Doctoral Dissertation
Doctoral Program in Mechanical Engineering (37th Cycle)

Design and Testing of a Pipe Bundle Coupling Mechanism for Remote Maintenance in Nuclear Fusion Plants

By

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The transition from experimental fusion devices to commercial nuclear fusion power plants represents one of the most complex engineering challenges of the 21st century. Among the key issues is the development of fully automated remote maintenance systems capable of operating under extreme conditions—high temperature, intense neutron radiation, and limited access space. In particular, the inspection and replacement of pipe modules connected to plasma-facing components, such as blankets and divertors, require high-precision alignment, welding, and internal surface coating, all performed without human intervention.

This doctoral research addresses these challenges by designing and testing a new pipe coupling system, the Laser Bore Joint (LBJ), developed within the framework of the European DEMO fusion reactor, the first demonstrator plant intended to deliver electricity to the grid.

Objectives

The core aims of the research include:

- The mechanical design and optimization of the LBJ system;
- The development and validation of a multibody dynamics model simulating the pipe alignment process;
- A feasibility study of in-bore pipe coating technologies (ECX and APS);
- The construction of a scaled test bench to validate the system's performance in realistic remote-handling conditions.

The Laser Bore Joint (LBJ)

The LBJ enables in-bore remote alignment and welding of pipe bundles through the maintenance ports (upper, equatorial, or lower) of the reactor. It consists of two halves:

- the male cuff, attached to the replaceable pipe module;
- the female cuff, fixed to reactor components.

The system integrates metal bellows made of Inconel 625, which provide limited flexibility in axial, radial, and angular directions—crucial for compensating manufacturing tolerances and alignment errors (up to 3 mm). Sensors and robotic systems perform alignment in two stages: coarse alignment with a Primary Handling System (PHS), and fine alignment with a Secondary Handling System (SHS), guided by laser triangulation.

A Failure Modes, Effects, and Criticality Analysis (FMECA) was conducted to compare two LBJ design iterations. The revised design, featuring improved cuff geometries, significantly reduces the risk of failure while maintaining mechanical reliability.

In-Bore Coating Technologies

The thesis explores two candidate technologies for internal pipe surface coating:

- Electrochemical Deposition (ECX): Offers excellent tritium permeation resistance and corrosion protection but requires careful management of electrolytic liquids, heating, and seal systems.
- Atmospheric Plasma Spraying (APS): A well-established thermal spray process suitable for in-bore applications, though it involves complex powder delivery and cooling systems.

For each technology, conceptual tools were designed, including:

- Sealing systems (inflatable or compressive rubber seals);
- Heating and cooling strategies;
- Liquid or powder storage and delivery;
- Integration via umbilical cables connecting internal and external systems.

Both processes require strict geometric tolerances (e.g., minimal gaps between cuffs) to ensure effective coating and high-quality welds—making alignment precision a central design criterion.

Modelling and Validation

A high-fidelity multibody simulation model of the LBJ was developed to simulate the mechanical behaviour during the alignment process, including:

- Contact dynamics between cuffs;
- Compliance from bellows;
- Robotic actuation forces.

To validate the model, a scaled physical test bench was built. It featured:

- Laser displacement sensors to detect misalignment;
- Programmable actuators for simulated robotic manipulation;
- A Stewart platform for six-axis force and torque measurement.

Tests were conducted under different radial misalignment scenarios (0 to 3 mm). Results showed strong agreement with the simulations, confirming the model's accuracy and the system's mechanical feasibility.

Conclusions

This work makes a significant and original contribution to the field of remote maintenance in nuclear fusion plants. It combines mechanical design, modelling, experimental testing, and technology integration to advance the TRL (technology readiness level) of the LBJ mechanism. The results support the inclusion of LBJ in the DEMO reactor's maintenance architecture and offer a technological foundation for future in-bore welding and coating systems.

In sum, this research represents a crucial step toward the deployment of reliable, efficient remote handling technologies in the realization of commercial fusion energy.