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†Oak Ridge National Laboratory
‡Palomar College
◊Institute for Atomic and Molecular Physics
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ABSTRACT

Partial pressure neutral gas measurements have been made using a commercial Penning gauge in conjunction with an "active spectrometer." In prior work utilizing bandpass filters and conventional spectrometers, trace concentrations of the hydrogen isotopes H, D, T and of the noble gases He, Ne and Ar were determined from characteristic spectral lines in the light emitted by the neutral species of these elements. For all the elements mentioned, the sensitivity was limited by spectral contamination from a pervasive background of molecular hydrogen radiation. The active spectrometer overcomes this limitations by means of a digital lock-in method and correlation with reference spectra. Preliminary measurements of an admixture containing a trace amount of neon in deuterium show better than a factor of 20 improvement in sensitivity over conventional techniques. This can be further improved by correlating the relative intensities of multiple lines to sets of reference spectra.

I. INTRODUCTION

Studies of divertor impurity enrichment rely on measuring impurity concentrations in the core plasma, the divertor plasma and the divertor pumping plenum. Typically, noble gases such as helium, neon and argon are used because their recycling character permits active control of impurity sources and sinks, as well as precise knowledge of the source/sink locations and their quantitative values. These gases are typically introduced through an impurity gas injector. Since radiation from the multiply-ionized charge states of these elements degrade energy confinement in the core of the plasma column, tokamak experiments are usually conducted with small amounts of these elements relative to the deuterium fill. Optical detection in a commercial Penning gauge[1,2] of the characteristic atomic line emission produced by electron excitation has been employed to deduce the concentrations of these gases in the divertor plenum of several tokamaks.[3–7]

The sensitivity of the Penning gauge technique is limited by contamination of the measured signal with light from molecular deuterium, the vibrational-rotational spectrum of which forms a quasi-continuum at resolutions greater than 0.1 nm. When bandpass filters are used in the visible range, more light from molecular deuterium than from the gas of interest may pass through the chosen spectral bandpass. This background may be cancelled out by differential measurement of the signals in two close-lying spectral windows. Though this technique works well for gases with a single bright atomic line or atomic multiplet, it does little to improve the sensitivity limit for neon, a gas for which the atomic spectrum is comprised of numerous lines, with no single one dominant. The Penning gauge system on the lower divertor of the DIII–D tokamak has a detection limit for neon of 5×10^{-5} bar, compared with 2×10^{-6} bar for helium and 1×10^{-8} bar for argon.

In order to improve sensitivity to neon, an “active spectrometer” (U.S. Patent 5,675,411 and pending U.S. Patent S/N 08/838,298) has been applied to detection of the light produced in the Penning gauge. The active spectrometer repetitively scans a narrow spectral region at high resolution, permitting observation of a given emission line and its adjacent spectral background. For the case of a trace amount of neon in deuterium, measurement of the neon partial pressure is feasible even when the intensity of the neon line is only a fraction of that from molecular deuterium integrated over the width of the spectral scan region.

II. EXPERIMENTAL APPARATUS

The experimental setup is show schematically in Fig. 1. A commercial Penning gauge (Alcatel Model FA 101) serves as a volume source of trapped electrons which excite line emission characteristic of the neutral species of the noble gas. Viewed end on, the emission inside the magnetic trap forms an oval area, roughly 6 mm × 20 mm, centered about the median plane of the 75 mm-long gauge head. A video lens images this light onto a quartz fiber bundle containing ten 600-μm-core fibers arranged in a 2×5 rectangular array, with the axes of the fibers parallel to that of the gauge head. The same ten fibers form a single column in the bundle's output tip, which is butted against the spectrometer entrance slit.

The active spectrometer is a 1/4-meter-diameter, Rowland circle instrument[8] with a 1200 G/mm, aberration-corrected, holographic grating. It contains six exit slits distributed along its curved focal plane. The entrance and exit slits are both set to 100 μm, giving a triangular instrumental profile with a full width, half maximum (FWHM) of roughly 0.3 nm. This FWHM represents a tradeoff between optimizing spectral resolution and maximizing light throughput. A fiberoptic ribbon 200 μm wide couples each slit to a separate photomultiplier (PMT). To obtain high quantum efficiency in the red region of the spectrum, side-on phototubes with opaque GaAs photocathodes are employed. The slits are positioned to detect the brightest lines of neutral deuterium, helium, neon, argon and krypton lying between 400 and 850 nm, with three of the slits located so as to detect lines from two different elements during the 3 nm-wide spectral scan of the spectrometer. Table I lists the lines encompassed by each of the six channels.

A galvanometer mirror scanner situated between entrance slit and grating is driven with a sinusoidal waveform generated under PC control by a data acquisition (DAQ) board with both analog input and analog output channels. An audio amplifier in series with the DAQ board output prevents distortion of the sinusoidal waveform under inductive load of the galvanometer. The mirror motion causes a repetitive oscillation of the dispersed spectrum relative to the array of fixed exit slits. The wavelength of the light passed by each slit varies sinsusoidally in time and a temporal correlation exists between the wavelength and the intensity of the light detected by the photomultiplier coupled to the slit. After amplification, the photomultiplier signal is digitized by the DAQ board with a sampling frequency which is an integral multiple of the mirror drive frequency. As a result of the digital phase locking produced by this integer ratio, data from successive mirror scan cycles may be averaged together to improve photon statistics and reduce noise. For the present studies, the mirror scanner was driven at 500 Hz and the PMT signals were sampled at 50 kHz. The high pass filter between PMT and amplifier in Fig. 1 is designed with a cutoff frequency below that of the mirror scanner. Because the signal due to a spectral feature is

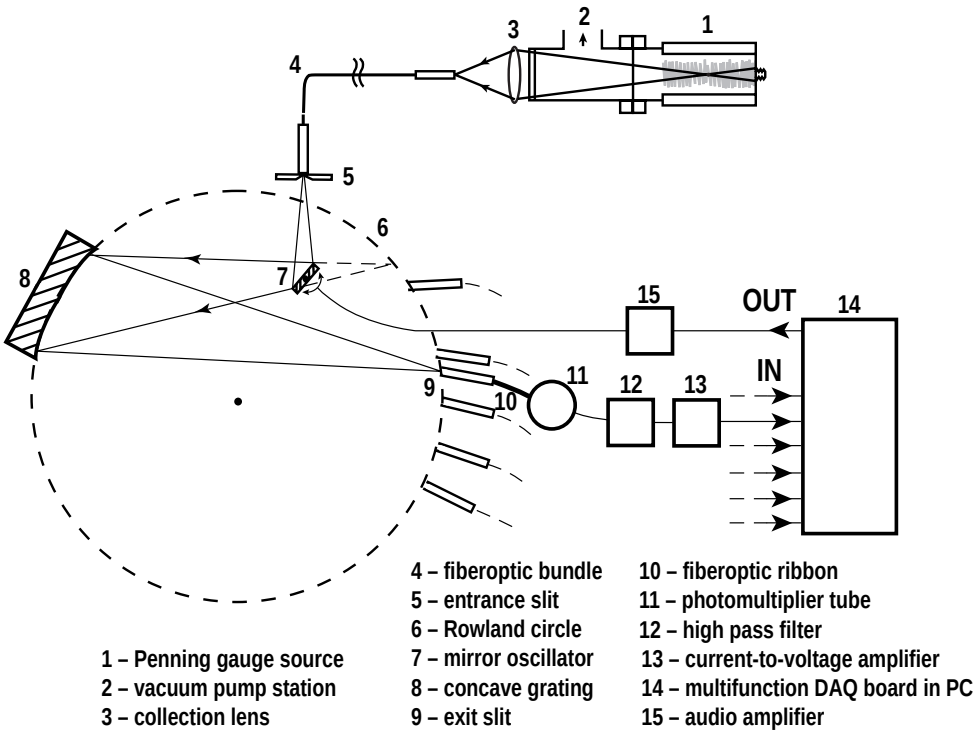

Fig. 1. Schematic of experimental setup: atomic line emission produced by electron impact excitation in the Penning gauge (1) is imaged onto a fiberoptic bundle (4) which conveys the light to the active spectrometer (5–15).

modulated while that due to continuum is not, the high pass filter rejects continuum radiation and permits observation of weak lines in the presence of intense continuum light. Its use was not required in the present work, because continuum radiation is weak in the cold-cathode Penning gauge discharge and, consequently, saturation of the amplifier is not a concern.

Figure 2 illustrates the correlation between wavelength and signal intensity on the argon detector (channel 6 in Table I) with pure argon gas fill in the Penning gauge. In each scan of the mirror, the wavelength of the light passed by the exit slit varies sinusoidally. Consequently, each component of the Ar I multiplet appears twice, once during the negative going sweep in wavelength and once during the positive-going. Since wavelength changes more slowly at the top and the bottom of the sine curve, the spectral line profiles of lines close to the wavelength of the mirror turning points are asymmetric. The Ar I 810.3 line profiles are clearely stretched out on the short wavelength side, closest to the mirror turning points. In Fig. 2(b), the intensity is replotted versus wavelength by replacing the independent coordinate t by sin(ωt). Within the accuracy of the display, both the 810.3 and 811.5 lines appear symmetric. The intensity trace displayed in Fig. 2 is the result of averaging 5,000 mirror scans (10 s).

Table I
Six detector channels of active spectrometer

No.	Center Wavelength (nm)	Spectral Lines in Scan Range		
		1st Gas	2nd Gas	3rd Gas
1	486	DI 486.0		
2	587	Ne I 585.3	He I 587.6	
		Ne I 587.3		
3	640	Ne I 638.3		
		Ne I 640.3		
4	656	D I 656.1		
5	705	Ne I 703.2	He I 706.5	
6	811	Ar I 810.3	Kr I 810.4	Ne I 811.8
		Ar I 811.5	Kr I 811.3	Ne I 812.9

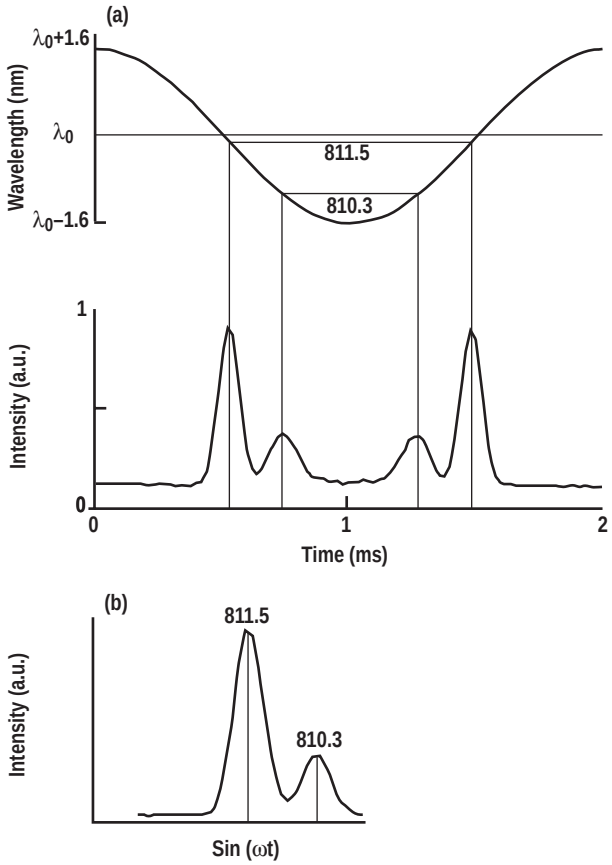

Fig. 2. (a) Plot of wavelength (upper curve) and intensity (lower curve) passing through the exit slit of channel 6 (argon multiplet at 8115) versus time within a single scan period of the oscillating mirror, and (b) Plot of intensity versus sin(ωt).

III. STUDY OF LIGHT EMISSION FROM THE PENNING GAUGE

Dependence of light emission on fill pressure in the Penning gauge was first studied with pure gases. As shown in Fig. 3, the neon intensity on channel 1 increases monotonically with the fill pressure of pure neon over the pressure range from 10^{-6} bar to 10^{-3} bar. The D_α intensity on channel 3 increases with the pressure of pure deuterium in a similar fashion. In a mixture of neon and deuterium with the neon partial presssure fixed at 4×10^{-5} bar, the neon intensity is constant as deuterium pressure is varied from 1×10^{-6} bar to 1×10^{-3} bar.

Saturation of the Penning gauge's I-V characteristic becomes evident as the deuterium fill pressure is raised to 1×10^{-2} bar, one order of magnitude higher than that plotted in Fig. 3. While the ion current approaches an asymptotic level, the D_α line emission passes through a maximum and then declines. With its partial pressure fixed at a trace level, the intensity of the neon line in channel 1 also falls. To avoid this behavior, the pressure in the Penning gauge on the lower divertor of DIII–D is maintained below 1×10^{-3} bar by means of differential pumping. With divertor plenum pressures in DIII–D as high as 3×10^{-2} bar in high density discharges, the differential pumping system must provide a pressure reduction greater than a factor of ten.

Small concentrations of neon in a mixture with deuterium may be accurately measured by fitting the shape of the composite spectrum produced by the limited spectral scan of the active spectrometer. Figure 4 illustrates the procedure. Reference spectra for pure neon and pure deuterium are digitally recorded for the spectral region spanned by each neon channel. Only channel 1 is shown in Fig. 4(a). These spectra are recorded with low noise by averaging many

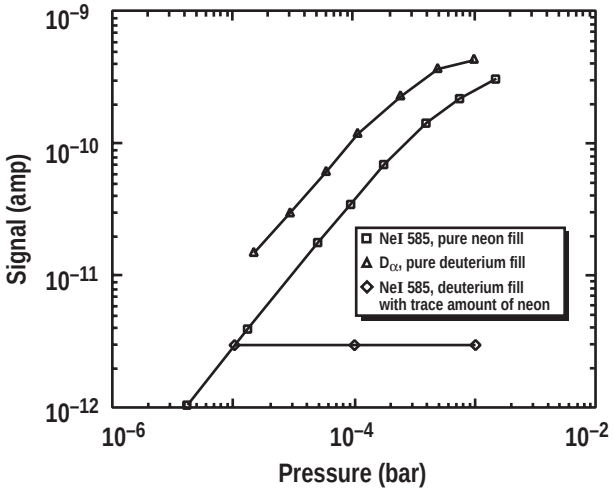

Fig. 3. Pressure dependence of light emission (a) Intensity of Ne I 585 line versus p(Ne), (b) Intensity of D_α versus $p(D_2)$, and (c) Intensity of Ne I 585 and D_α with p(Ne) fixed and $p(D_2)$ varied.

mirrors scans. The neon trace in Fig. 4(a) represent 25,000 mirror scans (50 s); the deuterium trace 100,000 mirror scans (200 s). Both spectra were measured at a fill pressure of 1×10^{-3} bar, this value being the pressure shown on the front panel meter of the Penning gauge controller without correction for the dependence of ion current on gas species. Note that the peaks in the deuterium spectrum are molecular features; atomic deuterium has no lines in this spectral range.

The composite spectrum due to an admixture of neon and deuterium is shown in Fig. 4(b); the data points represents an average over 5,000 mirror scans (10 s). A least squares fit to the measured data with a linear combination of the two reference spectrum yields a Ne/D_2 concentration ratio of 0.3% [p(neon) = 3.0×10^{-6} bar and p(deuterium) = 1.0×10^{-3} bar]. The fit closely matches the measured data points. Fig. 4(c) shows a measurement of the the same mixture averaged over only 50 mirror scans (0.1 s). Shot noise in the detector leads to a large scatter of the data points. Nevertheless, least squares fitting of the data for each of the hundred successive 0.1 s intervals in the 10 s long period of data acquisition yields p(neon) = 3×10^{-6} bar $\pm$ 1×10^{-6}, with the scatter about the 10 s average shown in Fig. 4(d). The neon partial pressure detected with the aid of the active spectrometer here is a factor ~20 improvement over that achievable with the present Penning gauge diagnostic on the lower divertor of DIII–D.

An attempt was also made to measure partial pressures by optical detection of light from an ASDEX high pressure ionization gauge.[9] This work was motivated by the fact that the ASDEX gauge, unlike the Penning gauge, may be operated inside the tokamak vessel in the strong toroidal magnetic field. If a measurement of the partial pressure was determined to be feasible using an ASDEX gauge, then measurements would be practical at the inner divertor plenum, which by virtue of poor conductance to external ports is inaccessible to measurement by the Penning gauge approach. Unfortunately, the single pass nature of the electron trajectory in the ASDEX gauge results in optical emission which is several orders of magnitude lower than in the Penning gauge. Although rejecting scattered light from the hot filament proved no problem for the active spectrometer, time resolutions of relevance to tokamak discharge durations seemed unachievable and the ASDEX gauge was abandoned in favor of the Penning gauge approach.

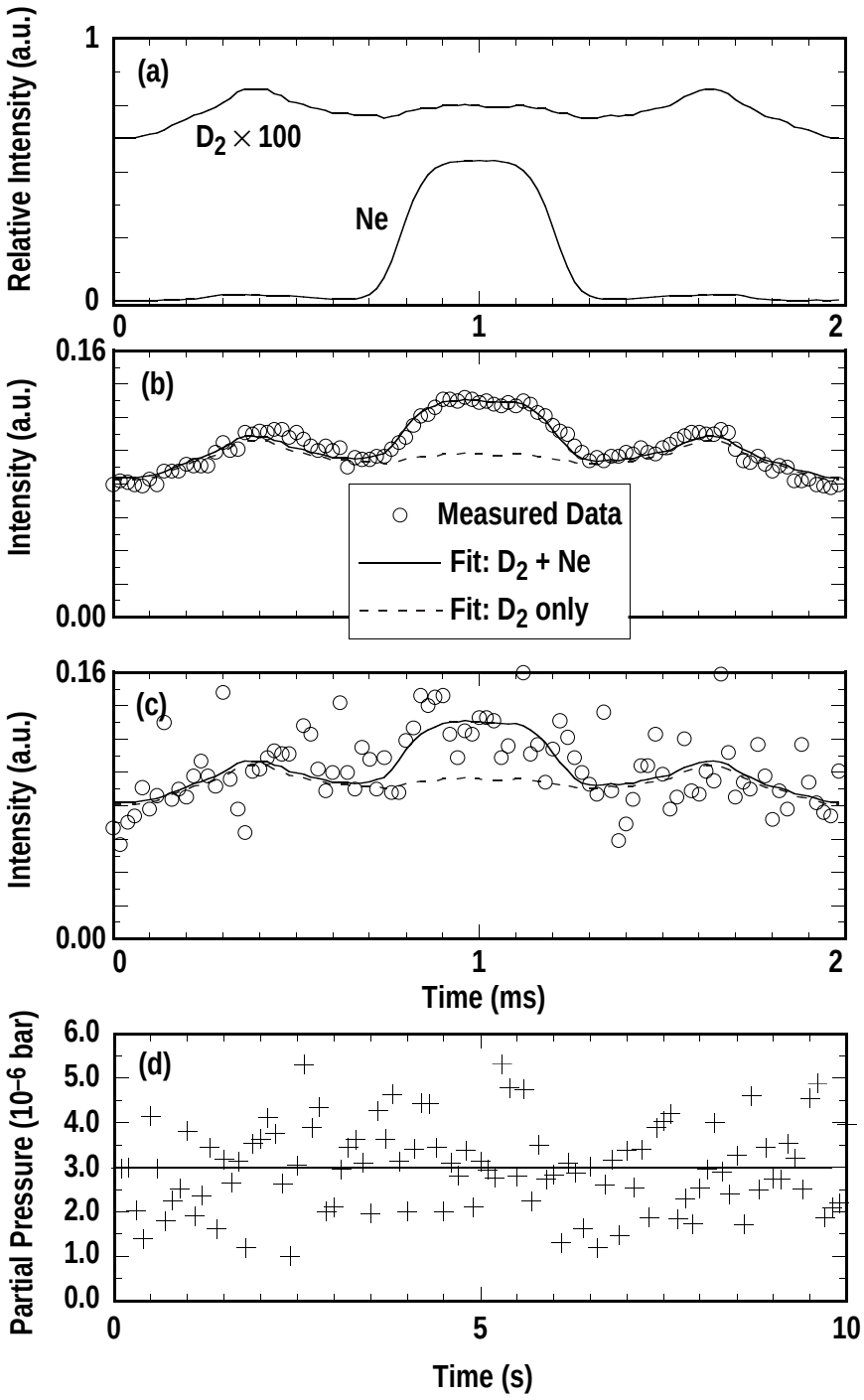

Fig. 4. Use of Ne and D_2 reference spectra in the analysis of measured data from a Ne/D_2 mixture (a) digitally stored intensity profiles of neon and molecular deuterium versus time within a scan period, (b) least squares fit to measured data scan-averaged over 10 s of a linear superposition of Ne and D_2 reference spectra, (c) least squares fit to data scan-averaged over 0.1 s, (d) scatter in the neon partial pressure for data scan-averaged over 0.1 s.

IV. SUMMARY

A significant improvement in sensitivity for measurements of partial pressures has been demonstrated by application of an active spectrometer to the optical detection of atomic line emission in a Penning gauge. The success of the technique relies on least-squares fitting of the measured data with a simulated spectrum comprised of a linear superposition of digitally stored reference spectra. The fit is performed over a range in wavelength that includes both the characteristic atomic line and its spectrally adajacent background.

In a long pulse discharge device, such as Tore Supra, lower concentrations than that shown in the present paper should be achievable by averaging a larger number of mirror scans.

If a Penning gauge is installed in the foreline of a vessel turbopump, optical detection of argon with an active spectrometer can provide a continuous measure of the global leak rate. Because the active spectrometer permits averaging over indefinitely long periods of time, global leak rates as low as 1×10^{-7} bar may be readily measured from the argon present in an air leak (1%) without isolating the vessel from its pumping system. The same combination of active spectrometer and foreline-mounted Penning gauge may be used to perform helium leak checking in the presence of high levels of deuterium.[10]

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