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The Beam Driven Plasma Neutralizer

E. Surrey* and A. Holmes†

*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK
†Marcham Scientific Ltd, Sarum House, 10 Salisbury Road, Hungerford, RG 17 0LH, UK

Abstract. The improvement of the efficiency of neutral beam systems to be compatible with the economic requirements of fusion power plants is a key theme in the European research programme. A novel plasma neutralizer, in which the negative ion beam itself is the source of the plasma, is described. Its success depends on the confinement of the free electrons generated by stripping from the beam and their generation of additional plasma. The device requires no additional power in contrast to the photoneutralizer, presently the main device of research interest. Although the efficiency of the plasma device is not as high as the photoneutralizer it is essentially of a low technological risk, inherently reliable and will not require a significant R&D programme to demonstrate.

Keywords: Negative ion beams, neutralization, neutral beam injection heating
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INTRODUCTION

The successful application of Neutral Beam Injection (NBI) on a fusion power plant is dependent upon the power efficiency that can be achieved for these systems. The ability of NBI to provide plasma heating, non-inductive current drive and q-profile control make it an attractive proposition, particularly for long pulse or steady state operation. For fusion power plants it is expected that beam energies of 1 MeV or above will be necessary to achieve penetration into the plasma, so the neutral beams will be created from negative ion precursor beams, due to the low neutralization efficiency of positive ions at high energy. Unfortunately the existing technology, the gas neutralizer, yields a maximum neutralization fraction of 58 % and this leads to power efficiency (defined as the ratio of power absorbed by the plasma to the total electrical power used by the NBI system) of the order 30 %. One of the most effective ways to improve this figure is to increase the neutralization fraction and various methods by which this can be achieved have been proposed [1]. One of these is to use a plasma in place of the neutral gas, in which the electrons more readily strip the negative ions. Usually the plasma is sustained by an external power source, typically between 0.5 MW and 2 MW, depending on design.

This paper describes a method for using the plasma created by the passage of the beam itself through a neutral gas background to enhance the neutralization efficiency with no additional power input. A zero dimensional model of the beam-gas-plasma system in the neutralizer is derived for the case where magnetic confinement is applied to the neutralizer walls. It is shown that this method can confine the electrons generated by stripping from the beam particles and by ionization of the background gas. Confining these electrons enhances the plasma production in the neutralizer to densities close to the optimum required for maximum plasma neutralization efficiency. Although the economy

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of power is marginal compared to the driven plasma concept there is significant value in reduced complexity and increased reliability.

THE NEUTRALIZER MODEL

The beam-gas-plasma system for a negative ion gas neutralizer has been described previously [2–4]. The key aspects of the system can be summarized as:

(i) the negative ion beam is subject to stripping reactions that convert some of the negative ions to fast neutral particles and fast positive ions

(ii) these stripping reactions create fast electrons with the same velocity as the precursor beam (equivalent to energy 272 eV for 1 MeV deuterium)

(iii) the beam particles (negative ions, positive ions and neutrals) ionize the background gas, creating slower electrons

(iv) the electrons created by the beam particles have an energy distribution [5] that peaks at several tens of electron-volts (62.5 eV for 1 MeV deuterium), thus a significant fraction of these electrons can also ionize the background gas.

When the neutralizer is a simple channel, filled with gas [2–4], the stripped electrons exit the neutralizer along with the beam components (at lower beam energy they can be thermalised with the background plasma as shown in [2]) and so their contribution to the background plasma is negligible. Similarly, the electrons created by beam ionization of the gas are lost to the walls of the neutralizer, making a small contribution to the background plasma [3]. As a result, the plasma density in a standard gas neutralizer is typically of the order 10^{14} m^{-3}, which should be compared to the typical average gas density of 10^{19} m^{-3}, so the gas is 0.001 % ionized. This degree of ionization is insufficient to influence the neutralization efficiency.

By contrast, if the plasma density can be increased to approximately 50 % of the gas density, the enhanced neutralization cross sections presented by the plasma electrons are sufficiently high to produce enhanced neutralization. The plasma neutralizer system was extensively described by Berkner [6], who showed that for deuterium beams in deuterium gas the neutralization efficiency is asymptotic with ionization fraction, approaching a maximum value of 83 %.

In conventional plasma neutralizers, the plasma is created by some external energy source (RF excitation for example) and typically a power of 1 MW is dissipated. In itself this is not a significant penalty to the NBI electrical system efficiency but it introduces an element of complexity and possible unreliability. All plasma neutralizers use magnetic confinement but it is shown below that the external source can be eliminated by confining the stripped and plasma electrons to create an enhanced plasma density.

Magnetic Confinement

It is assumed that the magnets are arranged in a series of hoops around the neutralizer of alternating polarity so that the magnetic field lines cover the whole neutralizer in a series of cusps with a spacing, D. If the neutraliser has dimensions, W, H and L then the total cusp length, C, is:

$$C = 2 \times (WH + WL + HL)/D \tag{1}$$

The magnetic field must be sufficiently strong to magnetize the electrons and prevent them reaching the neutralizer wall except where the field lines meet the wall. The effective loss area, A_{loss}, is given by the leakage aperture [7] of the ion-electron hybrid Larmor radius and the cusp length as:

$$A_{\text{loss}} = \frac{4C}{eB_c}\left[0.6(m_i e)^{0.5}\left(1+\frac{\phi}{T_e}\right)^{0.5}\left(m_e\frac{8e}{\pi}\right)^{0.5}\right]T_e^{0.5} \tag{2}$$

where B_c is the cusp strength at the wall, T_e the plasma electron temperature and ϕ the plasma potential with respect to the neutralizer wall and the ion flux has been multiplied by the sheath term to allow for acceleration of the ions across the sheath boundary. For molecular gases such as deuterium, the plasma ions can be atomic or molecular, so m_i will be the average value of a mix of ionic species.

From equation (2) it can be seen that as B_c tends to zero, A_{loss} tends to infinity. To avoid this, the model reverts to the geometric loss area of the neutralizer with no confinement if the calculated value of A_{loss} is equal to or greater than the geometrical area.

Two ends of the neutralizer must be open to allow the beam access and egress and this potentially creates areas with no confinement. For the neutralizer to generate sufficient plasma density the open ends must also be confined by a long range field across the gap. This is discussed in more detail in the section Application to Practical Beamline. For the purposes of the model, it is assumed that the confinement is identical on all sides of the neutralizer chamber.

Plasma Source Terms

The several sources of plasma electrons can be divided into "primary" sources — stripping and beam ionization — and "secondary" sources — ionization by the electrons resulting from the "primary" interactions.

Primary Sources

The first source is simple, direct beam ionization. The suffix, r, denotes that these are the Rudd electron/ion pairs and the initial energy of these electrons is the Rudd energy U_r, which is 62 eV for 1 MeV deuterium ions [5]. The total current of plasma electrons is:

$$I_{br} = I_b \int N\left(f^-\Sigma_{\bar{1}i}^- + f^0\Sigma_{0i} + f^+\Sigma_{1i}\right)dz \tag{3}$$

The fractions, f^x, are the average beam fractions along the length of the neutraliser for negative, neutral and positive beam particles and the cross sections Σ_{xy} indicate the incident particle type, x and the daughter particle, y.

The second source, the stripped electrons, including those released when some of the beam converts into positive ions, will have the same velocity as the beam ions, equivalent to energy, U_s. The current, I_{bs}, is given by:

$$I_{bs} = I_b \left(2f^0\sigma + 4f^+\right) \tag{4}$$

The reason for the factors of 2 and 4 is that average conversion is half of the total conversion and in the case of the positive ions, there are two stripped electrons formed. There is also a direct source of slow ions via charge exchange, which is almost negligible:

$$I_{bx} = I_b \int f^+ N\sigma_{10} dz \tag{5}$$

Equations (3) and (5) are solved iteratively as the fractions change with the increasing plasma target.

Secondary Sources

The direct ionization electrons and the stripped electrons can further ionize as they have a high kinetic energy. As there is no preferred direction in the model (unlike say a volume plasma source), a 0-D model based on a concept developed by Holmes [8] has been adapted.

A uniform plasma of the two types of fast ionizing electrons is assumed with density n and creation energy U. The losses are controlled by a confinement time, τ, and the electrons lose energy through inelastic collisions with a rate K_{in} given by Hiskes [9] as:

$$K_{in} = K_0 \exp(-28/U) \quad [\mathrm{eVm^3s^{-1}}] \quad K_0 = 2.4 \cdot 10^{-12} \tag{6}$$

The continuity equations take the form:

$$\frac{I_{bx}}{eV} = n_j \left(\frac{1}{\tau_j} + \frac{NK_0 \exp(-56/U_j)}{U_j/2}\right) \tag{7}$$

$$\frac{I_{j+}}{eV} = n_r \times N\sigma_i v_j \tag{8}$$

with $\sigma_i v_j = 5.3 \cdot 10^{-14} \exp(-22.5/(U_j/2))$ and the subscript, j, indicates a quantity specific to stripped or Rudd electrons. The confinement time is given by the cusp loss for these fast electrons (using the full creation energy for the Larmor diameter)

The plasma density is given by:

$$n = \frac{\sum I_{bj} + \sum I_{j+} + I_{bx}}{e\psi_i T_e^{1/2} A_{\mathrm{loss}}} \tag{9}$$

Eliminating n_s and n_r between equations (7) and (8) allows I_{r+} and I_{s+} to be derived from the values of I_{br} and I_{bs} and the average gas density.

The Plasma Potential

The plasma potential is determined by the balance of positive and negative current at the wall and is given by:

$$\frac{\phi}{T_e} = \eta = \ln\left[\frac{(\sum I_{bj} + \sum I_{j+} + I_{bx})\psi_e}{\psi_i \sum I_{bj}(1-k_j) + \sum I_{j+}}\right] \tag{10}$$

where k_j represents the fraction of the Rudd or stripped electrons that escape to the walls without creating ionization.

Electron Energy Balance

The plasma electrons gain energy from three sources: Coulomb drag of the primary beam ions, energy transfer from the Rudd electrons and the similarly from the stripped electrons. This is directly analogous to the energy transfer from primary electrons to plasma electrons in a DC volume discharge. Following ref [8] the rate of energy transfer to the plasma electrons is:

$$W_j = \frac{I_{bj}(1-k_j)nk[U_j^{0.5} - 2T_e^{0.5} - T_e/U_j^{0.5}]}{K_0 N \exp(-56/U_j) + 2nk/(U_j/2)^{0.5}} \tag{11}$$

where $k = 7.7 \cdot 10^{-11}$ $\text{m}^3\text{s}^{-1}\text{eV}^{-3/2}$ and is the electron-electron energy transfer rate with a Coulomb logarithm of ten derived from the NRL Formulary [10]. Direct coulomb energy transfer from the beam ions is governed by the expression [10]:

$$W_b = \frac{U_b I_b (f^- + f^+) 3.4 \cdot 10^{-9} m_b^{0.5} n}{U_b^{1.5}} \frac{L}{v_b} \tag{12}$$

Of the three powers, that transferred by the stripped electrons is the largest followed by the beam power. The sum of these powers is equal to the energy removed by the escaping ions and electrons:

$$W_s + W_r + W_b = T_e[\eta(\sum I_{bj} + \sum I_{j+} + I_{bx}) + I_w] \tag{13}$$

from which the electron temperature can be derived.

Calculation of Neutralization Fraction

The beam species evolution equations for a plasma neutralizer are given by Berkner [6], from which expressions for the maximum neutralization fraction, η, and optimum target, Π, are derived as:

$$\eta = \frac{\langle\sigma_{-0}\rangle}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle}\left[\frac{\langle\sigma_{0+}\rangle}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle}\right]^{\langle\sigma_{0+}\rangle/(\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle + \langle\sigma_{0+}\rangle)} \tag{14}$$

$$\Pi = \frac{1}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle + \langle\sigma_{0+}\rangle} \ln\left[\frac{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle}{\langle\sigma_{0+}\rangle}\right] \tag{15}$$

where $\langle\sigma_{ij}\rangle = \sum_s \sigma_{ij}^s n_s / n_{\text{tot}}$, i.e. the sum of all charge changing collisions from i to j for all gas and plasma species, s, weighted by their fractional density.

Results

The results are shown for a 1 MeV, 40 A deuterium beam in Figures 1a and 1b where the magnetic cusp field at the wall and the magnet spacing (cusp length) are the parameters. It can be seen that the optimum target and neutralization fractions are inversely related, through the increasing plasma density, as the confinement is increased through increasing field or reduced cusp length (larger cusp spacing). Of course, this model assumes that the cusp spacing is a free parameter, whereas in practise it will be restricted by the limitation of the proximity of the beam to the wall. The confinement field will extend into the neutralizer volume by a distance determined in part by the spacing D. It would be undesirable to allow the beam to interact with significant fields from the confinement magnets, so D will be limited.

It is clear from Figures 1a and 1b that neutralization fractions of ~ 80 % are possible for realistic values of cusp field and cusp spacing. This assumes that the field between magnetic poles is sufficiently high to maintain magnetisation of the electrons for all the values of D. Furthermore the optimum target is reduced to $\sim 6 \cdot 10^{19}\text{m}^{-2}$ compared to the value of $1.4 \cdot 10^{20}\text{m}^{-2}$ for ITER. This 50 % reduction in the required gas flow would also have benefits for the electrical efficiency of the beam system. Reduced gas flow in the neutralizer reduces the stripping losses in the accelerator, the re-ionization losses downstream of the neutralizer and the vacuum pumping demand. This is assessed in the section Application to Practical Beamline.

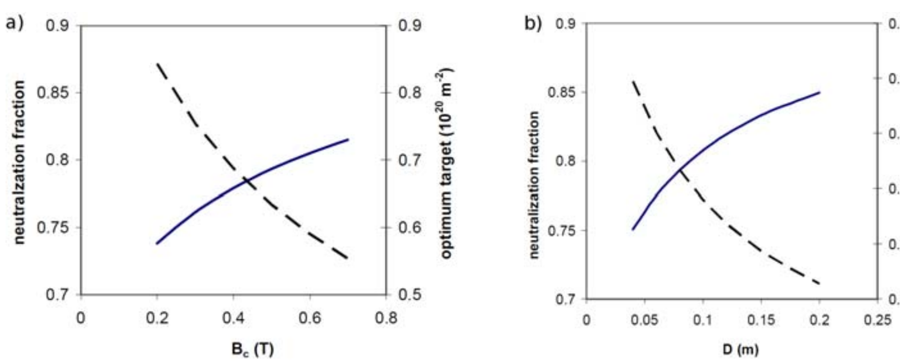

FIGURE 1. a) Neutralization fraction η (—) and optimum target Π (— —) as a function of the cusp field at the wall B_c. Cusp spacing 0.08 m. b) Neutralization fraction η (—) and optimum target Π (— —) as a function of the cusp spacing D. Cusp strength 0.5 T.

APPLICATION TO PRACTICAL BEAMLINE

It has been shown that the possibility of generating a plasma neutralizer with no additional driving power source could be feasible in theory; realising the conditions that fulfil the model will require experimental verification. Foremost is the magnetic configuration to achieve the confinement along the walls, including the two ends by which the beam enters and exits the neutralizer. Finally an estimate of the electrical efficiency of the system is made.

Magnetic Field Configuration

The sidewalls of the neutraliser are covered by rows of bar magnets, forming oblong rings around the beam axis with the result that the intercusp fields are predominantly parallel to the beam axis and hence induce no beam deflection. These fields will decrease with the cube of the distance from the neutraliser wall with a characteristic scale distance of $\delta/2$ where δ is the bar magnet height (nominally 0.03 m). The magnetic field in this region would have a component normal to the wall and to avoid unwanted deflection of the non-neutral components of the beam, a zone of dimension $\sim \delta/2$ near the wall would be necessary where the beam does not enter.

As discussed above, leaking of the electrons through the open ends of the neutralizer must be avoided. This can be achieved by establishing a long range field across the open end by placing magnets parallel to the vertical sides of the neutralizer. In order that the magnets are not too large, it is proposed that the magnets run between groups of apertures forming long channels reminiscent of the four channel neutraliser for ITER.

The stripped electrons will be confined in the neutralizer if their Larmor radius is significantly smaller than the characteristic dimension of the neutralizer in the bending plane. It is probable that the magnet width will be ~ 0.02 m and B_c will be ~ 0.5 T, hence the integrated flux is 0.005 Tm (note that the poleface flux is shared between the magnets on either side) The magnetic flux is approximately conserved across the inter-magnet gap of ~ 0.08 m, so the field in the centre of the gap is $B \sim 0.0625$ T. This gives a Larmor radius of ~ 0.001 m, well within the dimensions of the confining gap.

The presence of the confining field will also affect the beam particles. Initially the beam passes through a magnetic field orientated across the short axis of the neutralizer and then as it passes the other pole of the bar magnet it encounters the same field but in the opposite direction. As a result the net magnetic flux seen by the beam ions is zero, but there is a slight displacement of the beam in the vertical direction.

If the beam ion happens to be neutralised during this passage of distance, dz, then the maximum steering angle, Φ, is given by:

$$\Phi \leq \frac{v_\perp}{v_b} = \frac{e}{M v_b} \int_{-\infty}^{0} B \, dz \tag{16}$$

where $v_\perp / v_b$ is the ratio of the beam particle velocity in the direction of deflection to the beam axial velocity along z.

The integrated flux cannot be determined exactly without a neutralizer design but it is possible to form an approximate value from the poleface field, B_c and width of the bar magnet, as above. Substitution of values for a 1 MeV deuterium beam gives $\Phi = 0.024$ radians. As there is no plasma in this region and the gas density is low at the entrance to the neutralizer cell, the probability of conversion to D^0 is quite low.

The vertical beam displacement is given by:

$$\Delta = 2 \times \Phi \frac{X}{2} \tag{17}$$

where X is the magnet separation. For the example used above this would be 1.9 mm.

Thus from a simple assessment, it seems to be feasible to confine the stripped electrons without causing a major deflection to the beam.

Electrical Efficiency

The electrical efficiency of the entire beamline system is a key parameter for the economic application of neutral beams to fusion power plants. A steady state 1 GW thermal (2.7 GW fusion) power device might require some 200 MW of injected current drive power, so minimising the power re-circulating in the system is of great significance. The system codes that are used to determine the operating envelope of the power plant usually adopt a figure of merit, F, for current drive systems defined as:

$$F = \gamma \varepsilon \geq 0.25 \tag{18}$$

where γ is the current drive efficiency and ε is the electrical efficiency of the driving system. The value of γ depends on the plasma scenario but is generally in the range 0.4–0.6 $\mathrm{Am^{-2}W^{-1}}$ for neutral beam systems, thus electrical efficiency in the range 0.625–0.4 is required.

The electrical efficiency is calculated through a neutral beam system code [11] that includes all power consumption aspects of the beam system. The reduction in the target density will influence the beam losses and the pumping requirements as discussed earlier. Values for the efficiency are given in Table 1 together with those for ITER, a powered plasma neutralizer and a photoneutralizer at 90 % neutralization fraction for comparison.

TABLE 1. Electrical Efficiency for Gas, Plasma and Photo- Neutralizers.

Beam parameters: Energy 1.0 MeV, Current 40 A, Divergence 5 mrad				
Parameter	**Gas**	**Driven Plasma**	**Plasma**	**Photo**
Electrical Efficiency	0.35	0.49	0.52	0.58
Neutralization Fraction	0.58	0.8	0.8	0.9
Beam Losses	0.42	0.36	0.36	0.31
Auxiliary Power	6 MW	6 MW	5 MW	4 MW

CONCLUSIONS

In the drive for improved efficiency of neutral beam injection systems attention has been concentrated on the photoneutralizer, a device that offers up to 95 % neutralization fraction but at considerable technical risk. To minimise this risk a novel plasma neutralizer configuration has been modelled in which the plasma is primarily produced by the electrons stripped from the negative ion precursor beam. To achieve significant plasma densities, the stripped electrons must be magnetically confined within the neutralizer cell to ensure their energy is expended in ionizing the background gas. Additional sources of ionization exist from the beam particles and the electrons created by their interaction with the gas. It is shown that plasma densities sufficient to produce neutralization fractions of $\sim$ 80 % can be sustained and enhance efficiency compared to the gas neutralizer. In addition, the presence of plasma reduces the optimum target density and hence the gas flow. This also improves the efficiency through reduced beam losses and auxiliary power requirements. These improvements yield an efficiency greater than 50 % for no additional power requirement. The model used is simple and the success of the concept depends on the confinement efficiency of the fast stripped electrons. This could be tested experimentally by injecting electrons of the correct energy into a neutralizer chamber.

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