Design and Prototyping of Remote Handling Electrical Connector for Diagnostic Rack in ITER

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(Received 21 February 2023 / Accepted 3 July 2023)

The Remote Handling Electrical Connector (RHEC), crucial for in-vessel diagnostics in ITER, enables connection and disconnection through Remote Handling operations. Partitioning electrical lines between the Lower Port sidewall and the Diagnostic Rack, the RHEC connects the Mineral Insulated cable bundle. The design concept omits components like core wire extensions with ceramic sleeves, avoiding overheating and power loss due to impedance mismatching during the mirror cleaning system's plasma generation. The prototype was tested for torque measurements and positional misalignment, proving the RHEC feasibility and remote handling compatibility.

Keywords: Remote Handling Electrical Connector (RHEC), Mineral Insulated (MI) cable, ITER project

DOI: 10.1585/pfr.18.1405070

1. Introduction

The ITER Vacuum Vessel (VV) has diagnostic ports at upper, equatorial, and lower positions. The Lower Port (LP) #02 house Diagnostic Racks (DR). The DR provides structural support for diagnostics, neutron and gamma-ray shielding, and are inserted within the LP #02. Unlike upper and equatorial port locations, an electrical connector within the DR of the LP cannot be accessed from a hot cell and requires on-site connection and disconnection in the LP using the Divertor Remote Handling System (DRHS) [1], as shown in Fig. 1. This situation introduces a distinct set of constraints and requirements for a reliable electrical connector, such as those for the Remote Handling Electrical Connector (RHEC). RHEC plays a critical role in partitioning the electrical lines between the DR and the LP sidewall, which are necessary to operate the Divertor Impurity Monitor (DIM) [2]. The functionality and removability of the DR, facilitated by the DRHS without human intervention, is essential due to the activation of in-vessel components during the Deuterium-Tritium plasma operation phase.

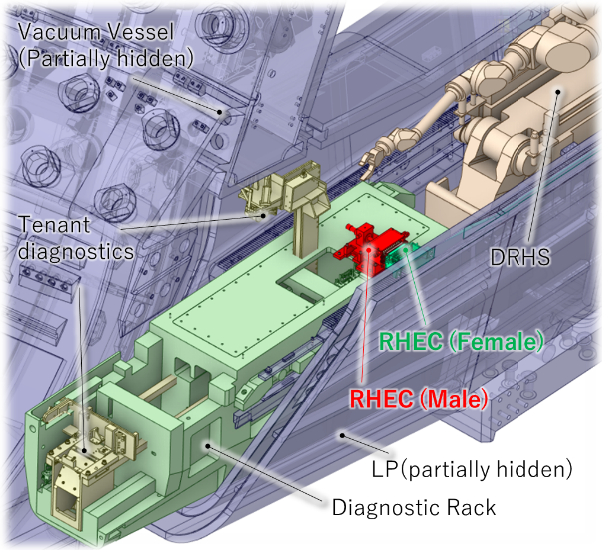

Fig. 1 Location of DR and RHEC.

Designing and implementing RHEC is challenging due to environmental factors such as vacuum, radiation, and magnetic fields, which prevent using standard resin coaxial cables, like polyethene or polytetrafluoroethylene. High-frequency transmission is required for mirror cleaning [3, 4], and overheating and power loss due to impedance mismatch needs to be avoided. In contrast to a previous study [5], this paper explores a design employing only Mineral Insulated (MI) cables for transmission lines, aiming to improve reliability. The MI cables, filled with oxidized magnesium or aluminum for electrical insulation and copper core wires, introduce an additional challenge due to their rigidity, which hinders manual bending and complicates Remote Handling (RH) operations. In this context, RHEC's efficient functioning becomes a project issue as inadequate removal of DR from the LP could impede Divertor maintenance.

The RHEC design presented in this paper addresses these challenges by incorporating an elongated, no-support MI cable segment. The feasibility of the design, includ-

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ing the MI cable bundle, which would be bent following a movement mechanism, is confirmed by structural analysis to estimate reaction forces and finally confirmed the validity of the design by the manufacturing prototype.

This paper presents the RHEC design in Sec. 2, the estimation of necessary torque with the stress assessment of the MI cable bundle in Sec. 3, and the validity of the design is described manufacturing the prototype in Sec. 4. Finally, this study is summarized in Sec. 5.

2. RHEC Design Description

The RHEC comprises a pair of connectors with MI cable bundles, a movement mechanism, and a positioning alignment mechanism, as illustrated in Fig. 2. The RHEC must accommodate 36 cables, including two pneumatic shutters, 4 RF cables, and 20 thermocouples. It is required to move approximately 60 mm during the removal of the DR. However, components causing RF power loss must be avoided. Consequently, the MI cable bundle is designed to provide flexibility, extending to approximately 1.2 m without the support and bending in accordance with the connector's movement.

The movement mechanism incorporates a gearbox with a hex head as the interface with the DRHS and linear guides. The gearbox has a 1/50 deceleration ratio and can generate 5000 N axial force with 1.3 Nm torque. The DRHS can rotate the hex head, allowing the gearbox to transmit torque to the movement mechanism's axial forces.

The positioning alignment mechanism is crucial in practice. Misalignment occurs due to the DR's positioning tolerance during remote handling and its movement under thermal loads. The thermal distortion degree varies between the RHEC (male side) on the DR and the RHEC

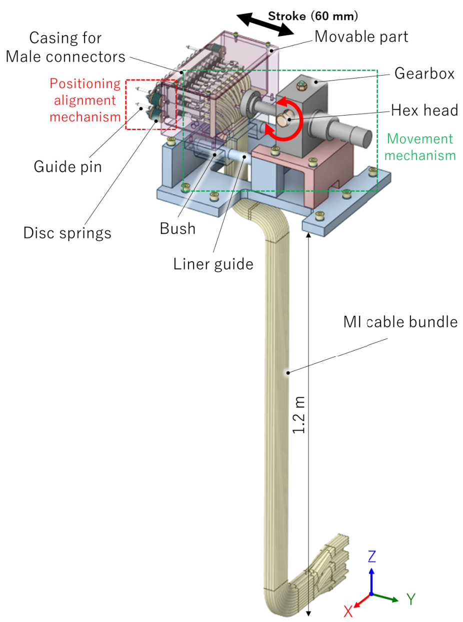

Fig. 2 Configuration of RHEC.

(female side) on the LP sidewall, owing to a temperature difference of approximately 40°C by cooling water temperature difference in the DR and LP. It is estimated to be +1.9/−1.0 mm (radial: X direction) and +/−0.06 degrees (angular: around Z and Y). Consequently, the positioning alignment mechanism compensates for misalignments of +/−2 mm (radial) and +/−1 degree (angular). Guide pins and disc springs for angular alignment and specialized guide washers for radial alignment facilitate this compensation. The guide pins and their inherent flexibility enable self-alignment.

3. Estimation of Axial Forces

In this section, we estimate the axial force at the normal position by measuring the terminal friction forces, conducting structural analysis using ANSYS Workbench, and performing hand calculations to estimate the necessary torque for the movement mechanism. The total axial forces amount to 632 N, calculated as 322 N (Sec. 3.1) + 97 N (Sec. 3.2) + 213 N (Sec. 3.3), equivalent to 0.17 Nm of necessary torque. This allows an 84% margin for the movement mechanism design.

3.1 Measurement of terminal friction force

Terminals are prototyped by Staubli Electrical Connectors SAS, equivalent to their CombiTac CT series. We measured terminal friction forces using a universal testing machine. There are three-terminal types: coaxial terminals for the mirror cleaning mechanism, thermocouples of twisted pair cables, and signal terminals of twisted pair cables. The maximum friction force is 16.1 N, which we use to estimate the insertion/removal force. With 20 terminals required, the total friction force is 322 N.

3.2 Analysis of MI cable reaction force

MI cables are modelled and analyzed using ANSYS. Pipes simulate MI cable models. The boundary condition dictates that the cable bundle end at RHEC is displaced by 60 mm, and the other end is fixed. As depicted in Fig. 3, the results show a 60 mm displacement and maximum stress at the MI bundle corner, approximately 115 MPa, lower than stainless steel's 0.2% yield strength. Reaction forces at the displacement boundary are X: 17 N, Y (Axial force): 97 N, and Z (Vertical force): 870 N. This vertical force generates friction force in the movement mechanism.

3.3 The friction force of the movement mechanism

Bushes slide on linear guides, as depicted in Fig. 2, generating the movement mechanism's friction force. Linear guide loads in the gravity direction comprise approximately 20 kg of movable parts and an 870 N reaction force due to MI cable bending (Sec. 3.2). Considering a friction coefficient of 0.2 for BTU40, equivalent to OILES CORPORATION's catalogue components, the friction forces

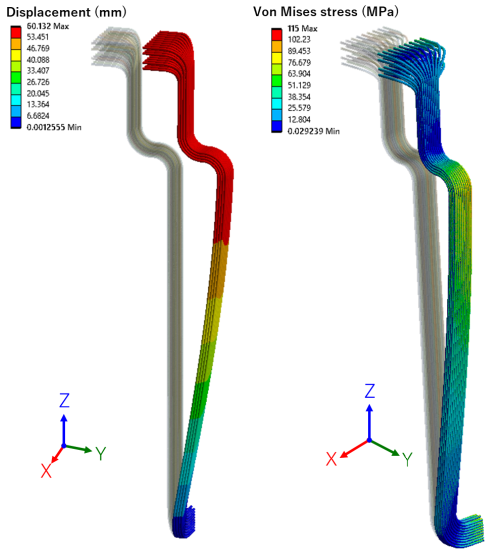

Fig. 3 Analysis result Displacement (left) and Von Mises stress (Right) showing the original position as the shadow.

amount to 213 N.

4. RHEC Prototyping

A prototype of RHEC was manufactured, as shown in Fig. 4, including the positioning alignment mechanism as magnified in Fig. 5, the movement mechanism, and an MI cable bundle simulated by stainless-steel pipes. Two sensor types, load cells and torque meters, measured axial forces and torque, respectively. The torque must be below 60 Nm to meet DRHS interface requirements.

Figure 6 displays the connection/disconnection test results using the RHEC prototype. Axial forces from load cells and torques from torque meters are plotted over time, with 0 - 400 s for connecting and 401 - 800 s for disconnecting during the 60 mm stroke. The figure demonstrates that axial force and torque variations are stable during movement and change direction when the connector connects at the normal position. The maximum torque is 0.3 Nm at the leading axial force of 0.38 kN, consistent with the estimated value of 0.31 kN from Sec. 3, including MI cable bending reaction forces and movement mechanism friction forces.

At misaligned positions, the male connector shifted +2 mm horizontally and vertically. It rotated +1 degree around the vertical and horizontal axes and −1 degree around the axial axis, causing significant axial force and torque fluctuations during connector connection/disconnection. The variations are categorized into three regions: (a), (b), and (c). The dominant forces in each region are (a) MI cable bending reaction forces, (b) guide pin and hole friction forces, and (c) compressed spring restoring forces. At 360 s, the axial force at region (b) end is approximately 0.7 kN, including MI cable bending reaction forces. In region (c), the axial force increases to 2.6 kN

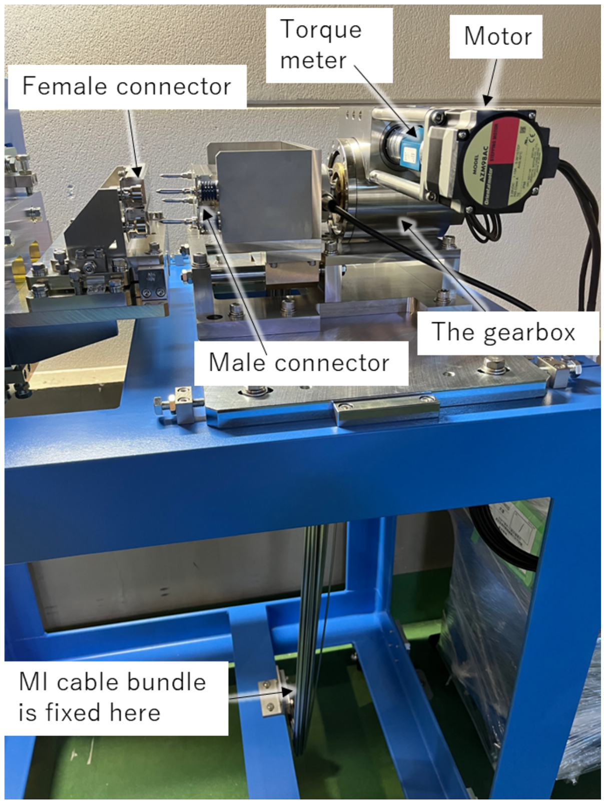

Fig. 4 The RHEC prototyping.

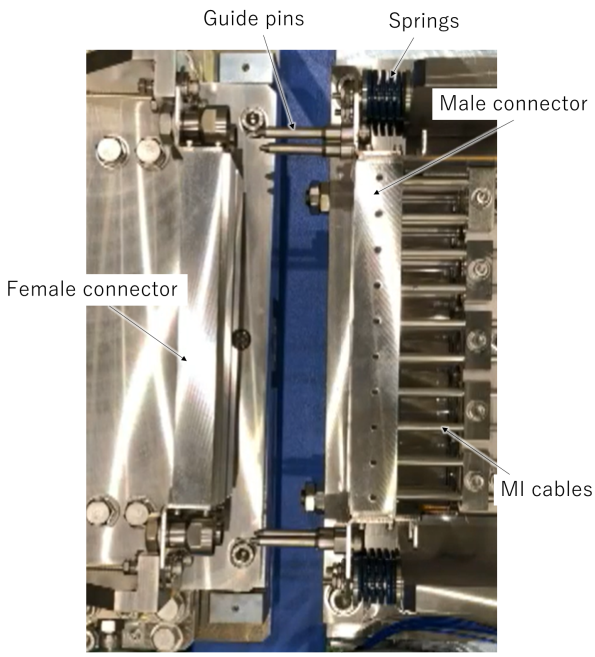

Fig. 5 The magnification picture of the connectors.

due to dominant spring restoring forces, with the gearbox operating at a torque of 1.1 Nm. The axial force difference between regions (b) and (c) represents the actual spring restoring force, approximately 1.9 kN. In the actual equipment, since rotation misalignment is estimated at +/−0.06

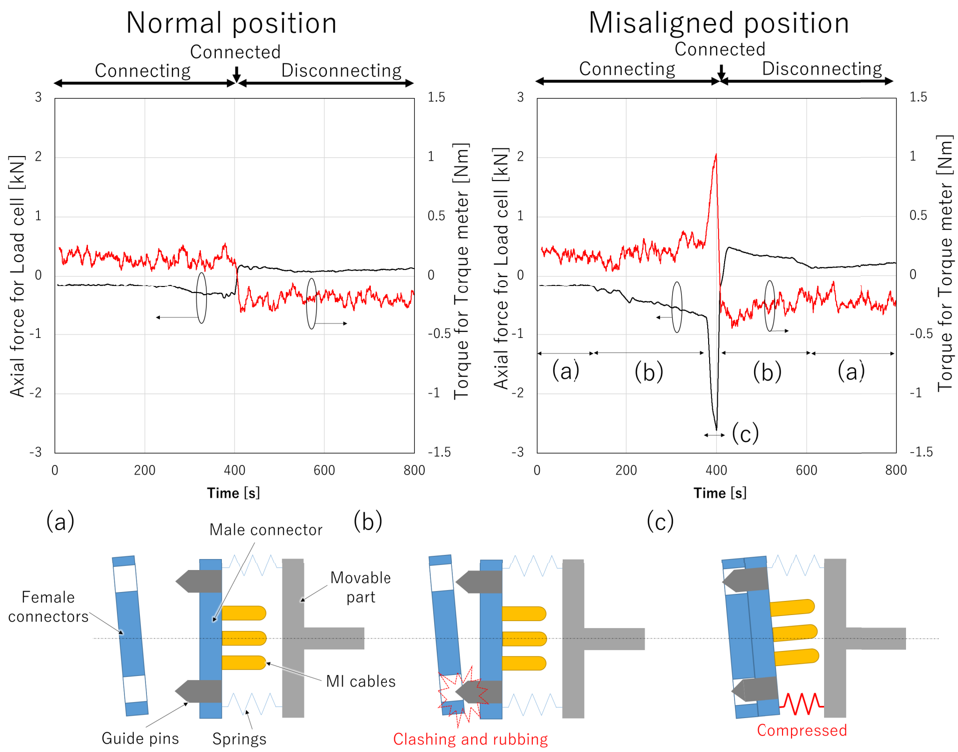

Fig. 6 The results of the axial force for the load cell and the torque for the torque meter, and pictures for each state; (a) connecting/disconnecting state, (b) touching/detaching state of the guide pins on the holes, and (c) Connected state.

degrees—almost 17 times smaller than +/−1 degree—the spring restoring force is considered to be about 0.1 kN at most. Consequently, there is an axial force margin of at least 1.8 kN.

In conclusion, we demonstrated that RHEC could be moved without issue using minimal torque, meeting DRHS interface requirements.

5. Summary and Future Plans

This paper presents the RHEC design, which eliminates the need for standard resin cables by utilizing MI cables and omits features such as ceramic sleeves for covering core wire, contributing to reduced overheating and electrical power loss. The no-support MI cable segment, approximately 1.2 meters long, allows for MI cable bending during RHEC connection and disconnection operations. RH operations for connecting and disconnecting the RHEC are simplified, requiring only the rotation of the hex head bolt by a small torque.

The necessary torque for connecting and disconnecting the connectors was estimated. A required torque of 0.17 Nm, generating an axial force of 632 N, is significantly less than 60 Nm. There was enough margin to rotate it by the DRHS. And the stress while bending the MI cable bundle was 115 MPa, which was less than 0.2% yield strength of stainless steel. We could confirm the feasibility of the RHEC design.

The prototype RHEC was manufactured to confirm the validity of the RHEC design. The prototype's axial force and torque measurements aligned with design estimates. At the normal position, the maximum torque was 0.3 Nm, generating an axial force of 0.38 kN, which agrees well with the estimated axial force of 0.31 kN. The gearbox efficiency appeared lower than the design assumption, as it generated 2.6 kN of force with a 1.1 Nm torque. The gearbox can generate more force with increased torque, up to a gear strength of 5 kN with 2 Nm. The positioning alignment structure functioned effectively; even with misalignments between male and female connectors by approximately 2 mm and a 1-degree rotation, force and torque remained within gearbox specification limits. The prototype demonstrated that the RHEC could be moved without issue using minimal torque that meets DRHS interface requirements with enough margin. Finally, we could confirm the validity of the RHEC design.

Acknowledgments

We would like to thank Daniel Nagy from ITER Organization for their support of the design.

Credit authorship contribution statement

Suguru TANAKA: Conceptualization, Methodology, Validation, Formal analysis, and Project administration. Toyoaki EGUCHI: Investigation. Yasushi ODA: Methodology. Eiichi YATSUKA: Writing- review& editing. Yoshihiko NUNOYA: Supervision.

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