The Role of KSTAR in Burning Plasma Research as an Innovative Control Test Bed

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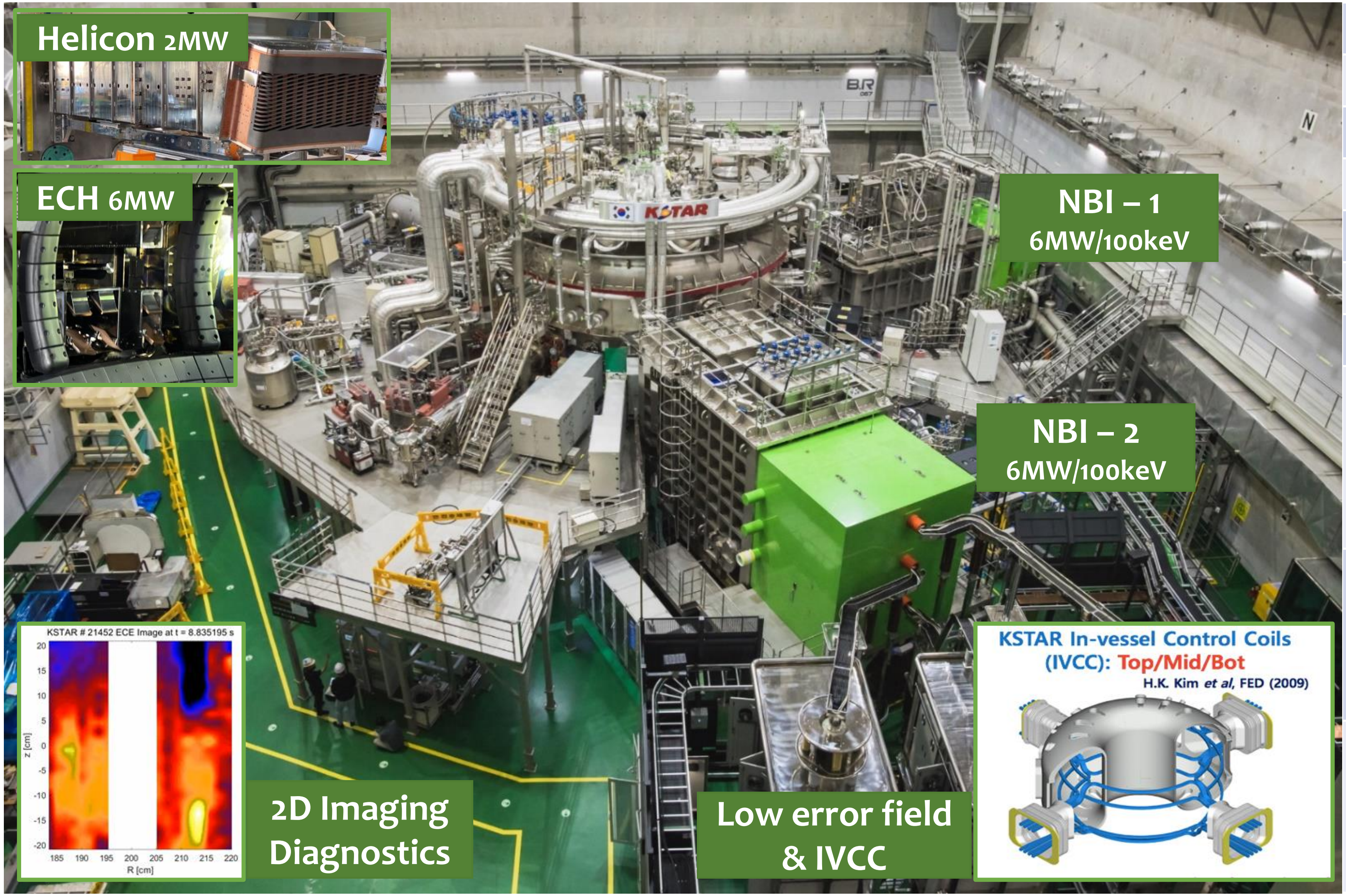
and on behalf of KSTAR Team and collaborators

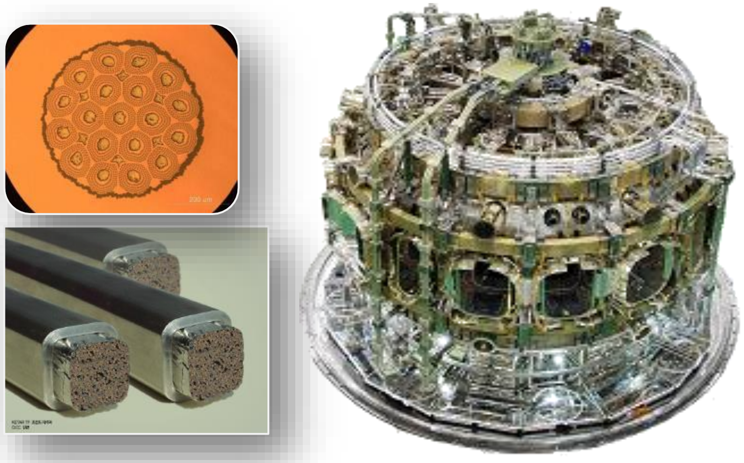
Korea Institute of Fusion Energy

KSTAR is a mid-size SC tokamak for high perf. & steady-state op.



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
<u>Pulse Length</u>	
designed	300 s
achieved	102 s (β_N > 2)
	48 s (high Ti)
<u>H & CD</u>	
NBI	12 MW
ECH	6 MW
Helicon	2 MW
<u>PFC</u>	
Wall	C tile
Divetor	W monoblock

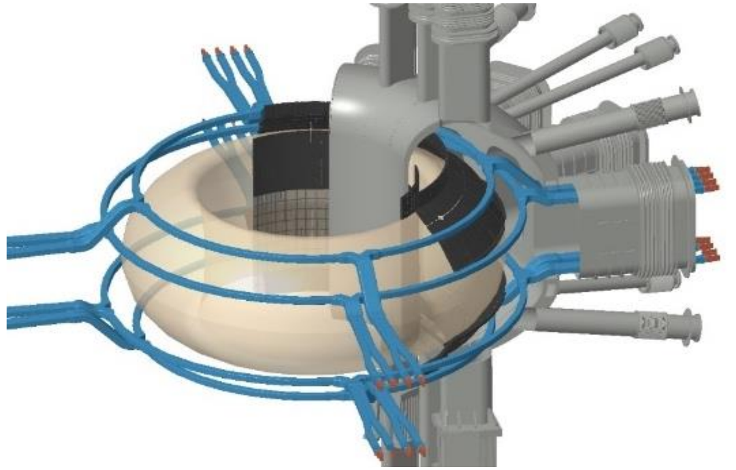
What makes KSTAR unique in the Fusion research landscape



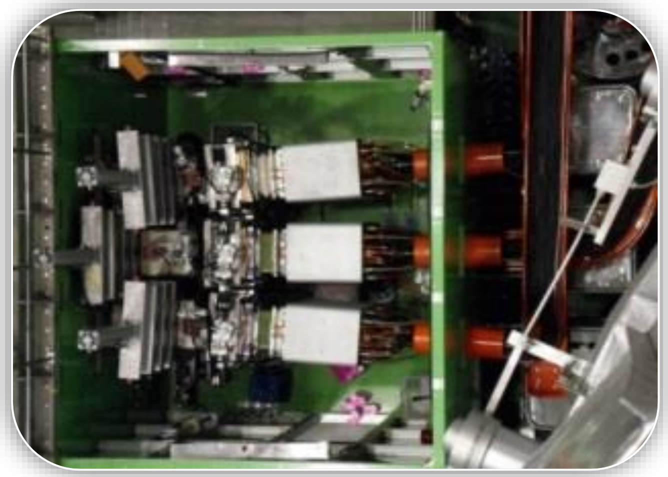
Highly engineered SC magnets with ideal symmetry & extremely low error field

Exceptional toroidal symmetry: with 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.



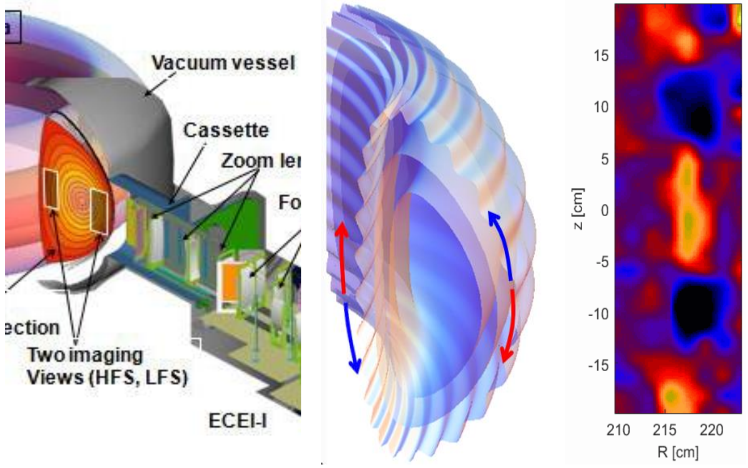
In-vessel coils with flexible 3D mode control (n=1, 2) up to 10 kHz



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

Long-pulse heating systems: Support sustained high-temperature plasma operation over 10 keV for long durations.

Advanced imaging diagnostics: Provide deep insights into plasma behavior and physics.

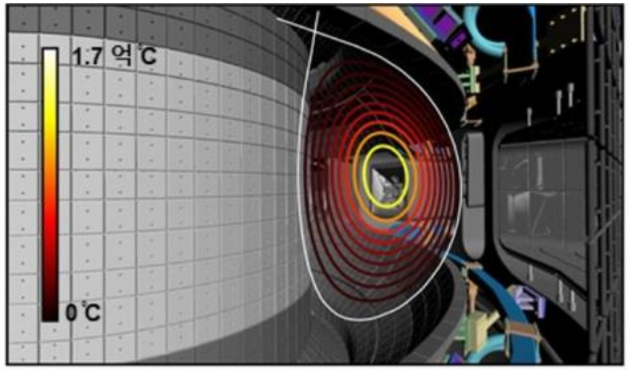


Advanced 2D/3D imaging diagnostics to validate fundamental plasma physics

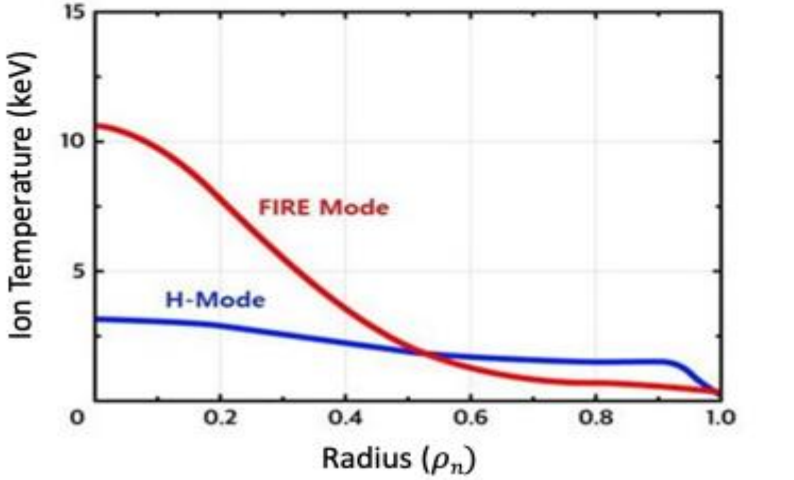
KSTAR achievements in advanced scenario development

- **Long-pulse operation in standard H-mode** (ITER-relevant, $\beta_N \approx 2$) : sustained up to **102 s**
- **Development of novel operation modes**
  - ✓ FIRE mode (Fast Ion Regulated Enhanced) with Ti > 10 keV : sustained up to **48 s**
- **High-pressure plasma operation** (β_N >3) : sustained up to 12 s

"Pioneering advanced scenarios for ITER and future fusion reactors"



KSTAR plasma operation reaches ion temperatures of 10 keV

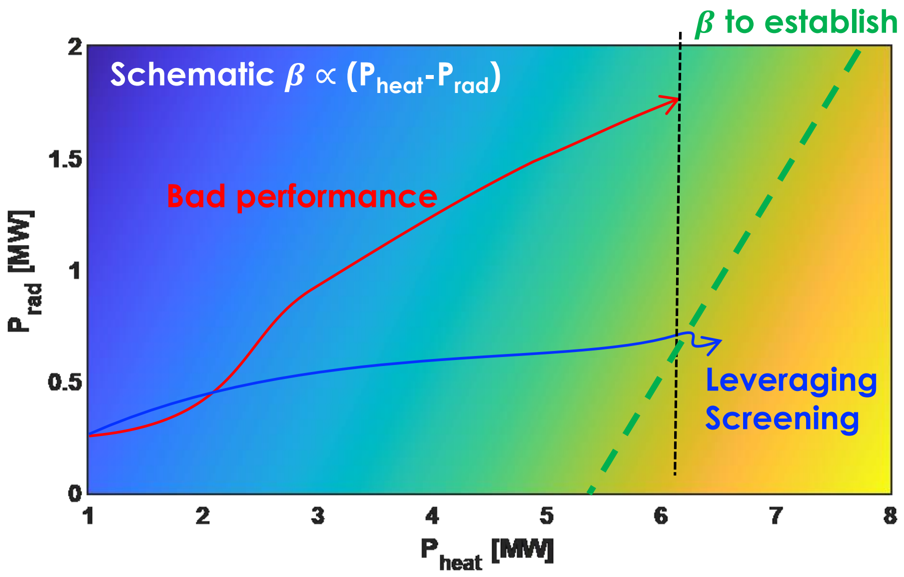


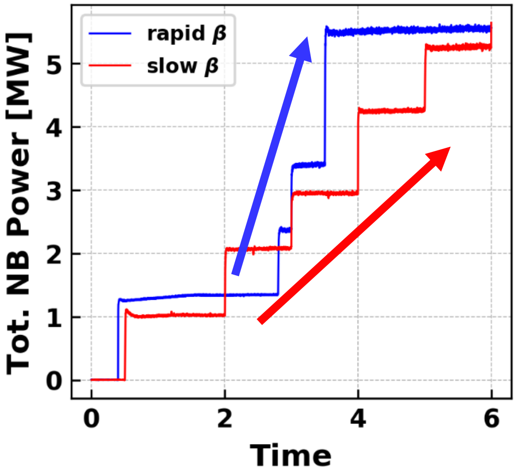
Comparison between standard H-mode & FIRE mode

Advanced scenario development on W divertor environments

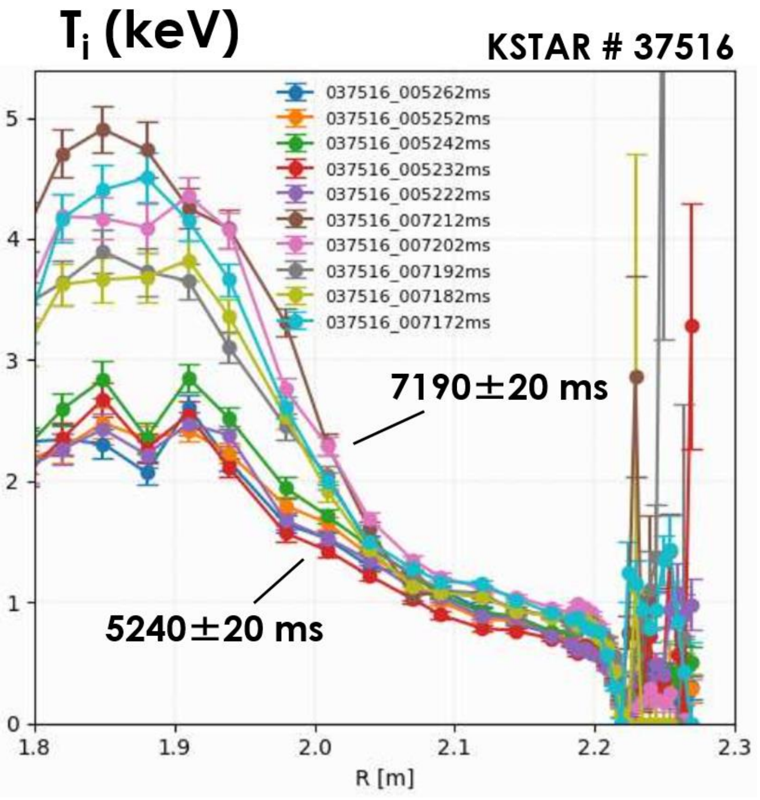
- **W accumulation mitigation with H-mode** :
  - ✓ fully recovered H-mode performance (H_{98} ~ 0.97, f_{rad} < 16%)
  - ✓ ECH + Strong shaping + PVD + Moderate P_{NB+EC}
- **Reproduce ITB formation with high $\beta_p$scenario** :
  - ✓ based on DIII-D high β_p scenario
  - ✓ more investigation require for higher confinement & larger radius

"Finding robust solution for high performance burning plasma operation"



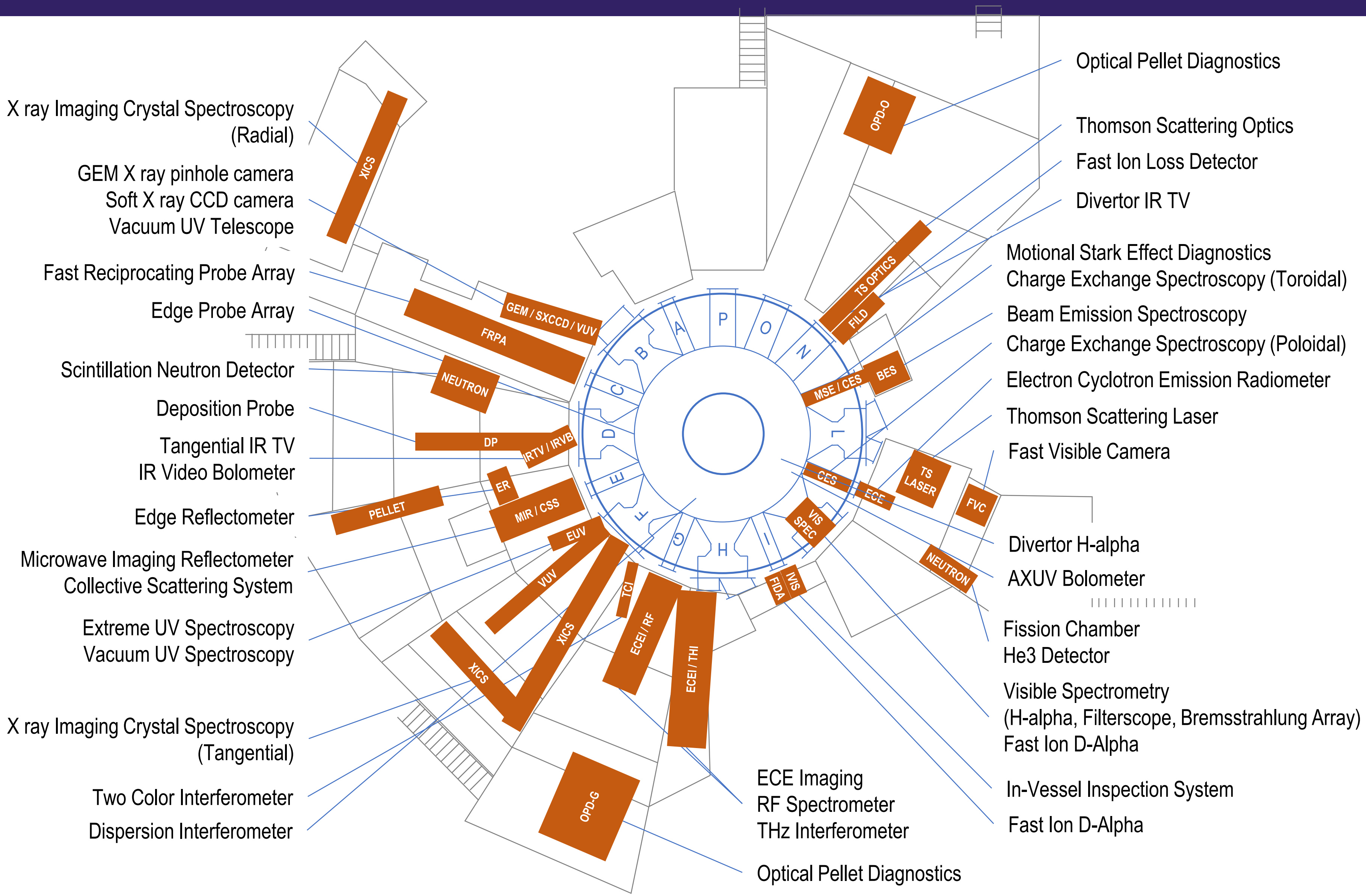


optimized recipe with "β kicking" for robust mitigation of W accumulation

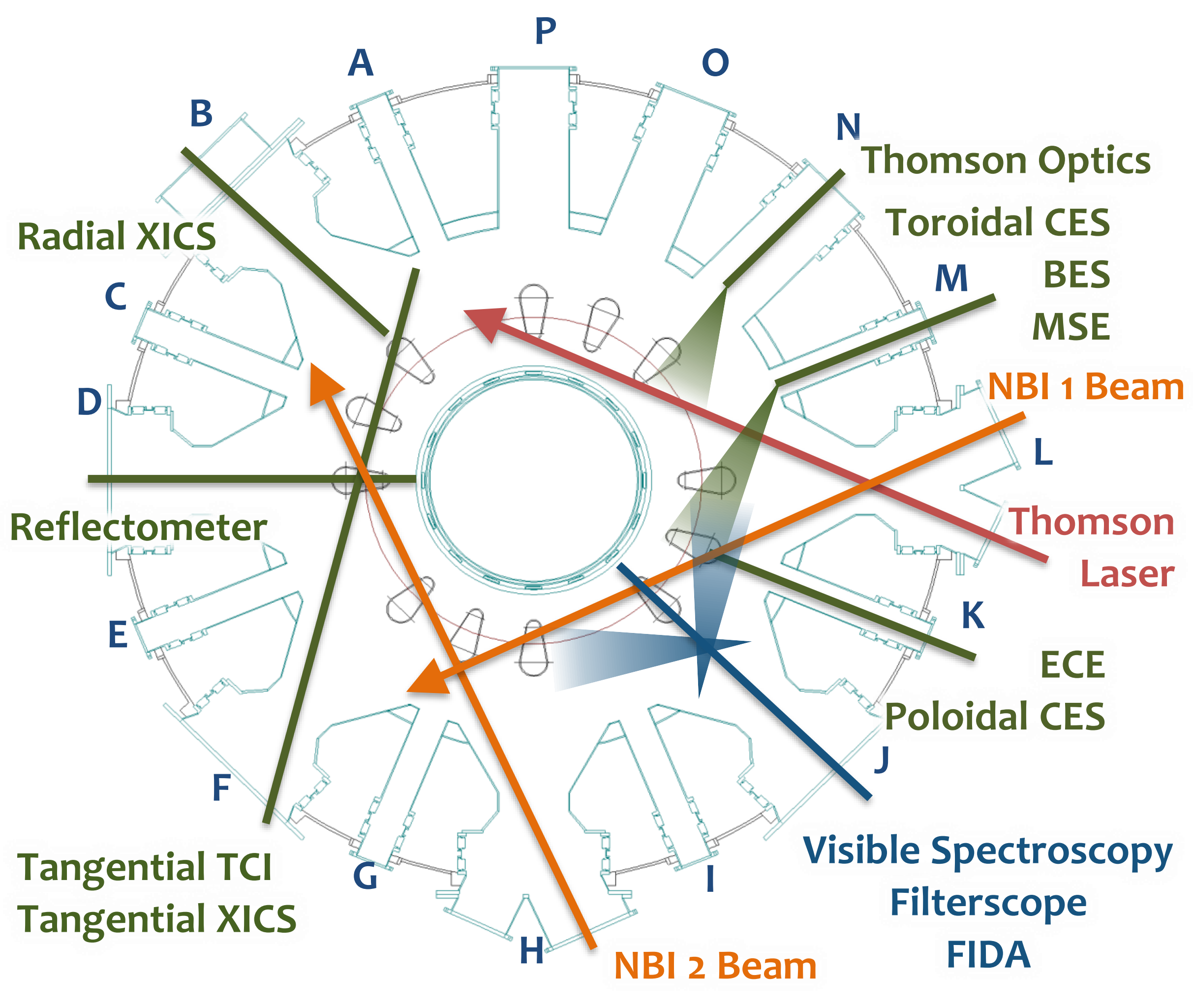


ITB (internal transport barrier) formation with high βp scenario

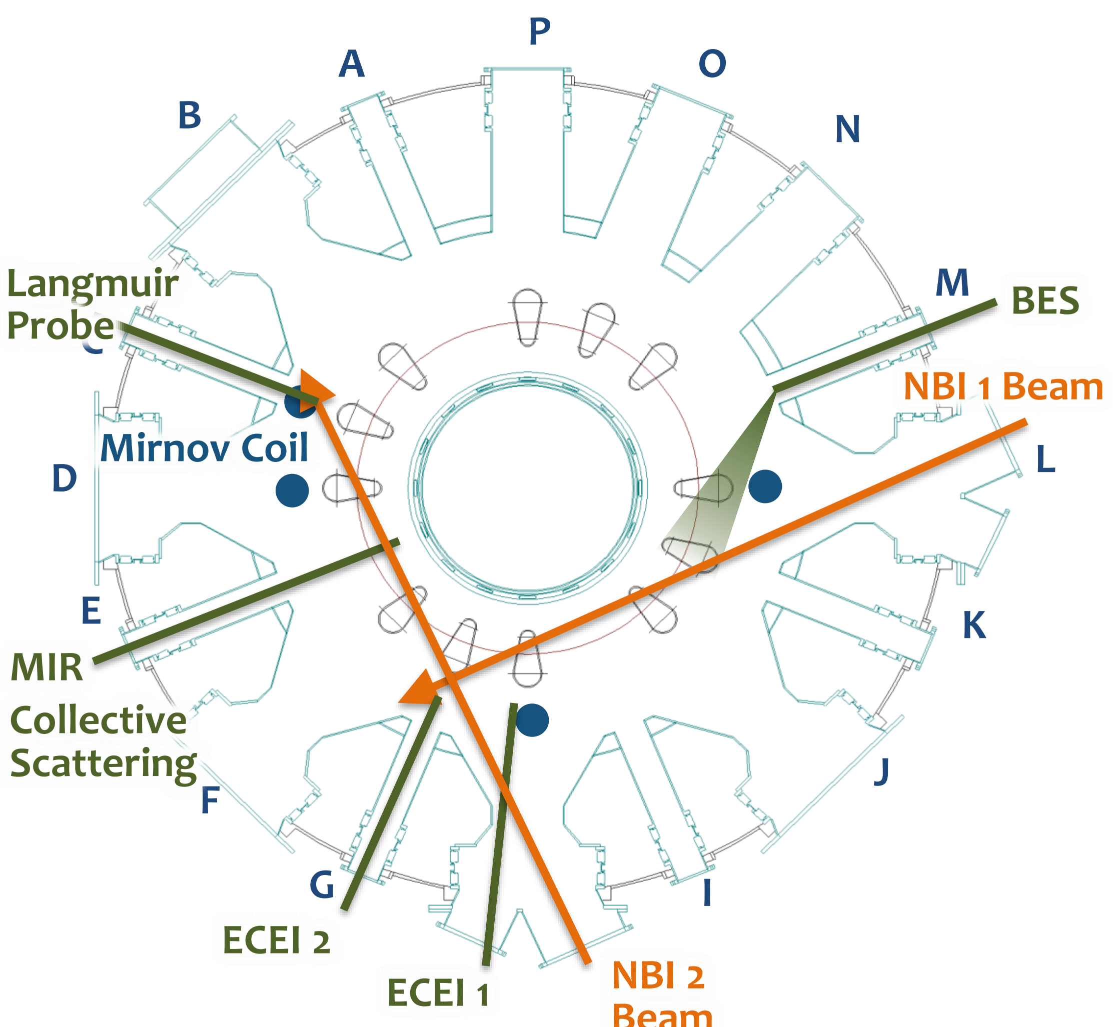
KSTAR Diagnostics - Overview



KSTAR Diagnostics – Toroidal Layouts

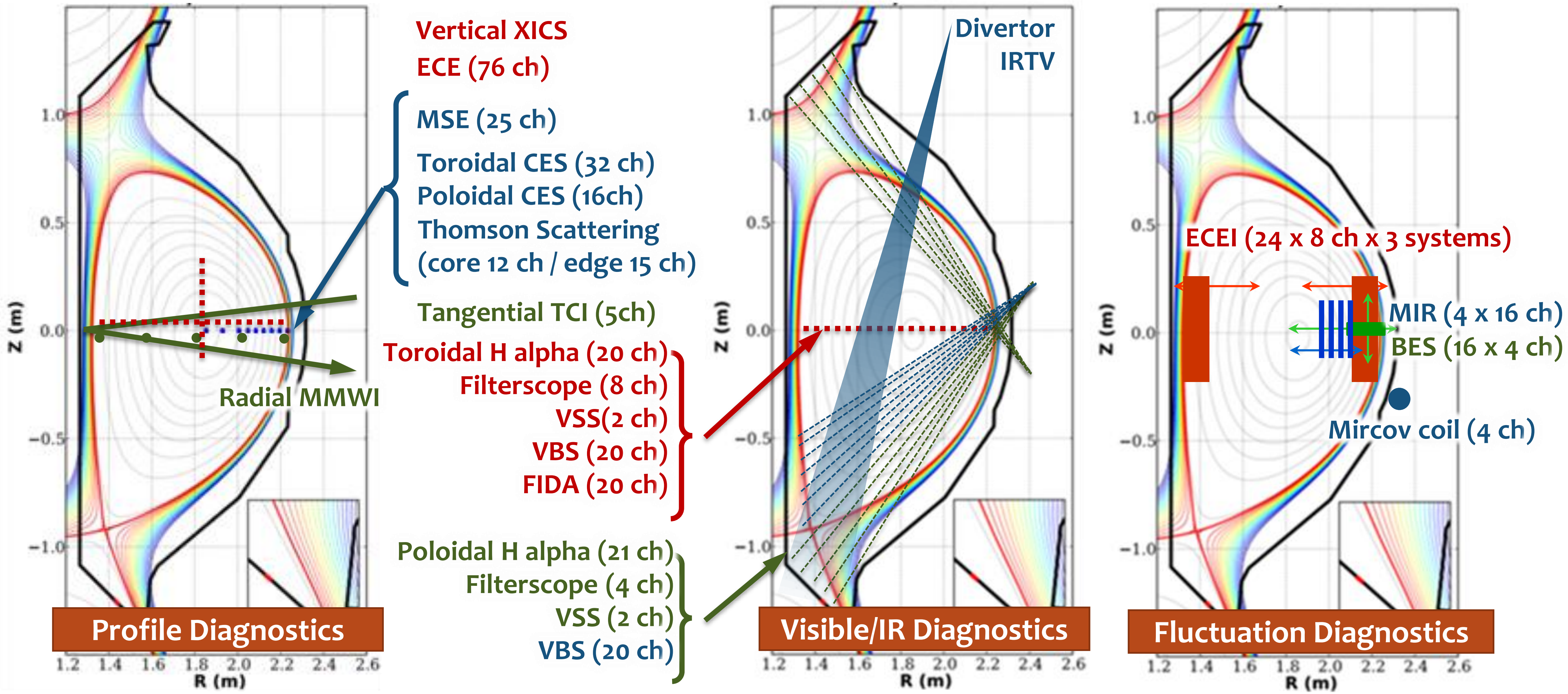


Profile Diagnostics



Fluctuation Diagnostics

KSTAR Diagnostics – Poroidal Layouts



KSTAR Diagnostics – Categories

Control Diagnostics

Provide optimum sensor data to control plasma in real-time

magnetics(position & shape), current, density*, profile, event(MHD, disruption)*

stable & reliable measurements, fast on-line data processing

MD, Interferometer, ECE (+ECEI, MSE, CES, TS)

Profile Diagnostics

Routine operation with sufficient resolution & accuracy

ne, Te, Ti, Vt, Ip, *impurities, Zeff, Rtot, etc*

INTEGRITY*, support kinetic reconstruction*

TS, Reflectometer, ECE, MSE, CES, XICS, Spectroscopy (+TCI, BES)

Fluctuation Diagnostics

Investigate underlying physics through comprehensive analysis

ne & Te */ core to edge / turbulence structure & transport*

2D measurements*, spatial & temporal coverage, correlation analysis*

ECEI, MIR, CSS, BES, RF Spectrometer, (+Doppler Reflectometer)

Radiation & EP Diagnostics

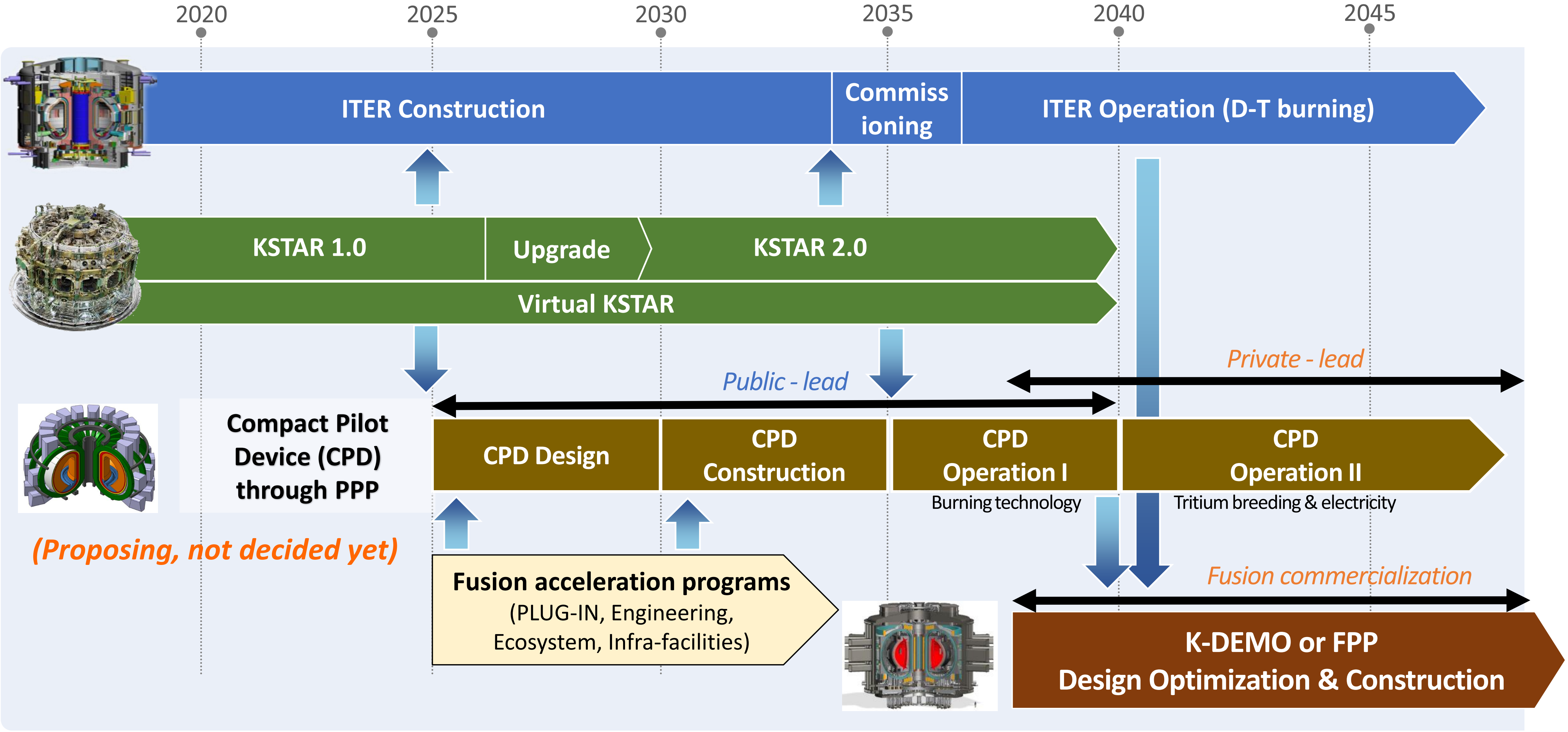
Research on transient event & specific physics phenomena

radiation & SPI IRVB, SXR, AXUV, FVC, OPD

energetic particle FILD, FIDA, neutron diagnostics

divertor LP, TS, VS, VUV, IR, neutral diagnostics

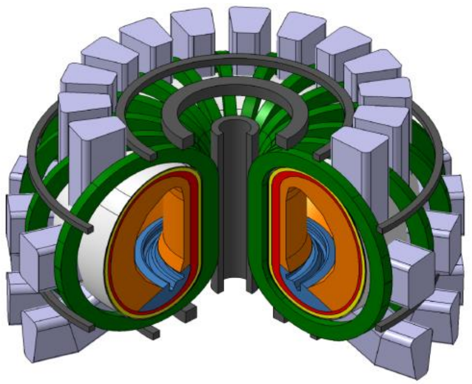
Korea will accelerate FPP development with CPD program (tentative)



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

Korea will accelerate FPP development with CPD program (tentative)

Parameters	KSTAR	CPD*	K-DEMO
Major radius, R0	1.8 m	~ 3.5 m	~ 6.8 m
Minor radius, a	0.5 m	~ 1.1 m	~ 2.2 m
Elongation, k	2.0	~ 2.0	~ 2.0
Field on axis, B0	3.5 T	> 6.3 T	~ 7.25 T
Plasma current, Ip	2.0 MA	~ 7.7 MA	~ 13 MA
betaN	> 3.0	~ 3.3	~ 3.0
H_{98}	~ 1.5	~ 1.5	~ 1.28
Q		~ 5.5	~ 20
fGW (ne/nGW)		**~ 0.95**	~ 1.1
Fusion power		~ 300 MW	~ 1500 MW
SC	NbTi, Nb3Sn	HTS / LTS	NbTi, Nb3Sn
Divertor / PFC	~ 10 MW/m^2 C, W	~15 MW/m^2 (W)	~ 20 MW/m^2



Strategic contributions from KSTAR experiments and collaborations

- CPD : Compact Pilot Device
- K-DEMO : Korean Demonstration Fusion Reactor

* Operational parameters of CPD are subject to change based on conditions.

KSTAR is optimal machine for high-performance long-pulse experiments (up to now)

- KSTAR can achieve high-performance plasma (with NBI & ECH)
- KSTAR has long-pulse capability (with SC magnet)
- KSTAR has advanced 2D diagnostics & actuators (RMP, SPI)

⇒ KSTAR can test advanced scenario with adaptive RT control schemes over the wall saturation time

BUT

- KSTAR has limited size & marginal heating power
- KSTAR does not planning DT operation

⇒ What can we do with KSTAR for DEMO study in future?

Innovative AI/ML based technologies could open high confinement window for compact devices

- BP requires advanced scenario currently not available, and CPD more
- Performance vs. Stability
- Issues of big machine are stability, CPD requires both
- CPD needs operation on marginal boundary, too narrow window
- Can Scenario make breakthrough? Control might

DARPA robotics challenge (2015)

Boston Dynamics (2018)

AI Can Be Widely Applied in Fusion Research

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

Why is AI well-suited for 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 efficiency, 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.

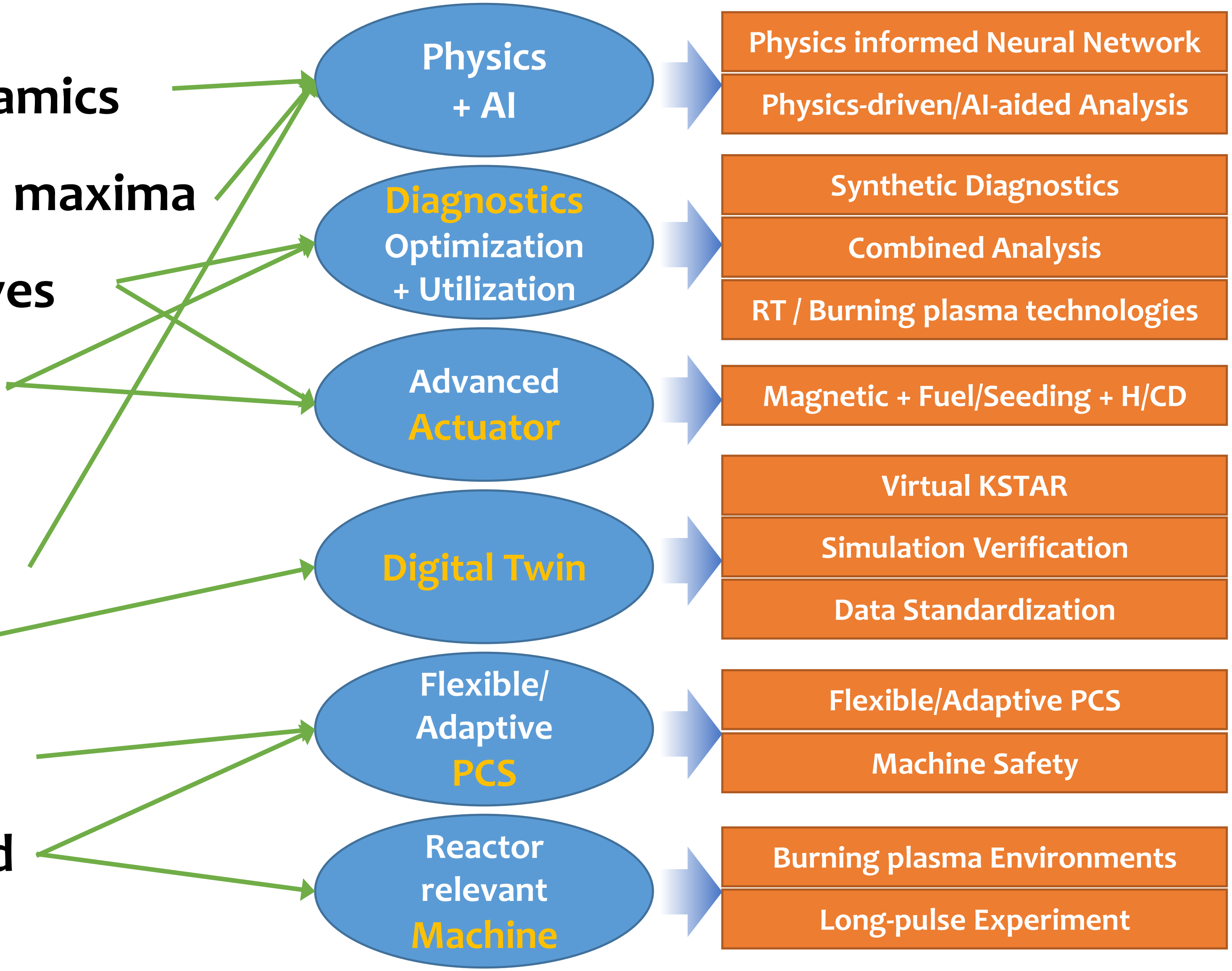
Why is AI not suited for plasma control

- 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.

How to develop KSTAR as an innovative AI control bed

- High-dimensional, nonlinear dynamics
- Global optimization beyond local maxima
- Optimization of multiple objectives
- Real-time decision-making

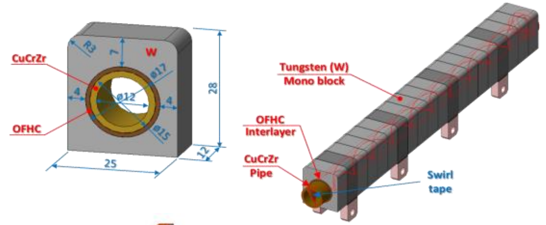
- Lack of physics understanding
- Data limitations
- Risk of catastrophic errors
- Extensive trial-and-error required

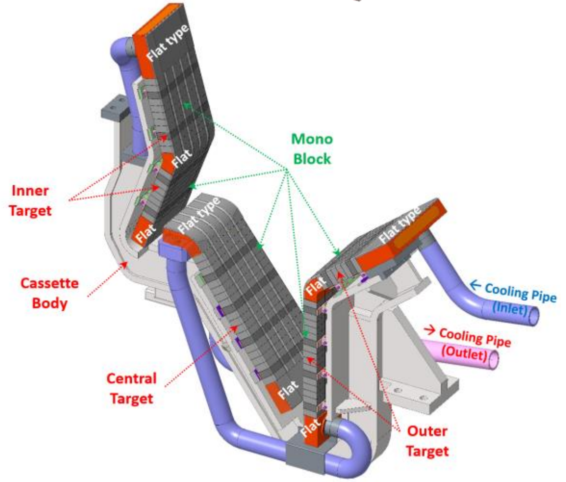


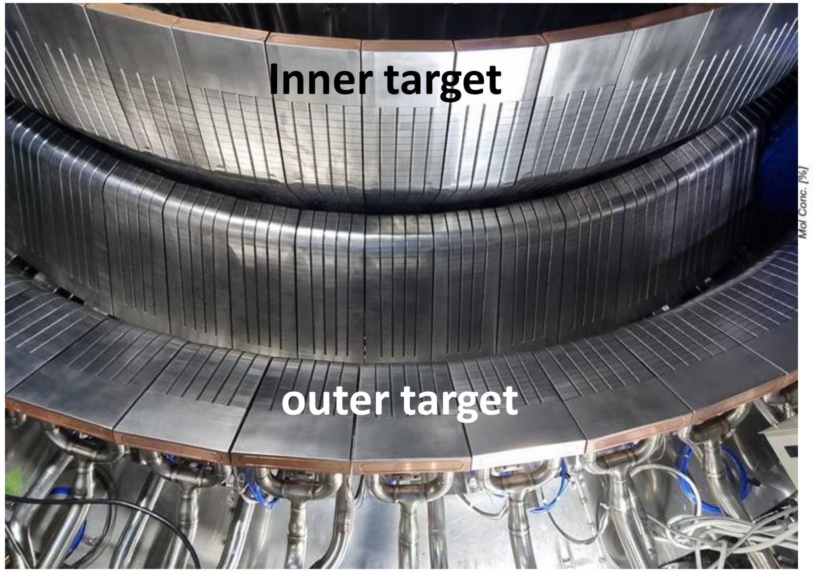
KSTAR will equip full W wall on 2027 campaign

Reacter relevant Machine

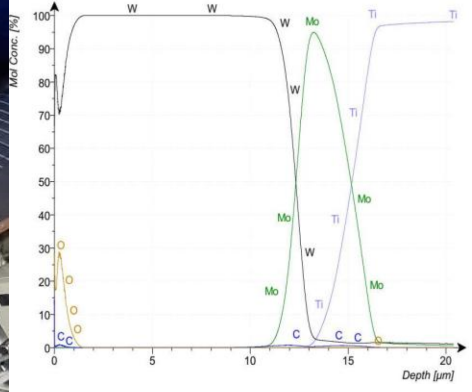
- W monoblock divertor + W coated tiles
- W divertor was installed & commissioned before 2023 campaign
- Peak heat flux: 4.3 MW/m2 (C) ⇒ 10 MW/m2 (W)
- W tile mock-up was fabricated & tested
- Tiles will be installed after 2025/2026 campaign

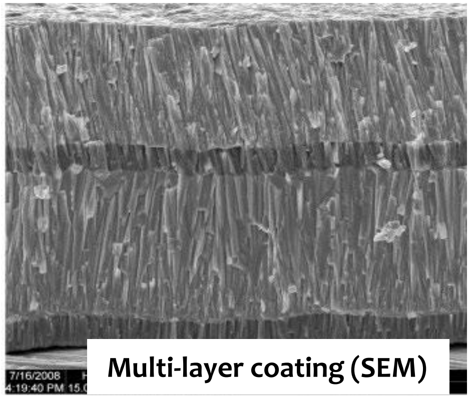






W coating equipments (NILPRP, Romania)



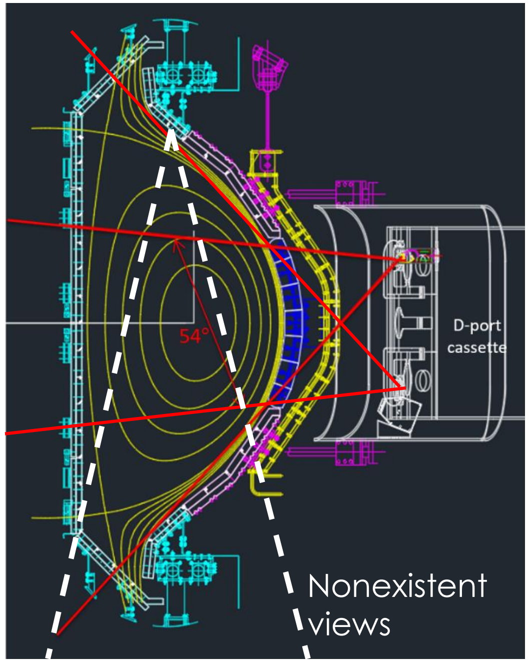


KSTAR in-vessel renovation offers more flexibility (or optimization for future device)

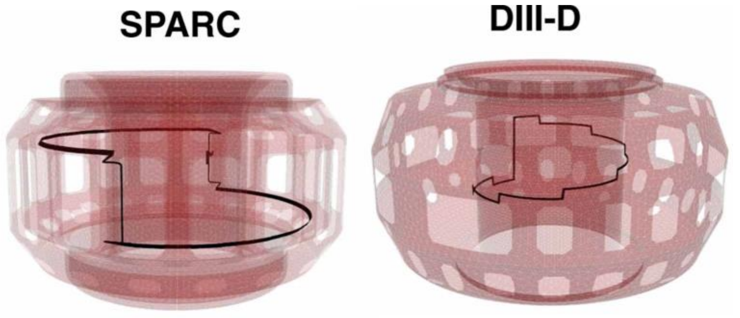
Reacter relevant Machine

- Diagnostics (sight of view secured)
  - Expanded access for edge/divertor imaging & probes
  - Improved resolution of boundary plasma & impurity transport
- In-Vessel Control Coils (rearranged)
  - Enhanced flexibility in plasma shaping
  - Better ELM/disruption control and advanced scenario development
- Advanced Divertor Concepts
  - Modular divertor with diagnostics & actuators
  - Options for upper divertor (double/single null)
- Enhanced Passive Control
  - Installation of dedicated runaway electron mitigation coil
  - Optimization of passive stabilizers for improved vertical stability

⇒ More flexible and robust plasma operation
Validated testbed for ITER/CPD optimization
Higher experimental efficiency & future device relevance



Expansion of diagnostics sight of view

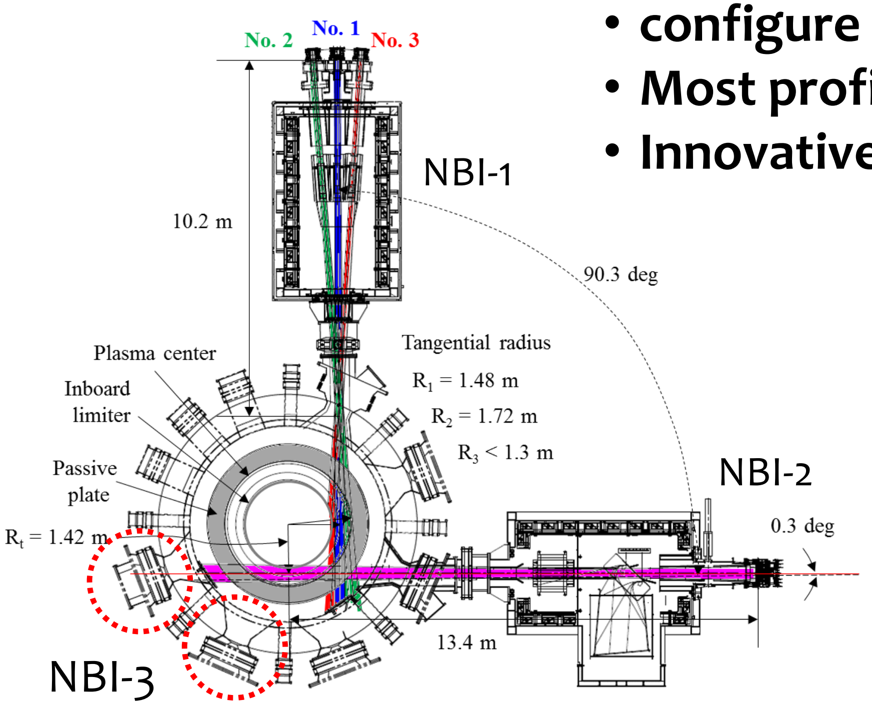


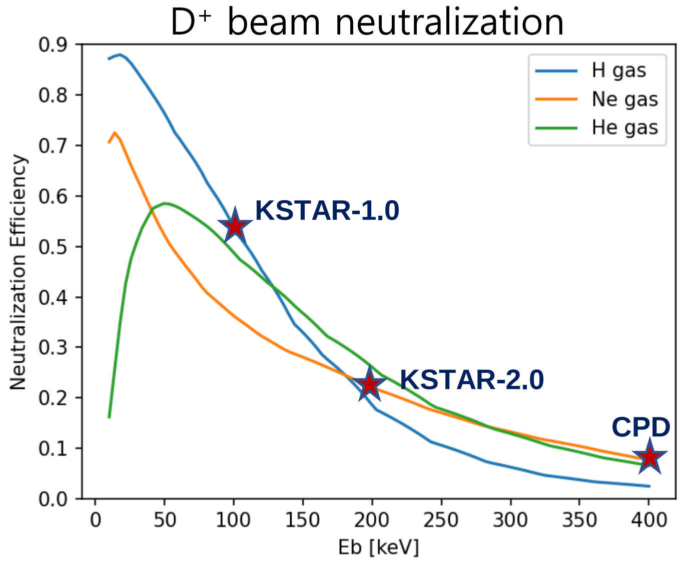
Exemple of RE mitigation coil

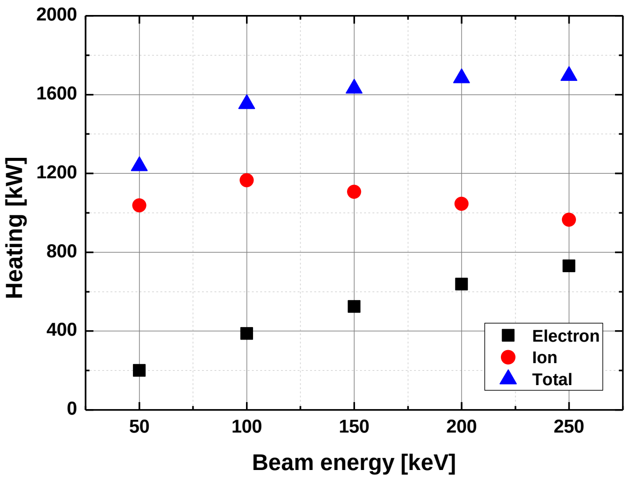
KSTAR requires more power to touch high pressure operation regimes

Reacter relevant Machine

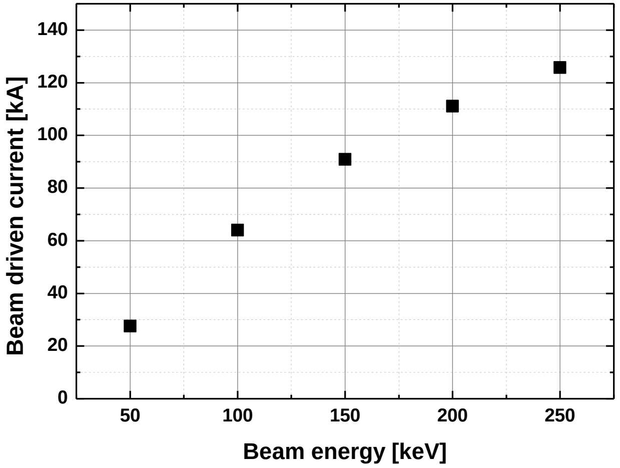
- **NBI-1 (operating) : 100 kV D+ / arc discharge**
  - **3 ion sources are arranged horizontally in the mid-plane**
- **NBI-2 (operating) : 100 kV D+ / arc discharge**
  - **3 ion sources are arranged vertically (two off-axis + one on-axis)**
- **NBI-3 (considering) : > 200 kV D+ beam**
  - **configure for efficient off-axis current drive.**
  - **Most proficient, versatile, and matured**
  - **Innovative; never tried seriously > 200 keV P-NB**







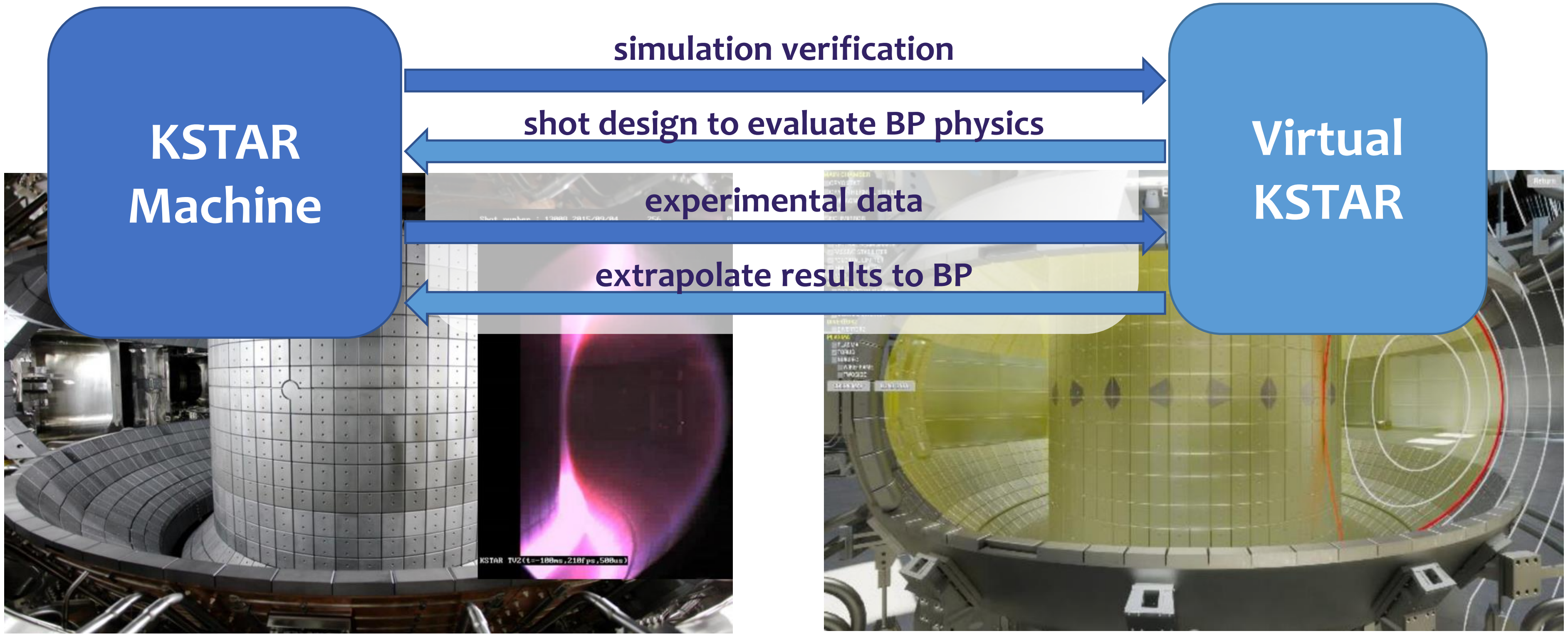
Under same beam power 2 MW



KSTAR will extrapolate experimental results using digital twin technology

Digital Twin

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



New KSTAR PCS based on ITER RTF proposes KSTAR as an universal control testbed

Plasma Control System

- Limited time for real-time operation
- Centralized diagnostics signal processing

→

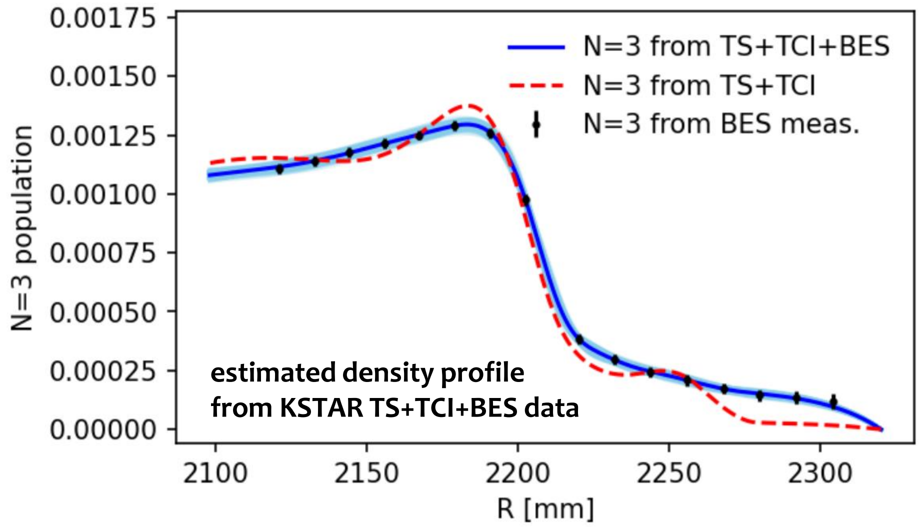
- Flexible interface for multi-channel networks
- Reduced hardware dependency and improved usability
- Fully isolated interlock system for device protection against plasma control failures
- Enhanced system interoperability and data consistency through IMAS-based standardization

- **Using ITER Real-Time Framework as a test bed for ITER-PCS,** supported by the ITER CODAC team and international collaborators (e.g., GA)
- **The current PCS will operate in parallel until the new PCS is fully established.**
- **Establishing the originality of KSTAR PCS while gaining development experience**
- **Exploring the expansion toward AI-based operation**

Diagnostics data should be fully utilized

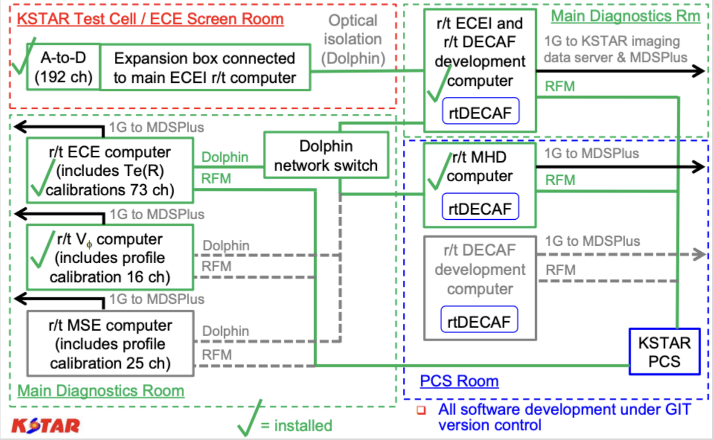
Diagnostics

- **Better control needs more data**
- **Diagnostics are limited in DEMO** (radiation hardness, limited space)
- **Conventional interpretation of diagnostics** (raw data to physics parameters) **causes loss of data**
- **Integrated analysis of multi-diagnostics supported by synthetic method maximizes data utilization**
- **Combined with control algorithm, design of diagnostics can be optimized**



KSTAR Diagnostics are equipping RT capabilities

RT Diagnostics

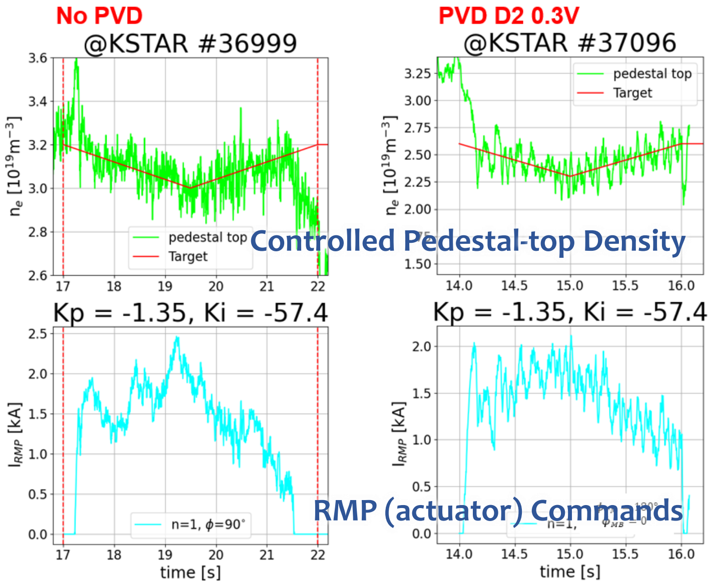
Short -	Full- name	Main Roles in RT	Progress/Current Status	Future Plans/Remarks
TCI	Two-Color Interferometer	RT Line- and Profile n_e Control	✓ Full 5-chord RT measurement is routinely available ✓ Density profile control was demonstrated by a collaboration with Princeton University	• Extends total chord 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.	• Will be integrated and tested in FY 2025
		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

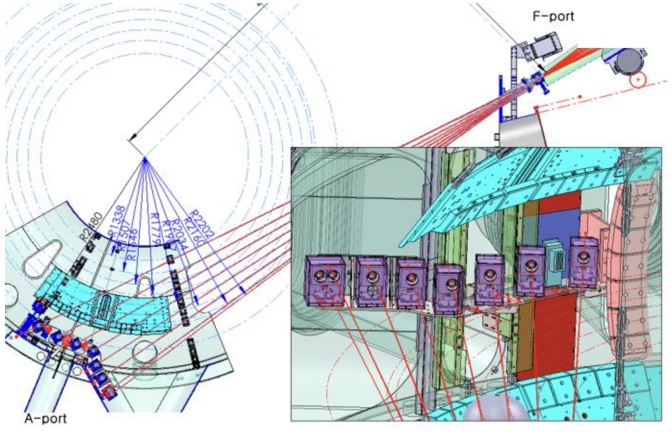
KSTAR RT Diagnostics – TCI & IRVB

RT Diagnostics

Two Color Interferometer

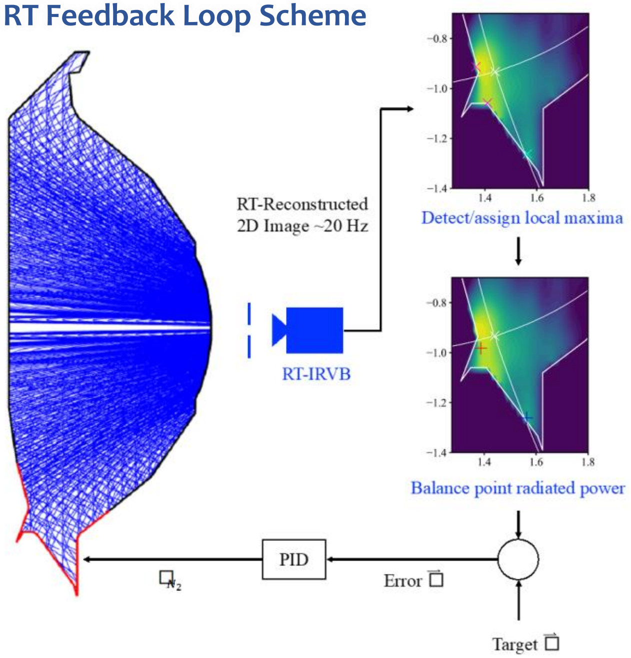
- **Real-time (RT) line-density and profile measurements from 5-channel Tangential TCI**
  - **Ready for RT density profile (distribution) control**
  - **Started with pedestal top control by Princeton Univ. (by M. S. Kim)**
- **Will be extended up to 10 chords with installation of a new 2nd unit. (8 of 10 as of 2025)**



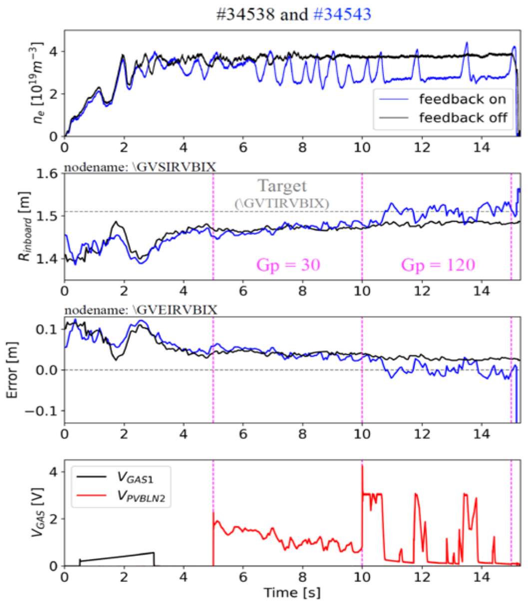


Infra-Red Video Bolometer

RT Feedback Loop Scheme



Radiation Front Control Results

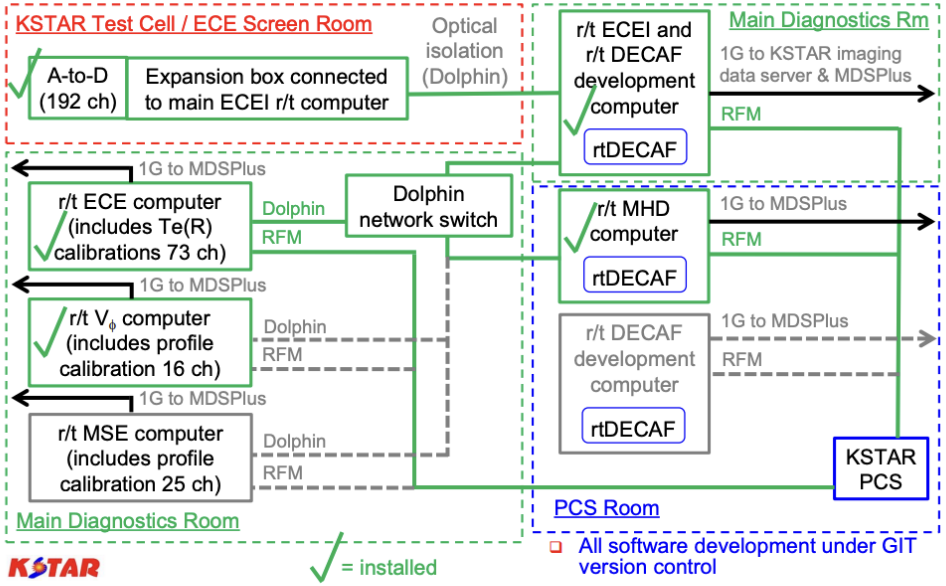


- **IRVB could capture the movement of radiation front which is important for detachment study**
- **A closed-loop established via RT-IRVB enabled the radiation front control in feedback.**

First demonstration of disruption avoidance using multiple real-time DECAF events

Physics based RT control

RT Diagnostics

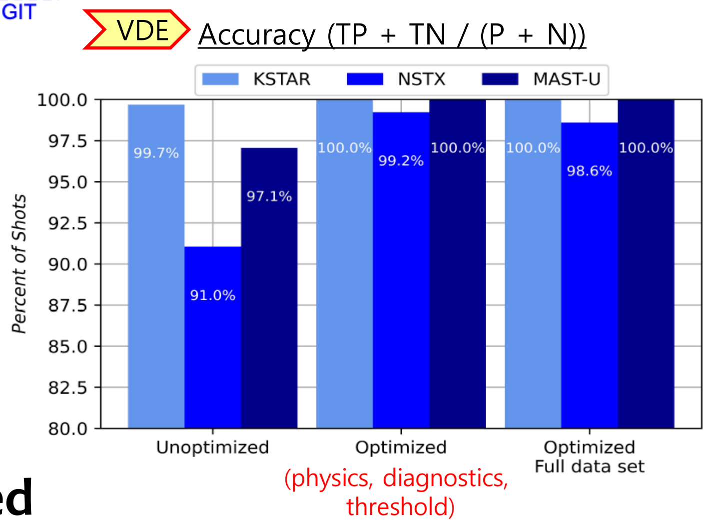


- Physic-based disruption event characterization and forecasting (DECAF*) has been implemented
- In 2024, the number of DECAF Events is expanded to eight to examine various physical phenomena
- DECAF successfully produced off-normal event onset forecasts with high accuracy and sufficiently early warning

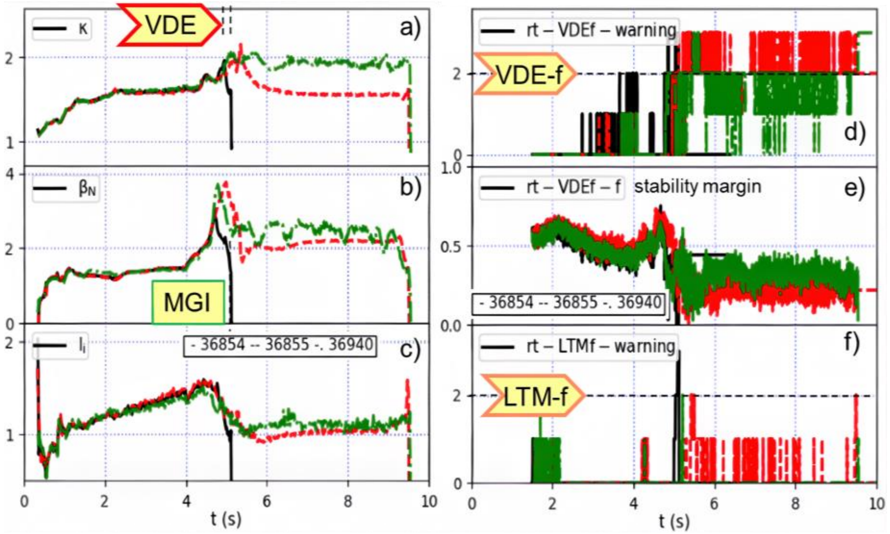
*S.A. Sabbagh, et al, *Phys. Plasmas* **30** (2023) 032506

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK   PPPL

- The multi-Event feedback now cues KSTAR actuators to produce disruption avoidance
- In the 2024 DECAF experiment, disruption avoidance is demonstrated



High accuracy disruption prediction by DECAF VDE Event in KSTAR, MAST-U and NSTX



Disruption avoidance with DECAF VDE-f Event feedback using plasma shape control

Synthetic diagnostics supports combined analysis and design optimization

- Integrates multiple diagnostics consistently
  - Enables simultaneous interpretation of diverse measurements within the same physics framework, improving reliability of plasma state reconstruction.

- Guides diagnostic system design
  - Allows virtual testing of diagnostic layouts and performance, supporting optimal placement, resolution, and coverage before hardware implementation.

- Provides realistic inputs for control
  - Generates measurement-like signals from simulations, ensuring that control strategies and scenario optimization are validated under practical diagnostic constraints.

⇒ Synthetic forward model developments for KSTAR diagnostics are ongoing

ECE, ECEI, BES, Lyman alpha, ...

Combined analysis of multiple diagnostics maximizes data utilization

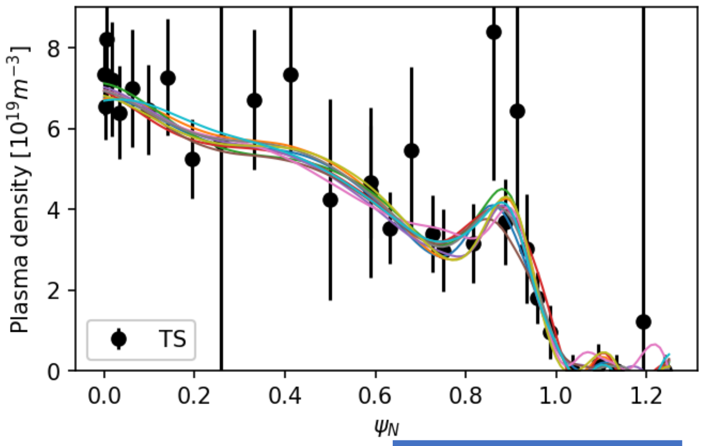
Combined Analysis

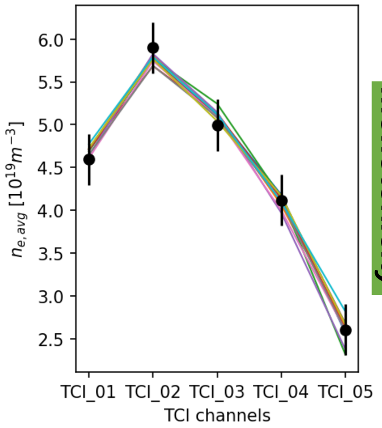
- **Compensates for limited measurements in burning plasmas:**
  - Data fusion methods (e.g., Bayesian inference) extract maximal information when diagnostic access is constrained by harsh reactor conditions.
- **Improves accuracy and robustness:**
  - Joint interpretation reduces uncertainties and resolves inconsistencies across different diagnostics.
- **Reconstructs hidden plasma states:**
  - Enables reliable estimation of key parameters not directly accessible by any single diagnostic.

Bayesian inference for plasma density profile estimation : TS + TCI + BES

Combined Analysis

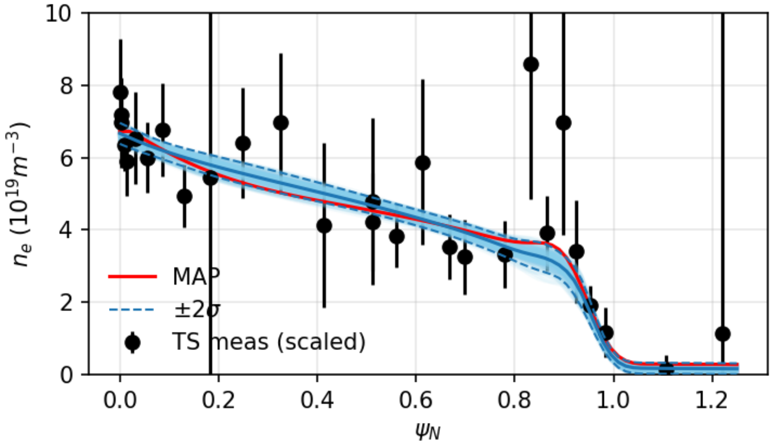
$P(\bar{n}_e|\bar{\theta})P(\bar{d}_{TS}|\bar{f},\bar{\theta})\ P(\bar{d}_{TCI}|\bar{n}_e,\bar{\theta})$

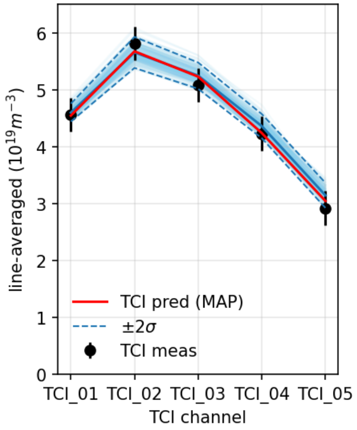




Add monotonicity

$P(\bar{n}_e|\bar{\theta})P(\bar{d}_{TS}|\bar{f},\bar{\theta})\ P(\bar{d}_{TCI}|\bar{n}_e,\bar{\theta})\Pi_i 1(n_{e,i+1}-n_{e,i}\geq 0)$

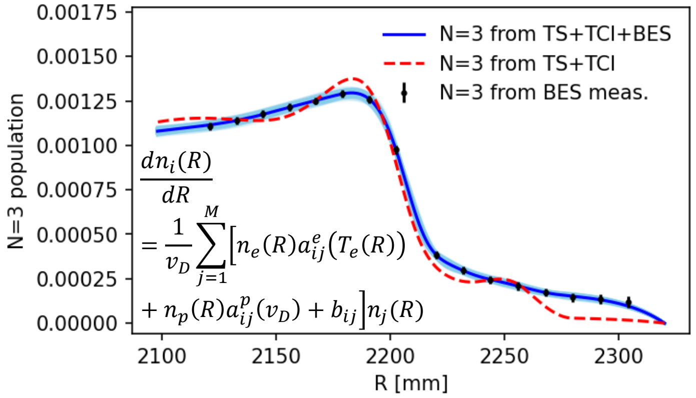


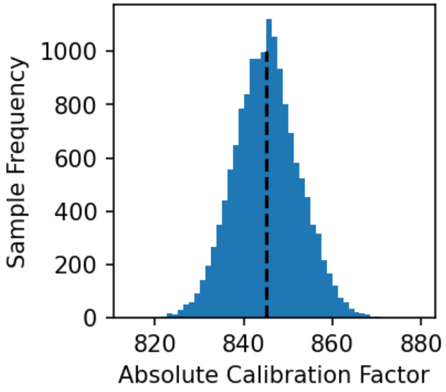


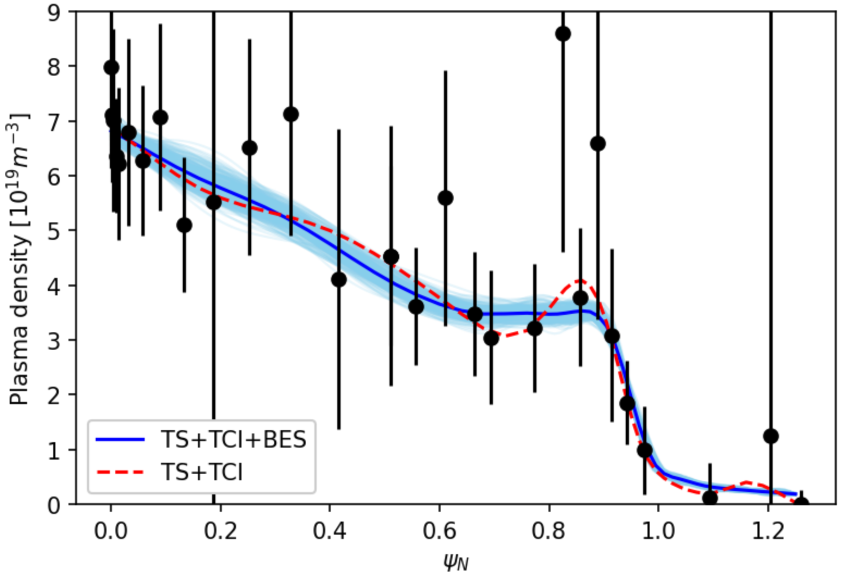
Add BES data and likelihood

Data Fusion for BES, Thomson scattering and TCI

$$P(\bar{n}_e|\bar{d}_{BES},\bar{d}_{TS},\bar{d}_{TCI},\bar{\theta}) \propto P(\bar{n}_e|\bar{\theta})P(\bar{d}_{BES}|\bar{n}_e,\bar{\theta})P(\bar{d}_{TS}|\bar{n}_e,\bar{\theta})\ P(\bar{d}_{TCI}|\bar{n}_e,\bar{\theta})$$

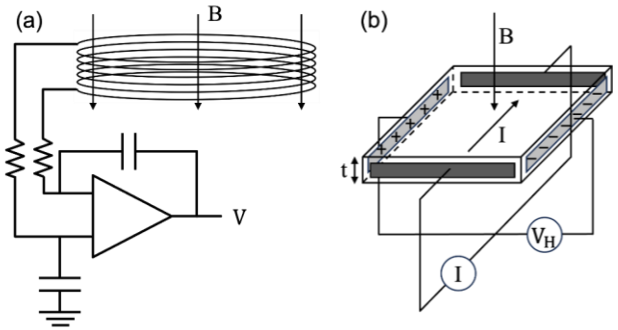




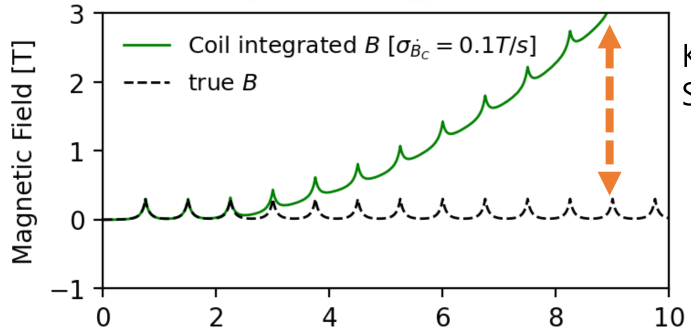


Sensor fusion: magnetic pick-up coil + Hall sensor

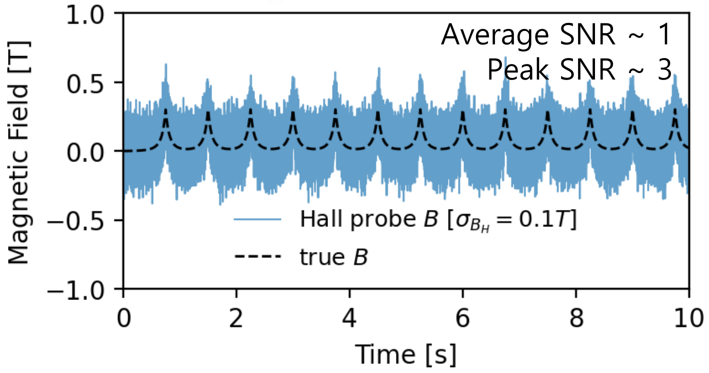
Combined Analysis



Synthetic Magnetic coil

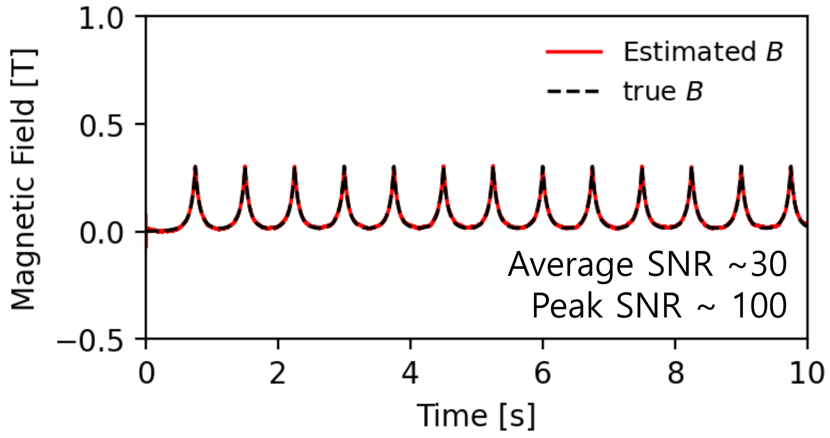


Synthetic Hall sensor

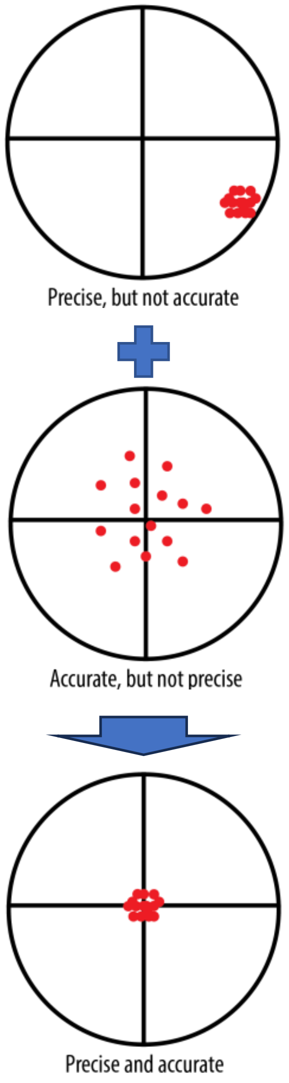


Kalman Filter
Sensor Fusion

- **Integrator generates "Drift" by offset**
  - **Radiation induced electromotive force**
  - **Thermo-electromotive force**
  - **Others…**
- **Hall sensor have "Low SNR"**
  - **Limited high-frequency response**
  - **Sensitivity to radiation**
  - **Susceptibility to electromagnetic noise**
- **Coil + Hall sensor : No drift and High SNR**



Data Fusion estimate magnetic field exactly

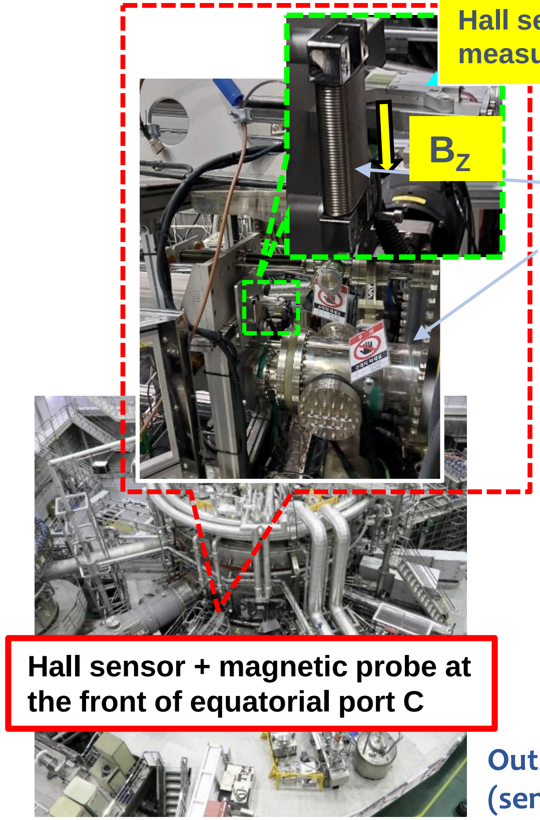


Jaewook Kim et al., Nucl. Fusion 65, 046008 (2025)

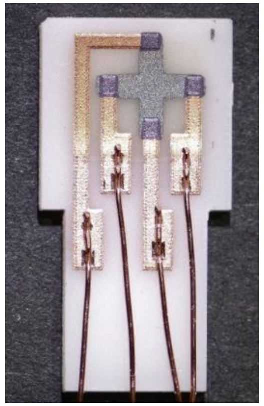
Hall sensor was installed on KSTAR & compared with Magnetic probe results

BP technologies

- The performance tests were carried out to resolve the nonlinear drift issue of inductive coil.
- The signal characteristics will be investigated for the heat-up due to the radiation from plasma column during long pulse discharge.

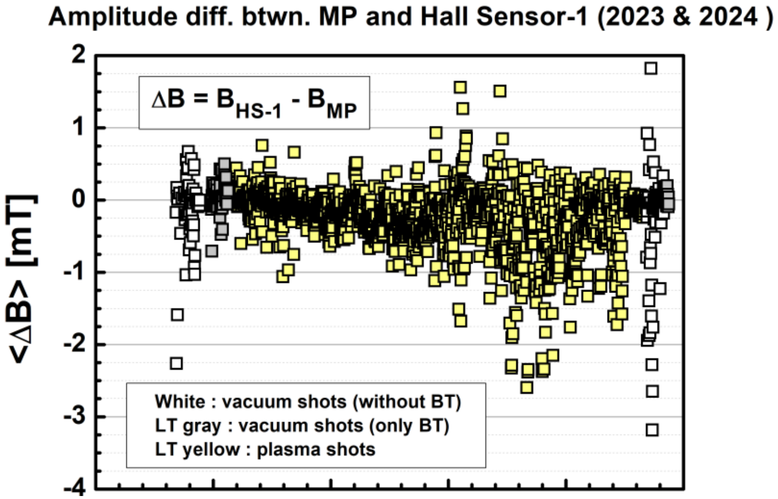


IPP
ELCERAM

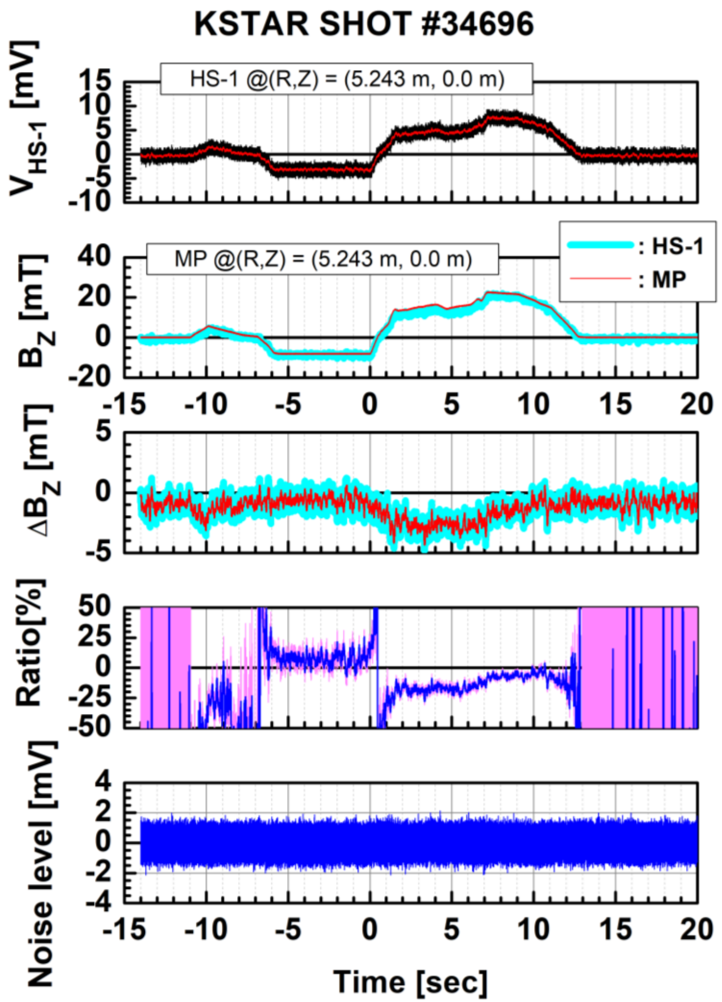


Outside VV : Hall sensor (sensitivity : 364.8 mV/T for B_Z)

The difference between HS & MP <ΔB> was mostly within +/- 1 mT (< 5%)



Typical time evolutions in the hall sensor measurement

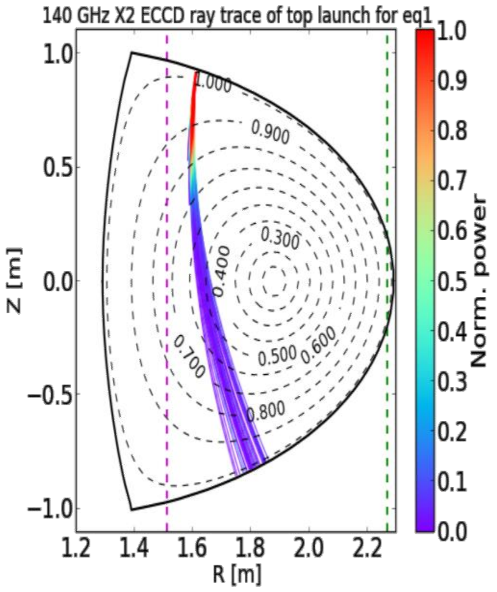


We need more actuators

Actuator

- **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**

Top ECCD



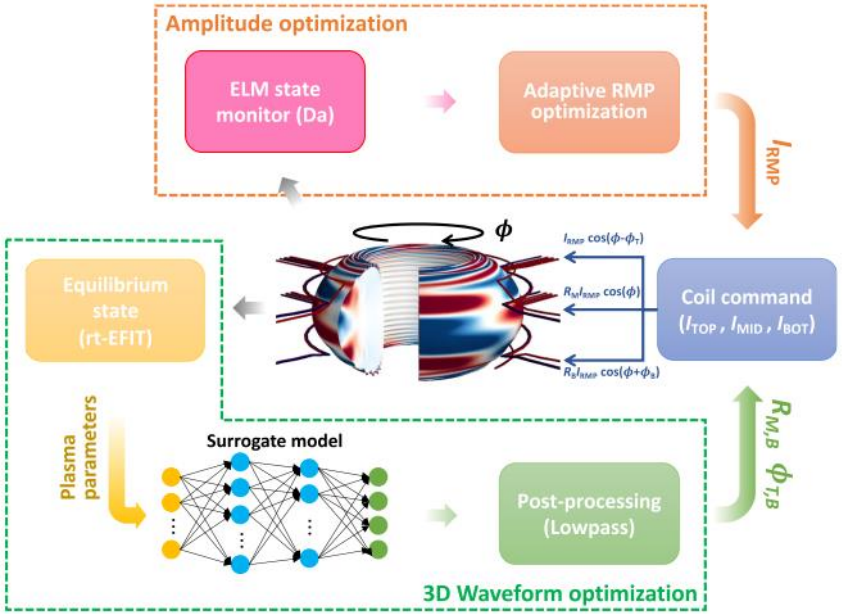
Actuator Candidates for KSTAR Upgrade

- **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)

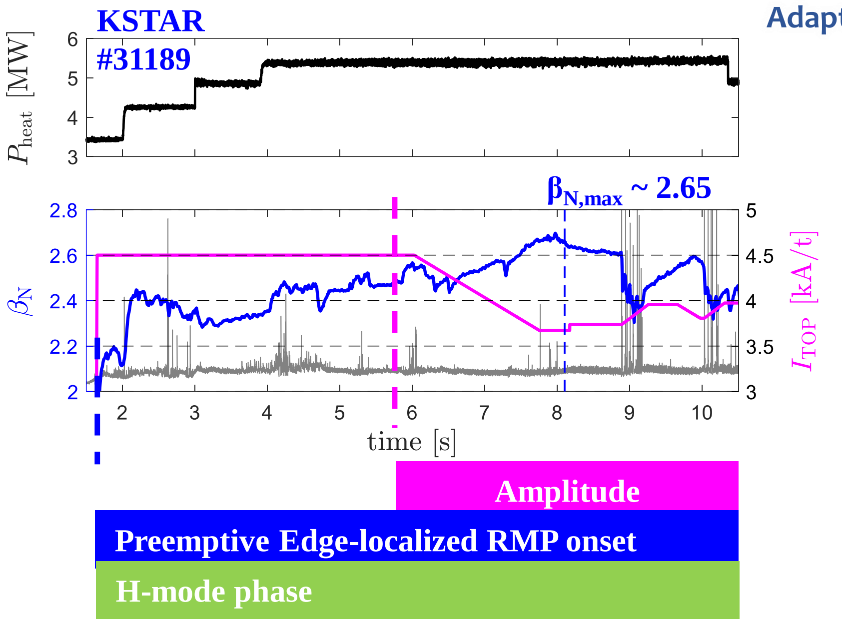
⇒ **KSTAR as the best machine to develop & verify AI/ML control algorithm for burning plasma high-performance operation**

IVCC is significantly beneficial for burning plasma but difficult to implement

Actuator - Coil

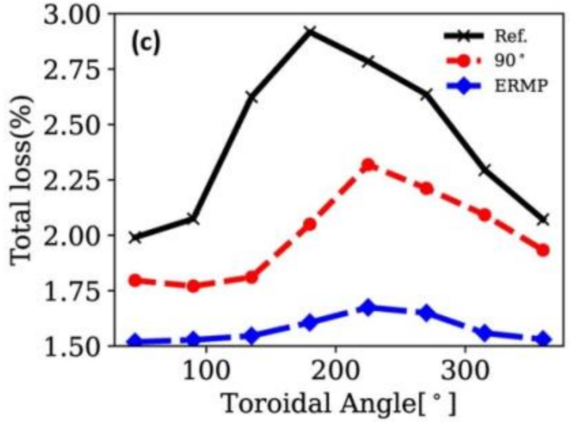


S. K. Kim, Nature Comm. (2024) / R. Shousha, Nucl. Fusion (2024)



M. Kim, Nucl. Fusion (2023)

Adaptive RMP ELM control w/ flexible IVCC



Fast ion confinement enhancement: reducing RMP-related disadvantage through tailoring spectrum

- IVCC is a powerful tool for stabilizing vertical instability, controlling ELMs and RWMs.
- Challenges at the reactor stage: massive radiation and heat threatening its availability, and difficult maintenance as an in-vessel component

⇒ (Under consideration) durable or disposable IVCC, ex-vessel CC

Burning plasma control is strengthened by diverse fueling and seeding strategies

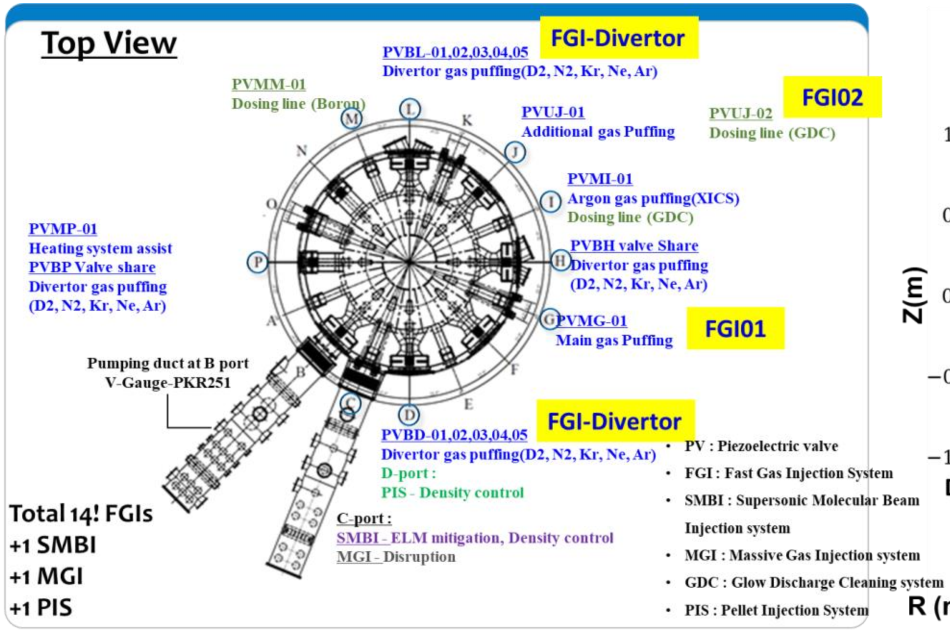
Actuator – Fuel/Seeding

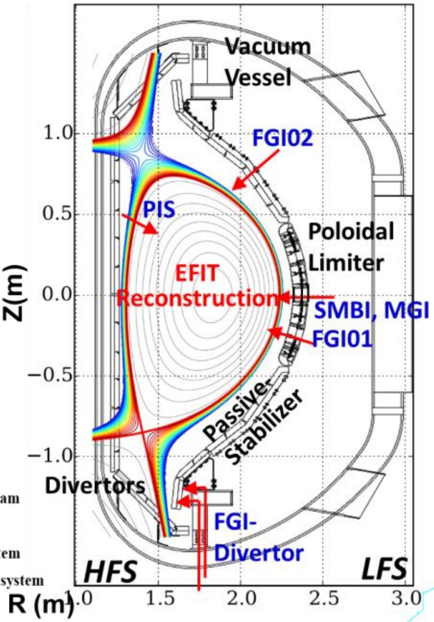
- Fueling
  - Sustains D–T density for self-sufficient burn while staying below disruption limits (e.g., Greenwald).
  - Shapes core and pedestal-top density, supporting helium ash transport and fusion power regulation.

- 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.

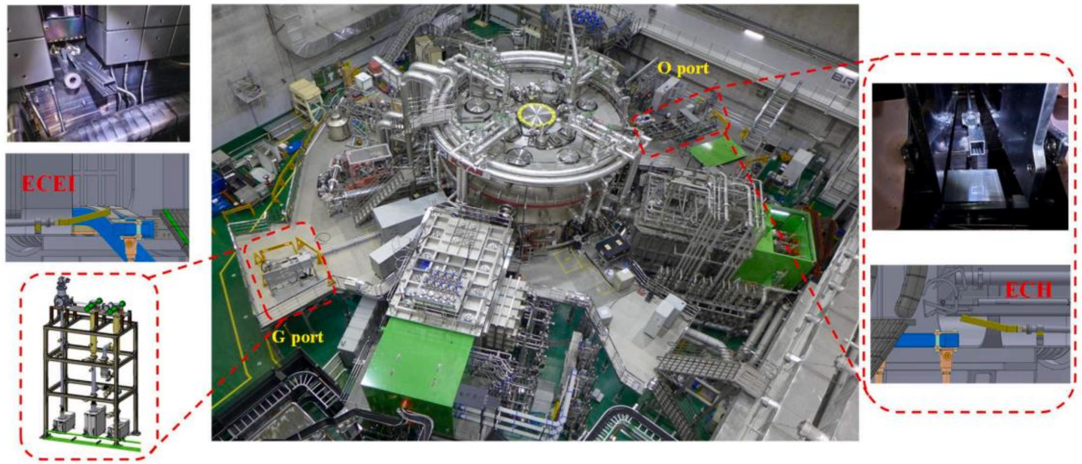
KSTAR is equipped with diverse fueling and seeding actuators

Actuator – Fuel/Seeding



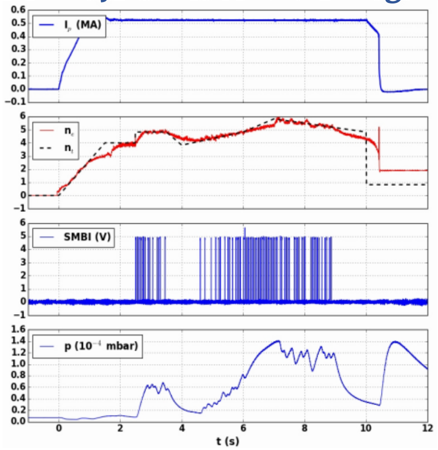


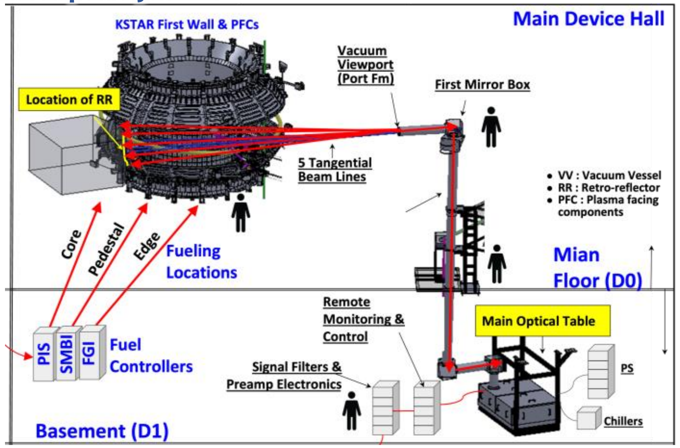
Locations of the Fueling Systems on KSTAR

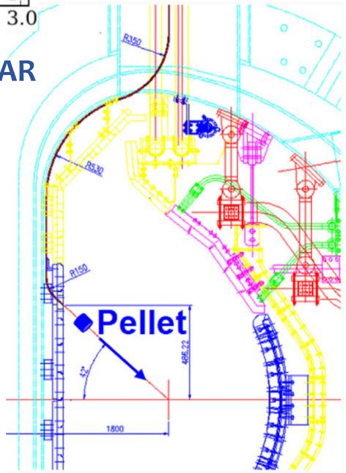


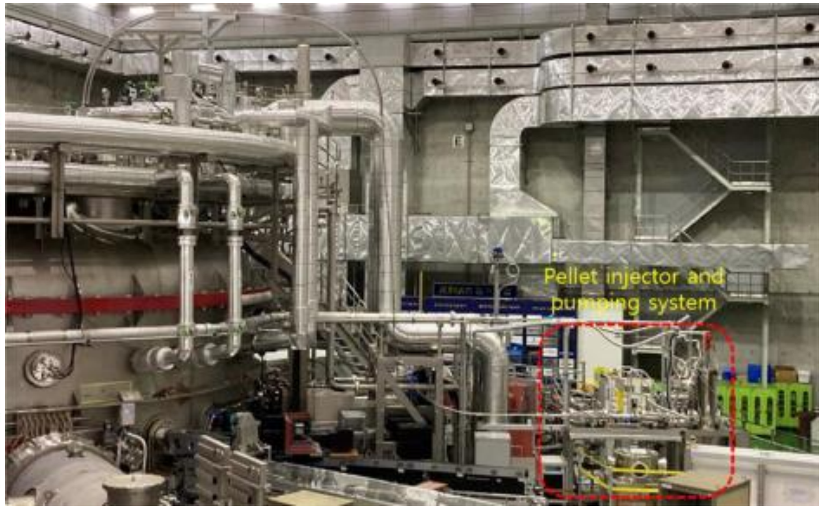
Duel Shattered Pellet Injector with relevant diagnostics

Density control results using multi-input system









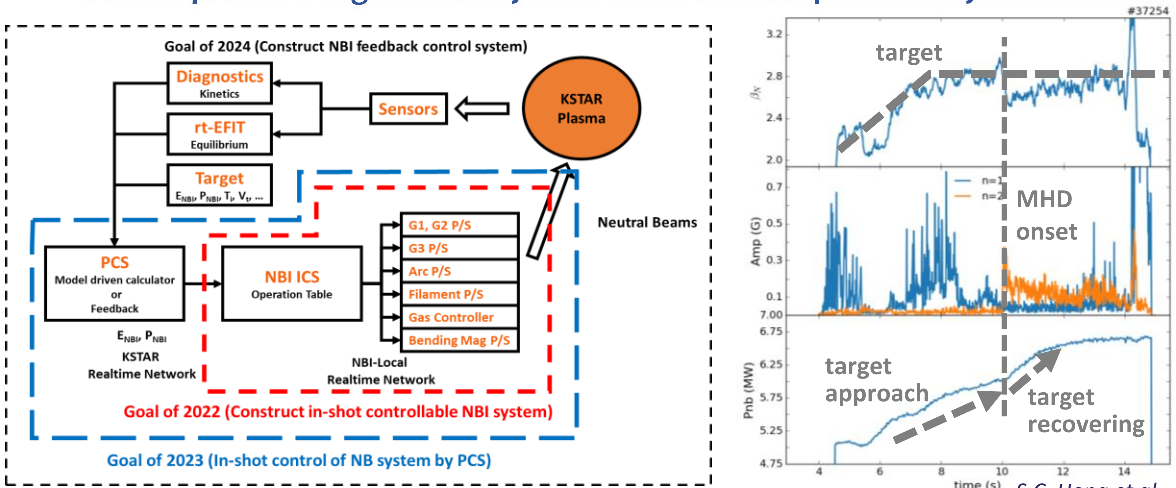
Pellet Injector system with guiding tube

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

Actuator – H/CD

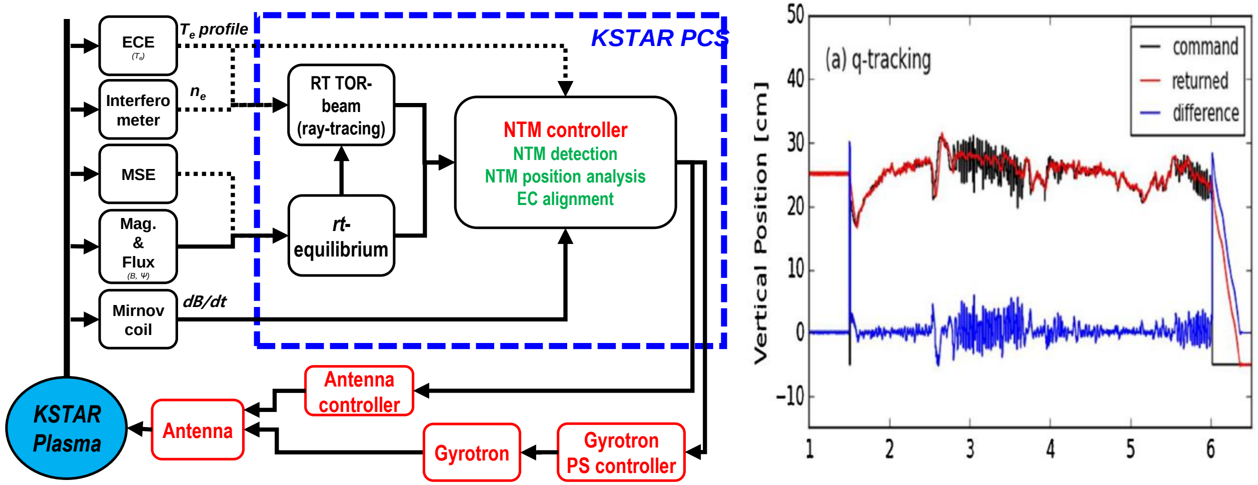
- **MHD Mode Stabilization**
  - Suppresses tearing modes and neoclassical tearing modes (NTMs).
  - Localized current drive techniques (e.g., ECCD, LHCD) are used for precise current profile shaping.
- **Pressure and Shape Control**
  - RF heating (ECH, ICRH) can modify local pressure profiles.
  - 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



KSTAR aims to develop burning plasma scenario by fully utilizing key features as a mid-size SC tokamak

BP Scenario Development

High β_N SS Operation

- W transport + Radiation control
- Energetic Particle Physics
- Non-inductive CD (BS + external CD)

Event Control

- Disruption avoidance / mitigation
- ELM suppression
- MHD instabilities
- RT event prediction using ML / AI

scenario & control algorithm

experimental data

KSTAR 2.0

KSTAR PCS

- ITER compatible hardware
- Advanced control algorithm
- Optimized sensor & actuator

Integrated Data

- Advanced diagnostics
- Integrated statistical analysis

Machine Upgrade

- Inner-wall renovation
- Negative-ion based NBI

Engineering Testbed

- Advanced divertor
- Remote maintenance
- High-temp superconductor
- Compact & robust sensors

Virtual KSTAR

scenario for burning plasma

Simulation

- Physics model for BP
- Verification & Validation

AI / ML

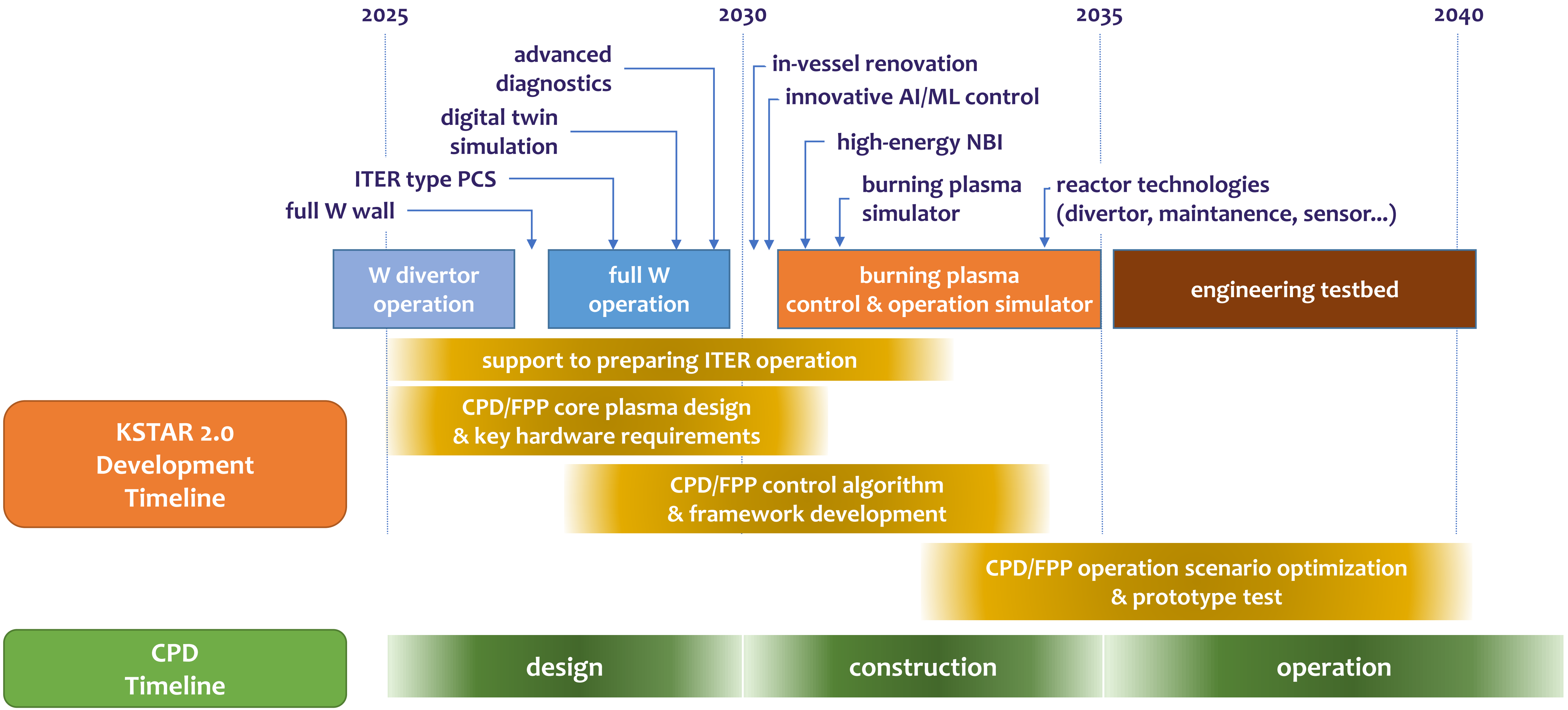
- Synthetic diagnostics
- Data for training

Machine Design

- provide equiv. parameter
- AI-aided design

key technologies for fusion reactor

KSTAR will support design, construction and operation of CPD



Strong contributions from domestic and international collaborators

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

KSTAR

ASIPP
SWIP
HUST

QST
NIFS
Kyoto U

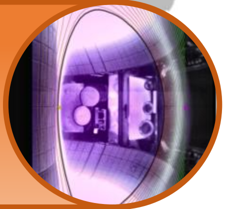
Tokyo U
Nagoya U
Kyushu U

Asia Austrailia

NCKU
IPR
TINT
ANU

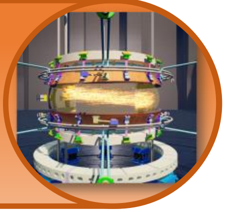
Heating & CD
NBI / RF Devices & Technologies

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 …

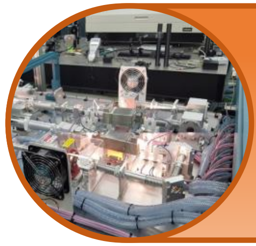


Theory & Simulation
MHD, Turbulence & Transp., PWI, …

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

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 …