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D. Allspach et al.

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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REFRIGERATED HYDROGEN GAS JET FOR THE FERMILAB ANTIPROTON ACCUMULATOR

D. H. Allspach,[1] C. L. Kendziora,[1] M. Marinelli,[2]
M. Macri,[2] E. Robutti[2] and G. Boero[3]

[1]Fermi National Accelerator Laboratory
Batavia, Illinois, 60510, USA
[2]University of Genoa
Department of Physics
16146 Genoa, Italy
[3]CERN
Geneva 23, Switzerland

ABSTRACT

A hydrogen gas jet has been built for use at Fermilab for the study of charmonium spectroscopy in proton-antiproton annihilations (Experiment 835). The hydrogen gas jet is part of an upgrade to a previous experiment (Experiment 760) which ran in the Fermilab 1990-1991 fixed target program utilizing a jet cooled to 80 K with liquid nitrogen. The jet delivers a defined stream of hydrogen gas which travels through a series of vacuum chambers and then intersects the circulating antiproton beam. The goal of the upgrade is to provide a hydrogen gas stream at least twice as dense as used for the earlier experiment to increase the interaction rate and allow an improved study of rare processes. This is achieved by cooling the stream to below 30 K using a Gifford-McMahon refrigerator. The jet apparatus is designed to allow motion in the plane perpendicular to the gas stream as well as angular positioning at the jet nozzle to provide a means of optimizing the interaction rate. Two skimmers located in the vacuum chambers are used to define the gas stream dimensions. The jet target vacuum chambers require constant pumping with turbomolecular pumps. The vacuum space around the jet is designed to have a large system pumping speed so that the chamber pressure can be maintained below an absolute pressure of 1 Pa. The jet will operate in the next fixed target run at Fermilab. Details of the design and test results are discussed.

INTRODUCTION

The hydrogen jet target, located on the Fermilab Antiproton Accumulator, will provide Experiment 835 with a jet stream of hydrogen to be utilized as the target for the antiproton beam. The jet stream is produced by flowing hydrogen gas through a converging-diverging nozzle with a small throat diameter (37 μm). During the expansion through the nozzle the hydrogen molecules undergo a process of condensation causing them to collect as clusters. Each cluster contains about 10^4 to 10^5 atoms.[1] A jet of clusters is thus formed which constitutes the core of the hydrogen jet stream.

The antiproton beam is produced in the Fermilab Antiproton Source. A 120 GeV proton beam focused on a fixed target yields approximately one antiproton for every 10^6 protons.

The initial energies of the antiprotons cover a wide range but they are "cooled" such that they are made equal. Roughly 10^{12} antiprotons can be collected over a period of 20 hours. With this quantity of antiprotons circulating in the Antiproton Accumulator, the beam has a current of 100 mA. In the absence of the hydrogen gas jet stream, the antiproton beam lifetime is around 400 hours.

Hydrogen is chosen as the target material rather than a heavier gas because the experiment depends on achieving a very well defined collision energy between target and beam. Even the spread in energies due to nucleon motion in a helium atom nucleus would be too large for the experiment to work. During experimentation an interaction rate of 5 MHz between the jet stream and the antiproton beam is chosen resulting in a beam lifetime of about 30 hours. Experiment 835 is designed to have an interaction rate at least five times greater than Experiment 760 in order that the study of the charmonium spectrum may be completed during the upcoming Fermilab Fixed Target Program. The upgraded hydrogen gas jet, producing a denser jet stream of hydrogen atoms, will help in meeting this goal.

OVERALL JET TARGET SYSTEM DESCRIPTION

The jet target (see Fig. 1) consists of several vacuum chambers which surround the Antiproton Accumulator beam-pipe (AA). The jet stream, originating in chamber J1, passes through each chamber and across the beam-pipe which are connected by small holes or "skimmers". The communication between chambers is limited to prevent uncondensed hydrogen gas from diffusing into the beam-pipe. This gas would act to reduce the beam lifetime without contributing to the experiment. Several vacuum pumps are utilized to maintain a very high vacuum in the beam-pipe. Ten turbomolecular pumps (TMP's) are installed directly onto the chambers. Eight of these have a capacity of 1000 L/s and two are rated for 3500 L/s. The pump names indicate their capacity, i.e., TMPAA1 1000 has a capacity of 1000 L/s. Two additional turbomolecular pumps are used as booster pumps downstream of the pumps on the J2, J3, AA1, AA2, R1, R2 and R3 chambers. Also included are two positive displacement blowers and two roughing pumps.

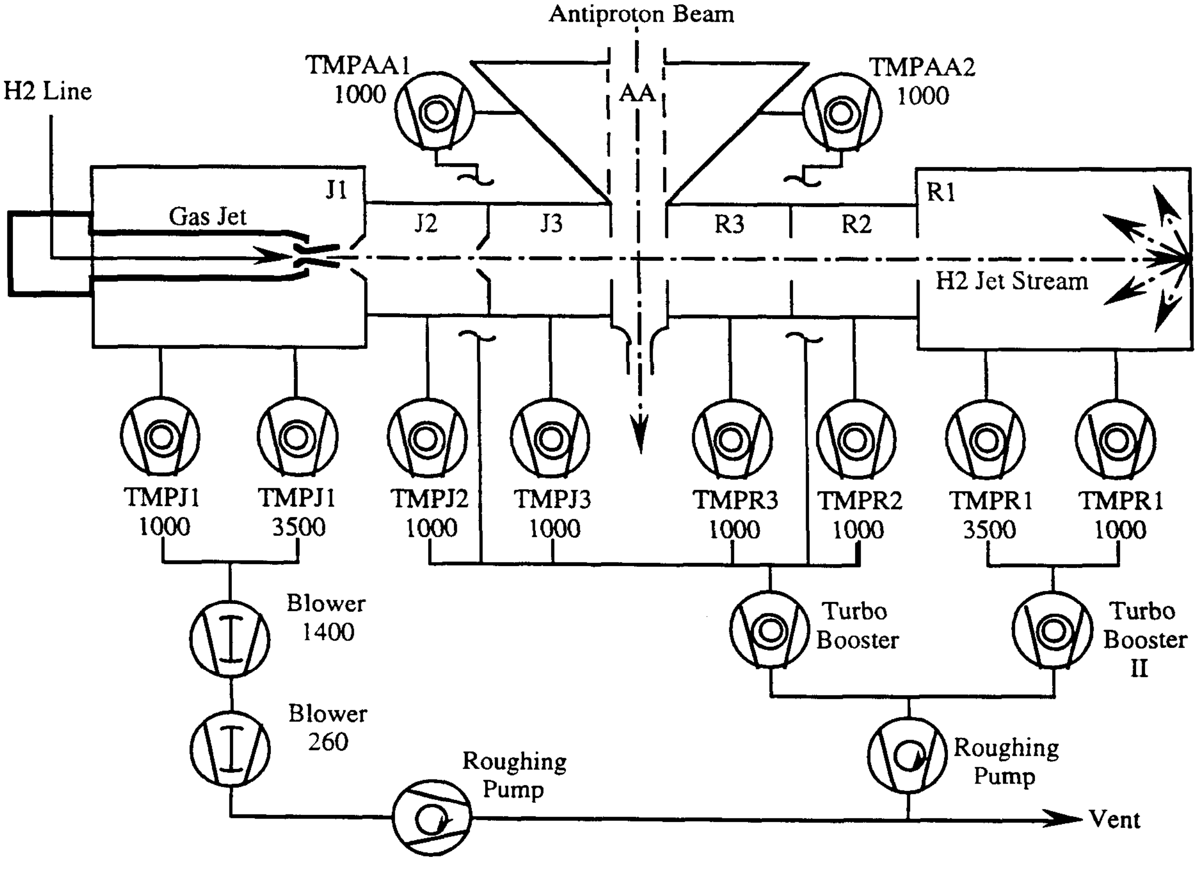

Figure 1. General Jet Target system components

The nozzle, located in chamber J1, has a hydrogen gas flow which can reach a maximum rate of 13 cm^3/s STP. The refrigeration system used to cool the hydrogen gas and the nozzle is located in chamber J1 as well. Roughly 10% of the hydrogen flow make up the jet stream of clusters that passes through the first skimmer. This skimmer is located on the wall dividing chambers J1 and J2 and has an aperture of 2.3 mm. The remaining 90% of the hydrogen gas exiting the nozzle is pumped from chamber J1 via TMPJ1 1000 and TMPJ1 3500. This "background gas" consists of the nozzle throughput which remains uncondensed and that which is "skimmed off" by the first skimmer. A second skimmer is located on the wall dividing chambers J2 and J3. With an aperture of 4.3 mm, this skimmer defines the diameter of the jet stream as it intersects the antiproton beam inside the Antiproton Accumulator beam-pipe. The jet stream measures roughly 7 mm in diameter at this point. After passing through the skimmers, much of the jet stream terminates in the R1 chamber. It follows that the chamber required to evacuate the second greatest amount of hydrogen gas is the R1 chamber. Immediately downstream of the interaction area the Antiproton Accumulator beam-pipe narrows in diameter and its wall thickness is significantly reduced. It is here that the detectors for the experiment are located.

DETAILS OF THE GAS JET UPGRADE

There are primarily three steps which have been taken to improve the performance of the hydrogen gas jet. This upgrade program includes:

(1) Lowering the stagnation temperature of the hydrogen gas supplied at the nozzle such that the density of the hydrogen jet stream is increased.
(2) Improving the system pumping speed of the vacuum chamber in which the gas jet is located to reduce the interaction of the background gas with the jet stream.
(3) Controlling the nozzle position in the plane normal to the jet stream (x-y plane) and its angular position to correctly locate the jet stream with respect to the antiproton beam.

The following paragraphs summarize the details of the upgrade program implementation.

Gas Jet Description

Lowered Gas Jet Operating Temperature. Through testing of the upgraded jet target system it has been determined that a successful hydrogen gas operating temperature is near 27 K. This distinguishes Experiment 835 from Experiment 760 for which the hydrogen was cooled to about 80 K. The operating pressure of the gas for the upgraded system is slightly less than the saturation pressure of hydrogen at 27 K to avoid condensation in the hydrogen circuit. The new gas jet is refrigerated by means of a cryocooler employing the Gifford-McMahon refrigeration cycle. The thermodynamic state of the hydrogen gas is precisely controlled to avoid oscillations in the density of the jet stream.

An APD Cryogenics Inc. closed cycle cryogenic system provides the refrigeration required to cool the hydrogen gas and the nozzle. This system includes an APD model DE-204SL cryocooler (commercially rated for 9 W at 20 K) and an APD helium compressor model HC-4. This system was chosen for its capacity, physical design and dimensions. The cryocooler includes two stages of cooling. In testing our system, we have found the cryocooler capable of cooling the nozzle to a temperature very near 10 K.

Gas Jet Design. The first stage of the cryocooler is used to precool the hydrogen gas on its path to the nozzle. The hydrogen flows through a 3.2 mm diameter copper tube which is wrapped and soldered around the first stage to achieve thermal coupling. Here, the hydrogen is cooled from room temperature to almost 50 K. The gas then continues through a stainless steel tube which attaches to the nozzle coupling (see Fig. 2). The nozzle coupling consists of a copper spool, a helically coiled stainless steel tube, copper cable and the "nozzle holder". The copper spool is bolted to the cryocooler second stage extension. An indium seal between the spool and the extension decreases the contact resistance between the two parts. The spool is bored to provide a flow path for the gas. The hydrogen circuit continues from the spool to the nozzle holder through the helically coiled tube. Twelve lengths of copper cable thermally connect the nozzle holder to the spool. The helically coiled tube and the copper cable are used in the nozzle coupling design to allow for angular and x-y positioning.

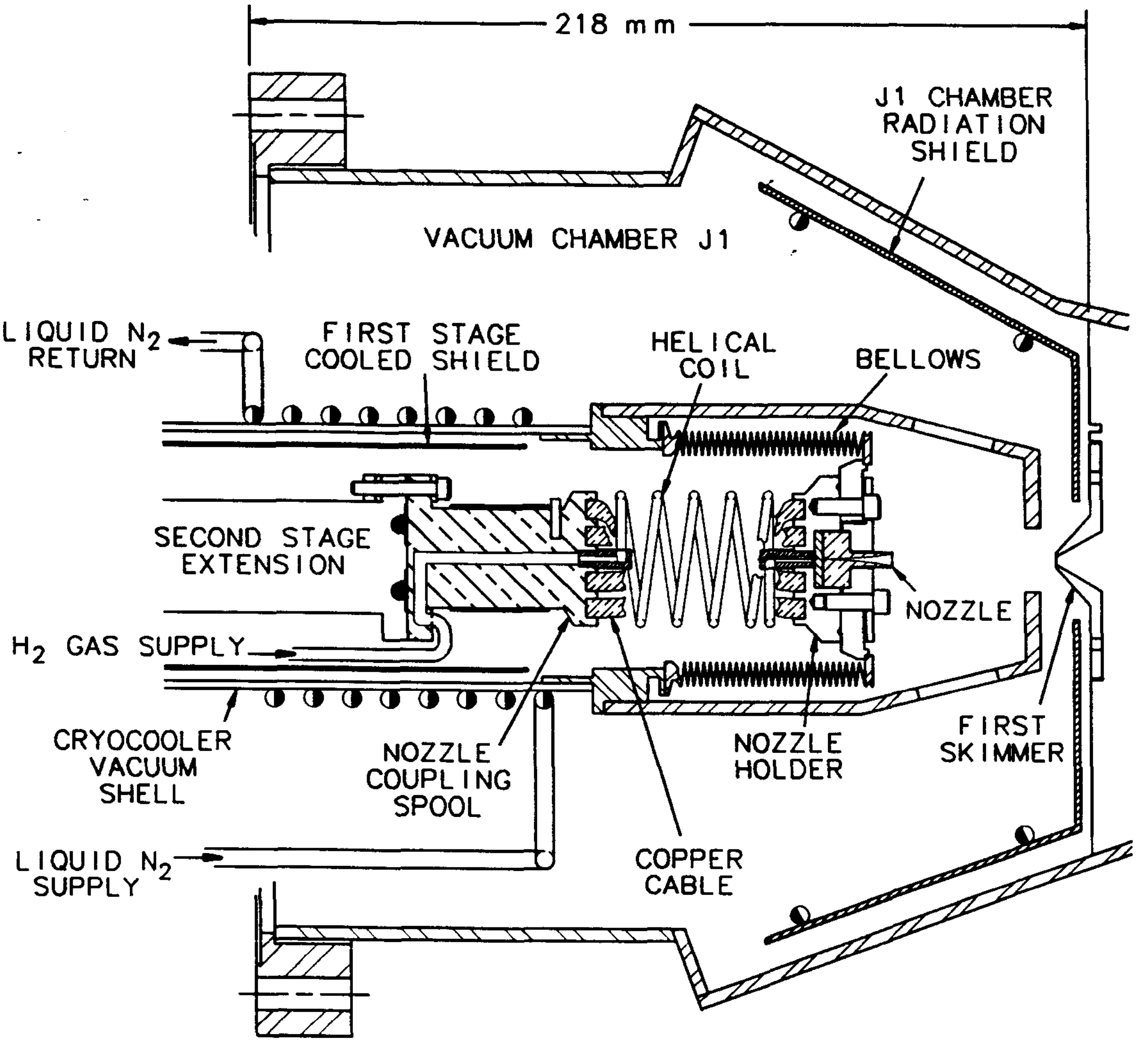

Figure 2. Hydrogen Gas Jet components located in the J1 Vacuum Chamber

Although the cryocooler is mounted into the J1 vacuum chamber, it is contained within its own insulating vacuum shell. This vacuum shell is attached to the cryocooler stainless steel mounting flange and extends to the nozzle. A welded metal bellows connects the cylindrical portion of the cryocooler vacuum shell to the nozzle holder. This bellows allows the angular motion required of the vacuum shell for nozzle angular positioning. A 50 L/s turbomolecular pump is used to evacuate this insulating vacuum space. Without a vacuum shell, the cryocooler would have a heat load imposed on it due to conduction through the background gas existing in the J1 chamber. Liquid nitrogen cools the insulating vacuum shell near the bellows. This cooling acts to intercept heat in the form of conduction between the room temperature portion of the vacuum shell and the 27 K nozzle.

The nozzle is a replaceable component secured with a retainer. An indium seal is used between the nozzle and the nozzle holder in order to prevent hydrogen gas from leaking into the cryocooler insulating vacuum from either the hydrogen gas supply circuit or from the J1 chamber.

The second stage, its extension and a portion of the nozzle coupling are protected from thermal radiation with a nickel plated copper shield. This shield is attached to and thus cooled by the first stage of the cryocooler.

Cryocooler Heat Load. As stated above, the first stage of the cryocooler precools the hydrogen gas flowing to the nozzle and provides refrigeration to the radiation shield surrounding the second stage, its extension and much of the nozzle coupling. Approximately 1.5 W of refrigeration is required for these heat loads.

The second stage of the cryocooler receives heat from several sources. The radiation heat load is minimal as the components attached to the second stage are well shielded by the first stage cooled shield, the liquid nitrogen cooled cryocooler insulating vacuum shell and a third shield cooled by liquid nitrogen in chamber J1 located in the nozzle area (see Fig. 2). The conductive heat load is of more significance. The nozzle holder thermally communicates with the liquid nitrogen shielded portion of the cryocooler vacuum shell via the welded metal bellows. The 0.127 mm thick diaphragms of the stainless steel bellows provide a good resistance to conduction. Both of the nozzle angle positioner arms are attached to the nozzle holder. Each of these arms is intercepted with a liquid nitrogen temperature copper braid to minimize the heat added to the nozzle holder. The face of the nozzle holder exposed to the J1 chamber vacuum space has a heat load due to the presence of the J1 background gas. The pressure of the gas in this location is such that free molecular conduction occurs. Barron[2] discusses the energy transfer rate due to molecular conduction. This heat load is determined with Eq. (1):

$$\dot{Q} = GpA_1(T_2 - T_1) \qquad (1)$$

It is seen that the energy rate is dependent on properties of the hydrogen gas (G), the pressure of the gas (p), surface area of the nozzle holder (A_1) and the temperature difference between the nozzle holder and the J1 chamber radiation shield in the nozzle area (T_2 -T_1). Lastly, the second stage of the cryocooler provides the cooling for the hydrogen gas supply to the nozzle. This occurs primarily inside the nozzle coupling spool. The summation of these heat loads equals approximately 2 W. Note that the available capacity of the APD model DE-204SL cryocooler provides the gas jet with a great deal of contingency.

Temperature and Pressure Control. It is critical to Experiment 835 that the hydrogen jet stream be a target of consistent density. For this reason, the state of the hydrogen gas supplied to the nozzle must be stable. Testing of the gas jet has shown that temperature control to within ± 0.1 K and pressure control to within ± 3500 Pa (0.5 psi) is required.

The nozzle temperature is sensed with a calibrated germanium resistance thermometer located on the nozzle holder. The sensor is positioned in a cavity whose dimensions create a close sliding fit with the sensor. A vacuum grease with good thermal conductance is used to minimize the contact resistance. A 16 bit temperature controller reads the nozzle temperature and provides an analog voltage output to a heater foil wrapped around the nozzle coupling spool. The temperature of the hydrogen gas entering the nozzle coupling spool is also controlled. The temperature here is measured with a platinum resistance thermometer. A temperature transmitter sends a conditioned signal to a multiple loop controller from the platinum resistor. The loop controller sends an output signal via a remote sensing power supply to heater foil wrapped on the tube leading from the first stage of the cryocooler to the coupling spool. Control of the gas temperature entering the coupling spool is necessary due to the temperature difference between the nozzle holder and the spool (about 2 K lower due to its 2 W heat load). The operating hydrogen pressure is very near the saturation pressure of the operating temperature. Thus, providing temperature control at the spool inlet avoids condensing the hydrogen as it passes through.

The multiple loop controller is used to control the hydrogen gas pressure as well. A high performance pressure transmitter provides the pressure reading to the controller. An electromagnetically operated flow control valve is then positioned by the controller in order to maintain the gas set pressure.

Hydrogen Gas Purification and Filtering. Before entering the refrigeration system, the hydrogen gas is purified. This is to avoid plating contaminants in the refrigerated hydrogen circuit and to prevent the small aperture of the nozzle from becoming partially or completely plugged.

Hydrogen is provided to the experiment from gas cylinders at a purity of 99.995%. Water vapor in the hydrogen is removed using a commercial water vapor purifier containing a 4A molecular sieve cartridge. The hydrogen next passes through a liquid nitrogen cooled activated carbon adsorber. The vacuum insulated adsorber contains about 2 kg of activated carbon (coconut) type PCB 4 x 8 inside a 10.2 cm tube. At both the inlet and outlet of the adsorber container, a combination of spun fiberglass, felt pad and screen are utilized to avoid carrying carbon dust throughout the hydrogen circuit. Given the small hydrogen flow rate and the relatively large amount of activated carbon, a purity better than 1 ppm is predicted. Pressure drop through the adsorber bed is insignificant. Additional filtering completely prevents particles from reaching the nozzle.

J1 Vacuum Chamber System Pumping Speed

The Experiment 760 J1 vacuum chamber was replaced with a larger chamber for Experiment 835 in order to maximize the evacuation of the J1 chamber background gas. As previously mentioned, two turbomolecular pumps are mounted on this chamber (see Fig. 1). Effective removal of the these hydrogen molecules from the space between the nozzle and the first skimmer minimizes their interaction with the jet stream. The new J1 chamber was designed to maintain a pressure below 1 Pa in the nozzle area. J1 system pumping speed measurements indicate an actual rate of about 1450 L/s.

Nozzle X-Y and Angular Positioning

Alignment of the jet stream through the skimmers to the interaction area inside the Antiproton Accumulator beam-pipe is accomplished with x-y and angular positioning of the nozzle (see Fig. 3). The positioners assure that the jet stream (along the z axis) interaction with the antiproton beam is maximized. The x-y positioner consists of a base supported by the cryocooler mounting flange, an x-axis slide and a y-axis slide. The x-axis and y-axis slides are each driven by a stepping motor. The x-y positioner range of motion is 3 mm in any direction from the gas jet centerline. Motion sensitivity is better than 10 µm. The angle positioner is supported from the y-axis slide of the x-y positioner. With its gimbal-like design, it allows nozzle positioning up to a 15 degree angle from the gas jet centerline in any direction. Two stepping motors are used to drive the apparatus. Arms extend from the motors to the gimbal rings which connect to the nozzle holder. Angle sensitivity is better than 0.05 degrees.

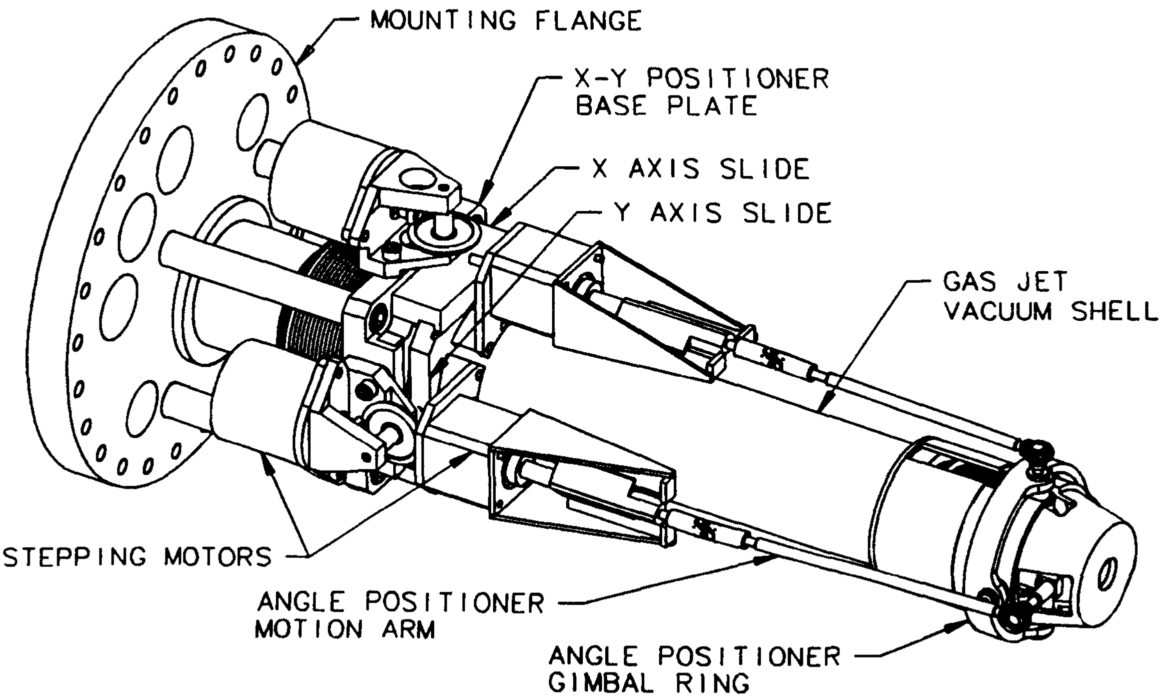

Figure 3. Components of the Nozzle X-Y and Angular Positioners

TEST RESULTS

Testing has been performed to evaluate the effectiveness of the upgraded gas jet on its ability to produce the specified increase in jet stream density.[1] To determine this increase the hydrogen supply operating temperature and pressure are optimized to avoid a nozzle throughput which is too high. Optimizing the nozzle throughput maintains the J1 pressure below 1 Pa and thus limits the amount of gas which diffuses through the skimmers to the Antiproton Accumulator beam-pipe to an acceptable level. Given the J1 chamber system pumping speed and nozzle characteristics, the nozzle throughput is limited to 8×10^{20} atoms/s for any hydrogen gas supply temperature to the nozzle. This value of throughput is plotted for a nozzle with a 37 μm aperture against supply temperature and pressure in Fig. 4. Also shown is the liquid-gas phase transition curve for hydrogen. Our operating point must be chosen below the constant nozzle throughput curve and to the right of the hydrogen phase transition curve. Condensation inside the hydrogen supply circuit will cause operational instability.

The average density (atoms/cm^3) of the jet stream is given in Eq. 2:

$$\bar{\rho} = \frac{\phi}{Av} \tag{2}$$

where ϕ is the jet stream throughput (atoms/s), A is the jet cross sectional area in the interaction area and v is the average speed of the jet stream over its cross sectional area. To increase the jet density, one must maximize the jet stream throughput and minimize the jet stream speed. The jet stream speed is dependent on the gas temperature supplied to the nozzle. This speed has been determined in our tests from 90 K to 16 K by performing "time of flight" measurements of the jet stream using a variable speed beam chopper. It was found that the jet stream speed was reduced from about 1300 m/s to roughly 300 m/s due to the lowered operating temperature. At 27 K the jet stream speed was measured at 600 m/s. Coupled with the increased throughput of the upgraded gas jet, the available increase in the average jet stream density exceeds five times that obtainable in the previous gas jet system. The upgraded gas jet is pictured in Figure 5.

CONCLUSIONS

The performance of the gas jet to be used in Experiment 835 in its ability to produce an increased jet stream density surpasses the experiment specifications. The refrigeration system and its control, a J1 vacuum chamber with improved pumping speed and nozzle positioners have all been successfully implemented into the jet target system. In addition, the

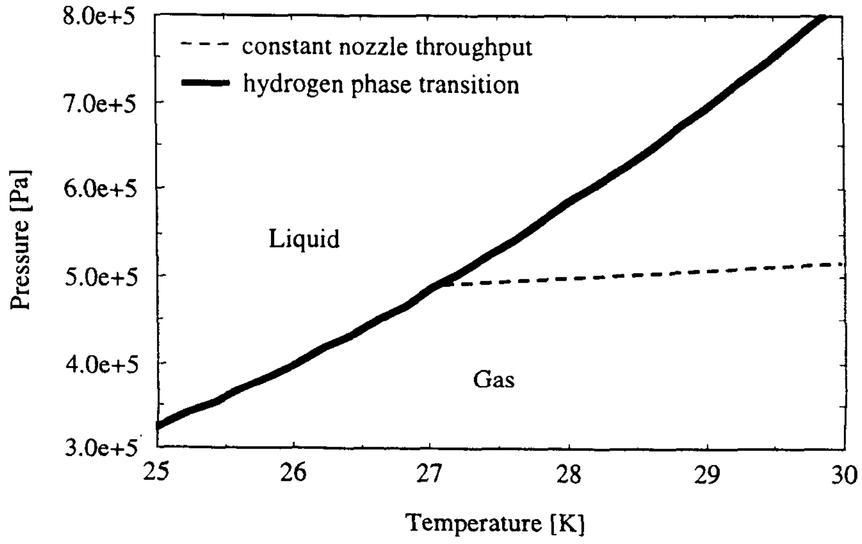

Figure 4. Hydrogen phase transition curve and constant nozzle throughput at 8×10^{20} atoms/s.

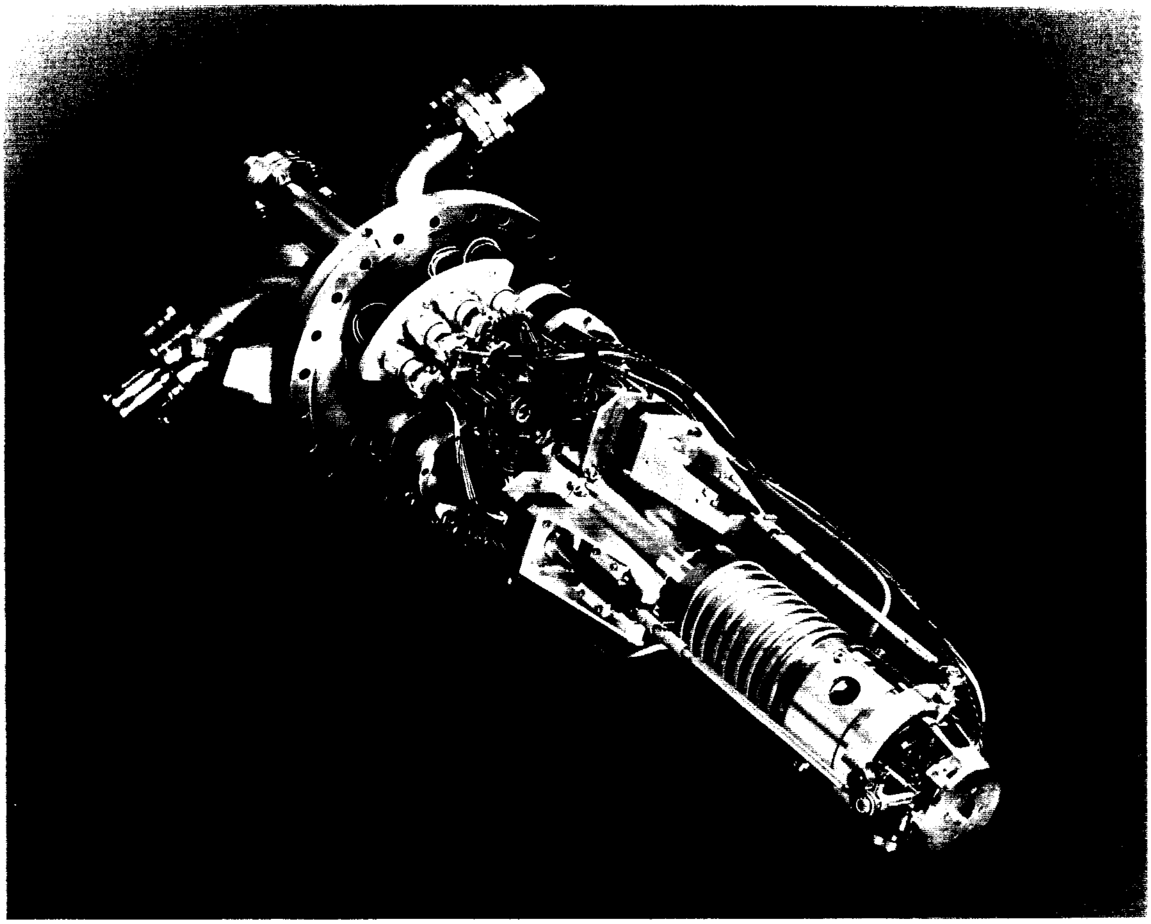

Figure 5. Experiment 835 Gas Jet

upgraded system offers the possibility of maintaining a constant interaction rate between the antiproton beam and the jet stream. As the intensity of the antiproton beam decreases over its 30 hour lifetime during which data is taken, the density of the jet stream may be gradually increased by properly raising the hydrogen supply pressure in order to achieve this constant rate. A constant rate of data production creates efficient use of the data detection system.

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