R&D Activities for ITER Blanket Remote Handling Equipment

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Abstract. R&D to clarify the specifications of a detailed design for an in-vessel transporter by the Japan Domestic Agency (JADA) has been performed with feasible outputs, examples of which include force sensors to avoid any overload between the blanket and keys during blanket installation and dry lubricant to prevent lubricant oil from spreading in the VV. In addition, the rail connection and cable handling in the transfer cask, which are critical issues for the IVT system, are in preparation for demonstration tests to finalize the design of the IVT system.

1. Introduction

Maintenance of the ITER blanket is carried out in the vacuum vessel (VV) by the remote handling equipment as shown in **Fig.1**. For this purpose, the in-vessel transporter (IVT) with a rail mounted vehicle manipulator, which consist of vehicle manipulators working on rail transporter forming a toroidal ring structure, has been adopted. Approximately 440 blanket modules are installed in the VV. The dose rate of gamma ray radiation is expected to be about 500 Gy/h during blanket maintenance [1][2][3]. The R&D to finalize the design of the IVT has been performed, outputs of which include force sensors to avoid any overload between the blanket and keys during blanket installation and dry lubricant to prevent the lubricant oil from spreading in the VV. In addition, the rail connection and cable handling in the transfer cask, which are critical issues for the IVT system, are under fabrication for demonstration tests[4][5][6]. The present paper describes recent progress of the R&D of the IVT system for blanket maintenance.

2. R&D of the IVT system

2.1 Force sensors

Blanket modules are installed on two keys that are part of the vacuum vessel (VV). The modules are designed to mitigate the large electro-magnetic loads that occur during plasma disruptions as shown in **Fig. 2.** Blanket maintenance requires the remote manipulation of the four-ton modules and specifies that final installation accuracy be within 0.5 mm between the

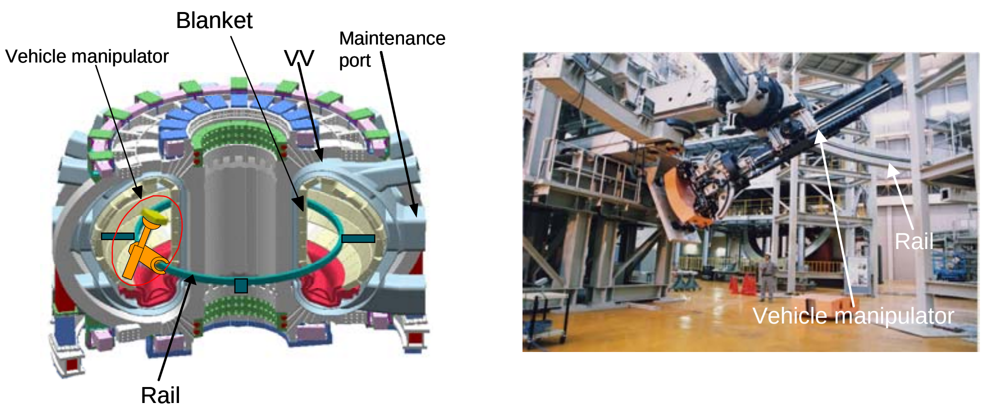


Fig. 1 In-vessel Transporter for ITER

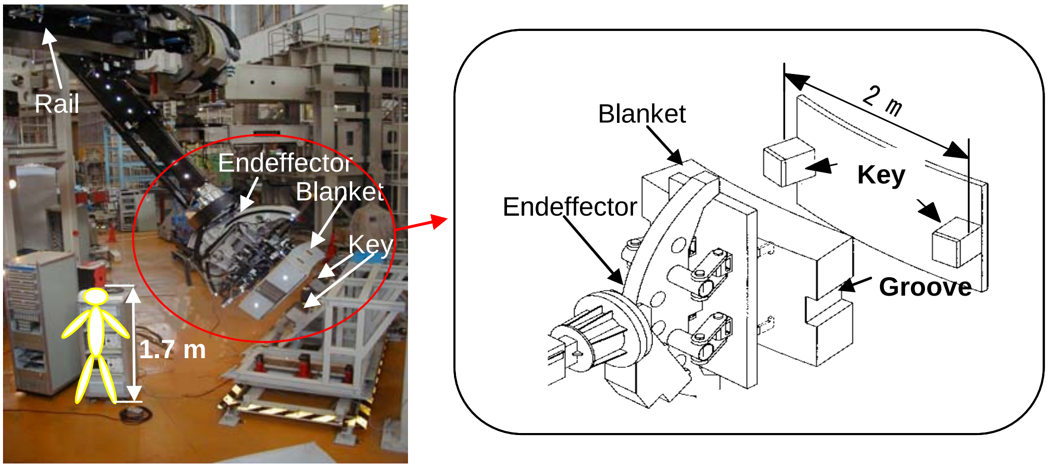


Fig.2 Installation of blanket module

module and the two key supports in the VV. Due to this very demanding specification, an end-effector which has five degrees of freedom (such as roll, pitch and yaw for determining position during blanket installation, etc.) may sustain damage due to excessive loads on the manipulator arising from jamming between the key and the groove during the process of installing the module on the two keys. The most critical issue is to avoid any jamming between the blanket module and the keys as a result of excessive loading during the module installation process, a process complicated by the limited clearance of 0.5 mm between the module and the keys. To solve this technical issue, excessive loads which may impact the end-effector should be correctly detected during key insertion. A 6 axis force sensor must satisfy two specifications (compact size and large load capacity) simultaneously in order to be able to access the entire blanket region within the confines of the VV during module handling. However, a 6 axis force sensor that satisfies the above two specifications currently does not exist in the commercial market of force sensors. It is therefore necessary to develop a new force sensor adapted for blanket installation. This section describes a force sensor to detect 6-axis loads with three translation and three rotation loads and then presents the verification test results of a proposed force sensor. A force sensor is proposed using grippers and strain gauges as shown **Fig. 1**. The number and location of the strain gauges on the gripper are determined by the optimization of the compliance of the gripper based on calibration results and the method of least squares.

2.1.1 Equation of forces acting on the gripper

The reaction forces acting on the gripper are assessed by **n** strain gauges attached to the gripper. The forces are determined by a compliance matrix for strain due to mechanical conditions, such as an external force acting on the gripper, the geometry of the gripper and related constraints. **Figure 2** shows the relationship between the reaction forces and the strain on the gripper. The strain $\boldsymbol{\varepsilon}_s$ and representative forces of the coordinates as measured by the strain gauges $\boldsymbol{f}_s = (\boldsymbol{F}_s, \boldsymbol{N}_s)$ are estimated by the following equations using a compliance matrix $\boldsymbol{C}_s$, a geometric coefficient for the gripper ${}^s\boldsymbol{T}_a$ and reaction forces composed of 6-axes $\boldsymbol{f}_a$.

$$\boldsymbol{f}_s = {}^s\boldsymbol{T}_a \boldsymbol{f}_a \qquad (1)$$

$$\boldsymbol{\varepsilon}_s = \boldsymbol{C}_s \boldsymbol{f}_s \qquad (2)$$

Where

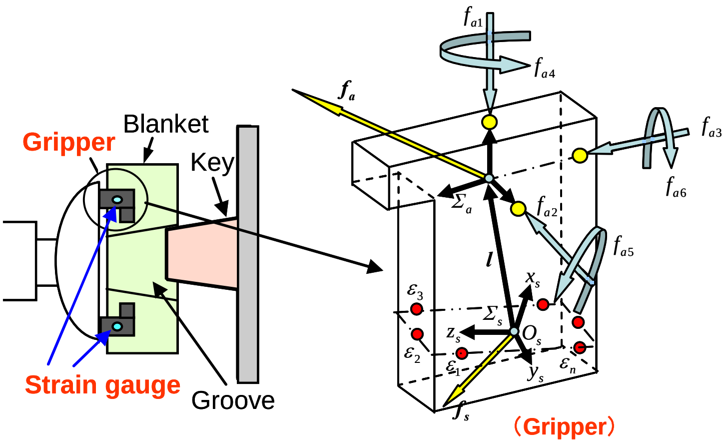


Fig.3 Forces acted on gripper during key insertion

$\boldsymbol{F}_s$: translation forces, $\boldsymbol{N}_s$: moment forces, and $\varepsilon_s = [\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \quad , \varepsilon_n]$: the set of strains impacting the gripper.

Equations (1) and (2) represent the balance equation for forces and Hooke's equation of elasticity, respectively. Therefore, $\boldsymbol{f}_a$ is given as follows:

$$\boldsymbol{f}_a = \boldsymbol{C}_s^+ \boldsymbol{\varepsilon}_s \qquad (3)$$

Where

${}^+\boldsymbol{C}_s$: Moore-Penrose inverse matrix of $\boldsymbol{C}_s$

The Moore-Penrose inverse matrix ${}^+\boldsymbol{C}_s$ of the equation (3) satisfies the following least squares solution regarding the relationship between $\boldsymbol{\varepsilon}_s$ and $\boldsymbol{f}_a$ in the calibration test.

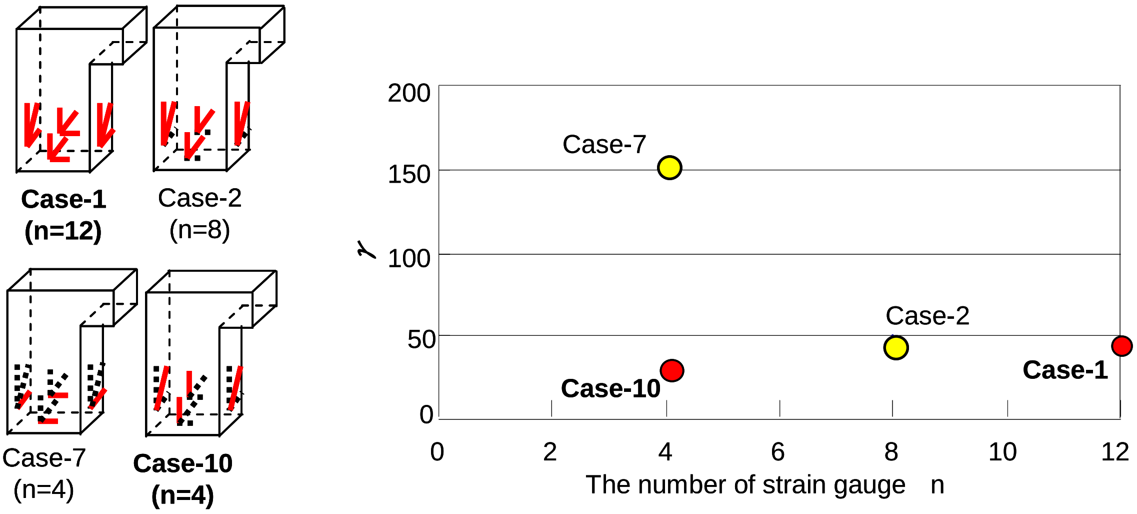
$$min \|\boldsymbol{\varepsilon}_s - \boldsymbol{f}_a \boldsymbol{C}_s\|_2 \qquad (4)$$

2.1.2 Assessment of $\boldsymbol{C}_s$ using singular value decomposition

We have determined the optimal location and number of strain gauges to be attached to the gripper by using singular value decomposition [7]. The red lines in **Figure 3** show the configuration of strain gauges on the gripper. It is possible to locate at a maximum 12 strain gauges on the gripper to assess the reaction force as shown **in Fig. 3 (a).** The optimal location for the strain gauges emerged from sensitivity analysis using a singular value decomposition of matrix $\boldsymbol{C}_s$ which is calculated by the least squares solution as shown in section 2.1.1. **Figure 4** shows the optimized results. The sensitivity of error γ for the longitude axis was inversely proportional to the linearity of $\boldsymbol{C}_s$. If γ is a high value, the linearity of $\boldsymbol{C}_s$ is low. As a result, we found that case 10 in **Fig. 3** optimizes the location of strain gauges (n=4) due to the high linearity of C_s.

2.1.3 Verification test results for the optimised $\boldsymbol{C}_s$

Figure 5 shows the verification test results for the optimised C_s. The longitudinal and horizontal axes show the estimated value of the reaction force using the optimised C_s and the real value obtained during calibration testing, respectively. Estimated values of the reaction forces of the gripper reveal good agreement with test results, as seen in **Fig.5**. Both cases of n=12 and n=4 indicate good approximations of the reaction force. The proposed force sensor is therefore judged to be a useful candidate for estimating reaction forces during module installation with the goal of avoiding any jamming between the module and the keys.



(a) Configuration *(b) The calculation results for optimization of configuration*

Fig. 4 The optimization of compliance matrix $\boldsymbol{C}_s$

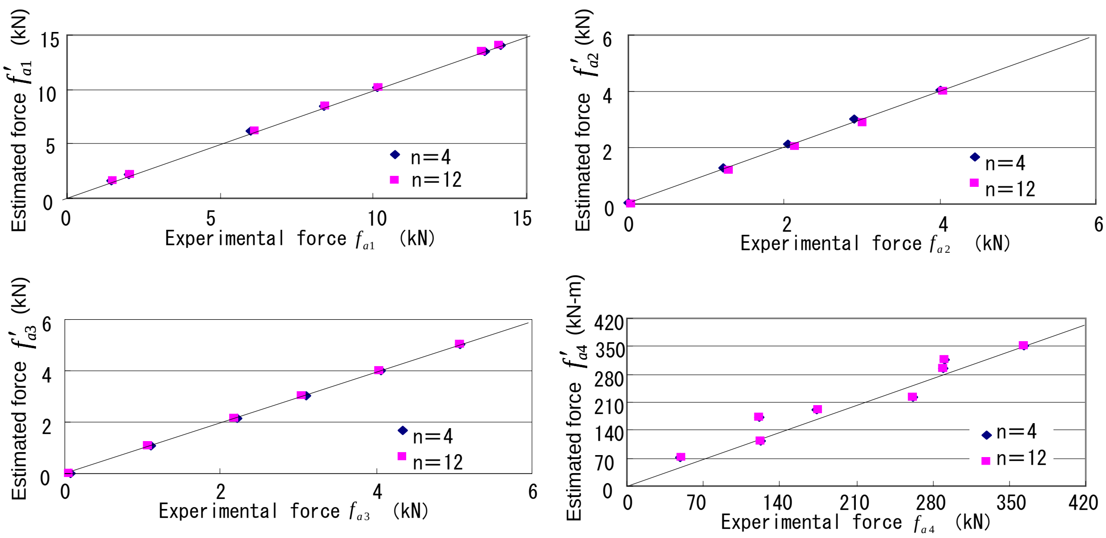


Fig. 5 Verification test results of the optimised $\boldsymbol{C}_s$

2.2 Dry lubricant

It is essential to prevent lubricants such as grease from spreading in the vacuum vessel because of problems the lubricants cause during subsequent plasma operations. Therefore, a solid lubricant for the IVT system is being developed. A Diamond-Like-Carbon (DLC) coating is a prime candidate as a substitute for liquid lubricants. The DLC coating utilizes a physical vapor deposition (PVD) method based on vacuum technology [8]. An abrasion resistance test under high contact pressure [9] was performed to determine the lifetime performance limits of three types of DLC coatings that differed in their degree of hardness. Test results satisfy the requirements as follows: contact pressure and lifetime performance are 2.5 GPa up to 3×10^4 cycles, and 4.2 GPa up to 10^4 cycles, for the DLC coating SNCM420. A different DLC coating which combined a soft DLC and SNCM420 shows the highest performance level at more than 10^4 cycles at a high contact pressure of 4.2 GPa. Therefore, this combination will be selected as the primary candidate for dry lubrication. In a seizure test, we tested the wear-resistance of DLC-coated gears so as to clarify performance criteria under realistic surface pressure loading conditions. This section describes the results of the abrasion resistance testing of gears coated with a combination of soft DLC and SNCM420.

2.2.1 Test conditions and test apparatus

Table 1 lists the gear specifications. **Figure 6** shows the abrasion resistance test apparatus. The test apparatus can simulate realistic surface pressures for a rotation drive mechanism as it moves around the rail. The surface pressure of both gears is about 1.5 GPa based on a JGMA (Japan Gear Manufactures Association) equation. The revolution speed of the meshed gears in the test device is about 2 rpm, which is about 20 times faster than expected in the real IVT, thereby to accelerate the test term. In addition, torque is measured to estimate the damage to the gears from friction, such as adhesion due to the abruption of the DLC film etc..

2.2.2 Test results

The combination of a soft DLC and SNCM420 coating on steel material shows the highest performance after more than 30000 cycles under 1.5 GPa at 2 rpm. Based on the results of the abrasion resistance test, additional testing was performed using the gears with a combination of soft DLC and SNCM420, as shown in **Fig. 7**. Results show that the lifetime of the gears coated with a combination of soft DLC and SNCM420 may be expected to exceed 30000 cycles beyond the requirement of 10000 cycles under the required contact pressure of 1.5 GPa. The feasibility of DLC has therefore been demonstrated for application to the transmission gears of the IVT.

Table 1 Specifications of gear

Specifications	Parameters
Pitch circle diameter	60 mm
Module	4
Face width	10 mm
Gear type	Involute
Base metal	SNCM420 (Ni-Cr-Mo steel)
DLC	Soft Type
Hardness	17.7 MPa
Thickness (average)	2.6 μm

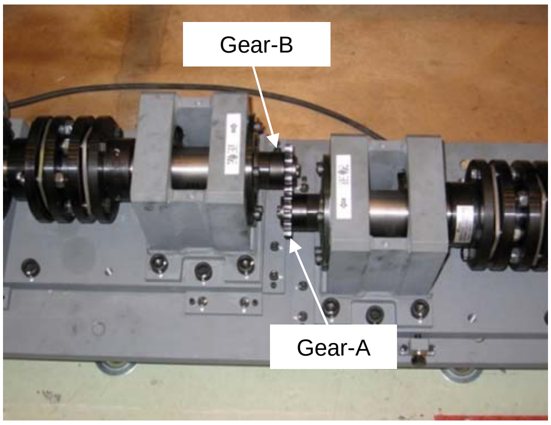
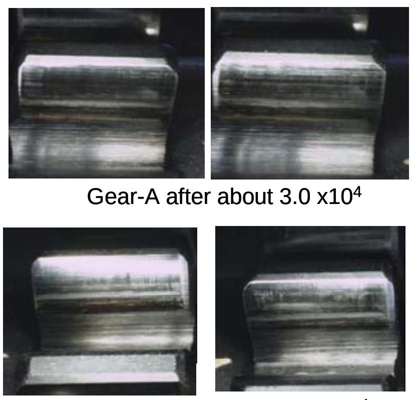
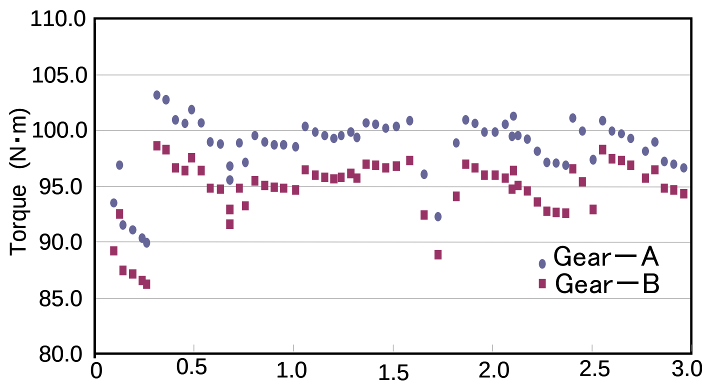


Fig. 6 Test apparatus



(a) Photograph using microscope



(b) Torque during the running of gear

Fig. 7 Test results for the abrasion resistance of gears coated DLC

2.3 Connection of rail joint and cable handling

Connection and disconnection of the rail joint for rail deployment and storage in the transfer cask are critical issues for the remote handling system. Therefore, the feasibility of the means for connecting and disconnecting the rail joint must be demonstrated to finalize the design. The facility for testing the connection and disconnection of the rail joint during deployment and storage consists of three rail segments, a locking mechanism for the rail joint, and a hinge connection, as shown in **Fig. 8.** Rail connection testing as part of an ITER R&D task was performed to clarify the specifications for procurement of blanket remote handling equipment. Results include the need for the oldham mechanism to accommodate position errors through use of a compliance mechanism that adjusts for potential angle errors (torsion or bending) during the process of connecting the rails.

Cable handling technology is also a critical issue for mobile robots. The length of cable is estimated to be about 60 m. Excessive tension of the cable should be avoided for stable movement of the vehicle manipulator along the rail. The feasibility of a new proposal for a drum cable winding mechanism, featuring a drum diameter of 750 mm and a slip ring to maintain electrical power and signal connections during drum rotation, is under evaluation to determine if it enables compact storage of the long cable in the cask. The design of a drum type cable winding mechanism includes the possibility of storing both the power and signal cables in a single co-axial cable. The test facility for cable handling consists of two drums (one for vehicle simulations), a multi-cable system that includes both power and signal cables, a guide mechanism for cable winding with traverse motion, and a simulated cable route with a guide mechanism at the front corner of a maintenance port, as shown in **Fig. 9**. Cable handling testing to verify the specifications of this procurement is underway and includes design verification and the impact of the noise from the AC servo motor driver on signal lines and on the slip ring.

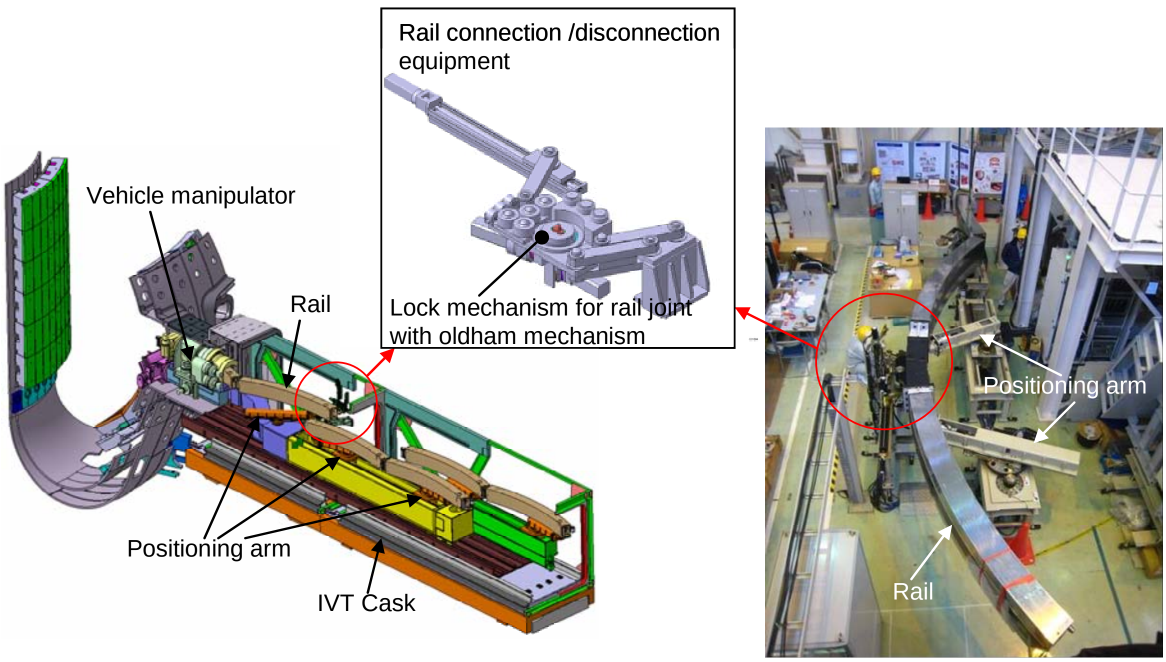


Fig. 8 Test facility for rail connection and disconnection

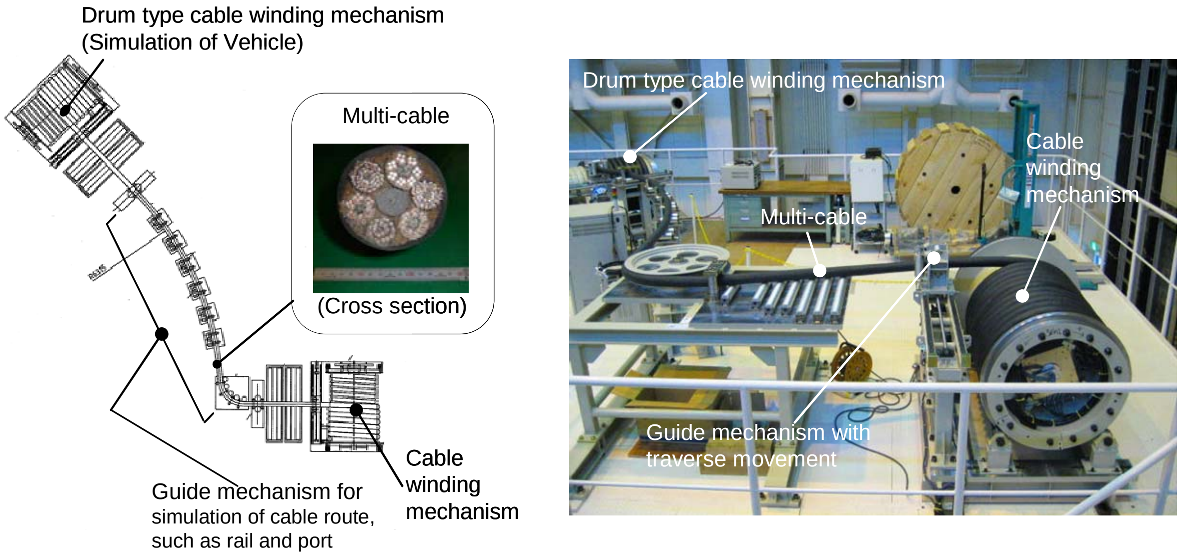


Fig. 9 Test facility of cable handling

3. Conclusion

The most critical issue for blanket module manipulation is to avoid jamming between the blanket module and keys due to overloading during module installation. Avoiding jamming becomes difficult due to the stringent clearance specification of 0.5 mm between the module and the keys. To solve this technical issue, excessive loads which may impact the end-effector should be correctly detected during key insertion. A 6 axis force sensor must satisfy two specifications (compact size and large load capacity) simultaneously in order to be able to access the entire blanket region within the confines of the VV during module handling. The proposed force sensor using an optimised compliance matrix is therefore judged to be a primary candidate for estimating reaction forces during module installation, thereby avoiding any jamming between the module and the keys. In addition, development of a dry lubricant is also a key issue for the vehicle manipulator to minimize lubricant contamination in the VV as much as possible. Diamond-like carbon (DLC) coating is a candidate and was applied in performance tests to assess the feasibility of dry lubricants. Abrasion resistance tests for DLC coated gears assessed basic performance characteristics. Test results satisfy the requirements of pressure at 1.5 GPa and up to 3 $x10^4$ cycles. The feasibility of DLC has therefore been demonstrated for application to the transmission gears of the IVT. Finally, facilities for testing the rail joint connection and cable handling have been installed at JAEA’s Naka Fusion Institute. Performance testing commenced in April 2008, for the purpose of clarifying procurement specifications of the blanket remote handling system.

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