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A HIGH EFFICIENCY IONIZER USING A HOLLOW CATHODE DISCHARGE PLASMA*

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ABSTRACT

A proposal for an ionizer using a hollow cathode discharge plasma is described. Ionization is via the very high current density electron beam component in the plasma, as well as from charge exchange with plasma ions. Extraction of a He^+ current corresponding to approximately 50% of the incoming atomic beam flux should be possible.

INTRODUCTION

A hollow cathode discharge (HCD) is a simple, efficient device for producing a highly ionized, dc plasma.[1,2] It has often been used as a plasma source for laboratory experiments. At BNL, in recent years it has been used to generate a plasma for an intense, steady state H^- source (I_{H^-} = 250 mA),[3,4] and in a plasma neutralizer for negative ions.[5] In addition, the possible use of the HCD as a very efficient ionizer has been considered with regard to the polarized H^- source development at BNL.[6] In this case, one would not ionize the polarized beam within the hollow cathode, but rather uses the external plasma and high electron current density for ionization. The extension of this ionizer concept to polarized ^{3}He will be discussed here. The evaluation of its use for ionizing other gases is straightforward.

PROPERTIES OF A HOLLOW CATHODE DISCHARGE

The HCD operates by feeding gas through the hollow cathode, which is at 2000-3000°C. This gas is essentially 100% ionized by electron bombardment within the cathode, and flows into the main vacuum region, forming a high density, external plasma. One typically operates with an axial magnetic field to confine the external plasma, although the field is not essential for the cathode operation. The location of the anode for the system is not critical, and is either the chamber walls or magnet coils. Initial ion bombardment heating of the cathode can be via an rf discharge, or by electron ionization from an appropriately placed and biased filament.[7] After this initial heating (< 30 seconds), the cathode

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CONCLUSIONS

A plasma generated by a hollow cathode discharge can be a very high efficiency ionizer. While the exact parameters for an optimum design will depend on the properties of the polarized ^3He beam (flux and optics), in principle an ionization efficiency of up to 50% can be obtained. For comparison, electron bombardment ionizers for polarized hydrogen sources at ETH, Zurich,[13] and Bonn University[14] have efficiencies of 5% and 6.2%, respectively (although cross sections favor the ionization of hydrogen over helium). Loss of polarization in the HCD-based ionizer due to wall recycling of gas and ionization in fringing fields should not be too severe.

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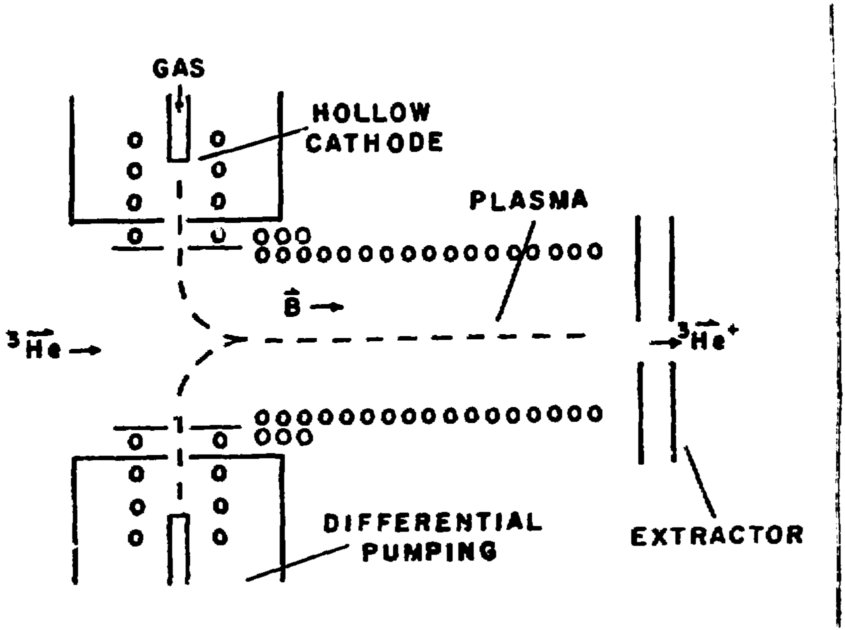

Figure 1. Schematic for an HCD plasma ionizer.

Let us first consider ionization by electron impact only. The cross section for ionization of He by electrons (σ_i) is approximately 2.5 x 10^{-17} cm^2 at 50 V. For an electron current density J_e, an ionizer length ℓ, and helium atomic beam velocity v, the fraction of the incoming flux which is ionized is $1-\exp(-J_e \sigma_i \ell/qv)$ (q is the charge of the electron). If one operates two cathodes, each at 50 A, and the plasma in the ionizing region has a cross sectional area of 2 cm^2, then one could get J_e = 25 A/cm^2. For a room temperature atomic beam (v = 1.45 x 10^5 cm/s), and a length of 30 cm, 54% of the incoming flux is ionized. With a lower temperature atomic beam, the ionization increases accordingly (essentially full ionization in less than 10 cm for a 4°K beam).

If the HCD is operated in ^{4}He, one gets additional ionization from the charge transfer reaction $^3\vec{He}^\circ + {}^4He^+ \rightarrow {}^3\vec{He}^+ + {}^4He^\circ$. The fraction of the incoming flux which is ionized from both charge transfer and electron impact is then

$$\eta = 1 - \exp\left[- \frac{J_e \sigma_i \ell}{qv} - \frac{n_{He} \langle \sigma_{CE} v_{rel} \rangle \ell}{v}\right] \qquad (1)$$

"ignites", and heating from plasma ion bombardment is enough to maintain the discharge (the filament is turned off). The HCD will then operate with a wide range of parameters. While the lifetime of a cathode depends on the cathode material, operating gas, gas flow, arc voltage and current, dc operation for more than a week is possible. The cathode is often Ta, although other materials also work. It can have a diameter from a few millimeters to tens of mm. It can run with many gases (noble gases, hydrogen, nitrogen). One can get a high plasma density with magnetic fields from a few hundred Gauss to a few kilogauss. The shape of this external magnetic field is not critical. Depending on the gas being used, the geometry of the cathode, the magnetic field, and the gas flow, the cathode voltage will be 30-100 V. The arc current can be varied over a wide range for a given cathode. As an example, a 3 mm diameter cathode was operated in Ar from a few amperes to several hundred amps.[1] Plasma densities in the 10^{13} to 10^{14} cm^{-3} range can be obtained, and the background pressure is typically in the 10^{-4} Torr range, or 10^{-5} Torr with sufficient differential pumping. The length of the plasma can be anywhere from a few centimeters to a few meters with almost no change in the discharge current and voltage.[8] The gas flow from a 3 mm diameter cathode would be < 0.1 T-ℓ/s when operating in Ar,[8] and 0.7 T-ℓ/s in helium.[1] There is an electron current which follows the magnetic field lines external to the cathode having an energy equal to almost the full cathode voltage. Approximately half of the total arc current is carried by these fast electrons, resulting in electron current densities of > 10 A/cm^2 (n_e> 10^{11} cm^{-3}). From this very general description, one sees the attractive features of the HCD.

IONIZER CONFIGURATION

This paper will consider the use of the HCD plasma as an ionizer in one of two ways. One possibility is to run the cathode with a gas such as Ar, and rely on the high electron current to ionize the ^{3}He. The second is to run the cathode in ^{4}He, where one gets an additional contribution to the ionization from charge exchange between ^{3}He and $^4He^+$. In both cases, mass separation would be required after extraction. Figure 1 shows the ionizer schematically. The cathodes are in individual solenoids at one end. Differential pumping would be incorporated near the cathodes to keep the pressure in the main solenoid as low as necessary. The plasma from the cathodes follows the magnetic field lines into the central field region. Polarized ^{3}He is injected axially into this central field and ionized by the fast electrons (and by charge exchange if the cathodes are operating with helium). At the opposite end one has an extraction system similar to electron beam ionizers. The electric field at the extraction end will enhance the oscillating electron current (reflex mode).

With the above ^4He plasma density, one can now evaluate the ionization efficiency including charge exchange, from Equation 1. Taking, again, $J_e = 25A/cm^2$, $v = 1.45 \times 10^5$ cm/s, $\ell = 30$ cm, and taking $v_{rel} = 7.8 \times 10^5$ cm/s ($T_i = 1$ eV), $\sigma_{CE} \cong 2.7 \times 10^{-15}$ cm^2, one calculates an efficiency of 64% (compared to 54% from electron ionization alone). If one were to run with a higher extraction voltage, the plasma density (and, therefore, the ionization efficiency) could be increased, at the cost of an even larger extracted $^4He^+$ current. It appears more practical, however, to concentrate on designing for ionization by the fast electrons, with the plasma ions primarily serving to preserve neutrality, thereby allowing the high electron current density. If one chooses to operate the cathode with argon, the extracted Ar^+ current will be lower than the $^4He^+$ current for the same plasma density (reducing power supply loading), and mass separation after extraction would be easier.

In order to maintain the fast electron component while keeping the plasma density in the ionizing region relatively low, a biased plasma collimator could be used near the cathode. In addition, increasing the strength of the axial magnetic field at the entrance to the ionizer will reduce the entrance of cathode plasma into the ionizing region, while at the same time acting as a mirror for plasma inside the ionizer, causing most of the $^3\vec{He}$ ions which are formed there to leave at the extraction end. In the same way, this field shape minimizes the extraction of ^3He ions formed in the fringing magnetic fields at the entrance (which could reduce the beam polarization).

The normalized emittance for a beam produced by extraction from a plasma can be calculated from[11]

$$\epsilon_N = 2r\ (kT_i/2)^{1/2}\ \pi\ \text{mm-mrad}\ (\text{MeV})^{1/2} \qquad (6)$$

where r is the aperture radius, in mm, and kT_i is the ion temperature, in eV. For r = 5 mm and kT_i = 1eV, one gets $\epsilon = 7\pi$ mm-mrad (MeV)$^{1/2}$. The growth in the effective emittance due to the extraction of the beam from the axial magnetic field is given by[12]

$$\Delta\epsilon_N = 0.345\ Br^2/\sqrt{M}\ \ \pi\ \text{mm-mrad}\ (\text{MeV})^{1/2} \qquad (7)$$

where B is the magnetic field, in kG, r is the aperture radius, in mm, and M is the mass, in amu. For B = 1 kG, r = 5 mm, and M = 3, $\Delta\epsilon = 5\pi$ mm-mrad (MeV)$^{1/2}$. The expected emittance, neglecting any emittance growth from the extraction optics, is then 12 π mm-mrad (MeV)$^{1/2}$. The energy spread of the extracted beam will be only a few eV.

The approximately 50% ionization efficiency has been calculated for $^3\vec{He}$ in its ground state. If the $^3\vec{He}$ is in the metastable state, this efficiency will be much better due to the larger electron ionization cross section. The fracton of $^3\vec{He}^{++}$ with this ionizer will be very low, since the electron energy is low.

where v_{rel} is the plasma ion velocity, n_{He} is the plasma density, and σ_{CE} is the charge exchange cross section. Before calculating this efficiency, there is another aspect of the ionizer operation which must be considered. The plasma in the ionizer region has four components, with $n_f^- + n_{th}^- = n^+_{3He} + n^+_{cg}$, whre the densities are for fast electrons, thermal electrons, ^3He ions, and ions from the cathode operating gas, respectively. When n^+_{cg} is large, a large $^4He^+$ or Ar^+ current is extracted, which, due to space charge forces, may spoil the extracted beam optics. One can estimate an upper limit this places on the background plasma density by neglecting n_f^- and n^+_{3He}. In this case, the extracted current density can be given by[9]

$$J_{ext} = 0.4\ ne \sqrt{\frac{2kTe}{M}} \qquad (2)$$

where n is the plasma density, M is the ion mass, and T_e is the electron temperature. To estimate the maximum current density that one can focus properly in an extraction system, we use the Child-Langmuir expression for space charge limited current[10]

$$J_{CL} = \frac{4\epsilon_o}{9} \sqrt{\frac{2e}{M}} \frac{V^{3/2}}{d^2} \qquad (3)$$

where V is the extraction voltage, d is the extraction gap, and ϵ_o is the permittivity of free space. For the extracted beam to be properly focused, one should have $J_{ext} = J_{CL}$. Then, from Equations 2 and 3, and solving for n, one gets

$$n = \frac{10}{9} \frac{\epsilon_o}{\sqrt{e}} \frac{1}{\sqrt{kT_e}} \frac{V^{3/2}}{d^2}. \qquad (4)$$

Transforming to more convenient units, one has

$$n = 6.15 \times 10^5 \frac{1}{\sqrt{kT_e}} \frac{V^{3/2}}{d^2}, \qquad (5)$$

where kT_e is in eV, V in volts, d in cm, and n in cm^{-3}. Note that this density is independent of the mass of the plasma ions. For satisfactory beam optics, $d \geq 2r$, where r is the radius of the extraction aperture. From this, one sees that if d = 1 cm, V = 20 kV and kT_e = 10 eV, then $n = 5.5 \times 10^{11}\ cm^{-3}$. If one were operating with ^4He, the extracted $^4He^+$ current in this case would be 60 mA.

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