A SIMPLE TECHNIQUE FOR INCREASING THE TEMPERATURE RANGE OF A CRYOGENIC FROZEN-GAS PELLET INJECTOR FOR OPERATION WITH VARIOUS GASES

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On the Madison Symmetric Torus magnetic fusion plasma experiment, frozen pellet injection is an established method of depositing deuterium fuel into the core of the plasma. To freeze deuterium gas into pellets, the injector is cooled to 10 K with a cryogenic helium refrigerator. To exhaust residual frozen deuterium following injection of each pellet, the injector is warmed by resistive heating to >18.7 K, the triple point of deuterium. Motivated by the desire to inject carbon-containing pellets, the injector was modified to allow the freezing and injection of methane. The triple point of methane, 90.7 K, is well beyond the capability of the resistive heating hardware. To supplement the resistive heating, a small, steady flow of room-temperature helium was introduced as a heat source. The flow rate was optimized to provide minimum and maximum injector temperatures of 24 and 95 K, respectively, sufficient for methane pellet formation and exhaust. The flow rate can easily be optimized for other gases as well.

KEYWORDS: *methane pellet injection, triple point, helium gas*

Note: Some figures in this paper are in color only in the electronic version.

I. INTRODUCTION

Frozen pellet injection is a well-established method of fueling the core of magnetically confined plasmas.[1,2] On the Madison Symmetric Torus[3] (MST), deuterium pellet injection has led to as much as an eightfold increase in the plasma density. To freeze deuterium gas into pellets, the injector is cooled to 10 K with a cryogenic helium refrigerator.[a] Pellets are then launched with either a burst of high-pressure hydrogen gas or a solenoid-driven mechanical punch. Following the injection of each pellet, the injector must be heated to >18.7 K, the triple point of deuterium. This allows residual frozen deuterium to be removed from the injector, a step critical to the successful formation and injection of subsequent pellets. This heating is provided resistively, temporarily overcoming the constant cooling provided by the cryogenic refrigerator.

Motivated by the desire to inject carbon into the core of MST plasmas, the capability to freeze and inject methane (CH_4) pellets was developed. Given the higher triple point of methane, 90.7 K, the operational temperature range of the injector had to be increased substantially. Without substantial modification, the existing resistive heating mechanism was unable to provide the needed temperature increase. Hence, as a simple alternative, a small, steady flow of room-temperature helium gas was introduced. When used in combination with the resistive heater, the helium provides an additional source of heat, and the helium flow rate was adjusted to raise the peak obtainable temperature to >95 K. Without the resistive heating, the base temperature of the injector increases to 24 K, still sufficient to allow formation of frozen methane pellets. While the helium flow rate was optimized in this case for methane

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[a] Leybold Coolpower 130.

pellet formation, the flow rate can easily be adjusted for other target gases and triple points.

In what follows, we describe in more detail the means by which deuterium pellets are formed, and we describe the means by which residual pellet material is removed after each pellet is injected. We then discuss the instrumental modification required for methane pellets, and we show an example of carbon deposition in the plasma core due to methane pellet injection.

II. PELLET INJECTION

The pellet injector on MST utilizes the pipe gun technique, wherein pellets are formed inside cryogenically cooled barrels and then launched with a mechanical punch or burst of high-pressure hydrogen gas at 1200 psi (8.3 MPa) (Ref. 4). To allow the barrels to reach a very low temperature, the barrels are housed inside a small vacuum chamber, referred to as the gun box. Figure 1 is a schematic of the gun box for the MST pellet injector. Two of the stainless steel injector barrels are shown. Each barrel is connected to a copper block assembly that is in turn attached to the cold head of the cryogenic refrigerator. The refrigerator runs continuously, providing a steady cooling power of ~15 W for operation at low temperature. Attached to one side of the gun box is a small (60 ℓ/s) turbomolecular pump, which under normal operation sustains a pressure <1 mTorr (0.13 Pa). The vacuum provided by this pump minimizes convective and conductive heat transfer between the room-temperature gun box and the barrels and prevents the condensation of atmospheric gases on the supercooled surfaces.

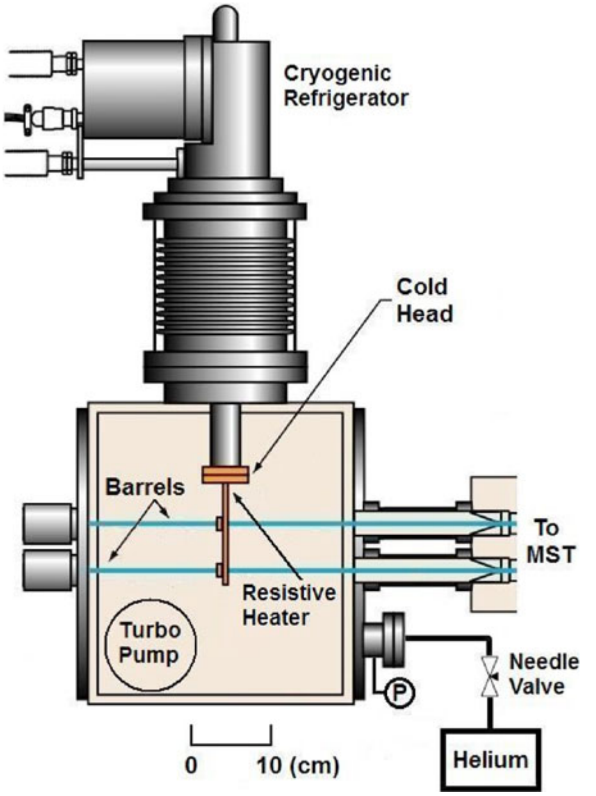

Fig. 1. Schematic of the pellet injector barrel housing (gun box) including the newly added helium supply and needle valve. Barrel heater wire (not shown) is attached to the copper block assembly, which connects the cold head to the barrels. Temperatures are monitored at this block as well as locally on each barrel.

II.A. Deuterium Pellets

To form deuterium pellets, deuterium gas is slowly introduced to the barrels, and the gas freezes in the small region where the cooled copper block is connected to the barrels. The size of the freezing zone is determined by the placement of metal braid heat shorts connected to the room-temperature gun box chamber. The 10 K freezing zone is a result of the equilibrium between the refrigerator cooling and the small ambient heat provided to the thermal load via radiation and conduction from the gun box chamber. After formation, the pellets are propelled through the barrels toward the MST experiment. Once the pellets have been expelled, the barrels are cleared of any remaining frozen deuterium by pumping simultaneously on one end of the barrels and resistively heating them above the triple point of deuterium. Comprised simply of a 25-Ω resistance attached to the copper block, the resistive heater provides a heating power of ~23 W and is capable of increasing the barrel temperature to a maximum <40 K, as shown in the <1 mTorr case of Fig. 2a, which illustrates the temporal evolution of the barrel temperature during heating.

The complex details of the dynamic thermal equilibrium in the gun box are beyond the scope of this paper, as a detailed understanding would require significant diagnostic improvements, e.g., an array of internal temperature measurements; however, some commentary is possible. The specific heat of copper increases with temperature, which results in a decrease in the rate at which the temperature increases; however, this does not explain the asymptotic behavior of the temperature in Fig. 2a. To achieve a temperature maximum as shown, the net heating power to the copper must also vary with the temperature, ultimately approaching equilibrium. Important to this equilibrium are the coupling efficiencies of both the barrel heaters and the cryogenic refrigerator, and all of the mechanisms by which heat can be gained or lost by the copper, including radiation.

II.B. Methane Pellets

To allow the formation and launch of multiple, successive methane pellets, the barrel temperature needs to

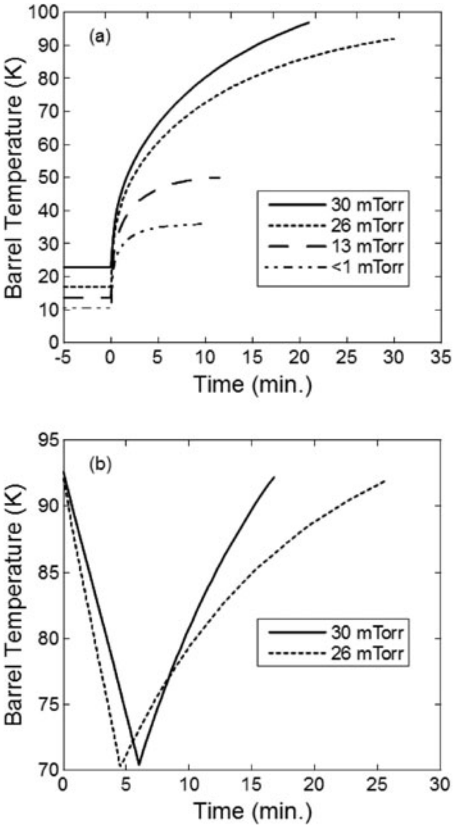

Fig. 2. Temporal evolution of barrel temperature (a) at various helium pressures before ($t < 0$) and after ($t > 0$) the barrel heaters are activated and (b) during a cycle of pellet formation and exhaust. Pressure <1 mTorr is below the measurement threshold for the Convectron gauge and refers to operation without helium flow, suitable for deuterium pellet formation. Pressures have been recalibrated for helium.

be raised to >90.7 K following each pellet launch, significantly above the temperature required for deuterium pellets. This proved to be beyond the present capability of the resistive heating hardware. Hence, a small, steady flow of room-temperature, high-purity helium was introduced into the gun box through an adjustable needle valve,[b] illustrated in Fig. 1. The pressure upstream of the needle valve was maintained at 50 psi (345 kPa). Utilization of high-purity helium prevents contamination of the gun box by trace impurity gases, and helium will not freeze on the supercooled injector surfaces. The impact of different helium flow rates on the injector base temperature is illustrated in Fig. 2a.

The gun box pressure, measured with a Convectron gauge near the helium inlet port (Fig. 1), is used as a rough proxy for the helium flow rate. Prior to $t = 0$ in Fig. 2a, the time at which the barrel heater is activated, the barrel temperature reflects the change in the thermal equilibrium provided by the added helium flow. As the gun box pressure increases to 30 mTorr (4.0 Pa), the base temperature rises from 10 to 24 K, still sufficiently below the triple point of methane for pellet freezing. At low pressure, the mean free path of the helium atoms is comparable to the dimensions of the gun box (~0.1 m). In this low-collisionality regime, the heat transferred to the copper block assembly is proportional to the pressure and the temperature difference between the copper block assembly and the gun box walls.[5] The primary source of heat is room-temperature helium atoms impacting the copper directly. As pressure increases, the mean free path decreases, and a more collisional regime is approached where the heating power is governed by the thermal conductivity of the gas and the temperature difference. After the barrel heater is activated, the barrel temperature increases, approaching a maximum value.

By testing a range of pressures, we determined the maximum attainable barrel temperatures. For the low pressures of <1 mTorr and 13 mTorr, the peak barrel temperature stabilized at values well below the minimum of 90.7 K required for methane pellet exhaust. For the higher pressures of 26 mTorr (3.5 Pa) and 30 mTorr (4.0 Pa), the required 90.7 K was achieved, and the highest pressure yielded the fastest temperature rise. For cryogenic systems other than that described here, the helium flow rate required for a given elevated temperature may differ depending on specifics such as chamber pumping speed and volume and the detailed balance of cooling and heating.

Similar results can be obtained with a static helium fill, but given the finite leak rate of the gun box, the dynamic fill results in a more stable pressure over the course of an MST run day. The continuous pumping also prevents the accumulation of atmospheric impurities in the gun box, which would eventually condense on cold surfaces and interfere with injector operation. Furthermore, the dynamically achieved pressure can be controlled with a single knob and can be adjusted higher or lower at will. Adjustment to a higher pressure with a static fill would be simple, of course, but any subsequent reduction in pressure would require pump out.

The barrel temperature range for which methane pellets form reliably is 70 to 75 K. Hence, for the injection of successive methane pellets, the injector temperature must cycle from <75 K to >90.7 K. Starting with the data from Fig. 2a, the optimal operating helium pressure was chosen to minimize the overall temperature cycle time. The temporal evolution of the barrel temperature during a pellet injection cycle is shown in Fig. 2b for the two highest pressures in Fig. 2a. The time evolution starts immediately after pellet residue is exhausted at high temperature. While barrel cooling requires less time at 26 mTorr (3.5 Pa), barrel reheating requires a substantially longer time. By choosing a helium pressure of

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[b] Nupro/Swagelok SS-4BMG-VCR.

30 mTorr (4.0 Pa), the total cycle time is decreased while maintaining an acceptable load on the turbomolecular pump, as reflected by the drawn current.

III. CARBON DEPOSITION

Methane pellets were injected into MST plasmas with a toroidal plasma current of 400 kA, a central line-averaged electron density of 0.8×10^{19} m^{-3}, and a central electron temperature of 1 keV. Just before each pellet was injected, inductive current profile control[6,7] was applied to reduce magnetic fluctuations and the rate of transport of particles and energy. Methane pellets provide a means of probing impurity particle transport in these plasmas. The temporal evolution of the carbon density following injection of a methane pellet is shown in Fig. 3. This specific pellet had a diameter of 1.0 mm and a length of ~1.5 mm and was injected shortly after 10 ms, propelled by a burst of high-pressure hydrogen gas. The resultant pellet speed was ~150 m/s, significantly slower than the typical deuterium pellet speed of 1200 m/s. This decrease in pellet speed is due to the higher mass density of the methane pellet. This speed is also significantly lower than that predicted by ideal gun theory.[1] Nevertheless, this speed was sufficient for the methane pellet to penetrate to the plasma core, resulting in a 12-fold increase in the central carbon density, measured with charge-exchange recombination spectroscopy.[8] This increase is with respect to the background concentration of carbon that is present in all MST plasmas due to partial coverage of the plasma-facing wall with graphite tiles. The methane pellet in Fig. 3 is completely ablated by 14 ms. Thereafter, the central carbon density decays.

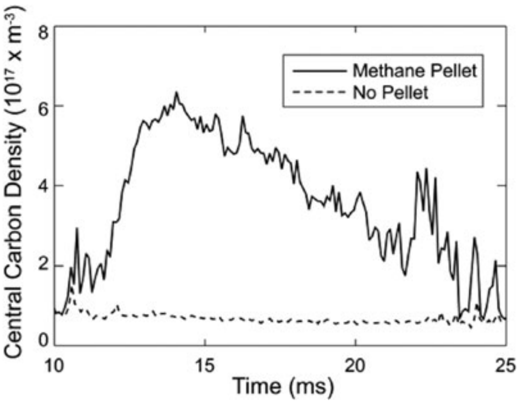

Fig. 3. Central carbon density with and without methane pellet injection in two otherwise similar discharges. In the pellet-injected case, the pellet arrives in the plasma at ~10 ms.

IV. SUMMARY

The addition of a steady flow of room-temperature helium allows operation of the MST pellet injector at an elevated temperature range suitable for the formation and injection of methane pellets. The flow rate can easily be adjusted to accommodate other pellet gases as well.

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REFERENCES

1. S. K. COMBS, "Pellet Injection Technology," *Rev. Sci. Instrum.*, **64**, 1679 (1993).

2. S. L. MILORA et al., "Pellet Fueling," *Nucl. Fusion*, **35**, 657 (1995).

3. R. N. DEXTER et al., "The Madison Symmetric Torus," *Fusion Technol.*, **19**, 131 (1991).

4. S. K. COMBS et al., "New ORNL Pellet Injection System and Installation/Initial Operations on MST," *Fusion Sci. Technol.*, **44**, 513 (2003).

5. G. S. SPRINGER, "Heat Transfer in Rarefied Gases," *Advances in Heat Transfer*, Vol. 7, pp. 163–218, T. F. IRVINE and J. P. HARTNETT, Eds., Academic Press, New York (1971).

6. J. S. SARFF et al., "Fluctuations and Transport Reduction in a Reversed Field Pinch by Inductive Poloidal Current Drive," *Phys. Rev. Lett.*, **72**, 3670 (1994).

7. B. E. CHAPMAN et al., "Reduced Edge Instability and Improved Confinement in the MST Reversed-Field Pinch," *Phys. Rev. Lett.*, **87**, 1 (2001).

8. S. T. A. KUMAR et al., "Behaviour of Carbon and Boron Impurities in the Madison Symmetric Torus," *Plasma Phys. Control. Fusion*, **53**, 032001 (2011).