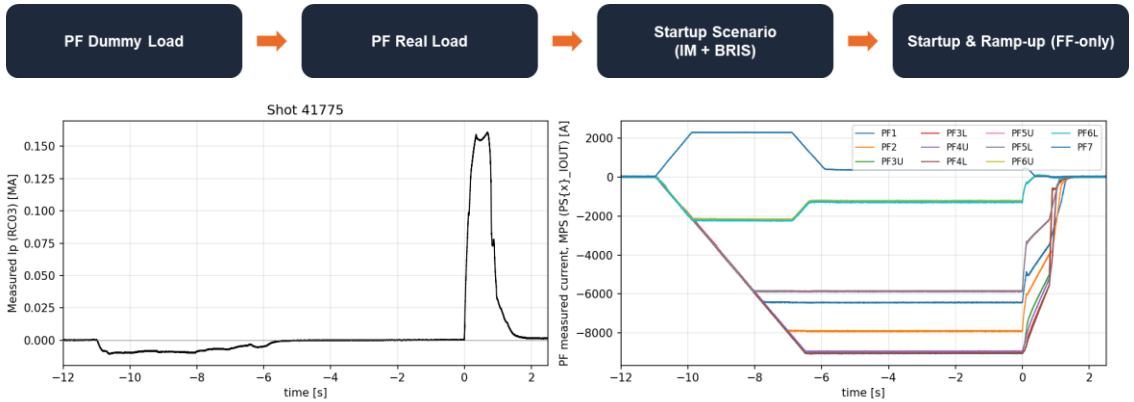
LPF ahead of KCURR — performance matches the KSTAR PCS PF controller





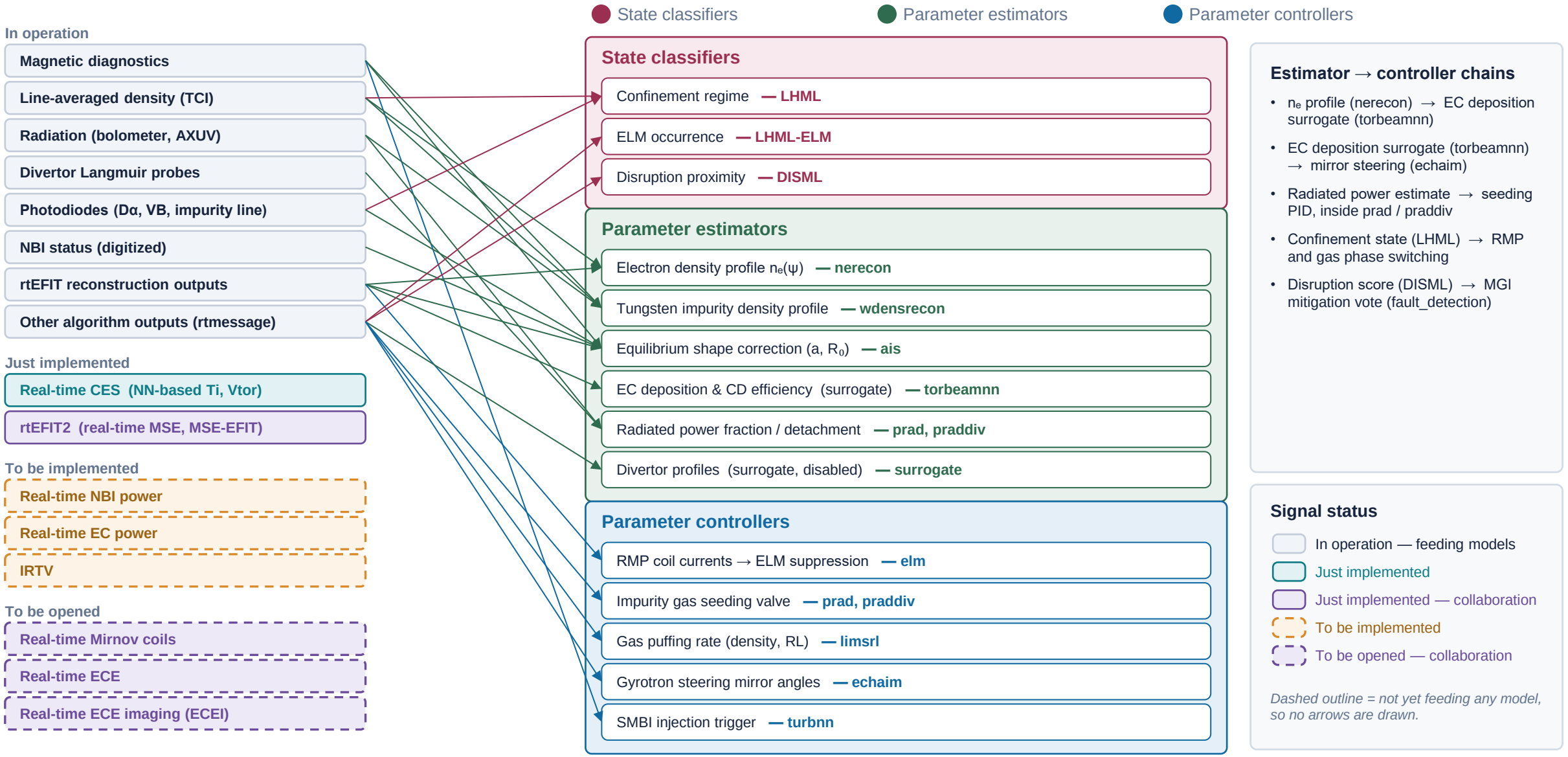
3 PF real load & plasma startup

Shot 41775 — prefill, breakdown and Ip ramp-up driven by the ITER PCS



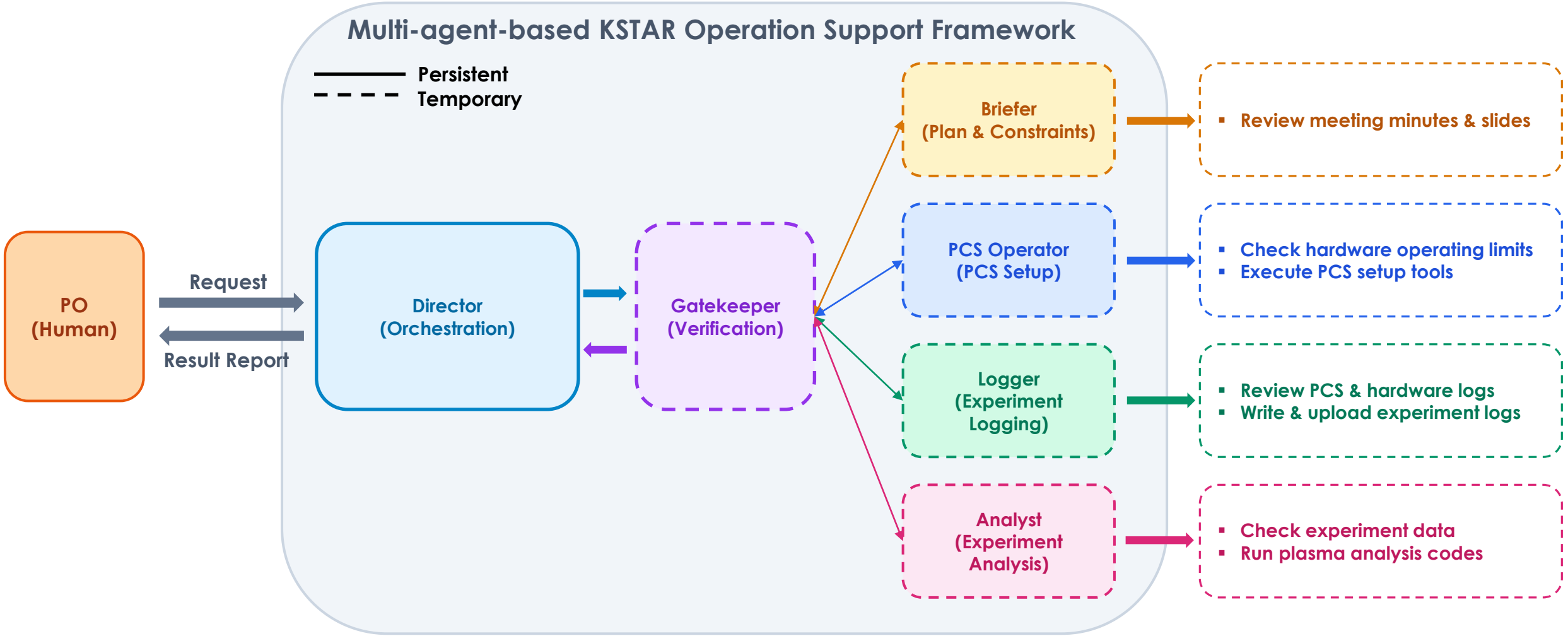
Details in poster — *"Validation of ITER PCS-Based PF Coil Control in KSTAR: From Simulation to Plasma Startup", Y. Lee et al., SOFT 2026*

Prototype AI/ML control modules are implementing on current PCS



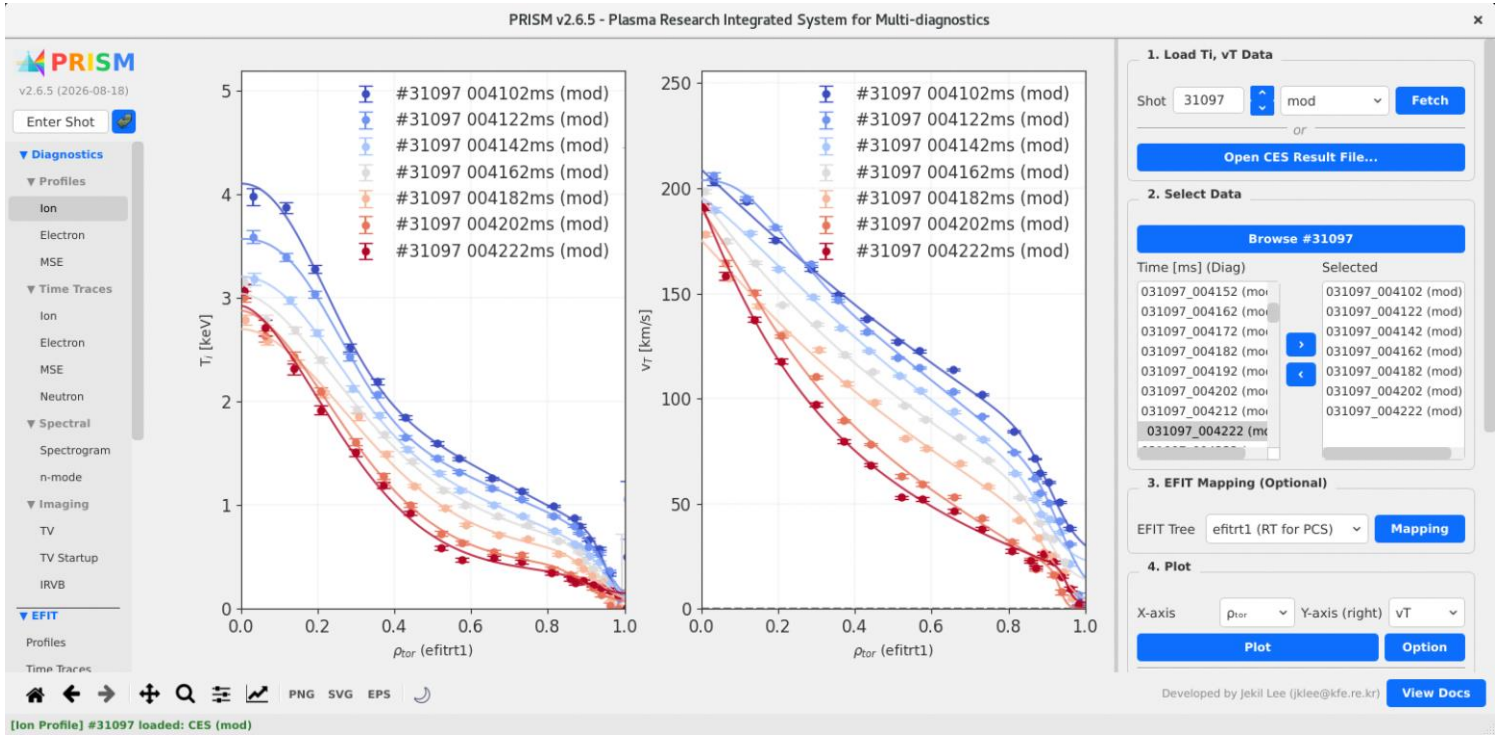
Multi-agent based KSTAR operation support system is under development

- **Implementation:** Planned for local deployment using local LLMs on an NVIDIA RTX 6000 (96GB) workstation.
- **Roadmap:** Scheduled for pilot operation and iterative refinement during the 2027 KSTAR campaign.

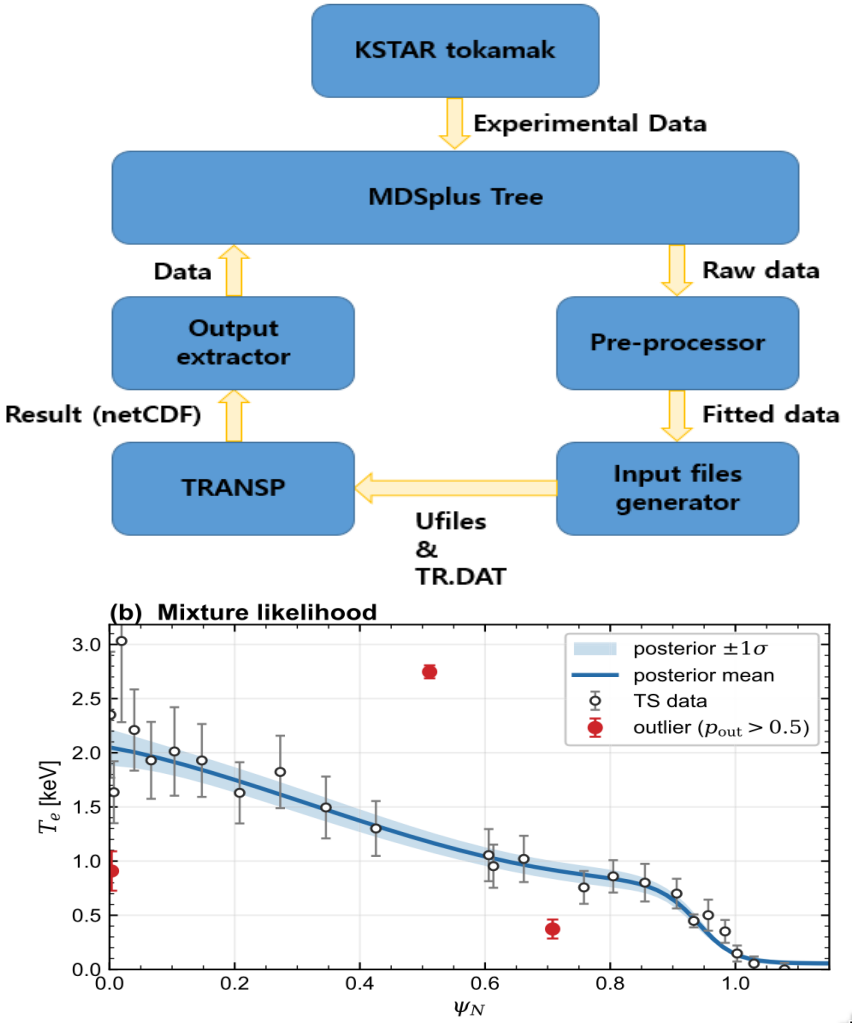


AI-based tools are already multiplying, and this roadmap will only accelerate that

- KSTAR's role is not to build those tools itself,
  but to provide the **experimental and data environment** that supports them
  digital twin, AI-ready data, synthetic diagnostics,
  open and ITER-compatible PCS, and well-connected sensors & actuators
- As each of these pieces comes online, the number of tools researchers can build on top of them will only keep growing



PRISM – KSTAR data visualization too in single GUI with modular architecture *(by J.K. Lee)*



TRANSP tool providing automated workflow based on Bayesian profile fitting capable of between-shot analysis *(by J.K. Lee)*

SUMMARY

KSTAR : what KSTAR is doing, and why

KSTAR develops high-performance, reactor-relevant plasma scenarios that ITER and future demonstration reactors will need meeting its strict performance-and-stability requirements together is what first calls for AI-based control

AI : why fusion needs AI, and where to use it

AI already reaches across fusion research and offers real advantages
but closing the remaining gaps in data, trial-and-error, and error tolerance requires a device prepared for that purpose.

Pathway : what KSTAR is preparing

KSTAR is building the digital twin, data, diagnostics, actuators, and control-system infrastructure
that provides the best environments for testing the AI control techniques for next-gen reactors
and let researchers develop and test their own AI-based tools.