THE EFFECTS OF NITROGEN GAS ON THE PRODUCTION OF NEGATIVE HYDROGEN IONS

Ernestine Chaco, Douglas Moehs, and C.W. Schmidt
Fermilab National Accelerator Laboratory
Batavia, IL 60510

Abstract

Modulation affects the quality of the ion beam extracted from an ion source. A decrease in modulation has been found in a Penning source by adding small amounts of nitrogen gas. The focus of this project is to improve the stability of the magnetron ion source through the use of a hydrogen-nitrogen gas mixture. Adding 1% nitrogen gas decreased the modulation by 30% at 36 mA compared to pure hydrogen gas. The 1% nitrogen gas mixture produced the best improvement in modulation. This data looks promising for improving the production of H^- ions.

I. INTRODUCTION

Fermilab's main mission is to understand the fundamental workings of our universe through studies of high-energy physics. Fermilab operates the highest-energy particle accelerator and collider. Beams of protons and antiprotons are guided and accelerated within the Tevatron (main accelerator at Fermilab).

The production of these proton/anti-proton beams begins with a magnetron ion source. The magnetron (Figure 1) produces negative hydrogen ions in a low-pressure hydrogen-plasma system. These negative hydrogen ions are then accelerated and stripped to protons. They are then further accelerated and directed through magnets to various locations throughout Fermilab.

Improving the production of negative hydrogen ions is beneficial for Fermilab. The focus of this project is to improve the stability of the magnetron ion source through the use of a hydrogen-nitrogen gas mixture.

II. MAGNETRON ION SOURCE

A surface-plasma process generates the negative hydrogen ions. This dense plasma occurs between the molybdenum cathode and anode, which are 1.0 mm apart. During operation a pulsed voltage (arc voltage) is applied to the cathode to create an electric discharge between the cathode and anode. Hydrogen gas is pulsed into the same region by a voltage-controlled crystal valve. When gas enters the system it ionizes, and the electrons are stripped from the hydrogen gas molecules by the applied arc voltage of 150 volts.

A detailed description of the production of negative hydrogen ions can be found in Reference [1]. Briefly, electrons in the plasma move in a spiral orbit around the cathode because the magnetic field is perpendicular to the electrical field, and the Lamour radius of the electron is smaller than 1.0 mm (Figure 2).

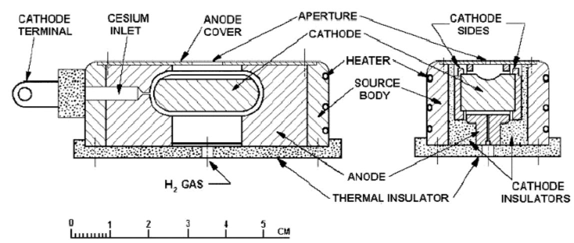


Figure 1. A schematic of the magnetron negative hydrogen ion source

The spiral movement of the electrons allows for more collisions with the hydrogen gas to occur. A plasma of H^+, H_2^+, Cs^+, H^0 and H_2, interacts with the cesium-covered cathode.

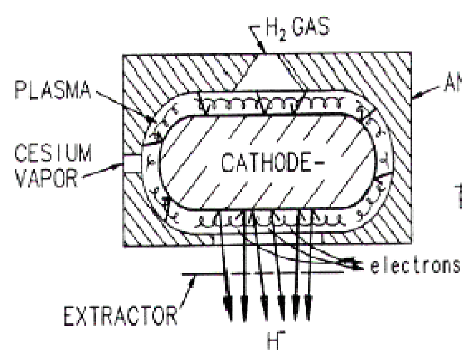


Figure 2. The extraction of the H- ions from the magnetron source.

Cesium is used to lower the work function of the cathode from 4.5 eV to about 1.6 eV. This decrease in work function lowers the amount of energy needed to free electrons embedded in the lattice of the metal. As a result, this increases the availability of the free electrons that are needed to sustain the plasma. Collisions on the cathode surface can release H^- ions through various reactions [1].

A pulsed voltage applied to the extractor produces an electrical field which pulls out electrons and the negative hydrogen ions toward a magnet, which bends the H^- ions through a 90-degree angle toward the accelerator. Since the mass of the electron is approximately 1860 times less than that of a proton the Lamour radius of an electron is drastically smaller compared to a negative hydrogen ion [2]. As a result, the electrons are deflected away from the path of the H- ion beam when it is bent by the magnet. This pulsed beam current is then measured by a current toroid, which sits at the end of the accelerator column.

III. BEAM CURRENT MODULATION

High pulse beam current and low beam fluctuations are two conditions that are needed to optimize the output of the H^- ion source. The pulse beam current is the number of H^- ions extracted from the source during the extraction pulse. In a "perfect" source the pulsed beam current has no fluctuations when it is extracted. This has been observed in Penning sources under optimal conditions [3]. However, fluctuations usually occur and are quantified by measuring the beam current modulation.

Modulation can be calculated with the following equation:

$$\mathrm{M} = \frac{1}{2}\left(\frac{I_{\max} - I_{\min}}{\bar{I}}\right) * 100\% \qquad (1)$$

Where I_{max} is the maximum current, I_{min} is the minimum current and $\bar{I}$ is the average pulsed beam current.

Modulation may be caused by plasma oscillations or other problems, which affect the pulsed beam current. Another factor that contributes to increased modulation is fluctuations in gas flow from the source. This causes the beam current to fluctuate and background gas atoms may collide with the H^- beam, freeing the weakly bonded electrons. This destruction process is called stripping, which decreases the beam current.

IV. EXPERIMENTAL PROCEDURE

Using a small amount of nitrogen gas with hydrogen has been seen as a way of stabilizing the plasma. Three different gas mixtures were compared with pure hydrogen operation: hydrogen gas mixed with 0.1% nitrogen, 1.0% nitrogen, and 10% nitrogen. Each test was implemented using the following technique.

Nitrogen Gas Mixture Preparations

Before the gas mixture was inserted into the source, the gas and air inside the connecting lines and tubes need to be pumped out by a roughing pump. After the connections are made between the nitrogen gas mixture and the line that goes to the source, all the connections and valves are checked for air leaks. The snooping method was used, which causes bubbles to form if an air leak exists. The final gas pressure in the evacuated line was 8 mtorr. A convection gauge was used to make this measurement before the nitrogen gas mixture valve was opened. The applied pressure supplied by a regulated gas bottle was 4 lbs./in^2 for all hydrogen and nitrogen gas mixtures during operation. This gave the proper amount of gas to the source through a pulsed valve system. This process was repeated for the different nitrogen gas mixtures.

Vacuum

The test bench vacuum system's minimum pressure is approximately 1.0x10^{-7} torr. The magnetron operates at a chamber pressure of 3.0x10^{-5} torr. This pressure is obtained by using two turbo pumps backed by one roughing pump, see figure 3. The effective pumping speed of this system was numerically compared to other arrangements using the standard parallel and series conductance equations [4].

$$C_{eff} = C_1 + C_2 \qquad (2)$$

$$\frac{1}{C_{eff}} = \frac{1}{C_1} + \frac{1}{C_2} \qquad (3)$$

The following was found: A single turbo pump system provides 120 l/s (liters/second). Adding a second turbo pump increases the effective pumping speed to 155 l/s. Placing a pump at location D in Figure 3 would produce an effective pumping speed of 149 l/s. Based on this comparison a two pump system was used to maintain the chamber pressure.

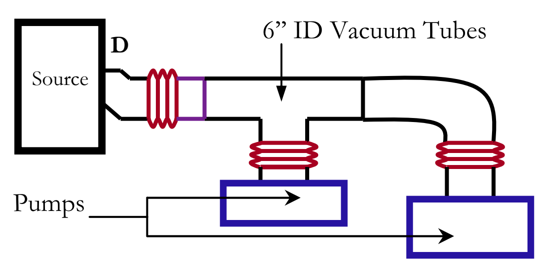
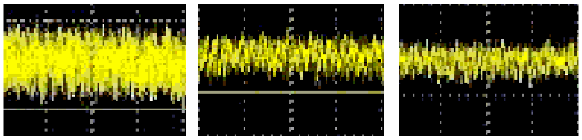


Figure 3. Schematic drawing of the vacuum pump system.

V. RESULTS AND ANAYLSIS

Raw Data



(a) (b) (c)

Figure 4. (a) An image of the modulation of pure hydrogen gas. The modulation is approximately 24.5%. (b) Image taken after 0.1% nitrogen gas mixture is added to the source. The modulation is approximately 18.35%. (c) Image of 1.0% nitrogen gas mixture. The modulation is approximately 15.4%. The time scale is 4.0 us per unit in all images.

In Figure 4, a decrease in modulation is seen. The modulation approximations given in the caption are based on estimates of the values of the minimum current, maximum current, and pulse beam current. When the nitrogen gas reached 10% the system begins to "die". The performance of the system decreased rapidly and it did not improve for a one-day period. This may be due to stripping of the negative ions. Nitrogen is a heavier and slower gas than hydrogen. This slowness increases the cross-section of the negative hydrogen ion with the nitrogen gas and causes more stripping of the H^- ion decreasing the H^- beam current. The pulse beam current of the 10% nitrogen gas mixture was approximately 12 mA, but this only lasted for a few hours.

Analyzed Data:

Images similar to those in Figure 4 were taken from a Tektronix oscilloscope and analyzed with ImageJ 1.32j, which is an image-processing program that can calculate pixel value statistics with user-defined scalings and selections. Peaks were analyzed in a 10 us square. The highest peak positions were recorded and then analyzed using Excel and Origin 6.1. The pulse beam current was found by averaging all the peak data samples from one image.

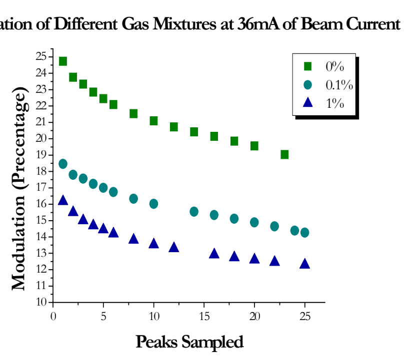


Figure 5. Represents data at about 36 mA of beam current. The calculated modulations as a function of the number of peak samples

The amount of nitrogen added to the hydrogen affects the modulation. The 1% nitrogen gas mixture decreased the modulation by 30% at 36 mA, independent of the number of peaks sampled (Figure 5). Modulation is inversely proportional to beam current, see equation 1. As can be seen in Figure 6, as the beam current increases the modulation decreases. The line depicts the downward slope of the trend.

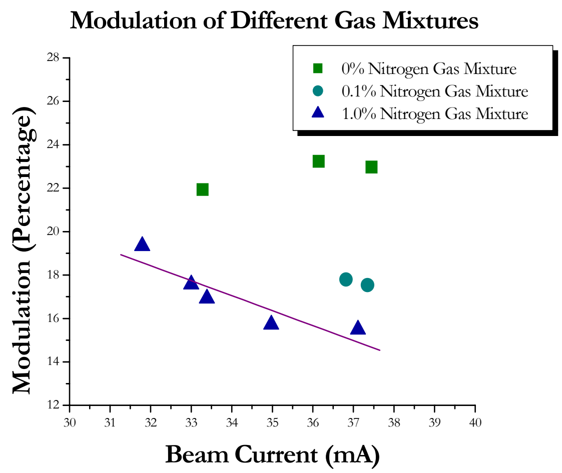


Figure 6. Modulation as a function of beam current. The analytical error of each data point is estimated to be about 5%.

VI. GAS ANALYZER

After, the measurements were completed the background gas inside the vacuum was tested by an AGA-100 Mux Gas Analyzer. The Gas Analyzer identifies gas components in a vacuum system by their atomic mass numbers, which are represented by peaks on a plot [5]. Peak numbers that range from 55 and higher are the atomic masses of hydrocarbons. The hydrocarbon concentrations measured in the test bench vacuum chamber are significantly greater than the concentrations in a clean system. The high concentration in hydrocarbons probably indicates oil contamination of the entire vacuum system. Hydrocarbons in the vacuum can decrease the performance of the magnetron by coating the internal surfaces decreasing the effects of the cesium.

The grooved cathode that was used in the test bench magnetron generally provides beam currents of about 70 mA. The average beam current that was measured using a grooved cathode in this test was less than 40 mA. This decrease in beam current is a further indication that the system was affected by the high concentrations of hydrocarbons.

VII. CONCLUSION

The goal of the project was to investigate the effects of hydrogen-nitrogen mixtures on H^- beam modulation from a magnetron. The data collected shows as expected that the modulation decreased as the beam current increased. At 36 mA the modulation decreased by 30% when a mixture of 1% nitrogen is used with the hydrogen as compared to pure hydrogen operation. This implies that a 1.0% nitrogen mix could lower the modulation of a 60mA beam current. However, this could not be verified due to the contamination of hydrocarbons in the test bench vacuum system.

Further studies of 0.5%, 2% and 3% nitrogen gas mixtures should be made to observe whether these gas mixtures perform better than the 1%. The data acquisition can be improved by using the envelope and average function on the Tektronix Oscilloscope. Moreover, increasing the number of data points as a function of current per mixture would improve the data analysis.

VIII. ACKNOWLEDGEMENTS

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