Tritium Operation of the JET Neutral Beam Systems and Tritium NBI Power Calculations

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Abstract*— Neutral beam injection (NBI) is a very flexible auxiliary heating method for tokamak plasmas, capable of being efficiently coupled to various plasma configurations required in the tritium and deuterium–tritium experimental campaign (DTE2) to be undertaken in the Joint European Torus (JET) device. In particular, experiments for high fusion yield and alpha particle studies require high-power NBI heating, and for maximum performance and optimum fuel mixture control in deuterium–tritium (D–T) plasmas, it is necessary to operate the JET NBI systems in both deuterium and tritium. The technical aspects of the JET NBI systems for compatibility with T operation are discussed, and the associated commissioning is described. The characterization of the JET NBI system in the tritium gas mode will be presented, with particular focus on the power and species mix measurements; this will be the first time that such data have been collected and analyzed for tritium neutral beams. Deuterium operation in the tritium gas mode was successfully carried out in 2019 with no loss in reliability. In this period of operation, the NBI power has been measured using beamline diagnostics and corroborated with plasma measurements. The species mix of the beam has been measured on the neutral beam test bed (NBTB) and also corroborated by plasma diagnostics on JET. These results will be presented alongside tritium NBI results allowing comparison of possible JET NBI performance between deuterium and tritium. Measurements of the NBI power in tritium show that there will be a higher neutralized fraction than in deuterium and a higher full energy fraction. When the effect of particle mass is also accounted for, this will lead overall to reduced beam penetration and lower particle flux per MW.

***Index Terms*— Joint European Torus (JET), neutral beam injection (NBI), tritium.**

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I. Introduction

The Joint European Torus (JET) has two neutral injector boxes (NIBs) each with up to eight injectors or positive ion neutral injectors (PINIs) [1]. These PINIs have all been the EP2 type [2] using a chequerboard ion source since 2011. These PINIs are capable of operating up to 125 kV and 65 A in deuterium resulting in a maximum deuterium neutral beam power of ∼2.2 MW injected into JET. Following extensive preparations, the tritium campaign on JET took place during 2021. This campaign has included phases where both injection boxes operated with tritium, and then one injection box operated in tritium and the other in deuterium. Initial expectations were that the PINIs would only operate up to 118 kV and 45 A in tritium with a power of ∼2.2 per injector; however, experience from more recent operation indicated that higher voltages and powers were possible.

This article describes the operation of the JET neutral beam system in tritium for the first time since 2003. It includes measurements of the neutralization efficiency and hence tritium beam power that have not been performed before. A key part of the results is the optimization of the gas flow into the beam system; this is to ensure that the maximum possible reliable power can be delivered by the system. There is a limit to the available tritium in a given operational day so it is also important to use the minimum gas flow possible.

II. Grid Gas Operation

The operation of the system requires the introduction of gas of the chosen beam particle. In standard operation with hydrogen or deuterium, the gas is injected into the ion source and the neutralizer separately [see Fig. 1(a)]. This allows separate optimization of the pressure required to form an ion source plasma and the neutralizer gas target while maintaining a low enough pressure in the accelerator to avoid HV breakdowns. Such a system is unsuitable for tritium due to the engineering difficulties of designing and manufacturing a long ceramic break in the gas line with secondary containment in case of a tritium leak. Instead, a special gas delivery system is used where the gas for both the source and neutralizer is fed to the injector one location at the earth grid as shown in in

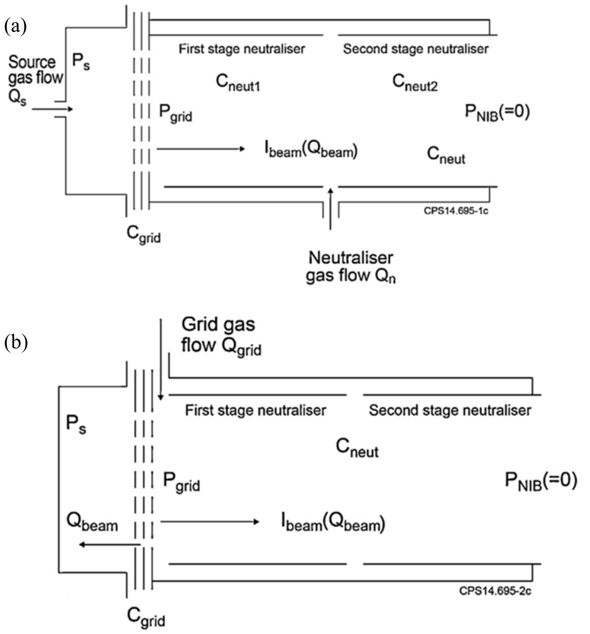

Fig. 1. Schematic of the gas flow in (a) normal gas operation and (b) grid gas operation.

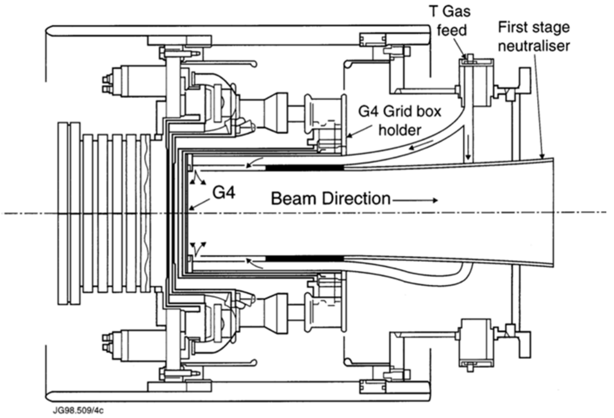

Fig. 2. View of JET PINI showing introduction of gas at the Earth grid, marked as G4 here.

Figs. 1(b) and 2. This is known as the tritium/deuterium gas introduction system (TDGIS) or the “grid gas” delivery system [3], [4]. The system delivers deuterium gas and tritium.

Details of the flow regime in PINI for standard and grid gas mode have been presented previously [5]. The ion source requires sufficient pressure to achieve the maximum beam current and in standard mode requires ∼12 mbarl/s of deuterium. In previous tritium operations on JET, low pressure in the ion source limited the achievable current and caused issues with the control of that beam current [4].

The neutralizer requires sufficient pressure to achieve a large enough neutralization target; if the pressure is too low, then the fraction of the beam that is neutralized will be lower, and hence delivered power will be reduced. During JET operations during 2016, it was found that for EP2 PINIs a 50% increase in neutralizer flow above standard levels increased the maximum beam power by 10% [6]. Hence, a higher flow in the neutralizer than previous tritium operation was also required.

Optimization of the total flow rate would be required to maintain high beam current and high neutralization while avoiding too high a pressure in the accelerator. Experience operating the neutral beam test bed (NBTB) in grid gas mode showed that this was possible [6]. It was necessary to install new components into the TDGIS to allow the remote control of this flow rate such that this would be possible in tritium operation.

III. DEUTERIUM OPERATION IN GRID GAS

In preparation for tritium operation, the beams were operated in grid gas mode using deuterium in 2016 and 2019. The goals of these rehearsals were to train staff, test the procedures and systems, and obtain data in deuterium grid gas operation on JET. These included operation of the beam system on its own and into JET plasmas for testing and for experimental campaigns.

During the 2019 rehearsal, a set of neutralization efficiency measurements were performed at different beam voltages and gas flows. These results showed that the power from standard gas operation could be replicated.

Further to this, a series of plasma experiments were performed, mirroring previous tests done in standard gas operation. A series of identical L-mode plasmas were carried out with single PINIs used in series throughout the pulses. The pulses were within the range of 95 205–95 216. Across the pulses, the gas flow was varied using a remote-controlled needle valve within the TDGIS. The average neutron rate over the time range for each PINI was then used as a proxy for neutral beam power. This measurement does not give an absolute beam power, but it scales directly with beam power allowing the optimization of the gas flow. The results from this experiment can be seen in Fig. 3 where the neutron rate is normalized to the rate at 43 mbarl/s; a flow rate of 42 mbarl/s was chosen as the optimum as above this flow rate there is little gain in beam power. The shape of this curve matches the neutralization efficiency versus gas target as calculated from atomic cross sections.

The beam generated by a positive ion source includes a full, half, and third energy component, and knowledge of this ratio is vital to the analysis of JET experimental data. During this experiment, the beam power fractions were measured using beam emission spectroscopy (BES) on JET. The results agreed with previous data in standard gas and theoretical values.

In agreement with the NBTB data, the target beam current was achieved, and the arc efficiency was acceptable for high-power operation.

IV. TRITIUM POWER CALIBRATION

Plasma experiments on JET require accurate data on the input power from neutral beam injection (NBI). In the previous tritium experiments, this was not available. Experience with higher power NBI systems on JET showed a reduction in beam power at higher beam voltages due to heating of the gas in the neutralizer; this effect is not adequately captured by calculations using atomic data.

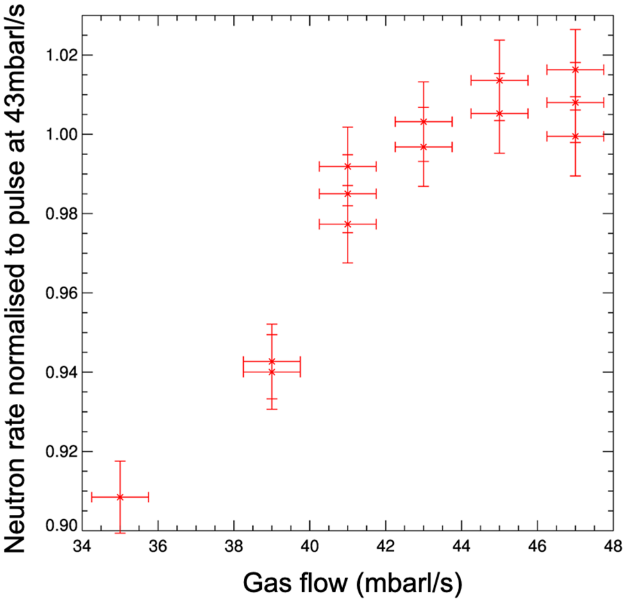

Fig. 3. Normalized average neutron rate versus gas flow as measured in JET pulses.

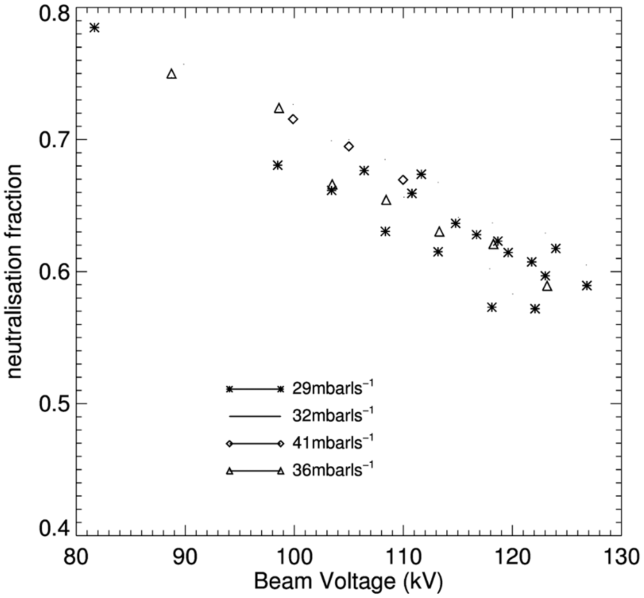

Fig. 4. Neutralization versus beam voltage for a range of gas flow rates.

A. Neutralization Efficiency

The NBI power on JET is calculated by multiplying the extracted ion power by a neutralization efficiency and a transmission factor. The method to measure this neutralization efficiency has been used for many years on JET with success [7]. Further to this, a series of plasma experiments have been performed over many years to provide confirmation of beam power calibration. From all of this, the error in the NBI power to JET is considered to be ~10% [7].

A calorimeter within JET beamline is used, and a series of pulses are performed with the beam deflection magnet on and off. By comparing the heat load on the calorimeter between the composite (ion + neutral) and neutral beam, a relative measurement of neutralization efficiency is obtained.

As the measurement is relative using the same instrumentation any errors in the data are minimized. The main limitations are the short pulselength possible on the calorimeter and the precision of the thermocouples.

In tritium, these measurements were performed for a range of beam voltages and gas flow rates on four different PINIs. The results are shown in Fig. 4. The scatter in the results is due to the resolution of the method, and the flow rate across the range measured does not appear to have a strong effect. The deuterium data would indicate that the optimum tritium gas flow would be 34 mbarl/s; however, scaling is not completely applicable due to the variations in the neutralizer gas heating. It was not possible to optimize the gas flow solely from the neutralization efficiency data.

B. Beam Species Fraction Measurements

NBTB is used in deuterium to provide beam power fraction data that are then checked on JET using plasma diagnostics. As the NBTB cannot operate in tritium, it was not possible to obtain these data before JET tritium operation. The initial data for tritium beam power fractions were an estimate based on deuterium data.

Once the initial commissioning of the beam system in tritium was complete, operation of tritium beams into JET plasmas began. This was carried out in hydrogen plasmas to reduce total tritium use and allow more data to be taken. A consequence of this was that neutron data, as in deuterium operation, could not be used.

A series of pulses were performed as in Section III with a variation in beam voltage and gas flow. The data from each of these pulses were then analyzed using the beam emission diagnostic on JET [8]. As only certain PINIs are within the line of sight of this diagnostic, only two PINIs were used in this experiment and the full range only on one PINI.

As the full energy power fraction varies with gas flow in the same form as the neutralization efficiency, it is possible to use these data to optimize the flow as well. Shown in Fig. 5 are the deuterium and tritium data of full energy fraction versus flow rate. The deuterium data show an optimum at the same flow as the neutralization optimum and the tritium data show weak scaling across the range tested.

Further data were available from the rate of heat rise on the beam ion dumps; this showed a similar form. Based on all of these data and the difficulty in the high-voltage conditioning of some PINIs at higher flow, an optimum gas flow of 31 mbarl/s was chosen.

The power fractions also depend on the beam voltage; JET experiments typically use beam voltages from 80 to 125 kV, so it is required to define these data across the entire range. The variation with voltage is shown in Fig. 6 where the calculation and data are shown. The full energy fraction shows very good agreement with the calculated value, while the half and third energy fractions disagree. This is typical for these data as the calculation defines the fractions as they exit the neutralizer while the data are from within the plasma. The beamline is

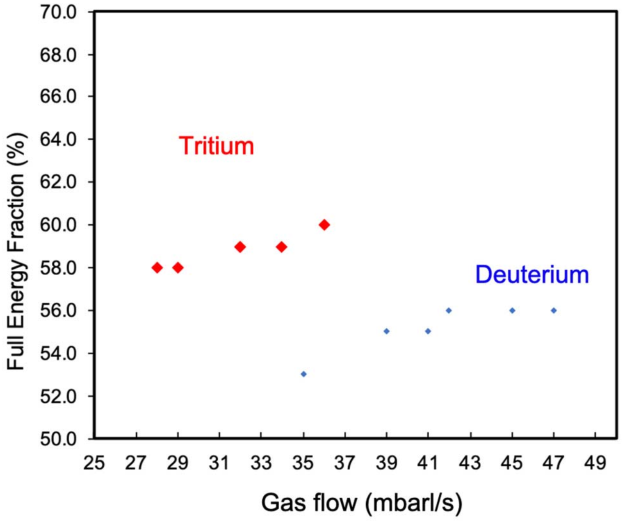

Fig. 5. Full energy power fraction of beam versus gas flow at fixed beam voltage for deuterium and tritium.

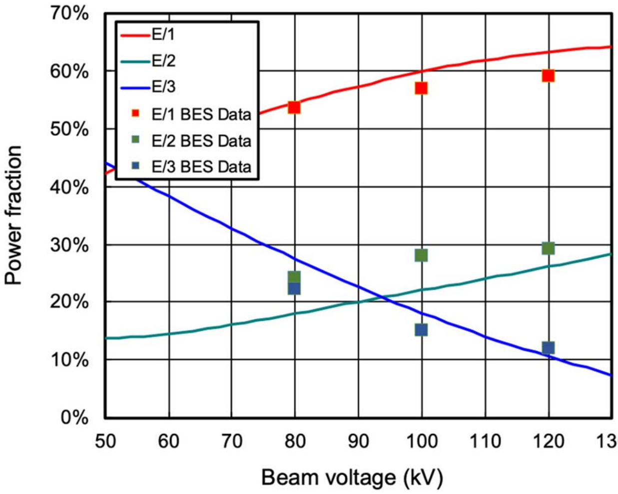

Fig. 6. Full energy power fraction of beam versus voltage for tritium. Lines are predicted values, and squares are data.

~10-m long and some reionization of the beam occurs the between neutralizer and tokamak plasma; the power fractions are affected differently by this and so there is a change in the ratio between the neutralizer and plasma.

V. TRITIUM OPERATING EXPERIENCE

A. Commissioning

The initial commissioning phase of the tritium beam operation was very successful. In the previous period, the PINIs had been operating at high voltage regularly in deuterium. Within a few days of operation in tritium, the same voltage as in deuterium had been reached in offline pulses and the characterization of the system described above was started.

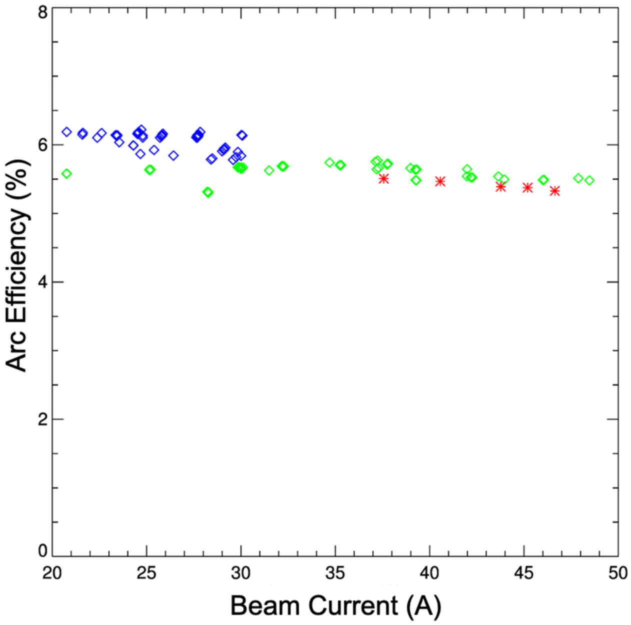

Fig. 7. Arc efficiency versus beam current for tritium operation in grid gas.

Over a period of three weeks, the offline commissioning and optimization was completed successfully on all 16 PINIs. This included tuning a number of beam parameters and power supply settings that are well-known in deuterium. The main limitation in this process was the number of pulses that could be carried out in a day within the tritium inventory limit of 44 barl. In deuterium operation, ~150 offline pulses can be completed on all PINIs within a day, while in tritium operation only a total of ~25 pulses could be completed on all PINIs or more if distributed on a subset of PINIs.

The expectation that full beam current operation was possible in tritium was demonstrated during the commissioning phase. Beam currents up to 50 A were achieved at flow rates of 28–40 mbarl/s. The JET NBI system is usually run at up to 10% above the optimum perveance to increase the available power without compromising beam performance. To operate at a voltage of 118 kV at optimum perveance and hence minimum beam divergence, a beam current of ~45 A is required, so achieving a beam current of 50 A allowed operation up to 125 kV and operation at high perveance.

The arc efficiency is shown from three different PINIs in Fig. 7; more data could be plotted but all PINIs achieved the same arc efficiency. In standard operation, an arc efficiency of >5% is typical and an efficiency of >4.5% is required to achieve the desired beam current. These data are comparable to plots from earlier data on JET and NBTB [5].

The exact perveance varies from PINI to PINI, both from the engineering parameters and the operating experience on the individual PINI. The bounds of perveance used in the commissioning phase are used in Fig. 8 to calculate the tritium beam power per PINI up to maximum voltage. It is clear that the achieved power per PINI in tritium exceeds the initial predictions; this is due to the higher gas flow that could be sustained allowing higher neutralization and higher beam current.

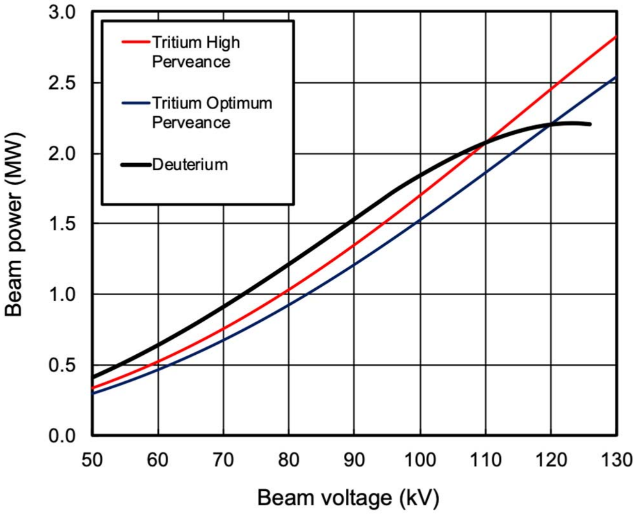

Fig. 8. Neutral beam power versus beam voltage for deuterium and tritium at variable beam perveance.

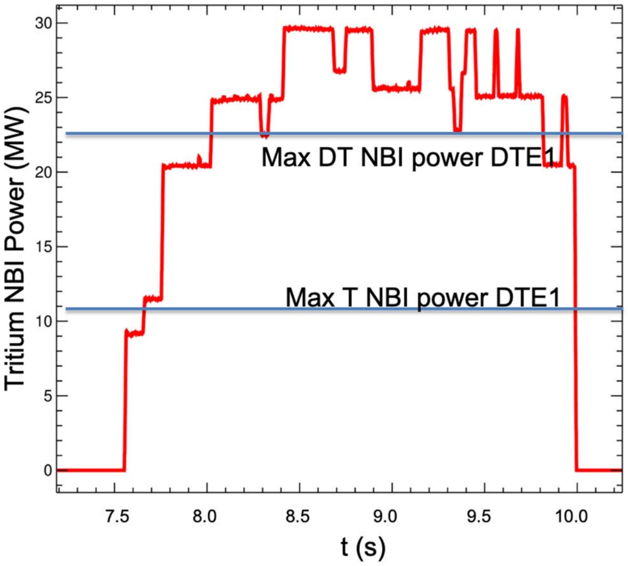

Fig. 9. Best achieved JET pulse in pure tritium operation.

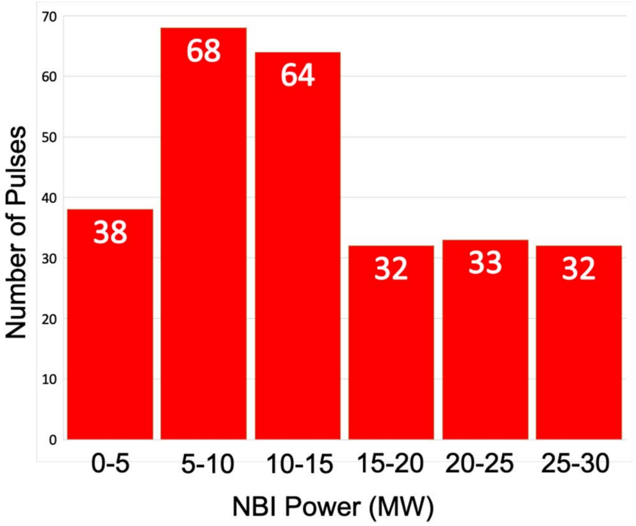

Fig. 10. Distribution of pulses by peak power through tritium beam operation.

There are many operating limits and procedures required for the safe operation of neutral beams on a tokamak. Input data on the beam power and power fractions are required to complete these calculations. In particular, the plasma density required to avoid excess beam shinethrough and the assessment of the neutral beam duct power load are vital to safe and reliable operation of JET NBI. A complete re-evaluation of these calculations was required due to the increased beam power available per PINI, and this was completed with no delay to plasma operations.

B. Operations

Following the commissioning phase of four weeks, the neutral beam system was available to JET to be used in the experimental campaigns, starting with pure tritium experiments. Although the initial operations achieved maximum beam voltages over time, the conditioning slowly degraded, and when plasma operations for the experiments began, the beam voltages achievable were lower. This was similar to the experience in DTE1 [3], although more significant.

Periods of dedicated beam conditioning pulses were carried out during the experimental campaign to achieve the beam powers required by certain plasma experiments. Strategies were developed to improve this process to account for the limited tritium available; this included operating with hydrogen plasmas, the use of plasmas without divertor cryo-pumping (reducing tokamak plasma gas required), and the precise planning each day of which PINIs would be conditioned for how many pulses.

It is possible to convert the beam system into deuterium for conditioning purposes and then back to tritium for experiments. This strategy was not used during the pure tritium campaign as it was necessary to avoid the introduction of residual deuterium into the plasma at this time.

The beam power was further affected by specific issues. One PINI developed a small water leak, and this would usually be resolved quickly on JET with the use of a spare PINI; however, the presence of tritium made this impractical in the available time. A further PINI developed a fault causing frequent high voltage breakdowns during a pulse.

The higher beam power per PINI on those that performed well helped to compensate for these issues; further optimization allowed for up to 2.7 MW to be delivered from some PINIs. The maximum power achieved during the experiments in pure tritium reached 30 MW and is shown in Fig. 9. Over the entire operational period in pure tritium, the distribution of maximum power in a pulse is shown in Fig. 10. This figure does not take into account the requested power and many pulses at the lower power range requested that power either for the program or as part of the beam conditioning described above.

VI. CONCLUSION

The JET neutral beam system was successfully converted into tritium operation for the first time since 2003. This was also the first time that this PINI type has been used with tritium. The beam system was completely characterized in tritium, in particular beam power and power fraction measurements that have not been completed before.

The achievable beam power per PINI exceeded the expectations; however, the reliable beam power available to the campaign was affected by high-voltage conditioning and PINI faults that could not be resolved during tritium operations.

Following pure tritium operation, a period of DT operation took place. Further analysis of data from the DT operation will be subject to a future publication along with information on isotope cleaning, corroboration of beam power calibration, and more details on operational experiences.

ACKNOWLEDGMENT

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