Study on the Sensitivity of Fast Ionization Gauge in Mixture Gas of Hydrogen and Helium*)

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The characteristics of the gas pressure measurement with the ASDEX type fast ionization gauge (AIG) in the mixture of Hydrogen and Helium is studied in this research. The calibration test stand capable of reproducing the mixture gas environment is assembled and used for the experimental calibration of the ionization gauge. In the experiment, the sensitivity of the AIG against pure hydrogen and pure helium is evaluated in order to eliminate the effect of individual differences among the AIG sensors. The mixture ratio of He in the test stand chamber is controlled from 3% to 15% to simulate the environment in divertor regions of fusion reactors. In the mixture gas, enhancement of the gauge sensitivity around 13% was observed. The enhancement of ionization due to the Penning Transferrer reactions, between the hydrogen atom and the metastable-helium atom is considered to be the main cause of the sensitivity change. Also it is found that the degree of enhancement of the AIG sensitivity can be changed drastically due to the condition of the AIG sensor. The monitoring or predicting the population of metastable-helium atoms will be important for the measurement of the mixture gas pressures.

Keywords: fast ionization gauge, divertor, gas pressure measurement, mixture gas, helium exhaust

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1. Introduction

In a fusion reactor equipped with radiator divertor, the neutral gas pressure at the divertor must be monitored and controlled properly since the amount of radiator impurity gas is one of the most important parameter to sustain detached plasma condition. The ASDEX type fast ionization gauge (AIG) is capable of measuring the gas pressure in strong magnetic field and gas pressure around 10 Pa is suitable for the measurement of gas pressures in divertors. However, carefull investigation of the AIG in a mixture of multiple species of gases is important because the gas in a divertor is expected to be a mixture of fuel-gas, helium-ashes and radiator gases.

In previous research, it was found that the sensitivity of the AIG changes due to the mixing of several gases like hydrogen-argon. In this research, the sensitivity of the AIG in the mixture of hydrogen and helium, which is the most probable combination of the gases in a fusion reactor, is investigated by using a small calibration test-stand. The mixture rate of helium in the measurements is controlled in order to simulate the mixture rate in future fusion reactors.

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2. ASDEX Type Fast Ionization Gauge

2.1 Gas pressure measurements by the AIG

The AIG is a kind of the ionization gauge and therefore the measurement of the electrical current due to the ionization is the basic method of the gas pressure measurement.

Figure 1 (a) shows the main components of the AIG. The AIG consists of the filament, the control grid, the acceleration grid and the ion collector plate aligned along the magnetic field line [1]. The linear geometry enables the AIG to work in a magnetic field without losing a linear dependence of its sensitivity on gas pressures.

The filament is made of tungsten and has thickness of 0.4 - 0.6 mm, which is much thicker than usual ionization gauges such as the Bayard-Alpert gauge (BA gauge). The thick filament is required to endure the strong electromagnetic forces from a plasma discharge experiments.

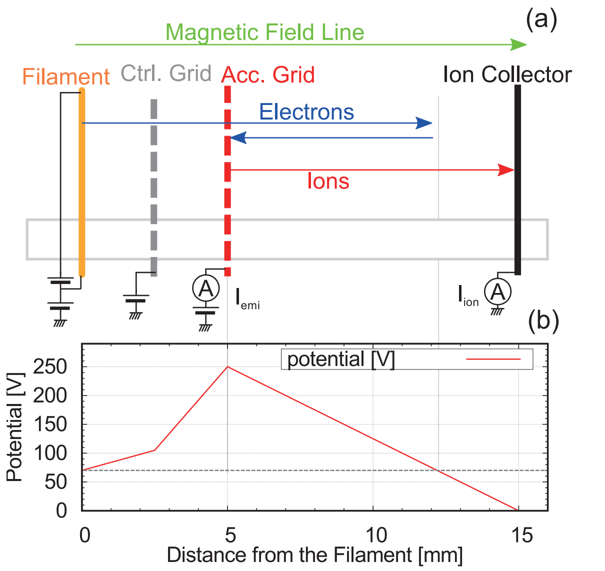

Fig. 1 (a): A schematic diagram of the AIG geometry with electrical circuits. (b): The spatial profile of the electrostatic potential applied to the filament and the grids [1].

As the electrical current is applied to the filament, the thermal electrons are emitted from the filament. These thermal electrons are extracted by the electrostatic fields around the control grid and the acceleration grid. Ionizations of gas atoms or molecules will occur when the thermal electron collides with the gas. the ions produced by the ionization will be extracted to the collector grid and detected as ion current I_{ion}.The number of thermal electron is monitored at the acceleration grid as the emission current I_{emi}. The spatial profile of the electrostatic potential in a standard operation of the AIG is plotted in Fig. 1 (b). The standard range of the collision energy of the electron impact is 0 - 180 eV.

The amount of ions detected at the collector plate is the measure of the amount of gas particle existing around the AIG. The gas pressure P around the AIG can be expressed as follows,

$$P = \frac{1}{S_{AIG}} \frac{I_{ion}}{(I_{emi} - I_{ion})}, \tag{1}$$

where S_{AIG} is the sensitivity of the AIG against the gas pressure. The value I_{ion} is the measure of the amount of ionized gas particles. Since the value I_{emi} includes both incident electrons and new electrons produced in the ionizations, the value $(I_{emi} - I_{ion})$ is used to indicate the actual amount of electrons used for the ionization reaction.

2.2 Sensitivity of AIG in pure gases

Since the AIG detects the electrical charges made by ionizations, the sensitivity is determined by the cross-section of the electron-impact ionization of gas species [2]. Therefore for pure gases, the sensitivity of the AIG is determined by the electron impact ionization cross-section

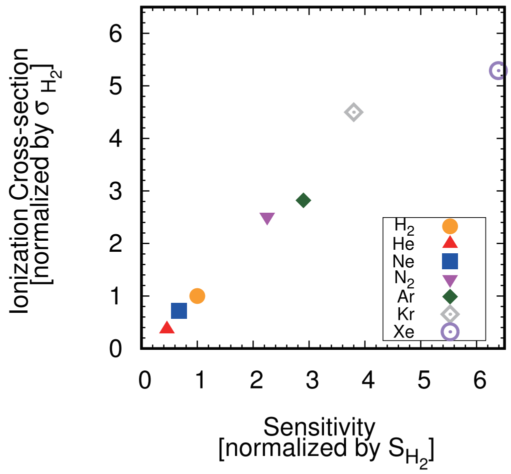

Fig. 2 The electron-impact ionization cross-sections of hydrogen, helium, neon, nitrogen, argon, krypton and xenon plotted against the sensitivity of AIG obtained by the calibration experiments.Both cross-sections and the sensitivities are normalized against the hydrogen [2].

of the target gas. Figure 2 is showing the electron-impact ionization cross-sections of many species of gases plotted against the sensitivity of the AIG obtained in the calibration experiment performed in the test stand in previous research [2]. The value of the ionization cross-section in the plot is obtained from the database at the collision energy of 90 eV [3]. As can be seen in the plot, the ionization cross-section and the sensitivity of AIG is in good linear co-relations. Assuming if the mixing of gases has no effect on the sensitivity, the sensitivity of the AIG can be expressed as the following;

$$PS_{AIG} \propto N_{H_2}\sigma_{e-H^+} + N_{He}\sigma_{e-He^+}, \tag{2}$$

where N_{H_2} is population density of hydrogen, N_{He} is population density of helium, σ_{e-H^+} is the total electron impact ionization cross-section of hydrogen, and σ_{e-He^+} is the total electron impact ionization cross-section of helium respectively.

2.3 Penning transfer in mixed gases

In the previous research it was observed that the sensitivity of AIG is affected by the mixing of multiple gases, such as argon-hydrogen or helium-hydrogen. the change of the sensitivity is considered to be the change of the ionization cross-sections due to the ionization by Penning transfer. For example, the Penning transfer in the mixture of helium and hydrogen is expressed as followings.

$$He + e \longrightarrow He^* + e, \tag{3}$$

$$He^* + H \longrightarrow H^+ + He + e, \tag{4}$$

In above, the first process is the excitation of the ground state helium atom to the metastable helium atom (He^*). Since the excitation energy of metastable helium is

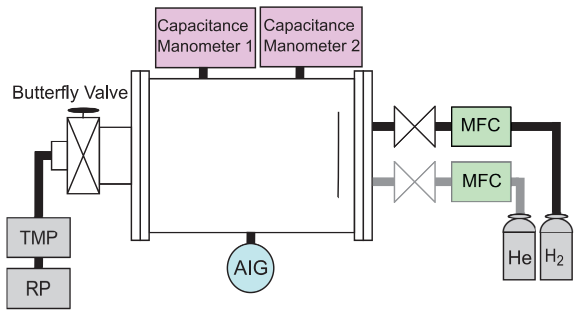

Fig. 3 A schematic drawing of the calibration test stand.

higher than the ionization energy of the hydrogen, ionization of hydrogen atom will occur when the hydrogen atom collides with a metastable helium.By taking the Penning transfer into account, the sensitivity of AIG in mixed gases ($S_{AIG_{mix}}$) can be written as;

$$PS_{AIG_{mix}} \propto PS_{AIG} + (N_{He}\sigma_{e-He^*})(N_H)\sigma_{He^*-H^+}, \quad (5)$$

where σ_{e-He^+} is the electron-impact ionization cross-section of helium, σ_{e-He^*} is the electron-impact excitation cross-section of metastable helium and $\sigma_{He^*-H^+}$ is the cross-section of the Penning transfer ionization. Typically, at the electron collision energy in the AIG, the value of N_H corresponds to 10% of N_{H^+}, the value of the σ_{e-He^*} corresponds to 1 - 2% of σ_{e-H^+} and the value of $\sigma_{He^*-H^+}$ is 100 times larger than σ_{e-H^+} [4]. Therefore if the Penning transfer is occurring, the sensitivity is expected to be increased by 10 - 20%.

3. Experimental Setup

In order to investigate the sensitivity of AIG in a variety of mixture gases, the test stand chamber is assembled [5]. Figure 3 shows the main components of the test-stand. Two mass flow controllers (MFC), two capacitance manometers (CM), AIG, butterfly valve and vacuum pumps (TMP, RP) are installed to the test-stand and two different gases can be injected to the chamber at different flow speeds controlled by MFCs individually. The absolute gas pressure in the chamber is monitored by using the CMs. Two CMs with different measurement resolutions and ranges of gas pressure are combined to cover wider range of gas pressure in the chamber. One CM is mainly responsible for the gas pressure around 10^{-2}~10^{-1} Pa, while the other CM measures the gas pressure around several Pa.

In the previous research, the change in the amount of $I_{ion}/(I_{emi} - I_{ion})$ in a mixed gas environments was observed [5]. Since the main cause of the change is considered to be the change of the ionization cross-section, the change of the AIG sensitivity can be varied by the collision energy of the electrons.

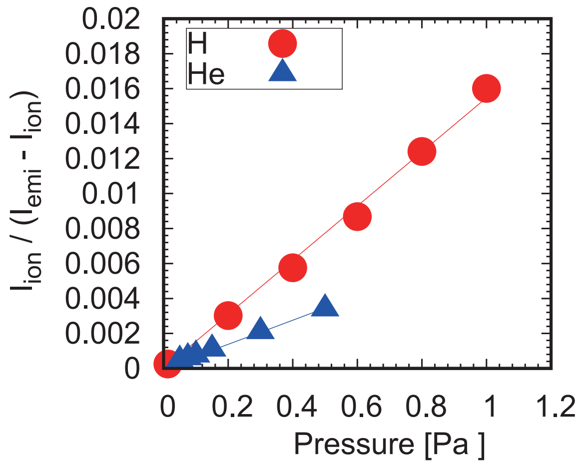

Fig. 4 Experimental results of the AIG sensitivity calibration against pure hydrogen gas and pure helium gas at the rage of the gas pressure used in the mixture gas experiments.

3.1 The concentration rate of helium gas in divertors

According to the requirements in ITER design [6], the concentration rate of helium atom should be smaller than 6% of the atoms in core plasma. By using the 6% of helium concentration and the helium enrichment factor, which is the requirements of helium exhaust speed in tokamak divertor [7], the lowest partial pressure of the helium in divertor region is 0.24% of that of the deuterium. Therefore the small concentration rate of helium in the mixture gas, such as 3 - 15% is mainly investigated in this research. Due to the controllability of the MFC in the test-stand, the lowest concentration rate of helium is 3%.

4. Experimental Results

4.1 Results in pure gases

In order to confirm the linearity of the AIG, calibration of the sensitivity against pure hydrogen and pure helium were newly performed. The results are shown in Fig. 4. The data points in Fig. 4 are newly obtained for this research in order to enhance the reliability of the sensitivity evaluation in the rage of the gas pressure used in the mixture gas experiments by eliminating the individual differences of the AIG sensors. In the measurement of pure gas, the sensitivity of the AIG is expected to be constant. Thus the value of the vertical axis in Fig. 4; the $(I_{ion}/(I_{emi} - I_{ion}))$ is a good measure of the number of ionization reactions in the AIG at the gas pressure. As can be seen in the plot, the AIG showed good linearity for both hydrogen gas and helium gas. Here, the slope of the plots corresponds to the sensitivity S_{AIG} of the AIG against each gases. The slope in Fig. 4 is evaluated by using linear fit.

4.2 Results in mixed gases

By using the two gas injection ports in the test-stand, the mixture of helium and hydrogen was produced. For

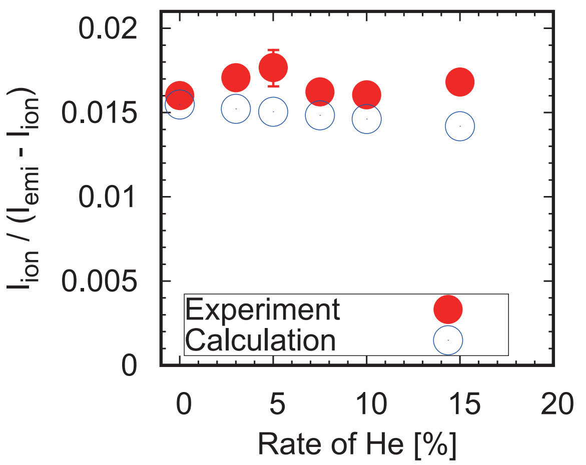

Fig. 5 Experimental results of the AIG sensitivity calibration against the mixture of helium and hydrogen. The total pressure is kept at 1.0 Pa. the calculation value means the AIG ion current evaluated from the partial pressure and the sensitivity against pure gases.The vertical error-bar indicates the typical standard deviation of the evaluation; ±6%.

the adjustment of the total and partial gas pressure, one of two MFCs was opened to set the partial pressure of one gas while the other MFC was closed. After that, MFC for the other gas was opened to achieve total gas pressure of 1.0 Pa. The concentrate ratio of helium was varied from 3% to 15% by controlling the partial pressures of the gases. The value of the ion current and the emission current of the AIG was recorded in each concentration rate. The experimental result is summarized in Fig. 5.

In the plot, the value of the $I_{ion}/(I_{emission} - I_{ion})$ measured in the mixture gas experiment is compared with that calculated from the partial pressure and the sensitivities of pure gases measured in the Fig. 4. It can be observed that the experimental values is higher than that of the calculations. The rate of increase in the sensitivity evaluated from the *Experiment*/*Calculation* is 3 - 18%. The results indicates that there was an interaction to enhance the AIG sensitivity in the mixture of hydrogen and helium.

5. Discussion

5.1 Effect of Penning transfer

As indicated in the last section, the sensitivity of the AIG is enhanced in the mixture of helium and hydrogen in the helium concentration rate of 3 - 15%. Assuming that the increase of sensitivity was caused only by the Penning transfer, the change of the AIG sensitivity is expected in the parameter of the AIG is around 10 - 20% [4]. Therefore the enhancement of the sensitivity observed in the current experiment can be explained well by the Penning transfer process.

5.2 Uncertainty of metastable atom population

On the other hand, the data of the gas mixing experiment done in previous work seems quite important for the discussion since the data is showing the much larger degree of sensitivity enhancement in the mixture of helium and hydrogen. The data of this current study focused on the smaller mixing ratio of helium is plotted together with the previous experimental results of helium-hydrogen mixture with wider range of the mixing ratio in Fig. 6 [5].

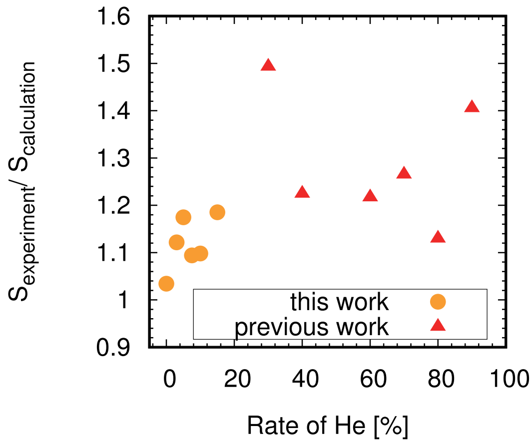

Fig. 6 Summarized plot of the sensitivity enhancement effect in the helium-hydrogen mixture at pressure of 1.0 Pa [5].

In the plot, theoretical value of the sensitivity $S_{calculation}$ for each mixture ratio of the mixture gases is evaluated as the following method;

$$S_{calculation} = R_{He} S_{He} + R_H S_H, \tag{6}$$

where R_{He} is the rate of helium and the R_H is the rate of hydrogen in the mixture gas. Therefore, 1.1 in the vertical axis in Fig. 6 corresponds to the 10% enhancement of the AIG sensitivity. As shown in Fig. 6, higher enhancement of the AIG sensitivity can be observed in the helium mixing rate done in the previous works. In the previous work, 15 - 50% of the sensitivity increase was observed in the mixture rate of helium in 20 - 90%. Also the data points from the previous work seems to be scattered drastically while the data points from this work is crowded together. This degree of sensitivity changes can not be explained by the penning transfer of the helium atoms only excited by the electron-impact collisions. Therefore processes of helium excitation other than the simple electron-impact might need to be considered to explain those large sensitivity change. For example, recycling of the helium ions at the collector plate can be a source of excited helium around the AIG. Also the conditions of the AIG sensor such as filament temperature, surface contaminations and so on might have affected the production of metastable helium. The environment in the divertor region of the fusion reactor is expected to be quite hard and therefore the effect of those parameters should be considered in the future works.

6. Summary

The sensitivity of AIG in helium-hydrogen mixture gas of helium concentration rate of 3 - 15%, which is the mixture rate close to the conditions in fusion reactor, was investigated. Enhancement of AIG sensitivity around 3 - 18% was observed in the gas. the enhancement of the sensitivity is considered to be the Penning transfer between the metastable helium and hydrogen atom. The result indicates that in future fusion devices, measurement of the gas pressure by using the method of the ionization gauge need to take the effect of Penning transfer into the account. The expected change of the sensitivity due to the Penning transfer is 10 - 20%, however, it is indicated that lager change in the sensitivity is also possible if more metastable atoms are produced around the ionization gauges. For the accurate measurement of the divertor gas pressure, further analysis with monitoring the existence of metastable atoms and the gauge status will be necessary.

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