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The suppression of electrons extracted from a negative-ion source

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When a suitable accelerating voltage is applied to extract negative ions from a volume production source, electrons are also extracted. If no means of suppression is utilized, the electron current in a hydrogen plasma would typically be of the order of 80–100 times the negative-ion current. In the accelerator designs in use at Culham Laboratory, electrons entering the accelerator are dumped in a trap within the second electrode at a small fraction of the beam energy. Even using this technique, a considerable amount of power would be expended unnecessarily in accelerating electrons to the trap. The suppression of electrons at the source/accelerator interface can be achieved by means of a magnetic field applied across the extraction aperture. This traps electrons, which are then collected on an electrically biased subsection of the first electrode. Experiments performed with an electromagnet configuration have shown that the electron flux entering the accelerator can be reduced as approximately the reciprocal of the square of the magnetic field strength.

INTRODUCTION

For heating and current drive applications in the next generation of tokamak-type fusion machines, neutral beams with energies of the order of 1 MeV will be required. The neutralization efficiency of a positive-ion beam decreases dramatically as the beam energy is raised. In contrast, the neutralization efficiency of a negative-ion beam in a gas cell has an almost constant value, a little under 60% for beam energies from around 100 keV to in excess of 1 MeV. It is therefore clear that a high-energy neutral-beam injection system must be based on negative ions. There are advantages to the use of volume-production negative-ion sources over other types of negative-ion sources which rely on charge-exchange processes, particularly in the area of beam divergence. The disadvantage, however, is that in a volume-production ion source, the ions are formed at rest within the bulk of the plasma, and so any extraction system used will also remove electrons.

With no electron suppression, even if some form of electron trap is provided at an intermediate electrode within the accelerator, the overall efficiency of the injection system would be reduced considerably due to the energy expended in accelerating electrons to the trap. A reduction in the electron current extracted from an ion source, by means of a permanent magnet electron suppressor, has been demonstrated by a number of workers.[1–7]

I. EXPERIMENTAL DETAILS

The ion source used was a multicusp bucket type, 550 mm × 310 mm × 210 mm deep, with a magnetic filter to separate the driver and extraction regions. The filter was created by reorientation of certain of the wall-mounted permanent magnets. A miniature diagnostic accelerator with a 1.5-mm-diam extraction aperture and total accelerating voltage of 10 kV was used. Electrons extracted from the source were magnetically deflected into a trap within the accelerator, while negative ions were collected on a Faraday cup. The "insert" device, used to suppress the electron current extracted from the source, is shown in diagramatic form in Fig. 1. The dipole magnetic field is imposed transverse to the extraction aperture, on the source side, with the field lines intersecting the positively biased wall of the insert. Electrons trapped on the field lines are then collected by this part of the insert.

II. EXPERIMENTAL RESULTS

Two different insert assemblies have been used: In one case the electromagnet was wound with a coil depth of 4 mm and a pitch of 4 mm, while in the other case the coil had the same pitch but a depth of 8 mm. In changing from the 4-mm-deep electromagnet to the 8-mm-deep version, the supporting structure increased the depth of the well in front of the extraction aperture from 9.5 to 13.5 mm.

Experimental measurements made with hydrogen as the source filling gas and a "tent" source filter are shown in Fig. 2. The extracted electron-current density is plotted against the peak field strength for the 4-mm-deep electromagnet. As the positive bias on the wall of the insert is increased, the gradient of the line fitted to the data becomes steeper until a limiting gradient of approximately -2 is observed. This occurs for a bias of $+3$ V, measured with respect to the remainder of the beam-forming electrode, which is at a potential close to the floating potential of the source plasma. For an increase in bias beyond $+3$ V, the gradient of the fitted line appears to remain approximately constant at a value of -2.

The near to $1/B^2$ dependence of the extracted electron current for a bias of $+3$ V or greater would be expected for classical diffusion across a magnetic field where the diffusion is reduced by a factor $1/(1+\omega_{ce}^2\tau^2)$. ω_{ce} is the electron cyclotron frequency, and τ is the collision time for the appropriate process.

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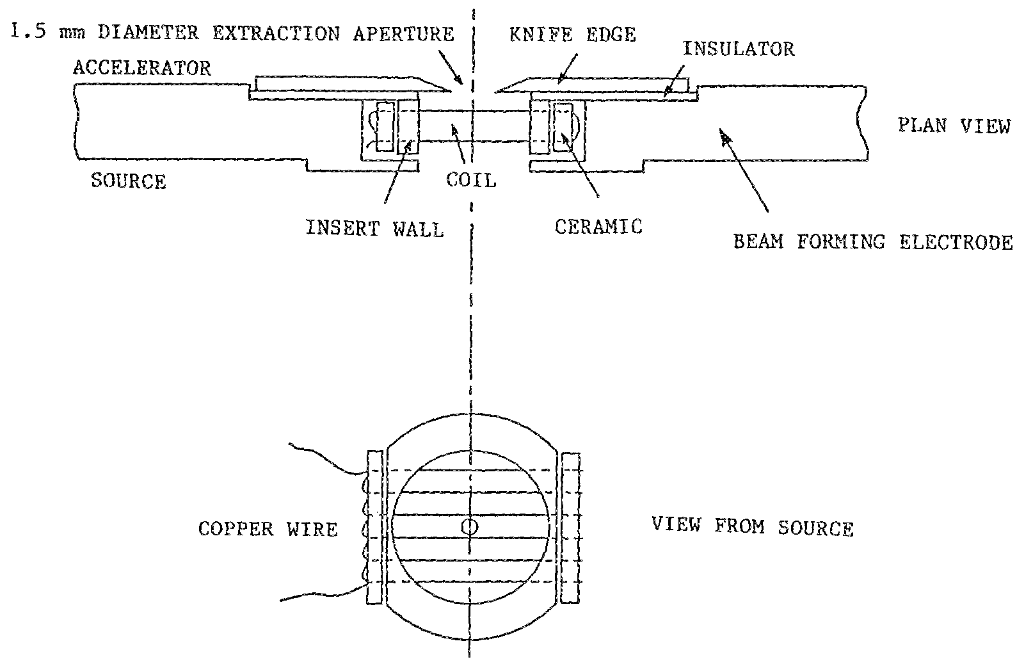

FIG. 1. The electromagnetic insert assembly.

For deuterium as the source filling gas, similar behavior is observed for the extracted electron-current data, with a gradient of near to − 2 also being obtained for a bias of + 3 V on the wall of the insert. When the 4-mm-deep electromagnet was replaced by the 8-mm-deep version, a bias voltage of approximately + 4.6 V was required before the gradient of the fitted line reached a value near to − 2.

The extracted negative-ion current increased rapidly in value at low insert field strengths (Fig. 3); at larger field strengths a gradual reduction in the current occurred. For the 4-mm-deep electromagnet, the maximum negative-ion-current density approached that seen in the undisturbed plasma with no insert assembly present. When the 4-mm-deep electromagnet was operated, a small reversed field was required to offset the residual field from the electron trap in the accelerator. This offset was not observed for the 8-mm-deep electromagnet.

From a simple geometrical consideration of the plasma loss to the walls of the well in the insert assembly, it would be expected that the negative-ion-current density measured with the 4-mm-deep electromagnet would be 0.42 of the value in the undisturbed plasma. For the 8-mm-deep electromagnet, the ratio should be 0.33. The experimental data provide a ratio close to the expected value for the 4-mm-deep electromagnet with no net magnetic field. The data for the 8-mm-deep electromagnet are not in such close agreement.

All the measurements described so far were made with the ion source configured with a "tent" filter. As part of the experimental program, the source magnets were reconfigured to provide line cusps at the wall and no magnetic filter.

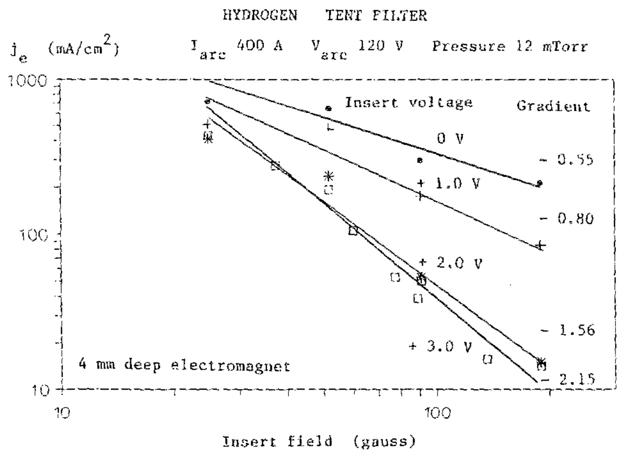

FIG. 2. Extracted electron current vs insert field. Tent filter in source.

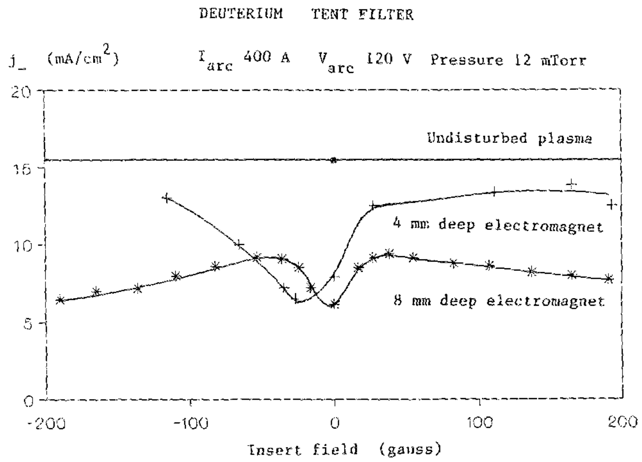

FIG. 3. Extracted negative-ion current vs insert field. Tent filter in source.

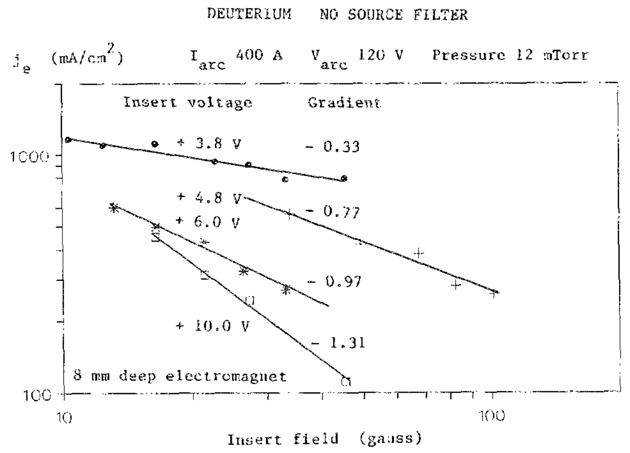

FIG. 4. Extracted electron current vs insert field. No source filter.

That no filter was present was verified by Langmuir probe measurements, which showed that the electron temperature near the extraction plane had increased from 1 eV when the filter was present to 5 eV with the magnets reconfigured.

Measurements of the extracted electron current with the 8-mm-deep electromagnet are plotted in Fig. 4. The results show that even with an insert wall bias of + 10 V, the gradient of the line fitted to the data points has only reached a value of − 1.31. The difference between plasma and floating potentials in a plasma is proportional to the electron temperature. The results are therefore consistent with the view that the positive biasing of the insert wall acts to remove the potential barrier to electrons trapped on the field lines. As the wall potential approaches local plasma potential, progressively lower energy electrons can reach it and be removed.

It is clear from Fig. 5 that even a relatively weak field from the insert electromagnet results in an enhancement of the extracted negative-ion current of almost a factor of 3 above the value observed with no insert field. The enhancement is considerably greater for the filterless source than for the source configured with the filter. Very few negative ions would be expected in a source with an electron temperature in the extraction region of 5 eV; due to their destruction by electron detachment, this low value is shown in the figure when no field was present.

III. DISCUSSION

The extracted electron current may be decreased by applying a magnetic field transverse to the extraction aperture when the insert wall is biased positive with respect to the rest of the beam-forming electrode. As the insert wall is biased increasingly positive, the electron suppression becomes more effective. When the wall is biased to near the local plasma potential, the extracted electron current varies as approximately $1/B^2$. For source operation without a filter field, the bias required to achieve a particular level of electron suppression was greater than when the source was configured with a filter, consistent with the increased electron temperature. Work is in progress to extend the database to higher field strengths.

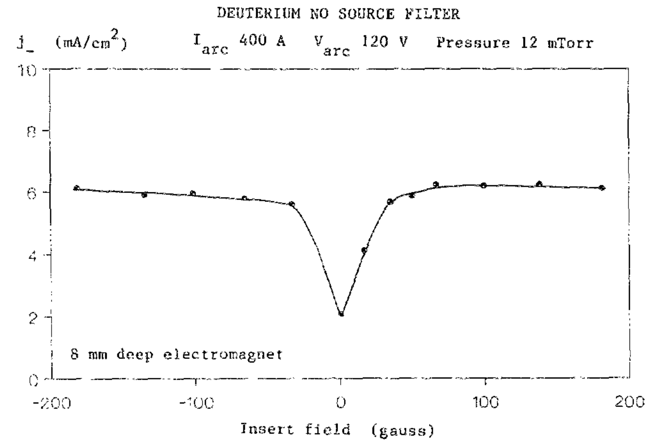

FIG. 5. Extracted negative-ion current vs insert field. No source filter.

With no magnetic field applied across the extraction aperture, the negative-ion-current density was reduced from the value in the undisturbed plasma by a factor related to the geometry of the well in the insert. When the field was increased, the negative-ion current increased rapidly at first, then decreased slowly at greater field strengths. The enhancement of the negative-ion current when the insert field was applied implies that a significant fraction of all negative ions were produced in the region of the aperture. The experiments performed with the filterless source, in which a large enhancement of the current density was seen, even though the negative-ion destruction rate near the extraction plane should have been high, give support to this view. If this is the case, then the magnetic field of the insert is acting in the same way as the source filter field, creating plasma conditions suitable for negative-ion production immediately in front of the extraction aperture. It may therefore be postulated that if an electron suppressor of the form described here is used in a multicusp source, the form of the source filter becomes of small importance, as most of the negative ions originate very close to the extraction aperture.

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