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Tracer-encapsulated pellet injector for plasma diagnostics

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An injector for making solid hydrogen pellets around impurity cores has been developed for plasma transport study in large helical device. A technique has been employed for automatic loading carbon or polystyrene cores of 0.2 mm diameter from a gun magazine to a light-gas gun barrel. The injector is equipped with a cryocooler and is able to form a 3.2 mm long and 3 mm diameter cylindrical solid hydrogen pellet at 7–8 K with an impurity core in its center within 6 min and to inject it in the light-gas gun up to 1 km/s. © 2005 American Institute of Physics. [DOI: 10.1063/1.1899323]

I. INTRODUCTION

Knowledge of plasma transport is a key for achieving high performance plasmas confinement in fusion devices. Experimental data on laser ablation or injection of shell-free impurity pellets show an extended profile for plasma perturbation, making transport coefficients difficult to measure, especially near the plasma column axis.^{1,2} Injection of impurity cores inserted into polystyrene capsules gives a local plasma perturbation, however, some extra impurities appear due to capsule evaporation and ionization.³ Professor S. Sudo came up with a proposal for using pellets made from ice of bulk plasmas components, i.e., hydrogen isotopes, as capsules.⁴ When such pellet enters the plasma, the outer solid hydrogen layer is ablated first, keeping the impurity core from ablation up to the plasma column axis. This results in an intensive ablation of the core providing the small localization of the deposited tracer ions. Experimentally observed evolution of the impurity ions gives data for analytical calculation of diffusion coefficient of the bulk plasmas.

Two attempts were undertaken in order to introduce an approach and tracer-encapsulated pellet injectors in plasma investigations. The reliability of a first injector was not enough due to problems with cores loading from a magazine into hydrogen pellets. The reliability and technology of pellet formation and acceleration in a second injector was sufficient and efficient, however, proof-of-principle operation was demonstrated using steel balls. When metal cores were changed to nonmetal carbon and polystyrene, some additional problems appeared. More light cores were blown away and were lost more easily in a loading unit. Besides, the injector cooling system was based on liquid helium heat exchanges, however, it requires a liquid helium flask to be placed near the injector. It is not acceptable for experiments on large helical device (LHD), so an injector with a cooling system based on a cryocooler and technology for making pellets with nonmetal cores has been developed for LHD plasma transport study.

II. TRACER-ENCAPSULATED PELLET FORMATION TECHNIQUE

In the above-mentioned first injector a core was input into two halves of a hydrogen pellet, which was transported to a light-gas gun barrel for injection. The basic concept of another technique of tracer-encapsulated pellet formation was a decision to generate a solid hydrogen pellet just inside the barrel (*in situ*), to whose axis before mounts an impurity core. In other words, to condense hydrogen around the core rather than input the core into solid hydrogen. The core can be moved to the barrel axis via vacuum pickup technique, where the core will be held at the top end of the injection needle, at the expense of no condensable gas continuously sucked up through the needle. The same gas may be used to push the core out of the gun magazine. Finally, showing through the inside duct of the barrel, one can observe the pellet formation process in real time and obtain reliable information about the presence of the impurity core inside the pellet. This drastically increases the reliability of injection, since an operator can see the pellet generated with an impurity core inside of it just before injection. In the event that the core is not mounted on the barrel axis before formation of the solid hydrogen pellet around it, the operator can proceed with the process of loading the next core from the magazine without hydrogen pellet formation. Such technology was proposed, patented, and employed in the second injector.^{6,7} However, carbon and polystyrene cores are nonmetal materials and they are easily taken off by suction gas to the barrel. So, a technology has been developed for such cores to be loaded.

The stages of tracer-encapsulated pellet formation are represented in Fig. 1. An injection needle is preset at the top of a gun magazine, where every impurity core is placed into a separate cell. A small amount of hydrogen gas is slowly admitted into the barrel and condensed on the walls of a pellet former creating a solid hydrogen shell, which is cooled to 8–9 K [Fig. 1(a)]. The needle comes down and is preset under the cell with the next core to be loaded [Fig. 1(b)]. The gas flow blows through the magazine cell and pushes the core out of it. Because the whole gas flow is sucked off

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FIG. 1. Sequence of operations for pellet formation around an impurity core.

through the needle and the formed shell closed a channel through which the needle can enter the barrel, the core fallen out of the magazine cell hits the top of the needle, trying to get inside of it together with the gas flow. However, the needle diameter is so chosen, that the core could not get through it, but closes the hole in the needle like a gag. The temperature of the pellet former is increased to 30 K and the hydrogen shell is evaporated being opened the channel into the barrel. A weak gas flow leaks through an untight sealing of the needle hole to hold the core on the needle top during its upward movement. The needle sets the core to the barrel axis as shown in Fig. 1(c). The pellet former is cooled to 9 K once more; at the time of hydrogen inflow, it condenses on the pellet former walls, gradually filling up the whole of its cross section and even getting inside the needle [Fig. 1(d)]. The needle is pulled out of the pellet back to the relatively warm magazine, leaving the core and an empty channel inside [Fig. 1(e)], and hydrogen, condensed in the top of the needle, sublimates from the needle and recondenses again in the channel formed by the extracted needle, filling it and completing the pellet formation as shown in Fig. 1(f). Thus, the needle is used as a vacuum tweezers to capture and hold up a core and as a source of hydrogen to complete the pellet formation. The pellet, formed around the impurity core, is located exactly in the injector barrel. It can be observed through the barrel duct subject to suitable illumination and availability of an optical system with long-focus lens. After visual confirmation of the presence of the impurity core inside the pellet, it is possible to inject it into plasmas.

III. INJECTOR DESIGN

A cold head of a cryocooler, named cooler, is connected to the pellet former and used to cool it down together with a thermal screen as shown in a schematic diagram in Fig. 2. Connected to the pellet former are an injector barrel with a heater wound on its walls, a loading unit, incorporating a needle movable by a step motor and a magazine including 50 cells with impurity cores, two heaters for rough and fine temperature regulation, a tube to supply a propellant gas from a fast valve, with an optical window located on the barrel axis to observe its bore and inner surface of the pellet former using a video camera, named barrel camera. Con-

FIG. 2. Schematic diagram of the injector.

nected to the barrel end is an illumination set, incorporating a mirror movable by an electromagnet and an infrared light emission diode. A gate valve, to which a diagnostic chamber with four optical windows is linked up, is attached to the illumination set. A laser with an expander and an optical fiber with two slits located in a distance of 5.5 mm connected to a photomultiplier, which is used as a photodetector, are placed on the axis of two windows to create a light barrier to the flying-out pellet. Mounted on the axis of the other two windows are another video camera, named pellet camera, and a pulse flash to photograph the pellet in flight. A microphone is attached to the diagnostic chamber flange, to capture the pellets after acceleration. The injector pumping system consists of two rotary vacuum pumps and one turbomolecular one. Cylinders of hydrogen for pellet formation and helium for pellet acceleration are connected to a gas supply system suitable for automatic remote control. The gas supply system consists of six valves with pneumatic actuators controlled by electromagnetic valves, two manual needle valves for accurate gas flow adjustment, and three pressure sensors.

IV. CONTROL SYSTEM

A control system provides remote operation of the injector and includes two main parts: (i) a programmable logic controller (PLC) with an analog inputs board and digital outputs boards installed in a PLC rack for low-level control and (ii) a personal computer (PC) for high-level control and man-machine interface. The PLC and PC are connected by a serial interface RS232 using a serial port COM1. A control software operates under OS Windows 2000. A video capture card is used for visual feedback control.

A control program provides automatic operation of the loading unit, a temperature controller, and the gas supply system. A main program window is shown in Fig. 3. There are four virtual button and a core numerical identification on the right side of the window: "load core," "form pellet," "injection," and "standby." When an operator presses the "load core" button, the loading unit automatically loads the

FIG. 3. Program window of the injector control system.

core whose number is preset in the frame of the core identification. To form a pellet around the core loaded into the barrel in automatic mode it is necessary to press the button “form pellet.” If one presses the button “injection” the injector is waiting for an external pulse for immediate shooting. One can make injection manually using a button with a small arrow in the fast valve voltage pictogram on the left side of the main window. The standby mode is used for keeping injector in cold state for a long period.

Besides main four buttons for the injector automatic remote control there are some buttons and frames for manual control and adjustment which are useful for checking the injector performance. In particular, every valve can be opened manually by clicking on its pictogram. The illumination set, the step motor of the loading unit, the barrel heater, etc., can be controlled manually also.

The control program uses a video signal to estimate the needle position on the computer monitor and to control its movement. This visual feedback is employed for more intellectual step motor operation. On the computer monitor with a picture of the barrel bore, shown by the barrel camera, a rectangular frame is set in such a way that its center just coincides with the center of the barrel cross section [Fig. 4(a)]. The needle is installed by the step motor at the maximum possible top position [Fig. 4(b)]. The step motor pulls the needle down, however, due to a mechanical backlash, the needle starts to go down after some steps of the motor operation, which are counted and recorded by the program. When the needle starts to go down a command from PLC gives a task to go down for 1.5 mm and simultaneously counts the number of motor steps. The top needle position on the monitor is calculated in pixels as the place of maximum gradient of intensity along the center vertical line, passed through the needle axis. The visual area should be lightened without significant imperfections for accurate calculations and correct needle positioning.

Counting the number of pixels, when the needle top goes down for 1.5 mm, and takes into account the linear travel of every motor step (0.005 mm), one can estimate the scale of pixels per one motor step. After that, the needle position in relation to the center of the rectangular frame as well as to any other position out of the visible area in the frame can be calculated. Further, the distance between the maximum top position of the needle and the magazine is equal to 39 mm, so the distance between the center of the frame and the magazine with cores are also calculated. The sizes of cells

a)

b)

FIG. 4. Photos illustrating the needle positioning and its movement control in the depicted rectangular frame inserted into the barrel cross-section.

(0.25–0.27 mm) and its distribution in the magazine are known and written in the program data file for every magazine.

To load a core the needle goes above the center and comes exactly to the center from the upper side to escape the mechanical backlash. Knowing the distance from the frame center to the definite core to be loaded, the necessary number of motor steps is calculated including steps to overcome the backlash during the needle upward movement. The needle goes down, captures the core, comes back, and stops for short period (1 s) a little bit below the frame center. The program determines the exact needle position on the visual area and sends a new command to put the core just in the center of the frame. So, when the needle is visible on the monitor a picture analysis is employed with feedback to control the needle movement. Step calculations without feedback control are used for the needle movement outside the visible frame.

To protect the needle from damages there are internal PLC limits for the step motor operation. The needle will be moved down, if the temperature of the pellet former is above 9 K, and moved up, if the temperature is above 16 K.

The control program allows using two different magazines with cores. To switch the current magazine one has to click on the button “magazine number 1 (or 2).” To save the computer monitor image, including automatic savings every predetermined time interval (1,2,3, and so on, in seconds), one can use a special video panel, which appears on demand.

FIG. 5. Carbon cores outside (a) and inside (b) the light-gas gun magazine.

V. INJECTOR OPERATION

Before operation the gun magazine was loaded by the carbon or polystyrene cores, as shown in Fig. 5, and mounted to the injector. The needle outer and inner diameters were 0.60 and 0.15 mm, respectively, so that cores ranging from 0.17 to 0.23 mm in size could not penetrate it. The cooler with 1 W cooling power at 4.2 K was able to reduce the pellet former temperature from 293 to 6 K within 45 min. The temperature was measured with a Lake Shore sensor and regulated with a temperature controller and two heaters over the range from 5 to 30 K due to the power release variation. The inside of the vacuum chamber containing the cryocooler and the gun barrel is evacuated by a turbomolecular pump, while the inside of the loading unit and the pellet former is evacuated only by the rotary pump with adjusting the pressure as shown in Fig. 6.

The technology for the formation of solid hydrogen pellets around impurity cores involved the sequence of operations shown in Fig. 7 with snapshots of capsule and pellet taken by charge-coupled device cameras.

The full cycle of tracer-encapsulated pellet formation and injection takes about 5–7 min. The typical temperature and fuel gas pressure dependences versus time during formation process and injection are shown in Fig. 6. Temperature variations are depicted by dash lines, pressure ones are given by solid curves during the pellet formation and injection. In the beginning of the cycle there is a temperature jump (1) in order to evaporate possible condensate from the barrel and loading unit. During this time the needle position is calculated and it is moved to the beginning of the magazine. A

FIG. 6. Temperature and pressure monitoring during pellet formation and injection cycle: dash lines-temperature, solid curves-pressure.

pressure jump to 30 mbar (a) appears due to gas admission and condensation into the pellet former during the temperature stabilization (2) at 11 K. A solid hydrogen shell is formed and the channel between the barrel and magazine is closed allowing the needle to move down and to capture a core from the magazine cell. Just after that, a temperature jump (3) is initiated by heaters to evaporate the shell. A pressure jump to 0.62 bar (b) is appeared due to shell evaporation and vapor and suction gas pumping through the needle. The core is installed in the center of the barrel cross section during this period. The temperature is reduced and maintained near the 13 K (4) for some seconds to sublimate a thin film formed from suction gas. This film is formed when the temperature is reduced from 15 to 13 K. At this period hydrogen gas at 50 mbar is admitted into the barrel instead of suction gas (c) to keep the core on the needle. The temperature is reduced to 9 K (5); pumping of the hydrogen gas is stopped and it is condensed inside the pellet former. When the pressure is increased to 30 mbar (d) the hydrogen admission into the barrel is terminated. After condensation the temperature is increased to 10–11 K (6) in order to pull away the needle from the pellet smoothly. The temperature is reduced to 7–8 K and a pressure jump (e) due to pellet shooting is appeared. The cycle can be started again.

In case of malfunction in the automatic motor-aided core positioning, the operator looking at the computer monitor is able to adjust its position by programming extra step motor revolutions for the needle to move up or down. The time for one core to be loaded ranged from 70 to 130 s, depending on the distance between the cell and the axis of the barrel bore. The capture and positioning of the core in the channel were reliable to 90%. To make the pellet length smaller, a heater wound around the barrel and the propellant gas delivery tube on both sides of the pellet former was used. The heater caused the hydrogen frozen up on its walls to sublimate.

Prior to injection, the shell temperature was decreased to 7–8 K to enhance the ice strength. The gate valve was opened, and the fast valve admitted helium under a pressure of 2 MPa into the barrel. The gas caused the pellet with the core to accelerate up to 1.0 km/s. Flying into the diagnostic chamber, the pellet intersected a light barrier. Two signals sent out from the photomultiplier were recorded in a digital oscilloscope and one of them triggered a pulse flash to make a snapshot of the pellet in flight. Photographs of the pellets containing impurity cores and without any core are shown in Fig. 8. The velocity of a pellet was estimated from the time it took to travel a distance of 5.5 mm from one slit to another one of the optical fiber connected to the photomultiplier. Representative velocities ranged from 0.7 to 1.0 km/s.

The technology for the production of visually controllable tracer-encapsulated pellets makes it possible to guarantee almost 100% presence of the impurity core at the pellet center prior to injection, since in its absence the operator will turn on the mode of loading a new core.

VI. DISCUSSION

The technology for the tracer-encapsulated pellet formation as well as a suitable injector for introducing these pellets

1. One can see the empty and transparent cross section of the barrel on the computer monitor and press the "Load Core" button to start the loading process.		Current Time, s 0		
2. After 3 seconds a frame for determination of the barrel cross-section center is appeared.		3		
3. After 10 seconds the needle of the loading unit has appeared and stopped at the top position. This is done for correct calculation of the mechanical backlash of the needle.		13		
4. The needle goes down and stops at the center of the frame.		20		
5. The needle goes down for the next impurity core.		21		
6. The visible part of the barrel cross-section becomes smaller. It means hydrogen has started to condense on the barrel walls.		70		
7. The hydrogen shell which is at 9 K closed the channel between the barrel and magazine. Gas pushing a core from the magazine can not come to the barrel. The needle goes down to the definite core and captures it during the shell presence for 20-40 seconds.		85		
8. The temperature was increased to 30 K and the shell was evaporated and opened the channel for the needle, which can go up. Gas pressure is 150 mbar.		110		
9. The needle with the core appears. If the core is absent, one can press button "Load Core" again.		120		
10. The core is installed in the center of the barrel cross-section. Now one can press the button "Form Shell" to start the pellet formation around the core.		125		
11. The temperature is reduced and maintained near the triple point of hydrogen for a few seconds. The thin film formed from suction gas is sublimated. Hydrogen gas at 50 mbar is admitted into the barrel instead of suction gas to keep the core on the needle.		170		

FIG. 7. Sequence of the tracer-encapsulated pellet operations with snapshots.

into a plasma have been developed and successfully tested before installation on LHD. Hydrogen pellets allow a non-metal impurity core to be introduced and provides experimental plasma transport characteristics in the LHD to a depth of about half the plasma small radius. A differential pumping system with a guide tube for pellet transportation to the

plasma and cutting off a propellant gas has to be designed and installed between the injector and LHD. In continuation of this development a technology of tritium-encapsulated deuterium pellets is under investigation. Such technology allows reduced tritium exhaust from the plasma column and tritium contamination of the reactor components. This

12. The temperature and gas pressure are decreased to 9 K and 45 mbar, respectively. Hydrogen starts to condense on the walls to form a pellet.		200
13. Hydrogen continues to condense. After the pressure reaches 30 mbar, hydrogen flow into the barrel is stopped. It is done to form a pellet with a short length.		220
14. Hydrogen continues to condense.		225
15. Hydrogen closed the barrel cross-section; the pellet is not transparent yet. Condensation continued to form plane edges of the pellet in the barrel axis direction. It can take 30-150 seconds.		250
16. The pellet temperature is increased to 10-11 K and it starts to be more transparent.		260
17. The pellet reaches its maximum transparency and the core is visible on the top of the needle.		270
18. The needle starts to go down step by step with intervals of 10-20 seconds. Hydrogen forms opaque clouds around the core and needle due to friction, destruction and heat release.		271

19. The needle is definitely removed from the center of the pellet leaving a channel inside the hydrogen.		280
20. The channel becomes thinner due to hydrogen recondensation. This process is continued for 10 seconds before the needle starts to go down.		290
21. The needle is removed from the pellet leaving the core in the center. The channel formed by the extracted needle becomes thinner.		305
23. The core is in the pellet center. The channel was closed by hydrogen recondensation.		320
24. One can press the button "Injection". The control system changes a video signal from barrel to pellet camera, reduces the temperature to 7 K, opens the gate valve and wait for an external pulse for shooting. After the shot the snapshot of the pellet in flight has appeared.		400

FIG. 7. (Continued).

FIG. 8. Snapshots of solid hydrogen pellets in flight with (a), (b), (c) and without (d) impurity cores inside.

prolongs a fusion device exploitation and reduces requirements to the wall reactor materials.

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