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

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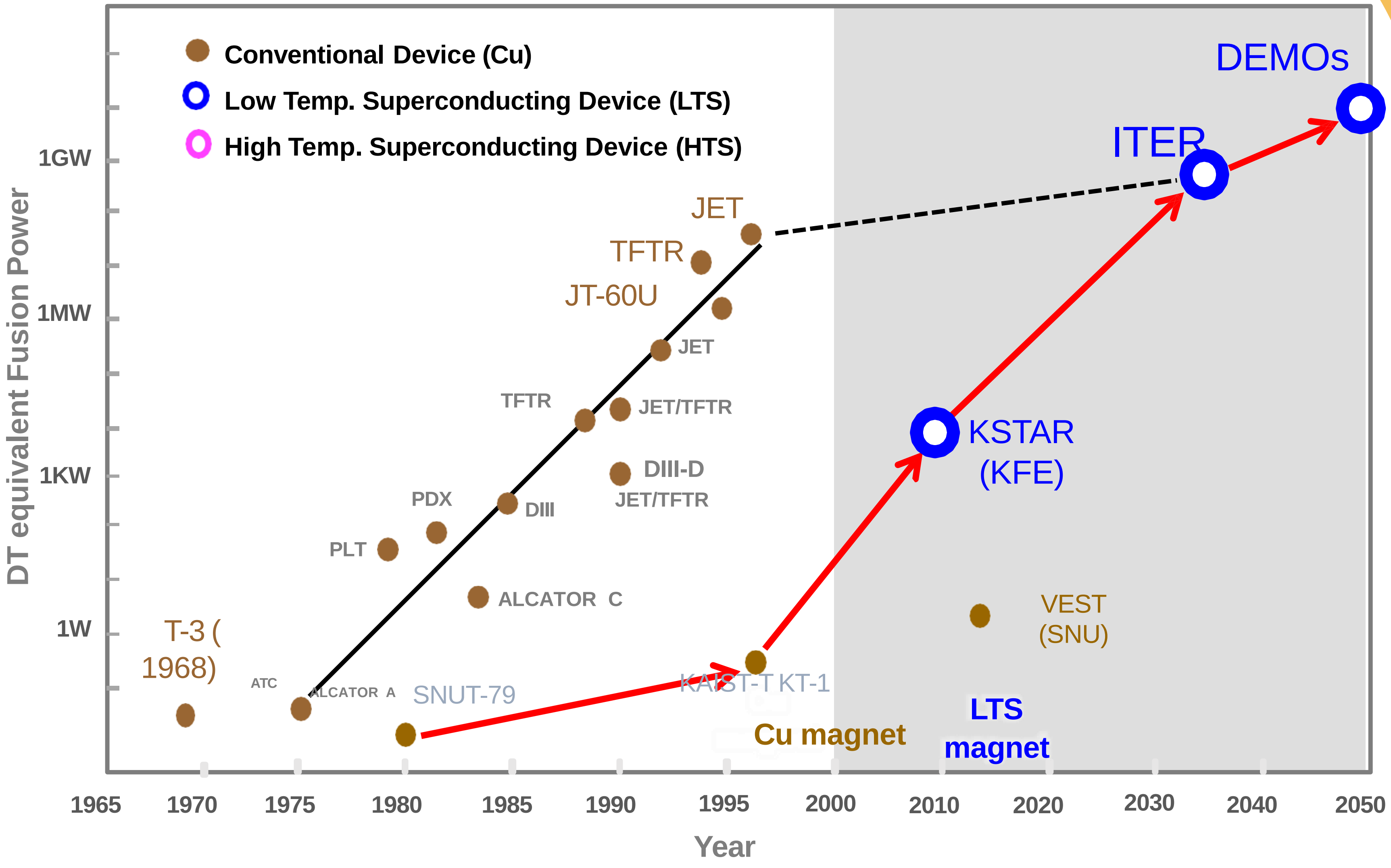
OUTLINES

I. Introduction of Korea National Fusion R&D

Korean Fusion R&D has been making steady progresses since the start of KSTAR

- 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)

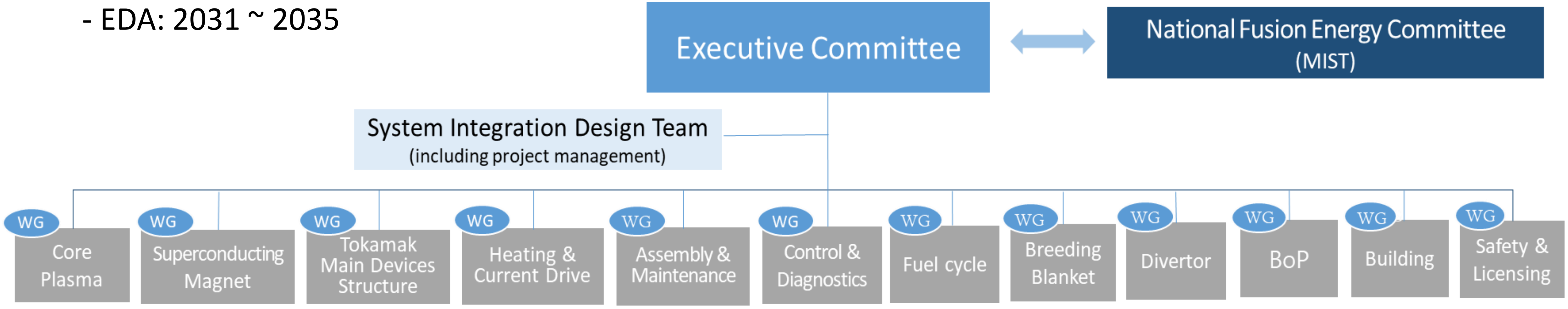
DEMO Design Task Force was established in 2023

- Categorized into 12 working groups, 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

Korean government approved Top Tier Requirements for K-DEMO in 2023

▪ The Basis for K-DEMO Design

[Top Tier Requirements]

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

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 ~ 0.82×10^{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	

Key parameters for a preliminary K-DEMO system design

Extensive System Analyses were performed for K-DEMO Scoping

- 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:

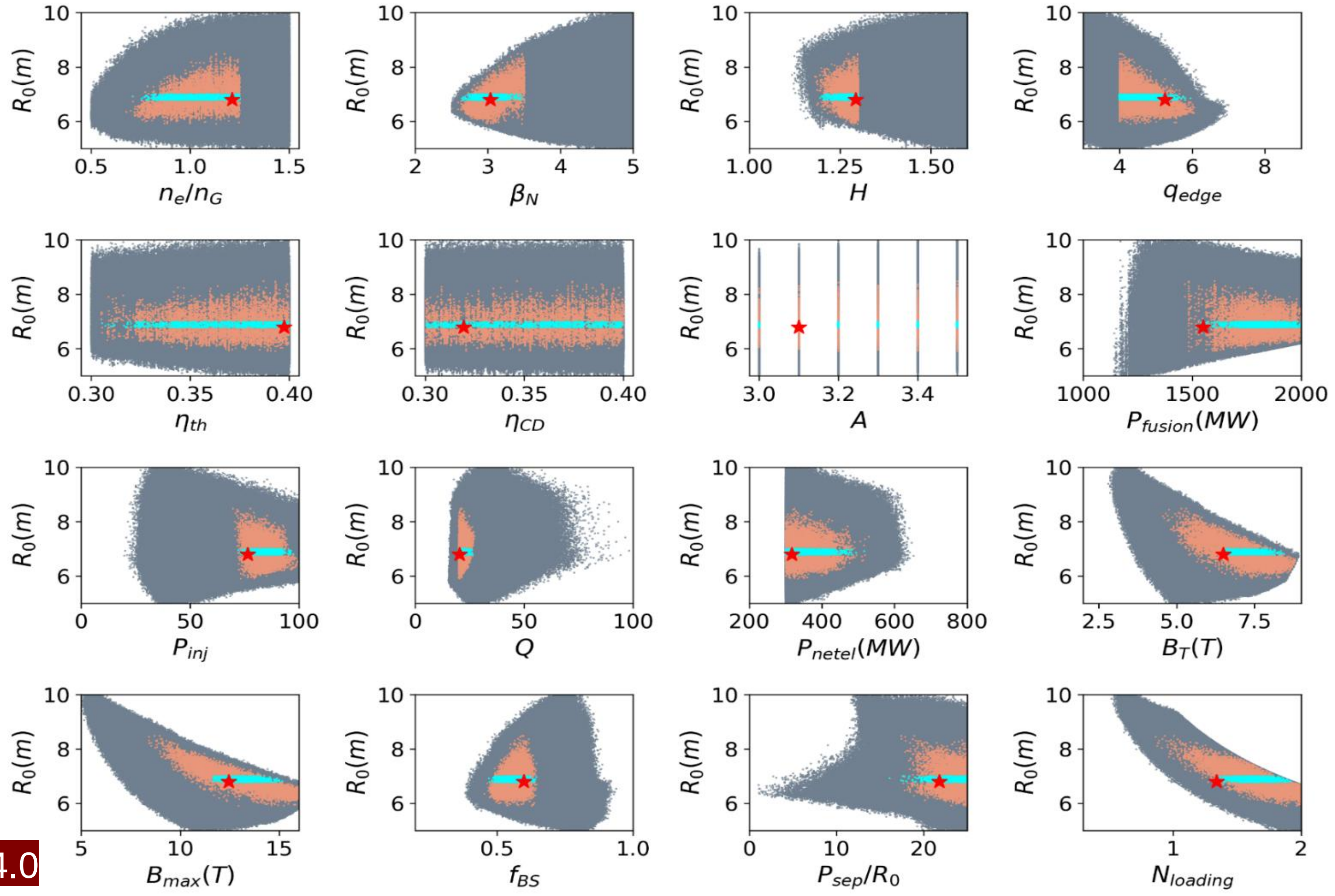
R_0 < 10.0 m, P_{netel} > 300 MW, Direct cost < 7.5 B$

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

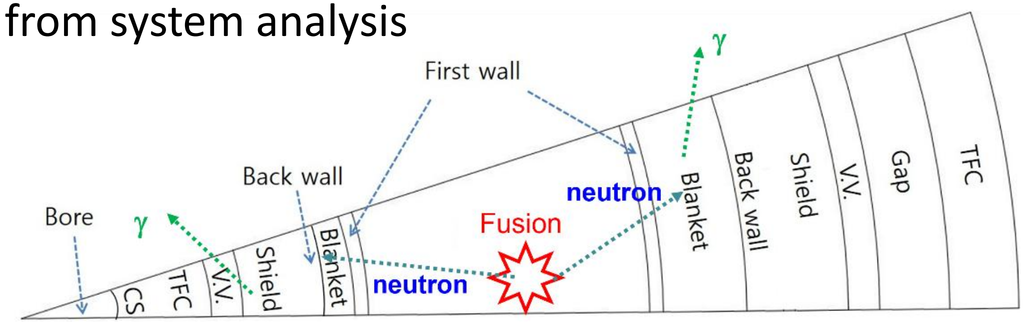
Design point (★): R_0 ~ 6.8 m, P_{fusion} < 1,600 MW

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



Neutronics calculations were coupled to the system analyses

- Assume simplified cylindrical geometry based on 1D 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 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

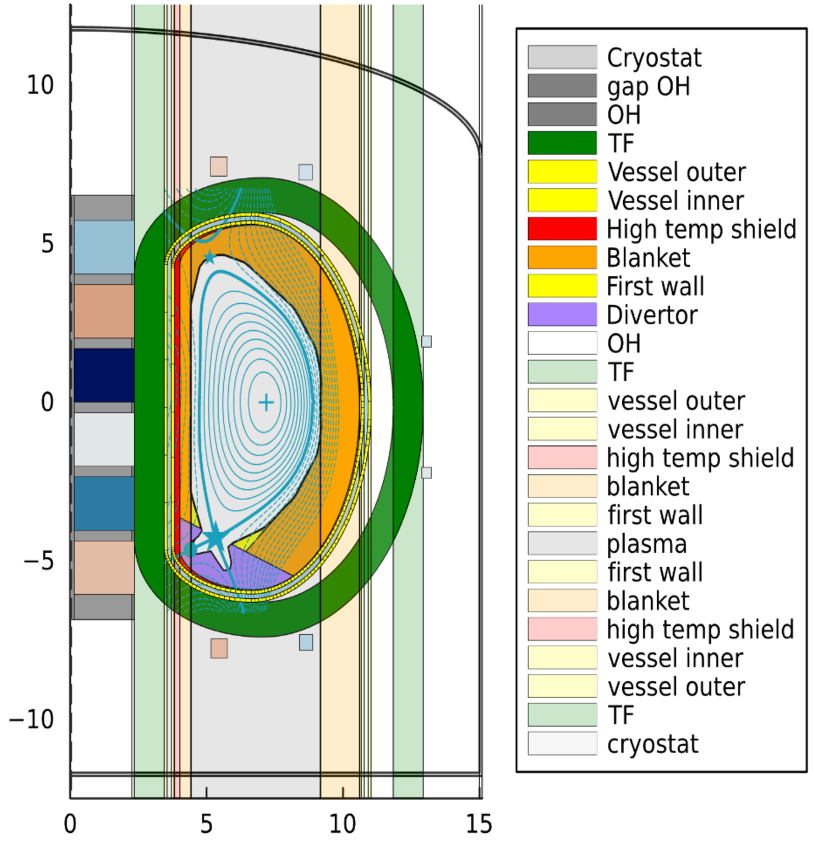
Materials for major components

K-DEMO Reference Design with $\boldsymbol{R_0 = 6.8m}$ & $\boldsymbol{B_T = 6.5T}$

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

2D Build and Reference Scenarios were generated

- The FUSE Code (O. Meneghini, GA) was used to generate 2D build and self-consistent plasma equilibria → Consistent with the 1D build from the system analyses



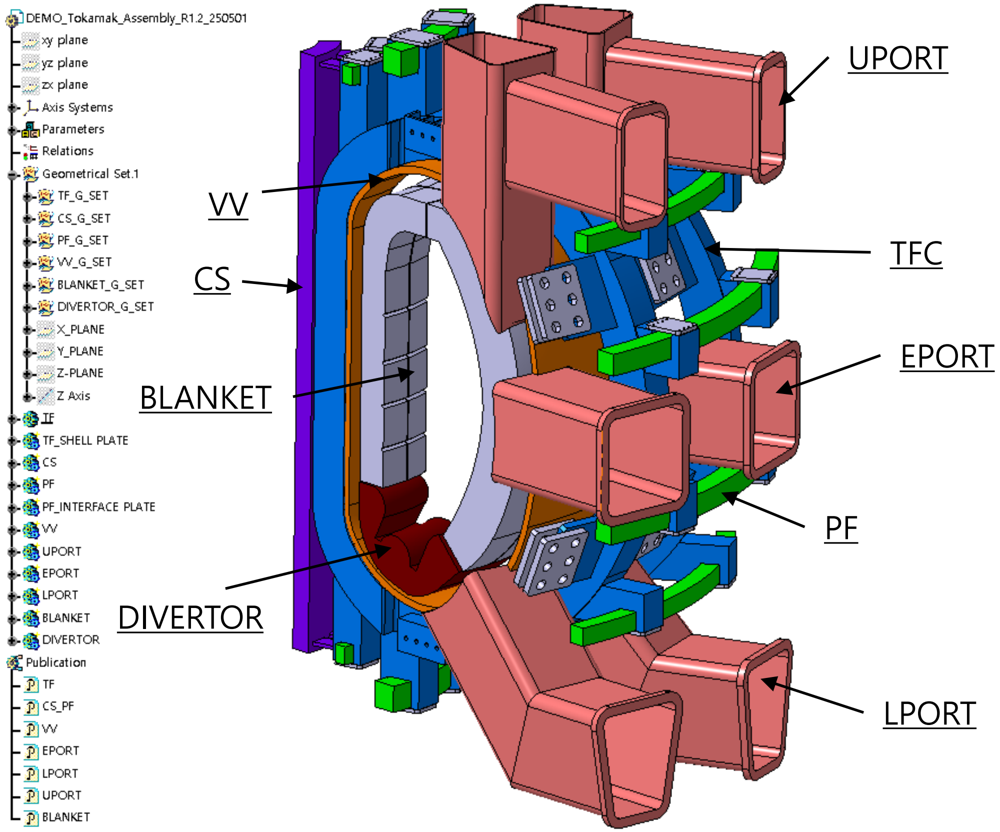
K-DEMO 2D Build generated by FUSE

Key Plasma Parameters for K-DEMO	
Elongation, κ	2.0
Plasma current, I_p (MA)	13.6
Electron density, $<n_e>$ ($\times$ 10^{20} m^{-3})	0.82
Electron Temperature, $<T_e>$ (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

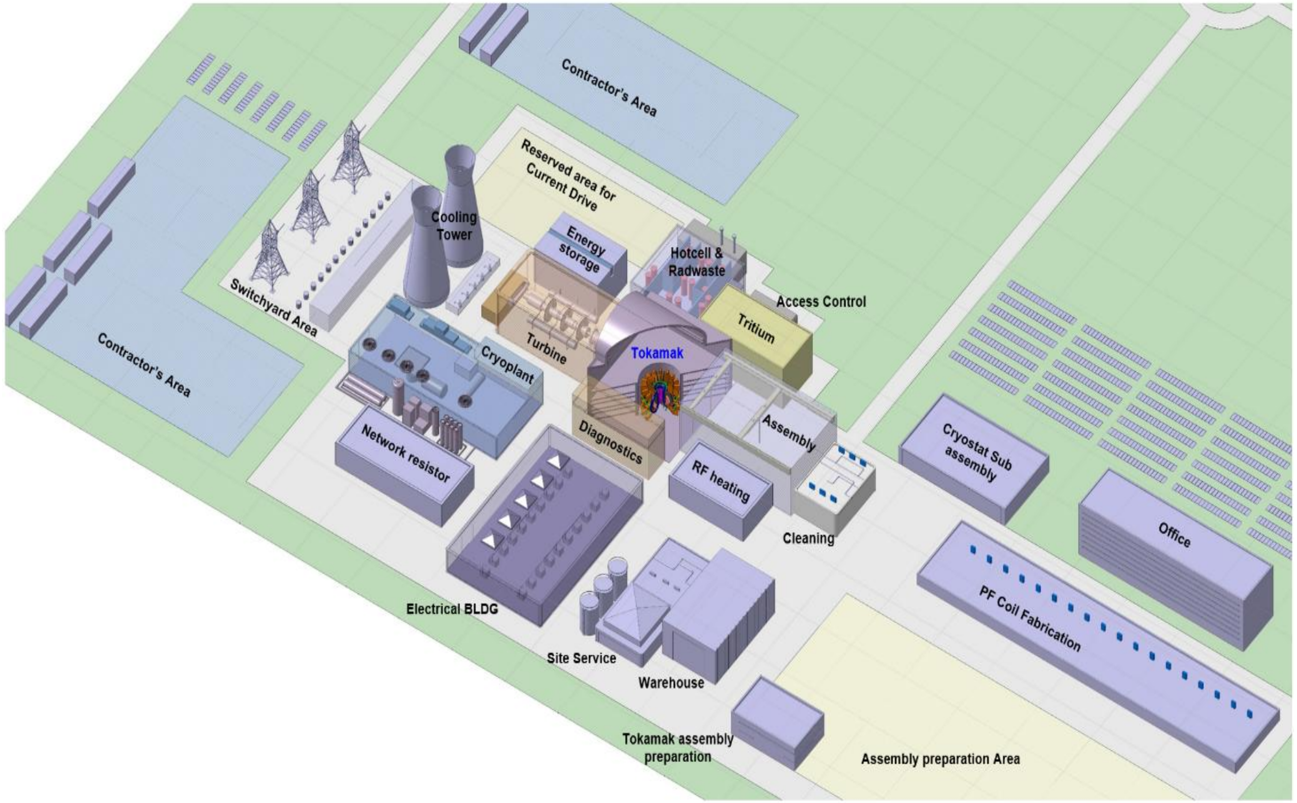
- K-DEMO requires plasma scenarios with significantly improved performance compared to standard H-mode → *hybrid or high-li (e.g. recent dedicated experiments on KSTAR)*

Preliminary 3D Build was generated with 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

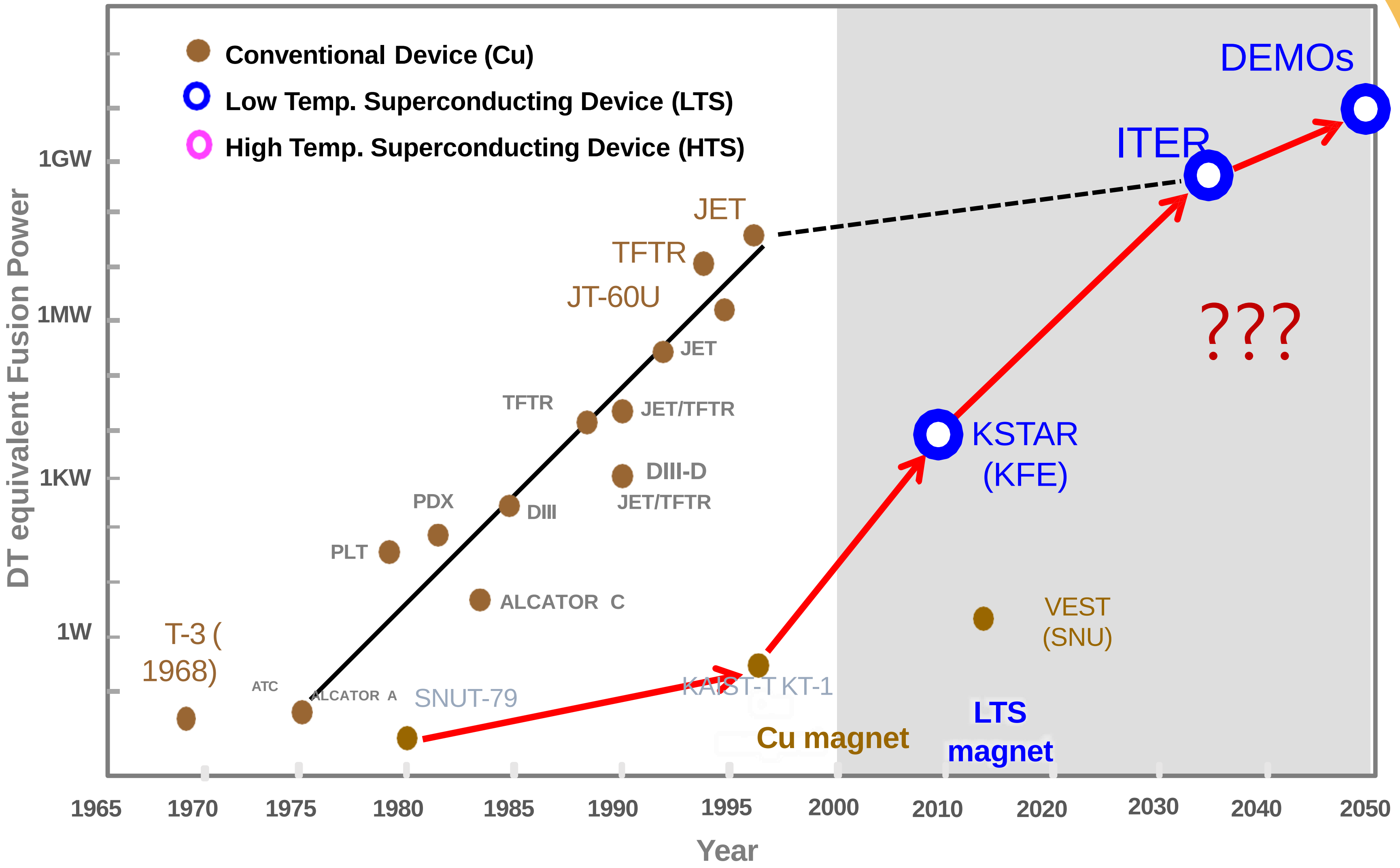


K-DEMO Site Layout

III. Strategy for Innovative Compact Pilot Device (CPD)

Growing Interests on Innovative Fusion Tech in Korean Fusion Community

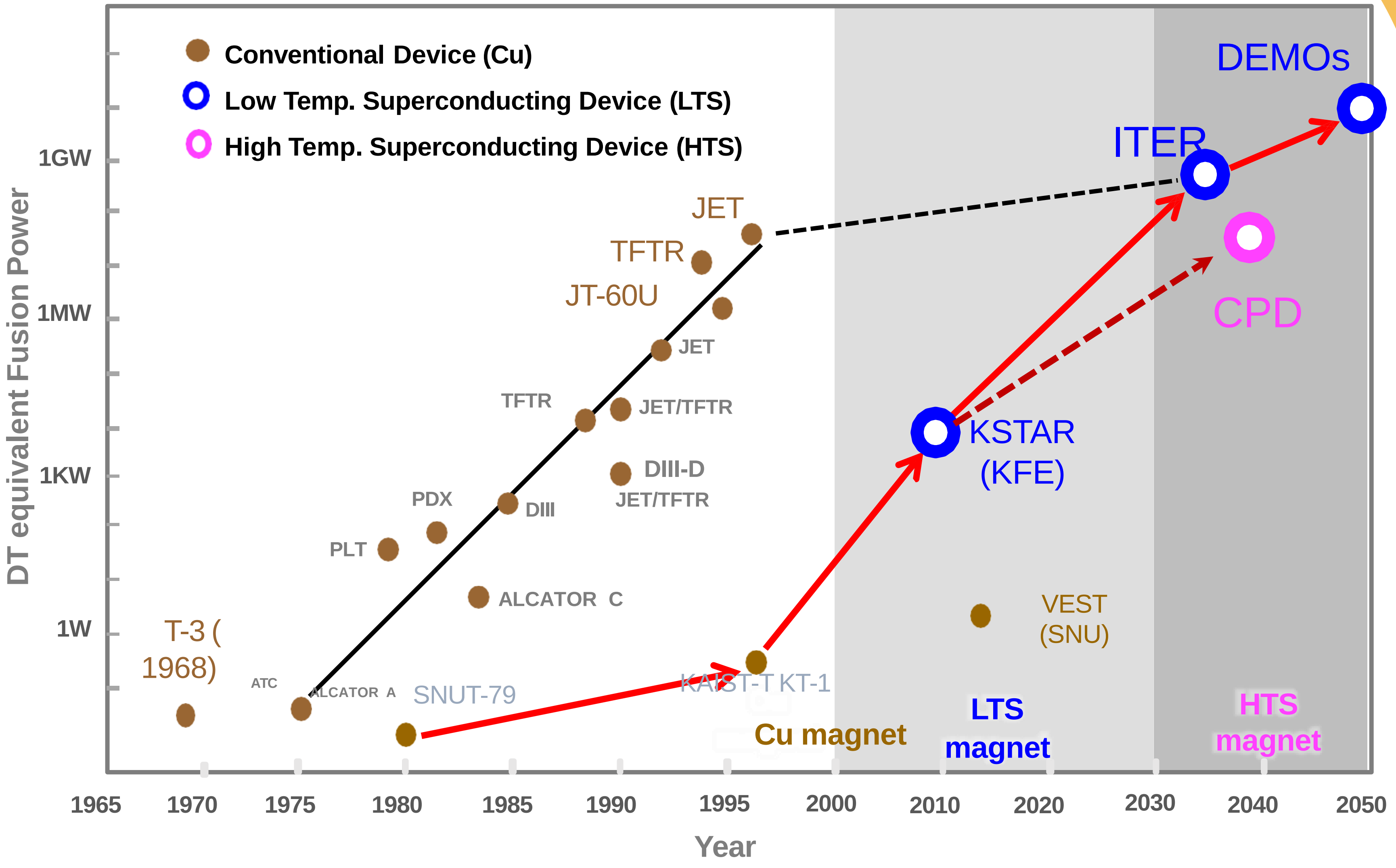
- Recently, a community-wise consensus was made to embrace these innovative technologies (e.g. HTS) to expand Korean Fusion R&D.



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

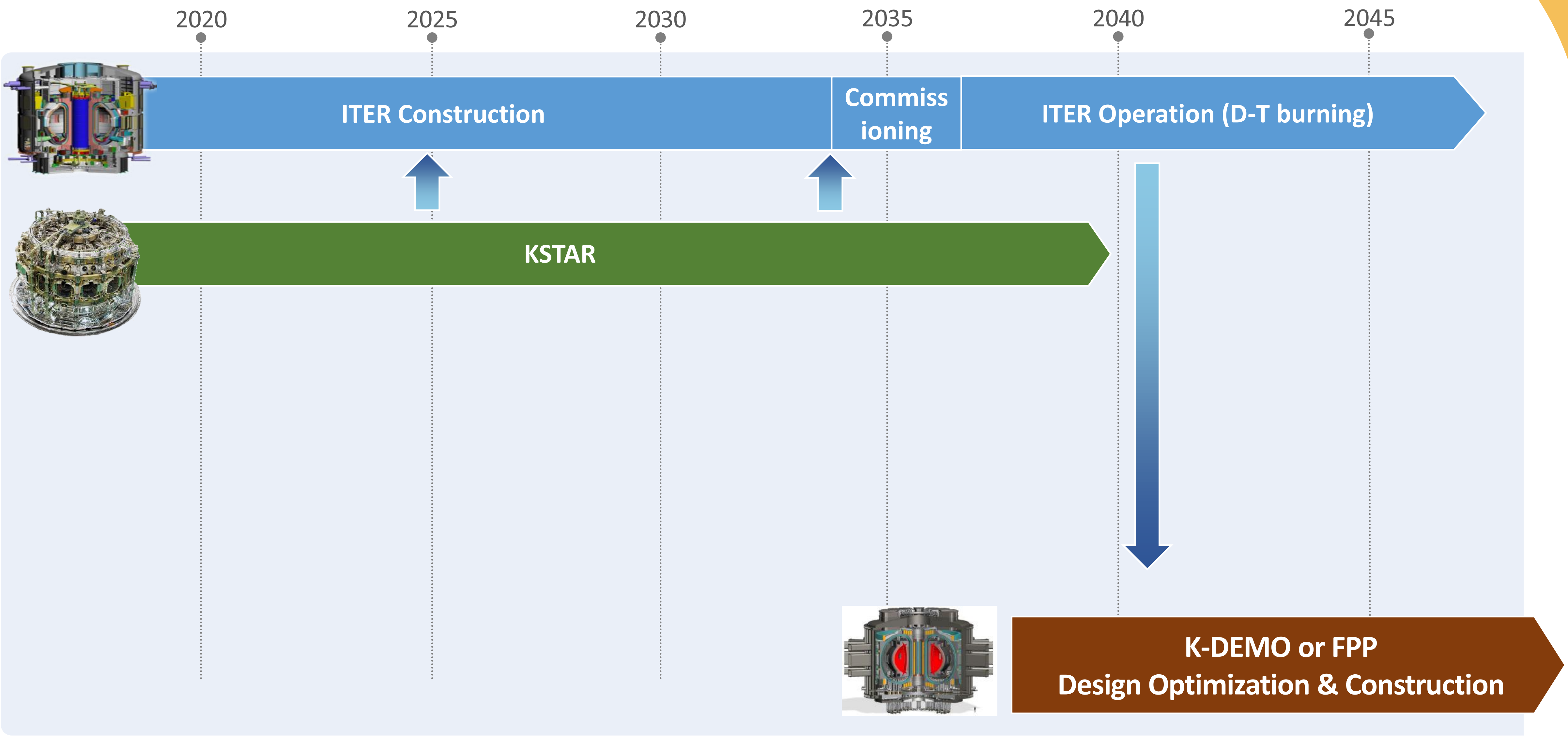
Expansion of Korean National Fusion R&D Path *(not approved yet)*

- Recently, a community-wise consensus was made to embrace these innovative technologies (e.g. HTS) 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.

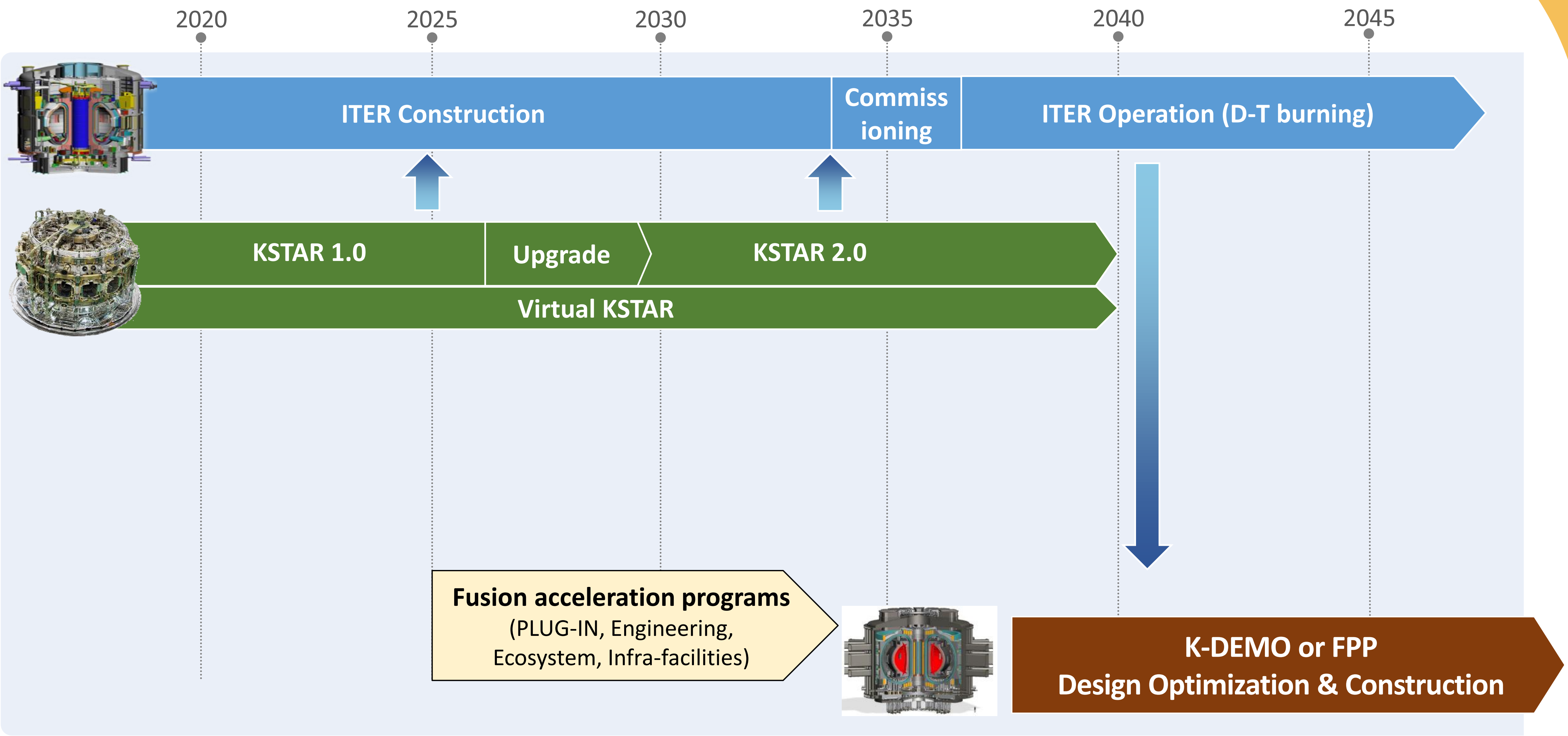


Newly Proposed Korean Fusion R&D including CPD based on HTS Technology

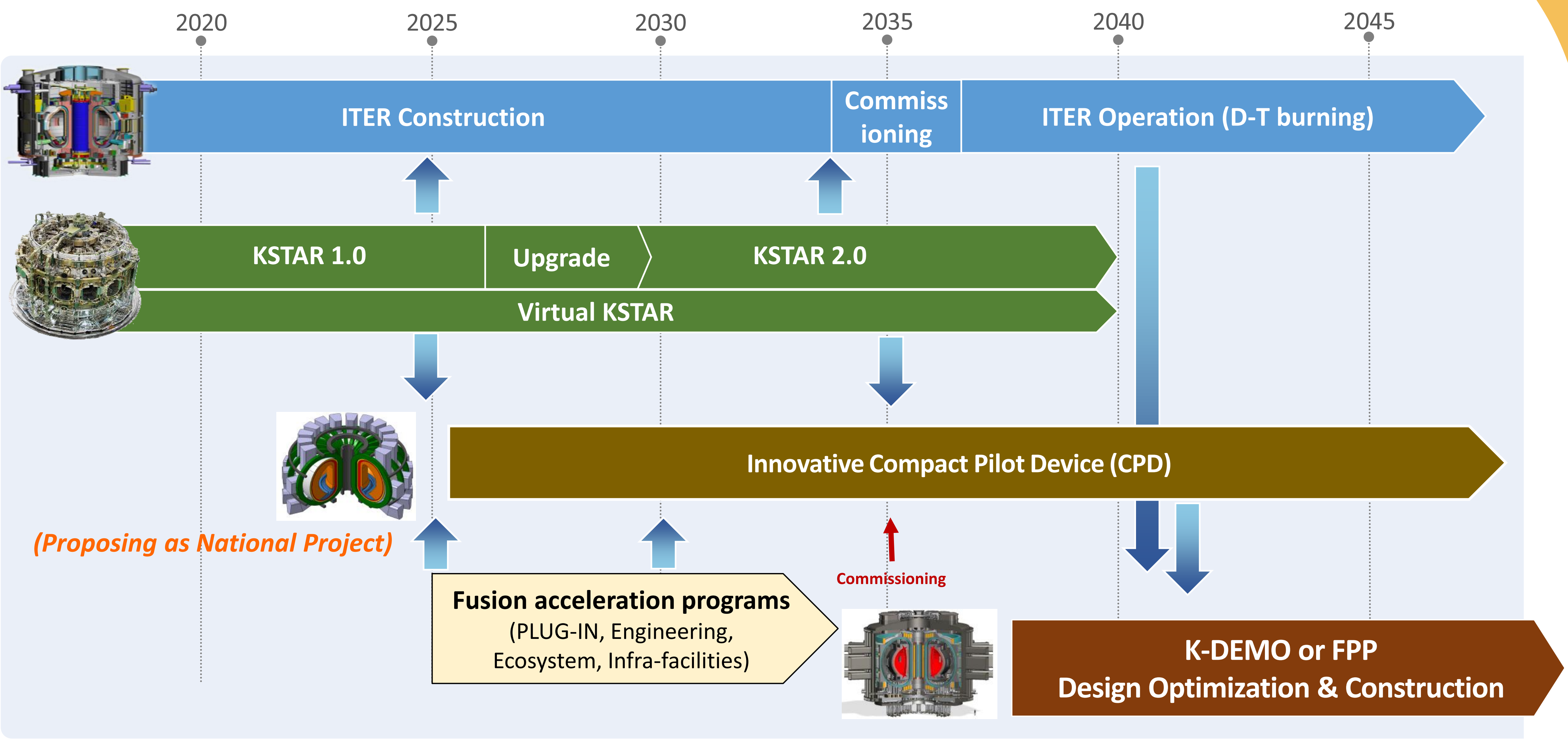
Proposed Timeline of Key Fusion Programs



Proposed Timeline of Key Fusion Programs



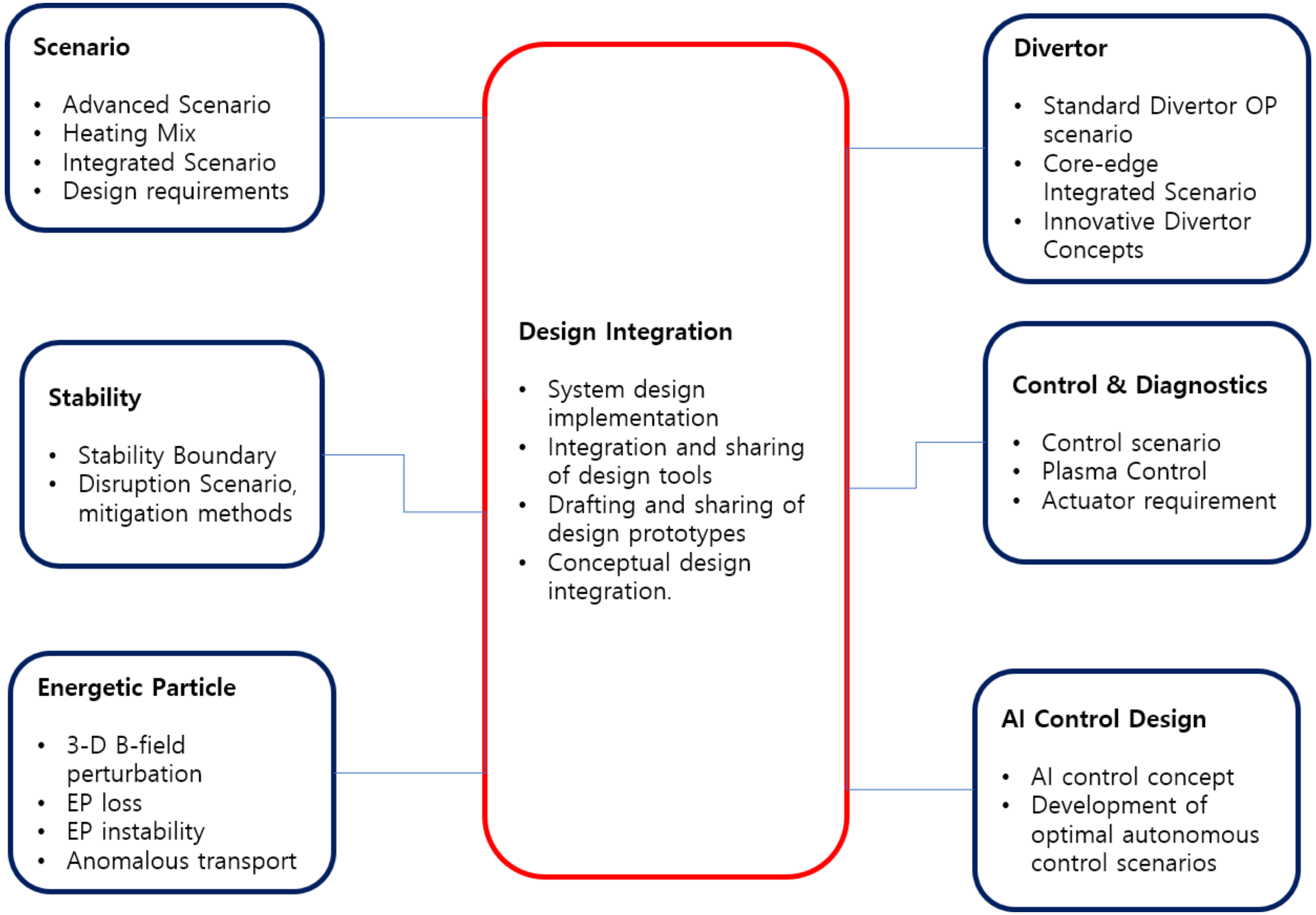
Proposed Timeline of Key Fusion Programs



IV. Preliminary Design Study for the CPD

K-DEMO design TF is 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

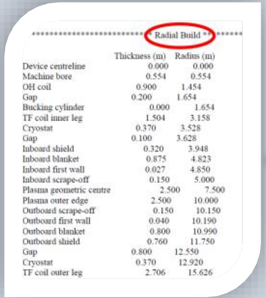
Advanced Design Tools are being developed for CPD

- 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

CAD Management Module

AutoFRD Defined Model

Output Serial K-Systems Code

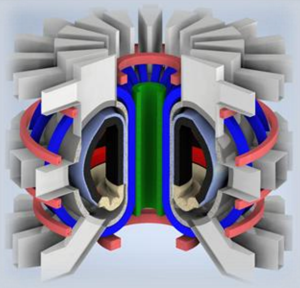


Radial Build

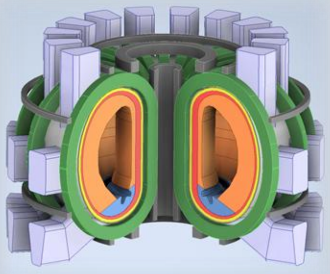
	Thickness (m)	Radius (m)
Device centreline	0.000	0.000
Machine bore	0.554	0.554
OH coil	0.900	1.454
Gap	0.200	1.654
Bucking cylinder	0.000	1.654
TF coil inner leg	1.504	3.158
Cryostat	0.370	3.528
Gap	0.100	3.628
Inboard shield	0.320	3.948
Inboard blanket	0.875	4.823
Inboard first wall	0.027	4.850
Inboard scrape-off	0.150	5.000
Plasma geometric centre	2.500	7.500
Plasma outer edge	2.500	10.000
Outboard scrape-off	0.150	10.150
Outboard first wall	0.040	10.190
Outboard blanket	0.800	10.990
Outboard shield	0.760	11.750
Gap	0.800	12.550
Cryostat	0.370	12.920
TF coil outer leg	2.706	15.626

Parameter Parsing from Loaded File

Automatic CAD DEMO Design



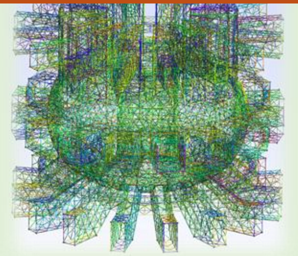
User Defined CAD Model



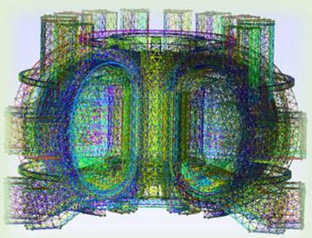
External CAD Loading

Meshing Module

Optional STP File Generation

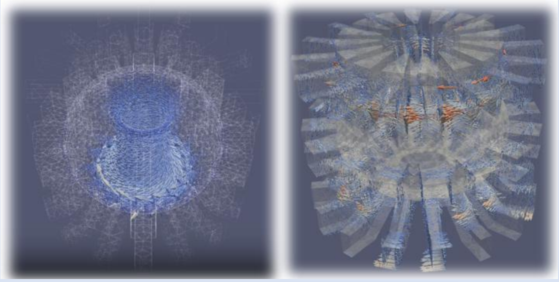


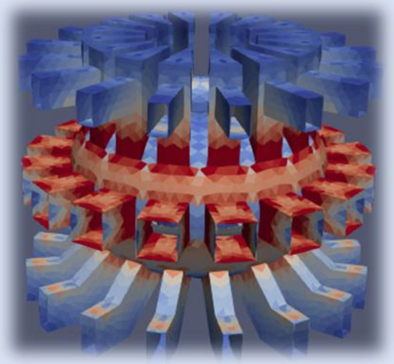
Automatic CAD DEMO Model Meshing



Simulation Module

Automatic Run of Necessary Routines for Physics Code Application



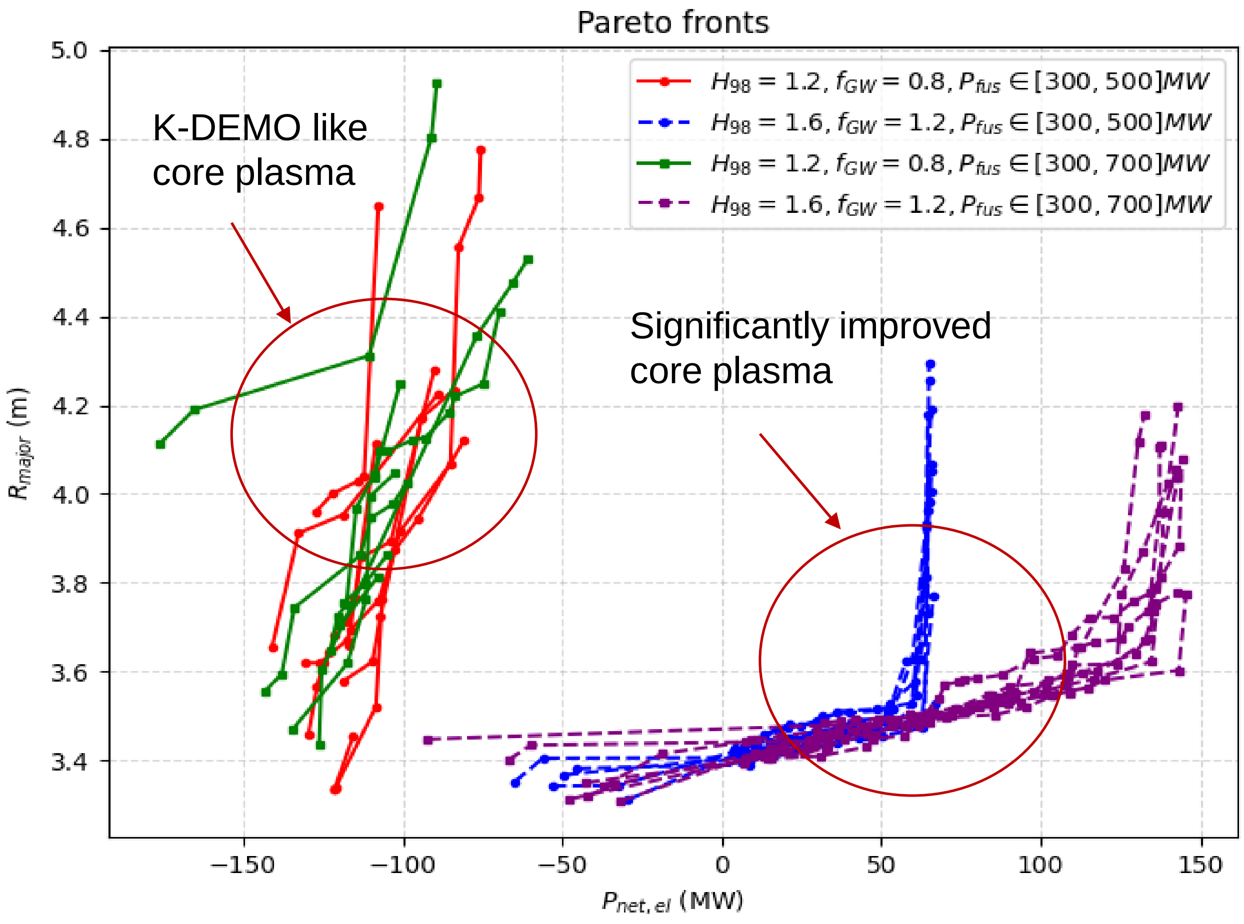


Optimizations of system design are enabled

- Multi-objective Bayesian optimizations of CPD were performed to set major parameters with different core plasma performances and maximum allowed fusion powers (500, 700 MW)

- Compared to K-DEMO, significantly improved plasma performance is required to achieve net electricity with $R_0 < 4m$
  - $H_{98} = 1.2 \rightarrow 1.6,$
  - $n_e/n_{GW} = 1.0 \rightarrow 1.2$
  - $f_{BS} = 0.6 \rightarrow 0.8$ etc.

- 60 ~ 150 MWe net electricity are expected for machines with major radius in [3.5m, 4m]



Optimization of Machine Size for CPD

A preliminary CPD Reference ($R_0 = 3.5m$ & $B_T = 8.2T$) is selected

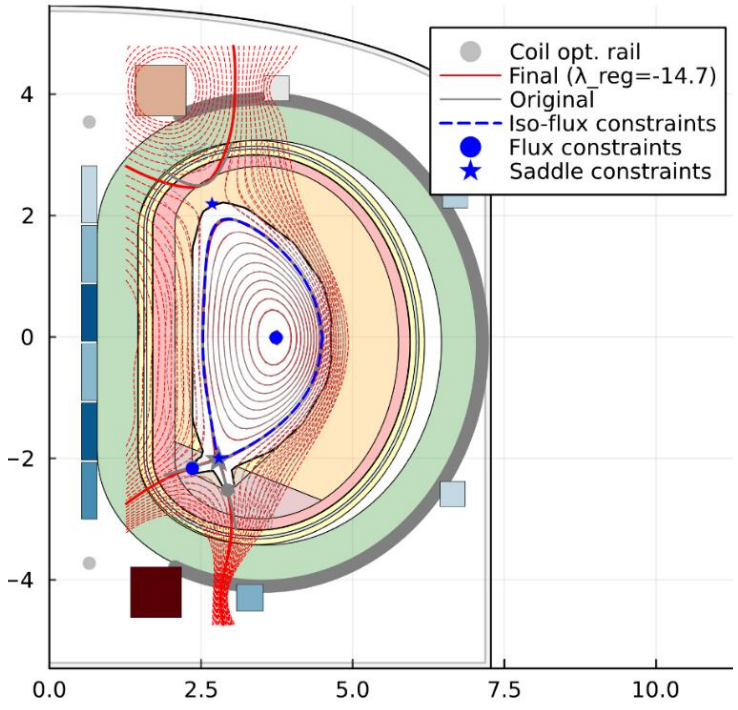
- Many similarities with previously proposed small reactor concepts employing HTS, allowing high B_T

	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 ?	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
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
B_T / B_{TF} (T)	9.2 / 23	5.9 / 13.4	8.3 / 19.4	8.2 / 18.3
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]

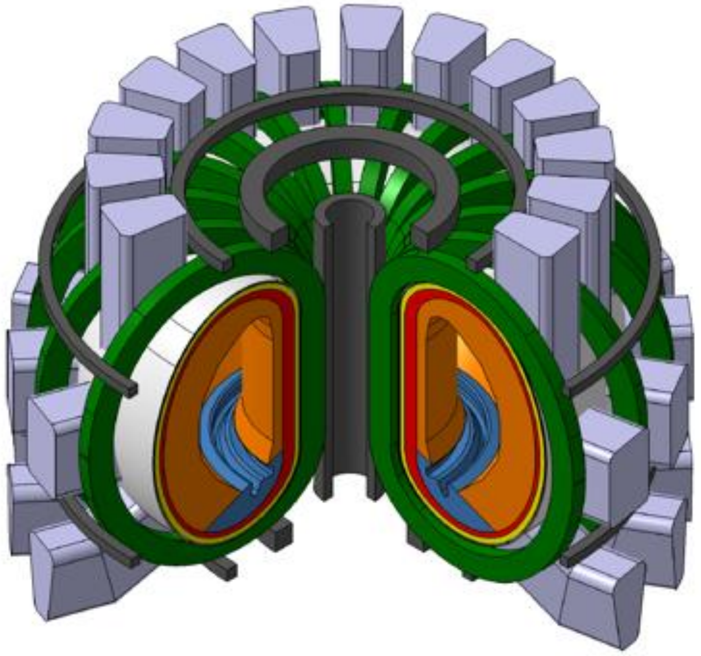
Major Device Parameters

CPD 2D/3D Builds and scenarios are being developed

- 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 developments are on-going:
  - Improved inductive scenarios 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

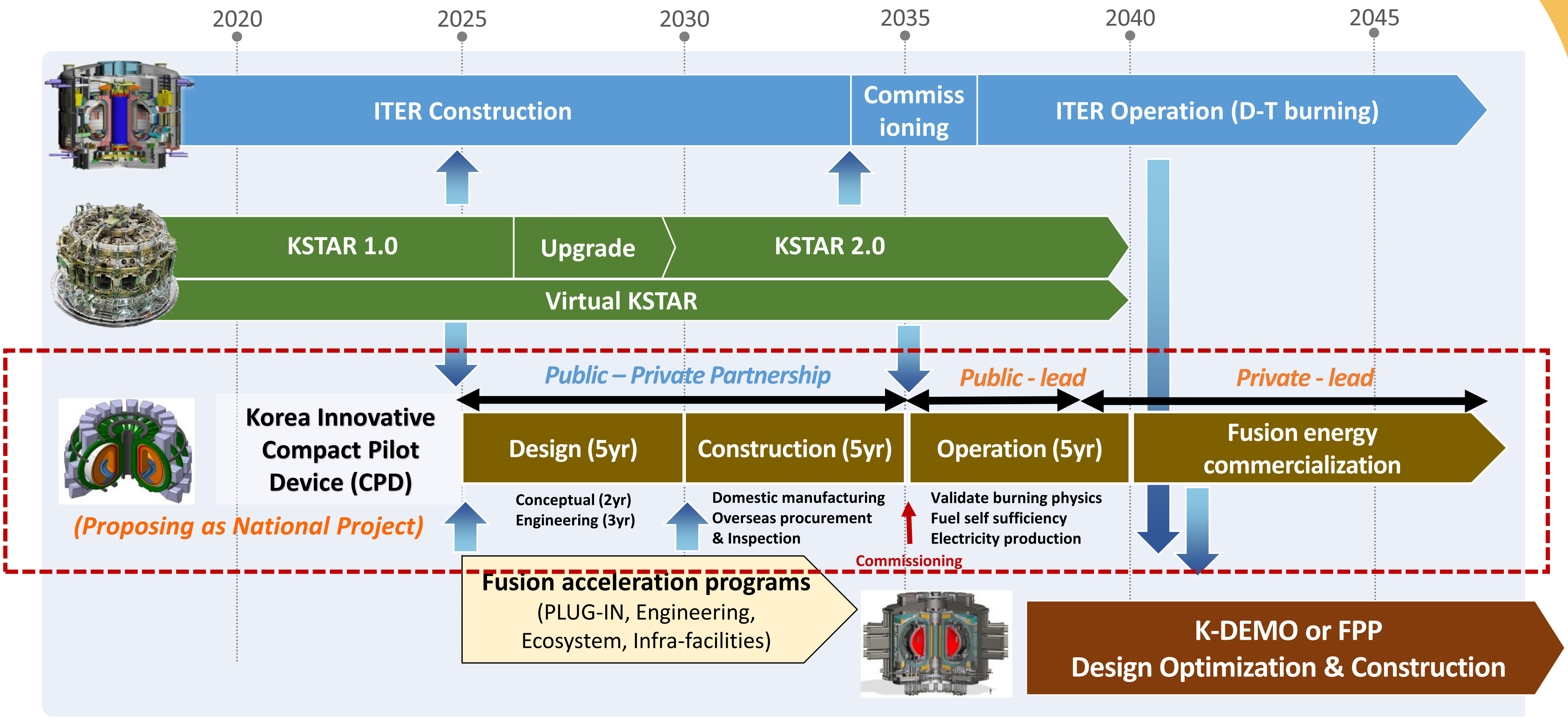
V. Summary and Future Perspective

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

CDP Design & Construction Schedule is being proposed



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