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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 the various plasma configurations required in the Tritium and Deuterium–Tritium Experimental campaign (DTE2) to be undertaken in the 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.

Technical aspects of the JET NBI systems for compatibility with T operation are discussed, and the associated commissioning is described. The characterisation 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 has been collected and analysed 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 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 neutralised 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— JET, Neutral Beam Injection, Tritium

I. INTRODUCTION

The Joint European Torus (JET) has two neutral injector boxes (NIBs) each with up to eight injectors or PINIs (positive ion neutral injectors) [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, 65 A in deuterium

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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 118kV and 45A 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 paper describes the operation of the JET neutral beam system in tritium for the first time since 2003. It includes measurements of the neutralisation efficiency and hence tritium beam power that have not been performed before. A key part of the results is the optimisation 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 neutraliser separately, see Fig. 1a. This allows separate optimisation of the pressure required to form an ion source plasma and the neutraliser 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 neutraliser is fed to the injector one location at the earth grid as in Fig 1b and Fig. 2. This is known as the Tritium/Deuterium Gas Introduction System (TDGIS) or the “grid gas” delivery system [3,4]. The

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system delivers deuterium gas as well as tritium.

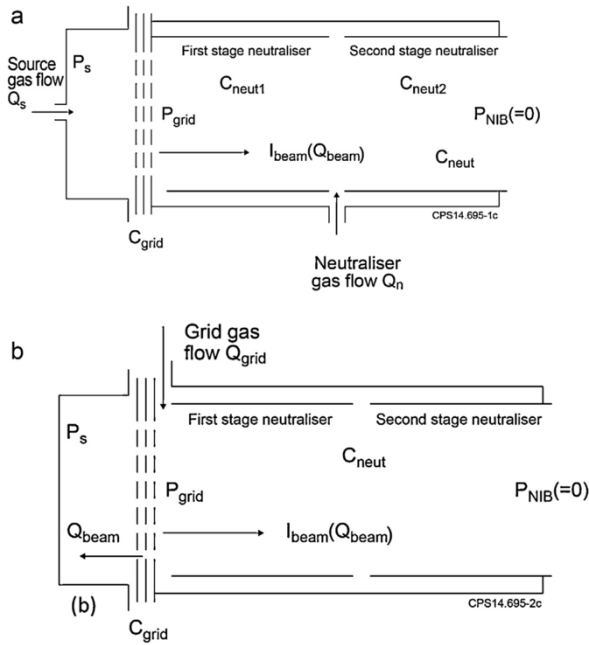


Fig. 1. Schematic of the gas flow in (a) normal gas operation, (b) grid gas operation.

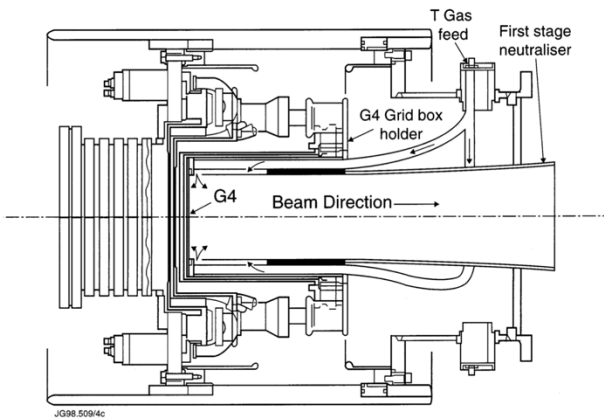


Fig. 2. View of JET PINI showing introduction of gas at the earth grid, marked as G4 here.

Details of the flow regime in the 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 neutraliser requires sufficient pressure to achieve a large enough neutralisation target, if the pressure is too low then the fraction of the beam that is neutralised 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.

Optimisation 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 was to train staff, test the procedures and systems and to 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.

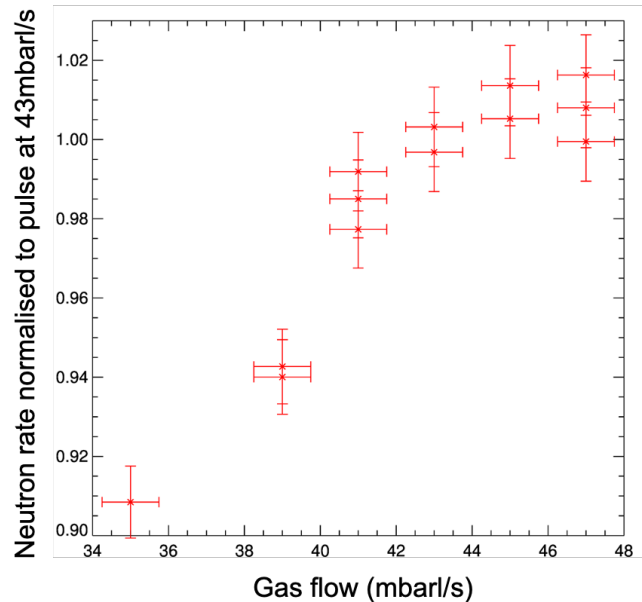


Fig. 3. Normalised average neutron rate vs gas flow as measured in JET pulses.

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 95205-95216. Across the pulses the gas flow was varied using a remote-control 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 43mbarl/s, a flow rate of 42mbarl/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 vs gas target as calculated from atomic cross sections.

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

In agreement with 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 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 neutraliser, this effect is not adequately captured by calculations using atomic data.

A. Neutralisation 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 the beam power calibration. From all of this the error in the NBI power to JET is considered to be $\sim 10\%$ [7].

A calorimeter within the 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 pulse length possible on the calorimeter and the precision of the thermocouples.

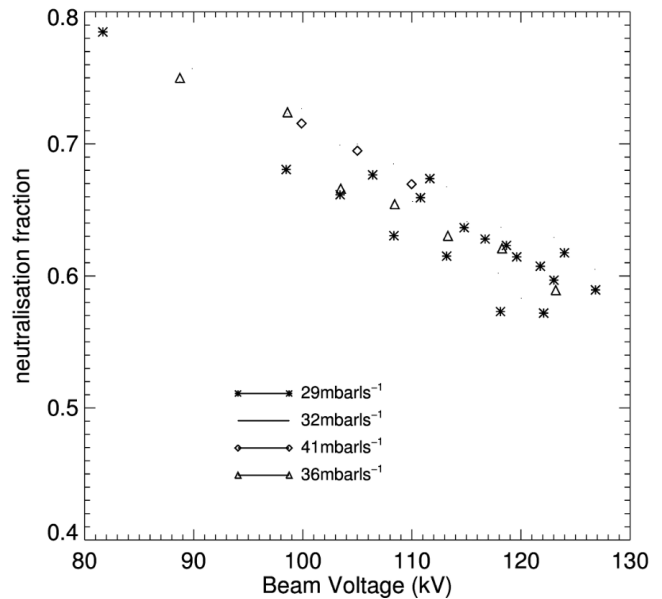


Fig. 4. Neutralisation vs beam voltage for a range of gas flow rates

In tritium these measurements were performed for a range of beam voltages and gas flow rates on 4 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 34mbarl/s, however the scaling is not completely applicable due to 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

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

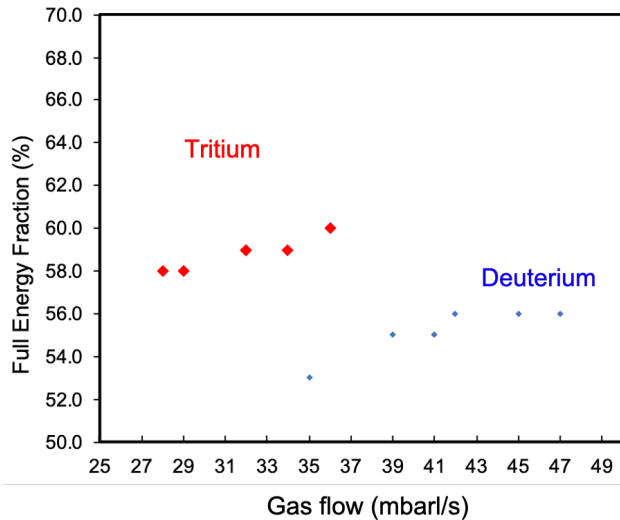


Fig. 5. Full energy power fraction of beam vs gas flow at fixed beam voltage for deuterium and tritium

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 was then analysed using the beam emission diagnostic on JET. As only certain PINIs are within the line of sight of this diagnostic only 2 PINIs were used in this experiment and the full range only on 1 PINI.

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

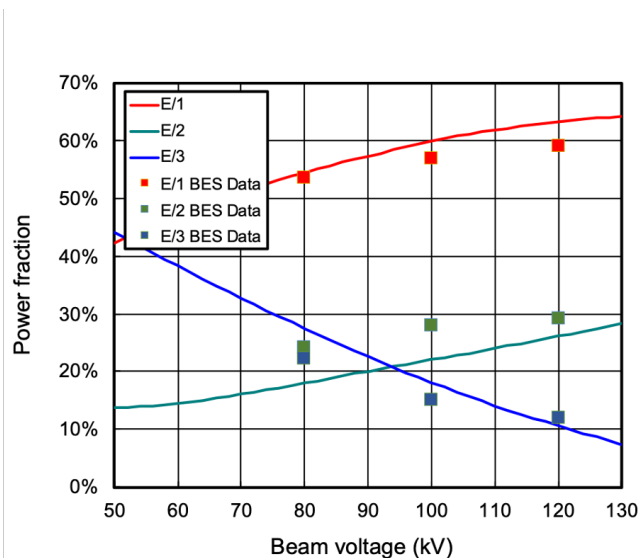


Fig. 6. Full energy power fraction of beam vs voltage for tritium. Lines are predicted values, squares are data

Further data was available from the rate of heat rise on the beam ion dumps; this showed a similar form. Based on all of

this data and the difficulty in the high voltage conditioning of some PINIs at higher flow an optimum gas flow of 31mbarl/s was chosen.

The power fractions also depend on the beam voltage, JET experiments typically use beam voltages from 80kV to 125kV, so it is required to define this 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 is from within the plasma. The beamline is ~10m long and some reionisation of the beam occurs between neutralizer and tokamak plasma, the power fractions are affected differently by this and so there is a change in the ratio between 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.

Over a period of 3 weeks the offline commissioning and optimisation 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 44barl. 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 50A were achieved at flow rates of 28-40mbarl/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 118kV at optimum perveance and hence minimum beam divergence a beam current of ~45A is required, so achieving a beam current of 50A allowed operation up to 125kV and operation at high perveance.

The arc efficiency is shown from 3 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. This data is comparable to plots from earlier data on JET and NBTB [5].

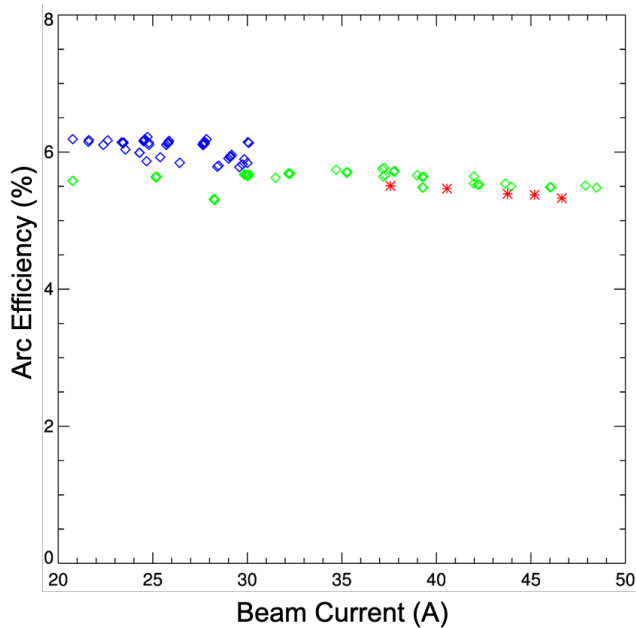


Fig. 7. Arc efficiency vs beam current for tritium operation in grid gas

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 thanks to the higher gas flow that could be sustained allowing higher neutralization and higher beam current.

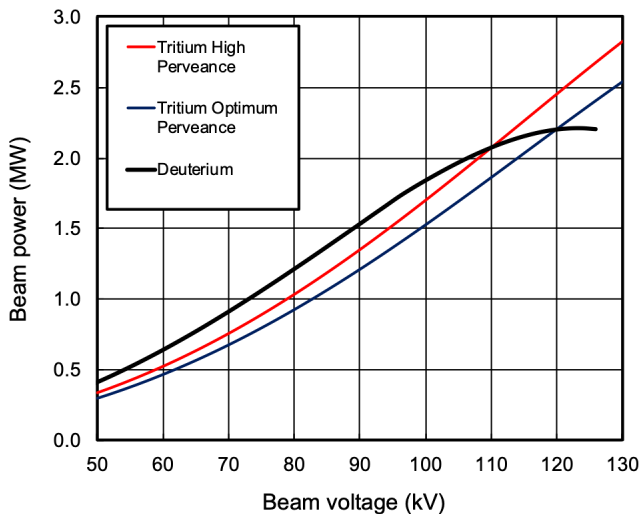


Fig. 8. Neutral beam power vs beam voltage for deuterium and tritium at variable beam perveance

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, this was completed with no delay to plasma operations.

B. Operations

Following the commissioning phase of 4 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 experience in DTE1 [3], although more significant.

Periods of dedicated beam conditioning pulses were carried out during the experimental campaign in order 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 cryopumping (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 to 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, 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.

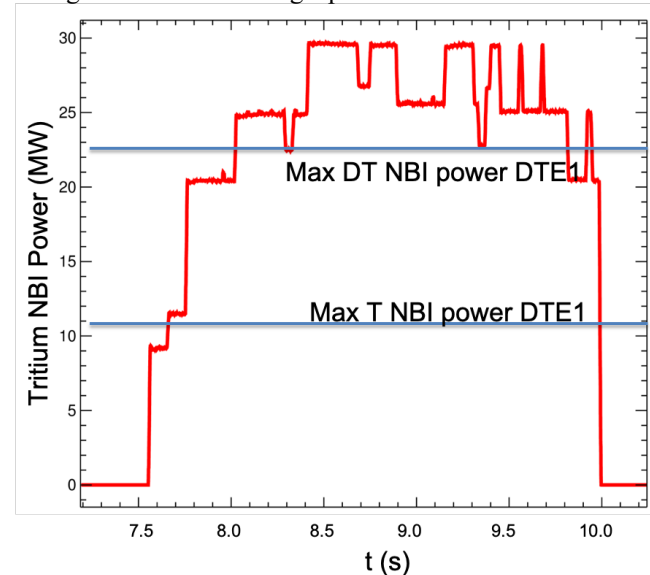


Fig. 9. Best achieved JET pulse in pure tritium operation

The higher beam power per PINI on those that performed well helped to compensate for these issues, further optimization allowed for up to 2.7MW to be delivered from some PINIs. The maximum power achieved during the experiments in pure tritium reached 30MW 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 requested power and many pulses at the lower power range requested that power either for the programme or as part of the beam conditioning described above.

[7] D. B. King et al, 2018 45th EPS Conf. on Plasma Physics, Prague, P4.1067

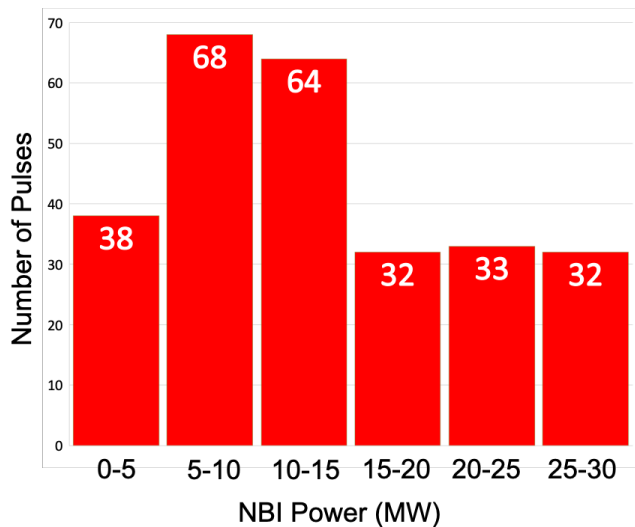


Fig. 10. Distribution of pulses by peak power through tritium beam operation

V. CONCLUSIONS

The JET neutral beam system was successfully converted to 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 the 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.

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