Establishment and Progress of Korean Fusion Reactor Design Activities: A Coordinated National Approach

Presented by Jae-Min KWON*

J. Kang, B.G. Hong, N. Her, W. Kim, Y.K. Oh, S.W. Yoon, G. Jo, G. Shin, S.-H. Hahn,

and *KFE researchers and domestic and international collaborators*

in Korea's fusion energy development.

한국핵융합에너지연구원 KOREA INSTITUTE OF FUSION ENERGY

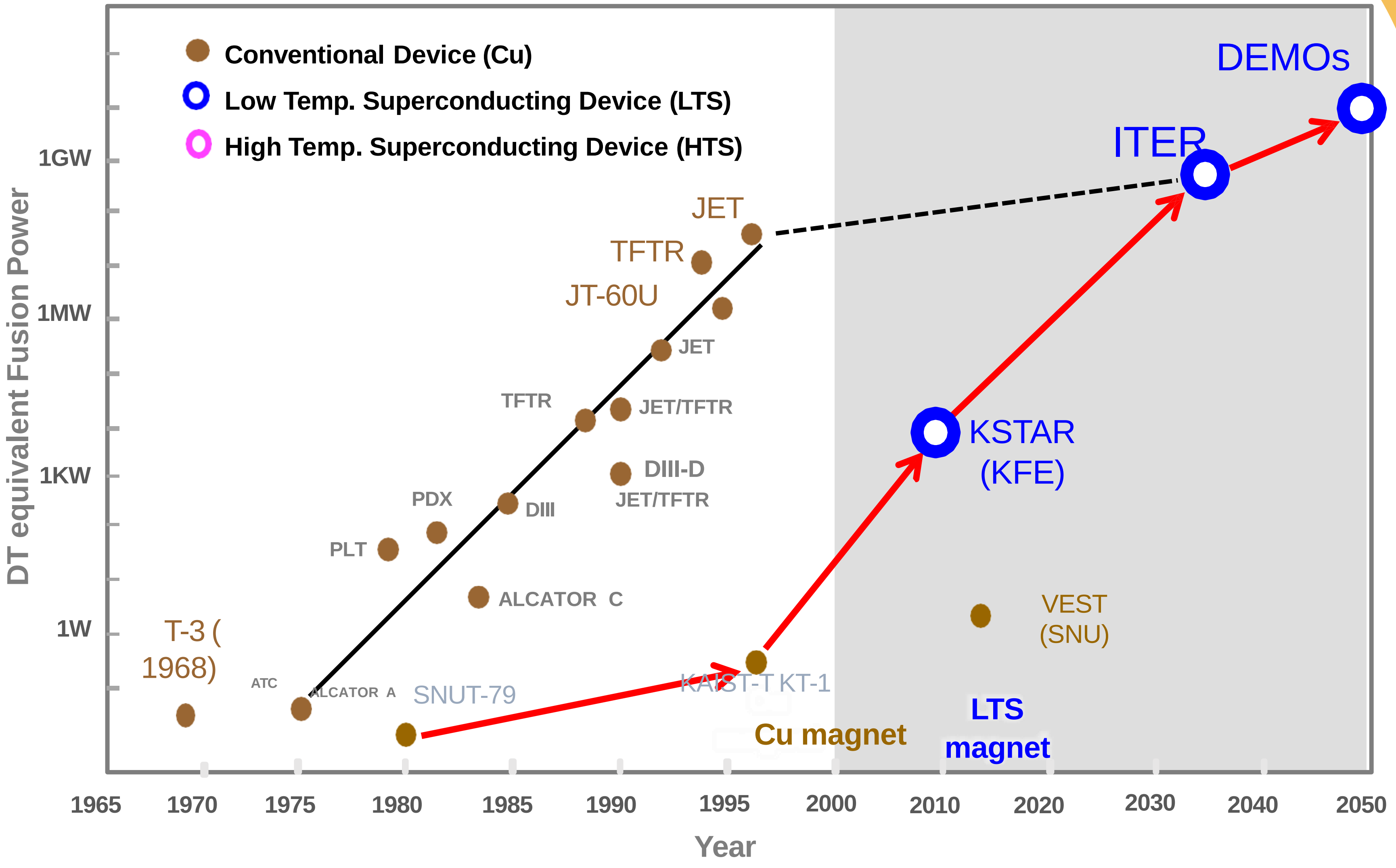
과학기술정보통신부 Ministry of Science and ICT

OUTLINES

I. Introduction of Korea National Fusion R&D

Introduction to National Fusion R&D in Korea

- The Korea National Fusion R&D has made steady progresses since the start of the KSTAR project in 1995.
- Fusion R&D is progressing under "Fusion Energy Promotion Act".
- Korean government establishes and updates the master plan for the Promotion of Fusion Energy Development for every 4 years.
- We are now in the middle of the period for the 4th master plan: 2022 ~ 2026.



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

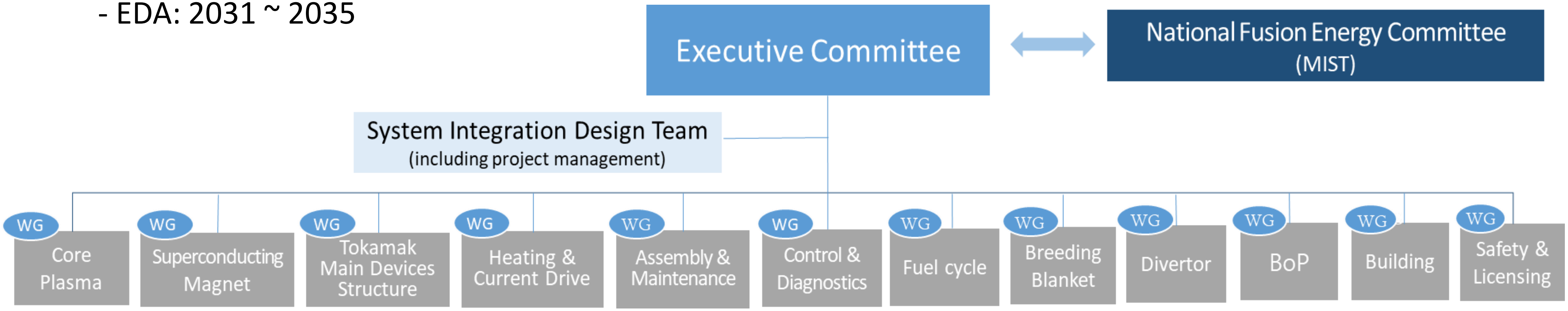
DEMO Design Task Force

- DEMO Design TF was established under the 4th Master Plan in July, 2023.
- Categorized into 12 sub-tasks, the System Integration Design Team organizes and integrates them.
- TF members are from National Labs, Universities, and Private Companies.
- Design Roadmap

  - Pre-CDA: 2023 ~ 2026

  - CDA: 2026 ~ 2030

  - EDA: 2031 ~ 2035



Structure of DEMO Design Task Force

II. Strategy & Design of the K-DEMO

Top Tier Requirements for K-DEMO

- As the basis for K-DEMO design, Korean Government approved in Feb. 2023.

[Top Tier Requirements]

① **Max. Electrical Power > $500MW_e$ ($\sim 1,500MW_{th}$)**

② **TBR (Tritium Breeding Ratio) ≥ 1**

③ **Verification of Intrinsic Safety for Fusion**

④ **Acquisition of data for Economic Evaluation**

[Major Design Requirements]

① **Major radius (R) <7m**

② **Reactor operation rate >60%**

③ **Reactor life >40 years**

④ **Seismic Safety up to 7.0 Richter scale (0.3g)**

Parameters	Designed	Remarks
Major radius, R_0	~ 6.8 m	6.8 m as reference
Minor radius, a	~ 2.2 m	
Elongation, κ	~ 2.0	κ_{95}
Triangularity, δ	~ 0.6	δ_{95}
Plasma shape	SN	Backup: DN
Density ($\langle n_e \rangle / n_G$)	~ 1.2	$n_G \sim 0.82 \times 10^{20}$ m^{-3}
Temperature(<T>)	> 13 keV	
Plasma current, I_P	~ 13 MA	
Toroidal field, B_0	~ 6.5T	High field TF (Nb3Sn)
β_N	~ 3.5	High beta operation
Fusion power	1500 MW	
Blanket	HCCP	
Heating/CD	> 60 MW	

K-DEMO Scoping by Extensive System Analyses

- Ranges of system parameters were scanned with engineering and physics constraints:
  - External power injection: P_{inj} < 100 MW
  - Neutron wall loading: Γ_N < 2.0 MW/m^2
  - Divertor FOM: P_{div}/R_0 < 25.0 MW/m
  - TF current density limit: J_{TF} < 2.5$\times$10^7 A/m^2
  - TF coil case stress limit: s_{TFcase} < 560 Mpa
  - Shielding requirements for TF coil
    - dose to the insulators < 1$\times$10^9 rad
    - displacement damage on Cu < 5$\times$10^{-5} dpa
    - fast neutron fluence < 10^{18} n/cm^2
    - nuclear heating rate < 5$\times$10^{-5} W/cm^3

- Additional filters were applied to narrow down feasible system designs:

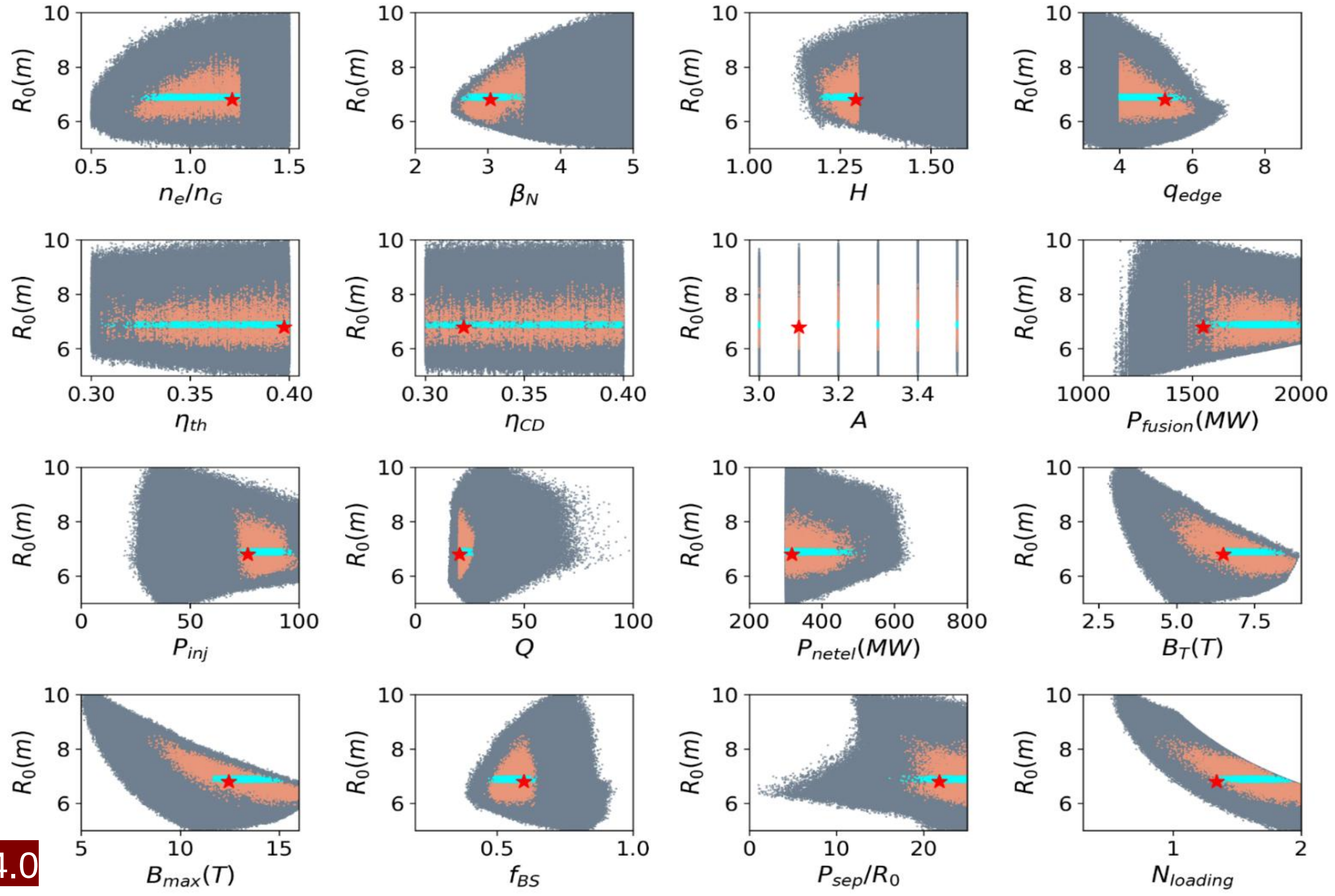
R_0 < 10.0 m, P_{netel} > 300 MW, Direct cost < 7.5 B$

above filters + Q > 20.0, n_e/n_G < 1.25, β_N < 3.5, H < 1.3, and q_{edge} > 4.0

above filters + 6.8 m < R_0 < 7.0 m, A = 3.1, 6.5 T ≤ B_T

Design point (★): R_0 ~ 6.8 m, P_{fusion} < 1,600 MW

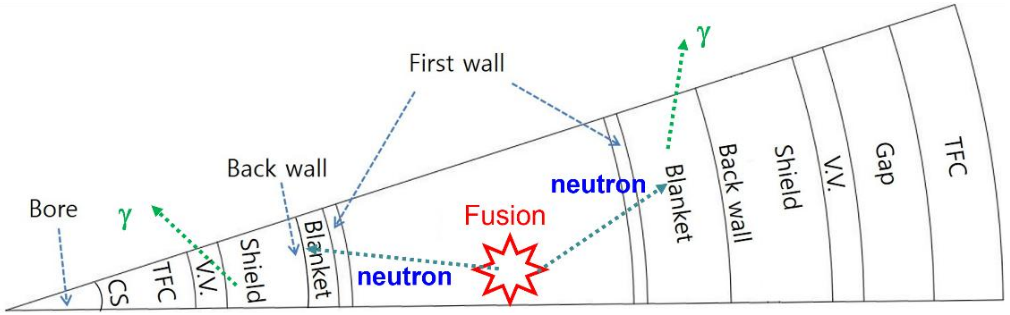
Scanning of K-DEMO system parameters with the IPB98(y,2) scaling



K-DEMO Reference Design Point with $R_0 = 6.8m$ & $B_T = 6.5T$

Key System Parameters	
Major radius, R_0 (m)	6.80
Aspect ratio, A	3.1
Magnetic field at plasma center, B_T (T)	6.55
Peak magnetic field, B_{peak} (T)	12.5
Stored energy of plasma (MJ)	750.3
Auxiliary heating, P_{inj} (MW)	73.7
Fusion gain, Q	20.4
Divertor power handling index, P_{sep}/R_0 (MW/m)	20.7
Neutron wall loading Γ_N (MW/m^2)	1.3
Net electric power, P_{netel} (MW)	329
Thermodynamic efficiency, η_{th}	0.39
Wall-plug efficiency of current drive system, η_{CD}	0.38
Thermal fusion power, P_{fusion}	1502
Inboard blanket thickness (m)	0.38
Inboard shield thickness (m)	0.40
TF coil thickness (m)	1.14
CS thickness (m)	0.64
CS bore radius (m)	1.67
Outboard (shield + blanket) thickness (m)	1.2
Direct cost (B$)	6.76

- System analysis combined with simplified neutronics calculation
  - Assume cylindrical geometry with 1D radial build from system analysis
  - ANISN radiation transport calculation including anisotropic scatterings of neutrons and gamma rays with detailed material compositions (FENDL-3.3 C.X. library)
  - Tritium Breeding Ratio calculation based on Li C.X. ENDF/B-VII.1 library

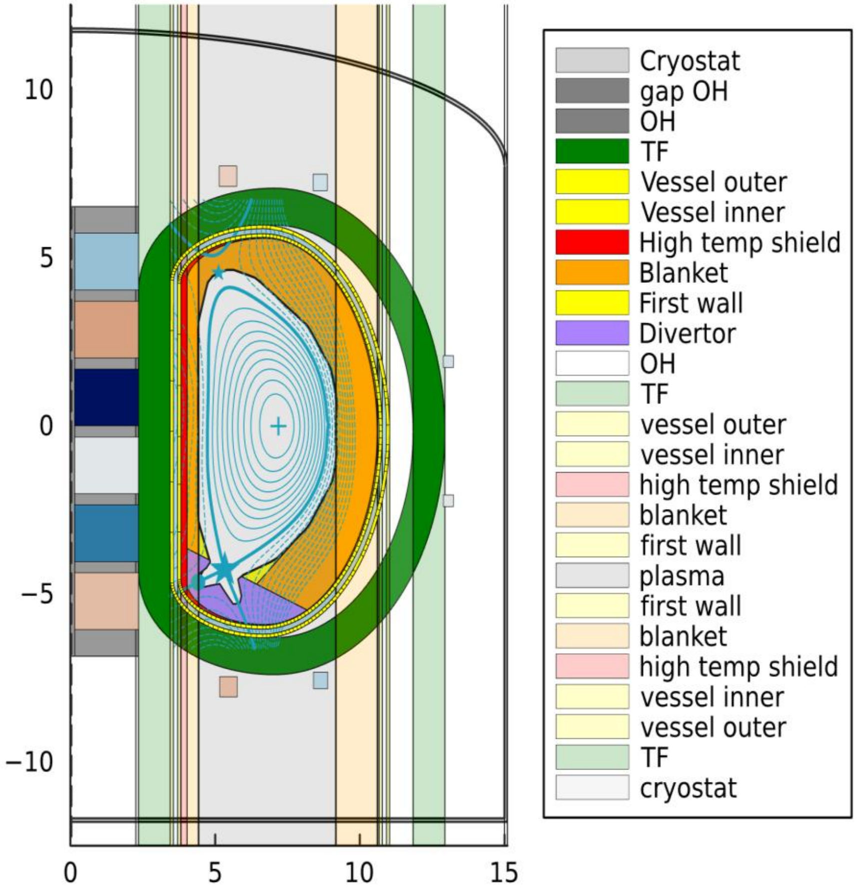


Component	Material (Volume%)
First wall	FMS (50), He (33), W (17)
Breeding blanket	Coolant (10), Breeder (80), FMS (10)
Back wall/Manifold	FMS (40), He (60)
Shield	FMS (5), WC (85), H_2O (10)
Vacuum vessel	Borated steel (60), H_2O (40)
Toroidal field coil	Nb_3Sn, Cu, Epoxy, SUS316, L. He

K-DEMO Pre-CDA: 2D Build and Reference Scenario

- Advanced System Code FUSE (O. Meneghini, GA) is being used for scanning and proto-typing of 2D Build with self-consistent plasma equilibrium.
- K-DEMO requires plasma scenarios with significantly improved performance compared to standard H-mode → *e.g. hybrid or high-li*

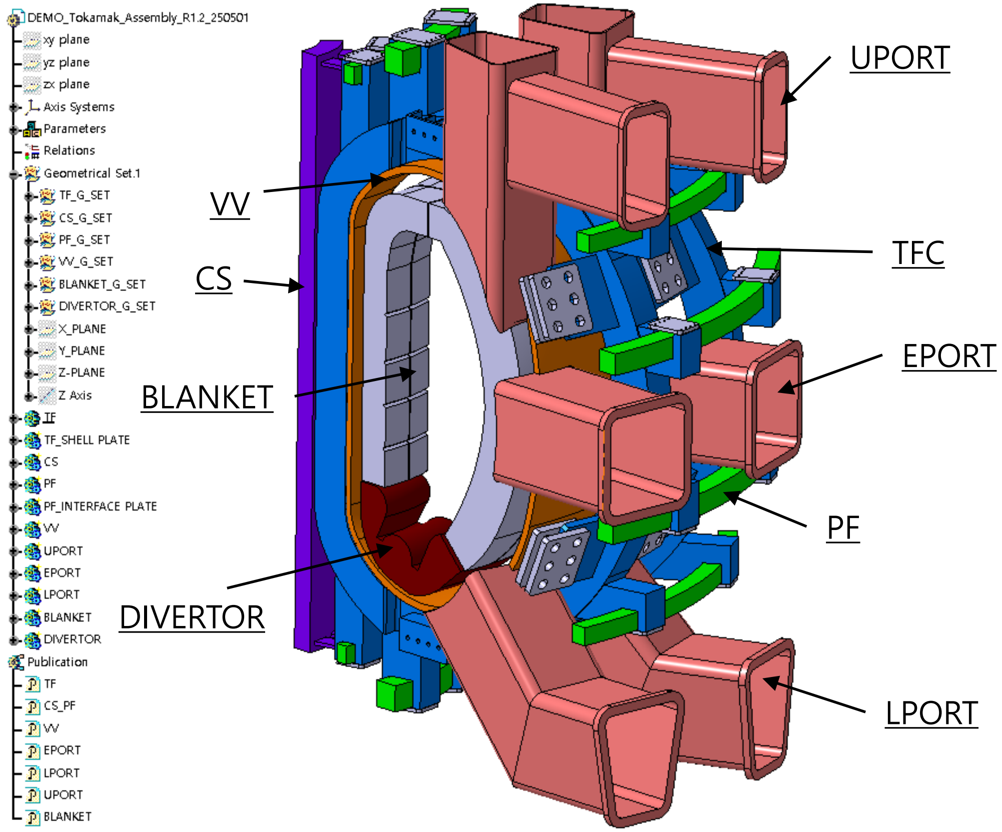
Key Plasma Parameters	
Elongation, κ	2.0
Plasma current, I_p (MA)	13.6
Electron density, $\langle n_e \rangle$ ($\times$ 10^{20} m^{-3})	0.82
Electron Temperature, $\langle T_e \rangle$ (keV)	13.5
Bootstrap current fraction, f_{BS}	0.57
Edge safety factor, q_{edge}	5.05
Greenwald density fraction, n_e/n_G	1.07
Normalized beta, β_N	2.97
Confinement enhancement factor, H	1.27



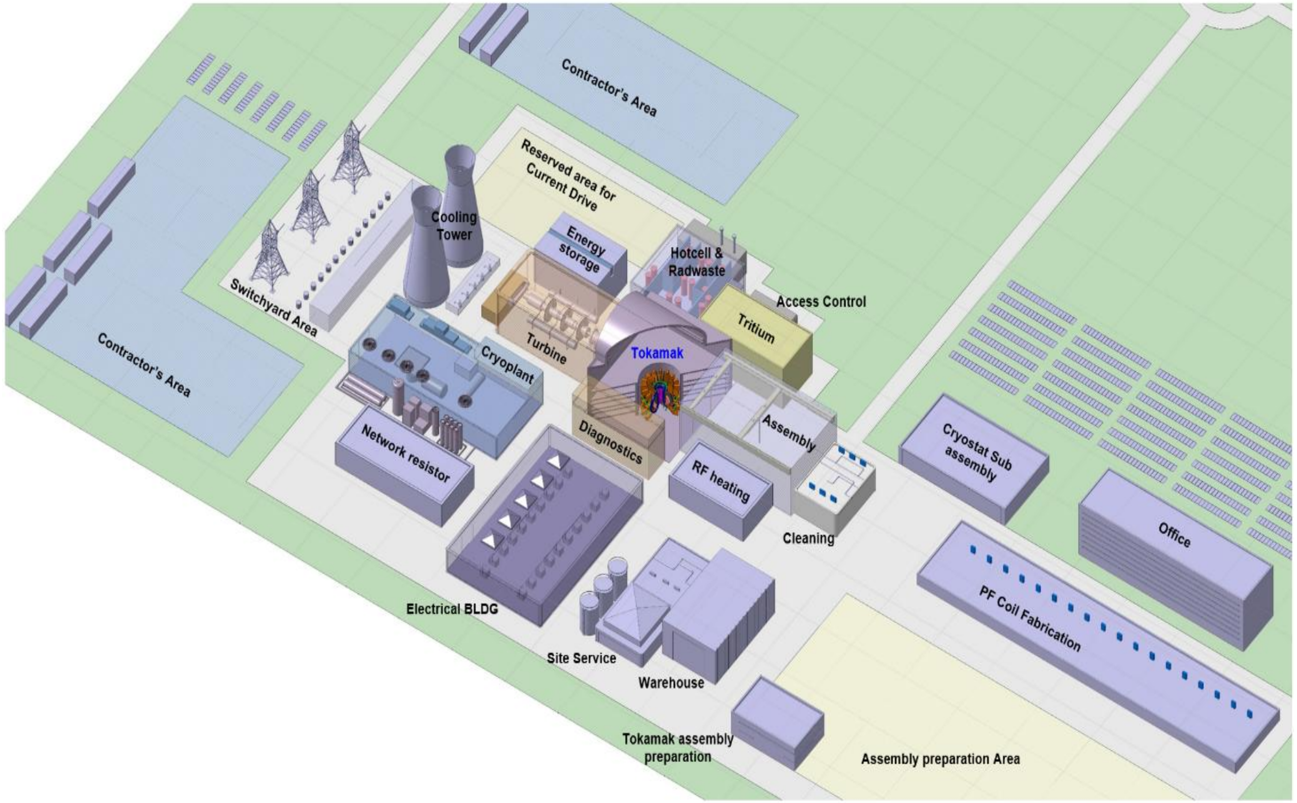
K-DEMO 2D Build generated by FUSE

K-DEMO Pre-CDA: 3D Build and Site Layout

- Tools and integration platform are prepared with Plant Breakdown Structure (PBS).
- 3D build was constructed with 2D build and consideration for remote maintenance.
- Site layout was made including buildings for main reactor and all necessary components.



K-DEMO 3D Build

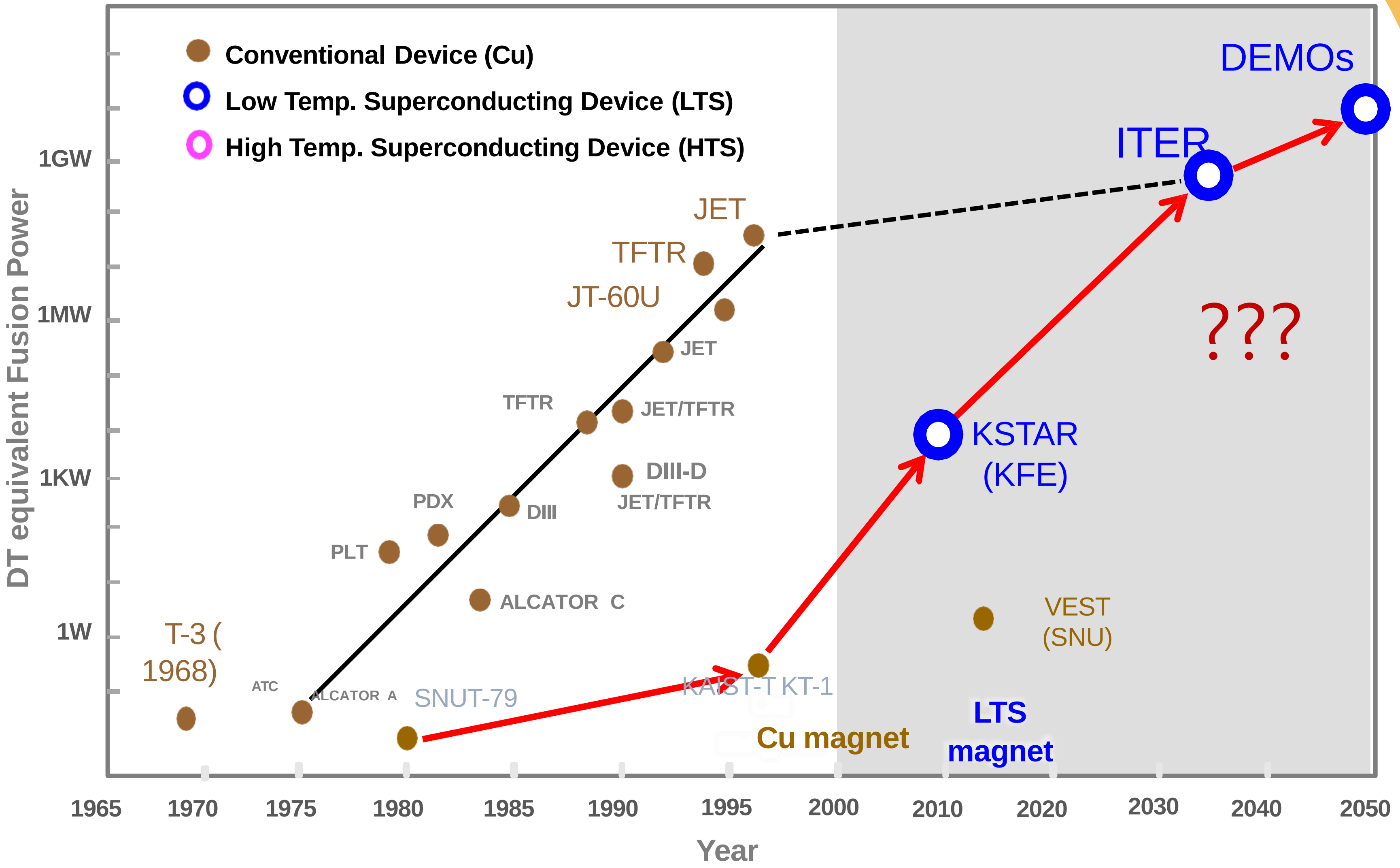


K-DEMO Site Layout

III. Strategy for Innovative Compact Pilot Device (CPD)

Expansion of Korean National Fusion R&D Path

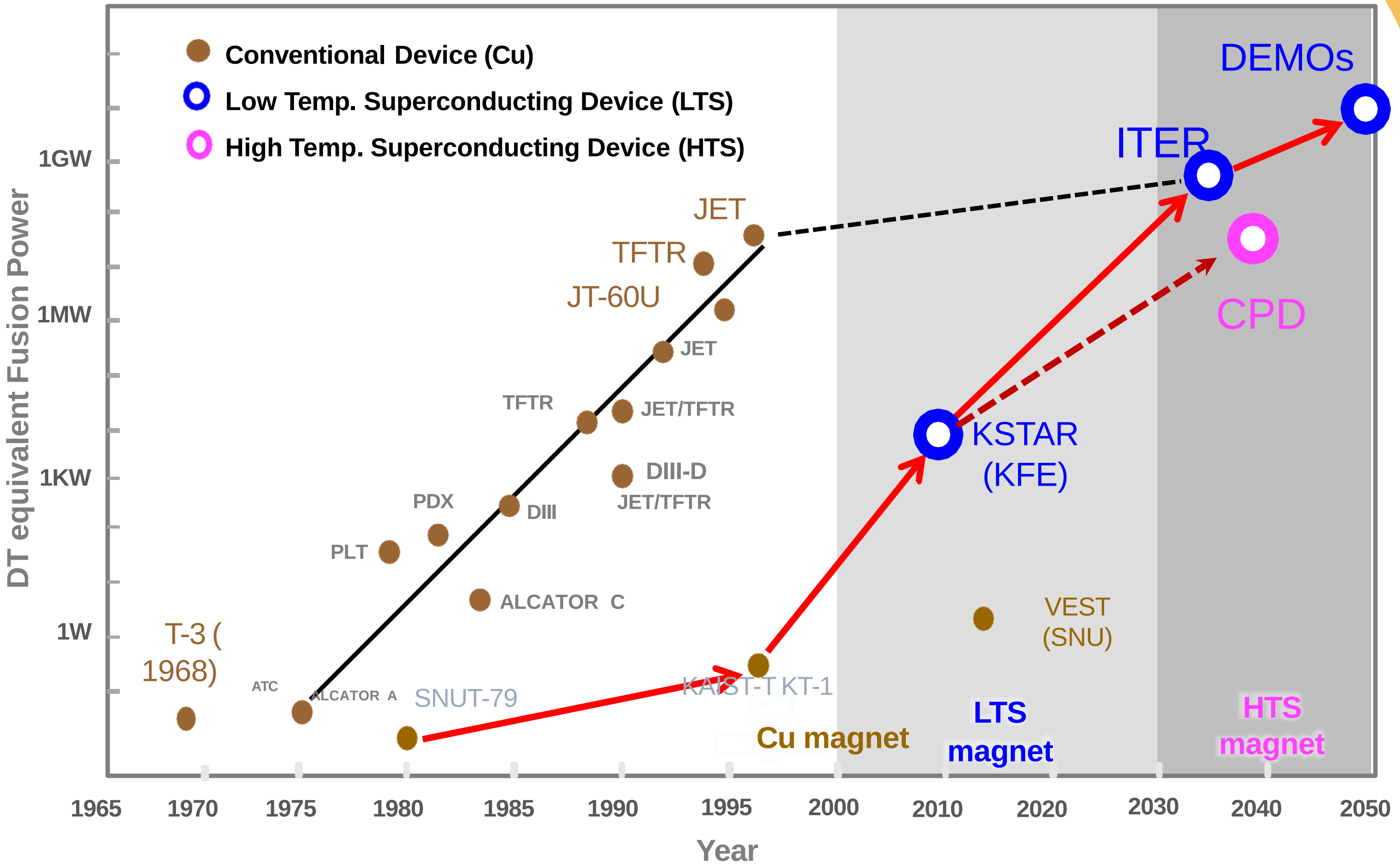
- There have been growing interests and discussions on newly emerging innovative technologies for fusion.
- Recently, a community-wise consensus was made to embrace these innovative technologies to expand Korean Fusion R&D.



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

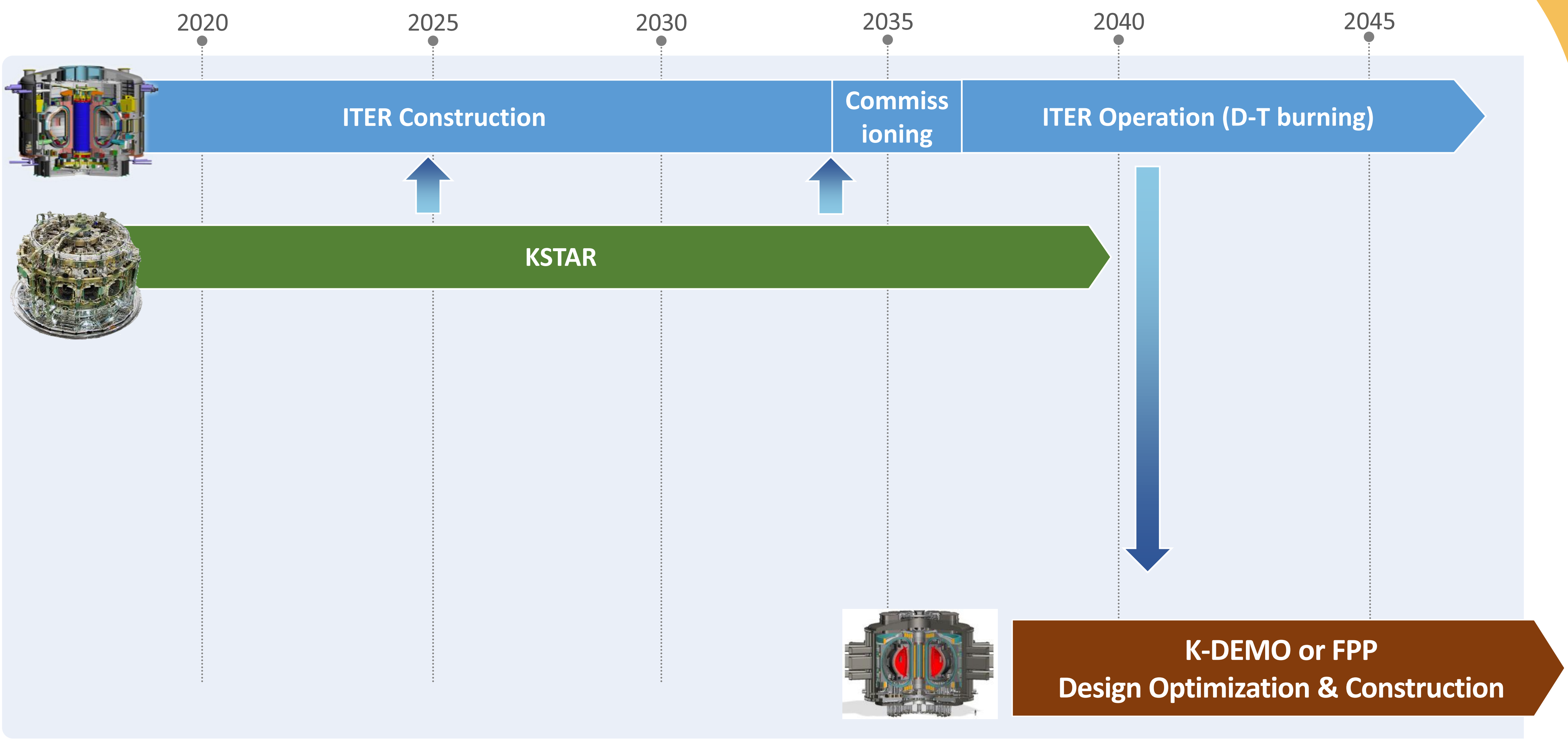
Expansion of Korean National Fusion R&D Path *(not approved yet)*

- There have been growing interests and discussions on newly emerging innovative technologies for fusion.
- Recently, a community-wise consensus was made to embrace these innovative technologies to expand Korean Fusion R&D.
- It is proposed to expand national fusion R&D projects including compact pilot device (CPD) employing HTS technology along with the conventional KSTAR→ITER→K-DEMO path *(not approved yet).*

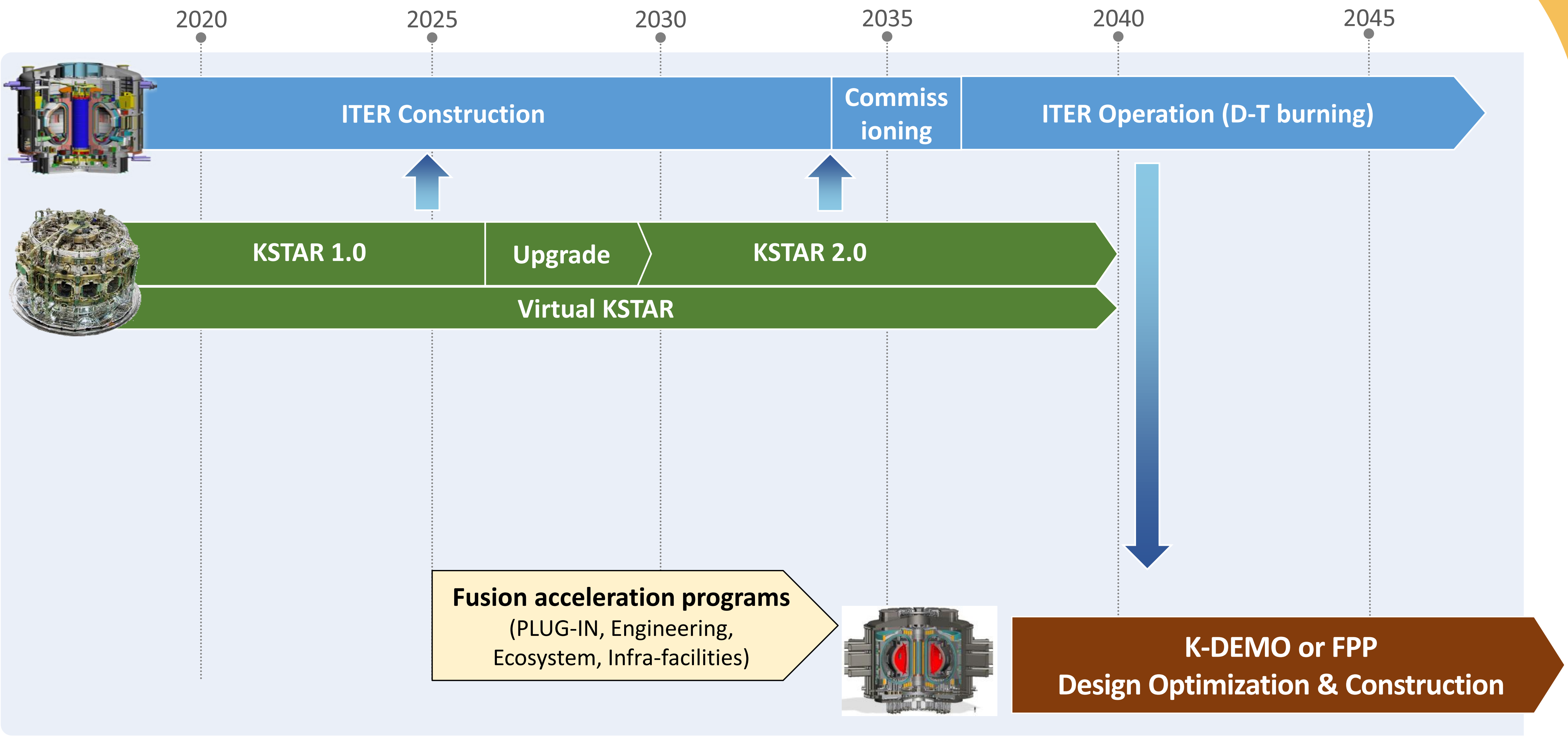


Newly Proposed Korean Fusion R&D including CPD based on HTS Technology

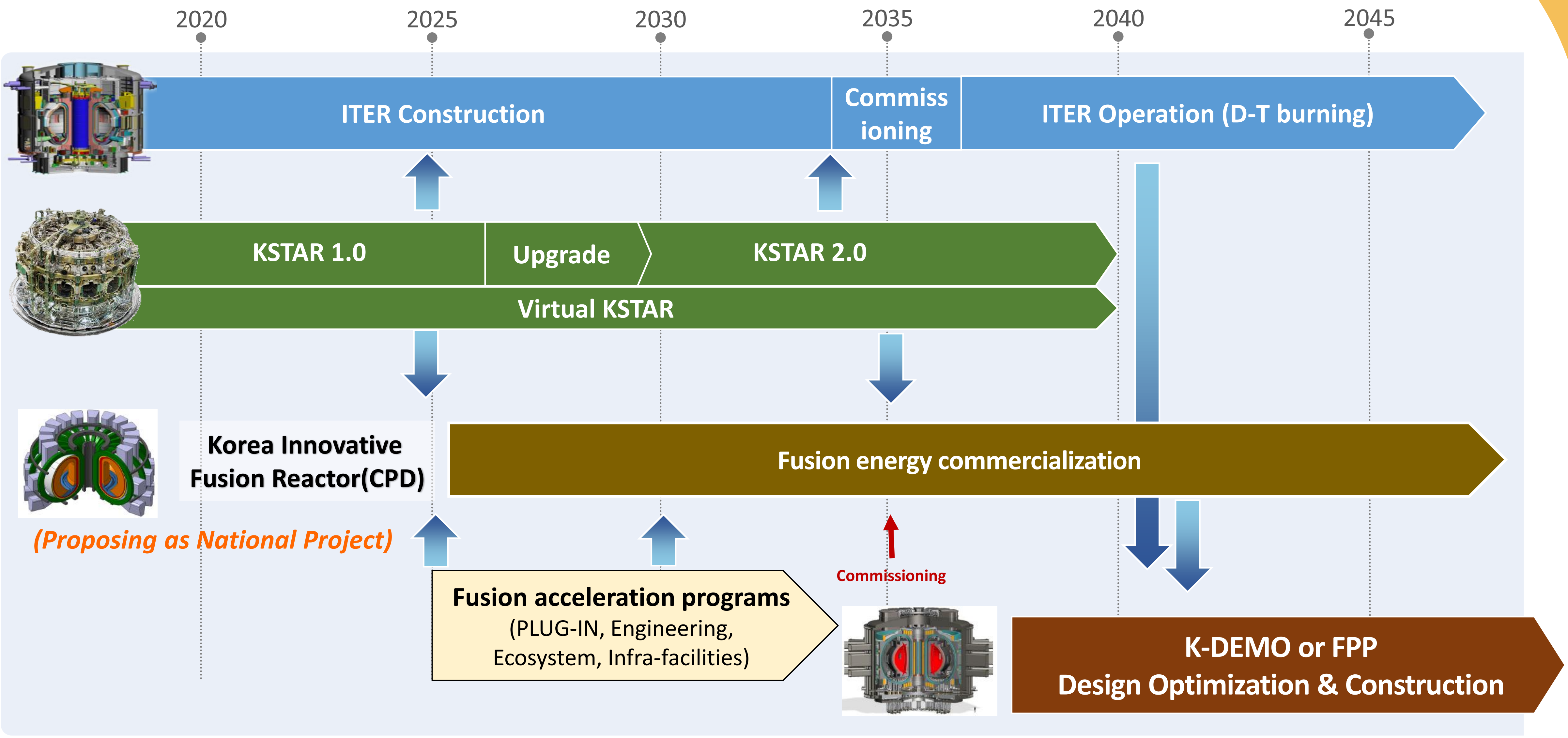
Proposed timeline of key Fusion programs



Proposed timeline of key Fusion programs



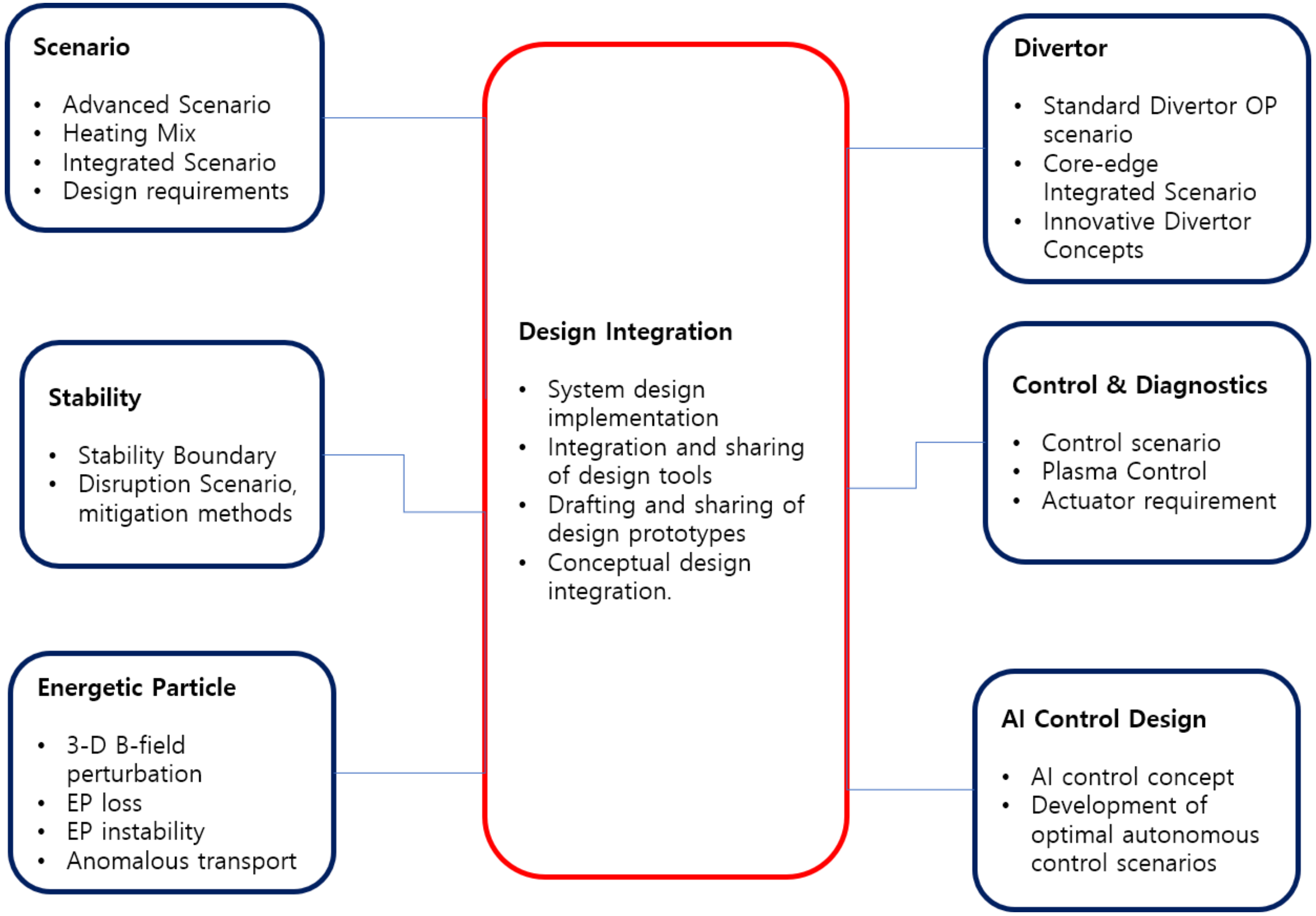
Proposed timeline of key Fusion programs *(being proposed)*



IV. Preliminary Design Study for the CPD

K-DEMO design TF moving toward the design of CPD

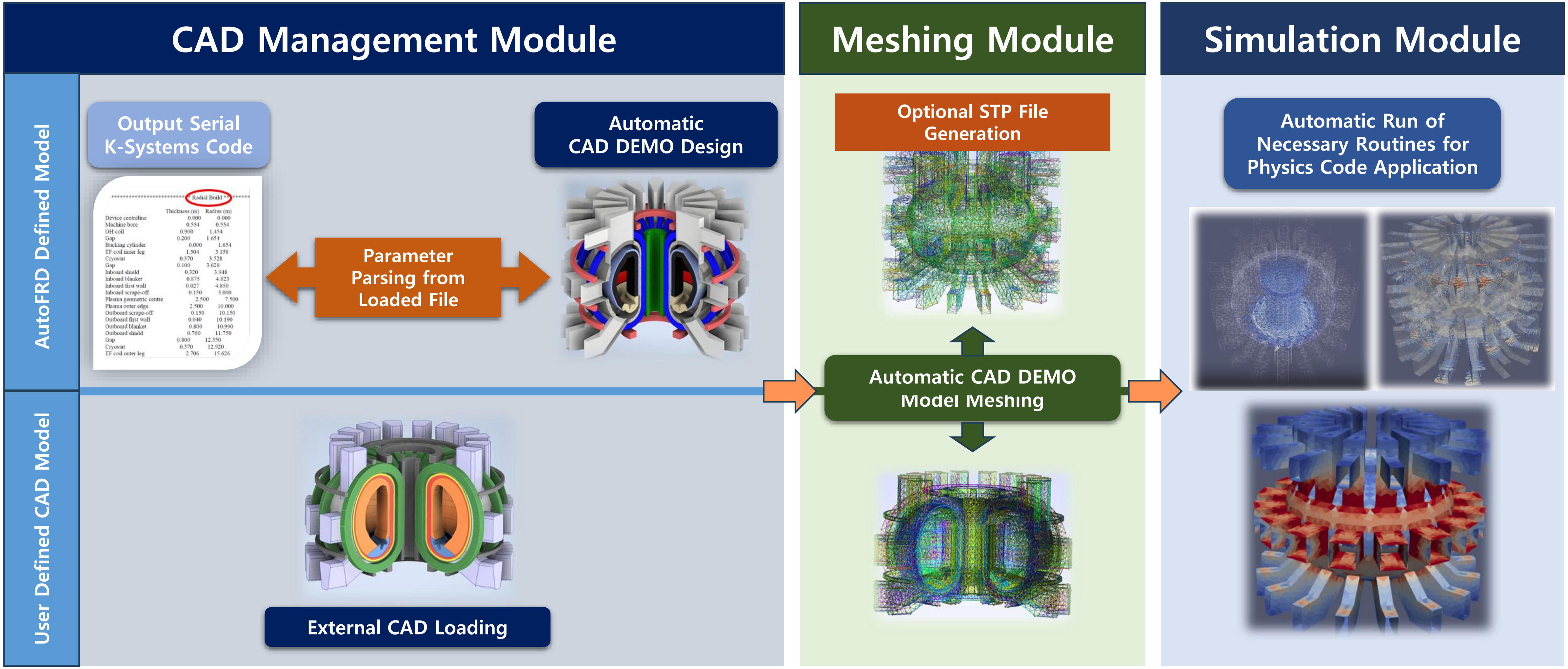
- A new sub-design TF is formed to conduct:
  - Development of advanced design tools for rapid proto-typing and design changes
  - System scoping for optimum radial build and physics parameters



Sub-design TF to explore the CPD concept

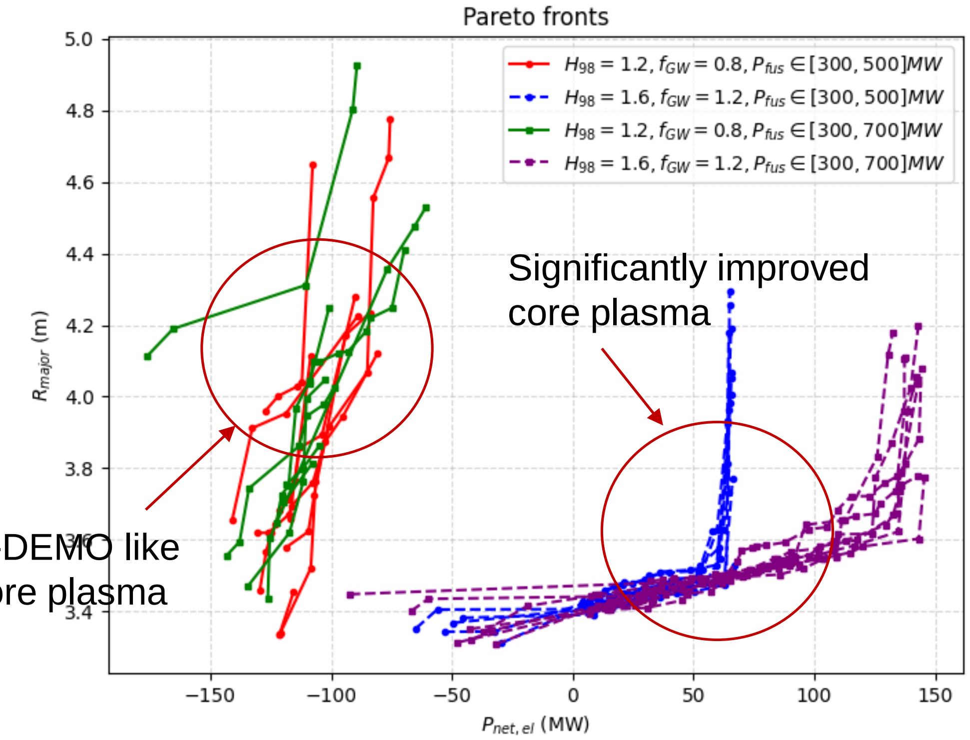
Development of Advanced Design Tools for CPD

- Automated 3D CAD generation and mesh generation for physics simulation and engineering analysis
- Aiming Bayesian optimization based design accelerations for as many design elements as possible

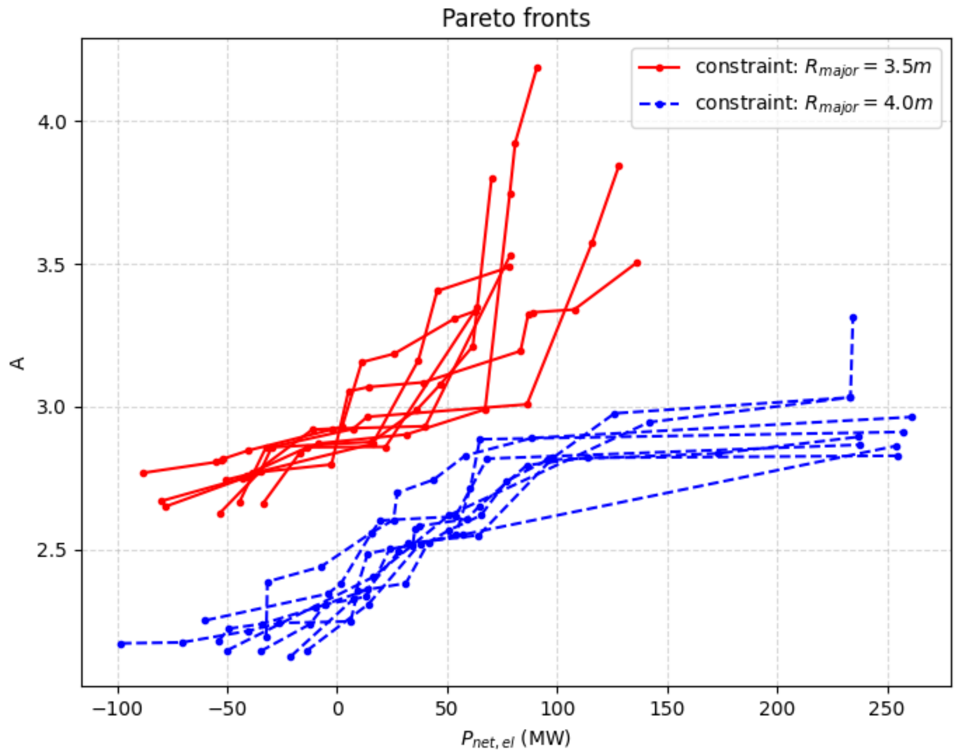


Optimization of System Parameters for CPD

- Multi-objective optimizations of CPD were performed to set major parameters:
  - Net electricity around 60 ~ 150 MWe with major radius in range [3.5m, 4m]
  - Limitations in reducing the aspect ratio due to engineering constraints
- Compared to K-DEMO, significantly improved plasma performance is required to achieve net electricity with $R_0 < 4m$
  - $H_{98} = 1.2 \rightarrow 1.6$, $n_e/n_G = 1.1 \rightarrow 1.2$, $f_{BS} = 0.6 \rightarrow 0.8$ etc.
- Due to the shielding, stress, flux consumption requirements, there are limits in reducing aspect ratio



Optimization of Machine Size for CPD



Optimization of Aspect Ratio for CPD

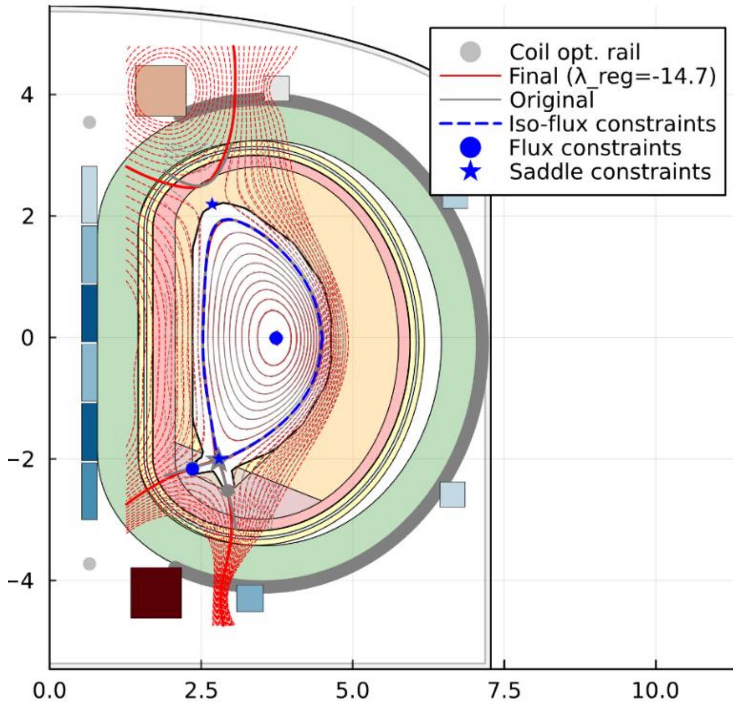
A CPD Reference with $R_0 = 3.5m$ & $B_T = 8.2T$

- Many similarities with previously proposed small reactor concepts employing HTS, allowing high B_T
- Aim to produce net electricity with power conversion ratios $\eta_{th}, \eta_{CD} \sim 0.4$

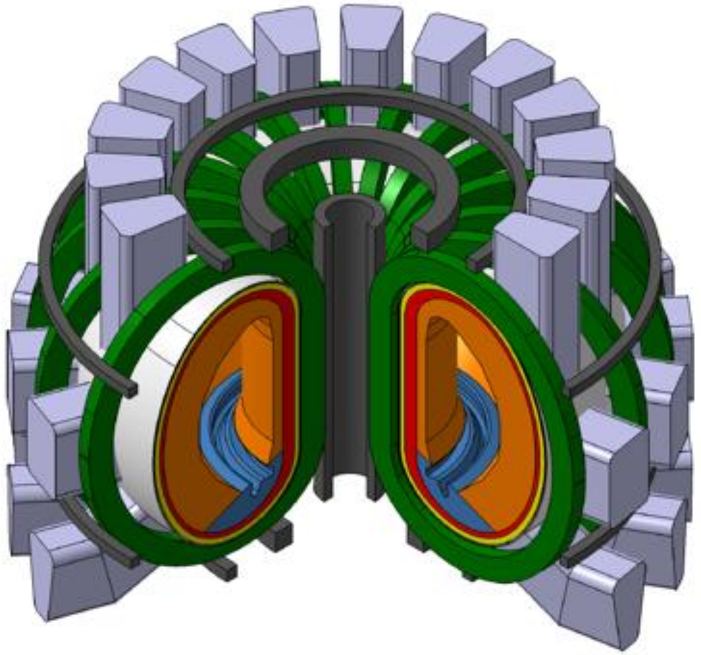
		ARC (FED 2015)	GA CTPP (FST 2021)	COMPACT (FED 2023)	CPD with $R_0 = 3.5m$
	CS role, τ_{pulse} (h)	I_p start-up, S-S	I_p ramp-up & burn, 1 ~ 2	10% flux for I_p ramp-up, S-S	50% flux for I_p ramp-up, S-S
	$B_{max, TF}$	23 T, REBCO	23 T, REBCO	23 T, REBCO	23 T, REBCO
	J_{TF} / J_{CS} (MA/m²)	44.0	39.1 / 64.6	40.0 / 40.0	40.0 / 60.0
	Δ_{TF} / Δ_{CS} / Δ_{plug} (m)	0.64 / 0.25 / 0.45	0.3 / 0.3 / 0.98	0.88 / 0.13 / > 0.2	0.69 / 0.28 / 0.56
	Δ_{SHi} / Δ_{BLi} (m)	0.55 / 0.31	0.45 / 0.3	0.5 / 0.18	0.37 / 0.30
	Shield	TiH_2, n fluence: 3x10^{18} n/cm²	WC ? n fluence: 1x10^{19} n/cm²	WC, n fluence: 1x10^{18} n/cm² 40 yrs and 75% availability	W_2B_5, n fluence: 3x10^{18} n/cm² 30 yrs and 50% availability
	Blanket	FLiBe	HCLL ? [Ref. Hong]	HCLL w. 90 % Li-6 (ref.)	HCLL/HCSB w. 90 % Li-6 (ref.)
	Thermal efficiency, η_{th}	0.4	0.4	0.4	0.4
Major Device Parameters	R_0 (m) / A / κ	3.3 / 3 / 1.84	3.72 / 3 / 1.84	3.63 / 3.2 / 2.0	3.50/3.5 /2.0
Major Device Parameters	B_T / B_{TF} (T)	9.2 / 23	5.9 / 13.4	8.3 / 19.4	8.2 / 18.3
Major Device Parameters	P_{fusion} / P_{CD} / P_{netel} (MW)	525 / 38.6 / 190	649 / 33.8 / 200	664 / 31.6 / 102	490 / 30.0 / 80
	Direct capital cost (B$)	~ 5.6 B$ (w.o. BOP) from V, m & unit prices	~ 4.2 B$ (w. BOP) from Sheffield [2016, 1986]	~ 4.0 B$ (w. BOP) from Sheffield [2016, 1986]	~ 4.2 B$ (w. BOP) from Sheffield [2016, 1986]

A CPD Reference with $R_0 = 3.5m$ & $B_T = 8.2T$

- FUSE was utilized to generate 2D build, which is consistent with the 1D build from the system analysis.
- 3D build was generated by the AutoFRD with 16 TF coils – 0.5% ripple without ferritic inserts.
- Scenario development is on-going:
  - Improved scenario based on conventional ones (e.g. hybrid) for pulse operation
  - Advanced Tokamak-like scenario (e.g. high-β_p) for steady state operation, especially with innovative actuators



2D Build by FUSE: REBCO for TF&CD and Nb_3Sn for PF



3D Build by AutoFRD with Parametric Model Variation and Optimization

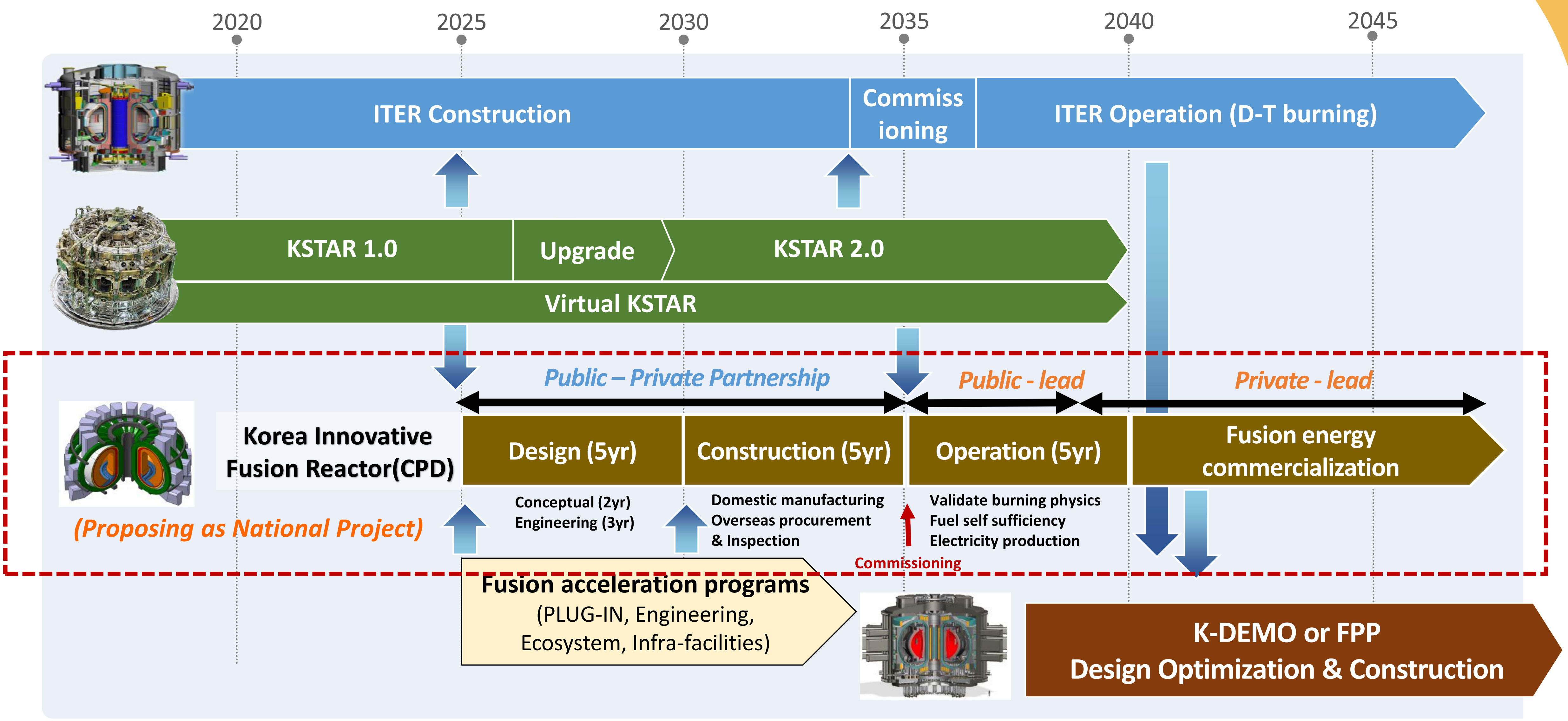
V. Summary and Future Perspective

Summary

- The Korea National Fusion R&D is making steady progress:
  - DEMO design TF launched in 2023 aiming Pre-CDA until 2026
  - Government approved the top design requirements of K-DEMO
  - Preliminary 3D build and site layout were produced

- Compact Pilot Device (CPD) is being proposed with growing consensus in Korean Fusion Community to embrace innovative technologies for the acceleration of fusion R&D:
  - Developments of AI-based advanced design tools
  - System scoping study to set reference design points and 2D, 3D builds with rapid proto-typing
  - On-going discussion for alignment with other national fusion R&D projects to develop key enabling technologies including innovative actuators

Proposed timeline of key Fusion programs *(being proposed)*



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

Many Thanks for Your Attentions!