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Overview of JET Restart: Integrated Commissioning and Plasma Commissioning

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Abstract.

The JET Restart process is a critical phase in the operation of the Joint European Torus (JET), enabling the transition of JET plant from Shutdown to experimental plasma campaigns. This paper provides a comprehensive overview divided into its two main stages. The first stage, Integrated Commissioning, encompasses the activation and synchronization of critical systems, from magnet energization to diagnostics calibration. The second stage, Plasma Commissioning, focuses on achieving reliable and sustained plasma initiation, conditioning plasma-facing components, and optimizing auxiliary heating and other systems. The paper details the sequential phases and steps of JET Restart, outlines the planning and coordination, and introduces how the commissioning procedures for Restart activities are reviewed, managed, and monitored. Special emphasis is placed on organization and coordination of the Shutdown-Restart transition. The paper also explores the specific commissioning activities required for deuterium-tritium (DT) experimental campaigns, highlighting the additional safety measures and operational adjustments needed for tritium handling. By documenting the JET Restart methodology and lessons learned, this paper provides valuable insights for the commissioning of next-generation fusion devices. As one of the most complex fusion facilities globally, JET's Restart activities serve as a critical benchmark for the operational procedures of future large-scale fusion devices.

1 Introduction of JET Restart

The term **JET Restart** refers to the integrated commissioning of the JET machine [1], including its associated systems and ancillary equipment, following a machine **Shutdown**, the period when the machine is not operating when maintenance and upgrades can be performed. The **Restart** period marks the beginning of **Operations**, the period during which the JET device is operational. **Restart** begins with the restoration of power to machine control cubicles and ends on the first day of the experimental campaign, which is designed with clear objective to study plasma behaviour, optimize fusion conditions and refine operational scenarios.

If the preceding **Shutdown** includes a vacuum break or modifications to sub-systems, then a certain amount of machine time is required for **JET Restart** before an experimental campaign can begin. **JET Restart** comprises two main stages:

- **Integrated Commissioning** of JET sub-systems
- **Plasma Commissioning.**

Integrated Commissioning ensures that JET sub-systems function together seamlessly by performing specific coordinated activities to deliver a plant ready for plasma operation. It is a series of actions defined by their specific outcome (for example energisation of the magnets), involving more than one system, requiring a set of processes and procedures, and having a set of prerequisites and conditions. The initial phase of JET **Integrated Commissioning** overlaps with the final phase of JET machine **Shutdown**. This **Shutdown-Restart transition** begins two weeks before the planned JET vessel pump-down and ends with the closure of the JET biological shield—a thick concrete structure that surrounds the machine to protect personnel from neutron radiation, especially during Deuterium-Tritium campaigns. Good coordination of maintenance, assembly, and commissioning activities during the Shutdown-Restart transition is crucial. It ensures smooth follow-up activities and a successful Restart campaign. Plasma Commissioning marks the resumption of Plasma Operations (First Plasma). It includes commissioning real-time plasma protection systems, conditioning the first wall and auxiliary heating systems, and calibrating diagnostic systems. Finally, it confirms readiness for scientific campaigns.

Targets for **Restart** activities are agreed between Operator and the JET Exploitation Unit (JEU) who represents the interest of the scientific programme since 2000, which is run by EUROfusion. The Task Force Leaders, who manage the scientific programme, are invited to comment and place requests for dedicated commissioning in preparation for the experiments (e.g. new plasma configuration tests, commissioning of unusual heating or diagnostic settings). The annual JET Operational Implementation Document (JOID) establishes the scope and timeline for **Shutdowns** and **Restarts**. This document, agreed upon by the JEU and the UKAEA as JET Operator, is reviewed and approved during the JET Coordination Meeting (JCM). With these targets in place, the Operator develops a detailed plan to commission the machine to the point of readiness for all activities. Progress against the plan is monitored at daily **Restart** meetings and at the weekly co-ordination meeting. The progress is reported at the JET Programme Execution Committee (JPEC) meeting which takes place every 2 weeks and can approve changes to the **Restart** schedule and content.

JET's scale and capabilities strongly impact operations and commissioning requirements. For example, the risk of machine damage from disruption forces due to JET's size and plasma current is significant and must be managed via procedures and protections. The use of tritium and the production of D-T neutrons lead to additional safety and budget management requirements that must be incorporated in the

operations and commissioning. These impacts are common to those that will affect ITER and other future devices and so the knowledge and lessons gained from JET's operations can make significant contribution to the development of processes and procedures for commissioning of future devices. Indeed, ITER has already considered much JET experience in the design of its commissioning processes [2] [3]. **JET Restart** commissioning can also be compared with that of other current tokamaks and stellarators such as EAST [4], Wendelstein 7-X [5], WEST [6] JT-60SA [7], KSTAR [8], and HL-3 [9] which provide additional and complementary good practices and procedures to help prepare future devices operations, especially for superconducting magnets and very long pulse operations..

The rest of this paper will give the details on how the **JET Restart** is managed and operated. Section 2 introduces the typical sequences and step for a **JET Restart** campaign; Section 3 covers the **Integrated Commissioning** stage, and Section 4 the **Plasma Commissioning** stage. Special commissioning activities for DT campaigns are presented in Section 5. Lessons learnt during **JET Restart** campaigns are discussed in Section 6. In Section 7, the results are summarised, and their implications discussed.

2 Typical sequence and steps for JET Restart activities

The **JET Restart** process follows a structured sequence and is carried out in strict order of priority:

- 1) Protection of personnel and public
- 2) Machine integrity
- 3) Ability to deliver programme requirements

As a UK-based facility operated by UKAEA, JET activities follow UK safety law and UKAEA safety rules, guidelines, and processes. A Safety Case [10] defines operational boundaries, supporting the issuance of an Authority to Operate (ATO) certificate. Key Safety Related Equipment (KSRE) and Safety Related Equipment (SRE) systems are maintained according to the Torus Safety Case, which outlines two regimes: **Shutdown** and **Operations**. Most maintenance and assembly occur during **Shutdown**, minimizing hazards to ensure risks remain As Low As Reasonably Practicable (ALARP). **Operations** begin when isolations are lifted, initiating the **Restart** process.

JET Restart begins with the activation of control cubicles, overlapping with final **Shutdown** tasks. The initial focus is commissioning critical control systems. KSRE/SRE and Integrated Operational Protection System (IOPS) commissioning is prioritized, along with turbopump and vacuum valve checks. The Central Interlock Safety System (CISS) and Off-coil power supply commissioning start early and continues throughout **Restart**.

Once **Shutdown** tasks are complete and isolations are removed, transitioning to the **Operations** regime starts. This transition is marked by the powering of the Limb Junction Boxes, the junction boxes through

which electrical power is provided to all tokamak systems. Following the limb junction boxes going live, the JET Control and Data Acquisition System (CODAS) [11] commissioning is normally carried out. It is designed to check the integrity of CODAS system and ensures that any changes to the hardware or software during the **Shutdown** has been reinstated and superficially working correctly. As KSRE/SRE and IOPS commissioning advances, critical services like baking system, cryogenics, and gas injection systems are activated. Diagnostics are also aligned or calibrated during this phase.

After vessel tasks and (K)SRE/IOPS commissioning, the vacuum vessel is pumped down and leak-tested. Repairs are made as needed. Diagnostics component outside the machine boundary may be installed and aligned, and gas injection and residual gas analysis systems tested. The machine is then ready for baking.

By this stage, all the shutdown tasks should be completed, and no one can carry out tasks in the torus hall, vessel will start baking at 200-320 °C removes moisture and impurities. Leak tests at various temperatures follow. If successful, Glow Discharge Conditioning (GDC) begins. A second inspection confirms readiness for electric power and cryopumps.

When PSACS commissioning is complete, the torus hall is secured, ensuring no personnel remain. Next, high-voltage coil tests and commissioning of coil protection systems and power supplies are conducted. Auxiliary heating systems, such as Neutral Beam Injection (NBI) [11] and Ion Cyclotron Resonance Heating (ICRH) [12] [13], are tested. Diagnostics are calibrated with vessel temperature at 200 °C as JET plasma operation usually carry out at this temperature. A final inspection ensures the torus hall is clear, and the machine is ready for **Plasma Operations**.

With diagnostics and power supply commissioning complete, JET transitions to **Plasma Commissioning**. After successful plasma tests, JET is ready for experimental campaigns.

During **JET Restart**, a minimum of three machine inspections should take place:

- **Machine Inspection 1** – prior to vessel bake. This inspection ensures no tools or scaffolding remain in the area where Shutdown and Restart tasks were carried out, and the machine is ready for baking.
- **Machine Inspection 2** – prior to on-coil commissioning of the tokamak power supplies. It verifies that no items, such as gas bottles or leak detection tools, are still attached to the machine and confirms it is safe to apply power.
- **Machine Inspection 3** – prior to JET plasma operation. This final check ensures that any unnecessary objects have been removed from the torus hall and that all necessary equipment is in place for operation.

Personnel involved in these inspections include the Torus ATO Holder (ATOH), JET Chief Engineer, and representatives from all relevant groups involved in machine installation and commissioning. The Tokamak Operations Unit manages and organizes these inspections, producing detailed reports and action lists required for further **Restart** activities. The action list from the final inspection constitutes a series of conditions which need to be met to handover the machine for experimental campaigns.

In practice, the scope of activities required for each JET Restart campaign varies significantly depending on the maintenance, services, and upgrades performed during the preceding shutdown and interventions. During 40 years of operation, JET has continually embraced innovation, adapting to new technologies and research areas. Several significant upgrades have been implemented to enhance performance and align with future fusion research goals [1]. A substantial upgrade occurred during the 18-month shutdown period from 2009 to 2011, when JET replaced its graphite first wall with an ITER-relevant beryllium and tungsten metallic wall. Following such major modifications, extensive commissioning of nearly all subsystems was required before plasma operations could resume. Consequently, the 2011 Restart campaign was highly complex and challenging, involving more than 300 individual activities.

The timeline and key activities for the **2011 JET Restart** campaign following the installation of the ITER-like wall are summarized in Table 1. Although the table highlights key milestones, the full campaign encompassed a vast number of tasks to ensure a safe and efficient return to operations. This **Restart** campaign was one of the most complicated **Restarts** in JET's history.

In contrast, some **Restart** campaigns require much fewer steps, particularly when shutdown periods are short and no major subsystem upgrades are undertaken. In such cases, the **Restart** process can be completed in a much shorter timeframe with minimal commissioning requirements. There are also some accelerated Restart activities in response to unplanned events rather than planned maintenance and upgrades, such as an unexpected water leak. In those cases, after detecting and repairing the issue, most of **Integrated Commissioning** activities are bypassed, the **Restart** primarily focuses on machine conditioning and attempting plasma operations.

Table 1: JET 2011 Restart timeline and key activities.

Phase	Key dates	Event	Key activities
Phase R1A (14 Feb -15 April)	14 th of Feb	R1A Starts	Shutdown-Restart Transition phase; remaining shutdown tasks continue; power-up selected cubicles; control systems, turbopumps and Vacuum Valve commissioning; (K)SRE &IOPS and off-coil PS commissioning starts; removal of isolations; services restore; diagnostics checks
	7 Mar – 4 April	CODAS Commissioning	
Phase R1B (16 April-17 May)	16 April	R1B starts	Vessel pump down and leak checks; (K)SRE &IOPS and off-coil PS commissioning continues; diagnostics installation and initial alignment; gas injection controllers, RGA and PSACS commissioning; Torus Hall doors closed; Machine inspection 1 performs; Raman calibration
	12 May	Torus Doors closed	
	12 May	Machine inspection 1	
Phase R1C (18 May – 1 Jul)	18 May	R1C starts Baking starts	vessel baking at 200-320 °C; leak checks at different temperatures; GDC at 200 °C and 320 °C; HV testing of coils, on-coil PS, Cryo-pump commissioning; NBI and HFPI async tests; final leak check; Magnetics calibration; diagnostics alignment at 200 °C
	6 June	Machine inspection 2	
Phase R1D (2 Jul - 5Aug)	2 Jul	R1D starts	Finish diagnostics alignment; finish on-coil PS commissioning; PPCC commissioning on coils; first technical plasma; NBI sync continues; plasma commissioning; PIW system tests
	5 Jul	Machine inspection 3	
	1 Aug	First Plasma	
C28A-C (8 Aug – 14 Nov)	8 -17 Aug	Campaign C28A	Ohmic plasma programme; NBI and ICRH Asyn commissioning
	12 -29 Sep	Campaign C28B	L-mode plasma programme; NBI and ICRH low power SYNC commissioning
	18 Oct – 14 Nov	Campaign C28C	H-mode plasma programme; NBI and ICRH high power SYNC commissioning
Phase R2-4 (18 Aug – 9 Sep)	18 Aug – 9 Sep	Phase R2	PPCC commissioning on new configurations and STOPS; PIW camera and ILW RT protection systems commissioning; diagnostics commissioning;
	4 – 17 Oct	Phase R3	Plasma commissioning on PPCC, WALLS new functionality, PIW systems; VDE tests for new/modified configurations; diagnostics commissioning continues
	15 -18 Nov	Phase R4	VTM commissioning; Basic' Kicks' and EFCC controller test; Neutron diagnostics calibration
Campaign C29	21 Nov	Experiment starts	Experimental Campaign starts, 46 sessions in total

3 The Integrated Commissioning of JET sub-systems

The **Integrated Commissioning** of JET systems is essential to ensure the machine is fully functional and ready for **Plasma Operations**. This process involves careful planning, coordination, execution, and monitoring, supported by a well-defined framework to manage procedures, resolve exceptions, and document progress. Each JET system has its own stand-alone activities which are conducted prior to integrated commissioning and do not require plasma or consideration of other systems. These are important as part of the commissioning process but are not discussed further here.

3.1 The JET Shutdown-Restart transition

As shown in Table 1, commissioning of JET sub-system already starts in the initial **Shutdown-Restart** transition phase (as **Phase R1A**) and all the commissioning activities in the phase should follow the same process as in the later phase. However, due to the complex of overlapping with **Shutdown** tasks, JET **Shutdown-Restart** transition phase has its own special rules and safety management, comparing with the following phases. To ensure a seamless transition, preparations for the **Shutdown-Restart** phase must start two months before the planned vessel pump-down. This preparation minimizes the risk of overlooking maintenance, installation, or local commissioning tasks that could delay **Restart** activities. **Shutdown** and **Restart** Plans must align, with focus on:

- **Shutdown** tasks critical to the timeline
- New system installations
- Services (power, vacuum, cooling, etc.) essential for commissioning

Co-ordination during this transitional period is managed through regular meetings:

- JET Coordination Meeting (JCM) – held fortnightly on Wednesdays
- Coordination Meeting (Design/Assembly) – held on Mondays;
- Coordination Meeting (Commissioning) – held on Fridays;
- **Shutdown** Planning Meeting – held on Thursdays;
- **Restart** Meetings – held daily, Monday-Thursday;

Both the **Shutdown** and **Restart** Managers report to the JCM and Coordination Meetings during this phase. **Restart** Meetings, which begin two weeks before the planned pump-down, are divided into two parts:

- Assembly Activities, chaired by the **Shutdown** Manager or delegate.
- Commissioning Activities, chaired by the **Restart** Manager or deputy.

Both parts of **Restart** Meetings should be attended by the representatives of all groups involved in maintenance, assembly, and commissioning activities. After the closure of the JET biological shield, daily **Restart** Meetings are chaired only by the **Restart** Manager or Deputy.

During the transition phase, the status of machine isolation transitions from the “**Shutdown**” regime to the “**Operations**” regime as defined by the JET Safety Case. Until the JET vessel pump-down, the work within JET operational areas is carried out according to the **Shutdown** Plan and is managed and approved by the **Shutdown** Manager and the Torus ATOH.

During the **Shutdown-Restart** transition phase, any assembly and commissioning work in the JET operational areas must be approved by both **Shutdown** and **Restart** Managers (or delegates) and the Torus ATOH. After the closure of the biological shield, any work in the JET operational areas must be approved by the **Restart** Manager and the Torus ATOH. If access is required at short notice during machine operational hours, the work could be approved by the Engineer-in-Charge if the **Restart** Manager and/or ATOH are not available.

Following the vessel pump-down, any work in the operational areas must be accompanied by an approved Request for Work in Operational Areas (RfW). The Requests for Work in Operational Areas must be submitted in advance of the planned work to the daily **Restart** Meetings or to the Co-ordination Meeting and must be recorded on the Weekly Work Plan or on the **Restart** Plan.

During the JET **Shutdown**, regular inspections of the Torus Hall are carried out by the Torus Hall Supervisor, the **Shutdown** Manager, and the Torus ATOH. During the transition from **Shutdown** to **Restart**, thorough machine inspections must be carried out to ensure safe operation and integrity of the JET machine. The Torus ATOH holds a ‘**Shutdown**’ regime interlock (Fortress) key which will only be released when conditions defined in the checklist have been fulfilled. The Torus ATOH may limit or impose conditions on the transition from one regime to another in order to ensure the safe working environment.

Key documents, including Requests for Work, isolation statuses, inspection reports, and handover documents, are archived by the relevant teams and made accessible via the UKAEA intranet.

3.2 Organization and coordination of Integrated Commissioning

The **Integrated Commissioning** activities are overseen by the **Restart** Management Team, comprising the following roles:

- **Restart Manager:** Leads the **Restart** process, prepares the **Restart** plan, oversees **Integrated Commissioning**, monitors progress, and ensures safe delivery in collaboration with the Torus Authority to Operate Holder (ATOH).
- **Deputy Restart Managers:** Assists the **Restart** Manager in all responsibilities.

- **Commissioning Coordinator:** Manages commissioning procedures, maintains the procedure database, facilitates approvals, and reports progress.
- **Restart Secretary:** Updates the commissioning database, archives documents, and supports the **Restart** Management Team.
- **Restart Meeting Secretaries:** Organize and record meeting briefings and maintain the **Restart** webpage.

Appointments for the **Restart** Manager and Deputy must occur 6–12 months before the planned **Restart** and require endorsement by senior management. The **Restart** Manager reports on progress during daily **Restart** Meetings, weekly coordination meetings, and senior management reviews. Commissioning requires precise scheduling and coordination, relying on the following mechanisms:

- **Daily Restart Meetings** – Address immediate progress, resolve issues, and synchronize activities.
- **Weekly Coordination Meetings** – Focus on progress updates, critical path analysis, and scheduling.
- **Fortnightly Reports** – Share **Restart** progress with JET Task Force Leaders and scientific teams.
- **Restart Plan Updates** – A dynamic document revised daily to reflect real-time progress, shared weekly.

3.3 The JET commissioning process

JET has developed and used a clear process and tools to manage commissioning activities. These include a clear categorisation, a standard procedure form, a clear review and approval process, a process to execute the activities and monitor progress and processes to deal with non-conformances and delays. The whole process is well documented.

3.3.1 Commissioning procedure

JET Commissioning procedures fall into three categories each with a recognised authority to approve it:

- **KSRE/SRE:** Ensures personnel and public safety and aligns with the JET Safety Case. Approved by the Torus ATOH.
- **IOPS:** Protects machine integrity during operation. Approved by the Machine Protection Working Group (MPWG) Chair.
- **Other Systems:** Covers services, heating, diagnostics, and other systems critical for program goals. Approved by relevant department managers (DM), the senior manager of the operational area (department) responsible for the system.

All procedures are produced using the same standard template including:

- **General Information:** Procedure category, identifier, title, hazards, constraints, and interfaces.
- **Scope and Systems:** A list of subsystems tested, services required, and system readiness criteria.
- **Test Descriptions:** Detailed steps for testing and verifying subsystem functionality.
- **Readiness for Operation (RFO):** A declaration of system readiness or identification of exceptions.

Each Commissioning Procedure is uniquely identified by a title and a number that clearly indicates the JET system or group responsible for the commissioning activity (e.g., RF, NBI) and the year the procedure is carried out.

Commissioning often involves multiple JET systems, and the front sheet of each procedure lists all relevant interfaces. These interfaces are reviewed and approved during the JET Coordination Meeting to ensure comprehensive coverage. The front sheet also includes four mandatory signatures that verify the procedure's adequacy for the specific commissioning activity and confirm that feedback from all interfaces has been addressed.

The body of the Commissioning Procedure provides detailed descriptions of all tests and measurements required to ensure the system reaches a safe and fully operational state. This document serves as a comprehensive guide for executing the commissioning activities.

The final page of the procedure is the **RFO**, which formally declares that the system is ready for operation. If the system is not fully commissioned, the RFO must clearly document any exceptions that might impact JET operations or the experimental program.

3.3.2 Review and approval

The approval of commissioning procedure (figure 1) is iterative and involves multiple reviews:

i. Identifying the Procedure Type

The Responsible Person (RP) consults with relevant authorities to classify the procedure and obtain a unique number for Commissioning Procedure.

ii. Preparing the Commissioning Procedure

The RP prepares the Commissioning Procedure, including a risk assessment if required and a proposed list of interfaces, and submits to the Commissioning Coordinator (CC) at least three months prior to the planned start.

iii. Iterative Review and Approval

The iterative nature of the process ensures that every step of review and approval is revisited as necessary to incorporate feedback and address concerns. The recognised authority for the particular commissioning procedure (see section 3.3.1) must provide approval before commissioning can begin.

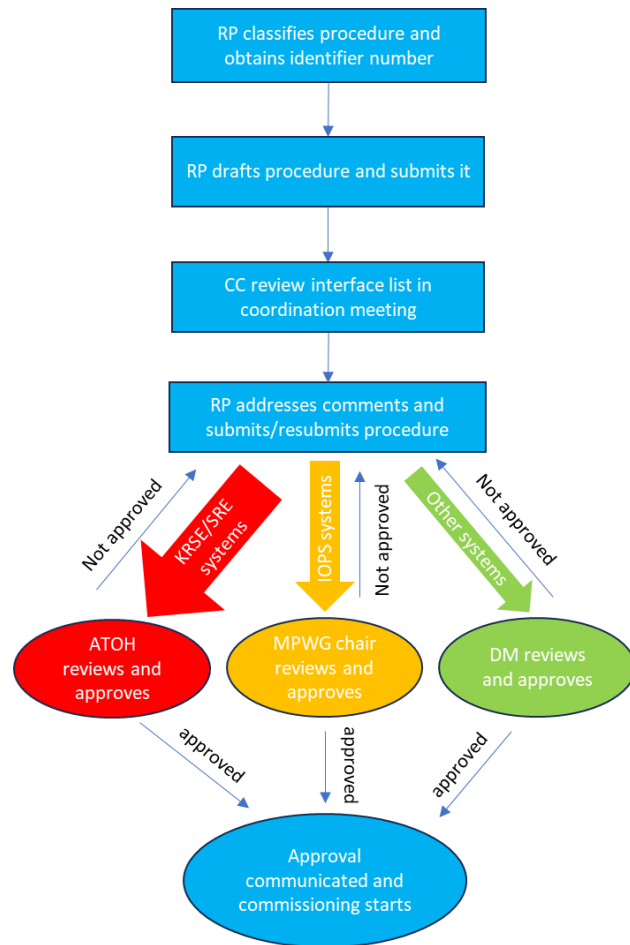


Figure 1. Flowchart of the iterative review and approval process for a commissioning procedure. All the abbreviations can be found in the text.

3.3.3 Execution and progress monitoring

The commissioning process is designed with a clear and structured framework to ensure that every step is closely monitored, and progress is tracked effectively. The **Restart** Manager and deputies monitor the review and approval of Commissioning Procedures continuously through meetings listed section 3.2.

3.3.4 Completion and exceptions

Once a JET subsystem has been successfully commissioned, the commissioning team, along with the responsible manager, completes and signs a **RFO** form. This form serves as a declaration of whether the subsystem is ready for operation. Any anomalies or exceptions in the subsystem's performance observed during the commissioning process are also documented on this form.

Exceptions are analysed by the Machine management team, in consultation with scientific Task Forces, to decide whether to:

- Continue commissioning without restrictions.
- Suspend commissioning and redesign subsystems.
- Continue with restrictions.

For **KSRE-related Hold Points**, the Torus ATOH must review and approve the exception before proceeding. The remaining steps of the commissioning process follows the procedure rules, ensuring the system is aligned with operational requirements and safety standards.

3.3.5 Documentation and Procedure Tracking tool

All **Restart** documents are accessible via the **Restart** Web Page on the JET Intranet. The **Restart** Management Team ensures information is up to date, including:

- **Restart** Targets and key dates.
- **Restart** Plans (Baseline and Live).
- Commissioning databases and templates.
- Meeting records and contact details.
- Historical documentation of previous **Restarts**.

Completed records are archived by the Management Systems Group.

Alongside the Restart webpage, JET has developed a dedicated web-based tool to track commissioning procedures throughout the Restart campaign. This tracking system enables real-time monitoring of the status and progress of various procedures. The tool allows users to search for procedures based on an identifier number, the specific Restart campaign in which they were performed, or their assigned category. The search results provide comprehensive details about each procedure, including general information, step-by-step execution, prerequisites, and test reports. This system enhances efficiency and ensures all commissioning activities are seamlessly monitored, thoroughly documented and easily accessible.

4 Plasma Commissioning activities

4.1 Dry run

Once the **Integrated Commissioning** is complete, or when the essential systems have been commissioned, the vessel is pumped down and a period of vessel conditioning will follow. This typically involves processes such as vessel baking or glow discharge conditioning. Following this, the system undergoes a series of dry-run pulses. These pulses are frequently reused in almost every **Restart**. Over time, JET has developed a set of standard pulse types specifically for certain purposes.

Dry-run pulses are typically designed to verify critical aspects of the system, including:

- Ensuring all circuits are properly connected and free from short circuits.
- Checking the correct operation of the Ohmic Heating (OH) switches.
- Confirming the functionality of the toroidal field (TF) circuits.
- Monitoring the functionality of diagnostics for magnetic control.

These pulses are also used to test the Plasma Position and Current Control (PPCC) system [14], ensuring that:

- The PPCC can control all poloidal field circuits in Absolute Control.
- Basic machine protection systems are operational.
- The PPCC Event Detection and Response functionality works as expected from end to end.

For example, a deliberate invalid PPCC request for positive current in the P1 poloidal field coil (after reconnection) is performed. This test is designed to trigger a PPCC control error, which should result in a soft stop. Such tests confirm that the soft stop is properly executed by the PPCC and recognized by the Plasma Termination Network (PTN) [15].

4.2 First Plasma

Once the dry run pulses confirm that all systems required for **First Plasma** are functioning and the necessary vacuum conditions have been achieved, the **First Plasma** phase begins. Over the years, JET has developed a standardized **First Plasma Operations** flowchart, as illustrated in figure 2. This ensures a set of pulse types (**pt**) which are repeatable, ready for use and adaptable to circumstances, such as different gas valve setups or cryo-pump states. These pulses also serve as a reference for comparing the machine's status following the conditioning cycle.

The first step of the phase is to achieve sustained plasma **breakdown (b/d)** and successful current rise, typically reaching ≥ 800 kA. This is first attempted with a vigorous breakdown in **Mode C** which involves no P1(central solenoid) and no plasma current I_p control. It usually starts with parameters adjusted to encourage sustained breakdown while minimizing the risk of runaway or slide-away electrons. These initial pulses often feature higher gas pressures (**prs**) from the feedback (**FB**) gas injection modules (GIMs), a gentle **aperture expansion (AE)** of the outer wall (**OW**), and specific adjustments to the loop voltage. If these attempts fail, modifications can include

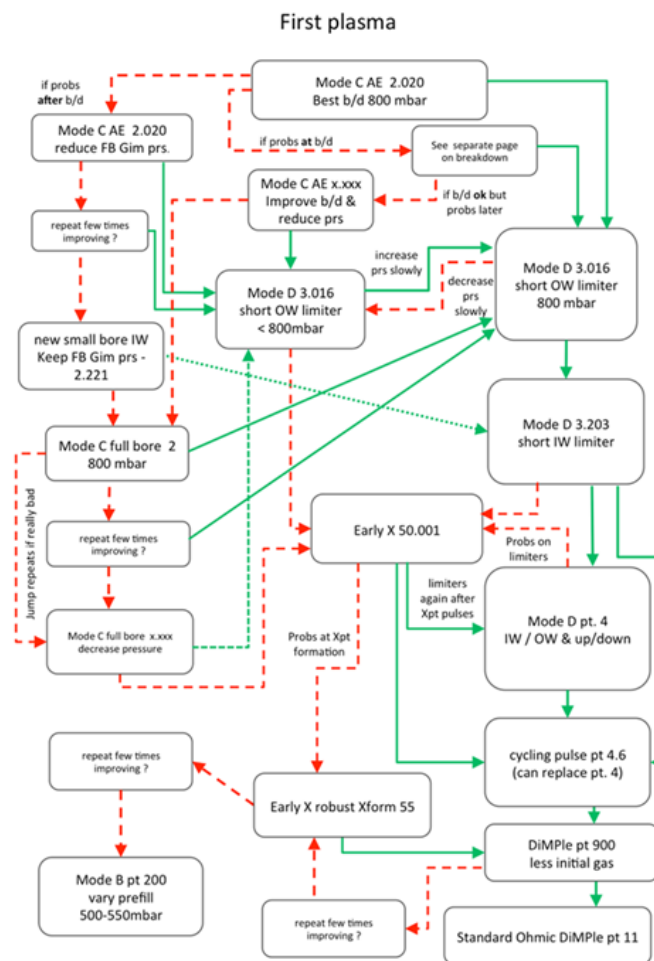


Figure 2: JET standard **First Plasma Operations** flowchart
Meaning of the abbreviation can be found in this paper.

reducing gas pressure, starting with the inner wall (**IW**) or full bore, or increasing the loop voltage. If a sustained ionization or plasma burn-through cannot be achieved, detective works are necessary to identify potential issues, such as faulty magnetics, gas system failures, or improper operation of critical switches. If the problem is related to machine conditioning (e.g., failed burn-through due to high impurity levels), a decision must be made on whether additional vessel conditioning is required or whether plasma attempts should continue.

Once **Mode C** breakdown achieves a plasma current of approximately 1.2–1.5 MA, operations switch to the standard **Mode D**, where it has the capability to control the plasma current, allows for full magnetic control and realize the different configuration. This typically starts with "limiter cycling pulses" which move the plasma-wall contact point slowly across all the main chamber PFCs. Following this, Divertor Monitoring Pulses (**DiMPLe**) are employed to evaluate and optimize divertor conditions. These pulses usually feature late X-point formation around 10 seconds after breakdown. However, if poor divertor conditions lead to highly radiative plasmas or disruptions during X-point formation, an alternative pulse type with earlier X-point formation, around 1second after breakdown, can be used.

The progress of **First Plasma** phase may differ depending on various factors, including **Shutdown** and intervention history, machine conditions, and campaign requirements.

4.3 Plasma Commissioning targets and important activities

Once the machine conditions and control systems required for **Plasma Commissioning** tasks are successfully demonstrated through dry run and **First Plasma Operations**, the primary phase of **Plasma Commissioning** begins. The overall targets and scope are agreed between the Operator and Task Forces, based on the campaign requirements. Requests from different groups are gathered and coordinated by the Plasma **Restart** Manager, who compiles a priority list. While the priority list outlines key objectives, the actual sequence of tasks depends on the machine conditions. Figure 3 shows an example of the **Plasma Commissioning** activities conducted during the JET February-March 2023 **Restart**. As it followed a short **Shutdown**, this was a reasonably short **Restart**, but contained all the main elements of a **Restart**. The priority list comprises the commissioning of the NBI and ICRH auxiliary heating system, commissioning of the Shatter Pellet Injection disruption mitigation system (SPI) [16], calibration of the main neutron yield diagnostic (KN1) [17] [18] and other key diagnostics and systems, and some conditioning and scenario optimisation tasks. The following sections will introduce some important activities during **Plasma Commissioning** using this **Restart** as a case study.

Month	Feb-March, 2023													
Day	Mon		Tue		Wed		Thu		Fri		Sat		Sun	
	27	28	1	2	3	4	5	6	7	8	9	10	11	12
Early (E) or Late (L) shift	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Session number	1	2	3	4	5	6	7	8	9	10				
NBI commissioning	if ready													
Main neutron yield diagnostic (KN1) calibration														
Demonstration that all ICRH operational														
Shattered Pellet Injection (SPI) commissioning														
Protection of ITER-like Wall camera (PIW) test. Includes firing disruption mitigation valves (DMV) 1 and 2.														
High Resolution Thomson Scattering diagnostic (HRTS) calibration														
Fast camera (KL8) sensitivity check														
Monitoring pulses to document N and O levels														
Consolidation of recipes and scenarios to avoid X-point formation near divertor tiles (Tile 5, stack B)														
ECE diagnostic (KK1) calibration														
Gas injection modules (GIMs) calibration checks														
Real Time Central Controller (RTCC2) tests														
Cleaning pulses in Mode B														
Other diagnostic calibration done parasitically														
Additional ICRH commissioning														
Error field correction coils (EFCC) test														
Conditioning duct parts for specified scenario (RT22-01) shape plasma to avoid duct pressure issue														
SPI test of Ar, Ne, and D ₂ pellets														

Figure 3. **Plasma Commissioning** plan for 2023 showing activities which are identified as high priority (red), high priority parasitic (pink), medium priority (yellow), low priority (green), and optional (blue).

4.3.1 NBI commissioning

The JET Neutral Beam Injection (NBI) system [11] consists of 16 Positive Ion Neutral Injectors (PINIs) capable of operating with hydrogen (H), deuterium (D), tritium (T), or helium-4 (He4) isotopes, delivering over 30 MW of power for plasma heating and current drive. As the primary auxiliary heating method, NBI commissioning is one of the most critical activities during JET **Plasma Commissioning** and has been given the highest priority. Achieving specific NBI performance targets—such as reliable beam operation at 110 kV across all 16 PINIs—has been designated as a major milestone for **JET Restarts** and is used as a Key Performance Indicator (KPI) to determine readiness for DT campaigns.

Based on the experience in the previous **Restart** campaigns, the expected duration of NBI commissioning can be estimated in advance. Similar to Ion Cyclotron Resonance Heating (ICRH, discussed in Section 4.3.2) and certain other systems, some components of the NBI can be tested independently of plasma, referred to as asynchronous (ASync) tests. Before injecting NBI power into plasma, all 16 PINIs are conditioned and optimized. This process involves calibrating filament and arc models, performing perveance scans, testing PINIs at varying flow rates to evaluate arc efficiency and high-voltage reliability, and optimizing other parameters. Real-time protection systems, such as the Permit Enable Window System (PEWS), the Bremsstrahlung Beam Interlock (BBI), and the Fast Beam Interlock System (FBIS), are also thoroughly tested. Neutralization efficiency is measured to calculate the actual power delivered to the plasma.

The first step of on-plasma, synchronous (SYNC) operation, where NBI power is injected into the vessel, begins with a test of the NBI system to make sure that all systems work correctly. In principle all SYNC interlocks and protection systems will behave the same but this should be confirmed. To allow sufficient time for troubleshooting, short pulses of NBI power, “blips,” are introduced into the plasma as early as possible during the commissioning period. These initial pulses are progressively increased in duration and power to evaluate high-power reliability and prepare for the upcoming experimental campaign. Figure 4 illustrates this gradual ramp-up process during NBI commissioning.

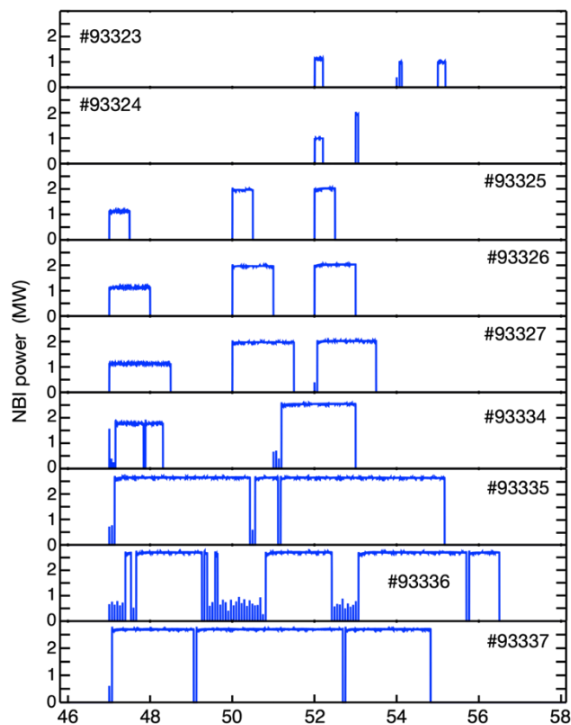


Figure 4: example of progressive NBI commissioning

4.3.2 ICRH commissioning

The JET Ion Cyclotron Resonance Heating (ICRH) system [12] [13] is a proven, versatile, and reliable component that significantly contributes to the success of JET research programmes. It delivers megawatts of additional RF heating and plays a key role in mitigating heavy impurity accumulation, developing new heating scenarios, enhancing wall-cleaning techniques, and refining plasma start-up strategies. Because of its importance, ICRH commissioning is a high priority during **JET Restart** campaigns. The timeline and tasks required for ICRH commissioning depend on the availability of power supplies to energize the generators, JET vessel conditions, and total time allocated for ICRH commissioning.

ICRH commissioning process typically follows the steps:

- Once High Voltage Direct Current (HVDC) is available, RF generator performance is tested across all operational frequencies, delivering RF power to dummy loads. This step can begin even if vacuum vessel conditions are not yet optimal. Repairs and fine-tuning are carried out as necessary.
- Once sufficient vacuum conditions are achieved, antenna and vacuum transmission lines (VTLs) undergo multipactoring to remove surface outgassing. This involves repeated short, low-power RF pulses across the full frequency band. The process continues until no outgassing is detected by the VTL Penning gauges. Depending on the vessel's condition, this step may take a few days or be completely unnecessary.
- After the multipactoring, long-pulse (5 – 15 sec) high-voltage antenna conditioning ('spot-knocking') in vacuum is done at all the typical operational frequencies ('ASYNCR' pulses). The procedure involves a series of pulses where the antenna voltages are increased pulse-by-pulse with monitoring for arcing events (protection trips). Depending on vessel conditions, this may take from one day to one-two weeks of double-shift operations.
- Once plasma is available, antenna conditioning continues during **Plasma Operations**. This step also verifies the functionality of all ICRH control loops and protection systems, such as the RF Local Manager, Real-Time Central Controller, and other interlocks. These tests ensure system reliability during experiments.

In practice, all the above activities were limited by the requirements and pressure of resuming the campaign operations as soon as possible and often ICRH **Plasma Operations** were resumed without completing the above procedures at reduced antenna voltages. During **Plasma Commissioning**, the plasma pulse type is generally flexible, as long as there is a robust central RF absorption mechanism (e.g., hydrogen minority heating) and consistent parameters such as plasma-antenna gap and gas injection rate. Depending on specific performance goals—such as optimizing antenna voltages, testing maximum power capabilities, or verifying machine controls—either L-mode or H-mode plasmas may be preferred, with larger or smaller gaps between plasma and antennas. Occasionally, specific plasma

configurations are requested during ICRH commissioning to establish reference settings for upcoming experiments. In such cases, the plasma should closely resemble the planned experimental conditions to save valuable campaign pulses.

4.3.3 Diagnostics commissioning

The commissioning of JET diagnostic systems varies depending on the campaign requirements and the extent of prior **Shutdown** activities. For shorter **Shutdowns**, where the vessel remains under vacuum, only a few diagnostic systems typically require recalibration, as seen during the February-March 2023 **Restart** (Figure 3). In this instance, only the neutron yield monitor (KN1) required a full session (about half a day) for calibration, while the High-Resolution Thomson Scattering (HRTS) system [19] [20] and the Protection of ITER-like Wall (PIW) cameras [21] needed a few plasma pulses each.

In contrast, after longer **Shutdowns**, involving complex maintenance or when the vessel is opened to the atmosphere, most diagnostics require extensive recalibration and re-alignment. In such cases, scheduling diagnostics commissioning becomes more challenging and demands careful coordination. Each diagnostic system has its own prerequisites and operational requirements:

- **No-plasma required:** Some systems, like pressure gauges, RGAs, and magnetics systems, can be commissioned without plasma using dedicated ASYNC pulses or dry runs. These activities are often scheduled early in the morning or during meal breaks.
- **Passive Diagnostics:** Most passive diagnostics require dedicated plasma pulses, either full pulses or parasitic ones. For example, TF ramps are used to calibrate the Electron Cyclotron Emission (ECE) diagnostic [22], long limiter pulses are used for HRTS, and divertor strike point sweeps are performed for spectroscopy. These are relatively straightforward to schedule.
- **Active Diagnostics:** Systems like Charge Exchange [23] and Motional Stark Effect [24] diagnostics require specific conditions, such as particular NBI PINIs being operational, or stable high-power heating. Others, like neutron monitor diagnostics, involve more complex requirements, including position scans of reliable NBI H-mode plasmas, avoiding ICRH to prevent neutron spectrum distortion, and maintaining disruption-free pulses to protect neutron activation samples.

Many diagnostics also rely on cross-checks with other systems, adding to the complexity. To manage this, a dedicated person is typically responsible for collecting and coordinating all diagnostics commissioning activities.

However, diagnostics commissioning often has a lower priority compared to other **Plasma Commissioning** tasks, except for systems essential to **Operations** or core scientific goals. As a result, many diagnostics activities are scheduled opportunistically whenever a suitable window arises.

4.3.4 Plasma Commissioning of other systems

Following a **Shutdown** or maintenance period, most recommissioning tasks for the High Frequency Pellet Injector [25] can be completed independently of **Plasma Operations**. This includes ASYNC pellet production and delivery to the Torus Isolation Valve. However, some tests on plasma are beneficial to confirm the system's full functionality. During these tests, care must be taken to manage the density limit risk associated with injecting fuelling pellets into Ohmic plasma.

A key requirement from the scientific program is to demonstrate the availability of high-power NBI and ICRH systems. This is sometimes done with a high-current, 3 MA pulse at maximum power but is more commonly achieved using lower-current pulses with power applied from each NBI octant separately. These pulses also help condition the divertor by sweeping the strike points across critical divertor tiles (specifically tiles 5 and 6).

If changes have been made to Real-Time control or protection systems, their recommissioning must also be included as part of the **Restart**, following formally approved Commissioning Procedures. Examples include:

- Testing updates to the Shape Controller, which involves approximately 70 checks to ensure proper control and exception handling.
- Recommissioning the Massive Gas Injection (MGI) system [26] for disruption mitigation.
- Calibrating gas injection systems.

Additionally, some unique activities may arise during the **Plasma Commissioning** phase. For example, when introducing a new plasma configuration, developing a new shape control scheme, or implementing new operational restrictions, pulse types must be refined and consolidated during this phase to optimize valuable campaign time.

5 Commissioning activities for DT campaigns

The commissioning activities during the standard **JET Restart** phase prior to the pure Tritium, DTE2, and DTE3 campaigns [27] [28] built on those used for DTE1 [29]. They followed the same rules, procedures, processes, and management principles as non-Tritium campaigns. As these campaigns were preceded by only brief **Shutdowns**, commissioning efforts focused specifically on systems that had been modified between non-DT and DT plasmas. The transition from standard plasma to DTE2 required commissioning systems unique to DT operations, including verifying additional control systems, enhanced interlock key systems, and extra pump safety systems designed for Tritium handling.

Beyond the standard **Restart** phase, an extensive preparatory effort was undertaken in the form of the JET DT (Deuterium-Tritium) rehearsal [30]. This special series of commissioning activities was a critical precursor to the DT campaign, aimed at ensuring operational readiness, safety, and efficiency.

The rehearsal encompassed a wide range of activities designed to simulate DT-like operations while addressing technical, safety, and logistical challenges.

One of the main areas of focus was the Neutral Beam System, where the Octant 8 beam box was converted to operate using Deuterium gas supplied by the Tritium facility (AGHS – Active Gas Handling System) [31]. The system's performance was rigorously assessed, while standard gas operations on the Octant 4 beam box were maintained to provide a baseline for comparison.

The AGHS played a central role in the preparations, supplying Deuterium gas to the beam box through uranium beds and local gas bottles. During the rehearsal, cryogenic forevacuum pumps were tested as part of cryopanel regeneration for both the torus and beam boxes. Emergency response exercises were also conducted to assess the facility's readiness for potential contingencies. At the same time, Tritium Operating Procedures were tested and refined, simulating realistic DT processes in both the JET control room and the Tritium facility. These included developing Tritium inventory procedures and conducting exercises to allocate and monitor neutron and gas budgets.

To further replicate DT operations, a DT-like operational framework was established. This involved commissioning the torus hall depression and depletion systems and restricting access to specific operational areas to evaluate their impact on workflows and schedules. The torus divertor and beam box cryopanel were regenerated daily over a two-week period, while a DT-like staffing model ensured continuous manning of the Tritium facility and JET control room for extended periods. Cybersecurity measures were also reinforced with the introduction of computer firewall restrictions.

Comprehensive training was an integral part of the rehearsal. Both theoretical and practical training sessions were conducted for control room personnel before and during the rehearsal, allowing staff to gain hands-on experience through controlled rotations. Additional optional activities included commissioning key safety-related equipment (KSRE) and safety management systems (KSMRs) under the DT Safety Case, as well as validating DT- and TT-relevant operating instructions.

The DT rehearsal proved to be a vital step in demonstrating the readiness of JET's systems, processes, and personnel for the upcoming DT campaign. By rigorously testing systems, refining safety protocols, and providing targeted training, the rehearsal ensured that all operations met the stringent requirements of Tritium-based plasmas while upholding the highest safety and operational standards.

6 Lessons learnt in JET Restart

Regardless of the time spend in the preparation and detailed planning, **JET Restart** activities rarely proceed exactly as scheduled. A minimum contingency of 25% must be included in the **Integrated Commissioning** plan to accommodate delays. Common causes of delays include:

Challenges in reviewing Commissioning Procedures

Comprehensive commissioning procedures for subsystems can be difficult to draft, review, and monitor. The approval process for the new installed systems can be slow, especially for machine protection-related procedures, as they require input from multiple stakeholders (e.g., computing, services, Chief Engineer, ATOH), leading to backlogs. Dividing procedures into smaller logical steps (e.g., signal continuity checks, functional tests, **Integrated Commissioning**) can improve efficiency.

Installation and Maintenance Overlap

Installation and/or maintenance tasks carried out during JET **Shutdowns** often run behind schedule and overlap with the initial phases of the machine **Restart** – in some cases installation tasks are carried out during machine operational periods during nights and weekends. This is also a period when personnel safety conditions in the operational areas are changed significantly due to the removal of **Shutdown** isolations to allow the start of machine commissioning. This phase of commissioning is hard to manage and requires very good cooperation between installation and commissioning teams. Linking installation and commissioning plans is absolute necessity to facilitate management of the transition. Access to the operational areas must be strictly controlled during this transitional period and must be approved by both installation and commissioning manager.

Local Commissioning and Service Availability

Local commissioning is often carried out towards the end of **Shutdown**, in parallel to various installation tasks, and requires availability of services (electrical power, cooling systems, compressed air, etc.), which are usually mechanically and electrically isolated during the **Shutdown**. It is very important to develop alternative isolation strategy that will allow local commissioning to go ahead and at the same time guarantee safety of the personnel involved in the installation work. At JET, most of the services become available only at the beginning of **Integrated Commissioning**. This means that a lot of equipment has to be turned on for the first time after a long non-operational period and various faults on the equipment might become apparent only during the start-up phase. The concept of local and remote plant control is a necessary tool to allow local commissioning and fault finding during initial phases of **Integrated Commissioning** as well during operational periods.

Vacuum Leak Checks

Vacuum leak checks are one of the most important tasks at the start of **Integrated Commissioning** and must be planned very carefully and carried out systematically. At JET, several sessions of leak checking are usually planned during **Integrated Commissioning**, each one taking about a week to complete. The first one is carried out immediately after vessel pump-down. Subsequent checks are carried out after every major change in the vacuum vessel temperature. If leaks are detected, their localisation and rectifications could require considerable time due to limited access to many areas of the machine – many weeks of **Integrated Commissioning** were lost at JET in leak localisation and rectification. Vacuum

instrumentation (gauges and residual gas analysers, RGAs) and continuous recording of vacuum signals must be commissioned at the very beginning of the **Restart** to facilitate leak localisation and rectifications.

Design and Installation Errors

Design errors are inevitable. Some will become apparent only during **Integrated Commissioning** and some will become apparent after many years of machine operation. Some errors will be introduced during the installation – the most typical ones are wiring faults. Early detection and rectification of these faults is essential. In some cases, faults on already tested and commissioned systems could be introduced by subsequent installation/maintenance work. Typical examples are control and instrumentation cables and fibres damaged during the installation of mechanical components, removal of scaffolding, etc. To minimise the delays in **Integrated Commissioning** caused by the design and installation errors, strict work control and decision-making chain must be established prior and during **Integrated Commissioning**.

Safety and Protection Systems

Safety and Protection System Issues. Commissioning of machine protection (IOPS) and safety (KSRE/SRE) systems at JET is mandatory, regardless of the level of modification to the machine carried out during JET **Shutdowns**. Commissioning of these systems and corresponding interlocks is usually carried out at the beginning of **Integrated Commissioning** and requires many subsystems to be in the operational state (vacuum, cooling, cryogenics, power supplies, etc.), which is not always the case in early phases of **Integrated Commissioning**. This task usually takes 6-8 weeks at the beginning of every machine **Restart**. Functional testing of these systems also requires that specific plant conditions are fulfilled (vessel vacuum, temperature, bio-shield, etc.) – not always the case at the beginning of machine **Restart**. Successful completion of the commissioning of these systems is the hold point in the **JET Restart** and often causes delays and increases the duration of the of the **Restart**.

Machine Inspections

Thorough inspections of the machine operational areas (particularly the torus hall and basement) are carried out multiple times during machine **Restart**. Each machine inspection takes at least one day (shift) and involves several specialists including responsible officers for various services, power supplies, heating systems, diagnostics, Chief Engineer (and deputies), ATOH, and Shift Technicians. Inspections are carried out using relatively long check lists, which include declaration of subsystem readiness by various responsible officers, followed by the report with list of actions to be taken and photographs of all anomalies and “unusual” objects (which have included spanners, screwdrivers, plastic bags, and scaffolding clamps). The **Restart** continues only when all anomalies are resolved, and actions closed.

7 Summary and implication of the results

The **JET Restart** process is a structured, multi-phase operation that re-establishes the machine's readiness for plasma experiments following **Shutdowns** for maintenance, upgrades, or unplanned interventions. As one of the most complex fusion facilities globally, JET's **Restart** activities serve as a critical benchmark for the operational procedures of future large-scale fusion devices such as ITER. This **Restart** process has been detailed, focusing on the phased integration and commissioning of JET's subsystems, the re-establishment of **Plasma Operations**, and the specific challenges associated with deuterium-tritium (DT) experimental campaigns.

The **Restart** process is divided into two primary parts: **Integrated Commissioning** and **Plasma Commissioning**. **Integrated Commissioning** begins with the **Shutdown-Restart** transition, a preparatory phase that overlaps with the final maintenance tasks of the **Shutdown** period. This initial phase focuses on reactivating JET's infrastructure, restoring power to control cubicles, and verifying the integrity of key subsystems. The transition is critical for ensuring that all subsystems are systematically reintroduced, and safety protocols are followed as the machine moves from maintenance to operational status.

Integrated Commissioning involves the synchronization and functional testing of subsystems, progressing through magnet energization, vacuum system reconditioning, cryogenics activation, and high-voltage testing. Critical safety and machine safety systems undergo comprehensive verification to ensure operator safety and machine integrity. The vacuum vessel is carefully prepared for **Plasma Operations** through a combination of vessel baking at high temperatures, leak detection, and Glow Discharge Conditioning (GDC) to remove impurities and condition plasma-facing surfaces. Machine inspections, conducted at pivotal points throughout commissioning, verify system readiness and address any anomalies before transitioning to **Plasma Commissioning**.

Plasma Commissioning represents the final stage of **Restart**, beginning with dry-run pulses that verify plasma control, heating systems, and magnet alignment in the absence of actual plasma. These tests ensure that circuits are functional, diagnostics are calibrated, and plasma protection systems are operational. Once successful dry runs are completed, initial plasma breakdown is attempted, progressing from limiter pulses to more complex plasma configurations. The commissioning sequence carefully escalates, introducing auxiliary heating systems, such as Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH), to refine plasma performance.

DT commissioning, where tritium introduces new layers of complexity and risk, introduced specific requirements unique to JET and important for future devices. DT operations necessitate enhanced safety protocols, additional infrastructure such as specialized gas-handling systems, and stricter access controls. The commissioning of DT systems involves rehearsals that simulate tritium operations, refining operational procedures and training personnel in the secure handling of radioactive materials.

Special measures include neutron activation monitoring, cryogenic panel regeneration, and emergency response exercises, all designed to ensure the highest safety standards during DT experimental campaigns.

Lessons learned from **JET Restart** campaigns have been compiled. Common challenges include vacuum leaks, unforeseen design or installation errors, and the overlapping of maintenance with commissioning activities. Adaptive planning, including integrating contingency buffers into the commissioning timeline, is seen as essential. Other key ways to improve **JET Restart** include: enhancing collaboration across operational areas (departments), systematic inspection protocols, and real-time progress monitoring to minimize delays and optimize the **Restart** process.

The communication, organization, and management of JET Restart campaigns, along with the safety and efficiency principles underpinning the process, offer critical lessons for the commissioning and operational management of future fusion facilities. The structured, safety-conscious approach adopted at JET has ensured the reliable operation of one of the world's most advanced tokamaks and provides valuable insights that can inform the development of ITER and next-generation fusion devices. Through the lessons learned at JET, the fusion community is better equipped to manage the complexities of large-scale fusion projects, bringing sustainable fusion energy closer to realization.

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