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Introduction to plasma and ion beam irradiation and NDT technologies for innovative fusion divertor development – a sub-project of the Global TOP Research Lab.

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Abstract

The commercialization of fusion energy requires robust solutions to withstand the extreme plasma, neutron, and heat exposure at the plasma facing components (PFCs), particularly the divertor. The divertor must simultaneously handle unprecedented heat fluxes, neutron irradiation, and transient plasma events while maintaining structural integrity and enabling efficient tritium breeding cycles. This paper provides an overview of the Global TOP Research Lab. for Innovative Fusion Divertor Development in Korea, highlighting its motivation, organizational structure, and expected impact. The program aims to achieve at least 50% enhancement in cooling performance compared with ITER divertors, develop advanced plasma-facing materials, and establish world-leading testing and non-destructive evaluation technologies. With five interlinked sub-projects, this program represents a comprehensive national effort to accelerate K-DEMO and Compact Pilot Device (CPD) readiness and contribute to global fusion commercialization.

1. Introduction

Fusion energy has emerged as a next-generation clean energy source that produces no greenhouse gas emissions and negligible long-lived radioactive waste. Unlike intermittent renewables, fusion reactors can provide continuous baseload electricity. The growing interest in fusion has recently attracted major investments from global technology companies such as Microsoft, Google, Amazon, and OpenAI, which recognize the potential of fusion as a scalable, carbon-free energy solution.

According to the Fusion Industry Association (FIA), cumulative investment in private fusion startups increased from 1.5 billion USD in 2020 to 6.2 billion USD in 2023, a four-fold growth in just three years. The number of startups has also risen from 27 in 2021 to 43 in 2023. While public fusion projects such as ITER and DEMO remain critical milestones, private initiatives are accelerating the timeline, with targets to achieve electricity generation by the 2030s–2040s rather than the 2050s.

Recently, intermediate device concepts such as CPD are under discussion to bridge the gap between ITER and DEMO, with public-private collaborations being actively pursued in Korea.

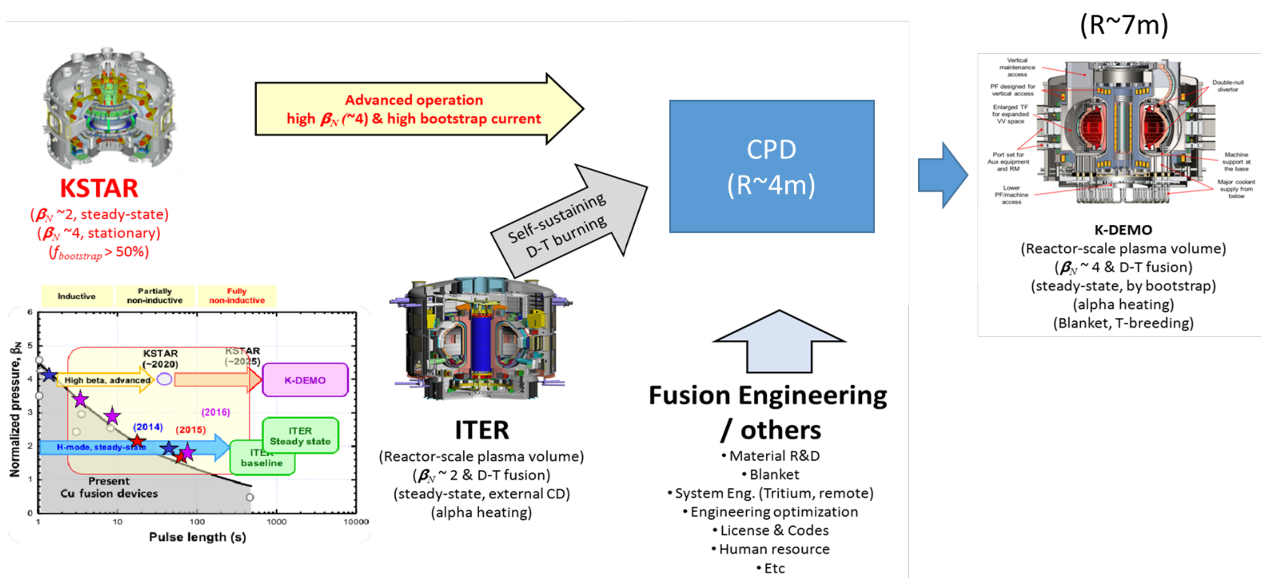

Fig. 1. Korea Fusion Energy roadmap including new CPD concept

Against this backdrop, Korea has launched the Global TOP Research Lab. for Innovative Fusion Divertor Development, recognizing the divertor as one of the most technologically demanding components in any fusion power plant.

2. Research Goals and Structure

2.1 ITER and International Programs

The ITER divertor is designed to extract up to 200 MW of heat and withstand steady-state heat fluxes of 20 MW/m². It consists of 54 cassette assemblies arranged in a toroidal array, each containing thousands of plasma-facing units (PFUs). Tungsten monoblocks HIPped onto CuCrZr cooling tubes form the main thermal armor, with a total of nearly 300,000 monoblocks required for ITER.

The divertor must also manage the following multiple extreme loads;

(1) Heat loads: both steady-state and transient (ELMs, disruptions), reaching tens of MJ/m².
(2) Neutron irradiation: producing displacements-per-atom (dpa) damage, embrittlement, and swelling.
(3) Electromagnetic forces: stresses exceeding hundreds of MPa during plasma instabilities.
(4) Erosion and sputtering: influencing divertor lifetime and impurity control.

2.2 New Project Goals

The program envisions the development of “the world’s most advanced divertor with at least 50% improved cooling performance and its lifetime compared with ITER,” and consists of five sub-projects:

(Sub-Project 1) Divertor Design and Integrated System Development (Korea Institute of Fusion Energy)
- ✓ Extraction of specifications and requirements for an innovative divertor system.
- ✓ Boundary plasma simulations for target and dome optimization.
- ✓ Digital twin modeling with machine learning for predictive performance evaluation.

(Sub-Project 2) Innovative Materials and Manufacturing Technologies (Korea Institute of Materials Science)
- ✓ Development of K-doped tungsten alloys and low-activation steels.
- ✓ Advanced manufacturing techniques including powder metallurgy, hot isostatic pressing (HIP), and additive manufacturing.
- ✓ Novel joining processes compatible with multi-material interfaces.

(Sub-Project 3) High-Efficiency Cooling Technology (POSTECH)
- ✓ Novel cooling channel geometries for enhanced heat removal.
- ✓ Multi-loop cooling system designs to improve redundancy and safety margins.
- ✓ Database of cooling performance under extreme conditions for future divertor designs.

(Sub-Project 4) Particle Effect Assessment and Non-Destructive Evaluation (KAERI)
- ✓ Accelerator-based ion irradiation facilities capable of achieving fluence up to 10^{28} m^{-2}.
- ✓ High-flux particle exposure facilities for erosion and retention studies.
- ✓ Neutron imaging techniques with sub-millimeter resolution applied to divertor components.
- ✓ Development of fusion component testing standards using KEPIC and collaboration with ASME.

(Sub-Project 5) Plasma-Facing Component Testing and Performance Evaluation (KFE)
- ✓ Construction of ultra-high heat flux facilities (>50 MW/m²) for prototype testing.
- ✓ Large-area simultaneous heating (1 m × 1 m) for near full-scale components.
- ✓ Feedback loop to divertor designers and fabricators based on experimental validation.

3. Expected Impact and Applications

The successful execution of the program is expected to deliver:
- ✓ Technical: A comprehensive domestic infrastructure for divertor R&D, spanning from materials to system-level testing.
- ✓ Industrial: Emergence of domestic suppliers capable of participating in global fusion component markets.
- ✓ Standardization: Contribution to international fusion codes and standards, enabling Korea’s presence in global rule-setting.

Socio-economic: Creation of a new fusion industry sector, with economic impact potentially amounting to trillions of KRW over the coming decades.

4. Conclusions

The divertor is widely recognized as one of the most critical bottlenecks for fusion reactor commercialization. Korea’s Global Top Research Lab. represents a holistic and forward-looking approach, combining fundamental plasma research with applied engineering innovation. Its success will position Korea as a global leader in divertor technology, accelerate the realization of K-DEMO and CPD, and contribute to the worldwide race toward practical fusion energy.

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