A species-selective Penning gauge, previously applied to He partial pressures, has been applied to the detection of small concentrations of Ne in a D₂ gas. This is important for the study of Ne in the boundary region of magnetic fusion devices, where this impurity is deliberately injected to enhance the radiated power in that region. The application of the technique to the detection of the partial pressure of a minority hydrogen isotope is also examined. In this latter application, the detection system and the data analysis are more complex, because of the proximity of the spectral lines from the isotopes. In both applications, it is found that use of a proper detection scheme permits reliable measurements of concentrations as low as 0.5% of the minority neutral species, without requiring changes to the standard commercial Penning gauge setup.

I. INTRODUCTION

A technique for the detection of partial pressures of He in a H₂ or D₂ neutral gas, originally developed at KFA-Juelich for use on the TEXTOR tokamak, used the optical emission from neutrals excited in the discharge of a commercial Penning-style pressure gauge [FINKEN]. This development was motivated by the fact that it is difficult to distinguish He from D₂ using quadrupole mass spectroscopy [HIROKI]. The simplicity of this technique and the possibility of relatively high time resolution (limited only by the conductance to the gauge),
has recently motivated its application to neon [DENNER, MANK], which is the preferred gas for radiative cooling of the plasma boundary.

As will be seen in more detail in Section II, the spectral lines of Ne I in the visible range of the spectrum are often comparable to the numerous D₂ molecular lines in the neighborhood of these lines. This creates a cross-talk problem for the interpretation of the data, such as discussed by Finken [FINKEN] for the case of the He I lines. By cross-talk, we mean the appearance of a finite signal on the helium channel, even in an 100% hydrogen or deuterium environment. Difficulties in the interpretation of data from early attempts to carry-out Ne partial pressure measurements directly in the divertor of the DIII-D tokamak, motivated this study in our laboratory.

A schematic of the laboratory setup used for these studies is shown in Fig. 1. The commercial Alcatel model CF 2P Penning gauge head is used here, as it has been for all the tokamak applications mentioned above. The gases to be mixed are introduced successively into the mixing volume, MV, while monitoring the resulting total pressure using a capacitance manometer (CM) with a 1 bar head. This pressure was typically raised up to 0.5 bar, in order to assure complete mixing of the gases. The experiments were conducted with constant gas flow, manually regulated by means of a precision leak valve (LV). The pressure in the vacuum chamber is monitored with a 1 mbar head CM.

Like in the case of the He measurement, interference filters are also used for the selective detection of the neutral Ne and H/D spectral lines. The usual assembly, featuring a beam splitter to split the light from the optical fiber to the two channels is also used here. A 1mm core plastic-clad silica (PCS) optical fiber is used to conduct the light from the Penning gauge to the beam splitter assembly. Since it is impractical to use filters much smaller than 20Å in bandpass, it is useful to determine the calibration of a system with such filters, even if there is a cross-talk problem.

The application to hydrogen isotopes is largely motivated by the need to measure tritium concentrations in the JET tokamak, which is planning to soon enter into a D-T operation phase [HILLIS]. The inherent difficulty in this measurement comes from the proximity of the Balmer-α lines of the hydrogen
isotopes (H_α - 6562.79 Å, D_α - 6561.03 Å and T_α - 6560.44 Å), which precludes the use of interference filters. For this application, we used a 1 m Czerny-Turner spectrometer (McPherson 2051), equipped with a 1200 lines/mm grating and a Peltier-cooled frame-transfer CCD detector from Wright Instruments, Ltd. The resulting dispersion is 0.16 Å/pixel at the CCD detector (which has square pixels 0.022 mm wide). Then, the optical fiber, which is normally attached to the beamsplitter assembly, is redirected to the entrance of the spectrometer. As shown below, this setup is adequate for use with H/D. For application to T/D, the resolution of the system will have to be improved by providing a 2400 lines/mm grating, resulting in a linear dispersion of 0.08 Å/pixel, which will double the effective resolution.

The availability of this high resolution spectrometer in the calibration laboratory made it possible to also examine the spectra in the region of various Ne I lines in the Penning discharge with Ne mixed in at various concentrations of interest to the DIII-D application. This is important to determine the relative strength of the Ne I line of interest to any interfering lines within the bandpass of the interference filter.

II. TEST RESULTS WITH NEON.

The low sensitivity encountered in the DIII-D measurements of Ne in the divertor region can be understood by looking at such spectra. For example, the spectrum in the approximate bandpass (∼20 Å) of the Ne I 6929 Å interference filter is shown in Fig. 2. In this figure, offsets are introduced artificially to separate the spectra taken with different concentrations in D_2. We see that the line is generally weak and there are many molecular features in the spectral region. In particular, the D_2 molecular line at 6935 Å is more intense than the Ne I line at concentrations lower than 1%. A similar spectral survey in the region of the He I lines by Denner shows a much smaller contribution by the molecular lines [DENNER].

In addition, it is noted that the molecular lines are actually resolved parts of very broad molecular bands which span the entire region around this Ne I line (as well as all other lines that we have considered). As a result, reducing the bandpass of the interference filters, does not completely eliminate the problem.
Of course, the narrower bandpass complicates the design of the optical system and is usually associated with higher cost and/or reduced transmission.

Therefore, when using the standard detection system with photomultiplier tubes and interference filters, it is important to correct for the cross-talk in the analysis of the data. In our calibrations, even with only pure D\textsubscript{2} in the calibration chamber, we get a finite signal on the Ne channel, which increases linearly with the total pressure. In Fig. 3, we plot the Ne channel signal minus this pressure dependent "offset" as a function of the total pressure for various concentrations of Ne in D\textsubscript{2}. We note that, in the range of pressures that are of interest to pumped limiter or divertor systems (i.e. \(\sim 1-5\times 10^{-6}\) bar), neon concentrations as low as 0.5% can be clearly detected. Up to \(5\times 10^{-6}\) bar, the monitored D\textsubscript{\alpha} signal follows the same nearly-linear dependence on the total pressure as the neon (uncorrected signal) and is virtually independent of the neon concentration (for such small amounts). Above that value, the D\textsubscript{\alpha} signal clearly reflects the saturation of the Penning discharge. (Even with visual inspection of the glow one observes clear changes in the discharge at such high pressures).

III. NEON MEASUREMENTS IN THE DIII-D DIVERTOR.

The Penning gauge presently installed on DIII-D is mounted on a vacuum appendage of the DIII-D divertor pumping plenum. The primary purpose of this gauge is the measurement of helium partial pressures in this pumping plenum, but with the proper modifications to the detection optics, measurements of both neon and argon partial pressures have been made [MAINGI]. To measure neon partial pressures, the present system uses a 10-Å FWHM bandpass filter centered at 6401 Å (a different Ne I line) for the neon channel, a 20Å bandpass H\textsubscript{\alpha} filter for the H/D channel and differential pumping such that operation of the gauge up at high plenum pressures (\(>10^{-5}\) bar) is possible. Differential pumping is required because of non-linearities in the optical emission of the gauge at pressure above \(2\times 10^{-6}\) bar. Note that the time response of this gauge to changes in the plenum is conductance limited by the aperture necessary for differential pumping and is on the order of 250 ms. This system has also been calibrated in situ over a wide range of conditions with deuterium pressures ranging from \(0.01-20 \times 10^{-6}\) bar and neon concentrations from 0.25-10 %. 
As an example of the capabilities of this gauge to measure neon partial pressures in the presence of deuterium, the raw and analyzed data from a calibration sequence specifically designed to measure the neon pumping speed of the divertor cryopump in the presence of deuterium is shown in Fig. 4. In this sequence, steady injection of D$_2$ gas between 0 and 70 s coupled with simultaneous pumping leads to a steady D$_2$ pressure of 2.5x10^{-6} bar. Short neon gas puffs are injected at 10 s, 25 s, 40 s, and 55 s allowing sufficient time for the neon to be exhausted by the divertor cryopump subsequent to each puff. The proper correction for the cross-talk in the analysis is evident from the fact that the resulting partial pressure measurement returns to zero at the end of each puff and pump-down (Fig. 4d).

VI. TEST RESULTS WITH HydroGEN ISOTOPES.

The above mentioned spectrometer system has a linear dispersion that corresponds to 0.16Å/pixel at the CCD detector (which has square pixels 0.022mm wide). As a result, the H$\alpha$ and D$\alpha$ are separated by at least 10 pixels, as seen in Fig. 5a, where the H$\alpha$/D$\alpha$ spectrum is shown for equal partial pressures. We find, however, that for small concentrations of one of the isotopes this resolution is minimal. As seen in Fig. 5b, the shape of the spectral profile of each line can be separated into two Gaussian components. The narrow component is unresolved and therefore appears the same as the instrumental function (which in the case of the non-intensified CCD detector is a simple Gaussian). The "hot" component has typically a FWHM of about 1.12Å (7pixels) corresponding to a "temperature" of about 5eV.

Figure 6 shows the dependence of both components and of their ratio as a function of the pressure (data taken with only H$_2$ in the test stand). While both components increase monotonically with the pressure, the ratio clearly changes, with the hot component playing a somewhat lesser role at higher pressures.

The presence of two distinct components in the H$\alpha$ spectral profile can be understood by examining the various dissociation channels of the H$_2$ molecule [JANEV]. To dissociate H$_2$ into H$^0$ and H$^0$ requires electron energies of at least
10 eV. Furthermore, the dissociation into H+ and H0 requires electron energies of at least 20 eV. And while the electrons in the main glow of the Penning discharge are likely to be at a low temperature (T_e~5eV), one would expect significant electron population at both 10eV and 20eV, and above, both in the tail of the thermal distribution, but in the cathode fall (the bias of the anode ring is about 2.5kV with respect to the cathode plates). These high energy electrons are responsible for most of the excitation and ionization of the neutrals, which is essential for the operation of the gauge.

At electron energies below 26eV, the dissociation into H+ and H0 produces H neutrals with mean energy of 0.25eV. The Doppler shift corresponding to 0.25eV is too small to resolve from the instrumental function. As a result, the effect on the spectral profile appears as a component similar to the instrumental function. At electron energies above 38eV, the same dissociation produces H neutrals with a mean energy of 7.8eV. On the other hand, the dissociation into H0 and H0 produces neutrals with a mean energy of about 3eV. The measured spectral broadening, which corresponds to about 5eV, is most likely a hybrid of contributions from both dissociation channels. Curiously we find that with pure D2 in the calibration chamber, the hot component is systematically broader, corresponding to a 4.8 eV average energy, compared to 4.3 eV for pure H2 and 4.5 eV for a 50/50 H2/D2 mixture. We suspect that operation in deuterium changes the characteristics of the Penning discharge, which in turn affects the energy distribution of the electrons.

Figure 7 shows the dependence of the relative intensity of Dα to total Dα+Hα (including both hot and narrow components in the integration under the spectral lines) on the known concentration of D2 in the H2 and D2 mixture. All the points shown are at the same total calibration chamber pressure (1x10^-6 bar). The resulting linear dependence makes this a promising diagnostic for isotopic ratio measurements on fusion devices.

V. DISCUSSION AND CONCLUSIONS

In this study, the characteristics of a species-selective Penning gauge, when applied to partial pressure measurements of Ne and of hydrogenic isotopes,
have been systematically examined. In the case of neon, it was found that the simple detection method of using reasonably narrow (~20Å) interference filters and photomultiplier tubes, is sufficient for measurements of neon concentrations as low as 0.5% in the pressure range of interest (0.1-5x10^{-6} bar). The cross-talk, which results from molecular lines of H₂ or D₂ in the neighborhood of the neutral Ne lines, can be corrected in the calibration, as shown above. The simplicity and the fast time response capability of this diagnostic (compared to a quadrupole mass analyzer, for instance) has made it a choice diagnostic for radiative divertor experiments on DIII-D.

In the case of the separation of the hydrogen isotopes, it was shown that a standard spectrometer system, equipped with a state-of-the-art CCD detector can provide sufficient resolution to determine partial pressures in the range of 10^{-7} to 10^{-5} bar. The lower limit for determination of a minority isotope is about 0.5%. These results make this a promising diagnostic for T/D isotopic detection and such a system is presently being installed on the JET tokamak.

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REFERENCES


FIGURES CAPTIONS

Fig. 1. Schematic of the Penning gauge calibration setup (MV: Mixing volume, TMP: 150 l/s turbomolecular pump).

Fig. 2. Ne spectra with various percentages of Ne in D$_2$ (the only line that changes is the Ne I line at 6929.4Å; the other features are D$_2$ molecular lines).

Fig. 3. Ne I signal (corrected for the cross-talk from the molecular lines) vs total pressure for various concentrations of Ne in D$_2$.

Fig. 4. Time evolution of the D$_2$ and Ne during an in-situ calibration on system installed at DIII-D (a&b). Calibrated partial pressures are also shown (c&d).

Fig. 5. H$_\alpha$/D$_\alpha$ spectrum for a (a) 50/50 and (b) 90/10 H$_2$/D$_2$ mix. A fit of the data to a 2-Gaussian model is shown in (b) for the H$_\alpha$ only. (The difference in the central pixel position between (a) and (b) is due to a slightly different spectrometer setting).

Fig. 6. Intensities (from area under the curve) of H$_\alpha$ hot and narrow components vs total pressure.

Fig. 7. The ratio of intensities D$_\alpha$/(H$_\alpha$+D$_\alpha$) vs the known concentration of D$_2$ in the H$_2$+D$_2$ mixture, for constant p(H$_2$+D$_2$) = 1x10$^{-6}$ bar.
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Fig. 2

Intensity (a.u.)

Wavelength (Å)

Ne I 6929 Å

2%Ne
1%Ne
0.5%Ne
0%Ne
Fig. 3
Figure 5

(a) Graph showing relative intensity vs. pixel number with peaks labeled $D_\alpha$ and $H_\alpha$.

(b) Graph showing relative intensity vs. pixel number with peaks labeled $D_\alpha$ and $H_\alpha$. Annotations include 'Narrow' ~3 pixels and 'Hot' ~5eV.
Hydrogen only

Broad ("hot") component

Narrow (unresolved) component

Intensity (a.u.)

Pressure ($10^{-6}$ bar)

\[ f_i \]
The diagram shows the relationship between $D_2$ pressure normalized by total pressure and $D_\alpha$ intensity normalized by $(D_\alpha + H_\alpha)$ intensity. The data points form a straight line, indicating a linear relationship between the two variables.

$D_\alpha$ intensity / $(D_\alpha + H_\alpha)$ intensity

$D_2$ pressure / total pressure