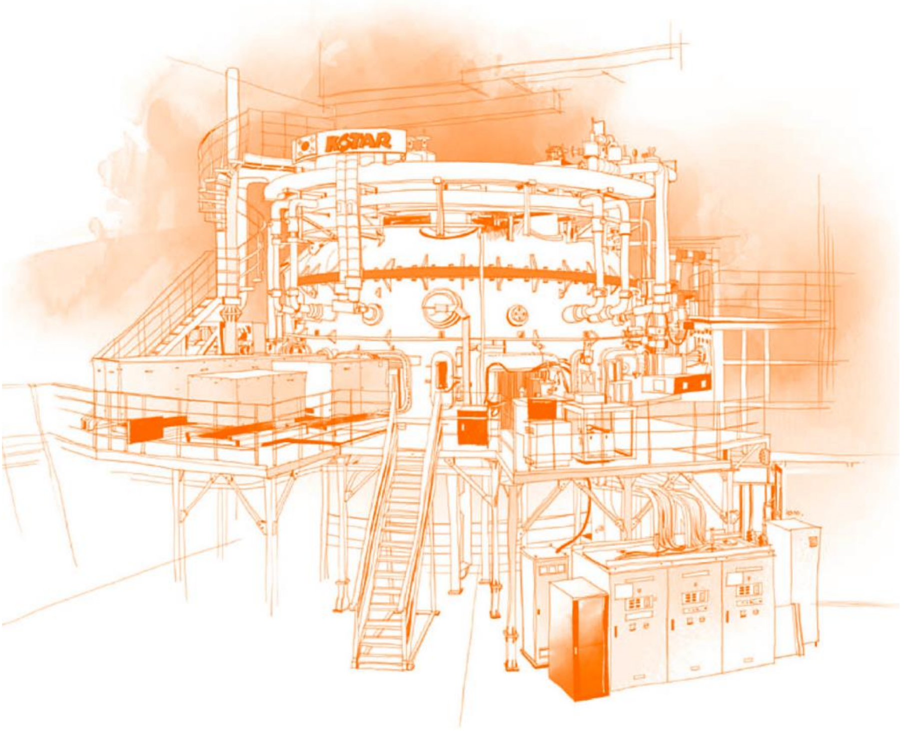
Fusion Power Associates, 45th Annual Meeting and Symposium,
Fusion Energy: Progress, Challenge and Promise, Dec. 2-3, 2024, Grand Hyatt Washington

KFE

Korea's Strategies for Accelerating Fusion Energy Realization and Key Research Activities



December 3rd, 2024

Presented by Yeongkook OH

Korea Institute of Fusion Energy (KFE)

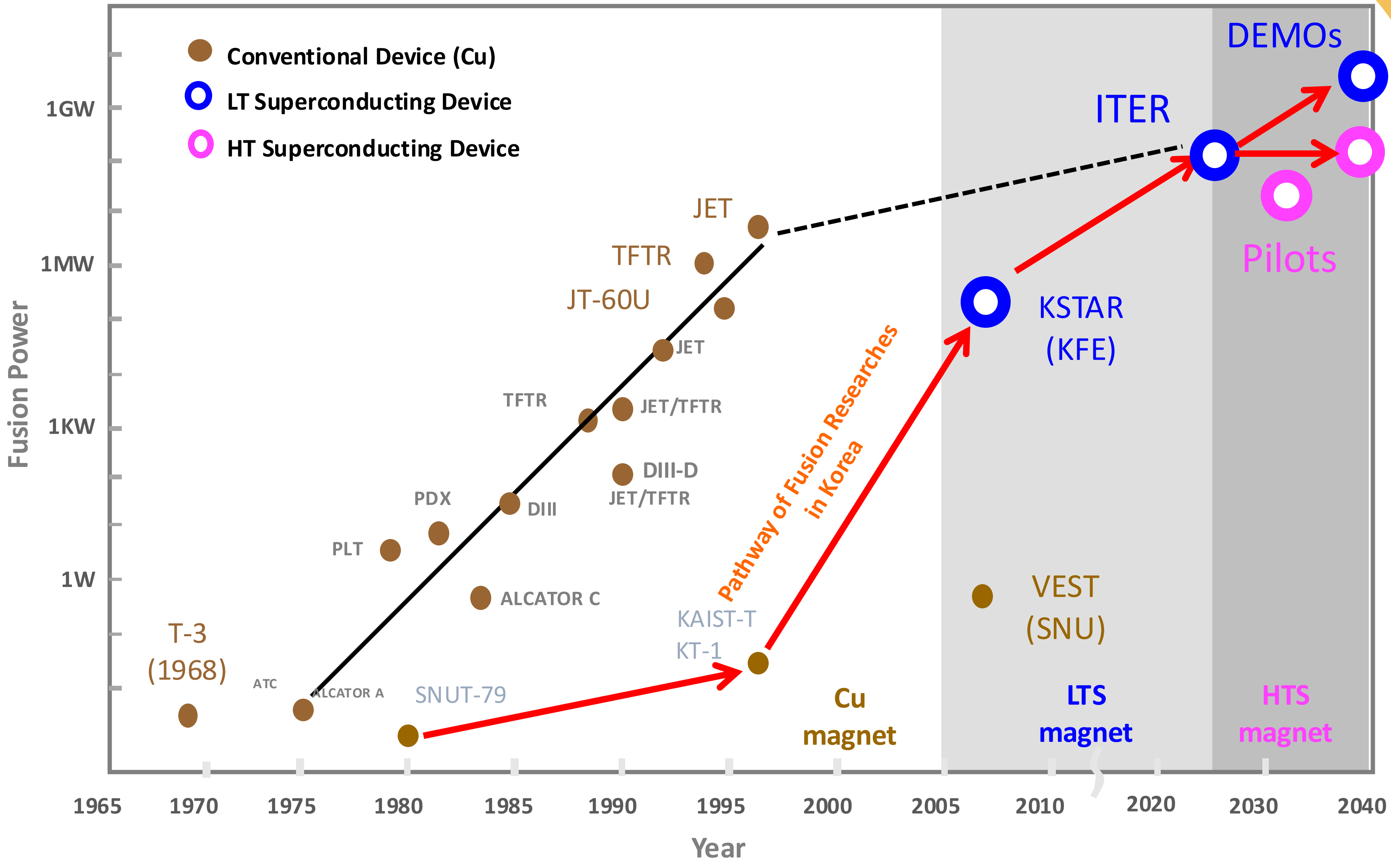
한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

과학기술정보통신부
Ministry of Science and ICT

OUTLINES

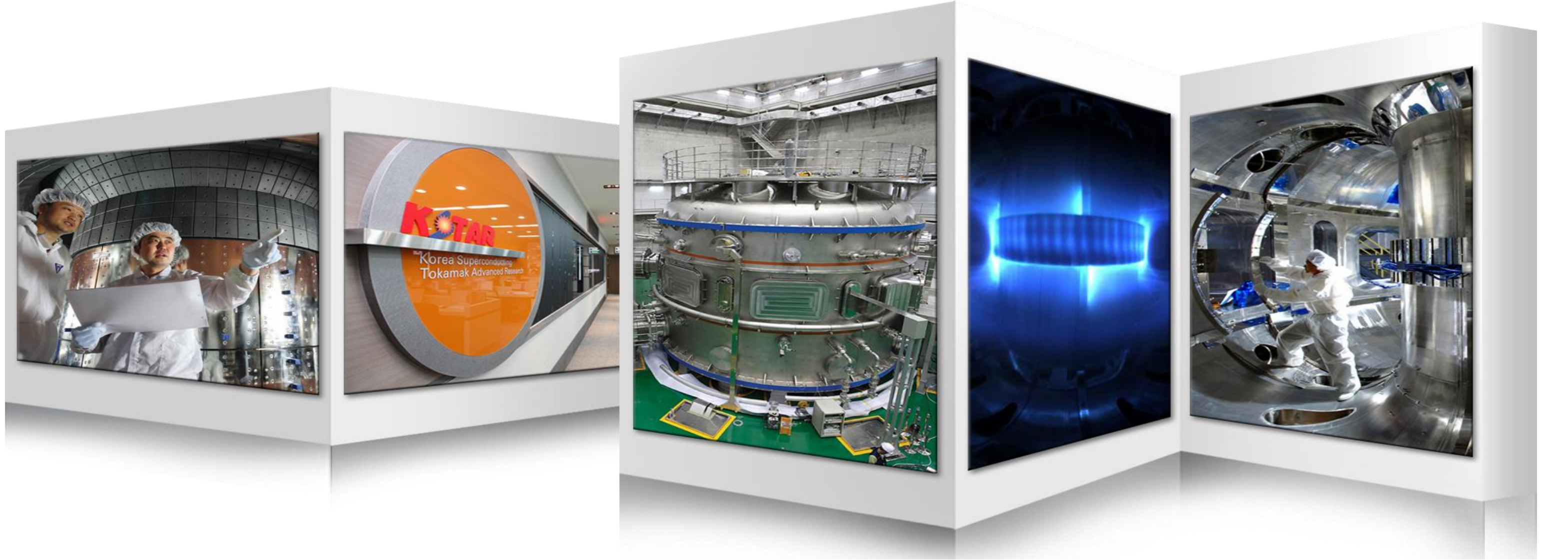
Global fusion R&D initiatives and shifting paradigms

- **Key directions for fusion reactor development:**
  - **Larger Devices:** Enhancing confinement and ignition.
  - **High-Field Superconductors:** Enabling steady-state operation.
- **Evolution of Magnet Technology:**
  - **Copper (Cu):** short pulse
  - **Low-Temp. Superconductors**
  - **High-Temp. Superconductors**
- **What comes Next?**
  - **DEMO with LTS: > ITER**
  - **Pilot with HTS: < ITER**



Global Fusion R&D and Korea's mid-entry strategy (1995)

Accelerating the path to Fusion Energy Realization



Strategy for accelerating fusion energy realization

- The **20th National Fusion Energy Committee** has approved the **“Strategy for Accelerating Fusion Energy Realization”** (July 22, 2024).
  - Keywords: technology innovation, public-private partnership, ecosystem

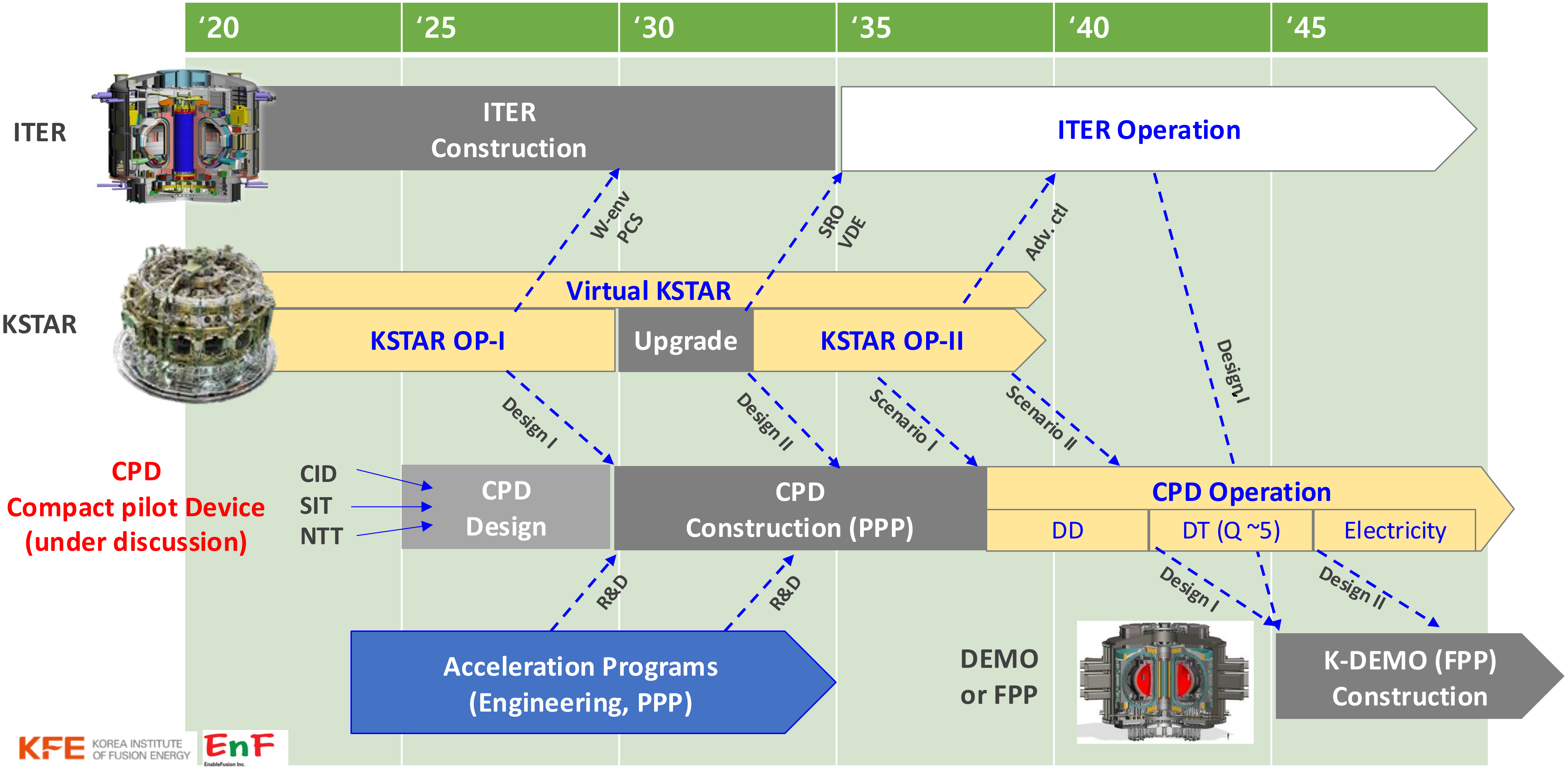
20th National Fusion Energy Committee in July. 2024.

Major strategies	Key tasks
1: **Fusion Technology Innovation** through Public-Private Partnership	• Fusion Engineering Innovation projects • Plug-in Program (PLasma for Unlimited power Generation & INnovation) • AI-driven Digital Innovation
2: Establishing the **Foundation for Fusion Energy Industrialization**	• Establishing a Private-led Fusion Industry Foundation • Supporting fusion companies in entering the global market • Expanding fusion R&D achievements
3: Creating an **Innovative Ecosystem** for Fusion Energy	• Strengthen the open research ecosystem • Training and securing Fusion energy specialists • International collaboration

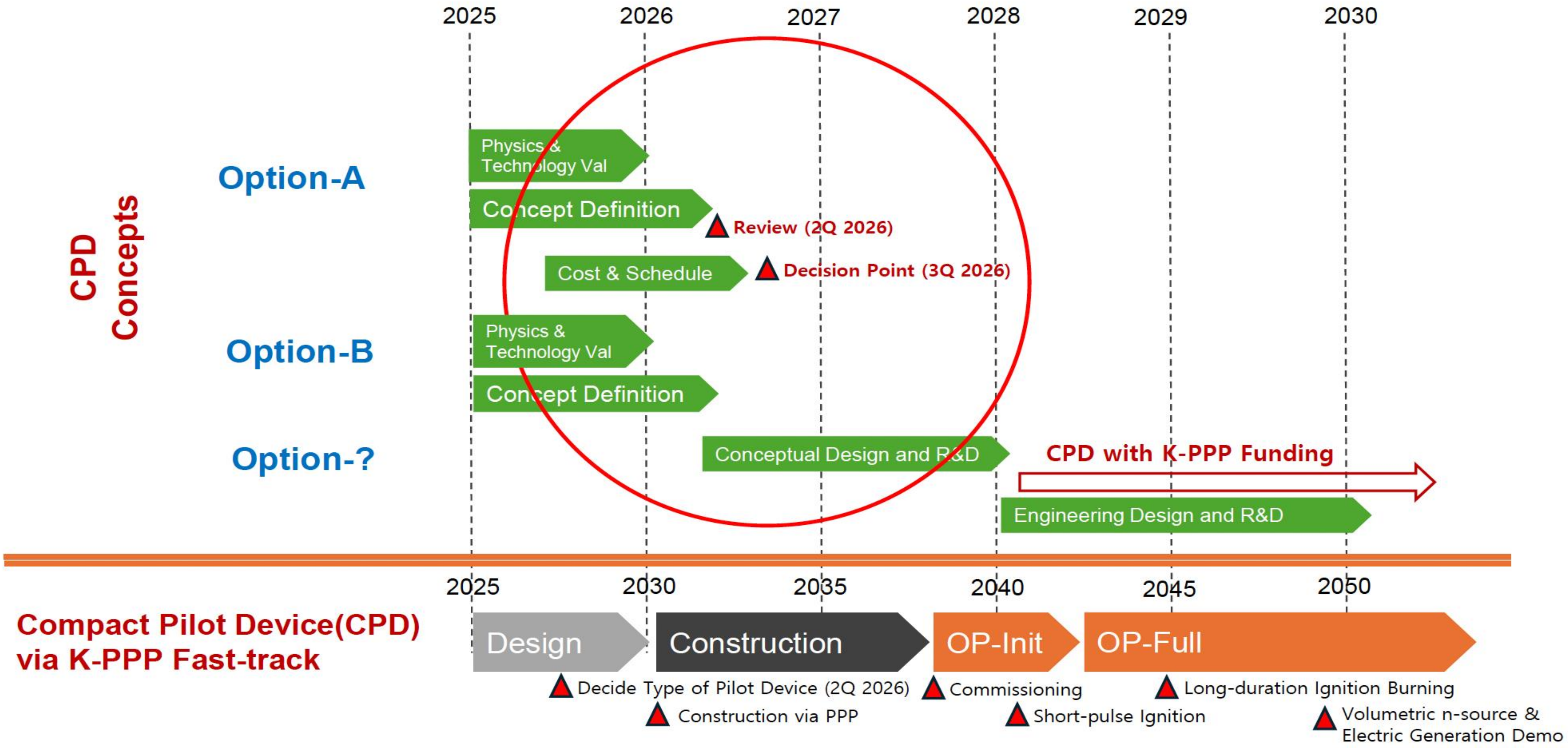
Strategy for accelerating fusion energy realization

- **Goal:** Establishing technological validation and industrial foundations for fusion energy deployment before achieving 2050 carbon neutrality.
- **K-DEMO:** Maintaining its construction schedule while re-assessing its design and role based on CPD and ITER operations.
- **Compact Pilot Device (CPD):** as precursors to K-DEMO, explore various design options, including conventional and spherical configurations, to advance fusion reactor development through public-private collaboration. (under discussion)
- **KSTAR:** transforming into a pivotal platform for optimizing operational scenarios for CPD, ITER, and K-DEMO, leveraging AI-driven advancements and collaborative experiments."
- **Fusion Engineering:** Key engineering technologies for innovative compact fusion reactors through public-private and international partnerships, revitalizing supply chains and driving innovation.
- **Ecosystem:** A robust fusion ecosystem is being cultivated through talent development, expanded facilities, large-scale collaborations, stable funding, and strengthened public-private and international partnerships.

Proposed timeline of Key Fusion Programs *(Subject to Discussion)*

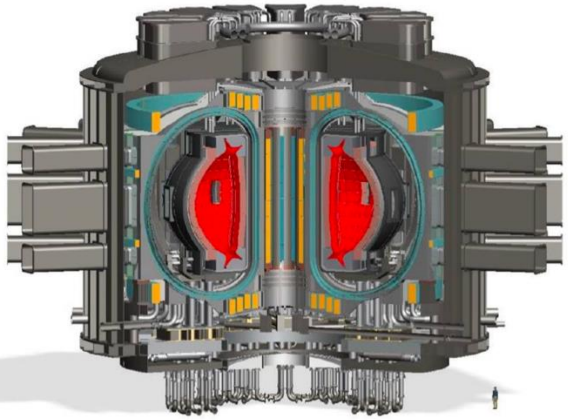


Proposed Plan for Defining and Deciding on the Compact Pilot Device (CPD)

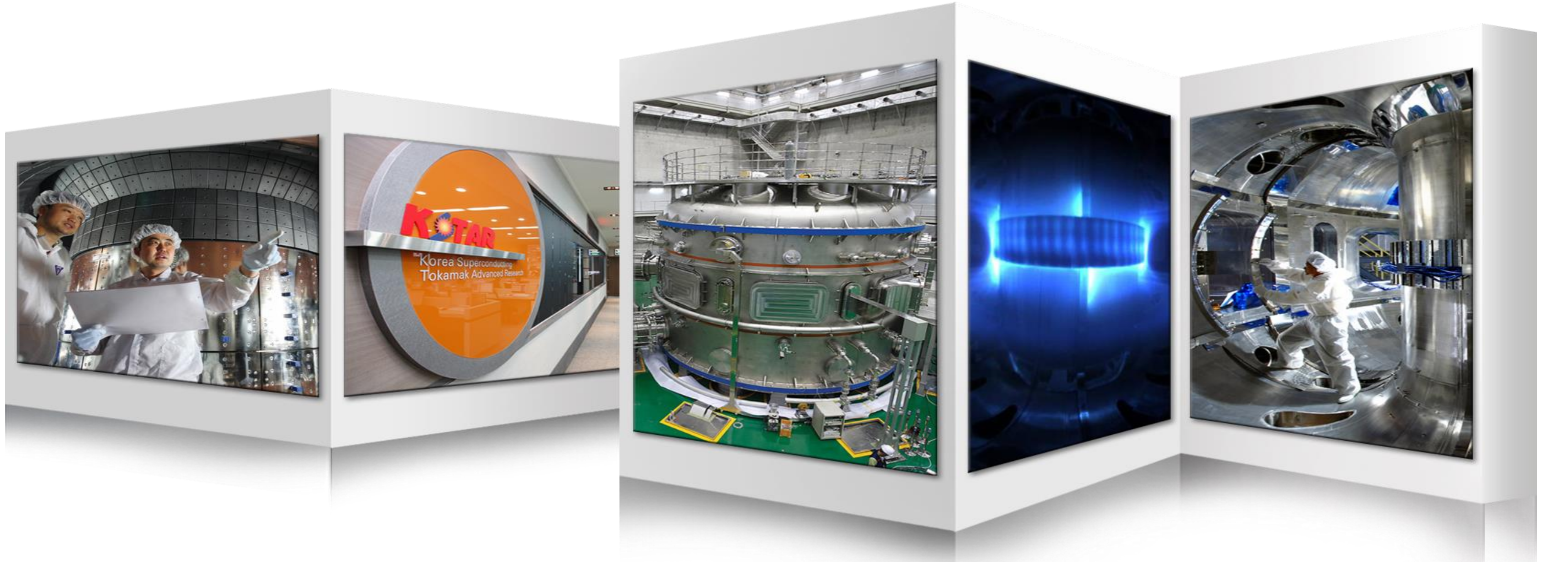


Comparison of Preliminary CPD Design Parameters with KSTAR and K-DEMO

Parameters	KSTAR	CPD (CID) draft	CPD (SIT) draft	K-DEMO
Major radius, R0	1.8 m	**~ 3.5 m**	**~ 2.0**	~ 6.8 m
Minor radius, a	0.5 m	~ 1.1 m	~ 1.2	~ 2.2 m
Elongation, k	2.0	~ 2.0	~ 2.0	~ 1.2
Field on axis, B0	3.5 T	> 6.3 T	~ 6.0 T	~ 7.5 T
Plasma current, Ip	2.0 MA	~ 7.7 MA	~ 9.0 MA	~ 13 MA
betaN	> 3.0	**~ 3.3**	~ 3.6	~ 3.0
H		~ 1.5	~ 2.9	~ 1.28
Q		~ 5.5		~ 20
fGW (ne/nGW)		~ 0.95	~ 0.65	~ 1.1
Fusion power		**~ 300 MA**	**~ 360 MW**	~ 1500 MA
SC	NbTi, Nb3Sn	**HTS / LTS**	**HTS**	NbTi, Nb3Sn
Divertor	C, W	~15 MW/m		~ 20 MW/m



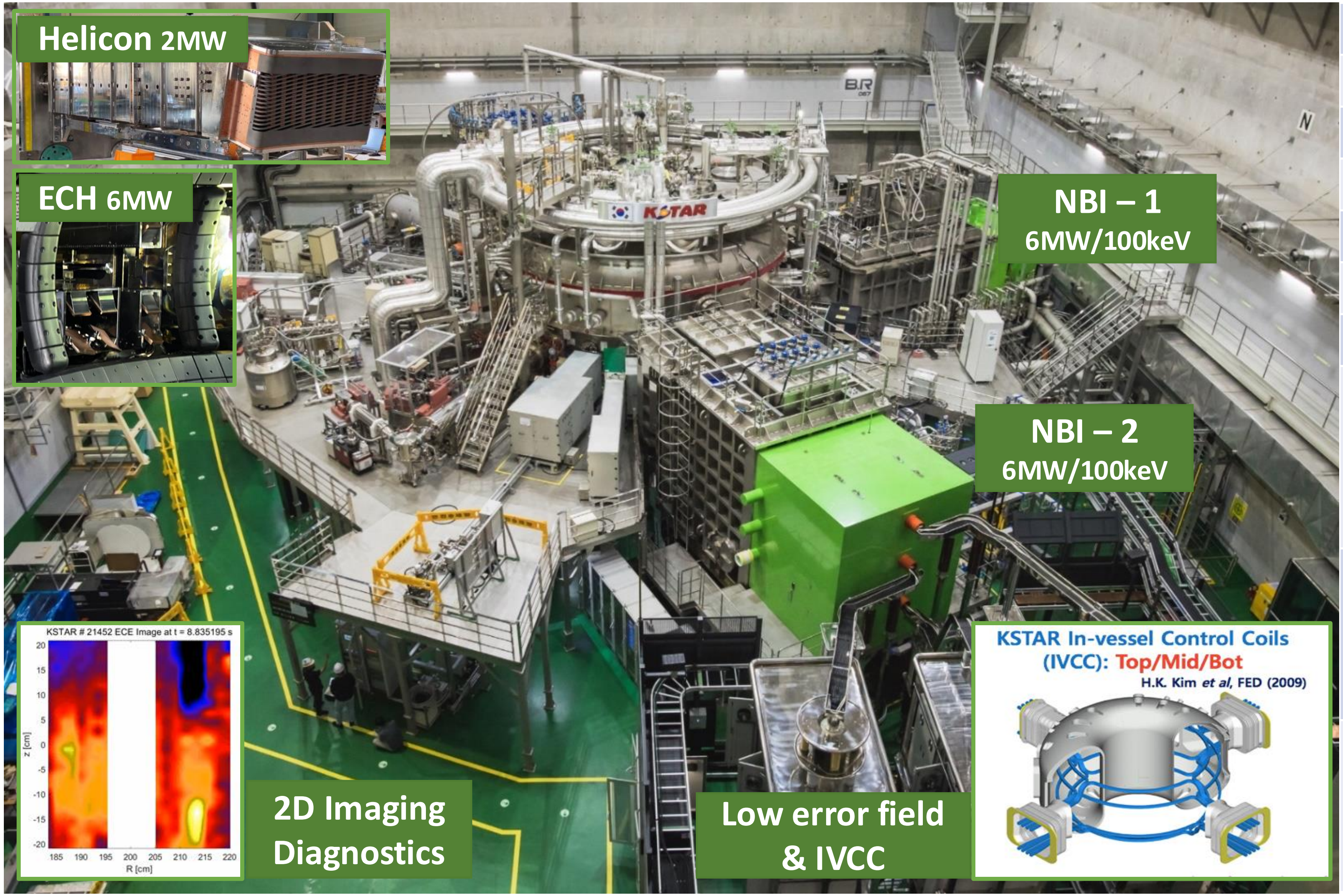
- ***Parameters can be changed according situation***



Korea’s Fusion Research Progress

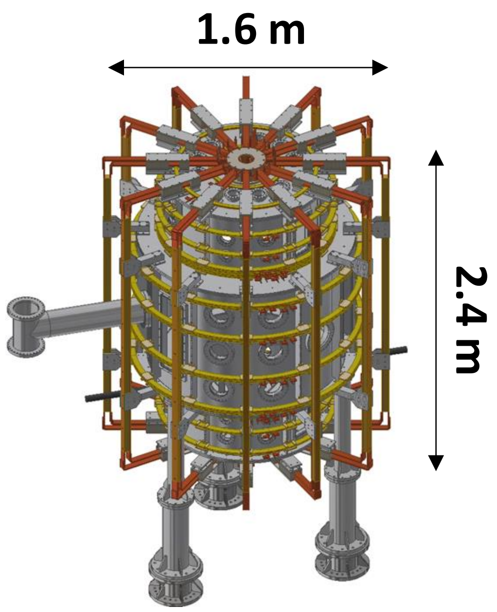
- **KSTAR**: Korea Superconducting Tokamak Advanced Research (at KFE)
- **VEST:** Versatile Experiment Spherical Torus (at SNU)
- **Virtual KSTAR**
- **ITER** Procurement and operation (KODA)

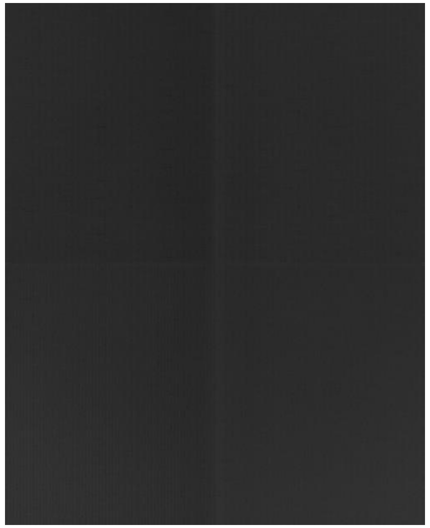
KSTAR (Korea Superconducting Tokamak Advanced Research): mid-size SC tokamak for high-perf. Steady-state Operation



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
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

VEST : (Versatile Experiment Spherical Torus)





➢ University-scale Spherical Tokamak (ST) device in SNU

- ECH-assisted trapped particle configuration developed for efficient and robust start-up
- Internal reconnection events for the study of disruption

SEOUL NATIONAL UNIVERSITY

➢ Specifications

	Present	Future
Toroidal B Field	0.05 – 0.18 T	< 0.3 T
Major Radius	0.45 m	< 0.45 m
Minor Radius	0.33 m	< 0.3 m
Aspect Ratio	>1.36	> 1.5
Plasma Current	≤ 300 kA	> 300 kA
H & CD (ECH, NBI, HI)	ECH (7.9GHz, 3kW) ECH (2.45GHz, 15kW) NBI (15keV, 600kW) HI (1.05 MW / 10ms)	ECH (5GHz, 30kW) NBI (12keV, 300kW) NBI (18keV, 700kW) HI (1.05 MW / 10ms)

KSTAR Uniqueness: Tungsten (W) monoblock divertor, providing opportunities to study tungsten transport and control

➢ W-monoblock installation at lower divertor

- Preparing high-power (max 24MW) long-pulse operation
- Peak heat flux: 4.3 MW/m2 (C) ⇒ 10 MW/m2 (W)
- Successfully installed & commissioned
- W transport & retention experiments enabled
- Full W wall is planned (W coated carbon PFC)

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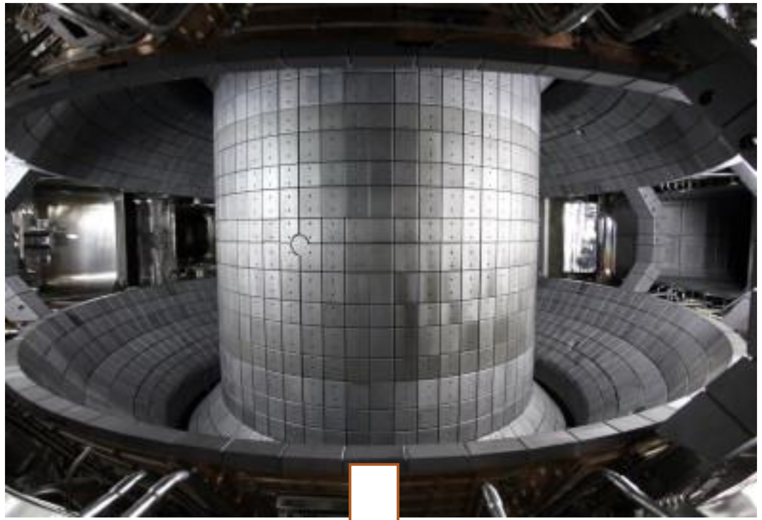
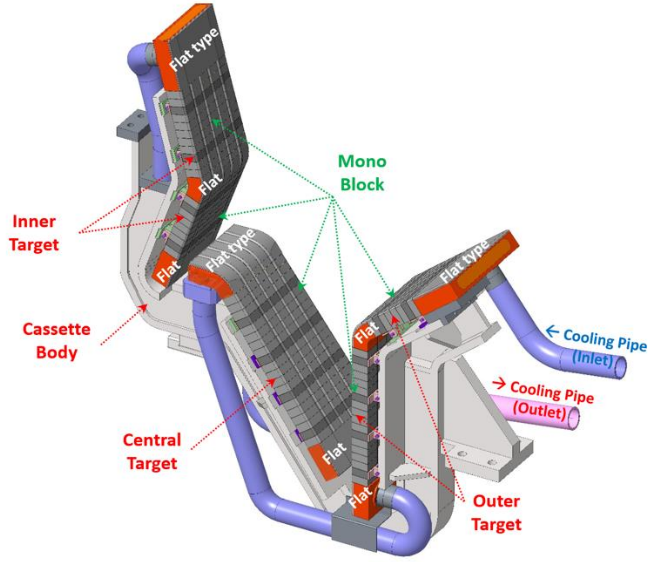
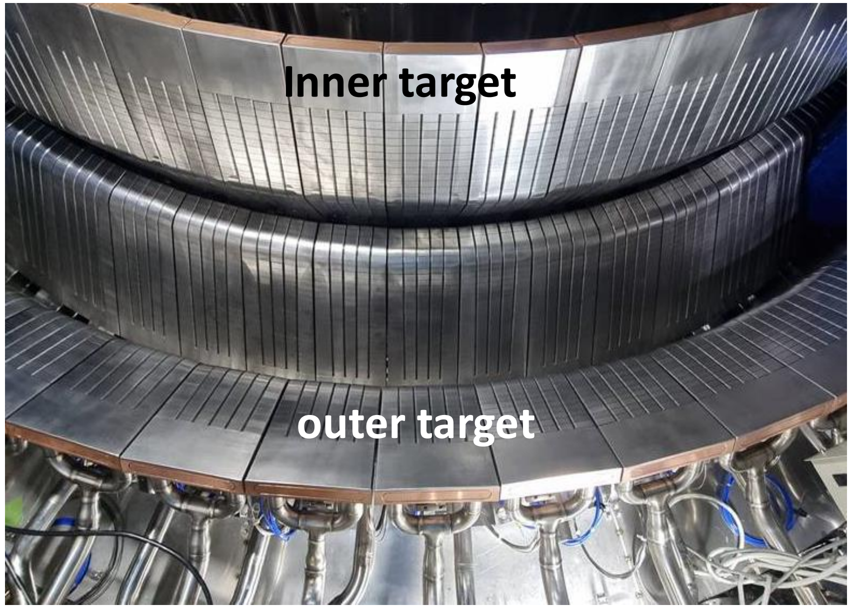
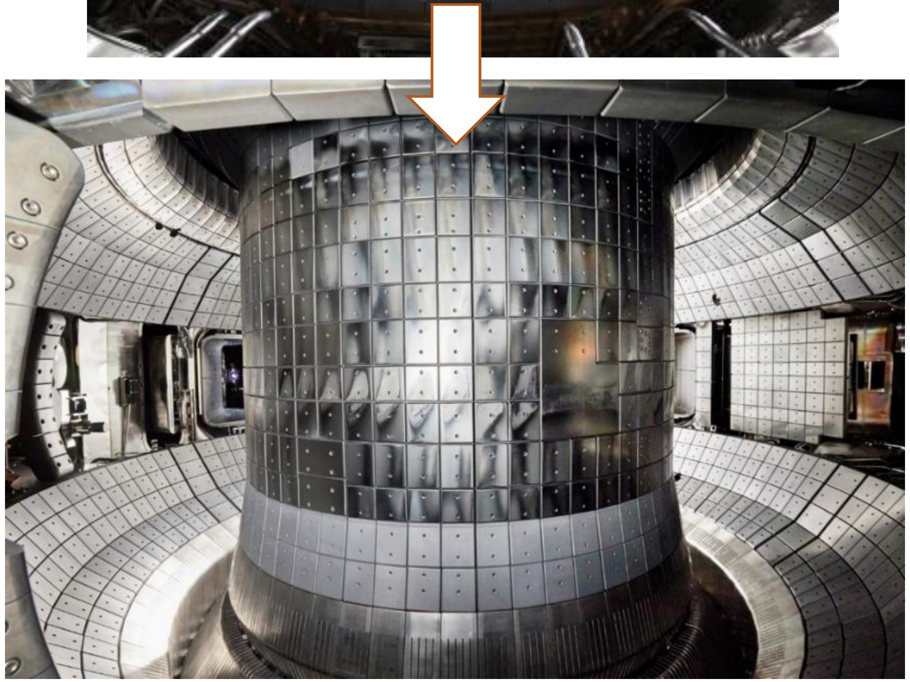


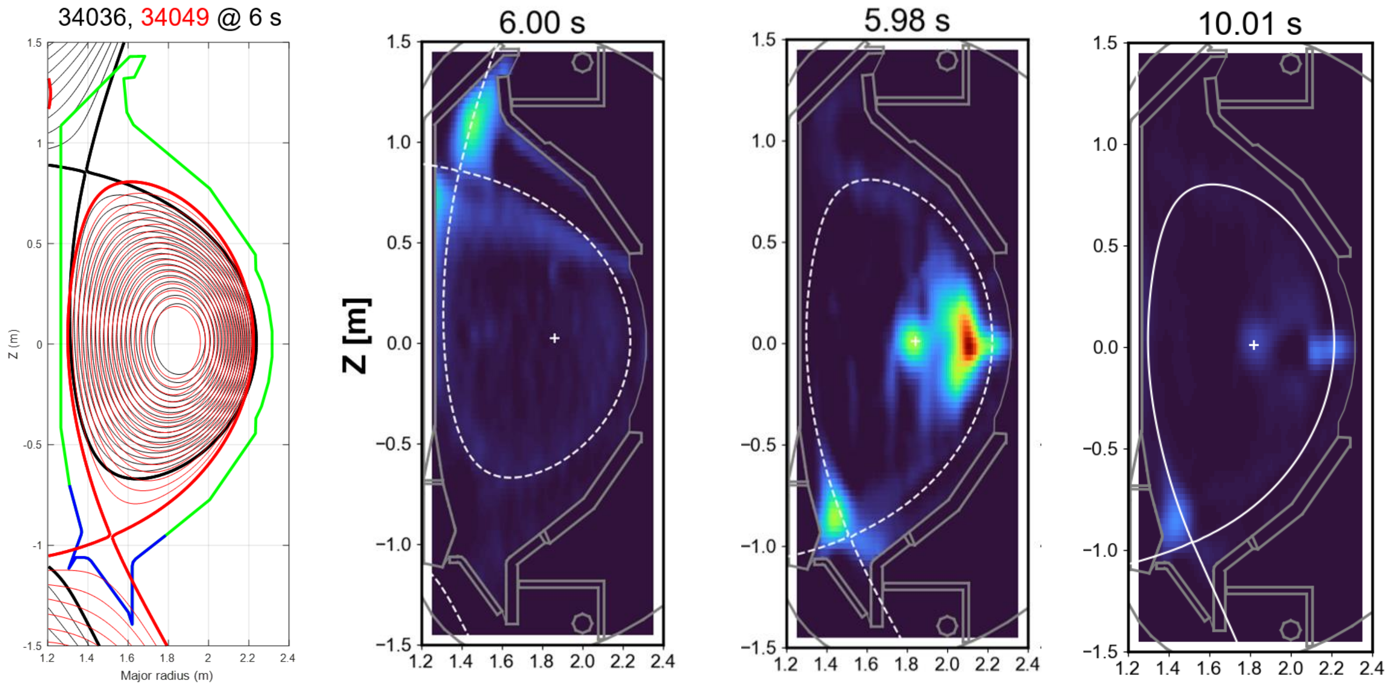






W Impurity Control: Investigated Tungsten (W) impurity effect after W divertor installation

- W impurities is easily penetrated into the core plasma
- W impurities is localized in the low field side due to the high toroidal rotation speed
- W impurities dominate the plasma radiation loss
- W impurities is reduced by the application of RMPs (due to ELM suppression or transport)

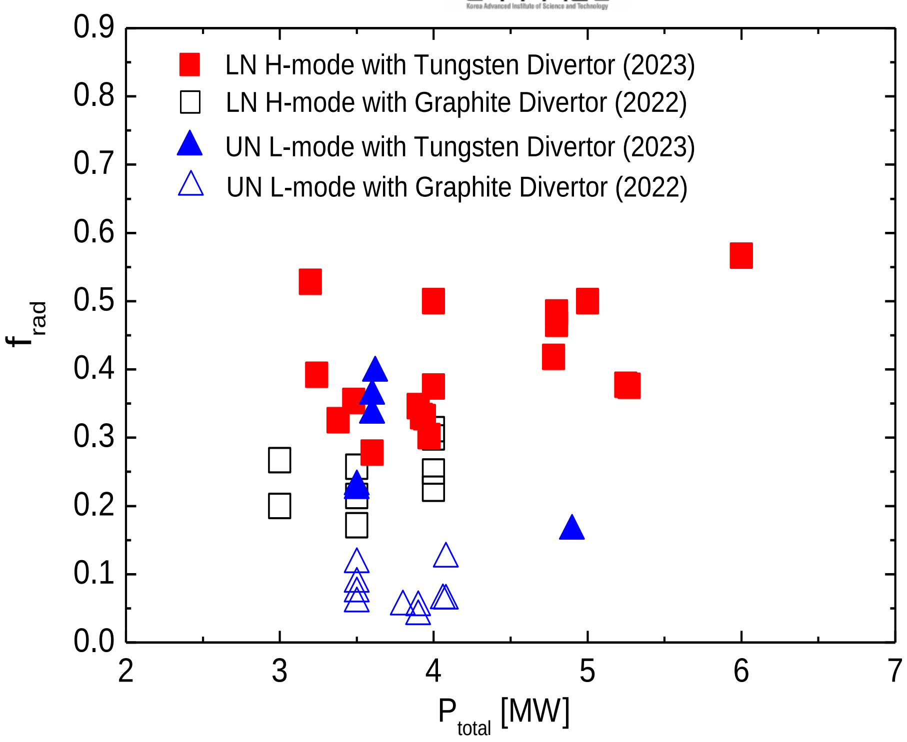


34036 (UN)
Carbon target

34049 (LN)
W target
w/o RMPs

34049 (LN)
W target
w/ RMPs

W impurity penetration and effect of RMP application



Advanced scenarios: Investigated high-performance scenarios with long-pulse operation

- High-performance long-pulse achieved (LSN) : up to 102s
- High ℓ_i scenario achieved stationary β_N ~ 3 at ℓ_i ~ 1
- FIRE (fast ion regulated enhancement) mode maintaining Ion temperature of about 10 keV (≈120 million kelvin) : up to 48 s

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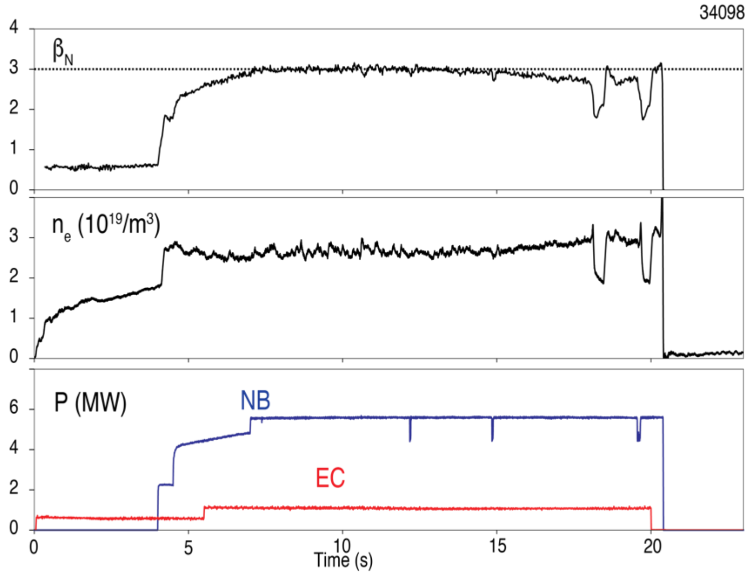
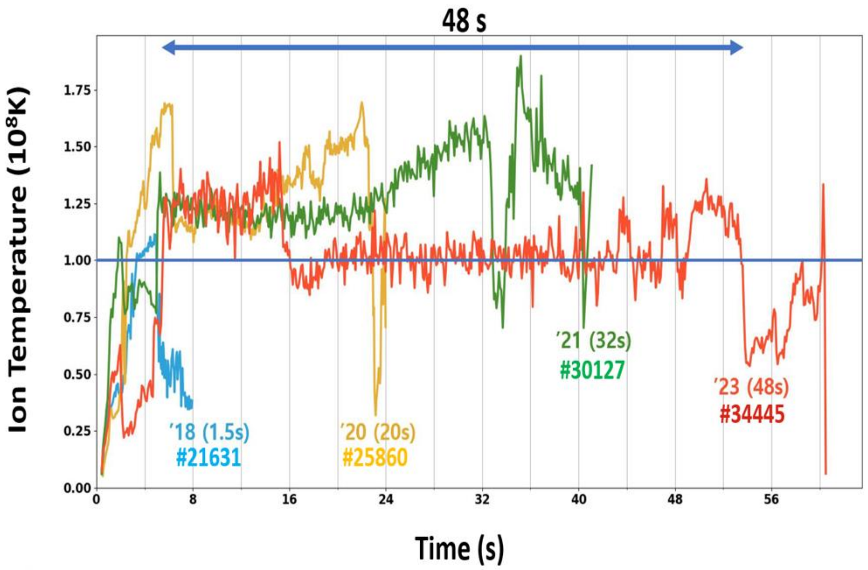
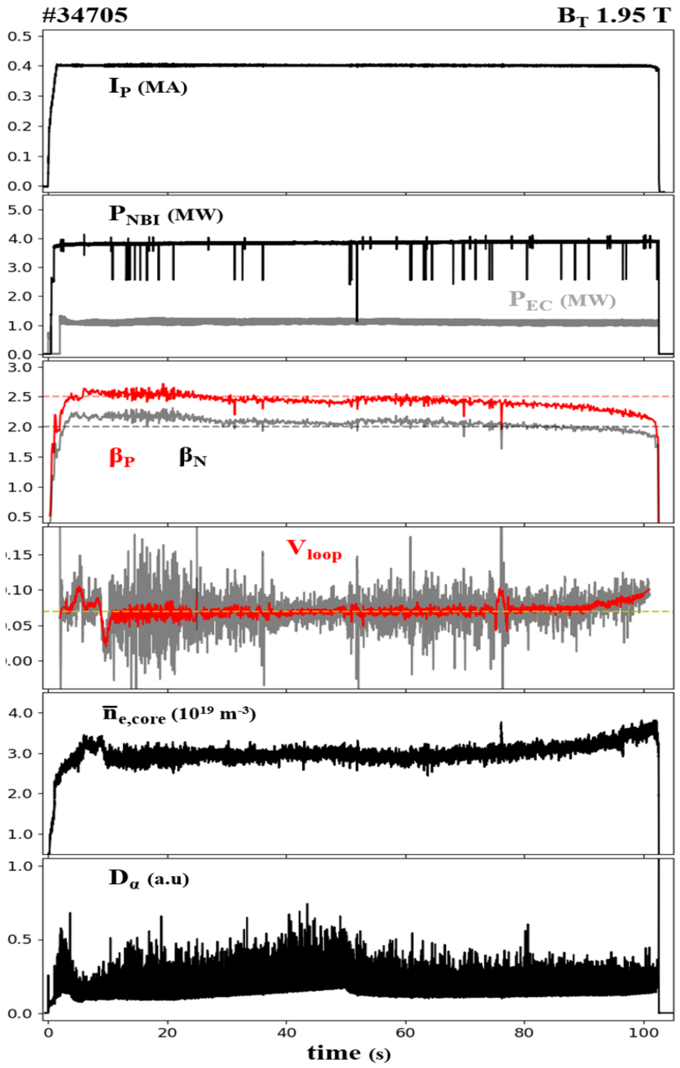


High ℓ_i scenario with β_N ~ 3, 12 s



High T_i scenario (>10^8 K), 48 s



H-mode with β_N > 2, 102 s

Instability Control: Advanced actuators & fast diagnostics enables real-time control of hazardous events

➢ ELM and Disruption Control:

- Edge localized RMP (ERMP) ensures safe access to ELM suppression with improved confinement and reduces core response without penalty at the edge
- DECAF disruption prediction and avoidance research produces 100% forecasting accuracy in the first real-time operation on KSTAR

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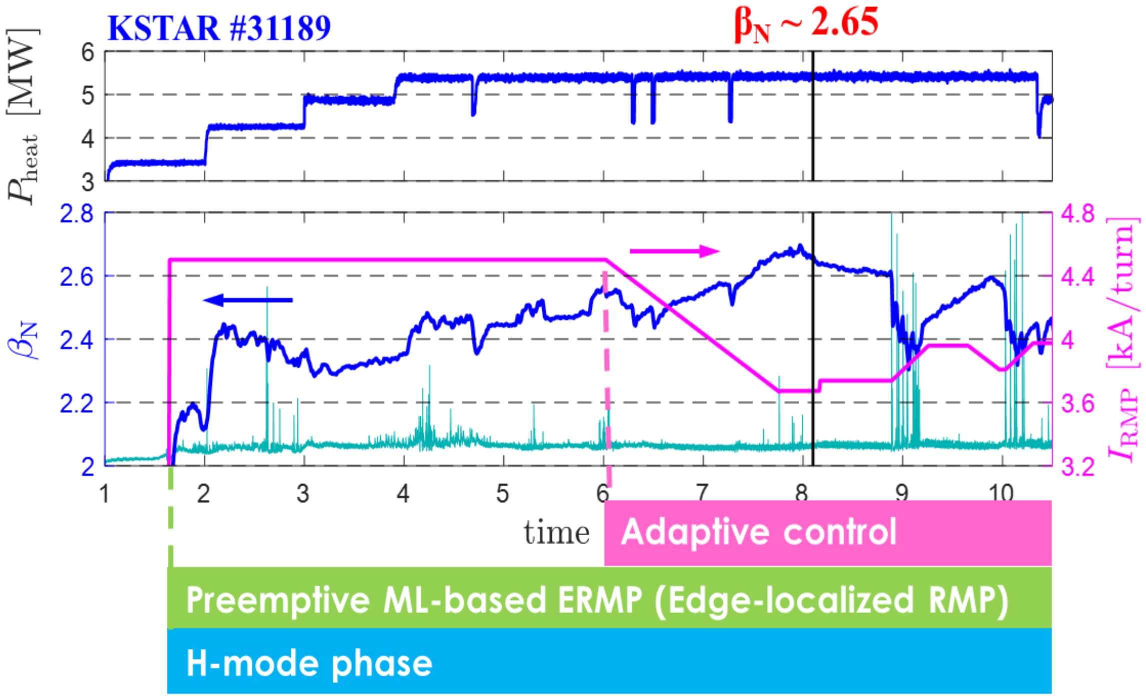
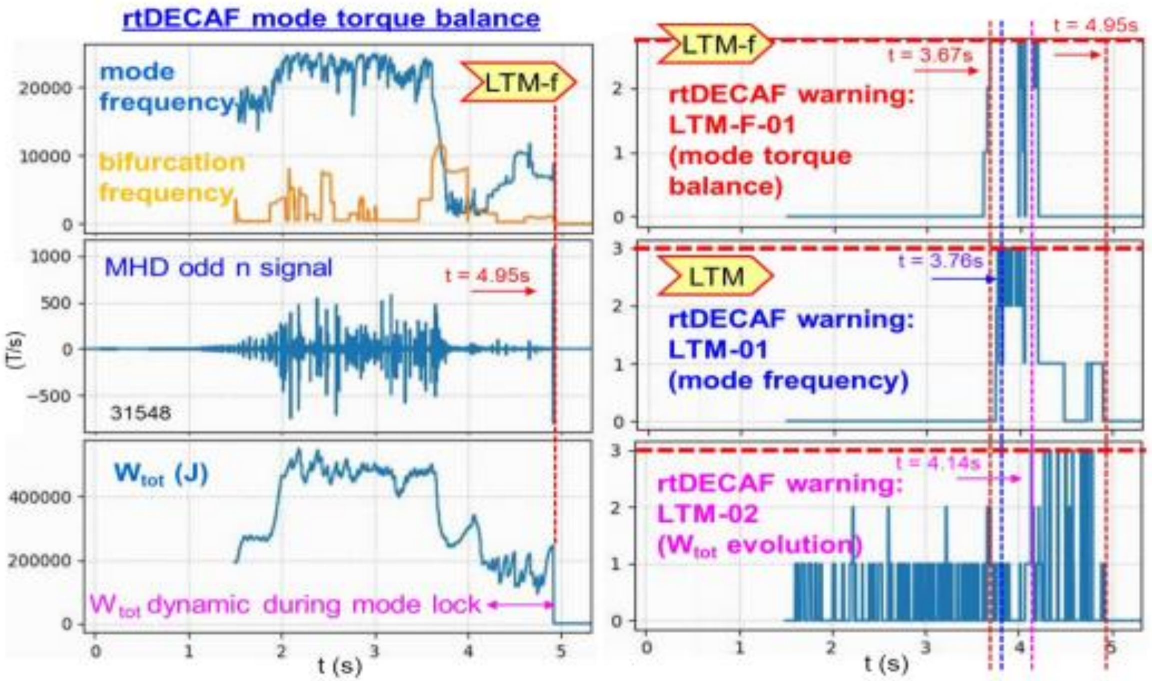


S.M. Yang (2020)

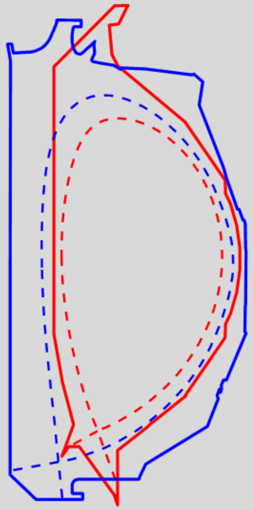


S. A. Sabbagh, (2023)

Joint experiments: KSTAR will test DIII-D adv. scenarios with long-pulse capabilities

- **DIII-D Joint on-site experiments were successfully conducted within KSTAR constraints**
  - Develop high-confinement DIII-D hybrid scenario with KSTAR operation constraints
  - Steady-state hybrid scenario with W radiation and control strategies for KSTAR long pulse operation
  - Neoclassical Ti screening of W in pedestal of hybrid steady-state scenario with grassy ELMs
  - Establish high-βp scenario with large-radius ITB using KSTAR-like constraints
- **Experiments on hybrid, high-βp, and IBS are planned on 2024 KSTAR campaign**

Superconducting magnets
& Newly installed W-divertor



	DIII-D	KSTAR
I_P	0.9-1.4 MA	0.4-1.0 MA
dI_P/dt	~ 1.0 MA/s	< 0.5 MA/s
P_{NB}	~ 10 MW	< 8 MW
P_{EC}	3 - 4 MW	1 - 3 MW
A	2.9	3.7
V	18 m^3	13 m^3
R_0	1.68 m	1.76 m

→ q_{95}
→ τ_R
→ P/V

KSTAR-Compatible	
B_T	1.9 T
q_{95}	5.8
dI_P/dt	0.5 MA/s
P_{NB}	10 MW
P_{EC}	3 MW

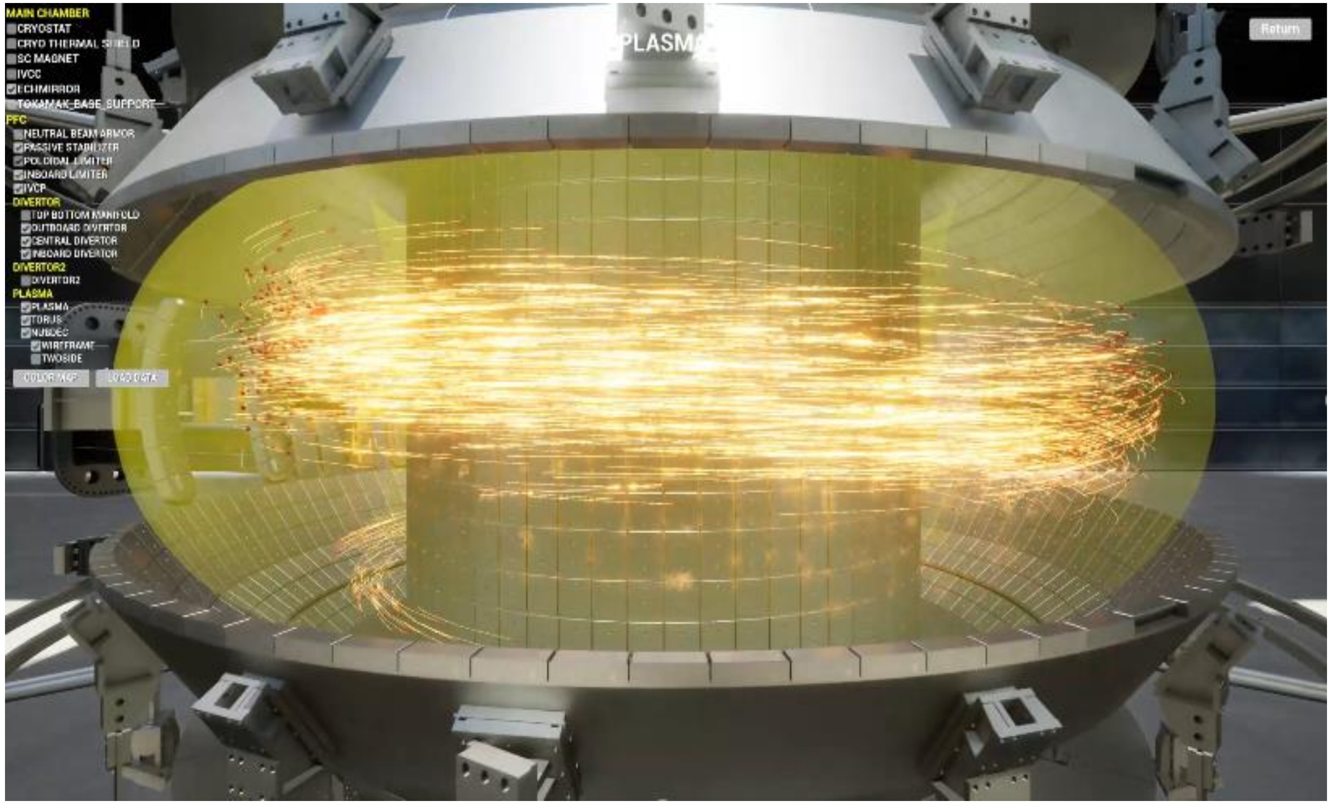
& KSTAR-like shape

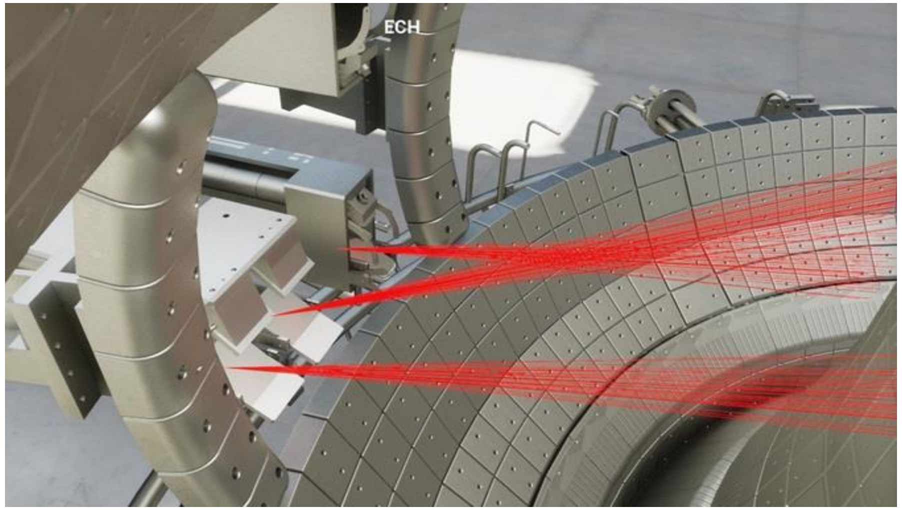
courtesy of J. Chung

Oak Ridge National Laboratory
PPPL Princeton Plasma Physics Laboratory
Columbia University
Lawrence Livermore National Laboratory
DIII-D National Fusion Facility
General Atomics

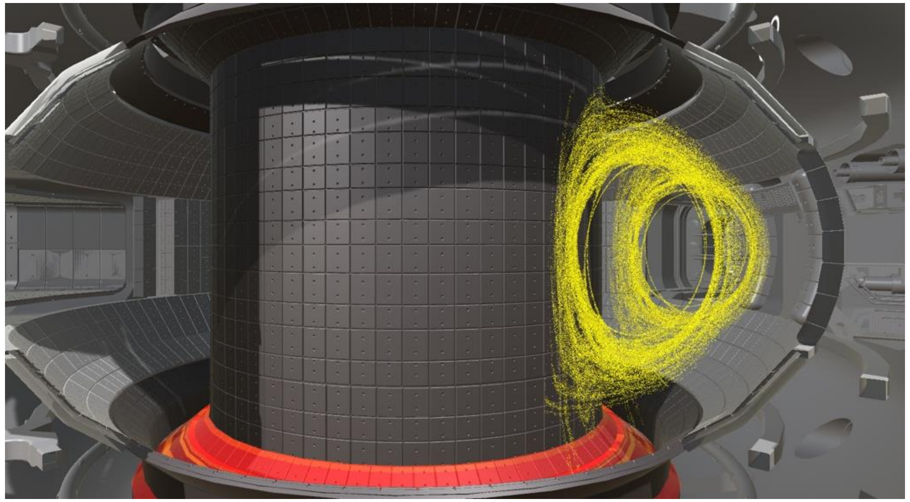
Digital Twin: Virtual KSTAR based on Digital Twin Technology

- high-performance plasma simulation techniques with supercomputers and game graphics technology.
- Successful achievement of the real-time 3D virtualization of the KSTAR device and plasma (V-KSTAR)





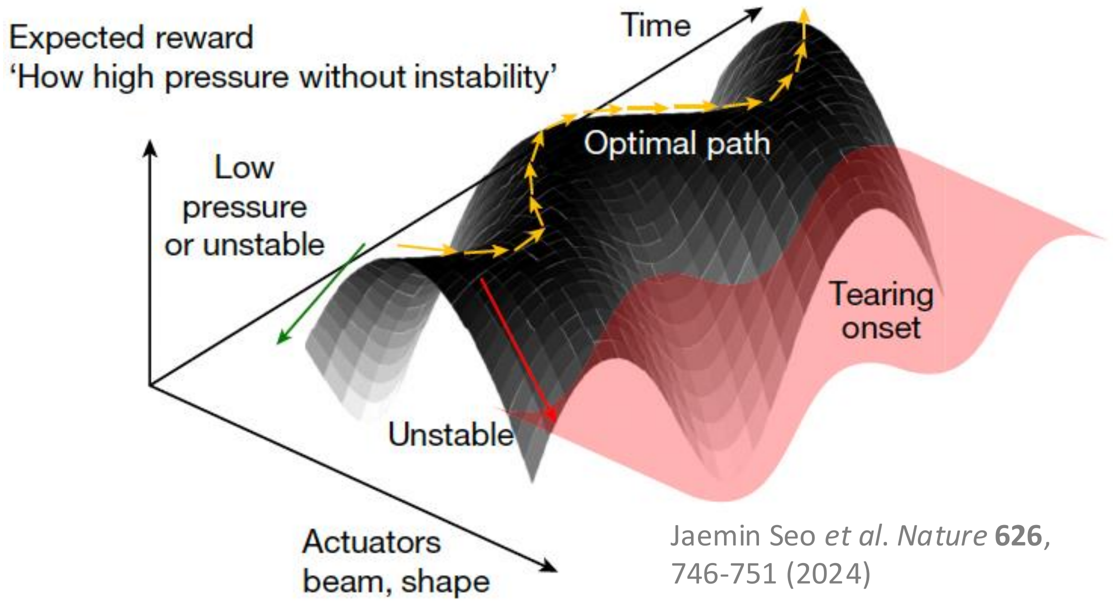
3D ECH ray-tracing within V-KSTAR using TORAY



3D magnetic field line tracing within V-KSTAR

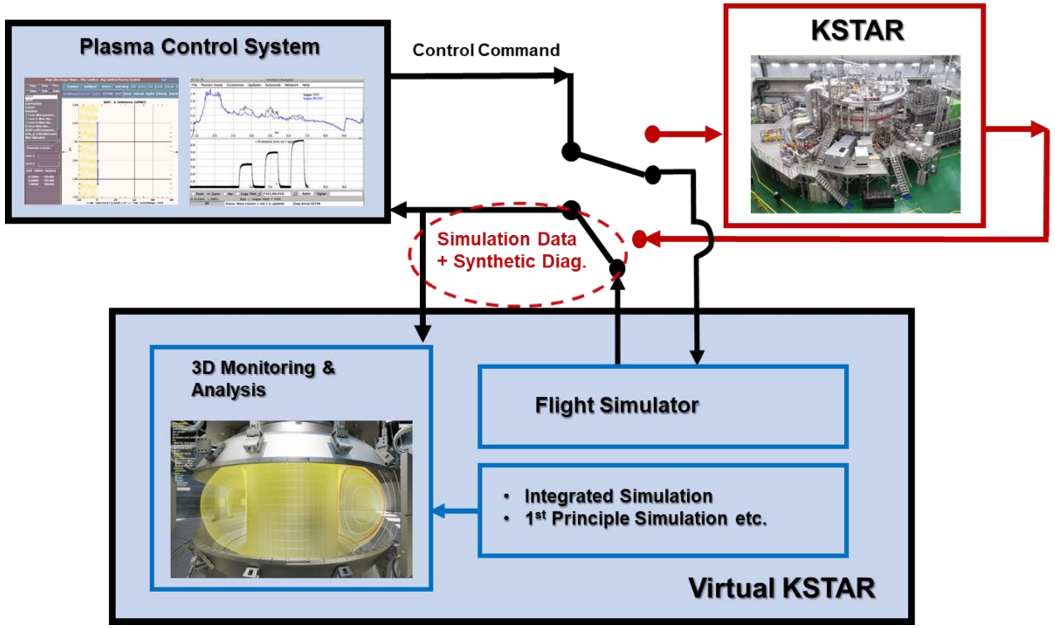
Plasma control upgrade plan: Combining ITER CODAC, Digital Twin and AI-based PCS

- Overcome limitation on current PCS (long-pulse compatibility, expandability)
- Require collaboration with ITER CODAC/GA
- Support for ITER first plasma, SRO
- Testbed for innovative AI based PCS for instability avoidance



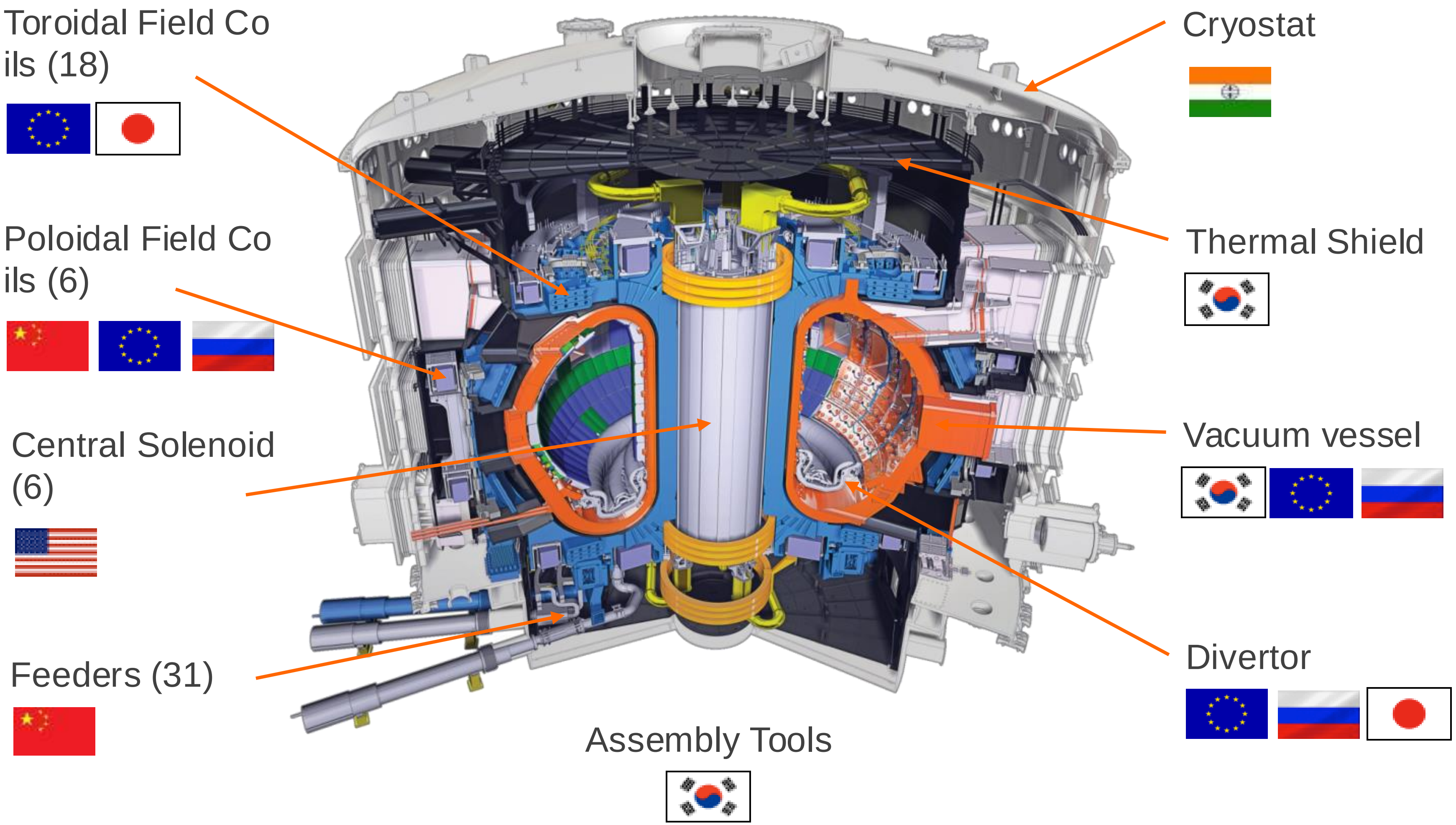
Jaemin Seo *et al. Nature* **626**, 746-751 (2024)

Tracking the high performance plasma avoiding plasma instability with ML / AI



enhance the simulation capabilities of Virtual KSTAR by integrating a fusion flight simulator

Korea's ITER procurement



China EU India Japan Korea Russia USA

ITER Procurement:
Most contributions will be delivered in the form of completed components, systems or buildings, with little monetary contribution for labor and operational cost.

Contribution: EU 45.46%, Others 9.09%

All ITER members share the resulting intellectual property.

Supply chain: Emphasizing the importance of maintaining a sustainable supply chain after ITER procurement completion

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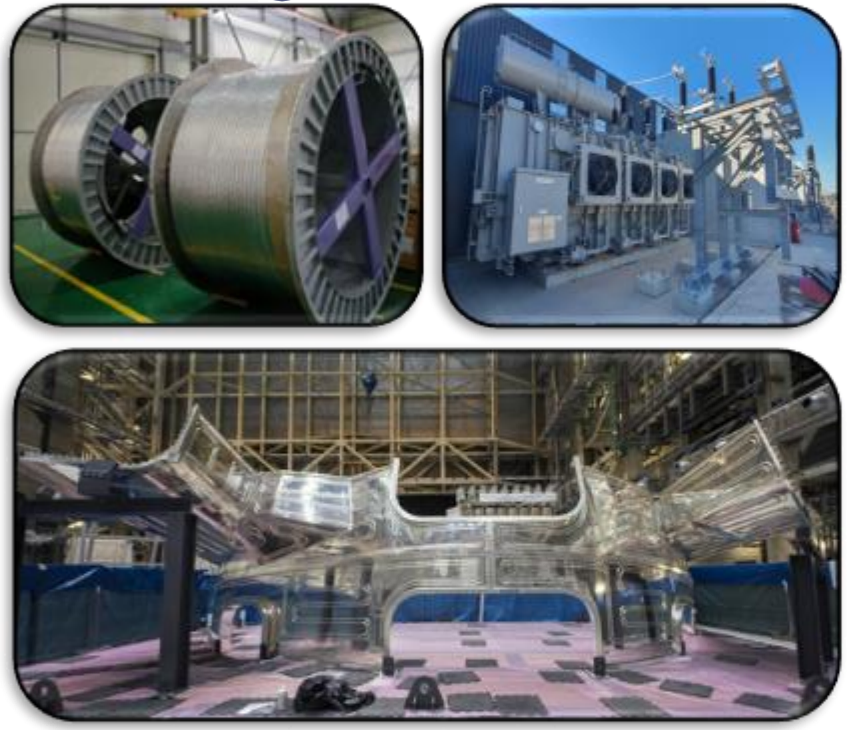
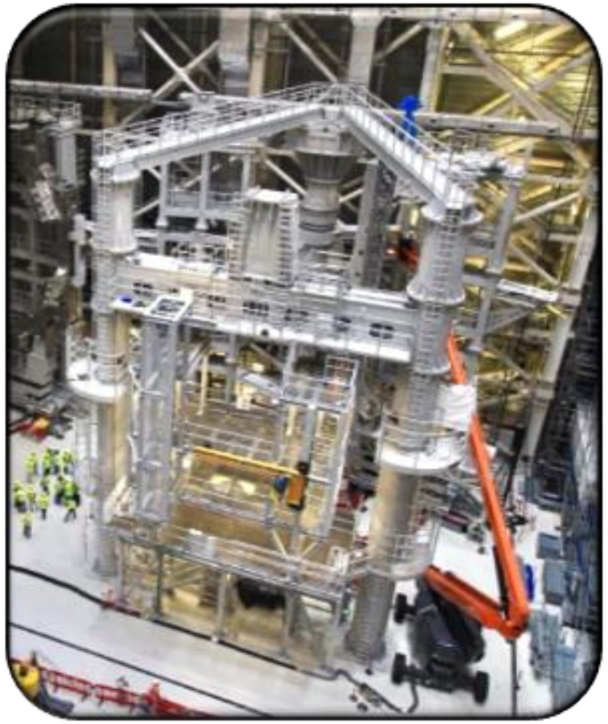
- Korea has played a key role in the manufacturing of major structural components for the ITER tokamak, such as: Vacuum vessel, Thermal shields, Assembly tools. (last VV sector delivery)
- With the ITER construction nearing completion, there is an urgent need to establish strategies for maintaining and sustaining the fusion-related supply chains.

HD현대중공업 SamHong Machinery DAWON UNIVERSE Kiswire KAT [주]유진엠에스 MECHATRONICS KOREA iter iter

Last VV sector delivery ceremony (Nov. 2024)



SC conductor, AC/DC convertor, thermal shield



Assembly tools

ITER Operation: Collaboration and contribution to ITER prior to its operation

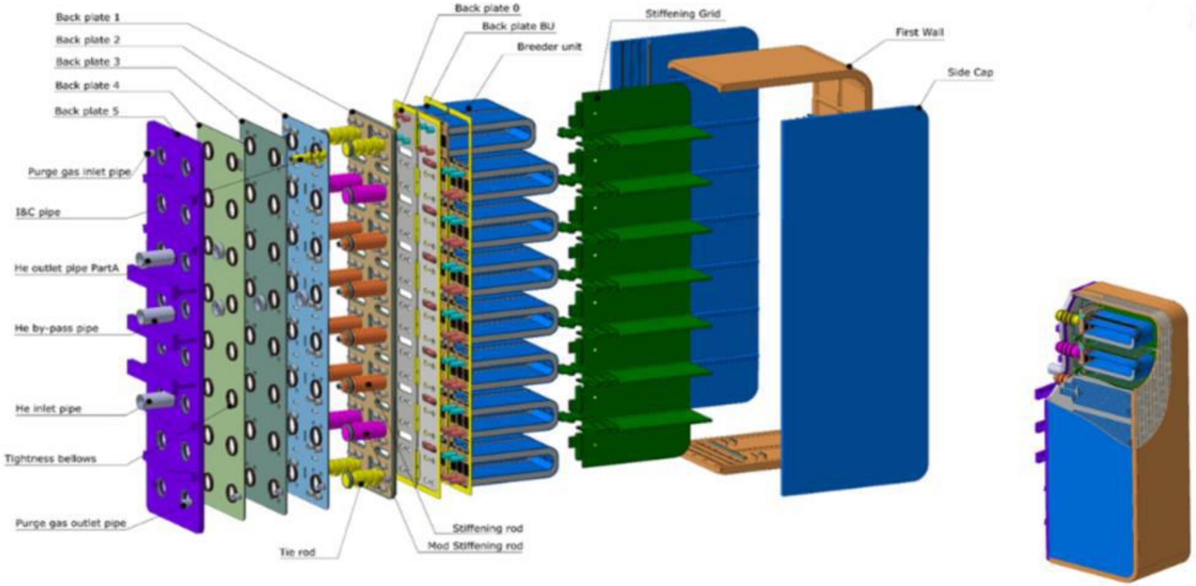
➢ KO's contribution & benefits:

- Qualification during assembly & integrated commissioning based on KSTAR experience
- Plasma control validation of SRO in KSTAR
- Operation with ELM & disruption mitigation
- Operation with W impurity control
- Experts training & remote participation

KFE-ITER MOU renewal (Nov. 2024)

➢ Test blanket module :

- KODA - F4E collaboration on TBM:
- Helium Cooled Ceramic Pebble (HCCP)-type blanket module
- Verification of TBM design and key technologies



HCCP TBM module

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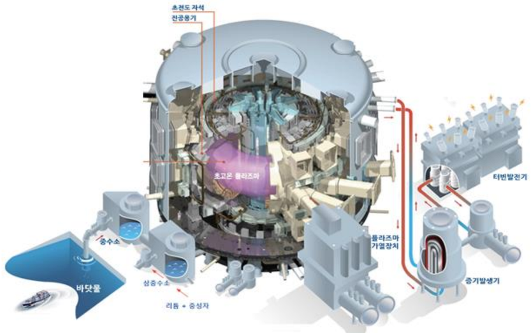
Fusion R&D programs

Compact Pilot Device / DEMO / Fusion Power Plant

- Contribution to the energy mix by 2050.



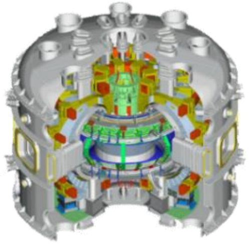
Research collaboration & expert cultivation

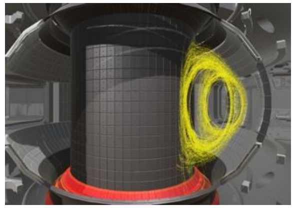
International collaboration

Public-Private Partnership

KSTAR & V-KSTAR

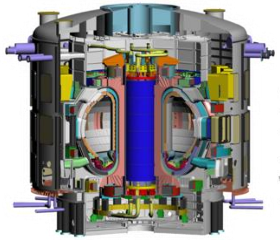
- Upgrade & advanced operation
- AI-based plasma control
- High performance scenarios (high betaN)
- Avoidance disruption & instabilities
- Optimized Divertor (W) & heat removal
- Innovative Heating & CD (ECH, NBI, etc)

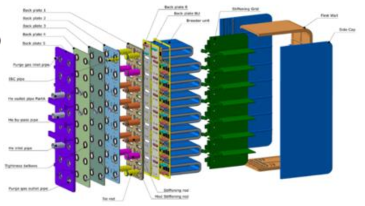




ITER & TBM

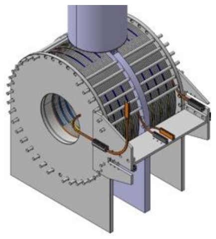
- Large-scale tokamak integration qualification
- Burning plasma operation (Q=5, 10)
- Test blanket module integration
- Safety, remote handling, waste
- International collaboration

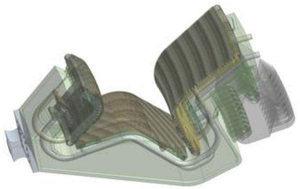




Innovative design & engineering R&D

- Innovative design (compact & advanced)
- SC magnet engineering (LTS, HTS, test)
- Innovative control & diagnostics
- Innovative Divertor, blanket, materials
- Heating, fuel cycle
- Remote handling, Safety & license, etc





Summary

Strategy for Accelerating Fusion Energy Realization

- Establish technological validation and industrial foundations for fusion energy deployment before 2050 carbon neutrality.

KSTAR:

- Advanced plasma control and diagnostics.
- Developing operational scenarios for CPD, ITER, and K-DEMO through AI-driven enhancements.

Compact Pilot Device (CPD) (under discussion)**:**

- Precursor to K-DEMO, exploring conventional and spherical designs.
- Developed via public-private collaboration.

Fusion Engineering:

- Advancing key technologies through international and public-private partnerships.

Ecosystem Development:

- Revitalizing supply chains and fostering innovation.
- Focus on talent cultivation, facility expansion, stable funding, and collaborative networks.

Future Challenges:

- Address workforce and infrastructure limitations.
- Enhance global collaboration for sustainable innovation.

FUSION: Fundamental, Unlimited, Sustainable, Innovative, Overturning, No Radioactive Waste

"Thank you for your attention!"

"KFE's Vision:

Creating a New Sun

to Illuminate the Next Generation"

한국핵융합에너지연구원
KOREA INSTITUTE FOR FUSION ENERGY