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Test Strategy and Infrastructure for Breeding Blanket Development at KFE

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K-DEMO

- Top-level goals and key design criteria for K-DEMO approved by National Fusion Energy Committee
  - Currently, coordinated efforts are being made by experts from universities, industries and research institutes (i) to establish the detailed strategic roadmap for K-DEMO R&Ds and (ii) to operate the K-DEMO Design Task Force

Top-level goals

① Maximum electrical output of over 500MW

- Considering the potential for future scale-up to 1 GW of commercial output
- Ensuring sufficient heat output to validate and improve the performance and cost-effectiveness of key component

② Effective TBR > 1

- Ensuring stable fuel (tritium) self-sufficiency for maintaining fusion reaction and continuous operation

③ Verification of Intrinsic Safety for Fusion

- Verifying the safety management for handling tritium and disposing of low to Intermediate level radioactive waste
- Establishing a licensing procedure system

④ Acquisition of data contributing to economic evaluation

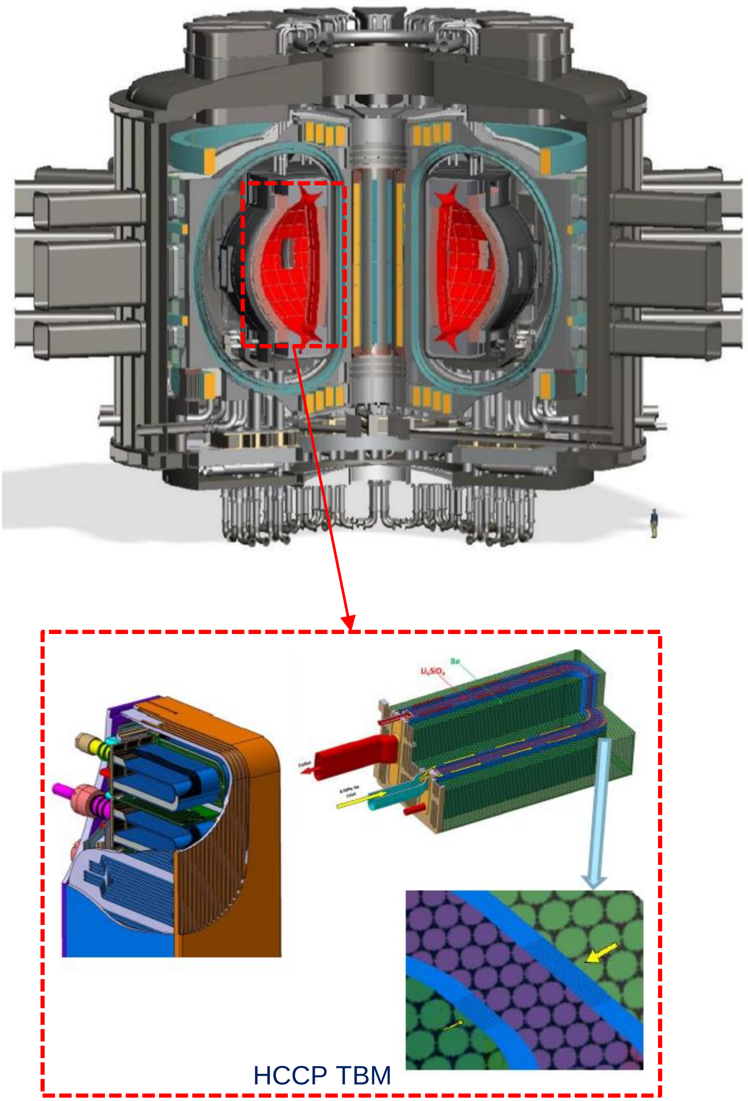
- Setting a target for competitive power generation cost (commercial output)
- Identifying and solving issues to improve economic feasibility

K-DEMO Blanket

- Reference breeding blanket design (pre-conceptual design in progress)

  - Features
    - Helium Cooled Ceramic Pebble concept following KO-EU Joint TBM Development (i.e. HCCP; He coolant, Li ceramic, Be alloy, RAFM steel, W armor, etc.)
    - Other concepts are being explored (ex. Liquid breeder blankets)

  - Major design requirements
    - Effective TBR > 1.0
    - Extraction of ~ 1,500 MW thermal energy to generate electrical power of ~500 MW
    - Operated in (quasi-) steady condition under NWL ~1.5 MW/m^2 and SHF ~0.5 MW/m^2
    - Material damage up to 20 dpa / 50 dpa / (100 dpa)
    - Compliant to (target) availability 60%



Strategy for Breeding Blanket Development

- Technologies for breeding blankets need to be developed and validated prior to construction of K-DEMO
  - Design & safety tools/modellings/data
  - Manufacturing technology
  - Tritium extraction (including tritium management) & cooling technologies
  - Materials and their database

HCCP TBM Project in ITER

- Demonstration of breeding blanket concepts in fusion environment, however, in ITER fusion environment (relevant neutron flux with engineering scaling but pulse operation with relatively short irradiation time)

Fusion(-like) Neutron Source for DEMO

- Verification of overall performance (tritium self-sufficiency, heat extraction capability) and acquisition of engineering data under DEMO-relevant irradiation time and scenario ((quasi)-steady)

Reliability and Safety Demonstration (non-neutron environment)

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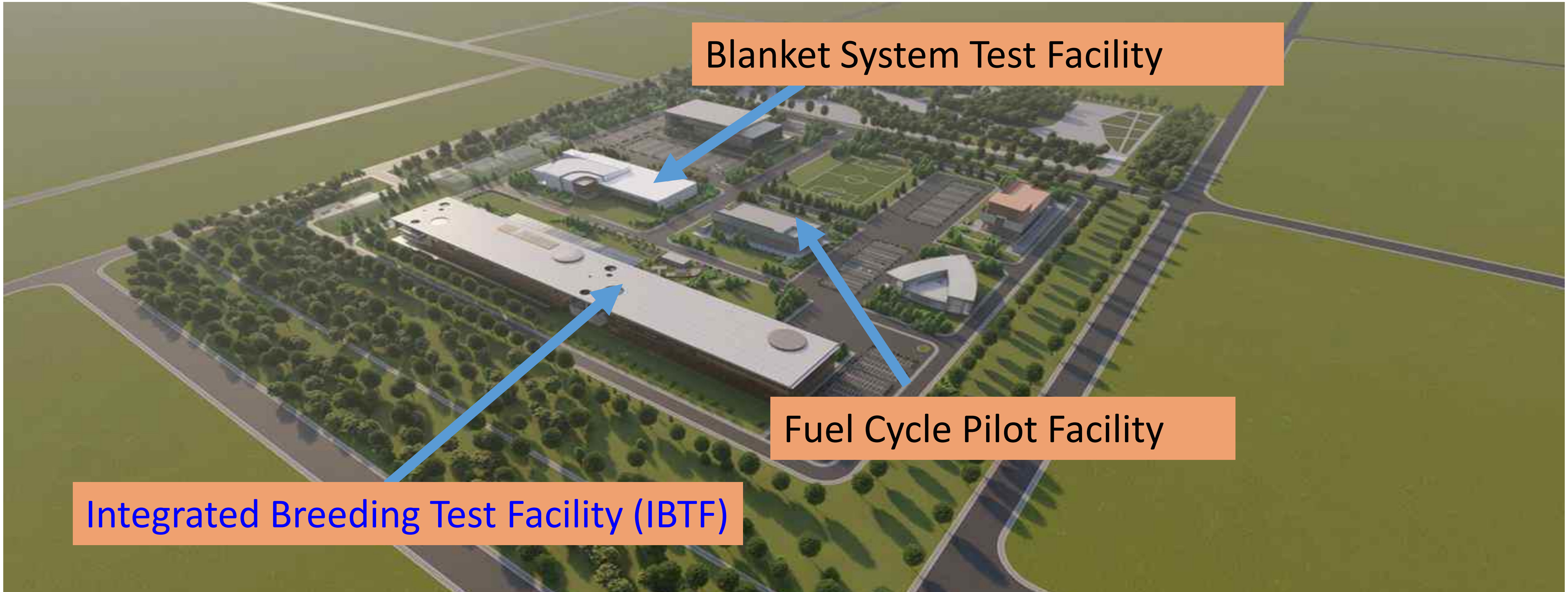
Korea Fusion Engineering Advanced Test (KFEAT) Complex



- The Integrated Breeding Test Facility for blanket component test utilizing 40 MeV deuteron accelerator-driven system with max 10 mA for fusion-like neutron generation
- The Blanket System Test Facility to demonstrate the reliability and safety of the blanket and its ancillary systems
- The Fuel Cycle Pilot Facility to verify the continuous fuel cycle operation using H2/D2 with 1/10 pilot scale

Main objectives (with focus on IBTF)

- A dedicated neutron irradiation facility for breeding blanket component test under fusion-like environment
  - Validation of overall performance under DEMO-relevant irradiation time and scenario ((quasi-)steady)
    - Demonstration of long-term structural integrity and reliability of breeding blankets
    - Verification of the design lifespan and integrity of blanket materials
    - Verification of long-term tritium production and extraction efficiency

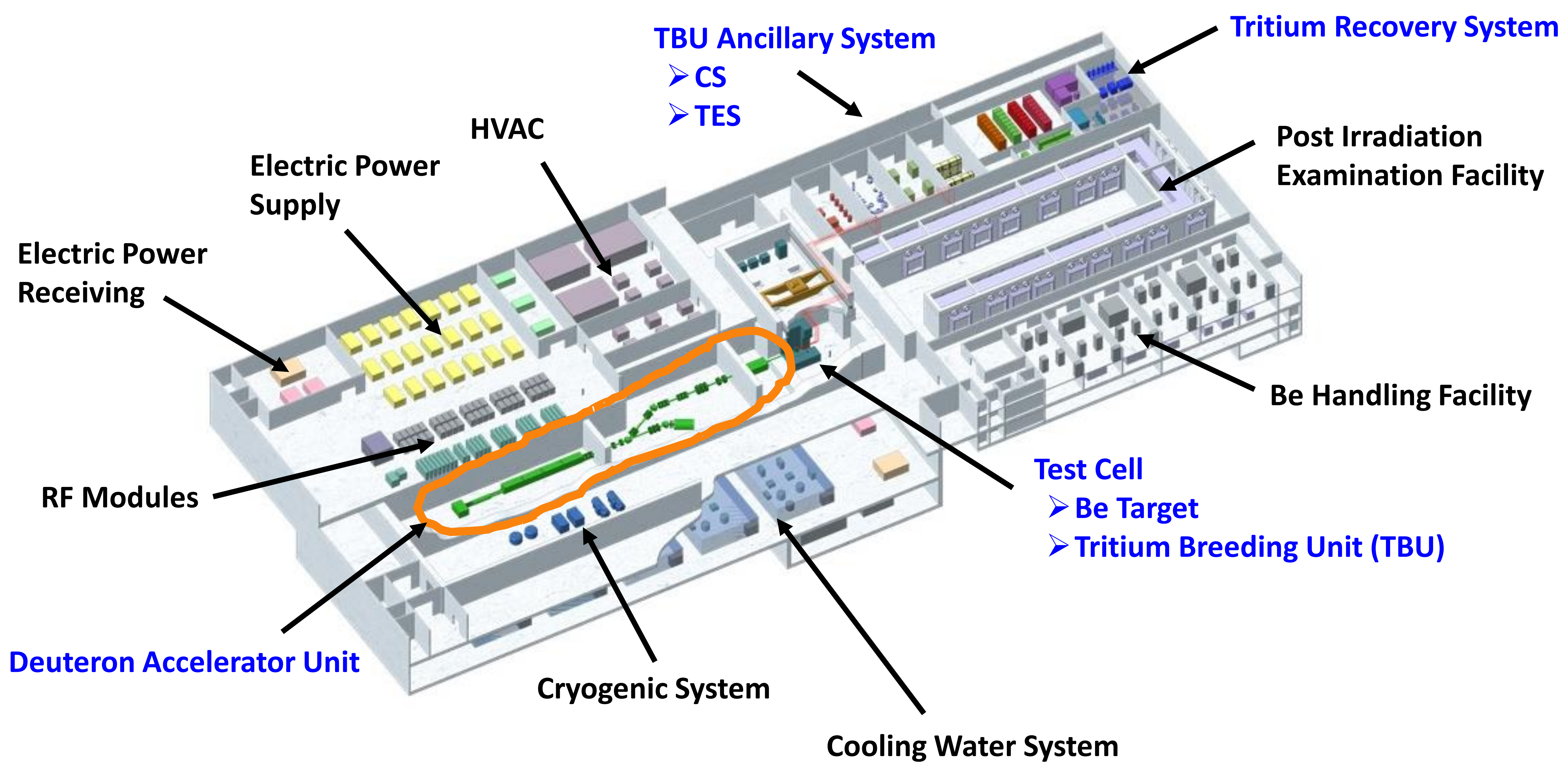
    ➡ Blanket overall performance through its lifespan to be verified

  - From the testing aspects,
    - Testing flexibility for DEMO blanket design candidates
    - Using breeding blanket 1:1 scale mockup (Breeding Unit) that reflects the actual design

    ➡ Securing engineering data for design and qualification of fabrication technology under fusion-like environment

  - Experience of tritium management and handling technology

Integrated Breeding Test Facility (IBTF)



Integrated Breeding Test Facility (IBTF) - DAU

- Deuteron Accelerator Unit
  - To accelerate deuterons up to 40 MeV with max 10 mA, and deliver the beam to target

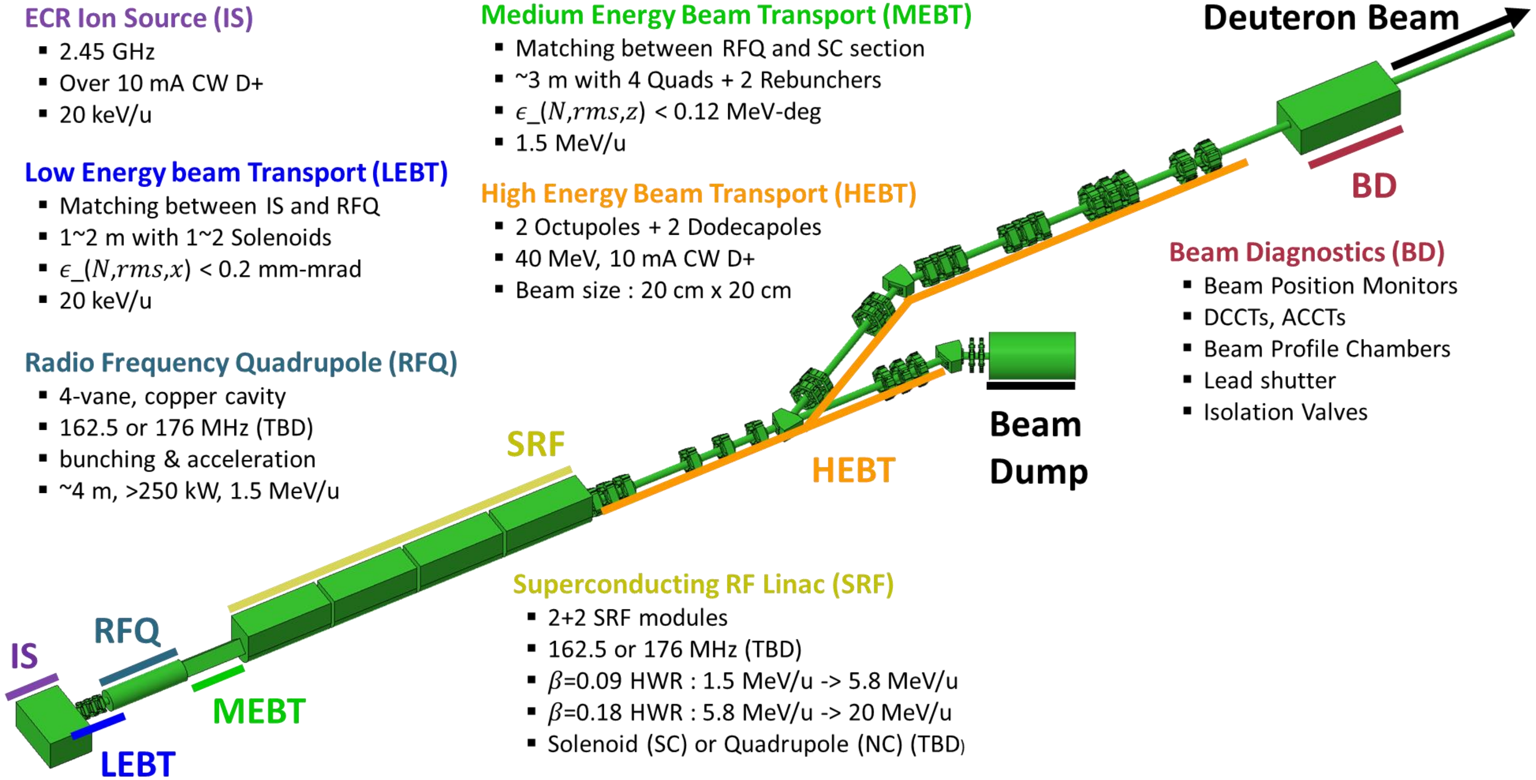
ECR Ion Source (IS)
- 2.45 GHz
- Over 10 mA CW D+
- 20 keV/u

Low Energy beam Transport (LEBT)
- Matching between IS and RFQ
- 1~2 m with 1~2 Solenoids
- $\epsilon_{N,rms,x}$ < 0.2 mm-mrad
- 20 keV/u

Radio Frequency Quadrupole (RFQ)
- 4-vane, copper cavity
- 162.5 or 176 MHz (TBD)
- bunching & acceleration
- ~4 m, >250 kW, 1.5 MeV/u

Medium Energy Beam Transport (MEBT)
- Matching between RFQ and SC section
- ~3 m with 4 Quads + 2 Rebunchers
- $\epsilon_{N,rms,z}$ < 0.12 MeV-deg
- 1.5 MeV/u

High Energy Beam Transport (HEBT)
- 2 Octupoles + 2 Dodecapoles
- 40 MeV, 10 mA CW D+
- Beam size : 20 cm x 20 cm



Beam Diagnostics (BD)
- Beam Position Monitors
- DCCTs, ACCTs
- Beam Profile Chambers
- Lead shutter
- Isolation Valves

Superconducting RF Linac (SRF)
- 2+2 SRF modules
- 162.5 or 176 MHz (TBD)
- β=0.09 HWR : 1.5 MeV/u -> 5.8 MeV/u
- β=0.18 HWR : 5.8 MeV/u -> 20 MeV/u
- Solenoid (SC) or Quadrupole (NC) (TBD)

Parameter	Value
Ion species	Deuteron
Max. beam energy	40 MeV
Max. beam current	CW 10 mA
Beam size	20 cm x 20 cm
Neutron yield	~2x10^{15} n/s (forward)
Neutron flux	~5x10^{12} n/cm^2·s
Operation	~7000 hours/year
Maintenance	Hands-on (+ Remote)
Target for 1st phase	Solid Beryllium

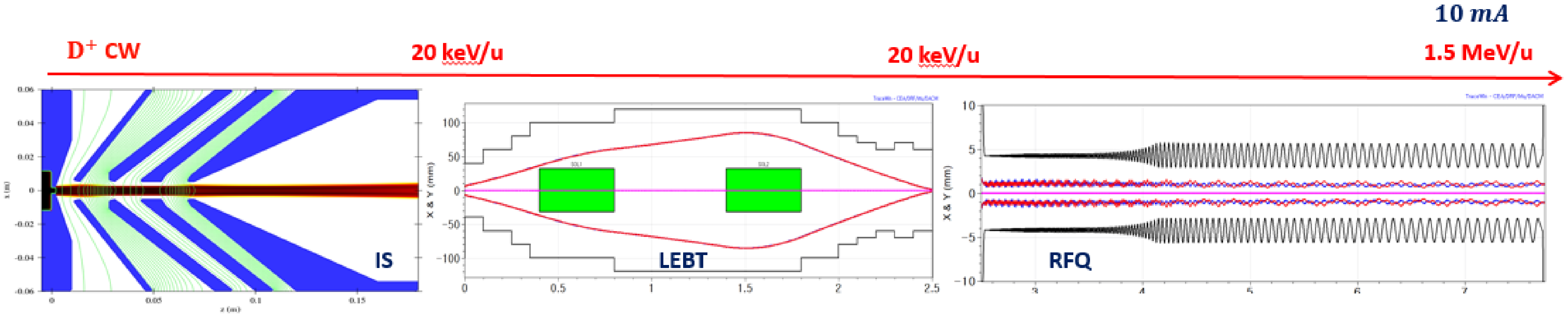
Benchmark: SARAF-Phase 2 accelerator (D+ CW, 40 MeV, 5 mA)

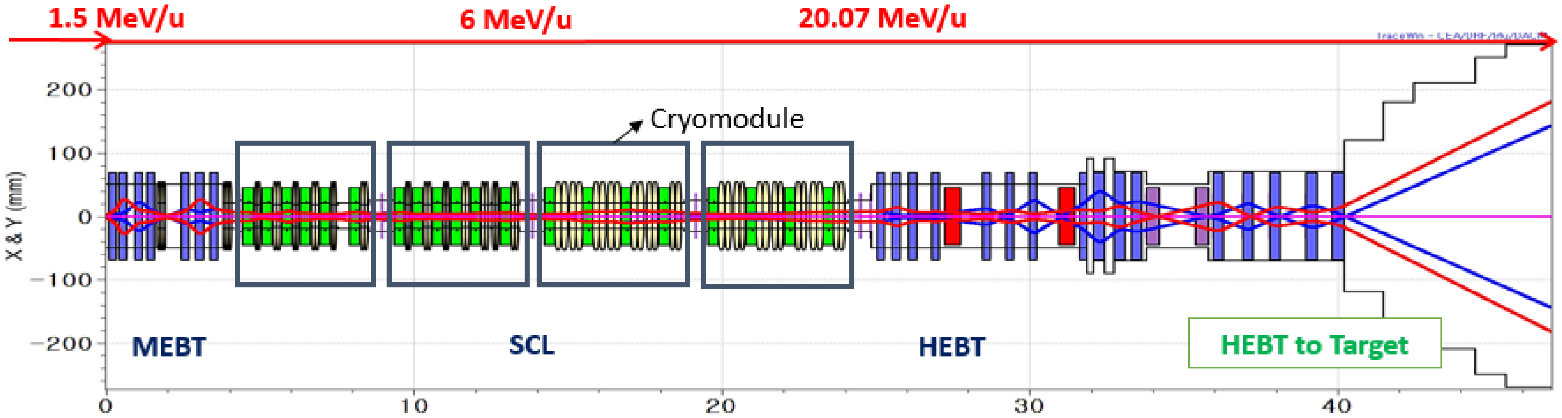
Integrated Breeding Test Facility (IBTF) - DAU

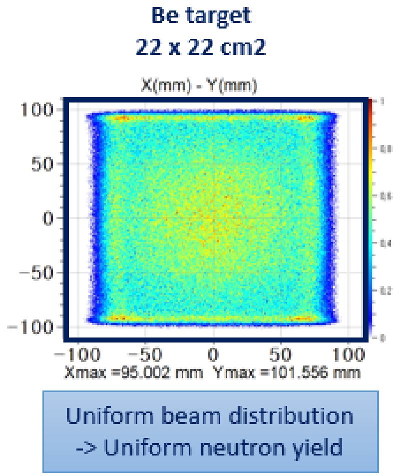
- Deuteron Accelerator Unit
  - Beam transport analysis results for DAU

Tot : ~56 m

Ion source	LEBT	RFQ	MEBT	SC Linac		HEBT	Target Cell
ECR IS (NC) 2.45 GHz	Matching between IS and RFQ	4-vane 176 MHz –bunching & acceleration	Matching between RFQ and SCL ❖ Space charge	HWR (SC) 176 MHz (2 cryomodules) $\beta_{opt} = 0.091$	HWR (SC) 176 MHz (2 cryomodules) $\beta_{opt} = 0.181$	2 Octupoles (For making rectangular shaped, uniform beam) Two 30° Dipoles (Achromatic) Beam diagnostics (~4 m)	(Solid Be 20 cm x 20 cm) Expected neutron flux : $\sim 5x10^{12}$ $n/cm^2/s$
D^+ CW Max 10 mA 20 keV/u	2 Solenoids 20 keV/u	172.3 kW 1.5 MeV/u	7 Quads + 2 Rebunchers 1.5 MeV/u	1.5 MeV/u -> 6 MeV/u	6 MeV/u -> 20 MeV/u		Beam Dump
				Solenoid (SC) L_{eff} = 250 mm			







Integrated Breeding Test Facility (IBTF) - Target

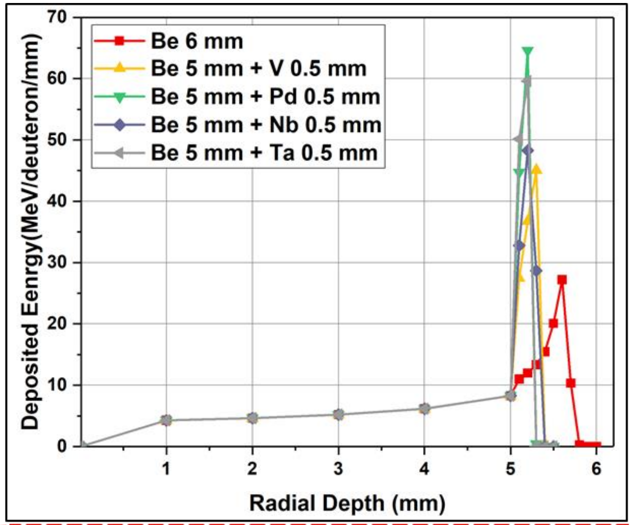
- Neutron Source Target
  - Generating neutrons by a nuclear reaction between a target and charged particles from the DAU

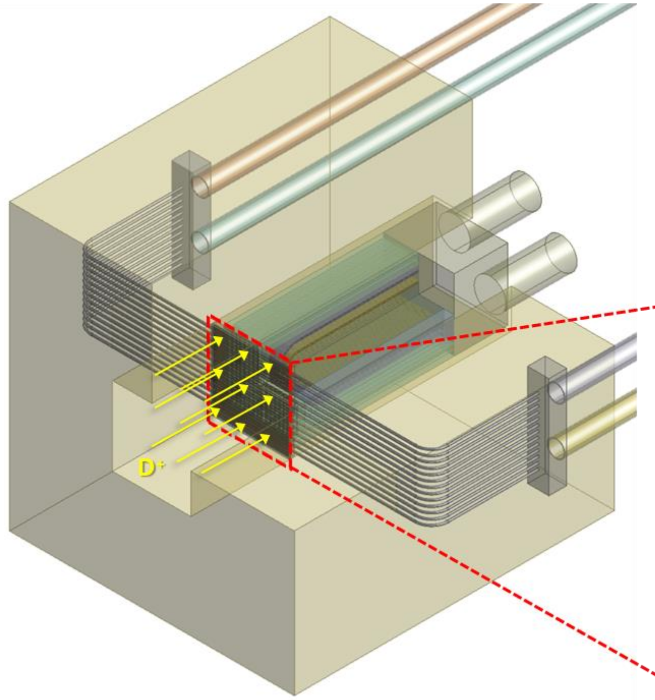
➢ **Target (solid)**
- Material: Beryllium
- Size : 220 mm x 220 mm x 5 mm
- Allowable Max. Temperature: 730 °C

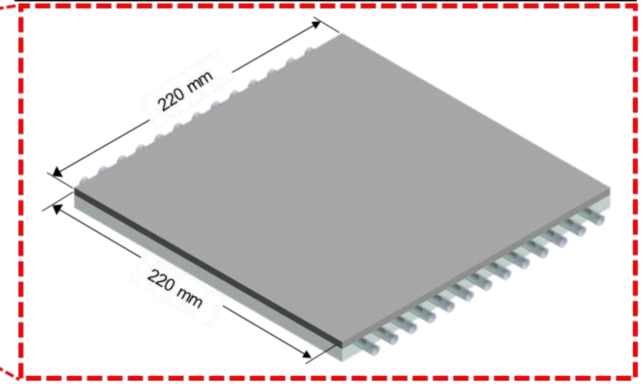
➢ **Blistering Mitigation Layer**
- Material: Vanadium
- Size : 220 mm x 220 mm x 0.3 mm
  (beam footprint: 200 mm x 200 mm)

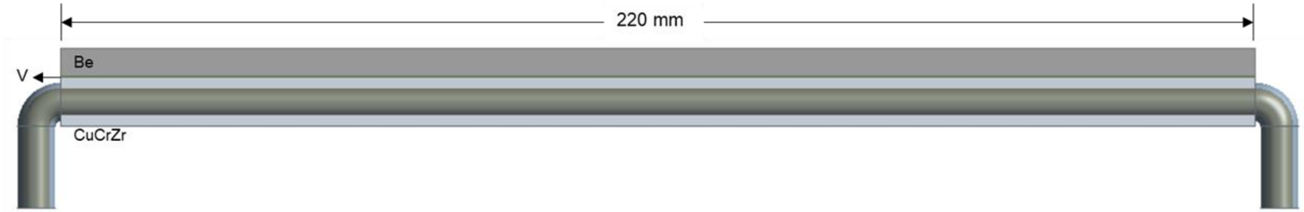
➢ **Back-plate & Tube**
- Material: CuCrZr
- Size : 220 mm x 220 mm x 9 mm
- Tube: Φ5, 1t

➢ **Coolant**
- Water
- 1 MPa, 25 °C, 15 m/s @ inlet



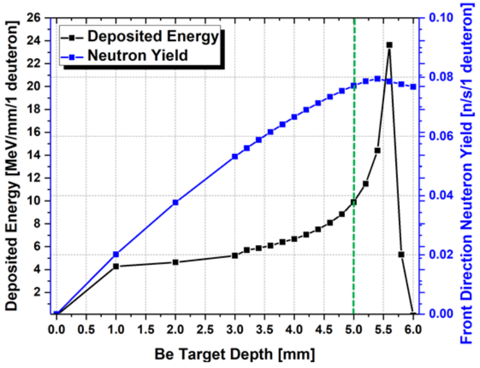


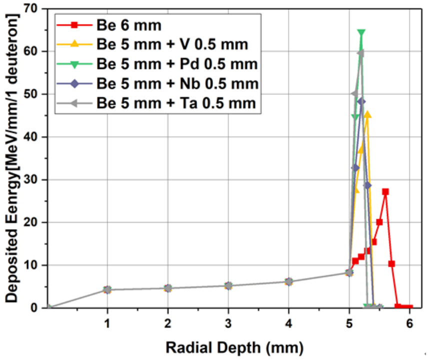


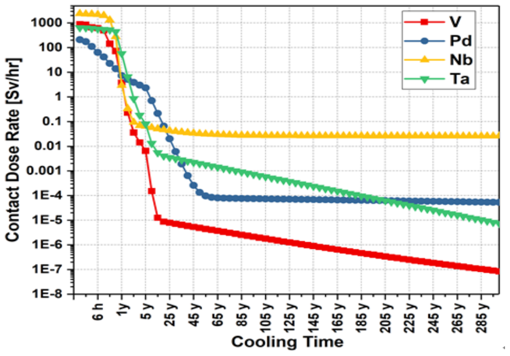


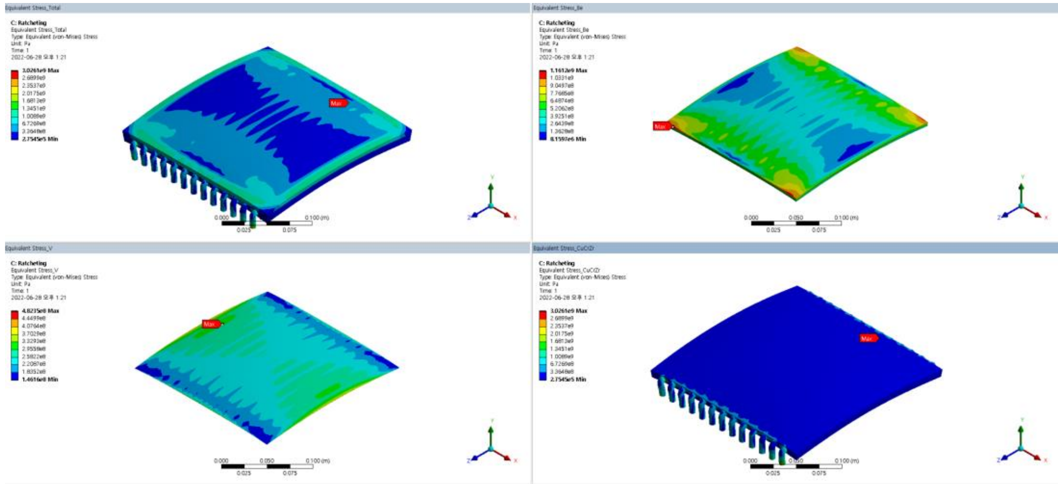
Integrated Breeding Test Facility (IBTF) - Target

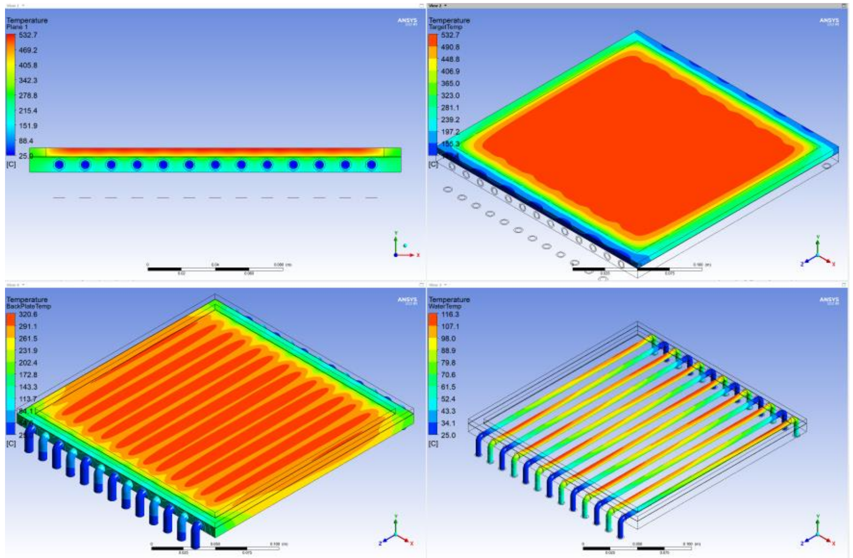
- Neutron Source Target
  - Nuclear and thermal/structural analyses results for the target

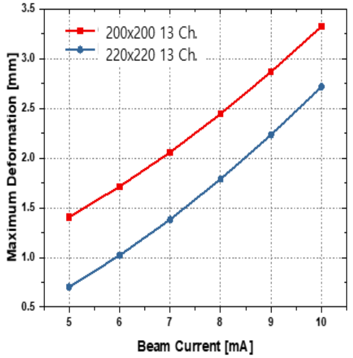


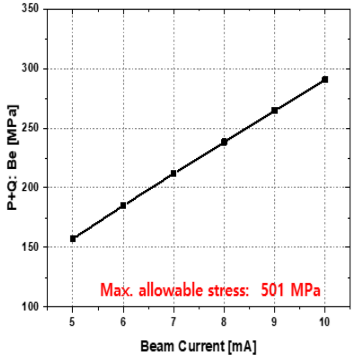


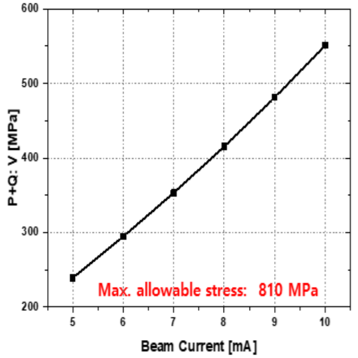






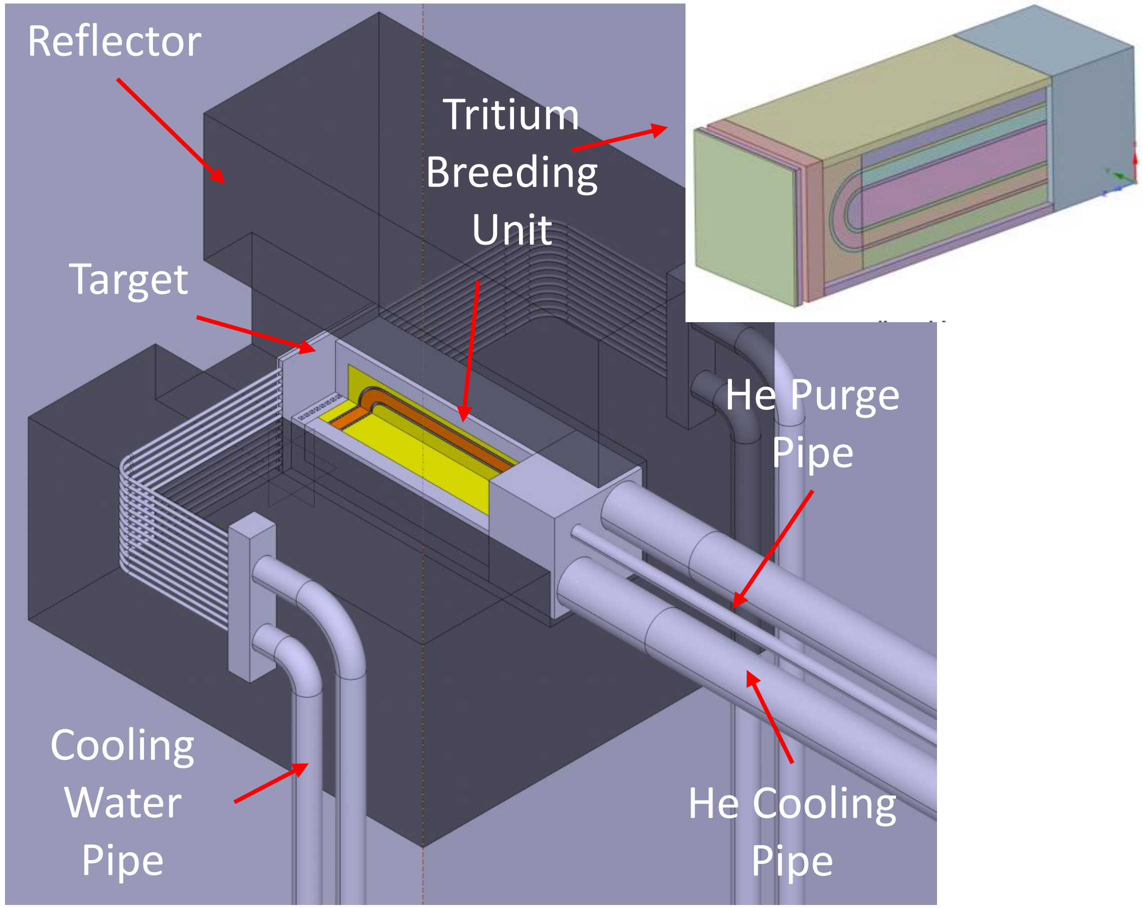






Integrated Breeding Test Facility (IBTF) - TBU

- Tritium Breeding Unit (TBU)
  - To validate long-term performance (Tritium production/recovery, heat extraction) and structural integrity of the DEMO breeding blanket candidates

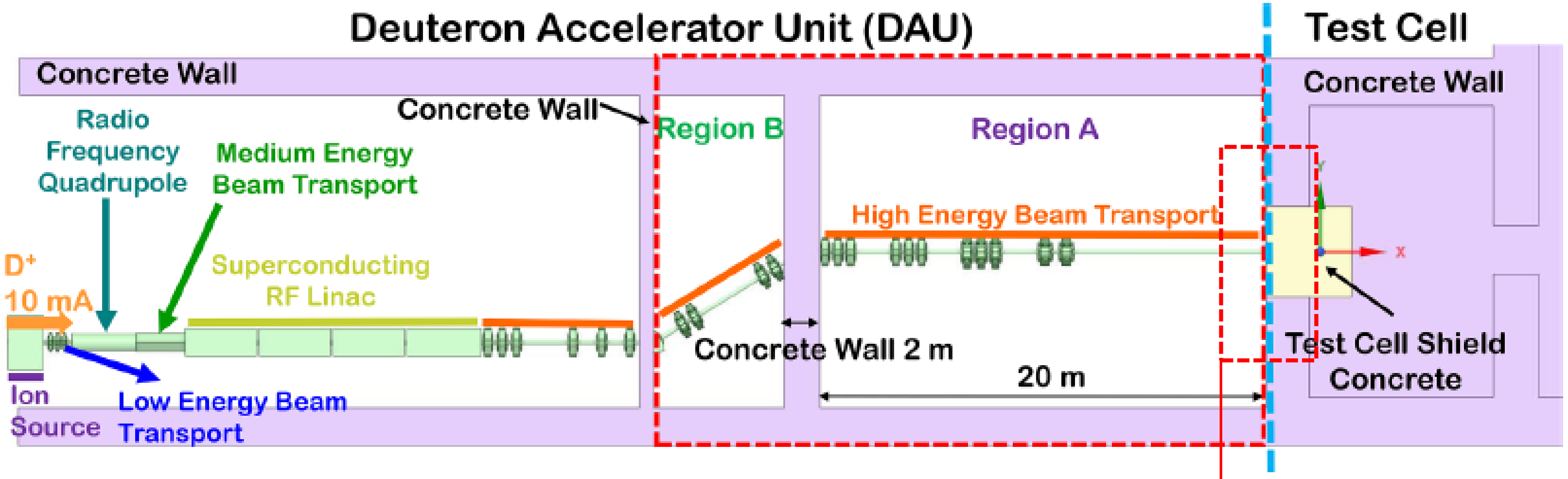


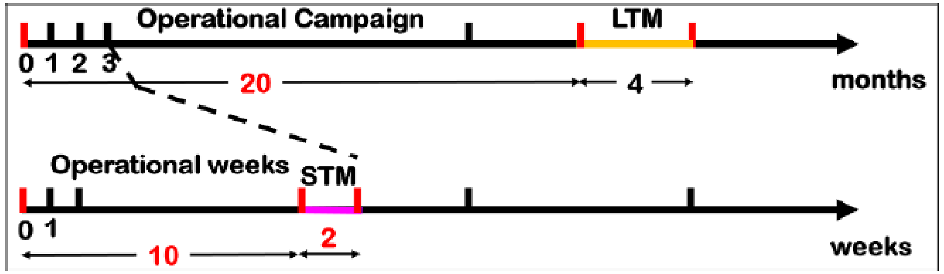
Parameter	Tritium Breeding Unit
Structural Material	ARAA
Neutron Multiplier	Be (or Beryllide)
Tritium Breeding Material	Li_2TiO_3
Coolant	Helium
Coolant Pressure	8 MPa
Coolant Temperature	Avg. 450℃
Neutron Irradiation area	0.2 x 0.2 m^2
Radial length	0.6 m
Tritium Production Rate	0.2 mg/day*

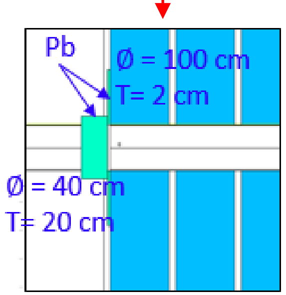
* To be updated

Integrated Breeding Test Facility (IBTF) - Shielding

- To provide nuclear shielding in order to keep radiation level under the given zoning requirements
  - Compliant to maintenance plans, hands-on maintenance (or human-assisted) for the DAU during STM or LTM, and full RH maintenance for the Test Cell

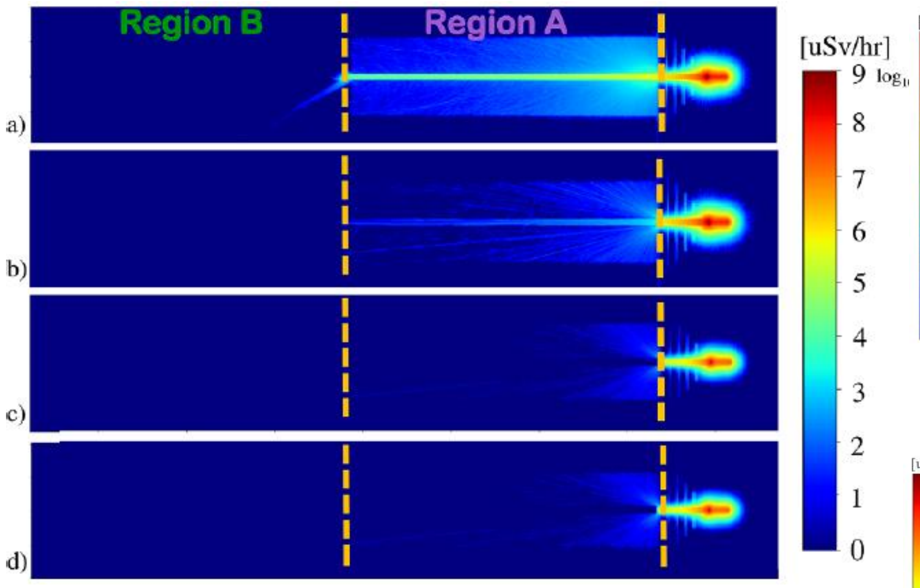




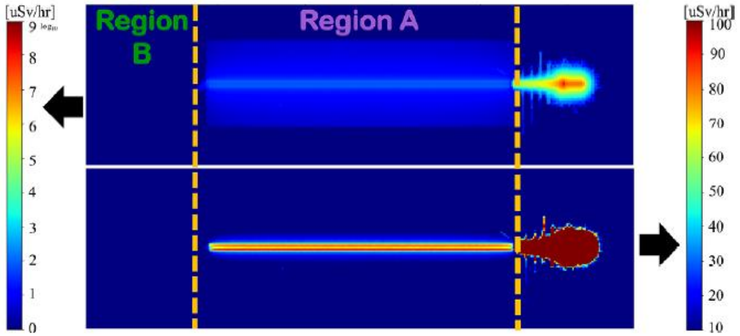


Integrated Breeding Test Facility (IBTF) - Shielding

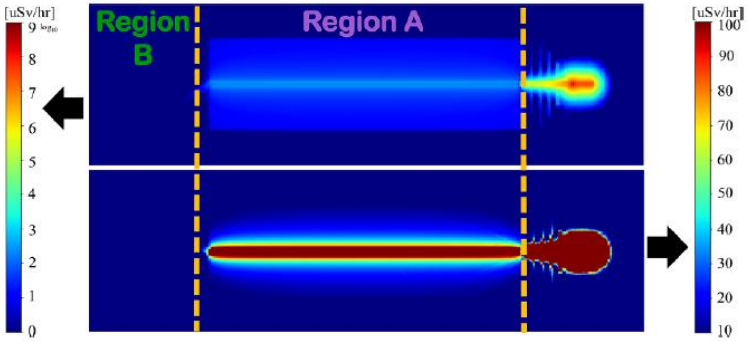
- To provide nuclear shielding in order to keep radiation level under the given zoning requirements
  - Shielding analysis for the HEBT and the Test Cell



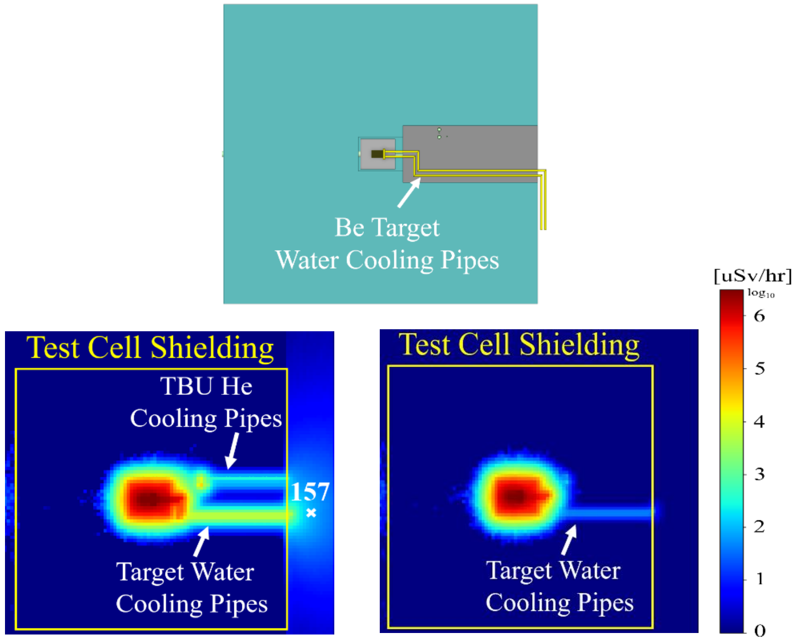
Dose rate based on the Pb shutter thickness
(a) 0 cm (b) 10 cm (c) 20 cm (d) 30 cm



Dose rate during the STM at a cooling time 1 week



Dose rate during the LTM at a cooling time 1 week



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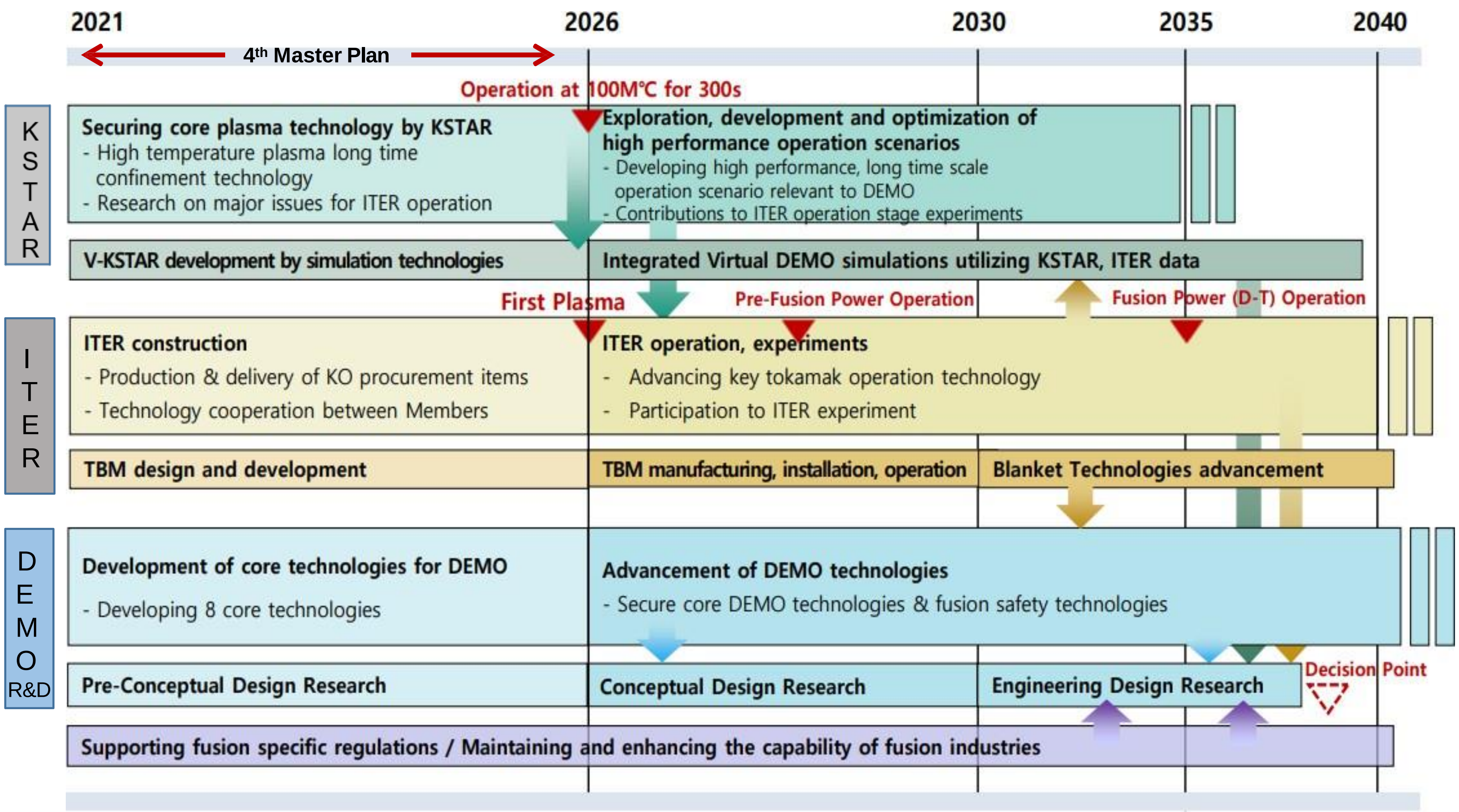
Roadmap for Fusion Energy Development ('22)

Roadmap is based on the ITER baseline (Dec. '21)

- Rolling plan for fusion electricity demonstration by 2050
- The plan will be updated every five years with the Master Plan

Updated roadmap for Korea fusion energy development is under discussion considering,

- ITER new baseline
- Innovative gap technologies
- Public-private partnership
- Electricity from fusion energy by 2050s



Strategy for Accelerating Fusion Energy Realization (July ‘24)

- Taking a **leading role in fusion energy commercialization** and emerging as a core pillar of energy security in the carbon-free era.
- The “**Strategy for Accelerating Fusion Energy Realization**” was approved at the 20th National Fusion Energy Committee on July 2024.

20th National Fusion Energy Committee in July 2024.

Major strategies	Key tasks
Accelerating **Fusion Innovation** through **Public-Private Partnership**	• Fusion **Engineering Innovation** programs • **PLUG-IN** (PLasma for Unlimited power Generation & INnovation) program • AI-driven **Digital Transformation** for fusion systems
Establishing the **Foundation** for **Fusion Energy Industrialization**	• Fostering a **Private-sector-led Fusion Industry Ecosystem** • Empowering **Fusion Companies to expand in Global Markets** • Strengthening **Fusion Technology Spin-off** Programs
Building an **Innovative Ecosystem** for Fusion Energy	• Promoting an **Open and Collaborative Research Environment** • Educating and Empowering the **Next Generation of Fusion Experts** • Deepening **Global Partnership** and scientific exchange

Top-tier Requirements of the Compact Pilot Device (CPD)

Objectives and Mission

- **C**onstruction of **innovative compact fusion pilot device** in a decade
- **P**roduction of **steady-state capable recirculating fusion power** in a decade
- **D**emonstration of **burning plasma with internal heating only** in a decade

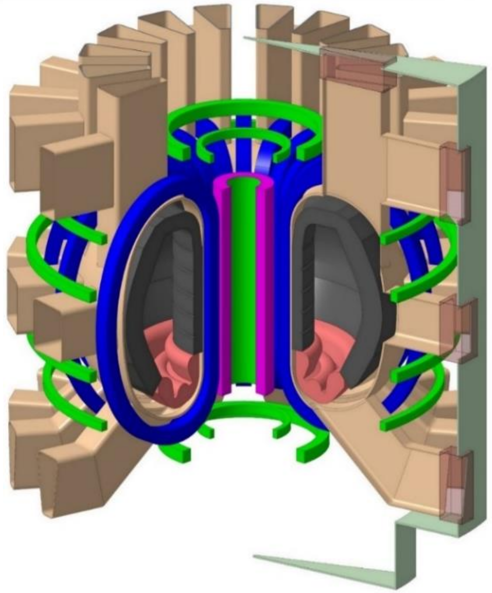
Operation Stages

- **Phase-I : Public-led (until end of 2030s)**
  - Demonstrate and validate burning plasma operation
  - Achieve **Q > 5** for up to 100 seconds
  - Validate **steady-state operation** for up to 1 hour

- **Phase-II : Private-led (from early 2040s)**
  - Demonstrate self-sufficient tritium production and electricity generation
  - Validate **tritium self-sufficiency**
  - Validate **electricity production** and commercialization up to ~100 MW

Preliminary Design Parameters of CPD

Parameters	KSTAR	CPD draft (Tokamak)	CPD draft (Spherical)	K-DEMO
Major radius, R0	1.8 m	~ 3.5 m	~ 2.0 m	~ 6.8 m
Minor radius, a	0.5 m	~ 1.1 m	~ 1.2 m	~ 2.2 m
Elongation, k	2.0	~ 2.0	~ 2.0	~ 2.0
Field on axis, B0	3.5 T	~ 8 T	~ 6.0 T	~ 7.25 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 MW	*~ 360 MW*	~ 1500 MW
SC	NbTi, Nb3Sn	HTS / LTS	HTS	NbTi, Nb3Sn
Divertor	C, W	~15 MW/m^2 (W)		~ 20 MW/m^2

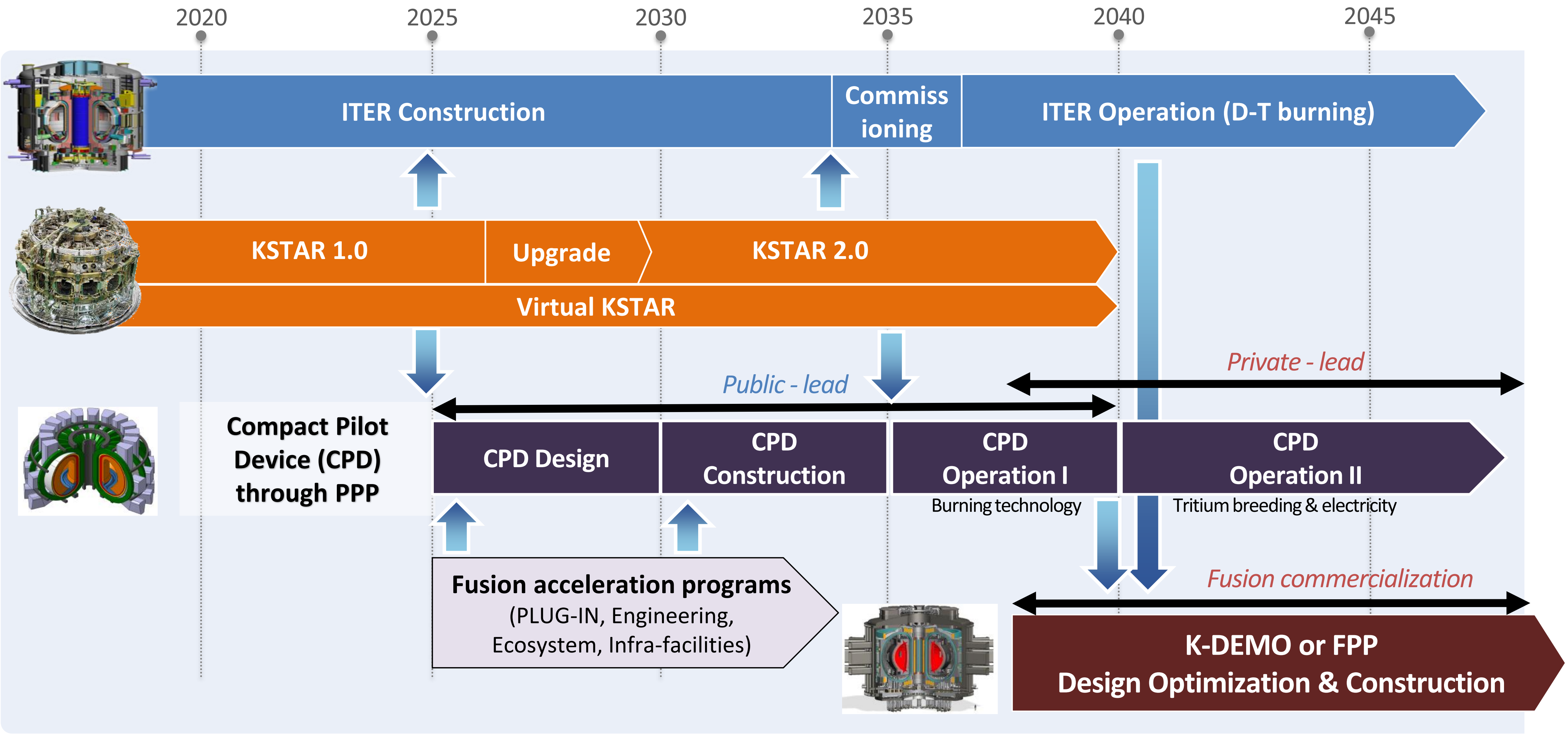


Major achievements from KSTAR experiments

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

- *Operational parameters may vary with circumstances.*

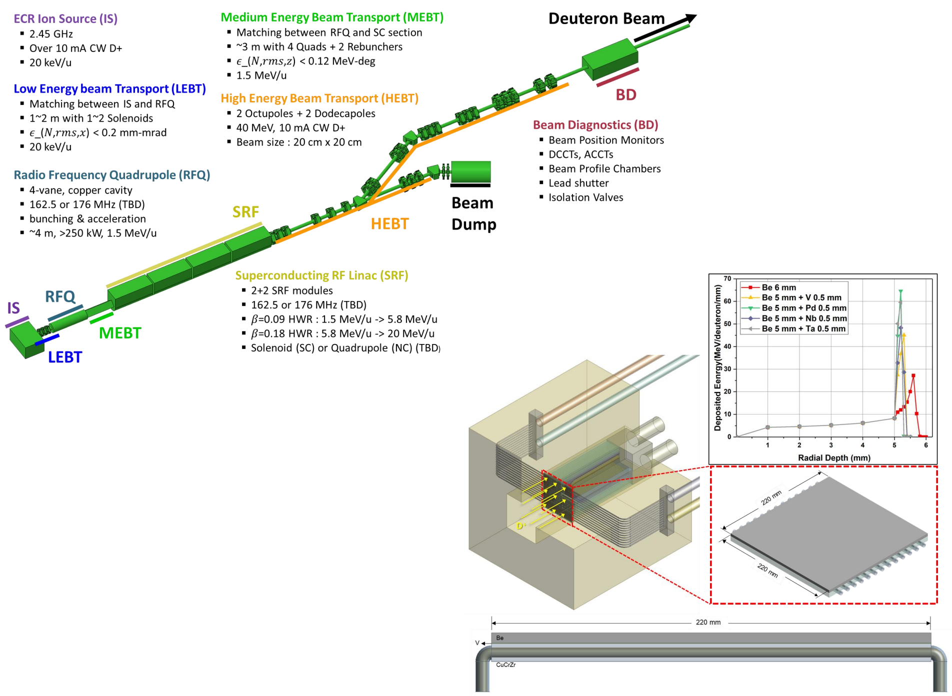
Proposed Timeline of Key Fusion Programs (to be discussed and approved by NFEC)



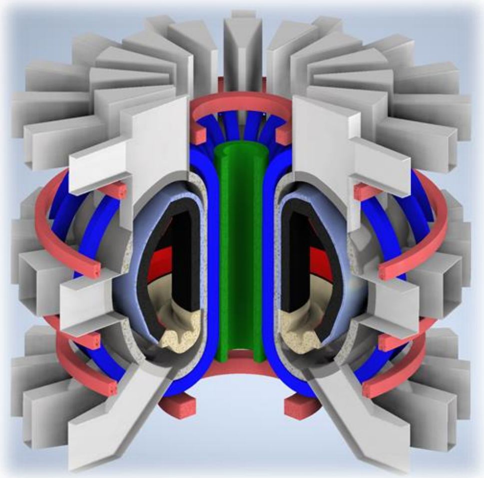
Fusion(-like) Neutron Source

- Conceptual study for the feasibility of blanket component tests using fusion(-like) neutron source has been conducted

  - The Integrated Breeding Test Facility (KFEAT) utilizing 40 MeV deuteron accelerator-driven system with max 10 mA for fusion-like neutron generation



  - Compact Pilot Device to be used for fusion Volumetric Neutron Source + Separate Neutron Source ?



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Summary

- Blanket test infrastructure equipped with neutron sources is being explored to fill key technology gaps in blanket development and qualification, including options such as Korea Fusion Engineering Advanced Test Complex (KFEAT)

- With the approval of “Strategy for Accelerating Fusion Energy Realization” in July 2024, the development of blanket technologies, which play a key role in fuel and energy production in fusion, is expected to be accelerated as well

- In accordance with this strategy, Compact Pilot Device(CPD) has been proposed as a platform to accelerate fusion energy realization, with the potential to serve as a volumetric neutron source for blanket qualification

- Technical discussions are underway in Korea on strategic alignment and complementary use of CPD with blanket test infrastructure to establish an integrated qualification pathway for blankets and other fusion components

Thank you for your attention

Q&A