Higher resolution helium measuring system for deuterium plasma on EAST tokamak via normal Penning gauge

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Abstract
Although the deuterium and helium have almost the same mass, a Penning Optical Gas Analyzer (POGA) system on the basis of the spectroscopic method and Penning discharging has been designed on EAST, since 2014. The POGA system was developed successfully in 2015, it was the first time that EAST could detect helium partial pressure in deuterium plasma (wall conditioning and plasma operation scenario). With dedicated calibration and proper adjustment of the parameters, the minimum concentration of helium in deuterium gas can be measured as about 0.5% instead of 1% on the other tokamak devices. Moreover, the He and D2 partial pressures are measured simultaneously. At present, the measurable range of deuterium partial pressure is $1 \times 10^{-7}$ mbar to $1 \times 10^{-5}$ mbar, meanwhile the range of helium is $1 \times 10^{-8}$ mbar to $1 \times 10^{-5}$ mbar. The measurable range can be modified by means of the adjustment of POGA system’s parameters. It is possible to detect the interesting part of the gas with a time resolution of less than 5 ms (the 200 ms because of conductance of transfer pipe at present). The POGA system was routinely employed to wall conditioning and helium enrichment investigation in 2015. Last but not the least, the low temperature plasma of POGA is generated by normal penning gauge Pfeiffer IKR gauge instead of Alcatel CF2P, which has been suspended for a few years and was used for almost all the POGA systems in the world.

Keywords: penning discharge, helium pressure detecting, low temperature plasma, PMT, IKR 251 gauge

(Some figures may appear in colour only in the online journal)

1. Introduction
Helium ash exhaust is one of the most important issues in future tokamak reactors, such as the International Tokamak Experimental Reactor and Steady State Tokamak Reactor [1, 2]. In the fusion reactors, high energy neutrons and high $\alpha$-particles (helium ions) are generated by the nuclear fusion reactions between deuterium and tritium ions. Based on the law of conservation of energy and momentum, 4/5 of the energy is transformed to neutrons and 1/5 transformed to $\alpha$ particles (helium). After slowing down of $\alpha$-particles, the accumulated helium ash in burning plasma will eventually dilute the fuel to discharge quenching [3]. Calculations show that the helium content should be less than 10% of the main plasma, otherwise the fusion process will be extinguished. To avoid reaching this limit, it is necessary to remove the helium in 7–15 times the energy confinement time [4].

Therefore the measurement of the relative and absolute concentrations of helium is one of the key issues for the tokamak device. Furthermore, the helium removal rate is one of the important criteria for deuterium wall conditioning. On the Experimental Advanced Superconducting Tokamak (EAST), the concentration of helium in divertor plenum of deuterium plasma via a helium injection at mid-plane is of
considerable interest for the investigation of the helium transportation. The measurement of helium in the plasma core has been detected by charge exchange spectrometer [5]. But for the neutral helium gas in the divertor plenum, the normal partial pressure analyzer via mass spectroscopy is impossible. The main reason is that both the measured gas helium and the working gas deuterium have almost the same atomic mass \( m(\text{He}) = 4.003 \text{ amu}, m(\text{D}_2) = 4.028 \text{ amu} \). Omegatrons is one kind of particular design analyzer to overcome this difficulty [6]. However, it could not be applied in EAST, because it is quite sensitive to magnetic field turbulence, and it works only below \( 10^{-3} \text{ Pa} \), last but not the least, the time resolution is as low as about 60 s [7].

However, the He-I and D-\( \alpha \) line emission is quite different (He-I: \( 5876 \AA \), D-\( \alpha \): \( 6561 \AA \)), and this dissimilarity highlights a feasible way to measure helium with deuterium as a working gas for tokamak. This paper investigates a novel diagnostic system to distinguish helium from deuterium via Penning discharge that generated by normal penning gauge Pfeiffer IKR gauge instead of Alcatel CF2P, in combination with filters, fibers, collimating and condenser lens, and photomultipliers. Although, D-\( \alpha \) makes a considerable contribution to line \( 5876 \AA \) (He-I), a dedicated calibration will easily reduce this disadvantage. Based on the quantitative calibration, the fitting formula of partial pressure of helium \( (P_{\text{He}}) \) and deuterium \( (P_{\text{D}_2}) \) determined by line intensities of He-I and D-\( \alpha \) lines are obtained.

POGA is a kind of diagnostic system which detects helium with deuterium as a working gas. POGA has been comprehensively developed and used on many advanced tokamaks (JET, TEXTOR, TFTR, ASDEX-U) to measure noble gas concentrations in deuterium environments, as well as H isotopic ratios [7–10]. The Alcatel CF2P has been suspended for a few decades, but up until now almost all the POGA systems used it to generate plasma. It is necessary to develop a novel economic POGA system with a higher resolution and lower noise via a commercial penning gauge. The new POGA on EAST base on Pfeiffer IKR gauge instead of Alcatel CF2P was developed successfully in 2015. This system has been applied to investigate the removal rate of helium/deuterium for wall conditioning and the helium enrichments for the plasma scenario. In this paper, the system will be introduced in section 2. The diagnostic system’s calibration will be illustrated in section 3. Primary results on the removal rate of helium/deuterium for wall conditioning and the helium enrichments for plasma scenario will be given in the section 4. The conclusion and discussion will be shown last.

2. Penning optical gas analyzer system

2.1. System setup

The main principle of a POGA system is that the residual gas in divertor plenum was detected by exciting the neutral gas by a Penning discharge of a normal Penning gauge Pfeiffer IKR and measuring the characteristic emission lines of helium and deuterium. The broad spectral lines from the deuterium molecules superpose the He lines and impact on the system’s measuring limits. Taking the advantages of collimating lens, high euphotic (transmissivity >99%) optical fibers and effective PMTs, the limits of EAST POGA system are evidently weakened.

The procedure of POGA to detect helium and deuterium pressure is as follows: (1) The neutral gas that consists of helium and deuterium is ignited in a commercial Penning gauge chamber via PFEIFFER IKR gauge. As figure 1 shows, in order to easily transfer as much light as possible into the fiber bundle the geometry of the Penning gauge’s polarity is modified. (2) Consideration of the fiber aperture and the concerned wavelength, the collimating lens is before fiber bundle parallel to the light fibers. (3) The transmission light is split 50%–50% via half mirror at the end of fiber bundle. (4) The filters require an incident angle less than 3 degrees, so the light from the half mirror needs another set of collimating lenses to fulfill this function, by the way, the difference of wavelength for helium and deuterium should be considered. (5) The filter’s diameter is \( \sim 50 \text{ mm} \) and the photomultiplier

![Figure 1. The modification of the IKR gauge’s polarity for POGA system on EAST. The left figure is the original polarity, and the right is the modified one. In order to reduce the polarity and to obstruct too much light, it was carved as much as possible.](image-url)
tube (PMT) effective area is just 8 mm. Consequently, the light is to be focused by condenser lens. (6) The currents of PMT are converted to voltage signal by $I/V$ unit. (7) At last with the assistance of computer and calibration formulas the pressure of helium and deuterium could be generated by the voltage signals of He-I and D-α. The whole schematic of this novel system is shown in figure 2, it consist of a Penning unit, fiber bundle, half mirror, filters, and so on. This diagnostic system was fulfilled and validated in 2014 and therefore is regularly used in 2015 for the wall conditioning and plasma operation phase.

2.2. POGA on the EAST

The experimental setup on the EAST is the same as shown in figure 2 except that the Penning gauge is mounted on the differential pumping system under the duct of a low divertor in order to maintain the vacuum chamber of POGA system as lower than 10 Pa, as shown in figure 2.

The residual neutral gas consisting of helium and deuterium enters into POGA’s chamber through a 21 mm in diameter and 3 m in length tube below the neutralization plate of the EAST lower divertor plenum. The neutral gas mixture is not be confined by the magnetic field and enters into the plenum, then is pumped by the differential pump of POGA system. It is fiber-optically coupled to the PMT located remotely from the tokamak hall (50 m as show in figure 3) and is a key component of POGA system sensor. This so-called long distance allows all of the high-gain electronics to be shielded from any noise pickup in the potentially high EMF fusion environment. This permits an easy exchange of the PMTs, lenses or filters during EAST operation, too. The PMT and fiber enable a sub-millisecond time resolution of the pressure measurement. Therefore, the time resolution of POGA system on EAST is determined by conductance of the transfer tube from divertor plenum to POGA. The tube response time could be calculated by equations (1)–(3) [11]. The simulation result in figure 4 shows that the time resolution of POGA is $\sim$200 ms for EAST.

$$\alpha = \frac{CL}{S}$$  \hspace{1cm} (1)
Figure 4. Tube response simulation for \( l = 3 \text{ m} \) \( d = 21 \text{ mm} \) in a molecular regime.

\[
P_{\text{b}}(x, t) = \frac{\alpha \pi}{L^2} \sum_{n=0}^{\infty} (-1)^n (2n + 1) \exp \left( -\alpha \pi^2 (2n + 1)^2 t \right)
\times \cos \left( \frac{\pi (2n + 1) x}{2L} \right)
\]

\[
P_m(t) = \int_0^t P_0(t') P_0 \delta(L, t - t') \, dt'
\]

Where \( L \) is the length of tube, \( S \) is the area of section, and the signals of the pressure at the entrance and end of the tube are \( P_0(t) \) and \( P_m(t) \), respectively. The flow regime, in the tube of conductance \( C \), is molecular. By the way, the Penning gauge is not shielded, because of the magnetic field surrounding the gauge is less than 0.0005 T. Considering the turbine molecular pump’s species-selective characteristics, the pump speed is greater than the transfer tube conductance by one order of magnitude.

3. System calibration for helium with deuterium as working gas

Figure 5 shows the experimental setup for the calibration of POGA system in a laboratory. The calibration system is composed of a vacuum vessel with a Penning gauge to ignite spectra lines, a few pressure gauges, high-pressure cylinder, pressure relief valves, and a vacuum chamber with a gas mixing and an inlet system allowing an arbitrary mixture of He/D\(_2\) through two throttle valves on the downstream of He/D\(_2\) gas flow at pressures between 1000 mbar and 2000 mbar. The pressure of this chamber is measured by capacitance diaphragm gauge, and the pressure of the Penning vessel is monitored by a hot ion gauge. Last but not the least, the whole system’s leak tests are fulfilled by a quadrupole mass spectrometer.

Before calibration, the chamber for mixing gas is baked to 100 degrees celsius pumped to \( 1 \times 10^{-6} \text{ mbar} \) more than 24 h to reduce the noise as much as possible. The Penning discharge vessel is baked to make sure the background vacuum is \( 1 \times 10^{-6} \text{ mbar} \). Different ratios of mixture gas (He/(He + D\(_2\)) = 0%, 0.5%, 1%, 5%, 10%, 20%, 100%) are produced by the throttle valves on the downstream of He/D\(_2\) cylinders. In order to get the relation of pressure and intensity of spectral lines, the Penning discharge vessel needs to keep vacuum constant from \( 8 \times 10^{-10} \text{ mbar} \) to \( 1 \times 10^{-2} \text{ mbar} \). Normally, the cold cathode gauge’s pressure is increased with an ion current following the power function. Furthermore, linear dependence is another common relationship for original signal to real data. Comparing of power function (figure 6(a)) and linear formula (figure 6(b)) regress stats, result shows that the pressure of deuterium is increased with the intensity of D-\( \alpha \) following power function, in range of \( 1 \times 10^{-7} \text{ mbar} \) to \( 1 \times 10^{-5} \text{ mbar} \) as shown in equation (4), instead of linearly. The reason is that \( R \) of power function is 0.9752 and its \( F \) is 630, but \( R \) and \( F \) of linear formula are 0.9421 and 298 respectively.

The strongest He line observed with the CCD camera in visible range is the 3d3D–2p3P line at 587.6 nm [7]. This spectral line will be influenced by the background light from molecular hydrogen isotopes strongly (for D-\( \alpha \) strongest emission line is 656.1 nm, but there is another emission line near 587.6 nm). Therefore, the helium pressure equation should not only consider He-I intensity, but also consider the intensity of D-\( \alpha \). By comparison of power function (figure 7(a)) and linear formulas (figure 7(b)), the linear formula is better for the helium pressure regress to intensity of spectral lines in pressure range of \( 1 \times 10^{-8} \text{ mbar} \) to \( 1 \times 10^{-5} \text{ mbar} \). Equation (5) shows the relation of helium pressure to intensity of He-I and D-\( \alpha \). For helium regress, the \( R \) of power function is 0.3856 and the \( F \) is 37.658, though, the \( R \) and \( F \) of linear regress are 0.9238 and 237, respectively.

\[
P_D = (I_{D-\alpha})^{0.9261/10^{6.82301}}
\]

\[
P_{He} = 7.94 \times 10^{-8} \times (I_{He-I}) - 1 \times 10^{-9} \times (I_{D-\alpha}) - 3.188 \times 10^{-7}
\]

Where \( P_{D2} \) is deuterium pressure, \( P_{He} \) is pressure of helium, \( I_{D-\alpha} \) is intensity of D-\( \alpha \), and \( I_{He-I} \) is intensity of He-I. By calibration, this novel system not only measures the quantitative pressure of deuterium and helium in a wide range, it detects the qualitative data of helium concentration as lower as \( \sim 0.5\% \).

4. Results for EAST wall conditioning and plasma scenario

The POGA system has been investigated since 2014, and it is routinely used for monitoring the He/D\(_2\) removal rate in D\(_2\)/He wall conditioning and in 2015 calculating the helium enrichment in a plasma scenario. For EAST ICRF wall conditioning operation, the frequency is 27.12 MHz, and the ICRF power is from 10 kW to 30 kW with a toroidal magnetic field in the range of 0.5–1 T, at present. It is well known that the relative high bonding energy impurity that is deposited or redeposited in plasma facing components (PFC) during plasma operation needs high energy ions to desorb. This wall
conditioning experiment is carried out after one day’s plasma operation, so the helium content close to zero. Therefore, at first, the He-ICRF is carried out to investigate its effect on deuterium removal, meanwhile, this procedure introduces helium into PFCs via absorption, deposition, diffusion, and so on. The D-ICRF is subsequently performed to study the helium removal.

All four Varian turbo-molecular pumps with a total effective pumping speed of $10^4 \text{s}^{-1}$ are used during ICRF wall conditioning, and helium is puffed by the gas filling system with the pressure feedback controlled at $3 \times 10^{-4} \text{mbar}$. The pulsed ICRF wave with the period of 0.3 s on and 1.03 s off is applied to generate plasma. Figure 8 shows the deuterium partial pressure measured via POGA

Figure 5. Experiment setup for the calibration in laboratory.

Figure 6. Compare the power function and linear formula (the formulas on the top left corner of each figure) with standard gauge for D$_2$ absolute pressure (6561 Å) (a) evaluate power function with standard gauge for deuterium pressure, (b) evaluate linear formula with standard gauge for deuterium pressure.

Figure 7. Compare the power function and linear formula (the formulas on the top left corner of each figure) with standard gauge for He absolute pressure (6561 Å/5875 Å). (a) evaluation of power function with standard gauge for helium pressure, (b) evaluation of linear formula with standard gauge for helium pressure.
system evolution during He-ICRF. When the 6 kWs ICRF pulse is applied, the deuterium removal rate increases to 0.155 Pa l s⁻¹ rapidly. Whereas, the rate decreases to 0.1 Pa l s⁻¹ in less than 20 min because of the lower power of ICRF wave. It is observed that the deuterium removal rate increases to the maximum value 0.135 Pa l s⁻¹ in about 20 min, the rate is maintained for a few minutes then decreases to 0.12 Pa l s⁻¹.

Figure 9 shows the time evolution of helium partial pressure detected by POGA system during D-ICRF with different applied ICRF power.

Figure 8. Time trace of deuterium partial pressure measured by POGA system during He-ICRF with different applied ICRF power.

Figure 9. Time trace of helium partial pressure detected with POGA system during D-ICRF with different applied ICRF power.

Figure 10. Typical plasma discharge (shot #48.525) for the He enrichment experiments, where 100% high pressure helium gas is injected into EAST from lower field side. From top to bottom: plasma current, central density, elongation ratio, intensity of He-I and D-α emission, partial pressure of D₂ and He, the ratio of He to D₂.

Figure 10. Typical plasma discharge (shot #48.525) for the He enrichment experiments, where 100% high pressure helium gas is injected into EAST from lower field side. From top to bottom: plasma current, central density, elongation ratio, intensity of He-I and D-α emission, partial pressure of D₂ and He, the ratio of He to D₂.

EAST is the first all superconducting tokamak with a double null divertor configuration. The first limiter plasma was obtained in September 2006, and the first divertor plasma was obtained in 2007 [12]. Helium enrichment is one of key issues to evaluate the divertor closure. To study the removal of helium ash in future tokamak, experiments with deuterium plasmas and helium puffing are carried out. Figure 10 shows the typical EAST shot (#48.525) plasma parameters and the partial pressures of helium and deuterium measured by POGA system. Compare with the ratio of the plasma core, which is provided by Thomson Scattering (TS) and multiply spectrometers in mid-plane, the enrichment of this shot calculated by formula (6) is about 0.23 at 3 s for shot #48.525 plasma (the ratio of divertor is 0.175, and the plasma ratio is 0.76).

\[ \eta = \frac{(P_{He}/2P_{D2})_{\text{Divertor}}}{(\bar{n}_{He}/\bar{n}_{e})_{\text{main plasma}}} \]  

5. Conclusion and discussion

The deuterium and helium have almost the same mass, a POGA system based on spectroscopic method and Penning discharging that is generated by normal penning gauge Pfeiffer IKR gauge instead of Alcatel CF2P, the latter has materials are tungsten, and the other PFC is Mo. As we all know, deuterium combines with PFC materials more easily than helium, especially for poly porous carbon. This is one of the reasons that the deuterium removal rate is one order of magnitude greater than helium removal rate, the other reason is that the He-ICRF wall conditioning energy is quite low compared with deuterium plasma operation for gaseous introduce into PFC.
been suspended for a few years and was used for almost all the POGA systems in the world. Since 2014, the system has been developed on EAST successfully. In 2015, the POGA system was applied for wall conditioning and plasma operation routinely. Take advantage of the collimating lens, high euphotic optical fibers and effective PMTs, the measurable minimum limits of this new EAST POGA system are extended evidently. Based on dedicated calibration, the concentration of helium in deuterium gas can be calculated from 0.5%. Moreover, the He and D₂ partial pressures are detected simultaneously. Based on the EAST operation zone, the system parameters are regulated to a proper value. At present, the measurable range of deuterium is $1 \times 10^{-7}$ mbar to $1 \times 10^{-5}$ mbar, meanwhile the range of helium is $1 \times 10^{-8}$ mbar to $1 \times 10^{-5}$ mbar. It is now possible to calculate the interesting part of the gas with a time resolution of less than 1 ms (it is 200 ms at present for EAST, because of conductance of transfer pipe). This system is employed to investigate the influence of ICRF power on wall conditioning effect in 2015. The results show that: The deuterium removal rate increases to more than 35% when the He-ICRF power raise from 6 to 12 kW; However, the helium removal rate increases not so obviously, the possible reason is that the helium retention is too low. The helium enrichment is investigated with this system, the result shows that the present enrichment is almost 0.23 for EAST shot #48 525 @3 s. The measurable range of deuterium and helium partial pressure can be changed via adjusting the POGA parameters. In order to improve the time resolution, a new design of POGA system is carried out for in situ measuring.

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