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JET machine operations in T&D-T

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Abstract

JET, the world's largest operating tokamak with unique Be/W wall and tritium handling capability, completed a Deuterium-Tritium (D-T) campaign in 2021 (Maggi *et al 29th Fusion Energy Conf.*) following a decade of preparatory experiments, dedicated enhancements, technical rehearsals and training (Horton *et al* 2016 *Fusion Eng. Des.* **109–111** 925). Operation with tritium raises significant technical, safety and scientific challenges not encountered in standard protium or deuterium operation. This contribution describes the tritium operational requirements, pulses and technical preparations, new operating procedures, lessons learned and details on the achieved operational availability and performance. The preparation and execution of the recent JET tritium experiments benefitted from the previous experience in 1991 (Preliminary Tritium Experiment), 1997 (DTE1 campaign) and 2003 (Trace Tritium Campaigns) and consisted of the following five phases: technical rehearsals and scenario preparation, tritium commissioning, 100% tritium campaign, D-T campaign (DTE2), tritium clean-up. Following the clean-up JET resumed normal operation and is currently undertaking a further D-T campaign (DTE3).

Keywords: JET, tritium, operations

(Some figures may appear in colour only in the online journal)

1. Introduction

The recent JET tritium experiments benefitting from the previous experience in 1991 (Preliminary Tritium Experiment), 1997 (DTE1 campaign) and 2003 (Trace Tritium Campaigns) consisted of the following five phases: technical rehearsals and scenario preparation, tritium commissioning, 100% tritium campaign, Deuterium-Tritium campaign (DTE2), tritium clean-up [1].

The key safety and technical requirements were assessed and are described in the JET D-T safety case [2]. Particularly, operating with injection of tritium gas, high D-T neutron flux and neutron activation involves:

1. The tritium stored in Uranium beds is injected into JET through five dedicated tritium injection modules (TIMs) and one or both of the JET neutral beam injection (NBI) boxes.
2. Tritium (11 g/44 bar·L) and hydrogen isotope gas limits (90 bar·L) apply to the cryopanels (JET divertor cryo-pump and NBI beam-line cryo-pumps) compared to the standard gas limit (3×330 bar·L). This limited the number of pulses between cryopanel regenerations; as these are typically performed every night the gas limits become a daily limit. To optimise the use of tritium, detailed pulse preparation and approval was required, as well as monitoring of the tritium usage and 14 MeV neutron budget.
3. The 14 MeV campaign budget was determined from long term activation considerations. Access to operational areas was restricted due to increased neutron activation and gamma radiation.

The tritium processing requirements meant that the standard 5 d/10-shifts operation was reduced to 3–4 d per week with every 3 week operation followed by a 1–2 weeks of tritium accountancy. There were 69 g of tritium available on site at the start of the campaigns and a total throughput of $\sim$1 kg over the entire period.

2. Preparation

In preparation for tritium operation, commissioning and operational procedures were reviewed, updated and tested in dedicated 1–3 week technical rehearsals [3, 4]. Tritium introduced extra requirements, some direct (e.g. double containment) and some indirect (e.g. improved remote monitoring) extra requirements. Multiple systems were upgraded to meet those requirements:

- A dedicated safety case was prepared describing the safety and technical requirements for operating JET with tritium [2, 3, 5].
- Upgrade and complete re-commissioning of the active gas handling facility (AGHS) [6] to allow the tritium storage, separation, and legally required tritium accountancy (see figure 1).
- Operation of the ICRH antenna in D-T compatible scenarios [7].
- Commissioning and optimisation of the NBI system with and without tritium [8].
- Deuterium operation to prepare the plasma physics scenarios required for T&D-T experiments.
- Review of the tritium capability of the JET diagnostics, and removal or replacement of specific diagnostics prior to tritium injection. The standard JET scientific and protection cameras were unusable and at risk in the presence of D-T neutrons. These cameras were and replaced by a D-T compatible system [9]. The reinstallation of these diagnostics took place a few months after the D-T campaign was completed when the activation had returned to a level where the work could be carried out.
- Multiple, dedicated exercises to test safety response and train staff.
- Security of the computer systems was increased.

A complete list of the requirements for a tritium campaign can depend on the machine, campaign requirements and regulatory framework, however some can be clearly stated. It is necessary to start from a clear set of physics or technology

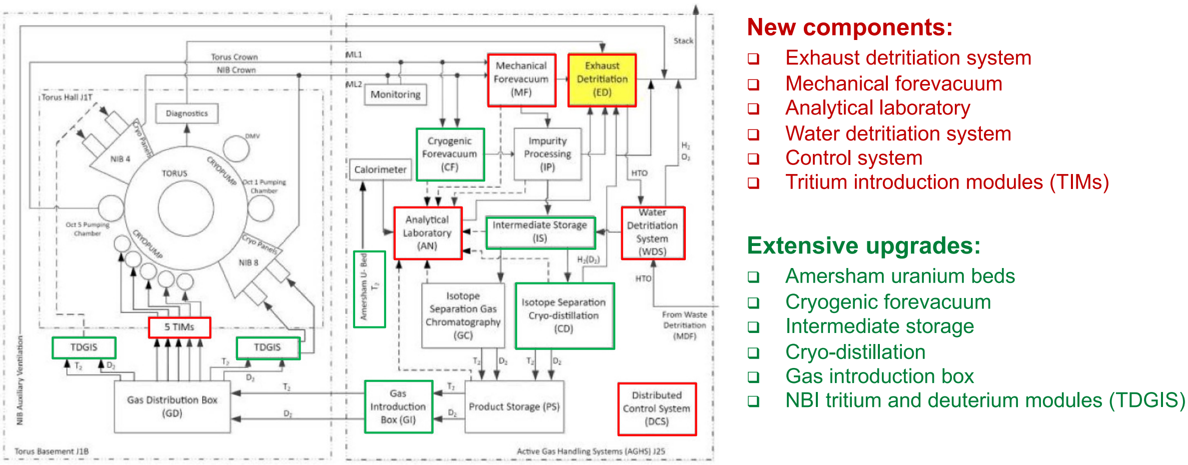

Figure 1. Gas cycle details on JET including upgrades to the active gas handling system.

goals of the tritium campaign. The regulatory requirements should be developed as part of a safety case preparation, the full details of the JET requirements are in [2, 3] and covers areas such as tritium containment, shielding and tritium recovery. It is necessary to consider how much equipment remains inside the shielded areas and remove as much as is practicable, particularly that which is subject to frequent reactive maintenance. Training of all the staff who may be involved in tritium operations, however small or large their role may be. Finally, a strategy for the clean up of tritium and further use or decommissioning of the systems should be considered before introducing any tritium.

3. Reduced/limited access to the jet building

The JET building layout is shown in figure 2. It includes the main tokamak hall (J1T), a basement area (J1B) below the tokamak which is housing many electronic cubicles, and a number of adjacent areas with key equipment including cryogenic systems, NBI power supplies, ICRH generators and vacuum electronics. Access to most of these JET areas is also not allowed during deuterium operation and requires an electrical isolation taking ∼1 h. To reduce risk in case of a tritium release, the atmosphere of the main tokamak hall is depressed during tokamak operations. The torus hall atmosphere is depleted to 15% oxygen level as a fire suppression measure. Entry to the tokamak hall or basement requires re-establishement of ‘normal atmosphere (in the case of J1T) and the recovery of any tritium outside AGHS by pumping back tritium and regeneration of all cryopanels (NBI and divertor). This process takes at least 6 h. Areas adjacent to J1T could not be accessed during a pulse due to possible doses generated by D-T operations but were accessible between pulses. Within all relevant JET areas, radiation monitoring was in place in the form of gamma-ray detectors checked biweekly by external consultants as per regulatory requirement.

These restrictions and modes of operation had a significant impact on fault recovery as access required more time or was not possible at all on the same day due to the cryopanel regeneration requirement. Delays were partially mitigated due to the number of pulses allowed to stay within the daily tritium limit and the need for extra checks between pulses to ensure both safety and correct physics/diagnostics setup. A lost day could in some cases be recovered within a week as the weekly tritium budget only allowed 3–4 d of operation, this was contingent on the overall tritium recovery requirements. In exceptional cases (twice during the TT campaign, multiple times during NBI commissioning), a regeneration was performed during the day allowing a greater total tritium daily budget. Ultimately, most of the experimental sessions were not limited by the tritium budget, but rather delays due to setup, faults or thinking time.

4. Daily operational plan

It has been routine to operate JET on a two-shift pattern and this is also how the tritium campaigns were planned. It was expected that due to the gas limitations some days would finish early, however this was rarely the case. The plan for the day was to begin at 06:30–08:00 with machine startup. This included the transfer of tritium to NIBs and TIMs while access to restricted operational areas was allowed for system start up and routine checks. Those areas were then be locked, and a dry run performed at approximately 08:00. Plasma operation for experiments then ran until the end of the early shift at 14:15.

Additional, short, daily meetings were implemented for various purposes:

- 13:00–13:20 Tritium monitoring meeting (review of daily tritium trends, inventory, interspace monitoring, etc)
- 13:30–14:00 Machine status meeting (review of status, including machine faults and remedial actions)
- 14:30–15:00 Shift changeover meeting (review of programme progress on early shift and plan for the late shift).

It was desirable to run the shift changeover meeting as efficiently as possible so that the rostered late shift could resume

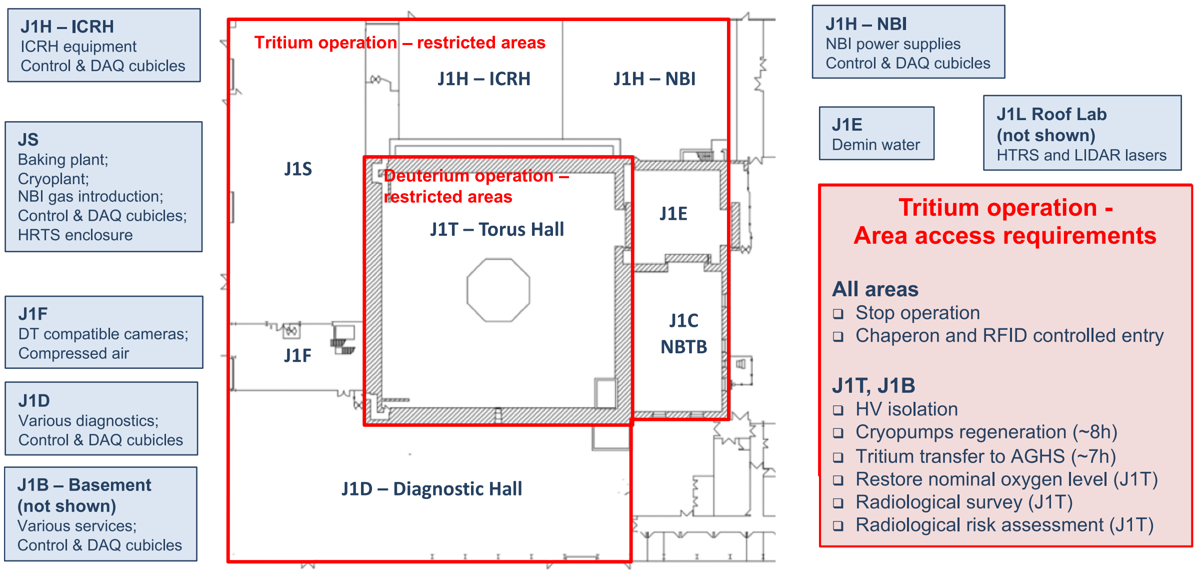

Figure 2. Plan of JET areas. Torus hall (J1T) and torus basement (J1B), in red, cannot be accessed while tritium is mobilised, other areas in blue cannot be accessed while JET is pulsing.

JET plasmas, which would continue until 22:00 or as soon as a tritium limit was reached. At this point access was allowed again for plant shutdown, although in some cases this would be delayed due to residual activation of the areas.

To prepare for the next day many overnight activities take place. All JET cryopumps go through regeneration process; off-line NBI commissioning might be required during nights to ensure best plasma heating performance; and AGHS group prepared for filling of tritium introduction modules if next day was operational or the transfer of tritium from TIMs to AGHS if next day was non-operational.

5. Operational statistics

Since the year 2000 JET operational statistics for subsystem delays during operation have been gathered, the purpose of this is to ensure appropriate targeting of any actions to improve performance. Any pause (delay) in JET operations is logged with the entries grouped by the main systems responsible, such as pulsed power supplies, heating systems, computer systems (CODAS), diagnostics and others. The results for the period 2000–2016 have been reported by Sips *et al* [10]. The results here are presented as delays whereas Sips *et al* [10] reports on availability. Availability is defined as 1—delays. The availability of all systems is defined as the percentage of time JET is operational as a fraction of the total time available for a shift (7$^1/_2$ hours). For JET machine operations in T and D-T a comparison was made using the same metrics as Sips *et al* [10] to assess the effect of T and D-T on machine availability. These results are shown in figure 3.

The D-T and T phases (C39T, C40, C41 and C40B) are compared with the campaigns immediately before and immediately after tritium operations. The delays for the period shortly before D-T and T are slightly less than the long-term delays reported by Sips which is not surprising for a mature machine such as JET. These statistics are used to plan and maintain the JET systems and address problems as they arise. It should be noted that the delays return to the same level in C41, the D-T campaign. Only the pure tritium campaigns C39T and C40 have increased delays.

Figure 3 also shows the reasons for the delays. In C39T there were a range of issues. CODAS caused 26% of the issues, these were mostly network problems. C39T was the first campaign with tritium and only a small fraction of the issues were related to new tritium systems, however many delays were due to processes in place during tritium operations e.g. the filling of the tritium modules. Magnet power supplies 34% along with neutral beam heating 16% were the main issues in C40. Some of these issues took longer to repair due to restricted access to certain areas during C40. Close radiation monitoring of these areas means that these restrictions are no longer in place for DTE3 where possible.

In addition to the collection of data on delays the number of pulses per shift are monitored. This data is shown in figure 4 for the period before, during and after T and D-T operation. As well as counting the number of pulses data is collected on whether or not it is a commissioning pulse or a plasma with a scientific aim. Additionally, the Session Leader marks the pulses on a star system from 0 stars to 3 stars for a pulse with high scientific interest. In figure 4 physics pulse score is the number of pulses with 2^* or 3^* per session, Successful pulse score is the number of successful pulses, including commissioning pulses per session. The net pulse score is the number of successful pulses divided by the net sessions, i.e. number of sessions—the total delay time expressed as sessions.

The use of tritium in JET is restricted as described above. For the C40 campaign this restricted the number of pulses that could be performed per day which can be seen in figure 4. This effect can be seen for all campaigns involving tritium, C39T-C42. During C41 the tritium gas budget was only reached on five occasions and in the pure tritium campaign

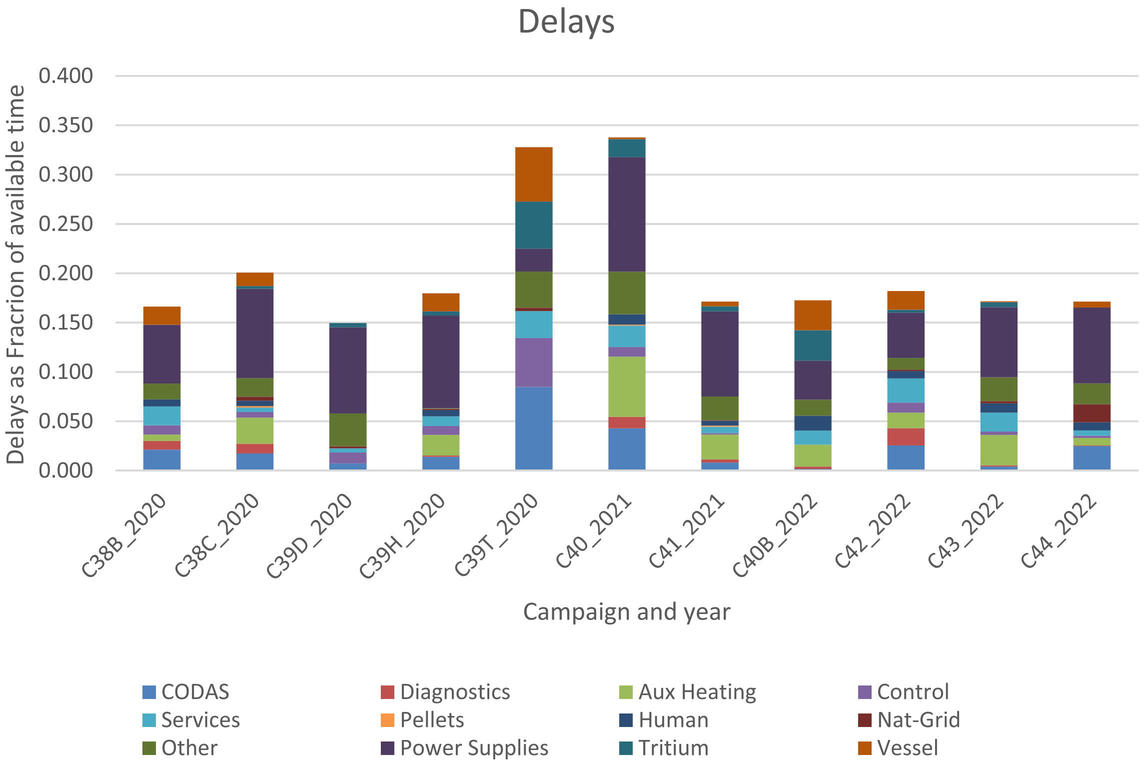

Figure 3. Net delays to JET operations reported for different campaigns before, during and after T and D-T operation showing the different systems responsible for the delays.

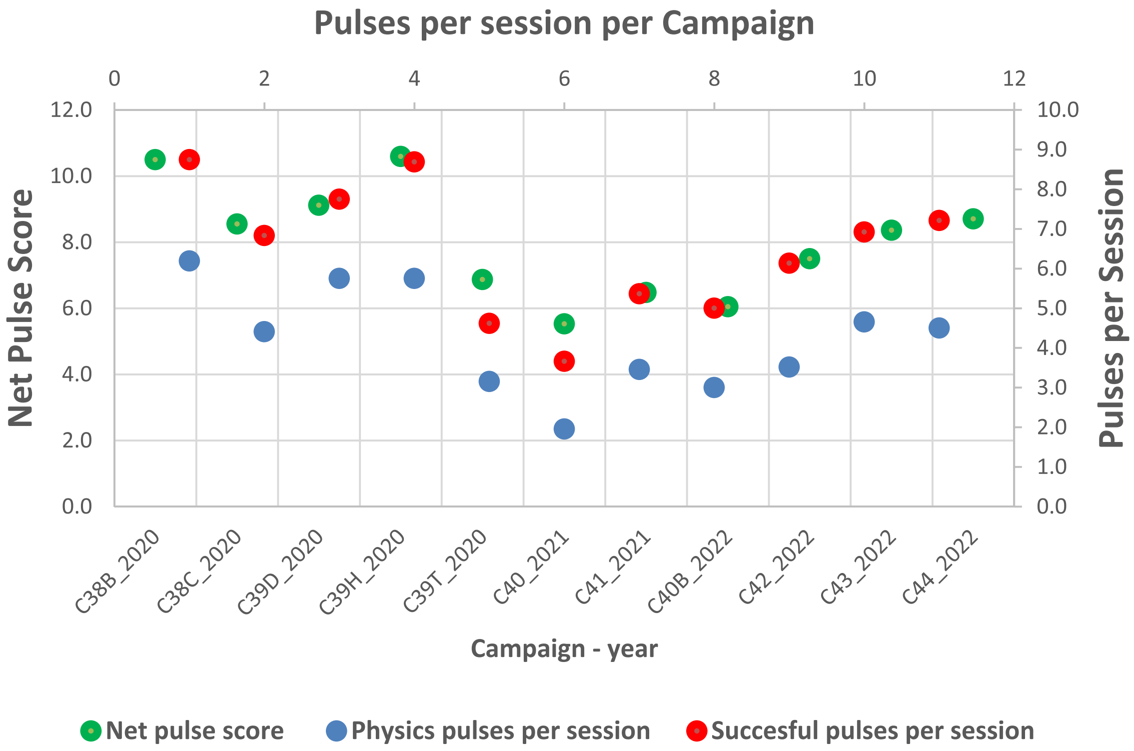

Figure 4. Number of pulses per session as a function of campaign before, during and after DTE2. The net pulse score in green corresponds to the left vertical scale, the physics pulses per session and successful pulses per session correspond to the left vertical scale.

C40 it was reached approximately 20 times. Once tritium was removed from the machine and normal gas handling was resumed then the number of pulses increased. However, interestingly the pulsing rate did not immediately return to the same level as seen in the C38 campaigns but by the 2023 campaign it had recovered. The reason for this would require further investigation but is likely a combination of many factors.

6. Lessons learnt

Following the D-T experiments, it was decided to collect lessons learnt in a similar fashion to the D-T rehearsal to help guide and possibly improve operations for DTE3. The assessment of the lessons learnt has been done with a view to how they could be useful to guide operations in DTE3. This lessons learnt exercise covered the whole of the D-T operation period from December 2020 to the conclusion of tritium operations in March 2022. Individual plant lessons learnt activities also took place and have been reported elsewhere [6, 11–13].

At the start of the D-T and TT lessons learnt exercise a meeting was held to describe how the data collection for the lessons learnt exercise would take place. It was organised so as to get comments from the widest range of people, and staff profiles/roles, as possible. Entries were obtained and several people helped by coordinating the response from different functional groups. One of the issues with the rehearsal lessons learnt was the categorisation for analysis of the different lessons learnt. To help with this, categories for the lessons learnt were suggested but it was left to various contributors to classify their own lessons learnt. This made it easier to assess the results. In addition, it was also suggested to include positive lessons learnt from tritium operation. One other feature that was requested was to also include an analysis of the statistics of the tritium campaigns to see if there was anything different in the campaigns compared to normal operation.

It should also be pointed out that the very collection of the lessons learnt data was valuable, in itself, by encouraging people to think of how they could do things better in the future and to pursue those ideas individually. In many cases the individual teams resolved or improved situations such that by the time actions were generated they had already been closed by those teams.

There were 114 lessons learnt received in five different categories. The breakdown of the lessons learnt into categories is given below in table 1.

Table 1. Breakdown of lessons learnt by category.

Category	Number
Operations	57
Plant issues/tools	20
Procedures	18
Programme	5
Safety case issues	14
Total	114

The categories were split into two different groups for assessment. These were plant issues/tools/procedures/programme and as a separate group for operations. A group of experts was assembled and went through the lessons learnt over a three-week period one by one, asking for clarification and then deciding how the issue would be addressed. Some issues had been overtaken by events and some issues were already addressed by the normal operations improvement procedures. The groups identified 30 actions were worth pursuing. Some of the key lessons are summarised in the sections below.

6.1. General

Many of the lessons learnt from the tritium campaigns are JET specific but there are general observations that can be applied beyond JET.

It was clear that the training and rehearsals performed before the campaign were important. Within this training it was also clear that the staff training should be done well in advance of tritium operation, but this should be combined refresher training closer to actual tritium operation. This training should then be tested in rehearsals where routine operation of the machine in deuterium or hydrogen should take place under the constraints during tritium operation, or at least some relevant subset of those constraints. These rehearsals not only provided suitable training for a staff of around 500 people but also led to many improvements in systems and procedures used when tritium operations began, in particular the access restrictions [2, 3]. These restrictions were found to cause delays to the start of operations, this was mitigated by adjustments to the procedures, providing extra staff to facilitate start up processes and through ongoing experience gained by the team. The rehearsals offered a chance to test the torus hall depletion and depression system highlighting issues which were repaired during the pre-D-T phase. These technical preparations and operational procedures contributed to a safe, extremely successful scientific campaign, achieving most of the physics objectives.

Given the above it was also necessary to ensure any work or access to operational areas is truly essential, hence all work must be planned and approved in advance by the Safety Manager and Operations Manager or the duty Engineer in Charge. This was managed via electronic forms and those forms had to be closed before operations resumed. Over two years 2165 of these forms were completed demonstrating just how much access can be required for maintaining tokamak operations, at least half of these were related to routine start-up and shutdown.

Operating on the limited number of days due to gas handling constraints was a change to the normal way JET is run. These constraints relate to the safety consideration of possible mobile tritium in the JET buildings and to the capacity and reprocessing capability in the tritium handling buildings. Increased capacity is possible with an expanded tritium plant but this must of course be balanced with cost, such decisions should be considered at the design stage of future devices. To minimise delays to the programme and avoid reactive maintenance during time experiments can be run it was decided to exercise essential systems on non-operational days without the use of tritium. Operational areas were locked up, followed by tokamak dry-run and NBI off-line pulses on non-operational days, this proved on many occasions to be useful by finding minor faults and resolving them before experiments on the following days. During the D-T part of the campaign this was further augmented by the NBI team operating night shifts, this not only saved time (enough time for 1–2 pulses per day) but increased reliability of the NBI system.

For plant reliability it is necessary to take extra actions in the case of D-T operation and this should be considered well in advance of any actual tritium operations. Maintenance procedure for tritiated/activated machine should be prepared years in advance and should be done in a way to minimise dose exposure in active areas and legislative inspections (e.g. of pressure vessels) should be planned early to fit with constrained maintenance periods. As far as possible there should be equipment redundancy of essential diagnostic systems and there should be a plan in place should there be a failure and loss of entire system.

With the difficulties of tritium operations, it was important to maintain patience and flexibility. It was necessary to adapt the plans very quickly and very often. This put an extra load on the team but by having backup experiments ready and being prepared to change the programme at short notice if machine status (e.g. heating power, faulty diagnostic) it was possible to achieve far more successful pulses than if the backup plans had not been available.

6.2. Plasma operations and scenarios

It was expected that the use of tritium would significantly change the plasma behaviour on JET and indeed this is the output of many of the scientific results and beyond the scope of this paper. Machine operations during tritium not only affected plasma operations through reliability but also in changes to the system that required integration with the development of plasma scenarios. The use of the TIMs presented a particular challenge as the characteristics of these was different to the standard gas introduction modules. Not only were new calibrations required but also an adaptation of the pulse design [14]. There are many changes to plasma behaviour with isotopic mass, among these the increased heat loads from in-vessel NBI reionisation caused by an interaction of different isotope effects limited the operational domain [15]. The plasma scenario development needed to consider these constraints.

As much as possible of the above was tested during the preceding operational periods including dedicated rehearsals, e.g. the use of TIMs in deuterium was performed as much as possible in the pre-tritium campaigns. However, there were still further adjustments required due to variable TIM speed, effective fuelling and the fact that the ELM frequency in tritium plasmas is typically lower than deuterium.

It was expected before the campaign that the main limitation on the number of achieved pulses would be the tritium or neutron budgets. Hence a very strict budgeting system using pulse based planning was set up to ensure appropriate split of those budgets across experiments. In reality, it was almost always the case that the budget was not reached for the day. Further to this, the enforcement of such budgeting caused additional delays, particularly when the plan had to change due to e.g. insufficient heating power. The general consensus was that there was too much focus on pulse budgets and that it would be more efficient to retain session based planning wherever possible on a machine of the size and complexity of JET.

Following the end of the campaign tritium removal was performed using a mixture of methods. Baking to 320 °C, glow discharge cleaning, ion-cyclotron wall cleaning and plasmas were performed, the results of this process formed an experiment providing important data [16]. The plasmas were partly done in parallel with experimental pulses, this was found to slow down the process and hence for DTE3 it was advised to have a longer period solely dedicated to clean-up plasmas.

6.3. Outcomes for DTE3

Where possible the lessons from DTE2 have been implemented at JET for the ongoing DTE3 campaign. Some of the key differences are:

- Further adjustment to the access restrictions, the processes are less onerous now relying on engineered safety more than procedures. It has also been possible to remove the auxiliary heating areas (J1H in figure 2) from the access restrictions thanks to data obtained during DTE2. This helps both with machine reliability and access related down-time.
- The use of NBI in deuterium rather than tritium. As T NBI was less reliable and more restrictive than D NBI the standard system was used for DTE3. This choice has only a small, manageable, impact on the specific physics experiments planned for DTE3. The use of D NBI allowed for lower reionisation head loads, larger amount of tritium available for the plasma, better reliability and also removed the need for a long restart phase before DTE3 could begin. In general, T NBI should be avoided and for larger machines (e.g. ITER) is not required due to the high beam energy and low fuelling rate.
- For most of the campaign it was decided to operate on the standard session-based planning rather than the pulse based used in DTE2. The part of the campaign dedicated to supplementing DTE2 experiments remains pulse based.
- The team is largely the same as the one that took part on DTE2, so the requirements for rehearsal and significant training are reduced due to the very recent experience. Training was provided for all JET staff but it was possible to reduce this significantly compared to DTE2.

7. Conclusions

Fusion experiments performed with tritium, whether 100% tritium or D-T mixtures, require long and thorough preparation to be successful and is a considerable challenge both scientifically and technically. Doing such a campaign with a team that has little direct D-T experience added to the difficulty but the use of those who had experience of the PTE and DTE1 campaigns on JET was invaluable. Despite the many challenges the experiments in tritium were very successful and completed without incidents, demonstrating the success of our tritium containment strategy. The experience the team gained has helped significantly in the preparation of the DTE3 experiments. The JET T & D-T operations experience will be useful for the technical and procedural preparation of the many proposed future D-T fusion devices.

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