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Electron suppressors for negative ion sources

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Two designs of electron suppressor have been tested in a volume negative ion source operating dc with a large extraction aperture diameter (16 mm). Both suppressors employ magnetic fields to divert the electrons near the extraction aperture onto collector electrodes. However, while one suppressor uses a fixed field produced by permanent magnets, the other employs a variable field produced by a solenoidal coil. These suppressors allow low values (3–4:1) of extracted electron to ion currents to be obtained. The results are compared with a diffusion model and a hydrodynamic model of the transport of the electrons across the magnetic field. They show that the hydrodynamic model gives a good description of the suppression and transport of the electrons.

I. INTRODUCTION

In any cw application of negative ion beams, the reduction of the flux of electrons leaving the source with the negative ions is of vital importance. If nothing is done to suppress the electrons in the source itself, the extracted electron current can be up to 50 times that of the negative ions. While the main engineering issue is one of heat removal, the presence of these electrons also has an influence on accelerator design, power supply ratings, and possibly on the quality of the negative ion beam itself.

This article reports on tests of an electron suppressor with variable electric and magnetic fields operating at the source/accelerator interface of a volume negative ion source. This type of suppressor has been tested previously[1] and has demonstrated the main desirable feature of suppression of the electrons without significant attenuation of the negative ions. However, whereas the experiments of Lea *et al.*[1] utilized small probe accelerator with an extraction aperture diameter of 1.5 mm, the experiments reported here have used a 16-mm-diam aperture. Finally, the results are compared to those obtained from a device which used a fixed-magnetic-field strength and a variable electric field.[2]

Two models[3,4] exist to describe the mechanism of electron suppression by this generic type of device. They have many similarities but differ in their prediction of the pressure dependence of the electron suppression. Results from both types of suppressor will be compared with the theoretical models.

The effect of electron suppression on the ion current is addressed to some extent[4] in one of the models but the result will not be investigated here.

II. EXPERIMENTAL DETAILS

A. The source and accelerator

The source used in this work is a volume negative ion source and has been described elsewhere.[2,5] It has dimensions of $195 \times 140 \times 85$ mm^3 and uses a multipole magnetic field to confine the plasma. The plasma is sustained by six filaments.

The magnetic field configuration required to produce the temperature distribution in the plasma necessary for the production of high densities of negative ions, can be in one of two forms as shown in Fig. 1. These are the so-called dipole field and the tent filter field. The integrated, dipole filter field from its peak to the extraction aperture is ~200 G cm. The tent filter field produces less field at the extraction aperture. This may lead to a more uniform plasma, but more importantly to a more easily controllable magnetic geometry.

In Fig. 2, a schematic diagram of the accelerator[2,5] is shown. The electrons and ions extracted from the source are accelerated by a voltage V_{ext} that is about one sixth of the final beam energy V_{beam}. Permanent magnets in grid 2 deflect the electrons in the beam into a trap region giving a current I_e. The negative ions are accelerated further to the final beam energy (80–100 keV). Further sets of magnets in grids 2 and 3 are used to resteer the beam onto the axis. The electron trap is not perfectly efficient and some small fraction, β (~1%–5%), of the current I_e is accelerated to full energy. A deflector magnet downstream of grid 3 ensures that no electrons are measured in the beam transformer which then records the negative ion current, I_{BT}, transported a distance of ~0.6 m. The source extraction aperture diameter was 16 mm. In all the experiments reported here the source was operated in hydrogen gas.

B. The electron suppressors

Fig. 3 illustrates the basic principle of electron suppression. A magnetic field close to the extraction aperture traps

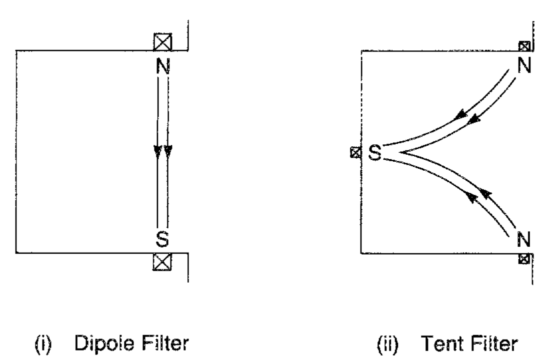

FIG. 1. The source filter field configurations.

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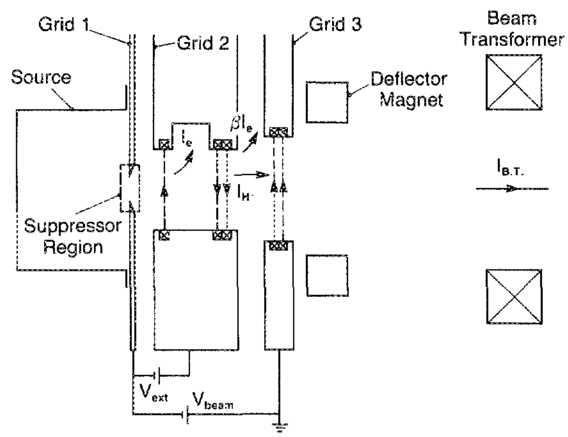

FIG. 2. The source and accelerator.

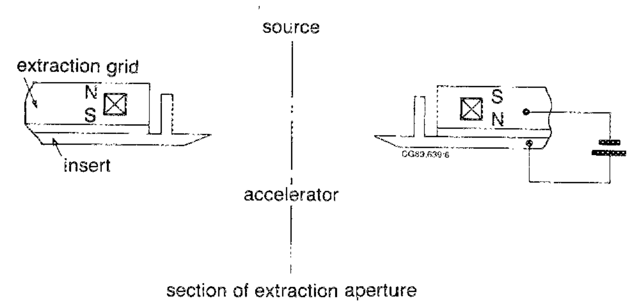

FIG. 4. The permanent magnet electron suppressor.

electrons which then move along the field lines. These field lines intersect electrodes that are biased to a low positive potential. This allows collection of the electrons. The suppressor lies within the dashed region of Fig. 2. Not all the electrons are collected and there is a transport of electrons across the magnetic field leading to their eventual extraction and it is via this transport that we have considered the suppression physics. The theoretical models summarized in the next section address this transport and the experiments described in this article are compared with these models.

Figure 4 shows the permanent magnet suppressor. A pair of $4\times4\times37$ mm^3 samarium cobalt magnets, spaced ~35 mm apart, are arranged in a quadrupole configuration. The field from these magnets intercepts the positively biased electrode allowing collection of the electrons. When the source filter field is in the dipole configuration, the quadrupole field adds to the filter field. The integrated field due to the magnets is ~100 G cm in the source. The field, which is in the first accelerator gap, then adds to the deflection field for extracted electrons. Part of the extraction electrode becomes the electron collection surface.

The experiments of Lea *et al.*[1] have shown the importance of the magnetic B field strength in the suppression of electrons. With this in mind, a device was designed with a variable B field using a flat solenoidal coil. This device is shown in Fig. 5. This device is sometimes known as the electromagnetic suppressor. Current is passed through the coils to produce the variable magnetic field with a full width half maximum of ~5 mm. Electron collection surfaces, at each end of the coil, intercept the field lines and, as in the case of the permanent magnet design, this collection surface is biasable with respect to the beam forming electrode. The peak field produced is of the order of 1 G/A.

III. THEORETICAL DESCRIPTION

In order to describe the transport of electrons across the suppressor magnet field, Green[3] used a model based on classical diffusion of the electrons by electron molecule collisions. The conservation and diffusion equations were solved and expressions derived which could be compared to experimental measurements.

In this model the extracted electron current I_e is given by

$$I_e = A_1\, n_{eo}\, \alpha\, D\, e\, \exp(-\alpha L), \tag{1}$$

where A_1 is the extraction aperture area, n_{eo} is the plasma electron density, D is the diffusion coefficient, e is the unit of charge, L is the suppressor length, and the parameter α is given by

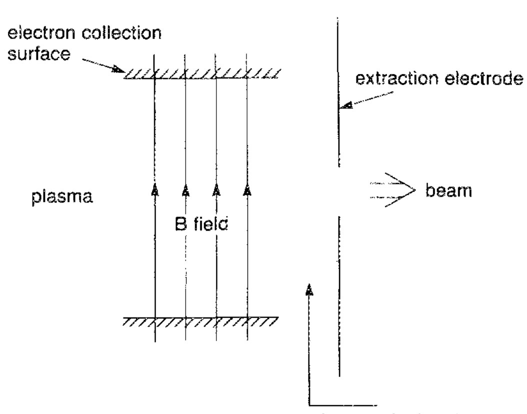

FIG. 3. Schematic of the electron suppressor.

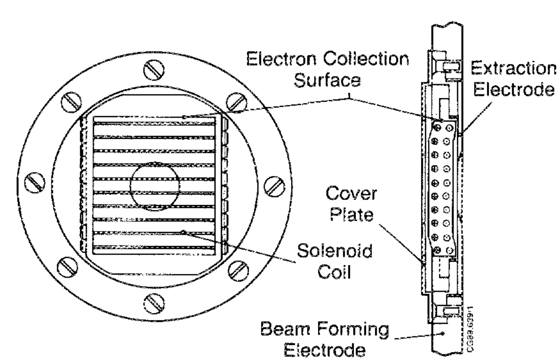

FIG. 5. The variable magnetic field suppressor.

$$\alpha^2 = (v_e/4Dk')\exp(-\eta), \qquad (2)$$

in which v_e is the electron thermal velocity, k' is the collection area per unit length of the device, and η is the reduced potential across the sheath. When the collector voltage $V_{\rm ins}$ is varied, it is this reduced potential η that changes, i.e., $\eta = e(V_p - V_{\rm ins})/kT$, where V_p is the plasma potential and T is the electron temperature.

For high magnetic fields the diffusion coefficient D is given by

$$D = kT/m_e\,\omega^2\,\tau, \qquad (3)$$

where kT is the electron energy, τ the time between electron-molecule collisions, and ω is the cyclotron angular frequency, i.e., $\omega = eB/m_e$, m_e being the electron mass and B the magnetic field strength.

Combining Eqs. (1), (2), and (3) produces an expression for the extracted electron current in terms of the magnetic field strength

$$I_e = (K/B)\exp(-\gamma B), \qquad (4)$$

where K and γ are given by

$$K = A_1\, n_{eo}\left(\frac{m_e v_e kTe^{-\eta}}{4k'\tau}\right)^{1/2}$$

and

$$\gamma = \left(\frac{v_e\,\tau\, e^{-\eta}}{4k'\,kT\,m_e}\right)^{1/2} eL.$$

The current collected by the suppressor, $I_{\rm ins}$, is given by

$$I_{\rm ins} = A_2\, n_{eo}\,\alpha\, De, \qquad (5)$$

where A_2 is the effective collection area of the suppressor. Using this expression and Eq. (1) we obtain

$$\ln\frac{I_e}{I_{\rm ins}} = \ln\frac{A_1}{A_2} - \left(\frac{v_e e^{-\eta}}{4Dk'}\right)^{1/2} L, \qquad (6)$$

which can be rewritten

$$\ln(I_e/I_{\rm ins}) = a - b\, I_{\rm ins}, \qquad (7)$$

where a and b are given by

$$a = \ln(A_1/A_2)$$

and

$$b = L/A_2\, n_{eo}\, De.$$

Substituting for the diffusion coefficient D in Eq. (6) and taking into account its pressure dependence, i.e., $\tau = 1/N\sigma v_e$, where N is the gas density and σ the collision cross section, we obtain:

$$\ln\frac{I_e}{I_{\rm ins}} = \ln\left(\frac{A_1}{A_2}\right) - \left(\frac{e^{-\eta}}{4k'\,kT\,m_e}\frac{1}{N\sigma}\right)^{1/2} eBL. \qquad (8)$$

Now if the electron temperature T did not vary with the pressure (or gas density), then this equation could be written in the form

$$\ln(I_e/I_{\rm ins} = a - (c/N^{1/2}), \qquad (9)$$

where

$$c = \left(\frac{e^{-\eta}}{4k'\,kT\,m_e}\frac{1}{\sigma}\right)^{1/2} eBL.$$

Equations (4), (7), and (9) represent experimental tests of the diffusion model for the two types of suppressor. Our experiments used only one particular geometry for the permanent magnet suppressor and so the test for the functional form of the extracted electron current as given in Eq. (4) cannot be applied.

It is known, however, that in volume sources the electron temperature is dependent on pressure, the electron temperature tending to decrease as pressure is increased and so the experimental test given by Eq. (9) may not be valid because of the term

$$\{\exp[-e(V_p - V_{\rm ins})/kT]/T\}^{1/2},$$

where, even if T varied only slowly with pressure, the exponential term may dominate, although Green[3] has shown data that supports this model.

A second model by Holmes and Haas[4] has solved the hydrodynamic equations in the suppressor region to describe the transport of the electrons across the suppressor field. This model balances the Lorentz force against the frictional force and the density gradient force.

This hydrodynamic model also produces expressions which can be tested by the two devices. The extracted electron current has a dependence on the magnetic field given by

$$I_e = K'\exp(-\gamma' B), \qquad (10)$$

where K' and γ' are given by

$$K' = A_1\, n_{eo}\,(e\, v_e/4)\, e^{-\eta}$$

and

$$\gamma' = (v_e\, e^{-\eta}/8T)\, L,$$

where, in the units of this model, T is in electron volts. This is a purely exponential form compared to the more complicated behavior for the diffusion model as given in Eq. (4).

The hydrodynamic model gives a result very similar to Eq. (7), i.e.,

$$\ln(I_e/I_{\rm ins}) = a' - b'\, I_{\rm ins} - \eta, \qquad (11)$$

where a' and b' are given by

$$a' = \ln(\nu_e A_1/4\, v_e\, a)$$

$$b' = \frac{B\,\nu_e L}{16\, TR\, a\, j_{ep}},$$

in which ν_e is the electron collision frequency, a is the depth of the collection surface, R is the radius of the collection surface, L is the length of the collector, and j_{ep} is the saturation current drawn by the insert.

This equation cannot be used to distinguish between the hydrodynamic and diffusion models as the equations are very similar except perhaps by comparison of the values of the gradient and intercept of the line.

The hydrodynamic model has no explicit pressure dependence except through an expression similar to Eq. (8) with the electron temperature inserted instead of pressure.

We go on now to describe our experiments in comparing two types of suppressor and to testing the validity of the above models.

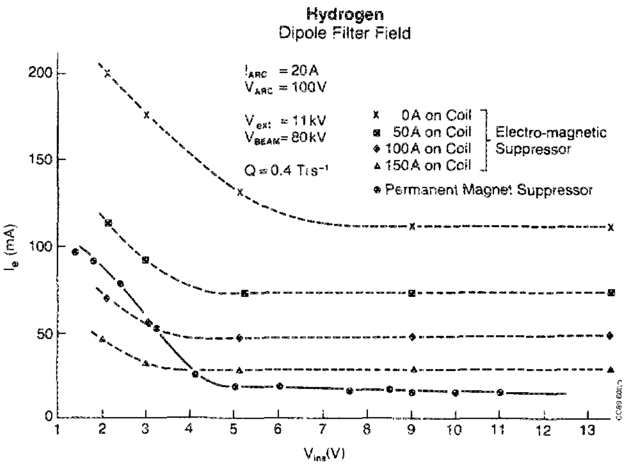

FIG. 6. The suppression of electrons at $I_{ARC} = 20$ A.

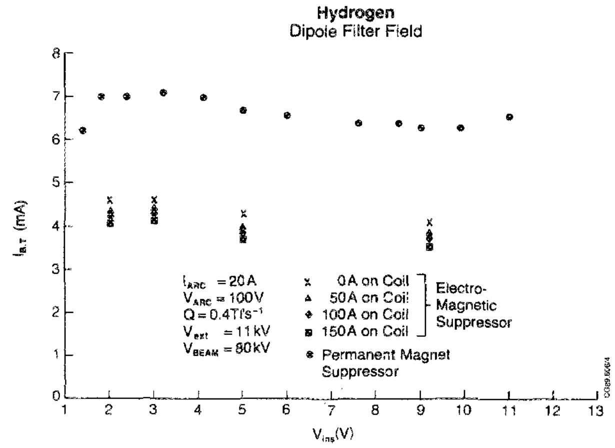

FIG. 8. The effect of electron suppression on the extracted negative ion current at $I_{ARC} = 20$ A.

IV. EXPERIMENTAL RESULTS

A. The action of the two suppressors

In this section we will demonstrate the action of both the permanent magnet and the variable magnetic field suppressors and discuss the relationship of the results to another experiment using the variable magnetic field suppressor.[1]

Figures 6 and 7 show the action of both type of suppressor in reducing the current of extracted electrons from the source at arc currents in the source of 20 and 100 A. In these experiments, the source was operated with the filter field in the dipole configuration. For the permanent magnet suppressor at sufficiently high voltage on the electron collection electrode, the electron flux is highly attenuated. However, in the case of the variable magnetic field suppressor, a coil current of > 150 A is required to equal the performance of the permanent magnet suppressor. The device was not operated at currents above 160 A since it was not cooled and the pulse length was 2–3 s long. Also, the forces of attraction and repulsion between the wires led to distortion of the device.

In practical applications, the effect of the suppressor on the negative-ion current is as important as it is on the electron current. Figures 8 and 9 show the corresponding dependence of the ion current measured at the beam transformer for the two suppressors. At an arc current of 20 A, the ion current is almost independent of collector voltage. In the 100 A data for the permanent magnet suppressor, there is a maximum in the ion current as the collection voltage is varied. This behavior has been observed previously by Bacal and co-workers[6] and Leung and co-workers.[7]

The difference between the suppressors is quite apparent. Only 50%–60% of the negative-ion current observed using the permanent magnet suppressor can be obtained using the variable field suppressor. One possible explanation is the geometric coverage of the extraction aperture by the wires. A single set of coil wires has a transparency of $\sim 75\%$. So, depending on where the negative ions are to be created and how they are transported, then the attenuation may be as high as $(0.75)^2 \sim 55\%$.

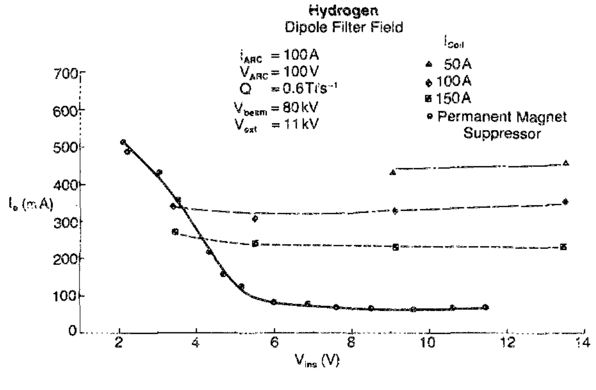

FIG. 7. The suppression of electrons at $I_{ARC} = 100$ A.

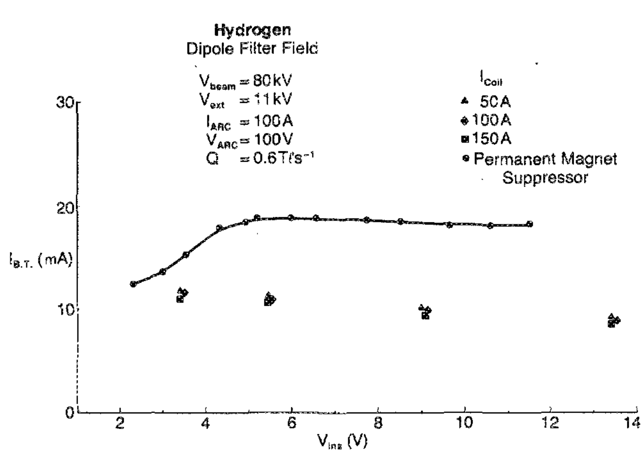

FIG. 9. The effect of electron suppression on the extracted negative ion current at $I_{ARC} = 100$ A.

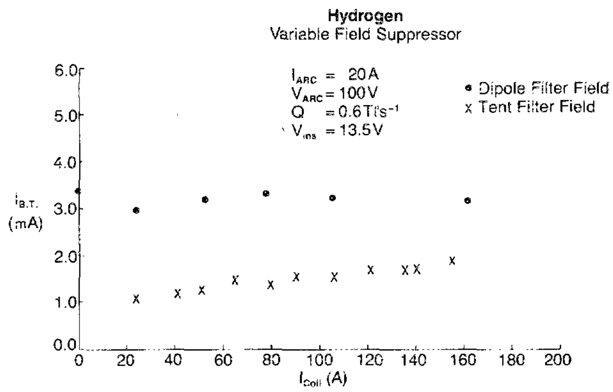

FIG. 10. The dependence of the extracted negative ion current on the magnetic field from the electromagnetic suppressor for both the dipole and tent source filter configurations.

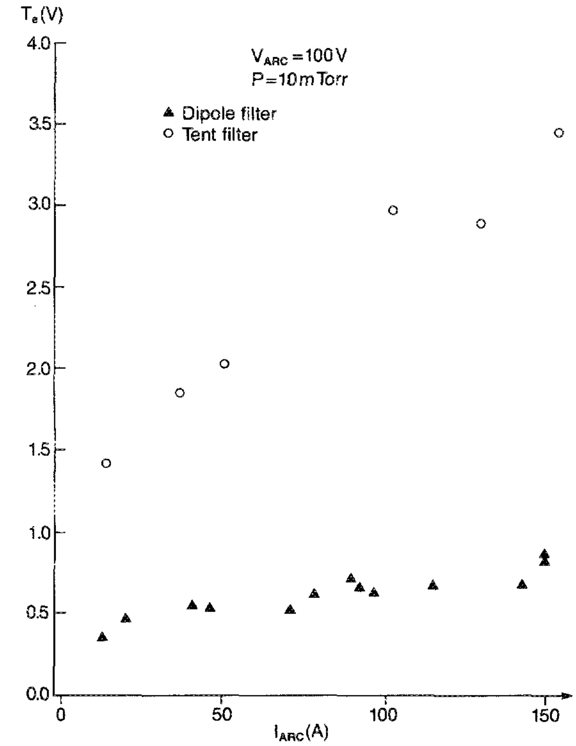

FIG. 11. The dependence of electron temperature on arc current for the source filter configurations.

The data in Figs. 8 and 9 show that for the variable magnetic field suppressor, as the coil current, and hence the magnetic field, is increased from 0 to 160 A there is gradual decrease of the ion current by about 10%. At first sight this is contrary to the result of Lea *et al.*[1] using a similar device but with a probe accelerator utilizing an extraction aperture of only 1.5 mm diameter. However, their source magnetic field was in the tent configuration, and they found that at approximately zero magnetic field the extracted ion current density was approximately 40% of that of the undisturbed plasma, i.e., with no suppressor. As the magnetic field was increased, the ion current density increased to approximately 80% of that of the undisturbed plasma. In our experiments though, even with no field from the coil there are field contributions in the suppressor region from the dipole filter field and the fields of the accelerator which total approximately 30 G.

In order to test this hypothesis, we repeated the experiment but with source filter field configured in the tent mode. The fields due to the source filter and accelerator then totalled approximately 5 G. Figure 10 shows comparison of the effect of the magnetic field on the transported ion current for both the dipole and the tent filter configurations. It can be seen that in the case of the tent filter, as the B field is reduced towards zero, then the ion current reduces as in the results of Lea *et al.*[1] Experimentally, zero magnetic field from the coil could not be reached even for the low arc current used because of the very high flux of electrons (~ 1 A) as this thermal load could not be handled in our accelerator. Notice also that the ion current is much less for the tent filter configuration than for the dipole filter. This is almost certainly due to the fact that in the tent configuration the filaments penetrate the filter field, thus producing an increase in the temperature of the plasma in the extraction region of the source, and a decrease in the production of negative ions.

That this is so can be seen from Fig. 11, where for both types of filter field we plot the electron temperature T_e as determined by a Langmuir probe in the extraction region as a function of arc current. It is apparent that the tent filter is inefficient in producing a cold plasma hence leading to lower densities of negative ions and higher densities of electrons. For this tent filter, the extracted electron current was approximately ten times that for the dipole filter.

As mentioned earlier in connection with Figs. 8 and 9, as the value of $V_{\rm ins}$ for the fixed field device is increased then the ion current reaches a maximum value and then decreases slowly. No tested explanation has even been put forward to explain this result. To show the origin of this effect, in Fig. 12 we plot the transported ion current as a function of extraction voltage for two different values of $V_{\rm ins}$. In both cases, the ion current rises and at a particular value of $V_{\rm ext}$ saturates. This saturation represents all the current available from the source (although it is not corrected for stripping). This saturation level is the same for both values of $V_{\rm ins}$.

At $V_{\rm ins} = 1.9$ V, the additional extracted electron contribution to the total space charge means that more voltage is required to transport all the ion beam beyond grid 2. At the higher value of $V_{\rm ins}$, because the electron contribution to the total space charge is negligible, then less extraction volts are needed to reach saturation. Thus, if the accelerator is operated at a value of $V_{\rm ext}$ lower than that required to extract the maximum available space charge then the transported ion current will appear to change at low $V_{\rm ins}$ when there are high levels of extracted electrons.

B. Comparison with theory

Equations (4) and (10) gives the dependence of the extracted electron current on the magnetic field in the

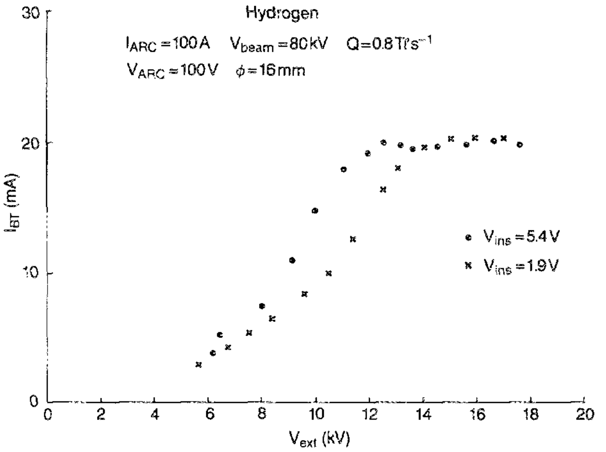

FIG. 12. Variation of transported ion current with extraction voltage for different values of suppressor voltage.

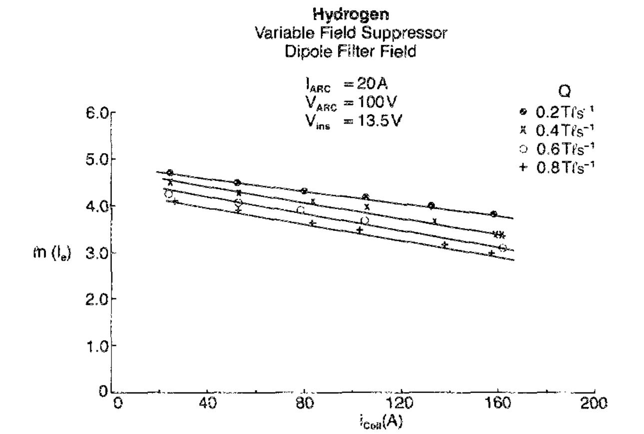

FIG. 13. The variation of extracted electron current on the magnetic field for the electromagnetic suppressor.

suppressor predicted by diffusion and hydrodynamic models. In the permanent magnet suppressor case, there is a fixed magnetic field strength and so this equation cannot be tested. However for the variable field suppressor, we have plotted in Fig. 13, the logarithm of the extracted electron current against the solenoid coil current (i.e., the magnetic field).

All the curves show a linear dependence that is in agreement with the hydrodynamic model as given in Eq. (10). The expected values for the intercept and gradient from the constants in Eq. (10) can be compared with those from the curves. Taking $A_1 = 2\times 10^{-4}\ \mathrm{m}^2$, $n_{eo} = 10^{17}\ \mathrm{m}^{-3}$, $v_e = 3\times 10^5\ \mathrm{ms}^{-1}$, and assuming a maximum value of $e^{-\eta}$ equal to unity since η is only defined up to the plasma potential and the value of $V_{ins} = 13.5$ V is expected to be greater than the plasma potential, $L = 5\times 10^{-3}$ m, and $T = 0.5$ eV for $I_{ARC} = 20$ A, we obtain a value of $\ln K' = 5.5$ when I_e is in milliamperes and a value of $\gamma' = 375\ T^{-1}$. Experimentally, we find $\ln K' \sim 4$–5 which is in agreement with the model, but $\gamma' = 60$–70, which is approximately five times lower than the value from the hydrodynamic model.

The data of Lea *et al.*[1] seemed to fit a power law dependence, i.e.,

$$I_e \propto B^{-n},$$

where the index n changes with increasing collection electrode voltage tending towards value of two. However, their data when replotted in the semilogarithmic form tend to support Eq. (10).

The diffusion and hydrodynamic models give the same form for the variation of $\ln(I_e/I_{ins})$ on the electron current collected by the suppressor, I_{ins}, as expressed through Eqs. (7) and (11). Figures 14 and 15 show data from the permanent magnet suppressor and the variable field suppressor, respectively, plotted in order to test the validity of these models. The experiment was carried out by varying the collector voltage on the suppressor, V_{ins}. For both devices, the curves have a linear portion at larger values of I_{ins} in agreement with the models. The non-linear behavior may arise in a number of ways. First, it could be because of the term η in Eq. (11) which does not remain fixed as V_{ins} is changed. Second, at values of V_{ins} lower than the plasma potential, ions are also collected by the suppressor and so the current collected is not comprised of electrons only.

Again, we can estimate the expected values of gradient and intercept for the two devices from Eqs. (7) and (11). In the case of the permanent magnet suppressor in the diffusion model, the intercept is given by $\ln(A_1/A_2)$, where $A_1 = 2\times 10^{-4}\ \mathrm{m}^2$ and $A_2 = 3\times 10^{-4}\ \mathrm{m}^2$, i.e., an intercept of ~ -0.4. In order to estimate the gradient, we use $L \sim 2\times 10^{-2}$ m, $n_{eo} \sim 10^{17}\ \mathrm{m}^{-3}$, and $D = 1.4\ \mathrm{m}^2\,\mathrm{s}^{-1}$ for which we have taken $kT \sim 0.5$ eV and v_e, appropriately,

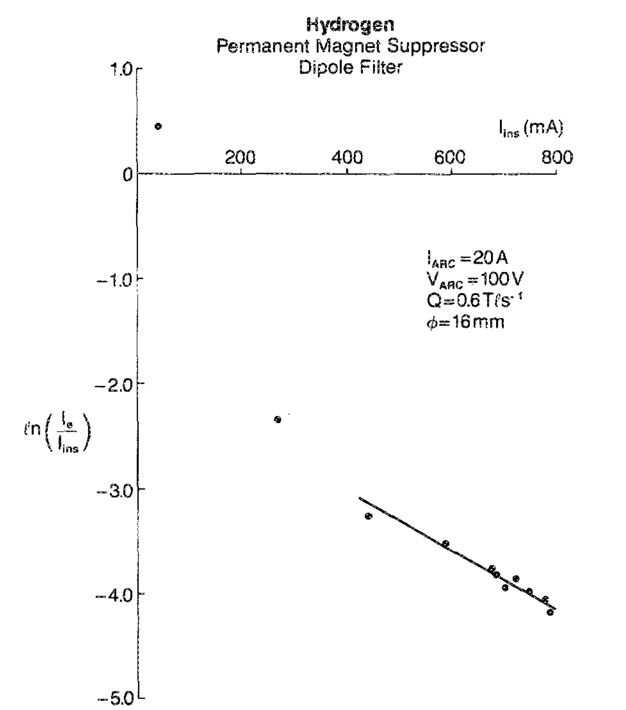

FIG. 14. The variation of $\ln(I_e/I_{ins})$ vs I_{ins} for the permanent magnet suppressor.

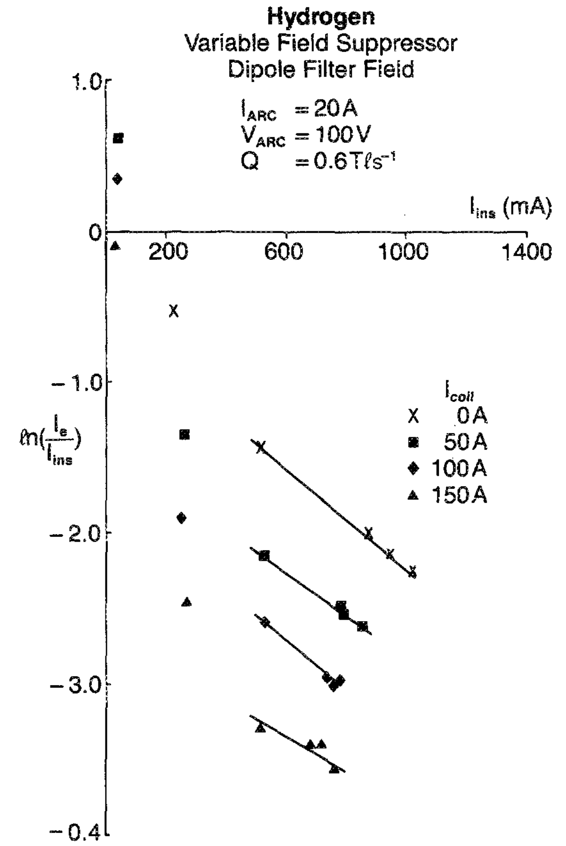

FIG. 15. The variation of $\ln(I_e/I_{ins})$ vs I_{ins} for the electromagnetic suppressor.

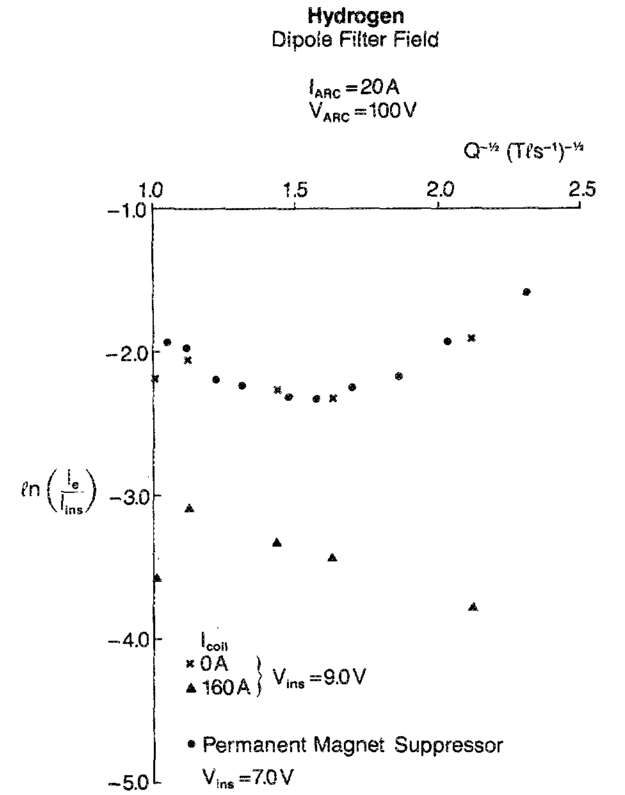

FIG. 16. The variation of $\ln(I_e/I_{ins})$ vs $Q^{1/2}$ ($Q \propto$ pressure) for the two suppressor.

$\tau \sim 10^{-7}$ s for $\sigma = 10^{-19}\,\mathrm{m}^2$ and $P \sim 5$ mTorr and $B \sim 50 \times 10^{-4}$ T, which gives a value of $\sim 3600\,\mathrm{A}^{-1}$ for the gradient. For the variable field suppressor, we take $A_2 \sim 2 \times 10^{-4}\,\mathrm{cm}^2$ and $L = 5 \times 10^{-3}$ m, which gives ~ 0 for the intercept and $\sim 1370\,\mathrm{A}^{-1}$ for the gradient.

Similarly, we can repeat this for the two suppressors in the hydrodynamic model. Estimating a collision frequency of $\nu_e \sim 10^7\,\mathrm{s}^{-1}$ and for the permanent magnet suppressor $a \sim 3 \times 10^{-2}$ m, $L \sim 2 \times 10^{-2}$ m and $R \sim 1.5 \times 10^{-2}$ m we obtain a value of ~ -2.9 for the intercept and a value of $\sim 1.74\,\mathrm{A}^{-1}$ for the gradient. The variable field suppressor has $R \sim 1.5 \times 10^{-2}$ m, $L \sim 5 \times 10^{-3}$ m, and $a \sim 1.5 \times 10^{-2}$ cm giving values of ~ -2.2 and $\sim 0.9\,\mathrm{A}^{-1}$ for the intercept and gradient, respectively.

The values obtained from the hydrodynamic model, even given a large range in the choice of parameters, are much more in line with the data from both suppressors. The diffusion model drastically overestimates the gradient.

Only the diffusion model of the transport gives an explicit prediction of the dependence of the suppression on the gas pressure as shown in Eq. (9). We have plotted $\ln(I_e/I_{ins})$ against $Q^{-1/2}$ for both suppressors in Fig. 16, where Q is the gas flow rate to the source which is proportional to the filling pressure and hence to the pressure in the suppressor region. The data from the permanent magnet suppressor clearly follow that of the variable field suppressor at zero applied magnetic field although there is still a residual field from the source and accelerator. The results show no really clear evidence for the linear form predicted by Eq. (9). Of course, one would not necessarily expect diffusion to dominate at all pressures and so perhaps at low pressures the diffusion may be through electron-ion collisions and as the pressure is increased, the diffusion mechanism will change until electron molecule collisions dominate and a dependence of the form of Eq. (9) would be observed. Perhaps it could be argued that there is some support for this in the permanent magnet suppressor data. Again we can estimate the intercept and gradient. As before, the intercept is calculated to be -0.4. The calculation of the gradient as given by the parameter c in Eq. (9) must be modified to account for the units used. This value of c must be multiplied by $(C/3.5 \times 10^{22})^{1/2}$ where C is the conductance in ℓ/s of the source and accelerator which is measured as being $\sim 80\,\ell$/s. Taking $L \sim 2 \times 10^{-2}$ m, $B = 50 \times 10^{-4}$ T, $kT/e \sim 0.5$ eV, $e^{-\eta} = 1$, $k' \sim 1.5 \times 10^{-2}$ m, and $\sigma = 10^{-19}\,\mathrm{m}^2$, we obtain a value of the gradient of $\sim 100\,(\mathrm{Torr}\,\ell/\mathrm{s}^{-1})^{1/2}$. Again these values are not borne out by the data. Green[3] observed some support for the diffusion model but his data were only in the high-pressure range, i.e., $Q^{1/2}$ values of 1.0 to 1.6 $(\mathrm{Torr}\,\ell/\mathrm{s}^{-1})^{-1/2}$ and the gradient was still much smaller than that predicted. The suppressor used then was of a slightly different design to that used at present. Instead of the collection electrode being flat it included a cylindrical upstand of height ~5 mm. This would have increased the collection area per unit length but since the gradient only depends on the inverse square root of this quantity, the predicted slope would not have fallen dramatically, whereas his data have a gradient of ~2.5 (Torr ℓ/s^{-1})$^{1/2}$.

V. DISCUSSION

We have tested two electron suppressors. Although different in design, they have the same basic operating principle: The electron flow is diverted by a magnetic field close to the extraction aperture and the electrons are collected on a biased electrode threaded by the magnetic field. In one design, the magnetic field strength is fixed by using permanent magnets whereas in the other design an attempt is made to optimize the field by using a flattened solenoid to produce a variable field.

In terms of the ability to suppress electrons, the data showed that in order to achieve the levels of extracted electron current obtained with the permanent magnet suppressor the variable field device needed currents in the coil of >150 A. These coil currents represented peak fields of >150 G with an integrated strength of ~150 G cm. The permanent magnet device had an integrated field strength of ~100 G cm although this had a range of 2–4 times that of the coil field. Thus, one can conclude that the permanent magnet device appears to be more efficient at the suppression of electrons, but there does exist the possibility that there may be some feature of the detailed mechanical design that brings this about.

For the case of the dipole filter in the source, if the variable field device is used, the magnetic field strength can always be increased (although what limits this is not known at present) to reduce the desired extracted electron current to a required load. However, the price that has to be paid for this (neglecting issues of thermal control) is a smaller extracted ion current compared to the permanent magnet device. The measurements showed a reduction of up to 50%. This was of the order of the transparency of the coil wires. The situation is more complicated in that the results of Lea *et al.*[1] showed that in the absence of a source filter, negative ions were still produced because the suppressor magnetic field acted as the filter field. Thus, negative ions are created between the suppressor and the extraction aperture and so the transparency is much higher. It could be that the structure itself has a greater loss area for plasma.

Our results, when using the tent filter, confirmed those of Lea *et al.*[1] and Bacal,[8] showing that the magnetic field strength at the extraction aperture will influence the production of negative ions. As the field strength is increased from zero, the negative-ion yield increases to a maximum value. However, it must be pointed out that in our experiments the efficiency of the tent filter was greatly reduced due to the penetration of the filaments. Thus the extracted negative ion current was lower and the extracted electron current higher than what could be achieved.

It could be that the negative ion yield will be greater for the tent configuration. However, if the variable field suppressor is used then the transparency problem may still have to be overcome if the enhancement effect is not sufficiently great for the negative ion current to exceed that obtained when using the permanent magnet suppressor.

The apparent enhancement that we observed of negative ion current as V_{ins} is increased was shown to be due to the reduction of the electron contribution to the space charge in the accelerator. It seems reasonable that part of the enhancement with increasing magnetic field of the suppressor is due to the same effect although this cannot be the full story, since in the case of the experiments of Lea *et al.*[1], this enhancement was observed even without a source filter.

In terms of a theoretical understanding of the suppressor action on the electrons, it must be concluded that the hydrodynamic model gives a better description of the data compared to the diffusion model. The former correctly gave the B-field dependence of the suppression. Although both models gave similar equations for the dependence of $\ln(I_e/I_{\text{ins}})$ on I_{ins}, the hydrodynamic model gave better quantitative agreement. Finally, there was no clear evidence from this design of permanent magnet suppressor to support the diffusion model pressure scaling although as pointed out this may depend on detailed design to some extent. This is not to say that the hydrodynamic model is ideal. Certainly its qualitative description appears to be good but quantitative agreement is not always good.

An understanding of the physics of the effect of the magnetic field is important not only to the understanding of the suppressor action but it could be applied to the source filter field itself thus leading to a quantitative optimization route for those aspects of the volume ion source.

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[1] L. M. Lea, A. J. T. Holmes, M. F. Thornton, and G. O. R. Naylor, Rev. Sci. Instrum. **61**, 409 (1990).

[2] R. McAdams, A. F. Newman, R. F. King, and A. J. T. Holmes, Rev. Sci. Instrum. **61**, 402 (1990).

[3] T. S. Green, SPIE Proc. **1061**, 628 (1989).

[4] A. J. T. Holmes and F. Haas (private communication).

[5] R. McAdams, A. J. T. Holmes, A. F. Newman, and R. F. King "Production and Application of Light Negative Ions," Proceedings of the 3rd European Workshop, Amersfoort (1988), p. 15.

[6] M. Bacal, J. Bruneteau, and P. Devynck, Rev. Sci. Instrum. **59**, 2152 (1988).

[7] K. N. Leung, K. W. Ehlers, and M. Bacal, Rev. Sci. Instrum. **54**, 56 (1983).

[8] M. Bacal (unpublished).