Articulated Inspection Arm for ITER, a demonstration in the Tore Supra Tokamak

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Abstract**. The aim of this R&D program is to demonstrate for ITER the feasibility of an in-vessel Remote Handling inspection using a long reach, limited payload carrier (1 to 10 kg) for penetration of the ITER chamber through the openings evenly distributed around the machine such as In-Vessel Viewing System (IVVS) access or upper ports access. This device is dedicated to close inspection processes of the Plasma Facing Components (PFCs).**

The work performed with a support of the EFDA-CSU Workprogramme includes the design, manufacture and testing of an articulated device demonstrator called Articulated Inspection Arm (AIA).

The first part of this work concerned the analysis of the requirements to perform a realistic inspection in the ITER vacuum and temperature ambiance (120°C at least). The conceptual design of the overall manipulator, completed in 2002, is based on a 5 modules kinematics with 11 actuated joints.

To support the feasibility demonstration of the technology, a scale one mock up of a single module has been manufactured and tested, focusing on its ability to withstand the most critical loads. The main results concern improvement in the design margin to enhance AIA performances under ITER Temperature and vacuum operational conditions. New AIA technologies, including components and materials have been qualified through outgassing tests at 230°C with success. An upgraded AIA single module has been designed and its manufacturing is launched. This prototype module will be tested on the CEA-Cadarache test facility under real vacuum and baking temperature conditions.

A feasibility study of a full AIA operation in Tore Supra was performed, taking into account ITER reference requirements. A scale one demonstration of the AIA under ITER relevant condition is feasible on Tore Supra and would give significant improvement in R&D results for ITER remote Handling equipment. The test of the AIA demonstrator behaviour is foreseen in 2005 in real Tokamak conditions.

The paper presents the full robot concept, the results of the first test campaign, the AIA new design and its integration on Tore Supra.

Several potential uses of the AIA for the in vessel components inspection are being studied such as PFC visual inspection, water loop leak testing, laser ablation for wall detritiation and carbon dust & flakes removal are foreseen as utilities to be placed at the AIA head. These various systems are described in the paper.

I. INTRODUCTION

TORE SUPRA is a rather large circular tokamak (R=2.3m, a=0.8m) designed for long pulse operation (1000s) at high level of additional power.

The foreseen enhancement of heating capabilities up to 20MW, in stationary conditions, has required a major upgrade of the actively water cooled high heat flux plasma facing components of the machine (CIEL project). Reliable plasma facing components based on copper alloy heat sink structures and a bonded carbon fiber composite armour, have been developed. The CIEL major in-vessel component consists of a flat toroidally continuous disk, located at the lower part (see Fig. 1). The TPL and the enhanced configuration of the machine, such as an actively cooled inner wall able to withstand radiated power, were successfully commissioned in 2002. Tore Supra is operating in same vacuum and temperature conditions as ITER (120°C to 200°C). Integration and operation of the AIA demonstrator in Tore Supra environment will have first to demonstrate the ability of PFCs inspection (viewing, erosion, co-deposition, thermal flux deposition, anomalous events). Robustness, reliability and flexibility will be tested and improved during successive plasma operating campaigns in a routine inspection mode. As Tore Supra aims to fulfil ITER specific inspection requirements (i.e. water loop leak testing, carbon dust & flakes removal), development of utilities are foreseen in parallel, to be fully tested using the AIA carrier under vacuum and temperature relevant conditions.

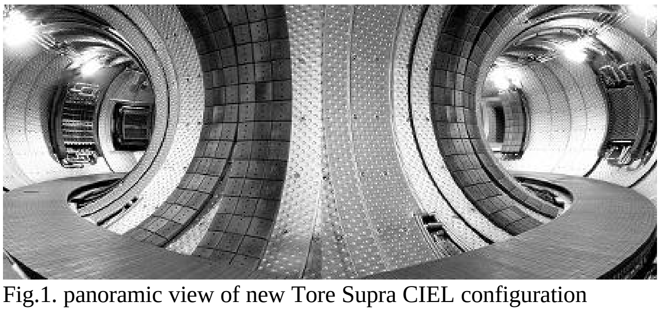

Fig.1. panoramic view of new Tore Supra CIEL configuration

II. AIA ROBOT CARRIER DEVELOPMENT AND QUALIFICATION PHASES

A. *Conceptual design*

A challenging problem is being addressed to improve significantly the operational range of inspection tools. A long reach multi link carrier, like the AIA, is characterized by its large workspace and reduced mass. Unfortunately, increasing the number of joints with reduction of mass increases significantly structural compliance. When considering the ITER requirements for AIA :

- Limited access,
- Large operational range,
- ITER ultra high vacuum and pollution avoidance,
- Temperature ambiance 120°C.

a great improvement in the technology is required.

Due to the kinematics (a lot of actuated joints), with respect to the small outer diameter of the carrier (160mm diameter), integration of actuators, sensors, electronics and wires is a major issue. Strong reduction of size and weight is required to successfully achieve the design. ITER in Vessel operational conditions have as well a strong impact on the design. The control of the system should also be able to provide easy driving. Full remote control under blind conditions requires on line collision avoidance and monitoring

The AIA is a 8 meter long multi link carrier with 5 identical modules of diameter of 160 mm and with two electrical joints. Each module includes pitch (+-45°) and yaw (+-90°) joints linked with a parallelogram structure (four bar mechanism) that keep yaw joints axis always vertical.

The robot is moved along its support with an additional linear joint called the deployment system.

A dedicated hardened electronic networked system (Neurobot prototype board) is on board of each AIA module.

B. *Demonstrator manufacture and test campaign*

A scale one mock up of the most heavily loaded module of the AIA, has been manufactured to prove the feasibility of such a design and to quantify the mechanical performances of the robot in terms of stiffness, payload, speed, accuracy and endurance (see Fig. 2).

Fig.2. AIA demonstrator module during endurance tests

The scale one mock up of the AIA went through a series of tests where the major results provide confidence in the ability to design a long reach inspection robot for ITER. The tests showed that:

- Design assumptions on the mechanical characteristics were satisfactory and relevant estimations were correct.
- Mechanical behavior under operational loading is satisfactory.
- Measured deflections are similar to those expected during the design phase,
- Joints are working properly with the relevant design margins,
- Endurance under cycling of the module was greater than 1500 cycle which is representative of a 1000 hour functioning without failure

C. *Vacuum and temperature technologies*

A feasibility assessment of suitable technologies to operate the AIA under the ITER conditions of vacuum and temperature was performed. Robotics components should sustain 120 °C during VV inspection and 240°C during the baking phase for AIA conditioning prior to enter the VV. Limits on out-gassing inside the VV impose serious constraints for the design (e.g. on material, on joints design …). This assessment was carried out through close collaboration and knowledge sharing involving robotics designers and operational Tokamak maintenance team.

The test of these suitable technologies were focused on both mechanical issues and electronics hardening (lubricant free joints, structural materials, tightness, actuator, sensors, on board electronics).

First design of lubricant free joints is based on thermal treatment with Teflon coating. Tests show good results in terms of friction and loading under ITER temperature and vacuum conditions with some limits in lifetime. Other principle of lubricant free joint are under development.

AIA electronics is based on HCMOS military components with ceramic housing. The wide list of HCMOS components, enables to design the required AIA electronics architecture (Neurobot). Main advantage of this networked hardened architecture is to limit the wiring inside the AIA, specially between each module.

A board was manufactured (see Fig. 3) and tested under temperature relevant conditions.

Fig.3. Prototype Neurobot board

After several hundred hours of test, it has been proved that the HCMOS electronics is very reliable. All the electronics have a good behaviour with respect to specifications (20°C up to 160°C). The baking temperature test was also a success, as the whole Neurobot board has withstood temperatures of 240°C.

First individual results give confidence, but feasibility proof requires results on integration of these technologies in a full prototype module.

D. *Prototype module design and manufacture*

To satisfy ITER operational condition (T° & Vacuum), AIA original design have been upgraded with all selected suitable technologies (see Fig. 4)

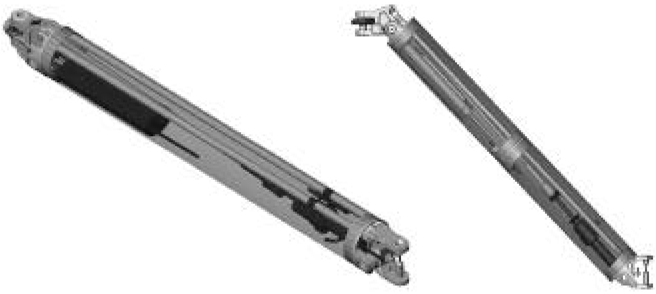

Fig. 4. Prototype vacuum and temperature module design

The main design options that were chosen are :

- Use of metallic alloys for the structure materials such as titanium.
- Some other non organic materials could also be used like Vespel.
- Use of welding processes for assembly of the structure parts.
- Use of temperature hardened DC motors for electric actuators.
- Gearbox will use standard reducers. Roller screw and gearbox should be lubricated and embedded in a tight sealed box with the motors.
- Use of jack like actuator when possible.
- Use of needle bearings with dry lubricant.
- Use of HCMOS military electronics components with a dedicated robot network. Electronics will be embedded in tight boxes with tight feed through or connectors.

The prototype module is now under manufacture. It is composed of structural elements that were qualified through the demonstrator mock-up and improvements that were performed on individual components described above.

E. *Prototype module qualification*

The prototype is designed as the rear or first segment, close to the carriage. It is the most heavily loaded module of the AIA. The maximum representative load will have to be applied to the segment in order to simulate the real conditions of torque and bending.

Preliminary tests are scheduled to be performed early 2004 at room temperature, under atmospheric pressure. Performances of the segment in terms of stiffness, induced deformations, endurance, dynamic behaviour under loading, will have to be fully checked and analysed.

The second phase of the campaign will concern qualification of the prototype segment under vacuum and temperature conditions.

The module will be set-up in a specific vessel that can be baked up to 230°C under high vacuum conditions. After a preliminary outgassing test of the whole component at 200°C in static conditions (ITER requirement), dynamic behaviour of the segment will be analysed in the ITER vacuum and temperature working conditions (120°C). Representative loading will be applied. Endurance of the segment will be tested.

F. *Design and manufacture of AIA robot*

The size of the AIA robot demonstrator is consistent with that required for ITER. The active part is composed of 5 identical segments in order to optimise its cost through series elements manufacture. Its length is 8m and the weight of the active part is about 120 kg.

AIA passive parts consist mainly of a motorised carriage and a passive segment that is going through the outer rectangular port and connecting duct. During AIA operation, the carriage is located behind the torus vacuum valve, in the storage vacuum vessel.

The detail design of the AIA robot will be performed in parallel to prototype segment qualification phase in early 2004.

Manufacture and integration of the AIA carrier is foreseen from mid 2004 to mid 2005. The set of components to be manufactured are the following :

- 5 identical segments,
- passive segment,
- motorised carriage,
- carriage linear guidance and supporting system,
- storage vacuum vessel and pumping .

The vessel is designed in order to allow the storage of full AIA robot and associated carriage in linear position. A vacuum valve isolates the AIA vessel from the plasma vessel.

Full remote control, enabling movement of the robot with on line collision avoidance derived from a numerical vacuum vessel model, will be developed by CEA Association.

Integration and test of the full AIA will be performed by the supplier. Preliminary qualification is foreseen in the CEA laboratory in order to fully validate the remote control system.

III. INTEGRATION ON TORE SUPRA

The AIA is planned to be set up on Tore Supra before the end of 2005. Integration on Tore Supra consists mainly in the assembly of robot active and passive parts in the storage vessel. One has to mention that the AIA vessel device is equipped of a double valve that allows disconnection of the vessel from the Tore Supra duct. Complete AIA stored in its vessel can thus be removed for maintenance.

IV. POTENTIAL USES OF AIA ROBOT FOR IN VESSEL INSPECTIONS

Several potential utilities are being studied to be carried by the AIA for the in vessel components inspection:

- PFCs visual inspection using high definition CCD camera (see Fig. 5 below).

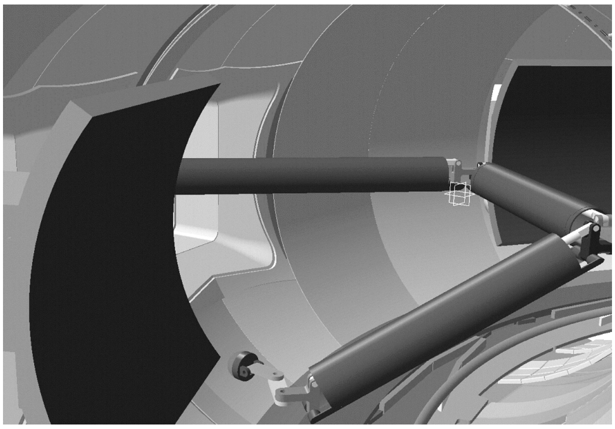

Fig. 5. CAD simulation of AIA inspecting a Tore Supra RF antenna (three of the five articulated head segments and viewing system are visible on the figure)

- water loop leak testing could be performed under dry nitrogen atmosphere, using a specific sensor placed at the head of the AIA carrier able to sniff helium. The AIA is developed to allow accurate displacements of the head, close to the first wall.

- In the frame of long plasma discharges performed on Tore Supra, Deuterium trapping effect is widely increased today. As carbon dust & flakes exist on Tore Supra in several configurations, it is foreseen to perform their removal under nitrogen dry gas at atmospheric pressure, using a sucking process. Analysis of flakes could be performed routinely through a specific analysis equipment connected to the AIA vacuum storage vessel.

- In situ laser ablation operation of carbon appears to be very promising for wall detritiation. Integration of 2 optical fibres could be added onto the AIA, both connected respectively to laser source and spectrometer located outside of the torus.

V. CONCLUSIONS

R&D Results on this multipurpose robotic device give new perspectives on maintenance and operating activities for a reactor like ITER and aim to enhance operator perception of in-Vessel situation.

Following promising first results obtained on individual main active components, a first prototype segment is manufactured that will be tested in relevant conditions in 2004. The complete AIA robot is foreseen to be available in mid 2005.

Demonstration of the AIA behaviour and reliability in real temperature and vacuum tokamak environment is planned on Tore Supra at the end of 2005. Several processes are foreseen to be developed and demonstrated on the AIA robot carrier that could be considered very useful for ITER maintenance.

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