Production of Negative Hydrogen Ions

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ABSTRACT

The focus of this paper is to explain the effects on the magnetron ion source when the leakage of hydrogen gas is abated. Several experiments were performed to measure the amount of background gas, hydrogen, released through leaks when the source is operating. By comparing data acquired when the source was sealed with Silver Seal II versus being unsealed, results suggest that the leakage is small and plays no major part in the production of negative hydrogen ions.

I. INTRODUCTION

Fermi National Accelerator Laboratory advances the understanding of the fundamental nature of matter and energy by conducting basic high-energy physics research. A significant amount of research engaged at Fermi involves analyzing the effects of colliding proton/anti-proton beams.

A magnetron ion source is indirectly responsible for the creation of the proton beam. The source generates a beam of negative hydrogen ions from hydrogen gas, which are later stripped of their electrons to form the proton beam. Due to the design of the magnetron, hydrogen gas leaks from the source. If the leakage is excessive and can be reduced, the gas efficiency and vacuum pressure may be improved and the production efficiency of negative hydrogen ions should increase.

The main objective of this experiment is to investigate the effects of reducing the leakage amount and determine how negative hydrogen ion production will change when the source is sealed with Silver Seal II.

II. BASIC PRINCILPES

A. H ion source

The magnetron source is a surface-plasma source that produces H^- ions by surface interaction with energetic plasma particles.[4] A molybdenum cathode exists in the center of the source and is thermally and electrically shielded by ceramics (Fig. 1). The outer shell that encloses the cathode is the anode. The separation distance between the cathode and anode is approximately 1 mm.[1]

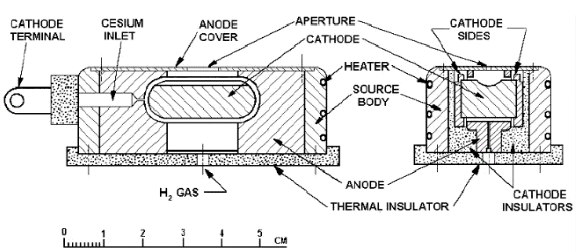

Fig. 1. Magnetron H^- ion source.

During operation, hydrogen gas enters through a pulsed gas valve. Once the hydrogen enters the system, a pulse voltage or Arc Voltage of ~150 V is applied between the anode and cathode to ionize the gas into a plasma.[1]

The plasma interacts with the cathode surface that has a cesium coating. Applying 0.6 monolayer of cesium to the surface lowers the work-function of the molybdenum from above 4.5 eV to approximately 1.8 eV.[3] The electrons liberated from the molybdenum due to the presence of cesium are captured in a magnetic field that is perpendicular to the electric field and parallel to the cathode axis (Fig. 2).

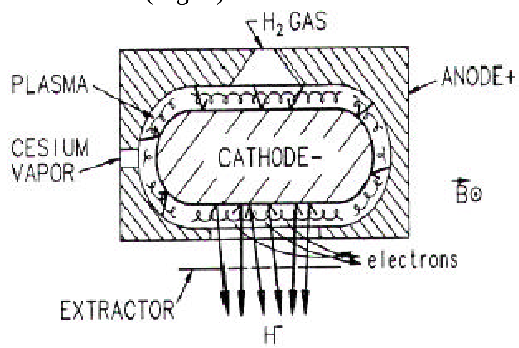

Fig. 2. Magnetron source displaying the extraction of H^- ions.

Since the Larmour Radius of the electron is much less than 1 mm, the applied magnetic field confines the electrons to create a dense plasma.

H^- ions are created by the absorption and reflection of hydrogen upon the cathode surface.[3] After the hydrogen is captured in the molybdenum lattice structure, free electrons interact with the hydrogen to form H^- ions. Incident particles and molecules strike the surface and cause the H^- ions to be liberated (Fig. 3).[3] H^- ions are also created by H_2 molecules striking the surface and reflecting back as H^- ions.

After the H^- ions are formed, an electric field accelerates negatively charge ions through the plasma towards the exhaust slit aperture. These negatively charge ions exit the source and H^- ions are further accelerated by the extractor while the free electrons are bent due to the magnetic field.

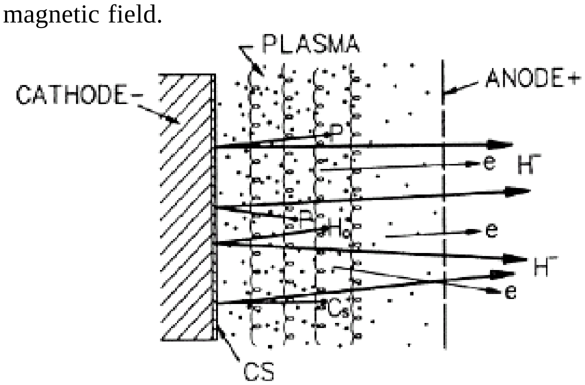

Fig. 3. H^- ions created by surface interactions with energetic plasma.

B. Analogous Relationship between Flow System and Electrical Circuit

When dealing with flow systems, there are many properties to consider. One important property is called conductance. Conductance is defined as the amount of flow at a specific pressure that crosses a given area of pressure change, and is geometrically determine by the flow channel. In a mathematical sense, conductance is modeled by the equation C = Q / ?P, where the conductance C equals the ratio of the throughput Q and pressure gradient ?P. The SI units for conductance are m^3/s.

Throughput is proportionally related to the volume metric flow rate by the equation Q = PF, where the pressure P is multiplied by the volume metric flow rate F. Substituting the product PF for Q, the equation for conductance becomes C = PF/ ?P. Assuming that P is one atmosphere, Q approximates to F and C ≈ F / ?P.

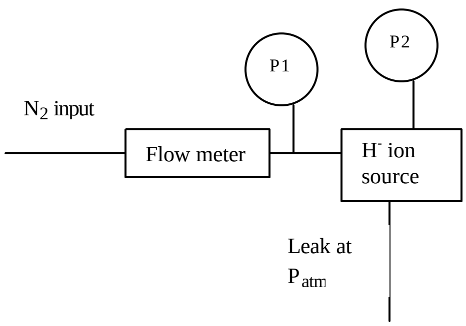

Fig. 4. Flow chart of the first preliminary experiment.

In Fig. 4 above, P1 is the pressure of the gas after leaving the flow meter and P2 is the pressure of the gas in the H^- source. These pressures are referenced to one atmosphere.

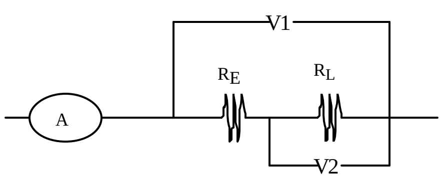

Fig. 5. An electrical analog representation of Fig. 4.

Analogous to a flow system is a simple electrical circuit.* The potential difference V is equivalent to the pressure gradient ?P, current I is similar to the flow rate Q, and the resistance of a electrical circuit R is the inverted conductance 1/C. If the mathematical definition of conductance is replaced with its electric circuit counterpart, the following relationship is obtained 1/R = I/V. By rearranging terms, the famous Ohm's Law, V=IR, is obtain.

Since there is an analogous relationship between a flow system and a simple electrical circuit, Fig. 4 is transformed to its counterpart in Fig. 5. The exhaust resistance R_E and leak resistance R_L in Fig. 5 are the inverse of exhaust conductance C_E and the inverse of leak conductance C_L, respectfully. Although the leak and exhaust conductance are not labeled in figure 4, the exhaust conductance is the pressure gradient between P2 and P1. The leak conductance is the pressure gradient between P_{atm} and P2.

III. EXPERIMENTS

A. Preliminary Experiments

The purpose of these experiments is to determine the ratio C_L/C_E. From this ratio, the amount of hydrogen that leaks from the source can be compared to the amount of hydrogen emitted through the exhaust slit. The information supplied by the ratio is a crude approximation but should be sufficient for determining if sealing the source is valuable.

Before explaining the experiments, the following assumptions must be stated. Although not at normal vacuum operating conditions, it was assumed that the system's behavior did not change. It also was assumed that nitrogen's behavior is similar to that of hydrogen. Hydrogen has less mass and a higher average velocity than nitrogen under same conditions. The higher average velocity would cause hydrogen to leave the source at a faster rate than nitrogen. The final assumption was that gas flow is path independent. This is approximately true since conductance is geometrically determined.

The purpose of the first experiment was to determine C_L and C_E by forcing all the nitrogen gas to flow into the extraction slit and out through the leaks of the source. The set-up for this experiment was unusual because the direction of flow was reversed relative to operating conditions. Fig. 4 gives the basic schematic of the experiment. Nitrogen gas was injected into the source through a flow meter and the flow rate was measured. While the gas flow was stable, the pressure P1, between the flow meter and source, and the pressure P2 at the normal gas valve location of the source were measured.

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* The analogous relationship V=IR is applicable in specific flow regimes. In different flow regimes (viscous flow), the conductance becomes nonlinear due to its dependence on the object's geometric shape; therefore, the flow system analogy to simple electrical circuit is not accurate to describe the behavior of a flow system.

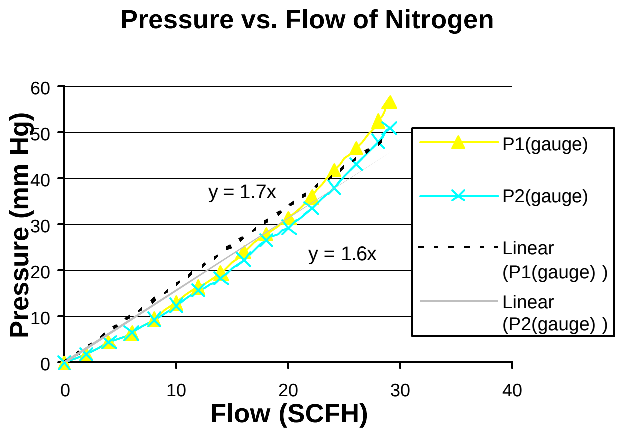

Fig. 6. Graph of pressure versus nitrogen flow from the first experiment.

From the data collected, the gauge pressures verses flow was plotted. The graph in Fig. 6 shows the pressure increasing as a function of flow. Although the curves appear nonlinear, a linear fit was used to reduce the complications of determining the curve's slope to a polynomial degree higher than one. From the linear fits, the slopes for P1 and P2 were calculated as 1.7 and 1.6, respectfully.

Using the analogous relationship V=IR, these equations are obtain $V1=I(R_L+R_E)$ and $V2=IR_L$. Recall that R is equivalent to C^{-1} and $C^{-1} \approx$?P/F, which gives the slopes in Fig. 6. Thus, the sum $(R_L + R_E) = 1.7$ and $R_L=1.6$. After algebraic manipulation, $R_E = 0.1$ and $R_L=1.6$. Using the analogous ratio R_E/R_L and converting back to conductance, it is evident that the ratio $C_L/C_E = (0.1/1.6) < 1$.

Under operating conditions, the physical meaning of the ratio C_L/C_E is that the amount of gas flowing through the leak is approximately 6% of the amount emitted through the exhaust slit. Thus, sealing the source should have little affect on the H^- ion source operation.

The same experiment was preformed with helium since it is closer in mass than nitrogen. The results from the experiment with helium mimicked the results obtained from using nitrogen. Hydrogen was not used during the preliminary experiments due to hydrogen's flammable nature.

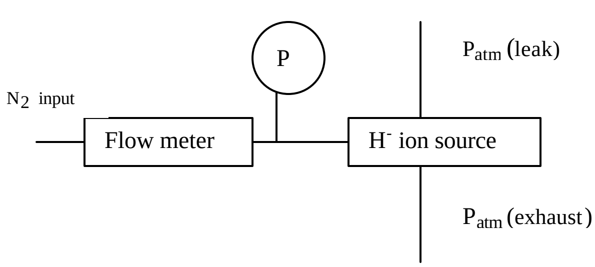

Fig. 7. Flow chart of the second preliminary experiment.

To verify this result, a second experiment was preformed. The set-up for the experiment is shown in Fig. 7. The nitrogen gas entered the flow meter and the flow rate was recorded. Under steady flows, the pressure between the flow meter and source was recorded. The nitrogen gas exited at atmospheric pressure P_{atm}.

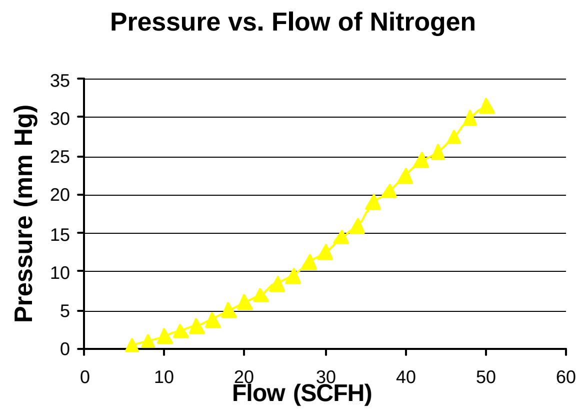

Fig. 8. Graph of pressure versus nitrogen flow from the second experiment.

The graph in Fig. 8 shows the pressure increasing as a function of flow. The difference between Fig. 6 and Fig. 8 in the pressure at the same flow rate is due to the extra conductance cause by the aperture where the gas pulse valve is normally located. Using the analogous relationship, the equation to describe the system is $V=I(R_A+R_LR_E/(R_L+R_E))$. Since there are three unknowns and one equation, there is not enough information to calculate R_L and R_E. Therefore, the ratio C_L/C_E cannot be determined. Unfortunately, this experiment gave no additional information and was not used.

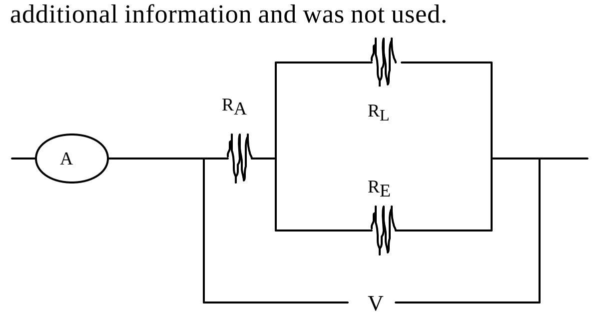

Fig. 9 An electrical analog representation of Fig. 7.

B. Sealed Source Experiment

The final experiment was to test the operation of a normal source operating in its usual manner with the leaks in question sealed.

After sealing the source with Silver Seal II, it was installed to test the predication of the preliminary experiments. Normally, an unsealed source running at a source pressure of 40 mTorr had a current output of 60mA.

Introducing a sealed source should increase the current output since the majority of the gas would exit the exhaust slit. Or, the sealed source should produce 60mA at a lower operating pressure than the unsealed source.

As predicted by the preliminary experiments, decreasing the source pressure showed little change in the output current of an operating source. An exception was a decrease in time between when the gas was injected into the source and when the arc was turned on, which was ~300µs. Further testing is needed to verify this effect.

CONCLUSION

Using the gas flow measurements and algebraic manipulations, the amount of gas flowing through the leak is approximately 6% or less of the amount emitted through the exhaust slit. This appears to be small; however, it is difficult to obtain a clean measurement to confirm the results from the preliminary gas flow experiment since the source is a multi-parameter system.

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