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WEST OPERATION – RELIABILITY AND AVAILABILITY OF A LONG PULSE FUSION TOKAMAK

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Abstract

Since 2016, the WEST tokamak has demonstrated its capability to perform long plasma discharges approaching 1000 seconds in a fully metallic environment. It operates with a permanent magnetic field of up to 3.65T generated by 18 superconducting toroidal field coils cooled at 1.8K with a helium cryogenic system. Since 2021, all plasma-facing components (PFCs), including the tungsten ITER-grade divertor, are actively cooled by pressurized water, making WEST representative of future superconducting fusion devices. Between 2022 and 2024, experimental campaigns achieved significant improvements in performance. The number of long-duration discharges (>100s) increased threefold thanks to the non-inductive current drive from the Lower Hybrid Current Drive (LHCD) system, culminating in a world record plasma duration of 22 minutes with 2.6 GJ injected energy. Total plasma time exceeded five hours per year, with over 70% of successful pulses. These results are enabled thanks to the availability of the WEST machine and all subsystems, higher than 70%. The study of downtimes recorded during experimental campaigns, shows four main elements/systems impacting WEST operation: the poloidal field, the water and air leaks in vacuum vessel, the CODAC (Control, Data Access and Communication) system and the cryogenic system. Key lessons for future fusion devices include robust water leak detection and management for actively cooled plasma-facing components, comprehensive thermal protection to prevent damage to uncooled vacuum vessel areas. These measures ensure reliable long-pulse operation and inform the design and operation of next-step superconducting fusion machines.

1. INTRODUCTION

Since 2016, the WEST tokamak has demonstrated its capability to perform long plasma discharges with 22 minutes world record plasma duration in a fully metallic environment. Designed for long-pulse, full-tungsten device, WEST provides an essential testbed for validating Plasma Facing Components (PFCs), operational strategies, and control systems relevant to next-step superconducting fusion machines.
After reviewing WEST main features and capabilities, this paper presents the WEST main achievements of the last three years. Performance indicators relating to machine operation, such as availability, pulse rating, and cumulative plasma time, are also reported. Finally, analysis of downtimes during experimental campaigns enables the identification of critical elements/components for a reliable operation.

2. WEST FEATURES AND CAPABILITIES

WEST is a mega-ampere plasma current class superconducting tokamak capable of achieving long plasma durations in a full tungsten environment. WEST is presently the only superconducting tokamak in operation in Europe and one of the five superconducting tokamaks in operation in the world. The main parameters of the WEST device are presented in the Table 1.

TABLE 1. WEST Features

Plasma current	1MA (q95~2.5)
Toroidal field	3.65 T @ R=2.5m
Major radius (R)	2.5 m
Minor Radius (a)	0.5 m
Plasma volume	15 m^3
P_{ICRH}	9MW
P_{LHCD}	7MW
P_{ECRH}	3MW (≥ 2026)
Flat-top duration	> 1000s

Whereas the Phase 1 (2016-2021) was with a mix of actively cooled ITER like tungsten (W) PFC and inertial W-coated graphite components in his lower divertor, in Phase 2 started in 2021, the lower divertor is equipped with a full ITER-like divertor, and almost all PFCs actively cooled. Over the past three years, with this full tungsten actively cooled environment, the WEST tokamak has enabled progress in obtaining long-lasting plasma.

The achievement of long plasma pulses requires key components and systems. Actively cooled PFCs must be able to sustain continuous high heat flux up to 10MW/m^2 on the lower divertor and few MW/m^2 on others PFCs without causing damage to the material. To obtain these conditions, all components inside the vacuum vessel are cooled by a high-pressure (up to 40 bar) and high-temperature (up to 200°C) primary water loop associated to a large cooling circuit network all around the machine. The secondary loop which extracts the heat from the primary loop and all the other dedicated water loops (power supplies, cryogenic system, heating systems, etc.) has been recently upgraded with an additional air-cooling tower to be able to reject in steady-state, a total power of 15 MW (see Fig. 1).

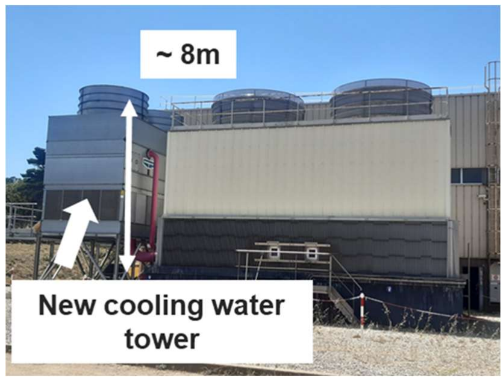

FIG. 1. WEST Air Cooling Towers (15MW)

Permanent magnetic field is also required for long plasma pulses. In WEST, it is produced by 18 niobium titanium (NbTi) superconducting winding operated at helium superfluid temperature 1.8K, encapsulated in thick casings cooled with supercritical helium at 4.5 K (see Fig 2). These coils are surrounded by inner and outer 80 K radiative thermal shields. The coils are cooled by an helium cryogenic system involving a warm compression station, a cold box equipped with cold compressors and several expansion machines (see Fig. 3), and cryogenic lines to the tokamak. The cold power is 3kW equivalent at 4.5 K (1/3 of JT-60SA cryogenic system) and the helium inventory can reach up to 3.5 tons.

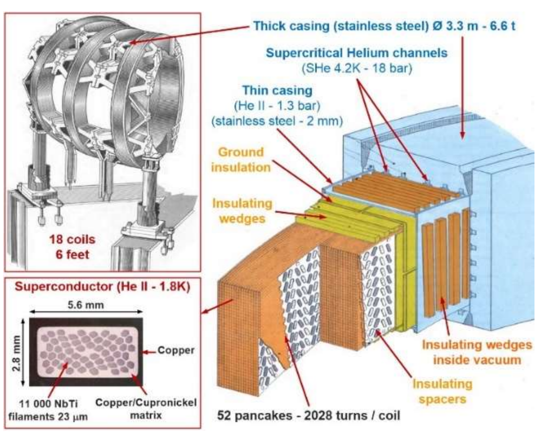

FIG. 2. WEST Toroidal Field Coils

FIG. 3. WEST Cold box

Heating and current drive systems, essential to perform long plasma pulses, are provided by radiofrequency (RF) waves (See Fig 4). The Lower Hybrid Current Drive (LHCD) system consists of two launchers supplying respectively 3 MW for the Full Active Multijunction (FAM) launcher and 4 MW for the Passive Active Multijunction (PAM) launcher, for 1000 s at 3.7 GHz. The system is powered by 16 klystrons from THALES. The Ion Cyclotron Resonance Heating (ICRH) system consists of 3 launchers supplying 3 MW steady-state (9

MW / 30s) at 45-60 MHz. In addition, a new Electron Cyclotron Resonance Heating (ECRH) system started commissioning at the end of 2024, with first plasma operation in early 2025 (500 kW-100 ms). The final system (3 MW, steady state, 105 GHz) will be powered by 3 THALES gyrotrons and will be fully operational in 2026. The launcher currently installed comes from the former ECRH Tore Supra system, with a capacity limited to 1 MW/30s per line of injection (one line/gyrotron). A maximum total steady-state power of 10 MW is therefore currently available, which could be improved to 13 MW (with an upgrade of the launcher) for heating the plasma.

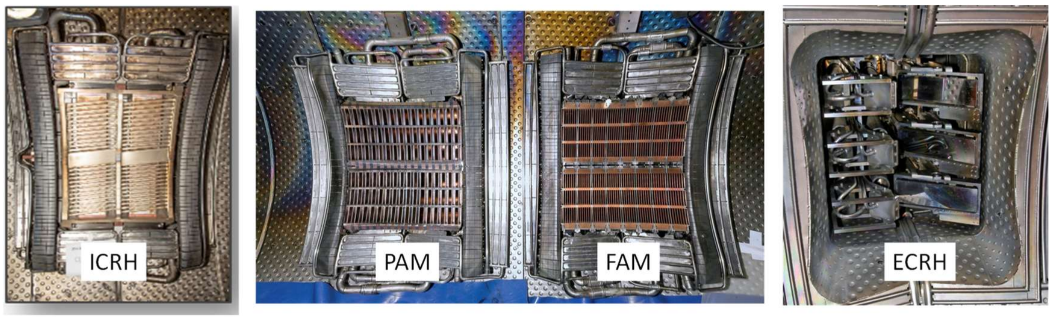

FIG. 4. ICRH, LHCD and ECRH launchers in WEST

3. WEST MAIN ACHIEVEMENST ON LONG PLASMA PULSES (2023-2024-2025)

Since the start of WEST Phase 2, rapid progress has been made (see Fig. 5), resulting in the achievement of a plasma discharge exceeding 22 minutes and 2.6 GJ of injected/extracted energy (see Fig. 6). This success is the combination of integrated modelling activities in order to identify and define the operating window in terms of plasma scenario to avoid tungsten accumulation in a fully non inductive regime. Specific plasma controls were also developed, in particular a double control to ensure the constant loop voltage (Vloop=0 for the long pulse operation) using the central solenoid voltage and to maintain the plasma current to the prescribed value by using the amount of power delivered by the LHCD system. Such controls are now routinely used at WEST. Such long discharges are a challenge in terms of plasma operation and sub-system reliability because any failure would result in the termination of the plasma discharge.

FIG. 5. Progress in long pulse duration

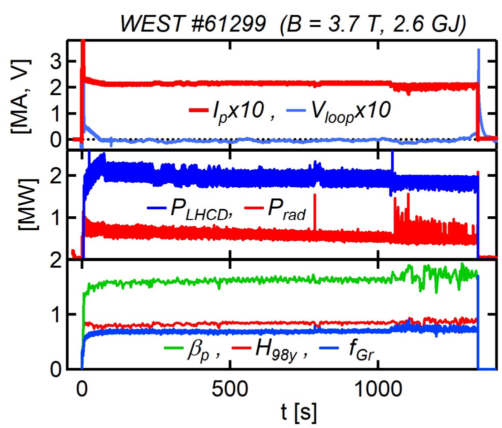

FIG. 6. WEST record plasma duration (22 minutes)

In parallel to the development of pulses lasting a significant fraction of hour, WEST has made a high fluence campaign in 2023. It consisted in a repetition of about 60 s long pulse during one month dedicated campaign. A total 30 GJ of injected/extracted energy was achieved. The fluence reached was [5×10^{26} D m^{-2}] at the outer strike point corresponding to ~2.5 nominal 200 s discharges in the ITER Pre-Fusion Plasma Operation phase. This campaign was an opportunity to has demonstrate the reliability of the WEST subsystems.

Moreover, the experimental campaigns show good progress in terms of cumulated plasma duration, with more than 5 hours, and in 2019 and from 2023 to 2025, a total of plasma pulses greater than 1200 per campaign (see Fig. 7). The WEST machine clearly demonstrates its ability to operate all systems efficiently. The years 2020-2022 were impacted by the COVID pandemic and by an incident on the cryogenic system, reducing significantly the number of campaign days. The average number of plasma pulses per day has remained steady at 20, with a maximum of 45 pulses in a single day and an average frequency of one plasma every 20 minutes. Moreover, the rating of plasma pulses shows that a high level of successful plasma pulses has been achieved with around 70% of discharges recorded without technical problems (see Table 2).

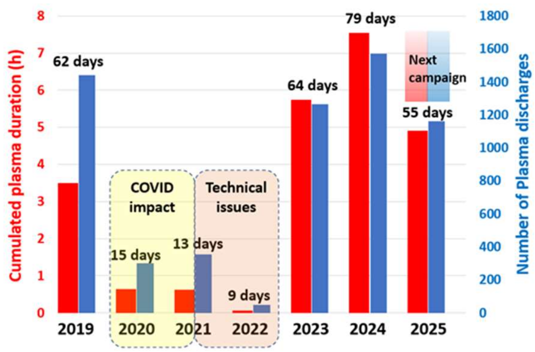

FIG. 7. Statistics over the years, number of days with plasma, number of plasmas, cumulated plasma duration

TABLE 2. *Statistics over the years, number of days with plasma, number of plasmas, cumulated plasma duration*

Year	Number of plasma pulses	Successful plasma pulses (%)
2023	1264	67
2024	1570	76
2025	1161	74

4. WEST OPERATION

The machine operates on a balanced annual cycle, alternating between 6 months of plasma campaigns and 6 months of shutdowns for maintenance and evolution of the systems. Restart phase follows shutdowns to bring the systems to the performance required for the plasma campaigns. The experiment timeline is defined by the experimental committee, based on the proposal from the Program Coordinator, Task Force Leaders and Commissioning Manager. Based on this timeline, the machine configuration is prepared to meet the requirements of the experimental program. The campaign, restart and shutdown phases are closely monitored with the goal of running the machine on 50% of working days each year. The WEST machine running time for experimental campaign was 42% in 2024, which reflects the effectiveness of the quality-controlled maintenance and evolution plans implemented by the operation teams (See Fig. 8). The operation is managed by an Operation Manager supported by a Coordinating Unit which interacts with the scientific and technical groups in charge of the various sub-systems, to build and monitor the overall schedule, taking into account co-activities, availability of the services, and safety regulations.

Experimental sessions are held 4 days per week, while Mondays are reserved for maintenance, testing, and wall conditioning. The experimental sessions are organized as follow:

- Tuesday and Thursday: plasma operation from 08:00 until 21:00 with two shifts
- Wednesday and Friday: plasma operation from 08:00 until 18:00 in a single shift.

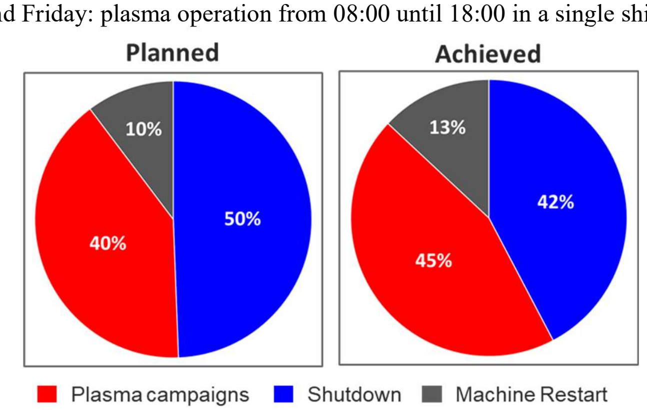

FIG. 8. Yearly distribution in 2024

Machine availability during an experimental day is a key performance indicator. Since 2017, it has consistently exceeded 70% (See Fig. 9), reflecting effective coordination of resources and good responsiveness to incidents. The higher availability score reached during the 2021 experimental campaigns and the lower availability score reached during the 2022 experimental campaigns are not representative, as the number of days of plasma operation were abnormally low. Indeed in 2021, a major failure of the helium tank of the cryogenic plant caused the interruption of the plasma operation during about 10 months. In 2022, a number of technical incidents hindered the start of WEST Phase 2 and the commissioning of the new ITER-grade divertor.

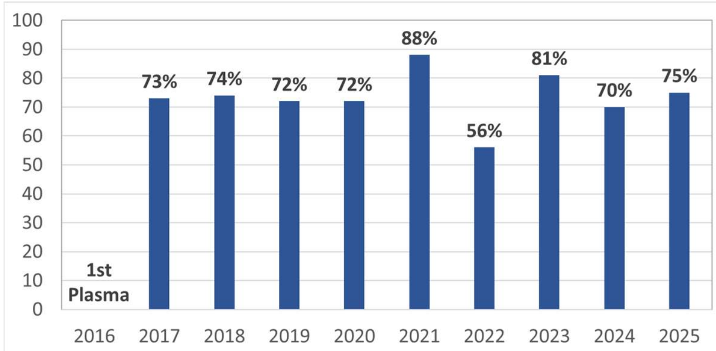

FIG. 9. Availability during experimental campaign

5. ANALYSIS OF OPERATION DOWNTIMES

During experimental campaigns, any operation downtime is systematically recorded in a dedicated database by entering the description of the incident, its duration, and the affected system. An incident classification, based on duration and cost criteria (> 4hours, > 30k€), is used to identify major incidents which are followed-up with a detailed analysis of the causes to elaborate a corrective action plan. Moreover, all incidents are reviewed annually in order to complete and prioritize actions for the maintenance plan of all subsystems.
The Figure 10 provides an overview of the operation downtimes during experiment campaign for the last three years. The total downtime amount represents ~ 40 days out of 200 days of experimental campaigns. Downtimes due to Poloidal field system, air and water leaks, CODAC (Control, Data Access and Communication) and Cryogenic system dominate the statistics, representing nearly 80% of the total.

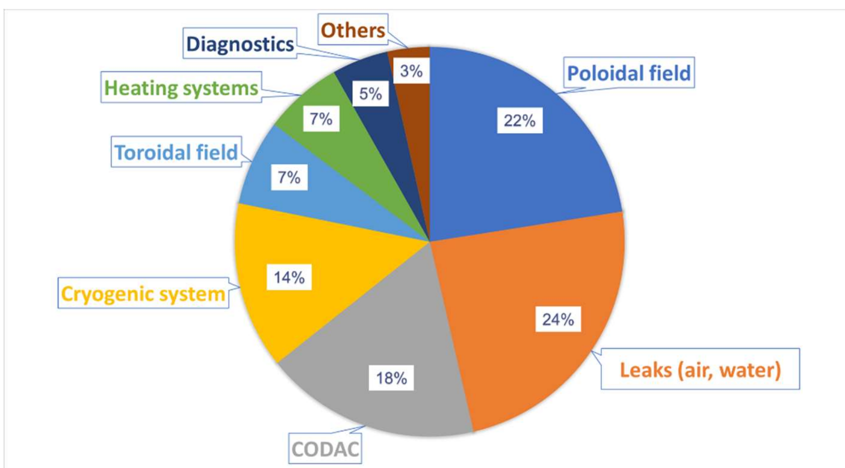

FIG. 10. Operation downtimes for 2023-2024-2025: Time contributions (%) of systems

6. LESSONS LEARNT ON COMPONENTS RELIABILITY

6.1. Poloidal Field System

Regarding Poloidal field, the system is aging as it was commissioned at the beginning of Tore Supra in the 1980s. The downtimes cause by the system, consist of multiple short shutdowns with few minutes interventions and a few longer shutdowns requiring interventions lasting up to one day. The involved components are the electrical power supplies (thyristors, diode bridge, control boards …) and high-speed switches used for each plasma discharge, on which troubleshooting is time-consuming due to the lack of instrumentation. The available spare parts currently ensure the operation of this pulsed system. Continuing the operation over a 10-year period, the power supplies is identified as one of the systems to be partially refurbished.

6.2. CODAC (Control, Data Access and Communication)

CODAC (including Plasma Control System (PCS), Plasma supervision, Data networks), is essential for real-time control and data collection. As shown in the Figure 11, in 2023, experimental campaigns were significantly impacted by technical issues due to upgrades performed in 2022. The situation has significantly improved over the last two years, with downtimes lower than 1%. The rehearsal sessions in the control room with operation team organized before each experimental campaign are essential for the test of integrated CODAC and machine protection schemes. A major step forward would be the capability to replay one selected pulse to test and validate the entire acquisition and control chain.

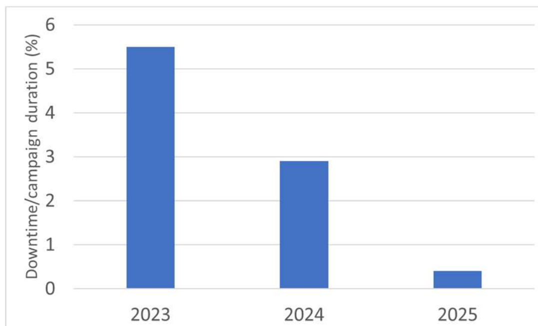

FIG. 11. Evolution of CODAC downtimes compared to campaign duration

6.3. Cryogenic System

Technical incidents on the cryogenic system usually result in long shutdowns because they require to warm-up and cool down of the magnetic system (~ 2 months). The downtime duration reported in Fig. 9, is mainly due to a single technical issue causing the campaign to be interrupted during 5 days: the cryogenic system stopped due to a protection alarm, caused a pressure increase in the helium volumes, followed by the opening of safety valves. For this event, no warm-up was necessary to restore the pressure safety component tightness and nominal temperature of the coils. In most incidents on cryogenic systems, backup modes are implemented and regularly performed to keep the coils at cryogenic temperature in case of PLC (Programmable Logic Controller), power supplies, water cooling system failure.

6.4. Plasma facing components leak management

Water and air leaks are identified by mass spectrometers connected continuously to the vacuum vessel. Leak localization and repair, whether or not this requires opening the vacuum chamber, are very time-consuming operations. Since WEST is equipped with actively cooled plasma-facing components, water leak management constitutes a critical operational consideration. Since the WEST beginning in 2016, seven events involving internal components have occurred. It should be noted that all components are qualified through specific test-bench procedures, under 45 bar pressure and at a temperature of 200 °C, in order to validate their helium leak-tightness. Moreover, the leak-tightness of the final hydraulic connections and welds performed in the vacuum vessel is tested under a pressure of 45 bar in helium and 28 bar in water. These tests have reduced the occurrence of leaks but do not eliminate them entirely. The leaks encountered involved two types of components, both new (3 leaks) and long operation ones (4 leaks) (See Fig. 12). Typical duration of an in-vessel water leak is 5 weeks for localization, isolation and draining of water-cooling circuits, repair and test in the vacuum vessel, refill of water loop and vacuum vessel pumping out in parallel. The leak localization has been significantly improved and is now faster thanks to isolation valves used to section off the numerous various hydraulic circuits and identify the leaking component before opening the vacuum vessel. The leak management will crucial for future machines so advanced detection techniques had to be developed, such as infrared water leak detection and remote sniffing inside the vacuum vessel.

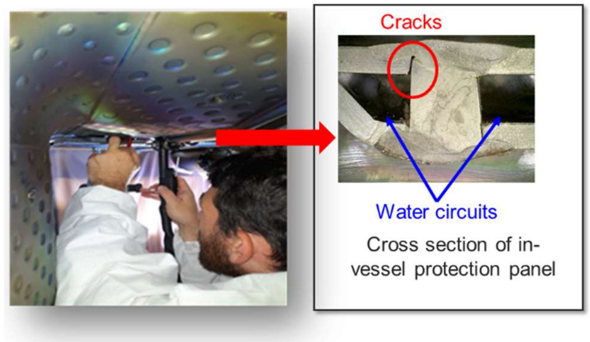

FIG. 12. Water leak repair on In-vessel protection panel in vacuum vessel

6.5. Challenge to reach 100% of actively cooled PFC

During plasma pulses reported in Fig. 13, a variation of density caused the stop of the pulse. This variation is attributed to surface outgassing, indicating inertial components reaching high temperatures. WEST targets 10 MW steady-state power, with about 50% radiated power, which would bring those components to higher temperatures. Simulations results on uncooled components, indicate that thermal loads up to 15 kW/m² would be observed on significant areas of the vacuum vessel such as bellows and support structures. The level of thermal loads would imply temperatures above acceptable limits and could cause damage on components. Actively cooled protections have been designed and integrated in WEST in most of the unprotected areas. However, passive protections had to be installed for some components (See Fig. 14), because of two main reasons. Firstly, the rooting of water pipes within the existing WEST environment is extremely complex, imposing dismantling of too many components, sometimes critical ones; and secondly the welding of those water pipes had to be compliant with pressurized water circuits and high vacuum, which wasn't always possible within the tight spaces available. Temperature measurement on passive plates protecting vacuum vessel bellows in the upper divertor region, shows nearly 300°C reached. For the future fusion devices, the configuration of vacuum vessel first wall is critical and had to take into account cooling needs for all components since improvements are too complex to integrate.

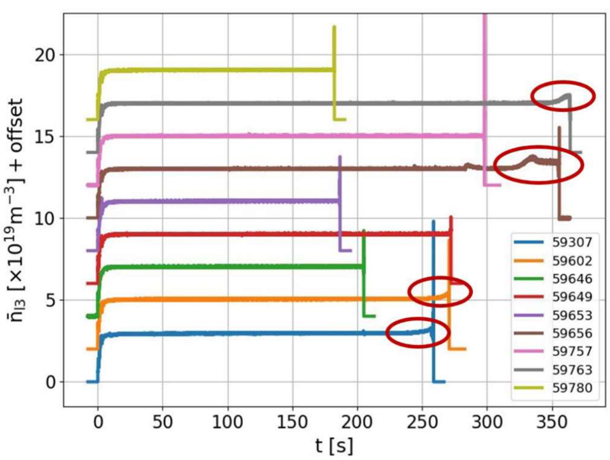

FIG. 12. Increased of plasma density: longest duration pulses display outgassing

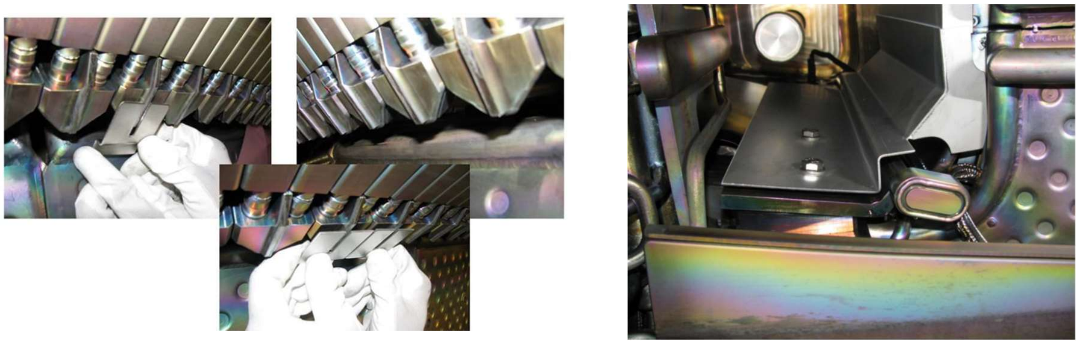

FIG. 14. Integration of passive protection in WEST vacuum vessel

7. CONCLUSION AND PERSPECTIVES

Over the past three years, the WEST tokamak has demonstrated remarkable progress in long-pulse plasma operation in a fully actively cooled tungsten environment. With a record plasma duration exceeding 22 minutes and a cumulative injected/extracted energy of 30 GJ during high-fluence campaigns, WEST has validated key technologies and operational strategies essential for next-step superconducting fusion devices.

The machine has shown high reliability and operational efficiency, with over 70% of pulses executed successfully and machine availability consistently above 70% during experimental campaigns.

Detailed analysis of downtimes has highlighted critical systems, including the Poloidal Field system, CODAC, cryogenic system, and water/air leak management in plasma-facing components, allowing targeted improvements and preventive measures. WEST has proven to be an effective testbed for long-pulse, high-fluence plasma operation and for advancing the technological readiness of components and subsystems.

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