Closed cycle cryogenic fiber extrusion system

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A fiber extrusion system is described that produces frozen fibers of almost any condensible gas. This extruder has the advantage of employing a closed-refrigeration system. To date, this system has produced fibers of H_2, D_2, and Ne of a diameter ranging from 100 to 130 μm. The extrusion occurs at a specific temperature which is several degrees below the triple point of these gases. Once the fiber is extruded it can survive in vacuum for 20 min if the nozzle (extrusion) temperature is lowered to 8 K. The length of these fibers can be of the order of 1 m. D_2 fibers will be used in a staged Z-pinch experiment as a fuel for thermonuclear fusion. For this application a guiding structure is needed to position the fiber between the electrodes with millimeter precision, without significantly affecting its quality. © *1996 American Institute of Physics.*
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I. INTRODUCTION

Frozen deuterium plasma sources have been employed in several experiments. The general advantages of freezing a normally gaseous source are high initial density, better control over initial conditions, and high purity (chemical compounding is unnecessary). Solid deuterium pellets have been produced for tokamak fueling[1–3] and as laser targets.[4–8] Deuterium fibers are used in a Z-pinch experiment where a current of several hundred kiloamperes is passed through these fibers. The current heats the fiber by Ohmic dissipation converting it into plasma that initially expands and finally implodes by its self-generated magnetic field. Several experiments have reported the production of a large flux of neutrons in these fiber pinch experiments. The origin of these neutrons is usually attributed to plasma instabilities, in particular to the sausage instability.

In order to produce deuterium fibers for these pinch experiments, open-cycle refrigerated systems are normally used, which require an expendable supply of liquid helium from an external Dewar. We have produced single deuterium fibers which can be used as loads for high density Z pinches[9,10] in a rather simplistic fashion and the expendable supply of liquid helium is no longer needed. In order to cool the gas and freeze, a closed refrigeration system is used that recycles the helium gas through a water-cooled compressor. Once the gas is trapped and frozen in a stainless steel tube, it is compressed by a piston and the fiber is fabricated by extruding it through an orifice into a vacuum system which also uses a cryopump with a similar closed system. The temperature of the cold head can be adjusted to any desired temperature ranging from room temperature to 8 K. This makes the extruder system so versatile that it can extrude fibers of almost any condensible gas. Trapping the gas, its liquification, solidification, and the extrusion of the fiber, are rather straightforward procedures. The length of fibers extruded so far are determined to be more than 50 cm long and appeared to only be constrained by the dimensions of the chamber.

These fibers are planned for use in the University of California Irvine (UCI) staged Z-pinch experiment where, after extrusion the fiber enters a guiding system and is placed in between two high current electrodes. This type of experiment requires a high level of accuracy in positioning the fiber on the axis of the system using a conical positioning system. After extrusion, the fiber glides through the throat of the conical structure, through the center of the nozzle, and is positioned between the electrodes. During this process the fiber maintains its integrity even if it apparently contacts a room-temperature surface.

II. APPARATUS

Figure 1 shows an assembly drawing of the multigas fiber extrusion system. Refrigeration is provided by a two-stage closed-cycle compressed He refrigerated cold head.[11] The cold head (stage 2) is heat sunk to the middle of an oxygen-free copper cylinder containing an inserted extrusion cylinder. The Cu cylinder conducts heat from the extrusion orifice assembly which is screwed onto its lower end with a tapered thread. Stage 2 is rated to cool down to 10 K with a 2 W thermal load. Its floor temperature, with the present system attached, is 7.8 K. Temperature control to within ±0.1 K is provided by a microprocessor controlled heating element on the cold head using information from a Si diode temperature sensor.[12] Two temperature sensors are used, one located on the cold head and the other located at the lower surface of the extrusion die. The first refrigeration stage cools a radiation shield surrounding the stage 2 components. This shield is essential for minimizing the heat load to, and temperature differentials in, stage 2 components. Stages 1 and 2 surface emissivities are minimized by nickel electroplating with a mirrorlike finish and by oil-free vacuum pumping.

Figure 2 describes the extrusion cylinder and the extrusion nozzle. Gas enters the system through a 304 stainless steel tube from above. The tube is interrupted halfway to the Cu tube by a reservoir which is heat sunk to the radiation shield. This allows the higher powered stage 1 to precool the gas, significantly reducing the time required to fill the extru-

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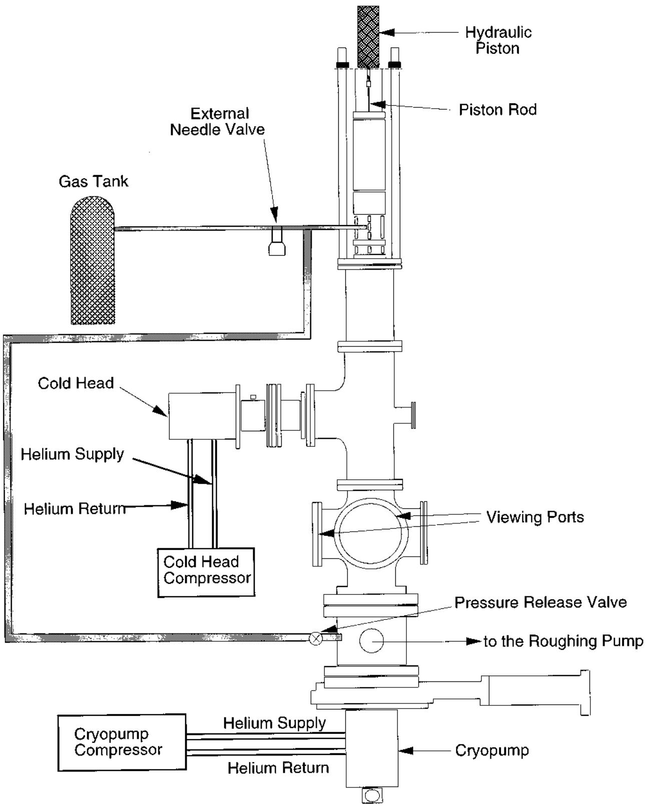

FIG. 1. Schematic of the multigas extrusion system with closed refrigeration.

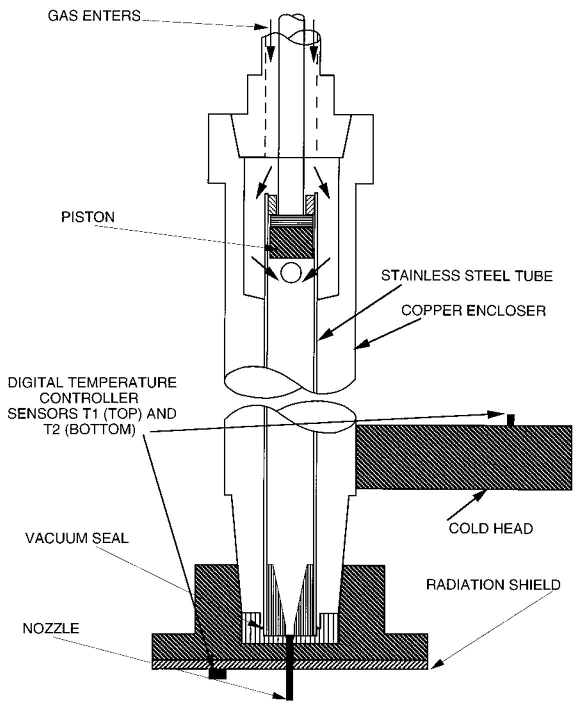

FIG. 2. Schematic of the extruder tube showing the entry of the gas, its solidification, and extrusion.

sion cylinder. The gas flow rate is controlled with an external needle valve to avoid thermal overload of stage 2 due to convective heat transfer, the heat of condensation, and conduction losses from gas escaping from the extrusion orifice before it can condense.

The extrusion cylinder can be filled in about 30 min as evidenced by a tapering off of the cold-trapping rate. As a system safety feature, a pressure relief valve is incorporated into the gas delivery system in case of thermal runaway of the refrigerated components, and subsequent rapid sublimation of the frozen gas.

The delivery tube is left free to slide up and down through its vacuum seal to accommodate thermal contraction/expansion during cooldown or warmup. The piston rod passes through the gas delivery tube. Once the tube is filled with the frozen gas, the tube is then locked into place with a half-nut needed to counter the force applied to the piston rod during extrusion.

The piston rod vacuum feedthrough shaft is 3.18-mm-diam high carbon steel a round drill stock heat treated and tempered to a Rockwell hardness *C* scale of at least 65. To minimize gas backstreaming during extrusion, the brass piston has a close sliding fit (CSF) within the 304 stainless steel extrusion cylinder insert in the Cu cylinder. The materials used all have sufficiently similar thermal expansion ratios at the temperatures of interest that the CSF could be established at room temperature. Unfortunately, the CSF causes the piston to jam easily within the extrusion cylinder. This problem is solved by mounting the piston to the piston rod with a wrist pin which passes through an oversized transverse hole in the end of the rod so that transverse torque on the piston cannot develop.

During the extrusion process, sublimation of the fiber compromises the vacuum insulation between stages 1 and 2. This is observed to lead to rapid fiber sublimation, excessive die temperatures, and possible thermal runaway resulting in the complete loss of the extruder's gas load. Large holes in the lower radiation shield, however, result in excessive die temperatures due to radiative load. The design illustrated helps meet the simultaneous requirements of high pump-out conductance and low line of sight exposure of the die to room-temperature surfaces.

III. TRAPPING PROCEDURE

Before cooling, the system is pumped to high vacuum using a roughing pump followed by a separate cryopump. The roughing pump evacuates the system down to 10^{-4} Torr while the cryopump cools down to its operating temperature of 20 K. This step takes ~90 min. The cryopump is then used to bring the system down to 10^{-7} Torr before starting the procedure for trapping a gas in the extrusion cylinder, open the gas tank, and fill up the gas regulator. Note the pressure reading on the gauge and again close the tank. This allows the amount of gas introduced into the cylinder to be measured.

The digital temperature controller gives a readout of the temperatures at the cold head ($T1$) and at the bottom of the cylinder close to the orifice ($T2$). If the system is cooled for an hour, $T1$ goes to 7.2 K and $T2$ to 8.2 K. These temperatures can be adjusted to any desired value by using a heater consisting of wire wrapped around the cold head. For trapping, liquification, and solidification of the gas in the stainless steel tube, $T1$ is set at an appropriate initial temperature. $T2$ can only be manipulated indirectly, by using the digital controller to change $T1$ and by using the external needle valve to regulate the flow of the trapping gas. The temperature for trapping a gas is determined by its triple point. The starting temperature is usually around 4° lower than the triple point. Ideally, one needs to trap the gas at the highest possible temperature. If the temperature is much lower than the triple point, the gas traps in the form of snow which fill the tube very quickly and the net mass will not be enough for extrusion. However, if the temperature is too close to the triple point, some of the gas leaks through the extrusion orifice raising the background pressure and deteriorating the temperature control. Once gas is introduced into the cylinder, $T2$ and the system pressure both rise initially. A needle valve is used to make sure that $T2$ does not reach the triple point and that the system pressure does not exceed 10^{-4} Torr. The gas regulator is also monitored to note when the gas begins flowing at an appreciable rate. If the regulator is not registering sufficient flow, T1 is gradually lowered, while using the needle valve to maintain a constant pressure in the system, until such a flow can be achieved. When the gas regulator is empty, the regulator is refilled. The number of times the regulator is refilled is noted along with the temperature and pressure data. In the early stages of trapping the difference between $T1$ and $T2$ is about 2–3 K. As the cylinder fills up, the difference between $T1$ and $T2$ narrows to nearly its original value of 1 K, and the pressure drops off appreciably as well. The cylinder is considered full when the rate at which it is filling as measured by the gas regulator slows considerably and no additional gas flows in. At this stage, even full opening of the needle value will not allow more gas to flow into the cylinder.

The full cylinder is once again cooled down to its floor temperature, usually 7–8 K. The remotely controlled hydraulic piston is carefully used to compress the ''snow'' down into a solid pack of ice, while watching the system pressure and the nozzle temperature $T2$ making sure they remain stable. The piston compresses the ice until the piston pressure gauge reads 100 psi. The cylinder is now ready to be warmed up for the fiber extrusion. To determine a definitive temperature range for the extrusion of a gas, begin by attempting to extrude with $T1$ 2–3 K below its minimum trapping temperature. After some compaction, the frozen gas then exits the extrusion orifice.

IV. EXTRUSION

Three different gases extruded: H_2, D_2, and Ne. The triple point data for hydrogen are 13.8–13.9 K, and we were able to trap it between $T1=8$–9 K. Extrusion of a hydrogen fiber was successful. Some bits and pieces of fiber came out, each hanging for less than a second accompanied by an ice spray of frozen hydrogen. In one event, the trapping of hydrogen was successful but as the piston was compressing the hydrogen snow, thermal runaway occurred in the cylinder causing the temperature and pressure to rise uncontrollably, ending the experiment. One problem with extruding hydrogen is that we are probably not able to get the nozzle temperature low enough to properly extrude the hydrogen; as suggested by subsequent experiments of D_2 and Ne.

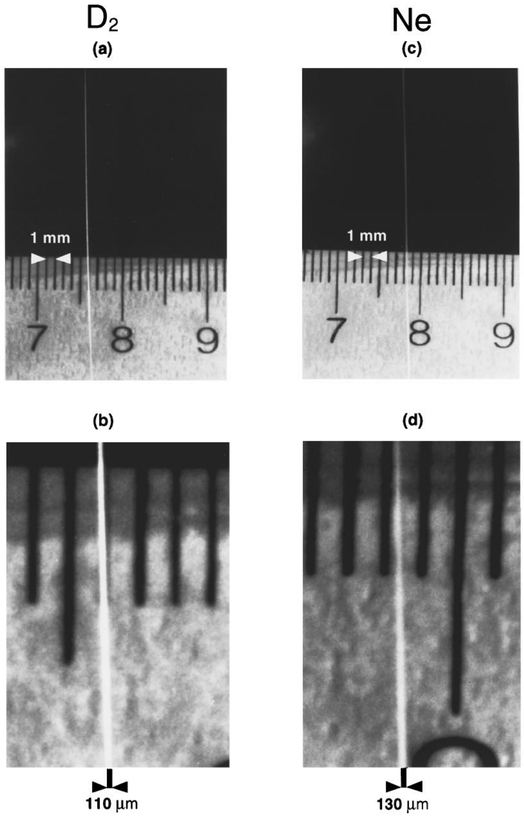

FIG. 3. Photographs of the D_2 and Ne fibers extruded from a 100 μm nozzle. The bottom panel shows the magnified images of the top photographs.

The data on deuterium are much more promising. The triple point for D_2 is 18 K. The trapping temperatures for deuterium are: $T1=12$–13 K and $T2=13.65$–16.16 K, with most of the gas trapped between $T2=14$–15 K. The extrusion temperatures range from $T1=12$–13 K to $T2=13.16$–14.40 K. At the lower limit of temperature the fiber comes out slightly curved whereas at the upper limit the fiber is straight. Figure 3(a) shows a photograph of the D_2 fiber with a ruler in the background for measurement of the diameter. Figure 3(b) is the magnified image of the same photograph shown in Fig. 3(a). The average fiber diameter for D_2 fibers is 110 μm. Note that the orifice diameter is only 100 μm. As reported earlier,[9] we suspect that the fiber extrudes through the orifice in liquid form and immediately solidifies by sublimation into a diameter slightly larger than the orifice diameter.

We have also studied extrusion of Ne which has a triple point at 24.4 K. The neon traps between the temperature of $T1=16$–17 K and $T2=19$–22 K, with most of the gas trapping between $T2=20$–21 K. Neon extrudes at $T1=20$ K and $T2=22.60$ K. Figure 3(c) shows a sample photograph of the Ne fiber with its magnified image shown in Fig. 3(d). The average fiber diameter is 130 μm again using an orifice of 100 μm. During the application of pressure on the piston, the fiber extrudes until the column pressure is reduced. To date the length of the fiber is up to 50 cm, apparently limited by the length of vacuum chamber. If we keep the system at

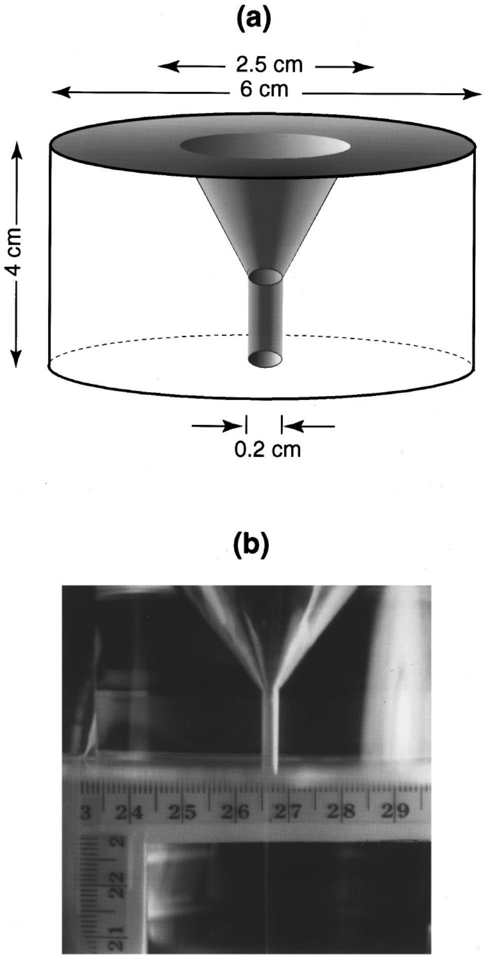

FIG. 4. Guiding of the fiber; (a) schematic of the guiding funnel, and (b) photograph of the Ne fiber guided through the funnel.

extrusion temperature the fiber continues to hang for up to 5 min and then it falls off. However, if we stop the heating after extruding the fiber, and then let the system cooldown to floor temperature of 8 K, the fiber remains hanging for up to 20 min.

V. EXTERNAL GUIDING SYSTEM

Since this extruder was designed to fabricate deuterium fibers for use in a staged *Z* pinch as a final load, the accurate positioning of the fiber on axis of the *Z* pinch is crucial. Our attempts at using an external guiding system to insure proper placement of the deuterium fiber were successful. The guide consists of a machined piece of plastic 3.4 cm tall, which was positioned inside the vacuum chamber at the desired location. The top 2 cm of the guide has a funnel which is 2.5 cm diameter, narrowing to a diameter of 2 mm. The bottom 1.4 mm of the guide is simply a 2 mm hole drilled through to the bottom. The schematic of the guide is shown in Fig. 4(a). This model, which was tested with neon, still allowed for a hang time of nearly three and a half minutes at extrusion temperature and up to 10 min if the system is lowered to floor temperature. A photograph of the Ne fiber gliding through the funnel is shown in Fig. 4(b). The fiber breaks first at the entry of the funnel while it keeps hanging in between the extrusion nozzle and guiding structure.

VI. DISCUSSION

Means to extrude and position 100 μm diameter, cryogenic fibers of H_2, D_2, and Ne have been demonstrated on a stand-alone vacuum test stand. The cryogenic fiber is prepared by condensing gas in a plenum near 10 K using a closed cycle helium refrigeration system. A hydraulic piston compresses the condensate into a packed snow while the temperature of a 100-μm-diam nozzle is raised near the melting point. Extrusion produces a solid fiber that freely hangs in vacuum for up to 10 min before evaporating.

This fiber extrusion system is presently coupled with a 50 kJ staged *Z*-pinch facility at UCI. As a final plasma load, D_2 fibers will allow us to study the MHD behavior of solid density *Z* pinches at temperatures up to a few keV. A numerical model predicts significant production of thermonuclear neutrons from pure D_2 fibers and close to break even energy if we use fibers made up of a 50–50 mixture of D_2 and T_2 by number.[13] The expectation is that the fiber plasma will remain stable in the staged *Z*-pinch configuration mainly because the full current flows through the fiber plasma for less than a nanosecond at the peak implosion of the outer pinch. The MHD instabilities may not have sufficient time to become dominant, resulting in the formation of a uniform plasma column. Such a plasma column may also have applications in the production of x-ray lasers if Ne is substituted for the D_2 fiber.

ACKNOWLEDGMENTS

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