Plasma neutralizers

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PLASMA NEUTRALIZERS

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ABSTRACT

Presented are results on the modelling of a cascaded arc. Under suitable conditions, the plasma effusing out of the arc has a high degree of ionization. It is proposed to use this arc as the plasma source of a plasma neutralizer in neutral beam injectors for fusion research. The neutralization of a D\textsuperscript{-} beam results in the generation of an electron beam. The power in this e-beam is too small to sustain the plasma in the neutralizer for the 1.3 MeV fusion beams.

INTRODUCTION

The neutral beams that at present are being discussed for heating of the plasma and partial drive of the toroidal current in next step fusion devices like NET and ITER, have particle energies between 1 and 1.3 MeV [1, 2]. These beams are obtained by the neutralization of negative ion beams, both H\textsuperscript{-} and D\textsuperscript{-}. The powers envisaged range from \(\approx 50\) (NET) to \(\geq 75\) MW (ITER). Therefore, it is important to generate these beams with the highest possible efficiency. Areas where efficiency gains are likely to be possible are the negative ion source and the neutralizer. Negative ion sources do get attention in the neutral beam community [see this conference], but this is not so with neutralizers. In the available designs of neutral beam injectors, the working hypothesis is to use a gas neutralizer. However, the use of a plasma neutralizer [3] would give a considerable increase of overall beam line efficiency, possibly from \(\approx 42\%\) to \(\approx 58\%\).

Neutralizers for negative ion beams have two particularities that distinguish them from those for positive ion beams. Firstly, one is dealing with three charge fractions, which, in the case of a deuterium beam, are D\textsuperscript{-}, D\textsuperscript{0}, and D\textsuperscript{+}. This property necessitates a modification of energy recovery techniques when they are carried over from positive to negative ion beams [4].

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Secondly, during the stripping of the negative ion, an electron is released that is travelling at approximately the same speed as the parent ion. At a $D^-$ energy of 1.3 MeV the neutralization results in the generation of 350 eV electrons. In the case of positive ion beams, there is no stripping and the ionization of neutralizer atoms or molecules results in electrons of low energy only.

Fast electron generation occurs in gas as well as in plasma neutralizers. The question then arises if these electrons can be used to simplify the neutralizer. In the case of a neutralizer to which only gas is admitted, they may ionize the gas and form a plasma. To create a sufficient number of ion pairs the fast electrons must be confined, for instance with a multi-pole magnetic field. Then, the situation is analogous to a negative ion source in which the hot-cathode discharge has been replaced by a negative ion beam. The comparison allows us to predict some aspects of this neutralizer. A preliminary estimate indicates that the beam current is too small to ionize the gas to the necessary high degree of ionization \cite{3}, $\alpha \geq 50\%$.

It follows that the plasma in the neutralizer needs to be generated by external means. We propose the use of cascaded arcs \cite{5,6} to inject plasma into a box lined with a multi cusp magnetic field. Presented will be the most relevant result of a modelling of this arc. It is found that the calculated degree of ionization in the arc is nearly 100%. The arc power required for a full scale neutralizer is estimated at 30 kW for a 8.3 MW neutral beam module.

A cascaded arc is a wall stabilized arc, consisting of a cathode, a stack of electrically insulated cascade plates, and an anode. The arc channel is formed in the central bore of the cascade plates, which are 5 mm thick, water cooled, copper plates, that are separated by 1 mm gaps maintained by PVC spacing rings. Gas is admitted to the arc channel at the cathode side and plasma flows out of the channel through a hole (a nozzle) in the anode. The arc plasma is characterized by high electron densities, high degrees of ionization, moderate temperatures, and a low power consumption.

**PLASMA NEUTRALIZER REQUIREMENTS**

Culham has proposed the use of a close coupled neutralizer in their design of a neutral beam injector for NET \cite{7}. As a result of the short distance between source and neutralizer, and because of the small divergence of a high energy negative ion beam, the individual beamlets do not merge. Therefore, neutralizers can have nearly closed front and back side, contrary to the open structures used on present fusion machines. A neutralizer can be envisaged as a box on all sides covered by permanent magnets, with $\approx 30$ mm wide slots in the front and back wall to allow the beamlets to pass through. Slots are needed because of the demand to sweep the beamlets in the vertical plane.
(beam profile control). The number of slots is equal to the number of aperture columns in the source. Using a Culham type source in the case of a 8.3 MW, 1.3 MeV module (ITER NB injector concept [8]), the neutralizer cross section would be approximately 1.5 by 1.5 m$^2$ and it would have about 10 slots [9].

In the following we give a rough estimate of the ionization rate needed to maintain the plasma in a neutralizer box of length $l$, and width and height $d$. The total ion flow to the walls (Bohm sheath criterion) is equal to,

$$\phi \approx 0.6 n_i c_s A_C,$$  \hspace{1cm} (1)

where, $n_i$ is the plasma density, $c_s = \sqrt{k(T_e+T_i)/m}$ is the acoustic speed with $m$ the ion mass, and the total loss area $A_C$ is given by the product of the length and the width $\delta$ of the cusp lines between the magnet rows. We assume linear line cusps perpendicular to the velocity of the negative ion beam at a pitch $D$. This way the magnetic field is mainly parallel to the beam and the perturbation on the beam is minimal. In the front and back wall, the magnet configuration is determined by the slots. Finally, we have $\delta = 4 \sqrt{\text{pepi}}$ [10], which is four times the hybrid Larmor radius. From these considerations we obtain,

$$A_C \approx \delta d (4l + d) / D.$$  \hspace{1cm} (2)

A further given fact is the optimum plasma target density $\Pi$, given by [3],

$$\Pi = n_i l = 2 \times 10^{19} \text{ m}^{-2}.$$  \hspace{1cm} (3)

With the aid of Eqs. (1, 2, 3) we can write,

$$\phi = 2.4 \Pi \sqrt{\frac{kT_e}{m}} \frac{d (4l + d)}{D l} \sqrt{\text{pepi}} \approx \frac{1}{B} \frac{4}{\sqrt{\frac{T_e^3 T_i}{m}}}$$  \hspace{1cm} (4)

The scaling law demonstrates that it is beneficial to increase the $B$ field, an approach being studied by Culham [9], or to reduce $T_e$. The ion mass has less influence, but switching from deuterium to argon ions, one gains a factor 2.1. As a numerical example, we take $T_e = 5$ eV, $T_i (D^+) = 0.4$ eV, (temperatures measured in buckets [11], in which the plasma is created by energetic electrons), $B = 0.15$ T, $d = 1.5$ m, $l = 1$ m, and $D = 5$ cm. We obtain $\phi = 2 \times 10^{22}$ s$^{-1}$; for an $Ar^+$ plasma the same quantity is $9 \times 10^{21}$ s$^{-1}$.

In the above derivation, wall losses were assumed dominant. With other types of plasma creation, the electron temperature may be much smaller than
the 5 eV quoted in the example, leading to smaller diffusion losses. However, volume losses like three-body and radiative recombination of D$^+$ ions become more important, as well as loss channels involving (vibrationally excited) molecule reactions. This suggests that there is an optimum temperature for which the flux $\varphi$ is minimal. This temperature may be quite different for atomic and molecular gases, because of the more complex chemistry of the latter.

**PLASMA CREATION**

As mentioned in the introduction, the neutralization of a negative ion beam is accompanied by the formation of a 350 eV electron beam. In the case of a module delivering a 8.3 MW, 1.3 MeV (D$^0$) beam, the electron current amounts to $\approx 6.5$ A, and represents a power of $\approx 2.24$ kW. Because the electrons are released inside the neutralizer, we assume that they are confined by the multi cusp magnetic field and loose their energy by ionization of the gas. Taking an expenditure of 64 eV per ion pair created [12], the electron beam could ionize $2.2 \times 10^{20}$ atoms per second. It is clear that in the case of beams for fusion the electron beam power is too small to establish the required plasma target. The situation becomes more favourable with beams of higher energy and higher current density.

We conclude that the plasma must be created by external power. We can choose between two approaches. (1): One can inject a plasma [5, 13]. Then the neutralizer must have an open structure to allow efficient pumping of the ions that neutralize on the walls. The gas volume to be pumped is found from $\varphi$. In the case of deuterium, it is $\approx 280$ Torr $\cdot$ s. (2): One can inject power and gas separately into the neutralizer and create the plasma in situ [9, 12]. In this case, the neutralizer must be closed for gas transport to reduce the pumping requirements. Taking again 64 eV for the creation of a deuterium ion pair, the required power is found to be 200 kW.

To learn about consequences of injecting plasma from an external source we studied cascaded arcs, because of their high power efficiency.

**ARC MODEL**

To describe the evolution of the arc plasma as function of the axial position along the channel between cathode and anode a self consistent one-dimensional model has been set up. A two-dimensional model, which takes into account the radial profiles, has been formulated [D. Milojevic, D.C. Schram, and P.M. Veilinga, to be published]. In this paper, we present the 1-D model results obtained by numerical integration of the conservation laws for mass, momentum and energy. Calculated as function of the coordinate $x$ are the
densities and the temperatures of heavy particles and of electrons, the pressure, and the directed flow velocity. A further result is the arc voltage. It is assumed that the heavy particle components D₂, D⁰, and D⁺, with densities \( n_2, n_1, \) and \( n_i \), are closely coupled and have the same temperature \( T_H \) and drift velocity \( u \). The electron component has a density \( n_e \) and temperature \( T_e \). Then, the degree of ionization is defined by \( \alpha = \frac{n_e}{n_2 + n_1 + n_i} \), the degree of dissociation by \( \beta = \frac{n_1}{n_2} \), and the reduced mass velocity by \( M = \frac{u}{c} \), with \( c = \sqrt{\frac{5kT_H}{3m}} \).

The energy input is to the electrons and is due to Ohmic dissipation, \( Q_{Ohm} \), of the arc current \( I_a \) in the arc channel of diameter \( D \). The electrons loose energy by dissociation of the molecules, \( Q_d \), by ionization of the heavy particles, \( Q_i \), by elastic energy transfer in electron heavy particle collisions, \( Q_{eh} \), by work performed on the plasma and leading to the plasma expansion, \( Q_u \), and through radiative processes like the escape of line radiation emitted by excited heavy particles, the escape of continuum radiation due to free–free transitions and recombination to excited levels.

Changes in the densities of species are brought about by direct or indirect electron impact ionization and dissociation, three particle recombination, and radiative recombination. Momentum transfer is by means of elastic collisions between electrons and heavy particles. In addition, also friction between the plasma and the wall is taken into account.

When performing a calculation, the input parameters are the arc current \( I_a \), the pressure at the channel entrance \( p_0 \), the channel diam. \( D \), the channel length \( l \), and the gas flow \( \phi \). Of these, one parameter is a dependent one because of the boundary condition that a sonic condition, \( M = 1 \), is reached at the end of the channel in the anode.

**SOME RESULTS**

The model described above has been applied to an arc burning on argon gas. Calculated values of \( T_e, n_e, \) and pressure \( p \), agreed within 5% with values measured at some ten different points along the arc channel, providing the channel was given a diameter of 38 mm, instead of the experimental value of 40 mm [6]. This difference is related to the existence of a 0.1 mm thick wall layer. These results give confidence in the applicability of the model to a deuterium arc, for which no experimental data are available.

The simulations in general show an increase of the degree of ionization \( \alpha \) with arc current and with channel length, and a decrease with gas flow. Fig. 1 illustrates the latter point with results for three cases in deuterium gas:
with further, \( D = 3.8 \text{ mm}, I_a = 95 \text{ A}, \) and \( p_0 = 0.35 \text{ bar}. \) As mentioned before, not all parameters are free. In this series of calculations, the arc length was adjusted to obtain in the anode the sonic condition \( M = 1. \) Starting values at \( x = 0 \) are \( \alpha, \beta \approx 0.01 \) and \( T \approx 1000 \text{ K}. \) The figure shows that \( \alpha \) increases approximately linearly with \( x \) and reaches a maximum value > 0.8 for the smallest flow. Also the degree of dissociation \( \beta \) is shown. In case A, nearly full dissociation is obtained in the first 40% of the arc length.

In case A, the gas is heated to \( T_h > 10^4 \text{ K} \) in the first 10% of the channel, in which thermal equilibrium is reached. From there on \( T_e \) and \( T_h \) increase nearly linearly from 13,000 K to 16,000 K at the anode side. The highest temperature is found for the smallest flow. The electron density is plotted in Fig. 2. The highest density is reached with the smallest flow. The initial increase in \( n_e \) is due to ionization of the gas; the decrease in the second half of the channel is related to the increase in plasma flow velocity. The combined result is a monotonic decrease of the pressure with position \( x. \) The major energy terms associated with these processes are plotted in Fig. 3 for case A. All terms are normalized to the Ohmic energy input. It is seen that the electron energy used for dissociation, \( Q_d, \) disappears at the position where \( \beta \) tends to one; ionization losses \( Q_i \) remain high up to the point where the electron density reaches its maximum. Beyond this position \( Q_i \) decreases, even though \( \alpha \) still increases. Saturation of \( \alpha \) only occurs near the end of the channel. Further is indicated the elastic energy transfer from electrons to heavy particles, \( Q_{eh}. \) This quantity becomes the dominating one at the end of the channel, where the plasma speed \( u \) increases rapidly and the sonic condition \( M = 1 \) is reached. \( Q_e \) is the sum of the three terms just discussed. In the energy balance, the radiation losses are unimportant. Together they contribute less than a few % and are not presented. Figure 4 presents the energy contributions related to the gradient terms. The energy needed for plasma acceleration is \( Q_U = \frac{5}{2} kT_e n_e (\nabla u), \) and the energy due to variations in electron density and temperature are \( Q_n = \frac{3}{2} kT_e u (\nabla n_e) \) and \( Q_t = \frac{3}{2} n_e u (\nabla kT_e), \) respectively. Again, the terms are normalized with respect to the Ohmic input. At the end of the channel, the dominant term is the plasma acceleration. It reaches a value of 0.6 at the anode and makes up for the deficit in Fig. 3. Due to the expansion the temperature decreases at the anode (\( Q_t < 0 \)).

The calculated cumulative plasma resistance, between the cathode and the anode amounts to 1.8 Ohm. With the chosen arc current of 95 A, we arrive
at an arc voltage of 170 V across the column of case A. So, this arc dissipates 16 kW:

**DISCUSSION**

With the aim to fill a given volume with plasma, the relevant question is the maximum flow of ion pairs provided by the arc. It is approximately attained for the conditions of case A, and amounts to \( \Phi_a = 3.8 \times 10^{21} \text{ s}^{-1} \). However, reducing the gas flow results in a higher degree of ionization and in relaxed pumping requirements. At \( \phi = 50 \text{ scc/s} \), calculations give \( \alpha = 100\% \) and \( \Phi_a = 2.4 \times 10^{21} \text{ s}^{-1} \). Taking this latter case, we find \( \Phi \Phi_a \approx 8 \). So, some 8 cascaded arcs would be needed for a full sized plasma neutralizer. This number is an upper bound, because we compared two situations with different temperatures and, therefore, different ion life times. We estimated \( \Phi \) using \( T_e = 5 \text{ eV} \), whereas in the plasma jet squirting out of the cascaded arc \( T_e \leq 1 \text{ eV} \). The scaling law in Eq. (4) suggests that the number of arcs might be as low as 3, implying a gas flow of 150 scc/s or 115 Torr 1/s.

The advantage of a cascaded arc is the small power consumption. From the calculated plasma flow and arc power, one obtains 26 eV per ion pair, a factor 2.5 more favourable than the low pressure discharge result [12]. Using this number, the required power is estimated at 30 kW, for three arcs of 50 scc/s gas flow.

The above estimates of gas flow and power indicate that plasma neutralizers form a realistic option besides gas neutralizers. Moreover, the scaling law suggests that many improvements are possible. Because of the important benefits possible with plasma neutralizers, such as a much smaller area occupied by the neutral beam system in next step fusion devices experimental efforts in this area deserve a strong support.

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REFERENCES

The calculated increase in the degree of ionization (solid lines) and dissociation (dashed lines) with axial position in a cascaded arc channel, normalized to the total arc length. The parameters are: the arc current, $I_a = 95$ A; the inlet pressure, $P_0 = 0.35$ bar; deuterium gas; gas flow rate and arc length are for case A) 100 scc/s and 118 mm, for case C) 150 scc/s and 55 mm, and for case D) 200 scc/s and 31 mm.

Axial density profiles, calculated for a cascaded arc in deuterium gas. Parameters are the same as in Fig 1.
Various electron energy dissipation terms, normalized to the Ohmic energy input, as function of the position in the cascaded arc channel. Parameters are those of case A in Fig 1. $Q_0$ is the sum of the three terms presented $Q_d$, the dissociation loss, $Q_i$, the ionization loss, and $Q_{eh}$, the energy transferred to ions in elastic collisions.

Terms in the electron energy equation, proportional to plasma gradients, like the density gradient $Q_n$, the temperature gradient $Q_t$, and the gradient in the directed velocity, $Q_u$. 

Figure 3.

Figure 4.
DISCUSSION

Hershcovitch: I’m not asking this question to promote our past program. Why don’t you consider hollow cathode discharges for which Daan Schram had an excellent program there. Hollow cathodes are much more efficient in terms of power and gas.

Hopman: In gas efficiencies matters, if the calculations give you a high degree of ionization better than 95%, it is equal to the hollow cathode. The advantage is, even though there is no hard number on it, that the lifetime of the elements in the cascaded arc is much longer in the case of the hollow cathode. There is no need to have a tip at 3000 K like in the case of the hollow cathode. This is the main advantage that I see.

Hershcovitch: There have been experiments and studies that showed that hollow cathodes operating with LaB$_6$ cathodes have a very long lifetime providing there are no contaminating elements. I would suspect a neutralizer would be a clean environment where the only elements would be the plasma.

Hopman: This is something that has to be discussed.

Moses: I certainly agree with your conclusion, I think we have to get to plasma neutralizers. The question of electron temperature, what was the electron temperature in your source?

Hopman: I forgot to bring the viewgraph, I think it’s 12,000 degrees, for the plasma flame that would be 1 eV?! It must be much colder than 1 eV.

Moses: We have plasma temperatures on the order of 6 to 8 eV so that is relatively cold. The reason why we have been advocating heavier gases in our work is since the ionization potential goes down, so you save that way. In a 21 liter volume, we have been able to produce densities on the order over 10$^{14}$, and in hydrogen in about 10$^{13}$. We have already used in that system the high field magnets, the neodymium magnets already so I don’t think we will be able to gain much more than any other magnets at least that are available now. The question about the degree of ionization, if you look at Berkner’s paper which is really the only thing we have to go by, because of the fact that the cross sections are not known for many of the cross sections we need for neutralization, you find that only 30% gets you almost to where you have to be as far as neutralization. Fifty
percent is overkill but would be nice, 100% is certainly not needed. We have achieved at about 2 milliTorr keeping the pressure down on the order of about 40% ionization, so we’ve already exceeded that at least in xenon. The heavier gas has some other advantages for fusion applications but these are things that will probably be discussed and argued and debated for a long time to come. I can only say that Andrew’s (Holmes) suggestion about putting back the magnets on the face is a very good one. We did not do that purposely because we wanted to test it out for the Berkeley beam source, and we were given specific instructions not to put any magnetic fields at the entrance and exit and we also allowed for about 125 square centimeter openings at both ends besides no magnets. So, that was a worst case situation. I agree that putting magnets on those ends would probably increase the lifetime of the plasma and reduce the power requirements greatly.

Hopman: Sure. I want to comment on one point. If you just fed power into your neutralizer and produced a plasma, and you want to reduce the pumping to have a high gas efficiency like in Andrew Holmes’ proposal, then your neutralizer with a length of about one meter will have on both sides the pipes or slots with lengths of over 2 meters. In those slots, you do not have plasma but you have gas. You have to look at the overall gas target density over the full five meter length, although the plasma target is only 1 meter long. This factor makes you require a higher degree of ionization than if you would have no reduction of your gas. As far as I am aware, no one has made a study of optimum lengths of your pumping looking at those two target densities. But you have to be careful.