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ABSTRACT.

Neutralisation efficiency is an important issue in the design of neutral beam injection (NBI) systems for heating and fuelling fusion plasmas. The JET Neutral Beam Injectors system does not reach the efficiency that is expected on the basis of current understanding of the neutralisation process. If this neutralisation efficiency deficit could be eliminated by re-design of the neutralisers, additional neutral beam heating power would become available.

The interaction of the high-energy beam ions and the gas in the neutraliser cell results in the partial neutralisation of the beam and also in the formation of a low temperature plasma inside the neutraliser. The interaction between this plasma, the neutral gas and the walls of the cell can give rise to various phenomena capable of depleting the neutral gas molecular density hence reducing the effective neutralisation target. For example, wall pumping, gas heating and modification of the flow regime are all possible effects.

This paper presents the results of a number of experiments that were carried out in order to measure the plasma and gas parameters inside the neutraliser. The plasma parameters were obtained using a combination of planar Langmuir probes and a novel electrical diagnostic called a ‘plasma eater’. The gas pressure was measured using hot cathode ionisation gauges and capacitance manometers. An attempt has been made to measure the neutral hydrogen gas temperature using a spectroscopic technique that requires the measurement of the intensities of the spectral lines of the hydrogen Fulcher-α system [1]. The experiments were carried out at the JET Neutral Beam Test Bed, which was modified by inserting a flange containing eight ports in place of the isolation gate valve between the first and second stage of the neutraliser neutraliser. The beam was produced from the recently upgraded JET Positive Ion Neutral Injector (PINI) which is capable of delivering a 130 kV/60 A deuterium beam. The measurements were made over a range of beam energies from 40 keV to 90 keV and the results include power, pressure and energy scans in hydrogen.

1. INTRODUCTION

Neutral hydrogen or deuterium beams are usually formed by passing energetic ions through a gas cell called a neutraliser. The efficiency of the neutralisation process depends on the linear gas density in the neutraliser $\int n(l)dl$ i.e. the gas target. Neutralisation efficiency measurements based on calorimetric data [2] and charged fusion products [3] show that the neutralisation process is not reaching the efficiency expected on the basis of neutraliser conductance measurements and known reaction cross sections. If this neutralisation efficiency deficit could be eliminated by re-design of the neutralisation cells additional neutral beam heating power would become available to the Tokamak. It has been proposed that the efficiency deficit is caused by a reduction in the linear gas density $\int n(l)dl$. This density reduction can be due to a number of factors [2] including wall pumping and modification of the flow regime but it is thought to be due principally to heating of the neutraliser [4, 5].

When an intense beam passes through the neutralisation cell, charge exchange and ionisation collisions result in the formation of a secondary, low temperature plasma. The interaction of this plasma and the neutral gas and the walls could results in substantial gas heating which may explain the neutralisation efficiency deficit observed in the JET neutral beam injectors.

In this paper we present the results of an initial experimental investigation which included measurements of the plasma parameters and the neutral gas temperature observed at the JET Neutral Beam Test Bed. The plasma measurements are used as input parameters for a gas heating model [4] and the results of this model are compared with a spectroscopic measurement of the neutraliser gas temperature.

2. EXPERIMENTAL SET-UP

The experiments were carried out at the JET Neutral Beam Test Bed. The hydrogen beam was produced by a 130kV/60A upgraded triode PINI (Positive Ion Neutral Injector) [6]. The 180-cm long neutraliser cell is divided equally into two stages, stage one is attached to the PINI grid stack, stage two is attached to the JET Neutral Injection Box (NIB). A stainless steel collar with eight diagnostic ports was placed between the first and second stage neutraliser. The plasma diagnostics included two planar Langmuir probes, two ‘plasma eaters’, a fibre-optic cable to transmit light for spectroscopic measurements, an ion gauge and a baratron gauge for pressure measurements. The data were recorded as a function of time for beam energies from 40keV to 88keV and neutraliser gas flows ranging from ~20 to ~250 $Pa.m^3/s$.

2.1 PLASMA DIAGNOSTICS

2.1.1 The Langmuir Probe

A planar graphite Langmuir probe was used to determine the neutraliser plasma parameters. The 2 mm radius probe was enclosed in a boron nitride sleeve which was mounted on a retractable stainless steel shaft. The Langmuir probe traces were taken at a rate of ≈30 Hz over a 3 second beam pulse in H_2. The bias voltage with respect to ground was –80 V to 80 V. The data acquisition system logged the data at a rate of 20 kHz, thus approximately 100 Langmuir probe traces each containing about 700 data points each, were obtained for every beam pulse. Standard planar probe theory was used to analyse the probe traces and determine the values of the principal plasma parameters, n_e electron density, T_e electron temperature, V_p plasma potential and the electron energy distribution function [7].

2.1.2 The Plasma Eaters

The plasma eater is a novel electrostatic plasma diagnostic that was used to determine the plasma ion flux to the neutraliser walls. The device, a photo of which is shown in Figure 1, consists of fifty alternately biased molybdenum plates. The distance between the fins is 0.1 mm (smaller than the Debye length of the plasma). The bias voltage is set at a few times the electron temperature the edges of the plates are exposed to the plasma through a 1 cm^2 orifice cut in the ceramic housing of the plasma eater. Such a configuration will not perturb the plasma since the combined electric field of both sets of plates will not penetrate beyond the plasma sheath thickness. Since the particle fluxes are determined by plasma conditions at the sheath edge, the electrons and ions travelling towards the wall will ‘see’ the device as just another part of the wall until they enter the sheath. When they arrive at the device the ions are collected by the negatively biased plates and the electrons are collected by the positively biased plates.

2.2 SPECTROSCOPIC MEASUREMENTS

Spectroscopic measurements were made to determine the neutral gas temperature of hydrogen in the neutraliser. The basis for the measurements is the theory of de Graaf [8], which relates the characteristic rotational temperature of the excited $d^3\Pi$ level of the hydrogen molecule to that of the ground state $X^1\Sigma_g^+$ which represents the thermal gas temperature. The spectroscopic measurements were made using the SPEX 0.5m 1800 gr/mm Czerny-Turner spectrometer normally used for the Doppler shifted spectrometry on the Neutral Beam Test Bed. Only one optical fibre was used positioned on a side port (ϕ = 63mmx50mm) of the Neutraliser Diagnostic Collar such that the plasma was viewed transverse to the beam axis. The fibre was positioned 200mm from the edge of the neutraliser box and viewed the plasma through a plain Crown Glass window. The spectra of the Fulcher a system were recorded as a function of time for beam energies from 40keV to 88keV and neutraliser gas flows ranging from ~20 to ~250 Pa.m^{3}s. Measurements were taken 0.5s after beam on for 5 seconds with an integration time of 0.25s. Four bands were visible corresponding to transitions between the vibrational levels 0, 1, 2 and 3 (there is no change in the vibrational quantum number for these transitions) in the $d^3\Pi$ and $a^3\Sigma$ levels. The wavelength of the spectral lines range from 601.8nm to 636.3, the change in sensitivity of spectrometer is negligible over this range so no calibration was required. The slit width was set to 70μm, for which the resolution of the instrument has been measured to be 0.0280(±0.0017) nm using the 650.653nm and 653.288nm NeI lines.

3. NEUTRALISER GAS HEATING MODEL

The energy balance equation that describes the equilibrium between the gas energy lost on the neutraliser walls and the energy gained from collisions with the beam and gas interaction with the neutraliser plasma is given as [5]

$$S_w \alpha k \left(\frac{nv}{4} \right) \frac{(T - T_0)}{(\gamma - 1)} = s(I_B, E_B, n, n_e, T_e, V_p, l, x, y) \qquad (1)$$

S_w is the neutraliser wall surface area, T is the gas temperature, T_0 is the wall temperature, α is the accommodation doefficient, γ is the specific heat capacity of the gas, n and v are the neutral gas density and mean thermal velocity, k is the Boltzmann constant, V_P, n_e and T_e are the plasma potential, the plasma electron density and plasma electron temperature, E_B and I_B are the beam energy and current, l, x and y are the length, width and height of the neutraliser.

The model considers three indirect heating mechanisms that contribute to the source term.

Table I: Processes that contribute to gas heating via molecular dissociation by the beam ions with their cross sections σ_j and the energy transferred to the dissociation products E_{dj}

j	*Reaction*	*Process*	$E_{dj}(eV)$	$\sigma(E_B)(10^{-17}cm^2)$
1	$\underline{H}^+ + H_2 \rightarrow \underline{H} + H + H^+$	Dissociative Charge Exchange	5	$\exp(2.6(1 - E_B/100)$
2	$\underline{H}^+ + H_2 \rightarrow \underline{H}^+ + H + H^+ + e$	Dissociative Ionisation	5	$.7 + (E_B - 40)/100$
3	$\underline{H}^+ + H_2 \rightarrow \underline{H}^+(\underline{H}) + H^+ + H^+ + e + (e)$	Double Ionisation	10	$\exp(0.79(1 - E_B/121))$
4	$\underline{H}^+ + H_2 \rightarrow \underline{H}^+ + H + H$	Simple Dissociation	2	$\dfrac{9.7\exp(-3.4(1 - (64.4/E_B))^2)}{1 + 10^5(E_B/39)^6}$

i. Molecular dissociation by the beam ions. For this mechanism the four processes detailed in Table I with their cross sections σ_j and the energy transferred to the dissociation products E_{dj} are considered.

ii. Molecular dissociation by plasma electrons. This mechanism is considered using the rate coefficient, $\langle\sigma_{de}v_e\rangle$, as parameterised by Jones [9] and Langmuir probe measurements of T_e and n_e.

iii. Collisional processes between neutrals which originate when plasma ions that are accelerated through the plasma sheath are neutralised and reflected from the wall with substantial energy.

$s(I_B, E_B, n, n_e, T_e, V_p, l, x, y)$ is the energy source term.

$$s(I_B, E_B, n, n_e, T_e, V_p, l, x, y) = \tag{2}$$

$$\left(\sum_{j=1}^{4}\sigma_j\,(E_B)E_{dJ}P(E_{dJ})\right)\frac{nlI_B}{e} + \tag{i}$$

$$n_e n\langle\sigma_{de}v_e\rangle VE_{de}P(E_{de}) + \tag{ii}$$

$$n_e S_w RV_p\frac{eT_e^{1/2}}{\sqrt{M^+}}(1-\exp(-\sigma_0 xn)) \tag{iii}$$

where, $P(E) = 1 - \exp(-\sigma_0 xn)$ this represents the probability for energy loss of the dissociation products in elastic collisions on gas molecules, V is the neutraliser volume, M^+ is the ion mass and v_e is the mean thermal velocity of the plasma electrons, σ_0 is the momentum transfer cross section and R is the reflection probability multiplied by the fraction of energy reflected.

4. RESULTS

4.1 TIME RESOLVED PLASMA PARAMETERS

The temporal profile of the plasma parameters and the gas temperature is shown in Figure 2. The results presented are for a 5 second beam pulse in H_2 at 80 keV and 32 Amps. It can be seen from Figure 2(a) and 2(b) the plasma parameters n_e,V_P and T_e vary slightly throughout the pulse, V_P and T_e decrease with time and n_e increases slightly with time. This variation can be explained by the fact that the gas flow to the neutraliser is not perfectly constant throughout the pulse, indeed the flow rate can increase by as much as 10% depending on the settings of the gas handling system. The fall in V_P and T_e and the rise in ne are consistent with such a variation in flow rate.

In Figure 2(c) the results of the spectroscopic measurement of gas temperature and the results of the gas heating model with measured plasma parameters as inputs are presented together. The two results show remarkably good agreement, however the error on the model could be as much as 15%.

4.2 VARIATION WITH POWER

The variations of the plasma parameters, gas temperature and the relative contribution of the three heating mechanisms considered are plotted as a function of extracted beam power in Figure 3. The data were taken for beam powers in the range 0.5–4MW, corresponding to beam energies of 40 keV to 88 keV.

The parameters n_e,V_P and T_e are found to increase with power as shown in Figure 3(a). Figure 3(c) shows the measured gas temperature and the gas temperature as derived from the gas heating model. The results show qualitative agreement over the range of power and quantitative agreement improving with higher power. The lack of agreement is in part due to fact that the model ignores certain phenomena, such as beam species composition, that become more important at low beam energy and hence Ion beam power. The relative contribution of the three heating mechanisms considered in the model are shown in Figure 3(c). The results show that the contribution from molecular dissociation by plasma electrons tends to saturate or even decrease with power while the contribution from plasma ions reflected from the walls as fast neutrals increases becoming the dominant term at higher power.

4.3 VARIATION WITH PRESSURE

In Figure 4 the results of a neutraliser pressure scan are presented. The pressure is measured by a Baratron and Ion gauges before the beam is turned on. The pressure range is limited at the lower end by the gas flow from the PINI and at the upper end by the operating limits of the neutraliser gas handling system. The measurements were recorded at 80 keV beam energies at 2.5 seconds after beam on. The parameters n_e,V_P and T_e vary as expected with pressure, as the pressure is increased the electron temperature decreases due to the increased number of electron-neutral collisions. The measured gas temperature and the gas temperature as derived from the gas heating model are shown in Figure 4(d). The results indicate that the gas heating effect saturates at the higher end of the pressure range, the saturation temperature is about 1100 K. Figure 4(d) shows the relative contributions from the three heating mechanisms. The contribution from mechanism (i) increases with pressure, the contribution from mechanism (ii) saturates at the higher end of the pressure range and the contribution from mechanism (iii) decreases due to the lower plasma potential at higher pressure.

DISCUSSION

The results presented above are the first measurement of gas temperature in a neutraliser and confirm that a heating mechanism is present. Direct measurements of the plasma parameters of the neutraliser plasma are found to support the gas heating model of Pamela [4, 5]. The measured gas temperature rise results in a significant reduction in the linear gas density that helps explain the neutralisation efficiency deficit observed in the JET neutraliser.

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REFERENCES

[1] T. Gans *et al.*, Plasma Sources Sci. Technol. **10** (2001) 17-23.

[2] H.D. Falter, D. Ciric, S.J. Cox and D. Godden ‘60 kV hydrogen Neutralisation Scan’ Report JET-R(98)10.

[3] P. Bayetti, F. Bottiglioni, G. Martin, and J. Paméla., Rev.Sci.Instrum. **57**, 62 (1986).

[4] J. Paméla, Rev.Sci.Instrum. **57**, (6), June (1986).

[5] J. Pamela, ‘Gas Heating Effects in the Neutralisers of Neutral beam Injection Lines’, Report EUR-CEA-FC-1279, CEN Fontenay-aux-roses (1985).

[6] E. Surrey, D. Ciric , D.J. Godden and B. Crowley, Proc. 19th SOFE, Atlantic City, January 2002.

[7] R.H. Huddlestone and S.L Leonard, Plasma diagnostic techniques, Academic press, New York 1965.

[8] M. de Graaf, Ph.D Thesis ‘A New Hydrogen Particle Source’, Technical University Eindhoven (1994).

[9] E.M. Jones, Culham report CLM-R 175, 1977.

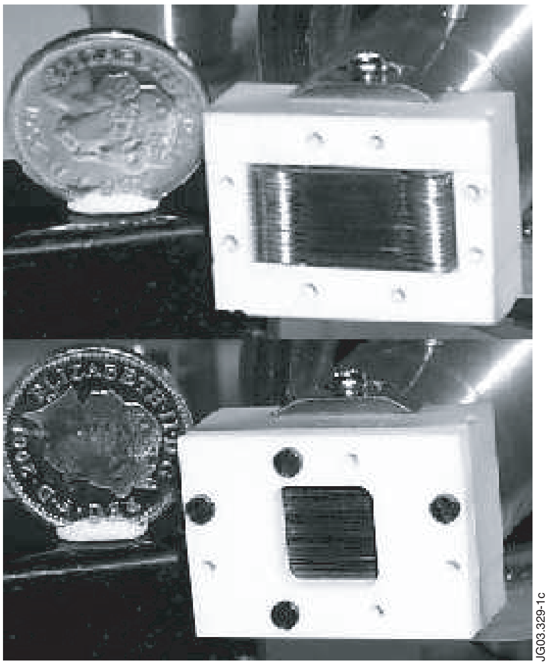

Figure 1: Photograph of 'plasma eater'.

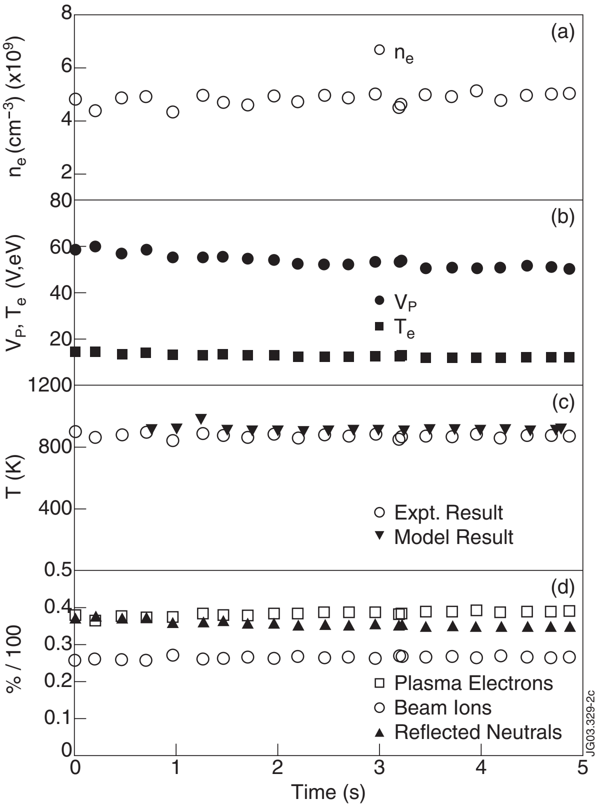

Figure 2: Plasma parameter, gas temperature and gas heating model measurements vs. Time for an 80 kV, 5 second beam pulse. (a). neutraliser plasma electron density, (b). Plasma potential and electron Temperature. (c). Gas temperature (d). Relative contribution of the three heating mechanisms considered in the model.

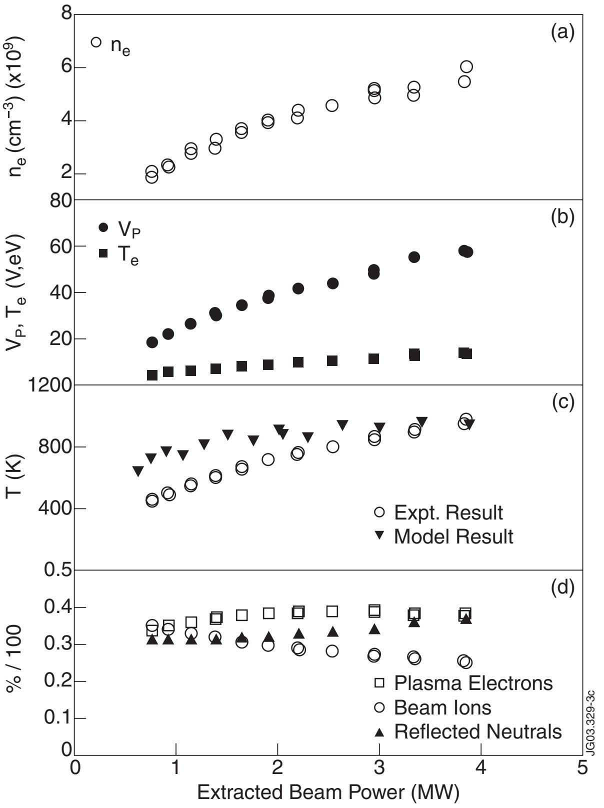

Figure 3: Plasma parameter, gas temperature and gas heating model measurements vs. Extracted Beam Power. (a). neutraliser plasma electron density , (b). Plasma potential and electron Temperature. (c). Gas temperature (d). Relative contribution of the three heating mechanisms considered in the model.

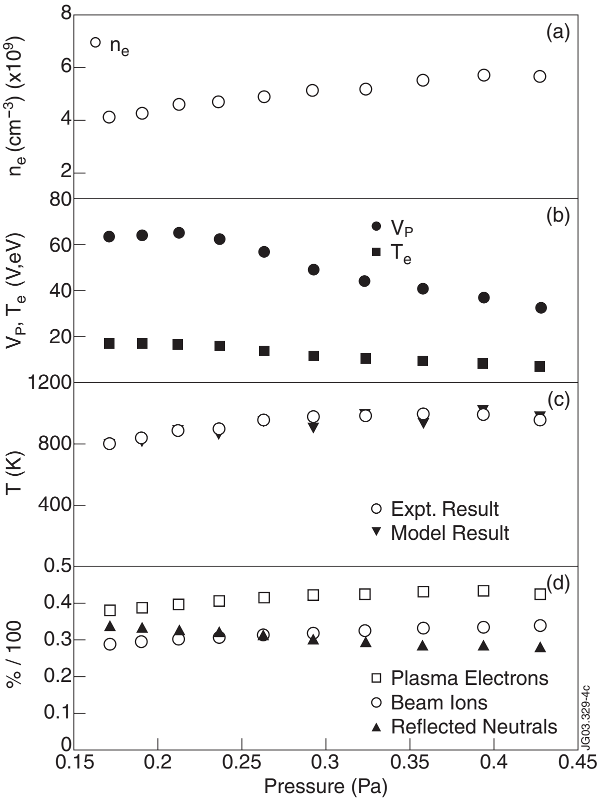

Figure 4: Plasma parameter, gas temperature and gas heating model measurements vs. Pressure for an 80 kV beam pulse (a). neutraliser plasma electron density , (b). Plasma potential and electron Temperature. (c). Gas temperature (d). Relative contribution of the three heating mechanisms considered in the model.