International Symposium on Fusion Nuclear Technology (ISFNT)
September 10-15, 2023
Auditorio Alfredo Kraus Las Palmas, Gran Canaria, Spain

Plan on Breeding Blanket Test Facility for DEMO in Korea

Mu-Young Ahn(KFE)
on behalf of Fusion Fuel System Infra TFT

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Content

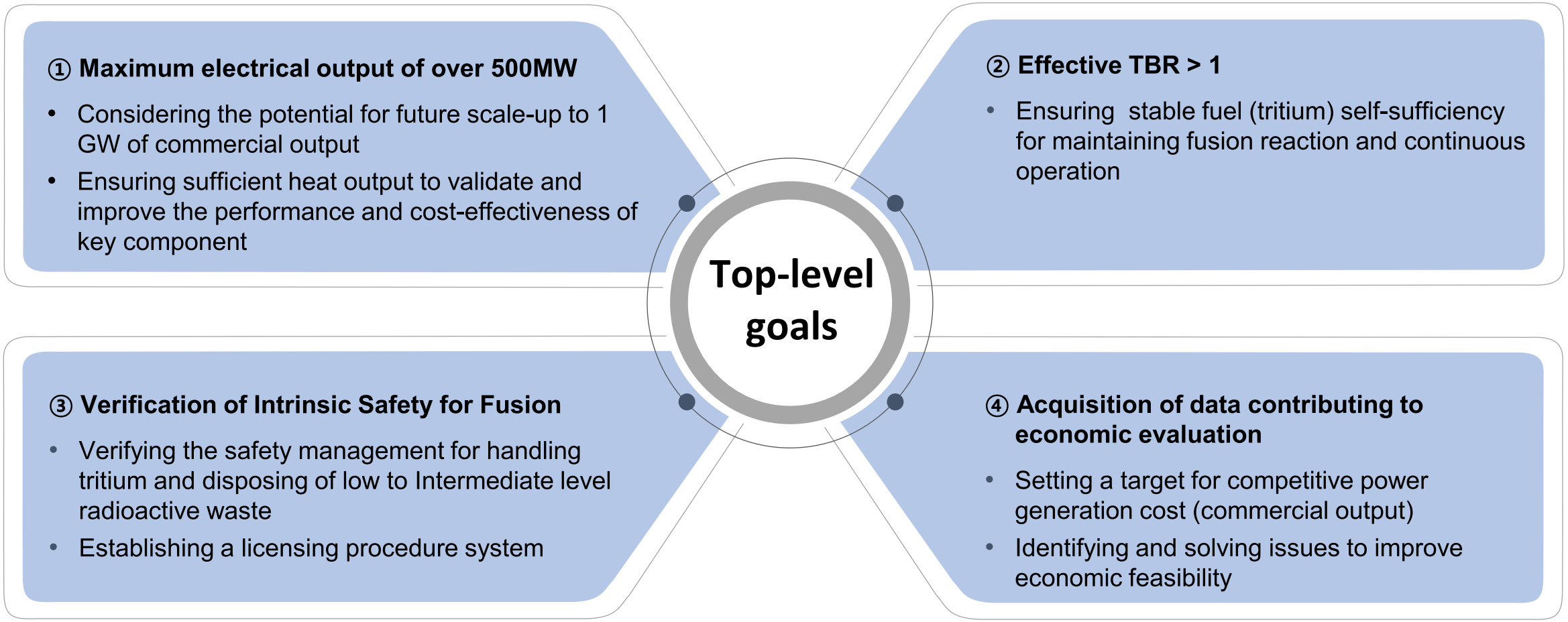
1

Introduction

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

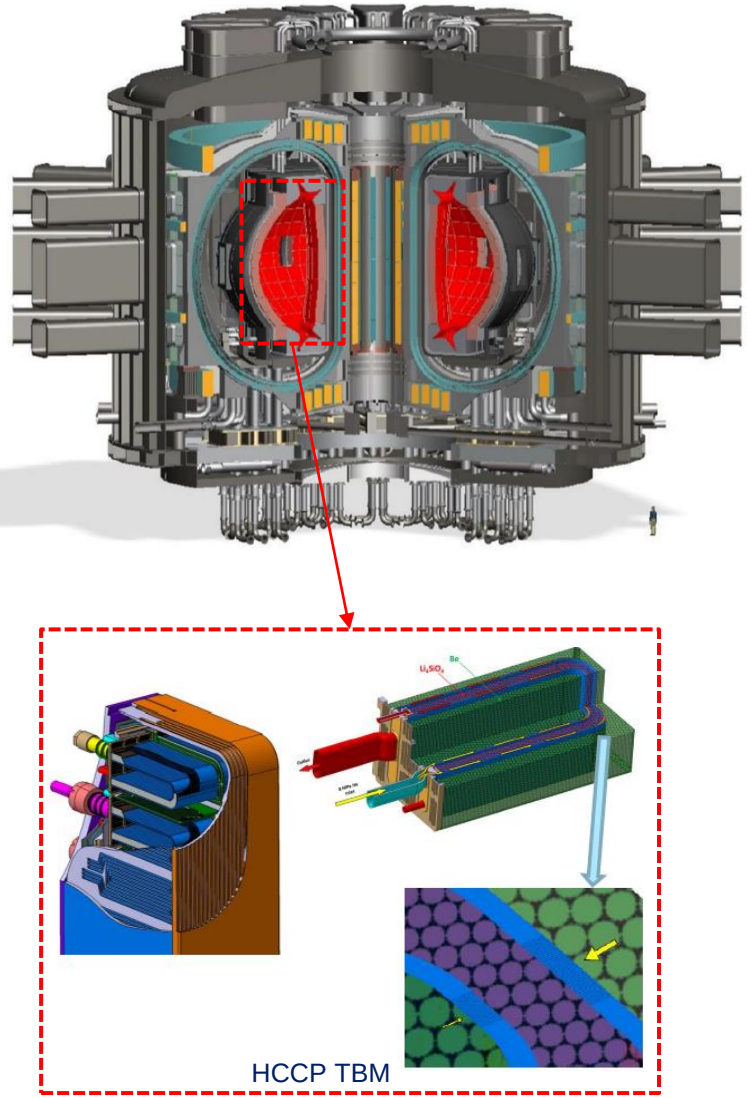
K-DEMO

- 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



Breeding Blanket for K-DEMO

- Reference breeding blanket design
  - Functions
    - Tritium breeding to ensure fuel self-sufficiency
    - Heat extraction at high temperature suitable for electricity generation
    - Radiation shielding
  - Features
    - HCCP concept (He coolant, Li ceramic, Be alloy, RAFM steel, W armor, etc.)
  - 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 and data
  - Fabrication/Demonstration of the performance and reliability
  - Tritium extraction(including tritium management) / Cooling
  - Materials and DBs

HCCP TBM Program in ITER

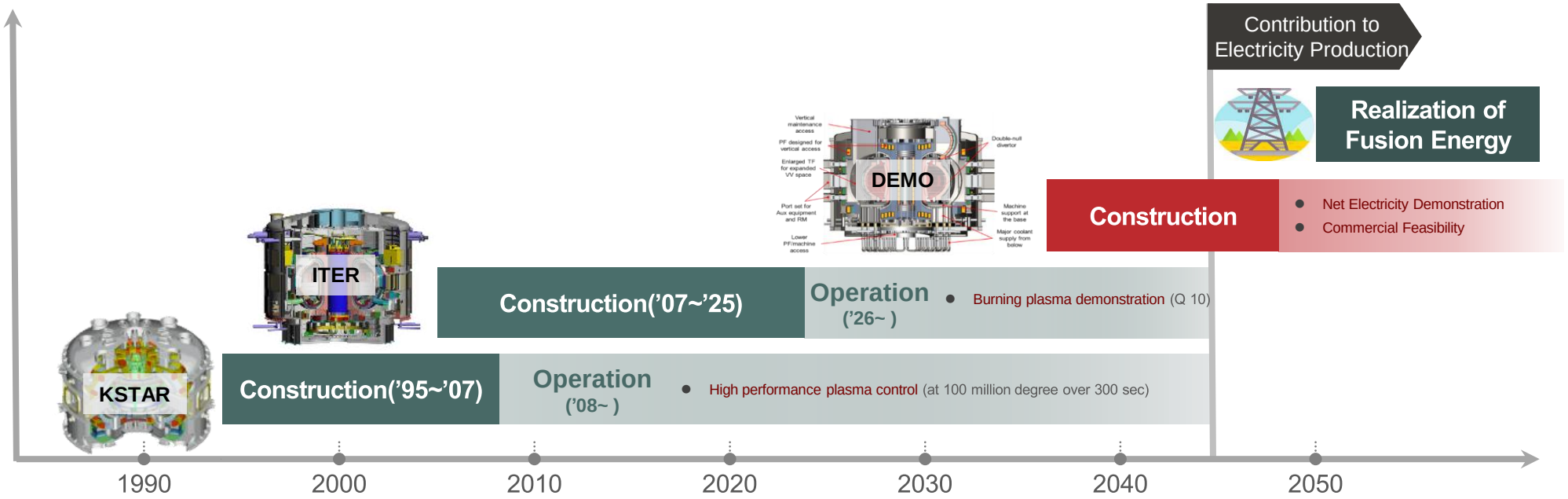
- Demonstration of breeding blanket concepts in fusion environment, however, in ITER fusion environment (pulse operation with relatively short irradiation time)

KFEAT for DEMO

- Validation of overall performance and acquisition of engineering data under DEMO-relevant irradiation time and scenario ((quasi)-steady)

Strategy for Breeding Blanket Development

- Technologies for breeding blankets need to be developed and validated prior to construction of K-DEMO
  - Design/Safety tools and data
  - Fabrication/Demonstration of the performance and reliability
  - Tritium extraction(including tritium management) / Cooling
  - Materials and DBs

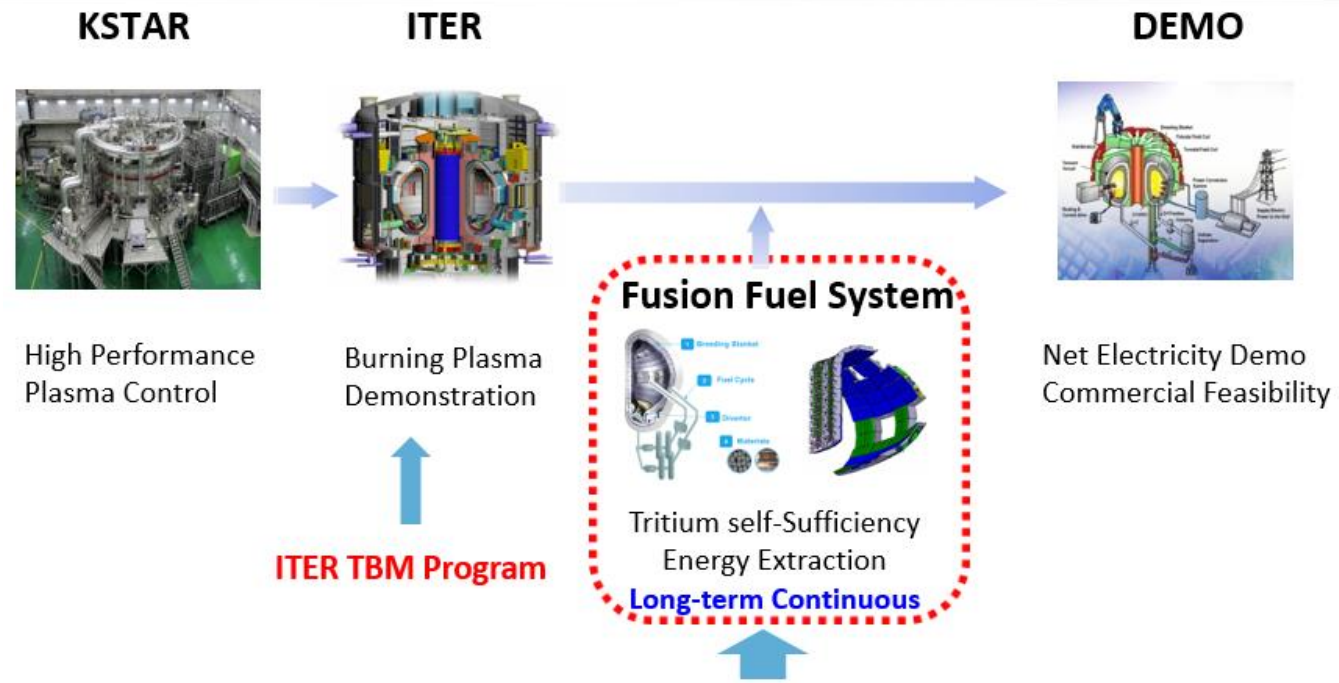


2

Objectives & Requirements of KFEAT with focus on the IBTF

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

To Bridge the Gap between ITER and DEMO



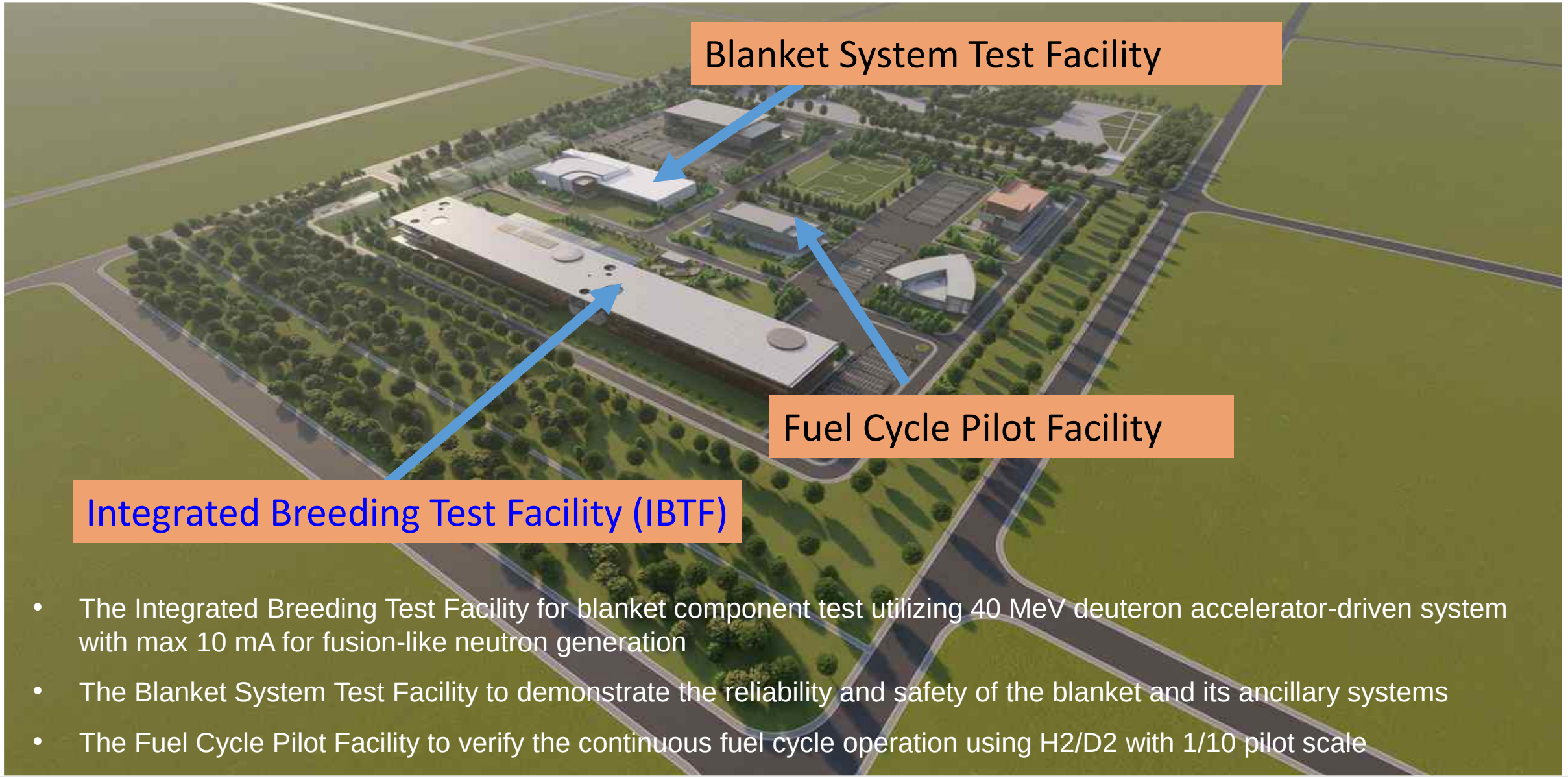
- Sustaining high performance burning plasma

KSTAR, ITER

- Verification of long-term fuel self-sufficiency
- Materials to survive in DEMO conditions

KFEAT

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

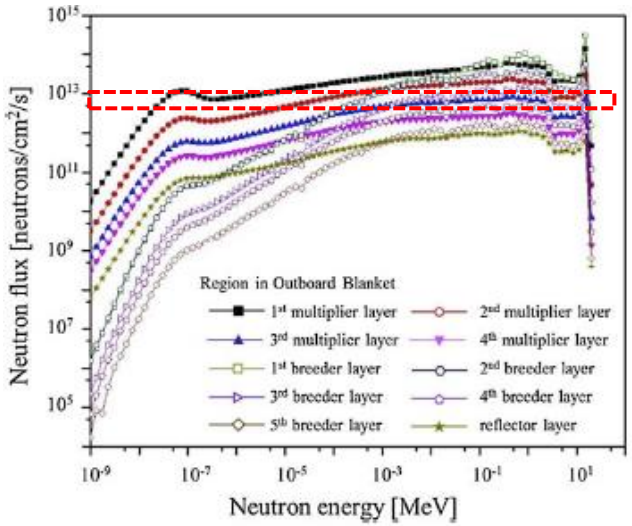
  - From the testing aspects,
    - Testing flexibility for DEMO blanket design candidates
    - Using breeding blanket 1:1 scale mockup (Breeding Unit) that reflects the actual design

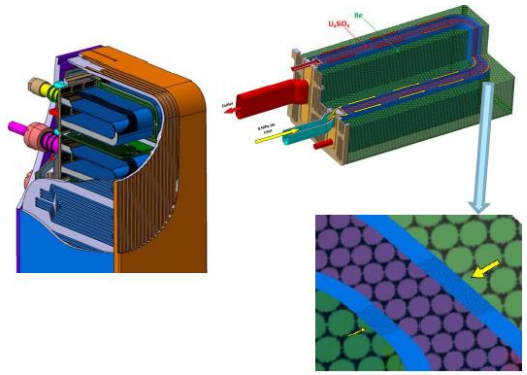
    ➡ Securing engineering data for design and qualification of fabrication technology under fusion-like environment

  - Experience of tritium management and handling technology

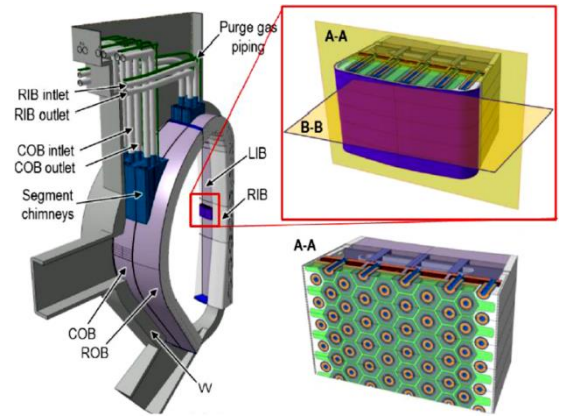
Requirements & Capabilities (with focus on IBTF)

- To provide fusion-like nuclear environments for the test of blanket mock-up (Breeding Unit)
  - Neutron flux ~5x10^{12} n/cm^2/s and neutron energy >10 MeV for more than 24 hours continuously
  - Irradiation area 20X20 cm^2 for Breeding Unit testing
  - Space/facility for installation/replacement of Breeding Units, and post-irradiation material testing
  - Neutron irradiation dose measurement for TBR evaluation of Breeding Unit, tritium on-line recovery and measurement system, and tritium handling facility
  - Complemented by comparison/validation tests with other facilities and computer modellings

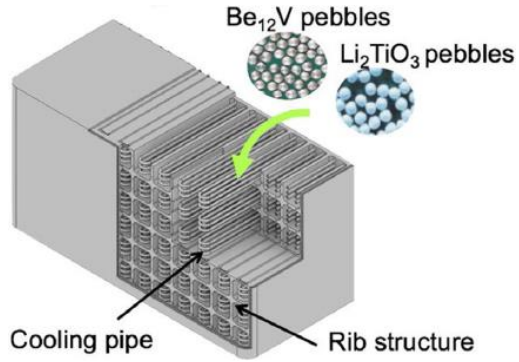




HCCP TBM



EU HCPB Blanket



JA WCCB Blanket

Requirements & Capabilities (with focus on IBTF)

- To provide fusion-like nuclear environments for the test of blanket mock-up (Breeding Unit)
  - Neutron flux ~5x10^{12} n/cm^2/s and neutron energy >10 MeV for more than 24 hours continuously
  - Irradiation area 20X20 cm^2 for Breeding Unit testing
  - Space/facility for installation/replacement of Breeding Units, and post-irradiation material testing
  - Neutron irradiation dose measurement for TBR evaluation of Breeding Unit, tritium on-line recovery and measurement system, and tritium handling facility
  - Complemented by comparison/validation tests with other facilities and computer modellings

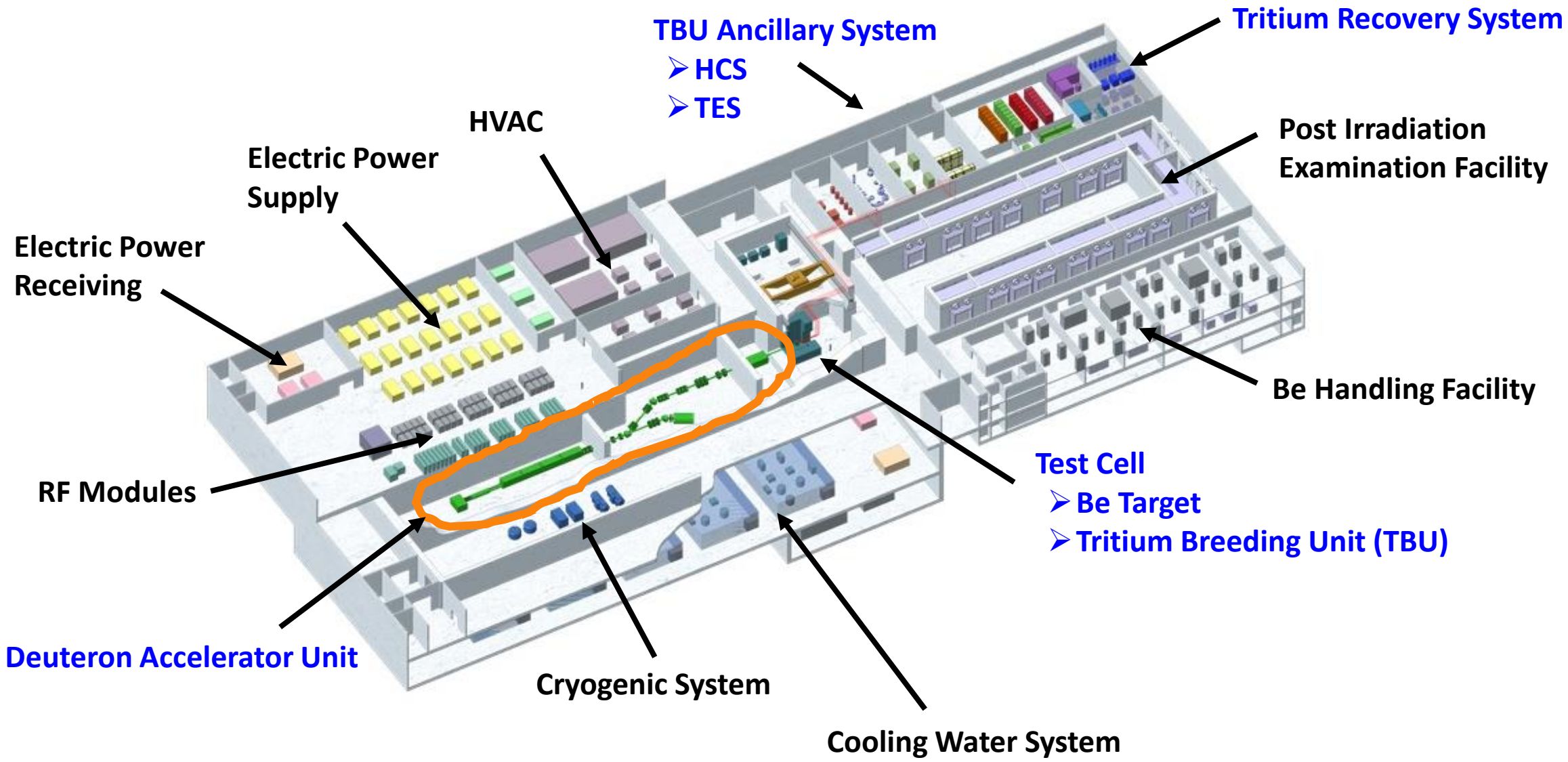
- To provide conditions for verification of design lifespan and integrity of breeding blanket materials
  - He production by high-energy neutrons: ~10 appm/dpa
  - Irradiation test ~0.6 dpa/fpy using 400 cm^2 specimens & ~1 dpa/fpy using 200 cm^2 specimens (D-solid Be; 1st phase)
  - Applicable to irradiation test ~5 dpa/fpy using 20 cm^2 specimens (D-liquid Li; 2nd phase)
  - Complemented by comparison/validation tests with other facilities and computer modellings

3

Pre-conceptual Design & Analysis for KFEAT with focus on the IBTF

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

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

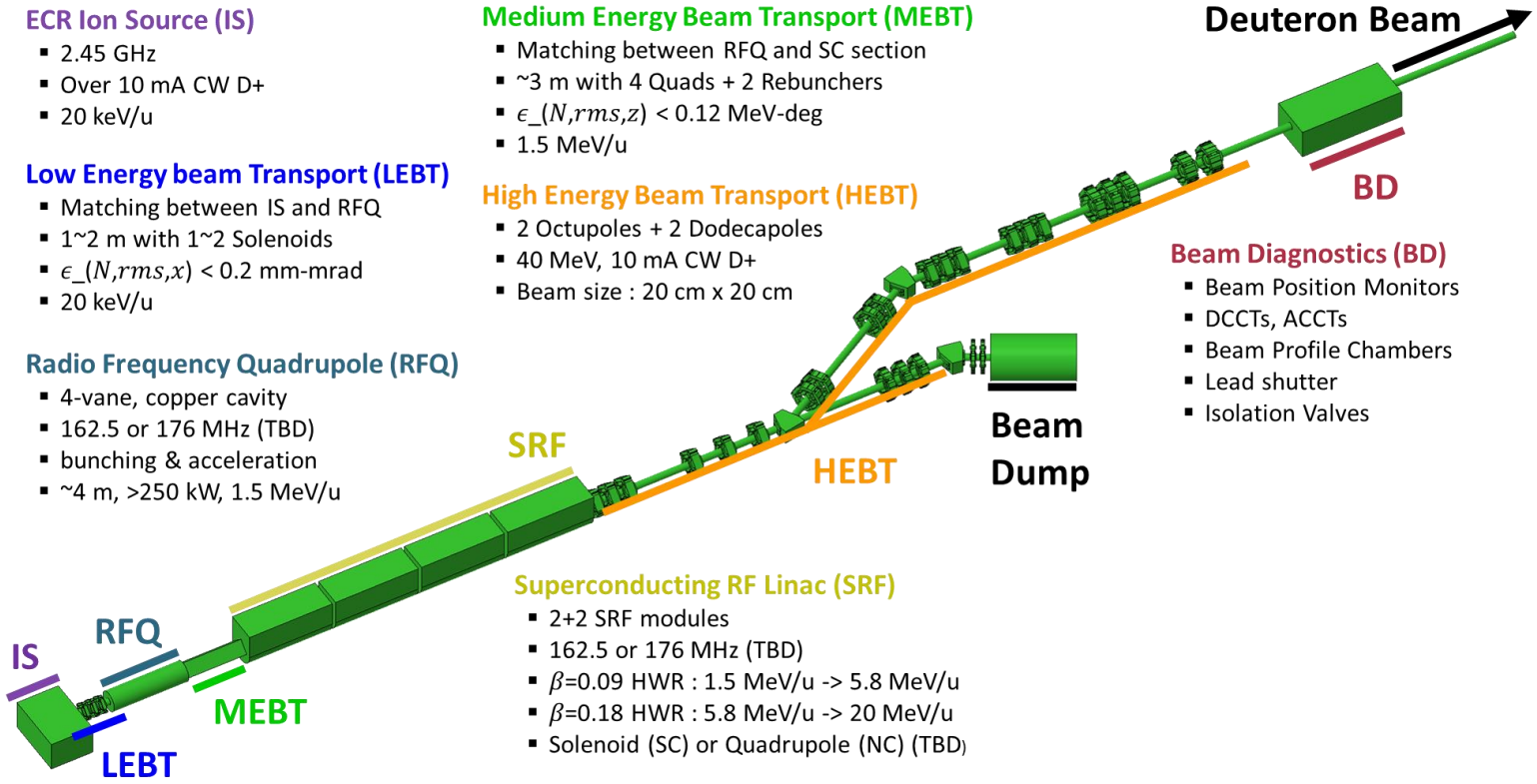
Radio Frequency Quadrupole (RFQ)
- 4-vane, copper cavity
- 162.5 or 176 MHz (TBD)
- bunching & acceleration
- ~4 m, >250 kW, 1.5 MeV/u

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

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)

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



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	~2×10^{15} n/s (forward)
Neutron flux	~5×10^{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

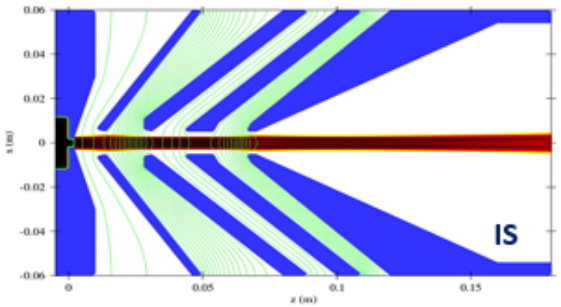
- Deuteron Accelerator Unit
  - Beam transport analysis results for DAU

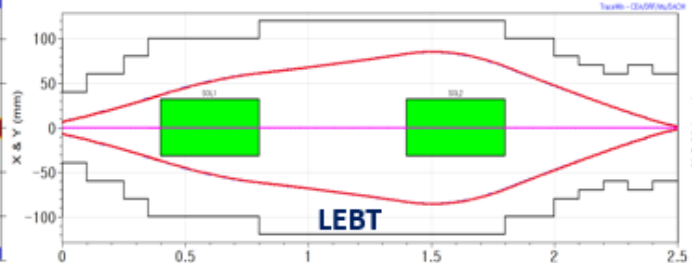
Tot : ~56 m

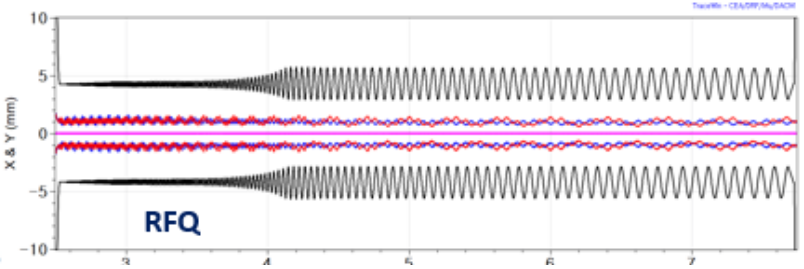
Ion source	LEBT	RFQ	MEBT	SC Linac		HEBT	Target Cell
ECR IS (NC) 2.45 GHz	Matching between IS and RFQ	4-vane 176 MHz –bunching & acceleration	Matching between RFQ and SCL ❖ Space charge	HWR (SC) 176 MHz (2 cryomodules) β_{opt} = 0.091	HWR (SC) 176 MHz (2 cryomodules) β_{opt} = 0.181	2 Octupoles (For making 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	2 Solenoids	172.3 kW	7 Quads + 2 Rebunchers	1.5 MeV/u -> 6 MeV/u	6 MeV/u -> 20 MeV/u		Beam Dump
20 keV/u	20 keV/u	1.5 MeV/u	1.5 MeV/u	Solenoid (SC) L_{eff} = 250 mm			

10 *mA*

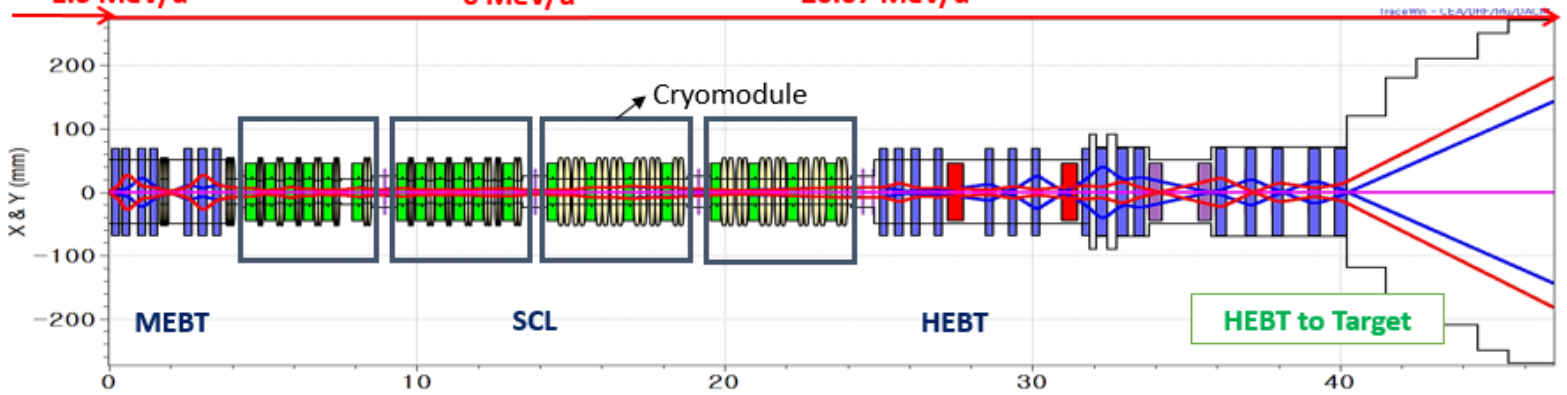
D^+ CW 20 keV/u 20 keV/u 1.5 MeV/u



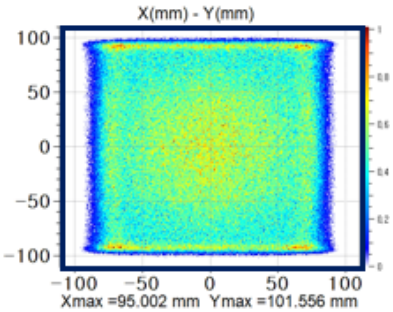




1.5 MeV/u 6 MeV/u 20.07 MeV/u



Be target
22 x 22 cm2



Uniform beam distribution
-> Uniform neutron yield

Refer “Overview of fusion-like neutron sources based on high-intensity linear accelerators” by Y. L. Cheon et al., JKPS (2023)

Integrated Breeding Test Facility (IBTF) - Target

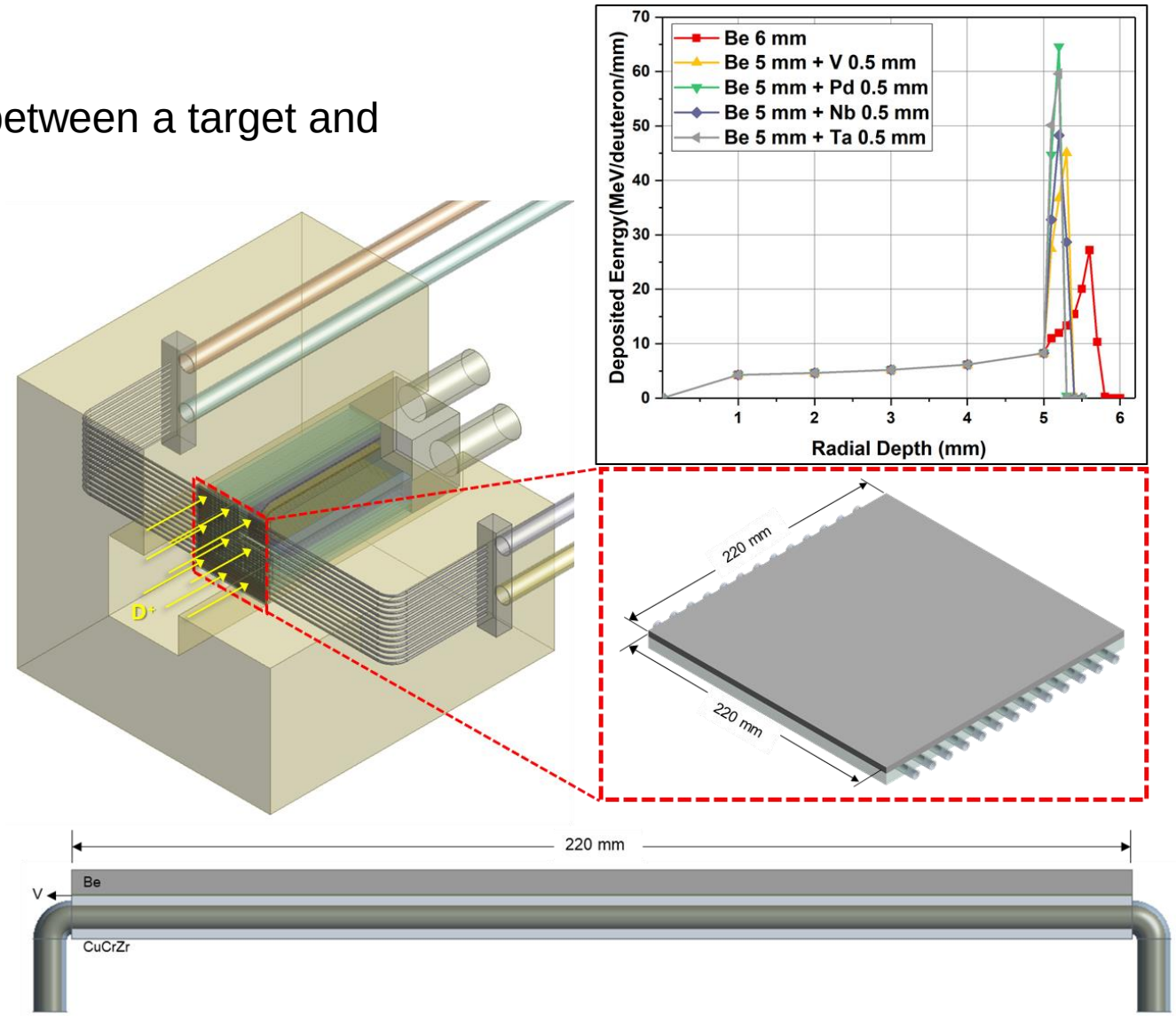
- Neutron Source Target
  - Generating neutrons by a nuclear reaction between a target and charged particles from the DAU

➢ **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

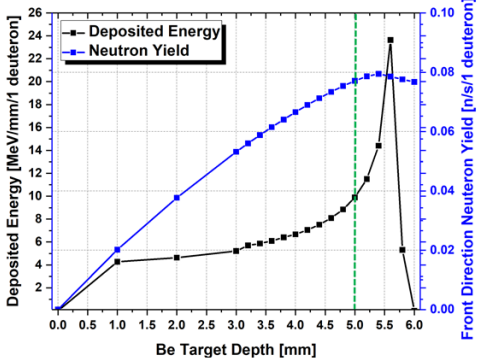
➢ **Coolant**
- Water
- 1 MPa, 25 °C, 15 m/s @ inlet

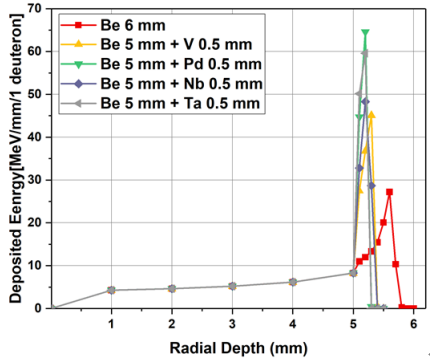


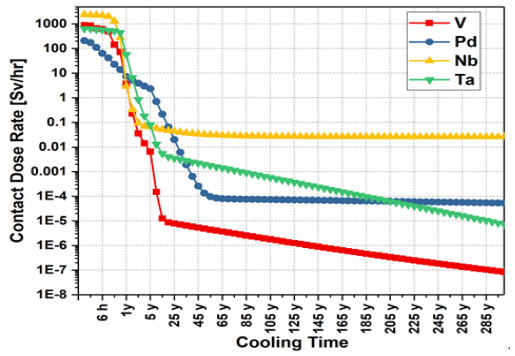
Integrated Breeding Test Facility (IBTF) - Target

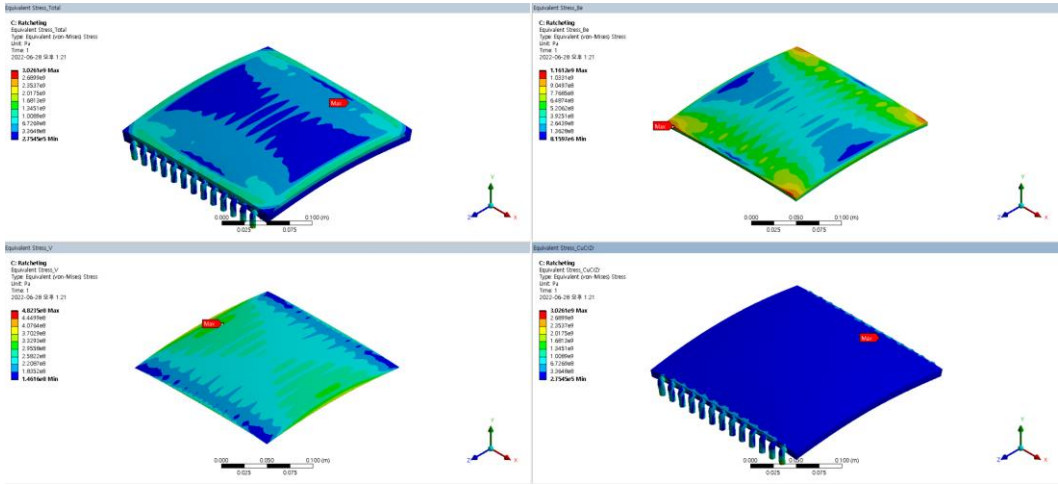
- Neutron Source Target
  - Nuclear and thermal/structural analyses results for the target

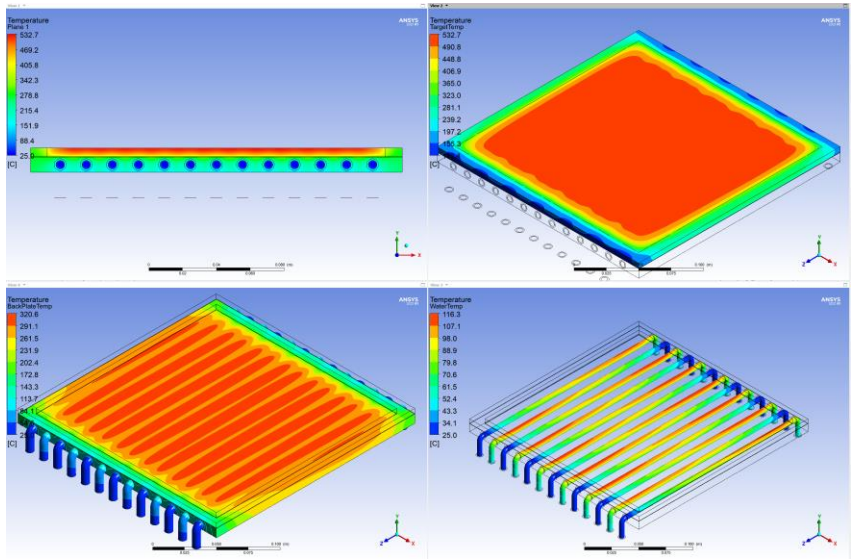
Refer “Preliminary design and analysis activities of the deuteron accelerator target for tritium breeding unit test”, to be presented by Sungjin Kwon in ISFNT-2023

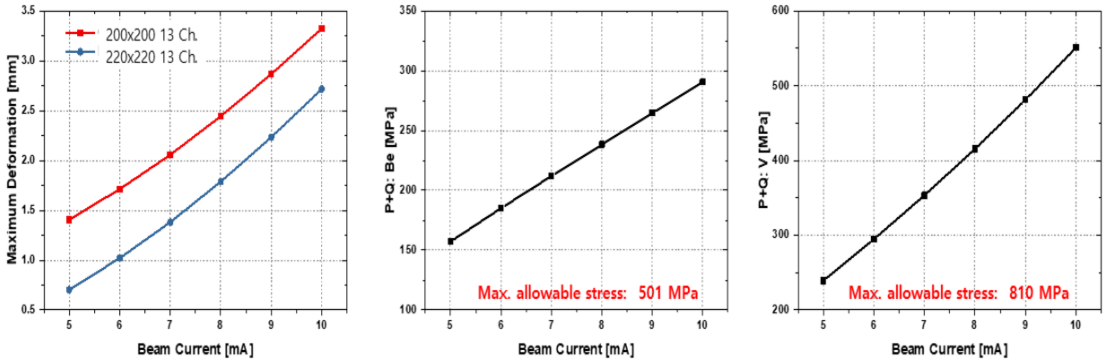






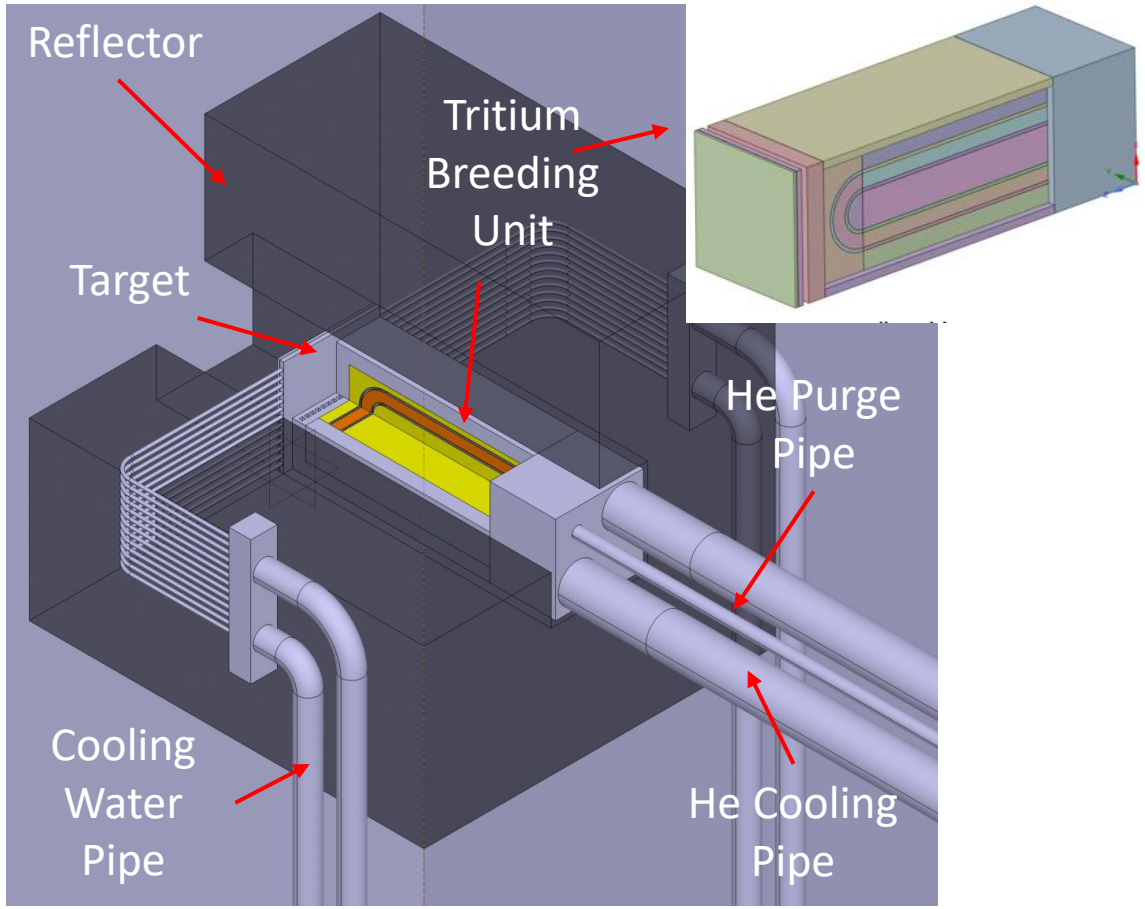






Integrated Breeding Test Facility (IBTF) - TBU

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

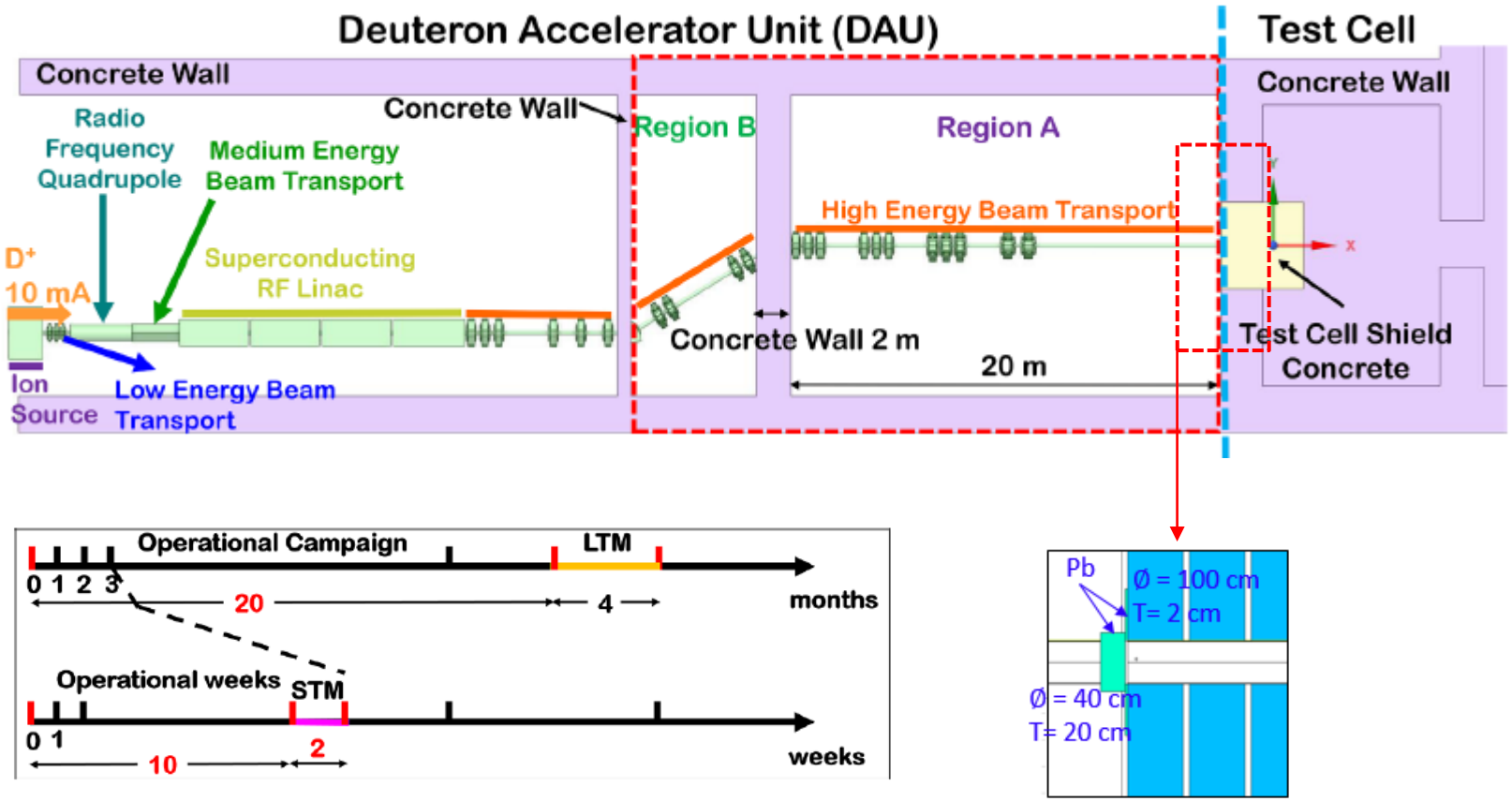


Parameter	Tritium Breeding Unit
Structural Material	ARAA
Neutron Multiplier	Be (or Beryllides)
Tritium Breeding Material	Li_2TiO_3
Coolant	Helium
Coolant Pressure	8 MPa
Coolant Temperature	Avg. 450°C
Neutron Irradiation area	0.2 x 0.2 m^2
Radial length	0.6 m
Tritium Production Rate	0.16 mg/day*

* To be updated

Integrated Breeding Test Facility (IBTF) - Shielding

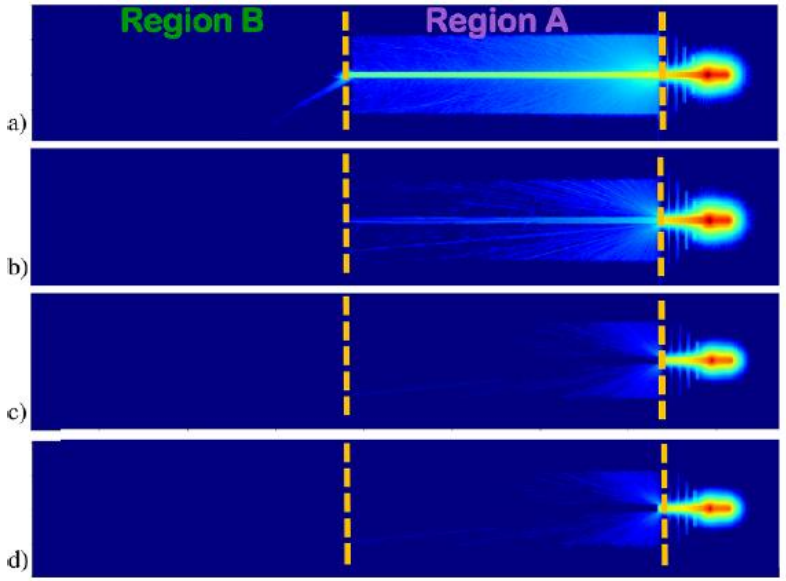
- To provide nuclear shielding in order to keep radiation level under the given zoning requirements
  - Compliant to maintenance plans, hands-on maintenance (or human-assisted) for the DAU during STM or LTM, and full RH maintenance for the Test Cell

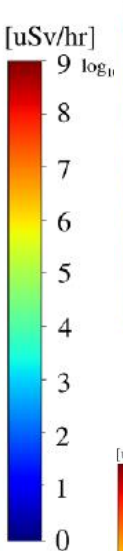


Integrated Breeding Test Facility (IBTF) - Shielding

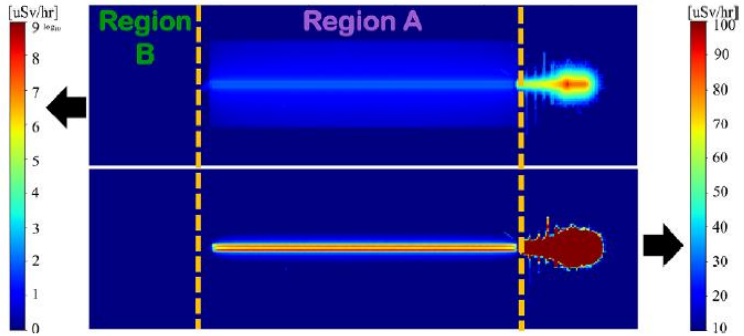
- To provide nuclear shielding in order to keep radiation level under the given zoning requirements
  - Shielding analysis for the HEBT and the Test Cell

Refer “Dose rate analysis for a pre-conceptual design of the high energy beam transport section in the IBTF” by S.H. Hong et al., FED 189 (2023)

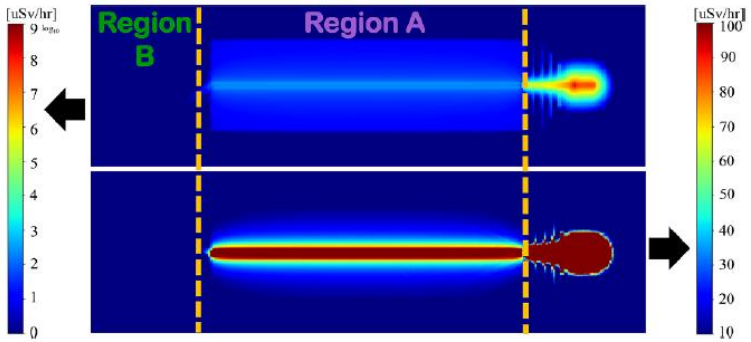




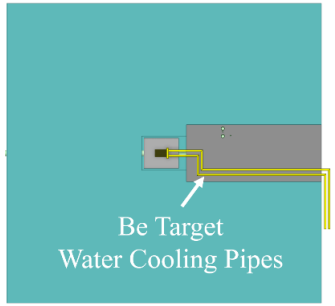
Dose rate based on the Pb shutter thickness
(a) 0 cm (b) 10 cm (c) 20 cm (d) 30 cm

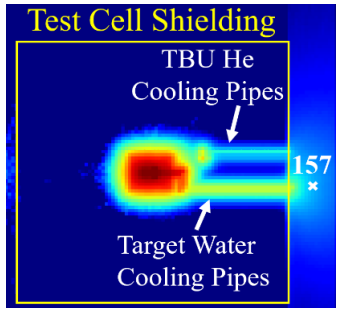


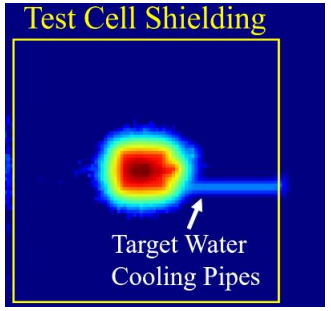
Dose rate during the STM at a cooling time 1 week

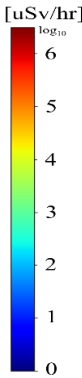


Dose rate during the LTM at a cooling time 1 week



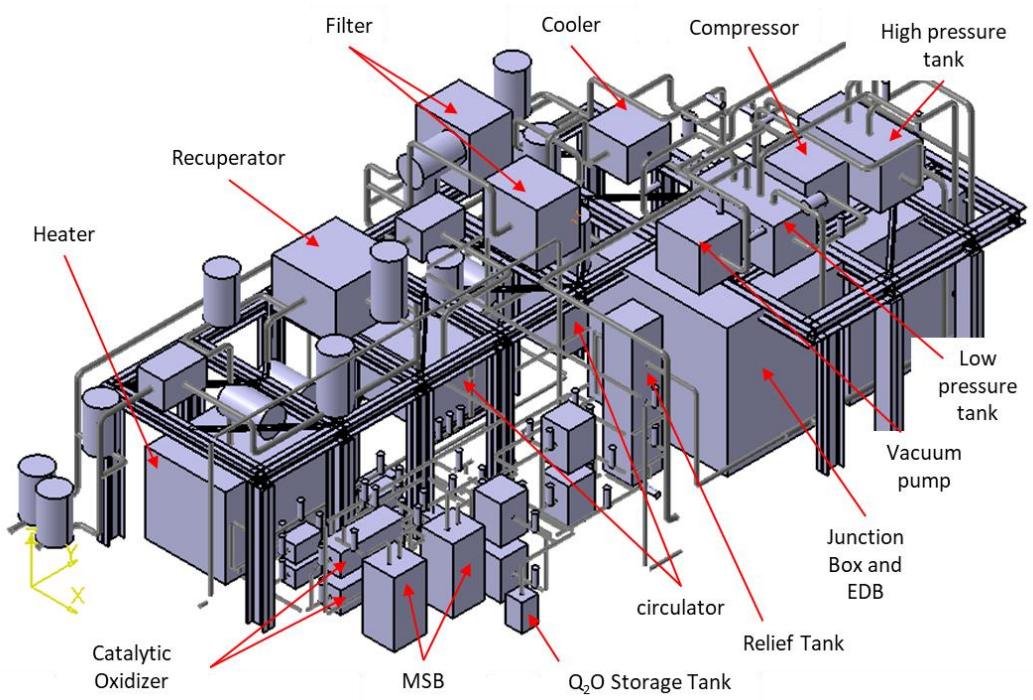




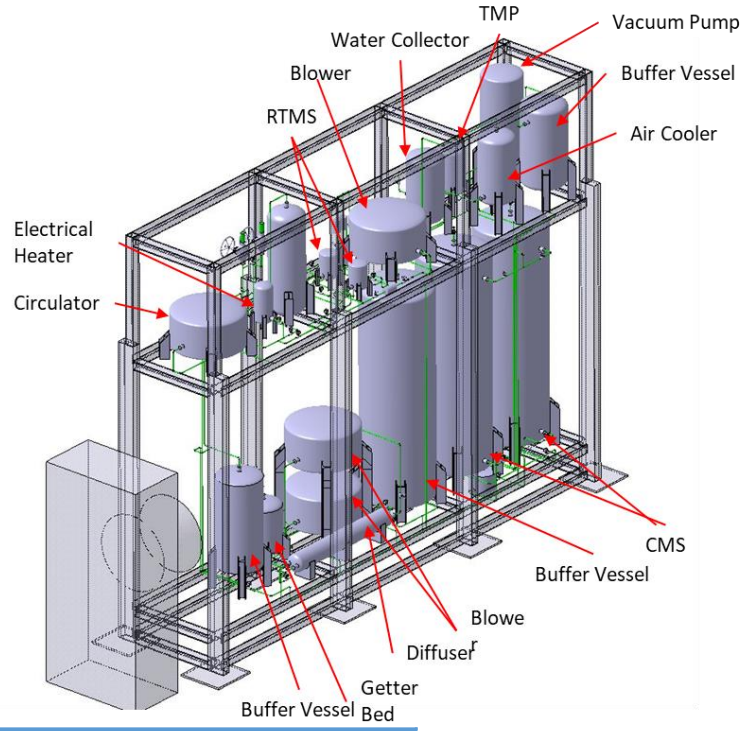


Integrated Breeding Test Facility (IBTF) – TBU Ancillary System

- TBU Ancillary System
  - Helium Cooling System (HCS)



  - Tritium Extraction System (TES)



Parameter	HCS	TES
Nominal Pressure (NP)	~ 8 MPa	0.1~0.4 MPa
Nominal Inlet Temperature (NT_{in})	Around 300 ^oC	25 ^oC
Nominal Flow Rate (NF)	~ 1.5 kg/s	~ 0.1 g/s

Integrated Breeding Test Facility (IBTF) - Tritium Recovery System

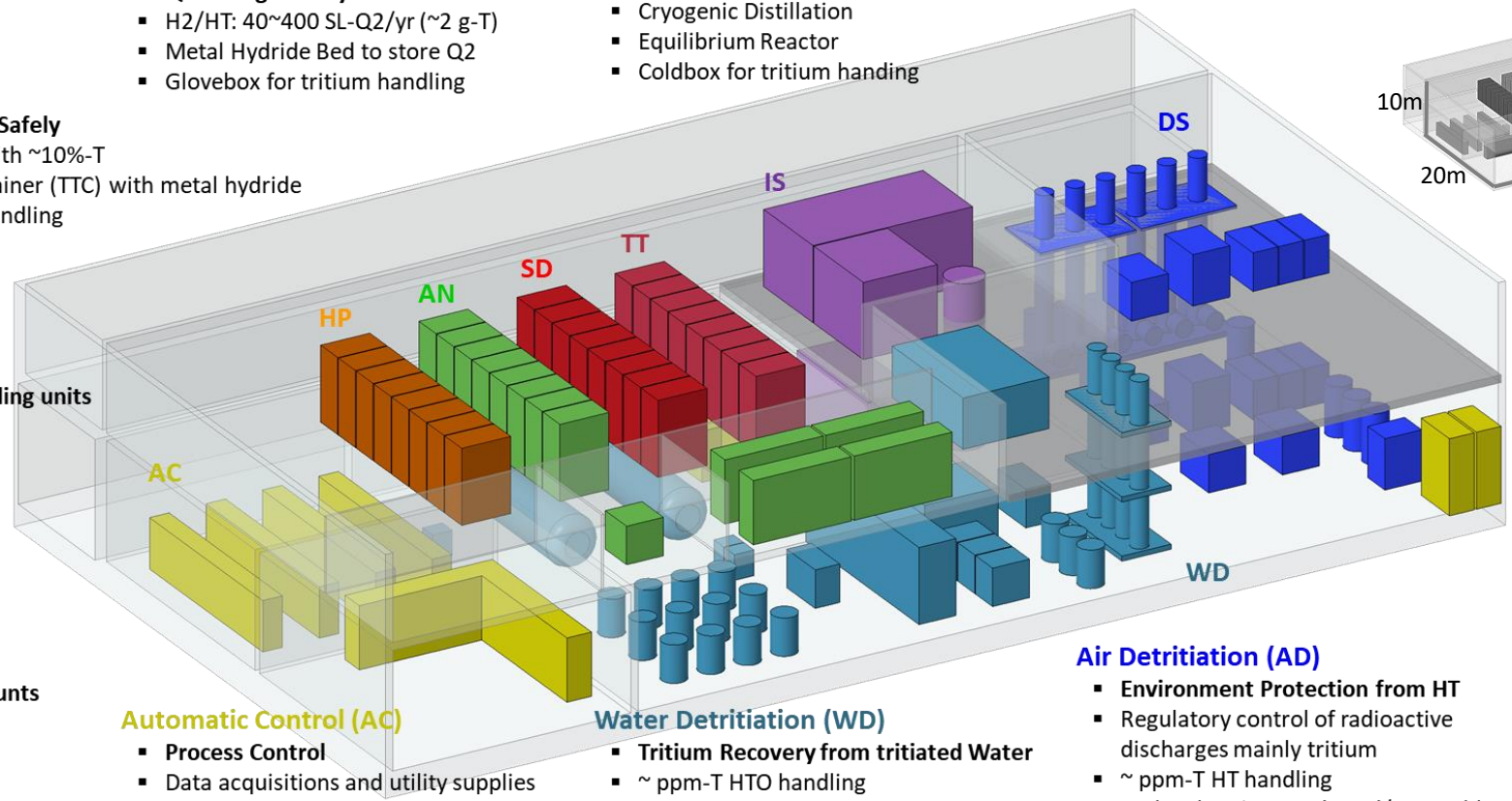
Tritium Recovery System

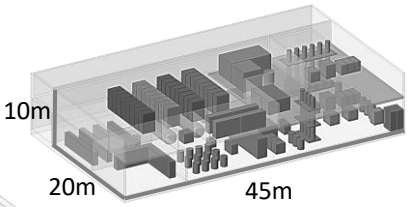
- 60 mg-T/yr produced in the tritium breeding unit shall be recovered: purified, separated, and stored.

Storage/Delivery (SD)
- **Q2 Storage Safely**
- H2/HT: 40~400 SL-Q2/yr (~2 g-T)
- Metal Hydride Bed to store Q2
- Glovebox for tritium handling

Isotope Separation (IS)
- **Hydrogen Isotope Separation (H2/HT/T2)**
- Products: 10%-T/10ppm-T
- Cryogenic Distillation
- Equilibrium Reactor
- Coldbox for tritium handing

Tritium Transport (TT)
- **Q2 Long-term Storage Safely**
- H2/HT: 1 g-T storage with ~10%-T
- Tritium Transport Container (TTC) with metal hydride
- Glovebox for tritium handling





Hydrogen Purification (HP)
- **Q2 Separation from the breeding units**
- H2/HT/HTO
  60 mg-T/yr (7000 hrs/yr)
  40~400 SL/yr
- Permeators to separate Q2
- Reactor to crack HTO
- Glovebox for tritium handling

Tritium Analytics (AN)
- **Measurement of tritium amounts**
- Process gas sampling
- TTC Calorimeter
- Enclosure air monitoring
- Low-T sampling in environment
- Glovebox for tritium handling

Automatic Control (AC)
- **Process Control**
- Data acquisitions and utility supplies
- Monitoring and cubicles

Water Detritiation (WD)
- **Tritium Recovery from tritiated Water**
- ~ ppm-T HTO handling
- Electrolyzer and Permeator
- Liquid Phase Catalytic Exchange (LPCE)

Air Detritiation (AD)
- **Environment Protection from HT**
- Regulatory control of radioactive discharges mainly tritium
- ~ ppm-T HT handling
- Molecular Sieve Beds and/or Scrubbers

4

Summary

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Summary: A Way to DEMO Blanket with KFEAT

- A plan for Korea Fusion Engineering Advanced Test Complex (KFEAT) is introduced as a way to DEMO blanket from ITER TBM bridging the gap technologies
  - A dedicated long-term neutron irradiation facility for breeding blanket test under fusion-like environment
  - Validation of overall performance under DEMO-relevant irradiation time and scenario ((quasi-)steady
  - Securing engineering data for design and qualification of fabrication technology under fusion-like environment

- Pre-conceptual design activities have been performed
  - DAU for 40 MeV deuteron acceleration with max 10 mA
  - Be target with V blistering mitigation layer
  - Tritium Breeding Unit, 1:1 scale blanket mockup (Breeding Unit)
  - Shielding
  - TBU ancillary systems
  - Tritium recovery system

- Need collaboration with other countries/organizations for the successful DEMO Blanket development

Gracias por su atención

Thank you for your attention

Q&A