Development and integration of a 50 Hz pellet injection system for the Experimental Advanced Superconducting Tokamak (EAST)

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Abstract: A 50 Hz pellet injection system, which is designed for edge-localized mode (ELM) control, has been successfully developed and integrated for the Experimental Advanced Superconducting Tokamak (EAST). Pellet injection is achieved by two separated injection system modules that can be operated independently from 1–25 Hz. The nominal injection velocity is 250 m/s with a scatter of ± 50 m/s at a repetition rate of 50 Hz. A buffer tank and a two-stage differential pumping system of the pellet injection system was designed to increase hydrogen/deuterium ice quality and eliminate the influence of propellant gas on plasma operation, respectively. The pressure of the buffer tank could be pumped to 1×10^2 Pa, and the pressure in the second differential chamber could reach 1×10^{-4} Pa during the experiment. Engineering experiments, which consisted of 50 Hz pellet injection and guiding tube mock-up experiments, were also systematically carried out in a laboratory environment and demonstrated that the pellet injection system can reliably inject pellets at a repetitive frequency of 50 Hz.

1. Introduction

In tokamaks, edge-localized mode (ELM) [1] is a threat to plasma facing components (PFCs) during high confinement mode (H-mode) operation. Over the past few decades, several techniques have been developed to trigger and/or mitigate ELMs, including pellet injection, supersonic molecular beam injection (SMBI), jogs to the plasma vertical position, and oscillating applied magnetic fields [1]. Compared to other ELM triggering methods, using pellets to control ELM (ELM pacing) has been widely accepted to have better H-mode confinement and less energy loss [2], and it has been carried out in several tokamaks [3–5].

EAST is a full superconducting tokamak with an advanced divertor configuration [6]. In 2014, a high-performance H-mode over 28 s was obtained with $H_{98} \sim 1.2$, which is better than the record 32 s H-mode achieved in the 2012 campaign [7]. In order to achieve better H-mode performance and longer durations, pellet ELM pacing can be used. Before running ELM pacing experiments on EAST two components should be designed: a buffer tank to increase ice quality by

reducing gas load on the extruder, and a two-stage differential pumping system that can eliminate the influence of propellant gas on plasma operation. Furthermore, the reliability and performance of the 50 Hz pellet injection system should also be verified in a laboratory environment.

In this paper, we will discuss the development and integration of the 50 Hz pellet injection system for EAST in detail. In section 2, the 50 Hz pellet injection system will be briefly introduced. The design of the pumping system will be demonstrated in section 3. Some preliminary test results and discussion of system reliability and performance will be shown in section 4. Finally, a summary will be provided in section 5.

2. 50 Hz pellet injection system

Figure 1. A 3D view of the 50 Hz pellet injector

A new pellet injector was designed for both ELM control and plasma fueling on EAST. A 3D view of this new pellet injector is shown in figure 1. This 50 Hz pellet injection system was developed in cooperation between ASIPP (China) and PELIN (Russia). Compared to the previous 10 Hz pellet injection system (PI-20) [8], the new system can operate either from 1–25 Hz with one injection module or from 1–50 Hz with both injection modules. Each module, which consists of a screw extruder and a pellet fabrication and acceleration system, can independently accomplish the whole pellet fabrication and acceleration process. The maximum 50 Hz injection of pellets with

both modules is synchronized through the programmable logic controller (PLC), which was designed by PELIN. During the first stage, only one module was installed on the system, and preliminary tests were carried out in Russia [9]. After successful exploitation of the single module operation, the system was tested with both modules at 50 Hz, and the reliability was monitored during normal operation, which will be discussed in section 4. The new pellet injection system can produce a hydrogen/deuterium ice rod continuously for more than 1000 s at 50 Hz. The cylindrical pellet has a diameter of 1.5 mm and an adjustable length that can be 1.2, 1.5, or 1.8 mm. The number of atoms in each pellet is approximately 1.28×10^{20} , 1.60×10^{20} , and 1.91×10^{20} , respectively. The pellets can be injected with a velocity of 250 ± 50 m/s, with a reliability of approximately 90% at all frequencies. Considering fueling and ELM pacing, the pellet parameters listed above were chosen. All experiments mentioned later in this paper were carried out with two injection modules that were set with two different pellet sizes (one with 1.5×1.2 mm, another with 1.5×1.5 mm) and used helium as the propellant gas.

Before injection, the system requires preparation. The extruder needs to be cooled down to approximately 10 K by liquid helium, which comes from the supply line connected to the extruder inlet, as shown in figure 1. Simultaneously, the corresponding vacuum environment needs to be maintained by the pumping system. After the pumping and cooling procedure above, deuterium/hydrogen gas continuously flows into the extruder where the gas starts to freeze and waits for extrusion. Then, a motor drives the screw of the extruder to push solid deuterium/hydrogen out continuously from the extruder through a nozzle, forming a rectangular, transparent rod. During the extrusion process, the helium flow regulator and heater stabilize the extruder temperature to ensure the quality of the ice rod. As the deuterium/hydrogen rod pushes out, the pellet fabrication and acceleration system in figure 2 cuts small pieces from the ice rod, and the pellets take shape. This newly designed pellet fabrication and acceleration system has a few improvements over the original 10 Hz pellet injection system. It has three additional vacuum chambers that can reduce the gas load on the extruder by a factor of four to five and increase the pellet injection reliability. While the cutter cuts off a pellet, the gas valve is opened to provide a pulse of high-pressure helium gas to accelerate the pellet through the gun barrels, which were assembled in the diagnostic chamber, as shown in figure 3. When the pellets fly through the diagnostic chamber, the pellet velocity is measured and recorded by the diagnostic system, as shown in figure 8. There are two laser beams spaced apart in the diagnostic chamber, and the pellet velocity is calculated by the time the pellet takes to pass through the two laser beams.

Figure 2. Schematic diagram of pellet fabrication and acceleration system:

1 – gas valve, 2 – vacuum valve, 3 – piston, 4 – cutter tube, 5 – barrel, 6 – extruded ice rod, 7 – extruder chamber, 8 – vacuum duct, 9 – flange, 10 – electromagnet. Chamber 1-3 are integrated as a buffer tank, which lies under the injector in figure 4, and chamber 4 represents the diagnostic chamber, as shown in figure 4.

Figure 3. Inside view of the diagnostic chamber shows the assembly of the two barrels.

Before the pellet enters the inner vacuum chamber of the EAST, it must go through a two-stage differential pumping system to reduce the gas pressure to a critical level (pressure of the second differential chamber must be approximately 10^{-4} Pa) to prevent the propellant gas from affecting plasma operation in the tokamak. The two-stage differential pumping system is shown in figure 4. Two differential chambers, each with a volume of 25 L, are pumped by an 870 L/s compound molecular pumping system. The two-stage differential pumping system is designed to eliminate helium gas and provide a clean passage to the inner vacuum chamber of the tokamak. In the next section, we will discuss the design of the vacuum pumping system in detail.

Figure 4. 3D view of the 50 Hz pellet injection system

3. Design of the pumping system

In order to provide a reliable vacuum environment and ensure ice quality, the pumping system for the 50 Hz working condition is an indispensable and important part of the pellet injection system. The pumping system for the 50 Hz pellet injection system was designed based on the preliminary results [9] and the PI-20 pumping system [8], as shown in figure 5.

3.1 Design of the buffer tank

As mentioned in section 2, the newly designed pellet fabrication and acceleration system has three additional vacuum chambers that are projected to reduce the gas load on the extruder. To accomplish this task, a buffer tank that consists of three vacuum chambers was designed, as shown in figure 6. During pellet injection, the propellant gas is expelled by the pumping system connected to the buffer tank. Therefore, it partially pumps out the propellant gas in the extruder chamber, which is beneficial for the improvement of the quality of the deuterium ice rod.

Figure 5. Schematic drawing of the pumping system of the 50 Hz pellet injection system

Figure 6. Schematic diagram of the buffer tank

Considering the preliminary tests of the injector [9], pumping sets (a Roots pump of 203 L/s, a Roots pump of 470 L/s, and an oil-free pump of 16.6 L/s) have been chosen for the three vacuum chambers owing to their high gas loads. This design reduces the pressure in the extrusion chamber during the 50 Hz pellet injection experiment. Propellant gas distribution data of the preliminary test [9] are listed in the table 1. The volume of each chamber is 21.43 L. Chamber 1 is connected to the 203 L/s Roots pump via a 3.3 m long pipe with an internal diameter of 100 mm. Chamber 2 is connected to the 470 L/s Roots pump via a 3.3-m-long pipe with an internal diameter of 150 mm. Chamber 3 is connected to the oil-free pump via a KF40 connector and a 1-m-long bellows with an internal diameter of 35 mm.

Table 1. Propellant gas distribution during each shot

Total	Chamber 1	Chamber 2	Chamber 3	Barrel
20-30 mbar·L	4-6 mbar·L	11-15 mbar·L	1-2 mbar·L	4-7 mbar·L

Considering the high gas load of the system, the pumping sets need to work at a pressure of

10^2 Pa to reach the maximum pumping speed. Therefore, the pressure of the chambers is assumed to be 500 Pa, which is in the range of the pumping sets' best working pressure during 50 Hz operation. Hence, the average pressure in the pipe is estimated as $\bar{P} = (P_{\text{chamber}} + P_{\text{pumpinlet}}) \approx 250$ Pa, and for all three chambers $\bar{P}D > 0.67 \text{ Pa} \cdot \text{m}$, which means that the flow in the pipes is viscous. Then, flow conductivity is given by

$$U = 1.34 \frac{D^4}{L} \bar{P}, \quad (1)$$

where U , D , L , and $\bar{P}$ are the flow conductivity, diameter, length, and average pressure of the pipe, respectively. When data are substituted into equation (1), $U_1 = 2.03 \times 10^4$ L/s, $U_2 = 1.02 \times 10^5$ L/s, and $U_3 = 1.0 \times 10^3$ L/s. The effective pumping speed can be calculated by

$$S_e = \frac{S_p U}{U + S_p}, \quad (2)$$

where S_e and S_p are the effective pumping speed and the rated pumping speed, respectively. In this experiment, the effective pumping speeds for chambers 1, 2, and 3 are 201 L/s, 467 L/s, and 11.5 L/s, respectively. Finally, the pressure of the chambers is given by

$$S_e P = Q, \quad (3)$$

where P and Q stand for the working pressure and the gas load of the chambers, respectively. The gas load, Q , can be roughly calculated by the combination of pellet injection frequency and the data of table 1. Hence, maximum frequency (50 Hz) is multiplied by the propellant gas distribution of every shot to get the gas load, Q . According to equation (3), the working pressures of the three chambers are determined to be 150 Pa, 161 Pa, and 869 Pa, respectively. Referring to the pumping speed vs the inlet pressure curve, all of the pumping sets can reach their maximum pumping speed. As all the flow conductivities of the pipes are high, the insignificant differences between the assumed pressure and the calculated pressure have little influence on the calculated results. Accordingly, the result is consistent with the assumption, and the design of the buffer tank is theoretically acceptable.

3.2 Design of the differential pumping system

Before a pellet enters the tokamak, it passes through a two-stage differential pumping system, as shown in figure 5, to pump out the extra propellant gas (helium) to a critical pressure, so the second differential chamber must be approximately 1×10^{-4} Pa. This two-stage differential pumping system has two similar vacuum chambers with a volume of 17 L, which is pumped by a compound molecular pumping set (870 L/s).

According to our simulation, approximately 1 mbar·L propellant gas will enter the first differential chamber. Because the molecular pump set is directly connected to the chamber, the effective pumping speed approximately equals the rated pumping speed. Referring to equation (3), the real pressure of the first differential chamber is 5.74 Pa at the 50 Hz injection frequency. When the pressure reaches 1 Pa, the molecular pump speed decreases, and the effective pumping speed

of 600 L/s is substituted into equation (3). The pressure of the first differential chamber is 8.33 Pa.

There is a 2-m-long pipe with a diameter of 6 mm between the first differential chamber and the second differential chamber. For this pipe, $\bar{P}D \approx 0.24 \text{ Pa} \cdot \text{m}$. This means that the flow in this pipe is viscous molecular flow. The flow conductivity is then calculated by

$$U = 121 \frac{D^3}{L} J, \quad (4)$$

where J is the $\bar{P}D$ associated function. Referring to the datasheets, J here is approximately 3.08, resulting in a flow conductivity of approximately $3.21 \times 10^{-1} \text{ Pa} \cdot \text{L/s}$. Referring to equation (3), the working pressure of the second differential chamber will be lower than $3.69 \times 10^{-4} \text{ Pa}$, which fits the requirement for the system to safely connect to the inner vacuum chamber of EAST.

3.3 Test result of the pumping system

After the successful integration of the pumping system, we tested the performance of the pumping system during the maximum 50 Hz deuterium pellet injection with helium as the propellant gas. The result shown in figure 7 indicates that the pressures in the buffer tank were at 10^2 Pa under 50 Hz operation. Moreover, it fits the theoretical calculation results in section 3.1 and 3.2 and verifies the feasibility of the design of the buffer tank. Ultimately, the test also shows that, during the 50 Hz operation, the pressure in the second differential chamber remained at 10^{-4} Pa , which satisfies the requirement needed to connect to the tokamak.

Figure 7. Pressures in buffer tank during one 50 Hz pellet injection test

4. Results and discussion

After the 50 Hz pellet injection system was integrated with both modules, experiments were carried out to investigate its reliability and performance at the maximum frequency. In order to reach the maximum frequency of 50 Hz, two injection modules should be working simultaneously at 25 Hz, which is a new challenge to the system. During the experiments, both hydrogen and deuterium were used to produce pellets (deuterium pellets have a little higher operation temperature than hydrogen ones) and test the working performance of the injector with a propellant gas (helium) pressure of 3–9 bar. A typical test result of pellet images and the number of intact pellets is shown in figures 8 and 9. This test of deuterium pellets was carried out with a propellant gas pressure of 8 bar and reliability of 95.6 %. It can be seen in figure 8 that the pellets were injected from the upper and lower channels one at a time with an interval of 20 ms. Moreover, the distribution of the injected pellets followed a Gaussian distribution with low variance, as shown in figure 9. Throughout the experiments, almost 20,000 pellets were injected, and the average pellet injection velocities of each test are depicted as a function of propellant gas pressure in figure 10. The scatter of velocities, which is approximately 10 % of the average velocity, has not been depicted in figure 10 to keep the graph clear. It can be seen in figure 10 that the average pellet injection velocity of each isotope increases with the rise of the propellant gas pressure. When the same propellant gas (helium) pressure was used, the average deuterium pellet injection velocity is lower than when hydrogen was used, owing to the higher atomic mass of deuterium. Fit lines for each isotope were also drawn in figure 10, and they show an increasing tendency, following the power function, especially in the deuterium case. This result means that, with an increase in propellant gas pressure, the average pellet injection velocity has a maximum value of approximately 250 m/s for deuterium pellets. Therefore, further enhancement of propellant gas pressure is not necessary, as it reaches 8 bar when deuterium is used.

Figure 8. Fifteen pellets were captured by the fast camera with injection sequence, time, and velocity shown on top left corner of each image.

Figure 9. Intact pellet number was plotted against the pellet injection velocity.

Figure 10. Average pellet injection velocities of each test plotted against the propellant gas pressure. The dashed lines are fit lines (black for hydrogen and red for deuterium).

In order to verify the reliability of the 50 Hz pellet injector, which is defined as the number of delivered pellets divided by the number of required pellets, the corresponding data, which includes pellet reliability and propellant gas pressure, were depicted in figure 11. It demonstrates that almost all pellet reliability data, except two cases, are located above 70 %, which is indicated by a red dashed line. It should be clarified that, under certain circumstances, long-time operation may give rise to a severe decline of the temperature of the cutter, which will influence the pellet fabrication procedure and reduce reliability of the pellet injection. Therefore, the two exceptional cases in figure 11 are reasonable. In order to avoid the situation described above, a regular warming-up of the pellet injector, which is carried out by shutting down the liquid helium supply until the temperature of the injector rises above 40 K, is necessary during long-time operation. Normally, the pellet injector can work continuously for more than 4 hours without requiring the warming up process. Alternatively, using the propellant gas to brush the injector cutter before injection is another effective way to avoid decline in injection reliability.

Figure 11. The reliability of injected pellets of each test plotted against the propellant gas pressure.

A simple mock-up test of the low field side (LFS) guiding tube was also carried out in a laboratory environment. Similar tests have already been carried out by Combs [11,12] and Lorenz [13], with interesting results. During our experiment, approximately 100 pellets were injected through the 6-m-long guiding tube, which is shown in figure 12. The average pellet injection velocity was approximately 250 m/s. An additional chamber, which was used for pellet collection, was connected to the end of the guiding tube. Aluminum foil was attached to the flange center at the end of the additional chamber, as shown in figure 13(a). At the center of the flange, a pit was designed for easier penetration of the aluminum foil to record the arrival of a pellet. A pellet causing damage and deformation of the aluminum foil is shown in figure 13(b), which means that the pellet had successfully passed through the guiding tube and penetrated the aluminum foil. Although this test is a little crude, the result can partially verify the feasibility of this type of guiding tube. An installation plan of the 50 Hz pellet injection system on EAST was recently made. The 50 Hz pellet injection system will be mounted on the C port near the main pumping pipe. The LFS guiding tube will be installed first, and preliminary experiments with plasma will be carried out such as plasma fueling and ELM control. Moreover, the high field side (HFS) guiding tube is being designed, and it will share part of the LFS guiding tube outside the C port.

Figure 12. The mock-up of the LFS guiding tube.

Figure 13. (a) The aluminum foil on the flange before the test, (b) The aluminum foil on the flange after the test.

5. Summary and future plan

A 50 Hz pellet injection system was developed with the joint effort of ASIPP and PELIN in 2015. The new pellet injection system is capable of injecting pellets with a velocity of 250 ± 50 m/s at a maximum frequency of 50 Hz. The design of the pumping system was shown in section 3, and it can meet the requirement of 50 Hz operation, as shown with theoretical calculations and experiments. Additionally, with the improved design of the pumping system, the deuterium/hydrogen ice quality and pellet injection reliability were better than the PI-20 system. Pellet injection experiments have also been systematically carried out in a laboratory environment. The data showed that the average pellet injection velocity and propellant gas pressure had a power-function relationship. Furthermore, the reliability of the injected pellets was around 90 %, which is higher than the PI-20 system, owing to the improved pumping system and the new pellet fabrication and acceleration system. The feasibility of the LFS guiding tube was also verified by a simple mock-up test.

Because this 50 Hz pellet injection system has a wider range of injection frequencies and

more pellet sizes compared to the PI-20 system, it can accomplish more complex experimental tasks in the future, such as plasma density control, L-H transition, and ELM control experiments. In the next campaign, the 50 Hz pellet injection system will be dedicated to the ELM control experiment, which has already been carried out by SMBI [10] and lithium granule injection [14] on the EAST. Owing to its high injection frequency and small size, it can be used to introduce a perturbation at the plasma edge and achieve the ELM control, which has shown desirable results of type-I ELM mitigation on other devices [3-5]. We are hopeful that we can obtain interesting data and a deeper understanding of the ELM pacing on EAST by using the 50 Hz pellet injection system in the future.

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