JET–R(97)08

Prospects for Determining the D-T Isotopic Ratio in the JET Plasma by Spectroscopic Observation of a Penning Discharge

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Abstract

Simulated spectra of the Balmer D_α and T_α lines from a Penning discharge in a D-T mixture have been used to assess the potential of the technique in determining the isotopic ratio in the JET divertor neutral gas. Results from measurements in a D-H mixture, with a spectrometer and CCD camera as detector, were used as starting point. The results of repeated multi-Gaussian fits to synthetic spectra, to which random noise had been added, were analysed to evaluate the errors in determining the T/D ratio, for a range of tritium concentrations. It is concluded that T/D ratios of 0.5% can be measured, with an uncertainty of ~ +/- 50% and time resolution 3s, whilst for a 1:1 D-T mixture an uncertainty of +/- 10% is achievable with time resolution ~100 ms. The equipment to make this measurement during JET D-T operation has been installed.

Introduction

A good knowledge of the D-T isotopic ratio in a tokamak plasma is an aid to optimising fusion power. There are no direct measurements that can be made on the plasma core, although the ratio can be measured in the plasma scrape-off layer by spectroscopic observation of the Balmer D_α and T_α lines. However, their close proximity in wavelength ($\Delta\lambda$ ~ 0.06 nm) makes line separation difficult at low ratios of T/D, because of blending due to Doppler broadening. This may be overcome by using a Penning discharge to analyse the spectrum of the gas exhaust from the divertor; the low temperature of the discharge leads to reduced broadening. The technique will be used at JET during the D-T campaign, DTE1, to measure the isotopic ratio in the divertor neutral gas, using a grating spectrometer and CCD camera for detection.

In this paper we present the results of applying a multi-Gaussian fit to synthetic D-T spectra, to determine the intensities of the D and T components. The results of measurements on a Penning discharge in a D-H mixture were used as a basis for generating the synthetic spectra. Noise was added randomly to them, both shot noise due to statistical fluctuations of the signal and readout noise. Spectra representing a range of D-T mixtures have been analysed, to quantify the errors inherent in determing the T/D ratio.

Method

A number of results from spectroscopic analysis using a Penning gauge have already been reported by several workers [1-4]; a brief resume of the salient features is given here. The pressure range over which measurements can be made is ~ 10^{-5} to ~$3x10^{-3}$ mb. Over this range, the light intensity from the Penning discharge varies linearly with the pressure of the gas (or gas mixture) being studied. At lower pressures the light intensity becomes too weak for useful purposes, whilst at higher pressures there is a transition to an arc discharge and non-linearity.

A Penning gauge has been used to make measurements on a D-H mixture in a test rig. The detection system comprised a 1-m spectrometer, equipped with a grating ruled at 1800 l/mm, and a Peltier-cooled CCD camera. Its spectral resolution was 0.011 nm/pixel at 656.1 nm, with an instrumental function of 0.016 nm using an entrance slit width of 50μm. The camera was capable of operating at a repetition rate of up to 25 Hz. The light from the Penning gauge was collected by an achromat lens and transported to the detection system by a PCS optical fibre, of core diameter 1 mm and length about 50 m. A similar arrangement will be used on JET.

The spectrum from a mixture of H_2 and D_2, Figures 1 and 2, reveals that each Balmer-α line is well fitted by two Gaussian components, one of energy ~4.5 eV and the other of energy ~0.3 eV - once account has been taken of the instrumental function of the detection system. This is because there are ten, or more, distinct channels for the dissociation of the hydrogenic molecules into atoms [5], which energy-wise fall into two separate groups. Each of the two components represents an average energy for the atoms in that group. The width of the hot and cold component for each species is remarkably constant with pressure, over the range of pressures utilised, Figure 3.

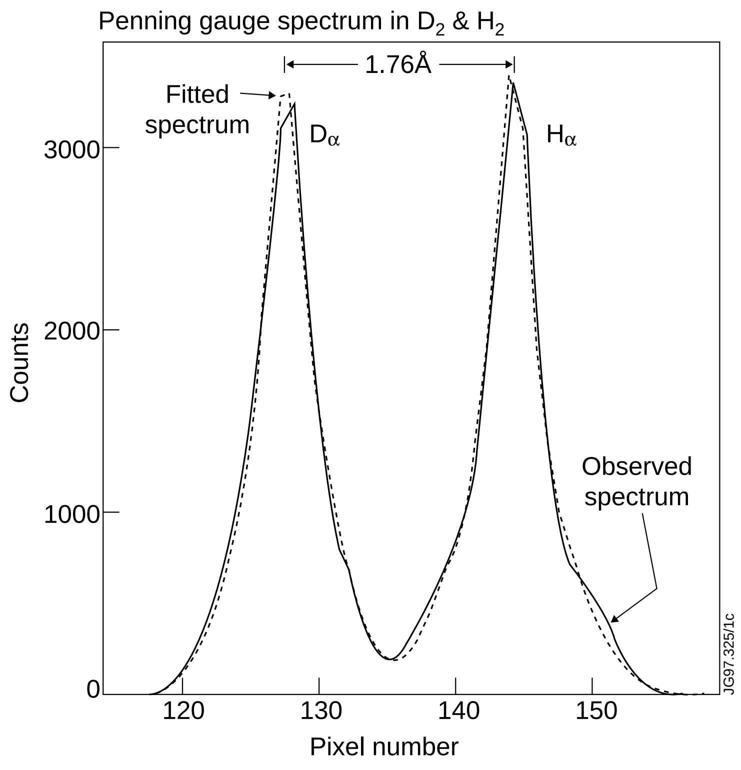

Figure 1: Penning-gauge spectrum from a mixture of D_2 and H_2, recorded with a grating spectrometer and CCD camera (solid line). The dotted line shows a multi-Gaussian best fit to the recorded spectrum.

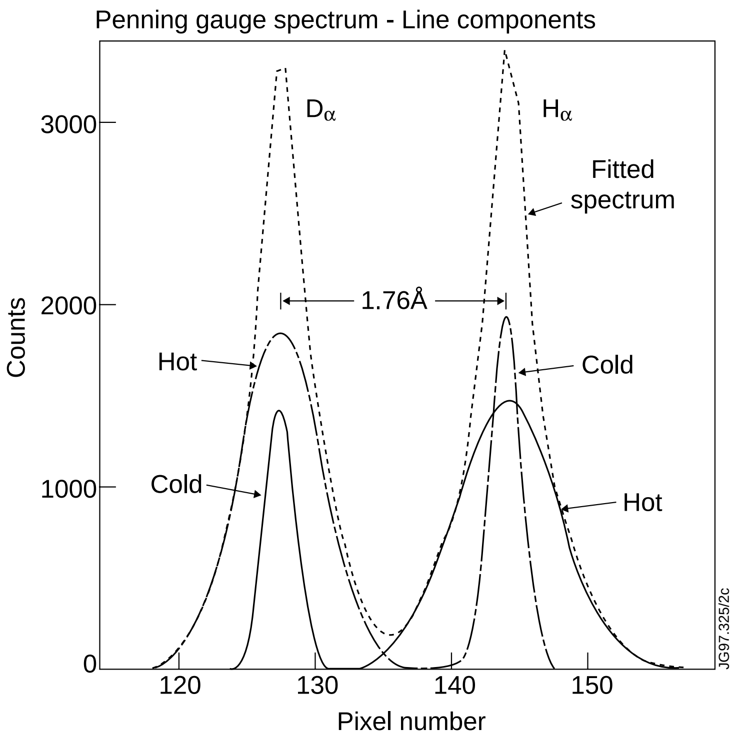

Figure 2: The four individual components of the multi-Gaussian fit shown in the previous figure.

In addition, the ratio of the cold-to-hot component intensities is constant for pressures greater than ~4x10^{-5} mb, being ~1.5 for H_2 and ~0.7 for D_2, Figure 4. At lower pressures, both ratios tend towards unity as the pressure is reduced to 1x10^{-5} mb.

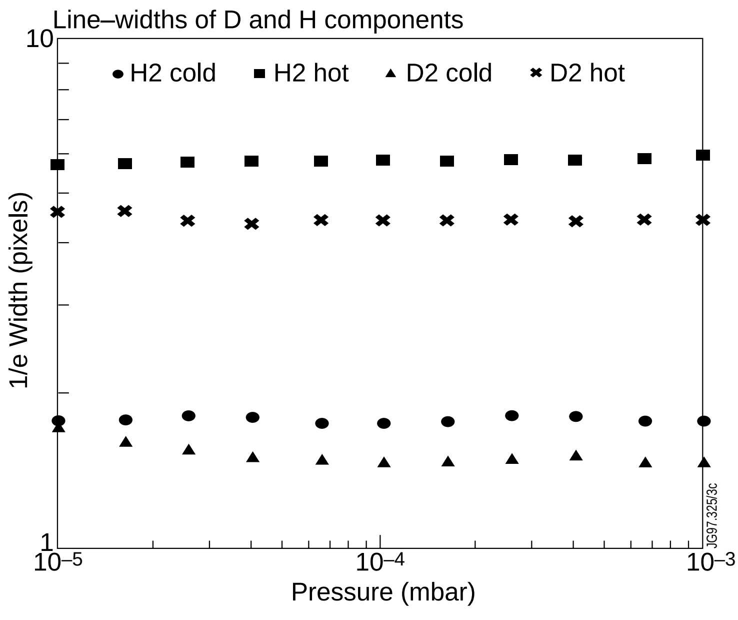

Figure 3: Line widths of the "hot" and "cold" spectral components from a Penning discharge (in pixels), versus pressure, for D_2 and H_2.

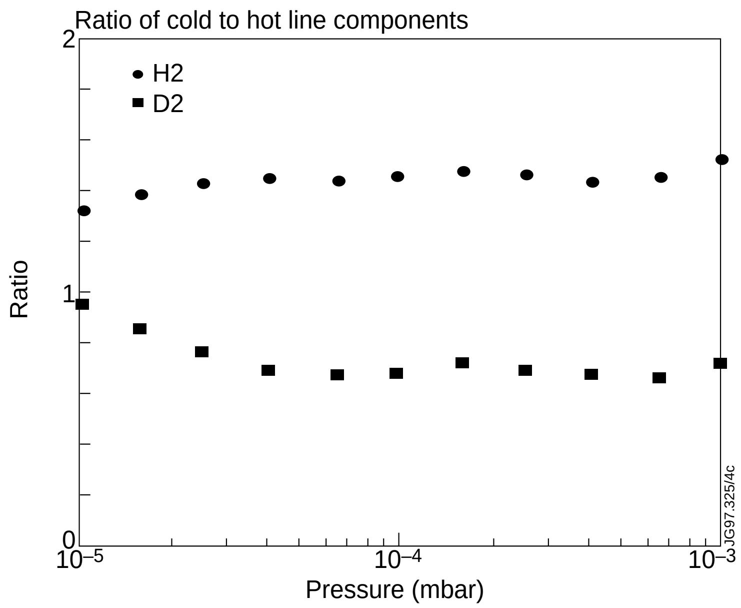

Figure 4: Ratio of "cold" to "hot" peak intensities from a Penning discharge, as a function of pressure, for D_2 and H_2.

The results from the measured D-H spectra have been used to generate synthetic D-T spectra, appropriate to the detection system in use, for seven T levels ranging from 100% of the D level to 0.5%. The line widths of the various components were scaled inveresly as the square root of the species atomic mass. This had been established from the measurements on H_2 and D_2. The ratio of the cold-to-hot line components for tritium was taken to be the same as for deuterium, viz 2:3. A noise-free spectrum for each mixture was constructed by summing the hot and cold Gaussian components for all the hydrogenic species. A peak intensity of 2000 counts was maintained in the pixel corresponding to the D_α line centre, for all D-T mixtures. Moreover, a hydrogen level of 10% of the level of the other species was set - with a ratio of cold-to-hot line components of 3:2 - as a residual quantity of hydrogen is invariably present in JET plasmas. The natural linewidths chosen, for each species, were 4.5 eV for the hot component and 0.3 eV for the cold, which were then convolved with the instrumental function of the detection system.

Shot noise was added to the noise-free spectra. The shot noise, from the statistical fluctuations in the current generated in a detector due to an incident photon flux, follows a Poisson distribution. Consequently, each point in a noise-free synthetic spectrum was used as the mean for input into a numerical Poisson random number generator [6], together with an unique "seed" number, which produced a string of 50 random numbers distributed about the input mean. These random numbers were combined to produce 50 separate "noisy" spectra, differing only in their random shot noise contributions. The intensities of the T_α and D_α lines in each noisy spectrum were determined using a multi-Gaussian fit to that spectrum, based on the minimization of the parameter "chi-squared" using the Levenberg-Marquardt method [6]. The positions of the line centres and

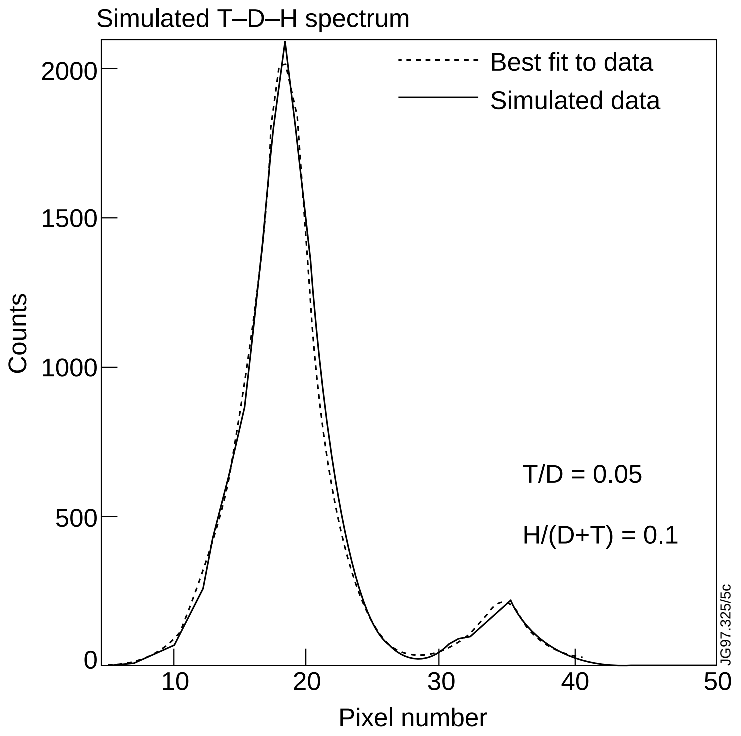

Figure 5: Simulated spectrum for a mixture of D_2, H_2 and T_2 in a Penning discharge (solid line). The dotted line shows a multi-Gaussian best fit to the synthetic spectrum.

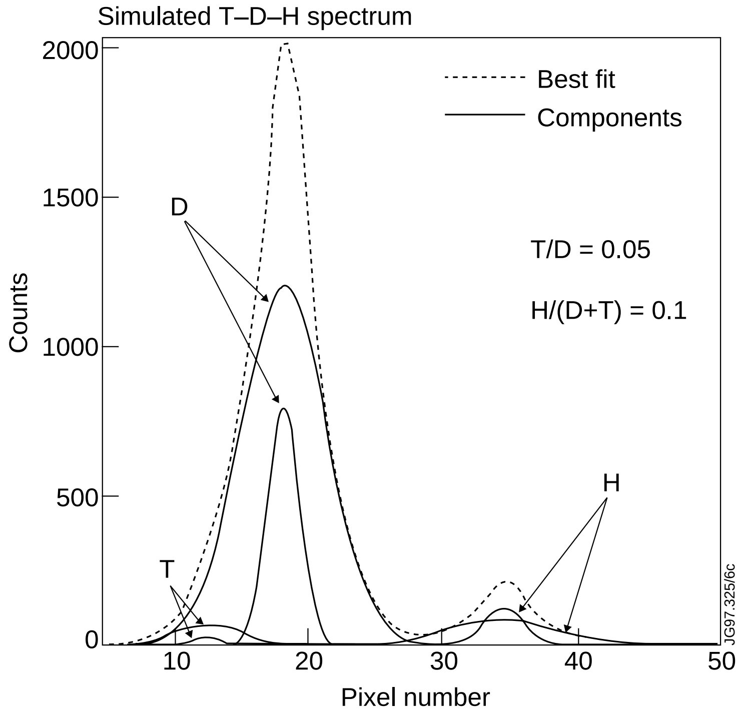

Figure 6: The six individual components of the multi-Gaussian fit shown in the previous figure.

the line widths of the various components were fixed, allowing only the peak intensities to be varied as free parameters to obtain the best fit. The process was repeated for each D-T mixture considered. Figure 5 shows an example of a synthetic spectrum for a T/D ratio of 0.05, along with the best six-Gaussian fit. In Figure 6, the individual Gaussians in the best fit are shown separately.

Discussion

An analysis was performed on the results of the fitting. For each of the seven D-T mixtures, from the 50 spectra the average intensity of each line component was obtained, along with its standard deviation. It was found better to combine the intensities of the hot and cold components for each of the 3 species, as this led to a reduced standard deviation. In essence, if the intensity of the hot component is overestimated the intensity of the cold component tends to be underestimated, and vice versa. Taking the sum of the two components cancels out part of the error.

The relative error (standard deviation / average value) in determining the T/D ratio is plotted against signal-to-noise ratio in Figure 7. The S/N ratio is defined as the mean value from 50 samples of the counts in the pixel at the T_α line centre, N, divided by the standard deviation of the mean due to shot noise, S_s. In situations where the detection process is governed by Poisson statistics, as is the present case, the standard deviation $S_s = \sqrt{N}$. Thus, the S/N ratio is given by $N / \sqrt{N}$.

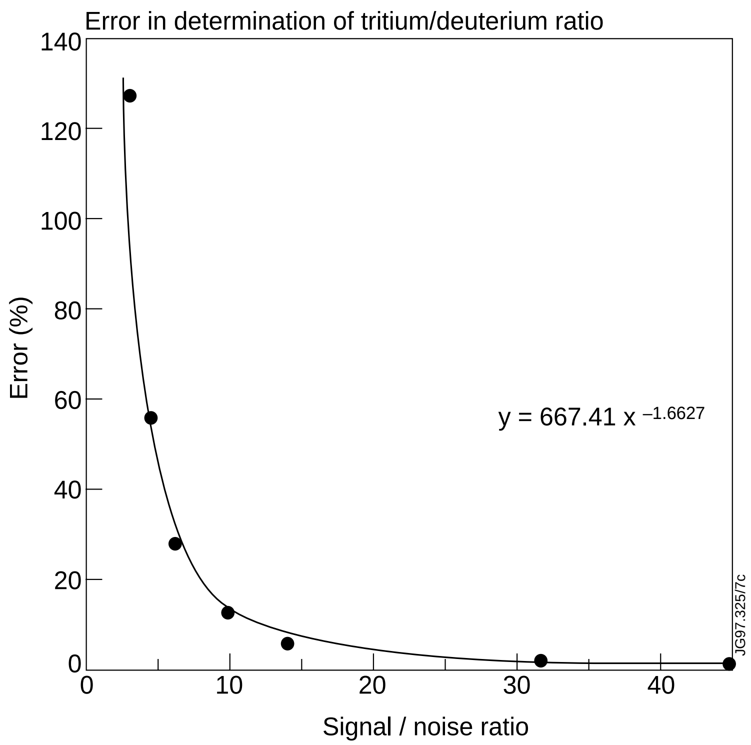

Figure 7: Simulated relative error in the determination of the T/D ratio versus signal-to-noise ratio.

The graph in Figure 7 shows that the error gradually decreases from 6% at a signal-to-noise ratio of 15 to ~1.3% at a value of 45, but increases dramatically with decreasing S/N ratios below 15. For a S/N ratio of ~ 3 the relative error is almost 130%. Above a S/N ratio of 25 there is little improvement with increasing ratio. The data are well fitted by a power curve of form $y = a.x^b$, where a = 667.4 and b = –1.663.

In addition to shot noise there is also noise associated with the readout process. This takes the general form of an offset Gaussian of mean value of order 25, with standard deviation S_r, of order 10. Noise spectra, from exposures without light on the detector, have been added at random to the synthetic spectra and the fitting process repeated. The results follow closely the power curve shown in Figure 7, except that for a given photon flux N with standard deviation S_s, the signal-to-noise ratio is degraded from N / S_s to $N / \sqrt{[S_s^2 + S_r^2]}$. At high values of the S/N ratio the contribution of the electronic noise is not significant but at low values of the ratio the noise dominates, resulting in a significantly larger error. The effect of dark current can be neglected as the CCD chip is cooled to ~ 200K.

To put the above onto a more quantitative footing, the exposure times needed to achieve a specified accuracy for a range of T/D ratios were calculated. From measurements on the test rig, it was established that an exposure of 0.5 s was needed to register 20,000 counts in the pixel at the D_α line centre, at a D_2 partial pressure of 10^{-3} mb in the Penning discharge. The detected signal varies linearly with pressure, within the operational limits set by the gauge, and with exposure time.

Using this information and the relationship between error and S/N ratio, in Figure 8 the exposure times needed are plotted against the required accuracy for a range of T/D ratios, at a total pressure of 10^{-4} mb. This is the anticipated pressure in the Penning gauge sampling the JET exhaust, for discharges with high levels of additional heating power. Assuming that an error of about 50% is the maximum permissible, Figure 8 shows that for a T/D ratio of 0.005 an exposure time of 3s is required, whilst for a ratio of 1 the same accuracy can be achieved with an exposure time of 30ms. Obviously, there is a trade-off between the desired time resolution and the achievable accuracy in determining the ratio. High time resolution tends to lead to low accuracy, and vice versa. In practice, the shortest exposure time on JET will be ~100 ms, set by the conductance of the Penning gauge vacuum system, whilst exposures longer than 10s will be unlikely, the maximum duration of the heating phase.

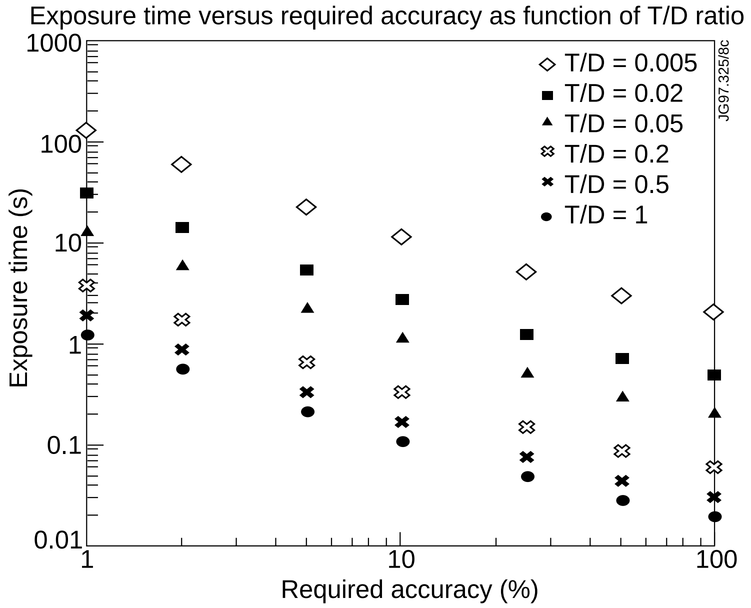

Figure 8: Dependence on exposure time of accuracy in determined T/D ratio, as a function of that ratio, from simulation. The effects of readout noise have been included, as well as those of shot noise.

Summary and Conclusions

By using a Penning discharge to analyse the exhaust gas from a tokamak operating with a D-T mixture, easy separation of the Balmer D_α and T_α lines may be achieved, even at low T/D ratios, because thermal broadening is restricted. This offers the prospect of measuring the T/D ratio over a wide range of T concentrations. Results from spectroscopic observations of the Balmer D_α and H_α lines in a Penning discharge, recorded using a 1-m grating spectrometer and CCD camera, have been used to synthesise the spectrum in the case of a D-T mixture. Noise was added to the synthetic spectra, generated for seven T/D ratios ranging from 1 to 0.005. The noise comprised both shot noise, from statistical fluctuations in the detected light signal, and electronic noise, due to the readout process in the CCD camera.

A multi-Gaussian fit was then performed to 50 “noisy” spectra generated for each of the seven D-T mixtures. For each mixture, the spectra differed only in their random noise components. The mean intensities of the D and T component, along with their standard deviations, were used to evaluate the error in determining the T/D ratio as a function of that ratio, for various light intensities on the CCD chip. It is concluded that T/D ratios of 0.5% can be measured, with an uncertainty of ~50% and time resolution 3 s, whilst for a 1:1 D-T mixture an uncertainty of 10% is achievable with time resolution ~100 ms. The results established during the simulation work described here will be of use in error assessment when interpreting experimental results.

This technique will be employed at JET during the D-T campaign, DTE1, to measure the isotopic ratio in the gas exhaust from the divertor, using the equipment described above [7]. The Penning gauge is situated ~3.5 m below the divertor in a pumped tube attached to the sub-divertor volume. Although not directly related to this study, a gas calibration sytem is attached to the diagnostic to enable in-situ calibration of the Penning-gauge emission-line intensities as a function of gas composition and pressure. The partial pressures determined for the D_2 and T_2 during plasma operation may then be related to the pressures in the divertor, using modelling and calculations based on the appropriate flow regime [8, 9]. In conjunction with other diagnostics, the Penning gauge can be used to study such processes as the transport and recycling of hydrogen isotopes, tritium removal from the vessel wall by cleaning discharges, the removal of particles by the divertor pump and divertor retention and compression.

Acknowledgements

The authors are grateful to J Ehrenberg and to D L Hillis for many illuminating discussions, and to T Denner and G Wilpers for assistance with the measurements. V Kumar also gratefully acknowledges financial support during his six-month stay at JET from the Department of Science and Technology, Government of India, under the BOYSCAST Fellowship Scheme (1996 - 1997).

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