NEUTRAL BEAM INJECTION IN THE JET TRACE TRITIUM EXPERIMENT

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Operation of the JET Neutral Beam Injectors with tritium is described. Supplying the tritium feed via the special electrically grounded gas feed compromised the performance of the up-graded high current triode Positive Ion Neutral Injectors (PINI) due to gas starvation of the source and the methods adopted to ameliorate this effect are described. A total of 362 PINI beam pulses were requested, circulating a total of 4.73g tritium, of which 9.3mg was injected into the torus. Safety considerations required a continuous, cumulative total to be maintained of the mass of tritium adsorbed onto the cryo-pumping panel; a daily limit of 0.5g was adopted for the Trace Tritium Experiment (TTE). A subsequent clean up phase using 115keV deuterium beams completed the isotopic exchange of components in the beamline.

I. THE JET NEUTRAL BEAM INJECTION SYSTEM

The JET NBI system consists of two Neutral Injection Boxes (NIBs) each equipped with up to eight Positive Ion Neutral Injectors (PINIs) [1]. Of the PINIs on the NIB located at machine octant 4, six operate at 80kV/56A in deuterium, one at 130kV/60A and the eighth at 140kV/30A. The PINIs located on octant 8 (NIB 8) were recently upgraded to operate at 130kV/60A in deuterium [2, 3] compared with 140kV/30A previously. An illustration of a JET NIB is shown in Fig. 1; the eight PINIs are mounted in two vertical banks of four. Each set of four is further divided into two pairs, each pair sharing a common deflection magnet. The ion beam extracted from the source is passed through a gas neutraliser and the subsequent mixed beam of ions and neutral particles passes through a deflection magnet. The magnet removes the unwanted ionic beam component and injection into the neutral beam either passes into the torus via the duct or is collected on the calorimeter.

For the JET Trace Tritium Experiment (TTE) [4] only two PINIs on NIB 8 were required to operate in tritium, the remaining six PINIs operating simultaneously in deuterium. The tritium gas feed is supplied to each pair of PINIs from the central Active Gas Handling System (AGHS) [5] by the Tritium-Deuterium Gas Introduction System (TDGIS) [6]. The gas is then delivered to an individual PINI via a single inlet in the ground-potential accelerating grid holder, avoiding the use of the frangible glass insulating break in the conventional gas feed. The TDGIS, its transfer lines and the AGHS share a common secondary containment envelope and thus the deuterium feed to the remaining six NIB8 PINIs is also supplied via the TDGIS. The single gas feed to each PINI must supply gas both to the ion source and the neutraliser and the consequent reduction in source pressure created additional operational problems as discussed in Section IIA.

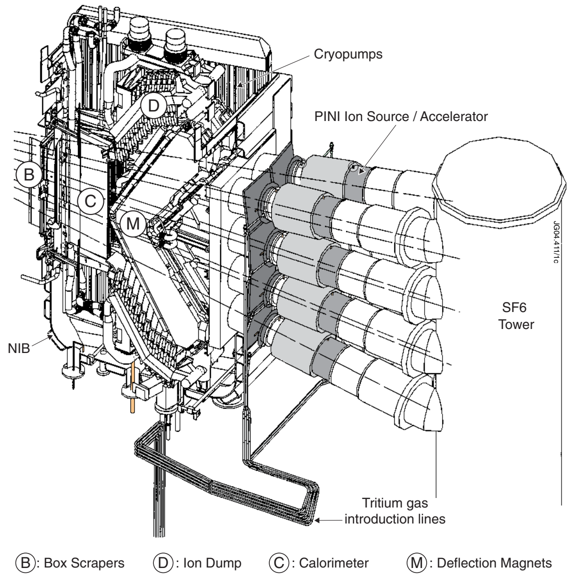

Fig 1. Illustration of a JET Neutral Injection Box.

The TDGIS was also used to maintain a continuous log of the amount of tritium delivered to the NIB, from which the mass of tritium condensed on the cryopump panels was obtained as described in Section III. Safety considerations imposed a daily maximum tritium inventory of 0.5g on the cryo-panel [4] and this too had consequences for the operation and commissioning of the tritium PINIs as described in Section II.

II. OPERATIONAL EXPERIENCE

II.A. Commissioning

The PINIs can be commissioned independently of JET operations in the asynchronous (Async) mode. In this case the two gates of the calorimeter (C in Fig 1) are opened to the beam and can be used to determine alignment and the beam profiles. Prior to tritium extraction, the calibrations for the four deflection magnets (M in Fig 1) for NIB8 were adjusted to accommodate the different species mass from the tritium PINIs.

The NIB 8 PINIs were first commissioned with deuterium. This provided two opportunities: firstly to optimise the gas and arc stabilisation times to minimise the throughput of tritium and secondly to determine the filament and arc control parameters for operation under the TDGIS.

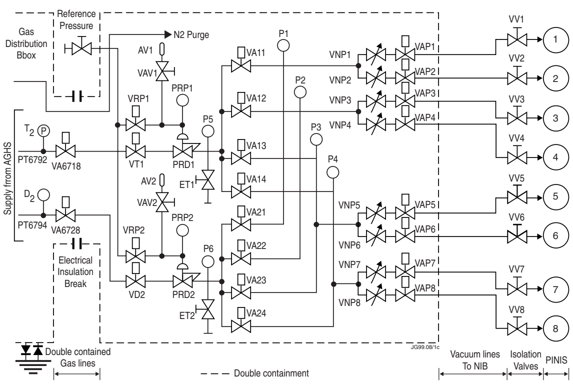

Fig. 2. Schematic diagram of the TDGIS.

A schematic diagram of the TDGIS is show in Fig 2. The dashed line indicates the extent of the double containment [6]. The lines shown between valves VAP and VV are those indicated in Fig 1 and represent ~30m of path length of 25mm internal diameter. These lines are held under NIB vacuum and only filled immediately prior to a beam pulse.

Under normal deuterium operation the valves supplying gas to the PINIs are opened three seconds before extraction is programmed to begin. The arc is then initiated some two seconds prior to extraction to allow the control system to regulate at the correct values of arc current and for beam extraction. Commissioning pulses are usually 400ms duration, this being the high power limit of the calorimeter.

To maximise the number of tritium beam pulses available within the daily tritium limit, it was necessary to reduce the equilibration times as much as possible. Initial trials with deuterium indicated that a gas equilibration time of 1200ms and an arc equilibration time of 700ms could be tolerated. The vacuum lines to the NIB constitute a gas reservoir and it was found that valves VAP1 and VAP2 (supplying the tritium PINIs) could be closed 400ms before the end of the beam pulse without affecting performance. Unfortunately when the commissioning phase changed to tritium feed, the reduced conductance compromised the arc equilibration time and a value of 800ms was necessary. Thus for a tritium flow rate of 2.4Pa.m^3/s a single commissioning pulse of 260ms beam duration consumed 0.012g of tritium.

Operation with the TDGIS, with gas introduced via the grounded accelerator grid, reduces the gas pressure in the source compared to normal operation, which can lead to a condition commonly known as "gas starvation". Operating in this mode reduces the source plasma density giving a slower rise in arc current and increasing the sensitivity of the plasma to extraction loss. The gas starvation was particularly acute for the two tritium PINIs. Fig 3(a) shows the arc current characteristics of one of the tritium PINIs compared with its operation in deuterium.

The arc current rises extremely slowly on ignition and this was the major factor determining the arc stabilisation time. The effect of gas starvation on the extracted tritium beam current can be seen in the fine curve of Fig 3(b). The beam current shows a sharp spike at the start of extraction due to the fact that the plasma density is higher at this point than later in the pulse. The extracted beam represents a loss to the source plasma and this effect is particularly acute in gas starved sources. To prevent this unwanted overshoot, which takes the beam away from optimum perveance, the arc voltage was reduced for approximately 50ms at the start of extraction. This has the effect of reducing the source efficiency and produces a constant beam current as shown in the bold curve of Fig 3(b).

A more serious consequence of operating under gas starved conditions was the limitation to the beam energy.

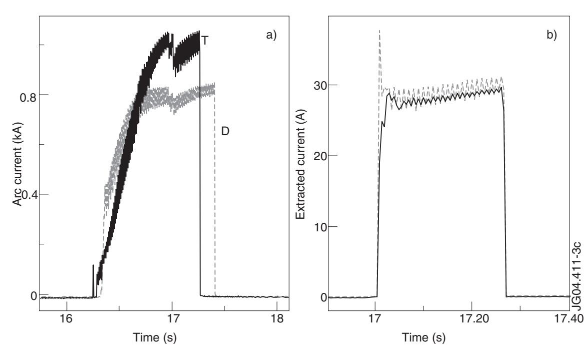

Fig. 3. Characteristics of gas starvation: (a) arc current for deuterium and tritium ; (b) extracted tritium current without arc voltage control showing overshoot and with voltage control.

The arc power supply is capable of providing up to 1400A, normally sufficient to allow beam extraction up to the maximum 130kV available form the high voltage power supply. Under the arc starved condition plasma production saturated at an arc current of ~1000A whereupon increasing emission from the filaments failed to produce an increase in arc current. The plasma density at this arc current produced a perveance-matched beam at 110kV/38A and this represented the upper operating bound of the tritium PINIs.

A total of 44 Async tritium pulses were required to complete the commissioning phase, which included alignment checks and measurement of the optimum tritium beam perveance. The vertical and horizontal beam profiles for a tritium beam of 95keV energy at optimum perveance is shown in Figure 4. The beam widths are similar to those recorded in deuterium.

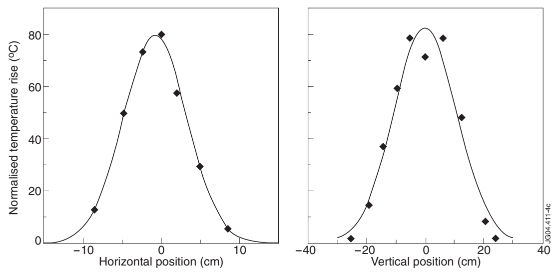

Fig. 4. Horizontal and vertical beam profiles measured on the calorimeter for a tritium beam of 95keV energy: ◆ thermocouple data, ── gaussian fit.

II.B. Injection into JET

Operation involving injection into the JET tokamak, known as Synchronous (Sync) mode, is achieved by closing the calorimeter, whereupon the beams from the upper and lower PINIs along the duct into the JET plasma.

At the start of each tritium operational day, a small number, between six and eight, Async pulses were needed to raise the PINI extraction voltage to 110kV.

The experimental programme utilised tritium beam pulses typically of 100ms duration. Providing such short pulses reliably is challenging for the PINI systems, which are designed to provide beam pulses of several seconds duration. In particular, recovery from a high voltage breakdown during such a short pulse will reduce the beam time by 40%. In order to improve reliability for such short pulses, the operating beam voltage was reduced to 102kV in most cases.

In total 362 PINI pulses were requested during TTE, of which 139 PINI beam pulses were fired in Sync mode. Of these 76 achieved >90% of the required beam on time, whilst 19 failed due to interlock alarms not directly related to the NBI system (the most common being insufficient plasma density in the torus) and 3 failed due to timing errors in the TDGIS. The remaining 41 pulses were affected by high voltage breakdown. This is a much larger percentage than usual and illustrates the effect of the reduced Async conditioning time imposed by the daily tritium inventory limit. The statistics for the tritium NBI are shown in Fig.5 as a function of date (the commissioning pulses are shown as a single total on 23rd September). The distinction between pulses fired and those deemed to have successfully delivered beam is important for tritium accounting purposes, as gas will be delivered to the NIB regardless of beam delivery unless either the countdown procedure is aborted, or a plasma-related fault inhibits the beams before the gas inlet valves open.

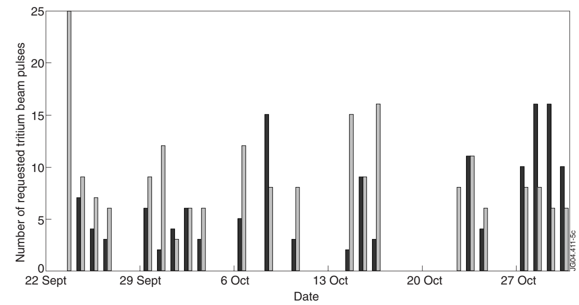

Fig. 5. Statistics for requested tritium PINI pulses during TTE. ▬ Async ▬ Sync.

II.C. Computation of Neutral Tritium Beam Power

The power delivered in the neutral tritium beam allows the total tritium fluence injected into the torus to be calculated and thus is a fundamental parameter for the analysis of the TTE data. Calculation of the neutral beam power requires knowledge of the target density in the neutraliser, which cannot be measured directly. It is known that heating of the neutraliser gas reduces the target density from that expected by simple gas flow considerations and that the degree of heating is a function of beam power and gas flow [7]. Unfortunately direct measurements of the gas temperature in the neutraliser only exist for hydrogen and deuterium and the situation is further complicated by the use of the TDGIS, which gives different distribution of pressures between source and neutraliser. To calculate the tritium neutral beam power it was necessary to derive some empirical scaling laws to estimate the neutraliser target. The power thus computed was later checked against a known deuterium beam power and shown to be correct within the usual quoted error of ±10%.

II.C.1. Estimation of Tritium Neutraliser Target

By comparing the response of the NIB 8 calorimeter to full (i.e. neutral and ionic components) and neutral beams it has been established that the neutraliser target density for the NIB 8 PINIs operating in deuterium has a value of $4.0\text{x}10^{19}$ molecules/m^2. Given that the target density will depend upon the conductance of the neutraliser and that mass flow is conserved, it was anticipated that, to first order, the target, P would scale as:

$$\frac{\Pi_T}{\Pi_D} = \sqrt{\frac{T_D}{T_T}} \qquad (1)$$

where T is the temperature of the gas in the neutraliser and the subscripts D and T refer to deuterium and tritium respectively. Thus the if the gas temperature in the neutraliser for tritium can be scaled from measurements in hydrogen and deuterium, the target can be obtained.

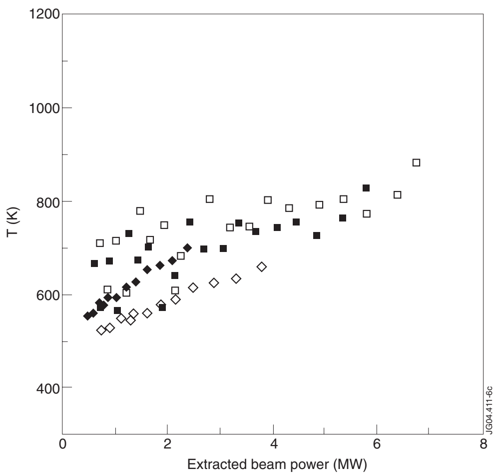

Fig. 6. Tritium gas temperature in the neutraliser scaled from measured values in hydrogen and deuterium. ■ Tritium temperature scaled from deuterium, ◆ tritium temperature scaled from hydrogen, □ measured deuterium temperature, ◇ measured hydrogen temperature.

Measurements of the gas temperature in hydrogen and deuterium [7] show it to be a function of extracted beam power (i.e. the ionic current leaving the source) and neutraliser gas flow rate. These results were obtained on the Neutral Beam Test Bed (NBTB) using the normal gas delivery, with separate feeds to the source and neutraliser. The NBTB can simulate gas delivery from the TDGIS by introducing gas via the grounded accelerator grid and by comparing the NIB pressure for identical beam currents in the two gas systems, TDGIS flow equivalence can be determined. The results showed that in deuterium a flow of 3.5 Pa.m^3/s through the TDGIS is equivalent to a combined source and neutraliser flow of 1.10 Pa.m^3/s and 1.3 Pa.m^3/s respectively. Calibration of the tritium flow from the DTGIS during commissioning gave a value of Q_T=2.4 Pa.m^3/s. Normalisation to the flow rate, Q, and square root of the mass, M, to eliminate the isotope effect evident in the NBTB results gives the gas temperature in tritium, at a given extracted beam power, via the scaling equation:

$$T_T = \frac{T_n Q_T}{Q_n} \sqrt{\frac{M_T}{M_D}} \qquad (2)$$

where n is either H or D for hydrogen and deuterium respectively. Figure 6 shows the scaled gas temperature in tritium and the original hydrogen and deuterium values.

It is clear that the temperature in tritium is similar to that in deuterium and so from equation (1) it follows that the target density will also be similar. The neutral beam power can then be calculated from the known charge exchange cross sections for tritium.

II.C.2. Measurement of Neutral Tritium Beam Power

The power in the neutral beam can be measured by comparing the response of the thermocouples in the calorimeter (C in Fig 1) to a tritium beam with that for a deuterium beam of known neutral power. The response of the thermocouples can be characterised by the parameter K defined as:

$$K = \frac{P_0 \Delta t}{whA} \qquad (3)$$

where P_0 is the neutral beam power, Dt is the beam pulse length, w and h are the horizontal and vertical beam gaussian widths and A is the amplitude (i.e. the maximum temperature rise) of the vertical profile. The parameter K is independent of isotope and can therefore be determined from the deuterium data, allowing the power in the neutral tritium beam to be obtained. A number of measurements confirmed a neutral tritium beam power of 1.1MW, agreeing to within 5% of the value calculated using the neutraliser target obtained from equation (1).

III. TRITIUM ACCOUNTING

A major constraint on the neutral beam operation was the daily limit to the total inventory of tritium on the NIB8 cryo-panel of 0.5g, adopted for TTE. A continuous record of the quantity of tritium introduced into the NIB by each beam pulse was maintained. The amount of tritium introduced to the NIB for each pulse was obtained from the product of pressure and volume measured at two points. Referring to Fig 2, the first quantity was obtained from the pressure, P_1 measured by gauge PT6792 combined with the volume, V_1 in the pipes upstream of valve VT1 and the reservoir in the supply from AGHS (not shown). The second quantity was determined from the pressure, P_2 measured by gauge P5 combined with the volume, V_2 contained in the pipes between valves VT1 and VAP1 and VAP2. Both volumes depend upon the exact arrangement of open and closed valves and, following calibration prior to TTE, a simple algorithm computed the true volume from the valve states. The quantity, q, of tritium introduced to the NIB was then obtained from:

$$q = \Delta(P_1 V_1) + \Delta(P_2 V_2) \qquad (4)$$

where D(PV) indicates the difference in that product before and after the beam pulse. Subtraction of the quantity injected into the torus (from the neutral tritium power calculation) then gave the quantity collected on the cryo-panel.

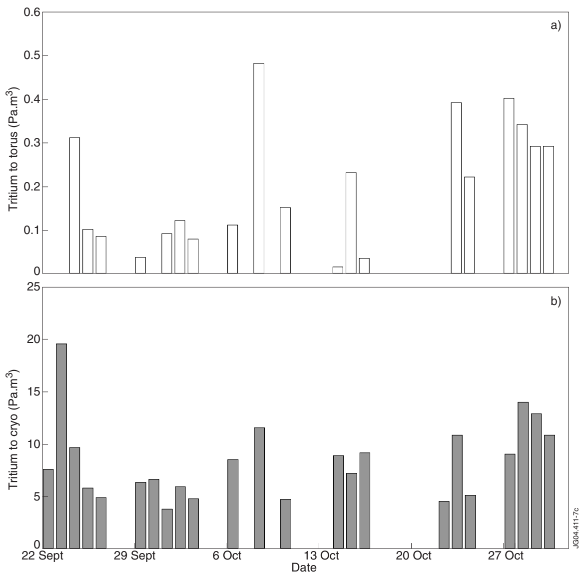

Fig. 7. Daily tritium consumption during TTE: (a) tritium injected into the torus by neutral beams; (b) tritium adsorbed onto the NIB8 cryo-panel.

The quantities of tritium injected into the torus and deposited on the NIB8 cryo-panel are shown in Fig 7 for each day of the TTE campaign. Note that the tritium injected into the torus is typically some two orders of magnitude smaller than that adsorbed on the cryo-panel. The total quantity of tritium supplied to NIB8 was also monitored independently by the Active Operations Dept. This showed good agreement with the values calculated from the DTGIS. The total mass of tritium circulated by the neutral beam system was 4.73 g, of which 9.3mg was injected into the torus in the form of neutral beam.

At the end of operation each day, the gas supply lines were emptied of tritium. The lines between the valves VA6718 and VV1 and VV2 (see Fig 2) were evacuated onto the cryo-panel and included in the daily total; the lines upstream of VA6718 were evacuated back to AGHS.

IV. TRITIUM REMOVAL BY ISOTOPIC EXCHANGE

During tritium operation, the isotope is implanted in various beam line components, with the residual ion dump and calorimeter (D and C in Fig 1) receiving the largest fluences [6]. A ^{235}U fission chamber is located on the JET machine adjacent to the NIB 8 beam line. This was used to monitor the neutron yield from interactions

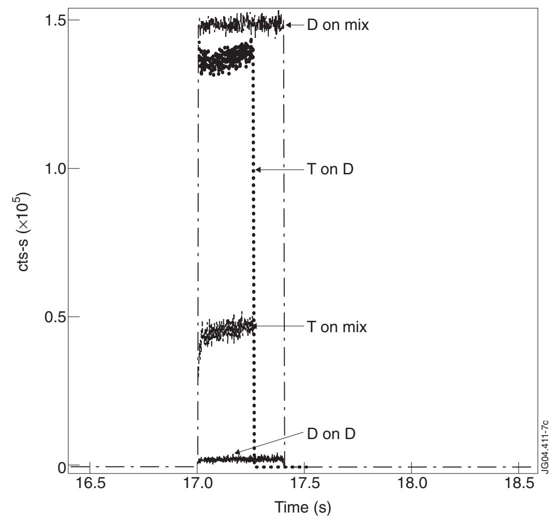

Fig. 8. Neutron count rates for different beam and target combinations at the full energy ion dump. "Mix" "indicates a target of deuterium and tritium.

between Async beam pulses and the implanted target isotope throughout TTE. Fig. 8 shows the neutron yield from the first quadrant for a number of beam-target combinations. The D on D curve was measured prior to TTE, the T on D (tritium beam, deuterium target) at the beginning of TTE and the D on mix (deuterium beam, mixed tritium and deuterium target) at the end of TTE. All the measurements were made with beam energy of 100keV and no scaling for the variation of cross section with energy per a.m.u. is included.

At the end of the TTE there followed a period of NIB 8 operation in deuterium in order to effect an isotopic exchange in the beamline components, removing the tritium for treatment by AGHS. A total of 674 PINI pulses was required to return the neutron yield to the level prior to TTE.

In Async mode most beam-target interactions occur on the calorimeter and ion dumps whereas in Sync mode the neutron detectors are dominated by reactions in the plasma; therefore only the former mode pulses can be used to monitor isotope exchange. Fig 9 shows the neutron yield per extracted coulomb, normalised to the pre-TTE value, as a function of the cumulative fluence, F, calculated from:

$$F = \left(f_1^0 + 2f_2^0 + f_3^0\right) I_{ext} \Delta t \qquad (5)$$

where f_1^0, f_2^0, f_3^0 are the fractions of monatomic, diatomic and triatiomic neutral species in the beam, I_{ext} is the extracted beam current and Dt is the beam pulse length. (The neutral fractions are used because previous experience showed that the signal from the neutron detectors is dominated by emission from the calorimeter [6]). The neutron yield was reduced to within a factor of two of the pre-TTE value (solid line) within a fluence of approximately 6000C, slightly less than required in the previous tritium campaign [6]. This is due to the reduced implantation energy of the tritium in TTE and the higher energy deuterium beams used for clean up. The implantation profiles for 100keV tritium ions and 115keV deuterium ions in copper are almost identical, therefore nearly all of the tritium deposited in the calorimeter should have been accessed by the clean up beams, giving almost complete isotopic exchange.

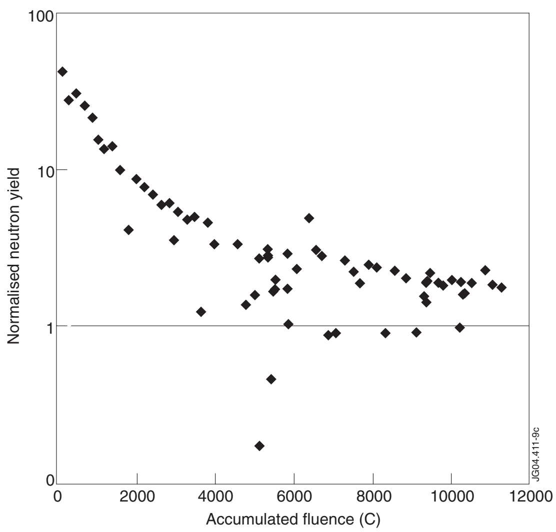

Fig. 9. Neutron yield per extracted coulomb normalised to pre-TTE value as a function of Async fluence. Solid line represents the pre-TTE value.

V. CONCLUSION

Two of the eight NIB 8 PINIs were successfully converted to tritium operation, despite some complications due to gas starvation of the PINI plasma source. Although gas starvation had been noted in the Deuterium-Tritium Experiment of 1997, the tritium PINIs in this case operated at 160kV/30A, requiring much lower arc currents, so the effect was mitigated to a large degree.

A total of 139 Sync mode tritium PINI beam pulses were requested, of which 136 resulted in injection into the torus, representing a tritium mass of 9.3mg. Of these Sync pulses approximately 55% achieved in excess of 90% of requested beam on time despite being required to operate at pulse lengths of 100ms, two orders of magnitude smaller than the design value.

A total mass of 4.73g of tritium was circulated through NIB8 during the TTE, including commissioning of the tritium PINIs. Operation in tritium with the DTGIS compromised the achievable tritium beam energy to less than 110keV. However this enabled a full isotope exchange to effected by 115keV deuterium beams during the subsequent clean up phase.

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