Modelling the Neutraliser Plasma of ITER Negative Ion Beams

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Indirect heating of the neutraliser gas by the beam has been shown to be responsible for the reduced neutralisation efficiency observed in positive ion neutral beam systems. The translational gas temperature can be predicted from the density and electron temperature and, in general, a higher gas temperature implies a lower neutralisation target. A simple, one-dimensional model, originally developed for the JET positive ion neutral injection system, has been adapted for ITER relevant negative ion systems. The results imply that gas heating for the ITER heating and diagnostic beams is unlikely to be severe and hence the neutralisation target might be expected to be close to the design value.

1 INTRODUCTION

The reduction in neutralisation efficiency of positive ion beam systems is now known to be largely due to gas heating effects [1]. The neutraliser gas target is not heated directly by the beam but as a result of processes involving the particles of the plasma created by the beam in the neutraliser, as described by Paméla [2]. Two of the most important processes are molecular dissociation by the plasma electrons and acceleration of plasma ions across the sheath at the neutraliser wall and their subsequent reflection as energetic neutrals. The heating of the neutraliser gas in the presence of a negative ion beam can therefore be predicted from the characteristics (density, electron temperature and plasma potential) of the resulting neutraliser plasma.

A model, originally developed for positive ion systems, has been adapted for application to ITER relevant negative ion beams, i.e. the heating (HNB) and diagnostic (DNB) cases to obtain a preliminary estimate of the significance of the gas heating effect. The beam is regarded as the source of ionisation, the negative, neutral and positive components being considered individually. The stripped electrons are treated separately to the plasma, as it was anticipated that, for both ITER beams, these electrons would not be thermalised by inelastic and coulomb collisions. Equilibrium between the rate of energy transfer from the three beam components (stopping power) and the stripped electrons and the power deposited on the neutraliser walls by the plasma provides an expression for the electron temperature and the plasma potential follows from the boundary condition at the wall.

The Paméla model can then be used in conjunction with the derived plasma density, potential and electron temperature to predict the gas temperature in the neutraliser. At this point it is necessary to make some assumptions regarding the ion reflection coefficient and accommodation coefficient at the wall; both these parameters can strongly influence the gas temperature if the heating effect is significant. The model has been benchmarked against measurements made on the JET positive ion based neutral beam injection system and has demonstrated reasonable agreement.

2 THE NEUTRALISER PLASMA MODEL

When considering the plasma created by the beam in the neutraliser, it is insufficient to treat the system as a "plasma in a box". There is no single source term, as the relative concentrations of ionic and neutral species vary along the length of the neutraliser. In the Paméla [2] and Ott [3] models (pertaining to positive ion beam systems), this was accommodated by adopting an average charge fraction and calculating an average cross section, that includes the contribution from charge exchange, for the production of ions by the beam. It is necessary, of course to include the charge exchange process to obtain the correct ion density but the corollary is a perturbation to the plasma boundary condition from the usual floating wall assumption. In effect, the positive ion current crossing the plasma sheath must exceed the electron current by an amount equal to the flux generated by charge exchange. In the case of a negative ion beam system the boundary condition is further complicated by the presence of electrons stripped from the negative ions. The influence of this group will depend upon the degree of thermalisation achieved with the background neutraliser plasma. It will be shown below that in the case of the HNB ITER negative ion beam, the stripped electrons are not thermalised and the plasma boundary condition reverts to that of the positive ion beam case. (In the case of the HNB the charge exchange current is relatively small but not zero). For the DNB, the stripped electrons are not so well distinguished from the plasma electrons and complete thermalisation may occur. The implications of this for the boundary condition are discussed.

The details of the neutraliser parameters are given in Table 1, all the parameters of the two ITER designs are taken from the ITER Design Description Document. A reasonable database of plasma measurements exists for the JET system [4] and this has been used to benchmark the model. To accommodate the variation of the plasma source term through the neutraliser, the latter is divided into a number of elements, each corresponding to an increment of target density of 1×10^{18} molecules/m^2, assuming a uniform pressure distribution. There is no inclusion of plasma or energy flow between elements, i.e. it is assumed that density and temperature gradients are negligible.

2.1 Beam Equations

The neutraliser model considers the beam processes shown in Table 2 where underscored symbols represent fast particles and the notation for the cross section [5] of each process is shown alongside. (Note that the symbol H is used to denote both the hydrogen and deuterium isotopes). The evolution of the beam species along the length of the neutraliser is described by the three simultaneous differential equations:

$$\frac{dn^{-}}{dt} = N\left[n^{0}\sigma_{0\bar{1}} + n^{+}\sigma_{1\bar{1}} - n^{-}\left(\sigma_{\bar{1}0} + \sigma_{\bar{1}1}\right)\right] \tag{1a}$$

$$\frac{dn^{0}}{dt} = N\left[n^{-}\sigma_{\bar{1}0} + n^{+}\sigma_{10} - n^{0}\left(\sigma_{0\bar{1}} + \sigma_{01}\right)\right] \tag{1b}$$

$$\frac{dn^{+}}{dt} = N\left[n^{-}\sigma_{\bar{1}1} + n^{0}\sigma_{01} - n^{+}\left(\sigma_{1\bar{1}} + \sigma_{10}\right)\right] \tag{1c}$$

These were solved numerically to provide the beam species fractions, f^{k}, as a function of distance through the neutraliser.

2.2 Neutraliser Plasma Equations

2.2.1 Beam induced ionisation

Assuming a uniform gas density, N, in the neutraliser, the plasma flux, j_x, to one wall of the neutraliser is given by:

$$j_x = \frac{NI_b}{A_b e}\left[f^{-}\sigma_{x\bar{1}} + f^{0}\sigma_{x0} + f^{+}\sigma_{x1}\right]\frac{w_b}{2} \tag{2}$$

where x=i, e denoting plasma ions and electrons respectively and σ_{xk} represents the cross section for ion or electron production by the beam species k. The parameters I_b, A_b and w_b are the beam current, the beam area (perpendicular to the beam axis) and the beam width, all given in Table 1 for both ITER negative ion beams and the JET positive ion beam. It is assumed that the plasma ions are predominantly molecular and dissociative recombination has been ignored as the cross section is almost an order of magnitude below that of ionisation.

The cross sections [5] $\sigma_{x\bar{1}}$, σ_{x0}, σ_{x1} are total cross sections for the production of slow ions (electrons) for each beam species; in fact there is no recorded cross section for production of slow ions or electrons from the negative ion so $\sigma_{x\bar{1}}$ was initially set to zero (see Section 2.3.1). Ionisation by plasma electrons has been ignored; Ott [3] has shown that the latter is only a small corrective term to the beam induced ionisation at 50keV.

2.2.2 Stripped Electrons

The stripped electron flux at a given point in the neutraliser is given by:

$$j_s = \frac{f^{-}I_b}{e}\left[1 - exp\left(-N\sigma_{\bar{1}0}\Delta z\right)\right] \tag{3}$$

where Δz is the increment in axial distance defined by the increment in target as described above.

The contribution to ionisation by the stripped electrons has been ignored, although the significance of this will depend upon their number and energy (hence on the beam energy). In the case of the two ITER beams the stripped electrons have an energy (on creation) of ~270eV for the HNB and ~55eV for the DNB, away from the cross section maximum at ~80eV for ionisation of H_2. Furthermore, for most of the neutraliser length, the flux of stripped electrons is an order of magnitude below that of the beam induced ionisation and so is not significant.

2.3 Energy Balance

2.3.1 Beam Stopping Power

The energy lost by the beam in various processes with the background gas (e.g. ionisation, dissociation), or "stopping powers" are used to determine the input power to the neutraliser gas/plasma system. The total power delivered by the beam to the neutraliser system is:

$$P = \frac{N\Delta z I_b}{e}\left[f^{-}S^{-} + f^{0}S^{0} + f^{+}S^{+}\right] \tag{4}$$

where S^k are the stopping cross sections for negative, neutral and positive species. For simplicity, total stopping power, which is well documented for the neutral and positive ions [6], has been used in the model. The model assumes that all this power is transferred to the neutraliser plasma, which is not, strictly, true and hence will over-estimate the electron temperature. Whilst the majority of the power is transferred to the plasma through ionisation and Coulomb scattering there are other processes such as dissociation and excitation which do not contribute energy not to the plasma but to the neutral gas. An alternative approach (adopted by Paméla [2] and Ott [3]) is to estimate the energy loss associated with each process contributing to plasma heating and to derive an effective stopping power from the cross section. This was considered too cumbersome for this model.

A more pressing problem is the dearth of stopping power data relating to negative ions. A theoretical estimate for H^- on atomic hydrogen exists [7] but the data ceases at 100keV/amu. An estimate of the stopping power at 500keV/amu can be made from the product of the initial energy of the stripped electron and the stripping cross section, $\sigma_{\bar{1}0}$. The value of $S^- \sim 3.5 \times 10^{-18}$ eV per molecule/m^2 at 500keV/amu. (At 100keV/amu, the same calculation gives 2.2×10^{-18} eV per molecule/m^2, which is an order of magnitude greater than the value in ref [7] of 2.4×10^{-19} eV per atom/m^2).

The stopping power derived above is, of course, the energy lost by the negative ion beam due to the detachment of the electron and, unless the stripped electrons are fully thermalised, only a fraction of this energy is transferred to the gas/plasma system. It could be argued therefore that the stopping power of the beam is irrelevant, provided the energy lost by the stripped electrons is taken into account. The negative ion must have some stopping power associated with energy transfer to the gas and to exclude this contribution would under-estimate the total energy transferred. Dalgarno and Griffing seem to imply that the total stopping power for a negative ion is the sum of the stopping power due to stripping and the proton stopping power. As the latter includes electron capture, this cannot be correct but a case could be made for including the neutral stopping power in the negative ion expression. The same remark could be made for the ionisation cross section, $\sigma_{\bar{1}\bar{1}}$; i.e. that this is best approximated by σ_{i0}. In Section 3 results for both cases are presented.

2.3.2 Thermalisation of Stripped Electrons

The electrons created by stripping from the negative ions have an initial energy, E_s given by [8]:

$$E_s = \frac{m_e}{m_b} E_b \tag{5}$$

where m_e is the electron mass, and m_b is the mass of the beam ion of energy E_b; the values for the two ITER beams are given in Section 2.2.2. (It should be noted that Michaut [9] gives a range of energies for the stripped electron; the simplicity of the model here does not warrant the inclusion of an electron energy distribution).

The influence of the stripped electrons upon the neutraliser plasma depends upon the degree of thermalisation achieved in their lifetime. If loss processes are sufficiently vigorous to cool the stripped electrons to an energy similar to the temperature characterising the plasma electron distribution, then they must be included in the plasma term. The two possible energy loss processes are inelastic scattering on the gas molecules and Coulomb scattering on the plasma electrons and ions. When the energy of the stripped electron far exceeds the plasma electron temperature the former is dominant and the energy lost can be characterised in terms of a total rate coefficient, K_{in}, given by an empirical fit [10] to the data of Hiskes and Karo [11]:

$$K_{in} = 2.4 \times 10^{-12}\, exp(-28/E_s) \qquad (\mathrm{eVm^3/s}) \tag{6}$$

The lifetime of the stripped electron in the neutraliser, τ_s, is approximated by:

$$\tau_s = \frac{L_N}{v_s} = L_N \sqrt{\frac{m_e}{2eE_s}} \tag{7}$$

where L_N is the neutraliser length. The stripped electrons should continue in a forward direction with the beam, and as stripping is predominant at the start of the neutraliser, equation (7) was used in preference to the expression for confinement time. From equations (6) and (7) and the values of E_s for the two ITER beams it is trivial to calculate the total energy loss of the stripped electrons to be 31eV for the HNB and 16.4eV for the DNB. For the HNB this energy loss is negligible but for the DNB represents 30% of the creation energy. So, whilst it is highly unlikely that the stripped electrons will be thermalised to the plasma of the HNB, the same statement cannot be made with confidence for the DNB.

2.3.3 Boundary Condition

Reference has already been made to the effect of the charge exchange and stripped electron currents on the boundary condition at the plasma sheath. The usual floating condition, j_e=j_i, is replaced by:

$$j_i - \frac{j_e}{4} e^{-\phi/T_e} - j_s\, e^{-\phi/E_{sB}} = j_{cx} - j_s \tag{8}$$

where j_i and j_e are defined in equation (2), j_s is defined in equation (3), j_{cx} is the charge exchange flux (obtained by substituting $f^+\sigma_{10}$ for all the terms in the square brackets in equation (2)), ϕ is the plasma potential in volts, T_e the plasma electron temperature in electron volts and E_{sB} is the energy in electron volts of the stripped electrons at the plasma boundary. It has been shown in Section 2.3.2 that for the HNB the energy loss of the stripped electrons is small, hence E_{sB}=E_s and the exponential might be expected to be approximately unity. The two stripping terms then cancel and equation (8) becomes:

$$0.6 n_i \left(\frac{eT_e}{m_i}\right)^{1/2} - \frac{n_e}{4}\left(\frac{8eT_e}{\pi m_e}\right)^{1/2} e^{-\phi/T_e} = \Psi n_i \left(\frac{eT_e}{m_i}\right)^{1/2} \tag{9}$$

where the factor of 0.6 represents the drop in ion density across the plasma pre-sheath predicted by the Bohm sheath model and

$$\Psi = \frac{j_{cx}}{j_i} = \frac{\sigma_{10}}{\left(\sigma_{i\bar{1}} + \sigma_{i0} + \sigma_{i1}\right)}$$

As n_e=n_i at the plasma boundary, it follows that equation (9) yields the ratio ϕ/T_e :

$$\frac{\phi}{T_e} = Ln\left\{\frac{1}{(1-\Psi)}\left(\frac{m_i}{0.72\pi m_e}\right)^{1/2}\right\} \tag{10}$$

The power balance equation at the boundary can be used to obtain T_e. At the boundary, the ions transport an energy eϕ to the wall, the plasma electrons an energy eT_e and the stripped electrons an energy E_{sB}. Assuming equilibrium between the power transported to the wall and the energy transferred by the beam and the stripped electrons gives:

$$\frac{N\Delta z I_b}{e}\left[f^- S^- + f^0 S^0 + f^+ S^+\right] + \frac{I_s N K_{in}\Delta z}{e\left(2eE_s/m_e\right)^{1/2}} = j_i e\phi h_N \Delta z + j_e e T_e h_N \Delta z\, e^{-\phi/T_e} + j_s E_{sB} h_N \Delta z \tag{11}$$

where h_N is the height of the neutraliser wall. The electron temperature, T_e, is then readily obtained by substitution from equation (10).

2.4 Gas Heating Model

The gas heating model is taken directly from Paméla [2], so only a brief summary is given here. The model assumes equilibrium between energy losses from the gas on the neutraliser walls and energy gained from the beam and plasma. This is expressed as:

$$h_N \Delta z \frac{Nv}{4}\alpha k\left(T - T_0\right) = (\gamma - 1) S\left(I_b, E_b, N, n_i, n_e, T_e\right) \tag{12}$$

where v is the gas mean thermal velocity, T the gas temperature, T_0 is the neutraliser wall temperature, α is the accommodation coefficient for gas molecules colliding on the neutraliser wall, γ is the specific heat of the gas and S is the total source term.

The source term is comprised of three mechanisms: (i) molecular dissociation by beam ions, (ii) molecular dissociation by the plasma electrons and (iii) collisional processes between the gas and fast molecules resulting from plasma ions accelerated across the sheath and reflected as neutrals at the wall. This process is characterised a reflection coefficient, R. Expressions for the cross sections for the processes are given in [2].

3 APPLICATION TO THE ITER NEGATIVE ION BEAMS

As there are no known measurements of the neutraliser plasma parameters in a negative ion beam system, the model has been benchmarked against measurements taken for the JET Neutral Beam Injection system based on positive ion, deuterium beams. The results for the ITER HNB and DNB are presented following the discussion of the benchmark tests.

3.1 Comparison with JET Positive Ion System

The gas temperature [1] and neutraliser plasma parameters [4] have been measured for deuterium beams of energy between 60keV and 130keV on the JET Neutral Beam Test bed. In addition, recent measurements of the neutralisation efficiency over the same energy range, performed on the JET Torus, have provided a value of the effective mean target in the neutraliser as a function of beam energy. All variables pertaining to the plasma are therefore known and the only free parameters in the model are the accommodation coefficient and reflection coefficient of plasma ions at the neutraliser wall.

All the plasma measurements are taken at a distance of ~1m along the neutraliser and Fig 1 shows the output from the model at three beam energies (60keV, 100keV, and 130keV). Individual data points mark the measured values of plasma density, electron temperature, plasma potential and gas temperature. The model assumes that all the ions are full energy, this is reasonable at high beam energy when 93% of the beam current is contained within the full-energy ion component.

Clearly the model over-estimates the electron temperature as predicted in Section 2.3.1, the error being largest at low beam energy (where the full energy component is lower); at the highest beam energy the value of T_e predicted by the model is within 35% of the measured value. The gas temperature appears to be relatively insensitive to the changes in T_e and n_i along the neutraliser and agreement at the point of measurement is quite good. The gas temperature is very sensitive to the values of α and R as the reflected ion component dominates the gas heating source term. To obtain the 130keV data, the accommodation coefficient was fixed at α=0.4 and the ion reflection coefficient was varied to obtain the best fit with R=0.8. This value is rather high (values of R~0.4 would be expected) and probably reflects the fact that there are other processes in the neutraliser that have not been included in the plasma model. (It should be made clear that the heating model closely reproduces the measured gas temperatures when used in conjunction with the measured plasma data [4]).

3.2 Predictions for ITER HNB System

The results of the modelling for the 1MeV D^- heating beam are shown in Fig 2 for the cross sections, accommodation coefficient and ion reflection coefficient shown in Table 1. The plasma densities are low compared to the JET case. This is partly due to the ionisation cross section, which are an order of magnitude lower but the primary cause is that the neutraliser is divided into four channels, with only 7.5A beam current per channel (after transmission losses are taken into account) compared to the 55A in the single channel neutraliser at JET. In addition, setting $\sigma_{i\bar{1}} = 0$, results in very low plasma flux at the start of the neutraliser when the beam is predominantly in the negative charge state. This results in a high value of T_e and consequently a low value of plasma density. The effect of an increasing fraction of neutral particles in the beam is clear, whereby after an approximate distance of 0.3m along the neutraliser the electron temperature is reduced and becomes almost constant. The gas temperature is still sensitive to α and R but with such a low plasma flux the gas-heating effect is still small with these parameters set to R=1 and α=0.1.

In Section (2.3.1) the correct form for the stopping power for the negative ion beam component was discussed, similarly, the cross section for ionisation of the neutraliser gas by negative ions. It was suggested that these values might be set equal to that for the neutral component, and the rate of energy loss from the stripped electrons added to the power input to the plasma. The effect of introducing these changes is shown in Fig 3. This restores the plasma flux at the start of the neutraliser and removes the large variation of T_e observed in Fig. 2. Note, however, that the gas temperature is almost identical, indicating the insensitivity of the gas heating process at such low plasma densities.

3.3 Predictions for ITER DNB System

The results of the modelling for the 100keV H^- diagnostic beam are shown in Fig 4 for the case where $S^- = 0$ and $\sigma_{i\bar{1}} = 0$. The electron temperature and plasma density is similar to the 1MeV case, primarily because a combination of cross section and beam current result in similar plasma fluxes. Again, the electron temperature is higher at the start of the neutraliser due to the low plasma flux. Similarly, the gas temperature is virtually identical to the HNB. Using the stopping power and ionisation cross sections for the neutral beam in place of S^- and $\sigma_{i\bar{1}}$ gives the results also shown in Fig 4, a similar effect to the HNB.

4 DISCUSSION AND CONCLUSION

The model predicts a much reduced plasma density for the two ITER negative ion beam systems compared to the JET positive ion based system. This is primarily due to the neutraliser being divided into four channels, so that the beam current per channel is relatively low (7.5A for the HNB) compared to the 55A for the JET system. Setting the beam current to 30A for the HNB case, corresponding to a single channel neutraliser, raises the plasma density by an order of magnitude and the gas temperature by ~20K. The electron temperature is relatively insensitive to changes in beam current as all the contributing terms scale linearly with this parameter. The electron temperature is most strongly affected by the ionisation cross sections for the background gas and these vary slowly between 100keV/amu and 500keV/amu.

The model uses the non-thermalisation of the stripped electrons to simplify the boundary condition. In the HNB this is acceptable, as the creation energy of the stripped electrons is 271eV, of which a total of 31eV is lost to the gas/plasma system, so these electrons will not be thermalised to the plasma. Furthermore as the stripped electrons are primarily forward scattered, they will follow trajectories that take them out of the neutraliser in the absence of magnetic fields.

For the DNB, however, the creation energy of the stripped electrons is ~55eV, of which 16.5eV is lost through inelastic collisions, so that the stripped electrons are only some 50% more energetic than the characteristic of the plasma electron distribution. Under these circumstances, Coulomb scattering becomes the major energy loss mechanism and the stripped electrons will be fully thermalised with the plasma. Equation (8) is now modified such that

$$j_i - \frac{(j_e + j_s)}{4} e^{-\phi/T_e} = j_{cx} - j_s \tag{13}$$

where j_s is independent of j_i so that the solution, unlike equation (10), contains density dependent terms.

Some further progress can be made by inspection: ignoring j_{cx} and re-arranging equation (13) gives the expression for ϕ/T_e :

$$\frac{\phi}{T_e} = ln\left\{\left(\frac{8m_i}{\pi m_e}\right)^{1/2} \frac{n_e}{2.4n_i}\left[\frac{1+n_s/n_e}{1+1.67(8m_i/\pi m_e)^{1/2}\, n_s/n_i}\right]\right\} \tag{14}$$

If the argument of the logarithm is less than unity, ϕ/T_e is negative and the plasma floats negative with respect to the neutraliser wall. Equation (13) is then modified so that the

Boltzmann factor is applied to the ions. Substituting values for hydrogen into equation (13) gives the condition for positive plasma potential:

$$40\frac{n_e}{n_i}\left(\frac{1+n_s/n_e}{1+161n_s/n_i}\right)>1 \tag{15}$$

Approximating $n_e \approx n_i$ gives a solution to equation (15) of $n_s/n_e \le 0.32$ for the plasma potential to be positive. In the case of the DNB model with $\sigma_{i\bar{1}} = 0$, this condition is not fulfilled at the start of the neutraliser but is after a distance of 0.3m. Exactly how the plasma would react to these conditions is intriguing but it can only be assumed that density and energy flows would lead to some smearing of the potential gradient.

To conclude, a simple model has been constructed to investigate the strength of the gas heating in the ITER negative ion based neutral beam injection system. Comparisons with the JET positive ion system shows that the model agrees relatively well with measured values of plasma density, electron temperature and gas temperature.

Applying the model to the two ITER negative ion beam systems predicts the gas-heating effect to be small, with temperatures only slightly above ambient. Both the HNB and DNB systems show similar gas temperatures, which is not surprising given that the major contribution to gas heating is reflected ions and the normalised accelerating potential, $\phi/\sqrt{m_i}$, is approximately the same for both systems.

The beam-plasma system is inherently more complicated for the negative ion system, however, not only because of the additional beam component but also due to the presence of stripped electrons. The effect of these electrons on the plasma depends upon their degree of thermalisation. It has been shown that for the HNB these electrons are not thermalised and play no role at the plasma boundary. For the DNB, however, the reverse is true and the stripped electrons will perturb the plasma boundary condition. A brief analysis of this situation has been presented that shows that under certain conditions the plasma can adopt a negative potential with respect to the neutraliser wall.

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Table 1 Neutraliser Model Parameters for ITER and JET

Parameter	ITER HNB	ITER DNB	JET
Beam Parameters			
Beam Ion	D^-	H^-	D^+
Beam Energy (keV)	1000	100	60-130
Total Current (A)	40	22	17-60
Dimensions in Neutraliser (m)	0.1(w) x 0.7 (h)	0.1(w) x 0.7 (h)	0.2(w) x 0.4 (h)
Neutraliser Parameters			
Dimensions (m) **width x height xl length**	0.1x 1.6 x 3.0	0.1x 1.6 x 3.0	0.2 x 0.4 x 1.8
No Channels	4	4	1
Beam Current per Channel (A)	7.5[a]	4.1[a]	16-55[b]
Target Density (molecules/m^2)	1.4×10^{20}	0.5×10^{20}	0.4×10^{20}
Accommodation Coefficient	0.5	0.5	0.4
Ion Reflection Coefficient	1.0	1.0	0.8

[a] Includes 75% transmission factor [b] Includes 92% transmission factor

Table 2 Charge Changing Processes in the Beam and Cross Section Notation

$\underline{H}^- + H_2 \to \underline{H}^0 + e + H_2$	$\sigma_{\bar{1}0}$
$\underline{H}^- + H_2 \to \underline{H}^+ + 2e + H_2$	$\sigma_{\bar{1}1}$
$\underline{H}^0 + H_2 \to \underline{H}^+ + e + H_2$	σ_{01}
$\underline{H}^0 + H_2 \to \underline{H}^- + e + H_2^+$	$\sigma_{0\bar{1}}$
$\underline{H}^+ + H_2 \to \underline{H}^0 + H_2^+$	σ_{10}
$\underline{H}^+ + H_2 \to \underline{H}^- + e + 2H^+$	$\sigma_{1\bar{1}}$

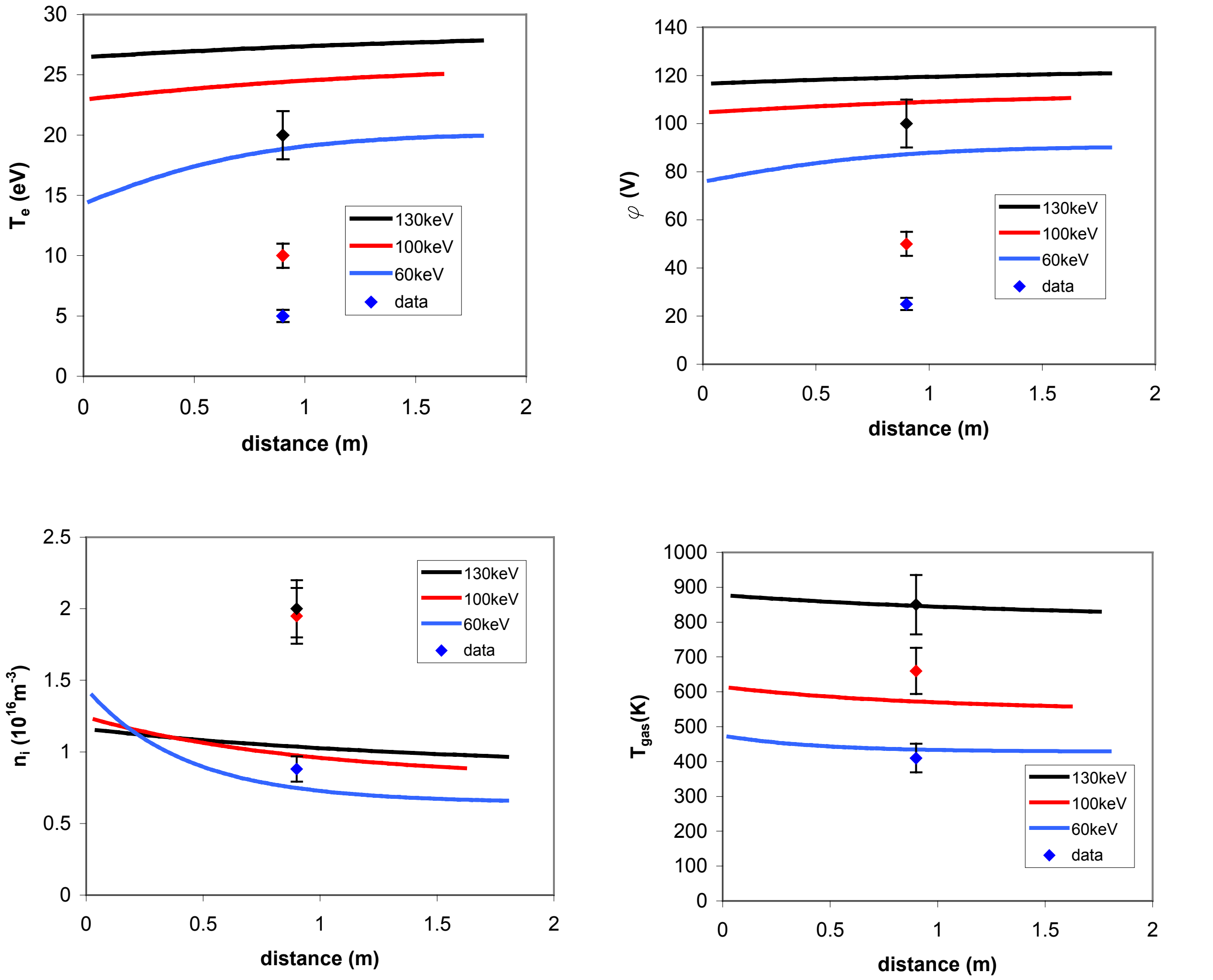

Fig. 1 Results of the model applied to the JET positive ion based neutral injection system. Clockwise from top left: plasma electron temperature, T_e; plasma potentia,l φ; gas temperature, T and plasma density, n_i. Solid lines are model, points are measured data.

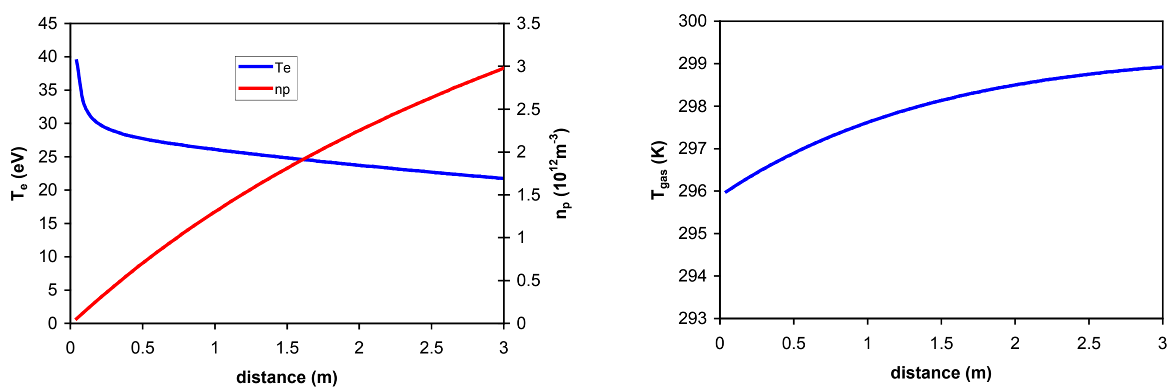

Fig 2 Results of the model applied to the ITER HNB neutral injection system. Ionisation cross-section for negative ions set equal to zero.

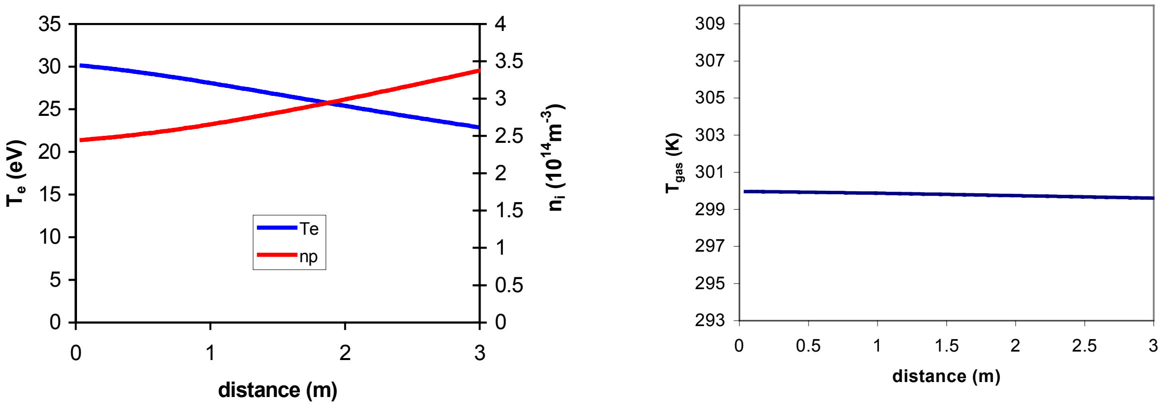

Fig 3 Results of the model applied to the ITER HNB with neutral particle values for negative ion stopping power and ionisation.

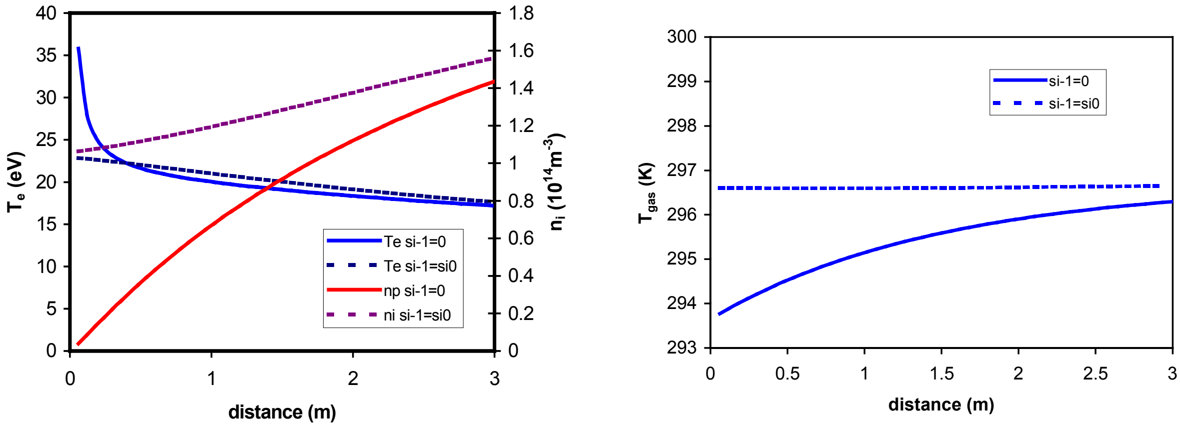

Fig 4 Results of applying the model to the ITER DNB system. The plots show the equivalent of Figs 2 and 3 combined. Solid line is model with $\sigma_{i\bar{1}} = 0, S^- = 0$ *, dashed line is with* $\sigma_{i\bar{1}} = \sigma_{i0}, S^- = S^0$