

# DEVELOPMENT STATUS OF IN-VESSEL COMPONENTS INSPECTION AND PIPE MAINTENANCE ROBOT FOR K-DEMO AND FUSION EXPERIMENTAL DEVICE

Dohee Lee  
KOREA INSTITUTE OF FUSION ENERGY (KFE)  
Daejeon, South Korea  
Email: dhlee@kfe.re.kr

Seung-Ju Lee, Hong-Tack Kim, KwonHee Hong, Hyun-Ki Park, Nam Il Her, Woong Chae Kim  
KOREA INSTITUTE OF FUSION ENERGY (KFE)  
Daejeon, South Korea

## Abstract

The operating environment of a fusion reactor such as K-DEMO involves harsh conditions including high neutron flux, vacuum, high temperature, and narrow accessibility. These conditions necessitate remote maintenance (RM) technologies capable of ensuring long-term operational reliability and safety. The paper reports the development status of two robotic systems designed for RM in fusion devices and reactor: (i) a Multi-Purpose Deployer (MPD) for in-vessel inspections and (ii) a laser-based robotic welding system for internal pipe maintenance. The MPD features 13 degrees of freedom (DOF), an 11 m reach, and minimized cross-sectional size to fit within equatorial ports, equipped with vision and gripping modules for inspection and light manipulation. The welding robot introduces a compact laser welding head optimized for curved pipes of 80 mm diameter and 5 mm thickness. Both systems are currently under design and fabrication. The paper discusses design concepts, technical challenges, and development progress, with particular focus on precision, adaptability, and operational feasibility under reactor-representative conditions. Future work involves full-scale validation under simulated environments to assess performance reliability, durability, and maintenance efficiency. The advancements presented by the MPD inspection system and the laser-based welding robot are expected to contribute significantly to the establishment of reliable RM procedures for K-DEMO, thereby enhancing the feasibility of fusion energy as a sustainable power source.

## 1. INTRODUCTION

Fusion energy has long been regarded as a promising pathway to sustainable, carbon-neutral, and virtually limitless power. To move from present experimental facilities to demonstration-scale power plants, reliable solutions for reactor maintenance must be established. The Korean Experimental Fusion Reactor (K-DEMO) is envisioned to play a central role in this transition: beyond demonstrating steady-state plasma operation and tritium self-sufficiency, it aims to provide a reliable basis for future commercial reactors.

Operating a fusion reactor requires repeated inspection, replacement, and repair of in-vessel components such as first-wall panels, blanket modules, divertor modules, and cooling pipe systems. These tasks must be performed under high radiation, vacuum, strong magnetic fields, and severe geometric constraints imposed by narrow access ports. Such conditions preclude direct human intervention and make remote maintenance (RM) indispensable. Consequently, RM systems must combine compact form factors with precise manipulation, high reliability, and robust sensing and control.

International efforts have produced a range of remote handling solutions—e.g., deployable inspection arms and cask-based manipulators—demonstrating the feasibility of in-vessel access in large fusion devices. At the same time, practical reactor operation requires capabilities that go beyond inspection alone: effective maintenance must also include targeted repair of internal piping and joints, where precision and repeatability are critical.

This paper reports the development status of two complementary robotic systems under development at KFE: (i) a long-reach Multi-Purpose Deployer (MPD) for in-vessel inspection, and (ii) a laser-based robotic welding system for internal pipe maintenance. The KSTAR tokamak is employed as an experimental platform and geometric reference for deployment studies, while the ultimate target application is K-DEMO RM.

The remainder of the paper is organized as follows. Section 2 summarizes RM requirements and the overall approach. Section 3 presents the MPD design and current progress. Section 4 describes the laser-based welding robot for internal pipes. Section 5 discusses integration and verification strategies. Section 6 concludes with planned future work.

## 2. RELATED WORK AND TECHNICAL CHALLENGES

Remote maintenance (RM) for fusion devices has advanced through a variety of deployable manipulators and inspection systems demonstrated in major programs and experimental platforms. Inspection-focused articulated arms have been used to perform visual tasks under vacuum (e.g., EAST's AIA), and DEMO-class studies have incorporated RM considerations from early design phases (e.g., CFETR) [1,2]. These efforts establish feasibility and provide useful references for geometry, deployment, and operability without attempting to replicate power-plant-scale availability.

In this program, the Multi-Purpose Deployer (MPD) is conceived for K-DEMO maintenance needs; however, the performance and environmental requirements for K-DEMO are sufficiently demanding, and the MPD has not yet been built or operated in a DEMO reactor environment. We therefore employ a staged pathway centered on KSTAR as an intermediate step. The current MPD configuration is designed and validated against KSTAR's equatorial-port envelope and vessel geometry to de-risk insertion, reach, and controllability. Technologies, calibration methods, and operational know-how obtained on KSTAR will be used to re-design and upscale an MPD variant that is specifically tailored to K-DEMO in a subsequent phase. The same stepwise logic applies to the pipe-maintenance solution: a compact laser-based welding head is developed and exercised off-vessel and on representative mock-ups before its specification is updated for K-DEMO routing constraints.

Several technical drivers shape the requirements. First, constrained access through equatorial ports forces a minimized cross-section while preserving stiffness and an approximately meter-scale reach for comprehensive coverage of plasma-facing regions. Second, precision is critical: inspection motions will be validated initially at sub-centimeter positioning accuracy, whereas repair tasks such as internal pipe welding set a long-term goal of sub-millimeter accuracy at the tool center point. Third, environmental robustness is necessary for operation in vacuum and elevated temperatures with radiation-tolerant routing of electronics and optics, alongside resistance to mechanical loads and vibration. Finally, reliability and recoverability are essential because maintenance campaigns can be extended in duration; systems must maintain availability and provide non-intrusive recovery strategies.

The design responses presented here address these drivers with two complementary systems. The MPD is an articulated in-vessel inspector providing 13 degrees of freedom and an approximately 11 m reach, with link sizing and joint placement optimized for equatorial-port insertion and a minimized swept envelope; interchangeable end modules include a high-resolution camera and a light-duty gripper for simple handling. The pipe-maintenance solution is a fiber-laser welding head aimed at 80 mm-diameter, 5 mm-wall-thickness curved pipes; the current capability addresses a ~1300 mm bending radius with an R&D target of ~600 mm to increase applicability in tightly routed segments. In the present phase, both systems are engineered and verified against KSTAR-referenced conditions; subsequent re-design will align specifications and interfaces with K-DEMO once sufficient performance data and operational experience are accumulated.

This staged, KSTAR-anchored approach links related work to concrete, reactor-relevant challenges and frames the remainder of the paper: Section 3 develops the MPD design and status; Section 4 details the laser-based welding system; Sections 5 and 6 outline integration, verification, and future work.

## 3. IN-VESEL COMPONENTS INSPECTION ROBOT

The Multi-Purpose Deployer (MPD) is being developed against K-DEMO maintenance objectives while following a staged pathway anchored to KSTAR as the intermediate design and verification platform. In this phase, port geometry, insertion clearances, and vessel layout are referenced to KSTAR so that reach, controllability, and sensing can be demonstrated under representative yet manageable conditions. The resulting calibration procedures,

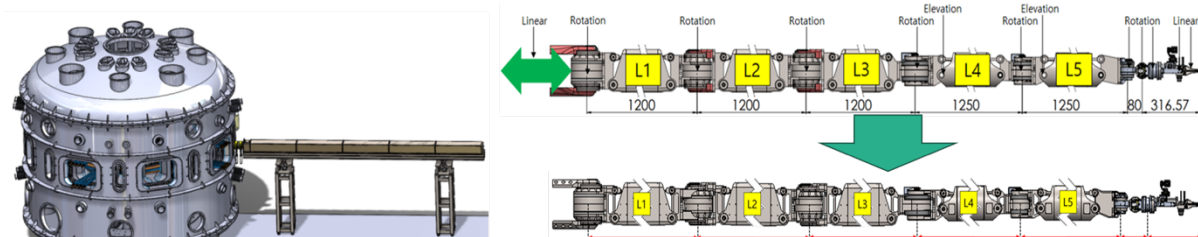


Figure 1 The overview of the robotic arm system and a length optimization of the robotic arm based on the reachability

deployment know-how, and recovery strategies will be transferred to a subsequent redesign that is tailored to K-DEMO requirements.

The MPD adopts an articulated architecture with thirteen degrees of freedom and an approximate reach of eleven meters. Link lengths and joint placements have been iteratively tuned to maximize in-vessel workspace while guaranteeing collision-free passage through the equatorial-port opening with clearance, and to minimize the arm's swept cross-section during insertion and deployment. During this process, individual link dimensions were adjusted to balance stiffness, payload margins, and geometric accessibility under KSTAR constraints.

To ground the optimized design in hardware, a partial mock-up comprising Link-4, Link-5, and the gripper assembly has been constructed. This substructure isolates the most compliance-sensitive portion of the distal chain and enables quantitative checks of clearance and end-effector stability. The mock-up also serves as a fixture for early calibration trials and operator procedure development under vessel-like constraints, as shown in Fig. 2.

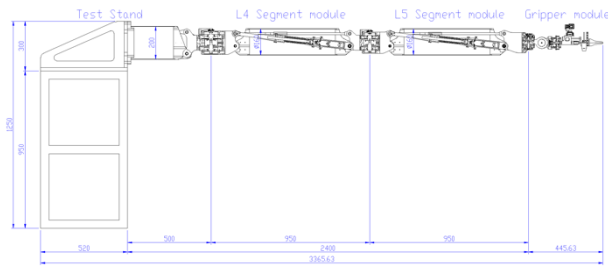


Figure 2 A design of substructure of robotic arm currently in production

Fabrication of substructure is scheduled, and the cable routing is intentionally kept external to the joints to accommodate a wide range of experiments and future sensor-fusion instrumentation. Verification will begin with joint characterization under motion—evaluating vibration, deflection, and load response—then proceed to full-scale mockup trials that exercise multi-joint coordination, telemetry, and operator workflows. Integrated dry-runs in vessel-like environments will validate collision-free insertion, confirming clearances and swept volume. The resulting datasets will quantify reach, coverage, and positioning accuracy; these outcomes will be incorporated into the KSTAR robot baseline, including potential adjustments to port interfaces and service-umbilical connections (power, data, and etc.). Operational results from the finalized KSTAR arm will then feed directly into the K-DEMO-specific redesign.

#### 4. LASER-BASED PIPE-WELDING ROBOT FOR K-DEMO

Inspection alone is not sufficient for sustained reactor operation; targeted intervention on in-vessel piping is also required. With this motivation, a compact laser-based welding system is being developed specifically for K-DEMO piping, where the routing curvature of coolant and breeding lines is part of the plant design. The welding head and its deployment concept are defined against the curvature envelope anticipated for K-DEMO service.

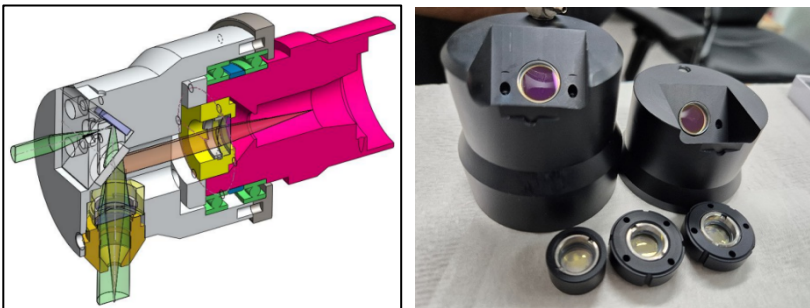


Figure 3 A welding device head design and a part of mock-up

The head is engineered as a compact in-pipe tool. At the present stage, development focuses on the head itself—its optical train, shielding provisions, cooling passages, and overall packaging—together with bench and vessel-like fixtures for positioning and access studies. No dedicated robotic carrier has been finalized yet; interface assumptions are therefore limited to generic mechanical mounting and service connections so that the head can later be mated to a selected carrier architecture without redesign. The current specification targets pipes of 80

mm outer diameter and 5 mm wall thickness, and the configuration accommodates a  $\sim 1300$  mm bending radius representative of K-DEMO routing. A design drawing and a bench-top mock-up have been prepared to verify assembly tolerances, fixturing, and access; these are summarized in Fig. 3. These mockups provide the basis for quantifying repeatability and for design parameter that reflect K-DEMO curvature and fit-up conditions.

Because K-DEMO maintenance planning depends on throughput as much as on weld quality, the program defines maintenance-time metrics tied to curvature and deployment mode (e.g., fixed fixture, guided positioning). For each joint, the cycle will be decomposed into setup and fixturing, alignment, path execution, in-situ inspection, and any rework; the resulting time-per-joint as a function of bending radius and joint orientation will serve as a planning indicator for K-DEMO outages. These metrics will be reported together with weld-quality indices such as bead uniformity, penetration, and defect rates, providing a direct link between geometric constraints and maintenance duration.

The outcome of this phase will be a validated head design, parameter windows for reliable weld formation on curved joints, standard operating procedures, and a curvature-indexed throughput model. These results will feed directly into K-DEMO remote-maintenance planning and will guide finalization of packaging and interfaces once a carrier architecture is selected, ensuring that piping curvature and access constraints are explicitly accommodated by the welding system.

## 5. DISCUSSION

This program integrates two tracks that converge on K-DEMO maintenance planning. The MPD is integrated and rehearsed against KSTAR-referenced geometry so that insertion, coverage, and operator workflows can be validated under vessel-like constraints. The laser welding head is developed as a stand-alone tool for K-DEMO piping; positioning and access are exercised with dedicated fixtures.

MPD integration proceeds from joint/link mechatronics to an assembled arm configured for passage through an equatorial-port opening. Full-scale mockups are used for collision-free movement, multi-joint coordination, and end-to-end procedures covering transport, deployment, inspection, and recovery. These rehearsals establish console operation, telemetry, and service connections in the same order they will be used in practice.

Welding-head integration focuses on the tool package—optics, thermal management, and cooling—verified on the bench for alignment stability and thermal behavior. Curved coupons and pipe mockups (outer diameter 80 mm, wall thickness 5 mm) provide access and repeatability studies around a bending radius of approximately 1300 mm.

Results are consolidated into standard operating procedures and design inputs for both systems, guiding the K-DEMO redesign.

## 6. CONCLUSIONS AND FUTURE WORK

This manuscript reported the development status of two complementary remote-maintenance systems aimed at K-DEMO design / operation. The Multi-Purpose Deployer (MPD) is designed against K-DEMO requirements but is presently engineered and verified using KSTAR-referenced geometry to demonstrate insertion, coverage, and controllability under vessel-like constraints. The current configuration adopts a 13-DOF articulated architecture with an approximate 11 m reach, and a partial mock-up of Links 4–5 with the gripper supports clearance and stability checks prior to full assembly. In parallel, a compact laser-based welding head is being developed specifically for K-DEMO piping. The head targets pipes of 80 mm outer diameter and 5 mm wall thickness and is configured for operation along curved segments with a bending radius of approximately 1300 mm; a design drawing and bench mock-up have been prepared for access and repeatability studies.

The integration strategy emphasizes staged verification under vacuum and elevated temperature. For the MPD, unit-level mechatronics progress toward full-scale mockups and vessel-like rehearsals, yielding procedures for transport, deployment, inspection, and recovery. For the welding head, coupon and curved-mockup trials establish parameter windows for consistent weld formation and provide the basis for defining maintenance-time metrics as a function of curvature and deployment mode. These results converge into standard operating procedures and design inputs that guide the subsequent K-DEMO-oriented redesign.

Next steps are to complete MPD assembly and mockup-based rehearsals, finalize calibration and trajectory planning in vessel-like environments, and consolidate coverage and accuracy data as inputs to K-DEMO port/interface definitions. For the welding head, the program will complete bench validation, expand curved-joint trials under vacuum and elevated temperature, and derive a curvature-indexed throughput model tied to setup, alignment, execution, and in-situ inspection. Once a carrier architecture is selected, mechanical and service interfaces will be finalized so that the validated head can be integrated without redesign. The combined outcome—early detection via systematic inspection and targeted intervention via in-pipe laser welding—is expected to reduce maintenance duration and improve availability in K-DEMO operations.

### **ACKNOWLEDGEMENTS**

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