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Tritium neutral beam injection on JET: calibration and plasma measurements of stored energy

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Abstract

Neutral beam injection (NBI) is a flexible auxiliary heating method for tokamak plasmas, capable of being efficiently coupled to the various plasma configurations required in the Tritium and mixed deuterium-tritium experimental campaign on the Joint European Torus (JET) device. High NBI power was required for high fusion yield and alpha particle studies and to provide mixed deuterium-tritium (D-T) fuelling in the plasma core, it was necessary to operate the JET NBI systems in both deuterium and tritium. Further, the pure tritium experiments performed required T NBI for high isotopic purity and reduced 14 MeV neutron yield. Accurate power calibrations are also essential to machine safety. Previously on JET there have been a number of questions raised on the NBI power calibration, in particular following the Trace Tritium Experiments (TTEs). Operator activities on the tokamak NBI system, including calibrations, were performed in 2020. Following these activities, a series of plasma experiments were devised to further corroborate the T NBI power by comparing the plasma response to the D NBI power. A series of stationary, L-mode plasmas were performed on JET with different beam combinations used in different phases of the same pulse. By comparing the plasma response for D and T NBI it was possible to corroborate the T NBI power calibration using the D NBI power calibration. The stored energy as measured by magnetic diagnostics, corrected for fast particle stored energy, show that the uncertainty in NBI power calibration in T is comparable to that in D.

Keywords: JET, tritium, NBI

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

[a] See the author list of "Overview of T and D-T results in JET with ITER-like wall" by C.F. Maggi *et al* to be published in *Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16–21 October 2023)*.
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1. Introduction

The Joint European Torus (JET) has two neutral injector boxes (NIBs) each with eight injectors or positive ion neutral injectors (PINIs) [1]. These PINIs have all been the Enhancement Programme 2 (EP2) type using a chequerboard ion source since 2011 [2]. These PINIs are capable of operating up to 125 kV, 65 A in deuterium resulting in a maximum deuterium neutral beam power of 2.2 MW injected into JET. Following extensive preparations the tritium and deuterium-tritium (D-T) 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 based on possible maximum beam current were that the PINIs would only operate up to 118 kV and 45 A in Tritium with a power of 2.2 MW per injector, however experience from more recent operations indicated that higher voltages and powers were possible.

Accurate knowledge of the input power is mandatory for the scientific programme. Without a calibration of the beam power it is not possible to safely operate the system or understand the physics results. As a major scientific output of the tritium campaigns was a study of the isotope dependence of energy, particle and momentum confinement and transport, the neutral beam injection (NBI) calibration had to be of similar accuracy in both D and T. A number of studies related to the discrepancy between measured and calculated neutron rate [3] and the energy balance on JET [4] have been carried out, the method used for calibration is described in the next section. In particular, there have been issues with the uncertainty in the NBI power in the past. Two examples are that when the upgraded triode PINIs were first used the power was not as expected due to heating of the neutraliser gas [5] and during the Trace Tritium Experiments (TTE) the neutron rate measured was significantly lower than expected from simulation [6, 7].

Since these questions have been raised, a greater focus has been given to the beam power calibration on JET. Dedicated calibrations take place routinely and in greater detail when any aspects of PINI operation are changed [8]. The mixture of full, half and third energy components of the beam, known as the beam species fractions, are checked using Beam Emission Spectroscopy (BES) [9] within the magnetic axis and edge of the main JET plasma at regular intervals and dedicated plasma experiments have been carried out to corroborate the calibration and further optimise the NBI system [8].

When the NBI system is used in tritium there is also a change in how the system works. The gas for the PINI is only introduced in one location rather than separately at the ion source and neutraliser, see figure 1, [10–12], this mode is known as 'grid-gas'. This can have a significant effect on the beam power as a lower gas pressure in the neutraliser can lead to lower beam power and a different species mix. Prior to any tritium operation an estimate of the tritium beam power was made assuming similar gas heating of the neutraliser to deuterium [2]. To ensure the tritium NBI calibration uncertainty was at least as low as deuterium NBI a full set of calibration measurements were completed but also an experiment to compare the plasma response to D and T NBI was designed and completed. This paper will focus on the results of those plasma experiments.

2. NBI calibration method

The NBI power on JET is calibrated with a combination of methods using instruments on the JET beamline and on the neutral beam test bed (NBTB). The total extracted power from each PINI is calculated using from equation (1) where N is the neutralisation efficiency and T is the beam transmission. The voltage and current are simple electrical measurements made with routinely calibrated instruments. The uncertainty in the neutral beam power to JET is primarily introduced via N and T. The transmission factor has been estimated to be 75% using calorimetry and thermocouple data from JET and NBTB combined with ray tracing simulations carried out using an internal code ('PINI Simulator') [13], this is the largest source of uncertainty at 6% in the beam power and this error is not affected by the change in beam isotope. The JET NBI system is typically used in the range 80–125 kV and over this range of beam energy the transmission does not change provided care is taken with the perveance matching. At lower beam energies it is likely the error is larger due to reduced focussing at lower acceleration energies but this is not of concern for our experiment

$$P = V_{\text{beam}} \times I_{\text{beam}} \times N \times T. \quad (1)$$

Prior to 2005 the neutralisation efficiency on JET was calculated by solving coupled differential equations using the atomic cross sections for the various processes and an estimate of the line integrated gas density in the neutraliser target. These calculations had proved appropriate when compared with NBTB and JET data. However, with the increase in beam power associated with the Enhancement Programme 1 PINI design the gas target was reduced due to heating from the beam [5]. This caused lower power (up to 20%) than calculated at high beam voltage (>110 kV). Following this a procedure for measuring the neutralisation efficiency on JET was introduced. Unfortunately there is no measurement of the gas density in the neutraliser or as a profile along the beamline available, within the beamline the only pressure measurement is a penning gauge at the top of the vessel.

A calorimeter within the actual JET beamlines 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 neutralisation efficiency is obtained. As the measurement is relative and uses the same instrumentation any uncertainty in the data are minimised. The main limitations are the short pulse length possible on the calorimeter and the precision of the temperature profiles given the total number of available thermocouples. In deuterium the method has

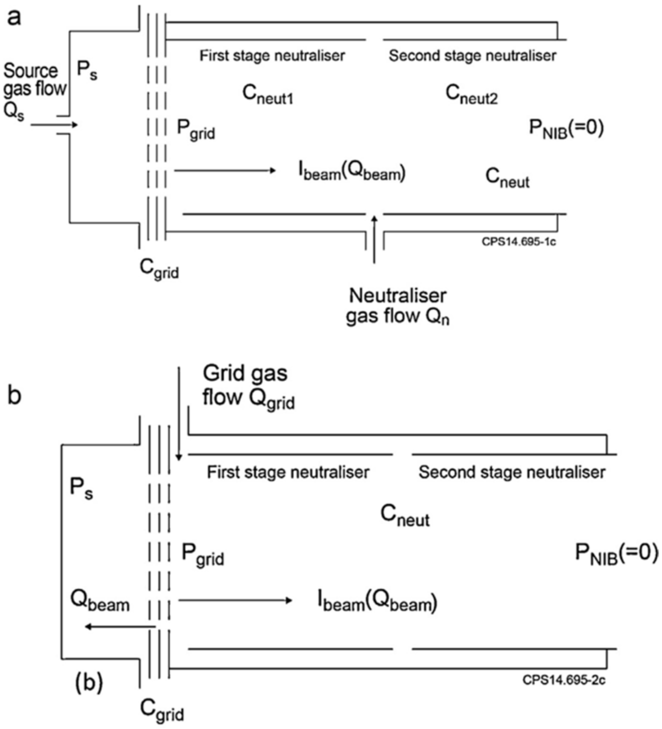

Figure 1. Schematic of the gas flow in (*a*) normal gas operation, (*b*) grid gas operation. Reproduced with permission from [12].

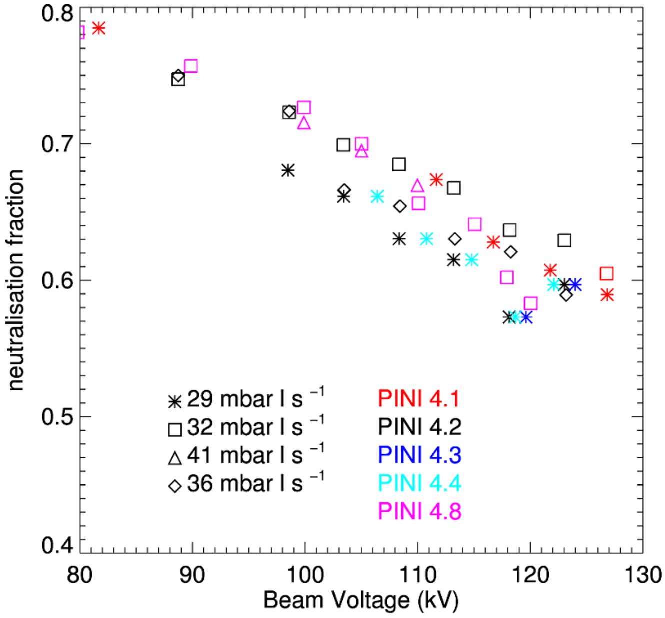

Figure 2. Neutralisation fraction of tritium beams as a function of beam voltage for a range of grid gas flows and different PINIs. Measurements using the JET NBI calorimeter. Reproduced with permission from [12].

been applied a number of times and the data is shown along with a total error estimate of 10% in neutral beam power to JET in [8].

It has been observed in deuterium operation that the beam power from the EP2 PINIs at high voltage (>110 kV) had a strong dependence on the gas flow rate from the neutraliser or the grid-gas feed. This has been shown in terms of neutralisation efficiency but more clearly by the variations of the neutron rate of JET plasmas when the gas flow is varied [12, 14]. The beam power can vary by $\gtrsim$10% over the possible range of gas flows. Due to this possible variation the neutralisation efficiency was measured for a range of tritium grid gas flow rates.

Obtaining neutralisation efficiency data requires a large number of offline pulses and hence a large throughput of tritium. Operational limitations on the use of tritium related to the JET safety case [15] meant that these measurements took more than one week of operations. It should be noted that this calibration took time and tritium that could have been used for other parts of the JET tritium campaign but was considered valuable enough to justify the consequent loss of experimental pulses. The data were taken on five different PINIs and four different grid gas flow rates. The data are shown in figure 2. 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 on the neutralisation efficiency. The neutron data from deuterium pulses during the tritium rehearsal [12] showed maximum neutralisation was reached at 42 mbar.l s^{-1} and scaling by the square root of mass would indicate that the optimum tritium grid gas flow would be 34 mbar.l s^{-1}. However, the scaling of gas flow rate from deuterium to tritium is not completely applicable due to variations in the neutraliser gas heating, extracted beam current and variation of species mix.

The grid gas flow rates used are higher than those assumed in the original tritium NBI power estimates (31 mbar.l s^{-1} compared to 25 mbar.l s^{-1}), as a result a higher beam current (>40 A) was achieved allowing operation at higher beam voltage while maintaining good optics. The neutralisation efficiency was also higher than estimated leading to higher beam power per PINI than expected. The difference is shown in figure 3 where the estimate and measurement agree closely at low voltage but disagree at high voltage. This is consistent with the earlier statements that higher beam voltages are more affected by changes in the neutraliser gas flow due to the greater heating of the gas target at high power. These results showed that >2.5 MW per PINI could be possible in tritium. While this would have been very beneficial to the JET physics programme the beam voltage required for this was only achieved on a few PINIs on a small number of pulses and the total available power was always lower than the notional power that 16 PINIs at >2.5MW could in theory provide. There were many factors to this but primarily due to limited HV conditioning time due to the tritium budget restrictions.

2.1. Tritium NBI species mix

The neutral beam on JET is composed of full, half and third energy components, the ratio of these is known as the beam species mix. The NBTB is used in deuterium to provide beam

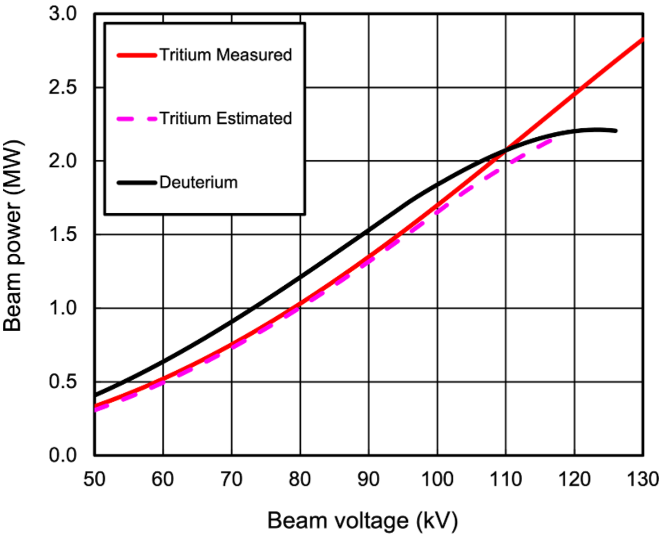

Figure 3. NBI power as a function of beam voltage for deuterium, estimated tritium and measured tritium. Reproduced with permission from [12].

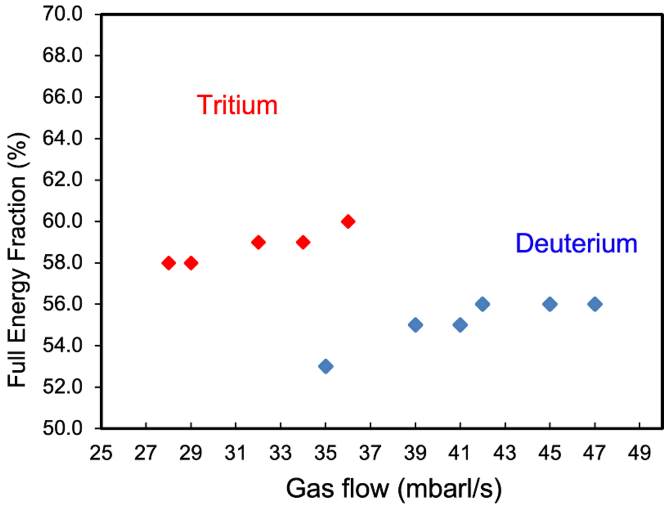

Figure 4. Full energy power fraction of beam vs grid gas flow at fixed beam voltage for deuterium and tritium. Reproduced with permission from [12].

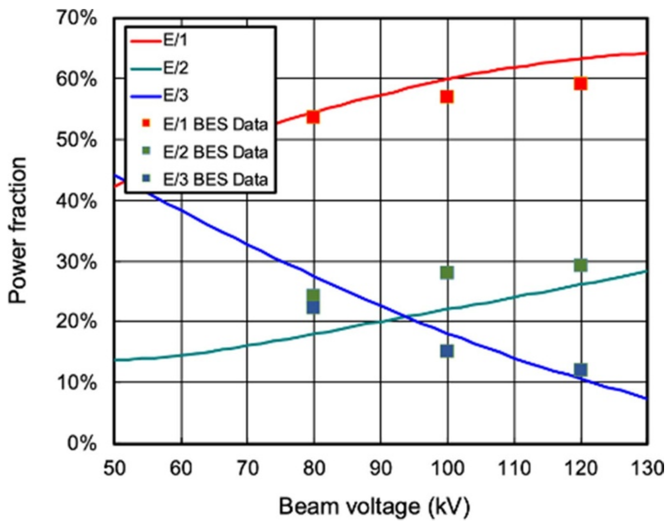

Figure 5. Beam power fraction vs voltage for tritium predicted values (lines) and data (squares). Reproduced with permission from [12].

species data that is then verified on JET using plasma diagnostics. As the NBTB cannot operate in tritium it was not possible to obtain tritium power fraction data before JET tritium operation. The beam species mix was also estimated before tritium operations using an estimate of the neutralisation target from deuterium operation. The species mix is important for machine safety, in particular for beam shinethrough calculations to determine the plasma density required during beam pulses to protect the first wall. The species mix is also important for plasma physics studies as the beam deposition will vary with species mix and the neutron rate is strongly dependent on the full energy fraction of the beam as the half and third energy components are far from the peak in fusion cross section vs energy.

Following the initial tritium commissioning and the neutralisation data above a series of identical L-mode plasma pulses were performed. The D_α spectrum as measured by the BES diagnostic can be used to determine what fraction of the beam has full, half and third energy. The power fractions are derived from the beam emission intensities after correction for the difference in the neutral beam attenuation up to the measurement position in the main plasma, using the latest ADAS data and the method described in [9]. A description of the instrumentation and a figure of the layout of the viewing geometry can be found in [16]. The power fractions derived this way are consistent over all radial viewing channels and an average is being used. Only certain PINIs are within the line of sight of the diagnostic that provides BES so only 2 PINIs were used in this part of the study. The species mix varies with grid gas flow rate similarly to the neutralisation so the data was collected for a range of grid gas flows as shown in figure 4. The equivalent deuterium data is also shown on this plot. The variation of the heat load on the beam ion dumps with grid gas flow was also examined. If the neutralisation increases then the heat load on the ion dumps will reduce. The ion dump heat load showed an equivalent form to the species mix with the temperature on the ion dump decreasing with increased grid gas flow rate and then reaching an asymptote. Due to high voltage conditioning and other operational considerations a grid gas flow of 31 mbar.l s^{-1} was used throughout the experimental campaigns.

The power fractions also depend on the beam voltage and JET experiments typically use beam voltages from 80 kV to 125 kV, thus it is required to define this data across the entire range. The variation with voltage is shown in figure 5 where the modelled and measured data are shown. The modelled data was obtained by solving the coupled differential equations for the different atomic processes with an assumption for the neutraliser gas target based on deuterium data [2]. 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 neutraliser while the data is from within the plasma. The beamline is 10 m long and some reionisation of the beam occurs between neutraliser and tokamak plasma. The power fractions are affected differently by this depending on the energy used and thus there is a change in the ratio between neutraliser and tokamak plasma. The corrected beam species mix is included in the JET pulse data produced by the NBI system.

3. Stored energy of D plasmas with D NBI

It was highly desirable to obtain further corroboration of the tritium calibrations and so a plasma experiment was planned during the preparations for tritium. Using the plasma response to directly calibrate the NBI power is not generally possible however some techniques are available that can aid in corroborating NBI data using the plasma response. In 2016 the use of the neutron production in L-mode plasmas was used to examine the difference between different PINIs and use the transient plasma stored energy response to confirm the beam power calibration [8]. In such studies an L-mode plasma with only 1-2 PINIs at a time is used so that the variation of the plasma behaviour is reduced. When the neutron rate is the parameter of interest then minimising large sawteeth is important as a significant redistribution of the fast particle population can affect the neutron rate and vary from pulse to pulse. Pulses with a plasma current of 1.2MA and toroidal field of 3.0 T were used to achieve a small volume within $q = 1$ and hence minimise the effect of sawtooth activity.

Plasma stored energy data was used during the JET carbon wall period to demonstrate the issues with NBI power [5]. At that time as well as the 130 kV triode PINIs in question there were 80 kV tetrode PINIs also installed. Those tetrode PINIs had been operated without issues in the past and at the lower voltage are not susceptible to neutraliser gas heating. Pulses were used that had the same input power from each PINI type sequentially with the 130 kV PINIs referred to as P_{test} and the 80 kV PINIs referred to as P_{ref}. The plasma thermal stored energy, W_{th} was seen to be lower during the phase with the 130 kV PINIs indicating they were delivering lower power than expected due to the neutraliser gas heating effect described in section 2 and in [5]. Further pulses were performed showing that 1 MW extra input power was required from the 130kV PINIs to achieve the same stored energy. The data from examples of these pulses are shown in figure 6.

In D-T operation there were again two modes of beam operation available, one which was well validated and one which was not at the time. The experiment was designed to compare the plasma stored energy response during D and T beam operation with both beams operating in the same discharge to remove any uncertainty generated between pulses. The pulses and the method for this experiment were rehearsed during the deuterium campaigns preceding D-T operations.

While all JET PINIs are now identical they are all routinely operated in a range of beam voltages between 80–125 kV. The

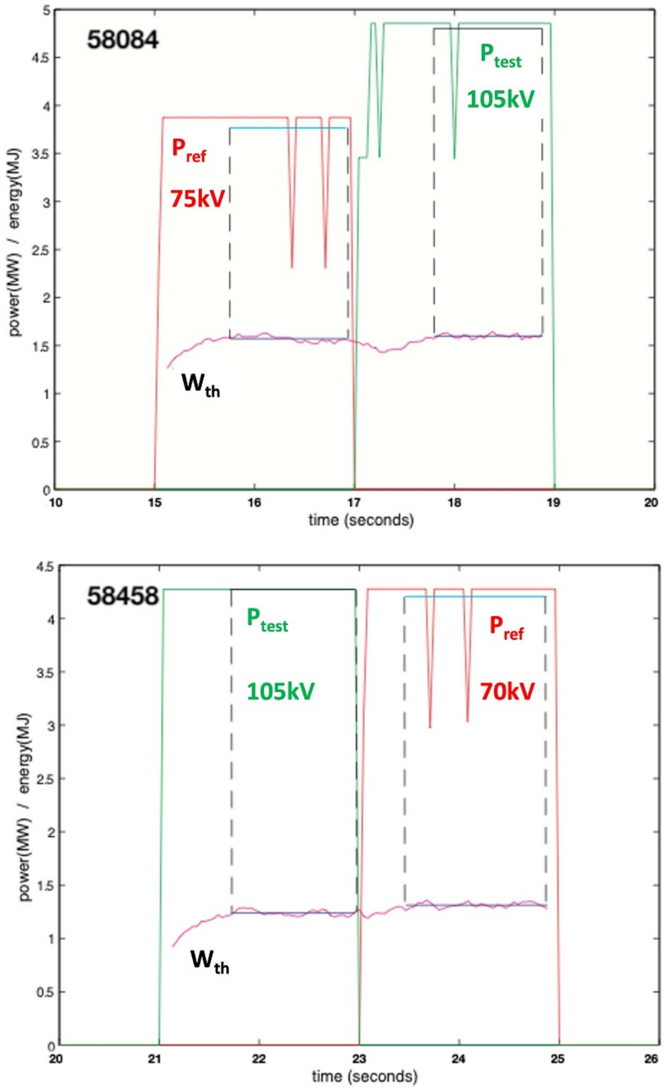

Figure 6. Stored energy and injected beam power using (*a*) different PINI types for varied input power and (*b*) constant input power.

calibration continues to have more scope for uncertainty at higher voltage as discussed in section 2 so an additional benefit of the deuterium preparation was the corroboration of the high voltage region of operation. An L-mode plasma was designed based on those used in isotope identity experiments [17]. The plasma was required to remain in L-mode when in T and D-T so the L-H threshold in D was examined as part of the experiment. Sufficiently high plasma density to operate the NBI was also required. The aim of this pulse development was not just to prepare a pulse but also to determine if the method would provide useful data in D-T.

Fortunately the power of 1 PINI operating at 120 kV is the same as 2 PINIs at 80 kV. A number of pulses at 2.5 MA/3.2 T were performed with different PINI combinations and an example is shown in figure 7. This pulse compares 4×80 kV PINIs with 2×120 kV PINIs. The plasma stored energy as measured by magnetic instruments is shown in the plot as W_{MHD}, this is the stored energy as calculated by the MHD reconstruction of the equilibrium . Given the high plasma

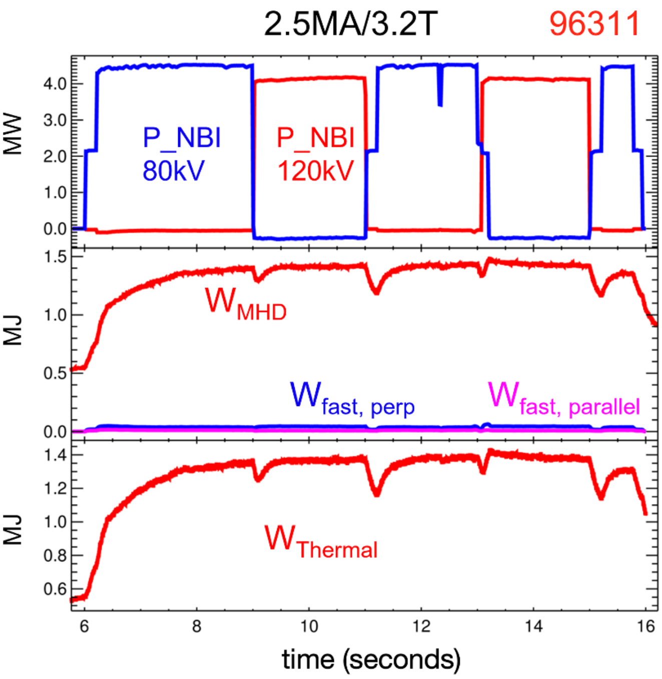

Figure 7. Comparison of deuterium plasma stored energy between 4 low energy deuterium PINIs and two high energy deuterium PINIs.

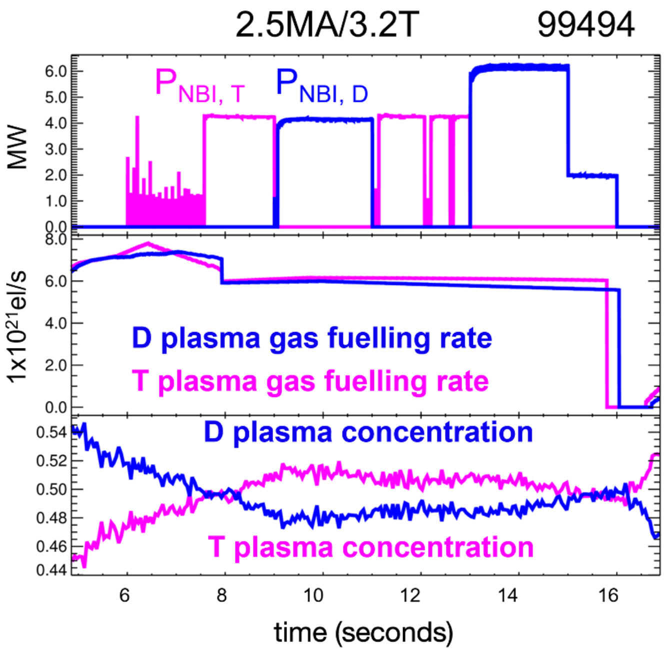

Figure 8. Overview of pulse 99 494, injected NBI power (top), D (blue) and T (magenta) plasma gas injection rate (middle), plasma D (blue) and T (magenta) fractions (bottom).

density and low input power the fast particle stored energy in all these pulses is negligible compared to the thermal energy. It can be seen that the plasma stored energy did not significantly change between the 80 kV and 120 kV windows while the input NBI power remains constant.

It was found that these plasmas would enter H-mode with approximately 8MW of input power and this provided some assurance that once the isotope was considered a T or D-T version of this pulse would remain in L-mode. To allow for some further margin a 3.4 T version of the same pulse was also prepared but it was necessary to shorten this pulse due to heating of the TF coils. It can be seen from figure 7 that the stored energy increases over an initial 2 s, then takes a further $\sim$2 s to reach a completely steady level and that this should be considered for the D-T pulses. It is not possible to perfectly align the transition from one PINI phase to another so the initial dip in stored energy must be disregarded for this analysis, however this phase can be used in another way as discussed in the next section.

4. Stored energy with D and T NBI

Following the tritium calibrations described in section 2 a pure tritium campaign was completed. During this campaign a further rehearsal of the pulse was carried out to check that with the NBI required power it remained in L-mode despite the lower power threshold for the L-H transition at higher main ion isotope mass [18, 19]. Pulse 99 140 remained in L-mode with 3 PINIs providing 5.5MW of power, hence no significant changes were made to the pulse for D-T.

In D-T one beamline (NIB4) operated in tritium while the other operated in deuterium (NIB8). To further reduce complications in the analysis the same PINI positions on each beamline were to be compared as different PINI positions can have different trajectories through the plasma and hence could cause a variation in plasma stored energy. This constraint limited the choice of PINIs that could be used in the experiment as it required reliable high voltage operation on the same PINIs on each beamline, in particular PINI positions 3 and 4. A total of three successful pulses were performed in D-T. While it would be desirable to repeat the study over more pulses with more variation in PINI positions this must be balanced with the constraints of operating in D-T mentioned in section 2.

One of the pulses, 99 494, is shown in figure 8. The input power, D and T plasma gas injection rate, and plasma D and T concentration as measured by sub-divertor penning gauges [20] are shown. It is vital that the D-T ratio of the target plasma remained constant during the test otherwise plasma isotope effects could alter the results. The later increase in NBI was used so that if a discrepancy were found in the T NBI power then it could be compared to different D NBI power levels in an attempt to fit the exact difference. However, this phase entered H-mode despite the preparation in D and T plasmas making this part of the pulse unusable. This was likely due to lower radiated power than the T plasma used and better high voltage conditioning of the PINIs during D-T compared to T operation. In a further pulse, 99 546, to ensure the plasma remained in L-mode a higher toroidal field of 3.4 T was used and the target plasma used only deuterium gas injection.

The plasma density in these plasmas is relatively high to avoid beam shinethrough issues at high beam energy. This

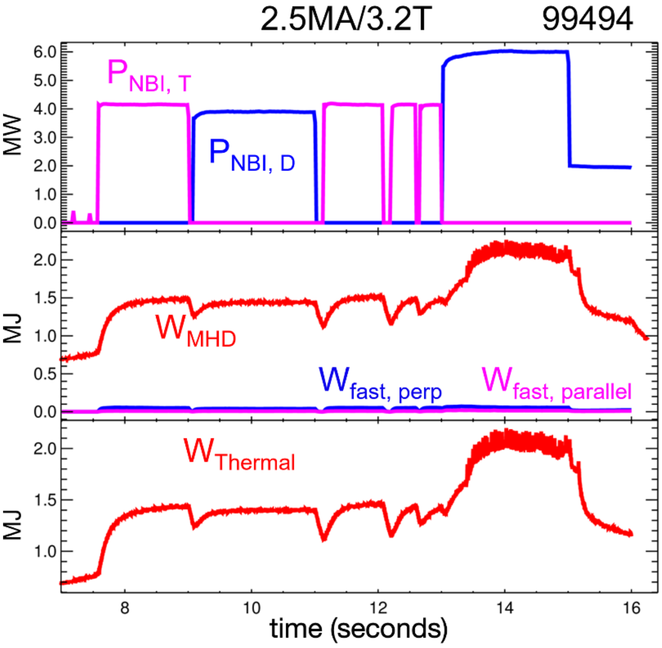

Figure 9. Comparison of plasma stored energy for D and T beams in a DT plasma. NBI power corrected for shinethrough losses (top), W_{MHD} and fast particle stored energy (middle), thermal stored energy.

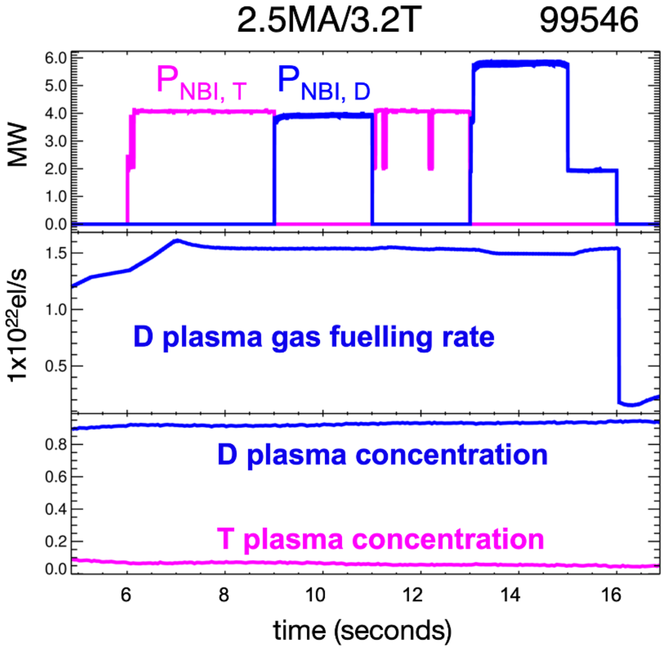

Figure 10. Overview of pulse 99 546, injected NBI power (top), D (blue) and T (magenta) plasma gas injection rate (middle), plasma D (blue) and T (magenta) fractions (bottom).

shinethrough power must still be subtracted from the NBI power as it will be different for the D and T NBI due to the variation in beam stopping rates with mass and the different beam species mix for D and T NBI. The shinethrough power is calculated by TRANSP [21]. As the beam power varies with beam voltage differently in D and T NBI the beam voltage was chosen to match the input power as closely as possible.

The plasma stored energy from different reconstructions has been examined using EFIT and pressure constrained EFIT (EFTP). In both cases the diamagnetic and MHD stored energies have been analysed. The MHD stored energy data for pulse 99 494 are shown in figure 9. Also shown in the second panel is the perpendicular and parallel fast particle stored energy as calculated by TRANSP, which is significantly lower than the thermal stored energy as expected. In the lower panel the thermal stored energy is shown, calculated using $W_{\mathrm{th}} = W_{\mathrm{MHD}} - 3/4W_{\mathrm{perp,fast}} - 3/2W_{\mathrm{parallel,fast}}$ [22]. Comparing the first two beam phases shown there is a difference in the input power between D and T of 6% once the shinethrough is considered and there is a difference of 2% in the stored energy. This should be compared to the uncertainty in the NBI power of 10% and the uncertainty in the stored energy of up to 8%. However, due to the dips in T power caused by high voltage breakdowns on the PINI the stored energy in the T phase has not reached its steady level by the time the switching occurs. The L-mode scaling with input power according to ITER97-L is $W_{\mathrm{th}} \sim P^{0.27}$ [23, 24] and the results from the isotope scaling experiment these plasmas were based on [17] shows a scaling of $W_{\mathrm{th}} \sim P^{0.37}$. According to these scalings a variation of input power of 6% would correspond to a change in stored energy of 3%–5%. The plasma stored energy would also vary with isotope content, however as comparisons are completed within the same pulse and the same isotopic content this will not affect the results of this analysis.

In figures 10 and 11 similar sets of data for pulse 99 546 are shown. In this case the beam power is steadier and a better comparison can be made. The difference in the NBI power corrected for shinethrough is 6% and the difference in thermal stored energy is 4%. Again, once the various input data uncertainties are considered there is no significant difference in the plasma response to D and T NBI power. Hence, the T NBI power calibration can be considered of similar quality to the D NBI power calibration.

As a further presentation of the data the calculation of thermal stored energy from TRANSP is shown in figure 12. This calculation is performed by integrating the plasma kinetic profiles so it should be considered to have a larger possible uncertainty than the above method in this case due to the lack of direct ion temperature data in these plasmas. The PINIs used in these plasmas were not ones that can provide ion temperature data via charge exchange, therefore the calculations were performed with $T_i = T_e$ and for $T_i = 0.9 \times T_e$ based on T_i data available from similar plasmas. Again, no significant change is seen between the D and T NBI phases.

4.1. Analysis of transient stored energy

It is possible to perform a further analysis by examining the change in plasma stored energy at the point when the NBI power is switched on or off. The power balance in a plasma obeys equation (2) and in the situation where the timescales are short such as a power step the transport and power losses can be ignored. Then the heating efficiency η can be defined by

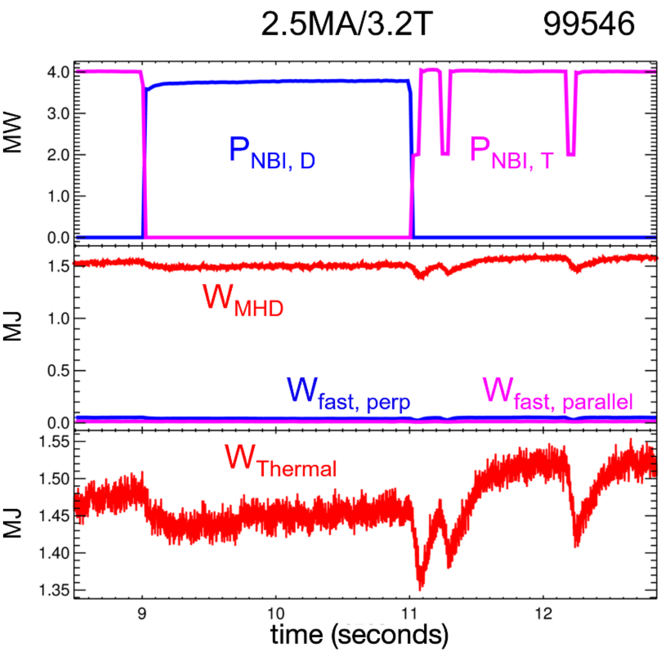

Figure 11. Comparison of plasma stored energy for D and T beams in a DT plasma. NBI power corrected for shinethrough losses (top), W_{MHD} and fast particle stored energy (middle), thermal stored energy.

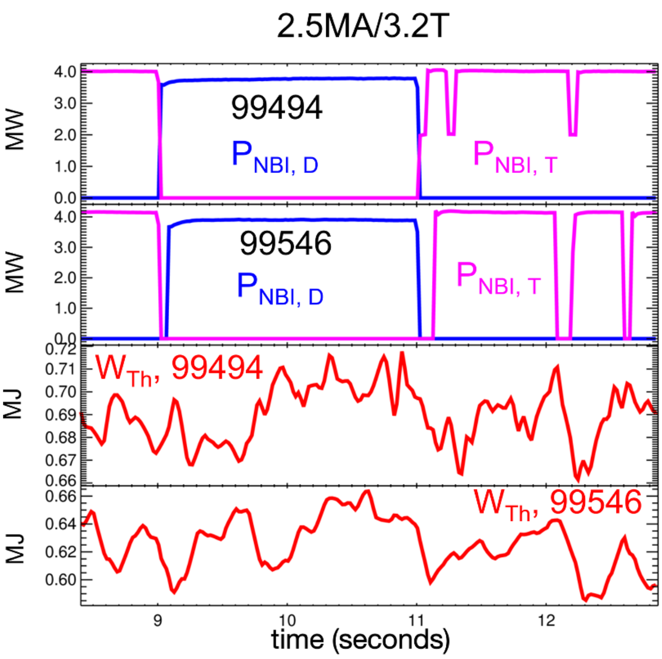

Figure 12. Comparison of W_{thermal} as calculated by TRANSP for two DT plasmas.

equation (3). If it is assumed that this applies here then there is a gap between the D and T NBI phases and it is possible to compare the heating efficiency of each.

$$\frac{3}{2}nk_{\mathrm{B}}\frac{\mathrm{d}T}{\mathrm{d}t} - \nabla.(n\chi\nabla T) = P_{\mathrm{in}} - P_{\mathrm{out}} \qquad (2)$$

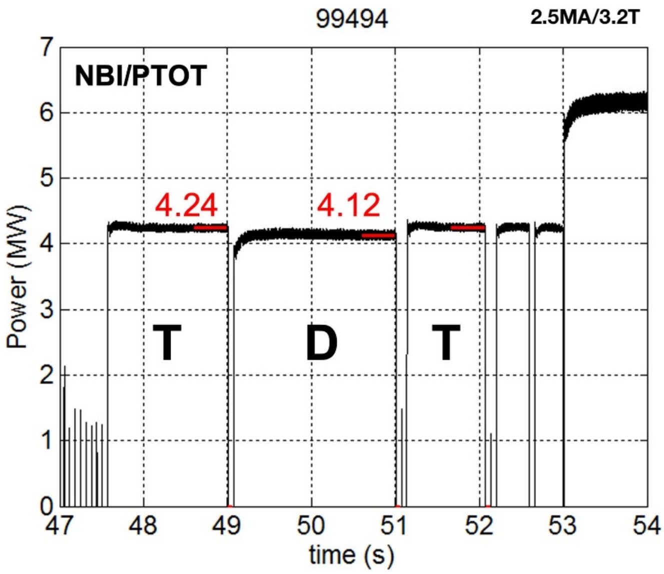

Figure 13. Input power from pulse 99 494.

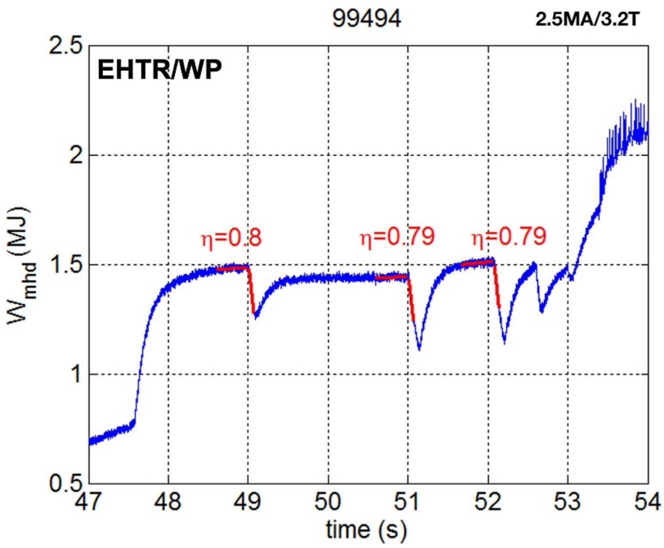

Figure 14. Plasma stored energy for pulse 99 494 with fit to slope to provide heating efficiency, η.

$$\eta = \frac{\triangle\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right)}{\triangle P_{\mathrm{in}}}. \qquad (3)$$

The input power and stored energy with the fit for the slope in the beam turn off is shown in figures 13 and 14. It can be seen that in both cases the heating power appears to be 80% of that expected, but this analysis does not include certain losses such as shinethrough and CX losses. There has also consistently been a discrepancy in such analysis as discussed in [4]. The key result here is that there is no difference seen again in the D and T NBI.

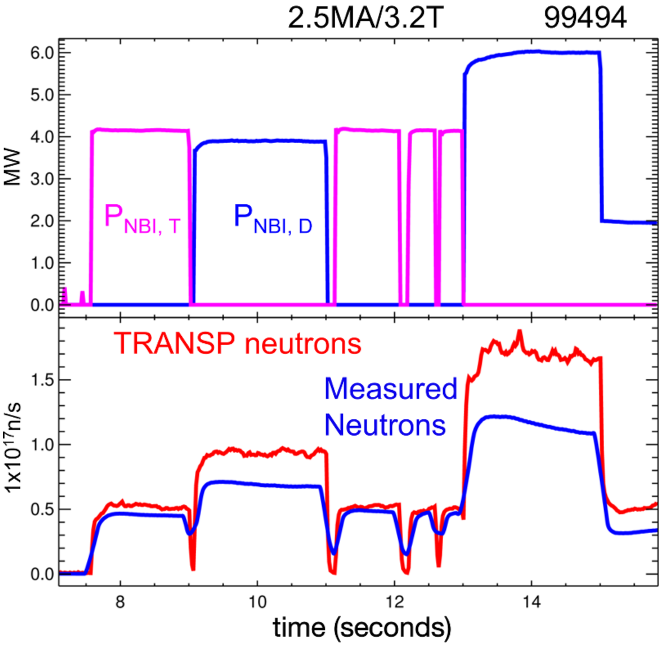

Figure 15. Input power and neutron rate calculated by TRANSP (red) and measured (blue) for pulse 99 494.

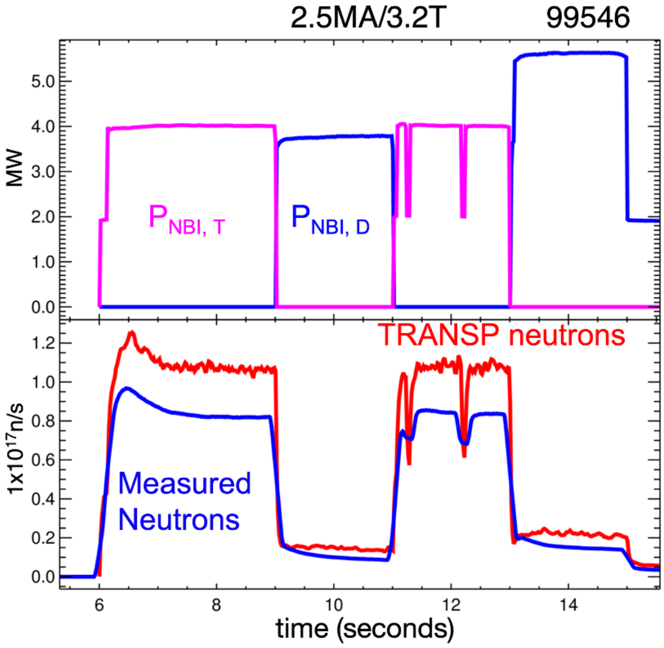

Figure 16. Input power and neutron rate calculated by TRANSP (red) and measured (blue) for pulse 99 546.

5. Neutron rate comparison with TRANSP data

When discussing pure deuterium results the neutron rate comparison between experiment and modelling has been useful in the past for analysing beam behaviour. However, in this case there is a variation in the neutron behaviour due to the changes in beam and target at the same time. Further to this, there are discrepancies between the measured neutrons flux and the one simulated by TRANSP in plasmas with low input power [25]. This discrepancy is increased by the choice of PINI as discussed above, PINIs 2 and 3 have significantly larger neutron discrepancies than other PINIs as shown in [8]. Hence the comparison of neutron rates in D and T phases and use of TRANSP output is unlikely to provide useful additional data for confirming the calibration of the beam power.

The data is presented for completeness in figures 15 and 16. In one case the D NBI phase shows a large discrepancy while in the other case it is the T NBI case that shows a discrepancy. The neutron rate will be sensitive to isotope ratio in opposite ways in each phase of this plasma, i.e. the neutron rate will increase with increasing tritium content for deuterium beams and decrease with increasing tritium content for tritium beams, hence small variations in the plasma isotope ratio between pulses could cause a different discrepancy between beam species between the two pulses. Also the lack of T_i data (which as discussed above is not measured here) this neutron comparison data is not considered conclusive.

6. Deviation of power and species mix with grid gas flow

The NBI power dependence on grid gas flow rate was discussed in section 2. This dependence is only significant at high beam voltage and as a result the calibration of the grid gas flow rate can also have an effect on the power calibration. In the final period of D-T operation it became beneficial for increasing available NBI power to operate a subset of the tritium PINIs in deuterium on a number of occasions, which required adjustments to the grid gas flow. While the grid gas flow was calibrated each time this occurred there was some scope for an error in grid gas flow to be introduced. An error of up to 2 mbar.l s^{-1} could have accumulated on these PINIs, which could correspond to a change in power of up to 5% on a PINI. If we assume that all of the PINIs on the beamline operated in tritium developed the maximum error then the total uncertainty for this period could increase to 12.5%. It should be noted that a drop in NBI power is unlikely for these pulses. This change in grid gas flow would only lead to a drop in NBI power if operated at >110 kV and these PINIs did not typically operate at those voltages in this phase. The higher uncertainty estimate applies to total beam power for pulses in the range 99 759 to 99 982.

7. Conclusions

A series of plasmas were used to compare different JET NBI calibrations and provide as much validation as possible to the input power values used in JET D-T experimental results. The initial calibration techniques used by the operational teams provided more accurate tritium NBI calibrations than used in the previous JET tritium campaigns DTE1 and TTE. By comparing the plasma stored energy it was found that there was no significant difference in the uncertainty in the T NBI calibration compared to the D NBI power calibration.

For the majority of JET D-T operation an uncertainty in input NBI power of $\pm 10\%$ must be used for all types on NBI operation. For a subset of pulses a higher uncertainty of $+10\%/-12.5\%$ must be used due to operational variations in the grid gas flow used. This uncertainty does not reflect an expectation of lower delivered power in that period, but that there is uncertainty in the exact grid gas flow rate that could in principle lead to reduced NBI power.

For all of the experiments performed in the T and D-T phases an accurate calibration of the neutral beam power was required. Calculations of Q, plasma confinement, L-H power threshold and many other parameters rely on accurate measurement of the input power. In addition, the calibration of the power provided by D and T beams must be accurate to minimise uncertainties in the comparison of NBI heated plasmas used to study isotope effects. The results shown have successfully provided the community with this data.

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